Optimization of intermittent aeration for increased Nitrogen Removal Efficiency
And
Improved Settling

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ABSTRACT

Nitrogen, when present in excess, can cause eutrophication in waterways, which may result in hypoxia and the desertion or death of aquatic life. As nitrogen continues to pollute our water, wastewater discharge limits are becoming more stringent with effluent limits based on preserving receiving waters.

This project took place at the Hampton Roads Sanitation District's, Chesapeake-Elizabeth Wastewater Treatment Plant; a High-Rate Activated Sludge (HRAS) plant with no primary clarifiers operating at an SRT of 1.5 – 2 days without biological nitrogen removal (BNR). BNR is considered more cost-effective than comparable chemical and physical processes, but it requires considerable resources to meet increasingly strict discharge limits. As these limits decrease, the resource requirement increases, making them no longer cost-effective. By 2021 HRSD anticipates the plant will be included in a bubble permit, resulting in a total nitrogen (TN) effluent target of approximately 5-8 mg/L. Conventional BNR plants remove carbon and nitrogen simultaneously, which requires both increased volume (capital costs) and aeration energy demand (operating costs). As an alternative, HRSD is pilot testing an A/B process; a two-sludge system comprised of a carbon removal stage followed by a nitrogen removal stage. The very high rate, low dissolved oxygen (DO) A-stage could reduce the organic load, allowing the B-stage to perform BNR within the existing reactor volume and eliminating the need for primary clarifiers. However, improper control of the carbon removal system can lead to carbon and alkalinity deficiencies, which results in poor nitrogen removal. This is mediated by employing a short-cut nitrogen removal technology.

A novel aeration strategy based on set-points for reactor ammonia, nitrite and nitrate concentrations with the aim of maintaining equal effluent ammonia and nitrate + nitrite (NO_x) concentrations was successfully employed. The goal was to inhibit nitrite-oxidizing bacteria (NOB) so the nitrification process stopped at nitrite. This helps promote an effluent with equal parts ammonia and nitrite, which is amenable to anammox polishing to achieve low effluent nitrogen concentrations. NOB suppression has been successfully applied in sidestream anaerobic digestion waste streams because NOB out-selection is favored in warm, nitrogen-rich conditions. However, the cold, dilute conditions of continuous mainstream processes are not favorable to NOB out-selection. The mechanisms employed to achieve sidestream NOB out-selection are not reasonable for mainstream applications. This study employed operational and process control strategies to aggressively out-select NOB based on optimizing the chemical oxygen demand (COD) input, imposing transient anoxia, aggressive solids retention time (SRT) operation approaching ammonia oxidizing bacteria (AOB) washout, and a dissolved oxygen concentration (DO) of 1.5 mg O_2/L during aeration. This pilot-scale study demonstrated that when run aggressively, the proposed online aeration control is able to out-select NOB in mainstream conditions and provide relatively high nitrogen removal without supplemental carbon and alkalinity at a low hydraulic retention time (HRT). Successful full-scale implementation would promote improved water quality that is economically sustainable.

The ability of two different process configurations (full intermittent aeration and Modified Ludzak-Ettinger [MLE]) to achieve high nitrite accumulation and nitrogen removal efficiencies in four equal volume tanks in series followed by a cone-bottom clarifier in a pilot scale biological nitrogen removal (BNR) process ($V=0.61\ m^3$) was evaluated. All four biological reactors were equipped with a variable speed mixer, a 17.7 cm membrane disc diffuser, and a Hach LDO probe. Aeration capacity in all four tanks allowed the system to be operated with or without a defined anoxic zone. Both processes utilized a novel aeration strategy based on set-points for reactor ammonia, nitrite and nitrate concentrations with the aim of maintaining equal effluent ammonia and NO_x concentrations. The B-stage had a variable HRT (2-7 hours) and a variable influent flow rate. When operating in the MLE configuration, an internal mixed liquor recycle (IMLR) line returned nitrified mixed liquor from the last aerobic reactor to the anoxic reactor using a peristaltic pump at a rate between 200-450% of the influent flow. When IMLR was used the first tank was not aerated. RAS from the clarifier was returned to the anoxic zone at 100% of the influent flow. SRT was controlled by wasting solids from the last aerobic tank. The wasting was automated to maintain desired SRT.

The nitrite accumulation ratio (NAR), NO_2^--N/(NO_2^--N+ NO_3^--N), was best under full intermittent aeration, achieving 0.43±0.10 at a 3 hour HRT and influent carbon to ammonia ratio (COD/NH_4^+-N) of 7.9±1.4. As an MLE, the NAR decreased with increasing internal mixed liquor return (IMLR); at IMLR of 200%, 325% and 450%, the NAR was 0.20±0.04, 0.17±0 and 0.14±0.03, respectively. The MLE did, however, improve the overall TIN removal efficiency compared to operation where all reactors were intermittently aerated. The TIN removal efficiency was best

under MLE operation, increasing as the IMLR and influent COD/NH_4^+-N increased. When the IMLR was 200%, 325% and 450%, the TIN removal efficiencies were 76.4±4.0%, 80.2±0% and 86.3±5.0%, respectively, which corresponded to an influent COD/NH_4^+-N and HRT of 9.2±0.8 and 4 hr, 9.8±0.4 and 6 hr, and 10.3±1.2 and 6 hr, respectively.

In addition to process operation, key issues of filamentous bulking were assessed. Concrete solutions to this continual issue are not available as the unique features of each plants influent and process dynamics prohibit the formulation of a universal solution. Filaments observed throughout this study included Type 0041, Type 0675, Type 0803, *Nocardia*, *Thiothrix* I and *Thiothrix* II. Type 0041 and Type 067 were observed throughout the study and are typical of BNR systems; they arguably do not contribute to settling issues. Type 0803 filaments are linked to low F/M, high SRT systems. It was present at the start of the experiment and then no longer detected. *Nocardia* made a brief appearance on day 72 causing temporary foaming issues. This was fixed by vacuuming the surface of the clarifier daily and may be attributed to the high surface area to volume ratio present in pilot-scale systems. *Thiothrix* I and *Thiothrix* II were observed after day 93, however, never as the dominant species. *Thiothrix* related bulking was observed in the A-stage (Miller et al, 2012), which was attributed to high sulfide and organic acids in the influent raw wastewater during high temperature periods and carryover of sulfide and *Thiothrix* from the over-sized A-stage clarifier. The goals of this evaluation were to identify favorable parameters of common filaments and establish their impacts on the system. Typically an SVI of 150 mL/g indicates good settling. Overall the study experienced good settling (128.3±36.3 mL/g), indicating that operating under different influent substrate concentrations and process configurations did not result in poor settling.

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Nitrogen and phosphorus are essential components in the life-cycle of the Chesapeake Bay. These nutrients support the growth of algae and aquatic plants, which provide food and shelter for aquatic species within the Bay. However, when present in excess, nitrogen and phosphorus pollute the atmosphere and water, resulting in serious environmental and human health issues, which go as far as to impact the economy.

At its healthiest in the early 1600s, the Chesapeake Bay watershed boasted lush forested buffers and wetlands that filtered nutrients prior to entering the watershed. Over time, rising infrastructure has destroyed these natural buffers, allowing pollution to flow freely. Most sewer drains carry polluted water with high nutrient loads to the sewage plant for removal, but urban and agricultural runoff runs directly into local waters, ultimately reaching the Bay. Each year, roughly 300 million pounds of nitrogen reaches the Chesapeake Bay (Chesapeake Bay Foundation). This excessive amount of nutrients in the water causes algae to grow faster than the ecosystem can handle. Large algae blooms reduce the oxygen in the water to deadly levels. Without sufficient oxygen, the marine life grows sick or dies. Humans also suffer due to elevated toxins and bacterial growth leading to illness upon contact with the water or consumption of the water or tainted fish or shellfish.

A portion of nitrogen and phosphorus pollution comes from sewage treatment plants. Because of this, increasingly stringent total nitrogen (TN) and total phosphorus (TP) limits discharged by wastewater treatment plants has been implemented to prevent eutrophication. This thesis will focus on the removal of nitrogen. The most basic form of nitrogen removal is complete nitrification followed immediately by denitrification. Nitrification is the oxidation of ammonia to nitrate via nitrite. Denitrification is the subsequent reduction of nitrate to nitrogen gas via nitrite.

As discharge limits on the TN concentration grow increasingly stringent, the cost increases. Recent research attempts to bypass the oxidation of nitrite and convert it directly to nitrogen gas through a process known as nitrite-shunt. Nitrite-shunt reduces the process costs of conventional nitrification-denitrification and increases the removal efficiency. Building upon this, deammonification (partial nitritation + anaerobic ammonia oxidation [anammox]), converts only half of the ammonia to nitrite, which is then combined with the remaining ammonia and converted directly to nitrogen gas anaerobically and autotrophically. Deammonification is even less resource intensive and capable of meeting very low TN effluent levels.

1.1 PROJECT OBJECTIVES

The project objectives outlined in this thesis are two part: 1) optimization of intermittent aeration for increased nitrogen removal efficiency and 2) identification of the filamentous population at various substrate loads and process configurations, and assessment of the impacts on settling and process performance. The aims are to meet these project goals through the operation of a pilot scale nitrogen removal A/B process operating under AvN process technology (Regmi, 2014).

The first objective implemented and examined mainstream NOB out-selection mechanisms through the use of AvN process technology in the B-stage of an A/B process. The A-stage is a high rate carbon removal process that operates strategically to control the effluent COD/NH_4^+-N ratio entering the B-stage. The goal of the A-stage was to find the lowest COD/NH_4^+-N ratio that optimizes B-stage nitrogen removal, allowing for more carbon capture from the A-stage for energy production and B-stage volume savings, yet still favors NOB out-selection and sufficient TN removal. The B-stage objective was to operate aggressively as a nitritation-denitritation process (AvN process) at varying HRT and SRT to observe the effects on the NOB out-selection resulting in nitrite accumulation and nitrogen removal efficiencies. Running the B-stage as a Modified Ludzack-Ettinger with a nitrogen recycle (NRCY) was also observed.

The second objective of this research identified and characterized the settleability issues observed within the B-stage of the pilot scale A/B process when operated under AOB versus NOB (AvN) control technology. Every new control technology and process configuration creates a unique environment favorable to different species of filamentous and floc-forming bacteria. These bacteria are both necessary for good sludge settling. However, when filamentous bacteria are observed in excess, they can contribute to the deteoriation of sludge settleability and ultimately the effluent released from the wastewater treatment plant.

In order to achieve improved settling, the following must be accomplished: 1) identify filamentous bacteria present within each phase of the experiment, 2) identify filamentous bacteria that have a negative impact on settling, 3) correlate the operational parameters and wastewater conditions (i.e. substrate concentration, F/M ratio, etc.) that favor particular filamentous bacteria, and 4) identify analytical measurement and monitoring for early indication of filamentous bulking. Literature has characterized filaments when they exist on their own, however, filaments exist within a community that is dependent on the process and the unique plant influent, making the development of a universal solution near impossible. It is necessary to identify the filamentous bacteria most common within this system under the unique AvN control system, and identify which are capable of degrading the sludge settleability.

2. LITERATURE REVIEW

2.1 BIOLOGICAL NUTRIENT REMOVAL

2.1.1 NITRIFICATION:

Nitrification is a two-step process in which ammonia (NH_4-N) is oxidized to nitrite (NO_2-N) and nitrite is then oxidized to nitrate (NO_3-N) (Figure 2-1). These two steps are carried out by two separate groups of autotrophic bacteria. Ammonia oxidizing bacteria (AOB) convert the ammonia to nitrite, shown in step 1 below. Nitrite oxidizing bacteria (NOB) convert the nitrite to nitrate, shown in step 2 below.

The two-step oxidation of ammonia to nitrate is:

Step 1:

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O \qquad (1)$$

Step 2:

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \qquad (2)$$

Total oxidation reaction:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \qquad (3)$$

Nitrification requires sufficient dissolved oxygen (DO) to be present, a pH range of 6.8 to 8.5, and very little inhibition due to toxic compounds (Metcalf & Eddy, 2003). Equation 3 above requires 4.57 g O_2/g N oxidized to completely oxidize ammonia; this does not take cell synthesis into account. When taking cell synthesis into account, only 4.25 g O_2/ g NH_4^+ is required. The majority of this oxygen, 75%, is used for nitrite production, whereas, the remaining 25% is used to convert the nitrite to nitrate.

$$NH_4^+ + 2HCO_3^- + 2O_2 \rightarrow NO_3^- + 2CO_2 + 3H_2O \qquad (4)$$

Further, the alkalinity of the influent wastewater is important because for each gram of NH_4-N converted, 7.14 g of alkalinity as $CaCO_3$ is required (eq. 4).

When temperatures are below 28°C and excess DO is present, ammonia-oxidation kinetics are rate limiting, thus the process should be designed according to AOB growth rate. The heterotrophic bacteria populations in conventional activated-sludge systems grow much faster than the nitrifying bacteria of BNR systems. To account for this, BNR processes have longer SRTs. Tchobanoglous et al. (2004) report typical SRT values may range from 10 to 20 days at 10°C to 4 to 7 days at 20°C.

2.1.2 DENITRIFICATION:

Biological denitrification is the reduction of nitrate to nitrite and then further to nitrogen gas, most commonly performed by heterotrophic facultative anaerobic organisms (Figure 2-1). Under anoxic conditions, the nitrate reductase enzyme in the electron transport chain is triggered, allowing nitrate to be utilized as the electron acceptor while an organic carbon compound acts as the electron donor and is oxidized. The equation below illustrates the heterotrophic denitrification reaction that takes place within wastewater. $C_{10}H_{19}O_3N$ is used to represent the biodegradable organic matter in wastewater.

$$C_{10}H_{19}O_3N + 10NO_3^- \rightarrow 5N_2 + 10CO_2 + 3H_2O + NH_3 + 10OH^- \qquad (5)$$

The above heterotrophic denitrification reaction produces 3.57 g of alkalinity as $CaCO_3$ per g of NO_3-N reduced. The previous nitrification reaction consumed 7.14 g of alkalinity as $CaCO_3$, so by combining nitrification with denitrification, approximately 50% of the alkalinity destroyed through nitrification can be recovered (Tchobanoglous et al. 2004).

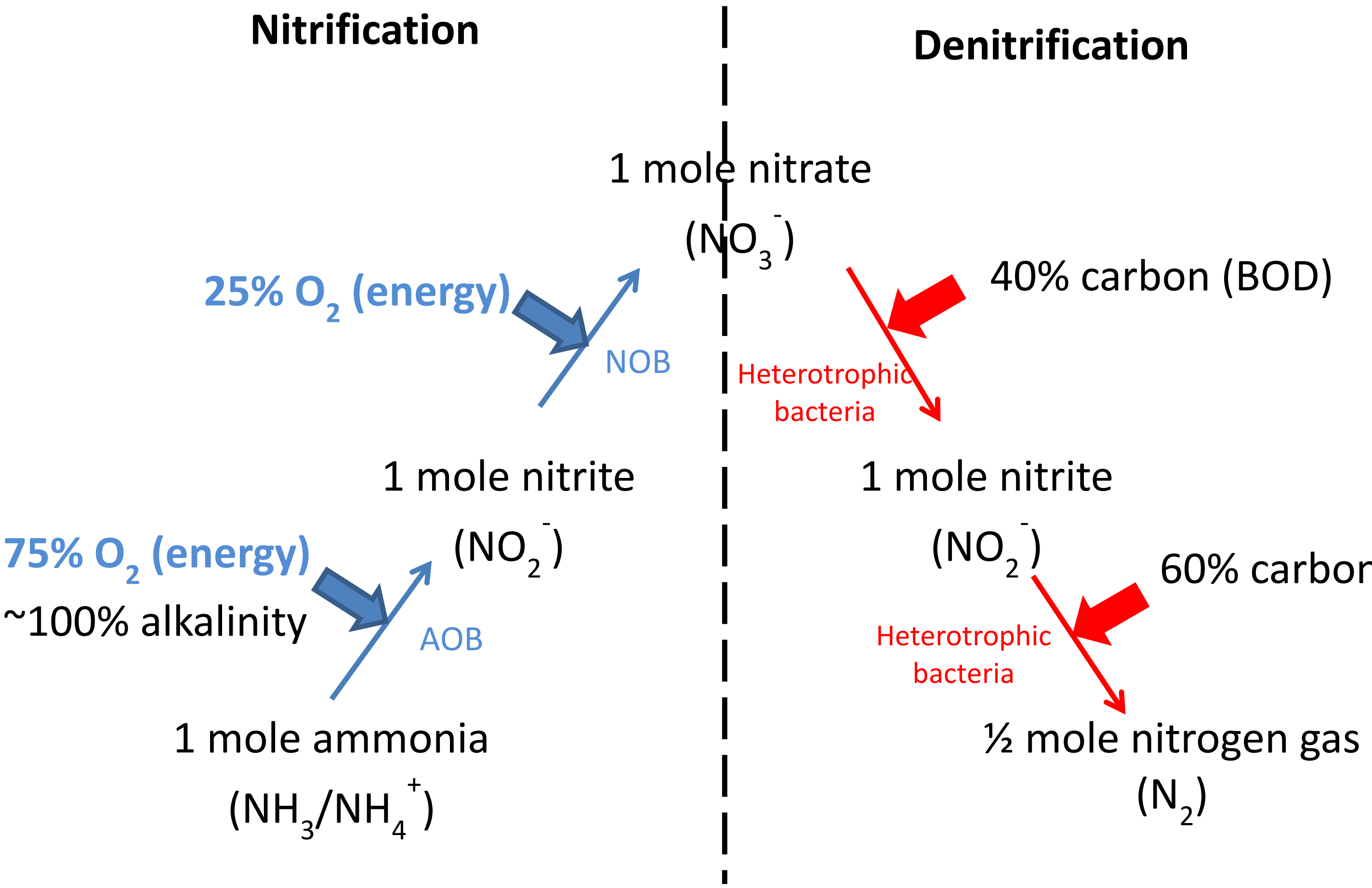

Figure 2-1: Conventional Nitrification/Denitrification. Blue arrows indicate an aerobic environment. Red arrows indicate an anoxic environment.

2.3 Modified Ludzak-Ettinger (MLE):

The Modified Ludzak-Ettinger (MLE) process is one of the simplest and most commonly employed BNR processes. A MLE process utilizes a single sludge for nitrogen removal and modifies the conventional activated sludge process by implementing an anoxic zone prior to the aerobic zone

(Figure 2-2). This pre-anoxic zone combines influent wastewater, return activated sludge (RAS) and an internal mixed liquor return (IMLR). The raw influent wastewater provides the carbon source for denitrifying bacteria. The RAS from the clarifier provides the microorganisms. The IMLR provides the nitrate, from nitrification occurring in the aerobic zone, as the electron acceptor for denitrification. The amount of nitrate removal is limited by the practical levels of internal recycle to the preanoxic zone, and the process is used more generally to achieve effluent total nitrogen concentrations between 8-12 mg/L with influent TKN in the range of 40-50 mg/L (Tchobanoglous et al. 2004). This process can achieve additional nitrogen removal with the addition of a second anoxic zone, seen in the 4-stage Bardenpho process (Figure 2-5).

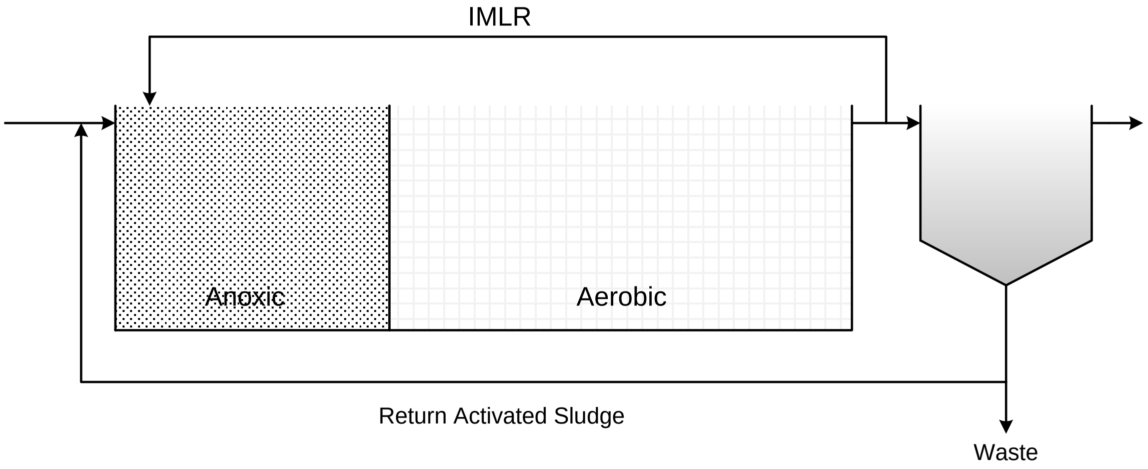

Figure 2-2: Modified Ludzak-Ettinger (MLE) process

2.4 STEP-FEED BNR:

The step-feed process is another preanoxic process capable of meeting total nitrogen concentrations of less than 10 mg/L in the effluent. The influent wastewater is divided symmetrically or asymmetrically between anoxic/aerobic stages (Figure 2-3). Symmetrical anoxic/aerobic stages are generally used to adapt to existing multiple-pass full-scale tanks. However, nonsymmetrical designs with smaller initial anoxic/aerobic stages can take better advantage of the higher MLSS concentration in the early stages, due to less RAS dilution, resulting in greater treatment capacity (Tchobanoglous et al. 2004). Because the portion fed to the last anoxic/aerobic zone will not be reduced further, it determines the final effluent NO_3-N concentration. However, with the addition of supplemental carbon, Tchobanoglous et al. (2004) found a concentration between 3 to 5 mg/L is possible with the use of internal recycle for the last pass of the anoxic-aerobic step-feed process. Like the MLE process, DO in the internal recycle needs to be monitored to ensure the amount of DO being fed to the anoxic tank is limited.

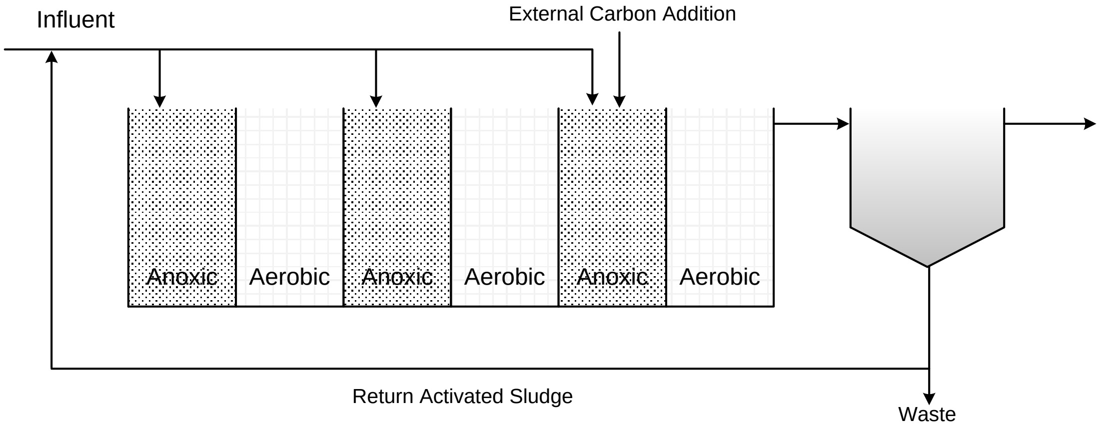

Figure 2-3: Step-feed BNR process

2.5 POSTANOXIC DENITRIFICATION

The basic postanoxic configuration (Figure 2-4) consists of an anoxic zone following an initial aerobic zone. In this type of system configuration, nitrification occurs in the aerobic zone followed by denitrification in the anoxic zone. The aerobic zone facilitates heterotrophic carbon oxidation, removing most, if not all, of the organic substrate present in the influent wastewater. Without the organic substrate, denitrification is not possible. Denitrification in a postanoxic system requires the addition of an external carbon source, typically in the form of acetate or methanol. Without oxygen as an electron acceptor, postanoxic processes rely on endogenous respiration of the activated sludge to provide an electron donor for nitrate consumption. Tchobanoglous et al. (2004) report a denitrification rate 3 to 8 times slower compared to preanoxic processes that use the influent BOD as the electron donor. Because the rate of denitrification is significantly slower, a long detention time is required in the postanoxic tank to achieve high nitrate-removal which requires very large reactor volumes. External carbon addition can be both expensive and difficult, requiring special care for safe storage, handling and application.

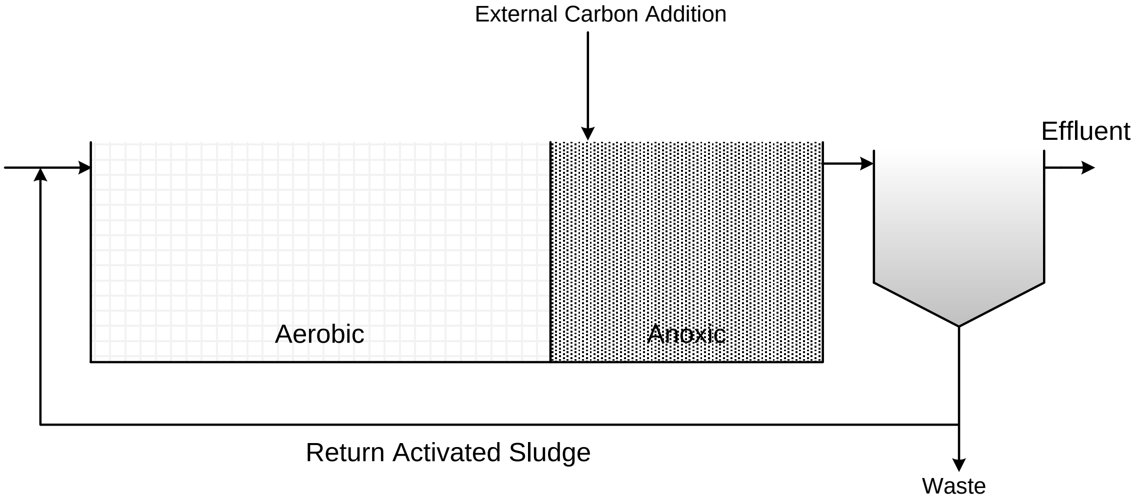

Figure 2-4: Basic Postanoxic process

2.6 4-STAGE BARDENPHO

The 4-stage Bardenpho process is another single-sludge nitrogen removal process that combines both preanoxic and postanoxic denitrification, with a small aerobic zone preceding the clarifier (Figure 2-5). The detention time of the postanoxic stage is about the same as or larger than that used for the preanoxic zone (Tchobanoglous et al. 2004). The second anoxic zone allows for greater denitrification capacity depending on the amount of soluble refractory organic N present and the reliability of TIN removal and the amount of particulate organic N removal. External carbon addition may be required in the second anoxic tank, due to a very low denitrification rate, to reduce reactor volume requirements. In the postanoxic zone, the NO_3-N concentration leaving the aeration zone is typically reduced from about 5 to 7 mg/L to less than 3 mg/L (Tchobanoglous et al. 2004).

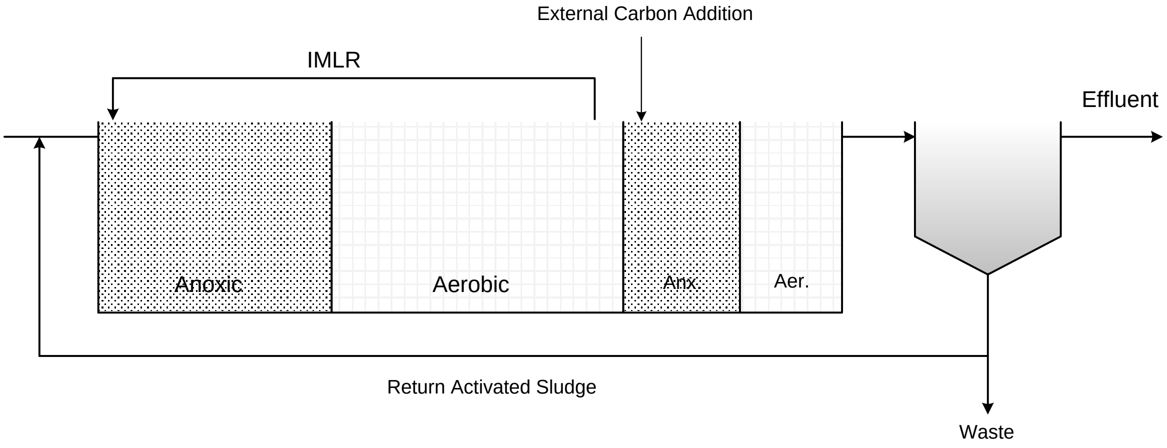

Figure 2-5: 4-stage Bardenpho process

Table 2-1: Comparison of advantages and limitations between different process configurations.

	Advantages	Limitations
Preanoxic-general	-Saves energy; BOD is removed before aerobic zone -Alkalinity is produced before nitrification	
MLE	-Very adaptable to existing activated-sludge processes -5 to 8 mg/L TN is achievable	-Nitrogen-removal capability is a function of internal recycle -Potential *Nocardia* growth problem -DO control is required before recycle

Step feed	-Adaptable to existing step-feed activated-sludge processes -With internal recycle in the last pass, nitrogen concentrations less than 5 mg/L are possible -5 to 8 mg/L TN is achievable	-Nitrogen-removal capability is a function of flow distribution -More complex operation than MLE; requires flow split control to optimize operation -Potential *Nocardia* growth problem -Requires DO control in each aeration zone
Bardenpho (4-stage)	-Capable of achieving effluent nitrogen levels less than 3 mg/L with the use of supplemental carbon.	-Large reactor volume -Higher operating cost due to purchase of methanol -Methanol feed control required -Potential *Nocardia* growth problem
Postanoxic with carbon addition	-Capable of achieving effluent nitrogen levels less than 3 mg/L -May be combined with effluent filtration	-Higher operating cost due to purchase of methanol -Methanol feed control required - Potential *Nocardia* growth problem

(Tchobanoglous et al. 2004)

2.7 A/B PROCESS:

An A/B process (adsorption/bio-oxidation process) is a two-sludge system in which the adsorption stage (A-stage) is primarily COD removal and the bio-oxidation stage (B-stage) is primarily nitrogen removal. The A-stage is a high-rate activated sludge (HRAS) process which then feeds the B-stage conventional biological nutrient removal (BNR) process (Figure 2-6).

This technology was first researched at a municipal treatment plant in Krefeld, Germany to address nitrification toxicity because the plant receives over 50% of its influent flow from various industrial sources (Boehnke et al., 1997). Before the upgrade, Krefeld utilized primary clarification followed by carbon and nutrient removal that occasionally experienced nitrification inhibition. Because of the extreme influent conditions that were constantly fluctuating, biological treatment was not considered feasible; however, a cost-effective biological treatment option was desirable to reduce chemical addition (Boehnke et al., 1998). The solution implemented in Krefeld was the A/B process; a high rate adsorption or A-stage followed by intermediate clarification and then the B-stage for nitrogen removal.

The A-stage process operates at a high F/M ratio (2 to 10 g BOD/g VSS/d), a short HRT ($\leq$30 minutes), and a very short SRT (0.25-0.5 days) excluding solids in the clarifier (Boehnke et al. 1997), to maximize the removal of soluble COD (sCOD) by storage and conversion to biomass and the bioflocculation of particulate COD (pCOD) and colloidal COD (colCOD) (Miller, et al., 2012).

Boehnke et al. (1997) found these conditions to be similar to the bacterial environment found in sewer systems.. This sewer environment encourages the growth of a microbial population similar to that of influent wastewater which is best suited to treating influent wastewater (Boehnke et al., 1997). This bacterial population is capable of removing up to 80% of the COD through bioflocculation and enmeshment in bacterial extracellular polymeric substances (EPS). This high F/M ratio and low HRT requirement keep the volume requirements for the A-stage low, and the low cost per gram of COD removed from the A-stage is attributed to both chemical and physical processes such as adsorption, flocculation and coagulation. The A-stage is minimally aerated to prevent fully anaerobic conditions from forming; however, the DO concentration typically remains below detection limits of on-line DO sensors.

Boehnke et al. (1997) claimed that the A-stage removes primarily readily biodegradable COD and breaks down complex molecules into readily biodegradable substrate for denitrification in the B-stage. The A-stage could remove particulate refractory COD, through bioflocculation and enmeshment but Boehnke does not further explain how the A-stage breaks down these complex organic molecules. Low molecular weight compounds and readily biodegradable substrate were shown to be removed in the A-stage in the A/B process at Strass WWTP in Austria, leaving more-slowly biodegradable organic molecules available to the B-stage (Bunce, 2003). The assumption is that when A-stage organisms are not substrate limitied, i.e. there is a lot of readily biodegradable COD (rbCOD) present, they function at their maximum growth rate taking up more rbCOD more quickly than they can utilize it for growth. As a result, they store this substrate aerobically by converting it to polyhydroxyalkanoates (PHA), or other intracellular storage products like glycogen. Once the influent substrate is consumed, the organisms continue to grow on the stored substrate. A-stage storage is beneficial because it requires less aeration energy than mineralization and retains the energy-rich storage compounds within the biomass, allowing it to be diverted to an anaerobic digestion process where it is converted into energy.

The majority of the waste sludge is taken from the A-stage, creating easily settleable (SVI ranges from 40 to 80 mg/L) and digestible sludge. A-stage sludge settles and dewaters better than typical sludge with less required polymer addition. By dewatering better, there is less liquid sludge volume resulting in less sludge to be sent to the landfill and an increased solids concentration in anaerobic digesters that can be converted to biogas. Anaerobic digestion takes advantage of increased carbon content of the A-stage. When the reduced organic compounds are converted into biomass at maximal yield, not broken down and mineralized, the carbon may be diverted to generate methane gas (CH_4) for energy production (i.e. electricity) which can result in energy-neutral wastewater treatment (Wett et al., 2007).

Initially, oxygen added to A/B processes or before preanoxic BNR processes would oxidize rbCOD and some sbCOD aerobically resulting in the need for supplemental carbon for the denitrification step. Readily biodegradable COD (rbCOD) is quickly oxidized aerobically during aeration. However, slowly biodegradable COD (sbCOD) will remain in the system longer, allowing denitrification to occur under low DO SND conditions resulting in increased nitrogen removal without the need for supplemental carbon addition. In a BNR plant, it is more cost-effective to remove COD through anoxic denitrification, making it desirable to minimize the amount of COD oxidized aerobically. Additional benefits are seen when AOB generate nitrite which is then reduced directly to nitrogen gas in a process called "nitrite shunt" (Marcelino et al., 2011). More savings in aeration energy are observed by eliminating the oxygen requirement for the oxidation of nitrite to nitrate, and reduced carbon demand for denitrification. However, these low DO concentrations (addressed in 2.14.2.2) and low F/M ratios (addressed in 2.14.2.1) favor filamentous bulking.

Boehnke et al. (1997) found that COD removal efficiencies increase with higher COD influent concentrations, acting as a buffer between fluctuating influent loads and the B-stage. This buffer allows the organic load to the B-stage to remain relatively constant. The A-stage is followed up by the B-stage for biological nitrogen removal or BNR. The A-stage may be used to control the amount of easily biodegradable COD that enters the B-stage for denitrification. A-stage effluent typically contains COD/N ratios of 5-7, which is insufficient to meet the carbon requirement for B-stage nitrogen removal. To overcome carbon-limited conditions, the B-stage can be operated under ammonia-based aeration to get SND and nitrite shunt (discussed below) to both meet effluent nitrogen limits and to avoid B-stage alkalinity limitations.

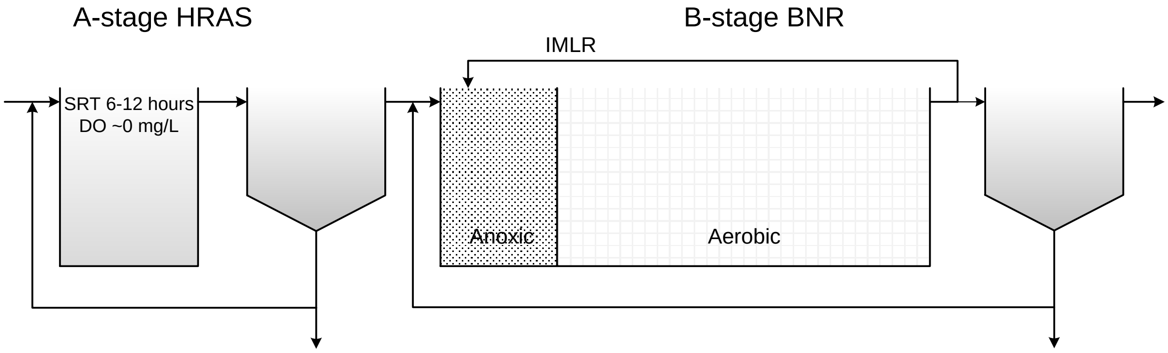

Figure 2-6: A/B Process

Winkler & Widmann (1994) compared a single sludge system to an A/B process for installation at the Innsbruck WWTP in Austria. They found the A/B process to offer reduced volume and nitrification rates 1.5 to 2 times that of a single sludge system. However, due to insufficient carbon, denitrification in the A/B process was slower when the B-stage was fed 100% A-stage effluent. Similar nitrogen removal rates were achieved between the two systems with the implementation of a 35% bypass of the A-stage. Despite the bypass producing similar results within the two systems, researchers deemed the single-sludge process to be the better fit for their plant (Winkler and Widmann 1994). This study occurred prior to the development of ammonia-based aeration control and is indicative of the need for such a control system.

The main treatment plnt in Vienna, Austria is a unique example of an A/B process that contains primary clarifiers and the A-stage operated at an SRT of 1 day (typical A-stages have an SRT of 0.25-0.5 days); both result in a reduced influent COD load to the B-stage. This plant is referred to as a semi-A/B process because it may be operated in two different modes to achieve the best nitrogen removal based on influent conditions. The first mode is Bypass mode where a set percentage of the primary influent bypasses the A-stage and is fed directly to the B-stage. The waste sludge from the B-stage is then returned to the A-stage to allow for nitrification. In the second mode, Hybrid mode, the A-stage is only bypassed in wet-weather conditions. In dry weather, sludge recycle lines pump B-stage nitrifying sludge to the A-stage for nitrification, and a different line pumps carbon-rich A-stage sludge to the B-stage for denitrification. These sludge recycle lines never exceed 5% of the influent flowrate. Both operational modes return effluent from the B-stage clarifier to the A-stage for denitrification (Wandl et al., 2006).

2.8 AERATION

The original and simplest, in terms of technology required, is to control the aeration by setting a constant airflow rate. This airflow setting does not adjust in response to influent variables. This simple scheme can easily result is unnecessary high airflow rates and oxygen concentrations, which result in decreased aeration efficiency and oxygen transfer (Olsson et al. 2005; Thunberg et al. 2009; Amand and Carlsson, 2012).

DO cascade control utilizes a DO set-point inserted into the controller by the plant operator. A controller adjusts the airflow rate into the reactor based on the difference between the DO set-point and an on-line DO sensor reading. In this control scheme, the airflow rate is measured and controlled in an inner (slave) loop that is dependent upon the outer (master) loop, which controls the DO that is given a controlled value (Amand et al. 2013).

2.8.1 AMMONIA-BASED AERATION CONTROL (ABAC)

To build upon the DO cascade controller, we improve control performance by having the set-point of the master loop, in this case the DO set-point, utilize a sensor to measure the ammonium concentrations to determine the value of the DO set-point. Figure 8 demonstrates the resulting ammonia concentration across a reactor as a result of ammonia-based aeration control (ABAC). All three lines start at the same ammonia concentration. Overaeration results in the sudden drop of the ammonia concentration to zero before the end of the reactor. The remaining distance to the end of the reactor is wasted capacity seeing as it could be treating more load aerobically, or it could be converted to an anoxic zone to increase denitrification, or lower the SRT to achieve the same degree of removal. Additionally, altering the DO set-point could create SND-type conditions which would result in more denitrification, as well. Underaeration (Figure 2-7) describes an elevated ammonia concentration leaving the reactor which could indicate the air demand of the substrate is greater than the DO set-point. Utilization of the ABAC (Figure 2-7) adequately utilizes the reactor capacity to nitrify the ammonia concentration with the least amount of oxygen necessary to reach a user-dictated set-point by the end of the reactor. This allows an ammonia concentration to be maintained in the reactor at all times, avoiding a sudden drop in oxygen demand and a spike in the DO concentration leading to overaeration.

There are two types of fully automated control for a more efficient process; feedforward and feedback control. Feedforward requires the use of a controller at the beginning of a process. The feedforward controller utilizes a process model to predict the impact of a disturbance, commonly the influent ammonium concentration and influent flow rate to the plant, and react quickly before this disturbance affects the process(Amand et al., 2013). The success and accuracy of this prediction is dependent upon the model quality. However, because the predictions of the feedforward controller are seldom perfect, they should be used in conjunction with feedback control to make the final correction based on the true measurement(Amand et al., 2013). Feedback controllers, usually situated at the end of the process in the effluent stream or at the end of the reactor, are used to determine if limits have been met by the system. A feedback controller reads the current reactor conditions causing a delay in the ability to react to a disturbance read by a probe.

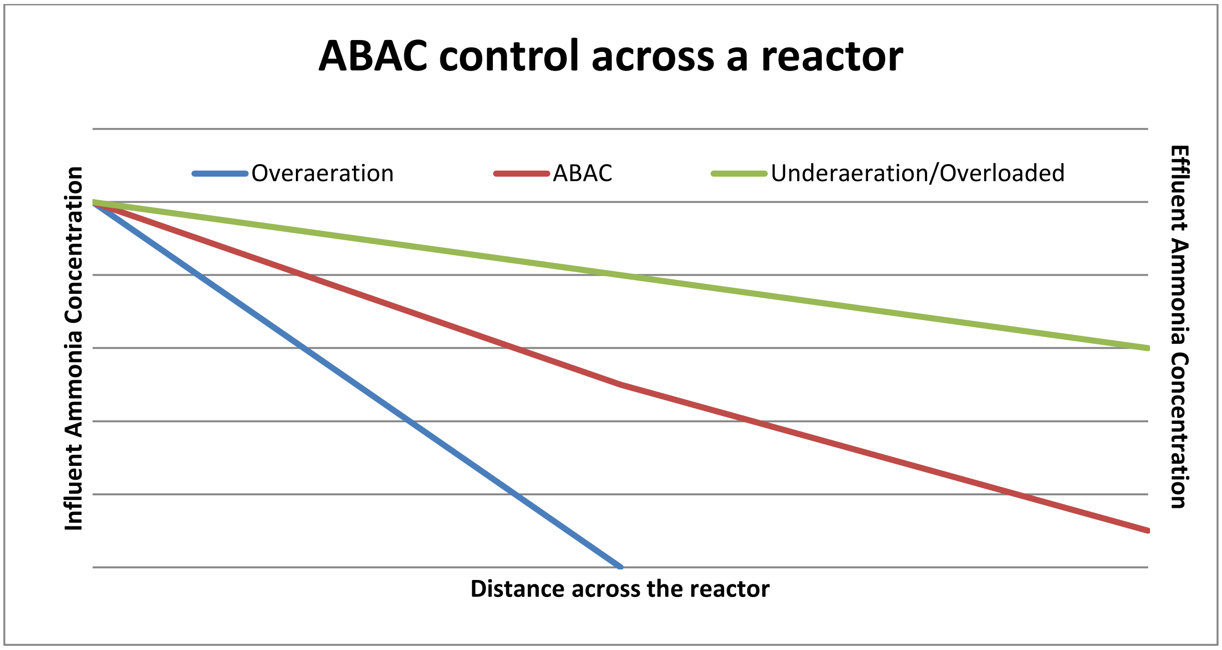

Figure 2-7: Representation of ABAC on the ammonia concentration across a reactor (developed from Amand et al., 2013 and Rieger et al., 2014).

Ammonia-based aeration control in plants requiring nitrogen removal has the ability to provide benefits through the following mechanisms: aeration at a lower average DO concentration, less COD used aerobically, maintaining a minimum ammonia concentration to maintain oxygen demand and prevent a DO spike, increased nitrogen removal with both reduced aeration costs and reduced supplemental carbon addition and more alkalinity return.

Aeration translates into energy costs, which is one of the major expenses associated with wastewater treatment. If the amount of ammonia leaving the system is being monitored, the aeration required to oxidize the ammonia to nitrite can be controlled, eliminating costs from over-aeration (Ingildsen, 2002; Amand & Carlsson, 2012). Ammonia control for limiting aeration also prevents complete nitrification, maintaining an effluent ammonia concentration. Without ammonia-based aeration control, complete nitrification results in complete ammonia removal, resulting in a sudden drop in oxygen demand. This step change in oxygen demand is difficult to account for in DO control loops, leading to over-aeration (Rieger et al., 2014). Over-aeration is common in plants that run at a fixed aeration rate or aim for a constant DO level as a result of fluctuations in ammonia concentrations (Shen et al., 2001).

Ingildsen (2002) compared four different controllers in full-scale experiments at the Kallby WWTP in Lund, Sweden. The four controllers were set-up as (1) a feedforward controller based on an ammonia sensor at the head of the aerobic zone, (2) a feedback controller based on a sensor located after secondary clarification, (3) a combination of set-up (1) and (2), and (4) a feedback controller based on a sensor located at the end of the aeration zone. Of the four experiments, control scheme (4) was the best, showing reduced airflow requirements of 10-15% and meeting effluent ammonia goals over a constant-DO system (Ingildsen, 2002).

Pilot testing by Vrecko et al. (2006) found a feedback system reduced aeration requirements by 23% and a feed-forward controller reduced aeration requirements by as much as 45%. Vrecko et al. (2011) built upon this research by comparing an ammonia model predictive controller (MPC) and the results from the previous study with the ammonia feedforward and ammonia feedback controllers. It was found that both the ammonia MPC and ammonia feedforward were better in terms of ammonia removal and aeration energy consumption than the ammonia feedback controller because of the measurable disturbances used. Between the two, however, the ammonia MPC proved to need more sophisticated control criteria than the ammonia feedforward to achieve similar results (Vrecko et al. 2011). The use of ammonia-based DO control helped mediate peak loads by reducing the variation in effluent ammonia levels (Ingildsen, 2002; Vrecko et al., 2006). These controllers are advantageous to a plant whose limits are measured over a shorter period of time; therefore they must maintain consistently low effluent ammonia.

Rieger et al. (2014) conducted research at the Nansemond WRRF which began as a three-stage Virginia Initiative Process (VIP) process and has undergone an upgrade to become a five-stage Bardenpho process to meet more stringent effluent demands. Previous research by Rieger et al. (2012) identified optimal aeration control strategies to reduce aeration energy. The potential benefits of adding an ammonia feedforward controller were assessed. Researchers found the ammonia-based aeration control is capable of reducing operating costs resulting in energy savings of 15 to 25%, increasing denitrification and reducing the external carbon dosage. However, Rieger concluded that feed-forward did not improve the energy savings enough to justify its use because feedback control is still needed as the effluent leaving the process should always be measured.

Potential problems of ammonia-based aeration arise when sensors malfunction or fail. There are two possible control schemes for implementing limited aeration ammonia-based control (Amand et al., 2013) that both require ammonia and DO sensors: 1) a cascade controller is used; the ammonia controller determines and changes the DO set-point for a controller adjusted air flow, 2) an ammonia controller directly manipulates the air flow. The first approach is generally preferred because the cascaded set-up has a built-in fall back. The ammonia control loop manipulates the set-point of the faster dissolved oxygen control loop, simplifying tuning (Rieger et al., 2014). Additionally, should the ammonia loop fail, the DO controller may serve as a stand-alone fall-back strategy. For the second approach, direct ammonia control only uses the DO sensor as a constraint to prevent over-aeration at high ammonia loads. Should the control system need to utilize this constraint, the control system may become unstable without careful tuning (Rieger et al., 2014). However, direct ammonia control is advantageous in terms of ware on equipment; ammonia concentrations change slower within a system resulting in fewer air flow changes.

In summary, application of ABAC leads to aeration savings, which though important is not its only application or the primary purpose within this study. ABAC is used within this study to promote nitrite-shunt and SND. The mechanisms of these reactions are discussed in the following sections.

2.9 SIMULTANEOUS NITRIFICATION-DENITRIFICATION (SND):

SND was originally thought to be impossible with the knowledge that nitrification requires an aerobic environment and denitrification requires an anoxic environment. However, SND utilizes DO control to allow both nitrification and denitrification to occur in the same tank simultaneously. There are two possible explanations for the occurrence of SND, one physical and one biological (Munch et al. 1996). The physical explanation is that SND occurs as a result of DO concentration gradients within microbial flocs due to diffusional limitations. However, large, dense floc structures are needed to prevent oxygen from reaching the innermost core of the floc, creating an anoxic environment for denitrification to occur. The biological explanations contradict the conventional views of nitrification and denitrification because they include aerobic denitrifiers and heterotrophic nitrifiers. However, the successes of both forms of SND are dependent upon the DO concentration (Rittman and Langeland 1985). Ma et al., (2009) also confirmed that SND activities increase with decreasing DO concentrations.

According to Rittman and Langeland (1985), SND includes more complete nitrogen removal and reduced aeration requirements due to more influent COD being utilized for denitrification, which also results in costs savings as more sbCOD is used anoxically to remove more TN without supplemental carbon addition. Additionally, nitritation-denitritation results in more alkalinity return compared to conventional nitrification-denitrification. Despite the arguments that SND is dependent upon the DO concentration throughout the bulk liquid of a reactor (Rittman and Langeland 1985) and novel microorganisms play a prominent role in SND (Littleton et al. 2003), the oxygen gradient that exists within the biological floc is the responsible mechanism in most cases (Daigger and Littleton 2000). This mechanism may only be employed if sufficiently large, dense flocs are formed to create this concentration gradient. On the outer edges of the floc structures, oxygen and substrate are easily accessible in the bulk liquid, which is ideal for nitrification and COD oxidation. However, depending on the levels of DO, ammonia, and COD in the reactor, oxygen has a harder time reaching the inner portions of the flocs without being consumed. Nitrate produced on the floc surface diffuses to the center, forming an anoxic zone. As a result, denitrifiers will be preferentially active in the inner floc zones with nitrate and very low to zero dissolved oxygen concentrations present (Munch et al. 1996). If enough COD is present to penetrate the floc structure, nitrate will be denitrified to dinitrogen gas (Tchobanoglous et al., 2004).

Three principle factors influence SND: carbon supply, oxygen concentrations and floc size (Pochana and Keller 1999). As is typical in conventional denitrification, Chiu et al. (2007) found that the influent carbon and nitrogen (COD/NH_4^+-N) ratio is an important control parameter in determining the success of an SND process. Jimenez et al. (2010) found a COD/NH_4^+-N ratio of 6-10 maximizes TN removal in SND processes. The second controlling factor is optimizing the oxygen concentration. The optimum DO level within an SND system supplies enough oxygen to allow for nitrification, while maintaining low enough levels to ensure adequate denitrification occurs. Because SND is a combination of aerobic and anoxic processes, neither process is optimized, but rather balanced, resulting in neither nitrification nor denitrification occurring at their maximum rates. However, less aeration also results in less COD used aerobically. Depending upon reactor design and specific operating conditions, optimum DO levels for SND are around 0.5 mg/L but can go as high as 1.0 mg/L (Munch, Lant, & Keller, 1996; Pochana & Keller, 1999). Finally, the final influencing factor of SND is the floc size. The flocs need to be sufficiently large to create an anoxic zone in their interior allowing for denitrification. Literature values vary greatly from 10-110 µm (Andreadakis, 1993; Pochana & Keller, 1999). When a system is unable to maintain floc size due to various factors, such as filamentous bulking, DO is able to penetrate the interior of the floc structure causing SND to deteriorate because no anoxic zone will form (Daigger et al., 2007). Filamentous bulking will be addressed in one of the following sections.

Katie et al. (2003) proposed the following equation to calculate the efficiency of the SND process:

$$Efficiency_{SND} = \left(1 - \frac{NO_{x\ remaining}^{-}}{NH_{4\ oxidized}^{+}}\right)100 \tag{6}$$

where $NO_x^-{}_{remaining}$ is the NO_x^- remaining after the reaction and $NH_4^+{}_{oxidized}$ is the NH_4^+ oxidized after the reaction.

Despite the potential decreased energy and carbon requirements of successful SND, challenges exist in design, control and operation due to generally large volume requirements, challenging control based on DO and/or ammonia concentration, and settling issues.

System control has a huge impact on the success of SND. Jimenez et al., (2010) assessed 3 different control strategies to achieve SND: 1) low DO control 2) ammonia-based aeration control and 3) ammonia-based aeration control with NOB suppression. However, issues arise in each of the 3 control designs in high loading situations where 1) nitrification capacity would be limited due to low DO possibly resulting in low DO bulking conditions 2) control would switch to a constantly high DO concentration to use the full nitrification capacity and 3) requires experimentation to select the minimum anoxic time period as this will limit the nitrification capacity. In the third situation, choosing too short of an anoxic period could stimulate NOB growth leading to full nitrification to nitrate and decreased nitrogen removal efficiency (Jimenez et al., 2010). Finding the proper control strategy is instrumental in the success of SND.

Typically, SND is accomplished in reactors with low DO concentrations. This encourages the creation of a DO gradient which facilitates nitrification and denitrification within the floc. The outer layer of the floc experiences a higher DO concentration. Less DO is able to reach the inner layer, creating an oxygen diffusion path resulting in an anoxic inner core. This creates flocs that nitrify in the oxic outer layer and denitrify in the anoxic inner core. The low DO level which achieves SND may vary in different wastewater treatment plants because sludge floc sizes, porosities, and respiration rates change as a function of the unique influent wastewater composition, and operation conditions (Jimenez et al., 2010).

2.10 NITRITE SHUNT:

Biological nitrogen removal conventionally requires two-step autotrophic aerobic conversion of ammonia to nitrite by ammonia oxidizing bacteria (AOB) and then to nitrate by nitrite oxidizing bacteria (NOB), followed by heterotrophic denitrification of nitrate to nitrite and then nitrite to dinitrogen gas (Figure 2-9). However, if the nitrification process can be stopped at nitrite (nitritation) and proceed directly to the reduction of nitrite to dinitrogen gas (denitritation), oxygen and carbon requirements can be reduced by 25% and 40%, respectively (Figure 2-8)(Turk and Mavinic 1989). This process, termed nitrite-shunt, has the ability to improve the nitrogen removal capacity of a BNR process. With carbon supply being a limiting factor in denitrification, nitrite-shunt should improve nitrogen removal for a given amount of carbon when compared to conventional nitrification-denitrification. In a carbon limited process, this would lead directly to cost savings, however, this is not the case in non-carbon limited BNR systems. Oxygen in nitrification typically aerobically oxidizes a portion of the influent carbon. Without this portion of carbon being oxidized aerobically, the influent carbon is not entirely consumed by denitrification though nitrite-shunt. The oxygen requirement by the “leftover carbon” negates the reduced oxygen requirement created by nitrite-shunt (Daigger, 2014). In order to benefit from the reduced aeration energy benefits of nitrite-shunt, influent wastewater carbon must be diverted in a cost-effective way. Carbon diversion can be accomplished through the implementation of an A-stage, which also allows more wastewater carbon redirection to energy producing processes such as anaerobic digestion.

2.11 SIDESTREAM NOB SUPPRESSION:

A “sidestream” in a wastewater treatment plant is the term used to describe a portion of the wastewater originating from dewatering of anaerobically digested solids. These “sidestreams” boast both high temperatures and high nutrient loads conducive to achieving nitrite-shunt. Nitrite-shunt relies on the ability of the process to effectively suppress NOB activity without reducing the activity of the AOB population (Figure 2-8). Known methods to effectively suppress or washout NOB are found in literature (Villaverde et al., 1997; Blackburne et al., 2008; Erguder et al., 2008; Tokutomi et al., 2010; Zhang et al., 2012), including free ammonia (FA) and free nitrous acid (FNA) inhibition (Anthonisen et al., 1976; Peng et al., 2008; Zhou et al., 2011), DO concentration (Ma et al., 2009), and the combination of high temperature and low SRT (Hellinga et al., 1998).

The concentration of FA and FNA compounds within the system are related to the pH, ammonia and nitrite concentrations within the system. The ammonia and ammonium species are present in equal concentrations at a pH of 9.25 and 20°C. As the pH decreases, the ammonia equilibrium adjusts and the FA concentration decreases. As the FA concentration decreases, the inhibitory effects on the AOB decreases and the total ammonia concentration decreases as it is oxidized to nitrite. As a result of this reduced stress on the AOB and NOB, complete nitrification to nitrate tends to occur.

Anthonisen et al. (1976) found these nitrifiers to be sensitive to the concentrations of their own substrates. The ammonium ion, and more so free ammonia, negatively impacts NOB. Nitrite depressed both respiration and growth of AOB. Nitrate is slightly toxic to both (Anthonisen et al., 1976). Anthonisen et al. (1976) found FA to be inhibitory to AOB at concentrations as low as 10 mg

N/L and inhibitory to NOB in concentrations as low as 0.1 mg N/L. Therefore, NOB will be initially suppressed by FA for a period of time. After NOB are exposed to FA for a period of time, they are able to acclimate, reducing inhibition somewhat, if not entirely (Turk & Mavinic 1987, 1989). Wong-Chong and Loehr (1978) observed NOB inhibition at FA levels of 3.5 mg/L, whereas acclimated NOB populations could withstand FA concentrations as high as 40 mg/L. Ford et al. (1980) reported inhibition at FA levels of 24 mg/L, but system recovery was possible at FA levels as high as 56 mg/L. Balmelle et al. (1992) reported that NOB could be inhibited at concentrations as low as 1 mg/L.

The pK_a of the nitrite/FNA acid-base pair is 3.40 at 20°C. At a pH of 3.40 at 20°C , the nitrite and FNA are present in equal concentrations. As this pH decreases, the FNA concentration will increase. When the pH drops low enough in the presence of high nitrite concentrations, it is possible to maintain high concentrations of FNA (0.02 mgHNO_2-N/L) compared to AOB inhibition which requires 0.4 mgHNO_2-N/L (Vadivelu 2007).

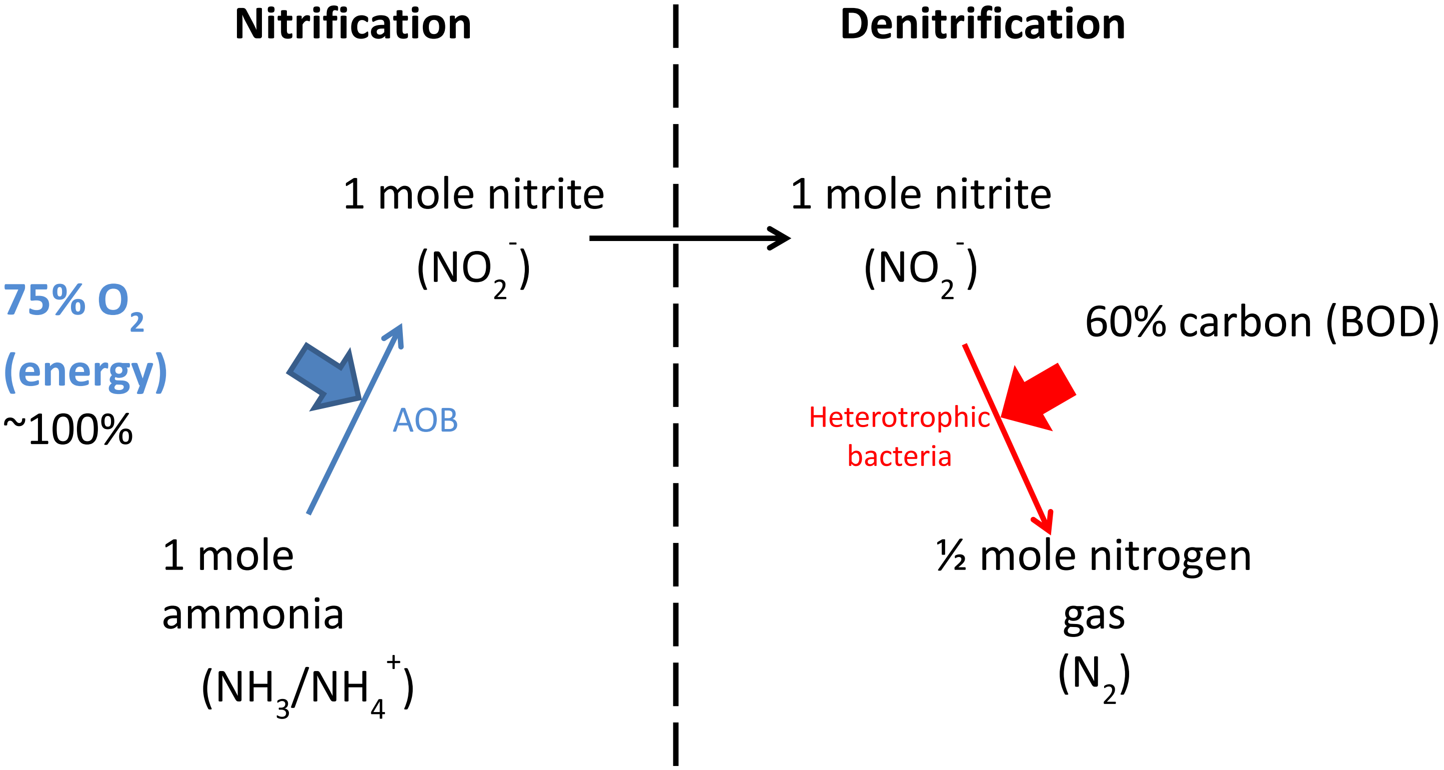

Figure 2-8: Nitrite Shunt: shortcut nitrogen removal. Blue arrows indicate an aerobic environment. Red arrows indicate an anoxic environment.

Successful NOB suppression has been demonstrated in wastewaters with high ammonium concentrations; for example, anaerobic sludge digestion liquor from high temperature recycle flows seen in the SHARON process (Hellinga et al., 1998; Fux et al., 2006; Peng et al. 2008). However, typical domestic wastewater has an ammonium concentration lower than 80 mg N/L. With such a low strength wastewater, FA inhibition to successfully suppress NOB is often unavailable (Peng et al. 2012).

A low DO concentration is effective at repressing NOB at 30°C and in conditions with high ammonia concentrations due to a greater oxygen affinity of AOB then NOB (Garrido et al. 1997). At higher temperatures, AOB exhibit higher growth rates resulting in a lower minimum SRT than NOB (Hellinga et al. 1998). These high NLR, carbon-deficient, warm conditions produced by anaerobic digestion are the ideal scenario to take advantage of novel SHARON, CANON and DEMON technology.

2.11.1 SHARON

The *SHARON*™ (Single-reactor High-activity Ammonia Removal Over Nitrite) process utilizes high temperature recycle flows, typically from dewatering of anaerobically digested solids with high ammonia concentrations, to remove nitrogen biologically. The higher temperature favors more rapid growth of AOB's over NOB's, allowing nitrification to be stopped at nitrite and AOB's to be retained in the reactor (Hellinga et al. 1998) (Figure 2-8). The *SHARON*™ process utilizes a complete-mix reactor without solids recycle, operated with intermittent aeration. The length of the aeration cycle is determined by the influent ammonia concentration, and DO is not limited during the aerobic period. Another advantage of this system is that without sludge retention, the SRT is controlled by the HRT, allowing for selective washout out of the NOB's (Hellinga et al. 1998). Within this process, pH is a governing process parameter due to the high ammonium conversion rates and the alternating nitrification (proton production) and denitrification (proton consumption)(Hellinga et al. 1998). Without proper pH control, these high levels of ammonia and nitrite can convert to free ammonia and nitrous acid at levels found to be inhibitory to AOB (Figure 2-9).

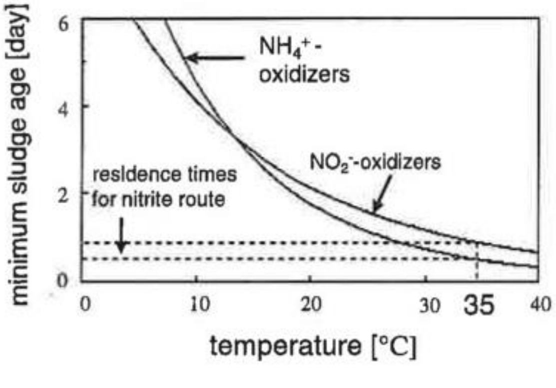

Figure 2-9: Minimum residence time for ammonium and nitrite oxidizers as a function of the temperature, Hellinga et al. 1998, used under fair use, 2014.

2.11.2 PARTIAL NITRITATION + ANAMMOX = DEAMMONIFICATION

To build upon the *SHARON*™ and eliminate the need for external carbon addition, deammonification for highly efficient N-removal was explored. Arrigo (2005) found that deammonification contributes up to 50% to the removal of fixed N from the oceans. It is then surprising that this process was not explored sooner. Deammonification takes place in two parts: 1) partial nitritation followed by 2) anaerobic ammonia oxidizing bacteria (anammox) (Figure 2-10).

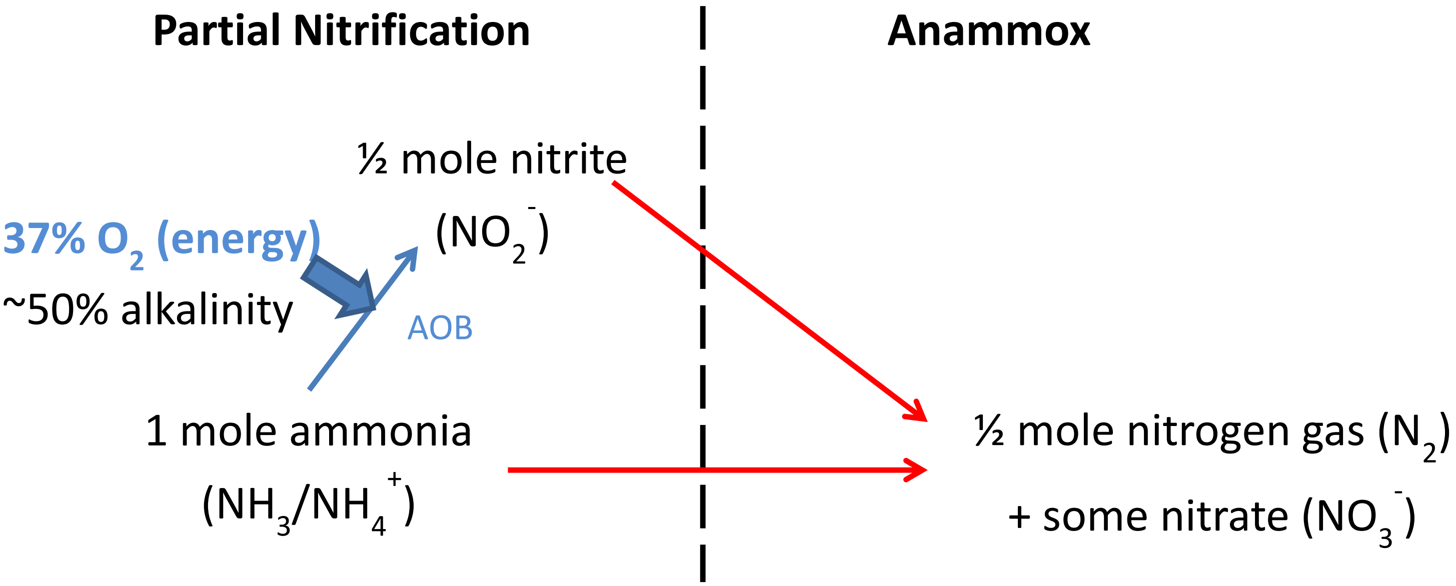

Figure 2-10: Partial nitrification – anammox = deammonification. Blue arrows indicate an aerobic environment. Red arrows indicate an anoxic environment.

Under anaerobic conditions, anammox bacteria are capable of removing ammonium from wastewater by directly oxidizing ammonia to dinitrogen gas by means of nitrite (equation 9). Identified in 1995 by Strous et al., (1995), anammox is the biological conversion of equal parts ammonium and nitrite to dinitrogen gas and 15% nitrate (equation 9).

The bacteria that carry out the anammox process belong to the bacterial phylum Planctomycetes. These organisms grow very slowly with a doubling time between 7-22 days (Kartal et al., 2011). Their slow growth rates cause them to require an extended sludge age (>20 days) making them perform best in a granular biomass or biofilm system. Possible reactors include sequencing batch reactors (SBR) and moving bed reactors (MBBR).

Anammox bacteria convert ammonium and nitrite directly to nitrogen gas anaerobically without aeration and other electron donors. Although aeration is required for partial nitritation, only half of the ammonia is being oxidized, greatly reducing aeration costs. The autotrophic nature of anammox bacteria and AOB guarantee a low yield (Hu, et al., 2013), allowing compliance with increasingly stringent total nitrogen (TN) discharge limits. Anammox bacteria have shown conversion rates up to 5-10 kg N/m^3 (Henze, et al., 2008).

The CANON (Completely Autotrophic Nitrogen-removal over Nitrite) process was created to utilize the combination of aerobic ammonia oxidizers and anaerobic ammonia oxidizers (anammox) to simultaneously oxidize ammonia to dinitrogen gas and a small amount of nitrate (according to equations 7, 8) in one single reactor under DO limited conditions.

$$1NH_4 + 1.5\ O_2 \rightarrow NO_2^- + 2\ H^+ + H_2O \qquad (7)^*$$

$$1\ NH_4^+ + 1.3\ NO_2^- \rightarrow 1.02\ N_2 + 0.26\ NO_3^- + 2\ H_2O \qquad (8)^*$$

$$\begin{aligned} 1\ NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \\ \rightarrow 1.02\ N_2 + 0.26\ NO_3^- + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O \end{aligned} \qquad (9)\ **$$

*Third *et al.,* 2001, **Strous *et al.,* 1997

The conversion of roughly half of the influent ammonia to nitrite is termed partial nitritation. From equation 9 above, for every mole of ammonia, 1.32 mole of nitrite are consumed and 0.26 moles of nitrate are produced. Having roughly equal amounts of influent ammonia and nitrite as the electron acceptor provide the anammox bacteria with the required substrates for final conversion to nitrogen gas. This combination of partial nitritation followed by anaerobic ammonia oxidation is termed deammonification (Wett, 2007). Successful deammonification is operated at low DO because anammox is reversibly inhibited by oxygen (Strous et al., 1995; Third et al., 2001). An excessive DO concentration does not suppress the NOB population and inhibits the anammox population, while a DO concentration that is too low decreases the activity of the AOB population which could limit the substrate available to the anammox by limiting the amount of nitrite available (Chang et al. 2013).

The CANON process is the simplest nitrogen removal process (Jetten et al., 1997; Chang, et al., 2013). Its' advantages lie in being completely autotrophic without the need of carbon source addition, as well as reduced energy costs and lower biomass production in comparison with other processes. The CANON process performs in conditions that contribute to stable NOB suppression. Under DO limited environments, NOB face competition for DO from AOB, as well as, competition for nitrite from anammox. Sliekers et al. (2002) showed that the higher process temperature washes out NOB through SRT control. The issue with the SRT needing to be low for NOB suppression is the slow growth rate of anammox bacteria, which requires a long SRT. The only way to achieve both NOB suppression and anammox growth is to separate the two SRTs, which relies on the ability of the anammox bacteria to form granular biomass or colonize on biofilm. The CANON process can then be operated to separate the biomass sufficiently (Sliekers et al., 2002, 2003). Strous et al. (1998) found the SBR to be ideal for anammox granule formation and retention. Vazquez-Padin et al. (2009) found the air pulsing SBR to be economical and easy to control at moderately low temperatures. These researchers also found inoculating anammox enriched biomass in a nitrifying reactor greatly accelerates the start-up process.

2.11.3 DEMON

The DEMON process (DEamMONification) is a two-step process that occurs in an SBR: aerobic ammonia oxidation to nitrite (by AOB) and anaerobic ammonia oxidation to nitrogen gas (by anammox) (Figure 2-10). This process utilizes a pH-based control system which monitors the deammonification reaction and adjusts the aeration intervals based on the production of H^+ ions or nitrite(Wett 2007). At longer aeration intervals, more ammonia is converted to nitrite. At this point, nitritation is running at a higher rate than anammox. This H^+ production drives down the pH-value, causing aeration to stop(Wett 2007). The DEMON process also uses a hydrocyclone to separate the floc-phase SRT from the granule-phase SRT (Nifong et al., 2013). Anammox bacteria are capable of forming dense granules which settle quickly. The AOB-rich flocs are lighter, and thus less likely to settle quickly. When the hydrocyclone is fed the mixed sludge, the anammox-rich granules are separated into the underflow, while the lighter AOB-rich flocs are separated into the overflow and then wasted.

2.12 MAINSTREAM NOB SUPPRESSION:

Mainstream NOB suppression is difficult because of low temperature and low nitrogen levels. While it is not cost effective to raise the temperature, pH or nitrogen levels in mainstream processes, it is possible to control the aeration. Turk and Mavinic (1896) found that in systems which transition between anoxic and aerobic conditions in a plug-flow pre-denitrification reactor, NOB experience an activity lag of several hours behind AOB. Turk and Mavinic observed high nitrite accumulation in the first aerobic cell, with a subsequent decrease in the following aerobic cells (HRT 3 hours per cell). They found the degree to which nitrite accumulation decreased to be inversely correlated to the FA level in the anoxic cell. Turk and Mavinic explain that high free ammonia levels in the anoxic cell (2-6 mg N/L) temporarily inhibit NOB but not AOB. This inverse relationship between nitrite accumulation and FA level could also be the result of the development of what is termed an “ammonia valley” (Alghusian and Hao, 1995). Ammonia oxidation to nitrite consumes approximately 100% of the alkalinity associated with nitrification, causing the pH to drop. As the aeration time increases, the stress on the NOB population decreases, resulting in a loss of nitrite build-up. By utilizing online aeration control that terminates aeration prior to complete ammonium oxidation, effective NOB out-selection has been shown in sequencing batch reactors (SBR) (Kornaros et al., 2008; Yoo et al., 1999).

Zeng et al. (2010) suggested that AOB outcompete NOB at low DO concentrations due to their higher oxygen affinity, resulting in NOB suppression. Maintaining a low DO concentration (0.4 mg/L) has been suggested as a key factor to washout NOB and maintain stable nitritation in continuous plug-flow processes (Blackburne et al., 2008). However, all constant inflow reactors who have operated at low DO concentrations have achieved nitrite accumulation, but have failed to meet stringent TN effluent limits. Regmi et al. (2014) proposed SRT control to establish a differential between AOB and NOB rates, selectively washing out NOB to obtain successful nitritation/denitritation. The limited SRT (6.5 ± 4.3 days) operated just above AOB washout, allowing only NOB to be out-selected (Regmi et al. 2014). Additionally, based on Monod kinetics, an AOB-NOB differential can be obtained by optimal oxygen and nitrogen substrate levels (Regmi et al. 2014). Operation at a DO concentration of 1.5 mg O_2/L with intermittent aeration resulted in successful mainstream deammonification, which requires efficient NOB out-selection (Wett et al., 2012; De Clippeleir et al., 2013).

Zeng et al. (2010) showed nitritation could be achieved in a continuous anaerobic-anoxic-aerobic (A^2O) process through a combination of short aerobic hydraulic retention time (HRT) and low DO levels (0.3-0.5 mg/L). The reactor was fed mainstream domestic wastewater with an average ammonia level of 69 mgN/L and average COD level of 177 mg/L. Initial attempts to suppress NOB by just using a low DO set-point were unsuccessful. They then increased the rate in internal recycle to reduce the aerobic HRT (from 1.03 h to 0.86 h) and effectively create a rapidly alternating aerobic/anoxic environment. This resulted in a nitrite accumulation of up to 80%. To confirm the shorter HRT was the cause of the nitrite accumulation, the aerobic HRT was then increased back to 1.03 h where NOB suppression was sustained for 60 days. After 60 days aerobic HRT was increased to 1.55 h. At a 1.55 h HRT, NOB suppression was lost and AOB growth declined. The researchers suspected that NOB were suppressed as a result of enzymatic lag. However, high free ammonia residual was maintained and could also account for NOB suppression. This process did not observe low DO sludge bulking as was reported in previous studies by Ma et al. (2009).

Although successful report of NOB out-selection are rare for mainstream continuous plug-flow processes, Ge et al. (2014) successfully achieved high nitrogen removal efficiency (86.0±4.2%) with an influent COD/NH_4^+-N ratio of 5. This reported a high degree of NOB out-selection (nitrite accumulation of 81.5±9.2%) at 16-28°C as a result of NOB inhibition under transient anoxic conditions and step feed in the anoxic zone to remove the accumulated nitrite following the aerobic zone.

2.13 AOB/NOB INHIBITION FROM ORGANIC MATTER:

Researchers have found that the nitrification in a system may be inhibited by the existence of organic matter. Readily biodegradable organic matter supports the growth of heterotrophic bacteria in wastewater. Heterotrophic bacteria compete with the autotrophic nitrifiers for oxygen, nutrients and space (Sharma and Ahlert, 1977; Zhu & Chen, 2001; Wu et al., 2013). Grady and Lim (1980) reported heterotrophic bacteria as having a maximum growth rate of five times and yields of two to three times that of nitrifiers. This was also found by Carley and Mavinic (1991) and Zhu & Chen (2001).

Most research attempts to assess the inhibition of AOB/NOB from organic matter have been carried out in biofilters used in domestic wastewater with high concentrations of both ammonia nitrogen and organic matter (Hanaki et al. 1990; Figueroa and Silverstein, 1992; Cheng & Chen, 1994; Ohashi et al., 1995; Satoh et al., 2000; Zhu et al., 2001), with one exception (Bovendeur et al., 1990) which utilized a fixed-biofilm reactor in an aquacultural water recycle system. Bovendeur et al. (1990) found nitrification limited by the transfer of oxygen into the biofilm layer. Researchers saw nitrification rates decreased as DO levels decreased and/or organic loading rates increased. Cheng & Chen (1994) found the addition of sucrose (as a carbon source) in a fluidized bed reactor produced an inhibitory effect on both AOB and NOB in the nitrification process. Satoh et al. (2000) used acetate as a carbon source, finding that an increasing C/N ratio induced a competition for DO between the AOB and heterotrophic populations at the outer region of a biofilm. Because the heterotrophic population out-competed the AOB population, the AOB fraction was reduced and ammonia oxidation slowed. Finally, Zhu et al. (2001) studied the effect of sucrose carbon on the nitrification rate of biofilters under steady-state conditions in a reactor series experimental system. They found that as the organic concentration increased, the nitrification decreased, but as the carbon concentration became sufficiently high (C/N above 1.0), the heterotrophic inhibitory impact lessened.

2.14 MAINTAINING GOOD SETTLING UNDER AVN PROCESS TECHNOLOGY:

2.14.1 FILAMENTOUS BULKING

Bulking sludge refers to the excessive growth of filamentous bacteria, a common problem in activated sludge processes, which leads to poor settling and degraded effluent quality returned to the natural environment (Donaldson, 1932; Krhutkova et al., 2002). However, conflicting hypotheses are present as to whether or not filamentous organisms contribute to good floc formation. The first hypothesis demonstrated a correlation between extracellular polysaccharide (EPS) polymer production and good floc formation (Ehlers and Turner, 2011, Ehlers et al., 2012). The second hypothesis found both floc-forming bacteria and filamentous organisms to be necessary in all wastewater processes; settling issues arise when one is present without the other.

Ehlers & Turner (2011) found that nutrient concentrations in activated sludge (AS) systems may drive floc formation and EPS production. The study fed simple available carbon wastewater to lab-scale continuous stirred-tank reactors (CSTR) and SBRs to investigate the relationship between nutritional factors and AS community floc formation. Their findings revealed an inverse relationship between food-to-microorganism (F/M) ratio and EPS production which promoted floc formation in the AS communities (Ehlers & Turner, 2011). With the recycling of RAS, floc size stabilized (Ehlers et al., 2012), which could have been a result of biomass and EPS digestion in the clarifier, coupled with a reduction in EPS production when the aerobic AS community was exposed to anaerobic conditions in the clarifier (Wilen and Balmer, 1999).

Literature demonstrated that when only floc-forming bacteria exist, activated sludge flocs are usually small (up to about 75μm), spherical and compact (Jenkins et al. 2004). The lack of sufficient bioflocculation can result in pin floc, which are sheared flocs from turbulent conditions introduced by an aeration basin (mechanical aeration or coarse bubble diffusers) and/or by turbulent pumping, free-fall weirs, and piping (Jenkins et al. 2004). Pin floc activated sludge settles rapidly, but it produces turbid supernatant. However, an overabundance of filamentous organisms results in filamentous bulking, which interferes with the settling and compaction of activated sludge. Long filaments stretch out to form a bridge between flocs, causing them to become less dense and settle slowly and prevent proper compaction. The extent to which filaments affect settling and compaction depends on the causative filamentous organisms present and can be seen in Table 2-1. When the filamentous bulking activated sludge settles, the filamentous organism network filters out the small particles that can cause turbidity, producing a very clear, low turbidity supernatant (Jenkins et al. 2004).

Overall, there are many different approaches and theories behind the causes of bulking sludge in activated sludge processes. First, there is the question of whether morphology, physiology and substrate kinetics are related and how they contribute to the growth of the dominate filament population. Then, there are general theories to explain the occurrence of bulking sludge. Most of these theories still lack experimental verification. Finally, there are a few remedial actions that may be employed, such as aerobic, anaerobic and anoxic selectors.

In wastewater treatment, settling is typically the final treatment step before discharge into receiving water. The effectiveness of this step is dependent upon the effectiveness of settling of activated sludge and the ability of the activated sludge to form flocs. However, filamentous bulking sludge is a term used to describe excessive proliferation of filaments leading to the deterioration of effluent quality (Martins et al., 2004). Although both filamentous organisms and floc-forming organisms are essential to a wastewater treatment process, an excess of filaments can collapse a system. This thesis will address filaments identified within the B-stage of the pilot scale A/B process at the Chesapeake-Elizabeth WWTP over a 242 day study.

Table 2-2: Filamentous organism characterization and control.**

Filamentous Organisms	**Bridging**	**Open Floc Structure**	**Features***	**Control ***
Type 0041	Yes	Yes	Abundant in anaerobic-anoxic-aerobic systems; present at high SRTs; and possible growth on hydrolysis of particulate substrates.	Still uncertainty but the most recommended solutions are: install a skimmer to remove particulate substrate; maintain a plug-flow regime in all the system; the several stages (anaerobic/anoxic/aerobic) should be well defined; maintain a relatively high oxygen concentration in the aerobic phase (1.5 mg O2/L) and a low ammonium concentration (<1 mgN/L).
Type 0675	No	Yes		
Type 0803	Yes	No		(no data)
Type 021N	Yes	No	Use readily biodegradable substrates, especially low molecular weight organic acids; present at moderate to high SRT; capable of sulphide oxidizing to stored sulphur granules; and rapid nutrients uptake rates under nutrient deficiency.	Aerobic, anoxic or anaerobic plug flow selectors; nutrient addition; eliminate sulphide and/or high organic acid concentrations (eliminate septic conditions).
Thiothrix I and II	Yes	No		
Haliscomenobacter hydrossis	Yes	Yes	Use readily biodegradable substrates; grow	Aerobic, anoxic or anaerobic plugflow selectors; and increase SRT;

			well at low DO concentrations; grow over wide range of SRTs.	increase DO concentration in the aeration basin (>1.5 mg O2/L)

*Martins et al., 2004
**Jenkins et al. 2004

The activated sludge process consists of two stages, a biochemical stage (aeration tank) and a physical stage (secondary clarifier). The secondary clarifier determines an activated sludge systems effluent quality based on its' ability to achieve good solids separation (settling) and compaction (thickening) (Martins et al., 2004).

2.14.1.1 Filament Identification Approaches

One approach to solving the mystery of bulking sludge involves microscopically identifying the predominant filamentous bacteria, based on morphotype, responsible for bulking. The next step is to identify relationships between the filaments and the operational conditions present when they occur (DO concentration, F/M, etc.) and defining strategies for their control. Results for the filaments seen within this research are shown in Appendix A.7.

The morphological-ecological approach recognizes the filamentous bacterial population as having a greater ability to grow outside a floc, allowing a competitive advantage under substrate limited conditions where they have easy access to bulk liquid substrate (Martins et al., 2003 ; Martins et al., 2004). Under this assumption, the morphology of filamentous organisms would give them an ecological advantage and imply that they are able to be present under non-bulking process condition. Understanding the potential for a ubiquitous filamentous population within activated sludge led to the suggestion that filamentous organisms form the backbone of activated sludge flocs, promoting the attachment of other cells by their extracellular polymeric substances (EPS) (Sezgin et al., 1978; Kappeler & Gujer, 1994). Further, this would imply that a filamentous population is necessary, which is still under debate.

Type 0041/0675 are the major filaments arguably responsible for the bulking events in biological nutrient removal (BNR) in activated sludge systems (Martins et al., 2004). Type 021N and *Thiothrix* sp. are controlled by anaerobic and anoxic stages. The filamentous bacteria found in BNR systems are usually Gram positive, implying their hydrophobic cell surface could easily adsorb compounds with a low solubility (Eikelboom et al., 1998; Martins et al., 2004), potentially giving them a competitive advantage over floc-formers under substrate limited conditions.

2.14.1.2 Diffusion-based selection

The diffusion-based selection theory goes hand-in-hand with the morphological-ecological approach to understanding bulking sludge. The filaments are able to easily extend outside of the floc structures, allowing them preferential access to substrate in diffusion dominated conditions (low substrate concentrations). Van Loosdrecht et al. (1995) and Picioreanu et al. (1998) saw this in biofilms as they become open and filamentous as a result of the diffusion-dominated conditions. When substrate is not limited, compact and smooth biofilms arise.

2.14.1.3 Kinetic selection theory

Chudoba et al. (1985) formulated the kinetic selection theory to explain filamentous bacteria in activated sludge systems. He hypothesized that the filamentous microorganisms (K-strategists) are slow-growing organisms that can be characterised as having maximum growth rates (μ_{max}) and affinity constant (K_s) lower than the floc-forming bacteria (r-strategists). The actual substrate rate depends on the substrate concentrations, where q_s is the substrate uptake rate and q_{max} is the maximum substrate uptake rate (equation 10).

$$q_S = q_{max} \frac{K_S}{K_S + C_S} \tag{10}$$

When the substrate concentration is low (typically $C_S<K_S$) filamentous bacteria have a higher substrate uptake rate than floc formers and consume more of the available substrate. When the substrate concentration is high, the filamentous bacteria are suppressed since their growth rate is below that of floc-forming bacteria. The kinetic selection theory gave rise to the selector reactor to control filamentous bulking.

2.14.2 FACTORS KNOWN TO CONTRIBUTE TO FILAMENTOUS BULKING

Research aims to develop an understanding of the main causes of bulking and identify stresses that favor filamentous over floc-former growth. Factors known to encourage bulking are oxygen deficiencies, nutrient deficiencies and a decrease in the food/micro-organisms (F/M) ratio.

2.14.2.1 Low F:M, high SRT filaments in BNR processes

Filamentous bulking within BNR processes could be attributed to substrate availability and the influent rbCOD concentration (F:M ratio). BNR processes require a sufficiently long solids retention times (SRT) and conventionally separate aerated and unaerated zones in order to develop nitrifying and denitrifying organisms capable of producing an effluent low in ammonia. At longer anoxic SRTs, more nitrate can be denitrified, but up to half of the nitrate denitrified in the primary anoxic zone is due to rbCOD (Henze et al., 2008).

Although a broad and poorly defined parameter, high SRT is generally associated with low food-to-microorganism (F:M) ratios, implying low loading rate of substrate to sludge mass (Ekama et al., 1995). Figure 2-11 outlines the specific filaments present in activated sludge systems at various loading conditions and SRT. Loading conditions are present as the F/M ratio, which for the purposes of this thesis, will use the units kg BOD_5/kg MVLSS/d. The SRT is a calculation of the average time biomass stays in the activated sludge system (equation 11). SRT is based on the daily amount of suspended solids in the influent flow and the total amount of solids in the system, as determined by the MLSS calculation:

$$SRT\ (d) = \frac{lbs\ biomass\ or\ solids\ (MLSS)}{lbs\ biomass\ or\ solids\ wasted\ per\ day}$$

(11)

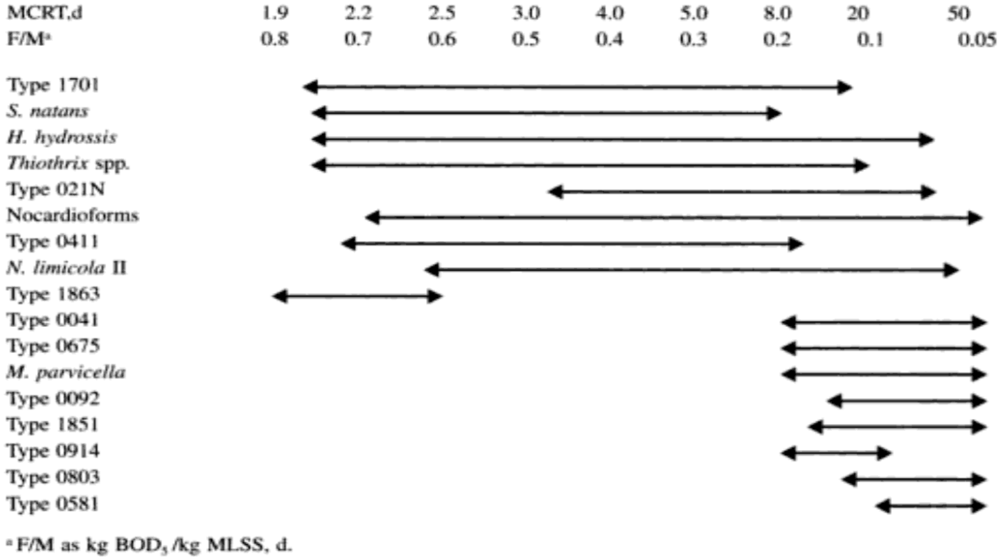

Figure 2-11: Relationship of specific filamentous organisms to MCRT and F/M in Activated Sludge, Richard 1989; Eikelboom 2000; Jenkins et al., 2004, used under fair use, 2014.

Scruggs & Randall (1998) assessed filamentous growth within four modified SBRs operated at four different F/M ratios of 0.02, 0.10, 0.28 and 0.70 lb sCOD/lb MLSS day at a constant DO concentration. Microbial populations in the mixed liquor were examined from each reactor at 0 and 12 hours, and at 24 hour intervals thereafter. Results confirmed ranges outlined in Figure 2-11, finding that bulking issues could be attributed to filaments associated with low F/M conditions. Typical low F/M, high SRT filaments in BNR systems include Type 0041, Type 0675, and *Microthrix parvicella.*

M. parvicella is the most common filamentous species linked to bulking and foaming problems in BNR systems. From a survey of Colorado (USA) plants treating domestic wastewater, *M. parvicella* have been shown to increase at high sludge ages (≥10 days) and cause operational problems (Richard, 1989). This sludge age value is common even if nitrogen removal is not necessary (Tchobanoglous et al., 2002) in order to maintain a safety factor against influent overloads. Another factor shown to promote the growth of *M. parvicella* is the availability of nitrogen compounds. Casey et al., (1994) hypothesized that filamentous bulking in nitrification-denitrification systems may occur as a result of competition for substrates between the filamentous and floc-forming organisms. Both the diffusion-based (section 2.14.1.2) and kinetic (section 2.14.1.3) selection theories support hypotheses that the growth of filamentous organisms under substrate limited conditions is favored. Further, the *NO Hypothesis* supports the accumulation of NO in floc-forming bacteria if denitrification is incomplete, thus exerting a toxic effect by preventing them from using sbCOD under aerobic conditions. This gives the filamentous bacteria the advantage to utilize rbCOD that is produced in low concentrations from hydrolysis of sbCOD, which occurs more in long SRT, low F/M systems.

2.14.2.2 Effects of low DO on filaments

Oxygen deficiency can cause the growth of several different types of filamentous organisms in activated sludge processes. Because filamentous bacteria have the capability of growing outside the floc structure, they have the competitive advantage over floc-forming bacteria in diffusional-resistant environments. Filaments are able to escape the confines of the floc, allowing preferential access to bulk liquid substrate (e.g. DO, nitrogen, sulphur, etc.) given their higher observed outward growth velocity (Martins et al., 2003; Martins et al., 2004). Van Loosdrecht et al. (1995) and Picioreanu et al. (1998) found these diffusion-dominated conditions to produce open, filamentous, biofilm structures. Martins et al. (2003, 2004) compared floc growth with biofilm growth, finding that low substrate or low oxygen concentrations lead to open, filamentous flocs resulting in poor settling.

Palm et al. (1980) determined the DO concentration required to prevent bulking within a municipal wastewater feed and continusously fed, completely mixed aeration basin. The DO concentration required was found to be a function of the F/M ratio; the higher the F/M ratio, the greater was the DO concentration required (Palm et al., 1980; Jenkins et al., 2004). Palm et al., (1980) showed that low DO bulking could be caused and fixed by manipulating F/M and DO concentrations; however, the fix takes much longer than the onset of bulking. When a quick fix is necessary, rapid nonspecific methods such as chlorine (Ramirez et al., 2000), ozone (Caravelli et al., 2006), and metal salts (Guo et al., 2012) may be used to lower the filamentous organism population.

Ma et al., (2009) operated a pilot-scale continuous pre-denitrification plant for the treatment of domestic wastewater at a low DO concentration (0.4-0.7 mg/L). The aim of this research was to achieve NOB out-selection in a mainstream simultaneous nitrification denitrification (SND) process. Researchers were able to successfully stop nitrification at nitrite demonstrating that over 95% of the oxidized nitrogen compounds at the end of the aerobic zone were nitrite. However, the nitrite accumulation deteoriated sludge settling regardless of the DO concentrations. The mechanism responsible for the strong correlation between nitrite accumulation and worsening sludge settling properties is unknown; however, Casey et al. (1994, 1999) hypothesized that nitric oxide (a denitrification intermediate) could inhibit the floc-formers but not the filamentous organisms, leading to poorer sludge settleability.

Gaval & Pernelle (2003) observed the impact of repetitive oxygen deficiences on the filamentous bacteria population in two activated sludge pilot plants. Low DO concentrations are considered stresses on a WWTP that frequently go unnoticed. However, as Gaval & Pernelle (2003) found, these stresses, when repeated, result in the proliferation of filamentous bacteria *Sphaerotilus natans, Haliscomenobacter hydrossis,* Eikelboom Type 021N and *Thiothrix* spp. As these filaments multiplied, the sludge volume index (SVI) of the system deteoriated, resulting in bulking (>200 mL/g).

2.14.3 SELECTORS

Although a general solution to bulking has yet to be discovered, there are rememdies to filamentous bulking that have shown limited success, such as selectors. A selector is defined as the initial part of a biological reactor, characterised by a low dispersion number and by an adequate macro-gradient of substrate concentration (Chudoba et al., 1973; Martins et al., 2004). Selectors subject microorganisms to subsequent feast and famine periods; feasting takes place in a high growth rate environment where microorganisms are able to store substrate (storage) and famine takes place in a low growth rate environment to reestablish the cells storage capacity. There are three types of selectors, aerobic, anoxic and anaerobic.

2.14.3.1 Aerobic selectors

Aerobic selectors are implemented to control bulking sludge attributed to the excessive growth of Type 021N, *Thiothrix* spp., *S. natans,* and sometimes *M. parvicella* (Martins et al., 2004). The most important design parameter for aerobic selectors is the contact time. Martins et al. (2003) found a strong, non-linear effect between the contact time and the sludge settleability. If the contact time is too short, soluble substrate is not consumed and flows into the main aeration basin. If the contact time is too long, too much soluble substrate is consumed which induces substrate limited conditions which favor filamentous bacteria over floc-forming bacteria. Another important parameter is the DO concentration. The DO sensor is best placed in the first compartment where the oxygen consumption is the highest to prevent poor sludge settleability as a result of a too low aeration rate (Martins et al. 2003).

2.14.3.2 Anoxic selectors

Anoxic selectors, or anoxic zones, are located at the front end of the aeration basin where the influent wastewater and the RAS mix. Similar to the aerobic selectors, anoxic selectors want to consume the soluble substrate prior to its' entrance into the aerobic stage to select against filamentous bacteria. Oxygen should also be absent in anoxic selectors. The main design parameter for anoxic selectors is the rbCOD/NO_3-N (readily biodegradable chemical oxygen demand/nitrate) ratio. The RAS supplies the NO_3^- concentration, while the rbCOD is present in the influent wastewater.

2.14.3.3 Anaerobic selectors

Anaerobic selectors contain no oxygen or oxidized nitrogen species and seeks to consume any rbCOD prior to the aerobic stage. The main design parameter is the ratio of rbCOD uptake rate to phosphorus release rate. In anaerobic selectors, phosphate accumulating organisms (PAOs) and glycogen accumulating organisms (GAOs) are able to store substrate, allowing them to remove the incoming organic load. As the PAOs and GAOs consumer more, there is less substrate available in the oxic stage allowing for improved sludge settleability.

Typical operational characteristics of aerobic, anoxic and anaerobic selectors is found in Table 2-3.

Table 2-3: Typical operational characteristics associated with selectors.

Selector type	Compartments	Contact time	Design parameter	Reference
Aerobic	≥ 3	10-15min	DO concentration: ≥ 2 mg O_2/L	Eikelboom et al., 1998; Martins et al., 2003; Martins et al., 2004; Daigger et al., 2007

Anoxic	≥3	45-60min	$(rbCOD/NO_3\text{-}N)_{CONSUMED}$: >79 mg rbCOD/mg NO_3-N due to storage	Albertson 1987; Jenkins, et al., 2004
Anaerobic	≥3, long channel (l:w larger than 10:1)	1-2 hours	$(COD_{VFA+fermentable}/PO_4\text{-}P)_{inf}$: 9-20 g COD/g P	Albertson 1987

*Data in table taken from Martins *et al.,* 2004

2.14.4 ANALYTICAL METHODS AND MONITORING OF SETTLEABILITY

The efficiency of activated sludge treatment plants is dependent on effective bioflocculation to create an efficient solid-liquid separation of activated sludge from treated wastewater. Without stable microbial floc formation, increased concentrations of suspended solids will be present in the effluent. Analytical methods and monitoring of settleability within a system warn operators when potential bulking issues arise that could deteriorate plant effluent. Although knowledge of the exact causes of filamentous bulking and the deterioration of floc formation is limited, the following represent known methods of early indication.

2.14.4.1 Sludge Volume Index (SVI)

The SVI is an attempt to quantify the settling characteristics of activated sludge (SM 18th 2710C). It is relatively easy to obtain and is an indicative parameter of the settleability quality of sludge. An index over 150 mL/g is considered bulking and rectifying measures are needed.

The SVI is the volume of 1 g of sludge after 30 minutes of settling. The SVI is determined by placing a mixed-liquor sample in a 2-L settleometer and measuring the settled volume after 30 minutes and the corresponding sample MLSS concentration (Tchobanoglous et al., 2004). Equation 12 computes the SVI from the settleometer reading and MLSS concentration:

$$SVI = \frac{\left(settled\ sludge\ volume, \frac{mL}{L}\right)\left(\frac{10^3 mg}{g}\right)}{\left(suspended\ solids, \frac{mg}{L}\right)} = \frac{mL}{g} \tag{12}$$

The SVI may be calculated after both 5 and 30 minutes of settling. This allows different processes to compare SVI values and understand the speed at which the solids interface reached its final compaction value and the type of settling that has occurred. Settling is categorized in four types: type I is discrete particle settling in dilute suspensions, type II is flocculent materials in dilute suspensions, type II is zone or hindered settling and type IV is compression settling (Tchobanoglous et al., 2004).

2.14.4.2 Zone Settling Velocity

The Zone Settling Velocity (ZSV) is described in SM 20th 2710E. According to Chen (1994), the zone settling curve is composed of four stages: the induction, constant-rate, falling-rate and the compression periods. The settling velocity is obtained from the plot of the time versus the interface height, isolating the constant-rate period. The initial settling velocity can be determined by isolating this constant-rate period of the graph and determining the slope.

The Vesilind equation (equation 13) theoretically describes the observed gravity flux curve with defined turning and inflection points (Giokas et al., 2003). The graph of the initial settling velocities versus the initial suspended solids concentrations (MLSS) are described by the Vesilind equation:

$$V_i = V_o e^{-kCi} \tag{13}$$

where V_i is the settling velocity (m/hr), V_o the initial settling velocity (m/hr), C_i the initial suspended solids concentration (kg/m^3) and k the empirical settling parameter (m^3/kg). However, to carry out this test, various ZSV versus MLSS concentrations are needed for the sample

2.14.4.3 Floc size

Floc size may be determined through direct, microscopic floc size measurements using a eyepiece micrometer. Measure 10 to 20 flocs and categorize them based on small ($\leq$150 μm), medium (150-500 μm) or large ($\geq$500 μm) if they are approximately spherical. Measurements of floc size and size distribution allow operators to predict negative changes in the structures of flocs in an activated sludge system (Barbusinski & Miksch, 1997).

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3. METHODOLOGY

3.1 PILOT SETUP

This thesis will focus on the operation and resulting performance of the AVN pilot. The A/B pilot study consists of a HRAS process (A-stage) for high rate carbon removal followed by a BNR process (B-stage) for nitrogen removal (Figure 3-1). The AvN pilot functions as a part of this larger configuration including a high rate activated sludge A-stage (HRT = 30 min, SRT = 0.25 days) for COD removal providing the influent for the AvN reactor (Miller et al., 2012, Figure 3-1) and a post anoxic anammox moving bed bioreactor after the AvN reactor (Figure 3-1) allowing for a final polishing of the treated sewage.

3.1.1 PRELIMINARY TREATMENT

Using a chopper pump, raw wastewater influent (RWI) for the pilot process was pumped from the effluent channel of the preliminary treatment facility (PTF) at Chesapeake-Elizabeth treatment plant (CETP). The PTF includes fine screens and forced vortex grit removal. Due to the inefficiencies of the PTF, the pumped RWI first passed through a 568 L drum equipped with a variable speed mixer that was operated at a speed that allowed grit to settle but kept particulate and colloidal organic matter in suspension. Accumulated grit was periodically removed 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 through basket screens with 2.4 mm openings into a temperature control tank. This tank contained submersible heaters and a finned-tube coil. Coolant was circulated through the coil and a water-cooled water chiller. A PLC controlled power to the heater and chiller based on a signal from a thermocouple in the temperature control tank and a user set-point. This setup provided the capability to provide a constant influent wastewater temperature to the biological processes anywhere from 15 to 25°C. The temperature control tank also contained a constant speed mixer. These processes were only necessary for the pilot and not intended for the full-scale process.

3.1.2 HIGH-RATE ACTIVATED SLUDGE PROCESS (HRAS-CONTROL)

From the temperature control tank, the wastewater was pumped to three HRAS reactors. These reactors were constructed from clear PVC pipe supported vertically on one end with an operating volume of 511 L, a hydraulic residence time (HRT) of 30 minutes and a side water depth of 3.4 meters (11 feet). Aeration was provided by an air compressor and a 17.7 cm membrane disc diffuser with the DO monitored by a Hach LDO probe. The desired DO set-point was maintained by a single-loop proportional-integral-derivative (PID) controller controlling a mechanically operated valve (MOV) on the compressed air line. The HRAS reactor was mixed by large bubble mixing every two minutes. The final reactor overflowed by gravity to a cone-bottom clarifier outfitted with a scraper mechanism that rotated at 0.25 rpm and directed settled solids to the bottom of the clarifier cone. The clarifier had a submerged vertical inlet inside of a center well. This configuration helped dissipate the influent hydraulic energy and allowed additional bioflocculation to occur before solids separation. Effluent from the clarifier overflowed to a 208 L (55 gal) drum that served as a flow through feed storage tank for the B-stage. A-stage effluent was pumped from the feed storage tank to the B-stage with a progressive cavity pump.

Optimization of A-stage control and operation was a separate research project conducted by Virginia Tech doctoral candidate Mark Miller. Details on this project can be found in *Mechanisms of COD removal in the adsorption stage of the A/B process*, with future publications to follow (Miller et al., 2013).

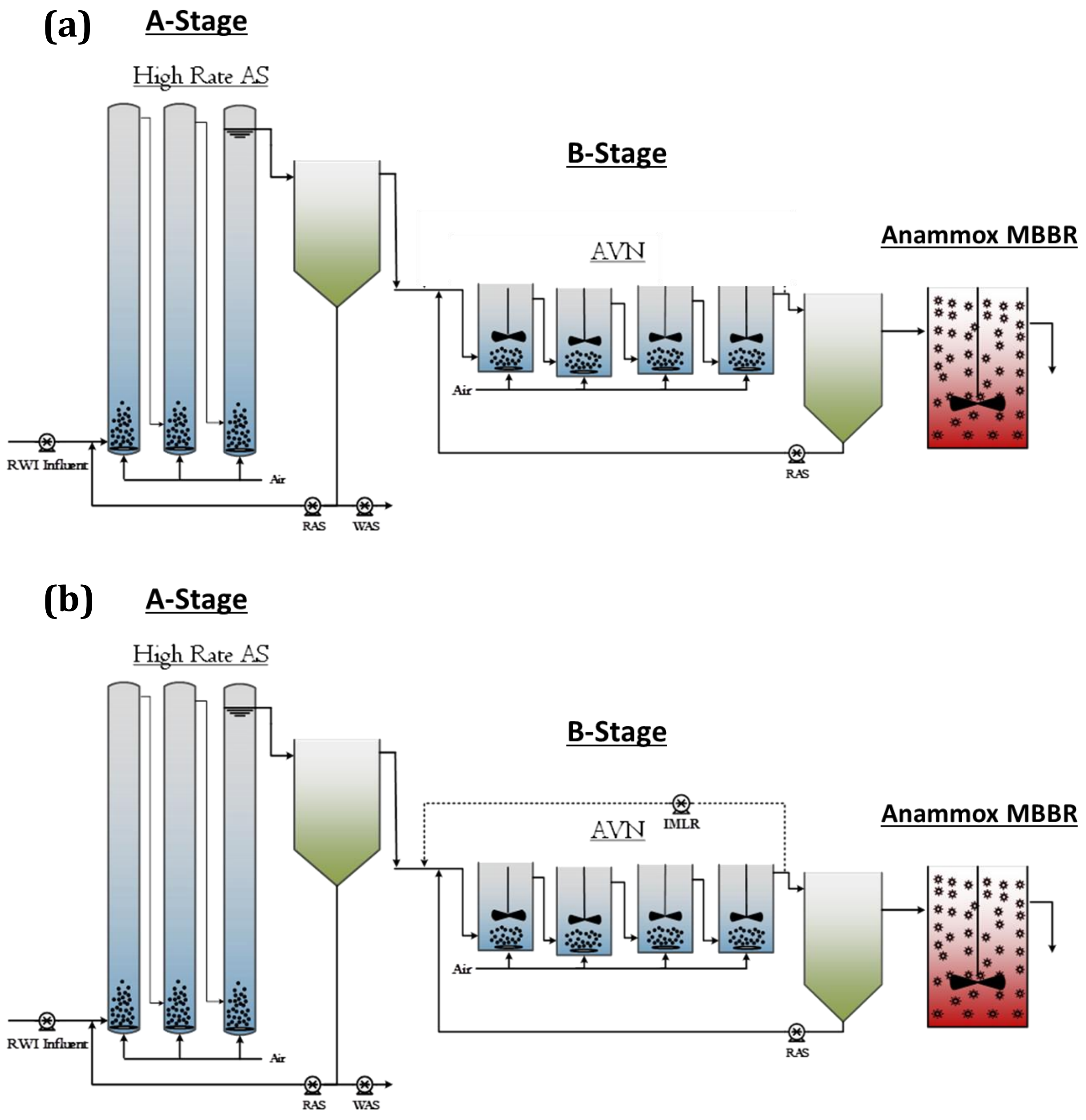


Figure 3-1: A/B pilot process flow diagram, (a) full intermittent aeration (b) Modified Ludzak-Ettinger (MLE) with IMLR line.

3.1.3 B-STAGE AVN

The B-stage consisted of four equal volume tanks in series, each 151 L for a total operating volume of 606 L , and a cone-bottom clarifier. The clarifier had a submerged vertical inlet inside of a center well. This configuration helped dissipate the influent hydraulic energy and allowed additional bioflocculation to occur before solids separation. The cone-bottom clarifier was outfitted with a scraper mechanism that rotated at 0.25 rpm and directed settled solids to the bottom of the clarifier cone. All four biological reactors were equipped with a variable speed mixer, a 17.7 cm membrane disc diffuser, and a Hach LDO probe. Aeration capacity in all 4 tanks allowed the system to be operated with or without a defined anoxic zone. The B-stage had a variable HRT (2-7 hours) and a variable influent flow rate. When operating in MLE configuration, an internal mixed liquor recycle (IMLR) line returned nitrified mixed liquor from the last aerobic reactor to the anoxic reactor using a peristaltic pump at a rate between 200-450% of the influent flow. When IMLR was used the first tank was not aerated. RAS from the clarifier was returned to the anoxic zone at 100% of the influent flow. SRT was controlled by wasting solids from the last aerobic tank. The wasting was automated to maintain desired SRT. The AvN process was equipped with sensors to monitor NH_4^+-N, NO_2^--N and NO_3—N. pH was monitored using a Foxboro pH probe in the last aerobic reactor.

3.2 START-UP AND LONG TERM OPERATION IN DIFFERENT PHASES

The B-stage reactors were seeded from the waste activated sludge (WAS) of the CETP.

Typical A-stage effluent is characterized by: pH 6.96 ± 0.08, COD 288 ± 69, sCOD 146 ± 35, pCOD 143 ± 45, NH_4^+ 32.6 ± 4.5, NO_2^- and NO_3^- are assumed to be 0, TKN 37.2 ± 4.9, sTKN 29.1 ± 4.0, OP 3.01 ± 0.89, TP 4.43 ± 0.88, sTP 2.17 ± 0.57, alkalinity 159 ± 15, cBOD 109 ± 33 and scBOD 45 ± 20. The B-stage was operated in different phases differentiated by operational mode and HRT. The total SRT was targeted to be around 6 days and temperature was maintained at 23ºC during the entire study. The aerobic SRT was controlled by online aeration controller to achieve the desired NH_4^+:NO_2^- ratio.

3.3 AVN AERATION CONTROL STRATEGY

To impose conditions favorable for NOB out-selection and to provide effluent suitable for anaerobic ammonia oxidation (AMX) polishing, an aeration controller was developed which uses on-line *in-situ* DO, NH_4^+, NO_2^- and NO_3^- sensors. The first component of AvN control was the aerobic duration controller based on the goal of maintaining equal effluent NH_4^+-N and NO_x-N (NH_4^+-N / NO_x-N = 1) in the final CSTR of the B-stage at all times. The latter would guarantee a treatable effluent for final polishing with AMX. The other component of the AvN control was the DO controller which maintains the DO set-point, set by the user, as desired during the aerated period (Figure 3-2).

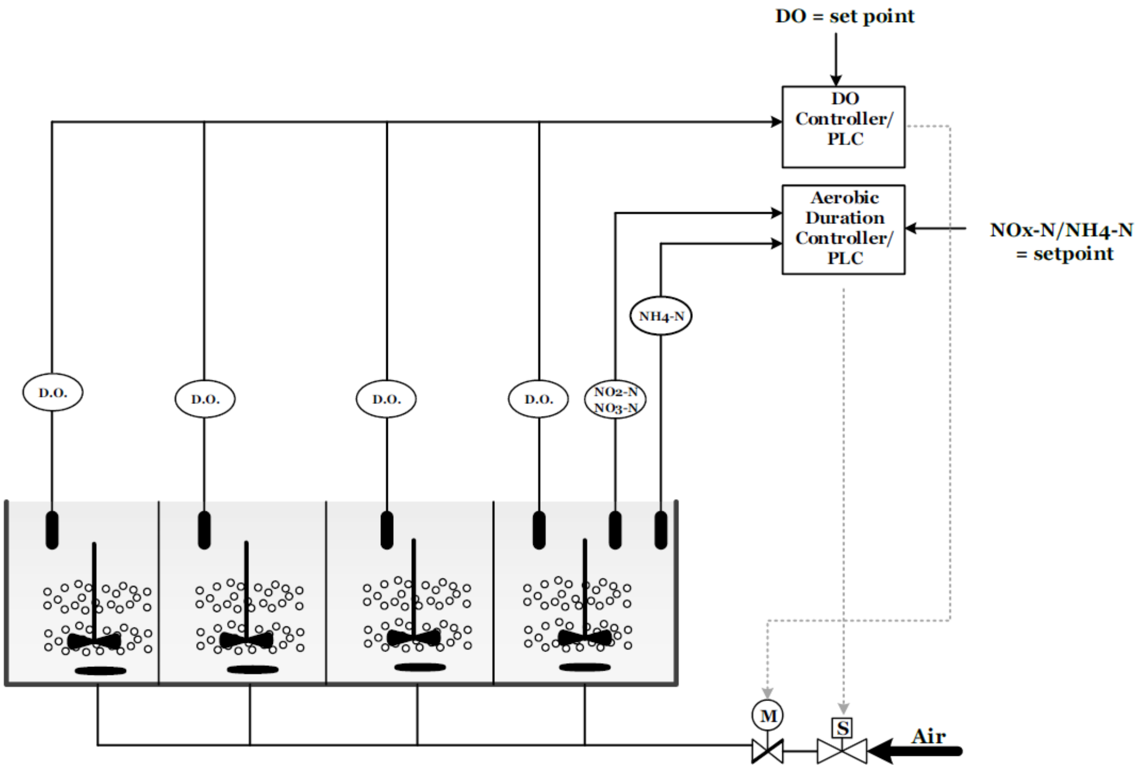


Figure 3-2: AvN controller set-up with four DO controllers sending dissolved oxygen signals, NH_4^+, NO_2^-, and NO_3^- signals to the aerobic duration controller.

Under the AvN control strategy, NH_4^+-N was compared to the sum of NO_2^- -N and NO_3—N (NO_x-N). To begin, the cycle duration (aerobic time + anoxic time) had a defined minimum and maximum aerobic time. The cycle time was kept constant at 16 minutes with a minimum and maximum aeration time of 4 and 12 minutes, respectively. These set-points were chosen to maintain a NH_4^+-N concentration of at least 1.5 mg-N/L to prevent a DO spike resulting in overaeration. The goal of the AvN controller was to maintain NH_4^+-N concentrations equal to NO_x-N, when the NH_4^+-N concentration was greater than NO_x-N, the aerobic time would increase. When the NO_x-N concentration was greater than the NH_4^+-N concentration, the aerobic time was decreased. The cycle duration was constant throughout. The aerobic time was allowed to fluctuate between the minimum and maximum set-points by a PID controller. When aerated, a PID controller controlled a MOV to maintain the target DO set-point of 1.5 mg O_2/L. The working of this controller can be seen in Figure 3-3.

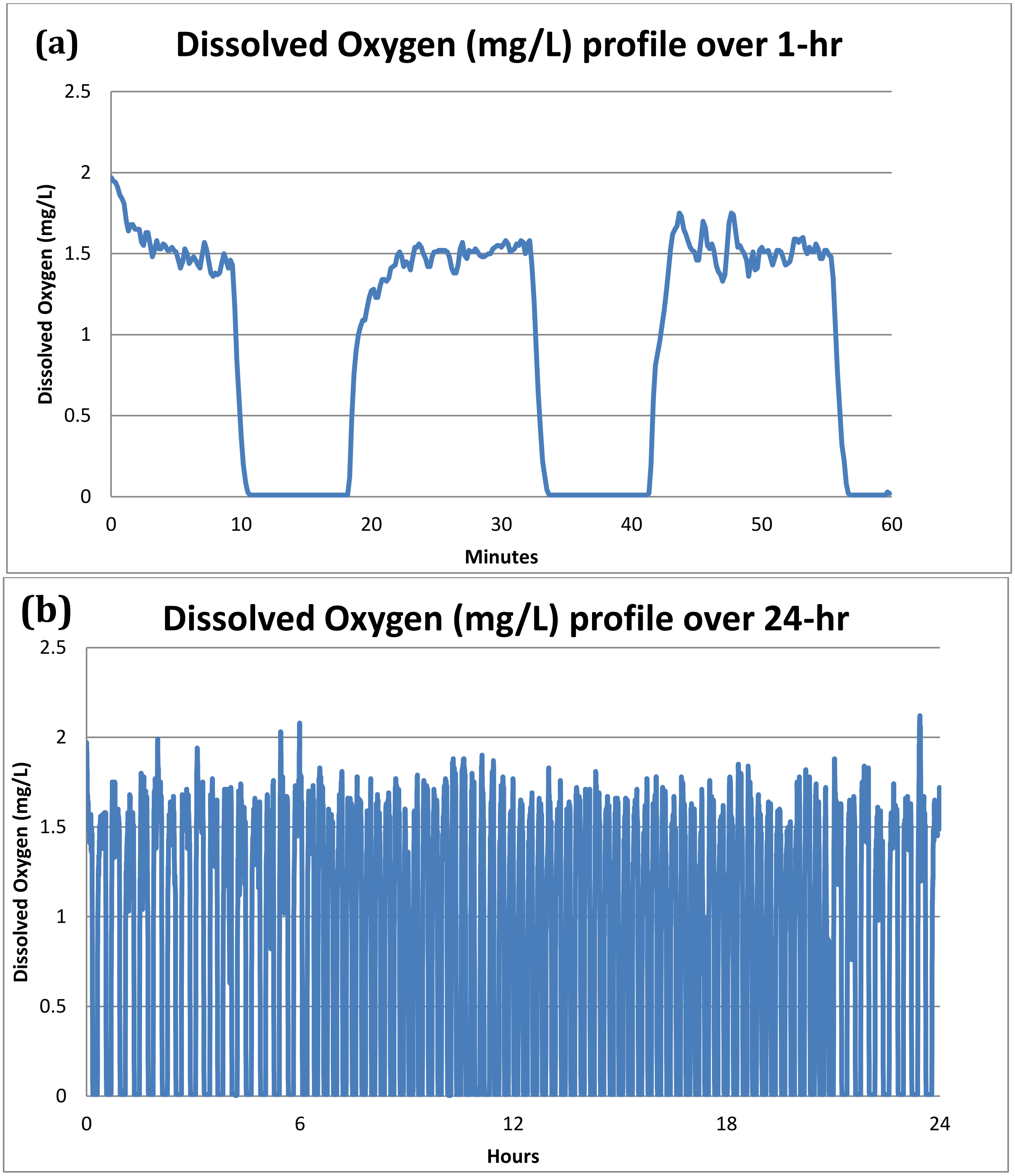


Figure 3-3: Example of Intermittent Aeration (a) Example of intermittent aeration over an hour (b) Example of intermittent aeration over a 24-hour period with a 12 minute cycle time (max aeration of 10 minutes, min aeration of 2 minutes per cycle) with a DO set-point of 1.5 mg O_2/L.

In order to examine the main objectives of this thesis, the B-stage was operated in eight different operational phases shown in Table 3-1.

Table 3-1: Operational phases of B-stage pilot.

Phase	Operation	HRT (hrs)	Number of days
I	All Reactors Intermittently Aerated	3	65
II	All Reactors Intermittently Aerated	4	12
III	MLE (IMLR 200%)	3	15
IV	MLE (IMLR 450%)	6	13
V	MLE (IMLR 325%)	6	11
VI	All Reactors Intermittently Aerated	6	17
VII	All Reactors Intermittently Aerated	2	43
VIII	All Reactors Intermittently Aerated	3	59

3.3 INFLUENT/EFFLUENT MONITORING

Performance of the AVN pilot was monitored by collecting 24-hr flow-weighted composite samples from the influent and effluent. Samples were analyzed for TSS, VSS, total, and soluble, COD, TKN, TP, OP, NO_3^--N, NO_2^--N, NH_4^+-N and alkalinity. All relevant analytical methods performed at the Chesapeake-Elizabeth wastewater treatment plant (WWTP) for solids and liquids are presented in Table 3-2.

Table 3-2: Analytical measurements performed at Chesapeake-Elizabeth WWTP in pilot study location.

Parameter	Reference Method	Description
TSS	SM 20th 2540D	TSS - Total Suspended Solids Dried at 103-105°C
NH_3-N	Hach 10205	-Ammonia TNTplus ULR (0.015 to 2.00 mg/L NH3–N) -Ammonia TNTplus LR (1 to 12 mg/L NH3–N) -Ammonia TNTplus HR (2 to 47 mg/L NH3–N)
NO_2-N	Hach 10019	-Nitrite NitriVer 3 TNT LR (0.002 to 0.500 mg/L NO2–N) -Nitrite TNTplus HR (0.6 to 6.0 mg/L NO2–N)
NO_3-N	Hach 10206	-Nitrate TNTplus LR (0.23 to 13.5 mg/L NO3–N) -Nitrate TNTplus HR (5 to 35 mg/L NO3–N)
OP	Hach 8048	Reactive Phosphorus TNT LR (0.6 to 5.00 mg/L PO43-)

COD	Hach 8000	-COD TNTplus HR (20 to 1500 mg/L COD) -COD TNTplus LR (3 to 150 mg/L COD)
SVI	SM 18th 2710C	Settled Sludge Volume
ZSV	SM 20th 2710 E	Zone Settling Rate

All relevant analytical methods performed twice a week by HRSD's Central Environmental Lab (CEL) are shown in Table 3-3.

Table 3-3: Analytical measurements taken and performed by HRSD's CEL.

Parameter	Reference Method	Description
TSS	SM 20th 2540D	TSS - Total Suspended Solids Dried at 103-105°C
TVSS	SM 18th 2540E	TVSS – Fixed and Volatile Solids Ignited at 550°C
TKN	EPA 351.2 Lachat 10-107-06-2-I	Determination of Total Kjeldahl Nitrogen by Flow Injection Analysis Colorimetry (Block Digestion)
NH_3-N	EPA 350.1 Lachat 10-107-06-1-C	Determination of Ammonia by Flow Injection Analysis Colorimetry
NO_2-N, NO_3-N	EPA 353.2 Lachat 10-107-04-1-C/A	Determination of Nitrate/Nitrite by Flow Injection Analysis Colorimetry
TP	EPA 365.1 Lachat 10-115-01-1-E	Determination of Total Phosphorous by Flow Injection Analysis Colorimetry (Acid Persulfate Digestion)
OP	Lachat 10-115-01-1-A	Orthophosphate in Waters
COD	Hach 8000	Chemical Oxygen Demand, Reactor Digestion Method
Alkalinity	EPA 310.2 Lachat 10-303-31-1-A	Determination of Alkalinity by Flow Injection Analysis Colorimetry

3.4 MICROBIAL ACTIVITY MEASUREMENTS

To measure AOB and NOB activity, 4 L samples were collected from the AvN CSTR and aerated for 30 minutes to oxidize excess COD, dispensed into 4L vessels and spiked with 20-30 mg/L NH_4^+-N (as ammonium chloride) and 2-4 mg/L NO_2^--N (as sodium nitrite), respectively and sampled continuously for 1 hour at 20-minute intervals. All collected samples were analyzed for NH_4^+-N, NO_2^--N, and NO_3^--N. Mixing was provided by a magnetic stir bar. The dissolved oxygen was maintained between 2.5 and 4 mg O_2/L. pH was maintained between 7-7.5 by adding sodium bicarbonate. The AOB rates were calculated as the slope of the NOx-N production and NOB rates were calculated as the slope of the NO_3—N production.

3.5 OXYGEN UPTAKE RATE (OUR)

To measure the OUR, 4 L samples were taken from each of the four tanks in the B-stage. A magnetic stir bar, DO probe and aeration stone were placed in each sample. Samples were initially aerated to 3-4 mg O_2/L, at which point the air was shut-off and DO measurements were taken every 10 seconds until the DO concentration falls below 1 mg O_2/L. This process was repeated 3 times. Results were graphed on three different time (hr) versus DO concentration (mg/L) plots. The slope of the graph represents the OUR (mg/L/hr). The average of the slopes of the three different plots was accepted as the OUR for each sample.

3.6 MICROSCOPY

Observation and counting of the different bacteria were performed using a Leica 2500 phase contrast microscope couple to a Leica DFC 290 camera. The Gram and Neisser staining techniques were used for identification. Based on the criteria suggested by Jenkins et al. (2004), the filamentous microorganism abundance and dominance were estimated and subjectively rated for overall abundance on a scale from 0 (none) to 6 (excessive). If three or more filaments are present within the sample, the filaments are ranked from dominant, secondary, tertiary in terms of abundance. Pictures taken throughout the experiment can be seen in Appendix 7.

4. MANUSCRIPT 1: PROCESS OPTIMIZATION FOR IMPROVED N REMOVAL EFFICIENCIES IN AN INTERMITTENTLY AERATED PILOT-SCALE BNR PROCESS

ABSTRACT

The ability of two different process configurations (full intermittent aeration and Modified Ludzak-Ettinger [MLE]) to achieve high nitrite accumulation and nitrogen removal efficiencies in four equal volume tanks in series followed by a cone-bottom clarifier in a pilot scale biological nitrogen removal (BNR) process ($V=0.61\ m^3$) was evaluated. All four biological reactors were equipped with a variable speed mixer, a 17.7 cm membrane disc diffuser, and a Hach LDO probe. SRT was controlled by wasting solids from the last aerobic tank. The wasting was automated to maintain desired SRT. This experiment was run over 242 days under various loading conditions at ambient temperature ($T=23.8\pm1.1°C$); therefore, the experiment has been divided into Phases I-VIII for ease of comparison. Operational and process control strategies were utilized to out-select nitrite oxidizing bacteria (NOB) based on optimizing the chemical oxygen demand (COD) input, imposing transient anoxia, aggressive solids retention time (SRT) operation towards ammonia oxidizing bacteria (AOB) washout and a dissolved oxygen concentration (DO) of 1.5 mg O_2/L during aeration. During Phase IV, the process was operated as a MLE demonstrating a total inorganic nitrogen (TIN) removal efficiency of $86.3\pm5\%$ within a hydraulic retention time (HRT) of 6 hours and a solids retention time (SRT) of 4.4 ± 0.7 days. This phase demonstrated a TIN removal rate of 113.6 ± 8.3 mgN/L/d at an influent COD/NH_4^+ -N ratio of 10.3 ± 1.2. Phase VIII was operated with all reactors intermittently aerated sustaining a nitrite accumulation ratio (NO_2^- -N/NO_x^- -N) of 0.43 ± 0.10 while AOB activity was greater than NOB activity [NOB rate/AOB rate, (%)=$67.1\pm8\%$] at a 3 hour HRT, 4.2 ± 1.0 day SRT and influent COD/NH_4^+ -N ratio of 12.1 ± 4.0. Therefore, this pilot-scale study demonstrates that when run aggressively, the proposed online aeration control is able to out-select NOB in mainstream conditions and provide relatively high nitrogen removal without supplemental carbon and alkalinity at low HRT. This process also has the ability to be run in conjunction with an Anammox process to act as a polishing step to achieve increased nitrogen removal.

Keywords: Modified Ludzak-Ettinger, Biological nitrogen removal, nitrite accumulation, nitritation, denitritation, AOB, NOB, NOB out-selection, transient anoxia, intermittent aeration, online aeration control

4.1 INTRODUCTION

Around the world, wastewater treatment plants (WWTP) face increasing financial pressures associated with increasingly stringent water quality standards. Nitrogen and Phosphorus are essential to the growth of algae and aquatic plants; however, when present in excess, they pollute the environment creating algal blooms. Strict nutrient standards have been created in response to degrading environmental and ecological conditions as a result of nutrient pollution. Biological nitrification and denitrification are commonly used to remove nitrogen from wastewater (Grady et al., 2011). However, these processes are resource intensive and not always capable of achieving low nutrient limits. This creates the need for innovative technology to help ease the financial burden and create a more efficient nitrogen removal process.

Nitrification is the conversion of ammonia (NH_4^+ -N) to nitrate (NO_3^- -N) through nitrite (NO_2^- -N) in an aerobic environment and denitrification is the subsequent conversion of nitrate to dinitrogen gas (N_2) through nitrite in the absence of oxygen. Nitrification requires energy in the form of aeration, whereas denitrification requires carbon. Nitritation-denitritation avoids the conversion of nitrite to nitrate by nitrite oxidizing bacteria (NOB) and allows for the reduction of nitrite to dinitrogen gas by heterotrophic denitrifying bacteria. In theory, repression of nitrite oxidation allows for a possible 40% reduction in the carbon requirement for full denitrification and a 25% reduction in aeration costs by avoiding the oxidation of nitrite to nitrate (Turk & Mavinic, 1987). However, successful nitritation-denitritation has been achieved predominantly in nutrient rich sidestream processes (Van Kempen et al., 2001). NOB are shown to be successfully out-selected in the following sidestream conditions: high temperature (Hellinga et al., 1998), low dissolved oxygen (DO) (Joss et al., 2009), low solids retention time (SRT) (Van Dongen et al., 2001) and residual free ammonia (FA) inhibition (Anthonisen et al., 1976).

However, these out-selection mechanisms are not realistic for typical mainstream processes: the influent ammonia concentrations (<80 mg N/L) are too low for a residual to accumulate and inhibit NOB and influent flow temperatures vary, making a high temperature parameter unreliable for consistent NOB out-selection. The main factors shown to accomplish mainstream NOB out-selection has been utilizing online aeration control to control ammonia concentration and DO concentration in sequencing batch reactors (SBRs) (Blackburne et al., 2008; Guo et al., 2009; Peng et al., 2007). When these approaches are applied to mainstream continous plug-flow systems, successful NOB out-selection is rare; nitrite accumulation is achieved, but commonly stringent TN effluent limits are not met. Recent research demonstrated nitritation could be achieved in a continuous anaerobic-anoxic-aerobic (A^2O) process through a combination of short aerobic hydraulic retention time (HRT) and low DO levels (0.3-0.5 mg/L), though TN removal efficiencies only reached 74% (C/N ratio of 2.3) (Zeng et al., 2010). Additionally, operation at a DO concentration of 1.5 mg O_2/L resulted in successful mainstream deammonification, which requires efficient NOB out-selection (Wett et al., 2012; De Clippeleir et al., 2013). Recently, Ge et al. (2014) successfully achieved high nitrogen removal efficiency ($86.0\pm4.2\%$) with an influent COD/NH_4^+-N ratio of 5 and a high degree of NOB out-selection (nitrite accumulation of $81.5\pm9.2\%$) at 16-28^oC as a result of NOB inhibition under transient anoxic conditions.

Based on these previous studies, four strategies for NOB out-selection in mainstream processes have been outlined in Table 4-1 by Regmi, et al. (2014) to achieve sustained NOB out-selection in mainstream conditions.

Table 4-1: Mainstream NOB out-selection strategies (Regmi, 2014).

Strategy	Action	Impact	Control Basis
1	$\frac{NH_4^+}{NO_2^- + NO_3^-} = 1$	Optimum aerated and unaerated volume for nitrification and denitrification. Optimum alkalinity for AOB growth. Residual ammonium supports higher AOB growth rates.	Control based on real-time effluent NH_4^+, NO_2^-, NO_3^- signals.
2	Intermittent aeration and bioavailable COD	Bioavailable COD allows NO_2^- consumption by denitrifiers	Upstream organic carbon treatment system.
3	DO>1.5 mg/L	AOBs to grow faster than NOB	Control DO set-point.
4	Aggressive low SRT	AOBs to grow rapidly, making them competitive relative to stressed NOBs due to strategies 1, 2 and 3.	Wasting.

In this study, an A/B pilot process was utilized to out-select NOB, with an anammox polishing step at the end (not addressed further in this paper). The A-stage is a high-rate activated sludge (HRAS) process that removes (or redirects for energy production) carbon prior to the B-stage. The A-stage was operated to control the influent carbon to ammonia ratio (COD/NH_4^+-N) and find the optimum ratio into the B-stage for nitrogen removal. The B-stage was operated at a short SRT and HRT as a novel nitritation-denitritation process named AOB versus NOB (AvN). The B-stage AvN process was operated under an intermittent aeration control strategy with a target effluent NO_x-N (NO_3^- -N + NO_2^- -N) to NH_4^+-N ratio of 1. Creating a B-stage effluent with equal parts NO_x-N and NH_4^+-N allows the anammox polishing step to achieve increasingly low nitrogen concentrations in the final effluent.

4.2 HYPOTHESIS/PROJECT OBJECTIVES

Current sidestream NOB out-selection parameters take advantage of high influent NH_4^+-N concentrations and free ammonia (FA) and free nitrous acid (FNA) inhibition, which are not always possible in mainstream wastewater treatment processes. The goal of this research was to effectively utilize information learned in sidestream applications and apply them to continuous plug-flow mainstream processes at ambient temperature. Regmi (2014) created a novel control strategy known as AOB versus NOB (AvN). This novel strategy utilizes intermittent aeration in all reactors to achieve NOB out-selection in mainstream plug-flow processes with low influent NH_4^+-N concentrations at ambient temperature to create a B-stage effluent with equal parts NO_x-N and

NH_4^+-N. However, effluent from the nitrogen removal stage (B-stage) containing NO_x-N and NH_4^+-N may not meet effluent nitrogen limits and may require anammox polishing. The AvN reactor configuration (all reactors intermittently aerated), as well as, a Modified Ludzak-Ettinger (MLE) process was implemented and analyzed at various loading conditions to achieve increased nitrite accumulation (NOB out-selection) and nitrogen removal performance.

Objective 1: Optimize and compare two different reactor configurations (intermittent aeration and MLE) to achieve NOB out-selection in a continuous mainstream plug-flow process.

Objective 2: Assess the effects of various loading conditions on NOB out-selection mechanisms to achieve successful nitrite accumulation and nitrogen removal performance.

4.3 METHODOLOGY

4.3.1 PILOT SETUP

This thesis focused on the operation and resulting performance of the AVN pilot. The A/B pilot study consists of a HRAS process (A-stage) for high rate carbon removal followed by a BNR process (B-stage) for nitrogen removal (Figure 4-1). The AvN pilot functions as a part of this larger configuration including a high rate activated sludge A-stage (HRT = 30 min, SRT = 0.25 days) for COD removal providing the influent for the AvN reactor (Miller et al., 2012, Figure 4-1) and a post anoxic anammox moving bed bioreactor after the AvN reactor (Figure 4-1) allowing for a final polishing of the treated sewage.

4.3.1.1 Preliminary Treatment

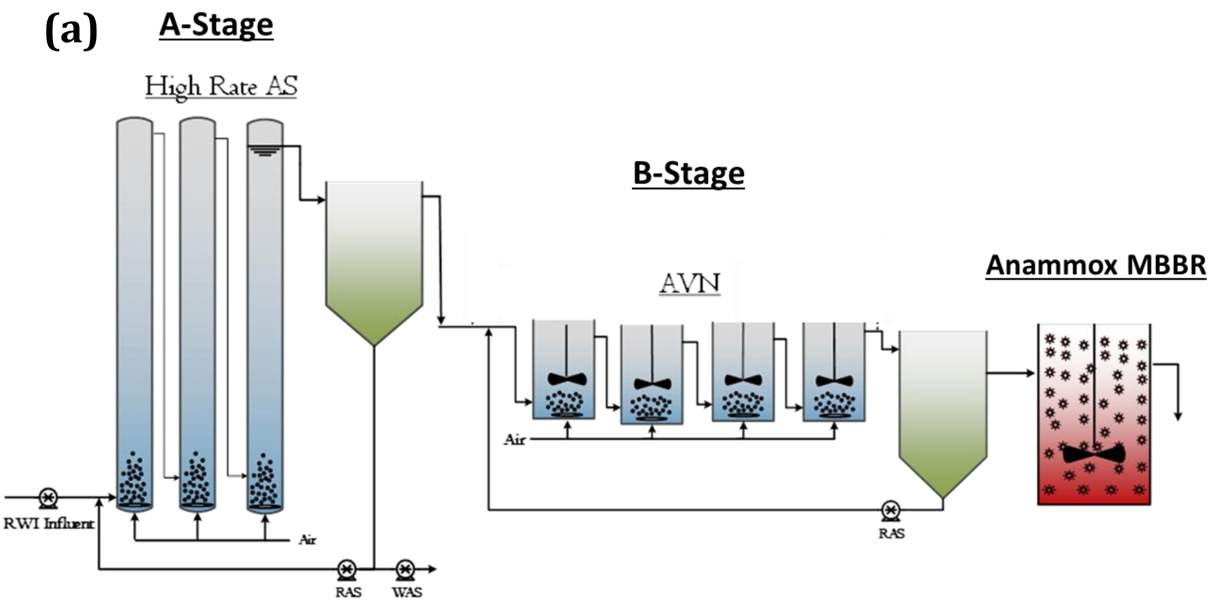
Using a chopper pump, raw wastewater influent (RWI) for the pilot process was pumped from the effluent channel of the preliminary treatment facility (PTF) at Chesapeake-Elizabeth Treatment Plant (CETP). The PTF includes fine screens and forced vortex grit removal. Due to the inefficiencies of the PTF, the pumped RWI first passed through a 568 L drum equipped with a variable speed mixer that was operated at a speed that allowed grit to settle but kept particulate and colloidal organic matter in suspension. Accumulated grit was periodically removed 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 through basket screens with 2.4 mm openings into a temperature control tank. This tank contained submersible heaters and a finned-tube coil. Coolant was circulated through the coil and a water-cooled water chiller. A PLC controlled power to the heater and chiller based on a signal from a thermocouple in the temperature control tank and a user set-point. This setup provided the capability to provide a constant influent wastewater temperature to the biological processes anywhere from 15 to 25°C. The temperature control tank also contained a constant speed mixer. These processes were only necessary for the pilot and not intended for the full-scale process.

4.3.1.2 High-Rate Activated Sludge Process (HRAS-control)

From the temperature control tank, the wastewater was pumped to three HRAS reactors. These reactors were constructed from clear PVC pipe supported vertically on one end with an operating volume of 511 L, a hydraulic residence time (HRT) of 30 minutes and a side water depth of 3.4

meters (11 feet). Aeration was provided by an air compressor and a 17.7 cm membrane disc diffuser with the DO monitored by a Hach LDO probe. The desired DO set-point was maintained by a single-loop proportional-integral-derivative (PID) controller controlling a mechanically operated valve (MOV) on the compressed air line. The HRAS reactor was mixed by large bubble mixing every two minutes. The final reactor overflowed by gravity to a cone-bottom clarifier outfitted with a scraper mechanism that rotated at 0.25 rpm and directed settled solids to the bottom of the clarifier cone. The clarifier had a submerged vertical inlet inside of a center well. This configuration helped dissipate the influent hydraulic energy and allowed additional bioflocculation to occur before solids separation. Effluent from the clarifier overflowed to a 208 L (55 gal) drum that served as a flow through feed storage tank for the B-stage. A-stage effluent was pumped from the feed storage tank to the B-stage with a progressive cavity pump.

Optimization of A-stage control and operation was a separate research project conducted by Virginia Tech doctoral candidate Mark Miller. Details on this project can be found in *Mechanisms of COD removal in the adsorption stage of the A/B process*, with future publications to follow (Miller et al., 2013).



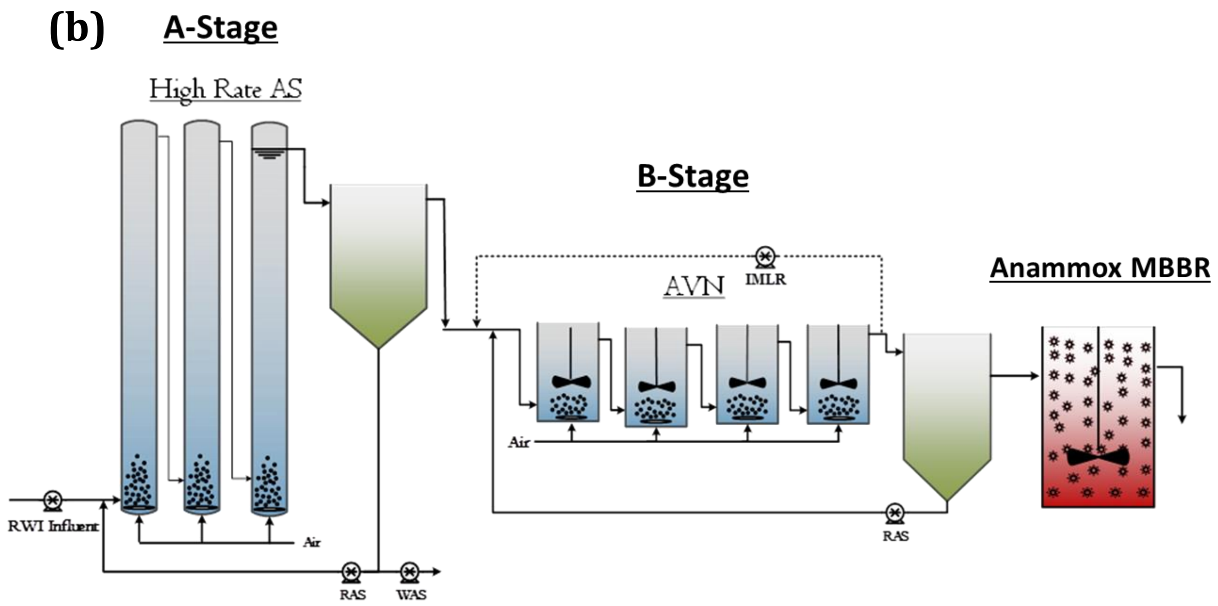


Figure 4-1: A/B pilot process flow diagram, (a) full intermittent aeration (b) Modified Ludzak-Ettinger (MLE) with IMLR line.

4.3.1.3 B-stage AvN

The B-stage consisted of four equal volume tanks in series, each 151 L for a total operating volume of 606 L , and a cone-bottom clarifier. The clarifier had a submerged vertical inlet inside of a center well. This configuration helped dissipate the influent hydraulic energy and allowed additional bioflocculation to occur before solids separation. The cone-bottom clarifier was outfitted with a scraper mechanism that rotated at 0.25 rpm and directed settled solids to the bottom of the clarifier cone. All four biological reactors were equipped with a variable speed mixer, a 17.7 cm membrane disc diffuser, and a Hach LDO probe. Aeration capacity in all 4 tanks allowed the system to be operated with or without a defined anoxic zone. The B-stage had a variable HRT (2-7 hours) and a variable influent flow rate. When operating in MLE configuration, an internal mixed liquor recycle (IMLR) line returned nitrified mixed liquor from the last aerobic reactor to the anoxic reactor using a peristaltic pump at a rate between 200-450% of the influent flow. When IMLR was used the first tank was not aerated. RAS from the clarifier was returned to the anoxic zone at 100% of the influent flow. SRT was controlled by wasting solids from the last aerobic tank. The wasting was automated to maintain desired SRT. The AvN process was equipped with sensors to monitor NH_4^+-N, NO_2^--N and NO_3—N. pH was monitored using a Foxboro pH probe in the last aerobic reactor.

4.3.2 START-UP AND LONG TERM OPERATION IN DIFFERENT PHASES

The B-stage reactors were seeded from the waste activated sludge (WAS) of the CETP.

Typical A-stage effluent is characterized by: pH 6.96 ± 0.08, COD 288 ± 69, sCOD 146 ± 35, pCOD 143 ± 45, NH_4^+ 32.6 ± 4.5, NO_2^- and NO_3^- are assumed to be 0, TKN 37.2 ± 4.9, sTKN 29.1 ± 4.0, OP 3.01 ± 0.89, TP 4.43 ± 0.88, sTP 2.17 ± 0.57, alkalinity 159 ± 15, cBOD 109 ± 33 and scBOD 45 ± 20. The B-stage was operated in different phases differentiated by operational mode and HRT. The total SRT was targeted to be around 6 days and temperature was maintained at 23ºC during the entire study. The aerobic SRT was controlled by online aeration controller to achieve the desired NH_4^+:NO_2^- ratio.

4.3.3 AVN AERATION CONTROL STRATEGY

To impose conditions favorable for NOB out-selection and to provide effluent suitable for anaerobic ammonia oxidation (AMX) polishing, an aeration controller was developed which uses on-line *in-situ* DO, NH_4^+, NO_2^- and NO_3^- sensors. The first component of AvN control was the aerobic duration controller based on the goal of maintaining equal effluent NH_4^+-N and NO_x-N (NH_4^+-N / NO_x-N = 1) in the final CSTR of the B-stage at all times. The latter would guarantee a treatable effluent for final polishing with AMX. The other component of the AvN control was the DO controller which maintains the DO set-point, set by the user, as desired during the aerated period (Figure 4-2).

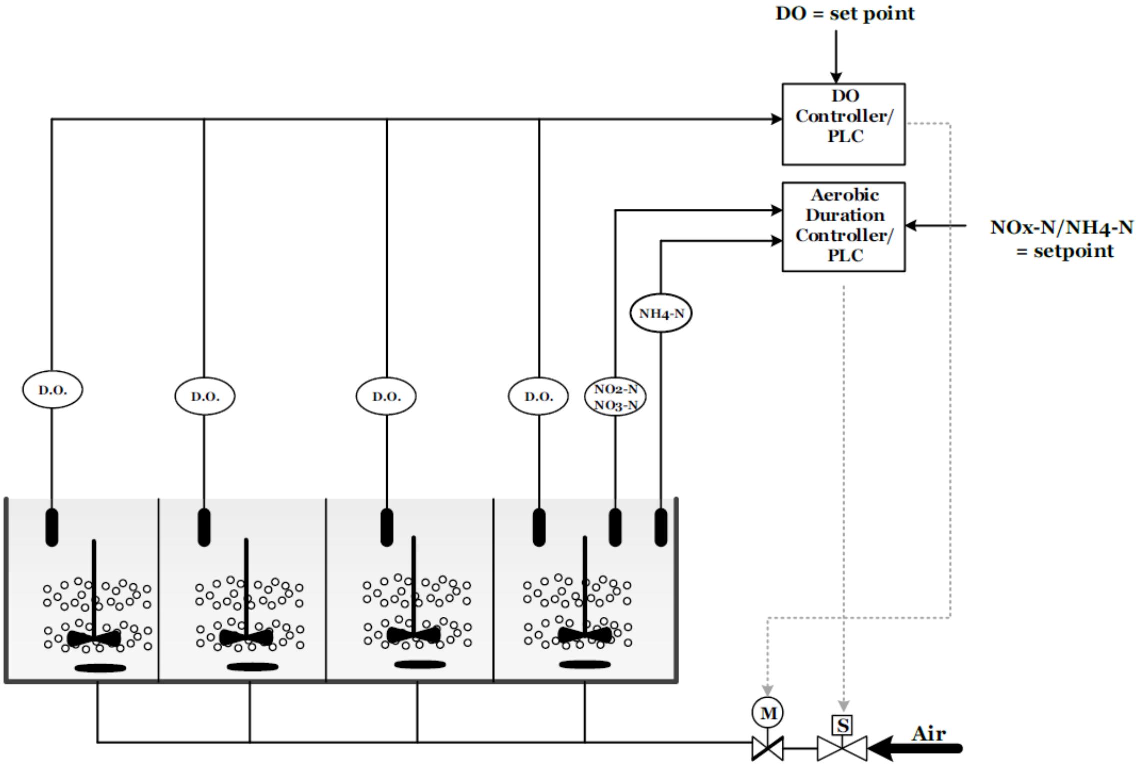
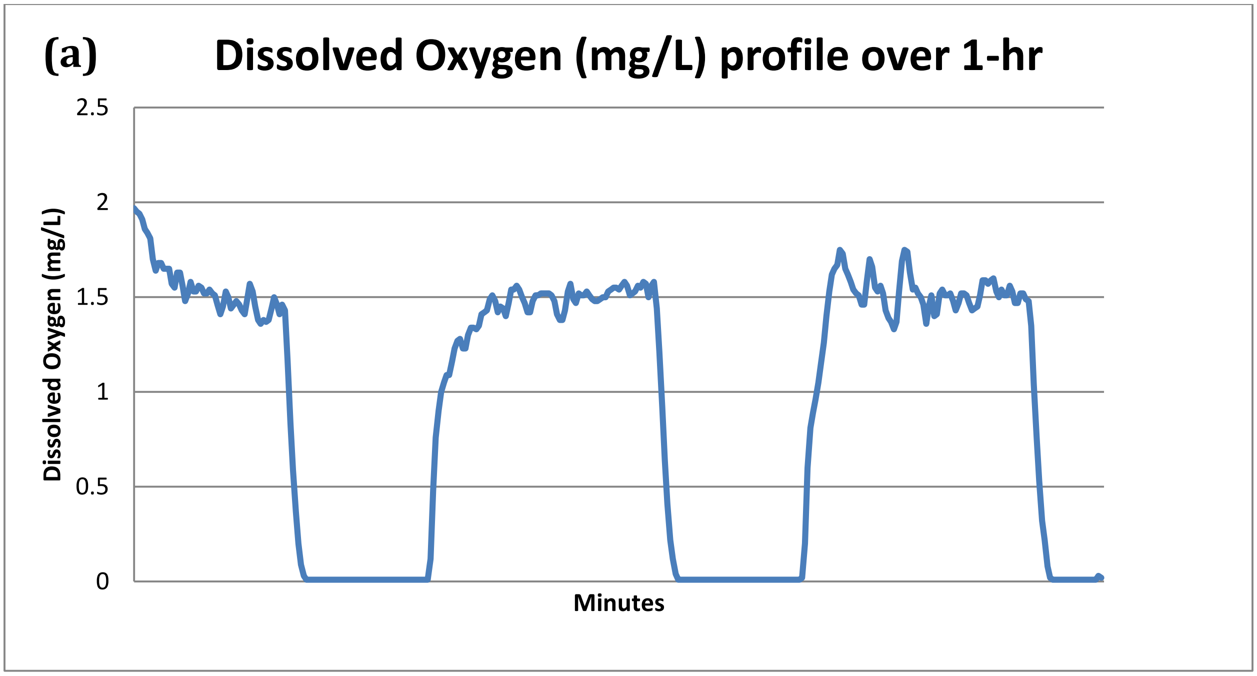


Figure 4-2: AvN controller set-up with four DO controllers sending dissolved oxygen signals, NH_4^+, NO_2^-, and NO_3^- signals to the aerobic duration controller.

Under the AvN control strategy, NH_4^+-N was compared to the sum of NO_2^- -N and NO_3—N (NO_x-N). To begin, the cycle duration (aerobic time + anoxic time) had a defined minimum and maximum aerobic time. The cycle time was kept constant at 16 minutes with a minimum and maximum aeration time of 4 and 12 minutes, respectively. These set-points were chosen to maintain a NH_4^+-N concentration of at least 1.5 mg-N/L to prevent a DO spike resulting in overaeration. The goal of the AvN controller was to maintain NH_4^+-N concentrations equal to NO_x-N, when the NH_4^+-N concentration was greater than NO_x-N, the aerobic time would increase. When the NO_x-N concentration was greater than the NH_4^+-N concentration, the aerobic time was decreased. The cycle duration was constant throughout.

The aerobic time was allowed to fluctuate between the minimum and maximum set-points by a PID controller. When aerated, a PID controller controlled a MOV to maintain the target DO set-point of 1.5 mg O_2/L. The working of this controller can be seen in Figure 4-3.



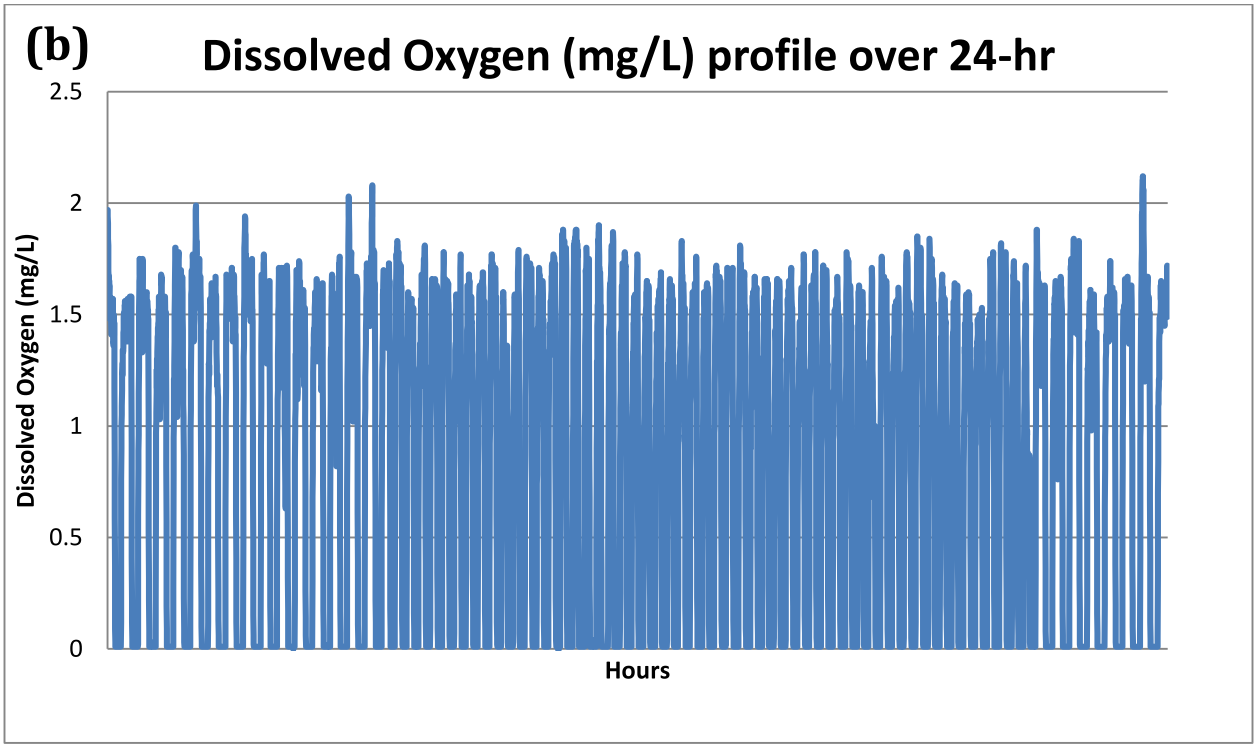


Figure 4-3: Example of Intermittent Aeration (a) Example of intermittent aeration over an hour (b) Example of intermittent aeration over a 24-hour period with a 12 minute cycle time (max aeration of 10 minutes, min aeration of 2 minutes per cycle) with a DO set-point of 1.5 mg O_2/L.

In order to examine the mainstream NOB out-selection objectives, the B-stage was operated in eight different operational phases shown in Table 4-2.

Table 4-2: Operational phases of B-Stage pilot.

Phase	Operation	HRT (hrs)	Number of days
I	All Reactors Intermittently Aerated	3	65
II	All Reactors Intermittently Aerated	4	12
III	MLE (IMLR 200%)	4	15
IV	MLE (IMLR 450%)	6	13
V	MLE (IMLR 325%)	6	11
VI	All Reactors Intermittently Aerated	6	17
VII	All Reactors Intermittently Aerated	2	43
VIII	All Reactors Intermittently Aerated	3	59

4.3.3 INFLUENT/EFFLUENT MONITORING

Performance of the AVN pilot was monitored by collecting 24-hr flow-weighted composite samples from the influent and effluent. Samples were analyzed for TSS, VSS, total, and soluble, COD, TKN, TP, OP, NO_3^--N, NO_2^--N, NH_4^+-N and alkalinity. All relevant analytical methods performed at the Chesapeake-Elizabeth wastewater treatment plant (WWTP) for solids and liquids are presented in Table 4-3.

Table 4-3: Analytical measurements performed at Chesapeake-Elizabeth WWTP in pilot study location.

Parameter	Reference Method	Description
TSS	SM 20th 2540D	TSS - Total Suspended Solids Dried at 103-105°C
NH_3-N	Hach 10205	-Ammonia TNTplus ULR (0.015 to 2.00 mg/L NH3–N) -Ammonia TNTplus LR (1 to 12 mg/L NH3–N) -Ammonia TNTplus HR (2 to 47 mg/L NH3–N)
NO_2-N	Hach 10019	-Nitrite NitriVer 3 TNT LR (0.002 to 0.500 mg/L NO2–N) -Nitrite TNTplus HR (0.6 to 6.0 mg/L NO2–N)
NO_3-N	Hach 10206	-Nitrate TNTplus LR (0.23 to 13.5 mg/L NO3–N) -Nitrate TNTplus HR (5 to 35 mg/L NO3–N)

OP	Hach 8048	Reactive Phosphorus TNT LR (0.6 to 5.00 mg/L PO43-)
COD	Hach 8000	-COD TNTplus HR (20 to 1500 mg/L COD) -COD TNTplus LR (3 to 150 mg/L COD)
SVI	SM 18th 2710C	Settled Sludge Volume

All relevant analytical methods performed twice a week by HRSD's Central Environmental Lab (CEL) are shown in Table 4-4.

Table 4-4: Analytical measurements taken and performed by HRSD's CEL.

Parameter	Reference Method	Description
TSS	SM 20th 2540D	TSS - Total Suspended Solids Dried at 103-105°C
TVSS	SM 18th 2540E	TVSS – Fixed and Volatile Solids Ignited at 550°C
TKN	EPA 351.2 Lachat 10-107-06-2-I	Determination of Total Kjeldahl Nitrogen by Flow Injection Analysis Colorimetry (Block Digestion)
NH_3-N	EPA 350.1 Lachat 10-107-06-1-C	Determination of Ammonia by Flow Injection Analysis Colorimetry
NO_2-N, NO_3-N	EPA 353.2 Lachat 10-107-04-1-C/A	Determination of Nitrate/Nitrite by Flow Injection Analysis Colorimetry
TP	EPA 365.1 Lachat 10-115-01-1-E	Determination of Total Phosphorous by Flow Injection Analysis Colorimetry (Acid Persulfate Digestion)
OP	Lachat 10-115-01-1-A	Orthophosphate in Waters
COD	Hach 8000	Chemical Oxygen Demand, Reactor Digestion Method
Alkalinity	EPA 310.2 Lachat 10-303-31-1-A	Determination of Alkalinity by Flow Injection Analysis Colorimetry

4.3.4 MICROBIAL ACTIVITY MEASUREMENTS

To measure AOB and NOB activity, 4 L samples were collected from the AvN CSTR and aerated for 30 minutes to oxidize excess COD, dispensed into 4L vessels and spiked with 20-30 mg/L NH_4^+-N (as ammonium chloride) and 2-4 mg/L NO_2^--N (as sodium nitrite), respectively and sampled continuously for 1 hour at 20-minute intervals. All collected samples were analyzed for NH_4^+-N, NO_2^--N, and NO_3^--N. Mixing was provided by a magnetic stir bar. The dissolved oxygen was maintained between 2.5 and 4 mg O_2/L. pH was maintained between 7-7.5 by adding sodium bicarbonate. The AOB rates were calculated as the slope of the NOx-N production and NOB rates were calculated as the slope of the NO_3—N production.

4.3.5 OXYGEN UPTAKE RATE (OUR)

To measure the OUR, 4 L samples were taken from each of the four tanks in the B-stage. A magnetic stir bar, DO probe and aeration stone were placed in each sample. Samples were initially aerated to

3-4 mg O_2/L, at which point the air was shut-off and DO measurements were taken every 10 seconds until the DO concentration falls below 1 mg O_2/L. This process was repeated 3 times. Results were graphed on three different time (hr) versus DO concentration (mg/L) plots. The slope of the graph represents the OUR (mg/L/hr). The average of the slopes of the three different plots was accepted as the OUR for each sample.

4.4 RESULTS

The operation of the B-stage can be divided into eight phases based on reactor configuration and HRT (Table 4-2). This data begins two weeks after seeding and start-up to allow for stabilization. The initial phase, Phase I, was operated under full AvN with an HRT of 3 hours beginning in September and running through the beginning of November 2013. Phase II continued in full AvN at a greater HRT of 4 hours from early to mid-November 2013. At the end of Phase II and into Phase III, there was a heater malfunction in the A-stage resulting in a temporary decrease in the influent carbon loading resulting in decreased nitrogen removal efficiency. Mid-November, Phase III began in MLE configuration with 200% NRCY return at a 3 hour HRT. Aeration to the first tank was shut-off. During the last 5 days of Phase III the NRCY was increased from 200-300% to help increase the biomass in the system after a wash-out due to clarifier malfunction. Phase IV continued in MLE mode with a NRCY of 450% at a 6 hour HRT for approximately two weeks before the NRCY was decreased to 325% in Phase V. Towards the end of Phase V the telog network went down, failing to relay pump failures and causing clarifier malfunctions in both the A-stage and B-stage. Tanks were refilled with NPW and returned to normal operation. The system returned to AvN operation in Phase VI at the end of December 2013 through mid-January 2014. AvN operation continued through Phases VII and VIII with HRTs of 2 and 3, respectively. During Phase VIII the alarms went off in the middle of the night with no one to correct this and all of the biomass in the nitrogen removal (B-stage) was lost. Data collected through April 30, 2014 will be presented.

The key characteristics of the B-stage effluent are shown in Table 4-5. For the purposes of this thesis, the experiments have been divided into eight phases (I-VIII) based on HRT and operation (Table 4-2).

Table 4-5: Comparison of different operational phases to achieve NOB out-selection in mainstream conditions. Phases indicated in orange distinguish an MLE process from an intermittently aerated process (black).

Phase	I	II	III	IV	V	VI	VII	VIII
NH_4^+-N loading rate (kg/L.d)	284±34	225±12	221±12	132±10	140±7	126±10	343±30	237±26
TIN removal rate (kg/L.d)	156±48	151±21	168±15	114±8	108±0	99±6	172±39	131±56

TIN removal efficiency (%)	55±15	67±8	76±4	86±5	80±0	78±3	50±10	54±20
Influent COD/NH_4^+-N	8.0±1.4	8.2±0.9	9.2±0.8	10.3±1.2	9.8±0.4	11.0±0.8	9.1±2.0	7.9±1.4
COD removal rate/TIN removal rate	13.0±2.4	10.2±1.4	10.7±1.0	10.4±1.3	10.1±0	11.9±0.9	14.1±3.1	12.1±4.0
Total SRT (days)	7.1±2.6	6.7±1.3	6.8±1.1	4.4±0.7	4.1±0.03	4.6±0.5	5.6±1.6	4.2±1.0
Aerobic SRT (days)	3.8	2.7	2.7	1.6	1.6	1.8	3.5	2.1
Aerobic SRT fraction	0.54±0.07	0.40±0.04	0.42±0.04	0.37±0.04	0.38±0.03	0.38±0.04	0.62±0.10	0.47±0.09
NH_4^+-N loading rate/Max AOB rate*	0.96±0.24	1.03±0.60	0.55±0	0.54±0.02	0.51±0	0.56±0.08	0.82±0.27	0.73±0.16
NAR**	0.30±0.08	0.23±0.04	0.20±0.04	0.14±0.03	0.17±0	0.19±0.08	0.34±0.09	0.43±0.10
Max NOB rate/Max AOB rate (%)	65±16	90±19	72±4	104±5	94±0	102±13	69±7	67±8
SVI (mL/g)	145±49	114±24	150±14	140±23	99±16	92±3	119±29	121±23
Effluent NO_x-N/Effluent NH_4^+-N	1.07±0.21	0.99±0.13	0.94±0.25	1.40±0.37	1.19±0.08	1.19±0.11	1.01±0.23	1.07±0.18

*Aggressiveness factor

**Nitrite Accumulation Ratio (NAR): NO_2^-- N/(NO_2^-- N + NO_3^- -N)

4.4.1 AVN NITROGEN REMOVAL PERFORMANCE

The trends of influent NH_4^+-N and NOx-N are presented in Figure 4-4, which demonstrates the effectiveness and consistency of AvN control in maintaining equal NH_4^+-N and NOx-N in the effluent before the anammox polishing step. Although these effluent nitrogen concentrations may not be sufficient to meet increasingly stringent nitrogen limits, they produce an effluent amenable to a final anammox polishing step capable of meeting stringent nitrogen limits.

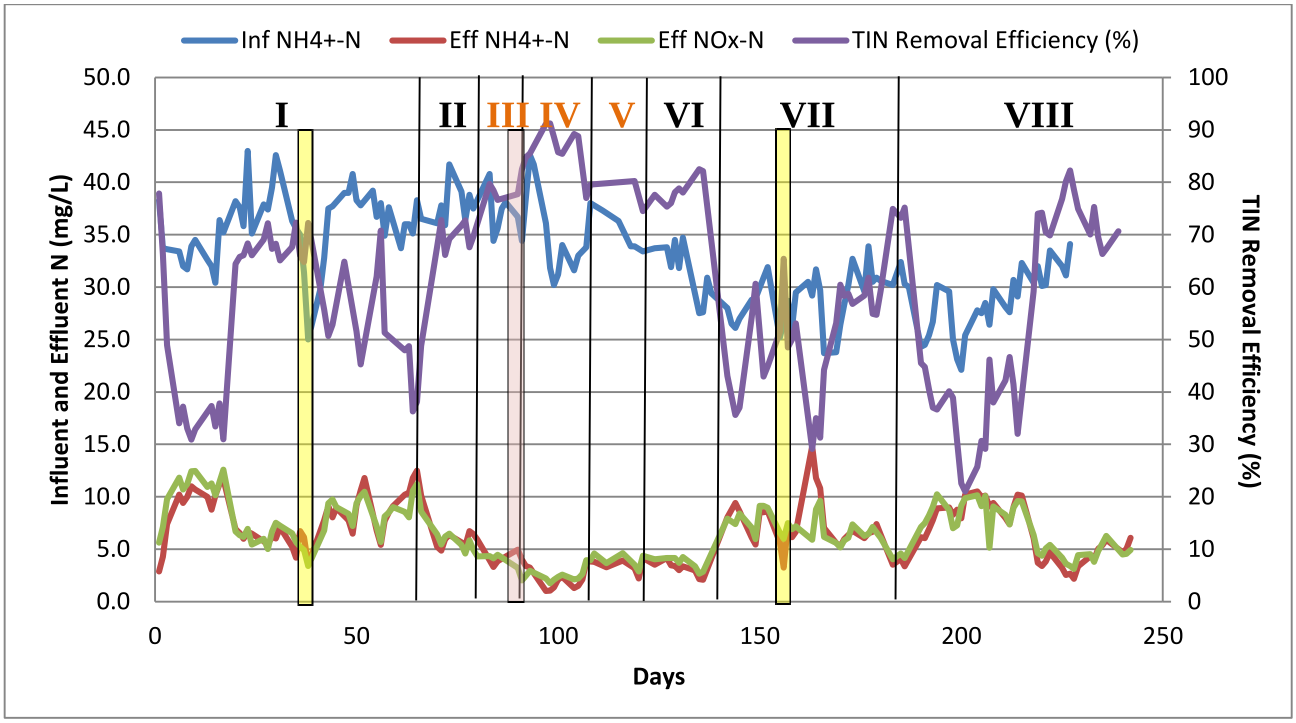


Figure 4-4: B-stage performance characterized by Influent NH4+-N, Effluent NH4+-N, Effluent NOx and TIN removal efficiency (%). Phases indicated in orange distinguish an MLE process from an intermittently aerated process (black). Yellow bar represents a wasting failure on day 43 and biomass washout on day 158. Red bar represents a five day period (91-94) where NRCY was sped up to help support biomass regrowth.

The influent NH_4^+-N loading rate and influent COD/NH_4^+-N concentrations fluctuated as a result of the A-stage, which impacted the total inorganic nitrogen (TIN) removal of the B-stage. The NH_4^+-N loading rate and COD removal rate can be compared with the TIN removal rate during each phase of the study in Figure 4-5. The general goal of the B-stage was to have an influent COD/NH_4^+-N concentration of 9.

The best TIN removal efficiencies were seen at an HRT of 6 hours over Phases IV, V and VI. Phases IV and V were operated as an MLE process with TIN removal efficiencies of 86% and 80%, respectively. In Phase VI the process remained at a 6 hour HRT, but was again intermittently aerated in all reactors (IMLR=0) and achieved 78% TIN removal efficiency. The improved nitrogen removal performance of Phases IV, V and VI corresponded with the lowest ammonia loading rates of 132±9.9, 140±6.8 and 126±10.4 kg/L/d, respectively, the lowest TIN removal rates 113.6±8.3, 107.7±0, 99.1±6.4 kg/L/d, respectively, and the highest influent COD/NH_4^+-N concentrations of 10.3±1.2, 9.8±0.4 and 11.0±0.8, respectively (Table 4-5).

These higher influent COD/NH_4^+-N concentrations corresponded with the best nitrogen removal efficiencies suggesting more anoxic oxidation of COD (using NO_x as the electron acceptor) than aerobic oxidation of COD was occurring. During phases IV, V and VI, the ratio of nitrogen loading rate to maximum AOB rate (NH_4^+-N loading rate/AOB rate) of 0.54±0.02, 0.51±0, and 0.56±0.08, respectively, which corresponded to aerobic SRT fractions of 0.37±0.04, 0.38±0.03 and 0.38±0.04, respectively. These high AOB rates allowed more anoxic time for denitrification, confirmed by lower aerobic SRTs, thus improving the overall TIN removal performance.

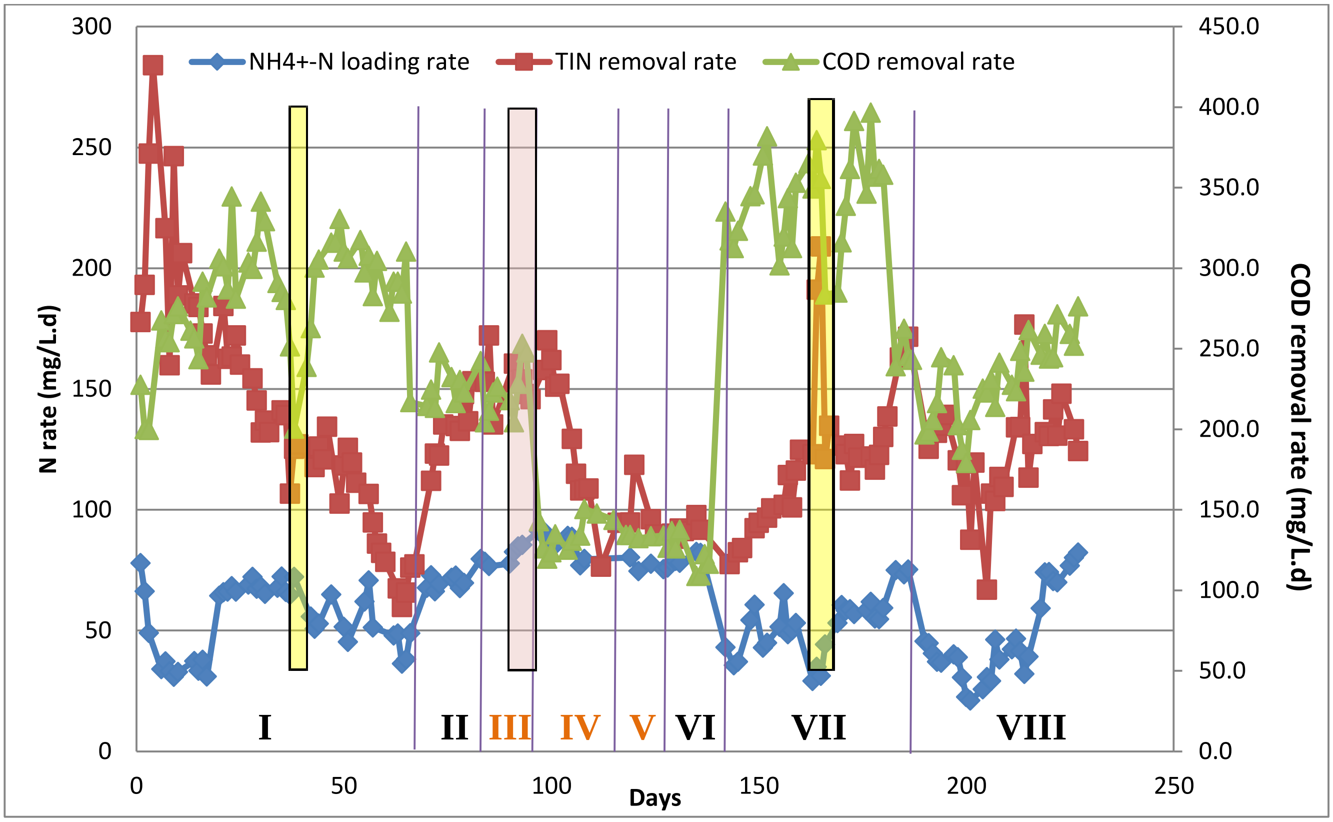


Figure 4-5: B-stage performance characterized by NH4+-N loading rate, TIN removal rate, and COD removal rate. Phases indicated in orange distinguish an MLE process from an intermittently aerated process (black). Yellow bar represents a wasting failure on day 43 and biomass washout on day 158. Red bar indicates a 5 day period where IMLR was sped up to 300% and allowed to stabilize before reaching 450%.

4.4.2 Nitrite Accumulation

Figure 4-6 illustrates the trend of the NAR (nitrite accumulation ratio, NAR = NO_2^-- N/(NO_2^-- N + NO_3^- -N)), which shows how much of the ammonia conversion was stopped at nitrite indicating the extent of NOB out-selection, and the aerobic fraction of the cycle time.

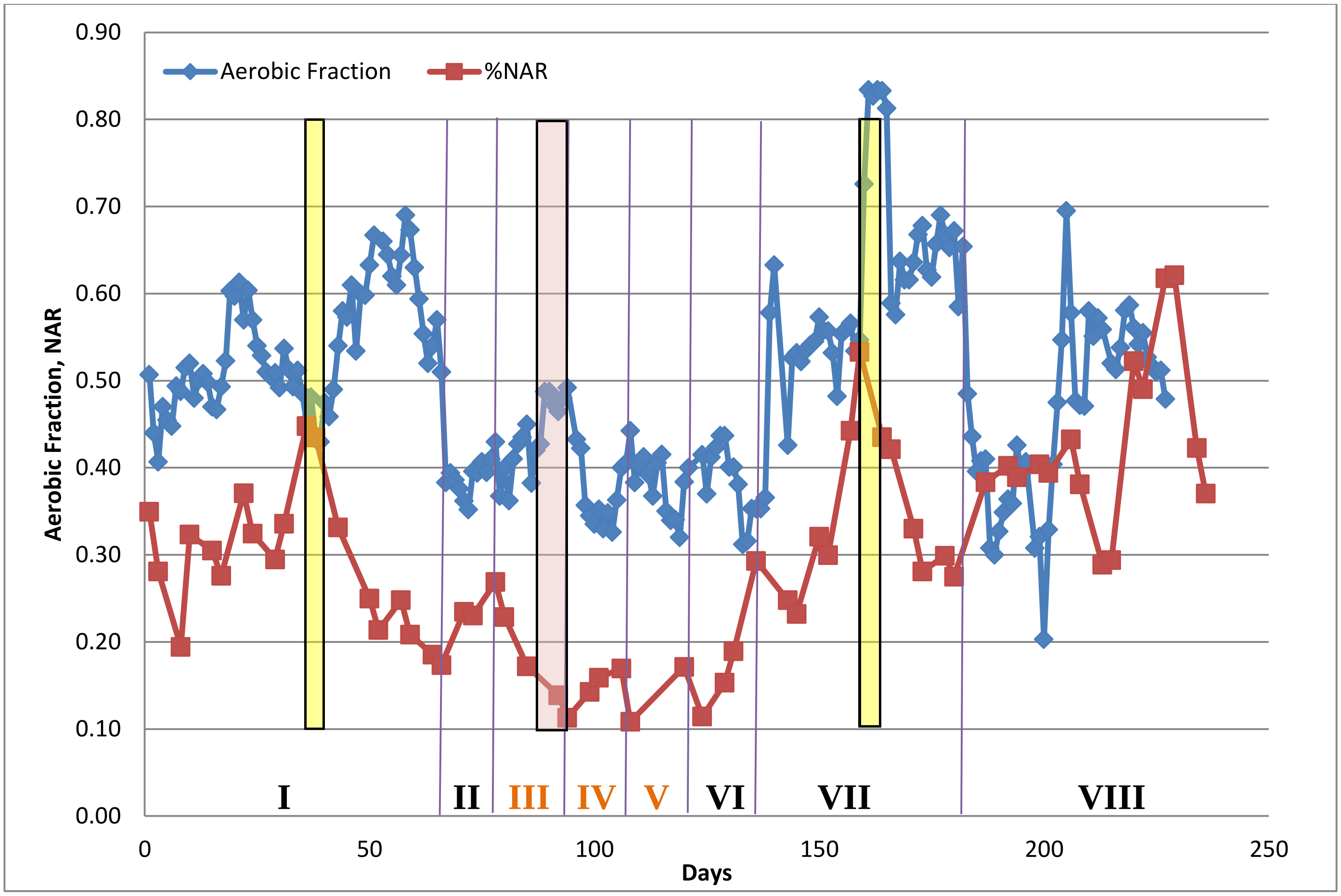


Figure 4-6: B-stage performance characterized by the Aerobic Fraction and NAR.. Phases indicated in orange distinguish an MLE process from an intermittently aerated process (black). Yellow bars represent a wasting failure on day 43 and biomass washout on day 158. Red bar indicates a 5 day period where IMLR was sped up to 300% and allowed to stabilize before reaching 450%.

From the data in Table 4-5 and Figure 4-6, the NAR is considered high ($\geq$ 0.3) in Phases I, VII, and VIII. This indicates successful NOB out-selection is occurring allowing nitrite to accumulate; also seen in Figure 4-7. Unfortunately, phases boasting the highest nitrite accumulation ratios do not correspond with high nitrogen removal efficiency phases (Phase IV, V and VI). The best nitrite accumulation was seen in phases where all reactors were intermittently aerated (Phase I, VII, and VIII). The high nitrite accumulation ratios of Phases I, VII and VIII also correspond with the lowest NOB rate/AOB rate of 65±16%, 69.3±7% and 67.1±8, respectively, and high NH_4^+-N loading rate/AOB rate of 0.96±0.24, 0.82±0.27 and 0.73±0.16, respectively. The former indicates that the AOB rate is much higher than the NOB rate, favoring nitritation. The latter indicates the system is being run aggressively toward limiting the SRT to select for AOB and washout NOB. AvN strategy actively pushes the system to washout NOB; if AOB are pushed toward washout, the aerobic fraction increases for the same influent COD/N (Regmi et al., 2014). Figure 4-4 illustrates this concept; when the system is being run aggressively (combination of SRT and nitrogen loading rate [NLR]) there is a visible increase in the aerobic fraction and NAR. The aggressiveness of the operation towards AOB washout as a result of variable SRT and NLR is captured in the ratio of nitrogen loading rate and maximum AOB rate (NH_4^+-N loading rate/AOB rate), also named the "aggressiveness factor".

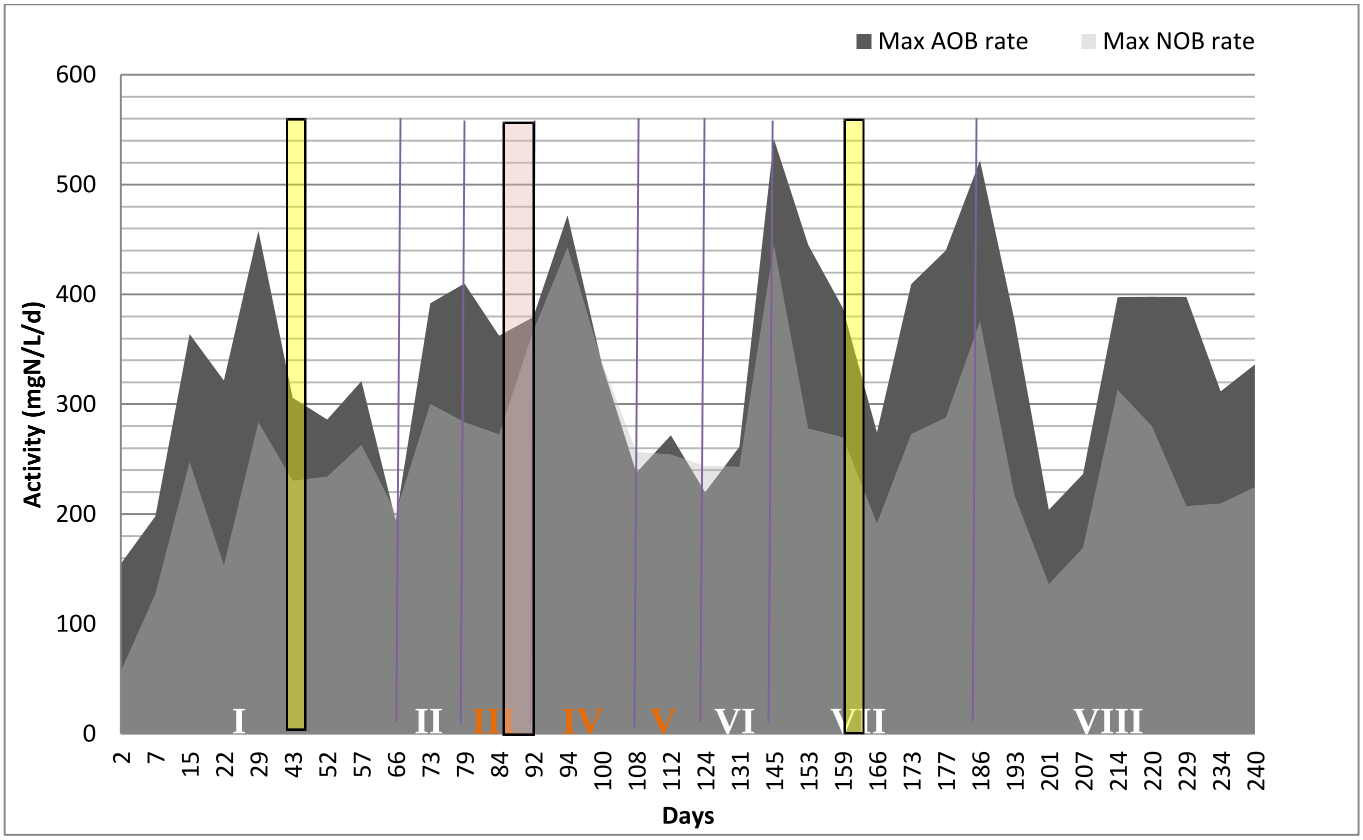


Figure 4-7: Weekly AOB and NOB activity measurements. Phases indicated in orange distinguish an MLE process from an intermittently aerated process (white). Yellow bar represents a wasting failure on day 43 and biomass washout on day 158. Red bar represents a five day period (91-94) where IMLR was temporarily sped up and data will not be discussed.

The dominance of the AOB population in Phases I, VII and VIII is apparent in Figure 4-7. The maximum AOB rate was higher than the maximum NOB rate in the majority of the study. Phases I, II, VII, and VIII saw high (≥ 0.7) aggressiveness factors of 0.96±0.24, 1.03±0.60, 0.82±0.27 and 0.73±0.16, respectively, which are also illustrated by the apparent dominance of AOB over NOB (Figure 4-5). This aggressive operation resulted in the highest NAR of 0.30±0.08, 0.23±0.04, 0.34±0.09 and 0.43±0.10, respectively. Partway through Phase VII (day 158) the biomass was completely washed out due to the waste pump running continuously. The maximum AOB and NOB rates declined rapidly for a period during regrowth.

4.4.3 COMPARISON BETWEEN FULL INTERMITTENT AERATION AND MLE

The impact of IMLR on TIN removal efficiency can be seen in Figure 4-8. As the IMLR increased from 200-450%, the TIN removal efficiencies increased from 76-86%. The TIN removal efficiency and influent COD/NH_4^+-N ratio were greater with 450% IMLR, 86.3±5.0% and 10.3±1.2, respectively, compared to the values at 200% and 325%, 76.4±4.0% and 9.2±0.8, and 80.2% and

9.8±0.4, respectively. Although the IMLR did improve the overall TIN removal efficiency compared to operation where all reactors were intermittently aerated, it did so at the expense of NAR. The NAR decreased as the IMLR and influent COD/NH_4^+-N ratio increased, as can be seen in Figure 4-8.

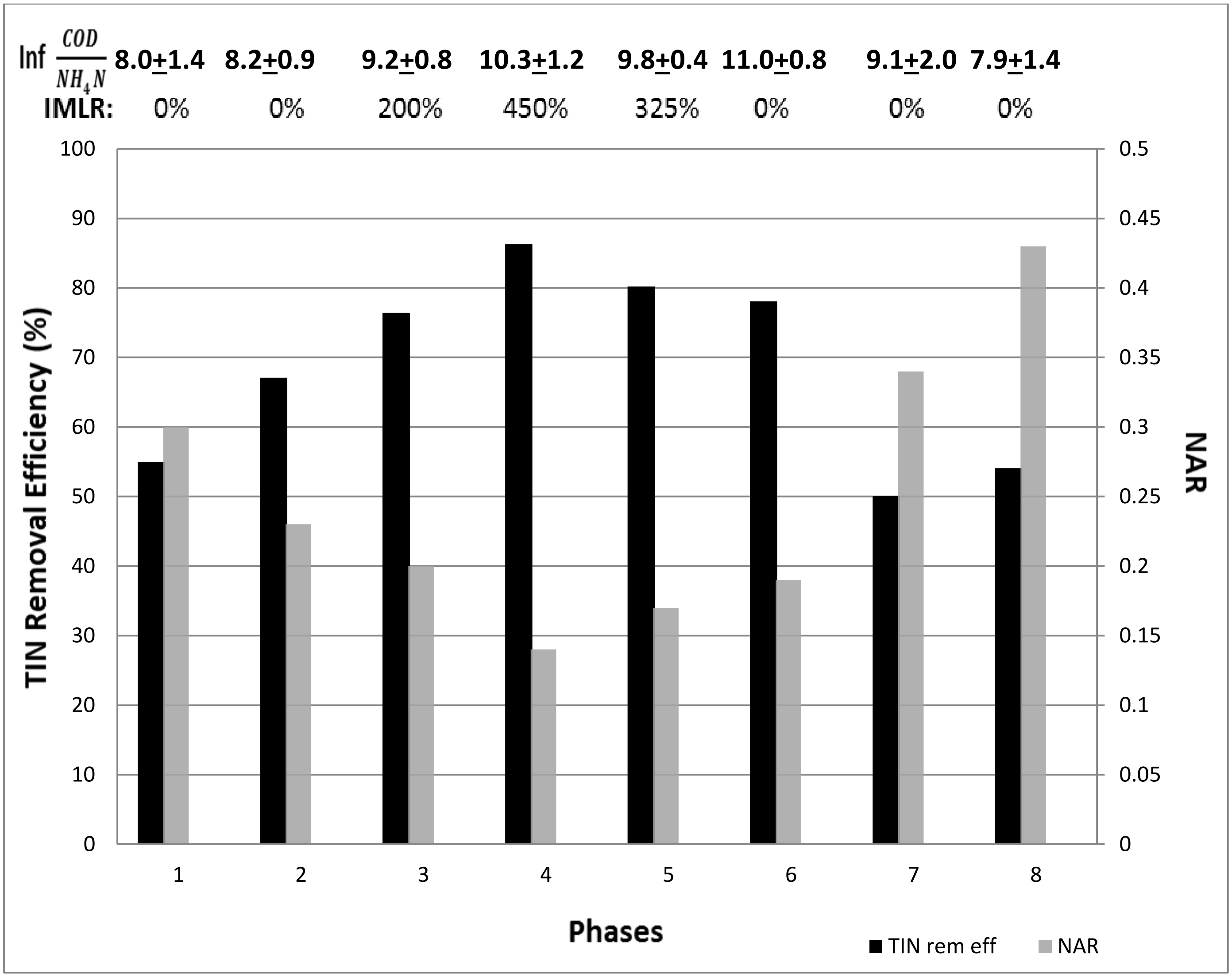


Figure 4-8: Comparison between nitrogen removal efficiencies and NAR under full intermittent aeration and MLE.

Operation under full intermittent aeration saw higher NAR than MLE operation (Figure 4-8). Phase VIII saw the highest NAR of 0.43 ±0.10 at a 3 hour HRT and an SRT of 4.2±1.0 days. Phase I saw a similar influent COD/NH_4^+-N ratio, HRT and aerobic SRT fraction as Phase VIII, however, the SRT was higher at 7.1±2.6 days with a slightly lower NAR of 0.30±0.08. There is no apparent correlation between TIN removal efficiency and NAR (R^2=0.0138) or influent COD/NH_4^+-N and NAR (R^2=0.0644). However, there is a moderate correlation between influent COD/NH_4^+-N and TIN removal efficiency (R^2=0.4693).

When TIN removal efficiency was highest in Phases IV, V and VI, the aerobic fractions were lowest suggesting that more influent COD was oxidized anaerobically resulting in improved denitrification (Table 4-5). When the NAR was the highest in Phases I, VII and VIII, the aerobic fractions were highest suggesting that more influent COD was oxidized aerobically resulting in improved NOB out-selection; however, less COD was available for denitrification causing TIN removal efficiency to be lower (Table 4-5).

4.4.4 A-STAGE EFFECT ON PERFORMANCE

The operation and performance of the A-stage was a crucial variable in the nitrogen removal performance of the B-stage. Although the initial goal was to feed the B-stage influent with a COD/NH_4^+-N equal to 9, process malfunctions and A-stage control strategy was still very much trial-and-error. As a result, the influent COD to the B-stage varied and was difficult to control.

Figure 4-6 shows that when the A-stage was removing COD more completely (the influent sCOD was lower), the total inorganic nitrogen (TIN) removal efficiency of the B-stage was lower, making it less effective. When A-stage COD removal was lower, the B-stage nitrogen removal was more effective. An influent sCOD of approximately 115 mg/L or greater resulted in generally good nitrogen removal which was consistent with the findings of Bunce (2003).

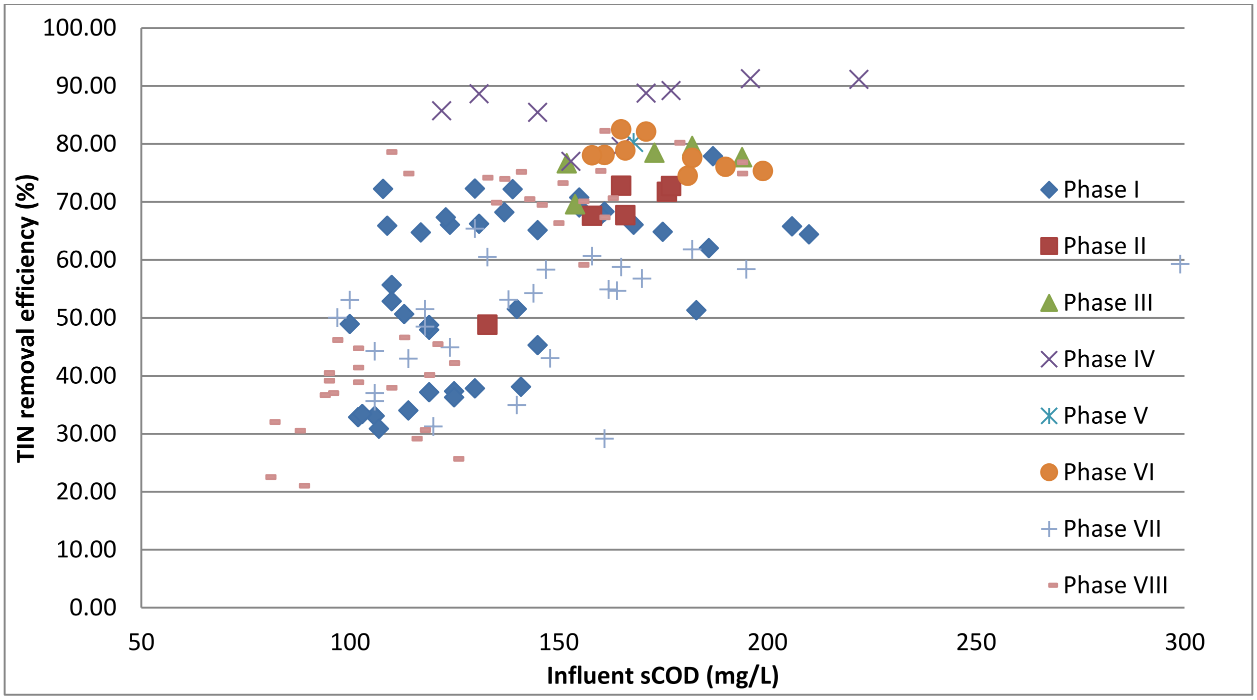


Figure 4-9: Correlation between influent sCOD (effluent from the A-stage) and TIN removal efficiency (%) in the B-stage.

Figure 4-9 illustrates the effect of the influent sCOD on the system with corresponding removal efficiencies for each phase found in Table 8. Phase I saw the stabilization period at the beginning, making the data more scattered. By Phase II, the sCOD input was relatively high (>140 mg/L) resulting in average TIN removals of 67%. Phase III was the first phase operated in MLE and saw even higher sCOD inputs (>150 mg/L) and an average TIN removal of 76%. Phase IV, still operated as an MLE, saw a range of sCOD inputs (115-225 mg/L), however the average TIN removal of the phase was even higher, being consistently above 80%. The final MLE phase, Phase V, saw influent sCOD greater than 170 mg/L with a corresponding TIN removal of 80%. The TIN removal increases greatly to consistently above 70% during Phase VI with sCOD inputs between 150-200 mg/L and the return to full intermittent aeration. The drop in sCOD inputs result in a significantly lower TIN removal efficiency in Phase VII which carries over into Phase VII.

4.5 DISCUSSION

Successful start-up directly to partial nitrification to nitrite in a continuous system treating low strength (mainstream) wastewater has proven difficult (Ma et al., 2009). However, Peng et al. (2012) achieved partial nitrification to nitrite in continuous reactors by switching from a batch start-up with aeration time control into continuous operation. Literature investigating the operational factors for achieving partial nitrification to nitrite in SBRs has been demonstrated at low DO concentration (Blackburne et al., 2008), combination of high temperature and low SRT (Hellinga et al., 1998), high FA and FNA concentrations (Vadivelu et al., 2007), online aeration duration control (Blackburne et al., 2008), and transient anoxia (Kornaros et al., 2010) to selectively inhibit the growth of NOB. Recently, Ge et al. (2014) demonstrated successful nitrite accumulation and TN removal efficiency in a mainstream continuous plug-flow step feed process. This study evaluated both the nitrite accumulation and TN removal efficiency using AvN controls [NH_4^+-N/NO_x-N = 1] in two process configurations: one process where all reactors are intermittently aerated and one process run as an MLE (IMLR and first reactor anoxic).

4.5.1 FACTORS AFFECTING NITROGEN REMOVAL

The AvN control strategy effectively maintained equal effluent NH_4^+-N and NO_x-N (NH_4^+-N/NO_x-N = 1) in both process configurations (Figure 4-1). However, this goal does not always equate to effluent levels that meet stringent nitrogen removal limits; for this reason, a process operating under AvN control would benefit from a final anammox polishing step.

Phases IV, V and VI were all operated at a 6 hour HRT, which decreased the ammonia loading rate, and ~4 day SRT (Table 4-5), achieving the highest nitrogen removal efficiencies of 86%, 80% and 78%, respectively. These phases also saw the highest influent COD/NH_4^+-N ratio of 10.3±1.2, 9.8±0.4 and 11.0±0.8, respectively, and the lowest aerobic fractions of 0.37±0.04, 0.38±0.03, and 0.38±0.03, respectively, suggesting that more influent COD was being oxidized anoxically using NO_x as the electron acceptor. This is in line with the decrease in the NAR for these three phases, as more nitrite was being consumed anoxically.

Regmi et al. (2014) demonstrated the use of the AvN strategy to control the aerobic SRT of the system to maintain optimum NH_4^+ oxidation for a given influent COD/NH_4^+-N ratio and SRT to allow the system to be run at the minimum SRT very close to AOB washout such that NOB were out-selected. Phases IV, V and VI were not run aggressively (NH_4^+-N loading rate/AOB rate= ~1.0) to out-select NOB, therefore achieving reasonable nitrogen removal efficiencies but low NAR of 0.14±0.03, 0.17, and 0.19±0.08, respectively. The HRT of these three phases was increased and maintained at 6 hours, decreasing the ammonia loading rates to each phase to 132±9.9, 140±6.8, and 126±10.4 kg/L.day.

Decreasing the ammonia loading rate results in less aggressive operation, 0.54±0.02, 0.51, 0.56±0.08, respectively, because AOB stimulation is reduced as a result of decreased substrate loads. Phases IV, V and VI saw the highest ratio of NOB rate to AOB rate of 104±5%, 94±0% and 102±13%, respectively, where Phases IV and VI actually saw a higher NOB rate than AOB rate. These results indicate that the HRT, influent COD/NH_4^+-N ratio, aerobic fraction and aggressiveness of operation play a more important role in efficient TIN removal than process configuration.

4.5.2 STIMULATION OF AOB AND INHIBITION OF NOB

Ge et al. (2014) hypothesized that the type of nitrification (full nitrification or nitrite accumulation) could be controlled by operation conditions. Previous research achieving successful nitrite accumulation under alternating aeration strategies were shown in a moving bed membrane bioreactor (Yang and Yang, 2011), an SBR (Li et al. 2008, 2011) and a continuous step-feed plug flow process (Ge et al., 2014). Yang and Yang (2011) found NOB activity to be inhibited when exposed to anoxic conditions under intermittent aeration. Within an intermittently aerated reactor, the aeration shuts off to create an environment called transient anoxia as the DO concentration drops to 0 mgN/L. The use of transient anoxia has been demonstrated to improve the AOB metabolic activity and achieve NOB out-selection (Pollice et al., 2002; Regmi et al., 2014). Chandran and Smets (2000) found the NOB lag-time to be a result of the anoxic phase fully denitrifying, resulting in nitrite limitation in the aerobic phase. Nitrite consumption during the anoxic period reduces the substrate available to the NOB population during the aerobic period, thus limiting the NOB population growth compared to AOB population growth based on substrate utilization. Kornaros et al. (2010) and Bournazou et al. (2013) found that the shift from anoxic to aerobic conditions inhibited NOB due to the deactivation of a critical enzyme shown by a reduced growth rate following transient anoxia; the inhibition effect was proportional to the duration of the anoxic disturbance. However, in this study, both process configurations were intermittently aerated, suggesting operational parameters played the larger role in NOB out-selection.

The AvN control strategy pushes the AOB towards washout, resulting in an increased aerobic fraction for the same influent COD/NH_4^+-N ratio. Phase VIII saw the lowest influent COD/NH_4^+-N ratio of 7.9±1.4, however, NOB were still out-selected presumably as a result of a high NH_4^+-N loading rate to AOB rate ratio (aggressiveness factor) of 0.73±0.16, and a lower HRT of 3 hours corresponding to a higher ammonia loading rate of 237±26.4 to provide adequate substrate to stimulate AOB growth. This NOB out-selection is surprising because at a lower influent COD/NH_4^+-N ratio there is less heterotrophic competition for nitrite with NOB (Regmi et al., 2014). Implications for NOB out-selection at a reduced influent COD/NH_4^+-N ratio would allow increased COD capture by the A-stage for energy production.

Results from this experiment found the highest NAR of Phases I, VII and VIII corresponded to the lowest ratio of NOB rate to AOB rate (%) of 65±16%, 69±7% and 67±8%, respectively, indicating the dominance of the AOB population over the NOB population under full intermittent aeration process operation at an increased ammonia loading rate and decreased HRT. Yu and Chandran (2010) found when AOB were exposed to anoxic conditions for long periods of time, they would acclimate themselves by initiating other metabolic pathways to consume the excessive mRNA, maintaining previously equal metabolic activities; as would NOB in similar situations. Phases I, VII and VIII with the highest NAR corresponded to the lowest anoxic duration in comparison to the aerobic duration with an aerobic SRT fractions of 0.54±0.07, 0.62±0.10 and 0.47±0.09, respectively. These phases were also run at the shortest HRTs of 3 hr, 2 hr and 3 hr, respectively, increasing the ammonia loading rate and the NH_4^+-N loading rate to AOB rate ratio (aggressiveness factor). This increase in ammonia provides adequate substrate to stimulate the growth of AOB while increasing the aggressiveness factor allows the AvN controller to operate at an SRT close to AOB washout such that NOB would be washed out. Additionally, heterotrophic denitrification pressure, high DO, and intermittent aeration provides unfavorable conditions for NOB to further select for AOB (Regmi, 2014).

Under MLE process operation, as the IMLR was increased from 200% to 325% to 450%, the NAR decreased from 0.20±0.04, 0.17 and 0.14±0.03, respectively, for Phases III, V and IV, respectively. Similarly, the ammonia loading rate decreased with increasing HRT causing the NOB activity to increase with an NOB rate to AOB rate ratio of 72±4%, 104±5% and 94±0%, respectively, as less substrate was available to stimulate AOB activity. The aerobic fractions during Phases III, V and IV were the lowest at 0.42±0.04, 0.37±0.04, and 0.38±0.03, respectively, indicating that NO_x was being oxidized anoxically which resulted in better TIN removal efficiencies and decreased NAR.

4.5.3 PROCESS CONFIGURATION VERSUS OPERATIONAL PARAMETERS

Results from Phases V and VI saw similar operational and influent characteristics resulting in similar results despite being run under two different process configurations. Phases V and VI were run as an MLE and as full intermittent aeration, respectively, both under a 6 hour HRT, with influent COD/NH_4^+-N ratios of 9.8±0.4 and 11.0±0.8, respectively, aggressiveness factors of 0.51±0 and 0.56±0.08, respectively, with aerobic fractions of 0.38±0.03 and 0.38±0.04, respectively. Similar results were seen in Phases V and VI with TIN removal efficiencies of 80.2% and 78.1%, respectively, and NAR of 0.17 and 0.19±0.08, respectively. This suggested that operational parameters played a larger role in TIN removal and NAR than process configuration.

When TIN removal efficiency was highest in Phases IV, V and VI, the aerobic fractions were lowest suggesting that more influent COD was oxidized anaerobically resulting in improved denitrification (Table 4-5). When the NAR was the highest in Phases I, VII and VIII, the aerobic fractions were highest suggesting that more influent COD was oxidized aerobically resulting in improved NOB out-selection; however, less COD was available for denitrification causing TIN removal efficiency to be lower (Table 4-5). Aerobic fraction, influent COD/NH_4^+-N ratio, loading conditions and aggressiveness of operation appeared to be the more important parameters which dictated the success of both TIN removal efficiency and NOB out-selection.

4.6 CONCLUSION

In this study we demonstrated that mainstream NOB out-selection in a continuous process is possible under AvN control (intermittent aeration to achieve NH_4^+-N/NO_x-N = 1) in both full intermittent aeration and MLE operation. The novel AvN aeration control strategy based on direct *in situ* measurement of NH_4^+, NO_2-, NO_3- successfully exploited NOB out-selection mechanisms under various loading conditions at ambient temperature (T=23.8±1.1°C). The NAR was best under full intermittent aeration, achieving 0.43±0.10 at a 3 hour HRT and an influent COD/NH_4^+-N ratio of 7.9±1.4. However, the TIN removal efficiency reached a high of 86.3% under MLE operation (450%

IMLR) with a 6 hour HRT and an influent COD/NH_4^+-N ratio of 10.3±1.2. Nitrite accumulation was shown to depend on influent nitrogen loading rates, aggressive operation to promote an SRT to selectively washout NOB and transient anoxia to stimulate AOB and inhibit NOB. However, nitrogen removal was best at longer HRTs with influent COD/NH_4^+-N ratios >10, lower loading conditions, and less aggressive operation (combination of SRT and nitrogen loading rate). The similar results of two phases with similar loading conditions and operational parameters under two different process configurations suggests that operational parameters play a larger role than process configuration. Therefore, this study supports the NOB out-selection mechanisms first proposed by Regmi (2014) to successfully achieve mainstream NOB out-selection in continuous BNR processes, while also allowing possible connection with Anammox process to achieve improved nitrogen removal.

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5. MANUSCRIPT 2: IMPROVED SETTLEABILITY IN A PILOT-SCALE BNR PROCESS

ABSTRACT

A pilot scale biological nitrogen removal (BNR) process ($V=0.61\ m^3$) was operated as two different process configurations (full intermittent aeration and as a Modified Ludzak-Ettinger [MLE]) in four equal volume tanks in series followed by a cone-bottom clarifier in a pilot scale biological nitrogen removal (BNR) process ($V=0.61\ m^3$). This experiment was run over 242 days under various loading conditions at ambient temperature ($T=23.8\pm1.1°C$). Throughout the study, filamentous organisms were identified and abundance was quantified on a scale of 0-6: 0 (none) to 6 (excessive). Compressibility and settleability were quantified in terms of sludge volume index (SVI) 30 and zone settling velocity (ZSV). Overall good settling (128.3 ± 36.3mL/g) was observed, with Type 0041 and Type 0675 present throughout, suggesting their presence did not indicate or cause poor settling. *Nocardia* appeared to be the cause of temporary foaming issues early in the experiment solved by vacuuming the surface to eliminate hydrophobic substances and substrate that could favor continued growth. *Thiothrix spp.* I and II appeared and could be related to sulfide and organic acid concentration carryover from the A-stage. Finally, *Haliscomenobacter Hydrossis (H. Hydrossis)* appeared 150 days into the study which could be a product of multiple low DO and operational malfunctions which induced stresses on the system which *H. Hydrossis* had previously been associated with. An inverse relationship existed between SVI 30 and ZSV. As the sludge compaction (SVI 30) was hindered, settling slowed possibly as a result of less dense floc. No correlation between nitrite accumulation and settling issues was observed; this study disagreed with the *Nitric Oxide hypothesis* first proposed by Casey et al. (1994). Finally, there was no apparent impact of process configuration on settleability.

Keywords: intermittent aeration, Modified Ludzak Ettinger (MLE), filamentous bulking, SVI, ZSV, ISV, Type 0041, Type 0675, Type 0803, *Thiothrix spp*. I and II, *H. hydrossis*

5.1 INTRODUCTION

The proliferation of filamentous microorganisms causes bulking and foaming in activated sludge wastewater treatment plants. Although typically associated with bulking, some researchers hypothesize that filaments may help to form the backbone to which floc-forming bacteria adhere (Sezgin et al., 1978). The hypothesis requires the presence of filaments within a system. However, a conflicting hypothesis attributes good flocculation to extracellular polymeric substances (EPS) (Ehlers and Turner, 2011, Ehlers et al., 2012). Activated sludge bulking or filamentous bulking describes a wastewater condition/process with poor settleability, poor compaction of the mixed liquor solids (MLSS) and degradation of the effluent quality typically attributed to excessive growth of filamentous bacteria (Eikelboom et al., 1998; Jenkins et al., 2004; Martins et al., 2004; Yang et al., 2013). Initially, filamentous microorganisms were described according to their morphology (Eikelboom, 1975). With the development of molecular methods (Manz et al., 1992; Wagner et al., 1994), filaments are more easily characterized allowing for the accumulation of data to help determine causes of filamentous bulking in various environments (Eikelboom, 1975; Jenkins et al., 1993). Filaments seen within this study included Type 0041, Type 0675, Type 0803, *Nocardia, Thiothrix spp.,* and *Haliscomenobacter Hydrossis.* Many hypotheses exist as to the causes of the proliferation of these filaments. Some hypotheses for each type of filament observed within the study is presented below.

Type 0041 and Type 0675 are major morphotype filaments typically observed during bulking events in biological nutrient removal (BNR) activated sludge systems (Martins et al., 2004). These filaments are usually Gram positive, implying that their cell surface is hydrophobic allowing the adsorbtion of compounds with a low solubility (Eikelboom et al., 1998). The B-stage utilizes a cyclic aeration scheme alternating between aerobic and anoxic environments within each reactor. Ekama and Marais (1986) postulated that slowly metabolizable and particulate organic matter degradation rates are lower in anoxic zones compared to rates in aerobic conditions. When the reactor is intermittently aerated, the particulates and slowly metabolizable substrates left from the anoxic phase are present in the aerobic phase where they are hydrolyzed and produce low concentrations of soluble organics that favor the growth of Type 0041 and Type 0675 (Jenkins et al., 2004). Type 0803 is commonly seen in systems with low F/M (0.02-0.2) and low organic concentrations..

Foaming within the pilot system was largely attributed to *nocardioforms*. According to Jenkins et al. (2004), *nocardioforms* possess hydrophobic cell surfaces. When these microorganisms with hydrophobic cell surfaces grow large enough in numbers in activated sludge systems, they form hydrophobic flocs which attach to air bubbles causing foaming. *Thiothrix spp*. are filamentous organisms capable of utilizing hydrogen sulfide as an energy source and oxidizing hydrogen sulfide to sulfur. In addition to consuming sulfide, *Thiothrix spp*. can thrive in septic situations by utilizing low molecular weight organic acids produced in septic sewage (Richard et al., 1985; Jenkins et al., 2004). The A-stage experienced *Thiothrix sp*. related bulking thought to be the result of high sulfide and organic acid concentrations in the influent raw wastewater during high temperature periods (Miller et al., 2014). Because we are not 100% certain that all of the sulfide and organic acid is removed in the A-stage prior to reaching the B-stage, *Thiothrix spp*. was recorded on multiple occasions and could be the result of carryover from the A-stage.

A stress can be created as a result of operation, such as the creation of low DO environments resulting from intermittent aeration, or unintentionally created, resulting from operation malfunctions (i.e. pump and clarifier failures). These stresses are predicted to create environments favorable to *H. hydrossis.* Pernelle et al. (2002) found *H. hydrossis* to increase 550-fold as a result of multiple stresses within an activated sludge pilot plant. They appear to be favored in low DO systems with high concentrations of easily metabolizable substrates (Jenkins et al., 1993).

Conventional biological nitrogen removal utilizes separate anoxic and aerobic zones to optimize the rate of both denitrification and nitrification. However, AvN control of intermittent aeration attempts to allow nitrification and denitrification to occur within one reactor to maximize nitrogen removal while minimizing aeration volume, aeration demand, supplemental carbon and alkalinity addition (Regmi, 2014). Under a set cycle time of 16 minutes, the controller determined the aerobic duration based on the non-steady influent flow. A minimum and maximum aerobic cycle time were set at 4 and 12 minutes, respectively. During the aerobic period, the controller aimed to achieve a DO concentration of 1.5 mg O_2/L. However, after the aerobic cycle, the aeration shuts off and the reactor becomes anoxic. This switch to anoxia was not immediate, which could have allowed the proliferation of low DO filaments. The common thread within the filaments observed within this system involved low F/M and low DO environments possibly in response to the continuous influent flow and the intermittent aeration AvN control strategy employed.

Martins et al. (2004) outlined four different general theories to explain bulking sludge: diffusion-based selection (Martins et al., 2003), kinetic selection theory (Lou et al., 2008), storage selection theory (Martins et al., 2003) and nitric oxide (NO) hypothesis (Casey et al., 1994). While these theories remain uncertain, common factors contributing to filamentous bulking have been identified: carbon, nitrogen or phosphorus deficiencies (Jenkins et al., 1994; Martins et al., 2003; Guo et al., 2012) and prolonged periods of anoxia (Nowak et al., 1986; Gaval & Pernelle, 2003).

In this study, the *NO hypothesis* proposed by Casey et al. (1994) was of particular interest due to the nature of the AvN control strategy. This system aimed to favor ammonia oxidizing bacteria (AOB), which convert ammonia to nitrite, over nitrite oxidizing bacteria (NOB), which convert nitrite to nitrate. The goal was to create an effluent with equal parts ammonia and nitrite. In doing so, this system saw the accumulation of nitrite, which has been linked in past research as one cause of settling issues (Blackburne et al., 2008; Ma et al., 2013), although the cause of filamentous bulking due to nitrite has not been confirmed (Casey et al., 2004; Guo et al., 2013), and the stimulation of AOB, which have been linked to N_2O and NO emissions.

Casey et al. (1994) was the first to propose a new hypothesis for the proliferation of low F/M filaments in BNR systems. His research found nitric oxide (NO) to be the inhibitory substrate to floc-former over filamentous bacteria; although, NO_2^- -N was seen as a contributor to the inhibition. NO and NO_2^- are intermediates of denitrification which result from the reduction of NO_3^- (Figure 5-1), hypothesized to accumulate in the floc-forming bacteria and not in the filamentous bacteria. This research postulated that some filaments are able to reduce NO_3^- to NO_2^- only and do not accumulate the intermediate inhibiting compound NO (Casey et al., 1994; Martins et al., 2004), whereas floc-formers were able to denitrify NO_3^- to N_2 gas. In this environment, filamentous bacteria would have the competitive advantage over floc-forming bacteria since they can utilize slowly biodegradable (sbCOD) under aerobic conditions. Since NO_2^- is a precursor to NO (Figure 5-1) and intracellular NO is difficult to measure, the NO_2^- concentration has been used as an indicator of the presence of NO (Martins et al., 2004). Lakay et al., (1999) and Musvoto et al., (1999) found that the inhibition of floc-forming bacteria under aerobic conditions was sustained by the presence of nitrite and the low rate of readily biodegradable COD (rbCOD) addition in the aerobic zone, which is continuously produced by the hydrolysis of sbCOD. However, this hypothesis, known as the "*NO Hypothesis",* does not apply to all filamentous bacteria and NO and nitrite concentrations have not been shown to be coupled during denitrification, leading Martins et al., (2004) to question its validity and widespread application.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

$$nitrate \rightarrow nitrite \rightarrow nitric\ oxide \rightarrow nitrous\ oxide \rightarrow nitrogen\ gas$$

Figure 5-1: Denitrification pathway.

To build upon the *NO Hypothesis*, nitrite is a precursor for nitrous oxide (N_2O) and NO emissions which are known to deplete ozone; N_2O is also a potent greenhouse gas. A large portion of the N_2O and NO can be produced by ammonia oxidizing bacteria (AOB) as they are credited with the ability to perform 'nitrifier denitrification'. AOB are able to use NO_2^- or hydrazine (N_2O_4) as electron acceptors and NH_3 or hydrogen gas (H_2) as electron donors to produce NO and N_2 under oxygen limited and anoxic conditions (Schmidt et al. 2004; Regmi, 2014); however, they primarily gain their energy through aerobic metabolic pathways (Chain et al., 2003). NO emissions have been observed in both aerobic and anoxic conditions (Yu et al., 2010), however, N_2O production by AOB is limited to aerobic or microaerophilic conditions. Yu et al. (2010) found that the transition from anoxic to aerobic conditions in the presence of ammonia has resulted in the production of N_2O by AOB. Nitrite accumulation may also contribute to the production of AOB NO and AOB N_2O emissions (Kampschreur et al., 2009).

This study seeks to stimulate AOB populations to allow nitrite accumulation to achieve shortcut nitrogen removal. Ahn et al. (2011) compared N_2O and NO emissions from a lab-scale bioreactor operated sequentially in full-nitrification and partial-nitrification modes and found an increase in these emissions when operating in partial nitrification conditions as a result of nitrite accumulation. Further, N_2O and NO may also be produced through hydroxylamine (NH_2OH), an AOB intermediate, chemodenitrification and autooxidation (Arp and Stein, 2003; Schmidt et al., 2004; Rodriguez-Caballero et al., 2013). Although the different mechanisms of N_2O and NO production are not completely understood, nitrite accumulation, ammonia concentration and DO concentration appear to affect N_2O and NO production during nitrification (Kampschreur et al., 2008). It addition to polluting the atmosphere, the production of N_2O and NO could inhibit settling as described by the *NO Hypothesis*.

Today, researchers are still unclear whether there is an interaction between morphology, physiology and substrate kinetics and how it may play a role in the dominance of filamentous bacteria in activated sludge (Martins et al., 2004). Current research distinguishes between focusing on filamentous bulking as a microbiological problem in need of case species-specific solutions, or viewing it as an engineering problem with a generic solution to filamentous bulking such as aerobic, anoxic and anaerobic selectors (Chudoba et al., 1973; Martins et al., 2004; Gray et al., 2010). Other solutions may include the addition of chlorine (Ramirez et al., 2000), ozone (Caravelli et al., 2006), and metal salts (Guo et al., 2012).

5.2 OBJECTIVES

The objectives of this research were to identify and characterize the settleability issues observed within the B-stage of the pilot scale A/B process when intermittently aerated using AOB versus NOB (AvN) control scheme. Every new control technology and process configuration creates a unique environment favorable to different species of filamentous and floc-forming bacteria. These bacteria are both necessary for good sludge settling. However, when filamentous bacteria are observed in excess, they contribute to the deteoriation of sludge settleability and ultimately the effluent released from the wastewater treatment plant.

The objectives of this research were to 1) identify filamentous bacteria present within different loading conditions, 2) identify filamentous bacteria that have a negative impact on settling, 3) find relationships between operational parameters and wastewater conditions (i.e. substrate concentration, F/M ratio, etc.) that favor particular filamentous bacteria, and 4) identify analytical measurement and monitoring for early indication of filamentous bulking.

Literature has characterized filaments individually, however, filaments within a community behave uniquely depending both on the process and the plant influent. It was necessary to identify the filamentous bacteria most common within this system under the unique AvN control system, and determine which are capable of degrading the sludge settleability.

5.3 METHODS

5.3.1 *PILOT SETUP*

This thesis will focus on the operation and resulting performance of the AVN pilot. The A/B pilot study consists of a HRAS process (A-stage) for high rate carbon removal followed by a BNR process (B-stage) for nitrogen removal (Figure 5-2). The AvN pilot functions as a part of this larger configuration including a high rate activated sludge A-stage (HRT = 30 min, SRT = 0.25 days) for COD removal providing the influent for the AvN reactor (Miller et al., 2012, Figure 5-2) and a post anoxic anammox moving bed bioreactor after the AvN reactor (Figure 5-2) allowing for a final polishing of the treated sewage.

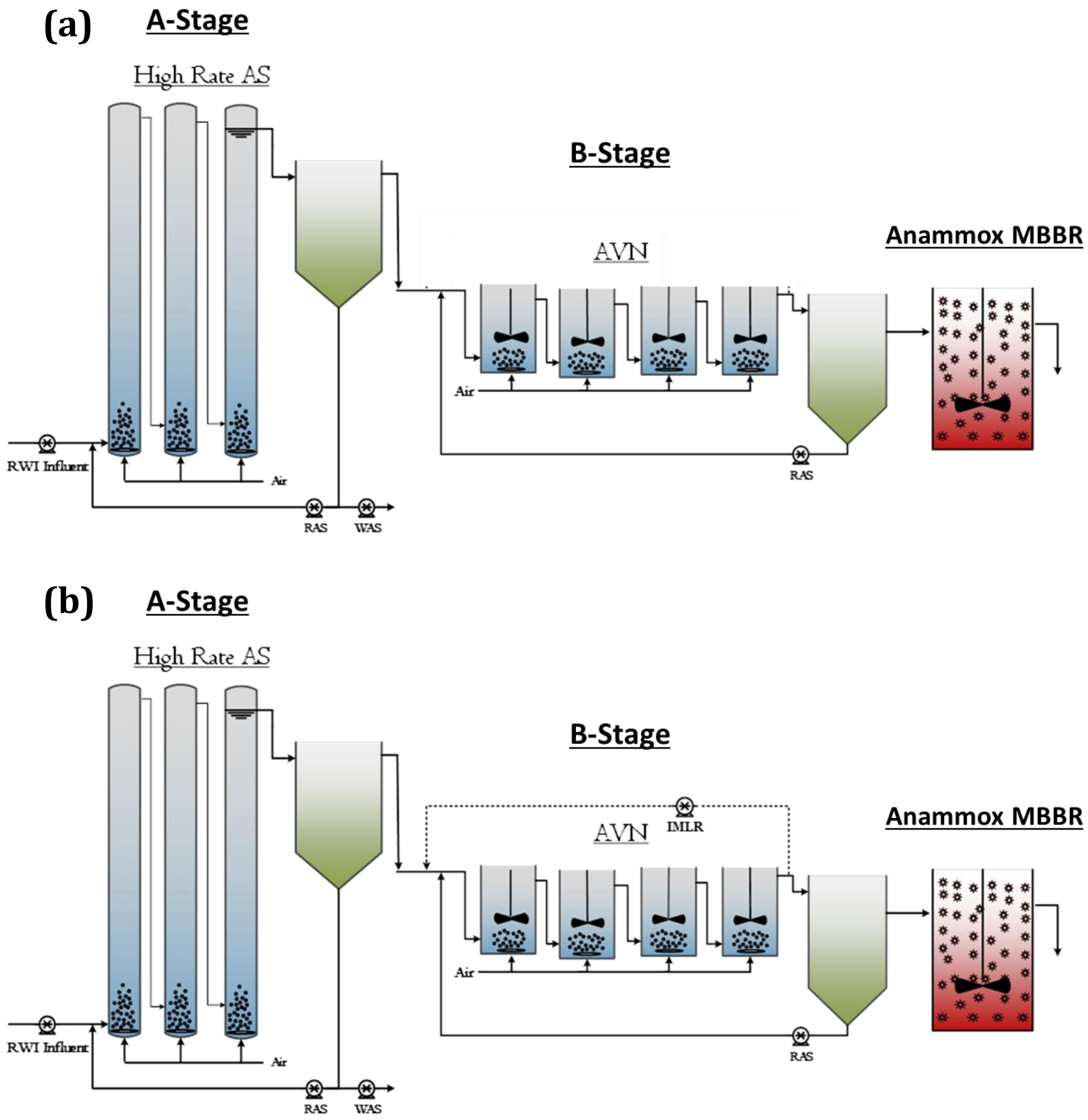


Figure 5-2: A/B pilot process flow diagram, (a) full intermittent aeration (b) Modified Ludzak-Ettinger (MLE) with IMLR line.

5.3.1.1 Preliminary Treatment

Using a chopper pump, raw wastewater influent (RWI) for the pilot process was pumped from the effluent channel of the preliminary treatment facility (PTF) at Chesapeake-Elizabeth treatment plant (CETP). The PTF includes fine screens and forced vortex grit removal. Due to the inefficiencies of the PTF, the pumped RWI first passed through a 568 L drum equipped with a variable speed mixer that was operated at a speed that allowed grit to settle but kept particulate and colloidal organic matter in suspension. Accumulated grit was periodically removed 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 through basket screens with 2.4 mm openings into a temperature control tank. This tank contained submersible heaters and a finned-tube coil. Coolant was circulated through the coil and a water-cooled water chiller. A PLC controlled power to the heater and chiller based on a signal from a thermocouple in the temperature control tank and a user set-point. This setup provided the capability to provide a constant influent wastewater temperature to the biological processes anywhere from 15 to 25°C. The temperature control tank also contained a constant speed mixer. These processes were only necessary for the pilot and not intended for the full-scale process.

5.3.1.2 High-Rate Activated Sludge Process (HRAS) Control

From the temperature control tank, the wastewater was pumped to three HRAS reactors. These reactors were constructed from clear PVC pipe supported vertically on one end with an operating volume of 511 L, a hydraulic residence time (HRT) of 30 minutes and a side water depth of 3.4 meters (11 feet). Aeration was provided by an air compressor and a 17.7 cm membrane disc diffuser with the DO monitored by a Hach LDO probe (Loveland, CO). The desired DO set-point was maintained by a single-loop proportional-integral-derivative (PID) controller controlling a mechanically operated valve (MOV) on the compressed air line. The HRAS reactor was mixed by large bubble mixing every two minutes. The final reactor overflowed by gravity to a cone-bottom clarifier outfitted with a scraper mechanism that rotated at 0.25 rpm and directed settled solids to the bottom of the clarifier cone. The clarifier had a submerged vertical inlet inside of a center well. This configuration helped dissipate the influent hydraulic energy and allowed additional bioflocculation to occur before solids separation. Effluent from the clarifier overflowed to a 208 L (55 gal) drum that served as a flow through feed storage tank for the B-stage. A-stage effluent was pumped from the feed storage tank to the B-stage with a progressive cavity pump.

Optimization of A-stage control and operation was a separate research project conducted by Virginia Tech doctoral candidate Mark Miller. Details on this project can be found in *Mechanisms of COD removal in the adsorption stage of the A/B process*, with future publications to follow (Miller et al., 2013).

5.3.1.3 B-stage AvN

The B-stage consisted of four equal volume tanks in series, each 151 L for a total operating volume of 606 L , and a cone-bottom clarifier. The clarifier had a submerged vertical inlet inside of a center well. This configuration helped dissipate the influent hydraulic energy and allowed additional bioflocculation to occur before solids separation. The cone-bottom clarifier was outfitted with a scraper mechanism that rotated at 0.25 rpm and directed settled solids to the bottom of the clarifier cone. All four biological reactors were equipped with a variable speed mixer, a 17.7 cm membrane disc diffuser, and a Hach LDO probe. Aeration capacity in all 4 tanks allowed the system to be operated with or without a defined anoxic zone. The B-stage had a variable HRT (2-7 hours) and a variable influent flow rate. When operating in MLE configuration, an internal mixed liquor recycle (IMLR) line returned nitrified mixed liquor from the last aerobic reactor to the anoxic reactor using a peristaltic pump at a rate between 200-450% of the influent flow. When IMLR was used the first tank was not aerated. RAS from the clarifier was returned to the anoxic zone at 100% of the influent flow. SRT was controlled by wasting solids from the last aerobic tank. The wasting was automated to maintain desired SRT. The AVN process was equipped with sensors to monitor NH_4^+-N, NO_2^--N and NO_3—N. pH was monitored using a Foxboro pH probe in the last aerobic reactor.

5.3.2 START-UP AND LONG TERM OPERATION IN DIFFERENT PHASES

The B-stage reactors were seeded from the waste activated sludge (WAS) of the CETP.

Typical A-stage effluent was characterized by: pH 6.96 $\pm$ 0.08, COD 288 $\pm$ 69, sCOD 146 $\pm$ 35, pCOD 143 $\pm$ 45, NH_4^+ 32.6 $\pm$ 4.5, NO_2^- and NO_3^- are assumed to be 0, TKN 37.2 $\pm$ 4.9, sTKN 29.1 $\pm$ 4.0, OP 3.01 $\pm$ 0.89, TP 4.43 $\pm$ 0.88, sTP 2.17 $\pm$ 0.57, alkalinity 159 $\pm$ 15, cBOD 109 $\pm$ 33 and scBOD 45 $\pm$ 20. The B-stage was operated in different phases differentiated by operational mode and HRT. The total SRT was targeted to be around 6 days and temperature was maintained at 23ºC during the entire study. The aerobic SRT was controlled by online aeration controller to achieve the desired NH_4^+:NO_2^- ratio.

5.3.3 AVN AERATION CONTROL STRATEGY

To impose conditions favorable for NOB out-selection and to provide effluent suitable for anaerobic ammonia oxidation (AMX) polishing, an aeration controller was developed which uses on-line *in-situ* DO, NH_4^+, NO_2^- and NO_3^- sensors. The first component of AvN control was the aerobic duration controller based on the goal of maintaining equal effluent NH_4^+-N and NO_x-N (NH_4^+-N / NO_x-N = 1) in the final CSTR of the B-stage at all times. The latter would guarantee a treatable effluent for final polishing with AMX. The other component of the AvN control was the DO controller which maintains the DO set-point, set by the user, as desired during the aerated period (Figure 5-3).

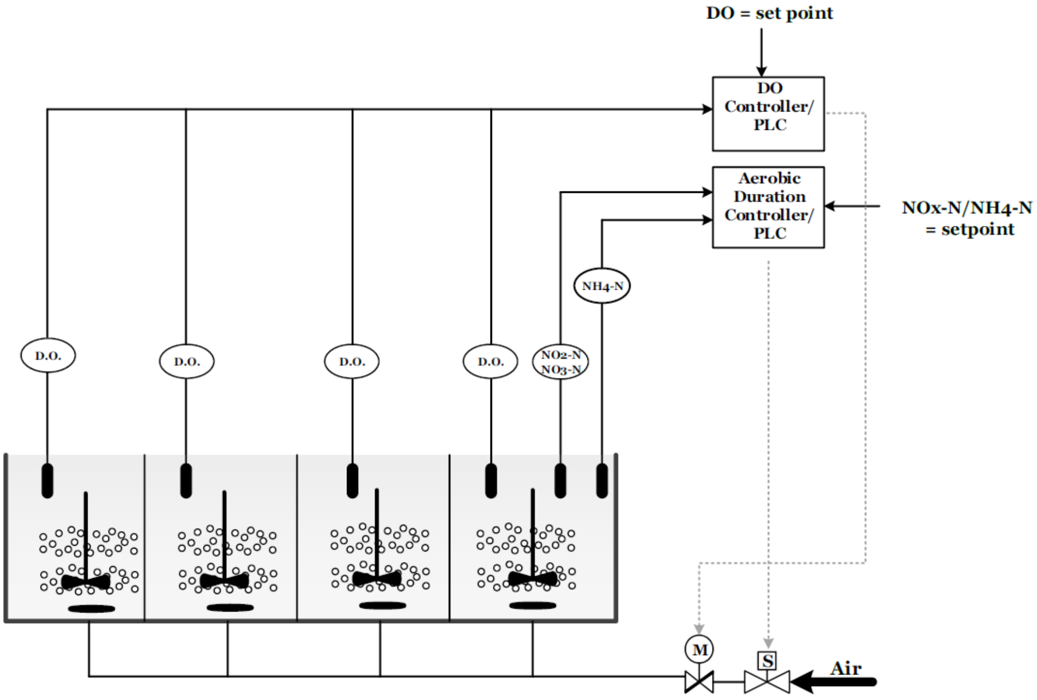


Figure 5-3: AvN controller set-up with four DO controllers sending dissolved oxygen signals, NH4+, NO2-, and NO3- signals to the aerobic duration controller.

Under the AvN control strategy, NH_4^+-N was compared to the sum of NO_2^- -N and NO_3—N (NO_x-N). To begin, the cycle duration (aerobic time + anoxic time) had a defined minimum and maximum aerobic time. The cycle time was kept constant at 16 minutes with a minimum and maximum aeration time of 4 and 12 minutes, respectively. These set-points were chosen to maintain a NH_4^+-N concentration of at least 1.5 mg-N/L to prevent a DO spike resulting in overaeration. The goal of the AvN controller was to maintain NH_4^+-N concentrations equal to NO_x-N, when the NH_4^+-N concentration was greater than NO_x-N, the aerobic time would increase. When the NO_x-N concentration was greater than the NH_4^+-N concentration, the aerobic time was decreased. The cycle duration was constant throughout. The aerobic time was allowed to fluctuate between the minimum and maximum set-points by a PID controller. When aerated, a PID controller controlled a MOV to maintain the target DO set-point of 1.5 mg O_2/L. The working of this controller can be seen in Figure 5-4.

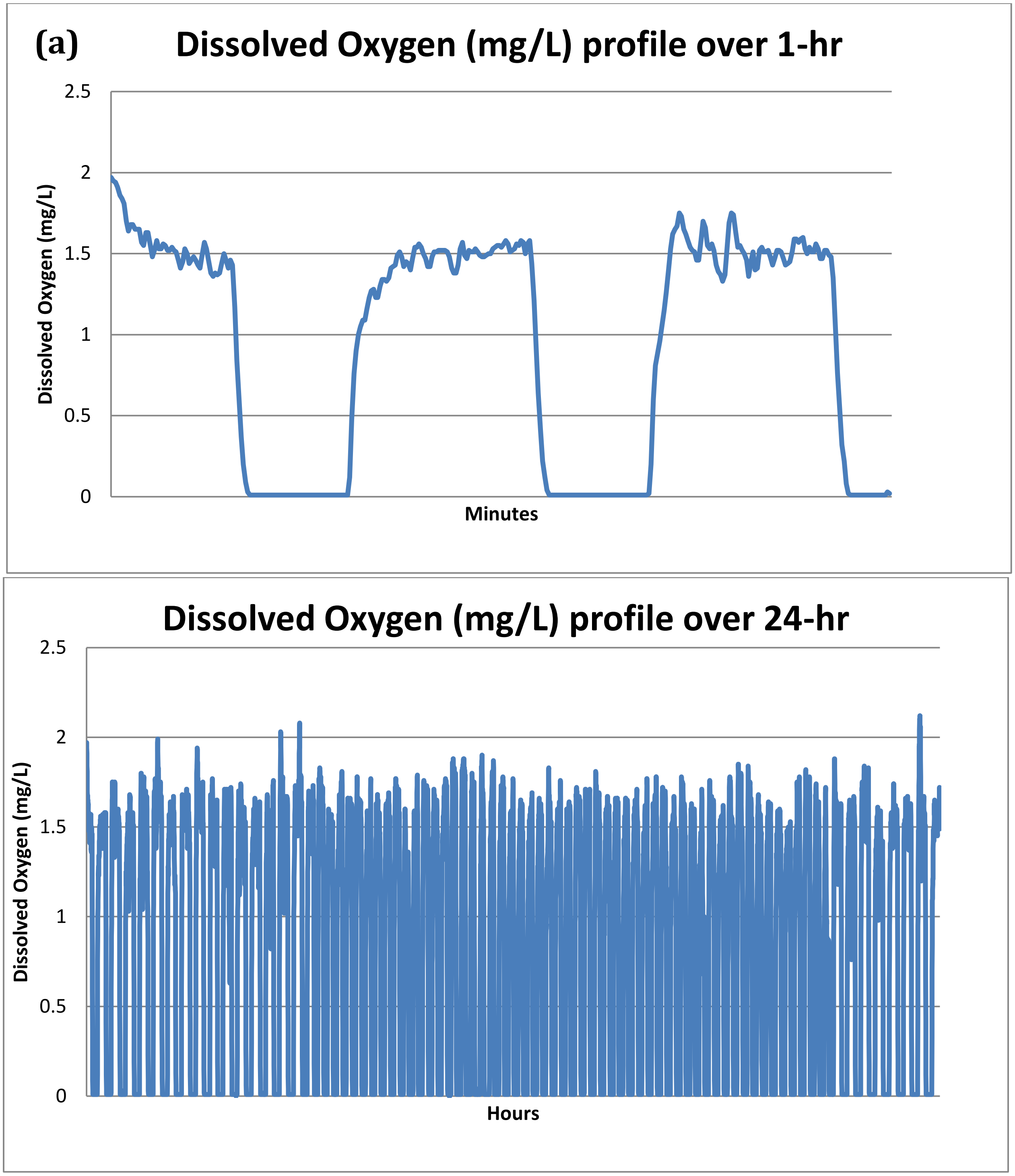


Figure 5-4: Example of Intermittent Aeration (a) Example of intermittent aeration over an hour (b) Example of intermittent aeration over a 24-hour period with a 12 minute cycle time (max aeration of 10 minutes, min aeration of 2 minutes per cycle) with a DO set-point of 1.5 mg O_2/L.

In order to complete the objectives, the reactor operation was divided into different phases (Table 5-1).

Table 5-1: Operational phases of B-Stage pilot.

Phase	Operation	HRT (hrs)	Number of days
I	All Reactors Intermittently Aerated	3	65
II	All Reactors Intermittently Aerated	4	12
III	MLE (IMLR 200%)	4	15
IV	MLE (IMLR 450%)	6	13
V	MLE (IMLR 325%)	6	11
VI	All Reactors Intermittently Aerated	6	17
VII	All Reactors Intermittently Aerated	2	43
VIII	All Reactors Intermittently Aerated	3	59

All relevant analytical methods performed weekly at the Chesapeake-Elizabeth WWTP shown in Table 5-2.

Table 5-2: Analytical measurements performed at Chesapeake-Elizabeth WWTP in pilot study location.

Parameter	Reference Method	Description
SVI	SM 18th 2710C	Settled Sludge Volume
ISV	SM 20th 2710 E	Zone Settling Rate
TSS	SM 20th 2540D	TSS - Total Suspended Solids Dried at 103-105°C
NH_3-N	Hach 10205	-Ammonia TNTplus ULR (0.015 to 2.00 mg/L NH3–N) -Ammonia TNTplus LR (1 to 12 mg/L NH3–N) -Ammonia TNTplus HR (2 to 47 mg/L NH3–N)
NO_2-N	Hach 10019	-Nitrite NitriVer 3 TNT LR (0.002 to 0.500 mg/L NO2–N) -Nitrite TNTplus HR (0.6 to 6.0 mg/L NO2–N)
NO_3-N	Hach 10206	-Nitrate TNTplus LR (0.23 to 13.5 mg/L NO3–N) -Nitrate TNTplus HR (5 to 35 mg/L NO3–N)
COD	Hach 8000	-COD TNTplus HR (20 to 1500 mg/L COD) -COD TNTplus LR (3 to 150 mg/L COD)

5.3.4 MICROSCOPY

Observation and counting of the different bacteria were performed using a Leica 2500 phase contrast microscope couple to a Leica DFC 290 camera. The Gram and Neisser staining techniques were used for identification. Based on the criteria suggested by Jenkins et al., (2004), the filamentous microorganism abundance and dominance were estimated and subjectively rated for overall abundance on a scale from 0 (none) to 6 (excessive). If three or more filaments are present within the sample, the filaments are ranked from dominant, secondary, tertiary in terms of abundance. Pictures taken throughout the experiment can be seen in Appendix 7.

5.3.4.1 Zone Settling Velocity (ZSV)

To measure ZSV, a 2 L sample was taken from the final reactor of the B-stage and mixed with a flat paddle. The sludge sample was then allowed to settle. Measurements of the sludge interface were recorded every 10 seconds for 5 minutes. The results were then plotted as time versus interface height. The initial linear portion of this graph, which represents the downward movement of the sludge-blanket surface after reaching a constant velocity characteristics of the suspension, was then isolated; the slope of the line was then recorded as the initial settling velocity (ISV). ZSV and ISV decrease with increasing initial concentrations of the same solids.

5.3.5 OXYGEN UPTAKE RATE (OUR)

To measure the OUR, 4 L samples were taken from each of the four tanks in the B-stage. A magnetic stir bar, DO probe and aeration stone were placed in each sample. Samples were initially aerated to 3-4 mg O_2/L, at which point the air was shut-off and DO measurements were taken every 10 seconds until the DO concentration falls below 1 mg O_2/L. This process was repeated 3 times. Results were graphed on three different time (hr) versus DO concentration (mg/L) plots. The slope of the graph represents the OUR (mg/L/hr). The average of the slopes of the three different plots was accepted as the OUR for each sample.

5.4 RESULTS/DISCUSSION

For ease of assessment of settling within the pilot-scale BNR system, the data was broken into Phases I-VIII based on operation and HRT (2). Wastewater characteristics (e.g. nutrients, readily biodegradable organics, dissolved sulfide, etc.), process design parameters (e.g. SRT, F/M, aeration basin configuration, wastewater feeding regime, etc.) and plant operating conditions (e.g. DO concentration, pH and temperature) have been shown to influence the filamentous organism population within activated sludge systems, which could lead to poor settling.

Table 5-3 details the wastewater characteristics of the final reactor of the B-stage that have been shown to influence filamentous bulking and settling issues. Overall, the system settled well with each Phase maintaining an average SVI $\leq$150 mL/g.

Table 5-3: Characteristics of each Phase of operation. Temperature was held at approximately 23°C. Reactors were intermittently aerated based off of AvN process control technology (cycle time of 16 minutes). Values in orange indicated operation as an MLE process. Values in black indicate full intermittent aeration.

Phase	I	II	III	IV	V	VI	VII	VIII
pH	6.65±0.09	6.72±0.06	6.72±0.07	6.69±0.04	6.71±0.02	6.71±0.07	6.76±0.07	6.60±0.07
F/M ratio (kgBOD/ kgMLVSS day)	0.057± 0.012	0.042± 0.005	NA	0.033± 0.010	NA	0.035±0	0.091± 0.020	0.079± 0.035
MLSS (mg/L)	3534± 708	3338± 406	4093± 188	3291± 860	2450± 211	2473± 139	3246± 477	2323± 835
MLVSS (mg/L)	2835±577	2654±294	3178±110	2601±540	1929±126	2184±113	3016±435	2294±983
Total SRT (days)	7.1±2.6	6.7±1.3	6.8±1.1	4.4±0.7	4.1±0.03	4.6±0.5	5.6±1.6	4.2±1.0
Aerobic SRT fraction	0.54±0.07	0.40±0.04	0.42±0.04	0.37±0.04	0.38±0.03	0.38±0.04	0.62±0.10	0.47±0.09
SVI 5 (mL/g)	237±62	198±56	228±10	231±33	172±26	153±9	226±48	241±43
SVI 30 (mL/g)	145±49	114±24	150±14	140±23	99±16	92±3	119±29	121±23
Turbidity (NTU)	3.5±3.1	2.8±2.5	1.7±0.3	5.1±2.4	5.0±1.1	4.3±0.9	7.4±4.5	6.4±2.4
Effluent TSS	25±4	32±9	18±4	27±4	43±28	30±11	23±8	27±5

NH_4^+-N loading rate (kg/L.d)	284±34	22512	221±12	132±10	140±7	126±10	343±30	237±26
TIN removal rate (kg/L.d)	156±48	151±21	168±15	114±8	108±0	99±6	172±39	131±56
TIN removal efficiency (%)	55±15	67±8	76±4	86±5	80±0	78±3	50±10	54±20
NAR	0.30±0.08	0.23±0.04	0.20±0.04	0.14±0.03	0.17±0	0.19±0.08	0.34±0.09	0.43±0.10

5.4.1 ENUMERATION OF FILAMENTOUS BACTERIA

Over the duration of this 242 day experiment (T=28.1±1.1^{0}C), various filaments were encountered as a result of altering operational parameters, stresses on the system, and temporary malfunctions such as pump and clarifier failures. As a result, the B-stage saw the development of *Haliscomenobacter Hydrossis*, *Thiothrix sp.* I and II, *Nocardia sp.*, Type 0675, Type 0041 and Type 0803 filaments (Figure 5-5).

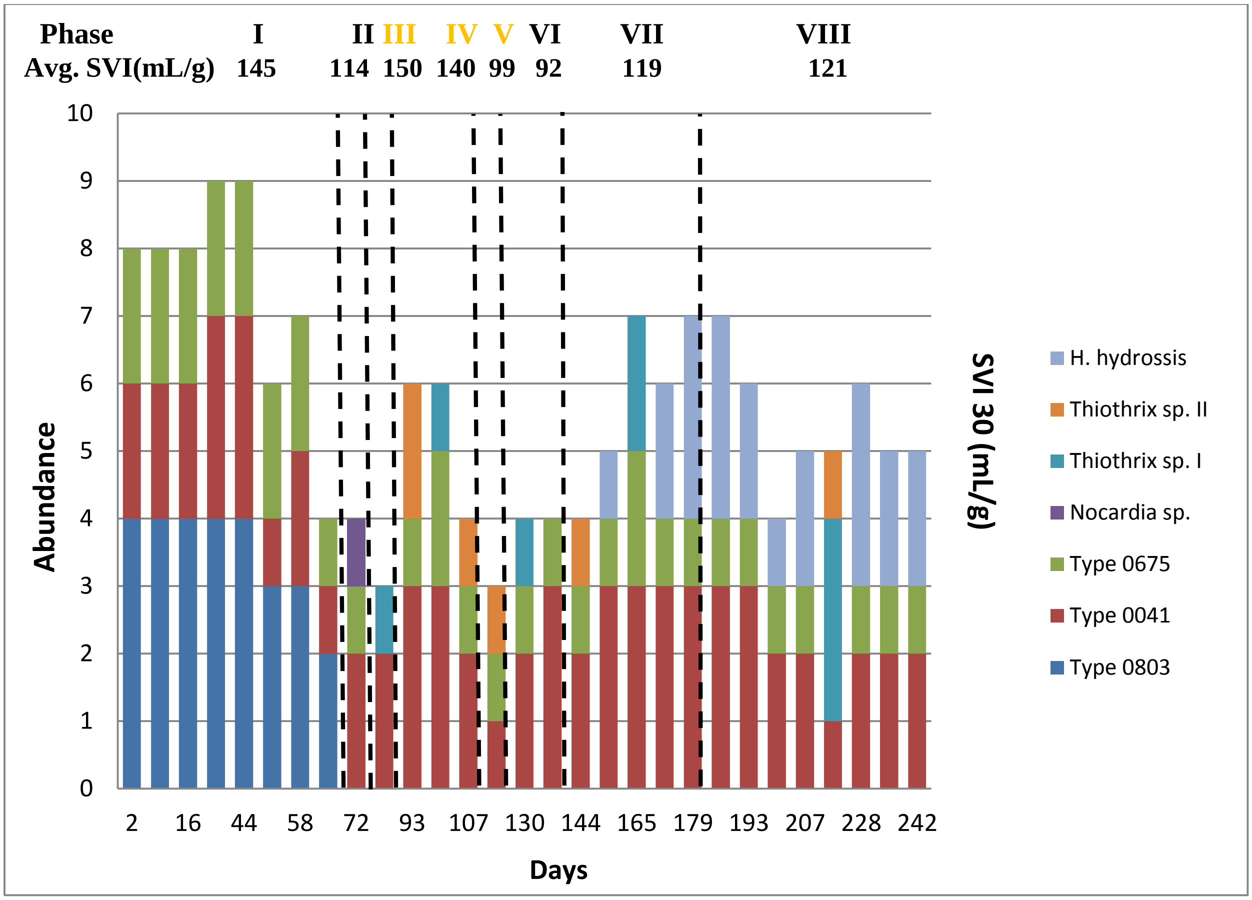


Figure 5-5: Represents the filamentous prevalence within the pilot scale BNR system over 242 days. Dominant filaments are represented on the bottom of each bar, followed by the secondary and tertiary above.

SVI values were unusually high during start-up with Type 0803, Type 0041 and Type 0675 present. Type 0041 and Type 0675 are common filaments observed in BNR activated sludge systems believed to be responsible for bulking events (Martins et al., 2004). Type 0803 filaments have been observed in systems with low F/M and low organic concentrations, which were characteristic of the beginning of Phase I (Table 5-3). Phase I saw the highest abundance of filaments which could be representative of the full-scale plant, as the pilot system was seeded from waste activated sludge (WAS) from the Chesapeake-Elizabeth Wastewater Treatment Plant (CETP). As the system stabilized, the SVI 30 slowly dropped by the end of Phase I (145.2±48.7 mL/g) and the filamentous abundance decreased, although Type 0041 and Type 0675, which are associated with low F/M, long SRT systems, were observed throughout the duration of the experiment.

The presence of *Nocardia* in Phase II caused foaming issues in the B-stage starting early November (roughly day 60). The foam was brown in color, sticky and viscous, and accumulated on the top of the reactors. Although no universal strategies exist for effective foaming control, vacuuming all of the foam off of the surface of the reactors and secondary clarifier appeared to remove the hydrophobic substances and substrate that could favor *Nocardia* growth. Foaming did not return again during the rest of the experiment. The presence of *Nocardia* temporarily caused the SVI 30 to increase above 200 mL/g; however, the average SVI 30 for the Phase was 114.2±24.4 mL/g.

Phases III, IV and V saw the first occurrence of *Thiothrix spp.*, filamentous organisms capable of utilizing hydrogen sulfide and low molecular weight organic acids produced in septic sewage as energy sources (Richard et al., 1985; Jenkins et al., 2004) (Figure 5-5). The A-stage experienced *Thiothrix spp.* bulking thought to be the result of high sulfide and organic acid concentrations in the influent raw wastewater during high temperature periods (Miller et al., 2014). Because we are not 100% certain that all of the sulfide and organic acid was removed in the A-stage prior to reaching the B-stage, *Thiothrix spp.* were recorded on multiple occasions and could be the result of carryover from the A-stage. Despite the presence of *Thiothrix spp.* I and II, the SVI 30 in Phases III, IV and V were, on average, 149.7±13.5 mL/g, 139.9±23.0 mL/g, and 98.6±16.0 mL/g, respectively. These three phases were also operated as an MLE, as opposed to full intermittent aeration, and are discussed further below.

Phase VI was returned to full intermittent aeration, however, the filamentous population did not change much. The SVI 30 decreased slightly to 92.1±3.3 mL/g.

Phases VII and VIII saw an increase in SVI 30 to 118.7±28.7 mL/g and 120.6±23.2 mL/g, respectively. The change could be attributed to the development of a *Halicomenobacter Hydrossis* (*H. Hydrossis*) population in Phase VII which continued through the end of the experiment (Figure 28). Prior to the first occurrence of *H. Hydrossis* (150+days after start-up), operational malfunctions (i.e. pump and clarifier failures), a complete biomass washout on day 158 and the continual switch to anoxia within the reactors creating low DO environments could have induced stresses believed to support *H. Hydrossis* growth. Pernelle et al., (2002) found *H. Hydrossis* to increase 550-fold after multiple low DO and low substrate related stresses within an activated sludge pilot plant. The beginning of Phase VII had an average SVI 30 of approximately 88 mL/g which increased to approximately 128 mL/g after the first *H. Hydrossis* observation.

It has been shown that SVI 30 is affected by the amount of filamentous bacteria present (Sezgin et al., 1978; Jin et al., 2003). The hypothesis exists that different types of aggregates exists. When a large amount of filaments exist, they protrude from the floc structure, causing “filament-to-filament” and “filament-to-floc” aggregation resulting in the development of large voids within the floc. These voids result in loose, low density flocs that settle and compact poorly (Jin et al., 2003). Good settling flocs are compact and dense; attributed to either a lack of filamentous bacteria resulting in “floc-to-floc” aggregation or already dense flocs preventing the growth of filaments. This would support the hypothesis that fewer filaments result in better sludge compaction; SVI 30 can be affected by the amount of filamentous bacteria (Sezgin et al., 1982). Thus, finding the operational parameters to support low filament abundance would be necessary to support improved settling.

This study saw a slight linear correlation (R^2=0.33) between filamentous abundance and SVI 30, agreeing with research by Sezgin et al., (1982). Next, the correlation between the particular filaments and the increasing SVI 30 values were evaluated. Type 0803 (R^2=0.56), *Thiothrix sp.* II (R^2=0.47) and Type 0675 (R^2=0.33), when evaluated separately, appeared to demonstrate the strongest correlation between abundance and degrading settleability. However, the filamentous communities as a whole were not taken into account

5.4.2 IMPACT OF SUBSTRATE CONCENTRATION ON SETTLING CONDITIONS

5.4.2.1 Sludge Volume Index (SVI) versus F/M ratio, ZSV (m/hr)

The SVI is an attempt to quantify the settling and compaction characteristics of activated sludge. The SVI is the volume of 1 g of sludge assessed after 5 and 30 minutes of settling. An SVI 5 values represents the settling characteristics of the sludge. The SVI 30 value gives insight into how well the sludge compacts. The SVI was determined by placing a mixed-liquor sample in a 2-L settleometer and measuring the settled volume after 30 minutes and the corresponding sample MLSS concentration (Tchobanoglous et al., 2004). Equation 15 computes the SVI from the settleometer reading and MLSS concentration:

$$SVI = \frac{\left(settled\ volume\ of\ sludge, \frac{mL}{L}\right)\left(\frac{10^3 mg}{g}\right)}{\left(suspended\ solids, \frac{mg}{L}\right)} = \frac{mL}{g} \tag{15}$$

The food (substrate) to microorganism (biomass) ratio (F/M) is a common parameter used to characterize process designs and operating conditions. Equation 16 shows how this value is obtained:

$$\frac{Food}{Microorganism} = \frac{Flow, \frac{ML}{d} \times BOD, \frac{mg}{L} \times 1\frac{kg}{M \times mg}}{Volume, ML \times MLVSS, \frac{mg}{L} \times 1\frac{kg}{M \times mg}} \tag{16}$$

Finally, the ZSV was calculated as the rate of downward movement of the sludge-blanket surface after reaching a constant velocity characteristic of the suspension. These values was recorded visually and plotted as time versus interface height. The ZSV was taken as the slope of the line during the first five minutes once a constant velocity was reached.

After the initial stabilization of the system of the first 30-40 days, the SVI remained around or below 160 mL/g (Figure 5-6a) with the exception of day 158 when the biomass within the system was washed out causing an upset. Research by Casey et al., (1992) found that the low F/M ratio caused a particular set of filamentous bacteria to thrive (called low F/M filaments) that correlated to the accumulation of nitrite. Typical low F/M filaments include Type 0041, Type 0675 and Type 0803, which were present throughout the experiment. However, results from this experiment did not find any consistent relationship between SVI, F/M, ZSV and SRT.

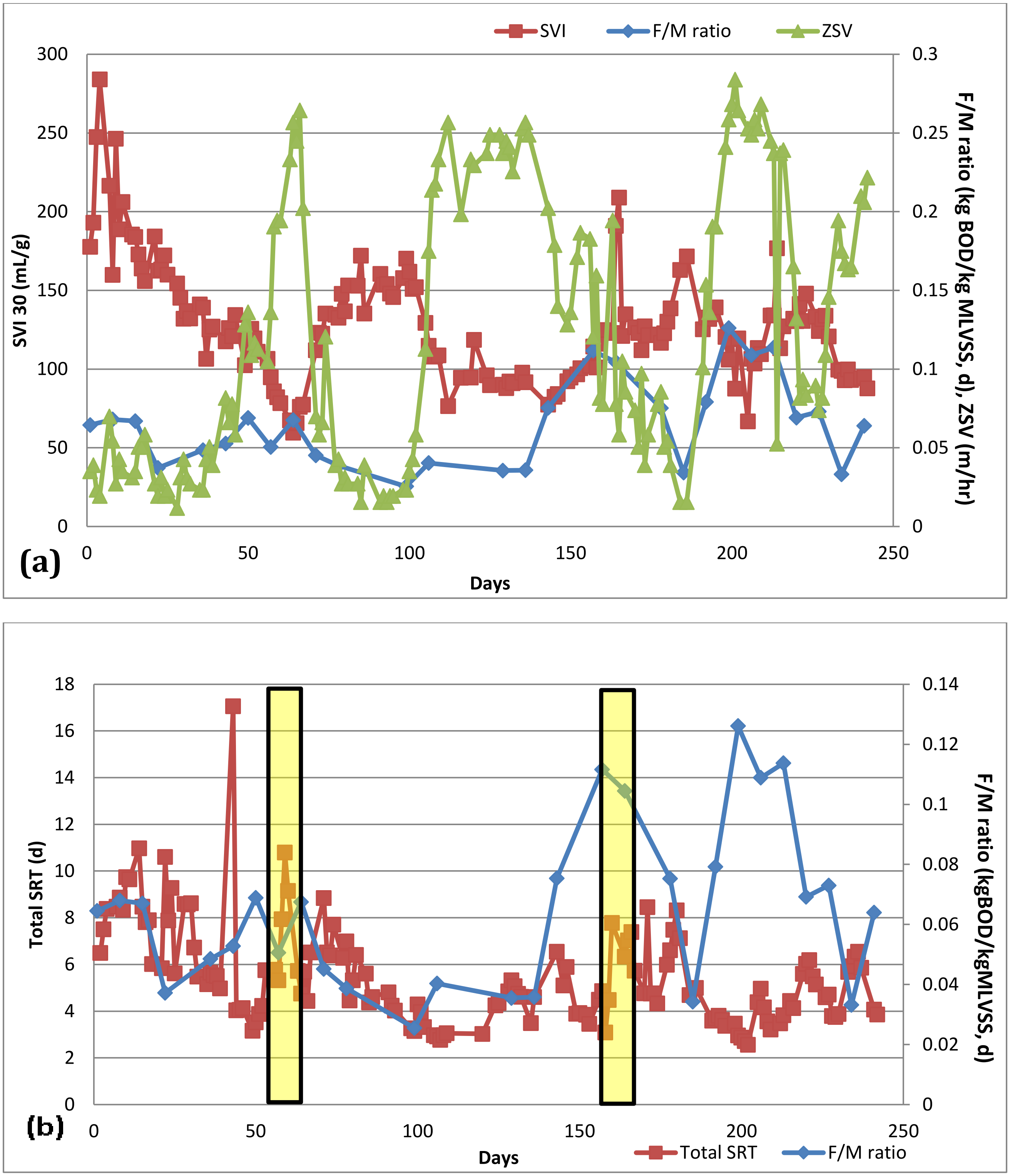
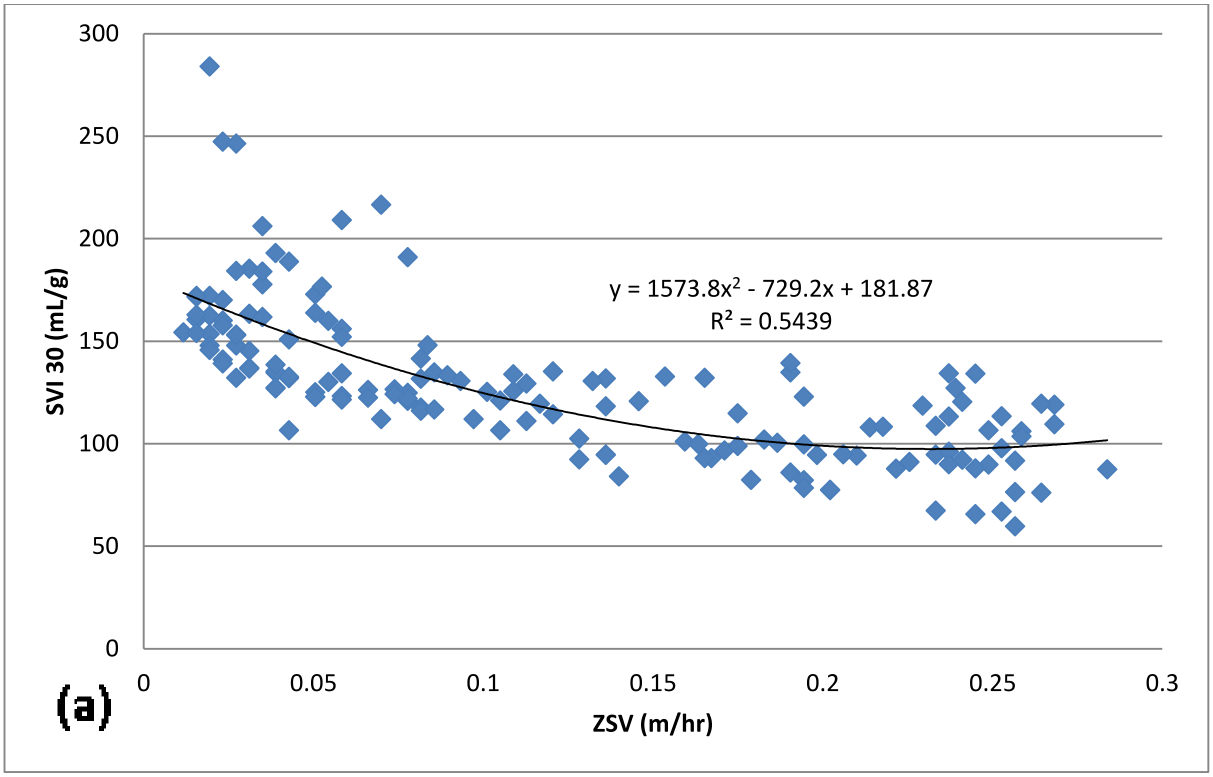


Figure 5-6: a) Sludge Volume Index (SVI) is compared with the F/M ratio and ZSV b) SRT is compared to the F/M ratio. Biomass washout on Day 158 caused a spike in SVI 30. Drained clarifier on day 58 to deal with foaming issues which caused a spike in SRT.

The activated sludges had SVI 30 values ranging from 60-284 mL/g representing the sludge compaction, and ZSV ranging from 0.012-0.284 m/hr representing settling ability. This study found an inverse correlation (R^2=0.54) between SVI 30 and ZSV (Figure 5-7b). It is known that SVI and ZSV are influence by the geometry of the settling device, the concentration of MLSS, the sludge volume, the temperature and floc structure (Dick & Vesilind, 1969; Daigger & Roper, 1985; Jin et al., 2003). This study used a 2 L settleometer. The accuracy of the settling measurements could be affected by the high surface area to volume ratio; "wall effects" would alter the recorded SVI in relation to an actually clarifier.



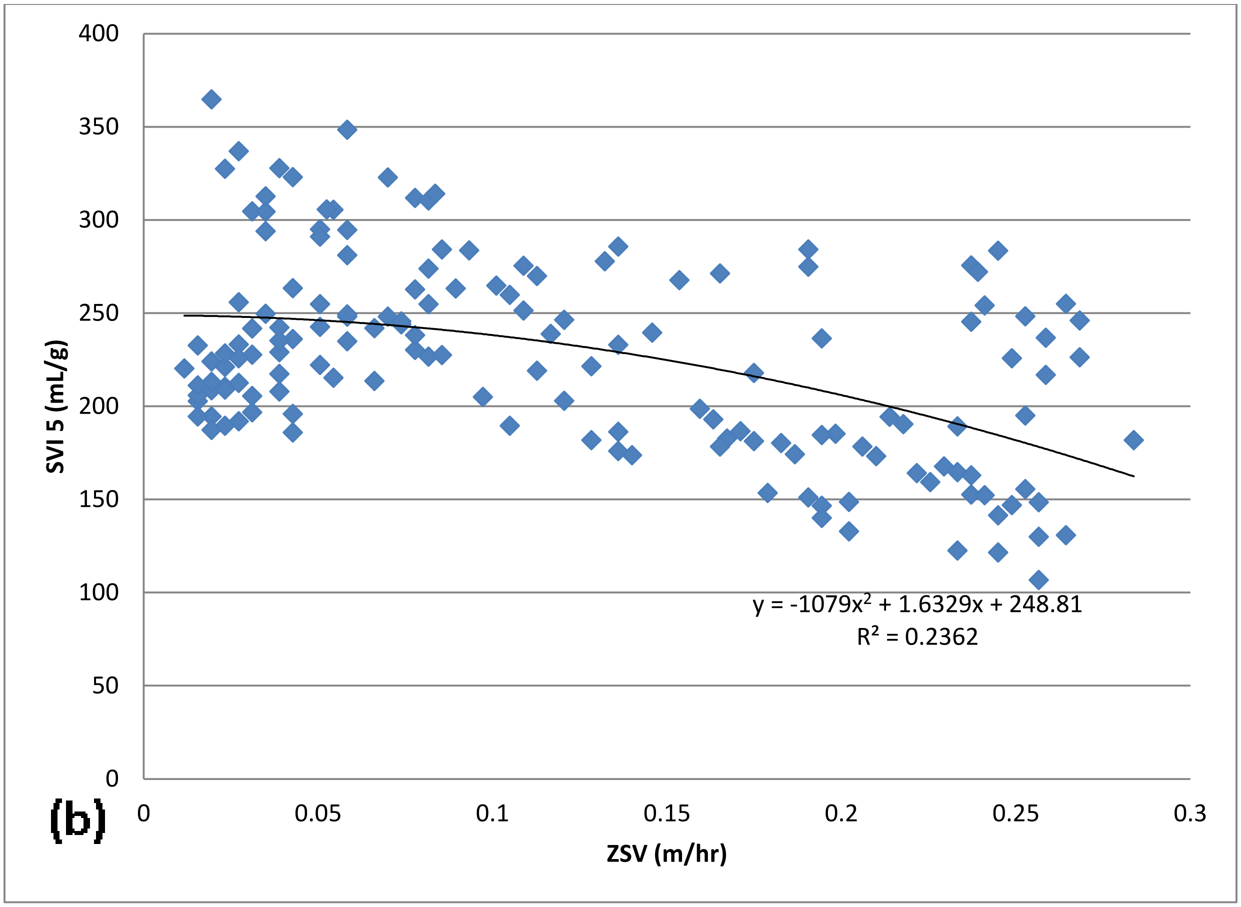


Figure 5-7: Relationship between a) SVI 30 and ZSV b) SVI 5 and ZSV.

This study can be compared with the results of three full-scale activated sludge WWTP results (Table 5-4).

Table 5-4: Comparison between results from this study with the floc characteristics of other activated sludge WWTP results.

		This Study	Gibson Island*	Wacol*	Oxley Creek*
Parameter	**Unit**				
Biological process		C, N	C, N	C, N, P	C
WW Source		Domestic	Domestic	50% Domestic/ 50% Industrial	Domestic
Filament Index		4-7	5	2	4-5
SVI 30	mL/g	128±36	255±5	97±18	235±11
ZSV	m/h	0.13±0.08	0.52±0.22	2.89±1.26	1.49±1.10
Volatile fraction (VSS/MLSS)	%	87±6	80±5	80±2	73±5

SRT	days	6±2	18	35	4

Biological processes are classified as carbon removal (C); nitrogen removal (N); and phosphorus removal (P).
*(Jin et al., 2003)

Despite an apparent correlation between MLSS and ZSV, there exists an argument as to whether SVI 30 and zone settling velocity (ZSV) can be correlated (Figure 5-7a). Dick and Vesilind (1969) reported no consistent relationship between SVI and ZSV exists. Bye and Dold (1998) called into question the relationship between SVI and the Vesilind equation. Literature surveys collected by Jin et al. (2003), however, found a positive correlation between SVI and ZSV concluding sludge that settles poorly also compacts poorly (Table 5-4).

The positive correlation between SVI and ZSV under poor settling conditions is expected as less compact flocs settle slowly and do not compact well. However, when settling is good, floc structures are usually denser, settling quickly and compacting well. SVI 30 does not give a clear indication of exactly how quickly sludge settles such that different plants could not use it as a basis for comparison; ZSV and/or the combination of SVI 5 and SVI 30 would give a more complete picture of sludge settling as they indicate "how" the sludge settled before compaction. SVI 5 gives an indication of how quickly the sludge interface begins to settle, similar to ZSV. It could be surmised that ZSV and SVI 5 would demonstrate a positive correlation at both good and bad settleability. However, this is not the case for this study (Figure 5-7b), which showed only the slightest correlation (R^2=0.24) between SVI 5 and ZSV possibly as a result of the filamentous population present and its potential effect on settleability which did not degrade sludge compaction.

5.4.3 NITRITE ACCUMULATION

Nitrite accumulation has been cited as one cause of settling issues (Blackburne et al., 2008; Ma et al., 2013), although the cause of filamentous bulking due to nitrite has not been confirmed (Casey et al., 2004; Guo et al., 2013). According to the *NO Hypothesis* proposed by Casey et al., (1994), the accumulation of nitrite could be used to indicate the presence of NO (Martins et al., 2004). Research found NO to be the inhibitory substrate to floc-formers over filamentous bacteria, with inhibition from NO_2^- -N, as well. NO and NO_2^- are intermediates of denitrification which result from the reduction of NO_3^- (Figure 5-1), hypothesized to accumulate in the floc-forming bacteria and not in the filamentous bacteria. This research postulated that some filaments are able to reduce NO_3^- to NO_2^- only and do not accumulate the intermediate inhibiting compound NO (Casey et al., 1994; Martins et al., 2004), whereas floc-formers were able to denitrify NO_3^- to N_2 gas. In this environment, filamentous bacteria would have the competitive advantage over floc-forming bacteria. The nitrite concentration is shown versus the sludge compaction ability (SVI 30) and the settling ability (ZSV) in Figure 5-8.

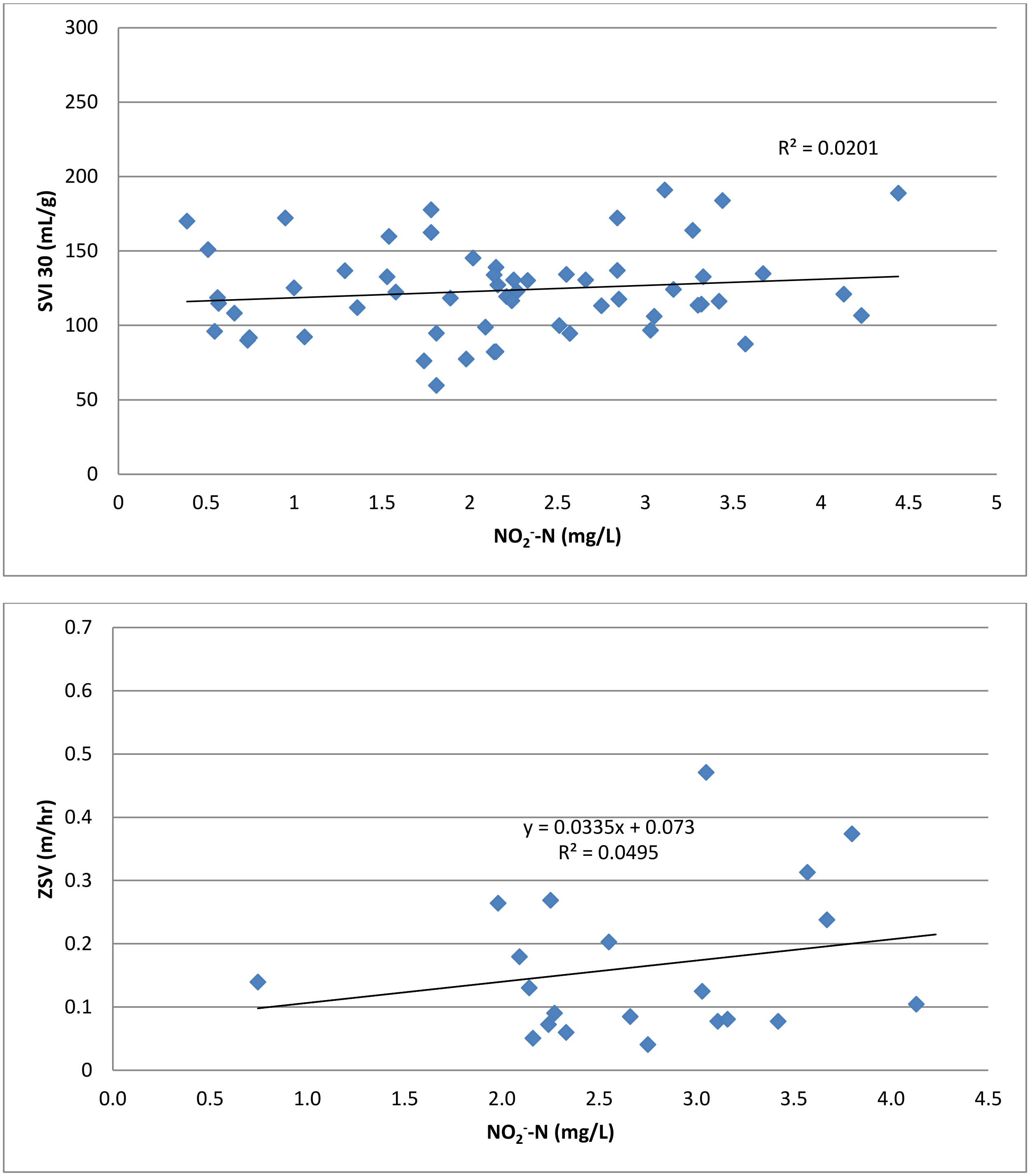


Figure 5-8: Nitrite accumulation versus SVI 30 and ZSV.

This study observed little to no correlation between nitrite accumulation and sludge compaction (p-value 0.33) or settleability (p-value 0.68) (Figure 5-8). There is no evidence of degrading settleability due to the accumulation of nitrite favored by the AvN intermittent aeration control strategy.

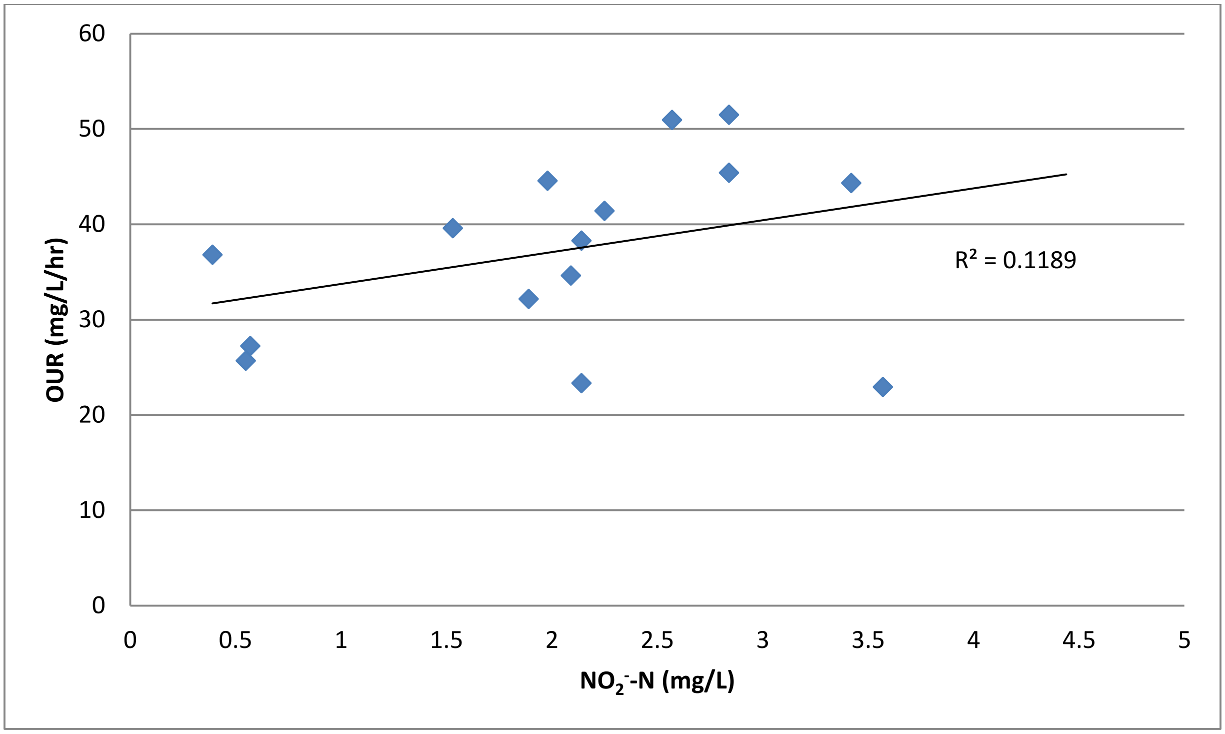


Figure 5-9: OUR versus nitrite accumulation.

Casey et al. (1992) proposed that low F/M filament bulking is caused by the intermediate NO, which inhibits the utilization of sbCOD by floc-formers under subsequent aerobic conditions, under high nitrite concentrations, thereby allowing filamentous organisms, which do not accumulate NO, to dominate. Oxygen uptake rate (OUR) inhibition by NO in sludge switching from anoxic to aerobic environments was found to do so in the presence of NO_2^- due to aerobic denitrification, however, this study found only a very slight correlation (R^2=0.12) between the OUR and nitrite accumulation (Figure 5-9).

5.4.3.1 Full Intermittent Aeration versus MLE

Figure 5-10 compares the effect of nitrite accumulation on sludge bulking for the different Phases of operation; either full intermittent aeration or MLE. The higher SVI values of 145±49mL/g, 150±14mL/g, and 140±23mL/g of Phases I, III and IV, respectively, correspond to lower ZSV values of 0.071±0.062 m/hr, 0.030±0.009 m/hr and 0.072±0.071 m/hr, respectively. This agrees with the notion that less compact flocs settle slower and do not compact as well as denser floc structures. A high accumulation of nitrite was not consistently present within all three of these phases. However, the better settling sludge did see lower nitrite concentrations, which could just be coincidence. Phase VI saw the best overall settling with an SVI of 92±3 mL/g and an average nitrite concentration of 0.77 mg/L.

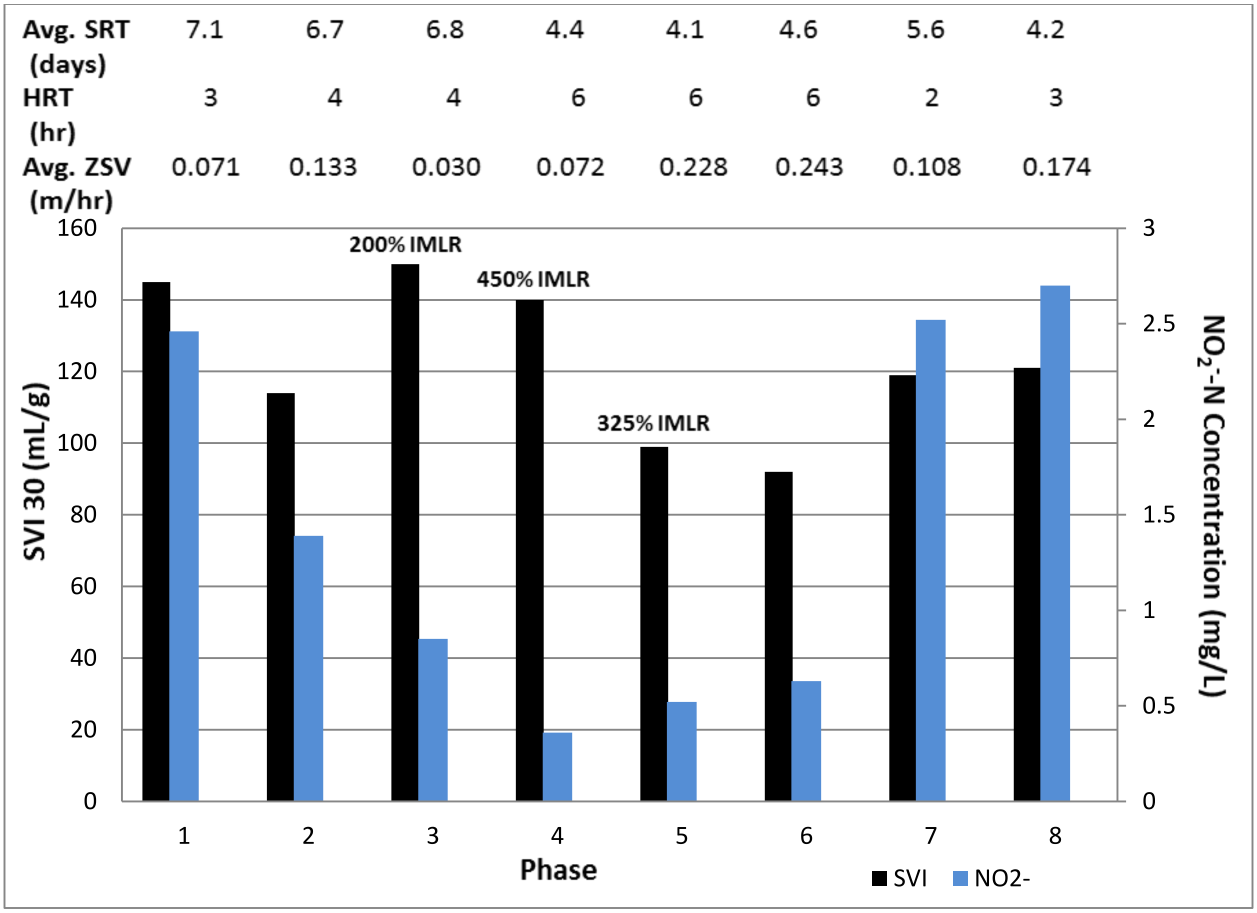


Figure 5-10: Variation in SVI and NO_2^- during each Phase.

This experiment experienced good overall settling (<150 mg/L), and good effluent quality (i.e. low turbidity and low effluent TSS)(Table 5-3), suggesting that operational parameters were not responsible for poor settling.

5.5 CONCLUSION

This study evaluated the settleability of an intermittently aerated pilot-scale BNR system over 242 days under various loading conditions operated under full intermittent aeration and an MLE process. Good settling sludge was maintained throughout the experiment at an SVI 30 of 128.3±36.3 mL/g at ambient temperature (23.8±1.1^{0}C). Type 0041 and Type 0675 were seen throughout the experiment implying they were not linked to poor settling; however, their presence has been typical of BNR systems. The presence of *Thiothrix spp.* were linked to the A-stage conditions; this research could not confirm that 100% of the sulfide and organic acids present within the A-stage were removed prior to the B-stage, which could favor *Thiothrix spp.* This study temporarily saw the development of *Nocardia* which caused foaming on the surface of the reactors and the secondary clarifier. Vacuuming the surface of the reactors and secondary clarifier appeared to remove the hydrophobic substances, which did not return. Finally, *H. Hydrossis* appeared 150+ days into the experiment and stayed through the end. Their development was attributed to the stresses (pump and clarifier malfunctions, continual low DO environments due to intermittent aeration, etc.) introduced both on the macro- and microscopic levels. Despite the development of various filamentous microorganisms, the AvN control of the intermittent aeration was able to maintain good settling throughout the experiment.

The accumulation of nitrite is believed to cause the degradation of settling within BNR systems according to the *NO Hypothesis*. This study saw the accumulation of nitrite as a result of the AvN control strategy; however, it did not correlate with high SVI values. Operation as an MLE saw some of the poorest settling, possibly a result of the increased HRT and low ammonia loading rate which resulted in a low F/M ratio allowing the proliferation of low F/M filaments Type 0041, Type 0675 and Type 0803, subsequently leading to the degradation of SVI; which correlated with the lowest nitrite concentrations. Therefore, the nitrite did not favor the growth of filamentous bacteria leading to poor settleability.

Intermittent aeration creates a low DO environment, and the AvN control strategy favors AOB which may lead to the accumulation of both nitrite and NO. These characteristics have been demonstrated to favor filamentous microorganisms; however, this study was able to maintain good settleability under AvN control of intermittent aeration as a fully intermittent aeration and an MLE process demonstrating its' applicability to be effectively implemented into mainstream intermittently aerated continuous plug-flow BNR systems.

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6. ENGINEERING SIGNIFICANCE

As the water quality around the world degrades, wastewater treatment plants face the difficult job of meeting increasingly stringent regulations aimed at preserving our natural resources. Cutting-edge technology in sustainable wastewater treatment has been present in Europe for quite some time, slowly making its way to the United States as restrictions on discharge limits tighten. Although this study specifically addressed requirements for an upgrade of the Chesapeake-Elizabeth WWTP, the process control techniques and underlying concepts have a broad range of application in wastewater treatment with the resulting environmental impact in mind. The A/B process utilized in this study consists of a very high-rate activated sludge (HRAS) A-stage for carbon removal followed by a B-stage activated sludge process for nitrogen removal.

The most widely applicable result of this study is the ability to use ammonia-based aeration controls to optimize resources within the system. Millions of dollars are spent annually on external carbon addition to promote denitrification while simultaneously spending more money to remove carbon upstream. When too much carbon is present in wastewater it is commonly oxidized aerobically; wasting of a valuable resource and creating excess biomass. Ammonia-based aeration control (ABAC) promotes the efficient utilization of carbon, even allowing cost-effective COD reduction options in treatment plants with sufficient influent carbon to nitrogen ratios. Options for cost-effective COD reduction include an A-stage, chemically enhanced primary treatment, or anaerobic digestion. The A-stage utilized in this experiment was manipulated to find the lowest possible carbon to nitrogen ratio to achieve mainstream NOB out-selection in the nitrogen removal stage, while maximizing the carbon diverted from the A-stage for energy production. NOB out-selection is a shortcut in nitrogen removal from the conventional nitrification-denitrification pathway. NOB out-selection aims to stimulate AOB (nitrifying bacteria that convert ammonia to nitrite) and suppress NOB (nitrifying bacteria that convert nitrite to nitrate), requiring less aeration for nitritation and less carbon for denitrification. Great success at achieving NOB out-selection has been seen in high ammonia and high temperature sidestream wastewater processes; however, success in dilute mainstream wastewater processes is slow, but essential to the development of a sustainable A/B process.

This process was maintained at ambient temperature (23.8 ± 1.1^{0}C) and operated under AvN control both under full intermittent aeration and as a Modified Ludzak-Ettinger (MLE) process. Operation as a full intermittent aeration process saw nitrite accumulation ratios (NAR) [NO_2^--N/(NO_2^--N+ NO_3^--N)] of 0.43 ± 0.10 at a 3 hour HRT and influent carbon to ammonia ratio (COD/NH_4^+-N) of 7.9 ± 1.4. Operation as an MLE improved the overall TIN removal efficiency compared to operation where all reactors were intermittently aerated. The TIN removal efficiency increased as the IMLR and influent COD/NH_4^+-N increased. When the IMLR was 200%, 325% and 450%, the TIN removal efficiencies were 76.4 ± 4.0%, 80.2 ± 0% and 86.3 ± 5.0%, respectively, at influent COD/NH_4^+-N and HRT of 9.2 ± 0.8 and 4 hr, 9.8 ± 0.4 and 6 hr, and 10.3 ± 1.2 and 6 hr, respectively. These results demonstrate the ability of AvN control to use intermittent aeration to allow nitrification and denitrification to occur within a reactor to maximize nitrogen removal while minimizing aeration volume, aeration demand, supplemental carbon and alkalinity addition (Regmi, 2014).

Further, this study demonstrated the ability of the AvN control to achieve and maintain good settling (overall SVI of 128.3±36.2 mL/g) throughout this study despite the accumulation of nitrite and the implementation of intermittent aeration, both of which have been linked with the degradation of settleability in BNR systems.

Currently, mainstream deammonification is the most sustainable nitrogen removal process. The key component to successful deammonification is achieving NOB out-selection, or partial nitritation. In order for mainstream deammonification to achieve near complete nitrogen removal, the partial nitritation step must produce an effluent that is 50% ammonia and 50% nitrite. Nitrite is difficult to measure precisely, so this study implemented an ABAC scheme (called AvN control) which successfully produced an effluent with equal parts ammonia and NO_x (nitrite+nitrate). Even without complete NOB out-selection, this robust control scheme produced effluent amenable to anammox polishing. Anammox bacteria remove equal parts ammonia and nitrite from wastewater capable of achieving extremely low nitrogen concentrations in the final effluent; the amount removed depends on the limiting substrate present.

Future work is needed to explore the effect of lower temperatures ($T<23^{0}C$) on the out-selection of NOB. As was done at ambient temperature, different operational parameters and loading conditions need to be tested to optimize nitrogen removal and stimulate AOB growth while simultaneously inhibiting NOB. Application of AvN control strategies need to be tested at all temperatures typically observed in a full-scale wastewater treatment plant throughout the different seasons. Further, the settleability will need to be reassessed at these lower temperatures. More in-depth analysis of the floc-structures and NO concentration would provide insight into the floc-forming and filamentous microorganism present and how they adapt to different operational parameters, process configurations, and temperatures indicative of full-scale BNR operation.

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A: APPENDIX OF DATA COLLECTED AND PRESENTED

A.1 INFLUENT CHARACTERISTICS

Average	32.63	2.92	284.24	143.51	8.8	141.45	
SD	4.56	0.91	69.25	35.83	1.69	43.18	0.88
Max	43.00	7.05	513.00	299.00	16.8	282.24	
Min	22.10	0.90	136.00	56.00	5.3	51.00	
	A-stage Effluent (Train B)						
Date	**TAN**	**OP**	**COD**	**sCOD (1.5)**	**COD/NH4-N**	**pCOD**	**TP**
	Comp	**Comp**	**Comp**	**Comp**		**Comp**	**Comp**
	Onsite	**Onsite**	**Onsite**	**Onsite**		**Onsite**	**CEL**
(dd:mm:yyyy)	**(mg N/L)**	**(mg P/L)**	**(mg/L)**	**(mg/L)**		**(mg/L)**	**(mg P/L)**
3-Sep-2013	38.3	3.20	393	187	10.3	206	5.42
4-Sep-2013	33.7	2.52	284	131	8.4	153	
5-Sep-2013	33.6	1.89	187	100	5.6	87	3.97
6-Sep-2013							
7-Sep-2013							
8-Sep-2013	33.4	1.54	216	114	6.5	102	
9-Sep-2013	32.0	1.55	233	119	7.3	114	
10-Sep-2013	31.7	1.86	194	106	6.1	88	4.04
11-Sep-2013	33.9	1.81	203	107	6.0	96	
12-Sep-2013	34.5	2.30	216	102	6.3	114	4.41
13-Sep-2013							
14-Sep-2013							
15-Sep-2013	32.6	2.01	217	114	6.7	103	
16-Sep-2013	32.0	2.03	225	125	7.0	100	
17-Sep-2013	30.4	2.11	204	103	6.7	101	4.04
18-Sep-2013	36.4	7.05	202	130	5.5	72	
19-Sep-2013	35.2	2.32					4.44
20-Sep-2013							
21-Sep-2013							
22-Sep-2013	38.2	3.63	405	210	10.6	195	
23-Sep-2013	37.6	3.61	392	206	10.4	186	
24-Sep-2013	35.8	3.27	361	168	10.1	193	5.28
25-Sep-2013	43.0	3.40	368	161	8.6	207	
26-Sep-2013	35.1	2.77	330	124	9.4	206	5.57
27-Sep-2013							
28-Sep-2013							
29-Sep-2013	37.9	2.82	366	155	9.7	211	
30-Sep-2013	37.4	2.64	328	139	8.8	189	

1-Oct-2013	39.5	2.29	286	123	7.2	163	5.00
2-Oct-2013	42.6	2.97	309	137	7.3	172	
3-Oct-2013	41.1	3.44	322	145	7.8	177	5.28
4-Oct-2013							
5-Oct-2013							
6-Oct-2013	36.3	2.54	332	160	9.1	172	
7-Oct-2013	35.6	2.17	333	130	9.4	203	
8-Oct-2013	35.0	1.11	280	109	8.0	171	3.83
9-Oct-2013	31.4	1.31	281	117	8.9	164	
10-Oct-2013	25.0	0.90	279	108	11.2	171	3.44
11-Oct-2013							
12-Oct-2013							
13-Oct-2013	29.8	1.10	237	126	8.0	111	
14-Oct-2013	32.8	1.64	267	110	8.1	157	
15-Oct-2013	37.5	2.27	305	113	8.1	192	4.25
16-Oct-2013	37.7	2.54	303	110	8.0	193	
17-Oct-2013							5.14
18-Oct-2013							
19-Oct-2013	39.0	3.22	359	175	9.2	184	
20-Oct-2013	39.0	3.17	361	170	9.3	191	
21-Oct-2013	40.8	3.13	363	147	8.9	216	
22-Oct-2013	38.3	3.31	357	140	9.3	217	5.92
23-Oct-2013	37.8	3.43	371	145	9.8	226	
24-Oct-2013							5.97
25-Oct-2013							
26-Oct-2013	39.2	3.39	387	176	9.9	211	
27-Oct-2013	36.7	3.05	372	186	10.1	186	
28-Oct-2013	38.0	3.49	366	155	9.6	211	
29-Oct-2013	34.9	3.14		183			5.87
30-Oct-2013	37.6	3.66		257			
31-Oct-2013							5.69
1-Nov-2013							
2-Nov-2013	33.7	3.10	301	135	8.9	166	
3-Nov-2013	36.0	3.16	309	119	8.6	190	
4-Nov-2013	36.0	3.16	309	119	8.6	110	
5-Nov-2013	35.1	3.20	302	125	8.6	116	4.89
6-Nov-2013	38.3	3.64	292	141	7.6	133	
7-Nov-2013	36.5	3.98	288	133	7.9	125	5.03
8-Nov-2013							
9-Nov-2013							
10-Nov-2013							
11-Nov-2013	36.1	3.92	307	166	8.5	157	
12-Nov-2013	37.8	3.26	312	165	8.3	157	4.20

13-Nov-2013	35.9		288		8.0		
14-Nov-2013	41.7		265.0		6.4		4.84
15-Nov-2013							
16-Nov-2013							
17-Nov-2013	39.1	3.5	350.0	176.0	9.0	167	
18-Nov-2013	36.4	3.4	338.0	177.0	9.3	168	
19-Nov-2013	38.8	2.9	327.0	158.0	8.4	150	4.75
20-Nov-2013	37.5	2.8	333.0	154.0	8.9	145.1	
21-Nov-2013							4.43
22-Nov-2013							
23-Nov-2013							
24-Nov-2013	40.8	3.76	358	182	8.8	173.2	
25-Nov-2013	34.4	2.91	318	173	9.2	163.8	
26-Nov-2013	35.6	3.11	317	152	8.9	143.1	
27-Nov-2013	37.5	2.76	333	154	8.9	145.1	
28-Nov-2013	38.1	2.38	328	195	8.6	186.4	
29-Nov-2013							
30-Nov-2013							
1-Dec-2013	36.7	3.72	398	194	10.8	183.2	
2-Dec-2013	34.4	4.01	423	239	12.3	226.7	
3-Dec-2013	38.4	4.40	413	189	10.8	178.2	5.78
4-Dec-2013	42.6	4.71	394	208	9.2	198.8	
5-Dec-2013	41.7	5.16	423	202	10.1	191.9	5.81
6-Dec-2013							
7-Dec-2013							
8-Dec-2013	36.1	4.87	435	222	12.0	210.0	
9-Dec-2013	31.8	4.41	412	196	13.0	183.0	
10-Dec-2013	30.2	3.41	292	131	9.7	121.3	4.40
11-Dec-2013	31.2		282	122	9.0	113.0	
12-Dec-2013	34.0	4.0	330.0	145.0	9.7	135.3	4.62
13-Dec-2013							
14-Dec-2013							
15-Dec-2013	31.6		335.0	177.0	10.6	166.4	
16-Dec-2013	33.0	3.6	338.0	171.0	10.2	160.8	
17-Dec-2013							4.78
18-Dec-2013	33.8	4.00	359	153	10.6	142.4	
19-Dec-2013	38.0	3.97	368	165	9.7	155.3	5.05
20-Dec-2013							
21-Dec-2013							
22-Dec-2013	37.3	4.57	368	193	9.9	183.1	
23-Dec-2013							
24-Dec-2013							

25-Dec-2013							
26-Dec-2013	36.3	4.42	335	173	9.2	163.8	5.54
27-Dec-2013							
28-Dec-2013							
29-Dec-2013	33.9	4.55	338	179	10.0	169.0	
30-Dec-2013	33.9	4.10	348	168	10.3	157.7	
29-Dec-2013							
30-Dec-2013	33.4	4.31	352	181	10.5	170.5	
31-Dec-2013							4.92
1-Jan-2014							
2-Jan-2014	33.7	3.48	369	182	10.9	171.1	
3-Jan-2014							
4-Jan-2014							
5-Jan-2014	33.8	3.45	365	199	10.8	188.2	4.76
6-Jan-2014	31.9	4.16	364	190	11.4	178.6	
7-Jan-2014	34.5	3.54	331	161	9.6	151.4	5.43
8-Jan-2014	31.8	3.74	353	166	11.1	154.9	
9-Jan-2014	34.7	3.97	376	158	10.8	147.2	
10-Jan-2014							
11-Jan-2014							
12-Jan-2014							4.22
13-Jan-2014	27.5	3.14	354	165	12.9	134	
14-Jan-2014	27.6	3.38	305	171	11.1	171	4.90
15-Jan-2014	30.9	3.49	316	137	10.2	179	
16-Jan-2014	29.4	3.44	319	125	10.9	194	
17-Jan-2014							
18-Jan-2014							
19-Jan-2014							3.68
20-Jan-2014	28.0	2.79	307	148	11.0	159	
21-Jan-2014	26.5		259	115	9.8	144	4.01
22-Jan-2014	26.1	1.96	223	106	8.5	117	
23-Jan-2014	27.0	2.15	245	106	9.1	139	
24-Jan-2014							
25-Jan-2014							
26-Jan-2014	28.8	2.51	272	144	9.4	128	
27-Jan-2014	28.9	2.93	265	158	9.2	107	
28-Jan-2014							4.40
29-Jan-2014	30.9	3.13	204	114	6.6	90	
30-Jan-2014	31.9	3.21	222	124	7.0	98	
31-Jan-2014							
1-Feb-2014							
2-Feb-2014	25.2	2.24	243	118	9.6	125	

3-Feb-2014	26.7	4.36	280	130	10.5	150	
4-Feb-2014	28.7	2.46	229	118	8.0	111	3.7
5-Feb-2014	26.1	2.16	210	97	8.0	113	
6-Feb-2014	29.5	2.45	218	100	7.4	118	3.9
7-Feb-2014							
8-Feb-2014							
9-Feb-2014	30.5	3.45	300	175	9.8	125	
10-Feb-2014	29.2	3.10	255	161	8.7	94	
11-Feb-2014	31.7	2.99	211	140	6.7	71	3.3
12-Feb-2014	29.7	3.28	209	120	7.0	89	
13-Feb-2014	23.7	1.55	190	106	8.0	84	2.5
14-Feb-2014							
15-Feb-2014							
16-Feb-2014	23.8	2.86	275	138	11.6	137	
17-Feb-2014	26.4	3.23	281	133	10.6	148	
18-Feb-2014	28.3	3.65	262	147	9.3	138	4.62
19-Feb-2014	30.2	4.02	269	165	8.9	156	
20-Feb-2014	32.7	3.88	287	170	8.8	161	4.84
21-Feb-2014							
22-Feb-2014							
23-Feb-2014	29.6	3.52	275	195	9.3	186	
24-Feb-2014	33.9	3.41	275	182	8.1	174	
25-Feb-2014	30.5	3.60	251	162	8.2	154	4.21
26-Feb-2014	30.9	3.71	287	164	9.3	155	
27-Feb-2014	30.6	4.10	513	299	16.8	282	5.52
28-Feb-2014							
1-Mar-2014							
2-Mar-2014	30.2	3.83	291	193	9.6	183	
3-Mar-2014							
4-Mar-2014	32.4	3.26	253	150	7.8	142	4.06
5-Mar-2014	30.3	3.09	286	140	9.4	131	
6-Mar-2014	30.0	3.12	275	126	9.2	117	4.42
7-Mar-2014							
8-Mar-2014							
9-Mar-2014	24.3	1.82	181	120	7.4	61	
10-Mar-2014	24.5	1.73	183	101	7.5	82	
11-Mar-2014	25.4	1.95	179	94	7.0	85	3.24
12-Mar-2014	26.7	2.23	171	95	6.4	76	
13-Mar-2014	30.2	2.28	177	93	5.9	84	3.37
14-Mar-2014							
15-Mar-2014							
16-Mar-2014	29.6	2.44	185	118	6.3	67	

17-Mar-2014	25.0	1.85	167	101	6.7	66	
18-Mar-2014	23.1	1.46	138	87	6.0	51	2.48
19-Mar-2014	22.1	1.82	162	80	7.3	82	
20-Mar-2014	25.4	2.05	179	88	7.0	91	3.26
21-Mar-2014							
22-Mar-2014							
23-Mar-2014	27.8	2.85	233	125	8.4	108	
24-Mar-2014	27.5	2.91	236	117	8.6	119	
25-Mar-2014	28.5	2.51	192	115	6.7	77	3.37
26-Mar-2014	26.4	2.36	156	96	5.9	60	
27-Mar-2014	29.8	2.65	185	109	6.2	76	3.45
28-Mar-2014							
29-Mar-2014							
30-Mar-2014	28.1	2.46	204	124	7.3	80	
31-Mar-2014	27.6	2.02	179	112	6.5	67	
1-Apr-2014	30.7	1.48	175	101	5.7	74	2.56
2-Apr-2014	29.1	1.58	207	81	7.1	74	
3-Apr-2014	32.3	1.57	170	94	5.3	89	2.76
4-Apr-2014							
5-Apr-2014							
6-Apr-2014	30.4	3.05	289	155	9.5	145	
7-Apr-2014	32	2.66	327	136	10.2	126	
8-Apr-2014	30.1	2.24	289	132	9.6	122	4
9-Apr-2014	30.2	2.41	265	142	8.8	133	
10-Apr-2014	33.5	3.2	252	134	7.5	126	4
11-Apr-2014							
12-Apr-2014							
13-Apr-2014	32	3.92	289	193	9.0	184	
14-Apr-2014	31.1	4.06	294	178	9.5	169	
15-Apr-2014	34.1	3.28	285	160	8.4	152	4
16-Apr-2014	24.7	2.09	230	109	9.3	121	
17-Apr-2014	31	2.41	224	113	7.2	111	3.99
18-Apr-2014							
19-Apr-2014							
20-Apr-2014	29.5	2.74	311	155	10.5	156	
21-Apr-2014	31.7	3.1	311	159	9.8	152	
22-Apr-2014	32.3	3.96	287	145	8.9	142	4.25
23-Apr-2014	32.5	2.83	286	149	8.8	137	
24-Apr-2014	37.2	3.16	294	160	7.9	134	4.63
25-Apr-2014							
26-Apr-2014							
27-Apr-2014	31.6	3.04	282	162	8.9	120	
28-Apr-2014	30.1	2.98	288	170	9.6	118	

29-Apr-2014	28.7	2.19	247	131	8.6	116	
30-Apr-2014	30.5	2.28	226	121	7.4	105	

A.2 INITIAL REACTOR

A.2.1 NITROGEN AND PHOSPHORUS GRAB SAMPLES

Average	1.6	0.88	2	15	3
SD	1.21	0.70	1.79	3.76	0.82
Max	4.3	2.64	6	22	6
Min	0.2	0.00	0	7	1
	Tank 201 (Initial Reactor)				
Date	**NO_3-N**	**NO_2-N**	**NOx-N**	**NH_3-N**	**OP**
	Grab	**Grab**	**Grab**	**Grab**	**Grab**
	Onsite	**Onsite**	**Calc**	**Onsite**	**Onsite**
(dd:mm:yyyy)	**(mg N/L)**	**(mg N/L)**	**(mg N/L)**	**(mg N/L)**	**(mg P/L)**
3-Sep-2013	1.83	1.30	3.13	10.7	1.95
4-Sep-2013					
5-Sep-2013	2.985	1.27	4.26	15.4	2.18
10-Sep-2013	2.81	0.557	3.37	17.6	2.13
11-Sep-2013					
12-Sep-2013	4.2	2.01	6.21	20.1	2.15
17-Sep-2013	4.03	1.72	5.75	18.3	2.96
18-Sep-2013					
19-Sep-2013	3.83	1.32	5.15	20.7	2.59
24-Sep-2013	0.65	0.010	0.66	8.34	2.74
25-Sep-2013					
26-Sep-2013	1.24	0.65	1.89	18.4	2.71
1-Oct-2013	0.6165	0.257	0.87	17	2.2
2-Oct-2013					
3-Oct-2013	0.913	0.58	1.49	16.7	3.58
8-Oct-2013	0.5125	0.19	0.70	14.2	1.53
9-Oct-2013					
10-Oct-2013	0.33	0.005	0.34	10.3	1.05
15-Oct-2013	2.16	1.09	3.25	16.5	1.28
16-Oct-2013					
17-Oct-2013	4.335	1.98	6.32	12.8	1.67
22-Oct-2013	1.27	0.43	1.70	18.3	1.82
23-Oct-2013					
24-Oct-2013	3.26	0.92	4.18	20.9	2.3
29-Oct-2013	1.29	0.65	1.94	18	
30-Oct-2013					
31-Oct-2013	3.29	1.15	4.44	20.7	2.24
5-Nov-2013	3.22	0.908	4.13	22.2	2.89
6-Nov-2013					
7-Nov-2013	3.12	0.817	3.94	21.2	3.62

12-Nov-2013	1.4	0.734	2.09	15.7	3.25
13-Nov-2013					
14-Nov-2013	1.855	1.04	2.90	16.4	3.09
19-Nov-2013	0.28	0	0.28	15.8	2.35
20-Nov-2013					
21-Nov-2013	0.278	0	0.28	14.5	2.5
26-Nov-2013	0.227	0.000	0.23	10.50	3.04
3-Dec-2013	0.275	0	0.28	10.1	5.77
4-Dec-2013					
5-Dec-2013	0.303	0.005	0.31	9.24	4.19
10-Dec-2013	0.31	0.002	0.31	6.61	2.14
11-Dec-2013					
12-Dec-2013	0.256	0.004	0.26	7.48	3.98
17-Dec-2013	0.33	0.003	0.33	7.37	2.9
18-Dec-2013					
19-Dec-2013	2.625	0.343	2.97	10.2	2.98
29-Dec-2013	0.234	0.001	0.24	8.07	2.86
2-Jan-2014	0.79	0.23	1.03	13.00	3.32
7-Jan-2014	1.22	0.43	1.65	11.90	2.60
8-Jan-2014					
9-Jan-2014	1.00	0.45	1.45	13.20	3.16
14-Jan-2014	0.83	0.49	1.31	10.20	2.54
21-Jan-2014	2.36	1.27	3.63	15.10	2.42
22-Jan-2014					
23-Jan-2014	2.68	1.47	4.15	16.50	2.56
28-Jan-2014	1.32	1.01	2.33	15.40	2.82
29-Jan-2014					
30-Jan-2014	1.70	1.60	3.30	17.20	3.30
4-Feb-2014	1.23	1.26	2.49	15.50	2.57
5-Feb-2014					
6-Feb-2014	0.35	0.24	0.59	15.30	2.44
11-Feb-2014	0.80	0.78	1.59	20.60	2.46
12-Feb-2014					
13-Feb-2014	1.54	1.87	3.41	17.00	2.49
18-Feb-2014	0.72	0.46	1.18	14.40	3.35
19-Feb-2014					
20-Feb-2014	0.69	0.45	1.14	16.40	3.53
25-Feb-2014	0.38	0.11	0.49	17.70	3.43
26-Feb-2014					
27-Feb-2014	0.32	0.03	0.34	19.70	5.23
6-Mar-2014	0.6	0.6	1.17	13.6	3.4
11-Mar-2014	2.4	1.7	4.08	13.6	2.2
12-Mar-2014					

13-Mar-2014	3.0	2.08	5.10	15.7	2.34
18-Mar-2014	2.3	1.8	4.05	13.7	2.1
19-Mar-2014					
20-Mar-2014	3.03	2.12	5.15	14.8	2.01
25-Mar-2014	2.4	2.6	5.06	16.5	2.9
26-Mar-2014					
27-Mar-2014	2.8	2.0	4.74	15.2	2.8
1-Apr-2014	3.2	1.6	4.78	14.7	1.7
2-Apr-2014					
3-Apr-2014	3.9	1.8	5.65	16.2	1.7
8-Apr-2014	1.1	1.1	2.15	11.2	1.6
9-Apr-2014					
10-Apr-2014	1.2	1.5	2.69	12.7	2.5
15-Apr-2014	0.6	1.1	1.72	12.7	3.5
16-Apr-2014					
17-Apr-2014	0.8	1.1	1.88	9.9	2.6
22-Apr-2014	1.1	1.0	2.01	13.7	2.6
23-Apr-2014					
24-Apr-2014	1.4	1.3	2.72	15.1	2.7

A.3 SECOND REACTOR

A.3.1 NITROGEN AND PHOSPHORUS GRAB SAMPLES

Average	2	1	4.0	11.7	2.5
SD	1.37	0.80	1.96	3.58	0.61
Max	6	3	8.9	18.9	3.8
Min	1	0	1.1	4.7	1.0
	Tank 202 (Second Reactor)				
Date	**NO$_3$-N**	**NO$_2$-N**	**NOx-N**	**NH$_3$-N**	**OP**
	Grab	**Grab**	**Grab**	**Grab**	**Grab**
	Onsite	**Onsite**	**Calc**	**Onsite**	**Onsite**
(dd:mm:yyyy)	**(mg N/L)**	**(mg N/L)**	**(mg N/L)**	**(mg N/L)**	**(mg P/L)**
3-Sep-2013	2.61	1.680	4.29	6.84	1.91
4-Sep-2013					
5-Sep-2013	4.61	2.190	6.80	11.80	2.16
10-Sep-2013	4.29	1.160	5.45	14.70	2.04
11-Sep-2013					
12-Sep-2013	5.77	3.180	8.95	16.70	2.21
17-Sep-2013	5.14	2.510	7.65	14.90	2.91
18-Sep-2013					
19-Sep-2013	5.24	2.080	7.32	17.70	2.62
24-Sep-2013	1.08	0.855	1.94	4.67	2.48
25-Sep-2013					
26-Sep-2013	3.05	2.130	5.18	13.10	2.59
1-Oct-2013	1.83	0.922	2.75	13.20	2.47
2-Oct-2013					
3-Oct-2013	2.64	1.870	4.51	11.70	3.41
8-Oct-2013	1.58	1.390	2.97	10.80	1.45
9-Oct-2013					
10-Oct-2013	0.69	0.800	1.49	8.02	0.99
15-Oct-2013	3.40	1.880	5.28	14.80	1.21
16-Oct-2013					
17-Oct-2013	5.17	2.310	7.48	11.70	1.59
22-Oct-2013	2.64	1.130	3.77	14.50	1.66
23-Oct-2013					
24-Oct-2013	5.05	1.690	6.74	17.90	2.16
29-Oct-2013	3.06	1.430	4.49	13.30	1.98
30-Oct-2013					
31-Oct-2013	4.55	1.730	6.28	16.10	2.12
5-Nov-2013	4.14	1.240	5.38	18.90	2.75
6-Nov-2013					
7-Nov-2013	4.10	1.130	5.23	18.40	3.54

12-Nov-2013	2.25	1.060	3.31	10.60	2.90
13-Nov-2013					
14-Nov-2013	2.26	1.150	3.41	13.10	2.91
19-Nov-2013	1.18	0.780	1.96	11.80	2.12
20-Nov-2013					
21-Nov-2013	0.86	0.324	1.19	11.60	2.11
26-Nov-2013	1.44	0.362	1.80	8.00	2.98
3-Dec-2013	1.29	0.230	1.52	8.27	2.38
4-Dec-2013					
5-Dec-2013	1.85	0.442	2.29	6.16	1.69
10-Dec-2013	0.92	0.240	1.16	4.67	1.24
11-Dec-2013					
12-Dec-2013	1.38	0.308	1.69	5.72	3.47
17-Dec-2013	1.14	0.365	1.51	5.23	2.12
18-Dec-2013					
19-Dec-2013	3.64	0.485	4.12	8.54	2.78
29-Dec-2013	1.45	0.462	1.91	5.49	2.51
2-Jan-2014	1.53	0.43	1.96	9.40	2.78
7-Jan-2014	1.54	0.49	2.03	9.23	2.60
8-Jan-2014					
9-Jan-2014	1.26	0.53	1.79	9.54	3.02
14-Jan-2014	0.73	0.39	1.12	8.08	2.40
21-Jan-2014	2.68	1.64	4.32	13.60	2.51
22-Jan-2014					
23-Jan-2014	3.02	1.96	4.98	14.10	2.65
28-Jan-2014	2.00	1.65	3.65	12.60	2.89
29-Jan-2014					
30-Jan-2014	2.71	2.18	4.89	14.80	3.28
4-Feb-2014	1.58	2.04	3.62	12.60	2.51
5-Feb-2014					
6-Feb-2014	0.72	1.78	2.50	12.60	2.37
11-Feb-2014	1.24	1.71	2.95	18.70	2.55
12-Feb-2014					
13-Feb-2014	2.37	2.70	5.07	14.30	2.58
18-Feb-2014	1.29	1.00	2.29	11.80	3.21
19-Feb-2014					
20-Feb-2014	1.92	1.20	3.12	14.00	3.49
25-Feb-2014	1.61	1.10	2.71	14.30	3.04
26-Feb-2014					
27-Feb-2014	1.30	0.73	2.03	14.90	3.81
6-Mar-2014	1.7	1.5	3.26	9.3	3.5
11-Mar-2014	3.3	2.7	5.98	9.8	2.2
12-Mar-2014					

13-Mar-2014	3.88	2.83	6.71	11.7	2.41
18-Mar-2014	2.9	2.3	5.20	12.0	2.2
19-Mar-2014					
20-Mar-2014	4.14	2.81	6.95	13	2.01
25-Mar-2014	3.0	3.3	6.30	14.8	2.9
26-Mar-2014					
27-Mar-2014	3.0	2.6	5.54	12.7	2.6
1-Apr-2014	3.8	1.9	5.74	12.7	1.7
2-Apr-2014					
3-Apr-2014	4.4	2.2	6.51	14.1	1.7
8-Apr-2014	1.3	1.6	2.87	8.2	1.7
9-Apr-2014					
10-Apr-2014	1.7	1.9	3.59	9.4	2.5
15-Apr-2014	1.0	2.0	3.00	8.6	3.4
16-Apr-2014					
17-Apr-2014	0.7	1.4	2.15	6.4	2.5
22-Apr-2014	1.6	1.2	2.81	10.8	2.6
23-Apr-2014					
24-Apr-2014	1.9	1.8	3.74	11.7	2.6

A.4 THIRD REACTOR

A.4.1 NITROGEN AND PHOSPHORUS GRAB SAMPLES

Average	3.6	1.9	5.5	8.7	2.5
SD	1.60	0.92	2.18	3.26	0.68
Max	7.7	4.0	11.7	16.2	3.6
Min	1.0	0.4	1.8	2.8	0.6
	Tank 203 (Third Reactor)				
Date	**NO_3-N**	**NO_2-N**	**NOx-N**	**NH_3-N**	**OP**
	Grab	**Grab**	**Grab**	**Grab**	**Grab**
	Onsite	**Onsite**	**Calc**	**Onsite**	**Onsite**
(dd:mm:yyyy)	**(mg N/L)**	**(mg N/L)**	**(mg N/L)**	**(mg N/L)**	**(mg P/L)**
3-Sep-2013	2.92	1.610	4.53	3.86	2.10
4-Sep-2013					
5-Sep-2013	5.65	2.370	8.02	8.91	2.30
10-Sep-2013	5.97	1.470	7.44	11.80	1.97
11-Sep-2013					
12-Sep-2013	7.69	4.000	11.69	13.40	2.25
17-Sep-2013	6.30	2.860	9.16	11.70	3.01
18-Sep-2013					
19-Sep-2013	6.75	2.840	9.59	15.10	2.72
24-Sep-2013	1.12	0.980	2.10	4.18	2.44
25-Sep-2013					
26-Sep-2013	4.34	2.570	6.91	9.01	2.78
1-Oct-2013	3.17	1.610	4.78	8.94	2.47
2-Oct-2013					
3-Oct-2013	4.25	2.580	6.83	8.15	3.45
8-Oct-2013	2.15	2.120	4.27	7.21	1.46
9-Oct-2013					
10-Oct-2013	0.99	0.980	1.97	5.80	1.01
15-Oct-2013	4.36	2.240	6.60	11.70	1.34
16-Oct-2013					
17-Oct-2013					
22-Oct-2013	4.35	1.650	6.00	11.60	1.72
23-Oct-2013					
24-Oct-2013	6.62	1.900	8.52	14.20	2.21
29-Oct-2013	4.55	1.850	6.40	9.41	2.03
30-Oct-2013					
31-Oct-2013	6.76	1.940	8.70	13.00	2.05
5-Nov-2013	6.30	1.500	7.80	15.10	2.63
6-Nov-2013					
7-Nov-2013	6.39	1.560	7.95	11.20	3.47

12-Nov-2013	3.47	1.350	4.82	6.52	2.86
13-Nov-2013					
14-Nov-2013	4.14	1.490	5.63	8.67	2.76
19-Nov-2013	2.74	1.280	4.02	7.98	2.11
20-Nov-2013					
21-Nov-2013	2.76	0.910	3.67	9.23	1.99
26-Nov-2013	2.75	0.730	3.48	5.47	2.95
3-Dec-2013	2.15	0.430	2.58	5.97	0.94
4-Dec-2013					
5-Dec-2013	3.21	0.617	3.83	3.17	0.66
10-Dec-2013	1.66	0.390	2.05	2.82	0.62
11-Dec-2013					
12-Dec-2013	1.94	0.447	2.39	3.95	3.37
17-Dec-2013	1.98	0.527	2.51	3.24	1.88
18-Dec-2013					
19-Dec-2013	3.81	0.385	4.19	6.90	3.38
29-Dec-2013	2.12	0.553	2.67	3.81	2.35
2-Jan-2014	2.89	0.51	3.40	6.43	2.55
7-Jan-2014	2.55	0.63	3.18	6.89	2.38
8-Jan-2014					
9-Jan-2014	3.09	0.86	3.95	6.19	2.87
14-Jan-2014	1.15	0.64	1.79	4.78	2.21
21-Jan-2014	4.04	1.91	5.95	10.1	2.58
22-Jan-2014					
23-Jan-2014	4.95	2.16	7.11	11.2	2.67
28-Jan-2014	3.46	2.30	5.76	9.4	3.03
29-Jan-2014					
30-Jan-2014	4.68	2.76	7.44	11.1	3.20
4-Feb-2014	2.69	2.94	5.63	10.1	2.70
5-Feb-2014					
6-Feb-2014	1.67	2.97	4.64	10.0	2.31
11-Feb-2014	2.57	2.46	5.03	16.2	2.58
12-Feb-2014					
13-Feb-2014	3.99	3.50	7.49	11.0	2.71
18-Feb-2014	3.03	1.83	4.86	8.3	3.13
19-Feb-2014					
20-Feb-2014	3.83	1.79	5.62	10.3	3.59
25-Feb-2014	3.53	1.85	5.38	9.98	2.92
26-Feb-2014					
27-Feb-2014	3.98	1.80	5.78	10.30	3.31
6-Mar-2014	2.5	1.9	4.40	6.3	3.41
11-Mar-2014	4.2	3.1	7.22	8.2	2.85
12-Mar-2014					

13-Mar-2014	4.76	3.38	8.14	9.27	2.42
18-Mar-2014	3.9	2.8	6.65	10.2	2.31
19-Mar-2014					
20-Mar-2014	4.505	3.14	7.65	11.7	2.06
25-Mar-2014	4.2	3.8	7.95	12.6	2.90
26-Mar-2014					
27-Mar-2014	4.1	2.9	7.03	10.7	2.69
1-Apr-2014	4.9	2.3	7.19	10.8	1.67
2-Apr-2014					
3-Apr-2014	5.5	2.5	8.01	12.1	1.62
8-Apr-2014	1.6	2.0	3.63	5.1	2.70
9-Apr-2014					
10-Apr-2014	2.4	2.4	4.73	6.4	2.49
15-Apr-2014	1.7	2.9	4.56	5.1	3.44
16-Apr-2014					
17-Apr-2014	1.2	2.1	3.28	3.5	2.53
22-Apr-2014	2.1	1.8	3.85	7.9	2.62
23-Apr-2014					
24-Apr-2014	3.2	2.2	5.40	8.3	2.64

A.5 FINAL REACTOR

A.5.1 NITROGEN AND PHOSPHORUS GRAB SAMPLES

Average	5	2	7.0	0.3	6.1	2.54
SD	1.89	1.03	2.50	0.12	3.04	1.06
Max	9	4	13.7	0.6	13.9	8.49
Min	1	0	2.3	0.1	1.2	0.32
	Tank 204 (Final Reactor)					
Date	**NO_3-N**	**NO_2-N**	**NOx-N**	**%NAR**	**NH_3-N**	**OP**
	Grab	**Grab**	**Grab**	**NO2-N/Nox-N**	**Grab**	**Grab**
	Onsite	**Onsite**	**Calc**		**Onsite**	**Onsite**
(dd:mm:yyyy)	**(mg N/L)**	**(mg N/L)**	**(mg N/L)**		**(mg N/L)**	**(mg P/L)**
3-Sep-2013	3.31	1.78	5.09	35%	1.33	2.11
4-Sep-2013					4.00	
5-Sep-2013	6.2	2.41	8.58	28%	6.54	2.50
10-Sep-2013	6.38	1.54	7.92	19%	9.27	2.82
11-Sep-2013						
12-Sep-2013	9.295	4.44	13.74	32%	10.50	2.38
17-Sep-2013	7.84	3.44	11.28	30%	8.77	3.12
18-Sep-2013						
19-Sep-2013	8.58	3.27	11.85	28%	11.70	8.49
24-Sep-2013	3.02	1.78	4.80	37%	2.85	2.41
25-Sep-2013						
26-Sep-2013	5.915	2.84	8.76	32%	5.61	2.72
1-Oct-2013	4.83	2.02	6.85	29%	5.70	2.39
2-Oct-2013						
3-Oct-2013	5.62	2.84	8.46	34%	5.26	3.61
8-Oct-2013	2.65	2.15	4.80	45%	4.76	1.53
9-Oct-2013						
10-Oct-2013	1.3	1	2.30	43%	3.85	1.08
15-Oct-2013	5.75	2.85	8.60	33%	8.88	1.35
16-Oct-2013						
17-Oct-2013						
22-Oct-2013	5.68	1.89	7.57	25%	7.90	1.75
23-Oct-2013						
24-Oct-2013	8.13	2.21	10.34	21%	11.10	2.52
29-Oct-2013	5.49	1.81	7.30	25%	5.30	1.91
30-Oct-2013						
31-Oct-2013	8.12	2.14	10.26	21%	8.48	2.10
5-Nov-2013	7.94	1.81	9.75	19%	12.10	2.64
6-Nov-2013						
7-Nov-2013	8.29	1.74	10.03	17%	11.20	3.46

12-Nov-2013	4.44	1.36	5.80	23%	3.90	2.85
13-Nov-2013						
14-Nov-2013	5.28	1.58	6.86	23%	5.62	2.68
19-Nov-2013	4.16	1.53	5.69	27%	4.86	2.21
20-Nov-2013						
21-Nov-2013	4.35	1.29	5.64	23%	6.28	1.99
26-Nov-2013	4.57	0.950	5.52	17%	2.77	2.87
3-Dec-2013	2.98	0.48	3.46	14%	4.17	0.32
4-Dec-2013						
5-Dec-2013	4.41	0.562	4.97	11%	1.19	0.33
10-Dec-2013	2.345	0.39	2.74	14%	1.32	0.45
11-Dec-2013						
12-Dec-2013	2.7	0.51	3.21	16%	2.34	3.35
17-Dec-2013	2.79	0.57	3.36	17%	1.70	1.39
18-Dec-2013						
19-Dec-2013	5.435	0.66	6.10	11%	5.12	2.58
29-Dec-2013	2.725	0.564	3.29	17%	2.51	2.31
2-Jan-2014	4.25	0.548	4.80	11%	4.15	2.43
7-Jan-2014	4.1	0.7	4.80	15%	2.9	2.5
8-Jan-2014						
9-Jan-2014	4.5	1.1	5.60	19%	3.3	2.8
14-Jan-2014	1.8	0.7	2.55	29%	2.2	2.2
21-Jan-2014	6.005	1.98	7.99	25%	7.07	2.59
22-Jan-2014						
23-Jan-2014	7.11	2.15	9.26	23%	8.3	2.78
28-Jan-2014	5.44	2.57	8.01	32%	5.49	2.99
29-Jan-2014						
30-Jan-2014	7.085	3.03	10.12	30%	7.53	3.26
4-Feb-2014	4.18	3.32	7.50	44%	6.81	2.65
5-Feb-2014						
6-Feb-2014	2.995	3.42	6.42	53%	6.95	2.35
11-Feb-2014	4.035	3.11	7.15	44%	13.9	2.66
12-Feb-2014						
13-Feb-2014	5.675	4.13	9.81	42%	8.73	2.82
18-Feb-2014	4.61	2.27	6.88	33%	5.66	3.17
19-Feb-2014						
20-Feb-2014	5.525	2.16	7.69	28%	7.03	3.54
25-Feb-2014	5.25	2.24	7.49	30%	6.65	2.95
26-Feb-2014						
27-Feb-2014	6.15	2.33	8.48	27%	6.43	3.72
6-Mar-2014	3.265	2.03	5.30	38%	3.64	3.39
11-Mar-2014	4.95	3.33	8.28	40%	6.58	2.35
12-Mar-2014						

13-Mar-2014	5.76	3.67	9.43	39%	8.17	2.57
18-Mar-2014	4.5	3.05	7.55	40%	8.63	2.42
19-Mar-2014						
20-Mar-2014	5.49	3.57	9.06	39%	10.1	2.1
25-Mar-2014	5.55	4.23	9.78	43%	10.4	2.88
26-Mar-2014						
27-Mar-2014	5.36	3.3	8.66	38%	8.49	2.69
1-Apr-2014	6.285	2.55	8.84	29%	8.61	1.69
2-Apr-2014						
3-Apr-2014	6.605	2.75	9.36	29%	9.82	1.68
8-Apr-2014	2.055	2.25	4.31	52%	2.75	2.35
9-Apr-2014						
10-Apr-2014	2.765	2.66	5.43	49%	3.88	2.53
15-Apr-2014	1.955	3.16	5.12	62%	2.5	3.44
16-Apr-2014						
17-Apr-2014	1.305	2.14	3.45	62%	1.89	2.53
22-Apr-2014	2.855	2.09	4.95	42%	5.3	2.6
23-Apr-2014						
24-Apr-2014	4.265	2.51	6.78	37%	5.39	2.59

A.5.2 Solids Characteristics, COD, TKN, TP done by HRSD's CEL

Average	3106.1	3119.68	2635.33	85			
SD	893.03	935.60	717.69	3.43	1029.32	72.31	18.15
Max	5070.0	5810.00	4822.30	91			
Min	1255.0	1410.00	1269.00	77			
Date	**MLSS**	**MLSS**	**MLVSS**	**MLVSS**	**COD**	**TKN**	**TP**
	Grab	**Grab**	**Grab**	**Grab**	**Grab**	**Grab**	**Grab**
	Onsite	**CEL**	**Calc**	**CEL**	**CEL**	**CEL**	**CEL**
(dd:mm:yyyy)	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(%)**	**mg/L**	**mg/L**	**(%)**
3-Sep-2013	3095						
4-Sep-2013	2745	2540	2108	83	2850	219	59
5-Sep-2013	2870						
6-Sep-2013	2605	2920	2424	83			
7-Sep-2013							
8-Sep-2013							
9-Sep-2013	2540						
10-Sep-2013	2815						
11-Sep-2013	2760	2440	2001	82	2870	236	56
12-Sep-2013	2755						
13-Sep-2013	2910	3040	2462	81			

14-Sep-2013							
15-Sep-2013							
16-Sep-2013	3020						
17-Sep-2013	2990						
18-Sep-2013	2950	3020	2507	83		179	44
19-Sep-2013	2990						
20-Sep-2013	2885	3020	2507	83			
21-Sep-2013							
22-Sep-2013							
23-Sep-2013	3635						
24-Sep-2013	4555						
25-Sep-2013	4040	4460	3657	82	4550	317	76
26-Sep-2013	4240						
27-Sep-2013	4250	4070	3337	82			
28-Sep-2013							
29-Sep-2013							
30-Sep-2013	4405						
1-Oct-2013	4475						
2-Oct-2013	4545	4840	3920	81	5520	334	86
3-Oct-2013	4675						
4-Oct-2013	4845	4660	3775	81			
5-Oct-2013							
6-Oct-2013							
7-Oct-2013	4465						
8-Oct-2013	4960						
9-Oct-2013	4785	4020	3296	82	4430	316	73
10-Oct-2013	3915						
11-Oct-2013	4330	4110	3288	80			
12-Oct-2013							
13-Oct-2013							
14-Oct-2013							
15-Oct-2013	3485						
16-Oct-2013	3885	3930	3183	81	4620	309	73
17-Oct-2013	3475						
18-Oct-2013	3425	3820	2941	77			
19-Oct-2013							
20-Oct-2013							
21-Oct-2013	3025						
22-Oct-2013	2790						
23-Oct-2013	2865	2700	2322	86	2780	256	60
24-Oct-2013	2930						
25-Oct-2013	3240	3150	2552	81			
26-Oct-2013							

27-Oct-2013							
28-Oct-2013	3850						
29-Oct-2013	3695						
30-Oct-2013	3375	3240	2689	83	3310	270	64
31-Oct-2013	3410						
1-Nov-2013	3570	2800	2296	82			
2-Nov-2013							
3-Nov-2013							
4-Nov-2013	3265						
5-Nov-2013	3185						
6-Nov-2013	3045	3180	2608	82	3240	256	57
7-Nov-2013	2445						
8-Nov-2013	3230	2860	2317	81			
9-Nov-2013							
10-Nov-2013							
11-Nov-2013							
12-Nov-2013	3305						
13-Nov-2013	3410	3360	2789	83	3440	265	56
14-Nov-2013	3430						
15-Nov-2013	3400	3440	2855	83			
16-Nov-2013							
17-Nov-2013							
18-Nov-2013	3715						
19-Nov-2013	3770						
20-Nov-2013	3990	3780	3100	82	4020	282	69
21-Nov-2013	3805						
22-Nov-2013	4375	3970	3255	82			
23-Nov-2013							
24-Nov-2013							
25-Nov-2013	4120						
26-Nov-2013	4125						
27-Nov-2013	4140						
28-Nov-2013							
29-Nov-2013							
30-Nov-2013							
1-Dec-2013							
2-Dec-2013	4735						
3-Dec-2013	4885						
4-Dec-2013	4935	5320.00		83.00	5230.00	404.00	95.90
5-Dec-2013	5070						
6-Dec-2013	4460	1550.00		85.00			
7-Dec-2013							
8-Dec-2013							

9-Dec-2013	4500						
10-Dec-2013	4115						
11-Dec-2013	3645	3680.00	2980.80	81.00	3940.00	304.00	84.50
12-Dec-2013	3380						
13-Dec-2013	3025	3190.00	2839.10	89.00			
14-Dec-2013							
15-Dec-2013							
16-Dec-2013	2630						
17-Dec-2013	2525						
18-Dec-2013	2315	2280.00	1983.60	87.00	4720.00	180.00	54.50
19-Dec-2013	2310						
20-Dec-2013	2115	2190.00	1839.60	84.00			
21-Dec-2013							
22-Dec-2013							
23-Dec-2013	2615						
24-Dec-2013							
25-Dec-2013							
26-Dec-2013							
27-Dec-2013	2645	2320.00	2018.40	87.00			
28-Dec-2013							
29-Dec-2013							
30-Dec-2013	2430						
29-Dec-2013	2445						
30-Dec-2013							
31-Dec-2013							
1-Jan-2014							
2-Jan-2014	2395						
3-Jan-2014	2450	2340	2059	88			
4-Jan-2014							
5-Jan-2014							
6-Jan-2014	2575						
7-Jan-2014	2555						
8-Jan-2014	2615	2680	2251	84	3160	215	49
9-Jan-2014	2495						
10-Jan-2014	2635	2710	2304	85			
11-Jan-2014							
12-Jan-2014							
13-Jan-2014	2250						
14-Jan-2014	2290						
15-Jan-2014		2440	2123	87	2620	181	39
16-Jan-2014							
17-Jan-2014		*		*			
18-Jan-2014							

19-Jan-2014							
20-Jan-2014							
21-Jan-2014	3615						
22-Jan-2014		3620	3186	88	4600	316	53
23-Jan-2014	3520						
24-Jan-2014	3685	4060	3573	88			
25-Jan-2014							
26-Jan-2014							
27-Jan-2014	3685						
28-Jan-2014	3490						
29-Jan-2014							
30-Jan-2014	3000						
31-Jan-2014	2985	2880	2563	89			
1-Feb-2014							
2-Feb-2014							
3-Feb-2014	2940						
4-Feb-2014	2800						
5-Feb-2014	2970	3020	2687.8	89	3270	270	48.5
6-Feb-2014	3100						
7-Feb-2014	3045	3140	2700.4	86			
8-Feb-2014							
9-Feb-2014							
10-Feb-2014	2115						
11-Feb-2014	2565						
12-Feb-2014	2440	2680	2412	90	3600	269	33.8
13-Feb-2014	2810						
14-Feb-2014	2745	2820	2566.2	91			
15-Feb-2014							
16-Feb-2014							
17-Feb-2014	3320						
18-Feb-2014	3415						
19-Feb-2014	3660	3530	3177	90	3620	110	54.7
20-Feb-2014	3930						
21-Feb-2014	3620	3800	3458	91			
22-Feb-2014							
23-Feb-2014							
24-Feb-2014	3360						
25-Feb-2014	3430.00						
26-Feb-2014	3585	3680	3348.8	91	3210	341	51.1
27-Feb-2014	3995.00						
28-Feb-2014	3825	3940	3506.6	89			
1-Mar-2014							
2-Mar-2014							

3-Mar-2014	4665						
4-Mar-2014							
5-Mar-2014	4545	4560	3967.2	87	5100	387.0	84.0
6-Mar-2014							
7-Mar-2014		3730	3245.1	87			
8-Mar-2014							
9-Mar-2014							
10-Mar-2014	2795						
11-Mar-2014	2260						
12-Mar-2014	2275	2410	2120.8	88	2520	256.0	37.8
13-Mar-2014	1855						
14-Mar-2014	1795	1970	1733.6	88			
15-Mar-2014							
16-Mar-2014							
17-Mar-2014	1495						
18-Mar-2014	1415						
19-Mar-2014	1260	1410	1269	90	1490	146.0	22.9
20-Mar-2014	1485						
21-Mar-2014	1255	1490	1355.9	91			
22-Mar-2014							
23-Mar-2014							
24-Mar-2014	1795						
25-Mar-2014	1595						
26-Mar-2014	1545	1670	1469.6	88	2110	170.0	28.2
27-Mar-2014	1410						
28-Mar-2014	1370	1530	1377	90			
29-Mar-2014							
30-Mar-2014							
31-Mar-2014	1305						
1-Apr-2014	1415						
2-Apr-2014	2830	1660	1477.4	89	1660	141.0	24.7
3-Apr-2014	1590						
4-Apr-2014	1415	1650	1468.5	89			
5-Apr-2014							
6-Apr-2014							
7-Apr-2014	2120	2820	2397	85	3130	234.0	47.9
8-Apr-2014	2375						
9-Apr-2014	2545	2890	2427.6	84			
10-Apr-2014	2680						
11-Apr-2014	2500						
12-Apr-2014							
13-Apr-2014							
14-Apr-2014	2925	3050	2592.5	85			47.5

15-Apr-2014	3300						
16-Apr-2014	2885	2740	2301.6	84			
17-Apr-2014	2615						
18-Apr-2014	2610						
19-Apr-2014							
20-Apr-2014							
21-Apr-2014	2710	3080	2587.2	84	3870		52.4
22-Apr-2014	3035						
23-Apr-2014	3120	5810	4822.3	83			
24-Apr-2014	3005						
25-Apr-2014	3225						
26-Apr-2014							
27-Apr-2014							
28-Apr-2014	2655						
29-Apr-2014	2635						
30-Apr-2014	2620	2830	2377.2	84	2740	218	43

A.5.3 SETTLING

Average	687.5321	403.7161	225.2345	128.3472	5.072632	#DIV/0!	1.640625
SD	220.0803	176.4827	52.60366	36.28441	3.397435	#DIV/0!	0.607005
Max	970	780	364.6833	284.0691	21.5	0	2.8
Min	270	120	106.7504	59.65463	0.79	0	0
Date	SSV5	SSV30	SVI5	SVI30	SVI30 End	DSVI	Sludge Blanket
	Grab	Grab	Grab	Grab	Grab	Grab	Depth
	Onsite	Onsite	Calc	Calc	Turbidity	Calc	Onsite
(dd:mm:yyyy)	(mL/L)	(mL/L)	mL/g	mL/g	NTU	mL/g	(ft)
3-Sep-2013	910	550	294.0226	177.706	2.01		
4-Sep-2013	900	530	327.8689	193.0783	2.14		
5-Sep-2013	940	710	327.5261	247.3868			
6-Sep-2013	950	740	364.6833	284.0691	1.6		
7-Sep-2013							
8-Sep-2013							
9-Sep-2013	820	550	322.8346	216.5354	3.07		1.5
10-Sep-2013	860	450	305.5062	159.8579	2.66		1.5
11-Sep-2013	930	680	336.9565	246.3768	1.77		1.5
12-Sep-2013	890	520	323.049	188.7477	1.5		
13-Sep-2013	910	600	312.7148	206.1856	1.37		1.3
14-Sep-2013							
15-Sep-2013							

16-Sep-2013	920	560	304.6358	185.4305	2.21		2
17-Sep-2013	910	550	304.3478	183.9465	1.24		2
18-Sep-2013	870	510	294.9153	172.8814	1.11		
19-Sep-2013	870	490	290.9699	163.8796	1.81		1.8
20-Sep-2013	850	450	294.6274	155.9792	4.47		2
21-Sep-2013							
22-Sep-2013							
23-Sep-2013	930	670	255.8459	184.3191	0.79		2.4
24-Sep-2013	950	740	208.562	162.4588	1.07		2
25-Sep-2013	920	660	227.7228	163.3663	3.43		2.5
26-Sep-2013	950	730	224.0566	172.1698	1.36		1.5
27-Sep-2013	940	680	221.1765	160	1.26		2
28-Sep-2013							
29-Sep-2013							
30-Sep-2013	970	680	220.2043	154.37	0.91		2.5
1-Oct-2013	920	650	205.5866	145.2514	2.96		2.4
2-Oct-2013	890	600	195.8196	132.0132	1.21		2.4
3-Oct-2013	920	640	196.7914	136.8984	4.38		2.4
4-Oct-2013	930	640	191.9505	132.0949	2.81		2.4
5-Oct-2013							
6-Oct-2013							
7-Oct-2013	940	630	210.5263	141.0974	1.33		2.3
8-Oct-2013	940	690	189.5161	139.1129	1.29		2
9-Oct-2013	890	510	185.9979	106.5831	1.32		2.2
10-Oct-2013	870	490	222.2222	125.1596	1.68		2.1
11-Oct-2013	900	550	207.8522	127.0208	1.86		2.1
12-Oct-2013							
13-Oct-2013							
14-Oct-2013							
15-Oct-2013	790	410	226.6858	117.6471	1.26		2
16-Oct-2013	830	490	213.6422	126.1261	3.93		1.5
17-Oct-2013	800	420	230.2158	120.8633	2.52		2
18-Oct-2013	850	460	248.1752	134.3066	2.43		1.5
19-Oct-2013							
20-Oct-2013							
21-Oct-2013	670	310	221.4876	102.4793	4.89		1.7
22-Oct-2013	650	330	232.9749	118.2796	4.46		2
23-Oct-2013	720	360	251.3089	125.6545	2.83		1.8
24-Oct-2013	700	350	238.9078	119.4539	4.08		2
25-Oct-2013	710	360	219.1358	111.1111	3.3		2
26-Oct-2013							
27-Oct-2013							
28-Oct-2013	730	410	189.6104	106.4935	6.35		1.8

29-Oct-2013	650	350	175.9134	94.7226	10.4		1.9
30-Oct-2013	510	290	151.1111	85.92593	7.8		2
31-Oct-2013	500	280	146.6276	82.11144	8.63		0.75
1-Nov-2013	500	280	140.056	78.43137	7.2		
2-Nov-2013							
3-Nov-2013							
4-Nov-2013	400	220	122.5115	67.38132	14.1		1.5
5-Nov-2013	340	190	106.7504	59.65463	12.2		1
6-Nov-2013	370	200	121.5107	65.68144	8.67		1
7-Nov-2013	320	186	130.8793	76.07362	7.85		
8-Nov-2013	480	250	148.6068	77.39938	4.31		0.9
9-Nov-2013							
10-Nov-2013							
11-Nov-2013							
12-Nov-2013	820	370	248.1089	111.9516	1.91		
13-Nov-2013	850	420	249.2669	123.1672	1.23		
14-Nov-2013	830	420	241.9825	122.449	1.46		1.9
15-Nov-2013	690	460	202.9412	135.2941	1.42		1.7
16-Nov-2013							
17-Nov-2013							
18-Nov-2013	900	500	242.2611	134.5895	1.41		2
19-Nov-2013	890	500	236.0743	132.626			
20-Nov-2013	930	590	233.0827	147.8697	2.24		2
21-Nov-2013	920	520	241.7871	136.6623	1.49		2
22-Nov-2013	930	670	212.5714	153.1429	1.45		2
23-Nov-2013							
24-Nov-2013							
25-Nov-2013	930	630	225.7282	152.9126	1.52		2.1
26-Nov-2013	960	710	232.7273	172.1212	1.75		2.2
27-Nov-2013	900	560	217.3913	135.2657	1.74		1.6
28-Nov-2013							
29-Nov-2013							
30-Nov-2013							
1-Dec-2013							
2-Dec-2013	960	760	202.7455	160.5069	6.52		2.3
3-Dec-2013	950	750	194.4729	153.5312	3.4		2.3
4-Dec-2013	960	760	194.5289	154.002	2.03		1.5
5-Dec-2013	950	750	187.3767	147.929	2.65		1.5
6-Dec-2013	950	650	213.0045	145.7399			2.4
7-Dec-2013							
8-Dec-2013							
9-Dec-2013	940	710	208.8889	157.7778	5.88		1
10-Dec-2013	940	700	228.4326	170.1094	4.07		2

11-Dec-2013	910	590	249.6571	161.8656	3.46		1.8
12-Dec-2013	890	510	263.3136	150.8876	2.69		1.6
13-Dec-2013	850	460	280.9917	152.0661	3.13		2.2
14-Dec-2013							
15-Dec-2013							
16-Dec-2013	710	340	269.962	129.2776	10.5		1.5
17-Dec-2013	550	290	217.8218	114.8515	4.65		1.4
18-Dec-2013	450	250	194.3844	107.9914	6.77		1.2
19-Dec-2013	440	250	190.4762	108.2251	4.52		2
20-Dec-2013	400	230	189.1253	108.747	6.55		1.3
21-Dec-2013							
22-Dec-2013							
23-Dec-2013	340	200	130.0191	76.48184	3.97		1.3
24-Dec-2013							
25-Dec-2013							
26-Dec-2013							
27-Dec-2013	490	250	185.2552	94.51796			2
28-Dec-2013							
29-Dec-2013							
30-Dec-2013	400	230	164.6091	94.65021	4.79		1.9
29-Dec-2013	410	290	167.6892	118.6094	4.51		1.8
30-Dec-2013							
31-Dec-2013							
1-Jan-2014							
2-Jan-2014	390	230	162.8392	96.0334	4.63		1.6
3-Jan-2014	360	220	146.9388	89.79592	5.05		1.3
4-Jan-2014							
5-Jan-2014							
6-Jan-2014	360		139.8058		4.74		0.8
7-Jan-2014	390	230	152.6419	90.01957	5.51		
8-Jan-2014	370	230	141.4914	87.95411	3.86		1.7
9-Jan-2014	380	230	152.3046	92.18437	5.55		1.8
10-Jan-2014	420	240	159.3928	91.08159	3.18		1.3
11-Jan-2014							
12-Jan-2014							
13-Jan-2014	350	220	155.5556	97.77778	2.91		1.3
14-Jan-2014	340	210	148.4716	91.70306	3.87		
15-Jan-2014	360	150			4.07		1
16-Jan-2014							
17-Jan-2014							
18-Jan-2014							
19-Jan-2014							
20-Jan-2014							

21-Jan-2014	480	280	132.7801	77.45505	3.29		
22-Jan-2014							
23-Jan-2014	540	290	153.4091	82.38636	8.35		2
24-Jan-2014	640	310	173.6771	84.12483	3.88		1
25-Jan-2014							
26-Jan-2014							
27-Jan-2014	670	340	181.8182	92.26594	3.25		2
28-Jan-2014	650	330	186.2464	94.55587	6.67		1
29-Jan-2014							
30-Jan-2014	560	290	186.6667	96.66667	9.03		1.6
31-Jan-2014	520	300	174.2044	100.5025	21.5		
1-Feb-2014							
2-Feb-2014							
3-Feb-2014	530	300	180.2721	102.0408	9.37		2
4-Feb-2014	690	320	246.4286	114.2857	7.64		1.8
5-Feb-2014	590	300	198.6532	101.0101	12		2.2
6-Feb-2014	790	360	254.8387	116.129	9.98		
7-Feb-2014	800	380	262.7258	124.7947	2.91		
8-Feb-2014							
9-Feb-2014							
10-Feb-2014	500	260	236.4066	122.9314	17.1		
11-Feb-2014	800	490	311.8908	191.0331	6.63		1.4
12-Feb-2014	850	510	348.3607	209.0164	5.14		2
13-Feb-2014	730	340	259.7865	120.9964	3.66		1
14-Feb-2014	780	370	284.153	134.7905	2.5		
15-Feb-2014							
16-Feb-2014							
17-Feb-2014	810	420	243.9759	126.506	8.25		0.5
18-Feb-2014	870	420	254.7584	122.9868	5.7		2.2
19-Feb-2014	750	410	204.918	112.0219	3.73		1.5
20-Feb-2014	900	500	229.0076	127.2265	3.94		1.5
21-Feb-2014	850	440	234.8066	121.547	9.47		2.2
22-Feb-2014							
23-Feb-2014							
24-Feb-2014	800	410	238.0952	122.0238	9.96		2.2
25-Feb-2014	780	400	227.4052	116.6181	7.44		2.2
26-Feb-2014	870	440	242.6778	122.7336	2.67		2.5
27-Feb-2014	860	520	215.2691	130.1627	11.9		2.25
28-Feb-2014	900	530	235.2941	138.5621	4.86		
1-Mar-2014							
2-Mar-2014							
3-Mar-2014	960	760	205.7878	162.9153	4.23		2.8
4-Mar-2014							

5-Mar-2014	960	780	211.2211	171.6172	3.72		2.8
6-Mar-2014							2.8
7-Mar-2014							
8-Mar-2014							
9-Mar-2014							
10-Mar-2014	740	350	264.7585	125.2236	3.69		2.2
11-Mar-2014	605	300	267.6991	132.7434	3.12		2
12-Mar-2014	650	300	285.7143	131.8681	4.78		
13-Mar-2014	510	250	274.9326	134.7709	9.7		2
14-Mar-2014	510	250	284.1226	139.2758	4.93		2
15-Mar-2014							
16-Mar-2014							
17-Mar-2014	380	180	254.1806	120.4013	4.5		
18-Mar-2014	335	150	236.7491	106.0071	5.53		0.5
19-Mar-2014	310	150	246.0317	119.0476	4.53		1.5
20-Mar-2014	270	130	181.8182	87.54209	13.9		1
21-Mar-2014	320	150	254.9801	119.5219	5.58		
22-Mar-2014							
23-Mar-2014							
24-Mar-2014	350	120	194.9861	66.85237	10.1		
25-Mar-2014	360	170	225.7053	106.5831	6.05		0.5
26-Mar-2014	335	160	216.8285	103.5599	7.25		
27-Mar-2014	350	160	248.227	113.4752	11		0.5
28-Mar-2014	310	150	226.2774	109.4891	8.51		0.5
29-Mar-2014							
30-Mar-2014							
31-Mar-2014	370	175	283.5249	134.0996	4.4		0
1-Apr-2014	390	190	275.6184	134.2756	11.2		0.5
2-Apr-2014	865	500	305.6537	176.6784	6.72		0.5
3-Apr-2014	390	180	245.283	113.2075	6.46		0.5
4-Apr-2014	385	180	272.0848	127.2085	7.35		0.5
5-Apr-2014							
6-Apr-2014							
7-Apr-2014	575	280	271.2264	132.0755	4.82		0
8-Apr-2014	660	310	277.8947	130.5263	5.25		1
9-Apr-2014	790	360	310.4126	141.4538	4.39		0.5
10-Apr-2014	760	350	283.5821	130.597	9.41		
11-Apr-2014	785	370	314	148	7.32		
12-Apr-2014							
13-Apr-2014							
14-Apr-2014	770	390	263.2479	133.3333	10.3		1.5
15-Apr-2014	810	410	245.4545	124.2424	6.2		1.5
16-Apr-2014	790	380	273.8302	131.7158	5.8		2.4

17-Apr-2014	720	350	275.3346	133.8432	3.57		1
18-Apr-2014	625	315	239.4636	120.6897	5.51		1
19-Apr-2014							
20-Apr-2014							
21-Apr-2014	500	270	184.5018	99.631	6.05		1.3
22-Apr-2014	550	300	181.2191	98.84679	6.94		1
23-Apr-2014	570	290	182.6923	92.94872	6.5		
24-Apr-2014	580	300	193.0116	99.83361	4.09		1.5
25-Apr-2014	575	300	178.2946	93.02326	6.24		
26-Apr-2014							
27-Apr-2014							
28-Apr-2014	460	250	173.258	94.16196	5.94		1.7
29-Apr-2014	470	250	178.3681	94.87666	5.65		1
30-Apr-2014	430	230	164.1221	87.78626	6.08		1

A.6 NITROGEN REMOVAL STAGE (B-STAGE) EFFLUENT COMPOSITE SAMPLE

A.6.1 NITROGEN CHARACTERISTICS

Average	4.402077	2.059891	6.461968	0.312355	6.326859	
SD	1.90432	1.062919	2.587309	0.131232	2.831494	0.234134
Max	9.3	4.34	12.59	0.658824	14.8	
Min	1.15	0.119	1.74	0.021919	1	
Date	NO3-N	NO2-N	NOx-N	%NAR	NH3-N	NOx-N/NH4-N
	Comp	Comp	Comp	NO2-N/Nox-N	Comp	Comp
	Onsite	Onsite	Calc		Onsite	Onsite
(dd:mm:yyyy)	(mg N/L)	(mg N/L)	(mg N/L)		(mg N/L)	
3-Sep-2013	3.61	2	5.61	0.356506	2.87	1.954704
4-Sep-2013	4.71	2.41	7.12	0.338483	4.27	1.667447
5-Sep-2013	7.16	2.6	9.76	0.266393	7.4	1.318919
6-Sep-2013						
7-Sep-2013						
8-Sep-2013	8.77	3.06	11.83	0.258664	10.2	1.159804
9-Sep-2013	7.53	3.16	10.69	0.295603	9.41	1.136026
10-Sep-2013	7.86	3.36	11.22	0.299465	10	1.122
11-Sep-2013	8.29	4.14	12.43	0.333065	11	1.13
12-Sep-2013	8.125	4.34	12.465	0.348175	10.7	1.164953
13-Sep-2013						
14-Sep-2013						
15-Sep-2013	7.5	3.42	10.92	0.313187	10	1.092
16-Sep-2013	7.84	3.44	11.28	0.304965	8.77	1.286203
17-Sep-2013	7.32	2.83	10.15	0.278818	10.1	1.00495
18-Sep-2013	8.23	3.2	11.43	0.279965	11.2	1.020536
19-Sep-2013	9.09	3.5	12.59	0.277998	11.7	1.076068
20-Sep-2013						
21-Sep-2013						
22-Sep-2013	4.12	2.58	6.7	0.385075	6.9	0.971014
23-Sep-2013	3.25	3.08	6.33	0.486572	6.54	0.96789
24-Sep-2013	3.77	2.39	6.16	0.387987	5.99	1.028381
25-Sep-2013	4.47	2.48	6.95	0.356835	6.66	1.043544
26-Sep-2013	5.31	0.119	5.429	0.021919	6.49	0.836518
27-Sep-2013						
28-Sep-2013						
29-Sep-2013	4.09	1.904	5.994	0.317651	5.74	1.044251
30-Sep-2013	3.345	1.676	5.021	0.333798	5.38	0.933271
1-Oct-2013	4.58	2.12	6.7	0.316418	6.21	1.078905
2-Oct-2013	4.78	2.74	7.52	0.364362	6.01	1.251248

3-Oct-2013	4.18	3.06	7.24	0.422652	7.1	1.019718
4-Oct-2013						
5-Oct-2013						
6-Oct-2013	3.6	2.9	6.5	0.446154	5.24	1.240458
7-Oct-2013	2.96	2.72	5.68	0.478873	4.18	1.358852
8-Oct-2013	3.035	2.18	5.215	0.418025	6.72	0.776042
9-Oct-2013	2.955	1.97	4.925	0.4	6.14	0.802117
10-Oct-2013	1.74	1.67	3.41	0.489736	3.53	0.966006
11-Oct-2013						
12-Oct-2013						
13-Oct-2013						
14-Oct-2013	4.28	2.5	6.78	0.368732	7.75	0.874839
15-Oct-2013	6.23	3.16	9.39	0.336528	9.11	1.030735
16-Oct-2013	6.43	3.3	9.73	0.339157	8.05	1.208696
17-Oct-2013	6.22	2.78	9	0.308889	8.92	1.008969
18-Oct-2013						
19-Oct-2013						
20-Oct-2013	5.73	2.64	8.37	0.315412	7.76	1.078608
21-Oct-2013	5.16	2.06	7.22	0.285319	6.49	1.112481
22-Oct-2013	7.29	2.1	9.39	0.223642	9.17	1.023991
23-Oct-2013	7.88	2.21	10.09	0.219029	10.6	0.951887
24-Oct-2013	8.32	2.15	10.47	0.205349	11.8	0.887288
25-Oct-2013						
26-Oct-2013						
27-Oct-2013	5.27	1.9	7.17	0.264993	6.77	1.059084
28-Oct-2013	4.2	1.5	5.7	0.263158	5.41	1.053604
29-Oct-2013	6.36	1.78	8.14	0.218673	7.7	1.057143
30-Oct-2013	7	1.5	8.5	0.176471	8.5	1
31-Oct-2013	7.25	1.76	9.01	0.195339	9.1	0.99011
1-Nov-2013						
2-Nov-2013						
3-Nov-2013	6.8	1.74	8.54	0.203747	10.2	0.837255
4-Nov-2013	6.58	1.47	8.05	0.182609	10.4	0.774038
5-Nov-2013	8.84	1.72	10.56	0.162879	11.8	0.894915
6-Nov-2013	9.3	1.91	11.21	0.170384	12.5	0.8968
7-Nov-2013	7.24	1.34	8.58	0.156177	10.1	0.849505
8-Nov-2013						
9-Nov-2013						
10-Nov-2013						
11-Nov-2013	4.95	1.47	6.42	0.228972	5.24	1.225191
12-Nov-2013	4.06	1.37	5.43	0.252302	4.85	1.119588
13-Nov-2013	4.75	1.44	6.19	0.232633	5.96	1.038591
14-Nov-2013	4.92	1.57	6.49	0.241911	6.35	1.022047

15-Nov-2013						
16-Nov-2013						
17-Nov-2013	4.14	1.26	5.4	0.233333	5.65	0.955752
18-Nov-2013	3.4	1.2	4.6	0.26087	5.32	0.864662
19-Nov-2013	4.42	1.43	5.85	0.244444	6.72	0.870536
20-Nov-2013	3.75	1.21	4.96	0.243952	6.44	0.770186
21-Nov-2013	3.3	1.02	4.32	0.236111	5.91	0.730964
22-Nov-2013						
23-Nov-2013						
24-Nov-2013	3.44	0.9	4.34	0.207373	3.96	1.09596
25-Nov-2013	3.3	0.816	4.116	0.198251	3.29	1.251064
26-Nov-2013	3.69	0.77	4.46	0.172646	3.85	1.158442
27-Nov-2013						
28-Nov-2013						
29-Nov-2013						
30-Nov-2013						
1-Dec-2013	2.84	0.38	3.22	0.118012	4.95	0.650505
2-Dec-2013	1.8	0.23	2.03	0.1133	4	0.5075
3-Dec-2013	2.14	0.323	2.463	0.131141	3.4	0.724412
4-Dec-2013	2.61	0.33	2.94	0.112245	3.25	0.904615
5-Dec-2013						
6-Dec-2013						
7-Dec-2013						
8-Dec-2013	2.05	0.15	2.2	0.068182	1	2.2
9-Dec-2013	1.52	0.22	1.74	0.126437	1.05	1.657143
10-Dec-2013	1.8	0.28	2.08	0.134615	1.35	1.540741
11-Dec-2013	2	0.35	2.35	0.148936	2.1	1.119048
12-Dec-2013	2.2	0.38	2.58	0.147287	2.37	1.088608
13-Dec-2013						
14-Dec-2013						
15-Dec-2013	1.74	0.37	2.11	0.175355	1.3	1.623077
16-Dec-2013	1.8	0.41	2.21	0.18552	1.5	1.473333
17-Dec-2013	2.23	0.412	2.642	0.155942	2.1	1.258095
18-Dec-2013	3.44	0.501	3.941	0.127125	3.83	1.028982
19-Dec-2013	3.44	0.501	3.941	0.127125	3.83	1.028982
20-Dec-2013	4.025	0.55	4.575	0.120219	3.8	1.203947
21-Dec-2013						
22-Dec-2013						
23-Dec-2013	3.14	0.523	3.663	0.142779	3.27	1.120183
24-Dec-2013						
25-Dec-2013						
26-Dec-2013						
27-Dec-2013	4.09	0.514	4.604	0.111642	3.9	1.180513

28-Dec-2013						
29-Dec-2013						
30-Dec-2013	3.005	0.516	3.521	0.146549	3.18	1.107233
29-Dec-2013	2.39	0.486	2.876	0.168985	2.19	1.313242
30-Dec-2013	3.92	0.44	4.36	0.100917	4.15	1.050602
31-Dec-2013						
1-Jan-2014						
2-Jan-2014	3.61	0.433	4.043	0.107099	3.51	1.151852
3-Jan-2014						
4-Jan-2014						
5-Jan-2014	3.6	0.571	4.171	0.136898	4.16	1.002644
6-Jan-2014	3.58	0.59	4.17	0.141487	3.47	1.201729
7-Jan-2014	3.55	0.609	4.159	0.146429	3.4	1.223235
8-Jan-2014	2.94	0.775	3.715	0.208614	3.01	1.234219
9-Jan-2014	3.48	0.761	4.241	0.179439	3.37	1.258457
10-Jan-2014						
11-Jan-2014						
12-Jan-2014	2.75	0.621	3.371	0.184218	2.96	1.138851
13-Jan-2014	1.995	0.676	2.671	0.253089	2.14	1.248131
14-Jan-2014	2.03	0.816	2.846	0.286718	2.08	1.368269
15-Jan-2014						
16-Jan-2014						
17-Jan-2014						
18-Jan-2014						
19-Jan-2014						
20-Jan-2014	5.85	2.07	7.92	0.261364	8.03	0.986301
21-Jan-2014						
22-Jan-2014	5.32	2.08	7.4	0.281081	9.4	0.787234
23-Jan-2014	6.25	2.14	8.39	0.255066	8.62	0.973318
24-Jan-2014						
25-Jan-2014						
26-Jan-2014	4.675	2.39	7.065	0.338287	6.11	1.156301
27-Jan-2014	3.675	2.27	5.945	0.381833	5.43	1.094843
28-Jan-2014	6.3	2.82	9.12	0.309211	8.51	1.07168
29-Jan-2014	6.3	2.82	9.12	0.309211	8.51	1.07168
30-Jan-2014	6.005	2.94	8.945	0.328675	8.63	1.036501
31-Jan-2014						
1-Feb-2014						
2-Feb-2014	3.585	2.99	6.575	0.454753	5.65	1.163717
3-Feb-2014	3.15	2.85	6	0.475	3.24	1.851852
4-Feb-2014	4.03	3.46	7.49	0.461949	7.29	1.027435
5-Feb-2014	3.685	3.23	6.915	0.467101	6.13	1.128059
6-Feb-2014	3.675	3.5	7.175	0.487805	6.67	1.075712

7-Feb-2014						
8-Feb-2014						
9-Feb-2014						
10-Feb-2014	3.38	2.51	5.89	0.426146	14.8	0.397973
11-Feb-2014	5.11	3.7	8.81	0.419977	11.8	0.74661
12-Feb-2014	5.53	4.08	9.61	0.424558	10.8	0.889815
13-Feb-2014	3.355	2.83	6.185	0.457559	7.03	0.879801
14-Feb-2014						
15-Feb-2014						
16-Feb-2014	3.3	2.28	5.58	0.408602	5.58	1
17-Feb-2014	3.13	2.05	5.18	0.395753	5.26	0.984791
18-Feb-2014	3.785	2.04	5.825	0.350215	5.97	0.975712
19-Feb-2014	4.235	1.86	6.095	0.305168	6.36	0.958333
20-Feb-2014	5.45	1.92	7.37	0.260516	6.76	1.090237
21-Feb-2014						
22-Feb-2014						
23-Feb-2014	4.45	1.83	6.28	0.291401	6.04	1.039735
24-Feb-2014	4.485	1.97	6.455	0.30519	6.5	0.993077
25-Feb-2014	5.13	1.98	7.11	0.278481	6.65	1.069173
26-Feb-2014	4.755	1.85	6.605	0.280091	7.39	0.893775
27-Feb-2014	4.585	1.49	6.075	0.245267	6.39	0.950704
28-Feb-2014						
1-Mar-2014						
2-Mar-2014	2.98	1.07	4.05	0.264198	3.53	1.147309
3-Mar-2014						
4-Mar-2014	3.24	1.35	4.59	0.294118	4.08	1.125
5-Mar-2014	2.93	1.22	4.15	0.293976	3.37	1.231454
6-Mar-2014						
7-Mar-2014						
8-Mar-2014						
9-Mar-2014	4.76	2.36	7.12	0.331461	6.13	1.161501
10-Mar-2014	4.77	2.73	7.5	0.364	6.04	1.241722
11-Mar-2014	5.1	3.12	8.22	0.379562	6.9	1.191304
12-Mar-2014	5.66	3.39	9.05	0.374586	7.77	1.164736
13-Mar-2014	6.205	4.02	10.225	0.393154	8.9	1.148876
14-Mar-2014						
15-Mar-2014						
16-Mar-2014	4.855	3.88	8.735	0.44419	8.98	0.972717
17-Mar-2014	3.98	3.02	7	0.431429	8.28	0.845411
18-Mar-2014	4.385	2.88	7.265	0.396421	8.78	0.827449
19-Mar-2014	5.745	3.43	9.175	0.373842	7.95	1.154088
20-Mar-2014	6.03	3.83	9.86	0.388438	10.2	0.966667
21-Mar-2014						

22-Mar-2014						
23-Mar-2014	6.175	3.98	10.155	0.391925	10.5	0.967143
24-Mar-2014	5.08	4.01	9.09	0.441144	9.98	0.910822
25-Mar-2014	6.005	4.09	10.095	0.405151	10.1	0.999505
26-Mar-2014	1.865	3.26	5.125	0.636098	9.08	0.564427
27-Mar-2014	5.645	3.42	9.065	0.377275	9.42	0.962314
28-Mar-2014						
29-Mar-2014						
30-Mar-2014	5.305	2.96	8.265	0.358137	7.98	1.035714
31-Mar-2014	4.93	2.44	7.37	0.331072	7.36	1.001359
1-Apr-2014	6.335	2.62	8.955	0.292574	9.02	0.992794
2-Apr-2014	6.935	2.65	9.585	0.276474	10.2	0.939706
3-Apr-2014	6.63	2.92	9.55	0.305759	10.1	0.945545
4-Apr-2014						
5-Apr-2014						
6-Apr-2014	3.92	2.44	6.36	0.383648	6.05	1.05124
7-Apr-2014	2.255	2.36	4.615	0.511376	3.71	1.243935
8-Apr-2014	2.05	2.31	4.36	0.529817	3.41	1.278592
9-Apr-2014	2.505	2.58	5.085	0.507375	3.83	1.327676
10-Apr-2014	2.585	2.82	5.405	0.521739	4.69	1.152452
11-Apr-2014						
12-Apr-2014						
13-Apr-2014	1.61	2.59	4.2	0.616667	3.21	1.308411
14-Apr-2014	1.239	2.38	3.619	0.65764	2.54	1.424803
15-Apr-2014	1.16	2.24	3.4	0.658824	2.65	1.283019
16-Apr-2014	1.15	1.96	3.11	0.630225	2.18	1.426606
17-Apr-2014	1.76	2.67	4.43	0.602709	3.35	1.322388
18-Apr-2014						
19-Apr-2014						
20-Apr-2014	2.15	2.38	4.53	0.525386	4.3	1.053488
21-Apr-2014	1.925	1.87	3.795	0.492754	4.03	0.941687
22-Apr-2014	2.76	2.07	4.83	0.428571	5.03	0.960239
23-Apr-2014	3.44	2.12	5.56	0.381295	5.38	1.033457
24-Apr-2014	3.84	2.43	6.27	0.38756	5.89	1.064516
25-Apr-2014						
26-Apr-2014						
27-Apr-2014						
28-Apr-2014	2.285	2.21	4.495	0.491657	4.72	0.952331
29-Apr-2014	2.38	2.19	4.57	0.479212	5	0.914
30-Apr-2014	2.55	2.38	4.93	0.482759	6.08	0.810855

A.6.2 PHOSPHORUS AND COD MEASUREMENTS

Average	2.489679	52.28377	28.85195		28.02727	24.17391	23.43182
SD	0.656655	12.47978	2.876163	9.46642	3.864266	5.823012	12.66254
Max	4.72	102	35.2		35.5	38.3	69.3
Min	0.12	25.3	21		22.1	17.8	-2.2
Date	OP	COD	sCOD		sCOD	ffCOD	pCOD
	Comp	Comp	Comp		Comp	Comp	Comp
	Onsite	Onsite	1.5		0.45	Onsite	Calc
(dd:mm:yyyy)	(mg P/L)	(mg/L)	(mg/L)		(mg/L)	(mg/L)	(mg/L)
3-Sep-2013	2.09	47.4	21.6	16.51568			25.8
4-Sep-2013	2.5	42.8	29.4	10.02342	30	35	13.4
5-Sep-2013	2.53	37.1	28.6	5.013514			8.5
6-Sep-2013							
7-Sep-2013							
8-Sep-2013	2.22	42.3	33.1	4.147059			9.2
9-Sep-2013	1.78	35.6	30.8	3.783209			4.8
10-Sep-2013	2.45	38.5	30.9	3.85			7.6
11-Sep-2013	2.41	25.3	21	2.3			4.3
12-Sep-2013	2.8	38.1	31.1	3.560748			7
13-Sep-2013							
14-Sep-2013							
15-Sep-2013	2.7	39.1	32.2	3.91			6.9
16-Sep-2013	2.5	31.9	33.2	3.6374			-1.3
17-Sep-2013	3.01	30.2	32.4	2.990099	32.6	38.3	-2.2
18-Sep-2013	3	35.3	30.5	3.151786			4.8
19-Sep-2013	3.15			0			
20-Sep-2013							
21-Sep-2013							
22-Sep-2013	2.92	53	33.1	7.681159			19.9
23-Sep-2013	2.52	32.7	31	5			1.7
24-Sep-2013	2.69	32.6	30.1	5.442404	33.1	33.3	2.5
25-Sep-2013	2.84	33.7	28.5	5.06006			5.2
26-Sep-2013	3.14	31.8	29.6	4.899846			2.2
27-Sep-2013							
28-Sep-2013							
29-Sep-2013	2.8	34.4	30.1	5.993031			4.3
30-Sep-2013	2.7	33.7	29.4	6.263941			4.3
1-Oct-2013	2.49	32.1	28.7	5.169082	35.5	32.1	3.4
2-Oct-2013	2.84	45.2	30.3	7.520799			14.9
3-Oct-2013	3.15	53.6	31.8	7.549296			21.8
4-Oct-2013							

5-Oct-2013							
6-Oct-2013	2.3	50.6	34.1	9.656489			16.5
7-Oct-2013	1.99	43.6	33.5	10.43062			10.1
8-Oct-2013	1.63	45.9	31.1	6.830357	30.7	25.8	14.8
9-Oct-2013	1.64	45.4	33	7.394137			12.4
10-Oct-2013	1.13	63.2	28.8	17.90368			34.4
11-Oct-2013							
12-Oct-2013							
13-Oct-2013							
14-Oct-2013	1.42	50.3	32.8	6.490323			17.5
15-Oct-2013	1.7	54.2	32.5	5.949506	31.8	26.5	21.7
16-Oct-2013	1.78	51.7	31.4	6.42236			20.3
17-Oct-2013	2.08	51.5	32.7	5.773543			18.8
18-Oct-2013							
19-Oct-2013							
20-Oct-2013	2.39	62.1	31.5	8.002577			30.6
21-Oct-2013	1.87	58.3	30.8	8.983051			27.5
22-Oct-2013	2.13	56.9	33	6.205016	32.3	28	23.9
23-Oct-2013	4.72	59.9	31.5	5.650943			28.4
24-Oct-2013	2.26	73.6	30.9	6.237288			42.7
25-Oct-2013							
26-Oct-2013							
27-Oct-2013	2.36	72.6	33.5	10.72378			39.1
28-Oct-2013	1.91	78.3	33.1	14.4732			45.2
29-Oct-2013	2.56	74.4	30.4	9.662338	27.3	19.8	44
30-Oct-2013	2.43	54.9	29.2	6.458824			25.7
31-Oct-2013	2.58	66.2	29.3	7.274725			36.9
1-Nov-2013							
2-Nov-2013							
3-Nov-2013	2.6	87.8	29.8	8.607843			58
4-Nov-2013	2.74	96.2	29.7	9.25			66.5
5-Nov-2013	3.13	91.4	28.2	7.745763	27.2	19	63.2
6-Nov-2013	3.51	75	30.6	6			44.4
7-Nov-2013	3.56	63.5	26.4	6.287129			37.1
8-Nov-2013							
9-Nov-2013							
10-Nov-2013							
11-Nov-2013	3.21	55.4	27.2	10.57252			28.2
12-Nov-2013	2.8	48.8	26.3	10.06186			22.5
13-Nov-2013	3.06	46	32.3	7.718121	32	27	13.7
14-Nov-2013	3.09	47.2	30.1	7.433071			17.1
15-Nov-2013							
16-Nov-2013							

17-Nov-2013	2.7	55.9	31.5	9.893805			24.4
18-Nov-2013	2.55	60.1	35.2	11.29699			24.9
19-Nov-2013	2.48	49	33.2	7.291667	31.3	26.3	15.8
20-Nov-2013	2.48	41.2	32.9	6.397516			8.3
21-Nov-2013	2.33	42.5	34.3	7.191201			8.2
22-Nov-2013							
23-Nov-2013							
24-Nov-2013	2.82	43.1	32.9	10.88384			10.2
25-Nov-2013	2.24	41.8	33	12.70517			8.8
26-Nov-2013	2.94	43.9	33.9	11.4026			10
27-Nov-2013							
28-Nov-2013							
29-Nov-2013							
30-Nov-2013							
1-Dec-2013	1.65	48.5	33.4	9.79798			15.1
2-Dec-2013	1.27	50.6	30.6	12.65			20
3-Dec-2013	0.45	50.7	30.8	14.91176			19.9
4-Dec-2013	1	56.7	30.8	17.44615			25.9
5-Dec-2013							
6-Dec-2013							
7-Dec-2013							
8-Dec-2013	0.33	45.2	32.1	45.2			13.1
9-Dec-2013	0.12	58.9	29.3	56.09524			29.6
10-Dec-2013	1.55	48.6	27.5	36		19.8	21.1
11-Dec-2013	3.1	48.3	23.4	23			24.9
12-Dec-2013	3.28	49.7	25.8	20.97046			23.9
13-Dec-2013							
14-Dec-2013							
15-Dec-2013	2.05	56.9	22	43.76923			34.9
16-Dec-2013	1.39	52.7	23.4	35.13333			29.3
17-Dec-2013	1.72	55.1	23.9	26.2381			31.2
18-Dec-2013	4.5	51.3	23.9	13.39426			27.4
19-Dec-2013	4.5	51.3	23.9	13.39426			27.4
20-Dec-2013	2.76	56.4	26	14.84211			30.4
21-Dec-2013							
22-Dec-2013							
23-Dec-2013	3.15	76.9	27.3	23.51682			49.6
24-Dec-2013							
25-Dec-2013							
26-Dec-2013							
27-Dec-2013	2.86	57.5	25.7	14.74359			31.8
28-Dec-2013							
29-Dec-2013							

30-Dec-2013	3.38	72.9	29.3	22.92453			43.6
29-Dec-2013	2.05	53.6	26.6	24.47489			27
30-Dec-2013	2.01	58.3	25.9	14.04819			32.4
31-Dec-2013							
1-Jan-2014							
2-Jan-2014	2.4	60.7	26.8	17.29345			33.9
3-Jan-2014							
4-Jan-2014							
5-Jan-2014	2.23	58.8	25.1	14.13462			33.7
6-Jan-2014	2.07	50.6	24.4	14.58213			26.2
7-Jan-2014	2.57	55.3	26.2	16.26471	23.1	19.7	29.1
8-Jan-2014	2.36	52.8	26	17.54153			26.8
9-Jan-2014	2.95	52.3	29.9	15.51929			22.4
10-Jan-2014							
11-Jan-2014							
12-Jan-2014	3.87	102	32.7	34.45946			69.3
13-Jan-2014	2.61	51.3	27.8	23.97196			23.5
14-Jan-2014	2.16	49.2	31.3	23.65385	27.3	17.8	17.9
15-Jan-2014							
16-Jan-2014							
17-Jan-2014							
18-Jan-2014							
19-Jan-2014							
20-Jan-2014	2.74	52.5	28.6	6.537983			23.9
21-Jan-2014							
22-Jan-2014	2.38	61.5	28.6	6.542553			32.9
23-Jan-2014	2.67	52.6	26.4	6.102088			26.2
24-Jan-2014							
25-Jan-2014							
26-Jan-2014	2.57	50.8	29.9	8.314239			20.9
27-Jan-2014	2.45	45.2	28.4	8.324125			16.8
28-Jan-2014	3.24	50.9	26.8	5.981199			24.1
29-Jan-2014	3.24	50.9	26.8	5.981199			24.1
30-Jan-2014	3.23	49.5	29.8	5.735805			19.7
31-Jan-2014							
1-Feb-2014							
2-Feb-2014	2.2	50.8	27.4	8.99115			23.4
3-Feb-2014	2.31	54.7	26.9	16.88272			27.8
4-Feb-2014	2.59	85.9	27	11.78326			58.9
5-Feb-2014	2.16	46.1	27.3	7.520392			18.8
6-Feb-2014	2.44	48.9	27.8	7.331334			21.1
7-Feb-2014				11.88836			
8-Feb-2014				9.510253			

9-Feb-2014							
10-Feb-2014	2.6	66	32				34
11-Feb-2014	2.83	57.6	33.6				24
12-Feb-2014	3.35	57.3	30.3				27
13-Feb-2014	1.91	59.9	28				31.9
14-Feb-2014							
15-Feb-2014							
16-Feb-2014	2.54	68.1	27.1				41
17-Feb-2014	2.74	49.9	28.2				21.7
18-Feb-2014	3.01	47.7	28.1				19.6
19-Feb-2014	3.06	54.6	26.2				28.4
20-Feb-2014	3.33	49.8	27.9				21.9
21-Feb-2014							
22-Feb-2014							
23-Feb-2014	2.79	56.7	32.5				24.2
24-Feb-2014	2.54	54.2	28.5				25.7
25-Feb-2014	2.95	47	28.3		26.3	22.3	18.7
26-Feb-2014	3.11	48.7	27.1				21.6
27-Feb-2014	3.04						
28-Feb-2014							
1-Mar-2014							
2-Mar-2014	2.74	45	27.4				17.6
3-Mar-2014							
4-Mar-2014	2.75	34.2	27				7.2
5-Mar-2014	2.79	45.4	27.9				17.5
6-Mar-2014							
7-Mar-2014							
8-Mar-2014							
9-Mar-2014	2.32	52.7	27.4				25.3
10-Mar-2014	2.16	48.1	24.6				23.5
11-Mar-2014	2.31	43.2	25.6		23.8	18.4	17.6
12-Mar-2014	2.54	45.3	27.6				17.7
13-Mar-2014	2.69	54.5	26.3				28.2
14-Mar-2014							
15-Mar-2014							
16-Mar-2014	2.63	53.1	26.8				26.3
17-Mar-2014	2.17	46.4	27.3				19.1
18-Mar-2014	1.99	44.6	27		25.4	21.2	17.6
19-Mar-2014	1.99	53.1	24.6				28.5
20-Mar-2014	2.18	57.6	26.1				31.5
21-Mar-2014							
22-Mar-2014							
23-Mar-2014	2.56	66	29				37

24-Mar-2014	2.6	63	29				34
25-Mar-2014	2.67	59.1	30.8		22.1	18.2	28.3
26-Mar-2014	2.6	79.2	27.2				52
27-Mar-2014	2.62	63.8	27.5				36.3
28-Mar-2014							
29-Mar-2014							
30-Mar-2014	2.34	67.3	29.5				37.8
31-Mar-2014	2.1	59	29.8				29.2
1-Apr-2014	1.65	51.6	31.2		26.6	21.7	20.4
2-Apr-2014	1.88	52.4	26.8				25.6
3-Apr-2014	1.89	49.5	27.6				21.9
4-Apr-2014							
5-Apr-2014							
6-Apr-2014	2.35	49	28				21
7-Apr-2014	2.16	45.9	26.9				19
8-Apr-2014	1.9	43.2	26.5		25.7	21.8	16.7
9-Apr-2014	2.22	50.4	27.7				22.7
10-Apr-2014	2.98	60.1	31.6				28.5
11-Apr-2014							
12-Apr-2014							
13-Apr-2014	3.44	53.3	28.7				24.6
14-Apr-2014	3.26	49.7	28.7				21
15-Apr-2014	3.03	40.2	26.1		24.1	23	14.1
16-Apr-2014	2.04	47	26				21
17-Apr-2014	2.31	44.5	25				19.5
18-Apr-2014							
19-Apr-2014							
20-Apr-2014	2.17	45.5	25.1				20.4
21-Apr-2014	2.16	48.4	26.9				21.5
22-Apr-2014	2.47	46.9	26.6				20.3
23-Apr-2014	2.25	41.4	26.6		24.2	19.9	14.8
24-Apr-2014	2.06	50.2	28.4				21.8
25-Apr-2014							
26-Apr-2014							
27-Apr-2014							
28-Apr-2014	2.41	46.5	26.9				19.6
29-Apr-2014	2.24	38.2	26.3		24.2	21.1	11.9
30-Apr-2014	2.06	37.5	27.9				9.6

A.6.3 Solids and COD Measurements

Average	25.48344	25.05968	22.27208	86.80645	#DIV/0!	#DIV/0!	23.5	#DIV/0!	#DIV/0!
SD	11.2297	9.96261	8.319536	6.362901	#DIV/0!	#DIV/0!	2.12132	#DIV/0!	#DIV/0!
Max	91	62	50.84	115	0	0	25	0	0
Min	6.75	8	9.96	69	0	0	22	0	0
Date	TSS	TSS	TVSS	TVSS	COD	sCOD	CBOD	sCBOD	pCOD
	Comp	Comp	Comp	Comp	Comp	Comp	Comp	Comp	Comp
	Onsite	CEL	Calc	CEL	CEL	CEL	CEL	CEL	Calc
(dd:mm:yyyy)	(mg/L)	(mg/L)	(mg/L)	(%)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
3-Sep-2013	20.5	20		86			< 17	< 17	
4-Sep-2013	21								
5-Sep-2013	12.75	8		83					
6-Sep-2013									
7-Sep-2013									
8-Sep-2013	15.5								
9-Sep-2013	17								
10-Sep-2013	19	13		85			< 17*	< 17*	
11-Sep-2013	13								
12-Sep-2013	14	16		78					
13-Sep-2013									
14-Sep-2013									
15-Sep-2013	10								
16-Sep-2013	10								
17-Sep-2013	11.5	12		84			< 21	< 21	
18-Sep-2013	11								
19-Sep-2013	25	27		85					
20-Sep-2013									
21-Sep-2013									

22-Sep-2013	24.5								
23-Sep-2013	8.5								
24-Sep-2013	10.5	12	9.96	83			< 17	< 17	
25-Sep-2013	6.75								
26-Sep-2013	44.25	47	38.54	82					
27-Sep-2013									
28-Sep-2013									
29-Sep-2013	10.75								
30-Sep-2013	12								
1-Oct-2013	11.25								
2-Oct-2013	22.25								
3-Oct-2013	24.5	28	22.68	81					
4-Oct-2013									
5-Oct-2013									
6-Oct-2013	26.25								
7-Oct-2013	18								
8-Oct-2013	19.75	21	18.48	88			<20	<20	
9-Oct-2013	19								
10-Oct-2013	24.5	21	17.64	84					
11-Oct-2013									
12-Oct-2013									
13-Oct-2013									
14-Oct-2013	25.5								
15-Oct-2013	26.25	26	21.32	82			<21	<21	
16-Oct-2013	22.75								
17-Oct-2013	20.25	25	20	80					
18-Oct-2013									
19-Oct-2013									
20-Oct-2013	34.25								
21-Oct-2013	27.75								
22-Oct-2013	29.25	27	24.57	91			<20	<20	
23-Oct-2013	31.5								
24-Oct-2013	43.25	45	36.9	82					
25-Oct-2013									
26-Oct-2013									

27-Oct-2013	44.25								
28-Oct-2013	43.5								
29-Oct-2013	43	45	38.25	85			<17	<17	
30-Oct-2013	31.25								
31-Oct-2013	37.75	38	32.3	85					
1-Nov-2013									
2-Nov-2013									
3-Nov-2013	56.5								
4-Nov-2013	64								
5-Nov-2013	61.25	62	50.84	82			22	<20	
6-Nov-2013	50.25								
7-Nov-2013	37	27	22.14	82					
8-Nov-2013									
9-Nov-2013									
10-Nov-2013									
11-Nov-2013	30								
12-Nov-2013	25	26	17.94	69			<21	<21	
13-Nov-2013	21.5								
14-Nov-2013	25.2	24	21.12	88					
15-Nov-2013									
16-Nov-2013									
17-Nov-2013	31								
18-Nov-2013	33.75								
19-Nov-2013	26	26	22.62	87			<20	<20	
20-Nov-2013	15.25								
21-Nov-2013	19.75	19	15.58	82					
22-Nov-2013									
23-Nov-2013									
24-Nov-2013	15								
25-Nov-2013	17.75								

26-Nov-2013	17								
27-Nov-2013									
28-Nov-2013									
29-Nov-2013									
30-Nov-2013									
1-Dec-2013	25								
2-Dec-2013	23.5								
3-Dec-2013	24	25.5		88			<21	<21	
4-Dec-2013	30.75								
5-Dec-2013		47		85					
6-Dec-2013									
7-Dec-2013									
8-Dec-2013	26								
9-Dec-2013	34.5								
10-Dec-2013	22	23.2		78			<19	<19	
11-Dec-2013	23								
12-Dec-2013	27.25	27.4		73					
13-Dec-2013									
14-Dec-2013									
15-Dec-2013	29.25								
16-Dec-2013	27								
17-Dec-2013	30	30		92			<20	<20	
18-Dec-2013	26.25								
19-Dec-2013	26.25	24.5		88					
20-Dec-2013	27.75								
21-Dec-2013									
22-Dec-2013									

23-Dec-2013	91								
24-Dec-2013									
25-Dec-2013									
26-Dec-2013		24		88					
27-Dec-2013	28.5								
28-Dec-2013									
29-Dec-2013									
30-Dec-2013	42.5								
29-Dec-2013	27.5								
30-Dec-2013	33.25								
31-Dec-2013									
1-Jan-2014									
2-Jan-2014	31.25	27	23.49	87					
3-Jan-2014									
4-Jan-2014									
5-Jan-2014	31.25								
6-Jan-2014	27								
7-Jan-2014	28.25	29	24.94	86			<20	<20	
8-Jan-2014	24.75								
9-Jan-2014	24.25	28.5	23.085	81					
10-Jan-2014									
11-Jan-2014									
12-Jan-2014	62.25								
13-Jan-2014	21								
14-Jan-2014	22.25	21	19.53	93			<19	<19	
15-Jan-2014									
16-Jan-2014									
17-Jan-2014									
18-Jan-2014									
19-Jan-2014									
20-Jan-2014	20								
21-Jan-2014		21	18.27	87			<20	<20	
22-Jan-2014	27								
23-Jan-2014	17.75	17.8	14.774	83					

24-Jan-2014									
25-Jan-2014									
26-Jan-2014	15.5								
27-Jan-2014	14								
28-Jan-2014	13.25								
29-Jan-2014	13.25								
30-Jan-2014	21.5	23.2	20.88	90					
31-Jan-2014									
1-Feb-2014									
2-Feb-2014	19.25								
3-Feb-2014	14.75								
4-Feb-2014	45.25	52.5	48.825	93			25	<22	
5-Feb-2014	20.5								
6-Feb-2014	25.25	20.8	18.72	90					
7-Feb-2014									
8-Feb-2014									
9-Feb-2014									
10-Feb-2014	28.75								
11-Feb-2014	22.5	27	24.3	90			<21	<21	
12-Feb-2014	24.25								
13-Feb-2014	25	17.3	16.954	98					
14-Feb-2014									
15-Feb-2014									
16-Feb-2014	40								
17-Feb-2014	15.25								
18-Feb-2014	24.75	19.5	22.425	115					
19-Feb-2014	26.5								
20-Feb-2014	29.25	28.3	26.319	93					
21-Feb-2014									
22-Feb-2014									
23-Feb-2014	29.25								

24-Feb-2014	25								
25-Feb-2014	20.75	23.2	21.576	93			<21	<21	
26-Feb-2014	18.75								
27-Feb-2014	12.25	14.5	14.21	98					
28-Feb-2014									
1-Mar-2014									
2-Mar-2014	23								
3-Mar-2014									
4-Mar-2014	21.25	16.3	14.344	88			<17	<17	
5-Mar-2014									
6-Mar-2014		18	16.56	92					
7-Mar-2014									
8-Mar-2014									
9-Mar-2014	29								
10-Mar-2014	21.25								
11-Mar-2014	19.25	14.6	12.848	88			<21	<21	
12-Mar-2014	18.75								
13-Mar-2014	23	21.2	19.928	94					
14-Mar-2014									
15-Mar-2014									
16-Mar-2014	24.25								
17-Mar-2014	25.25								
18-Mar-2014	24.5	22.4	19.264	86			<20	<20	
19-Mar-2014	30								
20-Mar-2014	29.5	26	23.14	89					
21-Mar-2014									
22-Mar-2014									

23-Mar-2014	33.5								
24-Mar-2014	25.75								
25-Mar-2014	29.75	29.5	23.895	81			<20	<20	
26-Mar-2014	30.75								
27-Mar-2014	33.5	34	29.58	87					
28-Mar-2014									
29-Mar-2014									
30-Mar-2014	32								
31-Mar-2014	27.75								
1-Apr-2014	25	24	21.6	90			<21	<21	
2-Apr-2014	24								
3-Apr-2014	22.75	21.5	19.565	91					
4-Apr-2014									
5-Apr-2014									
6-Apr-2014	19.5								
7-Apr-2014	18.25								
8-Apr-2014	17.75	19.5	16.965	87			<21	<21	
9-Apr-2014	25.75								
10-Apr-2014	25	26	22.62	87					
11-Apr-2014									
12-Apr-2014									
13-Apr-2014	29.75								
14-Apr-2014	22.5								
15-Apr-2014	20.25	18.5	16.465	89			<21	<21	
16-Apr-2014	19.25								
17-Apr-2014	16.75	21	18.06	86					
18-Apr-2014									
19-Apr-2014									
20-Apr-2014	18.5								
21-Apr-2014	24.25								
22-Apr-2014	19	15	13.95	93			<20	<20	
23-Apr-2014	18								
24-Apr-2014	22.25	22	18.92	86					
25-Apr-2014									
26-Apr-2014									

27-Apr-2014									
28-Apr-2014	19								
29-Apr-2014	18.25	17	14.45	85			<19	<19	
30-Apr-2014									

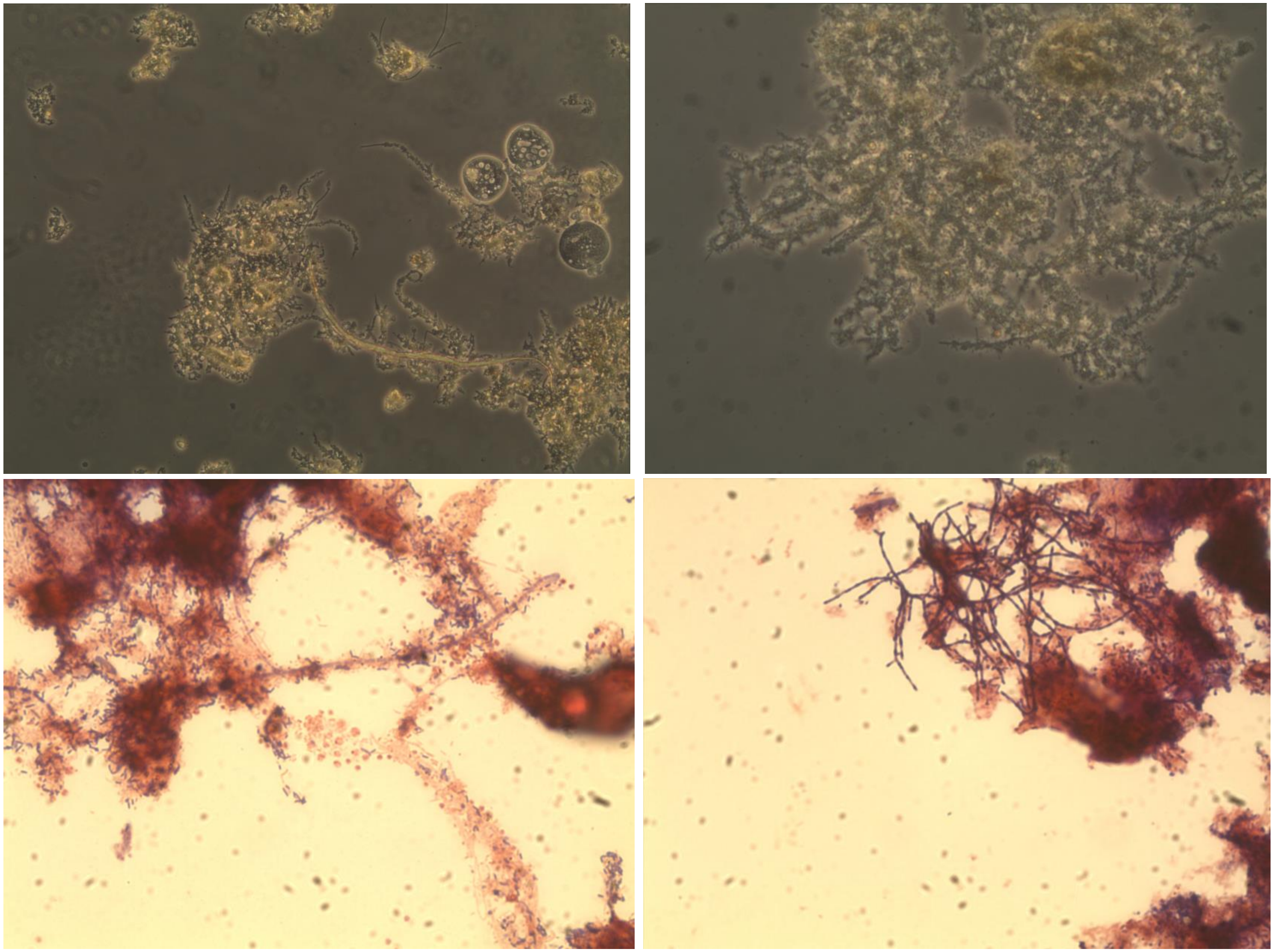
A.6.4 AMMONIA, PHOSPHORUS, ALKALINITY, CA, MG MEASUREMENTS

Average	9.043548	6.712667	2.941587	2.185	66.40351	26.08462	12.72
SD	3.440907	3.033443	0.622078	0.547053	11.0419	2.246051	5.635943
Max	19	13.2	5.29	2.98	116	30.1	25.1
Min	3.22	1.99	0.88	0.26	47	22.1	8.07
Date	TKN	sTKN	TP	TP Dis	Alkalinity	Ca	Mg
	Comp	Comp	Comp	Comp	Comp	Comp	Comp
	CEL	CEL	CEL	CEL	CEL	CEL	CEL
(dd:mm:yyyy)	(mg N/L)	(mg N/L)	(mg P/L)	(mg P/L)	(mg CaCO3/L)	(mg/L)	(mg/L)
3-Sep-2013	4.66	3.83	2.84	2.38	55	24.7	8.42
4-Sep-2013							
5-Sep-2013	9.44		2.97		52		
10-Sep-2013	11.5	11	2.93	2.61	58	25.8	10.9
11-Sep-2013							
12-Sep-2013	13.6		3.31		59		
17-Sep-2013	12.1	10.5	3.36	2.98	55	24.8	13.5
18-Sep-2013							
19-Sep-2013	14.7		3.6		52		
24-Sep-2013	7.47	4.94	2.76	2.44	63		
25-Sep-2013							
26-Sep-2013	10.3		3.89		56		
3-Oct-2013	9.28		3.7		69		
8-Oct-2013	7.69	5	2.32	1.89	56	30.1	25.1
9-Oct-2013							
10-Oct-2013	5.53		1.83		47		
15-Oct-2013	10.3	9.49	2.57	1.9	61	28.9	23.9
16-Oct-2013							
17-Oct-2013	11.5		2.93		69		
22-Oct-2013	12.4	9.7	3.06	2.18	59	25.1	9.82
23-Oct-2013							
24-Oct-2013	14		3.42		60		
29-Oct-2013	11.3	8.15	3.35	2.26	47		
30-Oct-2013							
31-Oct-2013	12.4		3.07		50		
5-Nov-2013	15.6	11.5	4.13	2.68	65	26.2	14.6
6-Nov-2013							
7-Nov-2013	13.4		3.77		64		
12-Nov-2013	6.59	5.18	2.92	2.46	61	22.1	8.54
13-Nov-2013							
14-Nov-2013	8.77		3.56		61		
19-Nov-2013	8.5	6.97	2.87	2.2	60	23.7	10.6

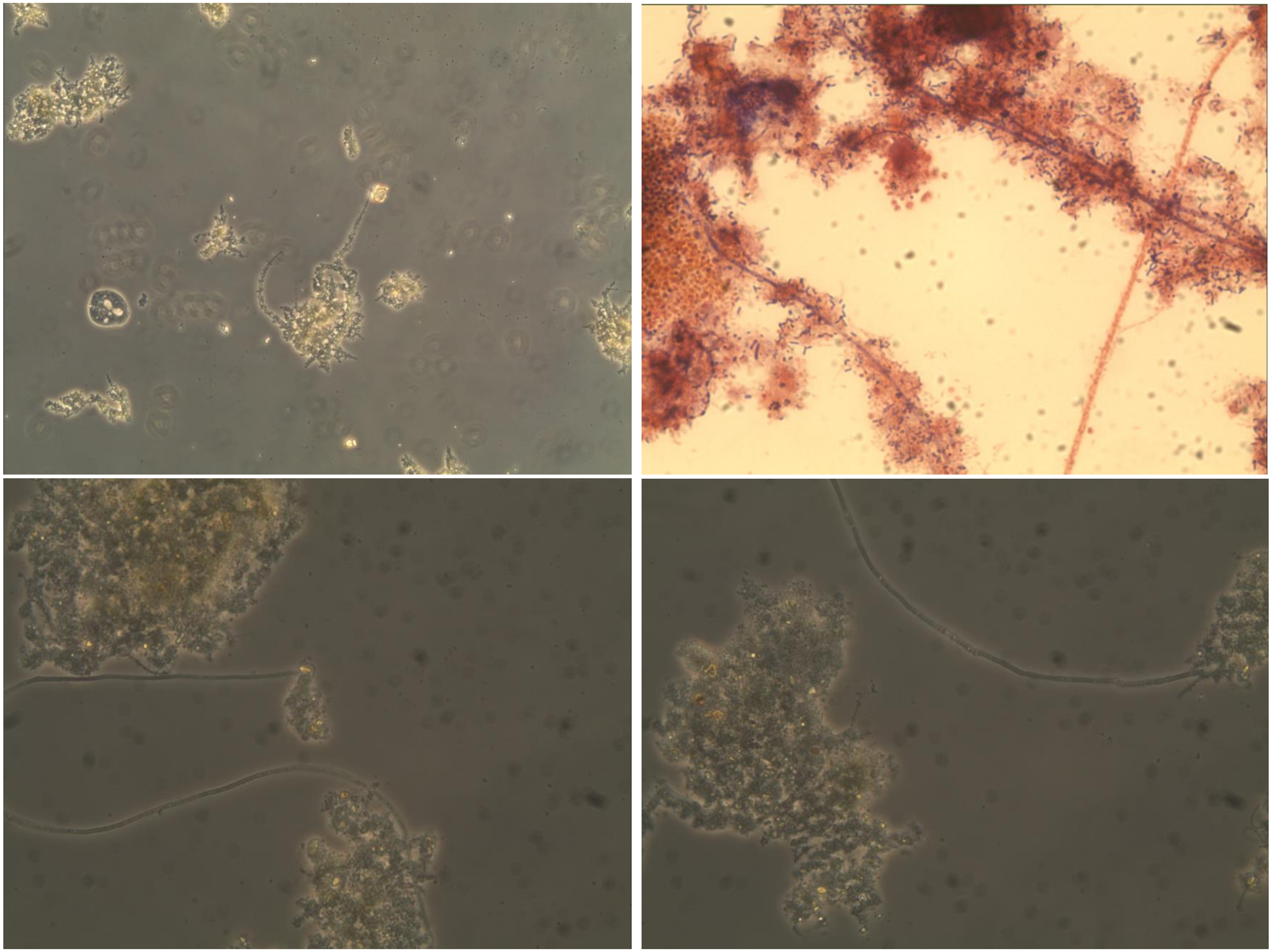
20-Nov-2013							
21-Nov-2013	7.2		2.53		64		
3-Dec-2013	5.73	4.13	0.88	0.26	71	28.6	13.4
4-Dec-2013							
5-Dec-2013	19		5.29		116		
10-Dec-2013	3.22	1.99	2.04	1.43	60	24.8	8.76
11-Dec-2013							
12-Dec-2013	4.53		3.34		68		
17-Dec-2013	4.26	2.83	2.26	1.45	66	27	8.07
18-Dec-2013							
19-Dec-2013	6.48		2.96		67		
26-Dec-2013	6.04		3.22		76		
2-Jan-2014	6.56		2.7		64		
7-Jan-2014	5.74	3.76	2.92	2.23	62	27.3	9.75
8-Jan-2014							
9-Jan-2014	5.57		3.13		70		
14-Jan-2014	4.06	3.51	2.14	1.77			
15-Jan-2014							
16-Jan-2014	6.15		2.79				
21-Jan-2014	10.2	8.32	2.89	2.44			
22-Jan-2014							
23-Jan-2014	10.7		2.96				
30-Jan-2014	11.1		3.32		65		
4-Feb-2014	12.4	7.55	3.19	2.44	67		
5-Feb-2014							
6-Feb-2014	8.77		2.72		68		
11-Feb-2014	13.9	13.2	3.03	2.53	96		
12-Feb-2014							
13-Feb-2014	8.73		2.23		71		
18-Feb-2014	4.64	4.44	3.1	2.64			
19-Feb-2014							
20-Feb-2014	9.99		3.71				
25-Feb-2014	9.06	6.86	3.27	2.63	71		
26-Feb-2014							
27-Feb-2014	8.26		2.99		78		
4-Mar-2014	6.59	3.12	2.88	2.76	75		
5-Mar-2014							
6-Mar-2014	6.05		3.44		75		
11-Mar-2014	7.89	7.01	2.61	2.18	65		
12-Mar-2014							
13-Mar-2014	11.6		3.07		65		
18-Mar-2014	9.72	8.58	2.27	1.82	71		
19-Mar-2014							

20-Mar-2014	12.6		2.55		71		
25-Mar-2014	12.7	10.5	3.09	2.63	81		
26-Mar-2014							
27-Mar-2014	12.7		3.14		74		
1-Apr-2014	13.8	10.2	2.42	1.61	64		
2-Apr-2014							
3-Apr-2014			2.08		68		
7-Apr-2014							
8-Apr-2014	5.42	4.32	2.03	1.67	63		
9-Apr-2014							
10-Apr-2014	4.67		3.17		82		
15-Apr-2014	4.5	3.35	3.09	2.74	72		
16-Apr-2014							
17-Apr-2014	6.04		2.65		69		
22-Apr-2014	7.67	6	2.75	2.34	70		
23-Apr-2014							
24-Apr-2014	8.89		2.88		71		
29-Apr-2014	6.54	5.45	2.43	2	70		
30-Apr-2014							

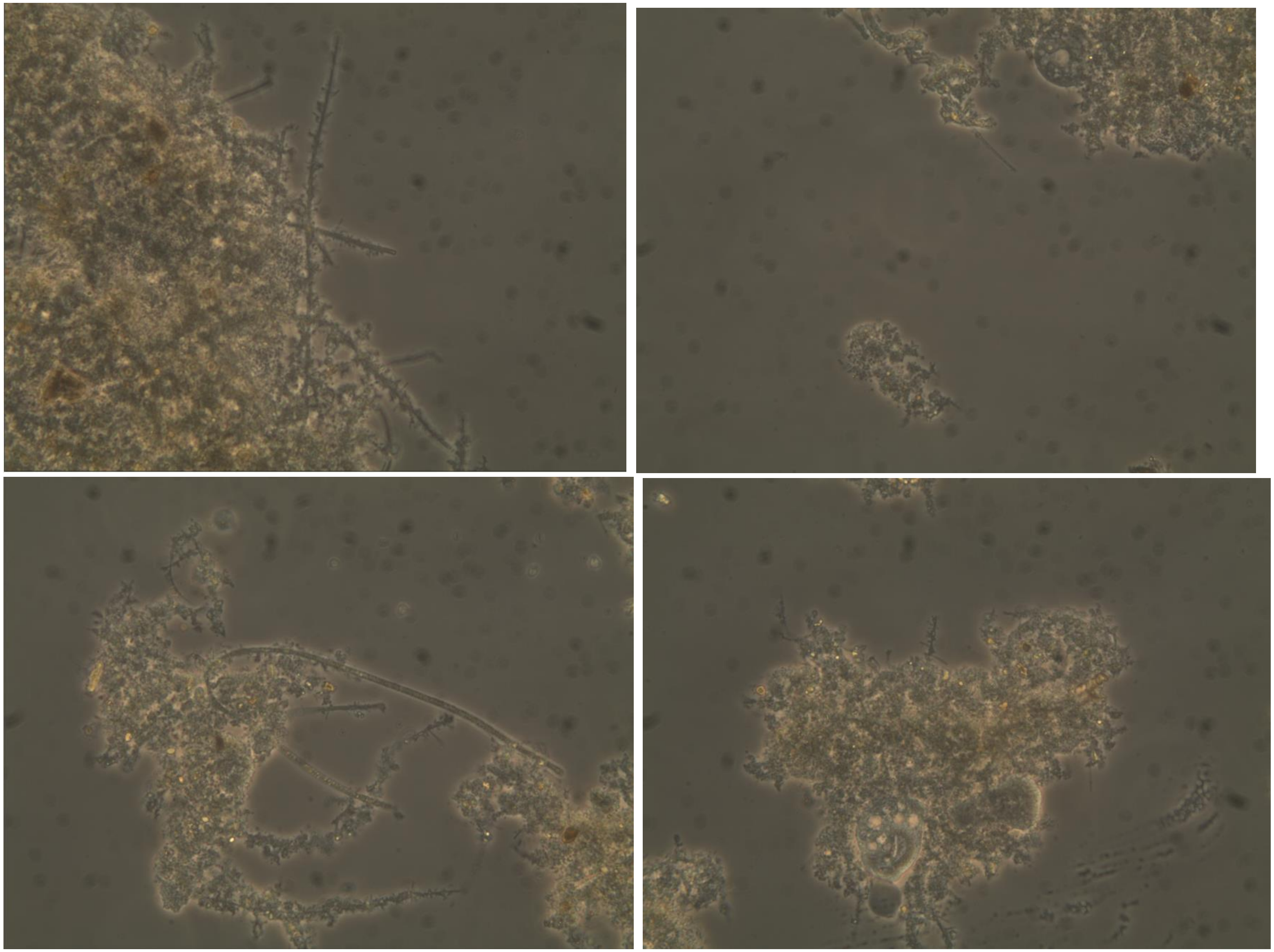
A 7 MICROSCOPE PICTURES OF GRAB SAMPLES FROM FINAL REACTOR OF B-STAGE. FILAMENTOUS ORGANISMS IDENTIFIED.



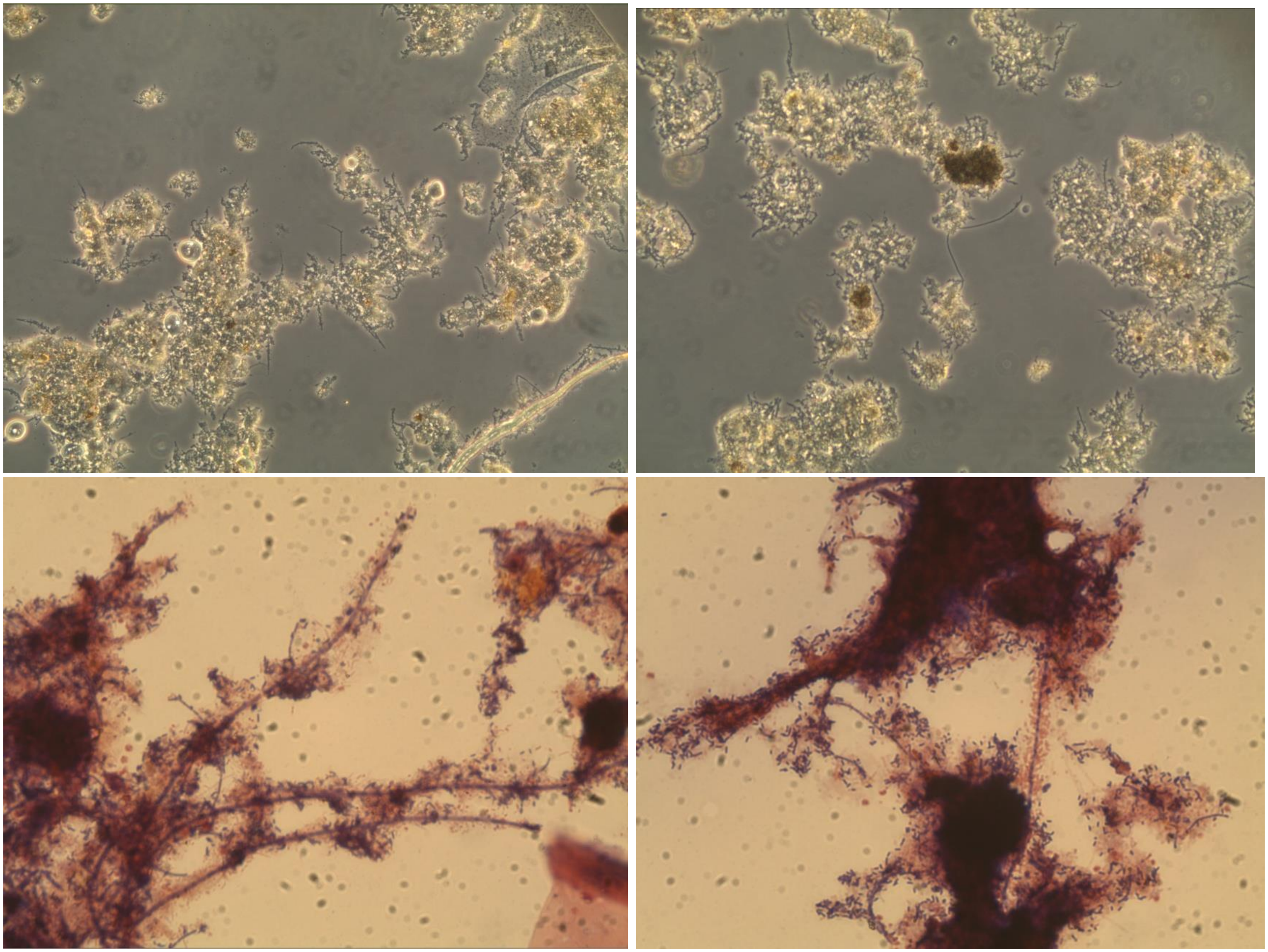
11/13/2013: a) Type 0041, stalked cilicates at 400x b) Type 0675 at 400x c) Type 0041 at 1000x gram stain d) Nocardia at 1000x gram stain



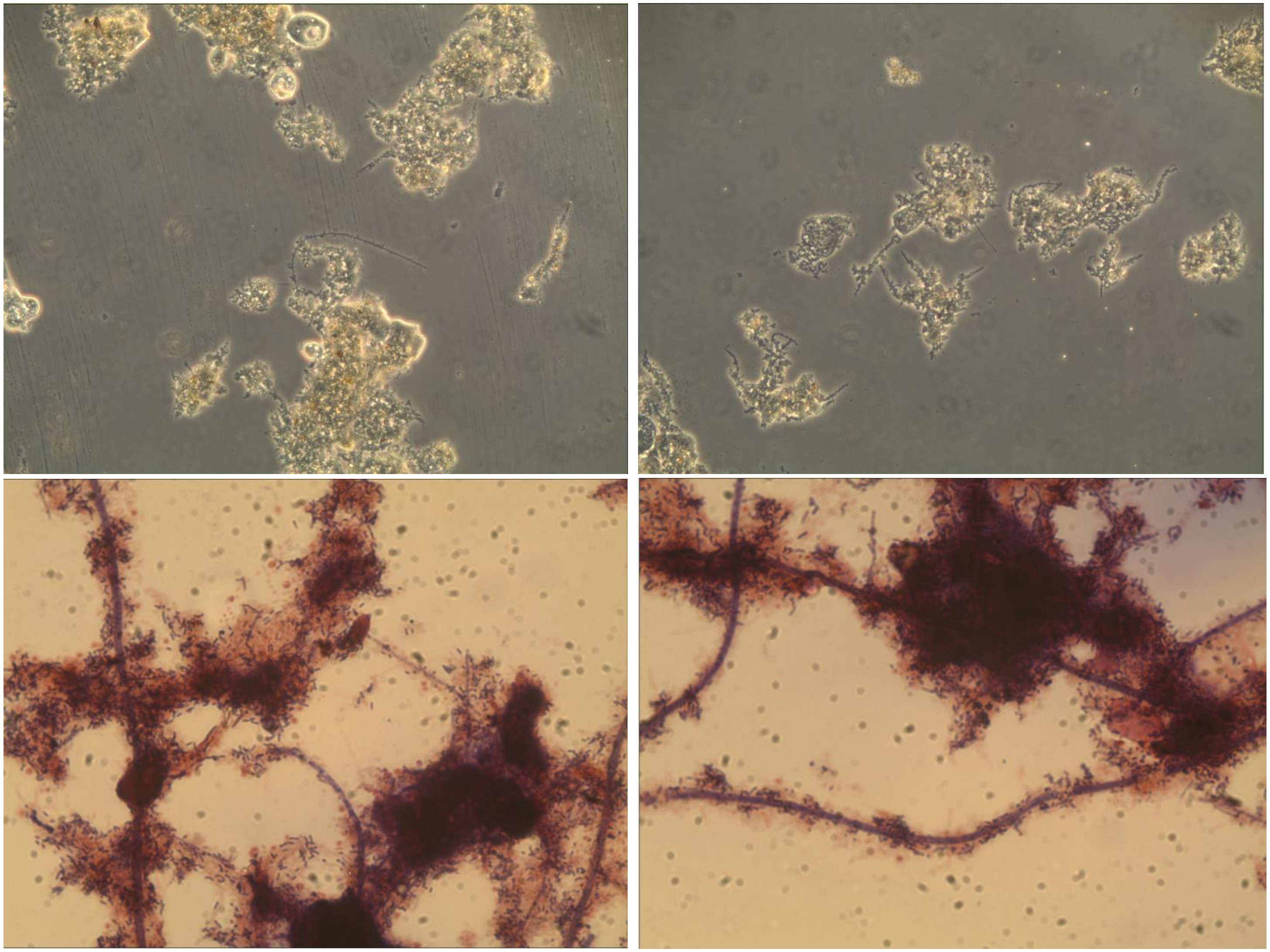
11/20/2013: a) Type 0041 at 100x b) Type 0041 at 1000x gram stain c) Thiothrix sp. I at 400x d) Type 021N at 400x



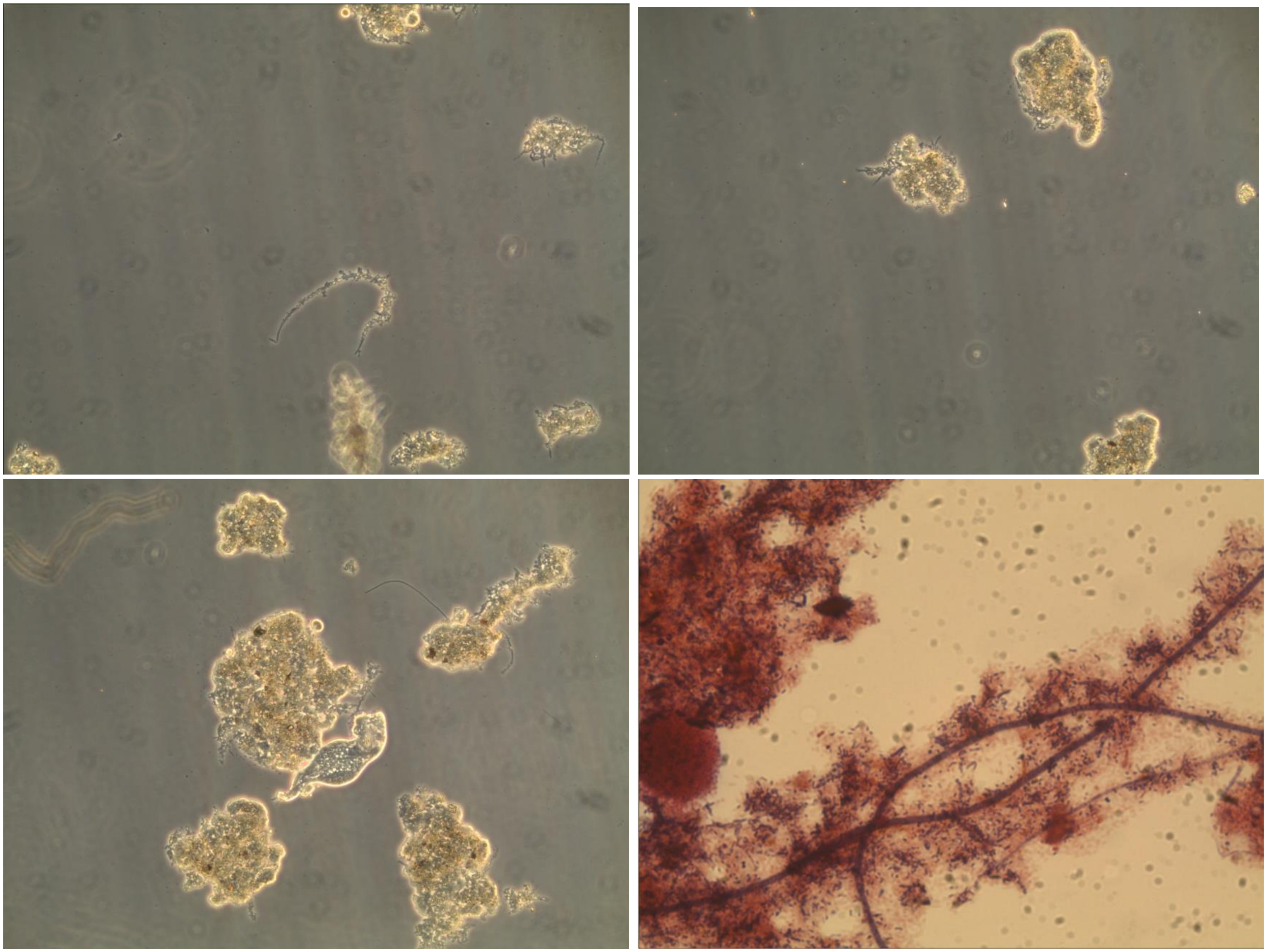
12/4/2013: a) Type 0041 at 400x b) Thiothrix sp. II at 400x c) Thiothrix sp. I, Type 0041 at 400x d) Type 0675 at 400x



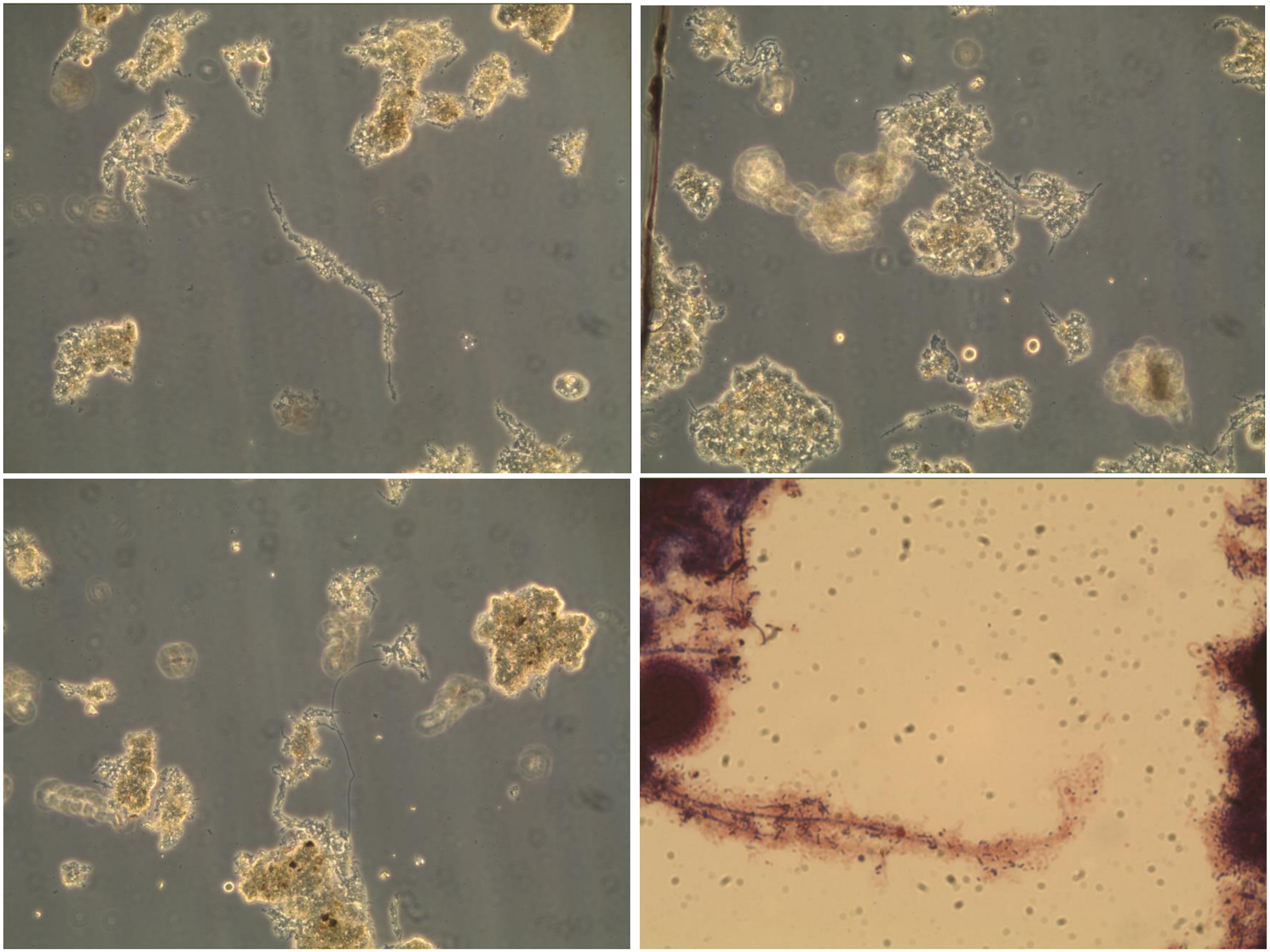
12/11/2013: a) Type 0041, Type 0675 at 100x b) Thiothrix sp. I at 100x c) Type 0041 at 1000x gram stain d) Type 0675 at 1000x gram stain



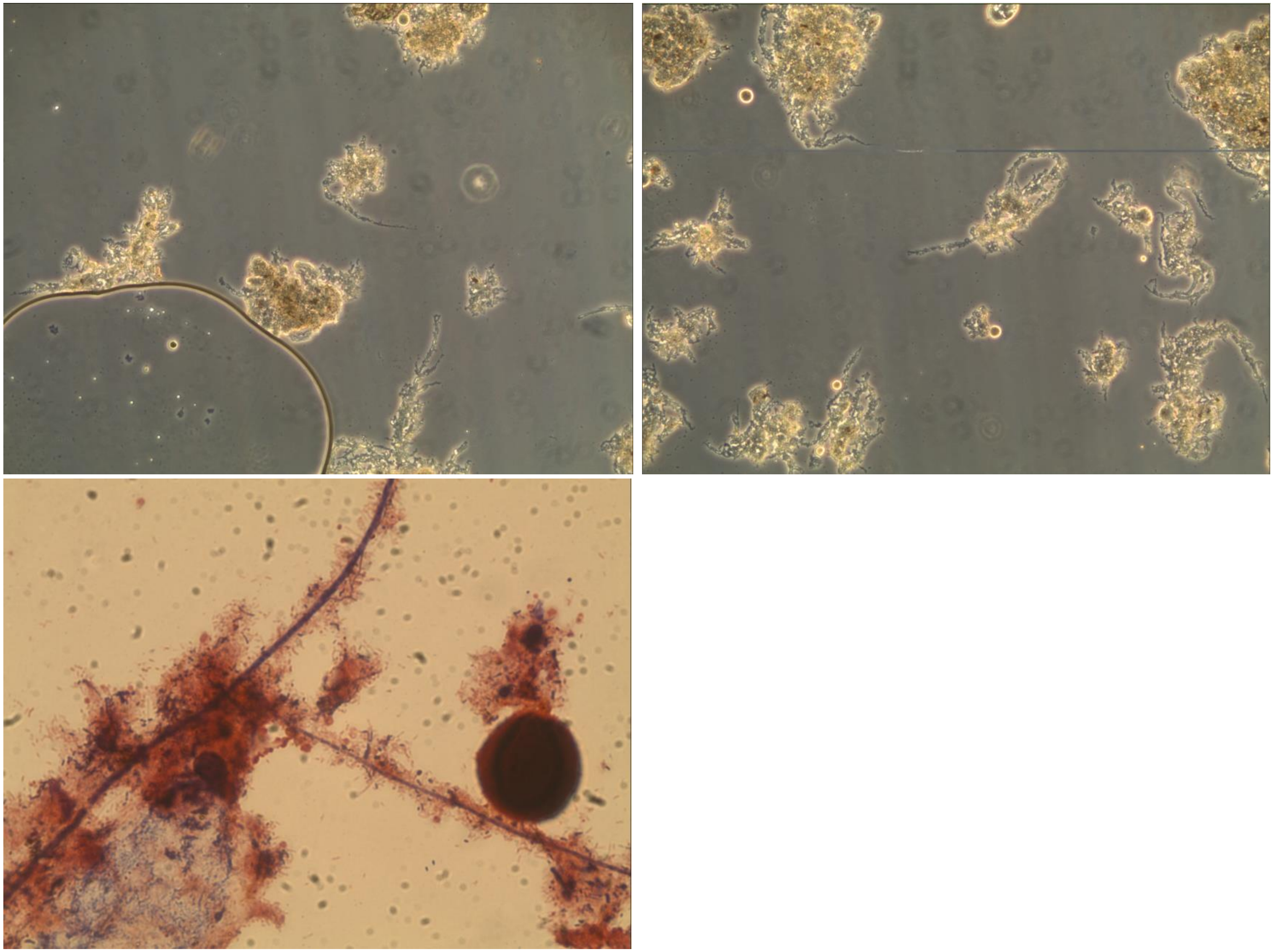
12/18/2013: a) Type 0041, Type 0675 at 100x b) Type 0041 and Thiothrix sp. II at 100x c) Type 0041, Type 0675 gram stain d) Type 0041 at 1000x gram stain



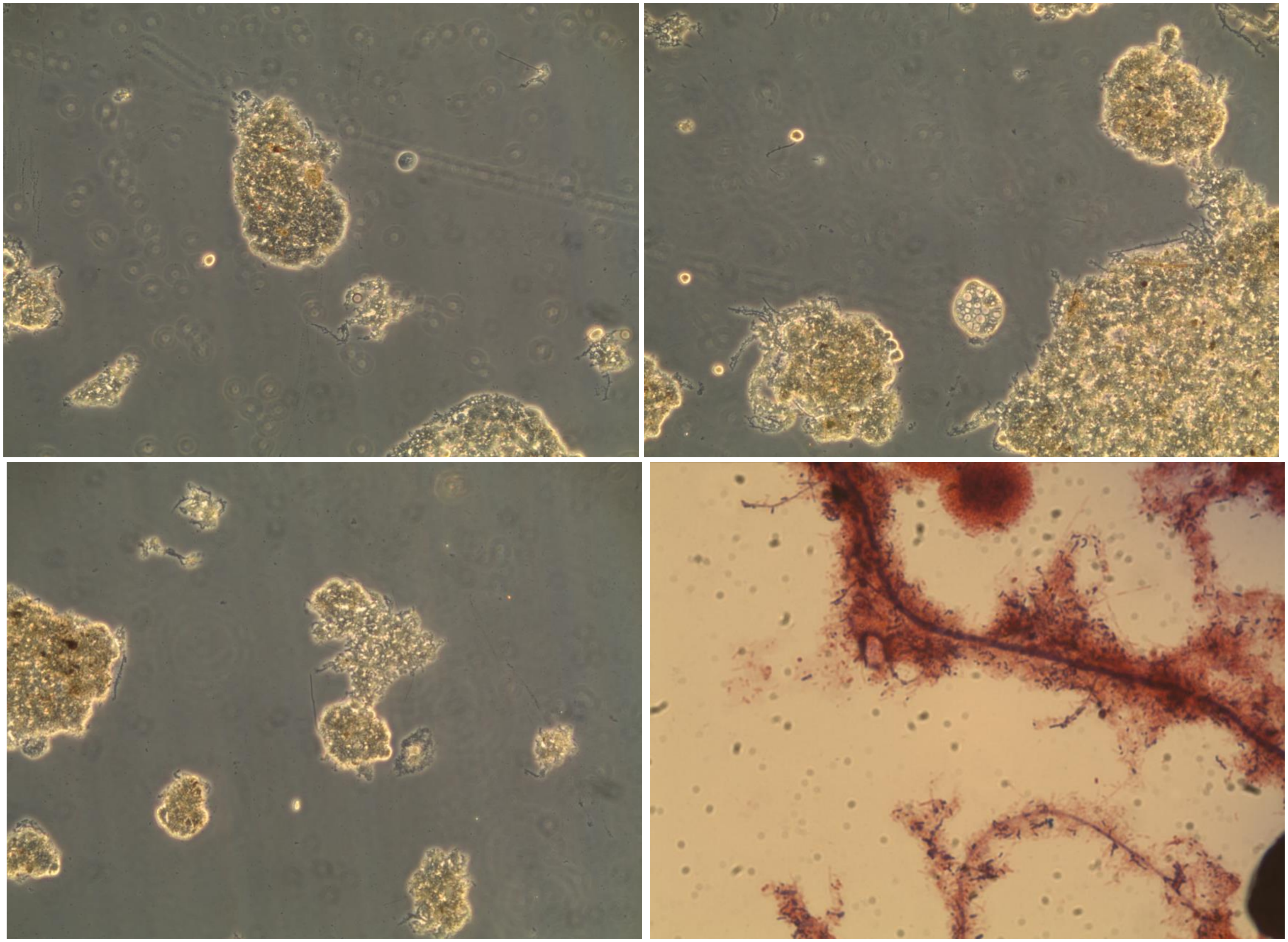
1/3/2014: a) Type 0041 at 100x b) Type 0675 at 100x c) Type 0041, Thiothrix sp. II, rotifer at 100x d) Type 0041, Type 0675 at 1000x gram stain



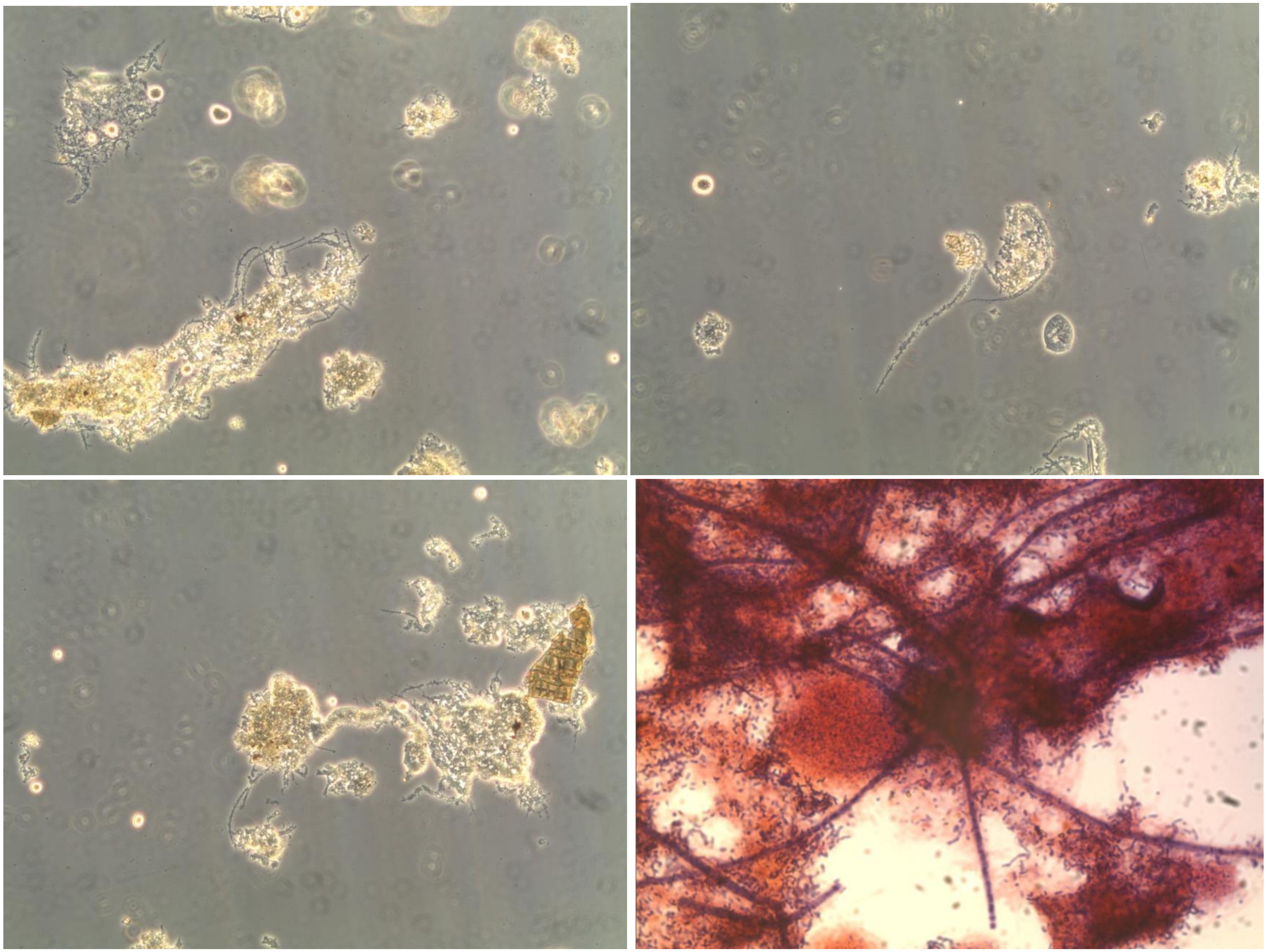
1/8/2014: a) Type 0041 at 100x b) Type 0041, Type 0675 at 100x c) Thiothrix sp. I at 100x d) Type 0041 at 1000x gram stain



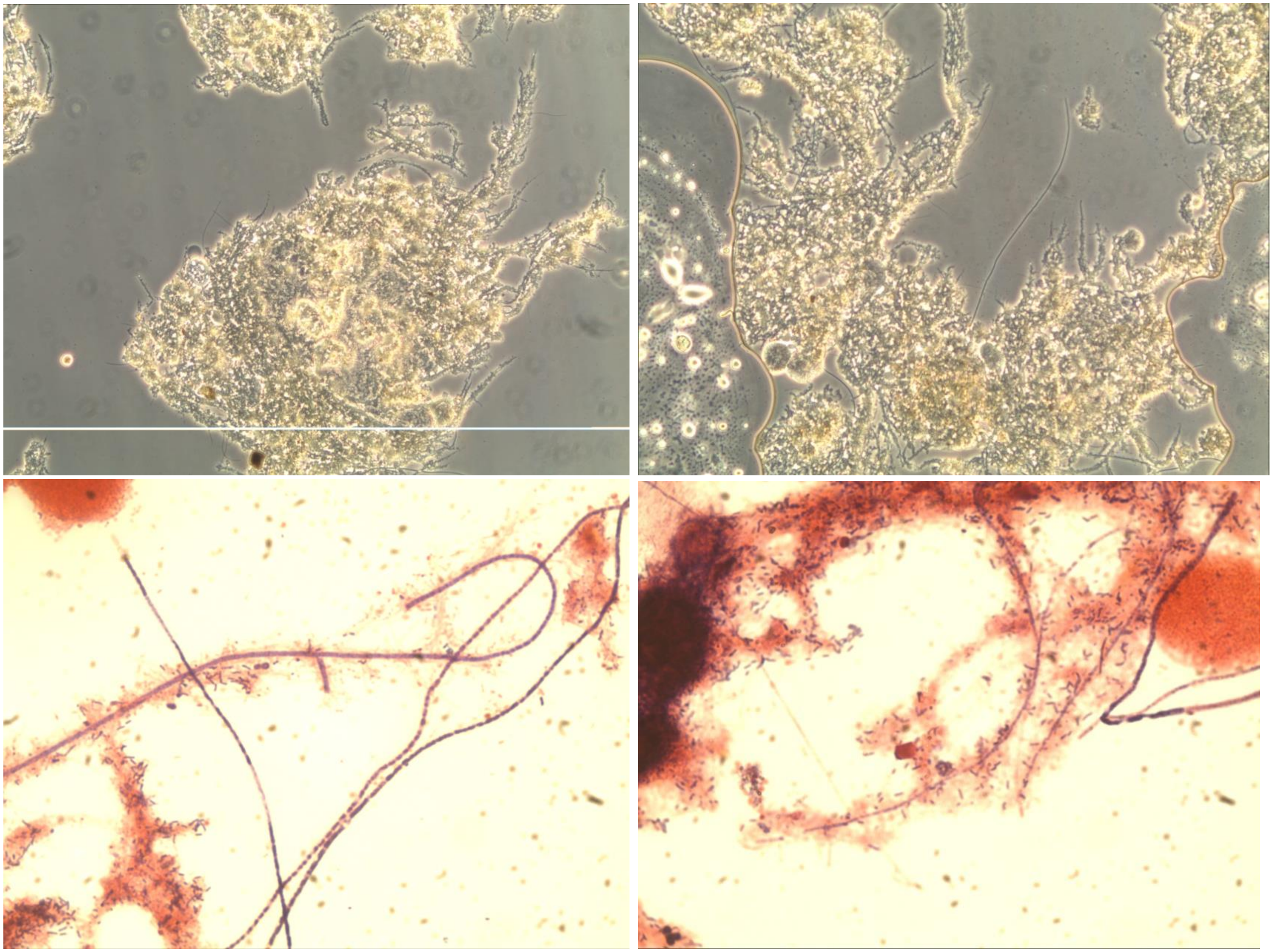
1/15/2014: a) Type 0041 at 100x b) Type 0041, Type 0675 at 100x c) Type 0041, Type 0675 at 1000x gram stain



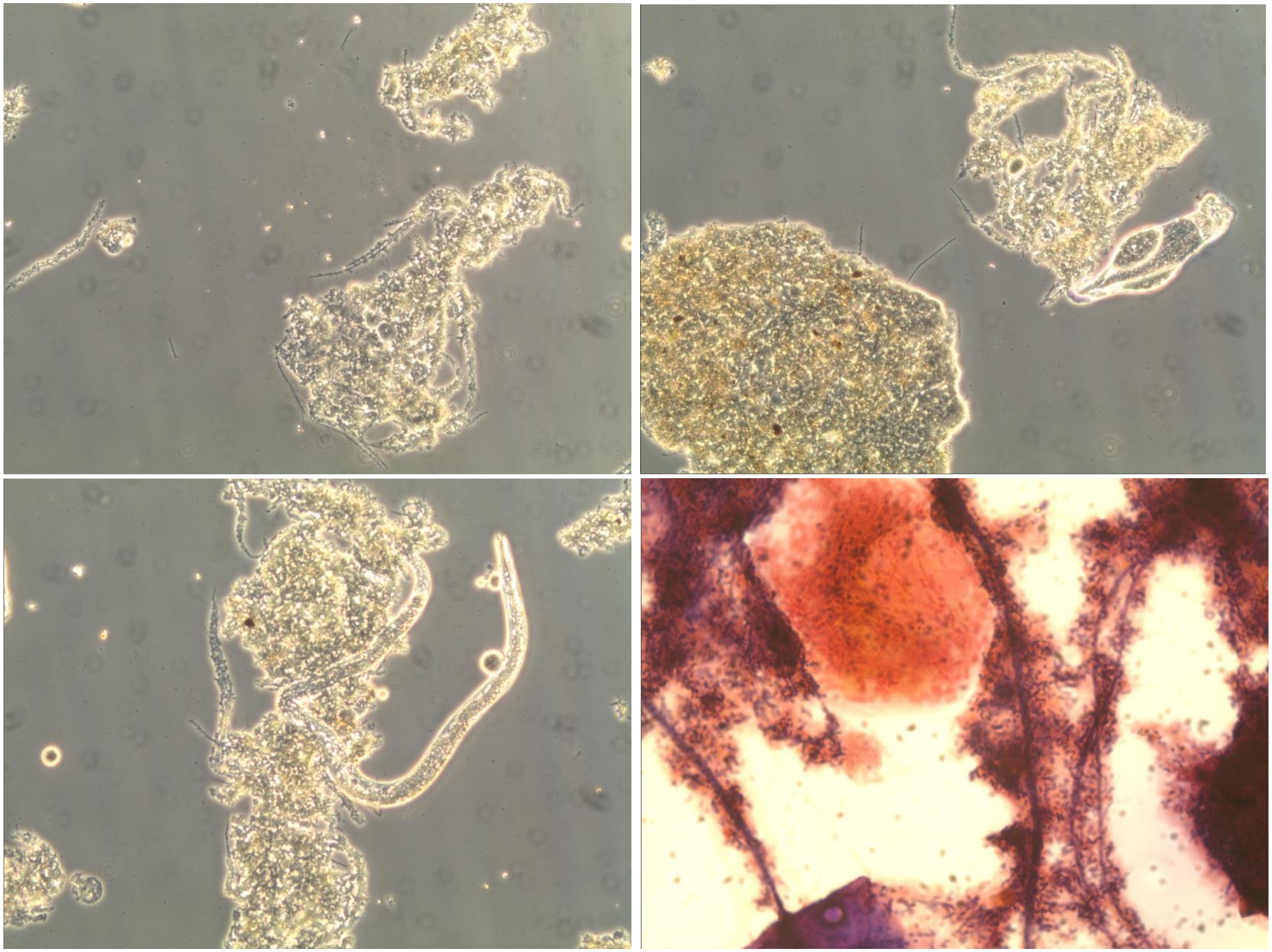
1/22/2014: a) Type 0041 at 100x b) Type 0041, Large floc at 100x c) Thiothrix sp. II at 100x d) Type 0041, Type 0675 at 1000x gram stain



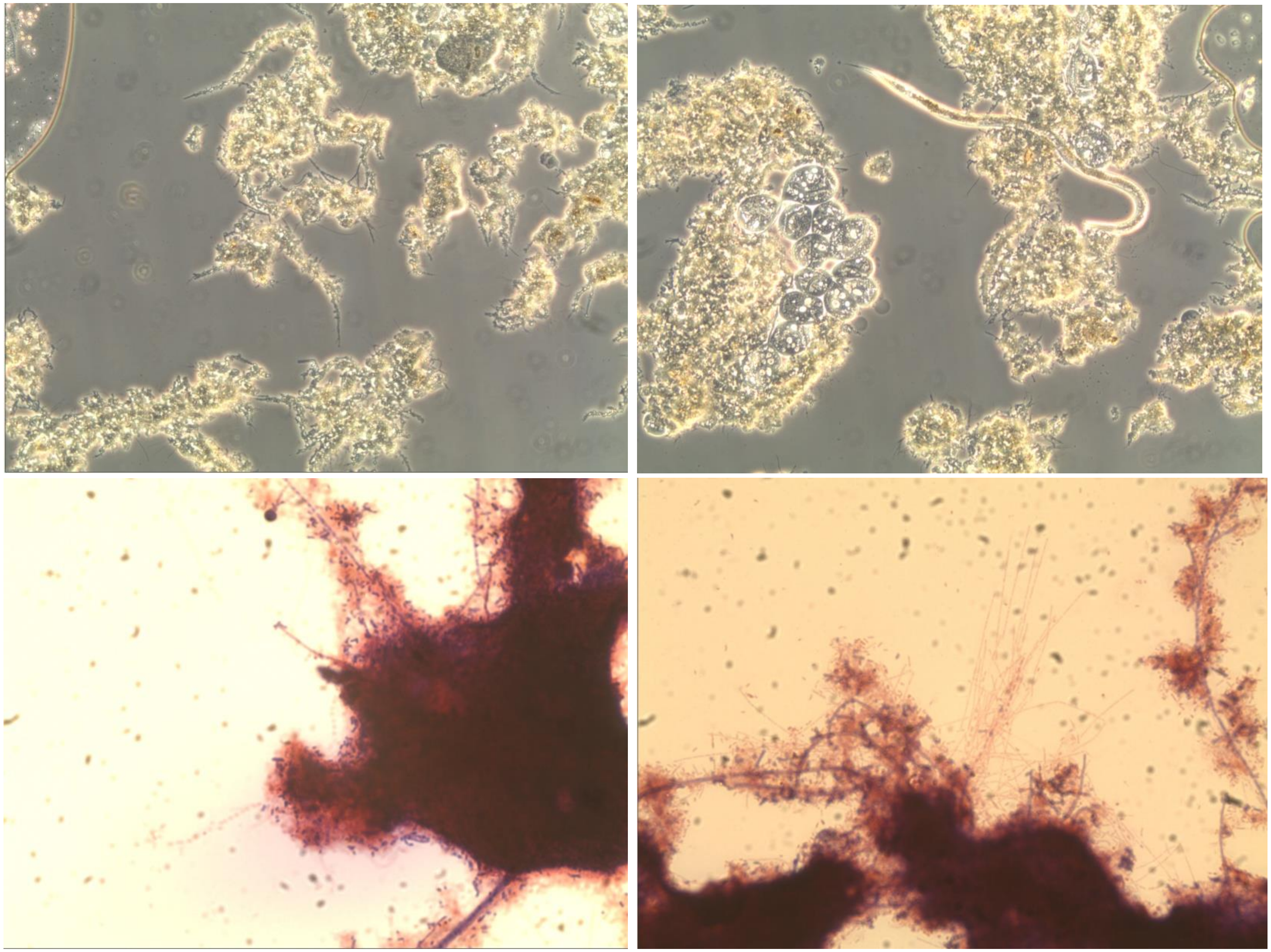
2/5/2014: a) Type 0041 at 100x b) Type 0041, Type 0675 at 100x c) Type 0041, H. hydrossis at 100x d) Type 0041 at 1000x gram stain



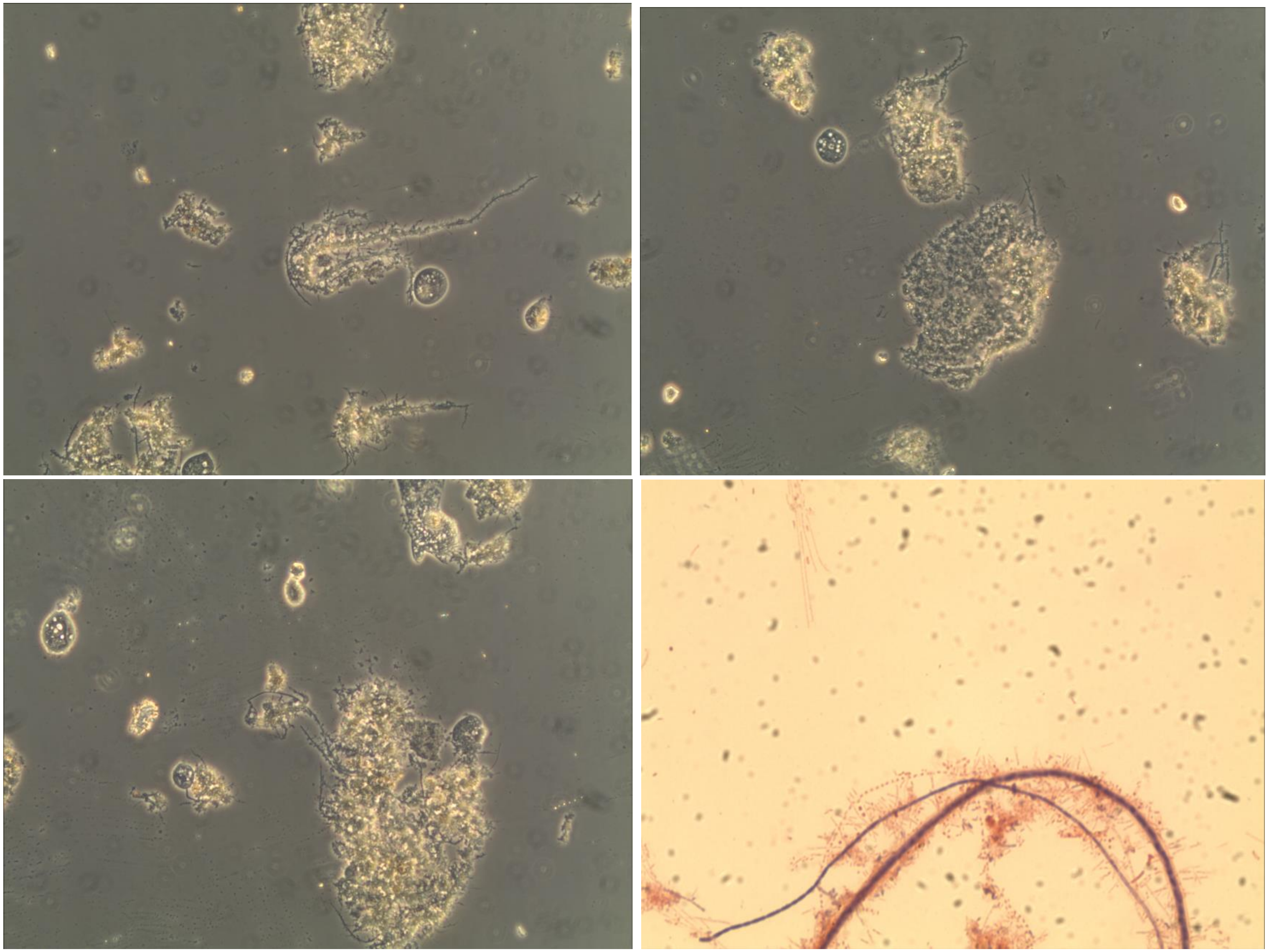
2/12/2014: a) Type 0041, Thiothrix sp. II at 100x b) Thiothrix sp. I, Thiothrix sp. II, Type 0041 at 100x c) Thiothrix sp. I (no growth), Type 0041 (growth) at 1000x gram stain d) Thiothrix sp. I (no growth), Type 0675 (growth) at 1000x gram stain



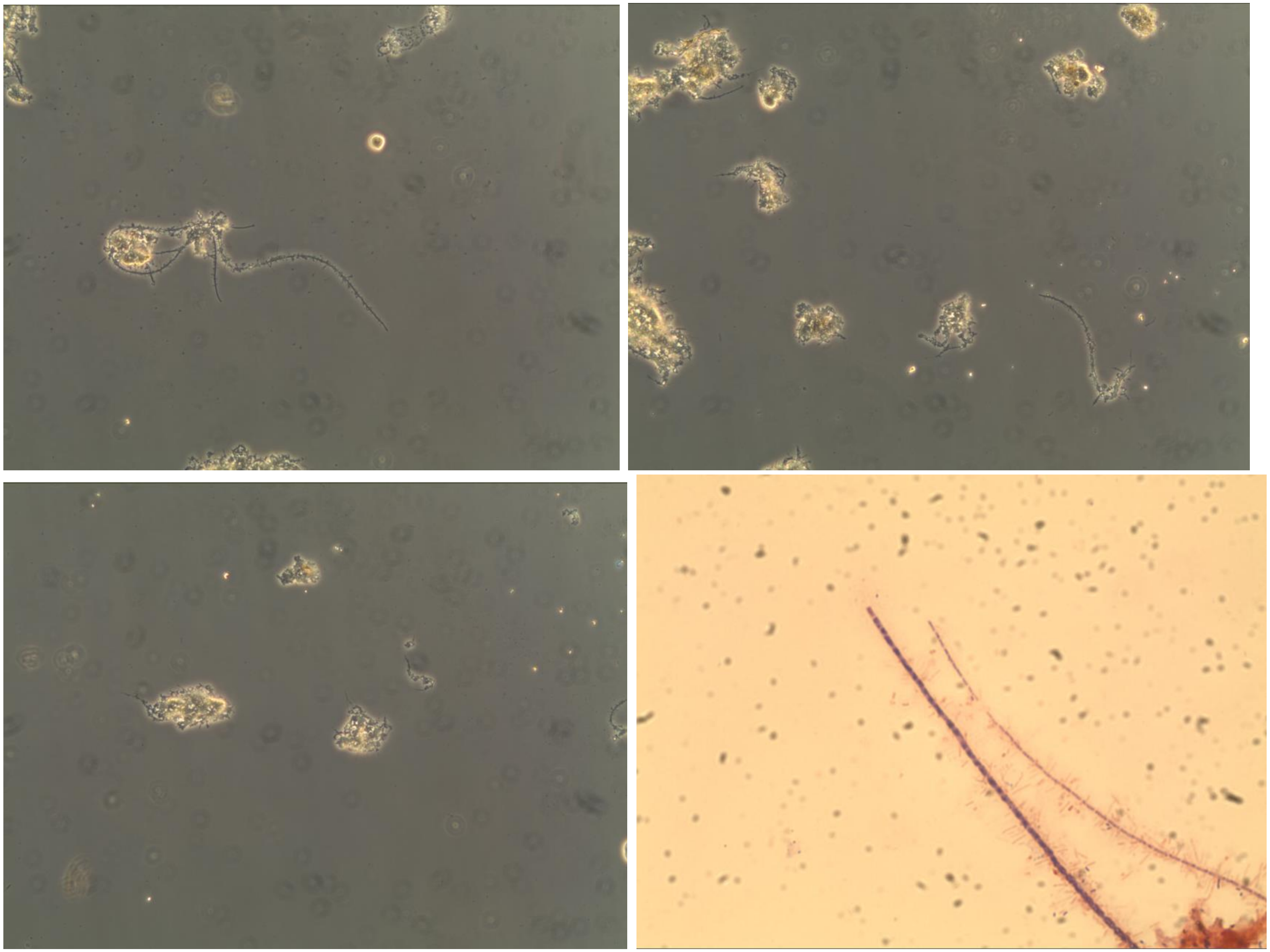
2/19/2014: a) Type 0041, H. hydrossis at 100x b) Thiothrix sp. I, Type 0675, Type 0041, rotifer at 100x c) Nematode, worm at 100x d) Type 0041, Type 0675 at 1000x gram stain



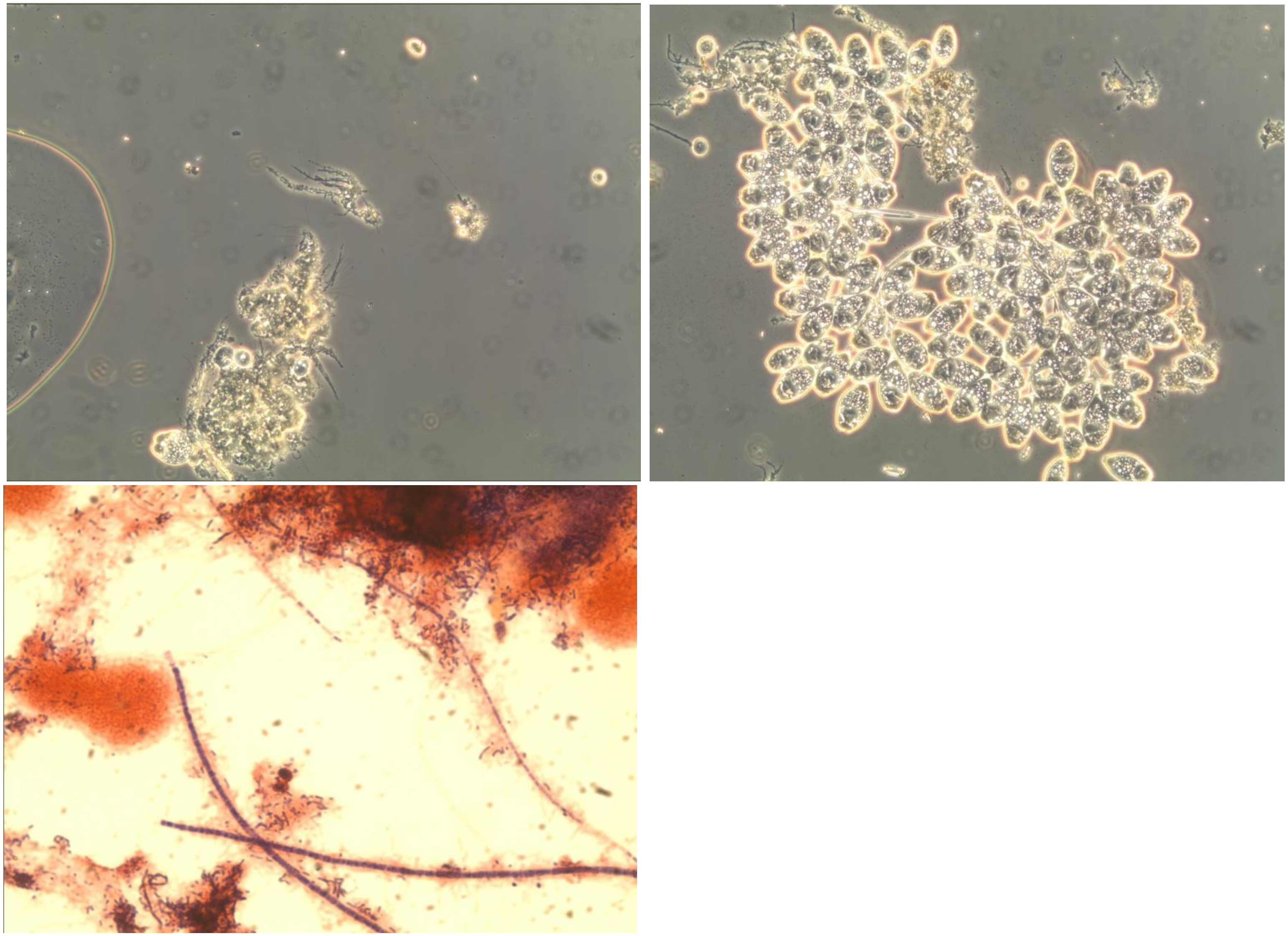
3/5/2014: a) Type 0041, H. hydrossis, Thiothrix sp. II at 100x b) Stalk ciliates, nematode at 100x c) Type 0675 (top), Type 0041 (bottom) at 1000x gram stain d) H. hydrossis at 1000x gram stain



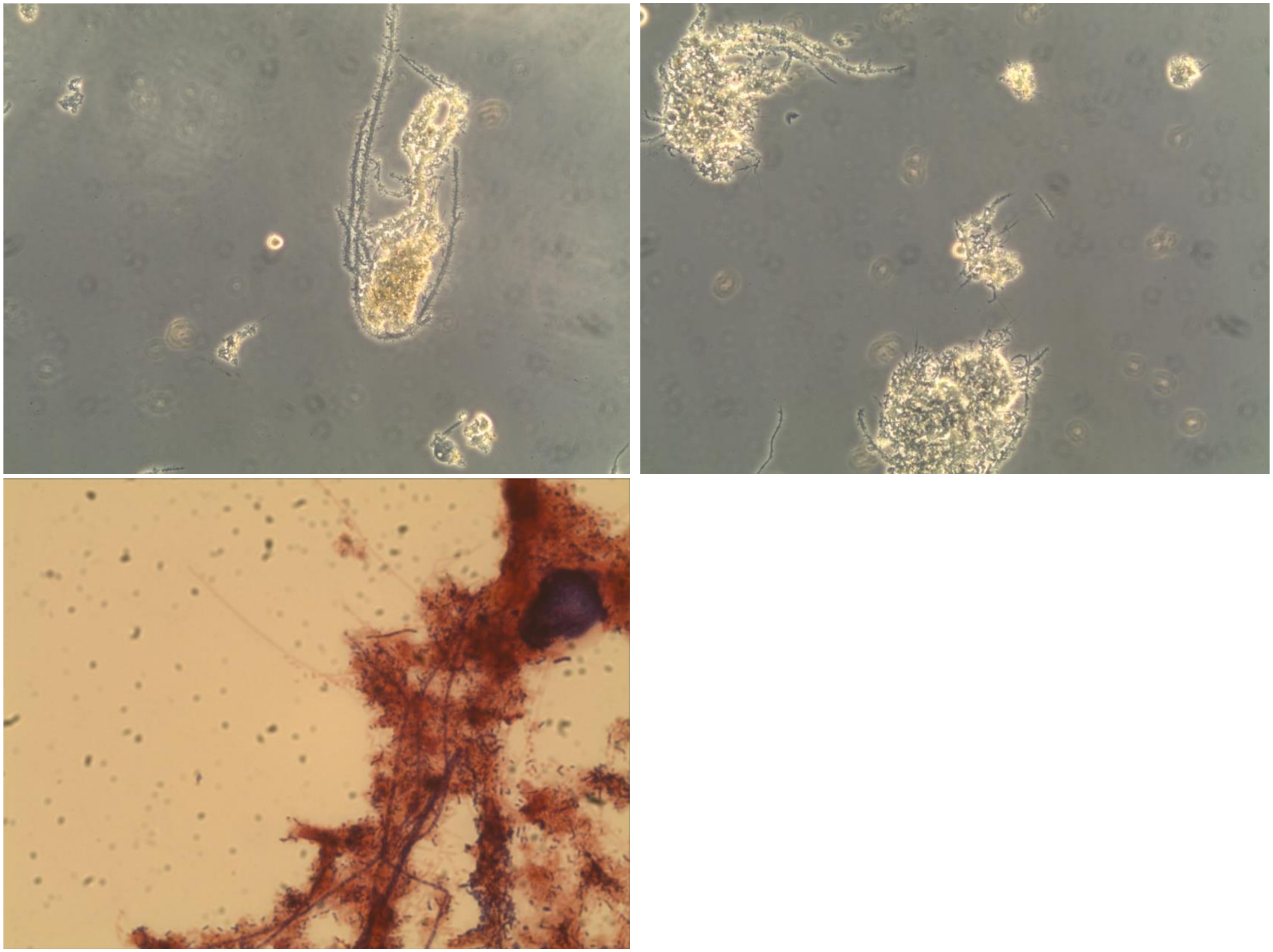
3/12/2014: a) Type 0041 at 100x b) Type 0041, H. hydrossis at 100x c) Type 0041, Type 0675 at 100x d) Type 0041, Type 0675 at 1000x gram stain



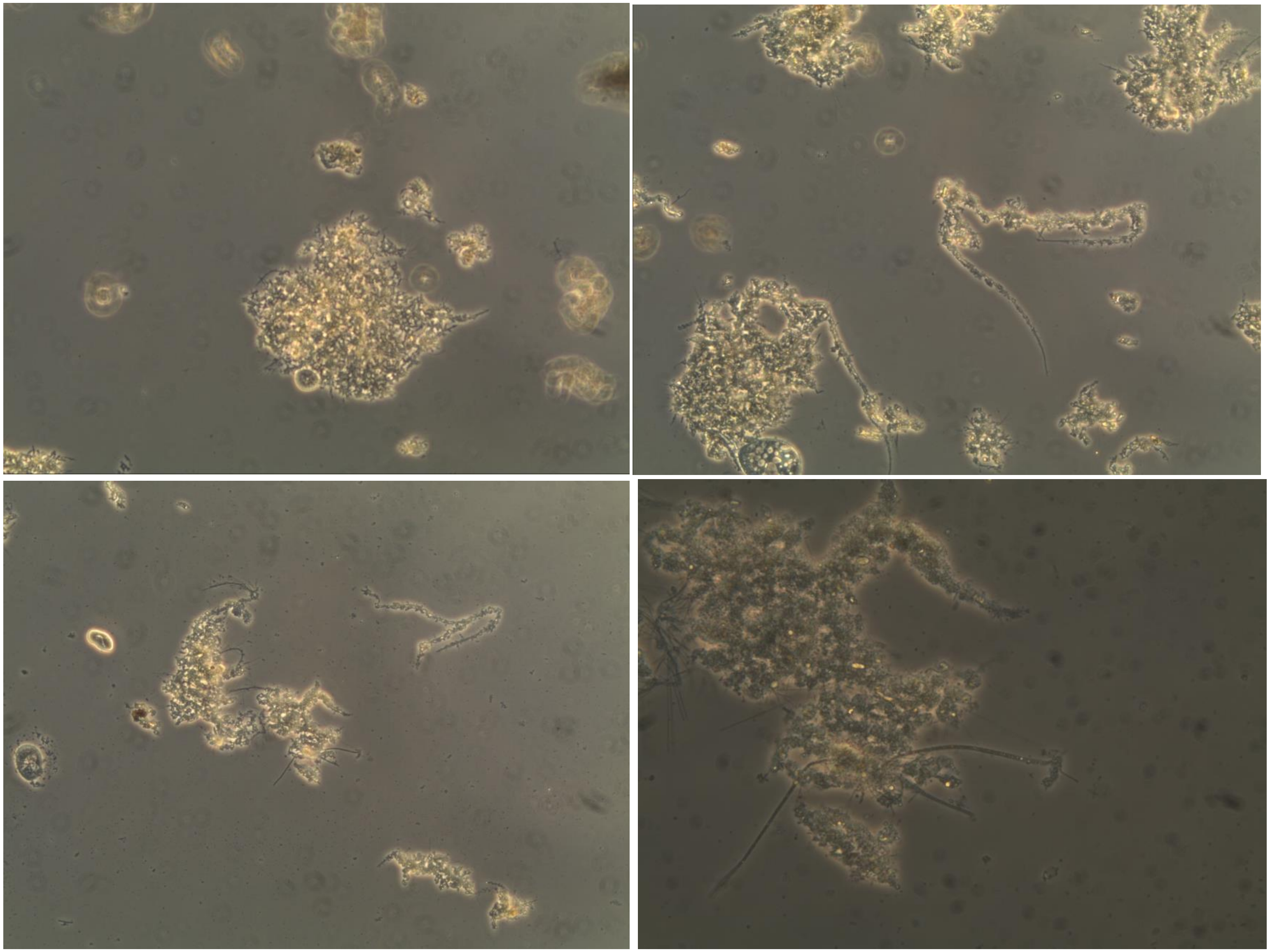
3/19/2014: a) Type 0041 at 100x b) Type 0041, Type 0675 at 100x c) H. hydrossis at 100x d) Type 0041 (thick), Type 0675 (thin) at 1000x gram stain



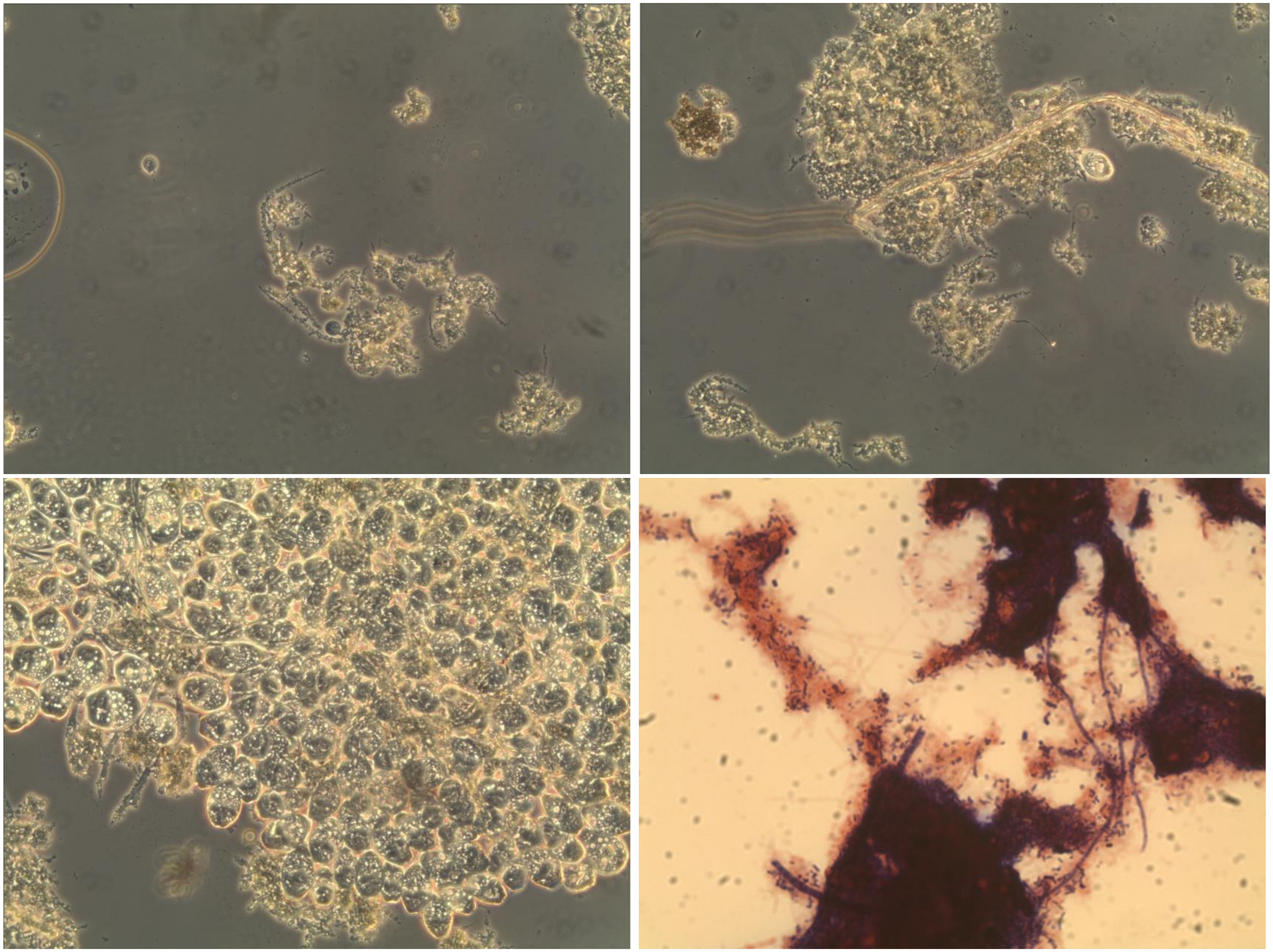
3/26/2014: a) Type 0041, Type 0675, H. hydrossis at 100x b) Stalk ciliate tree at 100x c) Type 0041, Type 0675 at 1000x gram stain



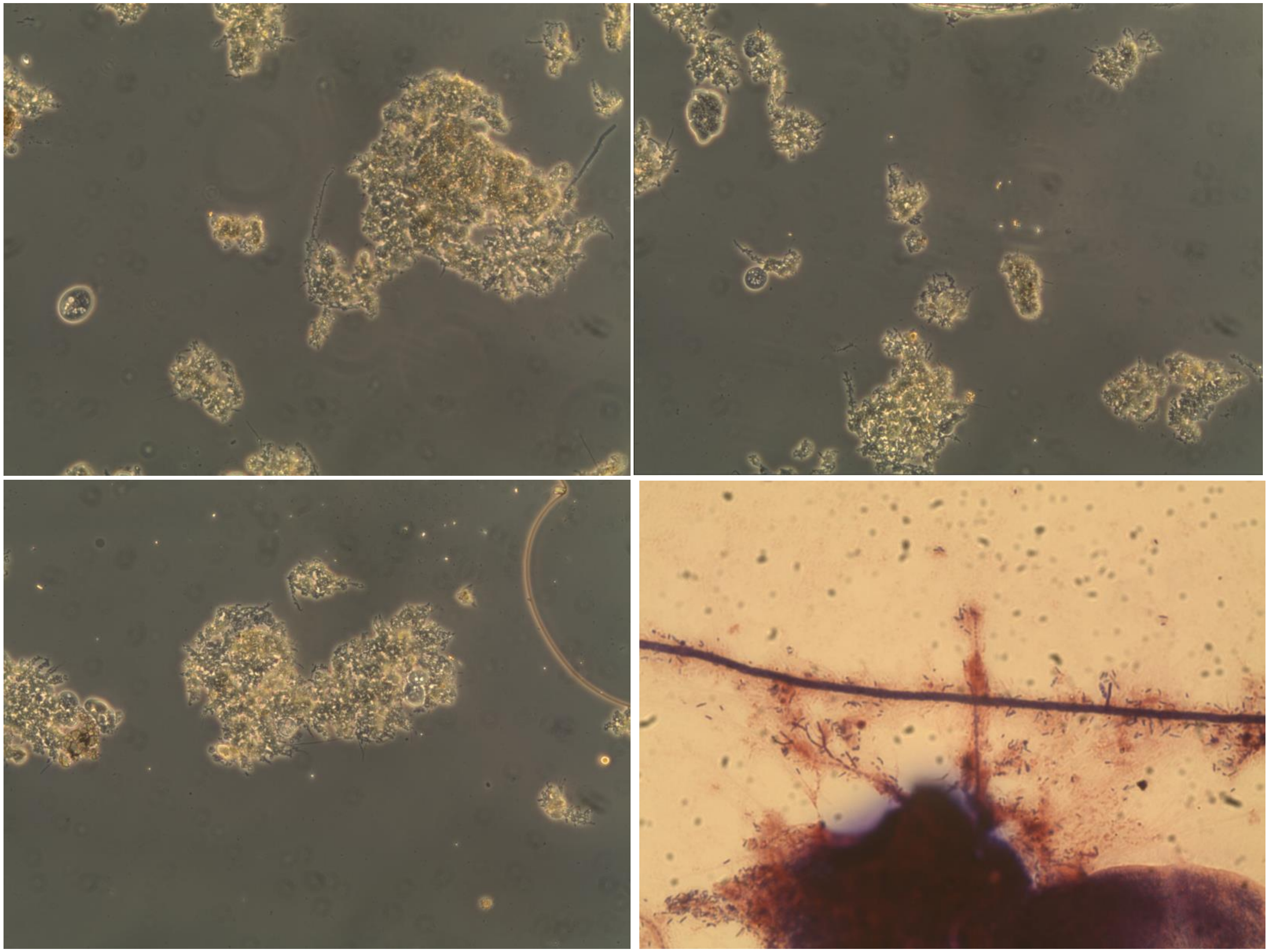
4/2/2014: a) Type 0041, Type 0675 at 100x b) H. hydrossis at 100x c) H. hydrossis, Type 0041, Type 0675 at 1000x gram stain



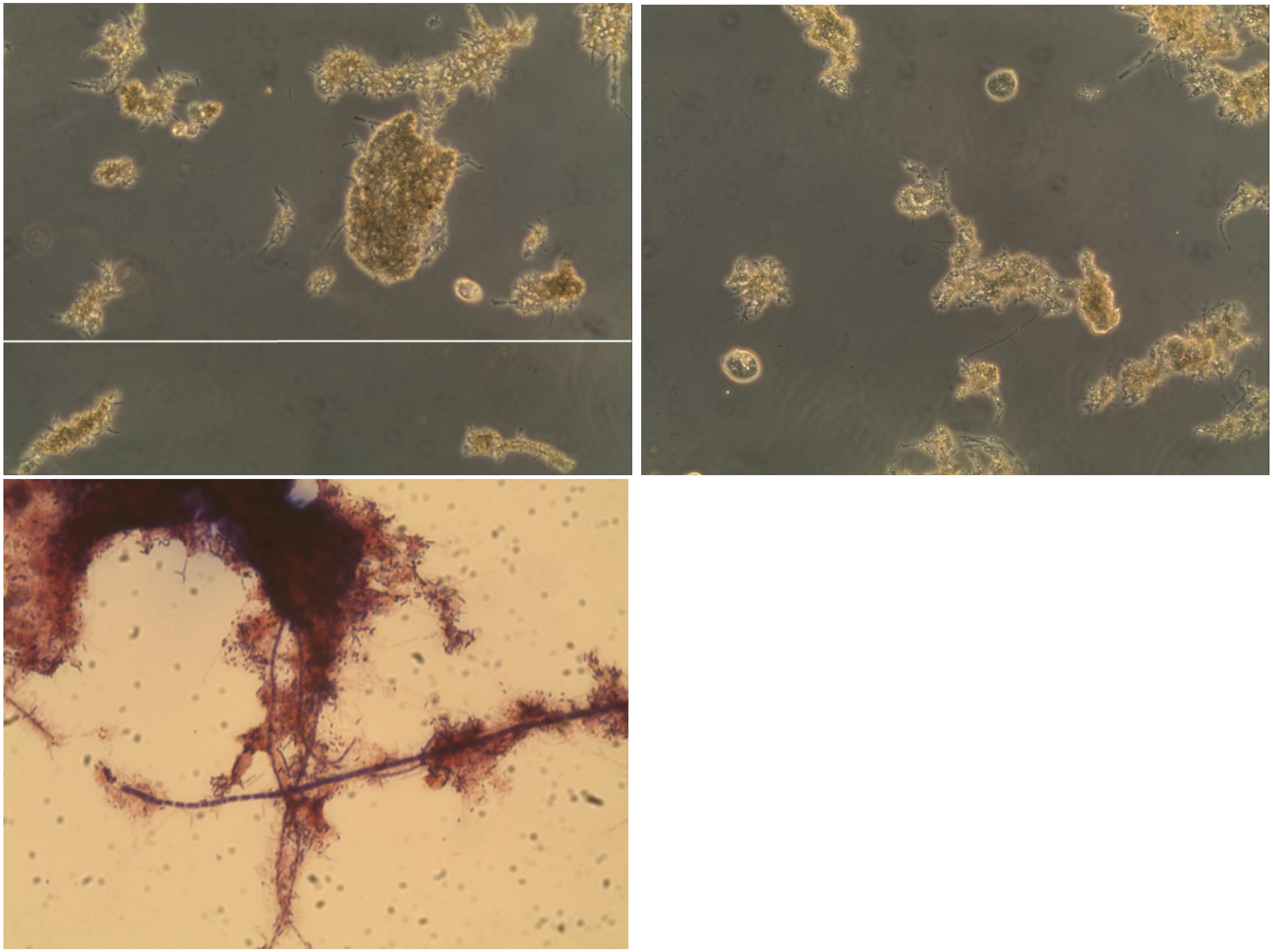
4/9/2014: a) H. hydrossis at 100x b) Type 0041 at 100x c) Thiothrix sp. II at 100x d) Thiothrix II, sulfur granules at 400x



4/16/2014: a) Type 0041, H. hydrossis at 100x b) Type 0675 at 100x c) Very large stalk ciliate tree at 100x d) Type 0041, Type 0675 at 1000x gram stain



4/23/2014: a) Type 0041 at 100x b) H. hydrossis at 100x c) Thiothrix sp. II at 100x d) Type 0041, Type 0675 at 1000x gram stain

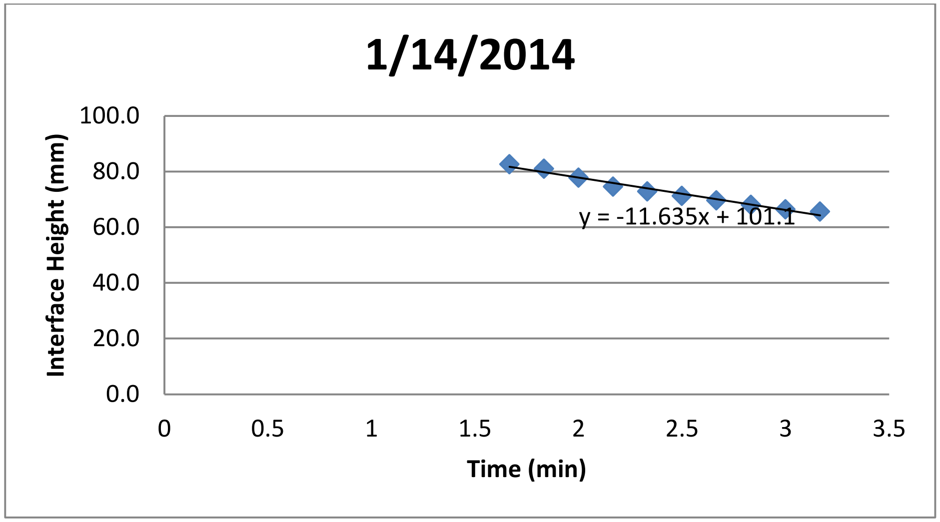


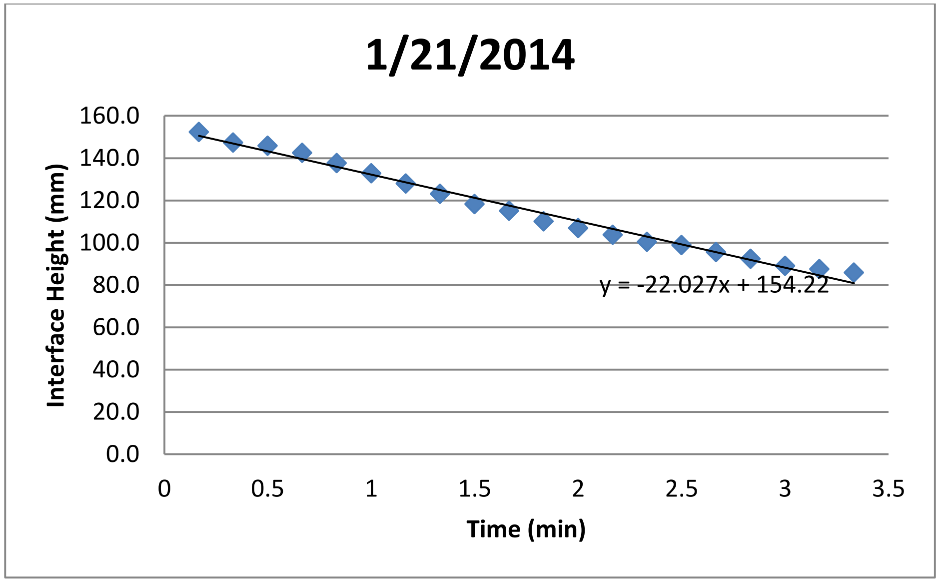
4/30/2014: a) Type 0041, Thiothrix II at 100x b) H. hydrossis, Thiothrix sp. I at 100x c) Type 0041, Type 0675 at 1000x gram stain

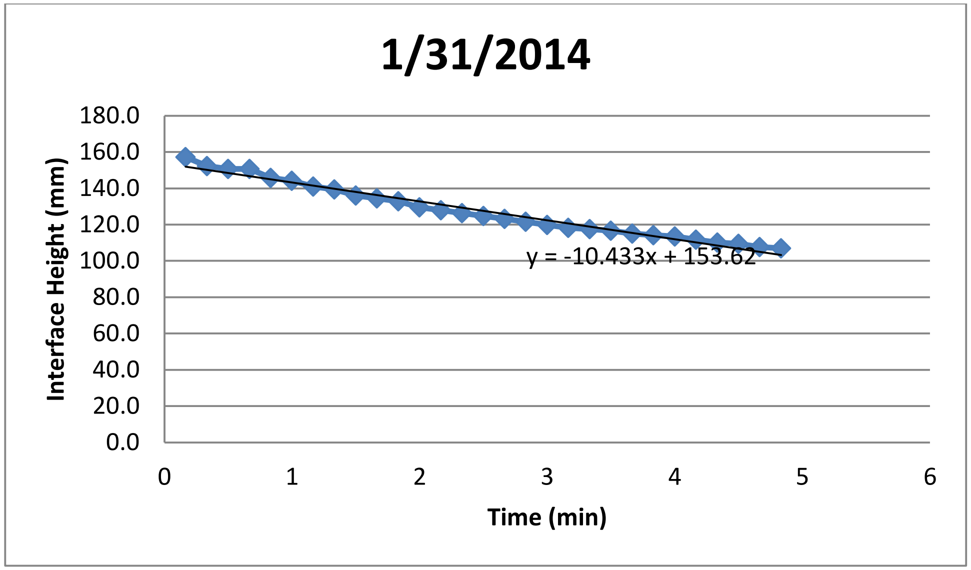
A 8 ISV DATA

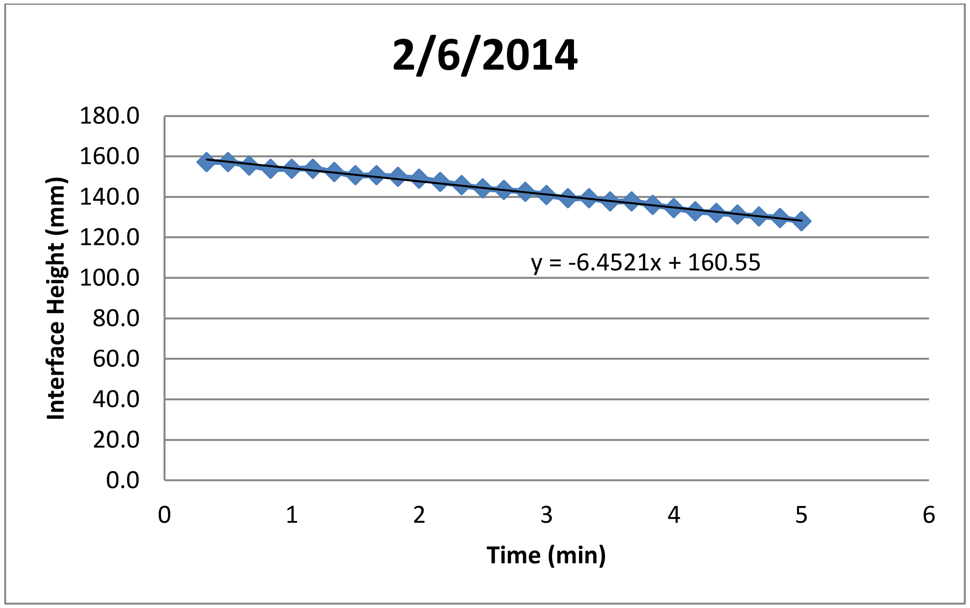
Date	MLSS (mg/L)	SSV5	SSV30	SVI	Slope (mm/min)	ISV (m/hr)	ISV (m/min)	ISV (gal/ft2-day)
1/14/2014	2290	340	210	91.70306	11.635	0.13962	0.002327	82.21747092
1/21/2014	3615	480	280	77.45505	22.027	0.264324	0.0044054	155.6514166
1/31/2014	3490	650	330	94.55587	10.433	0.125196	0.0020866	73.72366774
2/6/2014	3100	790	360	116.129	6.4521	0.0774252	0.00129042	45.59306782
2/7/2014	3045	800	380	124.7947	6.3099	0.0757188	0.00126198	44.58822688
2/11/2014	2565	800	490	191.0331	6.4616	0.0775392	0.00129232	45.66019855
2/12/2014	2440	850	510	209.0164	4.8514	0.0582168	0.00097028	34.28189415
2/13/2014	2810	730	340	120.9964	8.708	0.104496	0.0017416	61.53414154
2/17/2014	3320	810	420	126.506	6.4135	0.076962	0.0012827	45.32030509
2/19/2014	3415	750	410	120.0586	7.5554	0.0906648	0.00151108	53.38941812
2/21/2014	3620	850	440	121.547	4.9398	0.0592776	0.00098796	34.9065632
2/24/2014	3360	800	410	122.0238	6.7088	0.0805056	0.00134176	47.40701065
2/25/2014	3430	780	400	116.6181	6.0523	0.0726276	0.00121046	42.7679243
2/27/2014	3995	860	520	130.1627	4.8174	0.0578088	0.00096348	34.04163682
3/7/2014	3460	875	520	150.289	4.0383	0.0484596	0.00080766	28.53621081
3/11/2014	2260	605	300	132.7434	13.329	0.159948	0.0026658	94.18793897
3/13/2014	1855	510	250	134.7709	21.169	0.254028	0.0042338	149.5884522
3/18/2014	1415	335	150	106.0071	36.274	0.435288	0.0072548	256.3263034
3/21/2014	1255	320	150	119.5219	36.379	0.436548	0.0072758	257.0682746
3/26/2014	1545	335	160	103.5599	34.541	0.414492	0.0069082	244.0802461
3/31/2014	1305	370	175	134.0996	32.458	0.389496	0.0064916	229.3609515
4/2/2014	2830	865	500	176.6784	3.3935	0.040722	0.0006787	23.97980125
4/7/2014	2120	575	280	132.0755	14.763	0.177156	0.0029526	104.3211451
4/11/2014	2500	785	370	148	7.093	0.425560845	0.007092681	250.5983128
4/14/2014	2925	770	390	133.3333	6.7575	0.08109	0.0013515	47.75114394
4/18/2014	2610	625	315	120.6897	10.89	0.13068	0.002178	76.95300888
4/21/2014	2710	500	270	99.631	14.972	0.179664	0.0029944	105.798021
4/25/2014	3225	575	300	93.02326	9.867	0.118404	0.0019734	69.72408986

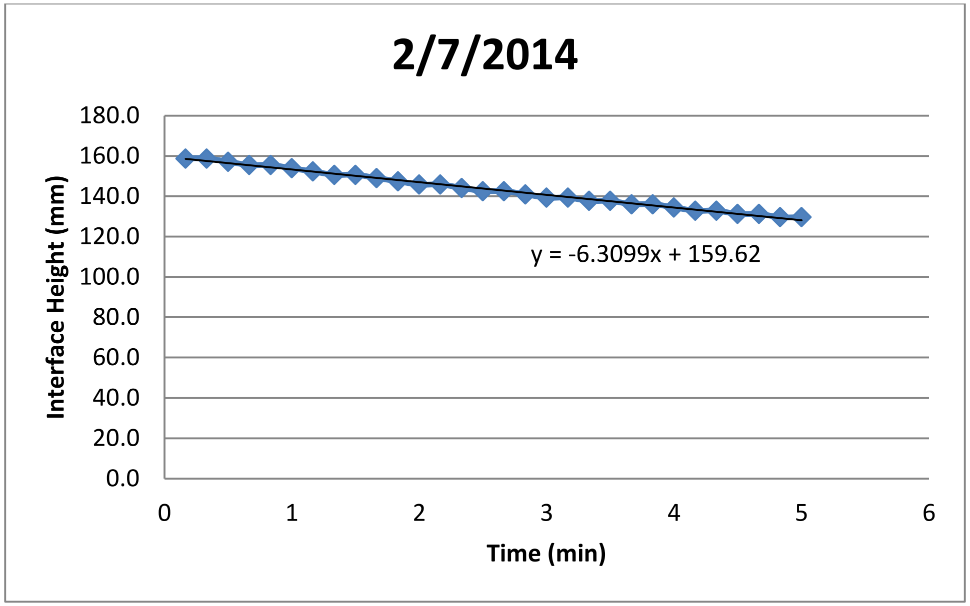
ISV Plots

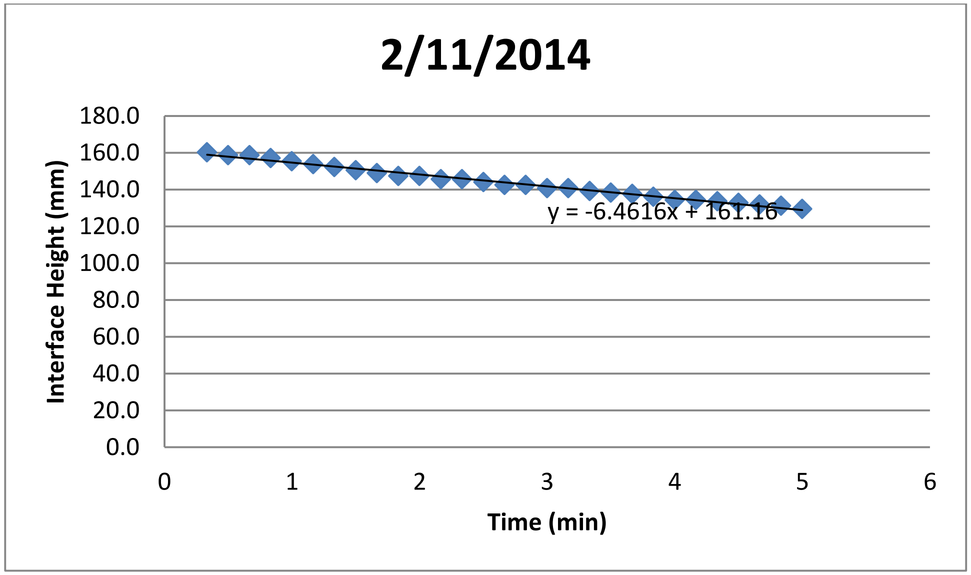

1/14/2014
Interface Height (mm)
100.0
80.0
60.0
40.0
20.0
0.0
y = -11.635x + 101.1
0
0.5
1
1.5
2
2.5
3
3.5
Time (min)

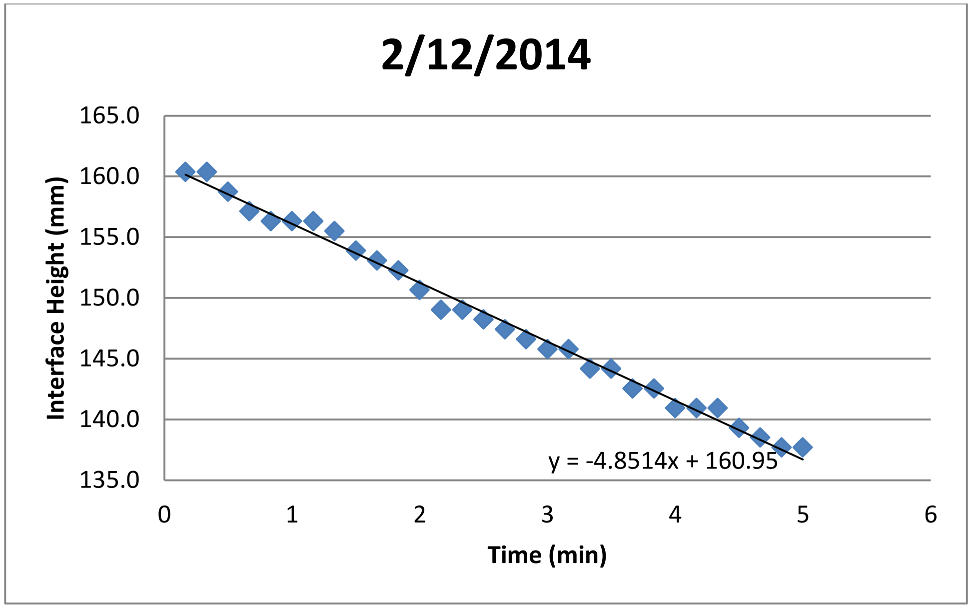

1/21/2014
Interface Height (mm)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
y = -22.027x + 154.22
0
0.5
1
1.5
2
2.5
3
3.5
Time (min)

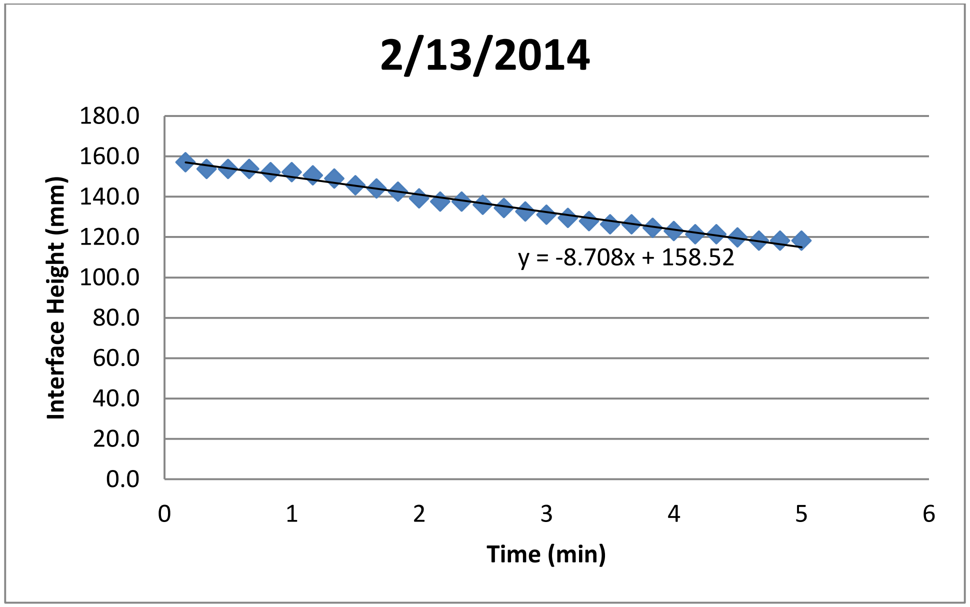

1/31/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -10.433x + 153.62

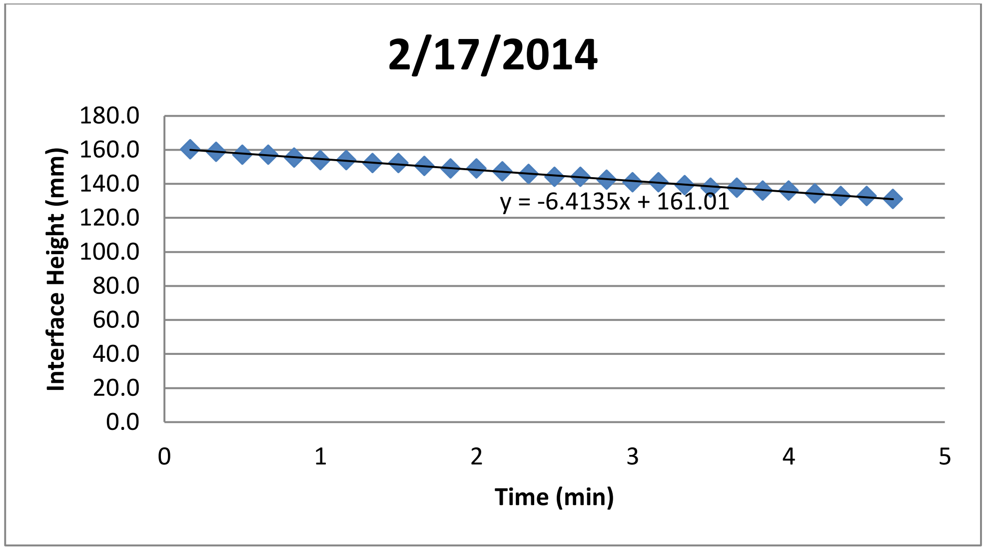

2/6/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -6.4521x + 160.55

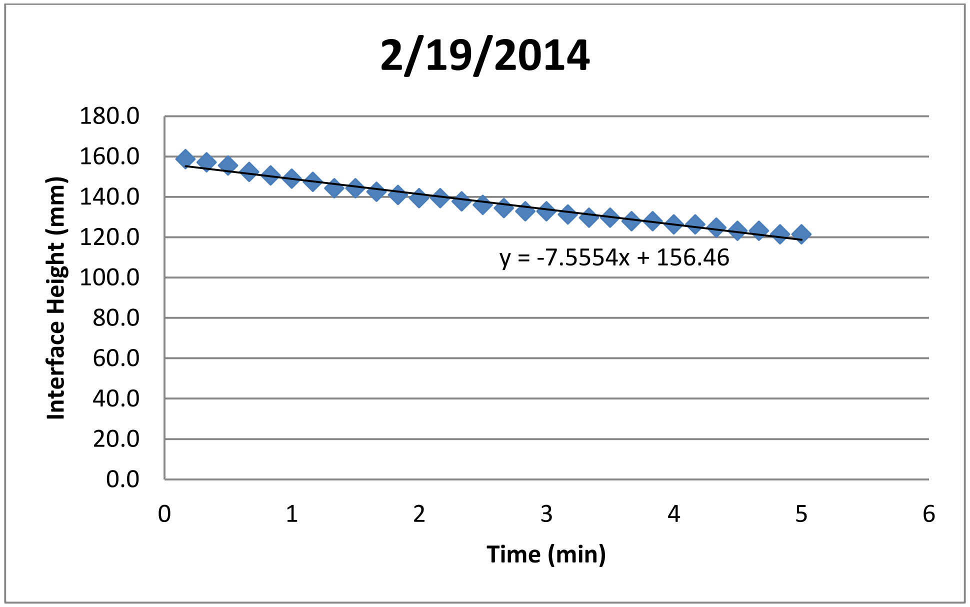

2/7/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -6.3099x + 159.62

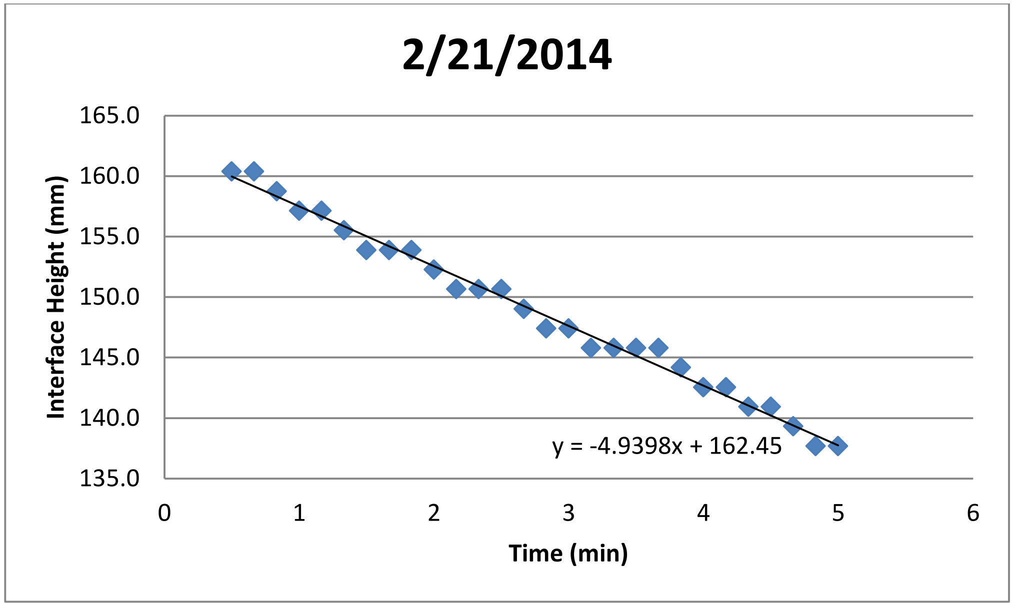

2/11/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -6.4616x + 161.16

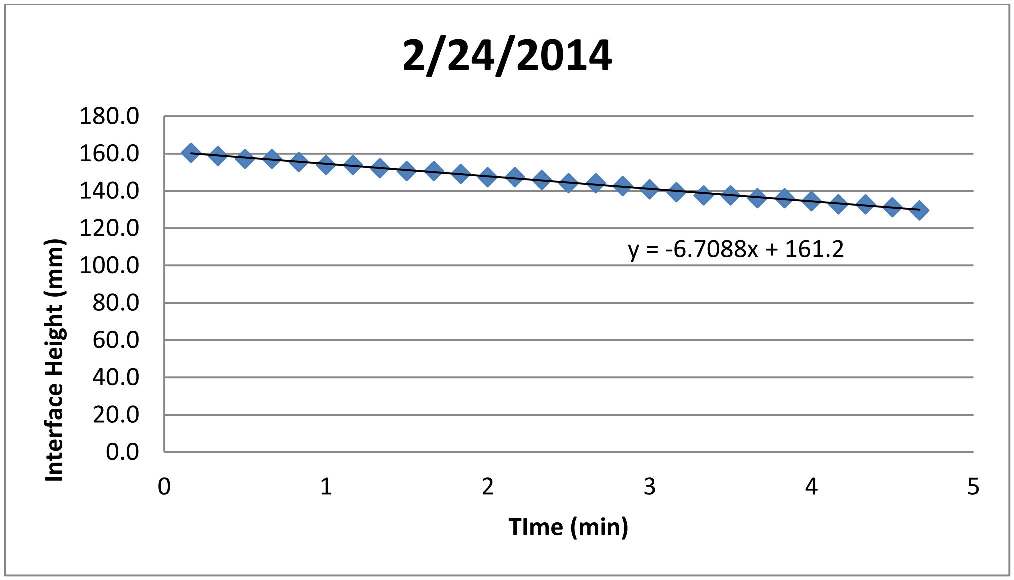

2/12/2014
Interface Height (mm)
165.0
160.0
155.0
150.0
145.0
140.0
135.0
0
1
2
3
4
5
6
Time (min)
y = -4.8514x + 160.95

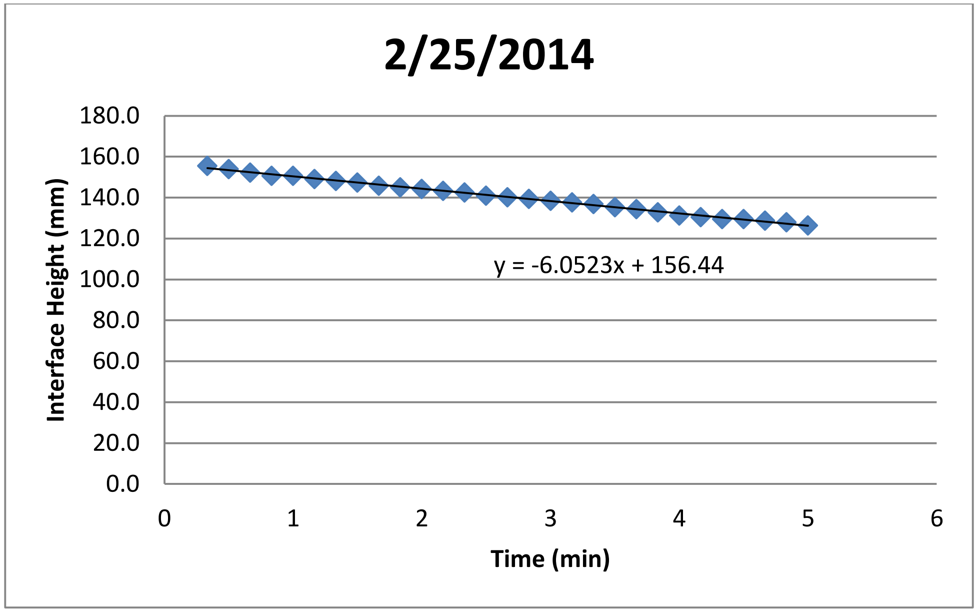

2/13/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -8.708x + 158.52

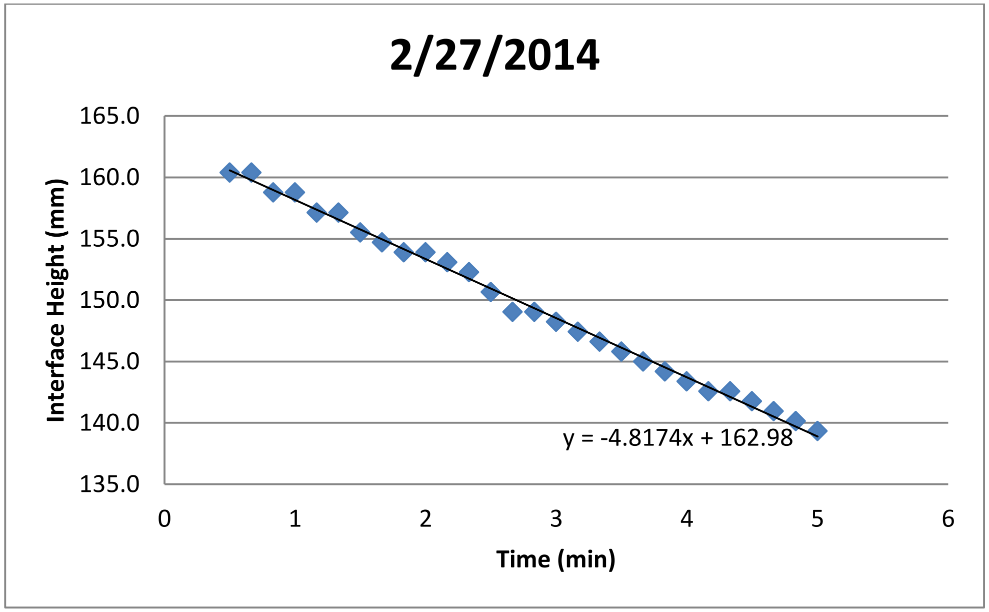

2/17/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
Time (min)
y = -6.4135x + 161.01

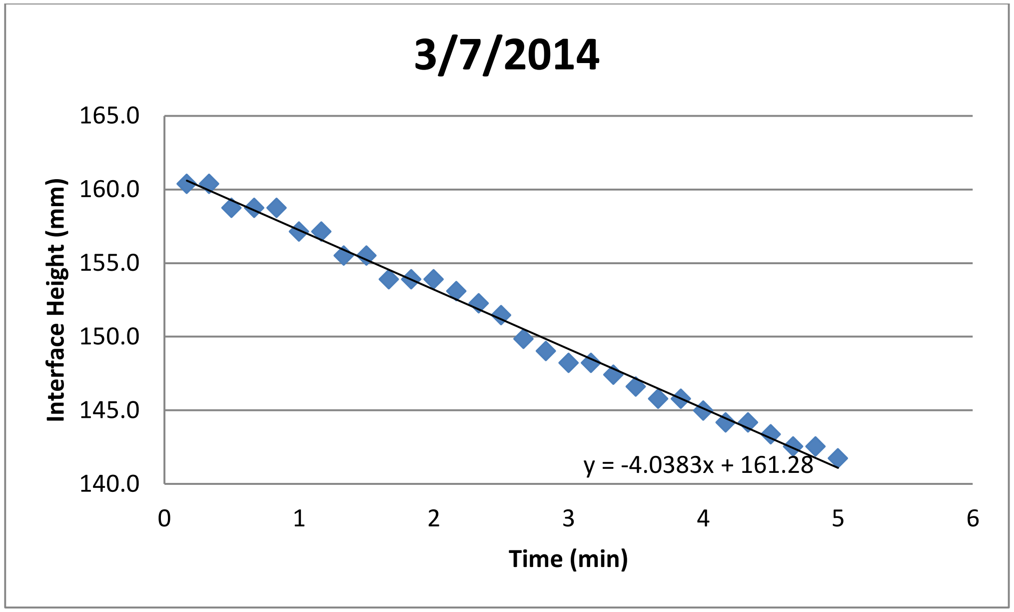

2/19/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -7.5554x + 156.46

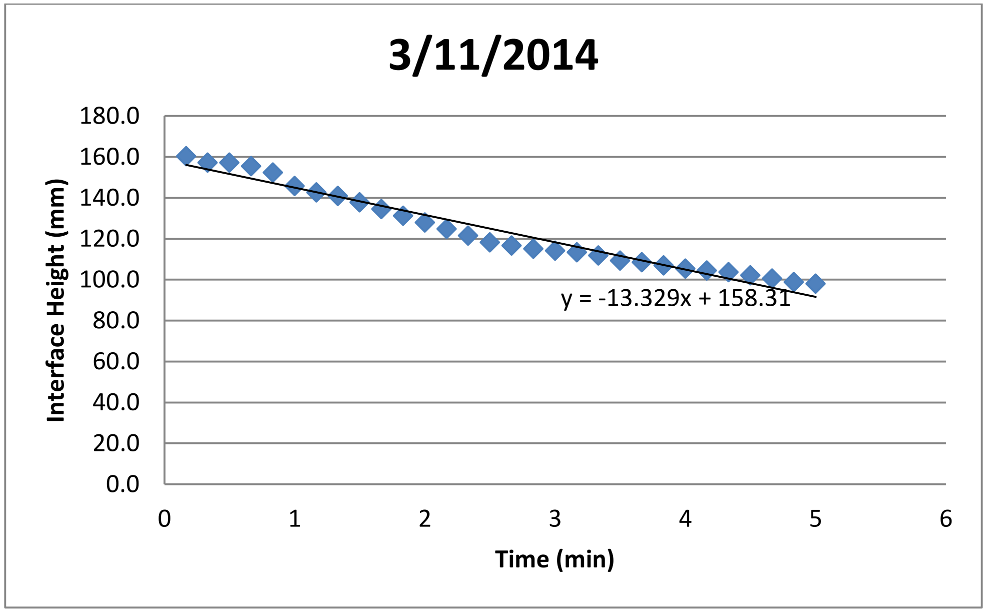

2/21/2014
Interface Height (mm)
165.0
160.0
155.0
150.0
145.0
140.0
135.0
0
1
2
3
4
5
6
Time (min)
y = -4.9398x + 162.45

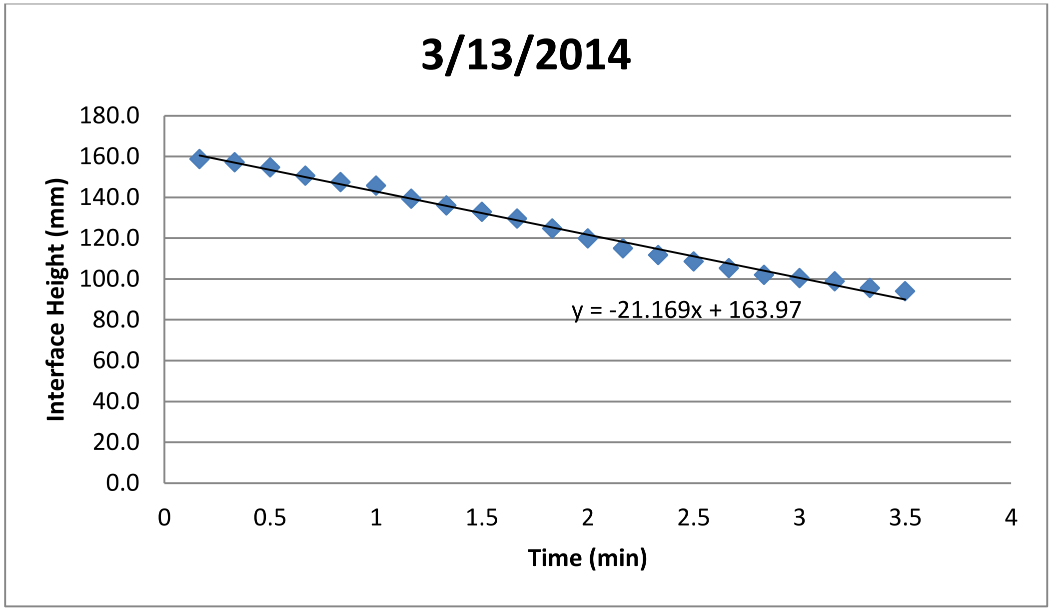

2/24/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
TIme (min)
y = -6.7088x + 161.2

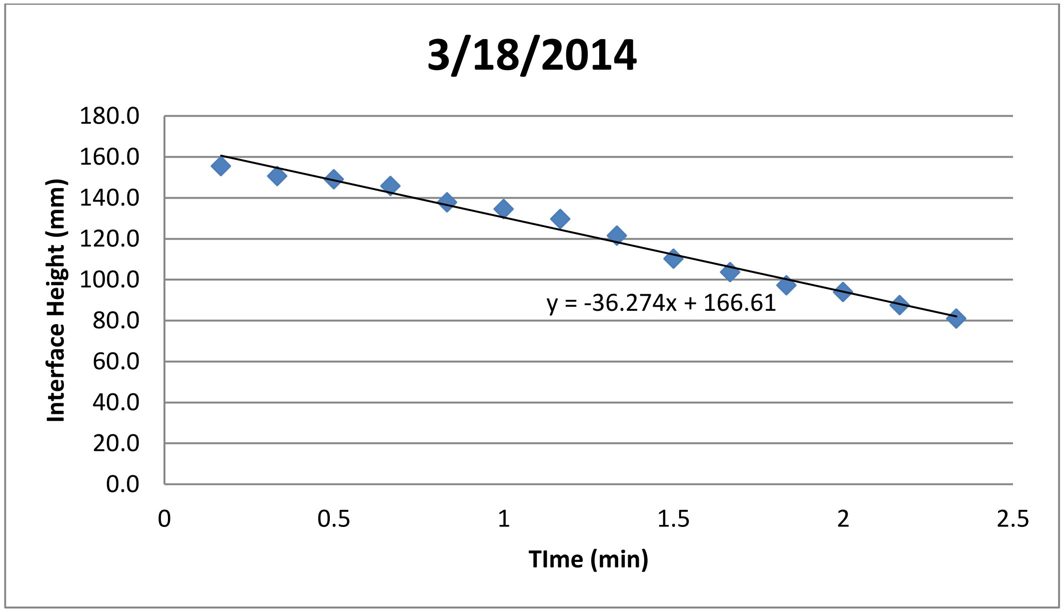

2/25/2014
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Interface Height (mm)
y = -6.0523x + 156.44
0
1
2
3
4
5
6
Time (min)

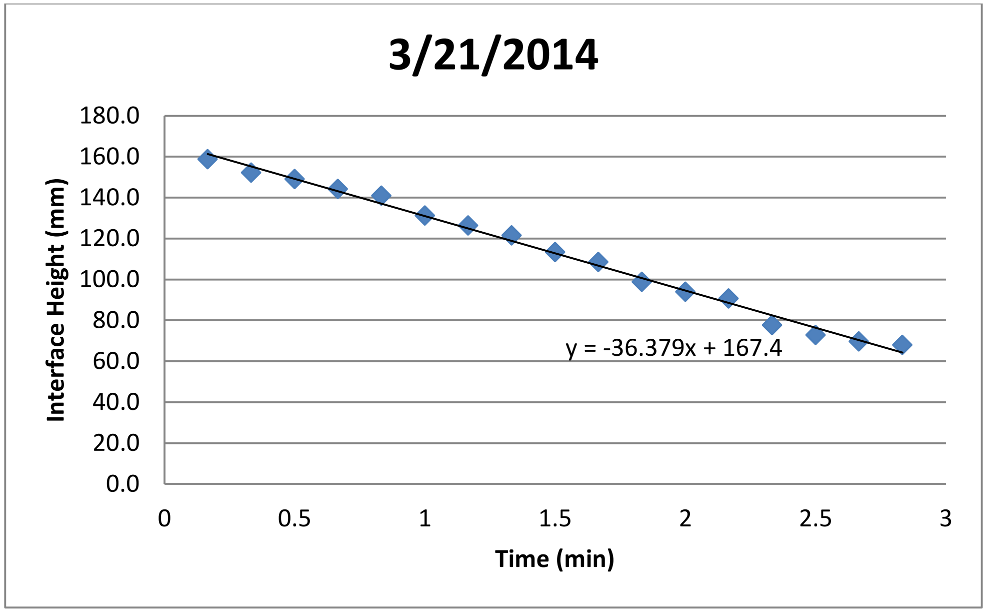

2/27/2014
165.0
160.0
155.0
150.0
145.0
140.0
135.0
Interface Height (mm)
y = -4.8174x + 162.98
0
1
2
3
4
5
6
Time (min)

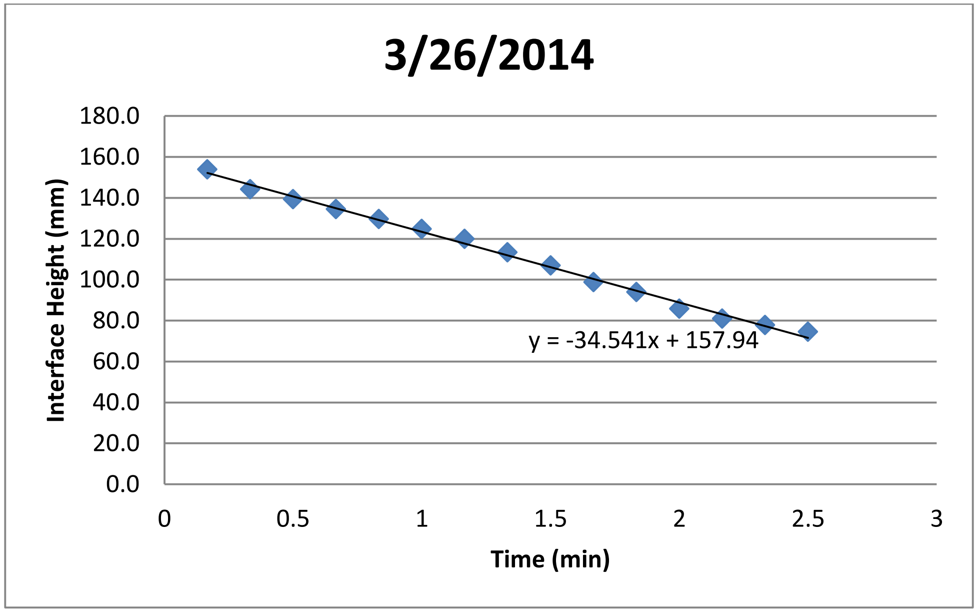

3/7/2014
Interface Height (mm)
165.0
160.0
155.0
150.0
145.0
140.0
0
1
2
3
4
5
6
Time (min)
y = -4.0383x + 161.28

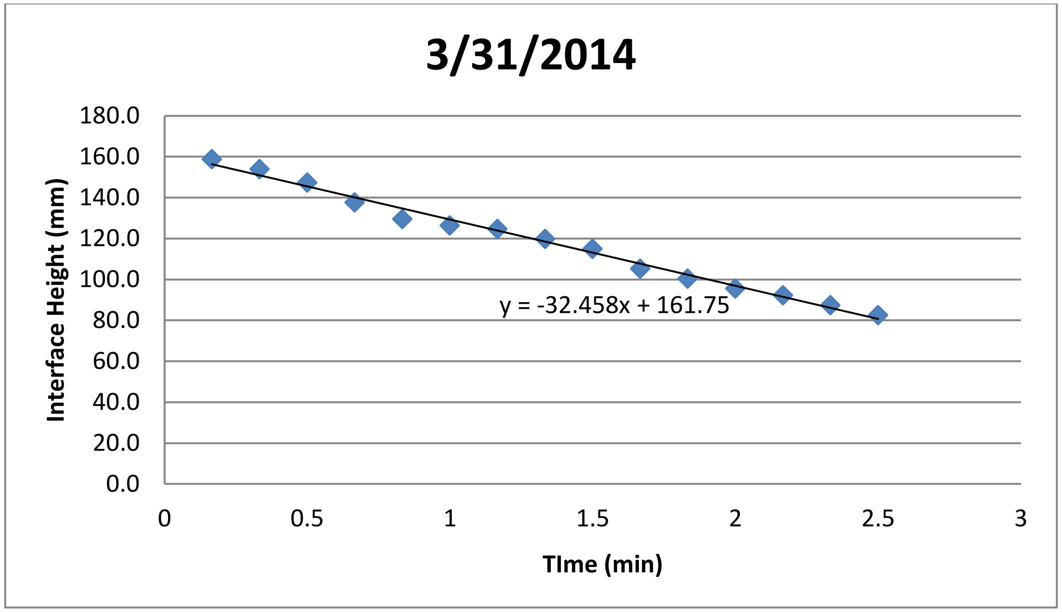

3/11/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -13.329x + 158.31

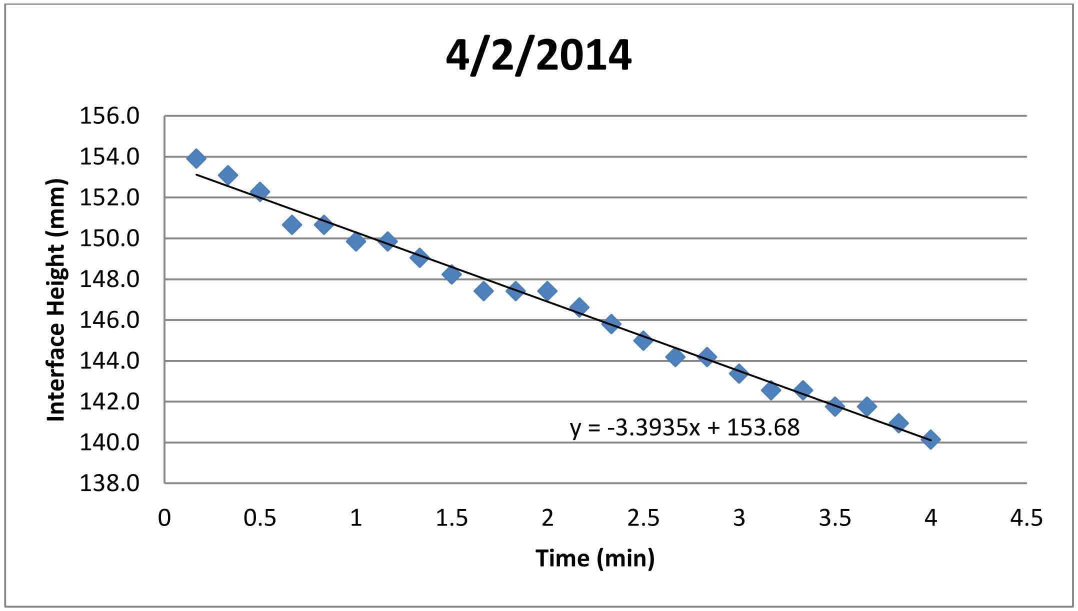

3/13/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (min)
y = -21.169x + 163.97

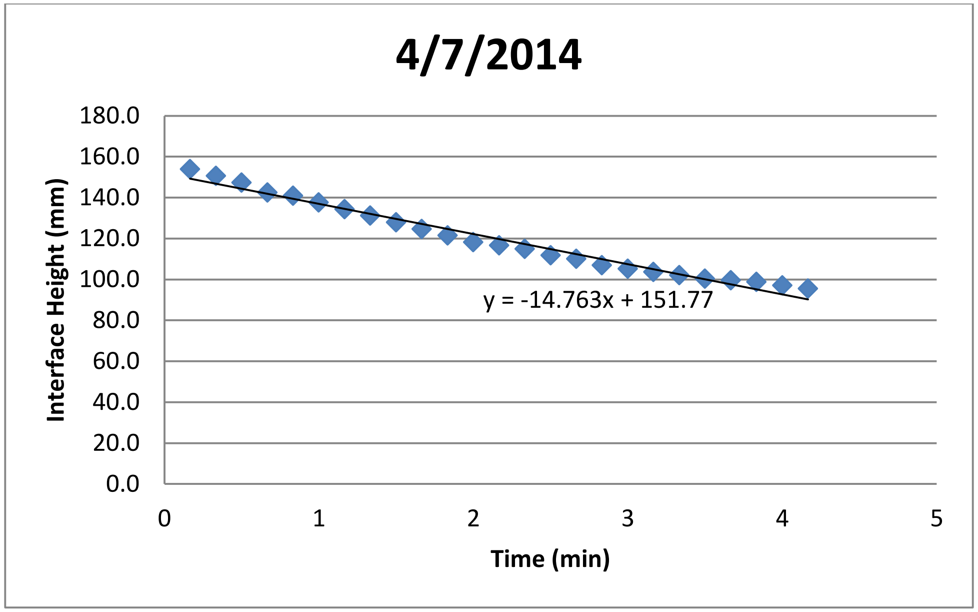

3/18/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
0.5
1
1.5
2
2.5
TIme (min)
y = -36.274x + 166.61

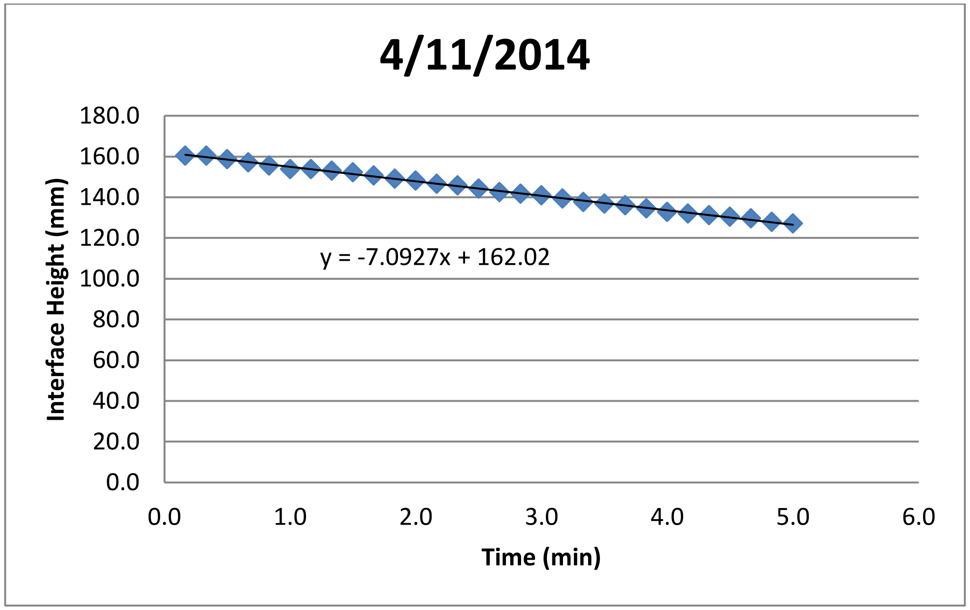

3/21/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
0.5
1
1.5
2
2.5
3
Time (min)
y = -36.379x + 167.4


3/26/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
0.5
1
1.5
2
2.5
3
Time (min)
y = -34.541x + 157.94


3/31/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
0.5
1
1.5
2
2.5
3
TIme (min)
y = -32.458x + 161.75


4/2/2014
Interface Height (mm)
156.0
154.0
152.0
150.0
148.0
146.0
144.0
142.0
140.0
138.0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (min)
y = -3.3935x + 153.68


4/7/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
Time (min)
y = -14.763x + 151.77


4/11/2014
Interface Height (mm)
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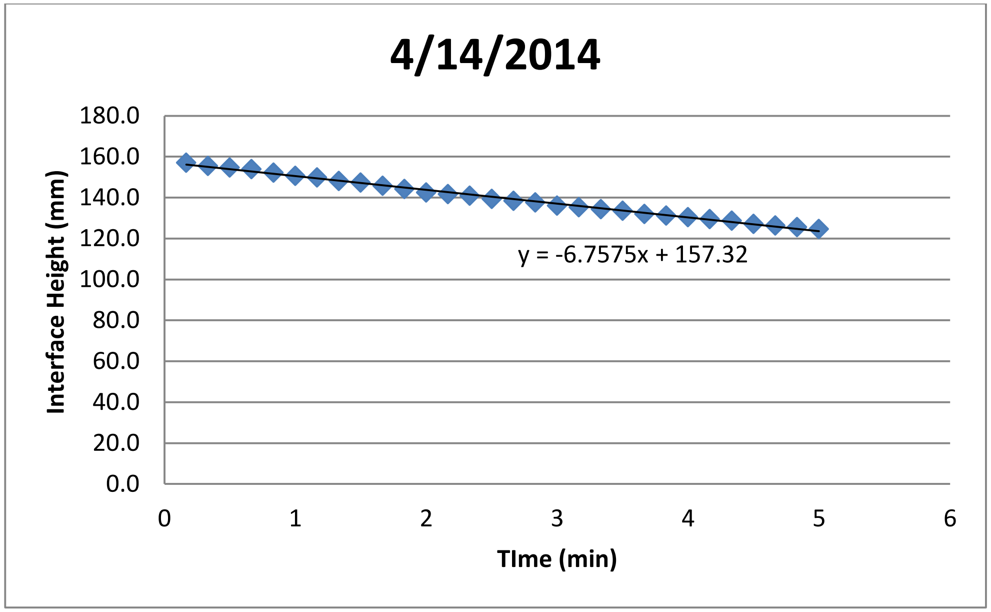
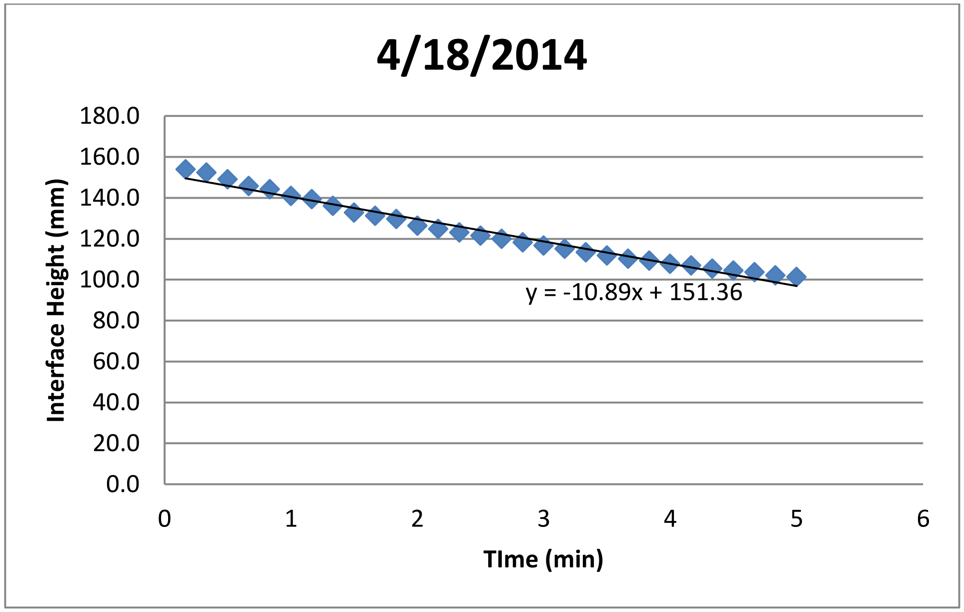
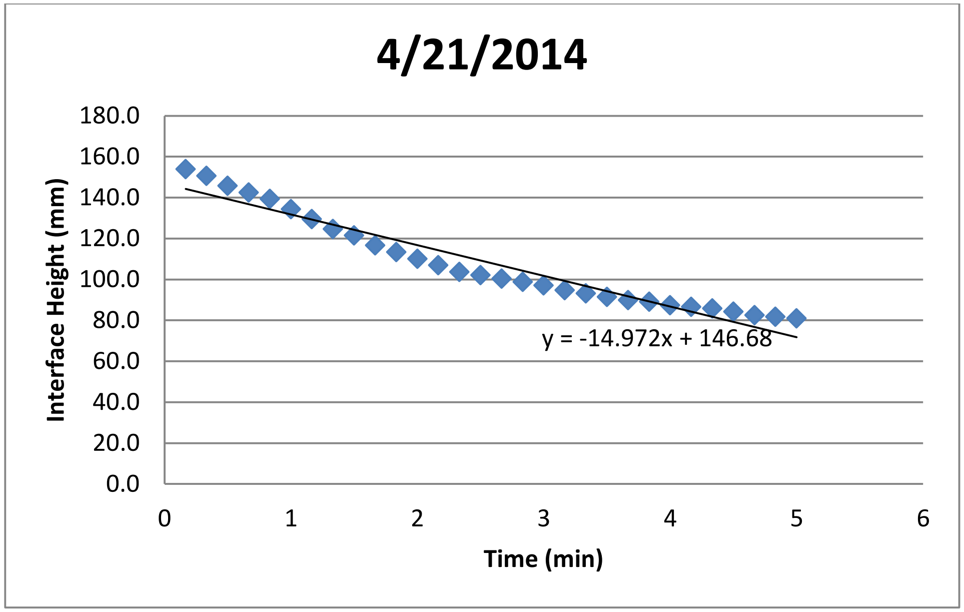
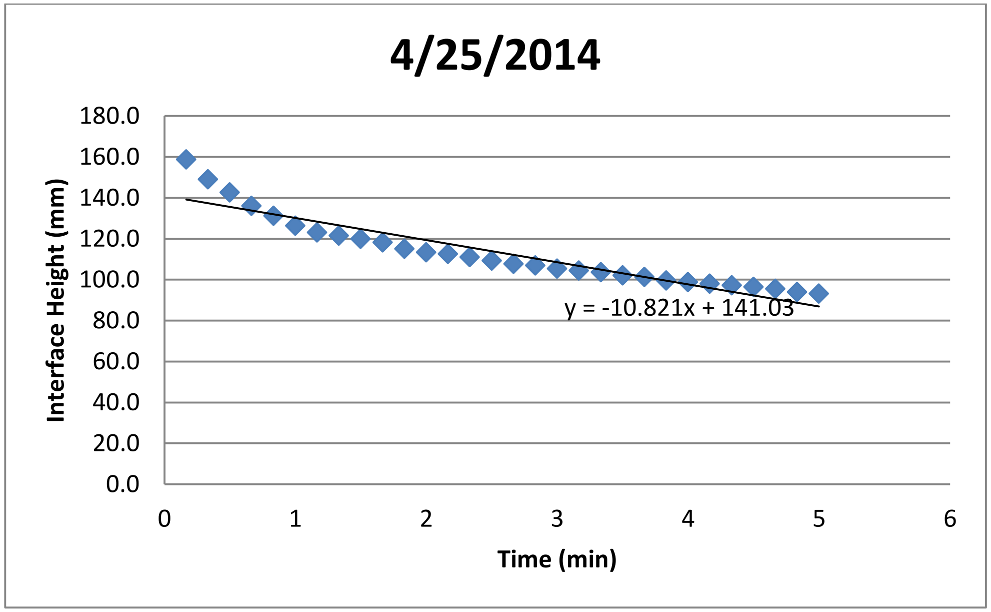
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Time (min)
y = -7.0927x + 162.02


4/14/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
TIme (min)
y = -6.7575x + 157.32


4/18/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
TIme (min)
y = -10.89x + 151.36



4/21/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -14.972x + 146.68

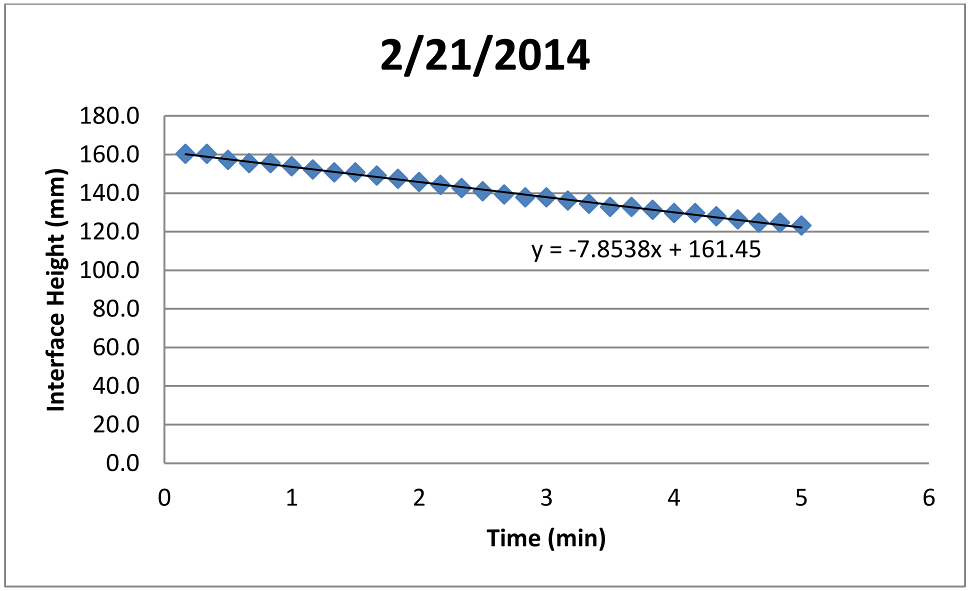


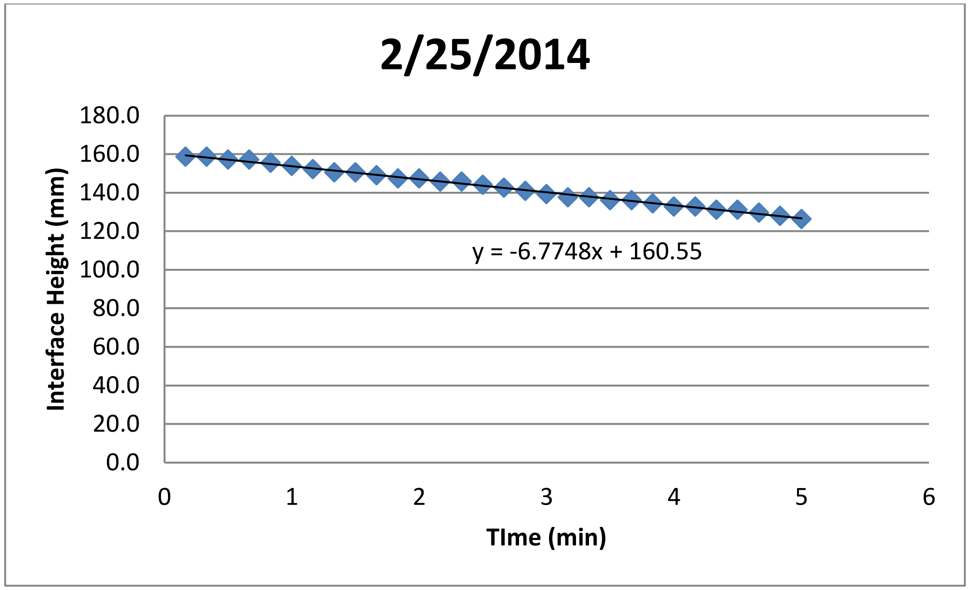
4/25/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -10.821x + 141.03

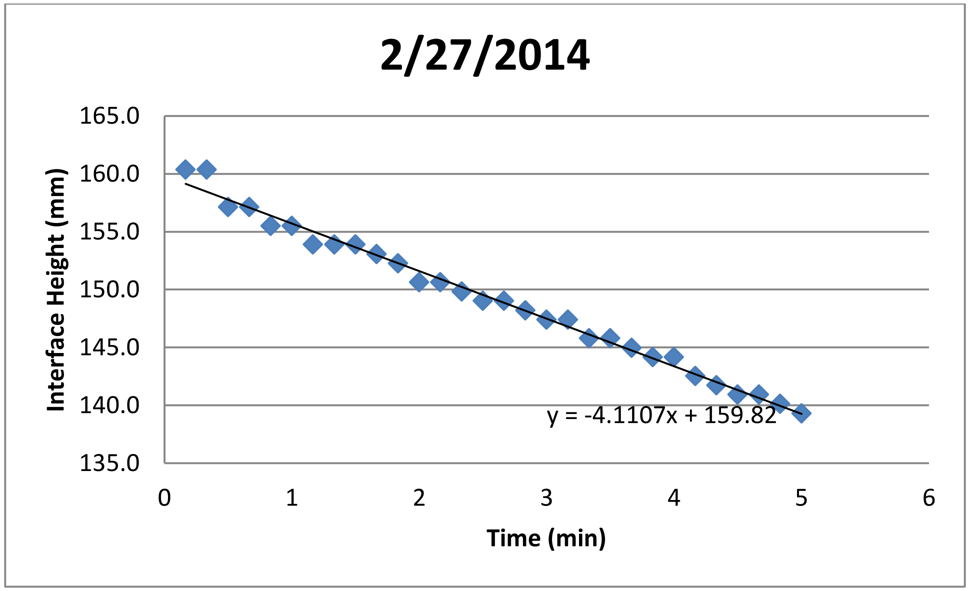
A 9 DISV DATA

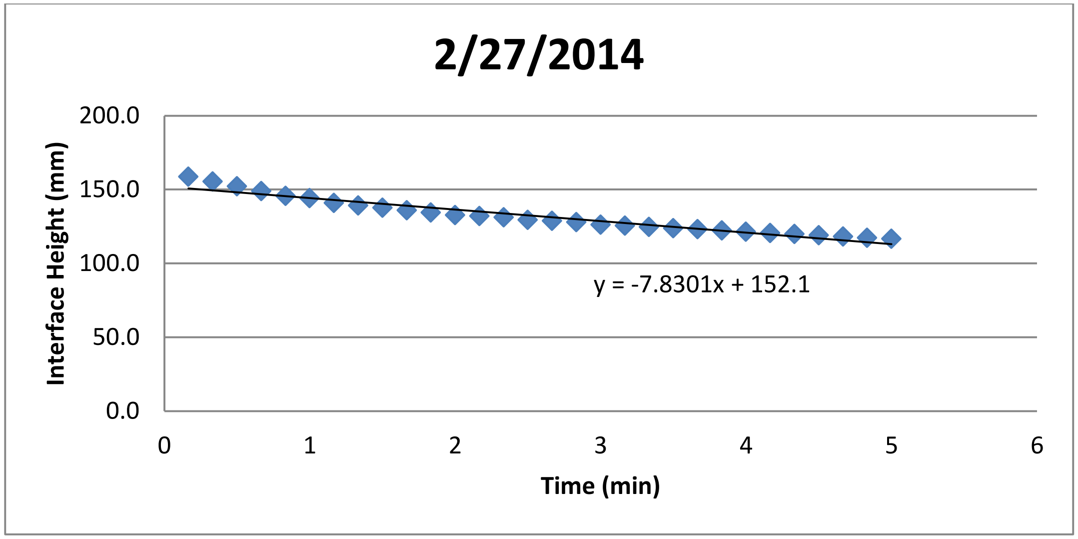
Date	MLSS (mg/L)	SSV5	SSV30	SVI	slope	DISV (m/hr)	DISV (m/min)	DISV (gal/ft2-day)
2/21/2014	3000	760	360	120	4.2243	0.0506916	0.00084486	29.85055973
2/26/2014	3000	780	370	123.3333	5.0063	0.0600756	0.00100126	35.37647827
2/31/2014	3000	860	470	156.6667	2.6498	0.0317976	0.00052996	18.72452552
3/7/2014	3000	720	440	146.6667	48.344	0.580128	0.0096688	341.6176548
3/13/2014	2880	895	510	177.0833	19.849	0.238188	0.0039698	140.2608148
3/18/2014	2840	775	390	137.3239	39.27	0.47124	0.007854	277.4972138
3/21/2014	2995	855	450	150.2504	26.076	0.312912	0.0052152	184.2632378
3/26/2014	3040	815	410	134.8684	31.155	0.37386	0.006231	220.1534428
3/31/2014	3830	870	540	140.9922	16.932	0.203184	0.0033864	119.6481493
4/7/2014	3180	870	500	157.2327	22.405	0.26886	0.004481	158.3225128

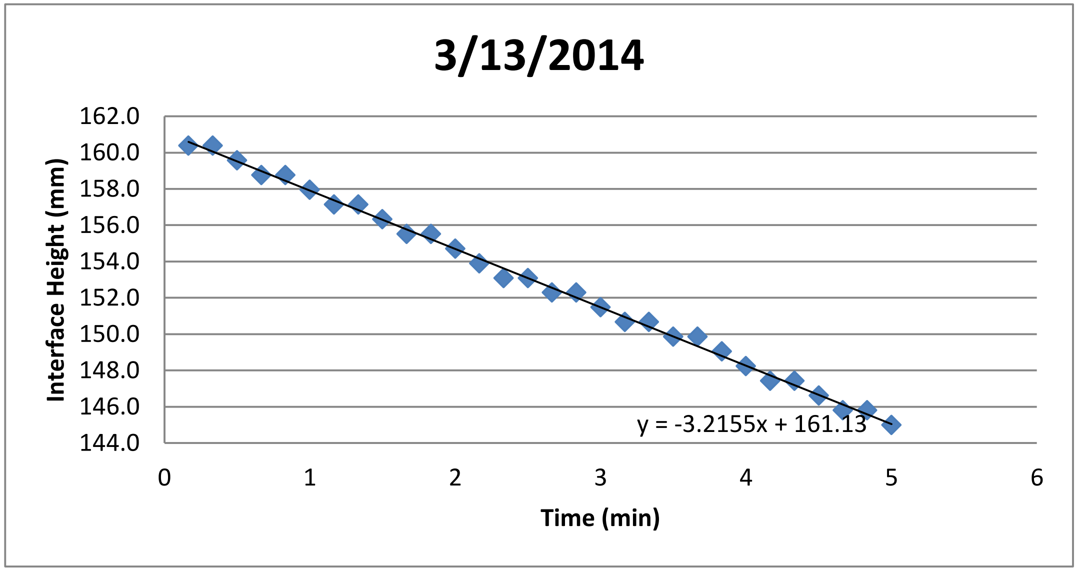
DISV Plots

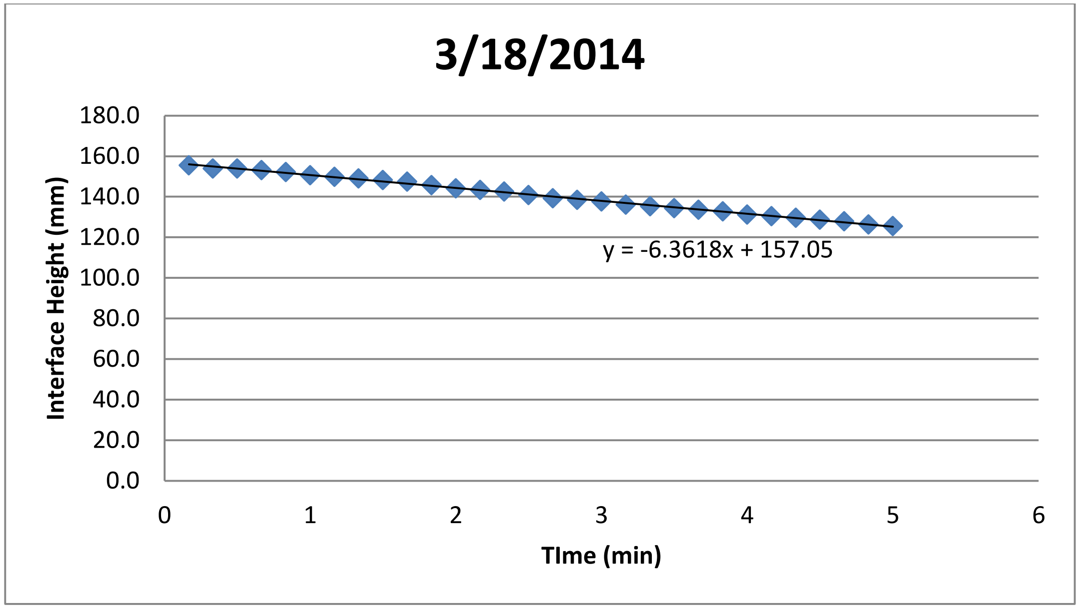


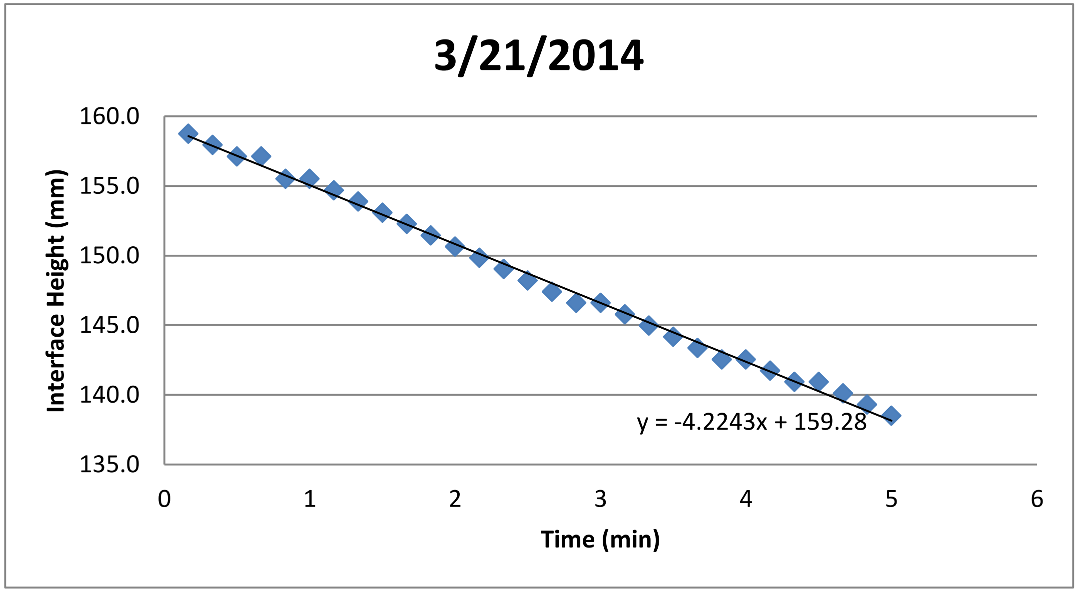

2/25/2014
Interface Height (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
5
6
TIme (min)
y = -6.7748x + 160.55

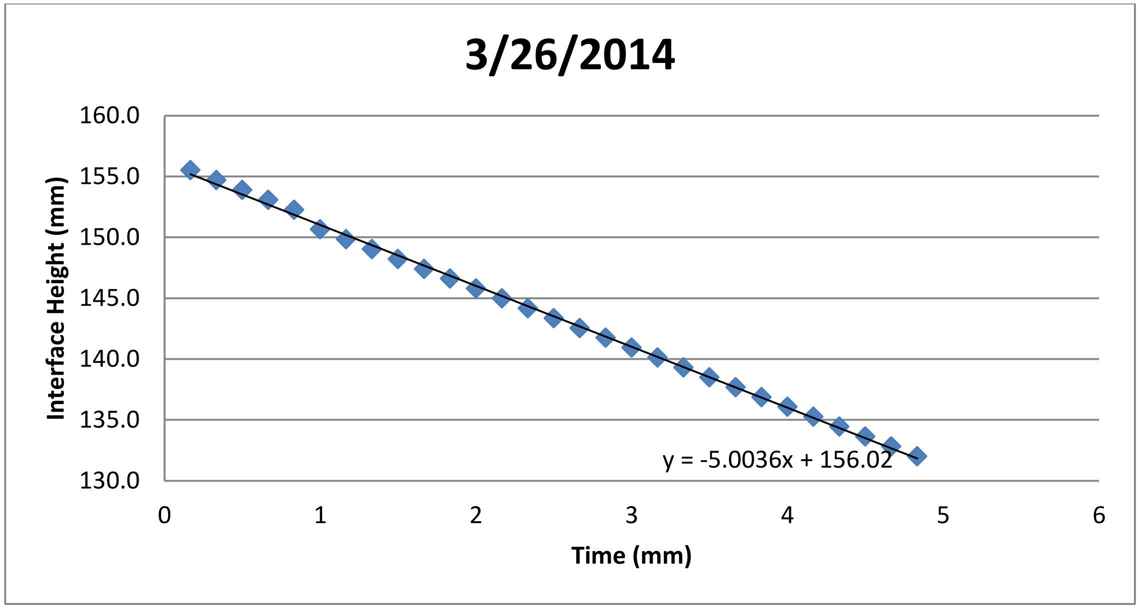

2/27/2014
Interface Height (mm)
165.0
160.0
155.0
150.0
145.0
140.0
135.0
0
1
2
3
4
5
6
Time (min)
y = -4.1107x + 159.82

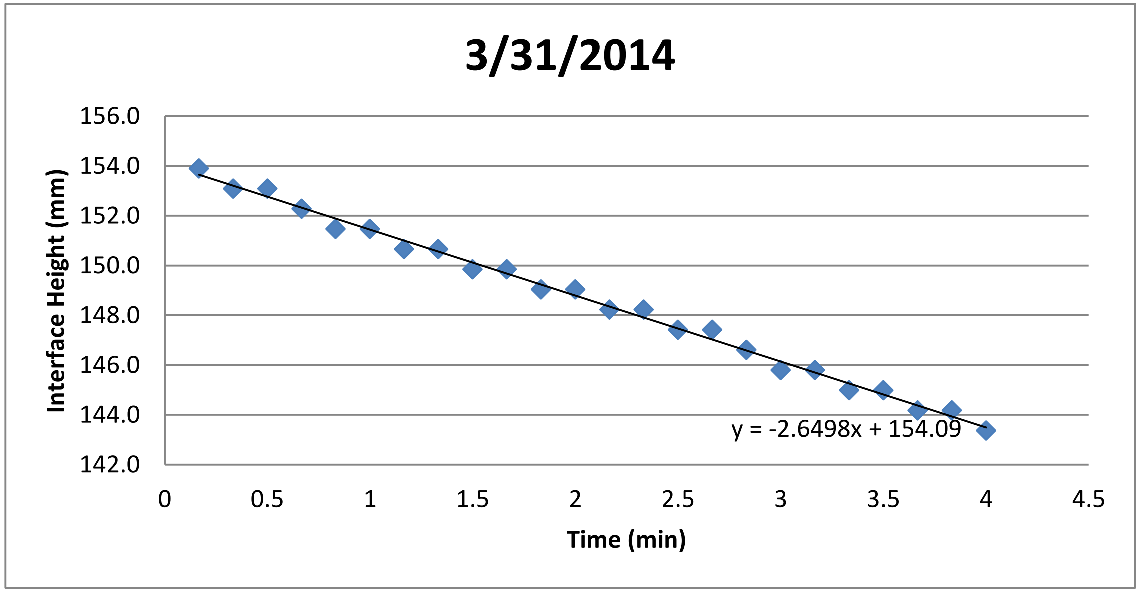

2/27/2014
Interface Height (mm)
200.0
150.0
100.0
50.0
0.0
0
1
2
3
4
5
6
Time (min)
y = -7.8301x + 152.1

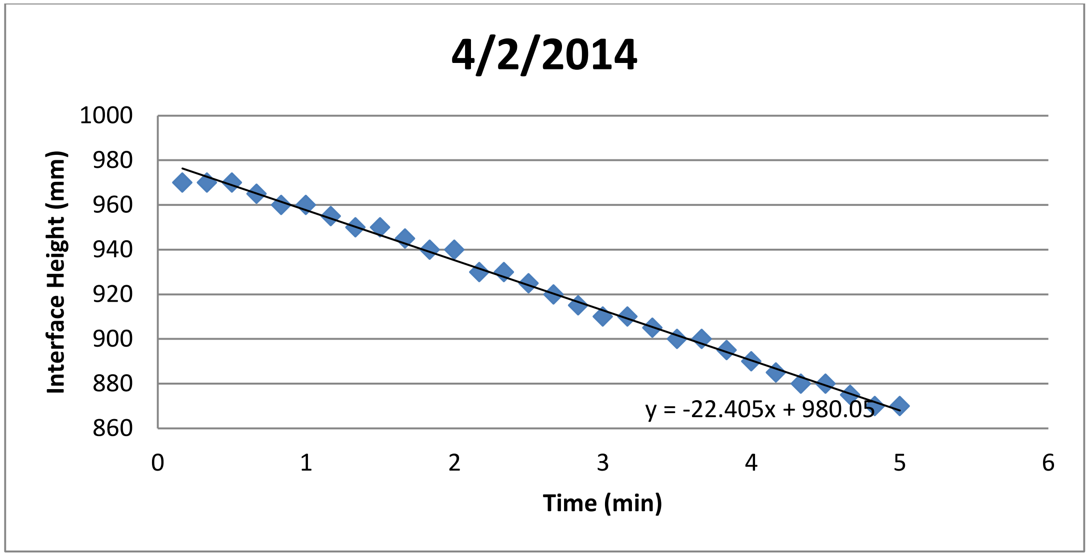

3/13/2014
Interface Height (mm)
162.0
160.0
158.0
156.0
154.0
152.0
150.0
148.0
146.0
144.0
0
1
2
3
4
5
6
Time (min)
y = -3.2155x + 161.13


3/18/2014
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Interface Height (mm)
y = -6.3618x + 157.05
0
1
2
3
4
5
6
TIme (min)


3/21/2014
160.0
155.0
150.0
145.0
140.0
135.0
Interface Height (mm)
y = -4.2243x + 159.28
0
1
2
3
4
5
6
Time (min)


3/26/2014
Interface Height (mm)
160.0
155.0
150.0
145.0
140.0
135.0
130.0
0
1
2
3
4
5
6
Time (mm)
y = -5.0036x + 156.02


3/31/2014
Interface Height (mm)
156.0
154.0
152.0
150.0
148.0
146.0
144.0
142.0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (min)
y = -2.6498x + 154.09


4/2/2014
Interface Height (mm)
1000
980
960
940
920
900
880
860
0
1
2
3
4
5
6
Time (min)
y = -22.405x + 980.05