ABSTRACT

Ridenoure, Jennifer Ann. Optimization of Nitrogen Removal from Anaerobically-Pretreated Swine Wastewater (APTSW) in Intermittent Aeration Reactors. (Under the direction of Jay Cheng, Francis de los Reyes III, and Philip Westerman.)

The swine industry is a large part of NC's economy generating over $2 billion in annual profit in the state. With a large hog production in NC, disposal of generated swine wastewater has entered the forefront of environmental concerns. Swine wastewater contains high levels of chemical oxygen demand (COD) and nutrients including nitrogen (N), phosphorus (P), and minerals. The most common treatment of swine wastewater in the southeast U.S. is the use of an anaerobic lagoon, which is an economical and practical way to provide reduction of COD through an anaerobic treatment and long-term storage. A lagoon, though easily maintained, does not provide significant reduction N and P which, if left untreated can lead to problems in water sources.

In this study an intermittent aeration (IA) reactor was used to remove nitrogen (N) from an influent of anaerobically pretreated swine wastewater (APTSW) (hog lagoon waste). The COD/TKN ratio, aeration to non-aeration ratio (ANA), and cycle time were varied to investigate their influence on N removal from IA reactors. The results show that removal of N was high for all ANA ratios and cycle times tested, 1h:1h (A), 1h:3h (B), 0.5h:1.5h (C), 0.5h:2.0h (D), and 1h:4h (E). It was evident that increasing the COD/TKN ratio did affect denitrification activity because effluent NO_3-N concentration in the effluent of the reactors tested decreased. A yearly average reduction of over 80% TN and 86% NH_3-N was obtained from all the reactors. Therefore there was no significant difference in removal of N from reactors with lower daily aeration

fractions (0.2), showing that reactor E (0.2 and 1h:4h ANA) is the best choice when selecting an IA systems.

Since all reactors operated with the similar N removal efficiencies, environmental parameters were monitored to establish differences within the reactors. Oxidation reduction potential (ORP), dissolved oxygen (DO), pH, and nitrogen species profile were measured through an ANA cycle. The profiles of ORP, DO, and pH established whether nitrification or denitrification N reactions were predominate. Nitrogen species profiles showed which N constituents were prevalent in nitrification and denitrification reactions. Rates for nitrification and denitrification were calculated based on N species profile.

OPTIMIZATION OF NITROGEN REMOVAL FROM ANAEROBICALLY – PRETREATED SWINE WASTEWATER (APTSW) IN INTERMITTENT AERATION REACTORS

By

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BIOGRAPHY

I was born in Exeter, NH and was transferred several times to southern locations. My parents reside in Wilmington, NC wanting to stay in the south. I got my undergraduate degree at Appalachian State University in the Biology department with a minor in Chemistry in May, 2001. I completed four years of undergraduate education while playing Division I field hockey at ASU. After graduation I worked for Duke University Medical Center, in a HIV vaccine trial network project funded by the NIH. I began my studies at North Carolina State University in May 2002 by taking undergraduate engineering requirements. I began working with Dr. Jiayang (Jay) Cheng on my project in Fall 2002. This will complete the requirement for a Master degree in Biological and Agricultural Engineering with a minor in Civil Engineering.

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CHAPTER 1

INTERMITTENT AERATION FOR NUTRIENT REMOVAL FROM SWINE WASTEWATER: A REVIEW

1.1 INTRODUCTION

The agricultural industry is a significant part of the United States economy, providing food and jobs for the American people. In recent years parts of the industry have suffered great losses due to overproduction of crops and dropping prices. As the industry continues, current trends find the family farm dwindling and large concentrated farming gaining growth. With animal production remaining a stable industry, environmental concerns with disposal of animal waste have emerged because of the high concentration of wastes produced. The animal industry suffering the most public detestment is swine production because of odor, waste disposal trends (lagoon and crop application usage), and potential for pollution of water systems. Iowa and North Carolina (NC) are the number one and two states in swine production in the United States, making them targets of environmental concerns. The industry is a large part of NC's economy having a market value near $2 billion in the state (www.usda.gov).

Swine waste contains high levels of chemical oxygen demand (COD) and nutrients including nitrogen (N), phosphorus (P), and minerals (Cheng and Liu, 2001; Obaja et al., 2003). The most common treatment of swine wastewater is the use of an anaerobic lagoon, which is an economical and practical way of providing reduction of COD through an anaerobic treatment and long-term storage. A lagoon, though easily maintained, allows significant amounts of N and P to remain after treatment which, if

left untreated can lead to problems in water sources (Obaja et al., 2003; Osada et al., 1991).

Reduction of nutrients is obtained by cropland application for nutrient utilization by plants (Maekawa et al., 1995; Osada et al., 1991). Application on land is again economical but can only take place in accordance with crop standards, and if land is nutrient deficient, and moisture content does not exceed soil standards (NC Division of Water Quality CZARA Section 6217). These swine waste management practices are outdated when compared to domestic waste technology standards. But they have been established for many years and are relied on by almost all hog farms in NC. Yet, currently there is a reason to believe that management practices have been a source of pollution. Growing concerns of lagoon leakage and overflow, odor emission, and eutrophication in waterways from nutrients have prompted NC to search for alternatives to lagoon usage and cropland application (Cheng and Liu, 2001; Westerman et al., 2000).

In 1997, NC passed a moratorium to ban the further construction of lagoons, eventually close existing lagoons, and conduct research on alternative technologies to current waste management practices (NC House Bill 515). The timeline for completion of original goals expired in 2003, with the initial plan incomplete. Instead of ending the initiative, it was modified to achieve realistic goals, by continuing innovative research. Focus on closing existing lagoons was no longer the main agenda; research would primarily be on full waste treatments for future hog farms and innovative technologies (for nitrogen removal after lagoon treatments) added to existing lagoons (House Bill 1113). The modified goals are being attained by several partnerships; a key group being

Smithfield and North Carolina State University (NCSU), and both facilities are conducting major research in innovative technologies for lagoons.

Finishing technologies that accomplish nutrient removal are important to NC's economy because they relieve environmental stress due to nutrient run-off. When P and N (mainly ammonium, NH_4^+-N) are applied to crops, adsorption into root systems for utilization is not instantaneous. Run-off of these nutrients into waterways is a source of eutrophication, adding to the surge of harmful algal blooms in NC's coastal areas (Burkholder and Glasglow, 2001). As well, NH_4^+ application onto soils allows its transformation into nitrate (NO_3^-) by nitrifying bacteria in soil, and nitrate could seep into groundwater. Consumption of contaminated ground water can possibly cause methemoglobinemia (blue baby syndrome) and formation of carcionogenic nitrosamines and nitrosamides (Crities and Tchobanoglous, 1998; Ferriera et al., 2003). Moreover, significant ammonia emission to the atmosphere occurs from the open lagoons and through spray irrigation to the cropland, a typical practice for cropland nutrient application. Thus, there is a great interest in developing new technologies for nutrient management to prevent environmental and health problems, but be of reasonable cost.

An innovative technology that addresses the above problems is the intermittent aeration (IA) process, alternating aeration and non-aeration in a reactor to provide a stable environment for N removal through biological nitrification/denitrification and allowing the possibility for P removal (Cheng and Liu 2001; Kimochi et al., 1998; Maekawa et al., 1995; Osada et al., 1991; Yang and Wang, 1999). IA has been used in treatment of domestic wastewater and anaerobically pretreated swine wastewater (APTSW); both being successful in nutrient removal. While successes are many in both

applications, domestic systems do not face as many difficulties as APTSW applications. The difficulties in treating APTSW include a high level of nutrients and deficiency in organic carbon for denitrification or a low Carbon (C)/N ratio in APTSW. Also, the ratio of aeration time:non-aeration time and the length of a cycle for IA process need to be optimized to improve the efficiency and reduce operational cost of the process (Cheng and Liu, 2001; Kishida et al., 2003; Ra et al., 1999). Overcoming these obstacles will permit IA to become an efficient technology for swine wastewater treatment.

1.2 INTRODUCTION TO INTERMITTENT AERATION (IA))

IA process is the alternating of aeration (air-on or oxic period) and non-aeration (air-off or anoxic period devoid of oxygen but oxygen containing molecules remain) in a cycle, providing nitrogen reduction through biological nitrification/denitrification and possible phosphorus reduction by uptake in phosphorus accumulating organisms (PAOs) (Bicudo and Svoboda, 1995; Hamamoto et al., 1997; Seo et al., 2000; Ujang et al., 2002). It is an excellent choice for use in swine wastewater treatment because it provides reduction in aeration costs and an energy saving compared to continuous aeration, while achieving nitrogen removal by denitrification in the anoxic period (Bicudo and Svoboda, 1995; Matsuda and Fuji, 1988; Osada et al., 1991; Yang and Wang, 1999; Zhu, 2001). IA has garnered support in swine wastewater treatment research because it offers benefits for the swine industry by controlling ammonia emission, reducing cropland application, and improving air quality in the swine houses if IA effluent is used for washing the pig manure out of the houses.

Cheng and Liu (2001) found that aeration could be reduced by 50%, with an aeration to non-aeration (ANA) ratio of 1 h:1 h, while providing 91% total Kjeldahl nitrogen(TKN) reduction from APTSW. Similar research suggests that this IA system uses a high ANA ratio and that further reduction is possible while still providing apt N removal from the wastewater. To reduce operational costs and optimize the ANA ratio and cycle length, on-line monitoring systems that measure parameters such as pH, oxidation-reduction potential (ORP), dissolved oxygen (DO), and/or nitrogen species have been used to control air-on/air-off periods (Al-Ghusain et al., 1994; Charpentier et al., 1989; Kim and Hao, 2001; Kishida et al., 2003; Paul et al., 1998; Spagni et al., 2001).

1.2.1 Nitrogen removal

Nitrification occurs during aeration. Autotrophic nitrifiers convert ammonia to nitrate with nitrite as an intermediate (Madigan et al., 2003; Prakasam and Loehr, 1972; Liu, 1999).

The reactions involved in nitrification include:

Ammonia-oxidation by *Nitrosomonas or Nitrosospira*

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+ + biomass$$

Nitrite-oxidation– by *Nitrobacter* or *Nitrospira*

$$NO_2^- + 1/2O_2 \rightarrow NO_3^-$$

Overall reaction is as follows:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ + biomass$$

Accordingly the major ammonia and nitrite oxidizers identified in IA process are the same found in other nitrifying systems, the microorganisms *Nitrosomonas* and *Nitrospira* (Metcalf and Eddy, 2003; Sharma and Ahlert, 1976). Nitrifiers are sensitive and their growth rate is affected by various parameters such as pH, NH_4-N concentration, inhibitory materials, dissolved oxygen (DO), and temperature (Madigan et al., 2003; Pochana and Keller, 1999; Strenstrom and Poduska, 1980; Zhao et al., 1999). Once a culture has been established in a reactor the rate at which nitrification occurs is mainly affected by DO and biomass content in the reactor, which can both be controlled by system operation (Hidaka et al., 2002; Matsuda et al., 1988; Pollice et al., 2002).

The United States Environmental Protection Agency (U.S. EPA) (1993), recommends DO values of over 2.0 mgDO/L for nitrification. Full nitrification has been achieved in systems that maintained a value lower than 2.0 mgDO/L. Full nitrification has been established in IA systems which sustained a value of DO less than 1.0 mg/L, reaching nitrogen removal rates comparable to higher DO systems (Holman and Wareham, 2003; Strenstrom and Poduska, 1980; Zhao et al., 1999).

Low levels of DO can be sustained in an IA reactor because: NH_4-N levels are low in the reactor; an increased solid retention time (SRT) allows the maintenance of sufficient biomass for complete nitrification; or nitrifying microorganisms are put under stress, increasing their oxygen uptake rate (OUR), thus enhancing ammonium oxidation (Henduit and Tevenot, 1989; Hidaka et al., 2002; Strenstorm and Poduska, 1979). In swine wastewater NH_4-N levels are much higher (as high as 2000 NH_4-N mg/L) than domestic wastewater (ranging from 30 to 60 NH_4-N mg/L). Therefore, a SRT of 20 to

25 days allows a low DO system to achieve high nitrification rates by increasing nitrifiers in the volatile suspended solids (VSS) (Cheng and Liu, 2001; Hidaka et al., 2002; Pollice et al., 2001; Strentstorm and Poduska, 1979).

An increased SRT also accommodates slower growing nitrifiers by establishing them in the VSS above washout levels. By exceeding the minimum SRT of these organisms, it allows the reactors to operate without the need for high DO concentrations (Grady et al. 1999; Pollice et al., 2001). Conversely independence of SRT is achieved by highly oxygenating a system; however, in swine wastewater treatment these systems increase expenses and are not practical in facilities (Pollice et al., 2001; Praksam and Loehr, 1972).

Consequently, swine wastewater nitrification could be hindered by insufficient SRT causing incomplete biomass growth of nitrite oxidizing bacteria, and halting nitrification after ammonia oxidation to nitrite. Instead of this occurrence, a reduced SRT could promote nitrification through a single reactor to achieve high activity of ammonia removal over nitrite (SHARON) process, in which nitrosomonas only oxidize ammonia to nitrite due to SRT constraints or DO (Hellinga et al., 1998; Pollice et al., 2001; Verstraete and Philips, 1998). The SHARON process can be more efficient than complete nitrification when wastewater is deficient of COD and oxygen sources; denitrification through nitrite utilizes less COD and oxygen. Researchers found that the SHARON process could use 40% less COD, making it possible to eliminate an addition of organic carbon source for denitrification (Abeling and Seyfried, 1992; Hellinga et al., 1998; Metcalf and Eddy, 2003). The theoretical nitrogenous oxygen demand (NOD) of nitrification is 4.25 mg DO per mg NH_4-N oxidation to NO_3-N, and 3.22 mg DO per mg

NH_4-N oxidation to NO_2-N (Metcalf and Eddy, 2003; Sharma and Ahlert, 1976). While these reductions are small, in constrained systems it can make all the difference in reaching high N removal. So, it is established that biomass in IA systems under stressed conditions can adapt to an environment they are forced to inhabit.

Denitrification can be inhibited by low levels of COD in the influent. When fulfilling complete denitrification, the reactions by microorganisms convert nitrate to nitrous oxide (N_2O), then nitric oxide (NO), and finally dinitrogen gas (N_2) (Madigan et al., 2003). Microbial reactions for this process occur in heterotrophic organisms which use NO_3-N or NO_2-N as an electron acceptor, and molecules that contain organic carbon as electron donors and carbon source. Denitrification can be described by the following reaction:

$$NO_3^- + COD \rightarrow N_2 + CO_2 + H_2O + OH^- + biomass$$

Since lack of COD can inhibit denitrification, COD/TKN ratio is an important parameter to monitor a reactor's potential for N removal. It has been suggested that the ratio needs to be maintained at or above 5.0 for complete N removal to occur in wastewater activated sludge systems without supplementing organics (Itokawa et al., 2001; Nagako et al., 2002). In APTSW, this ratio is unattainable with influent averages less than recommended; addition of organic carbon is one way to increase low COD. Since domestic treatment is run as a public works system, promotion of N removal by organic carbon addition is feasible. In contrast, for farmers this additional cost is prohibitively expensive to the marginal profit of hog production.

Researchers using IA for swine wastewater treatment have been able to overcome this challenge by running systems with N removal when the influent

COD/TKN ratio is as low as 0.18, while achieving good total nitrogen (TN) removal at this level (Osada et al., 1991). Reasons for enhanced performance in low COD/TKN ratio IA process can be due to carbon release from biomass decay accomplished by the high SRT. Since IA periods are carried out in the same reactor, COD is then readily accessible to denitrifiers for reduction of NO_3^- to N_2. Another way to add organic carbon is by combining raw swine wastewater with APTSW prior to IA treatment. Hu et al. (2003) found that increasing the ratio of raw swine wastewater to anaerobic-lagoon-treated swine wastewater in the influent of an IA system increased TN removal performance. When the ratio increased from 0:100 to 50:50, TN removal increased from 62% to 82% in a 1h:1h ANA semi-continuous reactor. The increase of TN removal was a result of a COD increase from 261 to 425 mg/L in the influent, causing a decrease in total NO_3N/NO_2N (NO_x-N) in the effluent because of enhanced denitrification.

Incomplete denitrification is not only due to an inadequate COD/TKN ratio; a short anoxic period would also result in high N level in the effluent. If there is sufficient organic carbon, increasing the anoxic period will allow enough time for denitrification. On the other hand, some researchers feel that reduction of TKN is more important than TN, because the goal of N removal is reduction of ammonia. This achievement may nevertheless be acceptable because the EPA still maintains that final disposal of animal waste is through crop application (National Environmental Policy Act, 1969).

Effluent with high nitrate concentration, thus high TN may suggest failure in an IA system but researchers found that some crop plants prefer nitrate to ammonia, and remove the nitrate more rapidly from soil. Olsson and Falkengren-Grerup (2000) found that acid in soil affects plants' preferences; less acid tolerant plants will uptake nitrate faster than ammonia and grow a larger plant mass. In wetland study testing levels of

nitrified waste, Poach et al. (2003) found that wetland plants preferred sewage that was more nitrified, containing higher levels of NO_3-N. Plants preferring nitrate as N nutrient rather than ammonia is an important argument to prove that even low-efficiency IA systems are an improvement from merely crop application. Making IA a resourceful addition to a swine waste treatment system for an environmental impact.

Niche establishment in the habitat of the reactor is also imperative for nitrate reduction through denitrification. During the anoxic period, the residual DO concentration must drop to near zero to create an environment stable for denitrification. When levels of DO do not drop to zero, denitrifiers prefer to reduce oxygen because it produces more energy compared to NO_3-N or NO_2-N (Cheng and Liu, 2001; Madigan et al., 2003; Zhao et al., 2003). Due to this preference, when oxygen is present, nitrate reductase production of denitrifiers is inhibited and they cannot use NO_3-N or NO_2-N as an electron acceptor (Madiagan et al., 2003). When levels of undetectable DO are not achieved in a system simultaneous nitrification/denitrification (SND) may occur instead.

SND arises when the conditions are suitable for nitrification and denitrification to occur at the same time. This will occur when the floc size is large enough to maintain an area devoid of dissolved oxygen in its interior space, there is a low organic loading rate, and a long SRT (Pochana and Keller, 1999; Zhao et al., 1999). The interior portion of the floc contains a habitat established by denitrifiers while the exterior is inhabited by nitrifiers allowing the microorganisms to lay in close proximity so that SND is possible without difficulty.

Pochana and Keller (1999) found that reducing floc size from over 100 µm to 80 and 40 µm reduced SND to 52% and 21% of the activity at 100 µm. Therefore, it is possible to maintain SND by providing both optimum habitats for both nitrifiers and

denitrifiers, by sustaining a floc size around 100 µm. This research is subject to scrutiny because floc size is dependent on a variety of factors and an IA system relies on the establishment of distinctly separate aerobic and anoxic periods. The occurrence of SND in IA systems is possible but it is usually minimal because the extended anoxic periods allows for the reactor to retain an optimum habitat for denitrification. Consequently, SND in IA swine wastewater treatment operations is probably not a large contributor to N removal because of the promotion of nitrification/denitrification by alternating periods (Cheng and Liu, 2001). Another possible way for N removal is the possible occurrence of anaerobic ammonium oxidation (ANAMMOX) in the system.

In ANAMMOX systems, N removal is through partial nitrification, nitrifier denitrification, and anaerobic ammonia oxidation (Verstraete and Philips 1998). Removal through this process requires a higher SRT because the growth rate of anaerobic ammonia oxidizers is very slow (Jetten et al., 2001). If occurring in an IA system, ammonia would be consumed during anoxic period by anammox bacteria. The occurrence of this in IA is not common, though not completely overlooked when examining nitrogen profiles.

1.2.2 Removal of Phosphorus

Removal of P from swine wastewater is possible with IA application however; it is usually not as efficient as N removal. The cycle time governs whether or not removal is considerable or not. When the anoxic period is long enough, there is sufficient time for the reactor to become devoid of NO_3-N, which will inhibit P release (Ujang et al., 2002). During anaerobiosis P is released from organisms, as polyhydroxyalkanoic acids (PHAs) or soluble P. Since phosphate accumulating organisms (PAOs) are out-competed by denitrifiers in growth, PHAs only develop in the absence of DO or NO_3^-

(Grady et al., 1999). A fermentative zone produces simple hydrocarbons such as volatile fatty acids (VFAs), which are taken up by PAOs for growth during this phase. During aeration, PAOs are able to accumulate polyhydroxybutyrate (PHB) because of anaerobic release, removing phosphorus from the effluent (Ujang et al., 2002).

Phosphorus removal requires a longer aeration and anoxic time to complete the P transformation from soluble into the biomass. Seo et al. (2000) found P removal was only 66% of the raw wastewater influent when using only IA with no anaerobic treatment. Therefore, adding an anaerobic period is essential because it allows PAOs to release P that will later be removed as solids. A longer aeration is also needed for P removal because PAOs are outcompeted by nitrifying organisms for oxygen. When nitrification is close to completion PAOs begin to accumulate P at an accelerated rate and remove it from the wastewater (Seo et al., 2000; Ujang et al., 2002).

1.3 CURRENT APPLICATIONS OF IA IN SWINE WASTEWATER TREATMENT

1.3.1 Manual Applications

These applications use set ANA and cycle time to govern the removal process. Setting of the ANA is based on the parameters to be treated, wastewater influent, and previous knowledge. These applications have had much success and have been found to be efficient in removing N and sometimes P (Bicudo and Svoboda, 1995, Cheng and Liu, 2001; Luo et al., 2002; Maekawa et al., 1995; Obaja et al., 2002; Osada et al., 1991, Sang-Ill et al., 1997; Yang and Gan, 1998; Zhu, 2001).

1.3.1.1 Sequencing Batch Reactor (SBR)

A SBR is the most frequently applied system using IA for N removal from swine wastewater. The complete SBR cycle occurs in a single reactor, divided into specific periods of mixing, aeration, settling, decanting in which reactions of removal occur (Hamamoto et al 1997).

Yang and Gan (1998) established that an IA SBR integrated into a swine farm treatment system could provide improved effluent quality. They tested an ANA ratio of 20 h:4 h and found that the effluent quality achieved removal of 64-70% TN, 72-83% COD, and 67% TP; ranges depending on the influent characteristics. These findings promoted further research of the same swine unit to achieve higher effluent quality. Yang and Wang (1999) continued this earlier research using farm quality swine wastewater testing different ANA ratios for best effluent quality, while also evaluating the economics of the treatment system. They tested four different ratios 60 h:30 h (mode 1), 5 h:1 h (mode 2), 4 h:2 h (mode 3), and 3 h:3 h (mode 4). They found that extended aeration periods in mode 1 & 2 produced a lower quality of effluent than mode 3 & 4. The decreased ratio of 3 & 4 promoted an increased oxygen uptake rate (OUR), causing microorganism to utilize NH_4^+ substrate faster, producing a better effluent quality. While 3 & 4 both had the same ANA ratio, they found that 4 had more N removal because of the 1 h longer anoxic period to promote denitrification.

In several other studies, researches have applied SBR that have not been truly IA, using cycles set oxic:anoxic:oxic, anaerobic:oxic:anoxic, and anoxic:oxic:anoxic. Alternating periods of anaerobic and anoxic provide two very different environments.

The anaerobic period is devoid of oxygen or oxygen containing molecules. Similarly the anoxic period is devoid of oxygen but instead oxygen containing molecules such as nitrate still remain in this period. These systems can be compared to true IA systems because they establish similar environments by cycling aeration and non-aeration. Since swine wastewater treatment can offer many complications in achieving good N removal, these different cycles may establish better effluent quality by providing a variable period for additional removal.

Obaja et al. (2002) tested an SBR reactor for maximum NH_4-N load removed, effect of temperature, and evaluation of biomass activity. The SBR operated with an anaerobic:aerobic:anoxic cycle at 2 h:4 h:1 h, with the seventh hour mixing and aeration for sludge drawing, providing an SRT of 11 days and a HRT of 1 day. Influent NH_4-N was tested at three values: 909mg/L, 1194mg/L, and 1509mg/L. After dilution, initial NH_4-N concentration for each run became 303mg/L, 398mg/L, and 503mg/L. A high level of N and P removal was achieved in all influent applications (99.7 % N and 97.3% P, for 1500mg/L NH_4-N influent), but an initial NH_4-N concentration above 500mg/L caused an incomplete removal of the substrate. While high levels of N removal were achieved, this was not without the addition of acetate for denitrification. COD levels in the reactor dropped before denitrification allowing high levels of nitrate in the effluent. Acetate was added to maintain a COD/TKN ratio of 1.7 to obtain complete N removal.

Addition of acetate as an organic carbon source will cause SBR applications to be costly. Sang-Ill et al. (1997) ran a similar SBR testing for the application of fermented swine waste compared to acetate as a supplemental carbon source for denitrification. The reactors were operated with an SRT of 20 days with a cycle of 13 h

oxic: 7 h anoxic: 3 h oxic, and addition of COD at the beginning of anoxic period. The results were promising, finding that adding both supplemental sources increased N removal from 76% to 90%, while P removal jumped from 15% to 89%. Addition of fermented swine waste to the reactors reduced nitrate in the effluent from 28-55mg/L to 5.2mg/L.

Maekawa et al. (1995) researched four different swine influents to examine their influence on N and P removal for an SBR operating with an ANA of 1h:1h and 1.25 h:0.75 h. One influent was pure swine wastewater (SWW), two were dilutions of SWW, and one was ammonium crystallized SWW. The ammonium crystallized SWW was precipitated using magnesium salt to remove nitrogen, phosphorus, and improve the C/N ratio prior to application as an IA influent. Each influent had variable concentrations of N, P, organic carbon, and other parameters; levels decreased as dilution increased and were lowest for crystallized SWW. Nitrogen removal was only good for the crystallized SWW because the C/N ratio increased from 1.98 to 8 in the crystallization process. TN removal achieved in descending influent concentration was 28.6, 31.2, 48.7, and 91.2 %, while NH_4-N removal was 32, 45, 57, and 99%. All reactors had insignificant P removal. Even though the operation that used SWW achieved a small percent removal, it still removed 1697 mg/L TN of 5930 mg/L. While the percent is viewed as failure, it is suggested that under different operations, such as increased anoxic period, it is possible to reach a removal comparable to that of crystallization.

Temperature limitations were also experienced by Obaja et al. (1999) when the temperature was decreased to 16°C for the two experiments with higher NH_4-N levels. Limitations were found in a reduction of ammonium uptake rate (AUR) and nitrite

uptake rate (NUR), verifying that inhibition of nitrification was due to inhibition of both ammonia oxidizing and nitrite oxidizing bacteria. The variation in temperature did not inhibit removal at low NH_4-N concentrations because substrate levels were low enough to allow sufficient growth of biomass to combat the temperature drop.

1.3.1.2 Single Reactor no SBR

Single reactor IA systems differ from SBRs because there is an absence of a filling and drawing period. Instead, influent is added at intervals throughout the day with biomass wasting during aeration to maintain a desired SRT. Researchers have examined variations in parameters which influence N removal from these systems and have had successes and failures.

Lou et al. (2002) tried to optimize IA conditions for nutrient removal from pig manure by testing a low aeration rate, 0.0667L/min per liter of manure while maintaining a redox potential below 0 mV. Nitrogen removal was low; only one-half of the removal achieved by continuous aeration at the same rate. On the contrary, under these low DO conditions; ortho-phosphate was successfully decreased by 75%. These results suggest that low N removal is due to low redox potential and DO. While good P removal was achieved by redox potentials as low as -300mV, which allowed the establishment of an anaerobic habitat. Under these operation conditions N removal is not significant compared to P.

In a more successful study by Cheng and Liu (2001), two semi-continuous flow reactors were operated with ANA of 1h:1h and 1h:3h, aeration rate of 83 std mL/L/min to sustain levels of DO as high as 6 mg/L during aeration periods, while ORP ranged

from 0 to 110 mV. These conditions provided enough oxygen and appropriate ORP to complete nitrification of the anaerobically pretreated swine wastewater. During the anoxic period, DO was less than 1 mg/L providing an adequate environment for denitrification to occur. Even though there was a fluctuation of of COD and ammonium concentrations in the influent, as time progressed, N removal in the reactors was quite stable, maintaining low N concentrations in their effluent. An average removal of 91% and 92% was achieved for TKN and NH_4-N, respectively.

Zhu (2001) examined aeration kinetics, the amount of oxygen needed for nitrification, in IA systems using swine wastewater. The aeration control was by DO, turning on every 3 hours and turning off once reaching the desired oxygen level. The research found that the reactor experienced rapid growth of aerobes escalating the OUR, increasing the oxygen demand. Therefore, because the reactor shut off at the chosen DO level, aeration time increased every period due to microorganism growth. It was concluded that a DO controlled system would become fully automated based on growth. During this study there was no wasting of effluent to maintain an SRT, thus all biomass was maintained in the reactor throughout the study. If the system was maintained with a SRT by wasting of the biomass, accumulation of nitrifiers would not occur. Therefore it is possible that continuous aeration would not be achieved by the reactor when the nitrifier population is regulated.

1.3.1.3 Activated Sludge

Activated sludge is a system which mixes influent with activated sludge (biomass in the system). It is a suspended growth microorganism system in an aerobic bioreactor

that employs biomass recycling (Grady et al., 1999). The use of activated sludge in IA process has also been studied with successful nutrient removal (Bicudo and Svoboda, 1995 and 1995; Osada et al., 1991). Activated sludge is the most widely used sewage treatment system in the United States. It has maintained wide use because it is reliable and successful. Its application in swine wastewater treatment offers the opportunity for enhanced removal of nutrients.

Osada et al. (1991) researched N and P removal from SWW using fill-and-draw activated sludge with IA versus a non-limited aeration process (NLAP) and IA at different N/BOD ratios of 0.18, 0.31, and 0.45. The IA ANA ratios were 1 h:1 h and 3 h:3 h while the SRT was around 18 days and the HRT was 3 days for both systems. They found that N removal for the IA reactors was greater (71.5-98%) than the NLAP (25.2-61.9%), due to denitrification in the subsequent anoxic period. Contrary to earlier research, N as well as P removal decreased in IA as the N/BOD ratio increased above 0.31. Ratios equal to 0.18 and 0.31 both achieved more than 95% TN removal, but efficiencies differed in P removal at 80% and 49.8% for these ratios, respectively.

Reasons for large fluctuations in efficiencies are related to N/BOD causing establishment of different habitats in the reactors. At the end of each aeration period, they found that 0.18 had both NO_2-N and NO_3-N, 0.31 had mostly NO_2-N, and 0.45 a large amount of NO_x-N (NO_3-N and NO_2-N). These differences in mixed liquor concentrations determine which reactions will occur at the beginning of non-aeration. A large NO_x-N concentration in higher ratios is due to increased nitrifier activity because of organic substrate availability. When the reactor enters the anoxic period an increased ion concentration requires a longer anoxic treatment, therefore reduction of NO_x-N was

not achieved because the anoxic period was not lengthened. A lowered P removal was due to increased NO_x-N because PAOs were inhibited by increased levels of NO_3-N in the mixed liquor. Further research could prove that increasing the anoxic period can aide in achieving significant P removal.

Bicudo and Svoboda (1995) also investigated the use of activated sludge for nutrient removal from swine wastewater. The SRT was extremely long (50-250 days) with low organic loadings to promote nitrification. They progressively shortened the aeration time from 19.5 h to 12 h and found that there was still noteworthy reduction of TKN by 95% and P by 40%. Similar to the report by Osada et al. (1991), a decrease in removal efficiency occurred as the N/BOD ratio increased from 0.3 to 0.5. By examining the relationships in the data of NH_4-N versus NO_3-N and TKN removal versus N/BOD ratio, it is found that effluent NO_x-N increases with decrease N/BOD ratio. Therefore, it is correct in saying that removal of TKN is large, but TN is not, and remedying this N removal difference is important to the swine industry. Again, the recommendation is to alter the ANA ratio to accommodate further N reduction through denitrifcation allowing the reactor to operate efficiently at increased N/BOD ratios.

1.3.2 Online Control Parameters

Manual operation of IA is delicate, relying on knowledge of previous research to establish much of the set operations. The dynamic swine wastewater profile may render manual operations with set ANA ratio and cycle time inadequate if a sudden increase in nutrient loading occurs. Therefore, application of online measurements of ORP, DO, and pH could be more reliable than manual applications. While application of online

measurements has limited research with swine waste treatment, it has had promising results in domestic operations (Choung and Kim, 1999; Demoulin et al., 1997; Holman and Warham, 2003; Plisson-Slaune, 1996; Wareham et al., 1994).

1.3.2.1 Oxidation Reduction Potential

ORP is a measure of a substance's tendency to become reduced or oxidized expressed in volts or millivolts. It is indicative of the potential for electrons to be transferred. A positive ORP indicates that a reactant is an oxidant or electron acceptor, while a negative ORP indicates that the reactant is a reductant or electron donor (Madigan et al., 2003). Because it is a tool to demonstrate where nitrification/denitrification is complete, ORP is a parameter that is monitored frequently in domestic and animal waste treatment systems (Choung and Kim, 1999; Demoulin et al., 1997; Holman and Warham, 2003; Plisson-Saune et al., 1996; Wareham et al., 1993).

Full nitrification/denitrification has been accomplished under varying ranges of ORP regulated systems. Therefore, researchers are in disagreement with the accepted range for complete nitrification/denitrification to occur within. It is accepted that a positive range must be maintained to have complete nitrification but there are differences in the accepted minimum value. Li and Bishop (2002) stated that the ORP must be maintained between 150 to 200 mV for good nitrification to occur. This was maintained by increasing the DO during the aeration phase. Choung and Kim (1999) found that several ranges were required for nutrient removal: nitrification +60 to +200 mV; denitrification -40 to +150 mV; and P removal -100 to -200 mV. Many more differences are set forth in research; consequently it is hard to pinpoint a minimum and

maximum value to be obtained for full removal to occur, presented in Table 1.1. As a substitute it may be easier to use bending points for ORP control rather than reaching a set maximum and minimum value.

Table 1.1 Intermittent aeration systems' ORP range for nitrification and denitrification.

Cycle	High ORP (mV)	Low ORP (mV)	%N removal	Reference
1 h aeration:1 h non-aeration	80-110	0	91 TKN 92 NH_4-N	Cheng and Liu, 2001
Real-time control	100	-150	93 TN	Klapwijk et al. 1998
4 h:4 h SBR	150	-325	1120 mg/L NH_3-N complete	Kishida et al. 2003
Real-time control 4:3	-25	-300	99.6 NH_4-N	Ra et al. 1999
Real-time control 5.5:2.5	40	-350	97.8 NH_4-N	Ra et al. 2000
3:3 and 4:2	DO=4	DO=0	92.7 TN	Yang and Wang 1999
1.5off:1.5on:2.5off:2.5on SBR	20, 30	-20, -10	75 TN	Lee et al. 2001
Real time control	100	-75	80 TN	Chen et al. 2002

Bending points in ORP profiles, such as, ammonia elbow, nitrate knee, and COD elbow, have all been used to initiate air-on/air-off in IA systems(Chang et al., 2002; Choung and Kim, 1999; Holman and Wareham, 2003). These bending points viewed on an ORP profile (Figure 1.1) specify changes in substrates which are being oxidized or reduced. During aeration, the ammonia elbow occurs as a bump (an increase in ORP) indicating all NH_4-N has been oxidized to nitrate, decreasing the OUR. The ORP then increases rapidly because the oxygen supply is not being utilized because of the decreased OUR. The ORP becomes high because of increased electron acceptors and at this point, air could be turned off to reduce costs. Also during aeration, the COD elbow occurs before NH_4-N utilization ends and it is usually viewed as a smaller bump than ammonia, indicating that COD is depleted. The nitrate knee occurs during non-aeration

indicating the end of denitrification and thus NO_3-N utilization. This bend is signified by a falling off of the ORP curve into large negative ORP values. If allowed to drop after the knee anaerobic zones will form in the reactor, allowing the possible achievement of both P and N removal, presented in Figure 1.1 (Charpentier et al., 1987 and 1989; Choung and Kim, 1999; Holman and Wareham, 2003; Plisson-Saune et al., 1996; Wareham et al., 1994; Zipper et al., 1998).

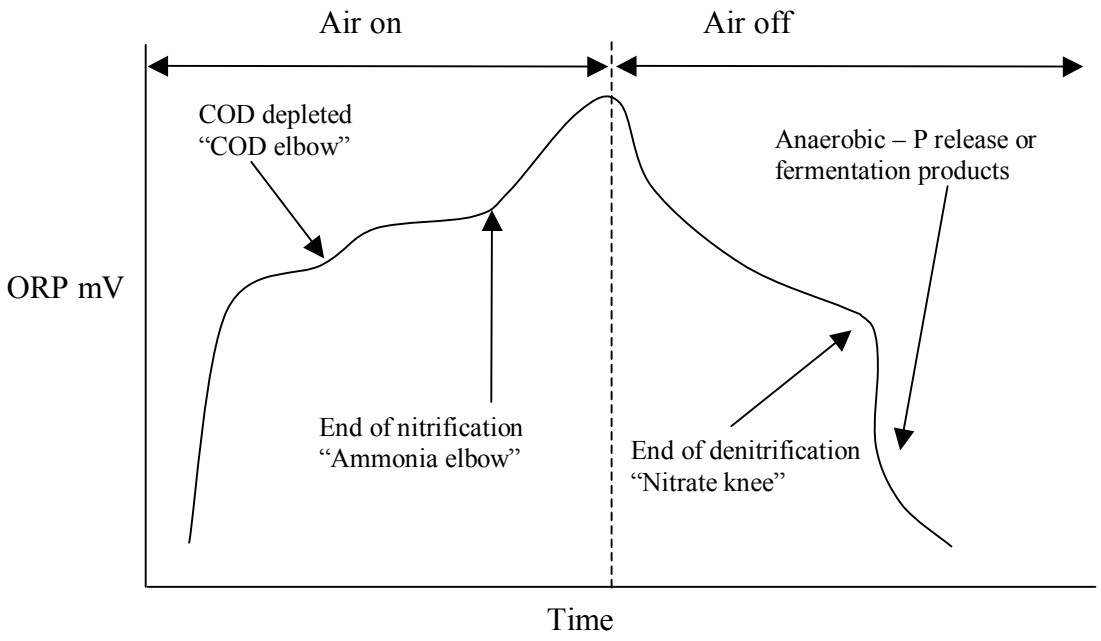

Figure 1.1 Exaggerated ORP profile for an intermittent aeration wastewater treatment system without P removal.

Bending points in ORP profiles have been used for on-line control, but there are several factors which influence whether bending points are evident when monitoring. When a system is fed, it experiences a large drop in ORP; this drop is due to addition of NH_3-N, COD, P, and other ions which contribute to the portion of the mixed liquor that

needs to be oxidized. When influent feeding is semi-continuous, it can cause a point reading to be masked or it does not provide sufficient organic carbon inhibiting denitrification; both problems can cause the failure of online systems by missing air-on or air-off period (Kim and Hao, 2001). Another problem that can occur with feeding, is when it does not occur at the onset of non-aeration, a residual DO can be present for sometime allowing the ORP to remain stable or even rise, inhibiting the onset of denitrificaiton (Kim and Hao, 2001; Lie and Welander, 1994). As a result, in online systems, it is preferred to feed at the beginning of the anoxic period, causing the ORP to decrease rapidly due to feeding and adding COD needed for denitrification. This allows the nitrate knee to be observed later in the period because it is not masked by additional feedings (Paul et al., 1998). Therefore, online ORP systems tend to work if there is no missed feedings and the ion concentration in the influent remains relatively constant.

Past research has proven that single probe monitoring with ORP is the main choice in online systems. In dynamic influent systems such as food processing plants, swine waste treatment, and chemical waste management, ORP systems could experience failure. Fluctuations in influent ion concentration, pH, and temperature will influence the profile, by making it larger or smaller, which may cause a failure in bending points in the systems (Al-Ghusain et al., 1995; Henduit and Thevenot, 1992). In systems which utilize a fairly homogenous influent, such as domestic wastewater, single probe ORP monitoring is possible, but there is still a possibility of failure due to masking by biological reactions. Treatment systems maintaining removal of P could fail because of major P uptake during aeration masking the ammonia breakpoint and fermentative products in the anoxic period mask the nitrate knee (Zipper et al., 1998).

Online ORP systems are also criticized because there is variation of ORP readings between probes. Changing a probe in a system has caused a large difference in reading and missed points (Al-Ghusain et al., 1995). Systems that utilize only ORP control must do so realizing that failure could occur with a switch in probe. So, while ORP appears efficient in some cases there is always the possibility of failure of the online system due to influx ions, missed feeding, and probe change. To combat these possibilities, additional probes which monitor online control of DO and pH will aide the system characterization. These curves also express bending points that visualize change in the substrate which occur in the mixed liquor of the system.

1.3.2.2 Dissolved Oxygen

Dissolved oxygen is an important parameter for waste management systems that use biological nitrification/denitrifcation for N removal. It is especially important for IA systems where all biological reactions occur within the same reactor. Inadequate or overabundance of oxygen can inhibit nitrification or denitrification, respectively. There is again a question of what level of DO must be reached to provide sufficient oxygen for complete nitrification to occur.

The U.S. EPA suggests that in an activated sludge system, a DO concentration of 2.0 mg/L be maintained for full nitrification (U.S. EPA, 1993). Since most IA systems run on reduced hydraulic retention times (HRTs), it is believed that an increased DO is required to reach full nitrification. Earlier researchers suggest that the DO should be maintained above 3.0 mg/L for nitrification to reach desired levels of removal (Choung and Kim, 1999). Again, similar to ORP, this level has been disputed, because N removal

has been achieved in extremely low DO environments of less than 1.0 mg/L (Holman and Wareham, 2003; Kishida et al., 2003; Murray et al., 1974). As a result, various levels of DO have achieved N removal.

While aeration must be provided for nitrification to occur, the denitrification occurs in the absence of oxygen. Oxygen levels must drop significantly for full denitrification to occur in the reactor environment; the USEPA suggests that levels less than 0.3 to 1.5 mg/L for activated sludge systems (U.S. EPA, 1993). Many researchers have found that a good habitat for denitrification is one devoid of any oxygen, finding that oxygen levels above 0 mg/L will inhibit denitrifying microorganisms (Lie and Welander, 1994). It is therefore important that IA reactors maintain a low level of DO during the anoxic period for denitrification to occur in a set cycle time.

The DO decrease in set-cycle IA systems is a parameter that is influenced by the reactor's feed cycle. If feed does not occur simultaneously with the beginning of anoxic period, DO drops slowly (Kim and Hao, 2001). During the period of descent, nitrification is still being achieved by autotrophic nitrifiers, while DO inhibits NO_3-N reduction by denitrifiers. This can hinder a system which is operating under reduced HRT to complete nitrification/denitrification in a set cycle time. Under a manually controlled system, it is recommended to feed at the onset of anoxic period to allow for complete denitrification in the set time. Feeding of the influent is less of an influence in online computer systems, because the system is controlled by the reading of a bend. It is still recommended to feed at the beginning of the anoxic period so no masking occurs with influent ion addition.

Online systems that utilize measuring DO curve as a basis for air-on/air-off are usually coupled with ORP because the end of denitrification is not indicated on the DO profile. Other reasons for probe coupling are DO probes have been shown to experience measurement problems by not dropping to 0 mg/L with low oxygen and systems with extensive amounts of floc (Lie and Wielander, 1994). These inaccuracies of probes only occur in these instances and DO profile almost always show the ammonia elbow better than ORP profile (Henduit and Thevenot, 1989). DO profiles which accomplish low levels of NH_4-N in their effluent show a low DO profile at the beginning of an aeration cycle and experience a sharp increase once NH_3-N utilization has been accomplished by nitrifiers, presented in Figure 1.2 (Cho et al., 2001; Demoulin et al., 1997; Henduit and Thevenot, 1989; Paul et al., 1998).

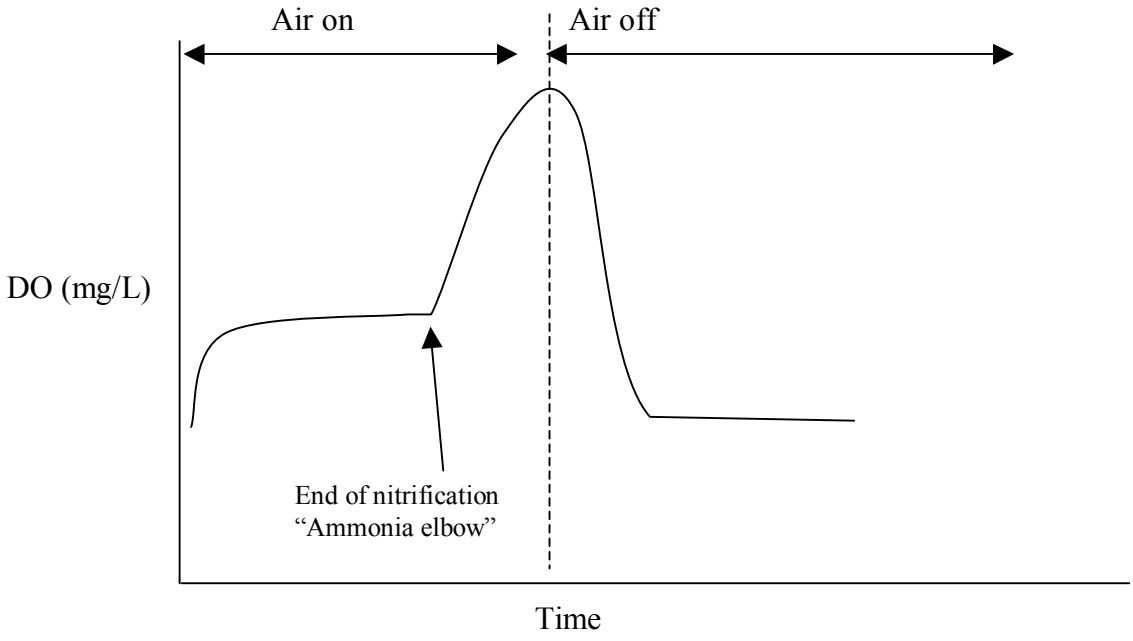

Figure 1.2 Exaggerated DO profile for an intermittent aeration wastewater treatment system without P removal.

This rapid increase is caused by a reduction in oxygen utilization rate (OUR) by the microorganisms because the NH_4-N is completely reduced to NO_3-N (i.e. nitrification was less than the amount of oxygen supplied) (Cho et al., 2001; Kishidia et al., 2003). If N removal is the target nutrient, after the peak has occurred the aeration period can conclude through online control but if P removal is desired aeration needs to continue for aerobic uptake (Kishidia et al., 2003).

Still, some IA systems never accomplish an ammonia elbow because they are maintained at low levels of oxygen or are fed high ammonia influent. In these cases, online control using a DO probe is inadequate because there is nothing to measure on the curve. The DO curve experiences a plateau because the OUR is greater than NH_4-N oxidation causing the peak to be absent (Paul et al., 1998). These systems can still maintain large amounts of N removal but again online control of DO is useless unless it is coupled with another parameter, such as pH or ORP.

1.3.2.3 pH

Controlling pH in systems that practice N removal is an important factor because there is a narrow range at which both nitrifying and denitrifying microorganisms perform optimally. Nitrifiers are not as resilient as denitrifiers so systems are usually run to optimize their growth while still allowing a minimal range for denitrifier growth (Praksam and Loehr, 1972). Maintaining a range could present a problem in systems that utilize separate tanks for aeration and anoxic periods, which is why IA presents an opportunity to maintain a stable pH.

Nitrification releases two hydrogen ions ($2H^+$) for every NH_4-N ion oxidized. This H^+ release could cause a drastic drop in pH if there is no hydroxyl ion (OH^-) recovery. Denitrification aides in recovery and pH maintenance with the release of one OH^- for every NO_3-N reduced (Madigan et al., 2003; Praksam and Loehr, 1972). In IA tanks with cycling of oxic/anoxic, there is usually no need for additional salts to maintain the pH range because there is a natural recovery (Cheng and Liu, 2001). The alkalinity of the influent wastewater is usually high enough to allow small fluctuations in hydrogen concentration to go unnoticed in the mixed liquor's pH. The small range of optimum growth and minimal change in pH present a problem in online control for IA systems.

Researchers first began controlling systems with pH by setting minimum and maximum values at which air would be turned on or off when the value was obtained (Al-Ghusain and Hao, 1995). Al-Ghusain and Hao (1995) set pH values for nitrification and denitrification, at 6 and 8, and found that it took several hours to reach these set values. Therefore, this control was quickly abandoned as they realized that biological reactions occurred too slowly and uneconomical. More research revealed an easier way to maintain control of a system through pH, again thru monitoring of the curve during the periods (Al-Ghusain and Hao, 1995; Al-Ghusain et al., 1994).

Plotting pH through oxic/anoxic periods revealed similar peaks and valleys to the ORP and DO graphs, Figure 1.3. Again, these bending points occur on the pH curve when the system terminates an oxidation/reduction reaction (Al-Ghusain et al., 1994 and 1995). During nitrification, the pH drops until all NH_4-N is oxidized to NO_3-N. This point is described as the ammonia valley which corresponds to the DO elbow on the

ORP and DO curve. Once this has occurred in the system, the pH tends to experience a small rise caused by stripping of carbon dioxide to the atmosphere. As denitrification begins, the pH shifts upwards as NO_3-N is reduced to N_2 gas and OH^- ions are released. Completion of denitrification is manifested by the nitrate apex appearing as the highest point during the anoxic period corresponding to the nitrate knee on the ORP curve (Al-Ghusain et al., 1994 and 1995; Kishidia et al., 2003; Spagni et al, 2001).

After the apex, the pH of the system begins to drop noticeably at the end of denitrification due to anaerobic conditions in the reactor. These conditions release H^+ ions from fermentation products which cause pH to drop.

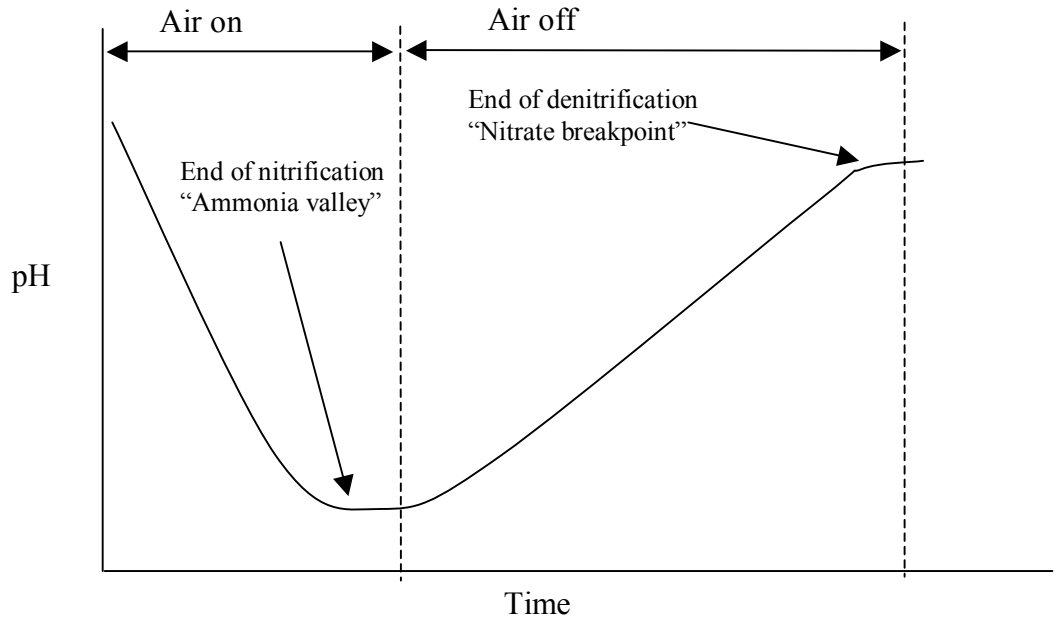

Figure 1.3 Exaggerated pH profile for an intermittent aeration wastewater treatment system without P removal.

Recognizing bending points on the pH curve can cut operation costs by realizing the dynamic waste profile and reacting to it. Nevertheless, most operations couple pH

with other online parameters to insure that points are not missed. Even though operator preference is coupling of probes, the pH curve is believed by some to be more reliable than ORP (Al-Ghusain et al., 1994 and 1995). The ORP is subject to varying readings due to ion concentration of the influent and probe switching, while pH is not. An online system using pH can exchange probes and experience no discrepancy in readings when compared to the previous probe. Like other online control systems, pH is not always reliable which can cause the system to fail because of misreading of points due to various parameters. The NO_3-N apex has a tendency to be masked because of feeding, continuation of nitrification, and the occurrence of biological processes in the waste.

1.4.1 Online versus Manual

Online systems appear to provide a more efficient control of wastewater treatment systems by reducing aeration costs and providing an optimum habitat for N removal. These controls also seem to meet difficulties in a dynamic, extreme, or deficient waste profile. Due to these problems, use for swine waste has met little research in online controls.

Kishidia et al. (2003) monitored SBRs for use of online control using ORP and pH for nutrient removal from anaerobic swine waste. They observed that the low C/N ratio inhibited the appearance of the nitrate knee (ORP) and the nitrate apex (pH) because denitrification was incomplete. This caused the accumulation of NO_3-N and thus failure of the systems online controls. To remedy the problem they added swine slurry as an external carbon source to enhance the C/N ratio. After this addition both nitrification and denitrification proceeded to completion. Online control of anaerobic

swine waste will only exhibit efficient results with the addition of an organic carbon source to allow bending point readings.

Domestic treatment on the other hand has meet many successes in online control. In one study, Spagni et al. (2001) experienced success in online control using ORP and pH for N and P removal from a synthetic domestic waste profile. They found that pH was more reliable to monitor P removal and uptake than ORP but full monitoring was not accomplished with the basic online system in use. The conclusion was to research a more complicated system that uses fuzzy logic and neural network to provide optimum removal using online controls. Applying the same system to swine waste will not accomplish the same results because the waste contains high substrate levels and inerts not found in synthetic waste. Using a similar system will take expansive research which uses both time and money; in short this is not useful to accomplish the goals of the industry. Instead manual monitoring systems with set ANA and cycle time will sufficiently achieve removal and be practical to the swine industry.

1.4 CONCLUSIONS

Online systems are more efficient with measuring complete nitrification and denitrification in domestic wastewater treatment systems. Online systems using swine wastewater as an influent have not been researched extensively. Therefore more research should be conducted before applying an online system to a full scale swine wastewater treatment facility. Once this criterion has been met and proved successful, online systems could be used. But in the mean time manual operation is the most efficient system to use for IA control.

1.5 RESEARCH OBJECTIVES

The purpose of this research was to expand on previous research by Cheng and Liu (2001) in intermittent aeration for nitrogen removal from swine wastewater by optimizing reactor performance. The objectives of this study were:

(1) To determine the influence of COD/TKN ratio on nitrogen removal by varying the percentage of anaerobically pretreated swine wastewater (APTSW) and raw swine wastewater (RSW) in the influent.

(2) To determine the influence of aeration/non-aeration (ANA) ratio on the removal of nitrogen from APTSW.

(3) To determine the influence of cycle time on nitrogen removal from APTSW.

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CHAPTER 2

OPTIMIZATION OF INTERMITTENT AERATION FOR N REMOVAL FROM SWINE WASTEWATER: INFLUENCE OF COD/TKN AND AERATION-TO-NON-AERATION RATIOS

2.1 MATERIALS AND METHODS

The purpose of this study was to determine the effect of chemical oxygen demand (COD)/total Kjeldahl nitrogen (TKN) and aeration-to-non-aeration (ANA) ratios on nitrogen (N) removal from swine wastewater in two intermittent aeration (IA) reactors (Cheng and Liu 2000). Different COD/TKN ratios were tested by varying the ratio of anaerobically pretreated swine wastewater (APTSW) to raw swine wastewater (RSW) in the influent of the IA reactors. APTSW was obtained from a hog lagoon and RSW from a settling basin, at North Carolina State University's Lake Wheeler Swine Unit weekly. Three different aeration-to-non-aeration (ANA) ratios were also tested in this study.

2.1.1 Intermittent Aeration

Two lab-scale semi-continuous flow intermittent aeration (IA) reactors were set up and operated in Weaver Labs at North Carolina State University (NCSU) at room temperature (23°C). Each of the plexi-glass reactors was 8 L in total volume with a separation board to provide 6 L of mixed liquor zone and 2 L of clarification zone. Compressed air of 20 psi was used for aeration. Airflow rate was regulated by mass flow controllers (Cole Palmer) before entering the reactors. Fine-bubble aeration was provided for each reactor through two cylindrical stone diffusers (Fisher Scientific Company) that were placed at the bottom of the mixed liquor zone. No mixing was provided during the non-aeration period.

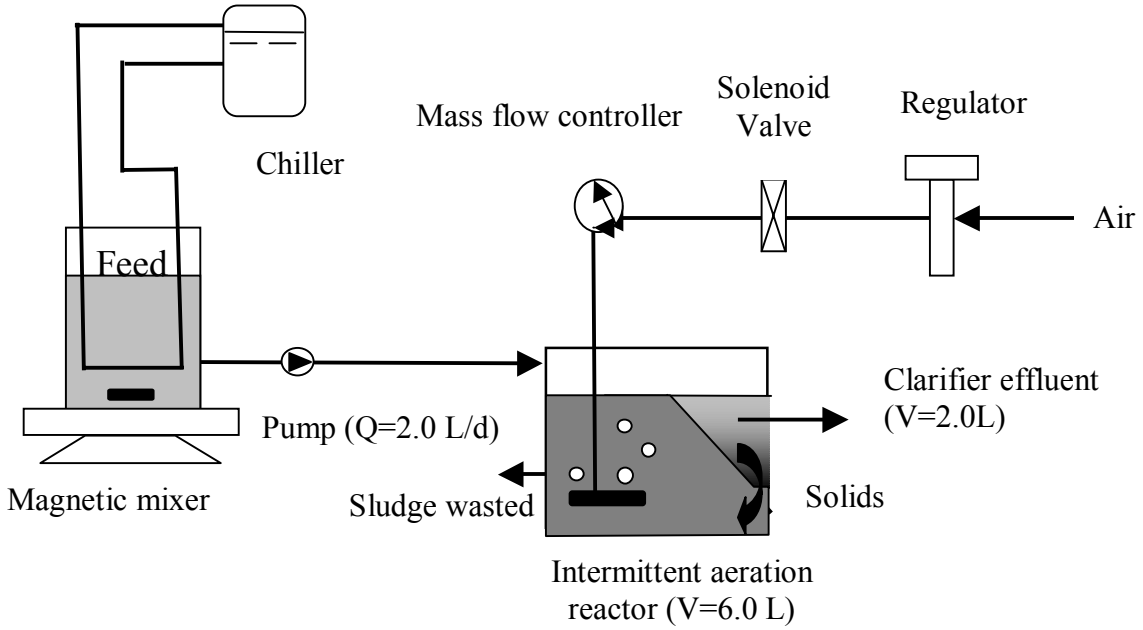

Figure 2.1 Diagram of intermittent aeration tank and influent feed for APTSW and RSW treatment.

Electronic timers (ChronTrol Corporation) controlled the operations of the solenoid valves that controlled the on and off of the aeration and peristaltic pumps that fed the reactors. Air flow was set at 500 mL/min by the mass flow controllers. Influent was delivered by peristaltic pumps (Masterflex Pump and Drive) at the beginning of each hour to maintain a 3 day hydraulic retention time (HRT). The influent APTSW and RSW was obtained from the Lake Wheeler Road Field Laboratory of NCSU and was held chilled at about 4°C in 5 gallon tanks (~18.93 L), to control odor and minimize biological reactions, with continuous mixing.

Sludge was wasted from a spigot in the IA reactor zone at a rate of 200 mL/day. Wasting occurred from the mixed liquor during aeration, when the solids appeared

mixed, to maintain a solids retention time (SRT) of 20 days. Different ratios of COD/TKN and ANA in the influent were tested during this study.

2.1.2 Measuring Influence of COD/TKN and ANA ratio on Nitrogen Removal

The study began with two reactors, A and B, from February 14, 2001 to May 19, 2002 (459 days). The COD/TKN was increased during this study by increasing the ratio of RSW to APTSW. Influent was adjusted as follows:

February 14 to November 26, 2001: 0:100 RSW to APTSW

November 26, 2001 to May 19, 2002: 50:50 RSW to APTSW

In the reactors A and B, ANA ratios were altered accordingly with COD/TKN influence to obtain data from each period:

February 14 to September 17, 2001: A: 1 h: 1 h and B: 1 h: 1h

September 17 to November 19, 2001: A: 1 h: 1 h and B: 1 h: 2 h

November 19, 2001 to May 19, 2002: A: 1 h: 1 h and B: 1 h: 3 h

Table 2.1 Qualitative representation of testing periods of parameters COD/TKN and ANA ratios tested.

0:100 RSW to APTSW, 285days		50:50 RSW to APTSW, 194 days
A 1 h: 1h, 459 days		
B 1h: 1h, 214 days	B 1h: 2h 64 days	B 1h: 3h 181 days

2.1.4 Analytical Methods

Samples, each 400 ml, were collected once a week from the influent and mixed liquor of the IA reactors. Sampling time was during the aeration period. The samples were analyzed for total nitrogen (TN), TKN, NH_3-N, NO_3-N, NO_2-N, COD, total organic carbon (TOC), total phosphorus (TP), ortho-phosphate (*o*-PO_4-P), total and

volatile suspended solids (TSS and VSS), chemical oxygen demand (COD), and pH in the Environmental Analysis Laboratory in the Biological and Agricultural Engineering (BAE) Department of NCSU. Standard Methods (APHA, 1995) were used for the analyses. TN in the effluent of the reactor was calculated based on the assumption that VSS from the clarifier was negligible. Therefore TN calculated in the effluent of an IA reactor contained little or no organic nitrogen (TKN-Organic Nitrogen + NO_3 + NO_2-N = TN).

2.2 RESULTS AND DISCUSSION

2.2.1 Influence of COD/TKN and ANA ratio on Nitrogen Removal

Nitrogen removal was observed in both Reactors A and B, with average TN removal of 78% (A) and 73% (B) February 14, 2001 to May 19, 2002. Fluctuations of SCOD and nutrient concentrations in the influent (Table 2.2) did not present problems for the NH_3-N (mg/l) removal performance of the reactors (Figure 2.2).

Table 2.2 Average and standard deviations of analyzed parameters for the Influent from February 14, 2001 to May 19, 2002.

	Influent
TN (mg/L)	210± 51
NH_3-N	140 ± 25
NO_x-N (mg/L)	
pH	7.76± 0.16
SCOD (mg/L)	365 ± 148

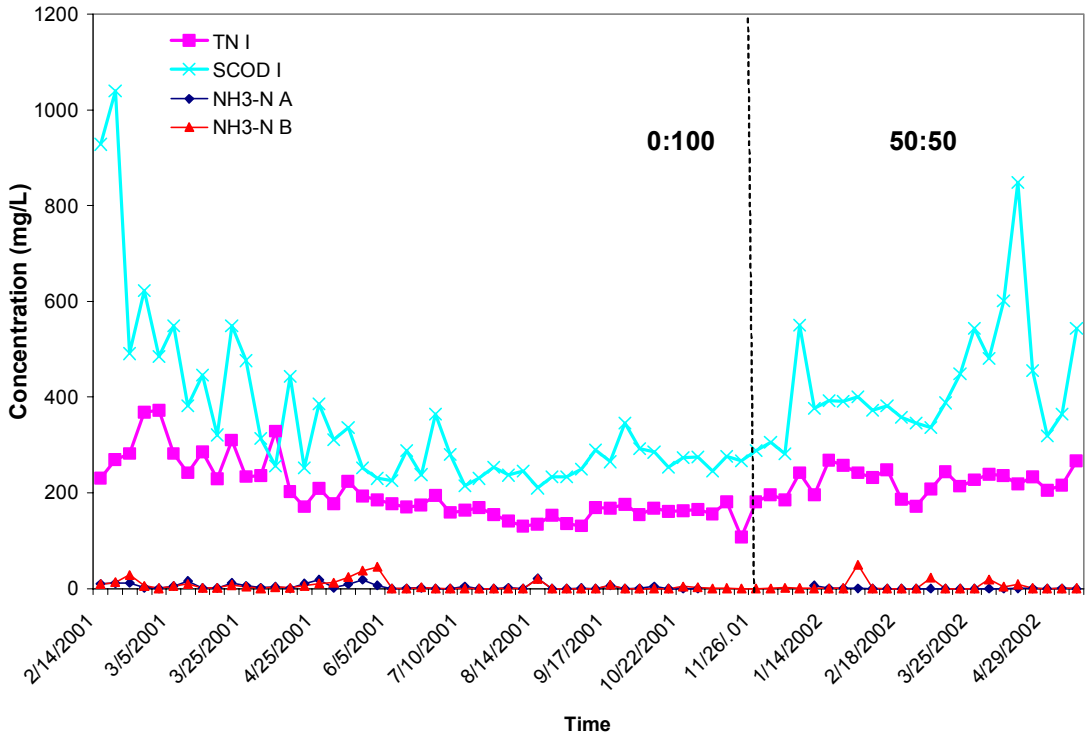

Figure 2.2 Influent concentration of TN and SCOD effect on Reactor A and B NH_3-N (mg/L) February 14, 2001 to May 19, 2002.

Low NH_3-N in the effluent of each reactor signified that nitrification was not influenced by SCOD and nutrient fluctuations in the influent (Figure 2.2). By providing the necessary dissolved oxygen through one hour of aeration, Reactors A and B both achieved high levels of nitrification.

As previously stated NH_3-N removal was unaffected by our test parameters SCOD/TKN and ANA ratio. SCOD is of special concern in N removal from anaerobically pretreated swine wastewater because of the high NH_3-N content and low TKN/COD ratio (Bicudo and Svoboda, 1995; Cheng and Liu, 2000). Reactor A did experience variation in TN% removal and NO_x-N (mg/L) concentration due to COD/TKN ratio; 0:100 February 14, 2001 to November 26, 2001 and 50:50 December 12, 2001 to May, 2002 (Figure 2.3 and Table2.3).

Table 2.3 Influence of COD/TKN ratio on average nitrogen removal from Reactor A (1h:1h).

	Influent		Effluent A 1h:1h	
	0:100	50:50	0:100	50:50
TN (mg/L)	200	227	55	30
NH_3-N (mg/l)	131	162	4.50	0.86
NO_x-N (mg/L)			50.7	30.0
TN % Removal			70%	86%
NH_3-N % Removal			97%	100%
SCOD (mg/L)	336	431	171	193
SCOD/TKN ratio	1.73	1.97		
TOC (mg/L)	186	303	93	69
TOC/TKN ratio	1.12	1.33		
VSS (mg/L)	673	703	2018	1312

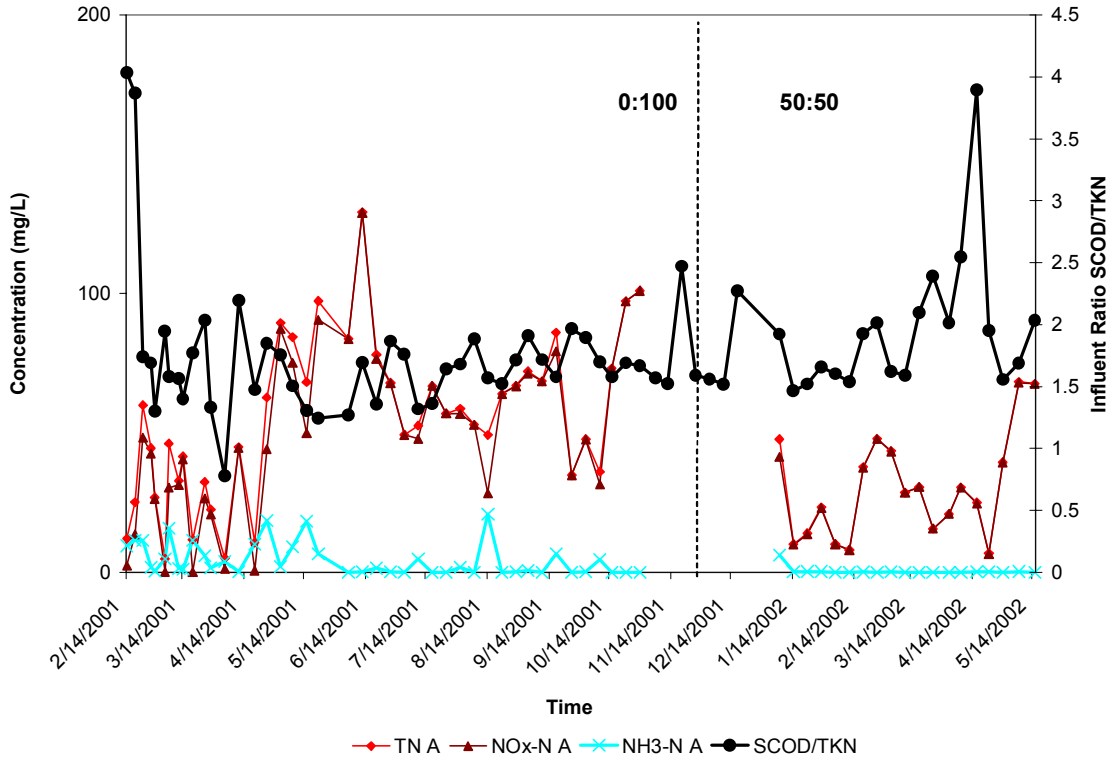

Figure 2.3 Influent SCOD/TKN ratio effect on Reactor A's N removal, February 14, 2001 to May 19, 2002.

Increasing the ratio of RSW to APTSW in the influent elevated levels of SCOD from 336 to 431 (mg/L). Conversely the SCOD/TKN ratio increased from 1.73 to 1.97. This small difference in SCOD/TKN ratio allowed TN% removal to increase from 70% to

86% in Reactor A (1h:1h). The increase was due to increased denitrification because NO_x-N concentration decreased in the effluent of the reactor, 50.7 to 30.0 (mg/L). Increased denitrification occurred in the reactor because SCOD (organic carbon) is the elector acceptor for microorganisms which perform nitrate reduction (Madigan et al., 2003). Therefore increased SCOD and SCOD/TKN ratio allowed the reactor to reduce additional N through denitrification.

Although the SCOD/TKN ratio increased it was still under the domestic wastewater treatment standards with a suggested range of 5.1 to 9.1 (Tseng et al., 1997). Tseng et al. (1997) found that a COD/N ratio below 5.1 allowed incomplete denitrification and accumulation of nitrite. In the IA reactor tested in our study there appeared to be no accumulation of NO_x-N at the 50:50 ratio influent. Therefore it is believed that our IA swine wastewater system was able to maintain significant denitrification without maintenance of high ratios because of solubilization of influent solids, degradation of biomass, and use of other available organics as an electron acceptor.

Using values in Table 2.3 we can evaluate where SCOD for denitrification was provided when the influent increased to a 50:50 ratio.

Calculation 1: If we assume that all TN was removed by denitrification via NO_3-N then there is a requirement of 2.86 mg/L COD per 1mg/L NO_3-N (USEPA, 1993).

TN removed =

$$227\,{}^{mg}\!/_{L}\,(0.86) = 195\,{}^{mg}\!/_{L}$$

SCOD required for denitrification =

$$195\,{}^{mg}\!/_{L} \times 2.86\,{}^{mgSCOD}\!/_{mgNO_3 - N} = 558\,{}^{mg}\!/_{L}$$

SCOD remains in effluent. Therefore, SCOD balance =

$$558\,{}^{mg}\!/_{L} + 193\,{}^{mg}\!/_{L} = 751\,{}^{SCOD}\!/_{L}$$

Then SCOD that comes from solubilization of solids or soluble microbial products =

$$751\,{}^{SCOD}\!/_{L} - 431\,{}^{mg}\!/_{L} = 320\,{}^{mg}\!/_{L}$$

Calculation 2: Assume that only influent VSS is degraded, COD/VSS ratio = 1.4 (Metcalf and Eddy, 2003), degradation of VSS creates 80% SCOD and 20% particulate COD (conversion never 100%).

Total SCOD available from influent VSS =

$$703\,{}^{mg}\!/_{L} \times 1.4 = 984\,{}^{mgSCOD}\!/_{L}$$

VSS to be degraded to satisfy denitrification using nitrate SCOD requirements =

$$320\,{}^{SCOD}\!/_{L} \div 0.80 \div 1.4 = 286\,{}^{VSS}\!/_{L}$$ (Around 40% of initial VSS)

Looking at the difference between influent and effluent VSS =

$$703\,{}^{mgVSS}\!/_{L} - 1312\,{}^{mgVSS}\!/_{L} = -609\,{}^{mgVSS}\!/_{L}$$

The difference between influent and effluent VSS is negative because microorganism growth within the reactor elevated the amount of VSS (biomass). Calculating solubilization of the influent waste stream based only on its VSS is an incomplete assumption. Therefore there were other mechanisms besides VSS solubilization allowing the denitrification to occur. Additional organic carbon was probably supplied by breakdown of other organic materials from the influent that were unmeasured in the lab.

Nitrogen removal was also effected by ANA ratio. By comparing reactors A (1h:1h) and B(1h:3h) at the same influent ratio (50:50), revealed differences in removal efficiency (Table 3.4).

Table 2.4 Influence of ANA ratio on nitrogen removal, November 19, 2001 to May 19, 2002

	Influent	Effluent A 1h:1h	Effluent B 1h: 3h
	50:50	50:50	50:50
TN (mg/L)	227	30.4	21.3
NH_3-N (mg/l)	162	0.86	5.69
NO_x-N (mg/L)		30.0	15.61
TN % Removal		86%	91%
NH_3-N % Removal		100%	96%
SCOD (mg/L)	431		
SCOD/TKN ratio	1.97		
TOC/TKN ratio	1.33		

When the non-aeration period (anoxic) increased in an IA reactor there was a significant NO_x-N (mg/L) reduction (Table 2.4). Recall the IA reactors operate with semi-continuous flow, therefore reactor B (1h:3h) had to efficiently remove two times more NH_3-N than reactor A(1h:1h). While increasing the non-aeration time increased the amount of NH_3-N that had to be oxidized in one hour of aeration it also supplied more SCOD from the two extra feedings. Therefore additional organic carbon and a longer anoxic reaction period enhanced denitrification in Reactor B. Similarly, Cheng and Liu (2000) found in their study that increasing the ANA ratio in semi-continuous feed reactors increased denitrification efficiency.

A slight reduction in NH_3-N removal efficiency occurred in Reactor B as compared to A, from 100% to 96% (Table 2.4). In similar studies when cycle time increased to 4 hours, nitrification efficiency decreased slightly and denitrification efficiency increased (Cheng and Liu, 2000; Bicudo and Svoboda, 1995; Osada et al.,

1991). This decrease in NH_3-N was not significant and other studies suggest that the aeration fraction could be reduced further while providing good TN removal, depending on the level of effluent quality that is desired (Cheng and Liu, 2000; Hu et al., 2003; Osada et al., 1991).

2.3 CONCLUSIONS

Based on the experimental results we can make the following conclusions:

(1) The amount of SCOD in the influent will influence the TN removal from swine wastewater in the IA reactor. Higher influent SCOD/TKN ratio would improve denitrification in the IA process and therefore increase TN removal efficiency. However, SCOD did not appear to influence NH_3-N removal, since nitrification is not dependent on SCOD.

(2) As ANA decreased, the NO_x-N in the effluent decreased in the IA reactor and TN removal efficiency increased because of improved denitrification with longer anoxic time with influent feedings, thus increasing denitrification.

(3) High TN and NH_3-N removal efficiencies can be achieved in the IA process with reduced daily aeration fraction down to 0.25.Cost reduction will be possible with IA process because of less aeration time when compared to full aeration systems, while still achieving significant NH_3-N removal efficiency.

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CHAPTER 3
OPITMIZATION OF INTERMITTENT AERATION FOR N REMOVAL FROM SWINE WASTEWATER: INFLUENCE OF AERATION TO NON-AERATION RATIO, CYCLE TIME, AND AMMONIA LOADING

3.1 MATERIALS AND METHODS

In this study, five IA reactors with different ANA ratios and cycle times were used for nitrogen removal from anaerobically pretreated swine waste (APTSW). The influence of ANA ratio, cycle time, and ammonia loading on N removal in the IA process were investigated. The source of influent was APTSW from NCSU's Lake Wheeler Swine Unit. Once a week four five gallon containers were filled with APTSW pumped from the lagoon using a hand pump (electric peristaltic pump beginning in March 2003). Oxidation reduction potential (ORP), dissolved oxygen (DO), pH, and N profiles during the IA cycles were also studied to better understand the fundamentals of the IA process.

3.1.1 Intermittent Aeration

Three new reactors C, D, and E were added in this study, plus the Reactors A and B described in Chapter 2 remained intact. The configuration of the new reactors was the same expressed in Chapter 2. The reactors were feed APTSW semi-continuously at the top of each hour. The SRT was greater than or equal to 20 days and was maintained by removing volatile suspended solids (VSS) from the mixed liquor zone every day or every other day based on lab analysis.

The five reactors were run from 5/20/02 – 9/23/03. Influent in this study was 100% APTSW. The operations of the reactors during this time are shown in Table 3.1.

Table 3.1 IA operations in five reactors testing the influence of ANA ratio and cycle time on N removal from anaerobically treated swine wastewater.

Reactor	Aeration: Non-aeration (hr:hr)	Cycle Time (hr)	Daily Aeration Fraction
A	1:1	2	0.5
B	1:3	4	0.25
C	0.5:1.5	2	0.25
D	0.5:2	2.5	0.2
E	1:4	5	0.2

3.1.2 Monitoring and Analytical Methods

Samples were collected once a week from the influent and effluent of IA reactors. Sampling time was during the aeration period. The amount sampled was 400 mL as specified by Standard Methods for the parameters measured (APHA, 1995).

The samples were analyzed by the Environmental Analysis Laboratory in the BAE Department at NCSU. The reactors were monitored for total nitrogen (TN), TKN, NH_3-N, NO_3-N, NO_2-N, COD, total organic carbon (TOC), total phosphorus (TP), ortho-phosphate (*o*-PO_4-P), total and volatile suspended solids (TSS and VSS), chemical oxygen demand (COD), and pH. All the analyses were conducted according to Standard Methods (APHA, 1995).

The DO, ORP and pH were continuously measured in each reactor over at least three ANA cycles for each reactor. A YSI 5739 oxygen probe and YSI 52 DO meter (YSI Inc., Yellow Springs, Ohio) were used to measure DO manually. The ORP was measured using an Accumet metallic combination platinum/Ag/AgCl electrode (EID Corp., Bridgeport, Connecticut) with data recording by LabView data acquisition software (Version 5.1, National Instruments Corp., Austin, Texas). The pH was measured with a pH probe connected to a pH meter with an internal data log (Denver

Instruments, Model 250 pH-ISE-conductivity meter). Set up for the measurements is presented in Figure 3.1.

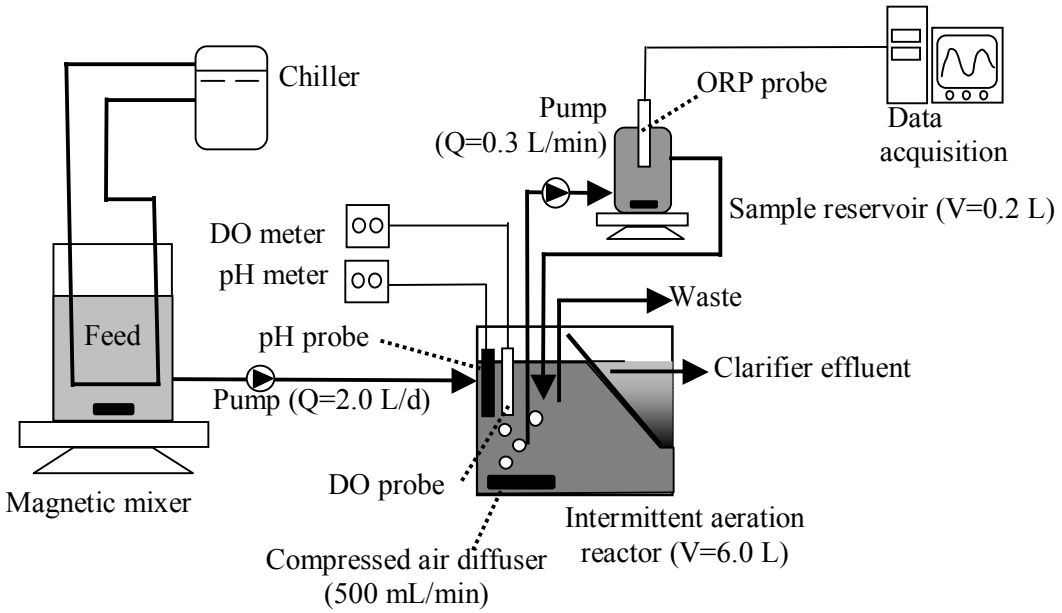

Figure 3.1 Configuration of intermittent aeration of APTSW with on-line DO, ORP, and pH measurement.

Profiles of N species (NH_3-N, NO_3-N and NO_2-N) were also monitored for the IA reactors. Samples were taken every 10 min during aeration and every 20 min during non-aeration in a cycle. The nitrification and denitrification rates were obtained by determining the slope of the best fit line during nitrification (aeration period only) and denitrification (non-aeration period only). By plotting time versus accumulation or assimilation of a N constituent rates were determined.

3.2 RESULTS AND DISCUSSION

3.2.1 Intermittent Aeration

3.2.1.1 Influence of ANA Ratio and Cycle Time on N Removal

Regardless of fluctuations in influent quality, removal of TN was good after microbial culture was established in the new reactors (Table 3.2).

Table 3.2 TN% Removal from all reactors during three periods in Phase II Start-up.

Period with TN% and NH_3-N% removal from Influent							
IA reactor	Influent TN (mg/L)	**5/16-6/24/02***		**7/2-8/12/02***		**8/13-9/16/2002***	
		TN	NH_3-N	TN	NH_3-N	TN	NH_3-N
A	**236 ± 37**	77%	100%	62%	48%	80%	75%
B		95%	100%	76%	66%	94%	98%
C		48%	36%	69%	66%	90%	99%
D		48%	34%	67%	56%	92%	98%
E		48%	26%	66%	55%	87%	99%

*Start-up time was chosen based on qualitative observation when new reactors C, D, and E began good N removal. Reactors A and B were continuously run from the previous phase. Periods were then divided to contain nearly two SRTs.

In the beginning (May 16 to June 24, 2002), TN removal was poor for all three new reactors. Because the microbial culture was not established in the reactors it took several months to maintain high TN removal. It takes at least three SRTs to establish a good culture to accomplish the desired nutrient removal. Reactor A also experienced TN removal difficulties in the first period with removal efficiency of 77%, due to deficiency in denitrification (Figure 3.2).

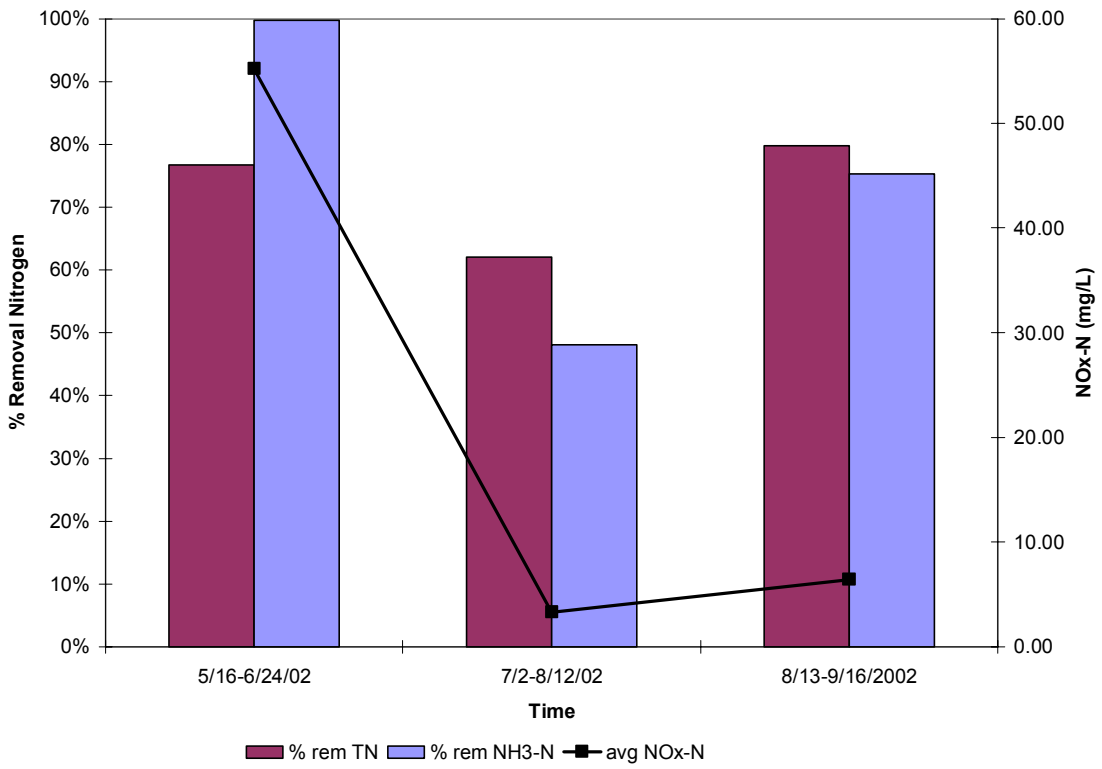

Figure 3.2 TN and NH_3-N % removal and average NO_x-N (mg/L) in Reactor A .

Reactor A (1h:1h) operates at the highest daily aeration fraction (0.5). Therefore reactor A was able to oxidize significant amounts of NH_3-N, 5/16 to 6/24/02 (Figure 3.2). Thus denitrification deficiencies were linked to overabundance of nitrification activity, lack of COD for denitrification, and insufficient mixing during non-aeration (Nagaoka et al., 2002).

Both reactors A and B TN removal efficiency drop (July 2 to August 12, 2002) this change was caused by decreased NH_3-N removal (Figures 3.2 and 3.3).

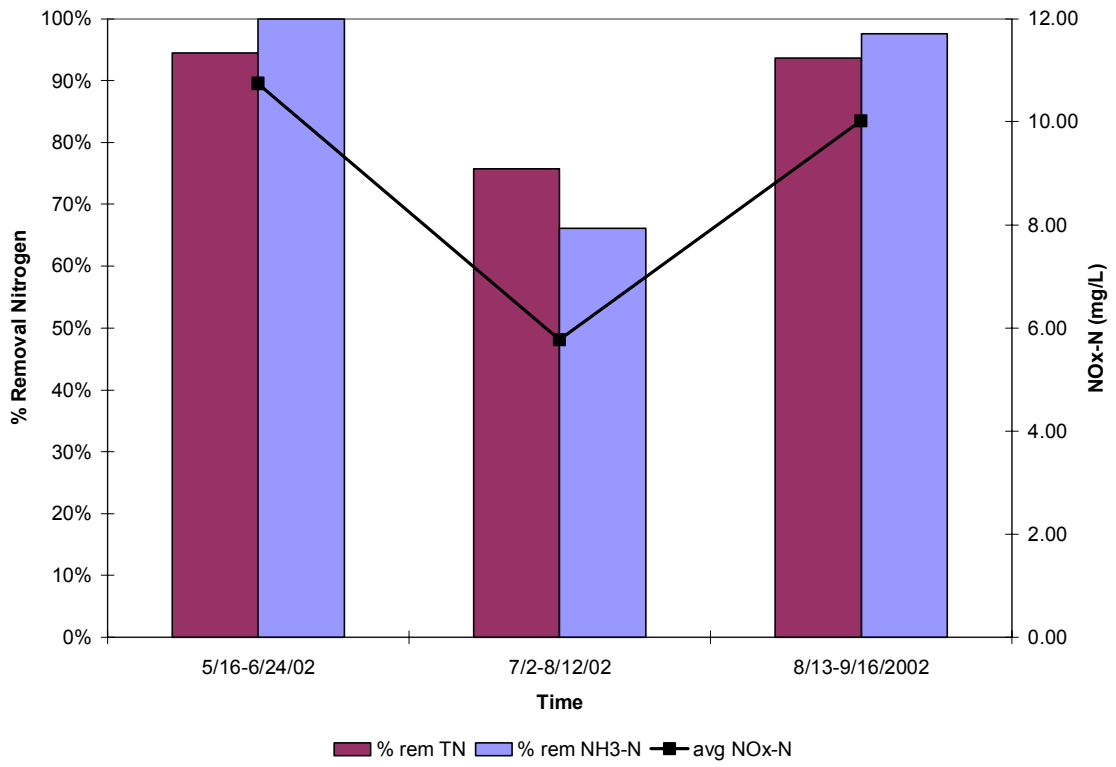

Figure 3.3 Reactor B TN and NH_3-N % removal and average NO_x-N (mg/L).

During this period nitrification, not denitrification, was inhibited in Reactors A and B, causing NH_3-N removal to decrease. Problems with TN removal were not due to NO_x-N removal because NO_x-N concentration decreased from 55 and 10.7 mg/L in the previous period to 3.3 mg/L and 5.8 mg/L in Reactors A and B, respectively. It appeared that denitrifying bacteria during the second period were performing good reduction of NO_x-N. Therefore, establishing cause for a decrease in NH_3-N removal required reviewing measured parameters such as VSS (mg/L) and pH (Figures 3.4 and 3.5). During the second period, the new reactors C, D, and E experienced a rise in TN removal (Table 3.2).

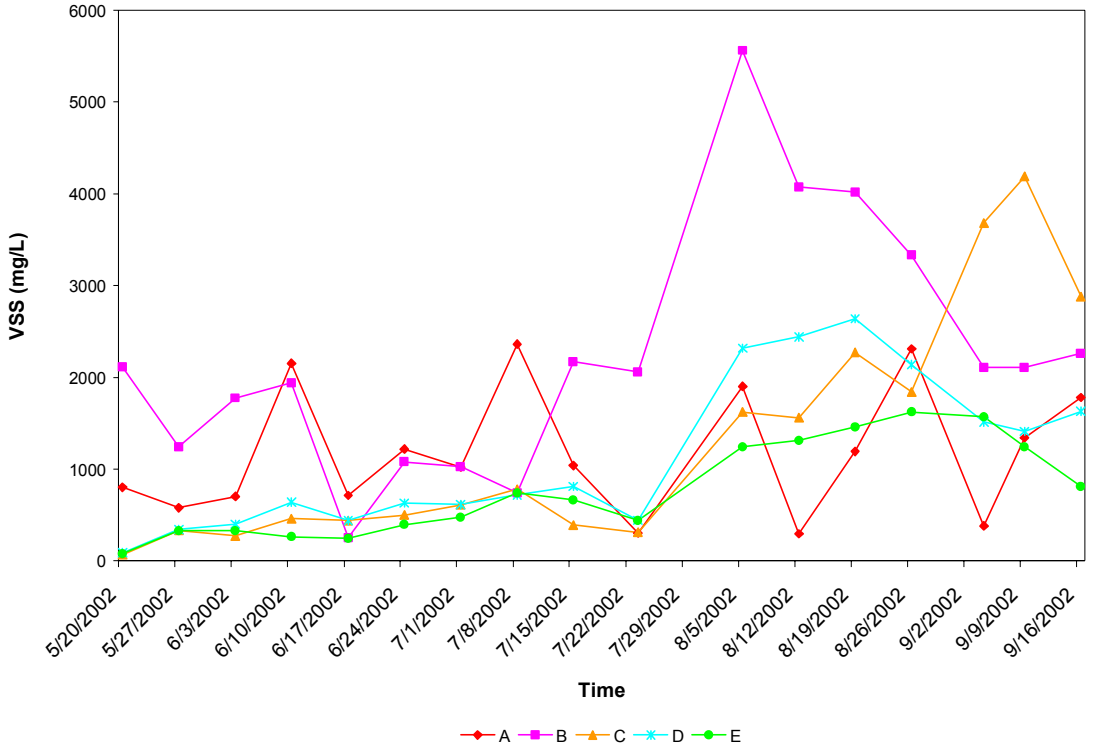

Figure 3.4 Volatile suspended solids (VSS) in the reactors during the start-up period.

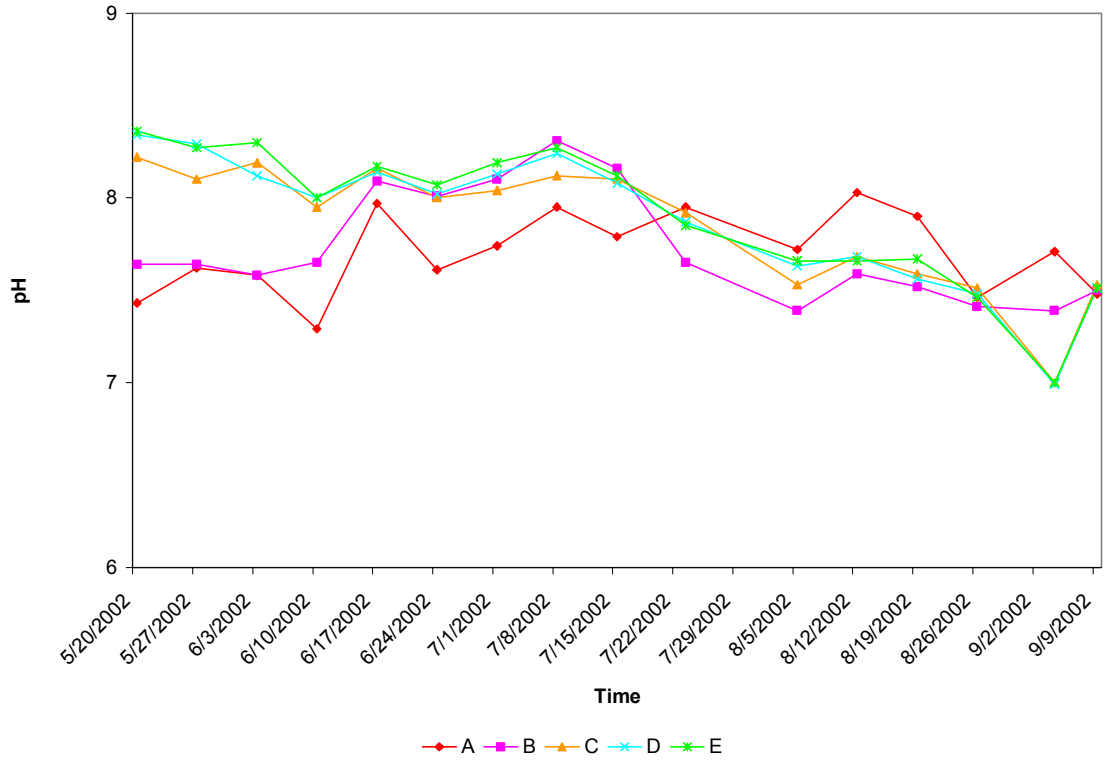

Figure 3.5 pH in the reactors during Phase II start-up.

VSS and pH in the reactors were important to the performance of the reactors. A rise or fall in pH can inhibit sensitive nitirifiers from performing NH_3 oxidation (Madigan et al., 2003). VSS must also remain stable to prevent washout of microorganisms that perform nitrification because they constitute a small fraction of the biomass (Madigan et al., 2003). For these reasons, Figures 3.4 and 3.5 show pH and VSS to help distinguish the cause of a drop in NH_3-N removal. VSS was low in reactors A, C, D, and E and high in Reactor B during the second period, while pH remained stable in all reactors. TN removal was higher than NH_3-N removal (Table 3.2) therefore it was probably insufficient nitrifying biomass that caused a decreased.

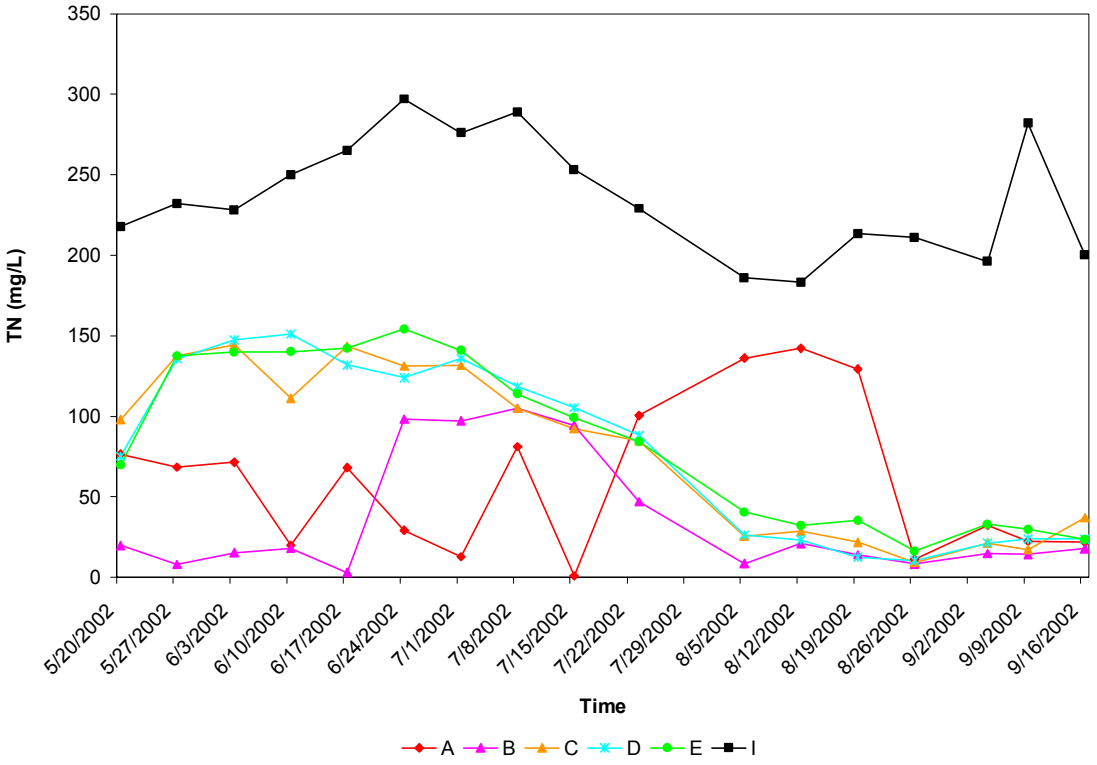

Figure 3.6 TN mg/L in reactors and influent throughout Phase II - Start-up[1].

[1] Symbol I represents influent TN.

The acclimation needed in reactors C, D, and E was visible in the profile of TN in Figure 3.6. After four months of acclimation, the new reactors achieved high rates of N removal.

All reactors were achieving an average of 80% or better TN removal in the last period (Table 3.2). New reactors C, D, and E have established good environments for nitrifiers and denitrifiers to perform N removal. Reactor A was still recovering from difficulty with removal in the last period (Figure 3.2), with 80% TN and 75% NH_3-N removal and average 6.4 mg/L NO_x-N in the effluent. Reactor B had fully recovered from the previous period, with 94% TN removal (Figure 3.3).

After analyzing the initial operations for three new reactors, it was reasonable to continue running them to establish the optimum ANA ratio and cycle time. The average experimental results from five IA reactors during the continued operations from September 23, 2002 to September 23, 2003 are shown in Table 3.3.

Table 3.3 Average influent and effluent nutrient concentrations and efficiency of N removal from IA reactors for September 23, 2002 to September 23, 2003.

	Influent	Effluent A	Effluent B	Effluent C	Effluent D	Effluent E
Daily Aeration Fraction		0.5 d/d	0.25 d/d	0.25 d/d	0.2 d/d	0.2 d/d
Aeration:Non-Aeration Ratio		1hr:1hr	1hr:3hr	0.5hr:1.5hr	0.5hr:2hr	1hr:4hr
TN, mg/L	330 ± 170	31 ± 26	33 ± 30	53 ± 36	42 ± 32	38 ± 32
NH_3-N, mg/L	220 ± 130	11 ± 24	20 ± 32	29 ± 42	25 ± 35	25 ± 35
NO_x-N	3.4 ± 11.4	20 ± 22	14 ± 6	25 ± 21	18 ±11	16 ± 10
OP, mg/L	180 ± 270	63 ± 24	52 ± 30	59 ± 23	54 ± 24	51 ± 25
SCOD, mg/L	330 ± 87	200 ± 51	240 ± 63	255 ± 150	250 ± 91	240 ± 43
pH, mg/L	8.0 ± 0.3	7.7 ± 0.3	7.7 ± 0.2	7.7 ± 0.3	7.7 ± 0.3	7.8 ± 0.3
FSS, mg/L	2900 ± 3000	2100 ± 1500	2200 ± 1200	1700 ± 1100	1900 ± 1000	2000 ±1100
VSS, mg/L	1700 ± 1300	1500 ± 940	1800 ± 900	1400 ± 1000	1600 ± 780	1500 ± 840
%TN		87 ± 12	88 ± 10	80 ± 14	85 ± 11	86 ± 12
%NH_3-N		93 ± 16	90 ± 17	86 ± 20	88 ± 19	86 ± 25

Swine wastewater contains high NH_3-N concentrations; therefore nitrification could promote large pH changes if the system is unmonitored (Bicudo and Svoboda, 1995). Osada et al. (1991) alleviated this problem by alternating nitrification and denitrification through an IA system so little pH change was expected. Nitrification of swine wastewater causes a pH drop from the release of hydrogen ions, but recovery of hydroxyl ions from denitrification in the same reactor allowed for the maintenance of near neutral pH (Cheng and Liu, 2001; Madigan et al., 2003; Osada et al., 1991). The pH profiles in our IA reactors are presented in Figure 3.7.

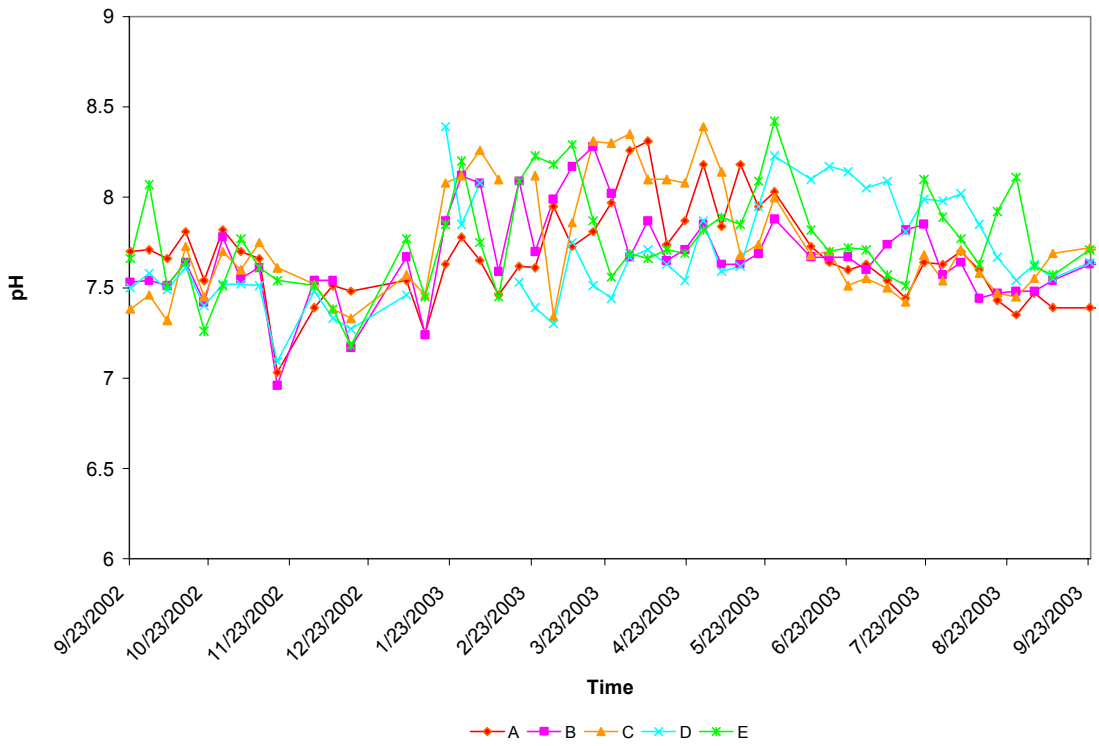

Figure 3.7 pH profiles in the IA reactors from Sept. 23, 2002 to Sept. 23, 2003

The pH range in the reactors was 7 to 8.4, which was within the range of optimum habitat for nitrifier and denitrifier growth (Madigan et al., 2003, Painter and Loveless, 1981).

Biomass, measured in the form of VSS (mg/L), was also important to achieve N removal from the swine wastewater. VSS concentrations in our IA reactors are shown in Figure 3.8.

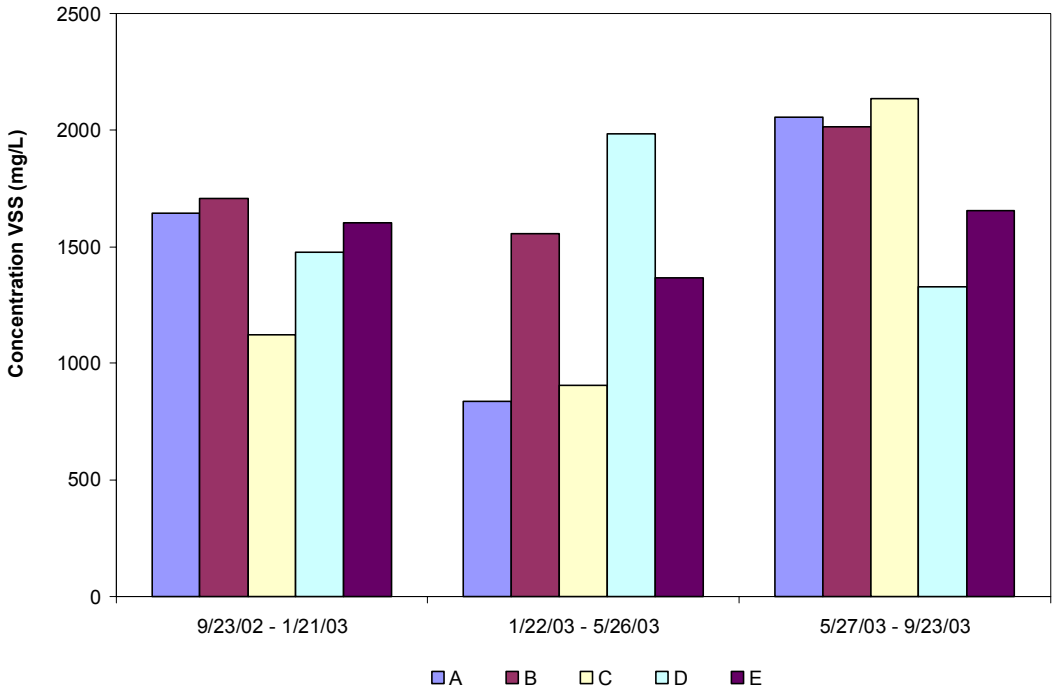

Figure 3.8 Average VSS (mg/L) profiles in the IA reactors from Sept. 23, 2002 to Sept. 23, 2003.

The VSS in all reactors was not stable during any period of operation. Ranges for all reactors fluctuated greatly from as low as 100 to near 4000 mg/L (Table 3.3). The largest range occurred in Reactor C average 1400 ± 1000 mg/L. Some N removal could still be achieved even at low levels of VSS. The low levels of VSS were probably due to over wasting or NH_3-N substrate increase in the influent causing a decrease in microorganism population (Madigan et al., 2003). Painter and Loveless (1981) found that growth rate of nitrifiers was proportional to the amount of NH_3-N oxidized; low

NH_3-N removal rates can be indicated by low concentrations of VSS. Therefore instability of VSS indicated that the reactors were not always operating at steady state.

In March 2003, sampling of influent electric pump began, and an alteration of some influent constituents (Figure 3.9). These alterations occurred because influent solids increased due to a lagoon sludge uptake from the force of the electric pump.

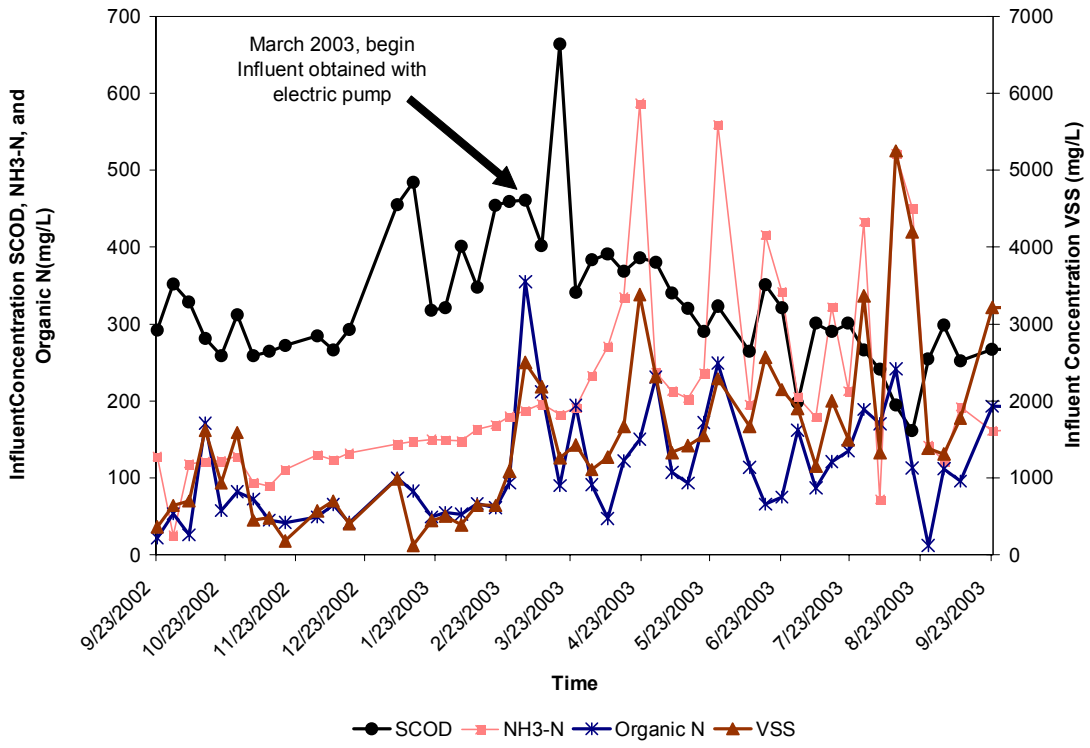

Figure 3.9 Influent SCOD, NH_3-N, VSS, and Organic N for the reactors from September 23, 2002 to September 23, 2003.

After March 2003, there was a considerable drop in SCOD in the influent and major fluctuations in N constituents (Figure 3.9). When SCOD drops there is less organic carbon to be utilized by denitrifying organisms to perform denitrification (Madigan et al., 2003). Without the necessary amount of SCOD, microorganisms will not fulfill N removal efficiently, resulting in low TN removal rates (Cheng and Liu, 2000). In our

experiments there was no addition of organic carbon to the IA reactors. Since TN concentrations in the influent fluctuated to as high as 800 mg/L there was not enough organic carbon within the reactors to maintain the high levels of denitrification.

It is believed that because of the organic carbon deficiencies in the influent other sources provided the necessary amount to perform high amounts of NO_x-N reduction. Alternative sources were provided by a high SRT that allowed biomass endogenous decay and solulibization of solid waste in the influent releasing additional organic carbon to be used by microorganisms in denitrification. To prove our theory we must make assumption for basic calculations 1) that all the influent organic nitrogen is transformed to NH_3-N within the reactor, 2) use the averages for the year analyzed and, 3) use the least efficient reactor, to perform nitrogen removal (Table 3.4):

Table 3.4 Average Influent and Reactor C's Characteristics for 9/23/02 to 9/23/03.

Influent	Effluent
sCOD = 326 mg/L	sCOD = 255 mg/L
TOC = 330 mg/L	TOC = 120 mg/L
TN = 330 mg/L	TN removal = 80%
NH3-N = 216 mg/L	NH3-N = 29 mg/L
TSS = 2900 mg/L	NOx-N = 24.7 mg/L
VSS = 1542 mg/L	VSS = 1384 mg/L

Calculation 1: If we assume that all TN in the reactors was removed by denitrification via NO_3-N then there is a requirement of 2.86 mg/L COD per 1 mg/L NO_3-N (USEPA, 1993).

TN removed =

$$330 \, {}^{mg}\!/_{L} \, (0.80) = 264 \, {}^{mg}\!/_{L}$$

COD required for denitrification =

$$264 \, {}^{mg}\!/_{L} \times 2.86 \, {}^{mgCOD}\!/_{mgNO_3 - N} = 755 \, {}^{mg}\!/_{L}$$

COD remains in effluent. Therefore, SCOD balance =

$$755\,{}^{mg}\!/_{L} + 255\,{}^{mg}\!/_{L} = 1010\,{}^{SCOD}\!/_{L}$$

Then SCOD that comes from solubilization of solids or soluble microbial products =

$$1010\,{}^{SCOD}\!/_{L} - 326\,{}^{mg}\!/_{L} = 684\,{}^{mg}\!/_{L}$$

Calculation 2: Assuming that all TN in the reactors was removed by denitrification via NO_2-N, requiring 40% less COD (USEPA).

TN removed =

$$330\,{}^{mg}\!/_{L}\,(0.80) = 264\,{}^{mg}\!/_{L}$$

SCOD required for denitrification =

$$264\,{}^{mg}\!/_{L} \times 2.86(1-0.40)\,{}^{mgCOD}\!/_{mgNO_3-N} = 453\,{}^{mg}\!/_{L}$$

SCOD remains in effluent. Therefore, SCOD balance =

$$453\,{}^{mg}\!/_{L} + 255\,{}^{mg}\!/_{L} = 708\,{}^{SCOD}\!/_{L}$$

Then SCOD that comes from solubilization of solids or soluble microbial products =

$$708\,{}^{SCOD}\!/_{L} - 326\,{}^{mg}\!/_{L} = 382\,{}^{mg}\!/_{L}$$

Calculation 3: Assume that only influent VSS is degraded, COD/VSS ratio = 1.4 (Metcalf and Eddy, 2003), degradation of VSS creates 80% SCOD and 20% particulate COD (conversion never 100%).

Total SCOD available from influent VSS =

$$1542\,{}^{mg}\!/_{L} \times 1.4 = 2159\,{}^{mgSCOD}\!/_{L}$$

VSS to be degraded to satisfy denitrification using nitrate SCOD requirements =

$$684\,{}^{SCOD}\!/_{L} \div 0.80 \div 1.4 = 610\,{}^{VSS}\!/_{L}$$ (Around 40% of initial VSS)

Looking at the difference between influent and effluent VSS =

$$1542\,{}^{mgVSS}\!/_{L} - 1384\,{}^{mgVSS}\!/_{L} = 158\,{}^{mgVSS}\!/_{L}$$

$$158\,{}^{mgVSS}\!/_{L} \times 0.80 \times 1.4 = 177\,{}^{mgSCOD}\!/_{L}$$

This is not enough extra SCOD from VSS to obtain a low effluent nitrate concentration in the IA reactors. Additional organic carbon is probably supplied by breakdown of organic compounds supplied from the influent that were not measured in our lab tested parameters.

Consequently, TN concentration in the effluent was not entirely affected by the deficiency of SCOD in the influent (Figure 3.10 and 3.11).

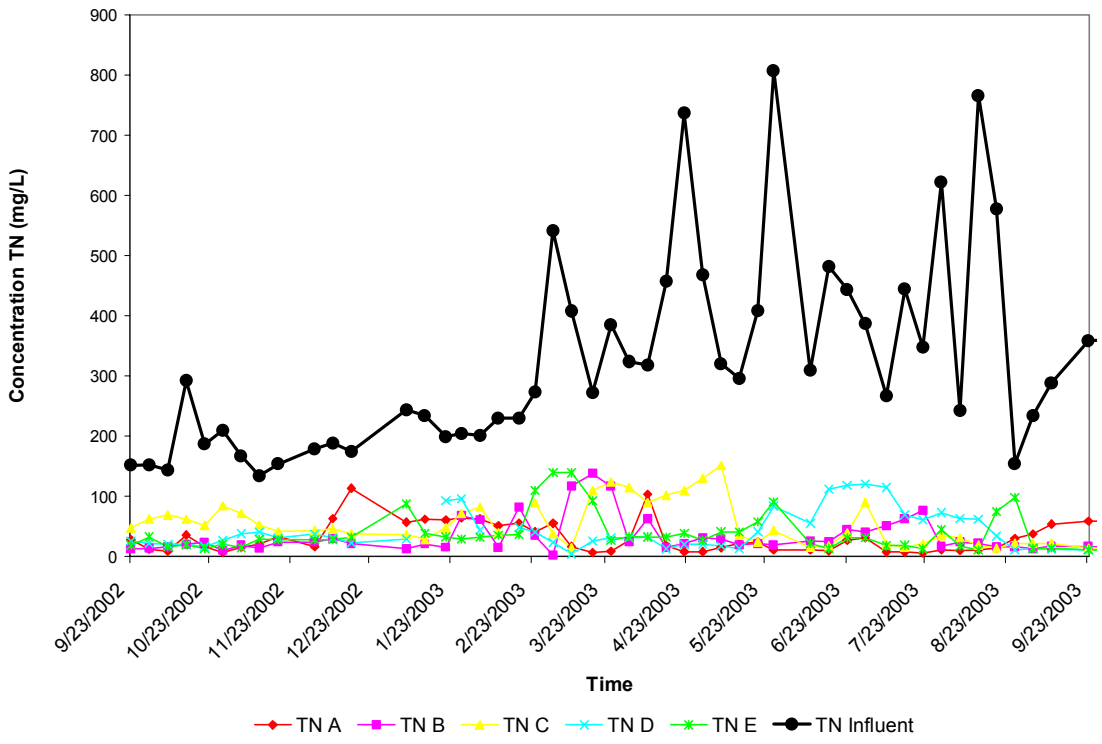

Figure 3.10 Effluent and influent TN (mg/L) for the reactors from Sept. 23, 2002 to Sept. 23, 2003.

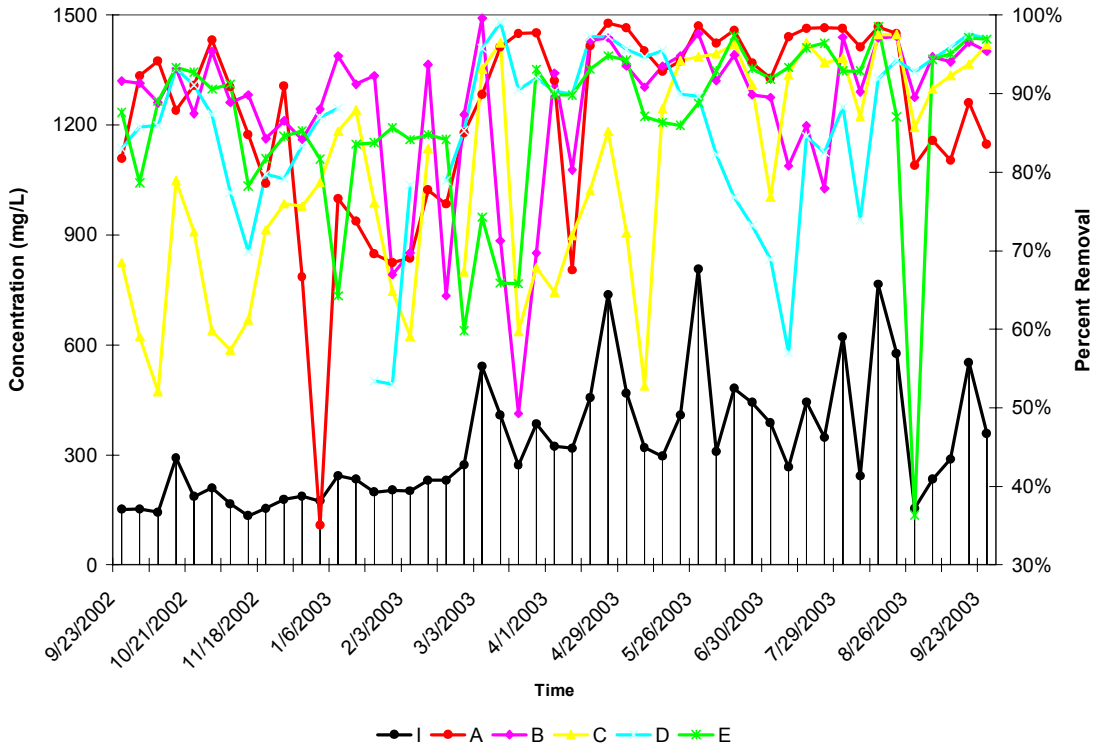

Figure 3.11 Influent TN concentration (mg/L) versus TN removal (%) in the reactors

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The reactors did experience difficulties with TN removal (Figure 3.11), but the TN and NH_3-N percent removal rates remained on average above 85%. The average TN and NH_3-N concentrations were lower than 53 and 29 mg/L, respectively, in all reactors. Because the anaerobic lagoon, where influent wastewater was obtained for the IA reactors, was uncovered, the characteristics of the wastewater were linked to climatic changes, causing influent fluctuations. For that reason it was reasonable to group the data into three periods, each containing nearly four months (around six SRTs). The periods would aide to identify the optimum performance time of each reactor in the year.

The data was divided into three periods, 9/23/02 to 1/21/03, 1/22/03 to 5/26/03, 5/27/03 to 9/23/03; each contained close to four months of data. New statistics were generated for N parameters, presented in Table 3.5a and Table 3.5b.

Table 3.5a Influent and reactors' average N concentrations for three seasonal periods in one year.

	[1]9/23/02-1/21/03			[2]1/22/03 - 5/26/03			5/27/03 - 9/23/03		
	Concentration (mg/L)			Concentration (mg/L)			Concentration (mg/L)		
Sample	[3]TN	NH_3-N	NO_x-N	[3]TN	NH_3-N	NO_x-N	[3]TN	NH_3-N	NO_x-N
I	187	118	X	382	247	X	405	273	X
A	46	17	19	33	14	19	24	2	22
B	18	3	15	49	38	10	30	15	16
C	52	3	49	74	63	11	49	9	18
D	28	3	25	30	9	21	59	48	11
E	49	10	20	57	41	16	28	17	11

Table 3.5b Effluent % removal of NH_3-N and TN from the influent for three seasonal periods in one year.

	[1]9/23/02-1/21/03		[2]1/22/03 - 5/26/03		5/27/03 - 9/23/03	
	% Removal		% Removal		% Removal	
IA Reactor	NH_3-N	TN	NH_3-N	TN	NH_3-N	TN
A	85	81	94	88	99	93
B	97	90	80	84	94	91
C	97	71	67	73	96	92
D	98	84	98	92	79	84
E	87	84	81	84	92	91

[1]9/23/02 – 1/21/03 Reactors A, B, C, D, and E data analyzed did not include the week of 11/24/02, no measurements taken. Reactor D data analyzed until 1/6/03, repair needed.
[2]1/22/03 – 5/26/03 Reactor C data analyzed excluded week 2/18/03, repair needed. Reactor D data analyzed excluded weeks 1/27/02 - 2/10/03, repair needed.
[3]TN in the influent included organic nitrogen and ammonia. TN in the effluent was ammonia, nitrate, and nitrite.

Dissimilarity of removal was evident throughout the seasonal periods. Change from cooler to warmer temperatures caused TN concentration of the influent to increase, from an average of 187 to 405 mg/L. Warmer climates and elevated pH allow lagoon microorganisms' metabolic rates to increase the conversion of organic nitrogen to ammonia, causing fluctuations and increased influent ammonia concentration (U.S. EPA, 2004). As shown in Figure 3.9, SCOD decreased in the latter portion of the year,

March 2003, due to influent sampling from the swine lagoon. As a result, the SCOD/TN ratio decreased (Figure 3.12), and caused a strain on N removal operations in the IA reactors.

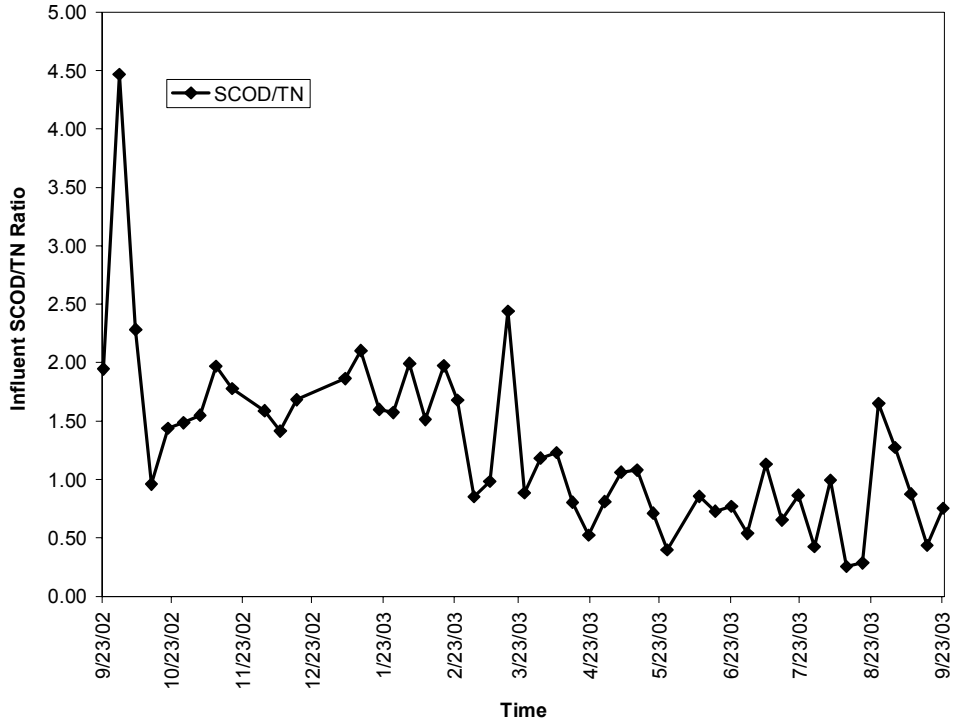

Figure 3.12 Influent SCOD/TN ratio September 23, 2002 to September 23, 2003.

More evidence can be found in Reactors C, D, and E (Table 3.5a and b). Nagaoka et al. (2002) found that the SCOD/TN ratio needed to be above 5.0 to perform N removal without addition of SCOD. This ratio was not established in the IA reactors in this study; instead the microorganisms had to acclimate to adverse conditions by culture growth. Once the microorganisms' culture grew, N removal was improved and achieved over 92% removal in all reactors by the last period of the experiment except Reactor D with 84% (Table 3.5b).

In the second period, 1/22/03 to 5/26/03, TN removal dropped in Reactors B and E. Reactors B (1h:3h) and E (1h:4h) were operated with longer cycle time than other reactors. Therefore, they had higher NH_3-N loading rate during non-aeration times than other reactors operating with shorter cycle times. Nitrifiers use oxygen as the electron acceptor for NH_3-N oxidation. An increase of the substrate without concurrently increasing oxygen will cause a strain on nitrifiers, therefore affecting effluent quality. Murray et al. (1974) expressed similar findings that increasing substrate load would lower oxygen and increase the concentration of oxidizable substrate, stimulating OUR but unfavorably affecting effluent quality. Therefore, when NH_3-N in the influent peaks either the concentration of oxygen or biomass must also increase to maintain the current rate of N removal (Murray et al., 1974; Painter and Loveless, 1981). In our experiment, operations were maintained at a stable oxygen rate, 500mL/min; as a result it took IA reactors several weeks to obtain amplified amounts of biomass to oxidize NH_3-N. By the third period, 5/27/03 to 9/23/03, Reactors B and E were adapted to support oxidation of NH_3-N at elevated concentrations, and were able to perform N removal of 91%

Reactors A (1h:1h) and C (0.5h:1.5h) were both operated with a 2 hour cycle time but different daily aeration fractions. They followed a similar N removal pattern, in the beginning of the year both Reactors had relatively low efficiencies, removing TN at 81% (A) and 71% (C). As the reactors enhanced nitrifier concentration, the TN removal efficiency increased from 81 to 93 % in Reactor A and from 71 to 92 % in Reactor C. TN removal efficiency in Reactors B and E had also increased during the one year of operation.

Reactors D (0.5h:2h) and E (1h:4h) operated with the same lowest daily aeration fraction (0.2) but different cycle times, 2.5 h for D and 5 h for E. However, the TN removal efficiency in Reactor E became higher than that in Reactor D, possibly through use of nitrite as an electron acceptor. It appears that the half hour aeration period in Reactor D did not provide enough dissolved oxygen (DO) to efficiently oxidize NH_3 to nitrate, thus decreasing effluent quality (Murray et al., 1974)

All reactors experienced some difficulties with TN removal during the operation of one year. The N species profiles in the reactors are shown in Figures 3.13 to 3.17.

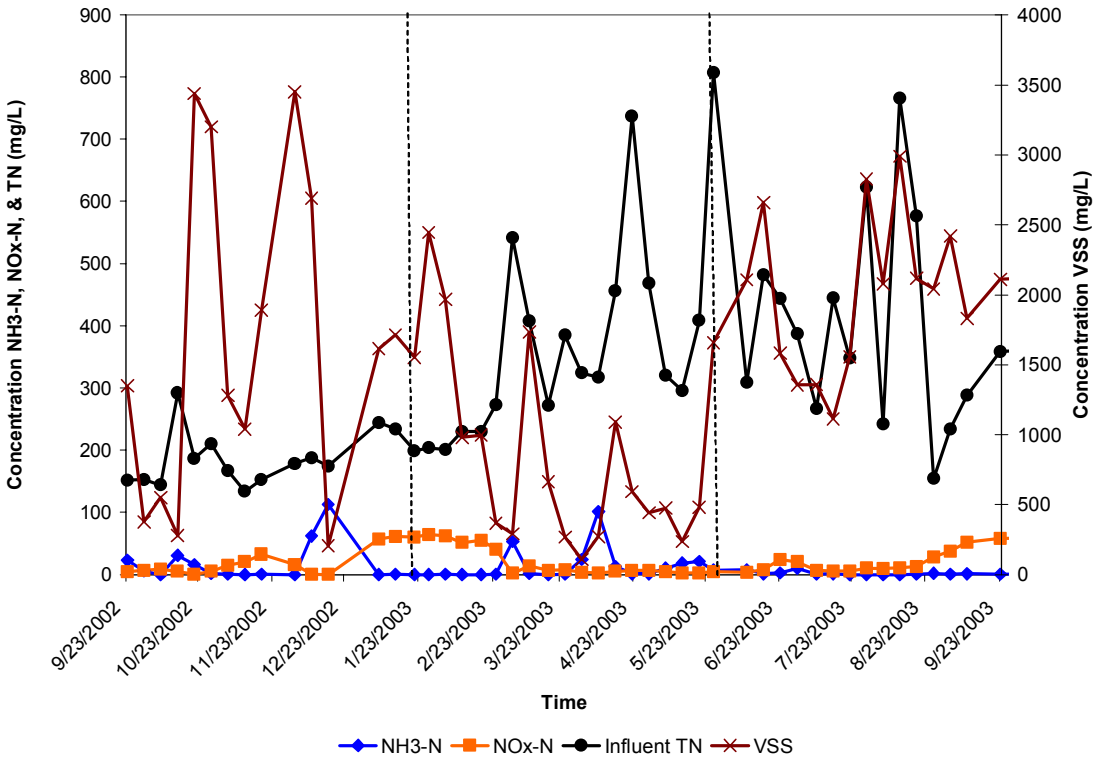

Figure 3.13 Reactor A's NH_3-N, NO_x-N and VSS (mg/L) profiles versus Influent TN (mg/L) from different seasons of a year.

The profile in Reactor A (Figure 3.13) shows the effect of influent TN on N removal in the reactor. There were several peaks in effluent concentration of NH_3-N, to as high as 113 mg/L, due to an elevated influent TN concentration. These peaks lasted

a short while, one to two weeks, which was enough time for microorganisms to adjust to higher N concentrations and increase nitrification rates. When nitrification was reduced, NH_3-N concentration was high and VSS was low; we found that NO_x-N (NO_3-N and NO_2-N, mostly NO_3-N) concentration was low at these times. Because nitrification was reduced, denitrifiers were able to reduce NO_x-N to low levels with available SCOD and the allotted anoxic period (Lee et al., 1996). Once the nitrifiers were able to oxidize relatively high amounts of NH_3-N, NO_x-N in the effluent increased because the denitrification rate was inhibited by available SCOD and anoxic period.

All reactors had NH_3-N peaks similar to those in A (Figures 3.14 to 3.17), however, recovery time for full oxidation of NH_3-N in B, C, D, and E were longer because of their shorter daily aeration fraction that provided less DO.

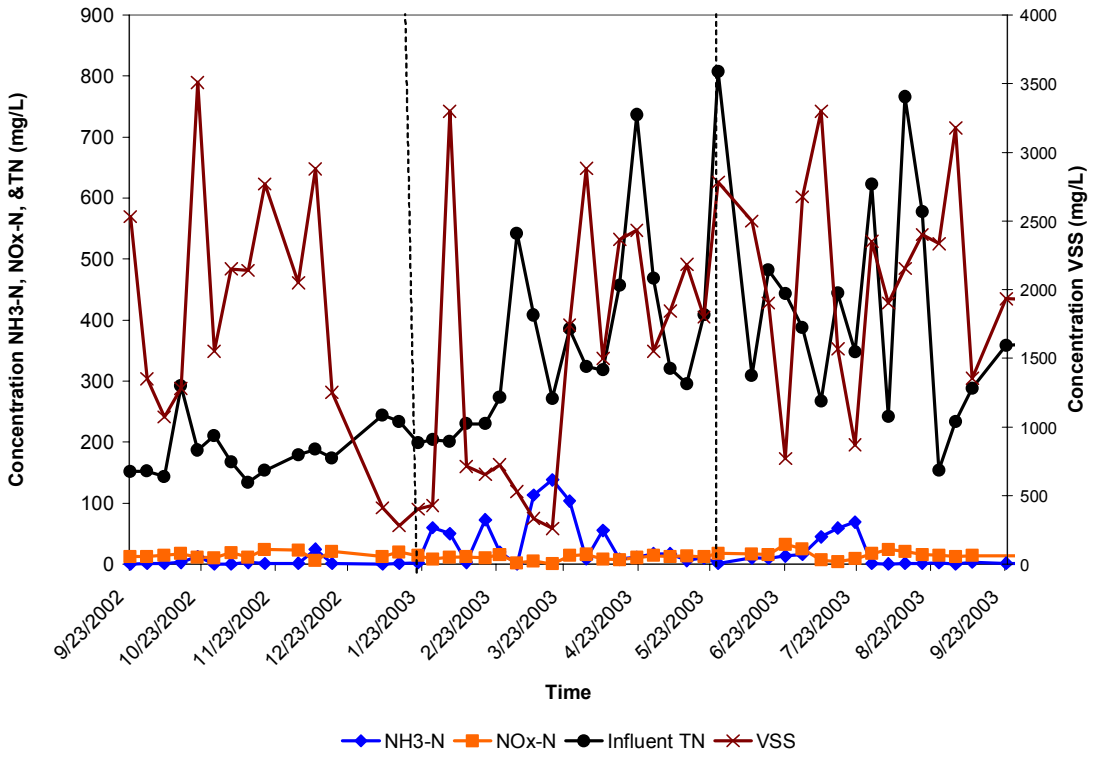

Figure 3.14 Reactor B's NH_3-N, NO_x-N and VSS (mg/L) profiles versus Influent TN (mg/L) from different seasons of a year.

The profile in Reactor B (Figures 3.14) exhibited several more NH_3-N peaks than Reactor A. In Reactor B (1h:3h), additional NH_3-N from three feedings during the non-aeration period and one feeding at the aeration period need to be oxidized. Therefore, when influent NH_3-N increased, two times as much NH_3-N needed to be oxidized in Reactor B as that in Reactor A because of an extended cycle. Again like in Reactor A, when NH_3-N was high, VSS and NO_x-N were low in Reactor B. When oxidation recovered to sustain high levels by increased VSS, NO_x-N again increased because denitrifiers were not able to fully reduce all NO_x-N due to insufficient SCOD. Even though Reactor B was operated with a longer cycle, denitrification was still low and

was comparable to Reactor A, because of deficient SCOD, no mixing during non-aeration, and possible need for longer non-aeration period (Lee et al., 1999).

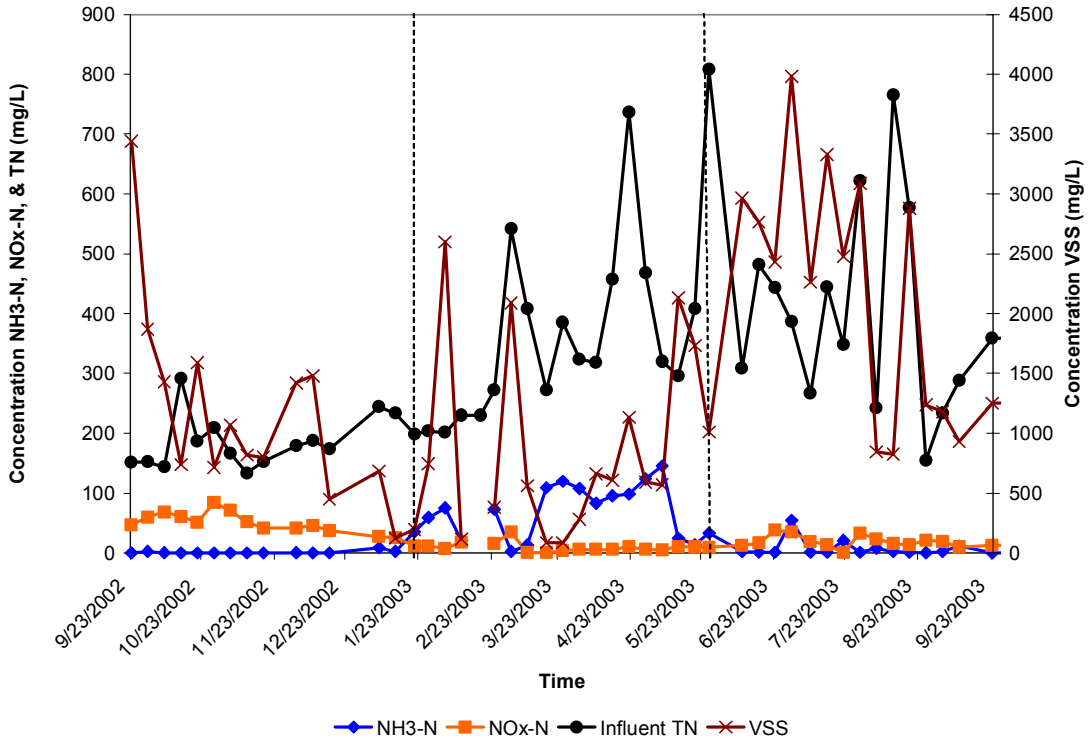

Figure 3.15 Reactor C's NH_3-N, NO_x-N and VSS (mg/L) profiles versus Influent TN (mg/L) from different seasons of a year.

The profile in Reactor C exhibited similar peaks as in Reactor B, probably because they were operated at the same daily aeration fraction (0.25) (Figures 3.14 and 3.15). However, in the second period there was a longer recovery time for acclimation to higher NH_3-N oxidation levels in Reactor C. Reactor C (0.5h:1.5h) was operated at one half of the operation time of Reactor B, thus aeration period does not provide enough DO to oxidize increased NH_3-N with lowered biomass in the reactor (Murray et

al., 1974). As in previous profiles, once the biomass concentration increased NH_3 oxidation would increase and NO_x reduction decrease.

Rectors D (0.5h:2h) and E (1h:4h) were run with the shortest aeration fraction, 0.2. The profiles in Reactors D and E are shown in Figures 3.16 to 3.17.

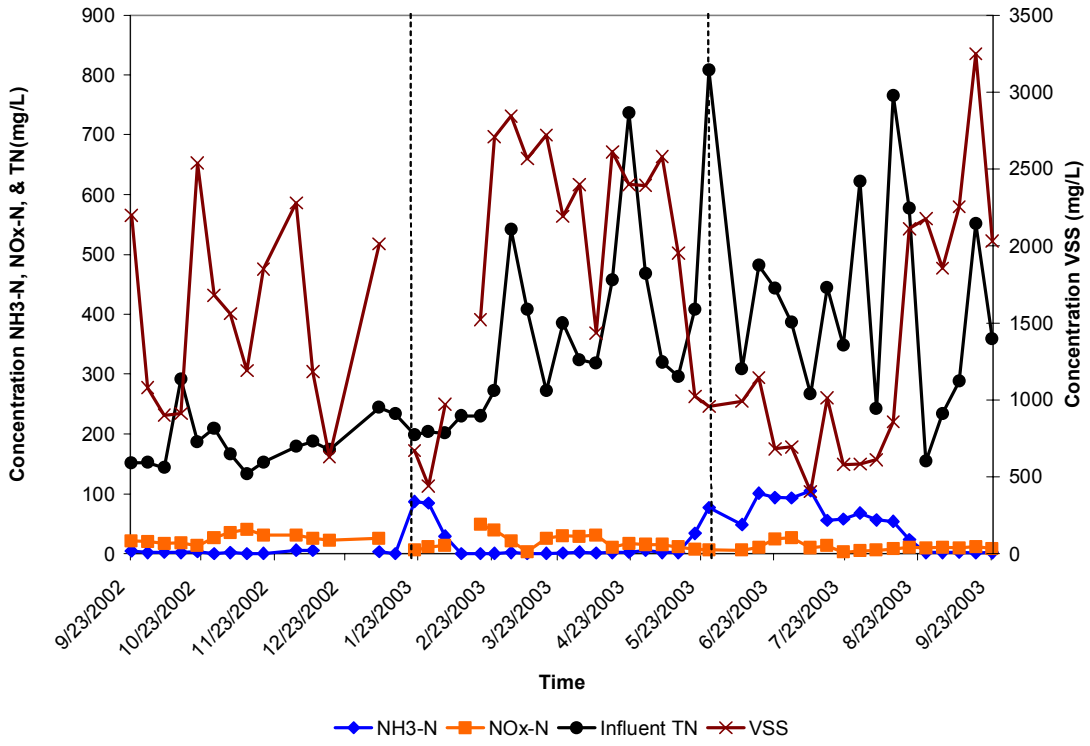

Figure 3.16 Reactor D's NH_3-N, NO_x-N and VSS (mg/L) profiles versus Influent TN (mg/L) from different seasons of a year.

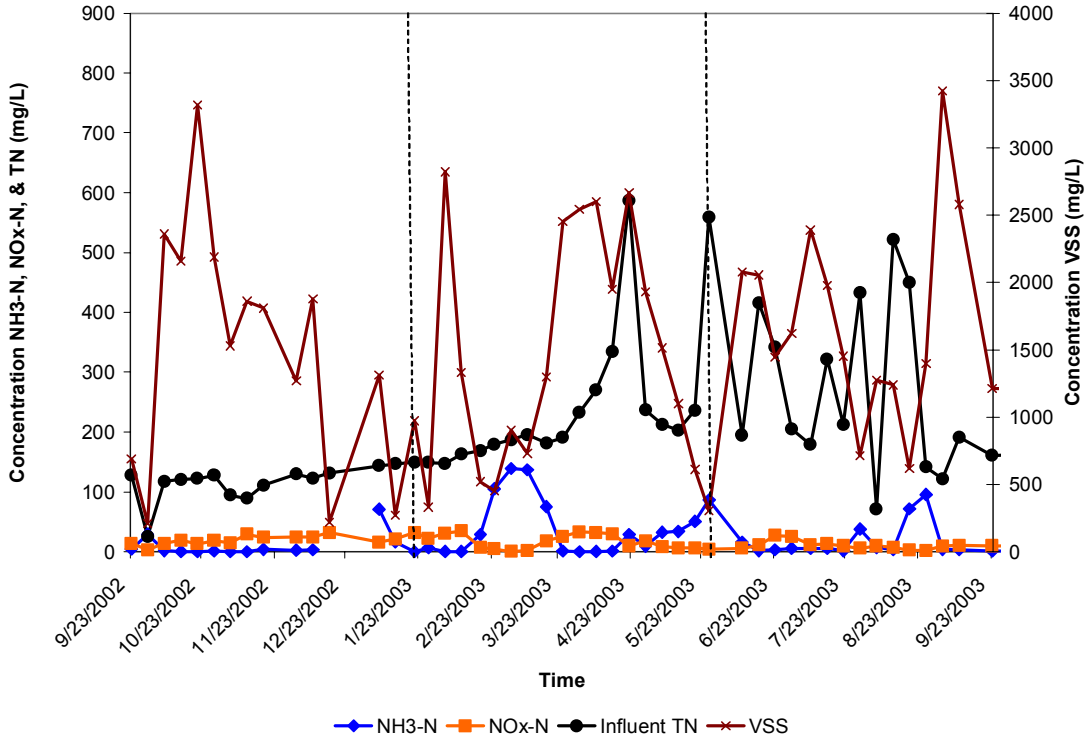

Figure 3.17 Reactor E's NH_3-N, NO_x-N and VSS (mg/L) profiles versus Influent TN (mg/L) from different seasons of a year.

As shown in the N profiles, Reactors D and E experienced instances when they had difficulties reaching low effluent NH_3-N concentrations. Because of the reduced aeration period, Reactor D took longer time than Reactor E in removing increased TN from the influent. In the last period Reactor D took over 12 weeks to stabilize removal of NH_3-N and sustain low level in the effluent. Although reactor E experienced more peaks throughout the year, at most it took 5 weeks to stabilize TN removal. Murray et al. (1974) expressed why removal differences occur. When substrate levels increased it caused low levels of DO and increased OUR, thus allowing the system to operate at higher rates of NH_3 oxidation. Reactor E had to oxidize two times as much NH_3 as Reactor D; therefore OUR in Reactor E was higher than in Reactor D despite the same daily aeration fraction. It appears that the one hour aeration period in Reactor E was

able to oxidize more NH_3 than the two half hour aeration periods in Reactor D because it provided constant N removal in Reactor E.

Because NH_3-N removal was similar to higher aerated reactors nitrification rates did not change significantly in Reactors D and E due to shorter daily aeration. Yet, the extended non-aeration of Reactor E did provide better denitrification during the allotted time of 4 hours (Hidaka et al., 2002). Reduction of NO_x by denitrification during non-aeration allowed reactor E to maintain a 91% TN removal and 92% NH_3 removal. Removal was elevated in the reactor because of extended anoxic period, increased SCOD from feedings, and decreased dissolved oxygen (Hidaka et al., 2002). Similarly, Yang and Wang (1999) found that decreasing the daily aeration fraction reduced NO_x-N in the effluent of IA reactors treating swine wastewater, and also allowed a reduction in energy requirements.

There are instances in each reactor where NH_3 and TN removals were low during the year. These problems were due to insufficient microbial culture (biomass) concentration and increased TN in the influent. The combination of the two caused a period of adjustment within the reactor. During the period microorganisms experienced culture growth to achieve removal of TN from an influent with increased N loading. From the variation of influent at the end of the year all reactors were removing additional TN with better removal efficiency.

There was no significant difference in removal efficiency between the reactors. When choosing to apply an IA system to swine wastewater treatment, it is suggested to use Reactor E. Reactor E operates with the lowest daily aeration fraction and longest cycle, therefore it required the least amount of electricity to run.

3.2.2 Environmental Differences in Reactors

3.2.2.1 Dissolved Oxygen, Oxidation Reduction Potential and pH

To understand the difference in the IA reactors, basic environmental parameters were monitored for the reactors, including dissolved oxygen (DO), oxidation reduction potential (ORP), and pH. They offered indicators of the reactions occurring in the IA reactors (Figures 3.18 to 3.22). It was expected that online analysis would reveal bending points indicating the end of nitrification and denitrification (Holman and Warham, 2003; Plisson-Saune et al., 1996). After performing the measurements it was evident which reactions were predominant for a specific N removal in the reactor.

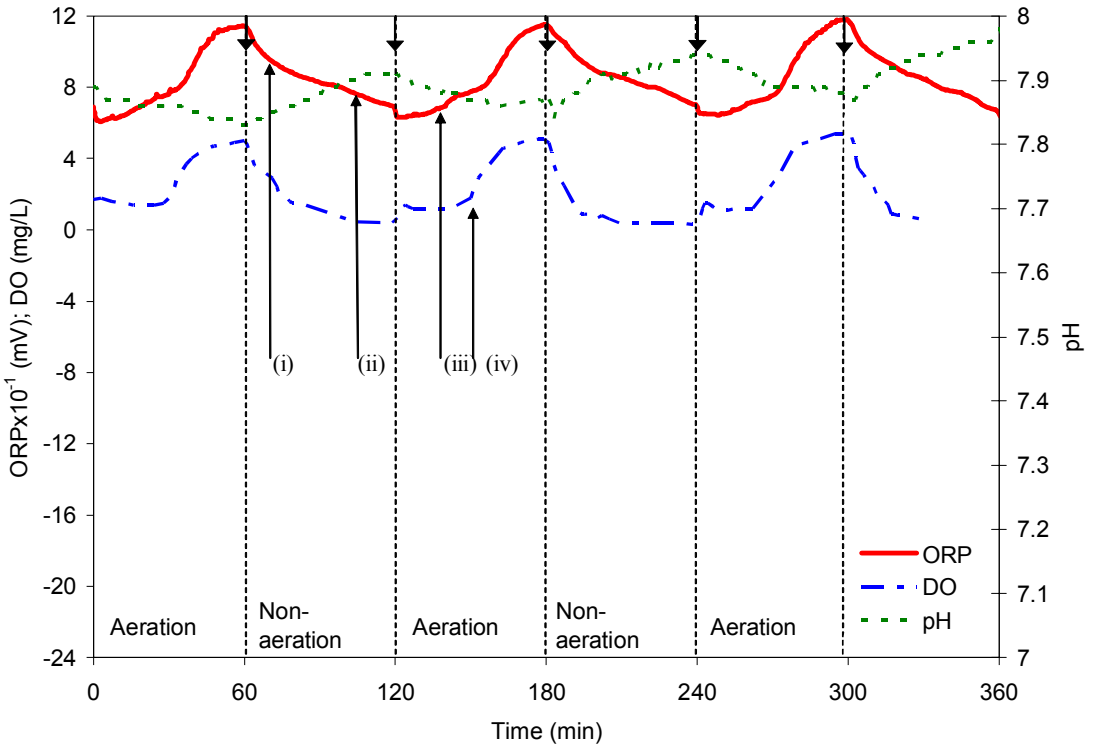

Figure 3.18 Reactor A: DO, ORP, and pH profiles.

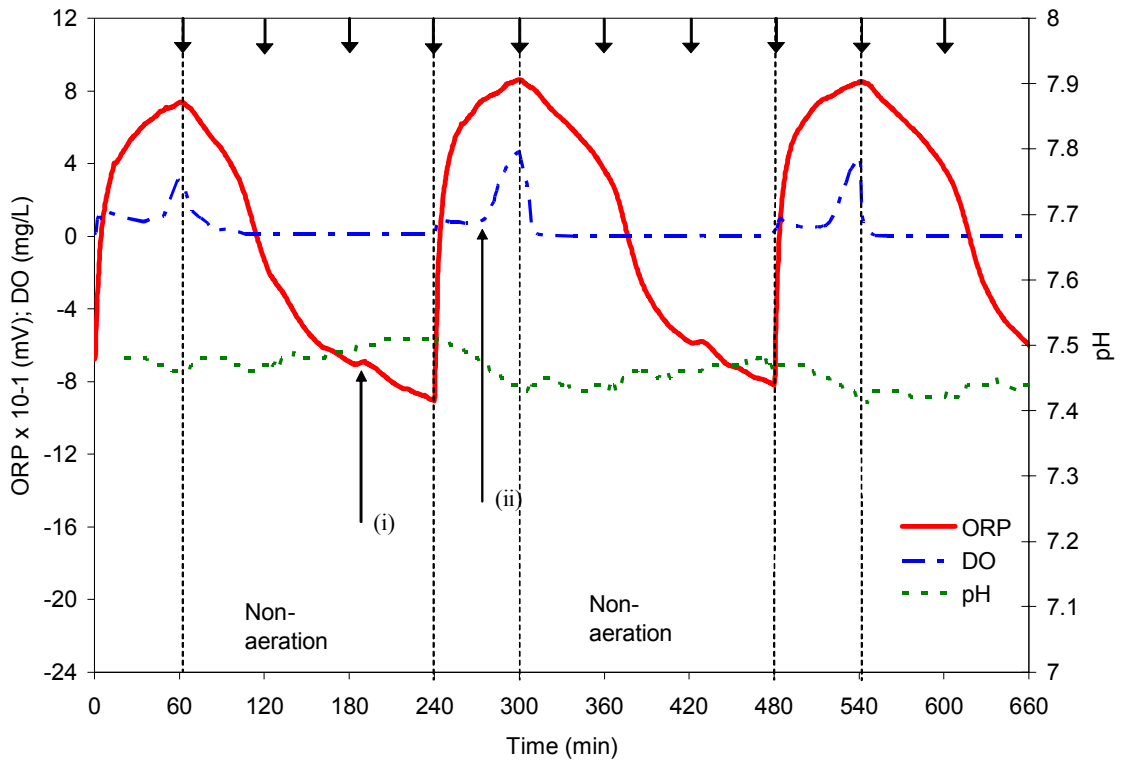

Figure 3.19 Reactor B: DO, ORP, and pH profiles.

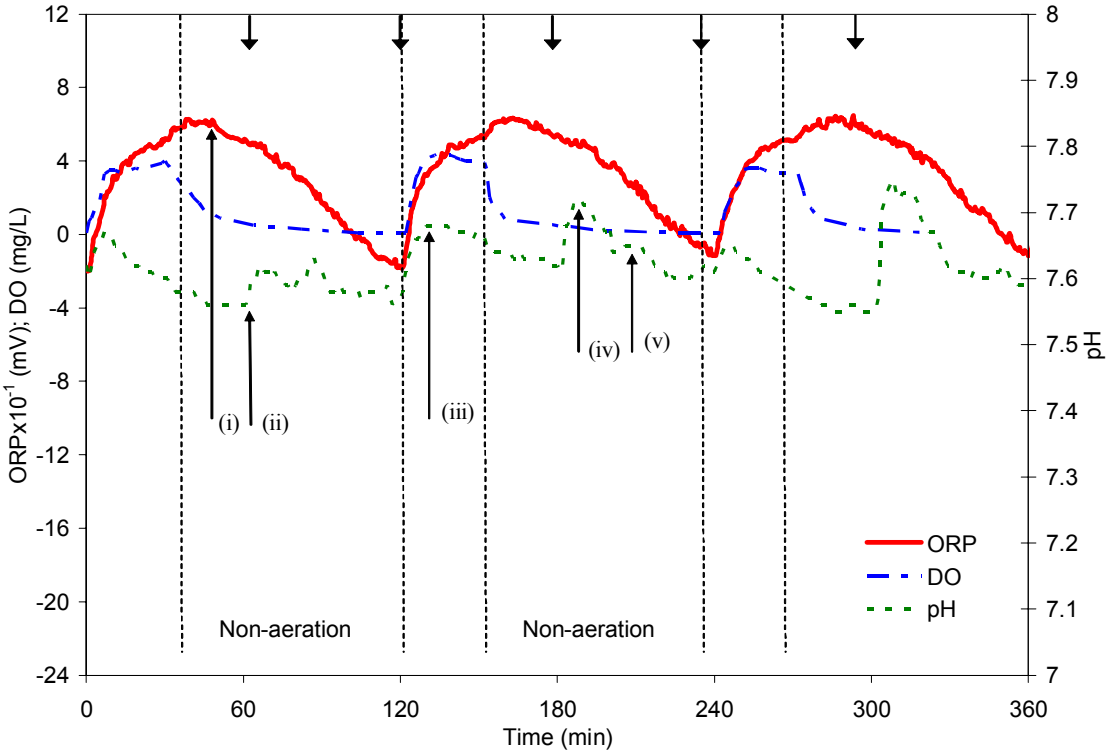

Figure 3.20 Reactor C: DO, ORP, and pH profiles.

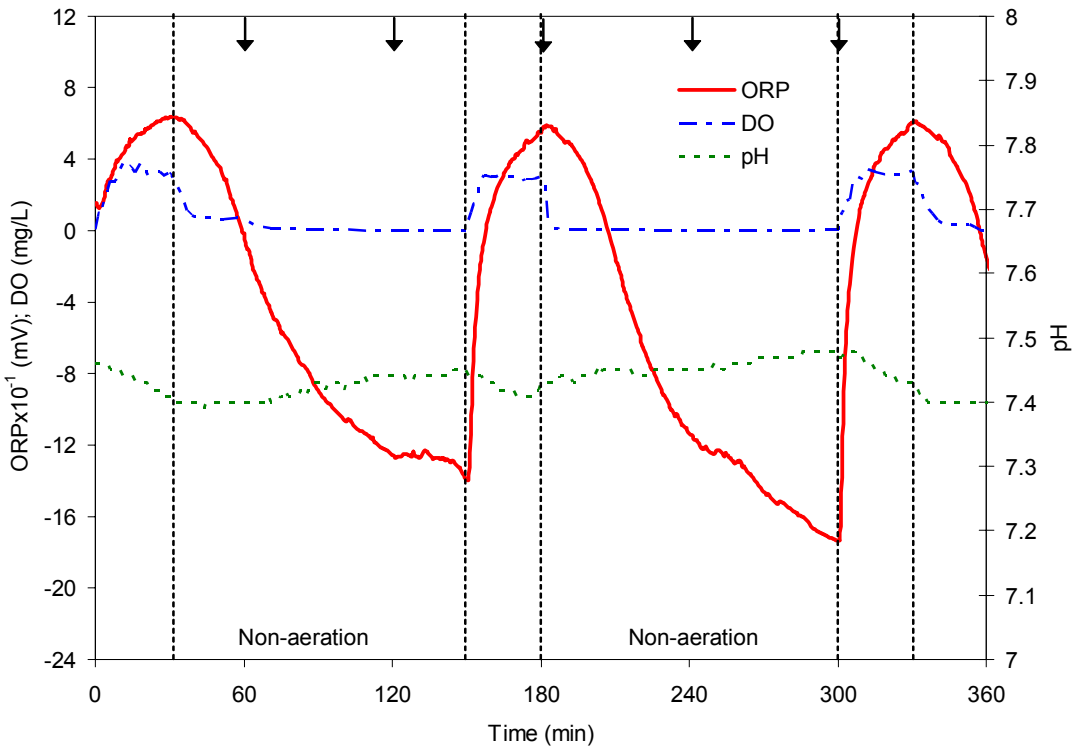

Figure 3.21 Reactor D: DO, ORP, and pH profiles.

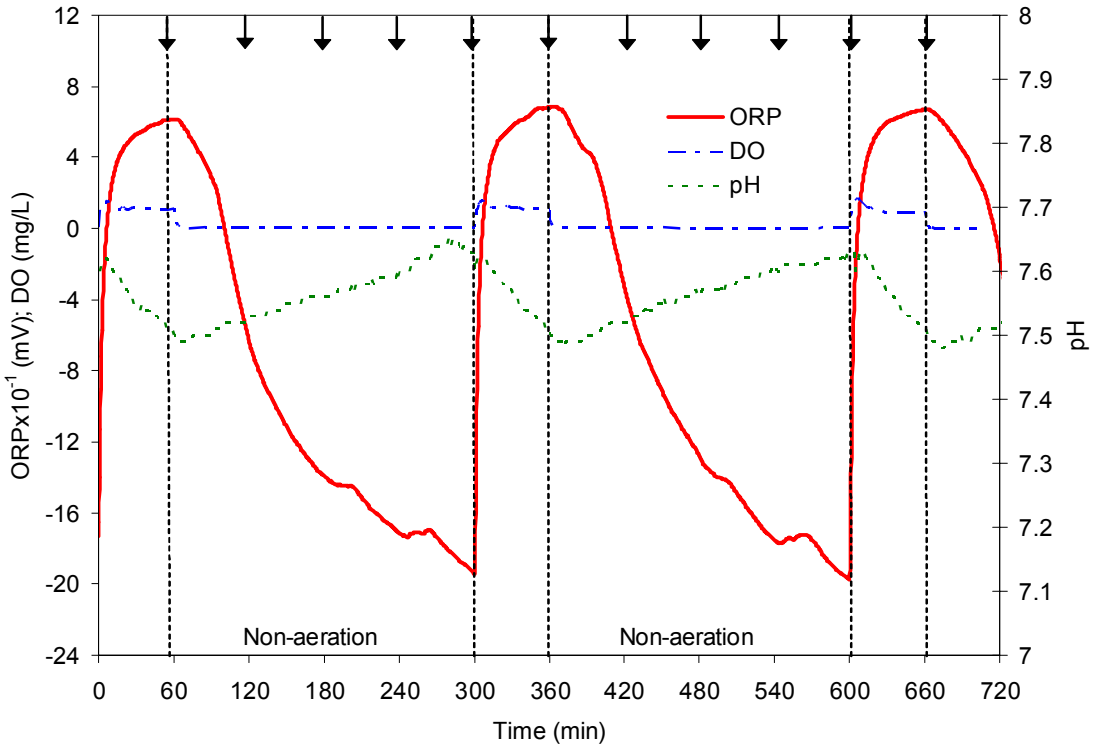

Figure 3.22Reactor E: DO, ORP, and pH profiles.

The aeration and non-aeration periods were clearly evident in DO, pH and ORP profiles of the reactors. Cheng and Liu (2000) also observed rapid changes in ORP and DO occurring at the beginning and cessation of aeration. For denitrification to occur in IA systems, DO should be below 0.3 to 1.5 mg/L while it is recommended that DO should be greater than 2.0 mg/L for nitrification (U.S. EPA 1993). All of the reactors in this study had DO concentrations suitable for denitrification but the maximum DO achieved depended on the length of the preceding non-aeration period and the number of feeding sessions that occurred during non-aeration. The highest DO peak (5.5 mg/L) was reached in Reactor A (1 h:1 h) while Reactor E (1 h:4 h) reached a maximum of 1.5 mg DO/L indicating sub-optimal conditions for nitrification. A summary of the DO, ORP and pH ranges in the IA reactors are shown in Table 3.6.

Table 3.6 Summary of ranges of the DO, ORP, and pH values in the IA Reactors.

IA Reactor	ORP (mV)	DO (mg/L)	pH
A	+60 to+120 Ammonia elbow	0.3 to 5.5 Ammonia elbow	7.8 to 8.0 No bends, normal
B	-90 to +70 No bends	0.1 to 4.7 Ammonia elbow	7.45 to 7.5 No bends, Normal
C	-20 to +60 Continue to rise after aeration, No bends	0.1 to 3.8 Plateau, slow descent after non-aeration	7.4 to 7.75 Unique profile, rise during aeration, two peaks during non-aeration
D	-170 to +60 No bends	0.03 to 4.0 Plateau	7.4 to 7.5 No bends, normal
E	-200 to +70 No bends	0.01 to 1.4 Plateau	7.5 to 7.65 No bends,

The maximum and minimum ORP values were also a function of the ANA ratio. The highest values over one entire ANA cycle were achieved in Reactor A while the lowest values were in Reactor E (Table 3.6). The pH followed the processes of nitrification and denitrification, decreasing in each of the reactors during aeration and increasing during non-aeration (Figures 3.18 to 3.22).

As indicated by Table 3.6 and Figures 3.18 to 3.22, the specific bending points on ORP, DO and pH profiles were absent from almost all the reactors. The absence of points in the reactors was due to multiple factors common in swine wastewater treatments, i.e. insufficient SCOD for denitrification, no mixing during non-aeration, masking from semi-continuous feedings, and low DO for nitrification (Bicudo and Svoboda, 1995; Osada et al., 1991).

Reactor A did exhibit four distinct regions on the ORP profile, presented in Figure 3.18. The first a rapid decline in ORP during non-aeration (i) corresponded to a feeding session and the rapid uptake of degradable carbon for denitrification. The second slope (ii) corresponded with continued denitrification after feeding was stopped. The slope of the ORP profile was slightly depressed for approximately 30 min after the onset of aeration (iii) due to a rapid uptake of COD and oxygen utilization for nitrification. Once nitrification was complete, the DO elbow (iv) was clearly visible in the DO and ORP profile and the ORP increases at an increased rate up to 120 mV. The DO concentration did not increase during aeration until nitrification was complete because oxygen was being consumed as fast as it was being supplied. During this time, the oxygen uptake rate (OUR) was high because the substrate concentration was high (Heduit and Thevernot 1989). After 30 minutes, nitrification was complete and the DO

concentration increased rapidly. The pH decreased continuously during aeration due to alkalinity consumption during nitrification and increased during non-aeration from the release of hydroxyl ions during denitrification.

Reactor B had three feeding sessions during non-aeration with one feeding during a one hour aeration period. The third feeding session during non-aeration is visible (i) in the ORP profile (Figure 3.19). The DO profile indicated a rapid increase (ii) 30 to 40 minutes after aeration was started. Again, this rapid increase was attributed to a reduction of NH_3 signifying the end of nitrification. Unlike Reactor A, there was no corresponding change in slope in the ORP profile with the rapid increase in DO. The pH decreased during each aeration period and increased during the non-aeration period but remained stable between 7.4 and 7.5.

The DO profile for Reactor C varied from the other reactors by decreasing more slowly after aeration was stopped (Figure 3.20). This was due to semi-continuous feeding sessions that did not coincide with the beginning of non-aeration. The rapid decrease in DO for the other reactors was a result of rapid uptake of readily degradable COD for denitrification. The ORP in Reactor C also continued to increase after aeration was stopped (i) and pH decreased until the DO concentration decreased to 0.5 mg/L. Similarly, Al-Ghusain et al. (1994) and Kim and Hao (2001) observed a "transient period" in the ORP profile during non-aeration due to residual DO. The continued decrease in pH indicated that nitrification was still occurring during the first few minutes of non-aeration. Once the DO decreased to 0.5 mg/L, the pH started to increase indicating that nitrification has ceased and denitrification was the dominant reaction (point (ii) of Figure 3.20). No nitrate knee was observed in the ORP profile.

The pH in Reactor C showed the greatest variation fluctuating between 7.55 to 7.74 units. There were three distinct peaks on the pH profile (Figure 3.20). Point (iii) indicates denitrification at the onset of aeration because of COD and mixing were provided while point (iv) corresponds with a feeding session. The end of denitrification is usually indicated by a peak in the pH during non-aeration (Kim and Hao, 2001); there were always two peaks in the pH profile (points (iv) and (v) during non-aeration in Reactor C. There were no distinct changes in the ORP profile at these points. The first peak (iv) was due to influent feeding and increased denitrification but there is no supporting evidence in research for the second peak (v).

In Reactor D, the DO increased and stabilized at 3 mg/L within ten minutes whether or not the aeration period corresponded with a feeding session (Figure 3.21). The ORP increased and during aeration did not appear to be affected by feeding. The second feeding session during non-aeration was visible on the ORP curve (140 min and 260 min). As expected, there was a slight decrease in pH during nitrification and an increase during non-aeration when denitrification occurred.

In Reactor E, the DO did not increase above 1.5 mg/L (Figure 3.22). Sub-optimal conditions for nitrification (*i.e.* low DO and low ORP), did not inhibit Reactor E from achieving high TN removal rates. The OUR was high at the beginning of aeration and was the reason for lowered DO concentrations in Reactor E. The first two non-aeration feeding sessions were not indicated by a change in the ORP profile. However, the last two were readily seen (180 to 200 min and 240 to 260 min). One feeding occurs during aeration but does not appear to suppress the rate of ORP increase.

Reactor E had the lowest ORP values of all the reactors (-200 mV to 70 mV). The pH decreased 0.2 units during aeration and increased continuously during non-aeration.

During the days of DO, ORP and pH monitoring, none of the reactors achieved complete denitrification. Therefore, true nitrate-knees in the ORP profiles should not have been seen during the non-aeration periods. The bending points seen in the profiles for Reactors B, D and E were caused by a rapid uptake of readily degradable COD that was added from the influent. In addition during influent feedings small amounts of DO contained in the stream also influenced ORP readings at these points. Similarly, Koch and Oldham (1985) attributed interference in ORP curves to inadvertent oxygen contamination during sampling.

All of the reactors achieved greater than 85% NH_3-N removal even though they exhibited variations in their profiles. Chen et al. (2001) showed that heterotrophic bacteria exposed to low ORP conditions in the presence of low substrate exhibited an elevated rate of substrate utilization upon exposure to more favorable conditions for growth (high ORP with substrate).

3.2.2.2 Nitrification and Denitrification Activities

During non-aeration, the increase of NH_3-N in each reactor was nearly equivalent to the mass of NH_3-N added with the influent (Figures 3.23 to 3.27 and Table 3.7).

Loading Rate Calculation:

Mass influent NH_3-N mg/L*Volume added during feeding*1/Volume of aeration zone

Example:

200 mg/L * 0.083 L* 1/6 L = 2.77 mg/L NH_3-N

Biomass decay, hydrolysis or assimilation, did not contribute significantly to changing the NH_3-N concentration under anoxic conditions. NH_3-N volatilization was previously calculated with similar IA systems by Cheng and Liu (2000) as 0.008% which was negligible. The NO_x-N (NO_2-N plus NO_3-N) production rates during aeration were always slightly lower than the rate of NH_3-N removal (Table 3.7). This may have been due to assimilation of NH_3-N by heterotrophic bacteria which is known to divert NH_3-N away from ammonia oxidizing bacteria (de Silva and Rittmann, 1999). The ANA ratio had no effect on the nitrification rates; all of the reactors had approximately the same nitrification rate, except reactor C (Table 3.7).

Table 3.7 Observed nitrification and denitrification rates in the IA reactors.

	Units	Reactor A (1:1)	Reactor B (1:3)	Reactor C (0.5:1.5)	Reactor D (0.5:2)	Reactor E (1:4)
Loading rate	mg NH_3-N/L•d	68	60	74	64	54
Nitrification rate	mg NH_3-N/L•h	9.09[1]	10.5	7.44	12.2	10.8
	mg NH_3-N/gVSS•h	2.00	2.02	2.24	2.83	2.61
	mg NO_x-N/L•h	6.61	7.74	3.10	3.91	9.28
Denitrification rate	mg NO_x-N/L•h	-	0.882	0.986	0.918	2.57
	mg NO_x-N/gVSS•h	-	0.165	0.297	0.213	0.620

[1]The nitrification rate for Reactor A was based on the decrease in reactor NH_3-N from 3.25 mg/L to 0.22 mg/L within 20 minutes.

Reactor A was able to completely oxidize NH_3-N to NO_3-N, while the proceeding anoxic stage was not conducive to complete denitrification (Figure 3.23). Nitrite-N was not present in significant quantities.

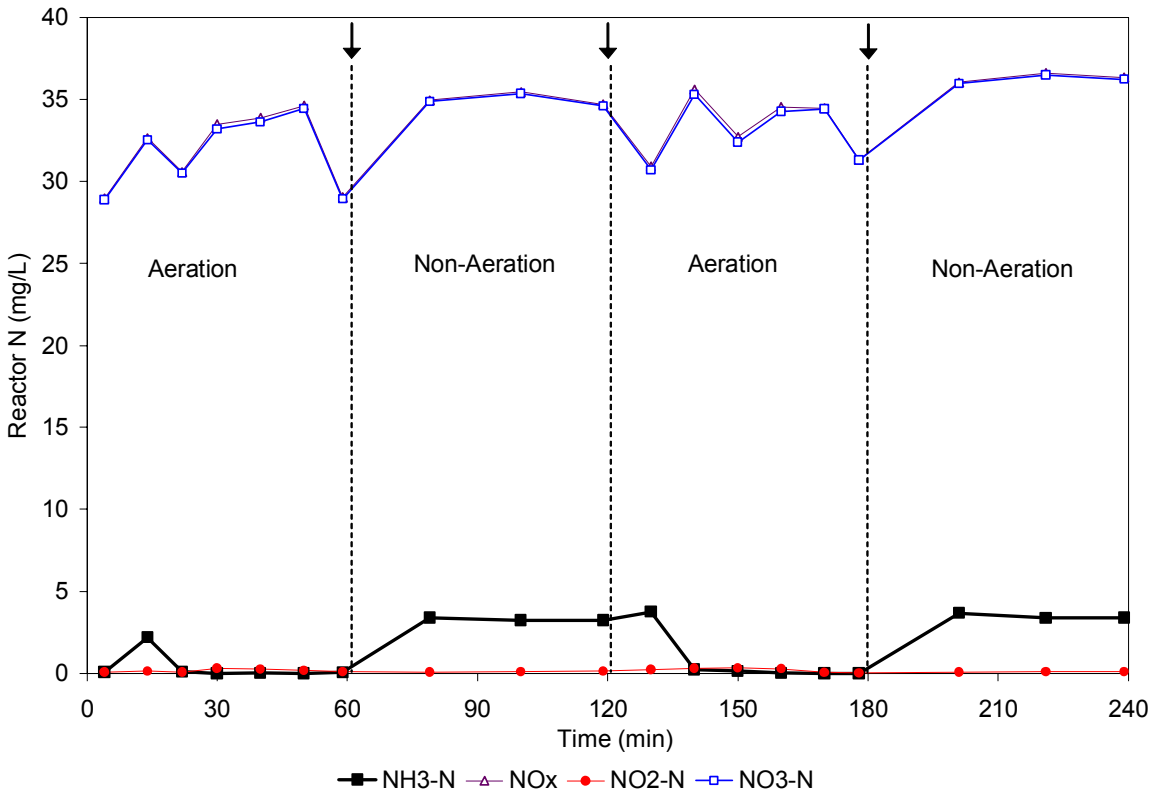

Figure 3.23 Nitrogen profiles in Reactor A.

Complete denitrification was not achieved because of high removal rates of NH_3-N and less available SCOD (Figures 3.23). Denitrifiers were not able to reduce NO_x-N in the allotted time provided for the anoxic period,1 h for reactor A. Even though the reported denitrification rate was unable to be calculated from the profile, NO_x-N removal was occurring. Every ammonia molecule oxidized by nitrification produces one NO_x-N molecule; therefore if no denitrification was occurring TN % removal would be low (Madigan et al., 2003). It was believed that denitrification was occurring but the anoxic period was not conducive for completion because of deficiencies in mixing and SCOD. It appeared that some NO_3-N removal occurred at the onset of aeration because it provided additional SCOD (from semi-continuous feeding) and mixing. The profile also suggests that some aerobic denitrification occurred signified by a drop in NO_3-N

occurring at the end of the aeration period. During non-aeration NO_3-N continues to accumulate, most likely due to residual DO and added NH_3-N from a feeding allowing oxidation.

During the ANA cycle shown in Figure 3.24, Reactor B achieved complete removal of NH_3 but did not have significant denitrification.

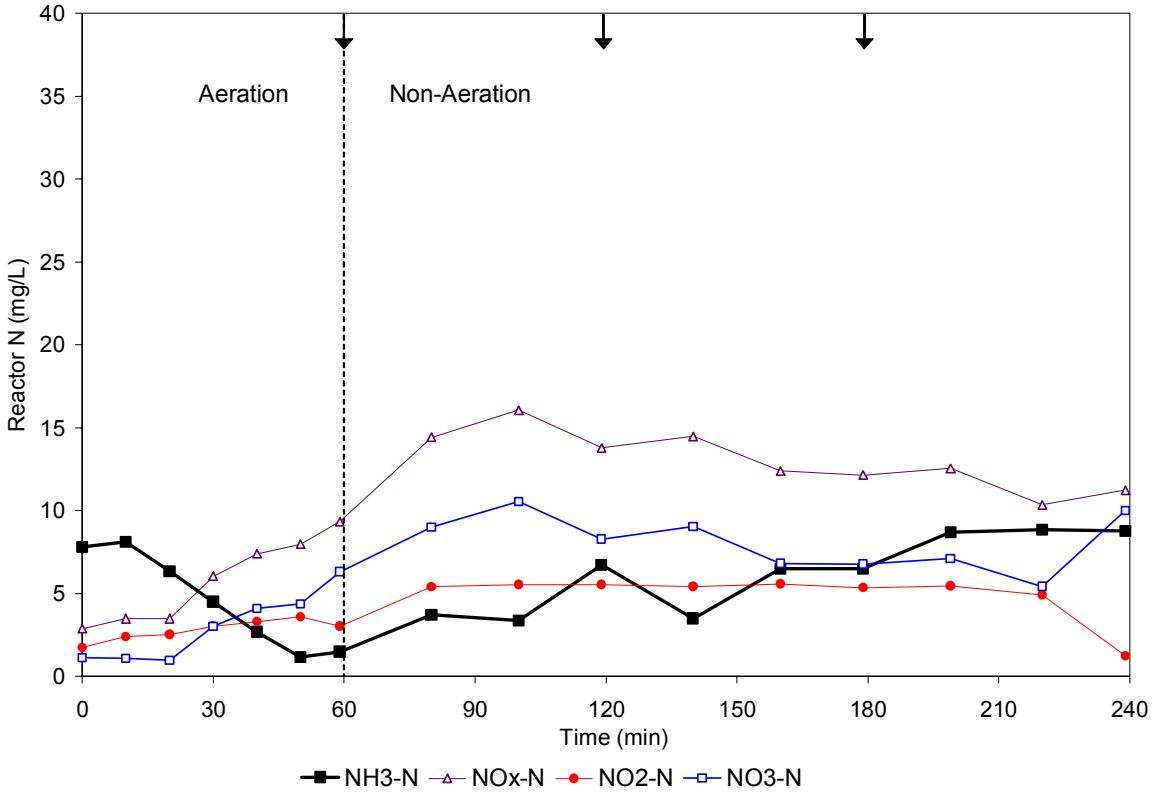

Figure 3.24 Nitrogen profiles in Reactor B.

This large oxidation of NH_3 and small reduction of NO_3 was previously explained by the appearance of DO elbow in the DO profile and the absence of a nitrate knee in the ORP profile (Figure 3.14). The nitrification rate during aeration was rapid (10.5 NH_3-N mg/L•h) while the denitrification during non-aeration was less than 1 mg NO_x-N/L•h (Table 3.6). Limited time only allowed tests to be done once and possible lab error may

support the difference in NO_3-N and NO_2-N points at the end of non-aeration. Because NO_3-N and NO_2-N concentrations were low at the onset of aeration it is reasonable to believe that the last non-aeration points may be outliers.

In Reactor C, the concentrations of NO_2-N and NO_3-N rapidly decreased immediately at the onset of aeration (Figure 3.25).

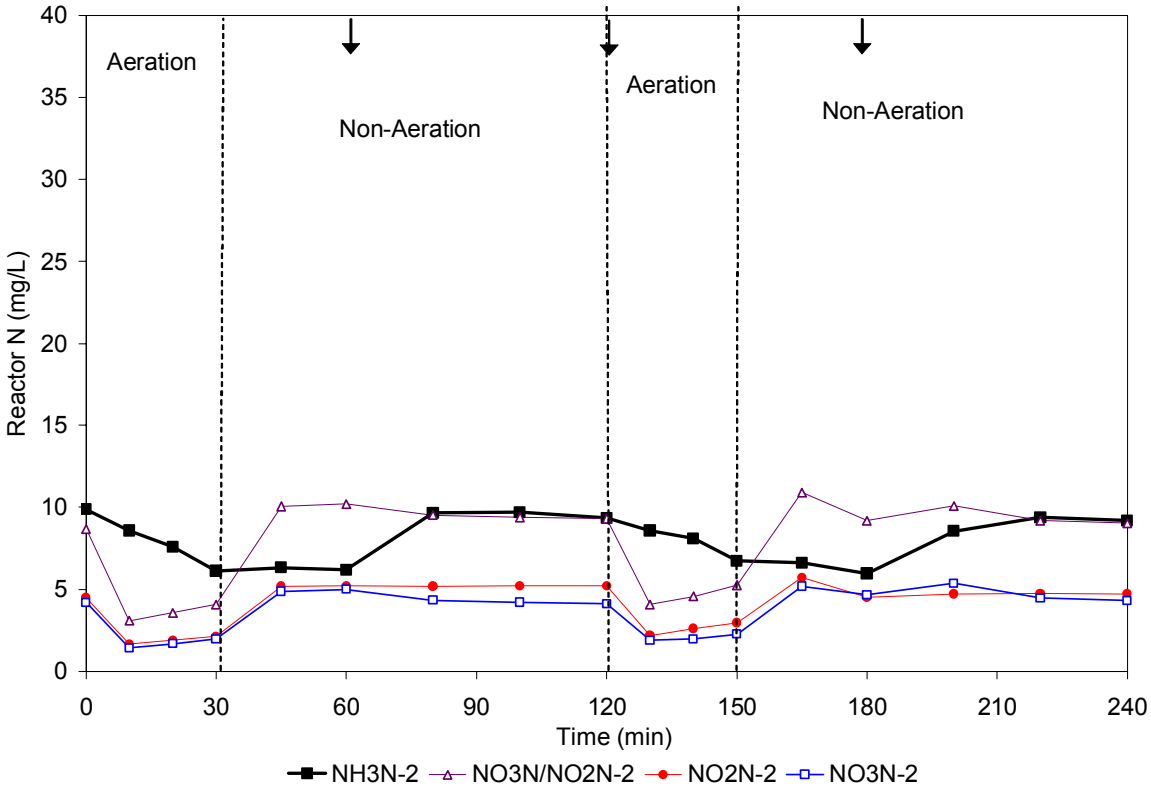

Figure 3.25 Reactor profiles in Reactor C.

Throughout the first few minutes of aeration, the DO concentration was still low which allowed denitrification to occur; particularly with the addition of organic carbon contained in the influent and rapid mixing provided by aeration (Pochana and Keller, 1999; Zhao et al., 1998). Lack of mixing during the non-aeration caused a more subtle decrease in NO_x-N after feeding. During aeration, the NH_3-N concentration decreased at a rate of 7.44 mg/L•h while the NO_x-N increased at a rate of 3.10 mg/L*h, after the

initial rapid decrease (Table 3.7). Therefore the large difference between the NH_3-N removal and NO_x-N accumulation rates suggests that SND was occurring.

During the ANA cycle shown in Figure 3.26, Reactor D was able to fully oxidize NH_3-N to NO_3-N with trace amounts of NO_2-N present (less than 1 mg/L).

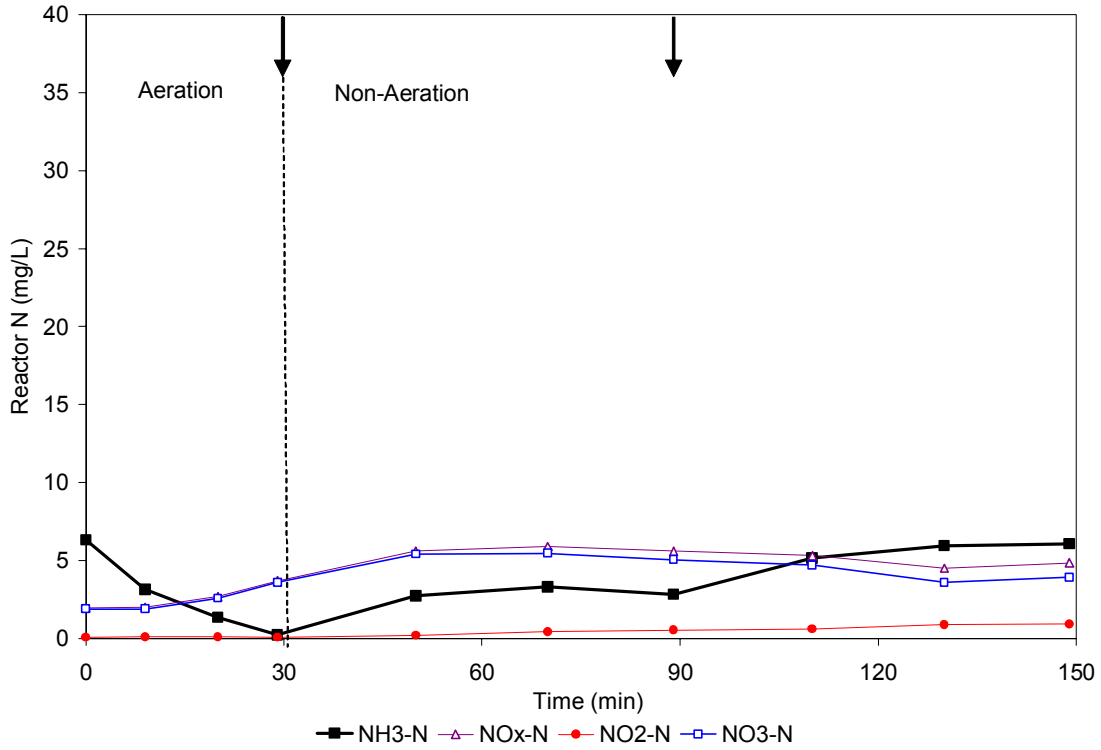

Figure 3.26 Nitrogen profiles in Reactor D.

The low initial concentration of NH_3-N in the reactor at the on-set of aeration and the complete removal of NH_3-N is consistent with the rapid rise in DO (Figure 3.21). The slow rate of NO_x-N accumulation compared to the NH_3-N removal rate during aeration also indicates the occurrence of SND. Comparable to Reactors A, B, and C, the denitrification rate in Reactor D was less than 1.0 mg NO_x-N/L•h. The presence of NO_x-N at the end of the non-aeration period suggests that bending points in the ORP profile were more likely from feeding sessions rather than the completion of denitrification.

In Reactor E, a one hour aeration time was sufficient to oxidize most of the NH_3-N that accumulated during the four hours of non-aeration (down to 3.6 mg/L) (Figure 3.27).

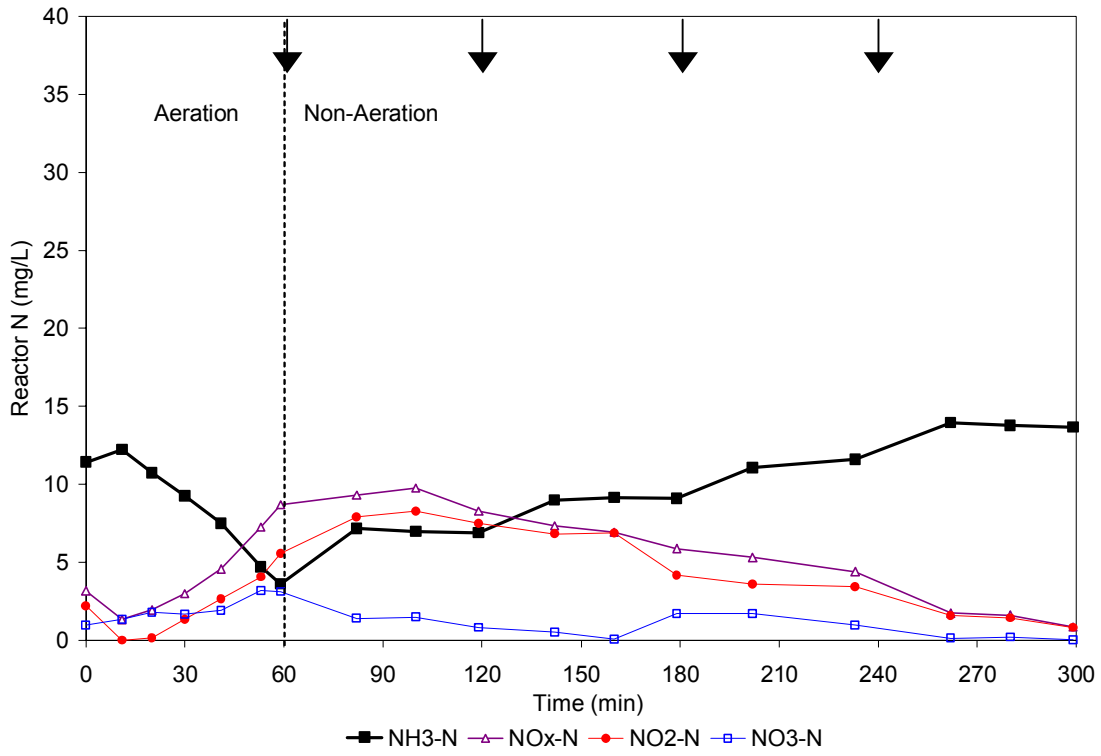

Figure 3.27 Nitrogen profiles in Reactor E.

Low DO in addition to relatively low ORP (less than 70 mV) were conditions favorable for simultaneous nitrification/denitrification (SND) during aeration and anaerobic ammonia oxidation (Anammox) during non-aeration (Jetten et al., 2001; Zhao et al., 1999). However, SND did not appear to be present in Reactor E because, during aeration, the accumulation of NO_x-N was equal to the removal of NH_3-N (Figure 3.27 and Table 3.6). Anammox was not occurring either, as the NH_3-N accumulation was equal to the mass added with the influent. Nitrite-N was the dominant result of NH_3-N

oxidation with NO_3-N present in low concentrations (less than 2 mg/L). Denitrification was rapid (2.57 mg NO_x-N/L•h) with N removal via NO_2-N reduction.

Reactors D and E had the same amount of aeration each day (0.2 d/d), differing only in the length of the cycles (2.5 h versus 5 h). However, the N profiles differed greatly with Reactor D accumulating NO_3-N (Figure 3.26) and Reactor E accumulating NO_2-N (Figure 3.27) during aeration. This suggests that nitrite oxidizing bacteria were inhibited in Reactor E due to an extended non-aeration period (4 h). Ammonia oxidizing bacteria had greater activity after the four hour non-aeration period than the nitrite oxidizing bacteria and out competed the nitrite oxidizers for oxygen during the aeration phase (Hoa et al,. 2002). It is thought that DO stress alone caused the inhibition of nitrite oxidizers because pH, free ammonia and nitrous acid (HNO_3) concentrations were not in the inhibitory range (Anthonisen et al., 1976).

The influent did not contain enough SCOD and TOC for denitrification. However, the high TN removal efficiency indicates that the required carbon must have been obtained from the solubilization of solids contained in the influent or from microbial decay byproducts. This deficiency may be the reason for the slow denitrification rates and incomplete denitrification. This is further illustrated by the lower denitrification efficiency of Reactor A which had the longest proportion of aeration time. The extended aeration fraction in Reactor A caused a greater consumption of degradable carbon than could have been used for denitrification during the subsequent non-aeration period. Aeration time should be minimized to retain carbon for subsequent denitrification (Ra et al, 1999).

Reactor E, the only reactor to accumulate NO_2-N, did have a substantially higher denitrification rate than the other reactors. Abeling and Syfried (1992) also found that denitrification via NO_2-N was faster than denitrification via NO_3-N. It was also likely that the SCOD deficiency in Reactor E was less pronounced because denitrification via NO_2-N requires 40% less COD than denitrification via NO_3-N.

Reactors B and C received the same amount of aeration per day; as did Reactors D and E. However, the environments created inside the reactors were very different because of the duration of each ANA cycle. From an economic stand point, Reactor E is the recommended ANA regime. This reactor achieved a comparable level of TN removal while utilizing the least amount of aeration. Reactor E also had the most efficient use of COD by allowing NO_2-N to accumulate during aeration and subsequently denitrifying via NO_2-N.

Despite daily aeration fraction differences, the reactors experienced similar nitrification rates. Lee and Oleszkiewicz (2003) showed that nitrifying bacteria under alternating aerobic/anoxic conditions have faster nitrification rates and lower decay rates than those under purely aerobic conditions. They attributed the increased nitrification rates to increased energy requirements for repairing damage that occurred during adverse conditions. This explains why NH_3-N removal was complete despite non-aeration periods of 1 to 4 h and relatively short aeration periods (0.5 to 1 h). During non-aeration, ammonia oxidizing bacteria were stressed in the presence of NH_3-N. Upon exposure to aerobic conditions nitrification occurred rapidly as the bacteria repaired damage incurred during anoxic periods in addition to meeting energy

requirements. This explains why reactors with long non-aeration periods still have the same nitrification rates as reactors with shorter non-aeration periods.

3.3 CONCLUSIONS

(1) An IA process offers the opportunity to eliminate much of the N from APSTW. A yearly average of greater than 80% TN removal was achieved with all of the ANA regimes tested. Effluent TN concentrations were affected by seasonal variations of the ammonia concentration in the influent, but reactor habitats were able to be acclimated to the variations.

(2) Ammonia removal efficiency from APTSW ranged from 85.5% to 98.7% in the IA reactors. The efficiency was affected by large increases of TN concentration in the influent, causing a decrease in ammonia removal. Nitrification recovery was dependent on the operating ANA ratio of the reactor. The reactors with lower ANA ratios took longer time to recover.

(3) The large reduction in ammonia from IA reactors suggests that the effluent could be used as pit recharge water to replace APTSW. Using IA effluent as recharge water will possibly provide a healthier environment for workers and hogs by reducing NH_3 associated odor emissions in hog production facilities.

(4) Performing the measurements of parameters ORP, DO, and pH provided insight into what reactions were occurring in the reactors. The reactors did not present all bends indicative of complete nitrification and denitrification in their profiles. Therefore application of online control using ORP, DO, and pH will not be a good option for the IA system.

(5) Cycle length was important in determining whether NH_3-N was oxidized to NO_2-N or NO_3-N. A four hour non-aeration period allowed NO_2-N to accumulate and SCOD to be used more efficiently than in the reactors with shorter non-aeration periods that oxidized NH_3-N to NO_3-N. The influent did not contain enough SCOD for denitrification; thus additional organic carbon had to be obtained from solubilization of solids or microbial decay.

(6) An IA regime decreases the aeration costs associated with traditional continuous aeration nitrification systems. A reduction of up to 60% in aeration requirements, when compared to continuous aeration systems, was realized while still achieving a yearly average of 80% TN and 86% NH_3-N removal.

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TABLE OF CONTENTS APPENDIX A

APPENDIX A

EXPERIMENTAL DATA

A.1 TN in influent and effluent (unit: mg/L)

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	230	12.06	208.95			
2/18/2001	269	25.23	226.89			
2/22/2001	282	59.95	288.16			
2/26/2001	368	44.52	326.85			
2/28/2001	373	26.9	264.94			
3/5/2001	282	4.92	142.42			
3/7/2001	242	46.21	182.27			
3/12/2001	285	32.91	229.25			
3/14/2001	229	41.69	291.6			
3/19/2001	310	11.75	137.03			
3/25/2001	234	32.44	177.62			
3/28/2001	236	22.59	287.77			
4/4/2001	329.25	5.18	232.41			
4/11/2001	202	44.93	77.28			
4/19/2001	171.05	10.8	30.88			
4/25/2001	209	62.8	80.13			
5/2/2001	177	89.44	125.7			
5/8/2001	224	84.38	107.54			
5/15/2001	193	68.23	91.35			
5/21/2001	185.13	97.32	129.1			
6/5/2001	180.82	83.81	74.88			
6/12/2001	178.69	129.21	85.9			
6/19/2001	198.56	78.1	98.27			
6/26/2001	201.33	67.98	105.62			
7/3/2001	165.42	49.41	88.82			
7/10/2001	171.7	52.67	85.06			
7/17/2001	174.63	66.86	85.48			
7/24/2001	157.25	56.96	75.8			
7/31/2001	141.41	58.77	80.65			
8/7/2001	133.17	52.94	73.43			
8/14/2001	150.34	49.36	83.09			
8/21/2001	164.41	63.99	79.19			
8/28/2001	149.44	67.01	79.22			
9/3/2001	149.18	72.14	86.64			
9/10/2001	169	68.61	88.54			
9/17/2001	169.72	86.08	92.6			
9/25/2001	176	34.92	46.11			
10/2/2001	154.24	47.87	62.28			
10/9/2001	169.83	36.13	67.22			
10/15/2001	164.51	73.11	69.89			
10/22/2001	166.67	97.26	65.79			
10/29/2001	172.13	101.02	72.24			
11/6/2001	166.3		65.14			
11/12/2001	189.2		77.91			
11/19/2001	139.23		67.43			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
11/26/2001	181.87		82.52			
12/3/2001	196		97.81			
12/10/2001	186.95		91.54			
12/17/2001	242		51.1			
1/7/2002	196.6	47.75	60.96			
1/14/2002	268	10.2	33.9			
1/21/2002	257	14.01	27.67			
1/28/2002	242	23.33	90.13			
2/4/2002	232	10.17	23.17			
2/11/2002	248	8.13	21.2			
2/18/2002	186.42	37.78	15.38			
2/25/2002	173.36	47.94	9.77			
3/4/2002	208	43.54	66.25			
3/11/2002	244	28.68	56.5			
3/18/2002	217.5	30.63	40.95			
3/25/2002	227.19	15.76	24.61			
4/2/2002	239	21	42.66			
4/8/2002	236.03	30.47	37.47			
4/16/2002	218	25.07	33.5			
4/22/2002	233	6.81	65.16			
4/29/2002	205	39.49	32.41			
5/7/2002	216.87	68.38	37.6			
5/15/2002	267	67.69	43.73			
5/20/2002	218	76.56	19.66	97.85	75.3	69.82
5/27/2002	232	68.51	7.99	137.7	135.67	137.32
6/3/2002	228	71.43	15.19	144.2	147.5	139.89
6/10/2002	250	19.66	17.98	111.12	151.1	140.12
6/17/2002	265	68.3	3.08	143.5	132	142.23
6/24/2002	297	29.17	98.12	131.2	123.95	154.19
7/1/2002	276	12.67	97.15	131.6	135.87	140.87
7/8/2002	289	81.13	105.03	104.9	118.4	113.80
7/15/2002	253	0.72	94.53	92.18	105.31	99.23
7/23/2002	229	100.52	46.94	84.68	88.22	84.22
8/5/2002	186	136.04	8.4	25.6	26.2	40.50
8/12/2002	183	142.16	20.89	28.36	23.22	32.29
8/19/2002	213	129.41	14.06	21.79	12.45	35.18
8/26/2002	211	11.27	8.32	9.15	10.39	16.15
9/4/2002	196	32.3	14.7	21.32	21.17	32.93
9/9/2002	282	22.4	14.17	17.24	23.68	29.62
9/16/2002	200	21.75	17.78	37.06	23.63	23.50
9/23/2002	152	27.75	12.73	47.77	25.77	18.77
9/30/2002	152	11.79	13.19	62.4	21.69	32.51
10/7/2002	144	8.41	16.04	69	20.27	15.77
10/14/2002	292	35.54	19.85	61.56	19.97	19.42
10/21/2002	187	16.71	23.5	51.56	16.63	13.56
10/28/2002	210	6.63	9.7	84.42	26.52	19.80
11/4/2002	167	15.29	18.563	71.228	37.7	14.62
11/11/2002	134	20.39	13.63	52.03	40.36	29.18
11/18/2002	153	32.87	24.11	41.9	31.1	28.01

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
11/24/2002						
12/2/2002	179	16.13	24.08	42.98	37.29	27.61
12/9/2002	188	62.7	29.74	45.7	31.15	27.72
12/16/2002	174	113	20.87	37.09	22.6	31.90
1/6/2003	244	57	12.73	36.16	29.05	87.20
1/13/2003	234	61.4	20.57	28.3	0	38.40
1/21/2003	199	60.57	15.4	47.63	92.71	32.33
1/27/2003	204	64.2	67.38	71.8	95.9	29.23
2/3/2003	201	62.33	60.9	82.41	43.6	31.95
2/10/2003	230	51.28	14.51	39.1	0	35.02
2/18/2003	230	55.36	82.24		48.43	36.35
2/24/2003	273	40.99	34.5	89.2	40.09	109.68
3/3/2003	542	54.92	2.25	37.13	23	139.45
3/10/2003	408	16.56	117.28	14.48	3.66	139.10
3/18/2003	272	6.37	138.05	109.68	25.75	93.00
3/25/2003	385	8.59	116.7	123.84	31	26.70
4/1/2003	324	27.11	24.04	114.29	31.37	33.06
4/8/2003	318	103.29	62.68	89.21	31.89	32.43
4/15/2003	457	17.87	14.85	102.15	12.49	31.59
4/22/2003	737	7.64	21.4	109	19.84	38.19
4/29/2003	468	7.78	30.5	129.85	20.65	26.82
5/6/2003	320	14.67	29.3	151.19	17.07	41.35
5/13/2003	296	21.27	19.27	35.3	13.28	40.46
5/20/2003	409	23.75	21.2	23.62	40.93	57.39
5/26/2003	808	11.23	19	42.94	83.72	90.44
6/9/2003	309	11.12	25.8	15.2	54.72	22.01
6/16/2003	482	9.34	24.51	17.8	111.8	12.96
6/23/2003	444	26.96	44.99	39.45	118.75	30.31
6/30/2003	387	31.15	40.68	89.74	120.29	31.42
7/8/2003	267	7.33	51.26	20.19	114.75	17.72
7/15/2003	444	7.43	62.47	15.56	68.76	18.50
7/22/2003	348	5.64	76.76	21.05	60.76	12.44
7/29/2003	623	10.53	17.48	34.26	73.03	44.36
8/5/2003	242	9.86	23.75	31.28	63.18	17.28
8/12/2003	766	11.26	21.88	18.79	61.79	10.86
8/19/2003	577	13.62	15.81	14.23	33.49	74.72
8/26/2003	154	29.53	16.18	22.04	11.15	98.11
9/2/2003	234	37.39	12.49	22.1	13.2	13.24
9/9/2003	288	53.32	17.14	22.12	11.81	14.10
9/16/2006	552	61.7	19.1	34.41	13.16	15.77
9/23/2003	359	58.94	16.56	13.66	10.78	11.11

A. 2 SCOD in influent and effluent (mg/L)

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	928	74	71			
2/18/2001	1040	173	169			
2/22/2001	491	152	141			
2/26/2001	622	186	203			
2/28/2001	485	163	159			
3/5/2001	549	206	178			
3/7/2001	382	197	171			
3/12/2001	446	172	171			
3/14/2001	321	188	178			
3/19/2001	549	221	181			
3/25/2001	476	214	179			
3/28/2001	314	187	165			
4/4/2001	256	154	146			
4/11/2001	443	164	144			
4/19/2001	252	149	125			
4/25/2001	386	154	150			
5/2/2001	311	195	192			
5/8/2001	337	175	187			
5/15/2001	252	169	185			
5/21/2001	230	181	221			
6/5/2001	225	149	152			
6/12/2001	288	211	161			
6/19/2001	238	160	179			
6/26/2001	364	159	347			
7/3/2001	280	148	142			
7/10/2001	215	148	145			
7/17/2001	230	141	143			
7/24/2001	253	160	140			
7/31/2001	237	149	139			
8/7/2001	245	150	173			
8/14/2001	210	154	146			
8/21/2001	233	145	147			
8/28/2001	233	157	147			
9/3/2001	250	170	153			
9/10/2001	290	220	171			
9/17/2001	265	210	180			
9/25/2001	346	165	181			
10/2/2001	292	237	182			
10/9/2001	285	213	223			
10/15/2001	254	152	179			
10/22/2001	274	143	169			
10/29/2001	275	175	190			
11/6/2001	245		158			
11/12/2001	276		237			
11/19/2001	267		168			
11/26/2001	288		177			
12/3/2001	306		185			
12/10/2001	281		190			
12/17/2001	550		211			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/7/2002	377	298	274			
1/14/2002	393	231	196			
1/21/2002	391	256	232			
1/28/2002	401	192	257			
2/4/2002	372	158	177			
2/11/2002	382	168	200			
2/18/2002	358	179	178			
2/25/2002	346	198	166			
3/4/2002	337	173	160			
3/11/2002	388	175	126			
3/18/2002	449	157	182			
3/25/2002	543	241	196			
4/2/2002	481	129	182			
4/8/2002	601	150	167			
4/16/2002	849	168	246			
4/22/2002	455	170	193			
4/29/2002	319	189	191			
5/7/2002	365	199	233			
5/15/2002	543	238	201			
5/20/2002	437	218	202	259	215	223
5/27/2002	261	158	195	293	307	308
6/3/2002	346	221	200	278	273	311
6/10/2002	353	175	200	306	314	322
6/17/2002	423	186	226	323	276	276
6/24/2002	484	268	339	315	292	419
7/1/2002	412	259	311	305	304	348
7/8/2002	352	359	307	328	230	218
7/15/2002	323	249	343	291	294	321
7/23/2002	392	353	271	396	354	364
8/5/2002	314	242	191	276	251	301
8/12/2002	348	285	208	255	251	274
8/19/2002	312	325	219	236	226	271
8/26/2002	357	205	185	199	213	242
9/4/2002	317	262	212	219	264	240
9/9/2002	318	235	219	196	340	229
9/16/2002	306	218	205	170	218	241
9/23/2002	292	247	199	221	235	246
9/30/2002	352	218	231	216	250	271
10/7/2002	329	335	266	229	264	233
10/14/2002	281	233	256	231	260	226
10/21/2002	259	205	214	220	225	197
10/28/2002	312	167	196	207	206	186
11/4/2002	259	184	200	214	219	200
11/11/2002	264	183	203	243	217	228
11/18/2002	272	185	249	213	189	223
11/24/2002						
12/2/2002	284	175	221	222	196	218
12/9/2002	266	244	170	202	214	196
12/16/2002	293	303	292	192	236	217
1/6/2003	455	115	139	221	214	228
1/13/2003	484	161	206	197		216
1/21/2003	318	156	189	253	253	231
1/27/2003	321	321	278	249	227	182
2/3/2003	401	179	221	252	245	176

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/10/2003	348	155	185	1243		198
2/18/2003	454	170	243		190	250
2/24/2003	459	171	59	259	244	281
3/3/2003	461	251	316	239	265	327
3/10/2003	402	240	328	229	220	331
3/18/2003	664	190	325	334	220	311
3/25/2003	341	154	244	291	198	218
4/1/2003	383	182	228	242	230	237
4/8/2003	391	272	289	276	237	245
4/15/2003	368	240	373	288	357	212
4/22/2003	386	208	304	302	270	290
4/29/2003	380	174	392	281	256	274
5/6/2003	340	224	320	254	247	272
5/13/2003	320	220	260	249	240	314
5/20/2003	290	274	296	256	241	256
5/26/2003	323	277	289	247	259	285
6/9/2003	264	201	294	195	272	286
6/16/2003	351	192	292	284	273	258
6/23/2003	321	170	248	237	216	229
6/30/2003	198	108	172	150	207	194
7/8/2003	301	201	261	256	239	266
7/15/2003	290	184	335	232	813	273
7/22/2003	301	190	262	291	218	239
7/29/2003	266	196	224	235	302	312
8/5/2003	241	187	223	249	259	254
8/12/2003	194	131	224	178	232	202
8/19/2003	161	84	124	127	139	174
8/26/2003	254	186	217	199	259	320
9/2/2003	298	182	205	223	236	309
9/9/2003	252	173	192	224	263	212
9/16/2006	239	145	179	201	222	202
9/23/2003	267	173	241	207	317	231

A.3 NH_4-N in the influent and effluent (mg/L)

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	164	9.54	9.03			
2/18/2001	156	11.5	13.4			
2/22/2001	169	11.6	28.6			
2/26/2001	174	1.92	5.78			
2/28/2001	168	0.52	0.76			
3/5/2001	160	4.82	4.86			
3/7/2001	155	15.8	9.51			
3/12/2001	155	1.46	1.25			
3/14/2001	148	1.2	1.67			
3/19/2001	161	11.6	7.65			
3/25/2001	148	6.01	3.72			
3/28/2001	140	1.67	0.28			
4/4/2001	146	3.87	2.9			
4/11/2001	144	0.23	1.49			
4/19/2001	131	10.1	6			
4/25/2001	152	18.6	10.5			
5/2/2001	150	2.15	12.6			
5/8/2001	158	9.13	23.7			
5/15/2001	154	18.4	37.1			
5/21/2001	148	6.7	45.2			
6/5/2001	141	0.09	0.23			
6/12/2001	127	0.21	0.14			
6/19/2001	122	1.54	2.51			
6/26/2001	124	0.19	0.26			
7/3/2001	126	0.05	0.09			
7/10/2001	120	4.78	0.34			
7/17/2001	109	0	0			
7/24/2001	105	0	0			
7/31/2001	111	1.85	0.26			
8/7/2001	110	0.01	0			
8/14/2001	92.3	21	20.4			
8/21/2001	97.1	0	0.03			
8/28/2001	96.7	0.19	0.19			
9/3/2001	96.4	0.79	0.17			
9/10/2001	121	0	0.01			
9/17/2001	116	6.68	7.88			
9/25/2001	123	0	0			
10/2/2001	122	0.32	0			
10/9/2001	116	4.51	0			
10/15/2001	113	0	0.02			
10/22/2001	107	0	4.22			
10/29/2001	109	0.02	2.4			
11/6/2001	110		0.26			
11/12/2001	112		1.01			
11/19/2001	83.2		0			
11/26/2001	116		0.06			
12/3/2001	131		0.61			
12/10/2001	123		1.72			
12/17/2001	171		0.67			
1/7/2002	159	6.26	0.21			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/14/2002	170	0.29	0.24			
1/21/2002	175	0.35	0.77			
1/28/2002	156	0.36	49.9			
2/4/2002	166	0.05	0.24			
2/11/2002	172	0.05	0.05			
2/18/2002	136	0.12	0			
2/25/2002	145	0	0			
3/4/2002	164	0.18	22.5			
3/11/2002	165	0.04	0.04			
3/18/2002	159	0	0			
3/25/2002	147	0	0			
4/2/2002	165	0	19.4			
4/8/2002	158	0	3.91			
4/16/2002	184	0.28	8.73			
4/22/2002	174	0.22	0.7			
4/29/2002	167	0	0			
5/7/2002	156	0.38	0.47			
5/15/2002	155	0	0.92			
5/20/2002	157	0.02	0	69.6	65.3	67.1
5/27/2002	164	0.01	0	123	129	136
6/3/2002	167	0.03	0.09	130	128	132
6/10/2002	162	1.56	0.08	108	124	137
6/17/2002	190	0	0	109	103	140
6/24/2002	181	0.67	97.4	114	122	144
7/1/2002	169	3.87	94	86.8	132	126
7/8/2002	173	74.3	98.3	69	105	110
7/15/2002	171	0.13	94.2	82.4	99.9	93.9
7/23/2002	146	98.2	33.4	78	81.2	78.6
8/5/2002	131	136	4.9	10.9	10.6	30.2
8/12/2002	148	141	13.48	3.96	3.52	2.89
8/19/2002	163	125	1.06	2.39	1.25	2.28
8/26/2002	160	4.7	8.2	6.3	4.2	2.7
9/4/2002	126	28.2	1	0.42	0.77	0.23
9/9/2002	185	10	6.4	0.24	2.48	3.12
9/16/2002	107	17.17	2.28	0.46	0.33	0.1
9/23/2002	128	23.2	0.03	0.27	4.67	4.67
9/30/2002	25.5	5.5	0.79	2.4	1.69	29.4
10/7/2002	118	0.03	1.44	0.5	2.87	1.87
10/14/2002	121	30.5	2.75	0.06	1.67	0.42
10/21/2002	122	16	13	0.1	3.2	0.06
10/28/2002	128	1.71	0.02	0.02	0.12	1.1
11/4/2002	94.3	0.69	0.063	0.028	2.2	0.02
11/11/2002	88.9	0.09	2.33	0.03	0.06	0.18
11/18/2002	111	0.37	0.81	0.1	0.5	3.81
12/2/2002	130	0.23	0.98	0.78	5.99	2.71
12/9/2002	123	62.3	24.1	0	5.25	3.02
12/16/2002	132	113	0.37	0.09		
1/6/2003	144	0.1	0.03	8.86	3.45	71.5
1/13/2003	147	0.6	1.17	2.4		16.8
1/21/2003	150	0.27	2	35.33	86.9	0.33
1/27/2003	149	0.2	59.3	59.5	84.8	6.43
2/3/2003	148	0.43	49.5	75	29.6	0.45
2/10/2003	163	0.08	2.91	21.4		0.62
2/18/2003	169	0.06	72.6		0.03	28.7

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/24/2003	180	0.89	19.3	73.4	0.59	105
3/3/2003	187	52.9	0.07	2.33	2	139
3/10/2003	196	2.16	113	13.2	0.03	137
3/18/2003	182	0.06	138	109	0.35	74.9
3/25/2003	191	0.94	103	120	1.1	1.5
4/1/2003	233	24.2	8.64	108	2.87	0.06
4/8/2003	271	101	54.6	83.3	1.49	0.53
4/15/2003	335	12.6	7.64	95.9	1.99	1.39
4/22/2003	587	1.1	10.8	98.4	2.84	28.4
4/29/2003	237	1.16	17	124	5.15	9.12
5/6/2003	213	10.2	17.2	146	1.77	32.7
5/13/2003	203	18.4	6.07	24.9	2.08	33.8
5/20/2003	236	20.9	9.6	13.7	33.7	50.8
5/26/2003	559	6.9	1.5	33.5	77	86.5
6/9/2003	195	7.4	9.6	2.7	48.6	15.8
6/16/2003	416	1.56	9.41	1.1	101	1.86
6/23/2003	342	2.86	13.19	1.55	93.95	3.11
6/30/2003	205	10.55	15.58	54.34	93.49	5.82
7/8/2003	179	0.96	44.59	1.09	105	6.02
7/15/2003	322	1.55	58.84	1.56	55.76	5.2
7/22/2003	213	0.12	68.59	20.36	58.12	2.14
7/29/2003	433	0.13	0.38	1.06	68.13	38.1
8/5/2003	71.9	0.18	0.15	7.88	56.89	7.08
8/12/2003	522	0.26	1.08	2.59	54.06	3.5
8/19/2003	450	0.92	0.61	1.03	22.99	71.92
8/26/2003	142	1.63	1.78	0.84	2.07	96.03
9/2/2003	122	0.39	0.29	2.5	2.3	4.08
9/9/2003	192	1.42	3.54	12.14	2.52	3.5
9/16/2006	407	1	3.5	27.89	1.06	3.17
9/23/2003	161	0.44	1.36	0.96	2.32	1.12

A. 4 pH in influent and effluent (mg/L).

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	7.76	6.72	6.67			
2/18/2001	7.7	7.34	7.35			
2/22/2001	7.67	7.23	7.44			
2/26/2001	7.5	7.22	7.11			
2/28/2001	7.74	7.55	7.41			
3/5/2001	7.71	7.39	7.47			
3/7/2001	7.88	7.65	7.6			
3/12/2001	7.83	7.38	7.36			
3/14/2001	7.78	7.5	7.37			
3/19/2001	7.87	7.62	7.58			
3/25/2001	7.7	7.56	7.5			
3/28/2001	7.8	7.6	7.64			
4/4/2001	7.78	7.28	7.4			
4/11/2001	7.66	7.68	7.47			
4/19/2001	7.83	7.49	7.51			
4/25/2001	7.78	7.68	7.53			
5/2/2001	7.87	7.33	7.49			
5/8/2001	7.84	7.61	7.74			
5/15/2001	7.73	7.63	7.75			
5/21/2001	7.58	7.12	7.53			
6/5/2001	7.92	7.56	7.58			
6/12/2001	7.82	7.03	7.48			
6/19/2001	7.75	7.4	7.39			
6/26/2001	7.62	7.58	7.41			
7/3/2001	7.89	7.72	7.67			
7/10/2001	7.91	7.8	7.88			
7/17/2001	8.07	7.81	7.56			
7/24/2001	7.91	7.41	7.63			
7/31/2001	7.98	7.93	7.7			
8/7/2001	7.78	7.78	7.5			
8/14/2001	7.74	7.66	7.6			
8/21/2001	7.67	7.87	7.69			
8/28/2001	7.72	7.73	7.57			
9/3/2001	7.84	7.71	7.62			
9/10/2001	7.44	8.16	8.01			
9/17/2001	7.97	7.91	7.78			
9/25/2001	7.68	8.3	8.31			
10/2/2001	7.75	7.68	7.73			
10/9/2001	8.29	7.95	8.03			
10/15/2001	7.79	8.16	7.95			
10/22/2001	7.77	7.84	7.73			
10/29/2001	7.64	7.99	7.79			
11/6/2001	7.36		7.48			
11/12/2001	7.6		7.4			
11/19/2001	7.87		8.1			
11/26/2001	7.62		7.69			
12/3/2001	7.68		7.5			
12/10/2001	7.56		7.66			
12/17/2001	7.89		7.73			
1/7/2002	7.66	8.05	7.85			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/14/2002	7.75	8.22	7.98			
1/21/2002	7.81	8.08	7.84			
1/28/2002	7.79	7.76	8			
2/4/2002	7.71	8.45	7.68			
2/11/2002	7.6	8.36	7.76			
2/18/2002	7.78	7.94	7.89			
2/25/2002	7.68	7.7	8.16			
3/4/2002	7.66	7.86	8			
3/11/2002	7.38	8.25	7.48			
3/18/2002	7.95	8.21	7.86			
3/25/2002	7.85	8.22	7.7			
4/2/2002	7.87	8.22	7.94			
4/8/2002	7.65	8.11	7.63			
4/16/2002	7.56	8.11	7.86			
4/22/2002	7.99	7.92	7.83			
4/29/2002	7.99	7.85	7.68			
5/7/2002	7.94	7.65	7.74			
5/15/2002	7.8	7.68	7.72			
5/20/2002	7.98	7.43	7.64	8.22	8.34	8.36
5/27/2002	7.97	7.62	7.64	8.1	8.29	8.27
6/3/2002	7.96	7.58	7.58	8.19	8.12	8.3
6/10/2002	7.86	7.29	7.65	7.95	8	8
6/17/2002	8.05	7.97	8.09	8.16	8.14	8.17
6/24/2002	7.89	7.61	8.01	8	8.02	8.07
7/1/2002	7.96	7.74	8.1	8.04	8.13	8.19
7/8/2002	7.95	7.95	8.31	8.12	8.24	8.27
7/15/2002	8	7.79	8.16	8.1	8.08	8.12
7/23/2002	7.91	7.95	7.65	7.92	7.87	7.85
8/5/2002	7.81	7.72	7.39	7.53	7.63	7.66
8/12/2002	7.92	8.03	7.59	7.68	7.68	7.66
8/19/2002	7.64	7.9	7.52	7.59	7.56	7.67
8/26/2002	7.75	7.46	7.41	7.51	7.48	7.46
9/4/2002	8.15	7.71	7.39	7	6.99	7
9/9/2002	7.99	7.48	7.5	7.53	7.51	7.51
9/16/2002	7.92	7.63	7.46	7.41	7.52	7.63
9/23/2002	7.5	7.7	7.53	7.38	7.5	7.66
9/30/2002	7.44	7.71	7.54	7.46	7.58	8.07
10/7/2002	7.87	7.66	7.51	7.32	7.49	7.51
10/14/2002	8.16	7.81	7.64	7.73	7.61	7.64
10/21/2002	7.43	7.54	7.42	7.45	7.4	7.26
10/28/2002	8.02	7.82	7.78	7.7	7.52	7.51
11/4/2002	8.07	7.7	7.55	7.6	7.52	7.77
11/11/2002	8.12	7.66	7.61	7.75	7.51	7.61
11/18/2002	7.55	7.03	6.96	7.61	7.09	7.54
11/24/2002						
12/2/2002	7.86	7.39	7.54	7.52	7.48	7.51
12/9/2002	7.86	7.51	7.54	7.38	7.33	7.38
12/16/2002	7.25	7.48	7.17	7.33	7.27	7.18
1/6/2003	7.67	7.54	7.67	7.57	7.46	7.77
1/13/2003	7.8	7.25	7.24	7.46		7.45
1/21/2003	8.14	7.63	7.87	8.08	8.39	7.85
1/27/2003	8.31	7.78	8.12	8.12	7.85	8.2

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/3/2003	8.47	7.65	8.08	8.26	8.08	7.75
2/10/2003	8.13	7.46	7.59	8.1		7.45
2/18/2003	8.09	7.62	8.09		7.53	8.09
2/24/2003	8.23	7.61	7.7	8.12	7.39	8.23
3/3/2003	7.89	7.95	7.99	7.34	7.3	8.18
3/10/2003	8.01	7.73	8.17	7.86	7.75	8.29
3/18/2003	7.93	7.81	8.28	8.31	7.51	7.87
3/25/2003	8.27	7.97	8.02	8.3	7.44	7.56
4/1/2003	8.45	8.26	7.67	8.35	7.67	7.69
4/8/2003	8.34	8.31	7.87	8.1	7.71	7.66
4/15/2003	8.25	7.74	7.65	8.1	7.63	7.71
4/22/2003	8.27	7.87	7.71	8.08	7.54	7.69
4/29/2003	8.39	8.18	7.85	8.39	7.87	7.82
5/6/2003	8.08	7.84	7.63	8.14	7.59	7.89
5/13/2003	8.16	8.18	7.63	7.68	7.62	7.85
5/20/2003	8.22	7.95	7.69	7.74	7.95	8.09
5/26/2003	8.28	8.03	7.88	8	8.23	8.42
6/9/2003	8.05	7.73	7.67	7.68	8.1	7.82
6/16/2003	8.33	7.64	7.67	7.7	8.17	7.7
6/23/2003	8.26	7.6	7.67	7.51	8.14	7.72
6/30/2003	8.1	7.63	7.6	7.55	8.05	7.71
7/8/2003	7.83	7.54	7.74	7.5	8.09	7.57
7/15/2003	8.04	7.44	7.82	7.42	7.81	7.51
7/22/2003	7.6	7.64	7.85	7.68	7.99	8.1
7/29/2003	8.13	7.63	7.57	7.54	7.98	7.89
8/5/2003	7.84	7.7	7.64	7.71	8.02	7.77
8/12/2003	7.94	7.6	7.44	7.58	7.85	7.63
8/19/2003	7.84	7.43	7.47	7.47	7.67	7.92
8/26/2003	7.82	7.35	7.48	7.45	7.54	8.11
9/2/2003	7.72	7.47	7.48	7.55	7.63	7.62
9/9/2003	7.98	7.39	7.54	7.69	7.55	7.57
9/16/2006	8.04	7.19	7.54	7.91	7.4	7.58
9/23/2003	8.08	7.39	7.63	7.72	7.64	7.71

A.5 Total Phosphorus in influent and effluent

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	44.6	86	90			
2/18/2001	67	147	121			
2/22/2001	85.5	139	126			
2/26/2001	190	184	171			
2/28/2001	191	145	140			
3/5/2001	68.4	359	117			
3/7/2001	58.6	169	119			
3/12/2001	62.8	220	125			
3/14/2001	56.2	246	179			
3/19/2001	99.9	168	105			
3/25/2001	57.9	152	128			
3/28/2001	56.7	120	265			
4/4/2001	116	437	211			
4/11/2001	36.1	40.9	31.6			
4/19/2001	27.8	63.4	49.1			
4/25/2001	44.1	44.2	38.5			
5/2/2001	36.3	48.8	41.6			
5/8/2001	52	51.5	48.9			
5/15/2001	27.4	42.5	37.4			
5/21/2001	31.3	48	38.4			
6/5/2001	33.1	42.6	40.4			
6/12/2001	36.9	53.5	43.7			
6/19/2001	44.3	63.7	52.2			
6/26/2001	63.5	73.8	67			
7/3/2001	34.7	50.5	51.5			
7/10/2001	43.1	51.2	56.2			
7/17/2001	41.8	56.8	52.5			
7/24/2001	47.6	50.9	53.3			
7/31/2001	39.6	46.5	50.7			
8/7/2001	47	45.7	51			
8/14/2001	48.3	50.3	50.8			
8/21/2001	71.2	59.9	50.4			
8/28/2001	59.7	61.6	61.6			
9/3/2001	55.8	55.9	60.3			
9/10/2001	59.3	61.5	73.8			
9/17/2001	61	71.2	65.9			
9/25/2001	66.6	49	40.3			
10/2/2001	30.7	56.3	53			
10/9/2001	50.7	56.8	57.8			
10/15/2001	49.2	50.6	53.8			
10/22/2001	53.4	48.8	47.8			
10/29/2001	63.5	51.6	53.1			
11/6/2001	63.1		54.3			
11/12/2001	67.4		65			
11/19/2001	56.8		57.8			
11/26/2001	65		55.8			
12/3/2001	55.6		57.5			
12/10/2001	63.7		51.1			
12/17/2001	62.2		50.8			
1/7/2002	49.2	41.8	47.1			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/14/2002	61.3	40	45.7			
1/21/2002	67.9	37.9	40.7			
1/28/2002	57.6	39.5	50			
2/4/2002	52.3	36.2	52.6			
2/11/2002	51.7	41.6	50.1			
2/18/2002	66.6	45.3	54.8			
2/25/2002	56.6	41.6	46.2			
3/4/2002	55.7	51.7	48.5			
3/11/2002	71.3	45.2	66.4			
3/18/2002	35.8	40.6	54.1			
3/25/2002	26.1	41	53.8			
4/2/2002	49.9	38.8	43.5			
4/8/2002	41.2	38.7	48.4			
4/16/2002	63	37.9	48.8			
4/22/2002	44.8	42.7	103			
4/29/2002	37.5	42.5	50.4			
5/7/2002	54.4	52.3	46.2			
5/15/2002	56.5	45.4	50.1			
5/20/2002	27.4	56.9	47.4	36.7	18.9	19.9
5/27/2002	34.2	62.3	58.6	20.4	17.5	17.5
6/3/2002	31.6	74.8	56.8	20	23.5	21.5
6/10/2002	31.3	58.3	49.4	44.6	35.7	36
6/17/2002	29.2	55.1	41.1	37.7	36.3	23.6
6/24/2002	30.9	65.7	39	33.1	35.3	30.3
7/1/2002	28.5	80.2	35.1	38.9	23.1	30.4
7/8/2002	73.7	60.4	38.3	48.6	43.6	38.8
7/15/2002	41.2	62.2	45.1	42.1	43.9	46
7/23/2002	39	67.5	47.4	43.2	42.4	49.9
8/5/2002	71.2	83.5	60.9	65.1	73.2	98.4
8/12/2002	49.42	53.95	214	114	117	118
8/19/2002	37.19	54.65	69.1	49.3	68.25	64.63
8/26/2002	34.0	85.8	58.4	46	57.2	47.2
9/4/2002	56.2	68.3	53.8	107	57.6	52.7
9/9/2002	151	108	78.8	170	84.41	63.6
9/16/2002	42.93	58.55	35.45	35.6	41.14	34.12
9/23/2002	50.75	55.7	44.2	68.4	47.4	36.6
9/30/2002	85.4	50.8	46.09	78.4	48.06	42.7
10/7/2002	74.03	45.3	44.5	73.7	42.2	45.3
10/14/2002	25	55.2	37.9	67.8	43.8	44.2
10/21/2002	91.22	69.7	62.7	72.4	54.3	66
10/28/2002	39.6	64.3	30.2	79.6	53.1	41
11/4/2002	35.7	54.5	37.7	78.2	43.8	44.7
11/11/2002	21.67	47.7	37.9	57.5	37.8	41.5
11/18/2002	40.1	43.9	16.5	68.7	42.9	56
11/24/2002						
12/2/2002	41.6	55.4	33	48	40.2	38.9
12/9/2002	49.4	55.4	38.2	41.8	40.9	38.8
12/16/2002	39.6	32.2	26.2	44	39.1	34.8
1/6/2003	110	43.2	30	37.9	17.1	20.2
1/13/2003	85	44.7	27.5	34.3		26.3
1/21/2003	40.6	40.6	30	41.7	25.4	25.5
1/27/2003	40.4	46.1	36.4	45.9	35.1	28.6

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/3/2003	52	46	33.1	43.2	28.9	28.4
2/10/2003	44.9	42	25	37.7		29
2/18/2003	45.3	40.4	30.7		25.6	31.5
2/24/2003	83.1	42.2	30.8	30.8	31.2	32.2
3/3/2003	584	51.7	34.2	30.8	36.3	26.3
3/10/2003	361	40.9	28.9	42	47.8	20.7
3/18/2003	82.1	43.8	20.07	25.3	45.1	39.9
3/25/2003	279	42	35.9	26.6	86.2	33.6
4/1/2003	169	47	68.8	49	86.6	63.7
4/8/2003	225	51.3	49.3	29	70.9	70.5
4/15/2003	445	87.6	76.1	52.1	94.4	55.7
4/22/2003	1027	69.9	79.2	67.2	80.1	150
4/29/2003	481	54	48.6	46.2	49.2	54
5/6/2003	72.5	57.6	60.6	45.8	81.6	92.4
5/13/2003	83	51.5	66.1	95.6	73.5	70.3
5/20/2003	260	44.2	59	79.3	71.4	35.8
5/26/2003	1046	78.1	93.1	96.7	97	35.2
6/9/2003	76.5	99	154	128	72.8	79.6
6/16/2003	669	109	159	101	70.6	70.5
6/23/2003	476	100	94.78	94.4	54.89	52.39
6/30/2003	149	88.76	149	91.8	60.98	53.49
7/8/2003	72.38	82.53	160	85.9	43.25	102
7/15/2003	478	80.98	83.52	65	66.74	74.69
7/22/2003	208	82.01	57.19	94.7	52.04	67.99
7/29/2003	832	110	82.86	90.6	57.74	73.21
8/5/2003	87.64	95.19	80.03	62.5	63.93	83.71
8/12/2003	244	120	86.61	72.5	77.12	71.25
8/19/2003	958	106	88.49	99.5	114	77.38
8/26/2003	18.04	104	86	77.4	107	80.41
9/2/2003	94.72	119	122	75.4	99.84	111
9/9/2003	272	112	79.28	79.8	121	104
9/16/2006	775	128	76.04	101	157	71.73
9/23/2003	422	65.04	59.93	58.1	70.74	51.75

A.6 o-PO4-P in influent and effluent (mg/L)

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	37.1	10.4	10.6			
2/18/2001	50.1	27	26.5			
2/22/2001	47.4	38.9	25.1			
2/26/2001	85.1	62.3	51.3			
2/28/2001	80.1	57.4	58.5			
3/5/2001	39.5	135	56.7			
3/7/2001	28.8	81.2	56.4			
3/12/2001	44	99.4	51.1			
3/14/2001	28.9	94.9	91			
3/19/2001	54.7	79.7	47.9			
3/25/2001	28.5	42.6	27.8			
3/28/2001	24.4	53.2	46.7			
4/4/2001	43.1	74.6	54.4			
4/11/2001	27.1	39.1	30.1			
4/19/2001	19.9	60.5	45.4			
4/25/2001	36.8	37	33			
5/2/2001	20	42.3	36.8			
5/8/2001	26.3	39.2	36.1			
5/15/2001	17.6	38.6	33.4			
5/21/2001	18.6	37.9	32.2			
6/5/2001	24.9	41.6	36.8			
6/12/2001	30.9	47.6	39.8			
6/19/2001	31.8	54.4	43.5			
6/26/2001	32.6	55.7	49.1			
7/3/2001	26.5	45.9	45.3			
7/10/2001	31.8	42.9	42.3			
7/17/2001	27.9	45.1	46.7			
7/24/2001	31	43.5	45.9			
7/31/2001	37.3	43.5	46.4			
8/7/2001	39.6	43	43.9			
8/14/2001	35.2	43.3	44			
8/21/2001	46.3	51.3	46.9			
8/28/2001	43.5	52	52			
9/3/2001	42	49.4	49.6			
9/10/2001	48.9	46.8	48.7			
9/17/2001	36.6	51.8	47.9			
9/25/2001	43.2	44.7	37.6			
10/2/2001	20.8	51.3	49.3			
10/9/2001	38.4	44.9	42.2			
10/15/2001	35.2	41.1	47.2			
10/22/2001	33.8	42.3	41			
10/29/2001	38	44.8	44.9			
11/6/2001	50.8		50.6			
11/12/2001	30.8		43.5			
11/19/2001	51.6		49.1			
11/26/2001	40.4		45.4			
12/3/2001	35		46.3			
12/10/2001	43.2		49			
12/17/2001	43.9		38.8			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/7/2002	47.2	37.4	41.2			
1/14/2002	29.9	33.9	38.9			
1/21/2002	30.1	34.3	27.3			
1/28/2002	31	34.3	28.5			
2/4/2002	35.2	33.4	42.9			
2/11/2002	49.1	39	44.2			
2/18/2002	35.1	68.7	44			
2/25/2002	30.4	33.9	38.5			
3/4/2002	35.6	43.2	40.5			
3/11/2002	40	36.5	45.4			
3/18/2002	31.3	35.8	46.7			
3/25/2002	22.1	36.5	44.1			
4/2/2002	37.1	33.1	34.6			
4/8/2002	27.5	25.7	35.3			
4/16/2002	46.4	34.3	41.5			
4/22/2002	27.1	35.7	43.5			
4/29/2002	24.4	35.1	35.4			
5/7/2002	22.3	48.3	39.8			
5/15/2002	14.8	27.2	36.3			
5/20/2002	18.9	42	29.2	27.5	17	16.3
5/27/2002	28.2	41.2	38.5	20.4	16.6	15.2
6/3/2002	21.2	49.6	47.3	17.4	20.2	16.7
6/10/2002	16.3	49.9	36.9	28.2	24.9	26.2
6/17/2002	17.7	49.1	35.5	27.3	26.8	23
6/24/2002	20.4	57.2	27.5	23.3	22.4	22.2
7/1/2002	22.7	54.7	22.8	26.2	18.7	21
7/8/2002	33.7	44.8	19.3	27.1	21.4	22.3
7/15/2002	20.2	38.7	22	27	21.6	25.9
7/23/2002	18.9	46	31.9	33.2	33	32
8/5/2002	28.12	42.26	34.03	50.1	57.5	51.67
8/12/2002	19.61	25.71	34.44	43.7	54.6	46.94
8/19/2002	29.2	33.3	29.21	48.9	43.6	42.04
8/26/2002	26.3	78.7	39.8	46	44.7	41.6
9/4/2002	17.91	50.24	34.35	105	42.7	38.41
9/9/2002	106	108	27.47	124	26	25.6
9/16/2002	13.49	56.08	33.3	21.1	14.9	15.3
9/23/2002	46.14	48.36	32.18	65.4	40.1	34.9
9/30/2002	83.86	50.7	35.7	66.9	38.5	34.4
10/7/2002	40	45.3	44.1	74.5	39.5	40.9
10/14/2002	18	44.8	32.4	72.6	38.5	37.6
10/21/2002	49.2	69.3	53.2	60.8	53.3	66.4
10/28/2002	17.6	58.6	30.2	69	50.7	40.4
11/4/2002	28.8	54.5	35.8	78.2	40.8	40.9
11/11/2002	19.7	41.3	34.9	46.1	31	29.41
11/18/2002	33.5	43.8	16.4	67.2	37.9	49.1
11/24/2002						
12/2/2002	12.7	53.5	33			
12/9/2002	16.7	52.6	28.8		39.6	36.8
12/16/2002	31.5					32.9
1/6/2003	52.2	37.9	27.9	36.7	16.9	18.5
1/13/2003	40.6	43.2	26.6	31.5		23.7
1/21/2003	20.5	39.9	28.6	38	19.4	24.7

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/27/2003	19.2	42.7	27.7	32.5	20.8	24.3
2/3/2003	36	42.3	18.3	35	25.2	28
2/10/2003	15.9	40.5	21.3	37.3		27.8
2/18/2003	17.8	39.8	17.6		20.6	26.8
2/24/2003	37.5	41.9	21.9	21.9	27.5	20.7
3/3/2003	81.4	44.3	25.3	23.3	32.6	15.9
3/10/2003	81.6	35.5	28.2	40.6	35.2	19.2
3/18/2003	37.2	41.9	17.2	22.3	42.9	38.3
3/25/2003	62.5	40.7	28	24.5	79.4	28.2
4/1/2003	123	46.2	60.5	29	83.3	63.7
4/8/2003	224	46.7	44.9	29	64.5	64.1
4/15/2003	356	72.7	72.1	42.9	84.1	53.3
4/22/2003	980	64.4	69	60.3	67.8	134
4/29/2003	156	48.1	31.4	28.9	38.3	52.2
5/6/2003	25.2	56.4	57.7	45.8	78.6	88.5
5/13/2003	60.8	49.2	65.4	80.1	65.2	63.7
5/20/2003	93.8	39.7	30.6	78	39.9	32.5
5/26/2003	970	76.2	80.4	78.3	79.5	32.3
6/9/2003	64.1	95.5	145	114	65.3	75.7
6/16/2003	650	101	59.3	92.5	62.6	64
6/23/2003	438	92.47	85.43	82.8	47.4	46.89
6/30/2003	128	84.02	132	83.7	54.8	52.59
7/8/2003	48.9	78.8	98.3	79.5	38.3	95.48
7/15/2003	437	74.19	77.13	64.1	56.6	70.22
7/22/2003	205	75.59	48.01	94.2	42.9	64.72
7/29/2003	828	103	78.25	84.6	47.4	62.22
8/5/2003	20.58	88.59	69.52	58.3	51.9	70.37
8/12/2003	116	110	77.17	69.5	53.3	60.36
8/19/2003	863	99.12	77.36	83.2	92.3	65.38
8/26/2003	85.19	102	85.05	74.6	98.6	77.91
9/2/2003	69.43	116	113	74	87.1	106
9/9/2003	221	102	71.74	69.6	106	95.26
9/16/2006	690	108	59.06	70.6	120	61.81
9/23/2003	135	59.44	49.73	49.8	59.6	45.41

A. 7 Nitrate and nitrite nitrogen in the effluent of the reactor (mg/L)

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	0	2.52	2.95			
2/18/2001	0	13.73	25.89			
2/22/2001	0	48.35	68.16			
2/26/2001	0	42.6	82.85			
2/28/2001	0	26.38	69.94			
3/5/2001	0	0.1	24.42			
3/7/2001	0	30.41	42.27			
3/12/2001	0	31.45	63.25			
3/14/2001	0	40.49	71.6			
3/19/2001	0	0.15	22.03			
3/25/2001	0	26.43	42.62			
3/28/2001	0	20.92	22.77			
4/4/2001	0.25	1.31	26.41			
4/11/2001	0	44.7	68.2			
4/19/2001	0.05	0.7	15.48			
4/25/2001	0	44.2	55.13			
5/2/2001	0	87.29	94.4			
5/8/2001	0	75.25	62.34			
5/15/2001	0	49.83	30.75			
5/21/2001	0.13	90.62	59.5			
6/5/2001	3.82	83.72	63.08			
6/12/2001	8.69	129	76.69			
6/19/2001	23.56	76.56	82.07			
6/26/2001	6.33	67.79	87.32			
7/3/2001	6.42	49.36	76.92			
7/10/2001	8.7	47.89	65.76			
7/17/2001	5.63	66.86	76.68			
7/24/2001	3.25	56.96	64.1			
7/31/2001	0.41	56.92	72.53			
8/7/2001	3.17	52.93	68.33			
8/14/2001	16.34	28.36	42.69			
8/21/2001	11.41	63.99	68.59			
8/28/2001	13.44	66.82	66.82			
9/3/2001	18.18	71.35	77.84			
9/10/2001	0	68.61	77.74			
9/17/2001	1.72	79.4	58			
9/25/2001	0	34.92	35.11			
10/2/2001	0.24	47.55	54.14			
10/9/2001	1.83	31.62	54.22			
10/15/2001	3.51	73.11	57.99			
10/22/2001	4.67	97.26	49.09			
10/29/2001	7.13	101	53.34			
11/6/2001	10.3		53.54			
11/12/2001	8.2		53.11			
11/19/2001	31.23		57.03			
11/26/2001	0.87		63.42			
12/3/2001	0		72.31			
12/10/2001	1.95		75.74			
12/17/2001	0		37.1			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/7/2002	0.6	41.49	37.16			
1/14/2002	0	9.91	22.6			
1/21/2002	0	13.66	5.57			
1/28/2002	0	22.97	3.13			
2/4/2002	0	10.12	9.37			
2/11/2002	0	8.08	11.37			
2/18/2002	0.42	37.66	8.28			
2/25/2002	1.36	47.94	4.46			
3/4/2002	0	43.36	23.65			
3/11/2002	0	28.64	32.2			
3/18/2002	3.5	30.63	31.17			
3/25/2002	0.19	15.76	12.81			
4/2/2002	0	21	4.06			
4/8/2002	0.03	30.47	14.07			
4/16/2002	0	24.79	13.1			
4/22/2002	0	6.59	2.06			
4/29/2002	0	39.49	19.31			
5/7/2002	0.87	68	23			
5/15/2002	0	67.69	19.23			
5/20/2002	0	76.54	19.66	28.25	10	2.72
5/27/2002	0	68.5	7.99	14.7	6.67	1.32
6/3/2002	0	71.4	15.1	14.2	19.5	7.89
6/10/2002	0	18.1	17.9	3.12	27.1	3.12
6/17/2002	0	68.3	3.08	34.5	29	2.23
6/24/2002	0	28.5	0.72	17.2	1.95	10.19
7/1/2002	0	8.8	3.15	44.8	3.87	14.87
7/8/2002	0	6.83	6.73	35.9	13.4	3.8
7/15/2002	0	0.59	0.33	9.78	5.41	5.33
7/23/2002	0	2.32	13.54	6.68	7.02	5.62
8/5/2002	0.01	0.04	3.5	14.7	15.6	10.3
8/12/2002	0	1.16	7.41	24.4	19.7	29.4
8/19/2002	0.37	4.41	13	19.4	11.2	32.9
8/26/2002	0	6.6	0.12	2.9	6.2	13.4
9/4/2002	0.02	4.1	13.7	20.9	20.4	32.7
9/9/2002	0.01	12.4	7.77	17	21.2	26.5
9/16/2002	0	4.58	15.5	36.6	23.3	23.4
9/23/2002	1.59	4.55	12.7	47.5	21.1	14.1
9/30/2002	73.5	6.29	12.4	60	20	3.11
10/7/2002	0.01	8.38	14.6	68.5	17.4	13.9
10/14/2002	0.24	5.04	17.1	61.5	18.3	19
10/21/2002	6.97	0.41	10.9	51.5	13.4	13.5
10/28/2002	0.01	4.92	9.68	84.4	26.4	18.7
11/4/2002	0.04	14.6	18.5	71.2	35.5	14.6
11/11/2002	0	20.3	11.3	52	40.3	29
11/18/2002	0.36	32.5	23.3	41.8	30.6	24.2
11/24/2002						
12/2/2002	0	15.9	23.1	42.2	31.3	24.9
12/9/2002	0	0.4	5.64	45.7	25.9	24.7
12/16/2002	0.01	0	20.5	37	22.6	31.9
1/6/2003	0.01	56.9	12.7	27.3	25.6	15.7
1/13/2003	3.79	60.8	19.4	25.9		21.6
1/21/2003	0	60.3	13.4	12.3	5.81	32

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/27/2003	0	64	8.08	12.3	11.1	22.8
2/3/2003	0.39	61.9	11.4	7.41	14	31.5
2/10/2003	0.01	51.2	11.6	17.7		34.4
2/18/2003	0.01	55.3	9.64		48.4	7.65
2/24/2003	0	40.1	15.2	15.8	39.5	4.68
3/3/2003	0	2.02	2.18	34.8	21	0.45
3/10/2003	0	14.4	4.28	1.28	3.63	2.1
3/18/2003	0	6.31	0.05	0.68	25.4	18.1
3/25/2003	0.18	7.65	13.7	3.84	29.9	25.2
4/1/2003	0	2.91	15.4	6.29	28.5	33
4/8/2003	0.01	2.29	8.08	5.91	30.4	31.9
4/15/2003	0.01	5.27	7.21	6.25	10.5	30.2
4/22/2003	0.03	6.54	10.6	10.6	17	9.79
4/29/2003	0	6.62	13.5	5.85	15.5	17.7
5/6/2003	0.4	4.47	12.1	5.19	15.3	8.65
5/13/2003	0.12	2.87	13.2	10.4	11.2	6.66
5/20/2003	0.55	2.85	11.6	9.92	7.23	6.59
5/26/2003	0.01	4.33	17.5	9.44	6.72	3.94
6/9/2003	0.14	3.72	16.2	12.5	6.12	6.21
6/16/2003	0.16	7.78	15.1	16.7	10.8	11.1
6/23/2003	26.7	24.1	31.8	37.9	24.8	27.2
6/30/2003	20	20.6	25.1	35.4	26.8	25.6
7/8/2003	1.1	6.37	6.67	19.1	9.75	11.7
7/15/2003	1.38	5.88	3.63	14	13	13.3
7/22/2003	0	5.52	8.17	0.69	2.64	10.3
7/29/2003	0.63	10.4	17.1	33.2	4.9	6.26
8/5/2003	0.24	9.68	23.6	23.4	6.29	10.2
8/12/2003	2.06	11	20.8	16.2	7.73	7.36
8/19/2003	14.3	12.7	15.2	13.2	10.5	2.8
8/26/2003	0.11	27.9	14.4	21.2	9.08	2.08
9/2/2003	0.05	37	12.2	19.6	10.9	9.16
9/9/2003	0.13	51.9	13.6	9.98	9.29	10.6
9/16/2006	4.78	60.7	15.6	6.52	12.1	12.6
9/23/2003	4.79	58.5	15.2	12.7	8.46	9.99

A.8 TOC in influent and effluent (mg/L).

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	488	60	65.1			
2/18/2001	215	70.4	71.8			
2/22/2001	355	146	130			
2/26/2001	373	219	218			
2/28/2001	391	98.8	105			
3/5/2001	244	162	73.9			
3/7/2001	235	204	97.7			
3/12/2001	247	256	111			
3/14/2001	167	192	118			
3/19/2001	399	206	118			
3/25/2001	201	86.3	107			
3/28/2001	166	97.4	144			
4/4/2001	309	127	94.4			
4/11/2001	232	67.7	57.9			
4/19/2001	159	79.3	60.6			
4/25/2001	144	76	64.2			
5/2/2001	203	68.3	61.9			
5/8/2001	210	24.8	64.2			
5/15/2001	197	79.3	84.1			
5/21/2001	120	67	79.7			
6/5/2001	156	49.2	53.2			
6/12/2001	161	55.1	53.7			
6/19/2001	275	85.1	101			
6/26/2001	344	74.6	76.1			
7/3/2001	192	62.6	64.6			
7/10/2001	177	91.6	98			
7/17/2001	244	61.5	54.2			
7/24/2001	230	53.6	54.3			
7/31/2001	232	69.7	64			
8/7/2001	157	57.3	51.7			
8/14/2001	185	81.2	77			
8/21/2001	189	50.2	47.3			
8/28/2001	147	45	42.4			
9/3/2001	146	57.6	54.1			
9/10/2001	169	79.7	53.5			
9/17/2001	186	52.2	84			
9/25/2001	199	56	53			
10/2/2001	213	83.4	105			
10/9/2001	128	71.6	71.8			
10/15/2001	184	56.7	98.9			
10/22/2001	232	156	72			
10/29/2001	135	54.4	61.7			
11/6/2001	145		61.2			
11/12/2001	231		75			
11/19/2001	152		72.7			
11/26/2001	215		69			
12/3/2001	222		105			
12/10/2001	154		70.5			
12/17/2001	707		124			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/7/2002	164	102	213			
1/14/2002	316	81.3	75.5			
1/21/2002	196	81.8	78.8			
1/28/2002	186	92.2	106			
2/4/2002	195	51.4	60.8			
2/11/2002	251	48	54.6			
2/18/2002	248	61.4	70.2			
2/25/2002	198	67.2	52.7			
3/4/2002	266	71.3	88.1			
3/11/2002	221	62	73.1			
3/18/2002	205	64.9	79.2			
3/25/2002	296	61.2	90			
4/2/2002	382	59.9	95.5			
4/8/2002	427	59.7	102			
4/16/2002	498	52.8	93			
4/22/2002	354	73.7	78			
4/29/2002	209	62.9	61.9			
5/7/2002	360	60.1	84.9			
5/15/2002	390	94.6	90.1			
5/20/2002	320	71.3	87.6	106	113	120
5/27/2002	266	64.3	66.04	128	139	146
6/3/2002	248	68.8	64.38	127	153	187
6/10/2002	291	80.2	86.09	209	205	203
6/17/2002	347	56.8	76.56	200	218	216
6/24/2002	372	73.5	228	214	270	257
7/1/2002	366	90.7	267	253	282	222
7/8/2002	519	178	303	225	279	261
7/15/2002	359	177	374	177	281	275
7/23/2002	266	127	197	116	142	196
8/5/2002	109	273	176	113	140	161
8/12/2002	403	210	168	104	130	134
8/19/2002	254	205	112	103	100	110
8/26/2002	297	180	157	95	112	115
9/4/2002	200	94.9	86.9	107	94.3	83.6
9/9/2002	240	97.4	100	100	110	99.4
9/16/2002						
9/23/2002	205	72	71	84	73	92
9/30/2002	179	86.9	80.2	77.2	85.2	116
10/7/2002	258	92.7	81	84.6	88.2	116
10/14/2002	217.9	106	102.9	101	100	91.42
10/21/2002	265	172	157	119	129	121
10/28/2002	653	109	105	143	108	119
11/4/2002	185	86.1	97.2	94.6	90.7	89.9
11/11/2002	227	99.8	117	105	111	119
11/18/2002	338	111	192	119	116	179
11/24/2002						
12/2/2002	310	88.8	93.2	85.2	77.1	101
12/9/2002	236	127	124	93.5	82.7	97.7
12/16/2002	238	174	96.4	81.5	83.4	82.3
1/6/2003	487	57.3	65.5	84.3	124	195
1/13/2003	614	59	94	109		112
1/21/2003	287	60.2	95.6	125	198	89.8

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/27/2003	385	65.5	195	193	207	86.4
2/3/2003	227	61.3	132	131	115	76.8
2/10/2003	384	66.8	80.7	95.7		78.8
2/18/2003	355	56.2	160		95.6	116
2/24/2003	238	61.1	102	134	84.2	152
3/3/2003	357	97.3	152	101	73.2	189
3/10/2003	286	99.4	130	90	84	173
3/18/2003	292	67.1	151	109	63.7	143
3/25/2003	354	53.6	268	115	80.5	140
4/1/2003	258	70.2	155	128	69.7	76.1
4/8/2003	217	74.3	127	115	66.7	73.9
4/15/2003	254	92.9	124	181	90.3	85.3
4/22/2003	324	69.2	105	164	90.7	120
4/29/2003	312	61.1	124	166	92	104
5/6/2003	277	75.6	141	179	110	111
5/13/2003	138	69.5	129	128	80.3	104
5/20/2003	331	107	170	201	126	156
5/26/2003	284	90.6	110	172	150	144
6/9/2003	457	88	166	174	156	158
6/16/2003	493	81.2	205	141	234	152
6/23/2003	299	61.5	132	105	133	85.6
6/30/2003	363	75.7	183	131	190	98.3
7/8/2003	327	71.6	203	98.1	171	120
7/15/2003	433	81.2	211	146	245	147
7/22/2003	547	95	260	171	183	136
7/29/2003	157	54.6	57.6	70.5	110	86.9
8/5/2003	385	72.4	87.5	84.3	140	123
8/12/2003	545	90.6	136	124	240	174
8/19/2003	498	82.4	139	129	269	199
8/26/2003	103	58.6	59.8	57.2	102	129
9/2/2003	466	64.8	93.1	86.5	164	206
9/9/2003	463	73.7	107	110	143	141
9/16/2006	358	60.6	79.2	101	96.7	75.8
9/23/2003	368	56.8	84.8	82.4	91.9	90.1

A.9 TSS in the influent and aeration zone (mg/L).

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	493	2280	2393			
2/18/2001	980	2133	1978			
2/22/2001	2013	2407	2187			
2/26/2001	2867	3233	2527			
2/28/2001	3244	2293	2507			
3/5/2001	697	6211	1197			
3/7/2001	760	2444	1923			
3/12/2001	992	3923	2107			
3/14/2001	1066	4270	3293			
3/19/2001	2507	2553	1577			
3/25/2001	1030	2291	1985			
3/28/2001	1037	1900	5080			
4/4/2001	2264	8553	3467			
4/11/2001	1352	3320	4970			
4/19/2001	1233	4390	2170			
4/25/2001	1383	1367	2140			
5/2/2001	780	2063	1680			
5/8/2001	937	1607	847			
5/15/2001	771	1450	873			
5/21/2001	880	1470	660			
6/5/2001	840	8233	1633			
6/12/2001	657	3800	1337			
6/19/2001	1207	3733	2427			
6/26/2001	600	3580	5307			
7/3/2001	1047	5820	2640			
7/10/2001	533	2037	2120			
7/17/2001	840	2520	3607			
7/24/2001	733	2330	6903			
7/31/2001	457	1483	1953			
8/7/2001	990	7907	3940			
8/14/2001	773	475	282			
8/21/2001	1223	2063	2267			
8/28/2001	647	1903	2577			
9/3/2001	138	2563	2280			
9/10/2001	220	6440	2647			
9/17/2001	303	2490	2571			
9/25/2001	543	587	1200			
10/2/2001	457	13900	3167			
10/9/2001	248	11087	2180			
10/15/2001	353	7313	3713			
10/22/2001	487	7740	1627			
10/29/2001	340	4853	2033			
11/6/2001	177		1617			
11/12/2001	437		1547			
11/19/2001	443		873			
11/26/2001	407		2807			
12/3/2001	553		1423			
12/10/2001	237		700			
12/17/2001	970		7440			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/7/2002	3440	250	2707			
1/14/2002	2487	537	259			
1/21/2002	1893	583	3573			
1/28/2002	480	769	1011			
2/4/2002	600	380	4733			
2/11/2002	1083	167	2650			
2/18/2002	887	1583	4100			
2/25/2002	573	2247	1667			
3/4/2002	560	3917	1267			
3/11/2002	303	953	3917			
3/18/2002	320	2245	3167			
3/25/2002	360	1900	5933			
4/2/2002	523	2027	4080			
4/8/2002	650	2613	3840			
4/16/2002	797	119	198			
4/22/2002	433	1177	3233			
4/29/2002	1747	927	3743			
5/7/2002	647	1333	3780			
5/15/2002	663	1200	3507			
5/20/2002	1097	853	2887	67	87	80
5/27/2002	805	720	3460	330	340	330
6/3/2002	630	940	2480	270	430	350
6/10/2002	670	2900	2560	510	680	284
6/17/2002	680	993	284	470	450	280
6/24/2002	660	1840	1380	540	710	475
7/1/2002	2020	1430	1238	750	675	560
7/8/2002	1030	3560	920	860	800	800
7/15/2002	2190	1370	2930	390	890	700
7/23/2002	347	344	2770	310	524	580
8/5/2002	1180	2840	8040	2260	3230	1840
8/12/2002	980	365	5890	2100	3490	1900
8/19/2002	760	1680	5480	3320	3640	2140
8/26/2002	460	3470	4490	2360	2960	2260
9/4/2002	2760	530	2750	5000	2010	1700
9/9/2002	2690	1840	2710	5810	1810	1570
9/16/2002	630	2550	2970	3940	2150	1025
9/23/2002	360	1990	3230	3440	2200	690
9/30/2002	6260	480	1650	2560	1330	225
10/7/2002	740	715	1280	1880	1100	3350
10/14/2002	3770	330	1510	900	1070	2850
10/21/2002	1090	5020	4690	2220	3370	4590
10/28/2002	2240	4700	2000	985	2160	2890
11/4/2002	480	1730	2800	1400	1990	2010
11/11/2002	500	1360	2730	1010	1430	2320
11/18/2002	280	3130	4110	1160	2560	2540
11/24/2002		3307	3197	1703	1873	3623
12/2/2002	610	6050	2930	2030	3150	1780
12/9/2002	850	4540	4380	2150	2770	2640
12/16/2002	443	240	1670	580	770	232
1/6/2003	1297	2410	443	850	2450	1447
1/13/2003	1143	4967	1767	833		2140
1/21/2003	610	2160	400	203	747	1084

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/27/2003	504	3553	486	867	424	346
2/3/2003	417	2633	3833	3256	1022	3133
2/10/2003	690	1327	803	126		1510
2/18/2003	644	1250	727		1739	560
2/24/2003	1176	442	795	403	3197	458
3/3/2003	4367	357	557	2383	3245	903
3/10/2003	3700	2216	353	619	2956	753
3/18/2003	1344	812	267	85	3078	1345
3/25/2003	2300	333	2060	87	2717	2970
4/1/2003	1783	109	3217	297	2767	2855
4/8/2003	2817	353	1891	789	1775	3256
4/15/2003	3733	1574	3433	902	3467	2653
4/22/2003	8100	758	2750	1164	2600	3100
4/29/2003	4133	566	1550	593	2711	2228
5/6/2003	1333	590	1933	574	3197	1856
5/13/2003	1483	297	2500	2350	2356	1231
5/20/2003	2647	607	2160	2220	1300	765
5/26/2003	5430	2273	3642	1220	1274	368
6/9/2003	1717	2625	2917	3500	1083	2489
6/16/2003	5067	3373	2167	3078	1156	2355
6/23/2003	3867	2056	875	2822	680	1800
6/30/2003	2167	1739	3183	4817	693	1689
7/8/2003	1155	1713	4367	2668	404	2900
7/15/2003	3583	1399	1756	3800	1078	2211
7/22/2003	2606	2012	947	3033	625	1817
7/29/2003	7567	3706	2628	3567	645	834
8/5/2003	1333	2687	2211	929	667	1534
8/12/2003	14733	3838	2356	939	903	1492
8/19/2003	10817	2744	2417	2967	2323	703
8/26/2003	1417	2655	2650	1439	2700	1655
9/2/2003	1308	3185	3844	1337	2269	4144
9/9/2003	2353	2376	1513	1036	2845	3208
9/16/2006	8567	3610	1228	2098	4100	1227
9/23/2003	6583	2727	2203	1516	2478	1464

A.10 VSS in the influent and the aeration zone (mg/L).

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
2/14/2001	473	2000	2087			
2/18/2001	853	1691	1564			
2/22/2001	1583	1987	1827			
2/26/2001	1978	2393	1913			
2/28/2001	2178	1673	1853			
3/5/2001	607	3932	900			
3/7/2001	630	1622	1330			
3/12/2001	839	2633	1450			
3/14/2001	904	2603	2233			
3/19/2001	1627	1572	1082			
3/25/2001	753	1231	1190			
3/28/2001	787	1137	3013			
4/4/2001	1800	4753	2143			
4/11/2001	933	1897	2527			
4/19/2001	877	2310	1307			
4/25/2001	637	840	1360			
5/2/2001	573	1130	1017			
5/8/2001	607	913	547			
5/15/2001	610	873	597			
5/21/2001	667	860	457			
6/5/2001	507	4191	1033			
6/12/2001	557	1972	810			
6/19/2001	747	1893	1467			
6/26/2001	580	1827	2860			
7/3/2001	840	2907	1600			
7/10/2001	457	1200	1320			
7/17/2001	667	1347	2007			
7/24/2001	440	1157	3440			
7/31/2001	377	77	1093			
8/7/2001	667	3600	2133			
8/14/2001	443	287	242			
8/21/2001	507	997	1187			
8/28/2001	493	957	1333			
9/3/2001	364	1233	1233			
9/10/2001	220	2873	1453			
9/17/2001	303	1147	1347			
9/25/2001	527	337	653			
10/2/2001	390	5833	1660			
10/9/2001	248	4547	1247			
10/15/2001	283	3060	1733			
10/22/2001	487	3273	1103			
10/29/2001	340	2020	1147			
11/6/2001	177		857			
11/12/2001	387		823			
11/19/2001	230		367			
11/26/2001	393		1450			
12/3/2001	527		827			

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
12/10/2001	237		483			
12/17/2001	880		3967			
1/7/2002	1653	178	1713			
1/14/2002	1420	350	176			
1/21/2002	1300	440	2333			
1/28/2002	480	468	734			
2/4/2002	513	260	2760			
2/11/2002	790	163	1620			
2/18/2002	620	813	2160			
2/25/2002	487	1153	1020			
3/4/2002	487	2183	793			
3/11/2002	263	511	2093			
3/18/2002	240	1100	1844			
3/25/2002	342	1176	3600			
4/2/2002	500	1140	2467			
4/8/2002	603	1413	2387			
4/16/2002	763	103	172			
4/22/2002	433	663	2033			
4/29/2002	1060	607	2433			
5/7/2002	633	897	2533			
5/15/2002	600	777	2373			
5/20/2002	801	800	2113	67	87	80
5/27/2002	720	580	1240	330	340	330
6/3/2002	580	700	1777	270	400	330
6/10/2002	610	2150	1940	460	640	264
6/17/2002	610	713	252	440	440	244
6/24/2002	620	1220	1080	500	630	395
7/1/2002	1190	1020	1025	610	613	473
7/8/2002	860	2362	740	780	720	740
7/15/2002	1490	1040	2170	390	810	660
7/23/2002	347	304	2060	310	444	440
8/5/2002	820	1900	5560	1620	2320	1240
8/12/2002	840	295	4070	1560	2440	1310
8/19/2002	660	1190	4020	2270	2640	1460
8/26/2002	445	2310	3330	1840	2140	1620
9/4/2002	1360	380	2110	3680	1510	1570
9/9/2002	1330	1340	2110	4190	1410	1240
9/16/2002	590	1780	2260	2880	1630	810
9/23/2002	360	1350	2530	3440	2200	690
9/30/2002	6400	375	1350	1870	1080	210
10/7/2002	700	550	1070	1430	900	2360
10/14/2002	1620	280	1280	740	910	2160
10/21/2002	930	3440	3510	1590	2540	3320
10/28/2002	1590	3200	1550	715	1680	2190
11/4/2002	450	1280	2150	1070	1560	1530
11/11/2002	480	1040	2140	820	1190	1860
11/18/2002	180	1890	2770	800	1850	1810
11/24/2002		2027	2200	1190	1433	2640
12/2/2002	570	3450	2050	1420	2280	1270
12/9/2002	700	2690	2880	1480	1184	1880
12/16/2002	403	205	1250	450	630	220
1/6/2003	990	1613	410	687	2013	1313

Date	Influent	Reactor A	Reactor B	Reactor C	Reactor D	Reactor E
1/13/2003	122	1713	280	123		273
1/21/2003	447	1553	400	196	670	973
1/27/2003	504	2445	427	745	440	332
2/3/2003	387	1967	3300	2600	972	2822
2/10/2003	647	980	710	117		1330
2/18/2003	644	997	653		1522	522
2/24/2003	1089	367	723	383	2711	453
3/3/2003	2500	289	527	2089	2844	903
3/10/2003	2183	1733	330	562	2567	730
3/18/2003	1256	662	258	85	2722	1300
3/25/2003	1430	268	1743	87	2193	2454
4/1/2003	1108	109	2883	283	2400	2545
4/8/2003	1267	270	1498	661	1433	2600
4/15/2003	1667	1091	2367	608	2611	1950
4/22/2003	3383	592	2433	1136	2400	2667
4/29/2003	2317	441	1550	593	2394	1931
5/6/2003	1333	475	1844	569	2581	1515
5/13/2003	1417	237	2183	2133	1955	1100
5/20/2003	1547	481	1800	1733	1023	613
5/26/2003	2290	1656	2783	1013	959	306
6/9/2003	1667	2108	2500	2967	992	2078
6/16/2003	2567	2660	1900	2767	1145	2056
6/23/2003	2150	1582	769	2433	680	1447
6/30/2003	1900	1355	2677	3983	693	1622
7/8/2003	1155	1358	3300	2263	404	2392
7/15/2003	2006	1112	1567	3333	1013	1978
7/22/2003	1494	1558	867	2478	581	1452
7/29/2003	3367	2826	2350	3089	582	712
8/5/2003	1333	2077	1900	844	612	1276
8/12/2003	5250	2988	2155	825	856	1241
8/19/2003	4200	2118	2400	2883	2113	617
8/26/2003	1383	2042	2333	1239	2178	1400
9/2/2003	1308	2421	3178	1181	1856	3422
9/9/2003	1777	1830	1352	932	2256	2580
9/16/2003	3617	2747	1067	1723	3250	1021
9/23/2003	3217	2110	1933	1251	2033	1213

A. 11 ORP, DO, pH in the aeration tank of Reactor A.

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
68.92	0	1.7	0	7.89	0
61.66	5	1.8	3	7.87	5
63.06	10	1.6	7	7.87	10
66.75	15	1.5	12	7.87	15
70.25	20	1.4	16	7.86	20
76.14	25	1.4	19	7.86	25
76.26	30	1.4	24	7.86	30
81.3	35	1.5	28	7.86	35
93.58	40	1.8	30	7.85	40
104.16	45	2.3	32	7.85	45
112.54	50	2.9	33	7.84	50
113.42	55	3.1	34	7.84	55
114.46	60	3.7	37	7.83	60
103.27	65	4	39	7.84	65
95.59	70	4.4	43	7.85	70
91.02	75	4.5	44		
87.57	80	4.6	46	7.86	80
84.99	85	4.7	48	7.87	85
82.74	90	4.8	52	7.88	90
81.24	95	4.9	56	7.89	95
79.16	100	5	60	7.9	100
75.99	105	4.8	61	7.9	105
73.31	110	3.6	64	7.91	110
71.02	115	3.2	68	7.91	115
67.11	120	2.9	71	7.91	120
63.96	125	2.4	73	7.9	125
64.65	130	2	74	7.89	130
66.83	135	1.9	75	7.88	135
69.47	140	1.8	76	7.89	140
75.91	145	1.8	77	7.88	145
77.51	150	1.6	78	7.87	150
80.54	155	1.5	79	7.87	155
89.21	160	1.5	80	7.86	160
101.45	165	1.5	82	7.86	179
109.23	170	0.5	103	7.86	184
113.15	175	0.4	116	7.87	189
115.34	180	0.3	118	7.89	194
107.72	185	0.7	121	7.9	199
100.24	190	1.2	122	7.9	204
93.84	195	1.3	123	7.91	209
88.97	200	1.4	124	7.92	214
87.44	205	1.3	125	7.92	219
85.55	210	1.2	127	7.92	224
82.9	215	1.2	129	7.93	229

ORP (mV)	Time (minutes)	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
80.38	220	1.2	131	7.93	234
79.27	225	1.2	133	7.94	239
76.08	230	1.2	140	7.94	244
72.6	235	1.2	142	7.93	249
69.15	240	1.8	150	7.93	254
64.91	245	2.2	151	7.91	259
65.26	250	2.9	153	7.9	264
67.13	255	4.3	161	7.89	269
71.07	260	4.6	163	7.89	274
72.81	265	4.9	170	7.89	279
75.38	270	5	172	7.89	284
84.61	275	5	174	7.89	289
97.47	280	5.1	177	7.88	294
106.97	285	5.1	179	7.87	299
112.32	290	5	180	7.88	304
116.66	295	4.9	181	7.9	309
117.43	300	4.4	182	7.91	314
105.12	305	3.7	183	7.92	319
98.72	310	2.9	185	7.93	324
94.51	315	2.5	187	7.94	329
90.38	320	1.2	192	7.94	334
87.15	325	1	193	7.95	339
84.66	330	0.9	194	7.95	344
80.9	335	0.9	195	7.96	349
78.25	340	0.8	198	7.96	354
77.02	345	0.6	200	7.98	359
73.65	350	0.8	202	7.96	364
69.04	355	0.6	205		
65.49	360	0.4	209		
		0.4	219		
		0.4	232		
		0.3	238		
		0.3	239		
		0.6	241		
		1.2	242		
		1.5	243		
		1.5	244		
		1.3	246		
		1.2	248		
		1.2	250		
		1.1	251		
		1.1	252		
		1.2	254		
		1.2	256		
		1.2	258		
		1.2	260		
		1.2	262		
		2.8	271		

Dissolved Oxygen (mg/L)	Time minutes
3.2	273
4.7	279
5.4	295
5.4	297
5.4	299
5.5	300
5.4	301
4.9	302
4.1	303
3.5	304
3.3	305
3.1	306
2.9	307
2.7	308
2.6	309
2.4	310
1.8	312
1.7	313
1.7	314
1.4	316
0.9	317
0.9	318
0.8	320
0.6	330

A.12 ORP in the aeration tank of Reactor B (mV).

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-67.84	0	0.1	0	7.61	12
2.27	5	0.2	1	7.64	17
27.04	10	0.9	2	7.65	22
40.18	15	1.1	3	7.65	27
46.32	20	1	4	7.65	32
52.68	25	1	7	7.65	37
56.76	30	1.3	8	7.66	42
61.18	35	1.2	9	7.66	47
64.17	40	1.3	10	7.66	52
67.46	45	1	22	7.66	57
69.74	50	0.8	35	7.66	62
71.18	55	1	42	7.66	67
73.82	60	1.1	49	7.67	72
71.83	65	3.1	59	7.67	77
68.28	70	2.9	63	7.67	82
62.55	75	2.7	64	7.67	87
57.45	80	2.3	65	7.68	92
52.22	85	2	66	7.68	97
47.83	90	1.9	67	7.69	102
41.58	95	1.7	68	7.7	107
34.48	100	1.4	69	7.7	112
25.28	105	1.1	73	7.7	117
12.5	110	1	75	7.7	122
-1.11	115	0.7	80	7.7	127
-13.06	120	0.6	81	7.7	132
-22.12	125	0.4	82	7.71	137
-27.53	130	0.3	83	7.71	142
-33.44	135	0.4	95	7.71	147
-40.41	140	0.1	107	7.71	152
-46.58	145	0.1	128	7.71	157
-52.19	150	0.1	135	7.71	162
-56.6	155	0.1	144	7.71	167
-60.23	160	0.1	230	7.71	172
-62.08	165	0.1	240	0	177
-63.99	170	0.4	241	7.66	182
-66.65	175	0.7	242	7.65	187
-69.15	180	0.9	243	7.63	192
-70.55	185	1	244	7.59	197
-69.15	190	0.9	246	7.57	202
-71.03	195	0.8	251	7.55	207
-73.56	200	0.8	257	7.58	212
-77.04	205	0.7	262	7.59	217
-80.14	210	0.7	267	7.58	222
-82.64	215	0.8	272	7.55	227
-84.1	220	0.9	275	7.54	232

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-85.76	225	1.2	278	7.62	242
-87.01	230	1.5	279	7.65	247
-88.64	235	1.9	282	7.66	252
-90.52	240	2.2	283	7.67	257
10.69	245	2.5	284	7.67	262
40.59	250	2.8	285	7.66	267
54.6	255	3.3	288	7.66	272
61.7	260	3.6	290	7.67	277
65.94	265	3.8	291	7.66	282
71.3	270	4	293	7.65	287
75.21	275	4.2	294	7.65	292
77.52	280	4.3	295	7.64	297
79.21	285	4.4	296	7.64	302
82.66	290	4.5	297	7.64	307
84.64	295	4.6	299	7.65	312
86.3	300	4.7	300	7.65	317
83.54	305	4.2	301	7.64	322
81.35	310	3.5	303	7.64	327
77.09	315	2.8	306	7.63	332
72.33	320	0.3	309	7.64	337
68.17	325	0.1	313	7.64	342
64.75	330	0	338	7.65	347
61.07	335	0	374	7.65	352
56.77	340	0	408	7.65	357
52.47	345	0	420	7.65	362
48.14	350	0.05	431	7.66	367
43.09	355	0.05	456	7.67	372
36.61	360	0.05	474	7.67	377
30.26	365	0.05	478	7.67	382
20.13	370	0.35	481	7.67	387
5.18	375	0.43	482	7.67	392
-9.34	380	0.76	483	7.67	397
-21.72	385	0.96	484	7.67	402
-31.37	390	1.03	485	7.67	407
-38.11	395	0.87	486	7.68	412
-43.49	400	0.82	487	7.68	417
-48.56	405	0.8	488	7.67	422
-52.36	410	0.72	489	7.64	427
-55.12	415	0.68	490	7.63	432
-57.92	420	0.63	491	7.62	437
-58.55	425	0.61	492	7.62	442
-58.09	430	0.57	493	7.61	447
-61.11	435	0.57	494	7.6	452
-65.44	440	0.55	495	7.59	457
-69.29	445	0.56	496	7.59	462
-71.19	450	0.54	498	7.58	467
-72.33	455	0.52	500	7.59	472
-74.7	460	0.54	502	7.62	477

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-77.33	465	0.51	504	7.65	482
-78.43	470	0.49	506	7.65	487
-79.97	475	0.5	508	7.66	492
-81.91	480	0.53	511	7.66	497
14.02	485	0.52	513	7.66	502
43.15	490	0.58	515	7.66	507
55.47	495	0.62	517	7.66	512
61.94	500	0.75	519	7.66	517
67.31	505	1.01	521	7.66	522
72.18	510	1.32	523	7.67	527
75.5	515	1.71	525	7.67	532
76.85	520	2.24	527	7.66	537
79.24	525	2.64	529	7.65	542
81.63	530	2.95	531	7.66	547
83.15	535	3.52	533	7.66	552
84.68	540	3.75	535	7.66	557
84.22	545	3.96	537	7.66	562
80.96	550	4.22	539	7.66	567
76.25	555	4.37	541	7.65	572
72.63	560	1.33	542	7.65	577
68.98	565	0.79	543	7.65	582
65.16	570	0.58	544	7.65	587
61.3	575	0.52	545	7.65	592
57.54	580	0.43	546	7.65	597
53.48	585	0.33	547	7.66	602
48.48	590	0.24	548	7.67	607
43.55	595	0.13	549	7.68	612
37.59	600	0.04	551	7.68	617
30.93	605	0.03	560	7.68	622
21.38	610	0.03	578	7.68	627
8.4	615	0.04	632	0	632
-6.35	620	0.05	678	7.63	637
-19.45	625			7.63	642
-29.06	630			7.63	647
-36.67	635			7.62	652
-43.03	640			7.61	657
-48.31	645			7.61	662
-52.19	650			7.6	667
-56.02	655			7.6	672
-59.79	660			7.59	677
-67.84	0			7.59	682
2.27	5				
27.04	10				
40.18	15				
46.32	20				
52.68	25				
56.76	30				
61.18	35				

ORP (mV)	Time minutes
64.17	40
67.46	45
69.74	50
71.18	55
73.82	60
71.83	65
68.28	70
62.55	75
57.45	80
52.22	85
47.83	90
41.58	95
34.48	100
25.28	105
12.5	110
-1.11	115
-13.06	120
-22.12	125
-27.53	130
-33.44	135
-40.41	140
-46.58	145
-52.19	150
-56.6	155
-60.23	160
-62.08	165
-63.99	170
-66.65	175
-69.15	180
-70.55	185
-69.15	190
-71.03	195
-73.56	200
-77.04	205
-80.14	210
-82.64	215
-84.1	220
-85.76	225
-87.01	230
-88.64	235
-90.52	240
10.69	245
40.59	250
54.6	255
61.7	260
65.94	265
71.3	270
75.21	275

ORP (mV)	Time minutes
77.52	280
79.21	285
82.66	290
84.64	295
86.3	300
83.54	305
81.35	310
77.09	315
72.33	320
68.17	325
64.75	330
61.07	335
56.77	340
52.47	345
48.14	350
43.09	355
36.61	360
30.26	365
20.13	370
5.18	375
-9.34	380
-21.72	385
-31.37	390
-38.11	395
-43.49	400
-48.56	405
-52.36	410
-55.12	415
-57.92	420
-58.55	425
-58.09	430
-61.11	435
-65.44	440
-69.29	445
-71.19	450
-72.33	455
-74.7	460
-77.33	465
-78.43	470
-79.97	475
-81.91	480
14.02	485
43.15	490
55.47	495
61.94	500
67.31	505
72.18	510
75.5	515

ORP (mV)	Time minutes
76.85	520
79.24	525
81.63	530
83.15	535
84.68	540
84.22	545
80.96	550
76.25	555
72.63	560
68.98	565
65.16	570
61.3	575
57.54	580
53.48	585
48.48	590
43.55	595
37.59	600
30.93	605
21.38	610
8.4	615
-6.35	620
-19.45	625
-29.06	630
-36.67	635
-43.03	640
-48.31	645
-52.19	650
-56.02	655
-59.79	660

A.13 ORP, DO, pH in the aeration tank of Reactor C.

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-19.27	0	0.1	0	7.62	0
6.5	5	0.7	1	7.66	5
30.29	10	0.9	2	7.66	10
39.16	15	1.3	3	7.63	15
44.7	20	1.7	4	7.62	20
47.88	25	1.8	5	7.61	25
52.15	30	2.6	6	7.6	30
57.93	35	3.3	7	7.58	35
61.58	40	3.4	8	7.58	40
60.9	45	3.5	9	7.57	45
57.76	50	3.5	11	7.56	50
52.99	55	3.4	13	7.56	55
50.28	60	3.5	15	7.56	60
49.07	65	3.5	17	7.6	65
42.35	70	3.6	19	7.61	70
36.57	75	3.5	21	7.6	75
31.07	80	3.6	23	7.59	80
26.88	85	3.9	29	7.62	85
16.89	90	4	30	7.61	90
9.43	95	3.8	31	7.58	95
2.05	100	3.6	32	7.58	100
-2.43	105	3.3	33	7.57	105
-10.75	110	3.2	34	7.58	110
-13.78	115	3	35	7.59	115
-17.68	120	2.8	36	7.57	120
16.09	125	2.7	37	7.65	125
31.95	130	2.4	39	7.68	130
39.36	135	2	41	7.68	135
48.47	140	1.7	43	7.67	140
48.85	145	1.3	45	7.67	145
52.91	150	0.9	51	7.67	150
59.71	155	0.5	64	7.65	155
61	160	0.3	82	7.64	160
62.85	165	0.1	104	7.64	165
58.82	170	0.1	120	7.63	170
55.63	175	0.1	122	7.63	175
54.42	180	0.3	123	7.62	180
49.25	185	0.8	124	7.69	185
50.7	190	1.4	125	7.71	190
42.55	195	1.8	126	7.68	195
36.82	200	2.3	127	7.68	200
32.58	205	2.5	128	7.64	205
28.44	210	3.1	129	7.65	210
16.94	215	3.3	130	7.63	215
8.89	220	3.7	131	7.61	220
4.53	225	3.9	133	7.6	225
-1.21	230	4.1	135	7.6	230

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-5.24	235	4.2	137	7.61	235
-11.7	240	4.3	139	7.61	240
12.98	245	4.4	141	7.65	245
30.74	250	4.3	143	7.64	250
40.78	255	4.3	145	7.62	255
47.06	260	4.2	147	0	260
50.79	265	4.1	149	0	265
50.87	270	4	151	0	270
58.31	275	4	152	0	275
62.67	280	3.9	153	7.57	280
61.62	285	4	154	7.55	285
60.44	290	3.9	155	7.55	290
59.83	295	3.6	156	7.56	295
55.11	300	3.5	157	7.55	300
53.3	305	2.3	158	7.72	305
48.27	310	2	159	7.72	310
44.58	315	1.7	160	7.73	315
42.29	320	1.6	198	7.68	320
36.55	325	1.4	227	7.67	325
27.66	330	1.2	234	7.62	330
19.6	335	1	240	7.61	335
14.02	340	0.8	242	7.61	340
10.71	345	0.2	243	7.6	345
-0.08	350	0.1	244	7.62	350
-7.43	355	0.1	245	7.6	355
-11.62	360	0.1	246	7.59	360
		0.1	247		
		0.2	248		
		0.5	249		
		0.8	250		
		1.2	251		
		1.6	253		
		1.9	255		
		2.2	257		
		2.6	259		
		2.7	262		
		3	271		
		3.5	272		
		3.6	273		
		3.6	274		
		3.6	275		
		3.5	276		
		3.4	277		
		3.3	278		
		3.3	279		
		3.1	280		
		2.8	281		
		2.4	282		

Dissolved Oxygen (mg/L)	Time minutes
1.9	294
1.5	296
1.4	322

A.14 ORP, DO, pH in the aeration tank of Reactor D.

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-139.16	0	0	0.09	7.46	0
-21.44	5	1	0.8	7.46	5
15.53	10	2	1.34	7.45	10
33.2	15	3	1.19	7.44	15
42.13	20	4	1.9	7.43	20
49.8	25	5	2.25	7.42	25
56.27	30	6	2.72	7.41	30
55.69	35	8	2.77	7.4	35
50.08	40	9	2.95	7.4	40
41.11	45	11	3.81	7.4	45
28.13	50	12	3.91	7.4	50
7.38	55	15	3.46	7.4	55
-17.31	60	16	3.24	7.4	60
-40.85	65	18	3.8	7.4	65
-61.14	70	20	3.52	7.41	70
-77.58	75	21	3.24	7.41	75
-93.66	80	22	3.01	7.41	80
-103.4	85	26	3.29	7.41	85
-114.32	90	28	3.09	7.43	90
-121.33	95	30	3.26	7.43	95
-124.25	100	31	3.09	7.42	100
-125.69	105	32	2.88	7.43	105
-128.19	110	33	2.55	7.43	110
-137.86	115	35	1.86	7.44	115
-146.63	120	37	1.14	7.44	120
-152.92	125	39	0.83	7.44	125
-155.28	130	40	0.8	7.44	130
-159.94	135	42	0.78	7.44	135
-167.33	140	47	0.69	7.44	140
-171.24	145	52	0.63	7.45	145
-173.68	150	57	0.68	7.45	150
-22.19	155	64	0.34	7.44	155
17.93	160	71	0.12	7.43	160
37.61	165	116	0.03	7.42	165
47.26	170	148	0.03	7.41	170
54.2	175	150	0.03	7.41	175
60.24	180	151	0.58	7.43	180
57.19	185	152	0.96	7.43	185
50.99	190	153	1.47	7.44	190
43.13	195	154	1.7	7.44	195
29.56	200	155	2.26	7.44	200
10.87	205	156	2.89	7.45	205
-16.91	210	157	3.08	7.45	210
-37.43	215	158	3.09	7.45	215
-58.34	220	160	3.03	7.44	220
-74.49	225	162	3.03	7.44	225

ORP (mV)	Time minutes
-89.97	230
-105.15	235
-114.32	240
-125.24	245
-133.93	250
-139.95	255
-146.27	260
-155.52	265
-158.08	270
-159.86	275
-156.75	280
-160.75	285
-164.22	290
-166.99	295
-172.96	300
-17.18	305
25.37	310
42.85	315
53.34	320
63.27	325
68.91	330
71.5	335
64.71	340
56.39	345
46.52	350
33.06	355

Dissolved Oxygen (mg/L)	Time minutes
164	3.17
166	3.02
168	3.05
170	3
172	2.84
174	2.9
176	2.87
178	2.95
180	3.01
182	2.51
183	0.68
184	0.38
185	0.23
186	0.16
187	0.12
188	0.1
199	0.04
246	0.03
256	0.03
290	0.03
298	0.04
300	0.04
301	0.62
302	0.96
303	1.34
304	1.67
305	1.77
306	2.58
307	3.03
308	3.04
310	2.87
312	3.44
315	3.27
317	3.24
321	3.15
323	3.16
326	3.14
328	3.26
330	3.34
331	2.64
332	2.61
333	2.22
334	1.96
335	1.47
336	1.29
338	0.89
340	0.54
342	0.4

pH	Time minutes
7.45	230
7.45	235
7.45	240
7.45	245
7.46	250
7.46	255
7.46	260
7.46	265
7.47	270
7.47	275
7.47	280
7.47	285
7.48	290
7.48	295
7.48	300
7.48	305
7.47	310
7.45	315
7.44	320
7.43	325
7.43	330
7.41	335
7.4	340
7.4	345
7.4	350
7.4	355
7.4	360

ORP (mV)	Time minutes
344	0.39
348	0.34
351	0.32
353	0.32
355	0.23
357	0.05
358	0.03
360	0.02

A.15 ORP, DO, pH in the aeration tank of Reactor E.

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-172.86	0	0.04	0	7.6	1
-19.47	5	1.14	1	7.62	6
21.5	10	1.44	2	7.6	11
37.57	15	1.44	3	7.59	16
45.2	20	1.5	4	7.57	21
49.37	25	1.51	5	7.56	26
52.69	30	1.5	6	7.54	31
54.64	35	1.56	7	7.54	36
56.84	40	1.43	8	7.53	41
58.46	45	1.44	9	7.53	46
59.48	50	1.33	10	7.52	51
60.99	55	1.22	11	7.51	56
61.49	60	1.16	12	7.5	61
60.02	65	1.11	13	7.49	66
55.17	70	1.09	14	7.49	71
49.48	75	1.06	15	7.5	76
43.4	80	1.09	16	7.5	81
36.62	85	1.04	17	7.5	86
29.13	90	1.12	18	7.5	91
19.32	95	1.2	19	7.51	96
2.85	100	1.1	20	7.52	101
-15.5	105	1.07	22	7.52	106
-32.74	110	1.05	24	7.52	111
-48.54	115	1.15	26	7.52	116
-62.71	120	1.19	28	7.53	121
-74.3	125	1.14	43	7.53	126
-83.05	130	1.09	55	7.53	131
-91.5	135	1.1	60	7.54	136
-98.28	140	0.42	61	7.54	141
-104.75	145	0.25	62	7.54	146
-111.15	150	0.12	63	7.55	151
-117.44	155	0.07	64	7.55	156
-122.29	160	0.04	65	7.55	161
-127.66	165	0.03	66	7.56	166
-131.23	170	0.04	85	7.56	171
-135.97	175	0.04	133	7.56	176
-139.01	180	0.04	231	7.56	181
-142.29	185	0.04	240	7.56	186
-144.13	190	0.04	290	7.57	191
-144.63	195	0.04	298	7.57	196
-144.88	200	0.04	300	7.57	201
-146.62	205	1.04	301	7.58	206
-151.27	210	1.08	302	7.58	211
-155.56	215	1.34	303	7.58	216
-159.41	220	1.44	304	7.59	221
-162.22	225	1.54	305	7.59	226
-165.5	230	1.53	306	7.59	231
-168.24	235	1.44	307	7.59	236

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-171.4	240	1.4	308	7.6	241
-172.93	245	1.31	309	7.6	246
-171.64	250	1.29	310	7.61	251
-170.7	255	1.32	311	7.62	256
-171.56	260	1.23	312	7.62	261
-169.74	265	1.14	313	7.63	266
-173.57	270	1.2	314	7.64	271
-177.76	275	1.2	315	7.64	276
-181.53	280	1.21	316	7.64	281
-184.97	285	1.11	321	7.65	286
-187.77	290	1.13	322	7.64	291
-190.37	295	1.12	324	7.63	296
-193.77	300	1.25	326	7.61	301
-16.09	305	1.19	328	7.62	306
25.31	310	1.21	334	7.61	311
41.61	315	1.08	340	7.6	316
50.34	320	1.13	345		
53.67	325	1.11	347	7.57	326
57.17	330	1.12	357	7.56	331
59.93	335	1.09	359	7.55	336
61.45	340	1.08	360	7.54	341
64.32	345	0.45	361	7.53	346
67.24	350	0.25	362	7.52	351
67.48	355	0.11	363	7.51	356
68.02	360	0.06	364	7.5	361
68.28	365	0.04	365	7.49	366
66.8	370	0.03	556	7.49	371
61.16	375	0.04	596	7.49	376
53.77	380	0.04	600	7.49	381
47.74	385	0.53	601	7.49	386
43.48	390	0.95	602	7.5	391
39.84	395	1.25	603	7.5	396
29.95	400	1.5	604	7.51	401
16.14	405	1.57	605	7.51	406
-0.91	410	1.61	606	7.52	411
-16.68	415	1.7	607	7.52	416
-32.23	420	1.53	608	7.52	421
-45.89	425	1.49	609	7.53	426
-58.04	430	1.41	610	7.53	431
-67.23	435	1.31	611	7.54	436
-75.04	440	1.25	612	7.54	441
-83.44	445	1.2	613	7.55	446
-91.35	450	1.15	614	7.55	451
-98.68	455	1.17	615	7.55	456
-104.97	460	1.17	616	7.55	461
-110.88	465	1.09	618	7.56	466
-116.57	470	1.08	620	7.56	471
-122.01	475	1.01	622	7.56	476
-127.94	480	1	624	7.56	481

ORP (mV)	Time minutes	Dissolved Oxygen (mg/L)	Time minutes	pH	Time minutes
-134.03	485	0.99	626	7.57	486
-137.25	490	0.95	628	7.57	491
-139.77	495	0.95	644	7.57	496
-141.04	500	0.89	657	7.58	501
-143.55	505	1	659	7.58	506
-148.97	510	1	660	7.59	511
-153.61	515	0.52	661	7.59	516
-159.26	520	0.26	662	7.59	521
-163.77	525	0.08	663	7.59	526
-167.93	530	0.04	665	7.6	531
-171.88	535	0.03	667	7.6	536
-175.3	540	0.02	690	7.61	541
-176.84	545	0.02	702	7.61	546
-174.27	550			7.61	551
-174.85	555			7.61	556
-172.82	560			7.61	561
-172.31	565			7.61	566
-175.22	570			7.61	571
-179.48	575			7.62	576
-184.6	580			7.62	581
-188.64	585			7.62	586
-192.28	590			7.62	591
-195.15	595			7.62	596
-197.69	600			7.63	601
-19.03	605			7.61	606
24.15	610			7.63	611
42.18	615			7.61	616
51.18	620			7.6	621
56.07	625			7.58	626
59.42	630			7.57	631
61.4	635			7.56	636
62.88	640			7.54	641
64.29	645			7.53	646
65.67	650			7.52	651
66.29	655			7.51	656
66.93	660			7.51	661
66.22	665			7.49	666
63.27	670			7.48	671
59.29	675			7.48	676
54.73	680			7.49	681
49.63	685			7.49	686
43.99	690			7.49	691
38.04	695			7.49	696
31.51	700			7.5	701
24.44	705			7.51	706
14.75	710			7.51	711
0.26	715			7.51	716
-16.2	720			7.52	721
				7.52	726

A.16 Reactor A Nitrogen time study (mg/L).

		NH3N	NO3N/NO2N	NO2N	NO3N
Influent	2/23/2004	204	0	0	
9:00	2/23/2004	0.07	28.94	0.07	28.87
9:10	2/23/2004	2.2	32.65	0.13	32.52
9:20	2/23/2004	0.09	30.58	0.08	30.5
9:30	2/23/2004	0.01	33.49	0.3	33.19
9:40	2/23/2004	0.03	33.88	0.26	33.62
9:50	2/23/2004	0.01	34.61	0.17	34.44
10:00	2/23/2004	0.05	29.02	0.1	28.92
10:20	2/23/2004	3.39	34.95	0.08	34.87
10:40	2/23/2004	3.25	35.45	0.1	35.35
11:00	2/23/2004	3.25	34.7	0.12	34.58
11:10	2/23/2004	3.75	30.92	0.24	30.68
11:20	2/23/2004	0.22	35.6	0.3	35.3
11:30	2/23/2004	0.14	32.73	0.33	32.4
11:40	2/23/2004	0.02	34.53	0.27	34.26
11:50	2/23/2004	0	34.45	0.05	34.4
12:00	2/23/2004	0	31.33	0.03	31.3
12:20	2/23/2004	3.68	36.04	0.07	35.97
12:40	2/23/2004	3.37	36.6	0.11	36.49
13:00	2/23/2004	3.39	36.33	0.11	36.22

A.17 Reactor B Nitrogen time study (mg/L).

		NH3N	NO3N/NO2N	NO2N	NO3N
Influent	2/24/2004	181	0	0	
9:00	2/24/2004	7.81	2.87	1.75	1.12
9:10	2/24/2004	8.1	3.48	2.4	1.08
9:20	2/24/2004	6.34	3.48	2.53	0.95
9:30	2/24/2004	4.5	6.04	3.04	3
9:40	2/24/2004	2.68	7.4	3.32	4.08
9:50	2/24/2004	1.15	7.97	3.59	4.38
10:00	2/24/2004	1.49	9.34	3.03	6.31
10:20	2/24/2004	3.7	14.41	5.41	9
10:40	2/24/2004	3.36	16.07	5.53	10.54
11:00	2/24/2004	6.71	13.8	5.52	8.28
11:20	2/24/2004	3.48	14.46	5.42	9.04
11:40	2/24/2004	6.49	12.41	5.59	6.82
12:00	2/24/2004	6.48	12.14	5.36	6.78
12:20	2/24/2004	8.69	12.56	5.46	7.1
12:40	2/24/2004	8.83	10.35	4.93	5.42
13:00	2/24/2004	8.76	11.23	1.23	10

A.18 Reactor C Nitrogen time study (mg/L).

		NH3N	NO3N/NO2N	NO2N	NO3N
Influent	3/15/2004	223	0	0	
8:00	3/15/2004	9.87	8.68	4.49	4.19
8:10	3/15/2004	8.57	3.09	1.67	1.42
8:20	3/15/2004	7.58	3.58	1.9	1.68
8:30	3/15/2004	6.12	4.08	2.11	1.97
8:45	3/15/2004	6.33	10.06	5.19	4.87
9:00	3/15/2004	6.17	10.22	5.22	5
9:20	3/15/2004	9.65	9.51	5.17	4.34
9:40	3/15/2004	9.7	9.4	5.2	4.2
10:00	3/15/2004	9.35	9.31	5.2	4.11
10:10	3/15/2004	8.57	4.08	2.2	1.88
10:20	3/15/2004	8.08	4.57	2.6	1.97
10:30	3/15/2004	6.74	5.25	2.97	2.28
10:45	3/15/2004	6.61	10.9	5.72	5.18
11:00	3/15/2004	5.97	9.2	4.53	4.67
11:20	3/15/2004	8.56	10.08	4.73	5.35
11:40	3/15/2004	9.4	9.2	4.74	4.46
12:00	3/15/2004	9.18	9.04	4.72	4.32

A.19 Reactor D Nitrogen time study (mg/L).

		NH3N	NO3N/NO2N	NO2N	NO3N
Influent	3/3/2004	192	0	0	
7:30	3/3/2004	6.31	1.96	0.07	1.89
7:40	3/3/2004	3.13	1.98	0.09	1.89
7:50	3/3/2004	1.36	2.69	0.1	2.59
8:00	3/3/2004	0.22	3.69	0.08	3.61
8:20	3/3/2004	2.74	5.61	0.21	5.4
8:40	3/3/2004	3.3	5.89	0.43	5.46
9:00	3/3/2004	2.83	5.59	0.53	5.06
9:20	3/3/2004	5.15	5.31	0.61	4.7
9:40	3/3/2004	5.96	4.5	0.89	3.61
10:00	3/3/2004	6.07	4.85	0.91	3.94

A.20 Reactor E Nitrogen time study (mg/L).

	DATE	NH3N	NO3N/NO2N	NO2N	NO3N
Influent	2/2/2004	162	0	0	0
857AM	2/2/2004	11.41	3.16	2.19	0.97
911AM	2/2/2004	12.22	1.33	0	1.33
920AM	2/2/2004	10.71	1.94	0.15	1.79
930AM	2/2/2004	9.24	2.98	1.32	1.66
941AM	2/2/2004	7.47	4.57	2.65	1.92
953AM	2/2/2004	4.7	7.25	4.07	3.18
959AM	2/2/2004	3.59	8.67	5.56	3.11
1022AM	2/2/2004	7.16	9.29	7.89	1.4
1040AM	2/2/2004	6.98	9.75	8.26	1.49
1059AM	2/2/2004	6.88	8.28	7.47	0.81
1122AM	2/2/2004	8.98	7.32	6.81	0.51
1140AM	2/2/2004	9.15	6.92	6.86	0.06
1159AM	2/2/2004	9.08	5.86	4.16	1.7
1222PM	2/2/2004	11.06	5.31	3.61	1.7
1253PM	2/2/2004	11.58	4.39	3.42	0.97
122PM	2/2/2004	13.94	1.73	1.59	0.14
140PM	2/2/2004	13.77	1.62	1.42	0.2
159PM	2/2/2004	13.66	0.85	0.82	0.03