Effects of Integrated Fixed Film Activated Sludge on Nitrogen Removal in Biological Nutrient Removal Systems

by

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EFFECTS OF INTEGRATED FIXED FILM ACTIVATED SLUDGE ON NITROGEN REMOVAL IN BIOLOGICAL NUTRIENT REMOVAL SYSTEMS

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(ABSTRACT)

The performance of Integrated Fixed Film Activated Sludge (IFAS) was evaluated for its effect on nitrification and denitrification in a bench scale biological nutrient removal (BNR) process configured as a Virginia Initiative Project (VIP) process. The IFAS systems consisted of a sponge - like biomass support system (Captor) operated in the aerobic zone of two independent treatment trains, and a fibrous biomass support system (Ringlace) operated in the aerobic zone of one independent treatment train. A fourth treatment train containing no biomass support system was operated as a control. A range of four aerobic MCRTs was studied, from 3.4 days to 1.7 days. All experiments performed for this research effort were conducted using domestic wastewater obtained directly from Blacksburg, VA and the Virginia Tech campus.

Results indicated that the presence of the sponge - like biomass support media (Captor) freely floating in the aerobic zone mixed liquor greatly increased the ability of that system to achieve nitrification at temperatures of 12 degrees Celsius and aerobic suspended growth MCRTs as low as 1.7 days. A statistical t-test analysis demonstrated this with 99% confidence. Results early in the research, as well as previous research by Mitta (1994) indicated that fibrous biomass support systems (Ringlace) did not perform as well with respect to nitrification as did Captor, and experiments on Ringlace were discontinued midway through the research.

Increased denitrification throughout the IFAS/Captor train was noted as a result of the increased nitrification. However, the use of Ringlace appeared to enhance denitrification which occurred in the aerobic zone. Further study is recommended to verify this data.

A decrease in sludge production in the IFAS train containing Captor could not be statistically established. However, observed sludge yield coefficients for the IFAS/Captor train were consistently lower than those for the Control train. A statistical analysis was not performed, but the values varied considerably so that direct comparison was difficult.

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CHAPTER ONE: INTRODUCTION

Many states, particularly in the Mid-Atlantic and Great Lakes regions, have tightened the regulations concerning the amounts of nitrogen and phosphorus that wastewater treatment plants can discharge to receiving waters. These elements are referred to as nutrients since they play a vital function in supporting the growth of algae in waters. For example, one gram of phosphorus is enough to produce 111 grams of algae (denoted by the formula $C_{106}H_{263}O_{110}N_{16}P$), provided no other elements are limiting. This is equivalent to 138 grams of Chemical Oxygen Demand (COD). Similarly, one gram of nitrogen can produce 16 grams of algae, or 20 grams COD (Randall, et al. 1992). The death and decay of algae causes oxygen demand in aquatic environments and contributes to eutrophication of the water body. Ammonia, in the form of NH_3, is also toxic to many forms of aquatic life.

As a result of these new regulations, many nutrient removal techniques are being developed and applied by treatment plants to meet them. Chemicophysical and biological processes both can be utilized, but biological processes have received the most attention, particularly for the removal of nitrogen. Biological nitrogen and phosphorus removal has been achieved for many years by using anaerobic and anoxic zones, combined with liquid recycles, ahead of traditional stand alone aerobic zones. An interesting modification of this general scheme has been introduced in the past few years; it involves the use of some type of submerged media to "fix" biomass within an activated sludge basin. This technology has been termed Integrated Fixed-Film Activated Sludge (IFAS) by researchers at VPI & SU, and forms the basis of this study. Anne Arundel County, MD, through the Maryland Department of the Environment (MDE) funded this study in an effort to improve the ability of their treatment facilities to meet stricter effluent guidelines in a cost effective manner.

Presently, many activated sludge wastewater treatment plants are not able to remove nitrogen because they fail to achieve the first step - nitrification - on a consistent basis. This process involves the oxidation of ammonia to nitrite and nitrate, and is achieved by slow growing, autotrophic nitrifying bacteria. The primary reasons nitrification is not achieved are the short Mean Cell Residence Times (MCRT's) of most activated sludge plants now in existence, and low winter temperatures that slow the growth rates of the nitrifying bacteria. The two options available to remedy this problem are: (1) Build new, larger plants or expand existing plants to achieve higher MCRT's, or (2) Effectively raise the MCRT and amount of biomass by "fixing" an independent population of bacteria within the aeration basin using a fixed film media. Option two has the potential to save as much as $1.30 in construction costs per gallon of flow treated, and has been shown to increase treatment effectiveness without overloading secondary clarifiers with the extra biomass. In addition, these systems can resist temperature and shock loads (Lessel, 1993).

Many types of media have been employed in nutrient and traditional COD removal roles. These include LINPOR by Linde AG, NOR-PAC by NSW AG, Captor by Simon Hartley, Inc., and Ringlace by the Japan Engineering and Trading Company. Captor sponges and Ringlace (a fibrous, rope type media) were both chosen for study during this research effort, with more detailed studies being conducted on whichever performed best. Both types of media had been previously studied in bench scale experiments at VPI & SU, as well as in a few full scale studies in Europe and the United States.

The overall objective of this research was to determine the optimum parameters for nitrogen removal using fixed film media placed in the aerobic zone of a municipal wastewater treatment system designed for biological nutrient removal. Specific goals included:

- Determine whether Captor or Ringlace performs best at low temperatures and low MCRT's, with respect to nitrogen removal.
- Optimize placement of biomass support media to achieve maximum nitrogen removal with minimal media.
- Verify and quantify the denitrification which occurs in the aerobic zone due to the presence of media.
- Quantify sludge production and COD removal in the IFAS systems and compare to a control containing no media.
- Observe nitrification rates and quantities of biomass growth on the fixed film media in various sections of the aerobic zones.

These objectives were investigated by comparing performance data aquired from a control system and similar systems containing media. All experiments were run at 12°C, but the Mean Cell Residence Time was changed after each experiment to provide greater insight into the mechanisms involved.

CHAPTER TWO: LITERATURE REVIEW

INTRODUCTION

Research into the uses of fixed film media has been ongoing for most of the 1980's and 1990's. This chapter presents a short summary of applicable research pertaining to the subject of this thesis.

BIOLOGICAL NUTRIENT REMOVAL (BNR)

In recent years, the interest in Biological Nutrient Removal (BNR) systems for the treatment of wastewaters has increased greatly. This is primarily due to their economic advantages. Many researchers (Dold and Marais, 1987; Randall et al., 1992) have established that significant cost savings can be realized by using BNR systems in place of conventional plants or physical/chemical nutrient removal processes. By incorporating anaerobic and anoxic zones prior to aerobic zones, aeration costs can be significantly cut because COD removal is accomplished by non-oxic mechanisms. For example, denitrification in the anoxic zone uses Nitrate (NO_3) as an electron acceptor for COD stabilization, thus reducing the amount of oxygen required for stabilization by 2.86 mg for each milligram Nitrate measured as nitrogen (NO_3-N) used (Dold and Marais, 1987). Placement of an anaerobic zone ahead of the aerobic zone results in substrate removal and stabilization, which also decreases aeration costs. Additional factors which reduces aeration costs are the high oxygen transfer efficiency realized when wastewater having zero dissolved oxygen (DO) leaves an anoxic zone and enters an aerobic zone, and the removal of organics which increases the aeration alpha coefficient. Ip et al. (1987), report that total aeration cost savings can be as high as 30%.

Further cost savings are realized by the reduction of sludge produced by BNR systems. Biological Phosphorus Removal (BPR) can achieve effluent phosphorus levels of considerably less than 1 mg/L (Randall, et al., 1992b), thus reducing or eliminating costs associated with purchasing chemicals as well as sludge handling and disposal. Laboratory and full scale data have shown that the incorporation of an anoxic zone ahead of the aerobic zone to achieve nitrogen removal reduces sludge production (Ip et al., 1987; McClintock et al., 1988; Waltrip 1990). Ip et al. (1987), reported that sludge reduction by denitrification can be as high as 15%.

The aerobic nitrification process consumes two equivalents of alkalinity per equivalent of ammonia nitrified. Denitrification in an anoxic zone, however, regenerates one equivalent of alkalinity per equivalent of nitrate reduced. This is an important factor in areas having poorly buffered wastewaters as it results in lower costs for buffering chemicals (Dold and Marais, 1987; Randall et al., 1992b).

It has also been shown that incorporating anaerobic and anoxic zones ahead of aerobic zones decreases the required aerobic volume for nitrification (McClintock, 1991, Randall et al., 1992a).

One key to BNR process operation is the proper selection of bacterial growth to achieve the desired biochemical reactions. Proper placement of unaerated zones ahead of aerated zones allows the phosphorus and nitrogen removing bacteria to have the first opportunity to utilize substrate, thus giving them a competitive advantage (Randall et al., 1992b). The most popular BNR systems today (estimated at 100 operating, full scale plants) are single-sludge, recirculation processes (Henze, 1991). Single-sludge implies that one secondary clarifier is used; recirculation means that biomass is recycled through all zones (Randall et al., 1992b).

Another key to BNR operation is the requirement for proper biodegradable substrate levels to be present in the anaerobic and anoxic zones. Work done by Abu-Ghararah and Randall (1991) indicates that (conservatively) for every 1 mg/L of phosphorus removed from municipal wastewater, approximately 50 mg/L COD is required. Additionally, 8.6 mg/L of COD from municipal wastewater is required for each mg/L of nitrate reduced to nitrogen gas. Thus the requirement for placing the unaerated zones ahead of the aerated zones is clear.

Many different configurations have been developed to optimize the requirements discussed earlier. The first was developed by Ludzack and Ettinger in 1962, then the modified Ludzack-Ettinger (MLE) and the Bardenpho. These were primarily nitrogen removal processes. The identical Phoredox and A/O processes were developed for phosphorus removal without nitrogen removal. Multi-stage BNR systems such as the modified Bardenpho, the A^2/O, the UCT and VIP processes, as well as modified sequencing batch reactors and oxidation ditches, were designed for both nitrogen and phosphorus removal (Randall et al., 1992b).

Biological Nitrogen Removal

Biological nitrogen removal is an effective, economical way of removing nitrogen from wastewaters, and is the most commonly used method. Physical methods, such as air stripping, are expensive and simply transfer the problem from water to air. The biological process in which nitrogen is removed consists of two stages. The first, which requires aerobic conditions, is nitrification. The second, which requires an absence of dissolved oxygen, is termed denitrification. These reactions take place in the presence of suitable electron donors and acceptors.

Biological Nitrification

Nitrification is simply the oxidation of ammonium measured as nitrogen (NH_4-N) to nitrite as nitrogen (NO_2^--N), followed by a second oxidation step to nitrate as nitrogen (NO_3^--N). Grady and Lim (1980) illustrate these two steps with the following equations:

$$55NH_4^+ + 76O_2 + 109HCO_3^- \text{--->} C_5H_7O_2N + 54NO_2^- + 57H_2O + 104H_2CO_3 \qquad (2\text{-}1)$$

and

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 \text{--->} C_5H_7O_2N + 3H_2O + 400NO_3^- \qquad (2\text{-}2)$$

where $C_5H_7O_2N$ is taken to be the structure of cell matter. As can be seen from the equations, stoichiometrically the reactions require 4.33 mg O_2 for every mg of NH_4^+ that is oxidized. However, on an oxygen demand basis, assuming no cell growth, 4.57 mg O_2 per mg of NH_4^+ is oxidized - the maximum amount of oxygen demand that can occur from nitrification. The latter value is considered to be acceptable and conservative for engineering calculations (Grady and Lim, 1980).

Over one hundred species of bacteria have been identified as NO_2^- producers; most are chemoautotrophs but some are heterotrophs. However, the contribution from the heterotrophs is so small it is commonly ignored (Grady and Lim, 1980, Rheinheimer, 1991). Rheinheimer (1991), lists those whose primary habitat is water as the genera Nitrosomonas (most common), Nitrosococcus and Nitrosospira. The genera responsible for taking NO_2^- to NO_3^- are Nitrobactor (most common), Nitrospina, Nitrococcus and Nitrospira.

Biological Denitrification

Denitrification consists of the sequential reduction of nitrate to nitrogen gas (N_2) as shown below:

$$NO_3^- \dashrightarrow NO_2^- \dashrightarrow NO \dashrightarrow N_2O \dashrightarrow N_2 \qquad (2\text{-}3)$$

This reaction, called nitrate respiration, is carried out by facultative anaerobic bacteria using nitrate and nitrite as electron acceptors and organic substrate as electron donors. Numerous genera are responsible for this; some of the most common are Acinetobacter, Alcaligenes, Flavobacterium, Pseudomonas, Aeromonas, Enterobactor, Escherichia, Paracoccus, Bacillus, Hyphomicrobium, and Spirillum (Rheinheimer, 1991).

FIXED FILM BIOLOGICAL PROCESSES

Attached growth biological treatment systems, also known as fixed film systems, differ from conventional activated sludge processes in that the biomass responsible for removing soluble contaminants from the wastewater is not freely floating in the basin. Instead, it is attached, or "fixed" to some type of support media. This concept has been put to use quite often since the early 1900's, and trickling filters, the first type of system to use this concept, were in widespread use throughout the 1940's and 1950's. Trickling filters were originally designed using crushed rock media, but design limitations, particularly weight, restricted their effectiveness. The development of light weight plastic media, Rotating Biological Contactors (RBC's), and Fluidized Bed reactors in the 1960's to the 1980's caused a resurgence of interest in fixed film technology.

The primary objective in using fixed film media in activated sludge is to maintain an increased biomass concentration for greater substrate removal without increasing solids loading to the secondary clarifier (Louis, 1993). Factors affecting the effectiveness of a biofilm are its ability to avoid clogging yet hold biomass, a high surface area, and the ability to maintain adequate permeability of substrate and oxygen into its deeper layers (Lessel, 1991).

While trickling filters and RBC's are normally not submerged in the wastewater, some of the newer fixed film processes are. These have been designed in response to tighter effluent regulations and the decreasing availability and increasing cost of land for construction of large treatment plants. Submerged fixed film reactors combine the advantages of a contact system such as trickling filters with the advantages of conventional activated sludge, resulting in higher treatment efficiencies in equal or less space than activated sludge alone. Ryhiner et al. (1993) states that "Fixed biomass systems - compared to activated sludge systems - offer more compact and flexible process solutions because of the higher degradation rates and the insensitivity against hydraulic variations...". For example, in the Geiselbullach sewage treatment plant, near Munich Germany, use of Linpor media resulted in more efficient treatment and roughly a 100% increase in biomass; to obtain the same biomass in an activated sludge basin would require an extra 8,000 m^3 (Lessel, 1993).

An additional advantage of fixed film processes, particularly submerged systems, is their ability to maintain a population of the slow growing autotrophic nitrifying bacteria under adverse conditions such as low hydraulic and solids retention times. This has been demonstrated by numerous researchers (Lessel, 1991 and 1993, Golla et al., 1993, Ryhiner et al. 1993, Tsuno et al. 1992, Sen et al., 1993, and others). Details of their research are given in following sections.

Submerged Biomass Support Systems

Many types of media have been employed in submerged biomass support systems. The most common are fixed bed media, free floating particles or beads, fibrous or rope-type media, and porous or sponge-like media.

Fixed bed media. Bonhomme et al. (1990) conducted a full scale study using the BIOFIX system which consists of modular, cross-flow corrugated plastic media. The study was performed using 20% to 40% media (by volume) in a full scale plant with a control operated in parallel. The results indicated improved COD and ammonia removal with the resulting higher sludge age keeping nitrifying bacteria in the system beyond normal limits. No evidence that the nitrifiers were attaching themselves to the media was found. A bench scale unit did, however, show nitrifier attachment when it was fed treated effluent.

Haseltine (1991), in bench scale studies conducted at Virginia Tech, used a media called NOR-PAC to enhance treatment of an industrial waste. This media consists of a single open cylinder; it is similar to rolled up plastic mesh. Attached growth was not observed except at a very low MCRT, but improved solid/liquid separation was noted. Growth did occur between interconnected cylinders. It was thought that excessive turbulence limited the amount of attached growth. Nitrification was not measured.

Lessel (1991) studied a media called BIO-NET which was very similar to NOR-PAC. The tests were done at the Geiselbullach WWTP near Munich, Germany. The submerged media, at 20% of the aerobic volume, was added directly to the aerated zone. A marked increase in ammonia removal was noted; 15.8% was removed by the control versus 94% by BIO-NET. Dark, anaerobic sludge accumulations were also noted on the media.

Ryhiner et al. (1993) studied a similar media called BIOPUR which consists of thin corrugated plastic sheets fitted together to optimize surface area. The media was installed in a denitrification (DN) zone and a nitrification (N) zone, both of which were aerated. Despite being aerated, the DN zone exhibited enhanced COD and nitrate removal, indicating that a significant portion of the biofilm was in an anoxic (absence of dissolved oxygen) state. The N zone showed an enhancement of ammonia oxidation at low COD levels, but little enhancement at higher COD levels. This indicated that heterotrophic competition for oxygen on the biofilm inhibited nitrification. It must be noted that no control was available to compare results.

In direct comparisons of fixed bed media to other types, fixed beds were found to be less effective or more difficult to maintain. Lessel (1991) chose a rope type media called Ringlace over BIO-NET because of the better attached growth it exhibited; Haseltine (1991) chose a sponge type media called Linpor over NOR-PAC for the same reasons.

Free floating particle media: Several researchers have conducted studies where small particles of plastic, glass or clay have been added to the aerobic volume, or have been used as a fluidized bed material. Hermanowicz and Cheng (1990) observed in a bench scale, denitrifying, fluidized bed reactor an optimum MCRT range in which nitrogen removal rates were maximized. At low MCRT's, excessive wasting of biomass resulted in a very thin biofilm on the support media, in this case, 0.5 mm glass beads. At high MCRT's, thick layers of biofilm developed resulting in substrate mass transfer limitations and decreased efficiency. In addition, they noted that when denitrification was high, nitrogen bubbles would attach to the media and free biomass causing it to float. This resulted in high solids concentrations in the effluent.

Sagberg et al. (1992) applied the BIOFOR process, already in use at approximately thirty full scale plants for carbon removal, to nitrogen removal at the Perroy WWTP in Switzerland. The media consisted of 3-4 mm expanded clay particles and the system operated as a fluidized bed. The system averaged 98.7% ammonia removal, but was not compared to a control, thus increased efficiency could not be determined. After more than six months of acclimation, it was noted that use of the media minimized temperature influences compared to activated sludge. The effect of high BOD loads on nitrification was also examined, and it was found that for very low BOD levels, very high ammonia removals were reached, and for high BOD levels, low ammonia removals were reached. This can be attributed to competition for oxygen between fast growing heterotrophic bacteria feeding on the BOD and slow growing autotrophic nitrifiers (Sagberg et al. 1992).

Studies conducted in Norway by Odegaard et al. (1993) have used small polyethylene cylinders with cross-hatched interiors having a density of just less than that of water. The elements move freely in the tank, using energy supplied by aeration (aerated tank) and mechanical stirrers (anoxic tank). Since the particles move vigorously within the reactor, excessive sludge accumulations do not occur, and head loss is a minimum. Most of the growth occurred on the inside of the cylinders and was protected from excessive turbulence which could limit substrate diffusion into the biomass. The conclusions of the study were:

- These systems were just as simple as activated sludge, but were much smaller
- Headloss was minimal and backwashing was not needed as it is for fluidized bed reactors
- Biomass was very active, i.e., it had a high biological activity per kilogram of attached biomass
- Liquid film diffusion was a significant factor affecting performance.

Dee et al. (1993) conducted pilot plant studies in which free floating media was placed in the anoxic zone of a pre-denitrifying wastewater plant (anoxic/oxic with recycle), and included a cost benefit analysis. They concluded that the media significantly increased denitrification such that total nitrogen levels in the effluent would meet the requirements of European Community legislation. In addition, they found that biological fluidized beds and free floating plastic media were the most cost effective of those studied and were competitive with tertiary denitrification systems.

Fibrous, or rope type media: Most studies using this media were conducted with Ringlace, which consists of strands of polyvinylidine chloride having numerous small fibrous loops on which biomass can grow. It is normally stretched vertically over a frame, and the entire unit is placed in the wastewater. Lessel (1991) studied the effects of Ringlace on nitrogen removal and found that ammonia removal increased from 15.8% to 94.9% when operating temperatures were above 12 °C. No noticeable increase was seen at temperatures under 12 °C. Later studies by Lessel (1993) indicated that nitrification could be maintained at temperatures as low as 8-10 °C. In addition, many higher organisms (tubiflex, nematodes etc.) that preyed upon the bacterial growth were noted; this could, under certain conditions, reduce the normal bacterial count to unacceptably low levels. An effect called "skinning" (Lessel, 1993), in which the attached growth changes from a high amount to very little over a period of one to two days was noted; however, this did not have any effect on system performance. This study was limited to reporting effluent data, and numerous changes in parameters other than that of the media rendered statistical analysis impossible.

Full scale studies conducted at the Annapolis, MD Water Reclamation Facility (Sen, 1993) found that over five phases spanning a temperature range of 15 to 26 °C and HRT's from 3.6 to 7.0 hours, Ringlace increased nitrification by an average of 256% over a control. Growth on the media was observed to be evenly dispersed and seemed to be mainly aerobic. As with previous studies using rope type media, predation from higher organisms was a concern; it was discovered that anoxic cycling (turning off the air supply for short periods) could be used to control the predator populations.

Bench scale studies were undertaken by Mitta (1994) to determine the effect of media on both nitrification and denitrification at 12 and 18 °C, and at aerobic MCRT's as low as 3.1 days. A control was also operated. While these conditions did not produce a statistically higher nitrification rate (all systems operated at nearly complete nitrification), it did show enhanced denitrification. The data also indicated a trend toward lower sludge production and yield coefficients, though a statistical analysis was not done. Predators were again present in significant quantities; in fact, at one point a bloom of red worms overwhelmed the aerobic zones. Anoxic cycling alleviated the problem.

Porous, or sponge type media: Porous media, usually in the form of polyurethane foam cubes or pads, have been used in a free floating form and as part of a fixed, submerged body. The free floating form is most common, and research into its advantages and applications have been conducted only in the late 1980's and 1990's.

In a summary of biological fixed film systems, Chen et al. (1992) reported that by attaching small foam pads to a rotating biological contactor in an aerobic zone, some potential benefits were noted. In fact, by using alternating oxic and anoxic conditions to promote nitrification and denitrification, less than 15 mg/L total nitrogen in the effluent was achieved at temperatures down to 13 °C. It was also noted that nitrifiers grew preferentially on the foam cubes (after Kondo, et al. 1992).

Other researchers chose to utilize the foam cubes in a free floating manner. Shin and Park (1991) inserted 1.5 cm cubed polyurethane sponges into a sequencing batch reactor and observed lower COD and NH_4^+ levels and slightly higher suspended solids levels in the effluent. It must be noted that only one of their test runs was not ammonia limited (effluent level greater than 2 mg/L); in this instance the improvement of the media system over the control was 289%. Scanning electron micrographs taken of both the sponges and the growth indicated that biomass grew within the pores as well as on the foam matrix, thus increasing the holding capacity of the media.

Haseltine (1991) and Louis (1993) both conducted bench scale tests using Linpor media (12 mm polystyrene cubes) to treat industrial waste waters. Haseltine found significant attached growth on the sponges, and while both the sponge and control systems were substrate limited (COD), he theorized that the advantages of the fixed film system would present themselves at low mixed liquor MCRT's. Louis, in treating a high strength, high ammonia wastewater, found that the greatest advantage of the sponges was the ability to maintain high nitrification levels. Increased media addition directly affected nitrification ability. For example, at a 2.5 day MCRT operated at 20 °C, nitrification increased from an amount not measurable using zero to 20% media (dry sponge volume/aerobic volume), to 98% using 40% media. He also noted that Total Volatile Solids (due to Mixed Liquor growth and Fixed growth) significantly increased with increased media addition; at the same time, MLSS values did not significantly increase. This indicated that media growth was in addition to the suspended growth, not a replacement.

Both Haseltine (1991) and Louis (1993) reported no improvement in sludge settling characteristics except at very low MCRT's (three days or less). Both also observed that the substrate utilization of the suspended growth dictated the amount of biomass attached to the media, i.e. at low MCRT's the suspended growth cannot take up as much substrate, leaving more for the fixed growth, resulting in a larger proportion of fixed growth. This trend indicates that the advantages of media are enhanced at low MCRT's.

Lessel (1993) noted an increase in nitrification from 15.8% to 95.6% after the addition of 25% Linpor media to the aerobic zone of the Geiselbullach Treatment Plant. The test period was short, and no statistical analysis was performed. Of interest, however, is the fact that the sponges tended to sink to the bottom of the tank and become coated with a dark, anaerobic sludge. With their existing air supply system, they were not able to re-float the sunken cubes and thus their usefulness was limited in this case.

Bench scale studies performed in Japan by Tsuno et al. (1992) using polyurethane foam cubes in a series of completely mixed reactors to treat municipal sewage for COD and ammonia removal indicated that COD removal occurred separately from, and prior to, nitrification. This indicated that nitrifiers grew preferentially once the COD was reduced to an acceptable level. This study must be looked upon as incomplete because nitrification was inhibited by the presence of certain organics in the wastewater.

Golla et al. (1993) summarized the results of three years of full scale study using polyurethane Captor sponges (1" x 1" x 1/2") in the Moundsville, West Virginia WWTP. The Captor process was a separate, front end process followed by an activated sludge basin. The system was not designed to denitrify. It was discovered that COD removal, ammonia removal and partial denitrification occurred in the Captor basin. In the basin, an average of 80% nitrification and 50% denitrification occurred using hydraulic detention times of 50 to 90 minutes and temperatures as low as 12 °C. The following aeration basin served as a polishing step. To avoid an overgrowth of biomass on the sponges which could result in them sinking, a sponge cleaning system was developed to separate solids from the media using an agitating pump. Due to the low effluent nitrate levels (below 2 mg/L) it was hypothesized that denitrification in the Captor zone was limited by the system's nitrifying ability. Sludge yield and settling characteristics were not studied. In summary, the use of Captor media significantly improved the plant's ability to remove both COD and nitrogen.

A bench scale study designed to determine ammonia removal rates in a VIP (Virginia Initiative Project) process indicated that nearly complete nitrification occurred in a system using free floating Captor sponges, while a Ringlace system and a control did much poorer (Mitta, 1994). The study was conducted at a temperature of 12 °C, and at MCRT's as low as 3.1 days. Little denitrification in the aerobic zone was noted, but based on the studies conducted at Moundsville, WV (Golla et al. 1993), significant denitrification can occur within sponges. Possible reasons for the lack of denitrification were the high operating dissolved oxygen levels (greater than 6 mg/L) in Mitta's sludge which could have reduced any anoxic portions of the sponges, and the fact that COD substrate levels required to support a denitrifying population were consistently low in the entire aerobic zone.

BIOFILM PROPERTIES

Biofilm Growth and Distribution

Zhang and Bishop (1993), using a micro-slicing technique, studied the spatial distributions and properties of biofilms. Of primary interest was the conclusion that thick (>500 μm) biofilms differ in many ways from thin biofilms. For thick films, the number of active bacteria in the surface layer was 78% higher than in the bottom layers, while in thin films, the active bacteria were only 24% higher in the top layer. They also found that biofilm densities changed dramatically as they moved from the surface to the deep layers, with the top layers exhibiting densities of one fourth to one seventh that of lower layers. This was attributed to the fact that surface bacteria can expand in all directions, while bacteria at lower layers have very little space to grow. In addition, it was noted that porosity decreased and specific surface area increased at lower layers (this was even more noticeable for thin biofilms), which supported the above assumption, and could have limited substrate and dissolved oxygen penetration. They concluded that bacteria in the top layers may all have been metabolically active while a majority of those in the lower layers were dormant or inert. Also, the common assumption that biofilms have uniform distributions and properties may not be valid except in specific cases.

Biofilm Attachment

Tijhuis et al. (1992) studied the phases of biofilm growth in a bioreactor containing 0.26 mm carrier particles with a specific surface area of about 2000 m^2/m^3. They hypothesized that three successive stages of growth occurred which they called bare carrier, intermediate phase and overall coverage. They also found that the bacteria colonized on the media in specific sites, forming microcolonies. Once established, these colonies gradually expanded to form a complete biofilm.

Heijnen et al. (1992), in a study similar to that of Tijhuis, expanded on the three stage growth hypothesis. They found that surface roughness and carrier diameter were the two primary characteristics which determined biofilm growth. Lava particles with a radius considered "fine" (0.15 mm or less) produced a very good biofilm, while the larger, or "coarse" particles produced only a moderate biofilm. This phenomena was noted with other media also, and the possible reason for it was thought to be the greater impact of particle/particle collisions with the "coarse" media, thus limiting the bacteria's ability to form the overall coverage. Surface roughness was shown to directly influence biofilm growth with rough particles showing a good, homogenous biofilm an average of 60 μm thick. Smooth particles showed little or no growth and moderate surfaces showed non-homogenous growth of thickness 0-40 μm. They hypothesized that the surface cavities in the rough surfaces give bacteria protected places in which to form microcolonies. Once established, the microcolonies form a biofilm that is more easily able to resist shear forces.

The ability to form biofilms was also shown to be related to the hydraulic retention time (HRT) of the reactor at constant COD mass loads (Tijhuis et al. 1992, Heijnen et al. 1992). Non-attaching microorganisms (i.e. suspended growth) were not washed out of the system as fast at higher HRT's, and thus were able to consume more substrate, limiting the amount available to the biofilm. This resulted in greater attached growth at lower HRT's, leading to higher sludge ages. At low HRT's, the suspended growth can also hydrolyze the attachment polymers exuded by the biofilm microbes, further limiting biofilm growth.

Biofilm Detachment

Biofilm detachment and loss rates are normally attributed to two factors: sloughing and shear. Sloughing occurs when the biofilm attains a thickness at which substrate and dissolved oxygen are depleted by outside layers so that the inner layers essentially starve. In order to survive, the innermost cells resort to endogenous respiration (using their own cytoplasm as a food source); at this point they lose the ability to cling and may dislodge from the media (Benefield and Randall, 1980). Shear occurs primarily as a result of aeration turbulence, and in the case of media systems, bumping together of media particles. Both processes dislodge chunks of biofilm.

Trulear and Characklis (1982) performed experiments using annular biofilm reactors in which they attempted to quantify the effects of shear stress on biofilm loss rates. Using a rotating drum set at various speeds to produce different shear strengths, and also studying the effects of changing biofilm mass rates, they concluded that shear loss was a major component of the specific loss rate for fluidized sand particles, but not for activated carbon fluidized beds or typical fixed bed reactors. The hypothesis given for this was that the carbon beds required much less fluid velocity to become fluidized, thus reducing shear effects. It must be noted, however, that the application of these results to future work must be done with caution as they were conducted for biofilms grown at one temperature and with a single substrate.

Heijnen et al. (1992), in their study of a biofilm airlift reactor, found that biofilm formation was balanced by detachment. Even when up to 99% of the reactor biomass was in the form of fixed biofilm growth, 90% or more of the growth detached and washed out of the system, resulting in very low accumulations and a constant biomass/area ratio. The mechanism assumed to be responsible for this was shear due to inter-particle collisions. Particle concentration and geometry influence the effects of those collisions. They also noted that the detachment rate of the biofilm decreased as their experiment progressed. They were unable to determine the factors which were responsible, but suggested that the decrease in surface area per unit volume as the biofilm spreads over the entire particle contributes to the lower rate. Also, the decreasing amount of bare carriers in the system as the experiment progressed may have led to less particle/particle shear; the sludge loading of the system also dropped, leading to a lower specific biomass production rate.

Tijhuis et al. (1992) also noted that a large percentage of the fixed biomass (up to 95%) detached and washed out with the suspended growth. No specific mechanisms were presented as to why this happened.

Simultaneous Nitrification and Denitrification

The occurrence of simultaneous nitrification and denitrification (SND) within a biofilm has been noted by many researchers (Mitta, 1994; Louis, 1993; Sen et al. 1993; Lessel 1991 and 1993; Watanabe et al. 1992; Masuda et al. 1991; Bonhomme et al. 1990), and is attributed to the inability of oxygen to penetrate to the interior of the biofilm, thus creating an anoxic region.

Masuda et al. (1991) conducted research on SND, with the goal of determining the factors governing it. Their guiding hypothesis was: "Nitrifiers and denitrifiers coexist in a biofilm, and the denitrifiers become active if the oxygen transfer rate to the biofilm decreases enough to result in the formation of a micro-aerobic environment". To verify this, they used a micro-slicer to study biofilm populations, spatial distributions and reaction rates as a function of depth in a biofilm grown in a hooded RBC in which oxygen pressures could be controlled. The slices were 100 to 400 μm thick, and once cut, they were measured precisely, homogenized and analyzed. It was found that as one moved from outer to inner layers, the density increased nearly three times, but reaction rates per unit of biomass did not change appreciably. This, combined with the fact that the numbers of nitrifiers, denitrifiers, and heterotrophs did not noticeably change led them to conclude that these bacterial groups coexisted throughout the biofilm.

Watanabe et al. (1992) continued this aspect of research, again using a micro-slicer to cut biofilms into top, middle and bottom layers of 20 to 50 μm. The results showed that the biofilm density again increased in deeper layers and zero order ammonia oxidation rates decreased in deeper layers, but most of the deeper biomass was inert meaning that the intrinsic ammonia oxidation rate was generally constant throughout the whole depth. However, they did find that the biofilm was aerobic only to a depth of approximately 100 μm and that nitrification occurred primarily in the 0-120 μm depths, thus showing that the activity of nitrifiers and denitrifiers is strongly influenced by dissolved oxygen levels.

Both Masuda et al. (1991) and Watanabe et al. (1992) achieved many of the results concerning biofilm composition later reported by Zhang and Bishop (1993).

Endogenous Denitrification in Biofilms

As noted by Masuda et al. (1991) and Watanabe et al. (1992), nitrifying and denitrifying bacteria coexist in biofilms, and biofilms greater than 100 μm in thickness may be DO limited in their lower layers. These conditions can lead to simultaneous nitrification and denitrification. Chen et al. (1992) showed that SND occurs even when organic carbon substrates are limited, and termed the process endogenous denitrification. Lysis of microorganisms serves as the carbon source, and since the density of organisms is considerably higher at lower layers of biofilms, the substrate generated during endogenous decay is much higher than that of activated sludge.

Competition in Biofilms

Competition in biofilms comes from multiple sources, but can be grouped into two categories: predator and bacterial competition. Predators can be rotifers, nematodes, worms, snails etc. and can significantly reduce biofilm efficiency. Lee and Welander (1993) conducted parallel studies in which two identical suspended carrier reactors were monitored; one having been treated with an inhibitory chemical to reduce predators and the other having not been treated. They consistently noted a decrease in rotifers and nematodes, and increase in bacterial clusters tentatively identified as agglomerates of nitrifying bacteria, and a 100% increase in the nitrification rate in the treated system versus the untreated system. Once the inhibitor was removed, the microbial population and nitrification levels reverted slowly to that of the control. At times, higher organisms have been known to completely overwhelm a system. Mitta (1994) observed a bloom of red worms (Bristle Worms and Tubiflex) that was so thick that the entire aerobic zone turned red. The effect was more severe in the systems which had media (Ringlace, in this case) in downstream sections of the aerobic zones where COD levels were low. The result of the bloom was a severe degradation of effluent quality, particularly high ammonia levels in the effluent. Klees and Silverstein (1992) also found that biofilms associated with low carbon concentrations were more prone to attack by higher organisms such as snails and worms.

Heterotrophs and autotrophs also compete against each other, specifically for dissolved oxygen. Klees and Silverstein (1992), studying the effects of effluent recirculation in RBC's, found that low carbon levels caused by dilution contributed to higher ammonia oxidation rates. This was due to the fact that when both COD and ammonia levels are high, heterotrophs will displace the autotrophic nitrifiers because the growth rate for autotrophs (indicated by a half velocity constant, K_s of 0.42 mg NH_4^+/L (Drtil 1993)) is so much lower than for heterotrophs (approximately 50 mg COD/L (Grady and Lim 1980)). In the later stages of RBC's where organic carbon levels are lowest, the specific growth rate of heterotrophs will decrease to a level less than the growth rate for autotrophs. At this point, which they found to be 15-20 mg/L COD, nitrification will increase, following a Monod expression. This phenomenon was also noted in biofilm studies by Mitta (1994), Sen (1993), Ryhiner et al. (1993), Sagberg et al. (1992), and Shin and Park (1991).

If the organic carbon levels fall to a level lower than approximately 10 mg/L, however, the biofilm tends to become thin and more prone to attack by predators, leading to a decrease in nitrification efficiency (Klees and Silverstein, 1992). Summarizing work done by Kinner and Maratea, Klees and Silverstein (1992) found a lack of cell diversity, unhealthy living cells and cell debris in the last stages of RBC's, resulting in very thin biofilms.

Sludge Production

Fixed film processes have long been thought to contribute to lower sludge production compared to conventional activated sludge systems. Wang et al. (1992) attributed the lower sludge production to the fact that biofilms contain a mixture of aerobic, anoxic, and anaerobic bacterial layers from the surface to the bottom. The anaerobic layers degrade the surrounding biomass and produce volatile acids and gasses such as CH_4, CO_2, H_2 and N_2, thus reducing surplus sludge. In addition, a significant amount of biomass is consumed by higher organisms such as Nematodes, Paramecium, Rotifers and Cladicera which are present in higher quantities in biofilm than in activated sludge. These higher organisms must convert a portion of the biomass into energy before they begin converting it into their own cellular mass, thus their replacement mass is less than that which they consume (Wang et al. 1992). Similar results were seen by Lessel (1993) in a study using Ringlace media as a biomass carrier.

Louis (1993) also noted lower sludge production for a bench scale aerobic CSTR Series system (treating synthetic waste) using Linpor sponges as a biomass carrier, but only at low sludge ages (2.5 days). At higher sludge ages (5 days) sludge production was equal for all experiments except one in which 40% sponges (by dry volume) were used; in this case sludge production was higher. This was attributed to a marked decrease in HRT caused by the addition of the media to the reactor. Mitta (1994) found a consistent decrease in sludge production in bench scale VIP systems (treating municipal wastewater) using Ringlace and Captor sponges compared to a conventional activated sludge system, but only when the sludge age was less that four days. He also noted that the Captor sponges produced significantly less sludge than did the Ringlace. At a 3.4 day MCRT, sludge production was 8% lower in the sponge system compared to the control, and the yield was 29% lower, while at a 3.1 day MCRT, the sludge production decreased even more, being 35% less while the yield was also 35% less. The lack of sufficient data points precluded a proper statistical analysis of these numbers, but the trend supports the results of both Haseltine (1991) and Louis (1993). From the results of these researchers, it seems that the main advantage in lower sludge production comes at lower MCRT's.

SUMMARY

Many researchers have investigated the effects of fixed film media addition to wastewater treatment schemes. The placement of the media, the quantity used and the type of media may have varied considerably, but the results have been consistent between all. Fixed film media systems have been shown to increase treatment effectiveness when compared to conventional treatment systems, particularly with respect to ammonia removal. An additional advantage was found to be the relative insensitivity to temperature that fixed film media systems developed. The results of these advantages were demonstrated by smaller treatment units required to treat wastes of equal strength, and costs savings in construction and operation of the treatment units.

Consistent among the research was the development of oxygen deficient zones within the biomass attached to the media under high substrate and/or low turbulence conditions, and a lack of biomass growth on the media during low substrate and/or high turbulence conditions. An optimum operating range must be maintained where biomass growth is allowed to attach itself in sufficient quantities to be of benefit, yet not in quantities which would contribute to oxygen deficiencies within the biomass, effectively neutralizing all but the exposed surface growth.

Many researchers did note the presence of denitrification in fixed film systems, even when the media was placed in aerobic zones, as a result of anoxic regions within the attached biomass where nitrate can be reduced to nitrogen gas.

Mixed results were seen when sludge production was studied. Many researchers noted decreased sludge production over a range of MCRTs in fixed film systems when compared to conventional systems, while others did not. At low MCRTs, the advantage of lower sludge production became more definite.

CHAPTER THREE: METHODS AND MATERIALS

INTRODUCTION

Research into the optimization of nitrogen removal using Integrated Fixed Film Activated Sludge (IFAS) systems was conducted using four bench scale activated sludge Biological Nutrient Removal (BNR) systems. The operation of the systems and the methods, materials and procedures followed are presented in this chapter.

PILOT PLANT CONSTRUCTION

Each BNR system was constructed following the Virginia Initiative Project (VIP) configuration, a schematic of which is shown in Figure 3-1. In order to evaluate the systems under the temperatures required (in all cases, 12° C), the systems were housed in a well insulated shed equipped with thermostatically controlled heating and cooling units. The temperature range was maintained within (+/-) one °C.

The VIP configuration is a combination of anaerobic, anoxic, and aerobic zones, in that order. The bench scale models consisted of these three zones, totaling 104 liters, and a 15 liter clarifier (not considered treatment volume) connected in series. A two liter deoxygenation zone whose function is described in subsequent paragraphs was also part of the system. Nalgene high density polyethylene tanks were used for construction. The anaerobic and anoxic zones comprised 17% each of the treatment volume, and the aerobic zone was the remaining 66% of the treatment volume. These fractions were selected from full scale suspended growth plants whose design had been modified to include nutrient removal. The treatment capacity of each system was 207.4 L/day, leading to a nominal hydraulic detention time of 12.2 hours. Table 3-1 summarizes the volumes and fractions for each system.

In order to more closely approximate plug flow conditions, each zone was converted into a series of CSTR's by dividing them into approximately equal sections with 3/8" porous Plexiglas baffles. The anaerobic and anoxic zones were divided by one baffle into two sections while the aerobic zone was divided by two baffles into three sections. Figure 3-1 details the use of the baffles.

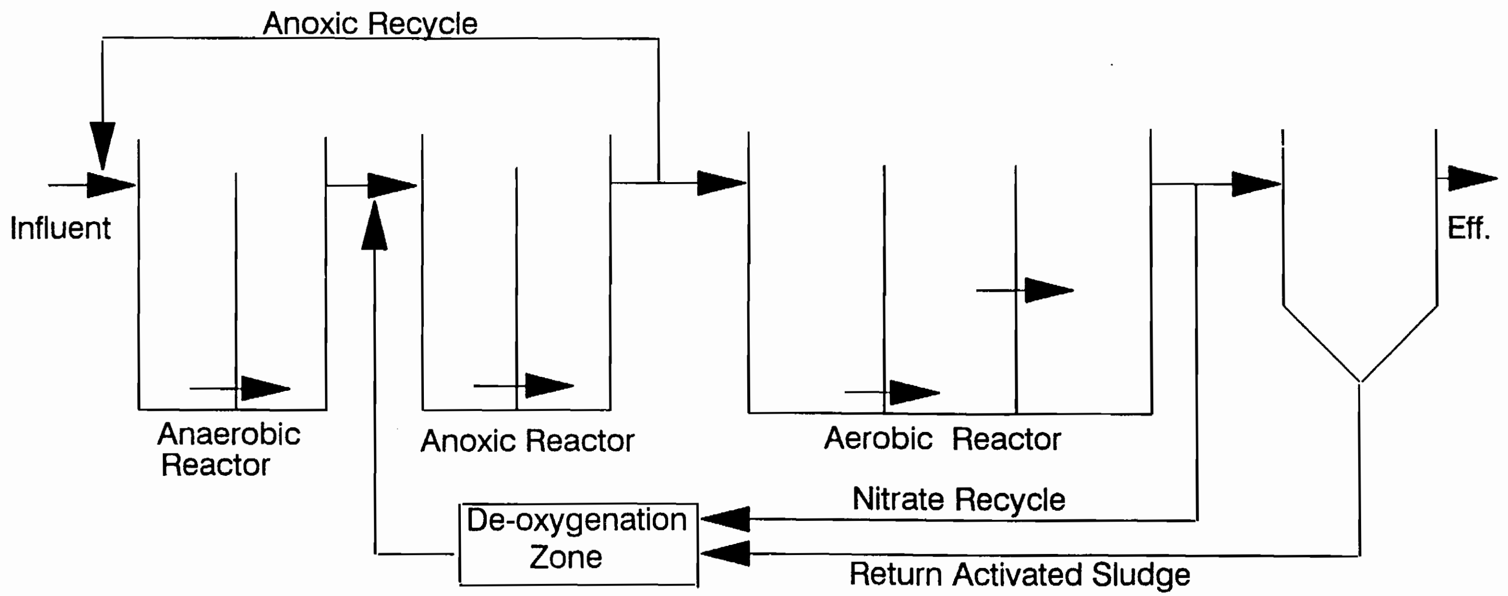


Figure 3-1. VIP Configuration

Table 3-1. Volumes and Flow Rates for Each Section, All Systems

System Component	Number of Cells	Volume of Each Cell (Liters)	Total Volume (Liters)	Total Percent of Volume
Anaerobic Reactors	2	8.7	17.4	17%
Anoxic Reactors	2	8.7	17.4	17%
Aerobic Reactors	3	23.1	69.2	66%
Deoxygenation Reactor	1	2	2	2%
Entire System	7	N/A	106	100%
Clarifier	1	15	15	N/A

Nominal Hydraulic Retention Time = 12.2 hours

Influent Flow Rate (Q) = 207.4 L/day

Mixed Liquor Return Rate (MLR) set at 1.0 Q during all phases

Nitrate Return (NR) and Return Activated Sludge (RAS) rates set at 1.0 Q during phases 1-3 and 1.3 Q during phase 4

A small deoxygenation zone consisting of a two liter graduated cylinder was placed in a position to receive flows from the return activated sludge and nitrate recycle lines (Fig. 3-1). The HRT of this zone was approximately seven minutes and was sufficient to reduce the DO level in the two streams to near zero prior to entering the anoxic zone.

Mixing in the anaerobic and anoxic zones was accomplished using electric motors set at 50 RPM, connected to shafts with mixing blades. Similar motors connected to one scraper blade and set at one RPM were used to scrape the bottom of each clarifier to prevent sludge accumulation. The aerobic zone was kept well mixed by air turbulence. The air supply to the aerobic zones was provided by a one horsepower Ghast Oil-Less compressor which fed a series of coarse and fine bubble diffusers. Coarse bubble diffusers provided more turbulence and were primarily used in the systems containing free floating media in order to ensure proper mixing and to minimize media settling.

Pumping operations required for influent feed, nitrate recycle, return activated sludge, and mixed liquor return were conducted by variable speed Cole Parmer Masterflex peristaltic pumps using size 17 pump heads. Each pump motor was capable of handling four pump heads, and to minimize variations one pump assembly was used to perform the same function for each treatment system whenever possible.

SYSTEM OPERATION

The wastewater used for all experiments was obtained directly from a main sewer line maintained by the Blacksburg/VPI Sanitation Authority. The sewer line was fed primarily from campus sources, and was influenced by changes in student populations and campus activities. The feed for the pilot systems was pumped into large storage containers housed within the temperature controlled shed. These containers served as primary settling tanks. Here the sewage would be allowed to settle for 24 hours and equilibrate to the operating temperature. This settling period also allowed for deoxygenation of the feed, which helped maintain DO free conditions in the anaerobic zone to which it was fed.

Sludge accumulations in the primary settlers were pumped out every other day at a minimum, and usually every day. This was to avoid excess sludge accumulations, anaerobic activity, and COD consumption associated with that activity.

Technical grade sodium acetate (COD source), urea (ammonia source), potassium phosphate (phosphorus source), and sodium bicarbonate (alkalinity source) were added to the sewage during the filling phase to increase the strength of the sewage and ensure that sufficient alkalinity would be maintained during the nitrification stage, when alkalinity is consumed. The desired ratios of COD, NH_3-N and PO_4^{3-}-P were approximately 45:5:1, with the COD being 450 to 500 mg/L.

Variations in raw sewage strength naturally occurred, but were exacerbated by heavy infiltration and inflow during extremely wet periods and by changes in student populations during breaks and summer sessions. To minimize the effects of these variations, influent characteristics were measured periodically and supplemental chemical doses were adjusted accordingly to maintain the proper ratios.

If, during the analysis phase, it was found that the effluent ammonia-nitrogen levels in any or all of the systems was less than 2 mg/L (the point at which nitrification becomes substrate limited), an ammonia spike was performed. This involved adding up to twice as much supplemental urea to the influent of all trains, with the goal being to force each system to "bleed" higher amounts into the effluent, allowing for the calculation of maximum nitrification rates. This was only done periodically, with two or more days between spikes for the systems to re-acclimate.

All four influent feed rates (Q) were adjusted to deliver 207.4 L/day with a variation of less than five percent from system to system. All recycle rates were operated at 1.0 Q (also with <5% variation), except for the return activated sludge and nitrate return during the fourth phase which were 1.3 Q. The recycles were set up as follows (refer to Fig. 3-1): mixed liquor from the last aerobic cell (nitrate return, or NR, designed to convey oxidized nitrogen from the aerobic zone to the anoxic zone) combined with return activated sludge (RAS, designed to convey settled sludge from the clarifier to the anoxic zone) from the clarifier, entered the deoxygenation zone where the DO was depleted. From there, it was gravity fed to the first anoxic zone. Mixed liquor from the second anoxic zone (mixed liquor return, or MLR, designed to convey suspended growth to the anaerobic zone) was pumped back to the first anaerobic zone where it combined with the influent. Table 3-1 also lists the pumping and recycle rates for each phase.

All systems were operated under equivalent aerobic MCRT's for suspended growth. Mitta (1994) found that when operating under conditions of equivalent total suspended growth MCRT's, the media displaced enough volume to significantly alter the HRT of the aerobic zones. This altered the aerobic MCRT's, depending on type and amount of media installed. In order to compute the actual aerobic MCRT for a system it was necessary to accurately calculate the volume displaced by the media. This was done for Ringlace by inserting a strand of Ringlace covered with growth into a one liter graduated cylinder half full of water and noting the volume displaced by it. The total aerobic volume displaced was the product of the volume displaced by one strand multiplied by the total number of strands used. The effective aerobic volume was then calculated by subtracting the volume displaced from the total aerobic volume. A similar procedure was used for the Captor sponges - immersing 20 sponges into 500 mL water and measuring the volume displaced. Another method was also used for sponges, involving the weight of water removed from the sponges after drying for 24 hours in a 103 °C oven. Four sponges were selected and drained of free flowing water by shaking in a plastic net. A wet weight was then taken, the sponges were dried, and a dry weight was taken. The difference in weight was equal to the water entrained in the sponge. The volume displaced and the total aerobic volume were calculated as before.

MEDIA INSTALLATION

Of the four systems in operation, one was continually operated without any media addition and used as a control with which to compare the media systems. During different phases, different amounts and types of media were used in the experimental systems.

Ringlace, being a rope type media, must be supported in some way in order to be effective. This was accomplished by constructing frames out of 3/8" by 1" Plexiglas strips and looping 36" sections of Ringlace onto the frame and securing it by tying the ends together at the top. The result was two strands, one inch apart (width of the frame) for each loop. Each frame was constructed to fit tightly within the confines of the aerobic zone, and each frame had seven loops on it. The Ringlace train had two frames in each of its three sections. This configuration was maintained through phases one and two, and discontinued for phases three and four.

Captor sponges were very simple to install. Sponges (1" by 1" by 1/2"; 30 pores/ inch) were added to the aerobic cells and kept afloat by air turbulence. The dry volume of Captor added to each cell was equal to 20% of the liquid volume in one system and 30% in another. This corresponded to 25 and 37.5 sponges per liter of mixed liquor, respectively. In phase one, aerobic cells one and two contained sponges; in phases two, three and four, each aerobic cell contained sponges. The system using 20% sponges was only operated during phase two. Table 3-2 summarizes the trains in operation, the media utilized, and placement of the media for each phase.

SYSTEM MONITORING

The primary parameter monitored, next to temperature, was the operating MCRT. This was done by measuring the effluent suspended solids and the mixed liquor suspended solids and using those numbers to calculate the required sludge wasting rate for a given MCRT. During the first phase, the wasting rate was calculated by the following formula, whose derivation is given in appendix A:

$$Q_w = (VX - \Theta_c X_e Q)/(\Theta_c X - \Theta_c X_e) \qquad (3\text{-}1)$$

where:

Q_w = Sludge Wasting Rate (L/day)
V = Total Volume of System (L)
X = Mixed Liquor Suspended Solids (mg/L)
X_e = Effluent Suspended Solids (mg/L)
Θ_c = Total Desired Sludge Age (days)
Q = Influent Flow Rate (L/day)

Since all systems had different media, different mixed liquor concentrations, and effluent suspended solids were slightly different, wasting rates varied between them. Actual sludge wasting was accomplished by a combination of mechanical and manual means. A waste pump was set to pump a volume slightly less than the lowest calculated waste rate. The remainder was wasted manually each day using one liter beakers. In phase one, the waste pump discharged directly back to the sewer; in phases two, three and four, the waste pump discharged into numbered, graduated carboys so that a visual check could be made daily as to how much had actually been wasted.

Table 3-2. Operating Parameters for Each Phase

Train	Cell	Phase 1	Phase 2	Phase 3	Phase 4
1	AER 1	Not In Use	20% Captor	Not In Use	Not In Use
1	AER 2	Not In Use	20% Captor	Not In Use	Not In Use
1	AER 3	Not In Use	20% Captor	Not In Use	Not In Use
2	AER 1	No Media	30% Captor	30% Captor	30% Captor
2	AER 2	30% Captor	30% Captor	30% Captor	30% Captor
2	AER 3	30% Captor	30% Captor	30% Captor	30% Captor
3	AER 1	14 Loops Ringlace	14 Loops Ringlace	Not In Use	Not In Use
3	AER 2	14 Loops Ringlace	14 Loops Ringlace	Not In Use	Not In Use
3	AER 3	14 Loops Ringlace	14 Loops Ringlace	Not In Use	Not In Use
4	AER 1	No Media	No Media	No Media	No Media
4	AER 2	No Media	No Media	No Media	No Media
4	AER 3	No Media	No Media	No Media	No Media

Key: AER indicates aerobic zone, the last number indicates the particular cell within the aerobic zone.

During phases two through four, the following sludge wasting formula, the derivation of which is in appendix A, was used:

$$Q_w = V_a * AVF/\Theta_{c,aSS} \tag{3-2}$$

where:

Q_w = Sludge Wasting Rate (L/day)
V_a = Volume of Aerobic Zone (69.2 L)
AVF = Aerobic Volume Factor
$\Theta_{c,aSS}$ = Aerobic Suspended Growth Sludge Age

and the aerobic volume factor was calculated by:

$$AVF = 1 - BVF \tag{3-3}$$

where BVF is defined as the Biofilm Volume Factor, calculated by:

$$BVF = (v_l/v_m)(mf) \tag{3-4}$$

where:

v_l = liquid volume displaced by biofilm and media
v_m = dry media volume
mf = media volume fraction (dry media volume/aerobic volume)

This method was considered more accurate for determining rates based on aerobic suspended growth MCRT's. Once the wasting rate was calculated, actual wasting took place as described earlier.

PERFORMANCE ANALYSIS

All reactors were allowed to reach steady state conditions with respect to mixed liquor suspended solids and effluent ammonia concentrations. An acclimation period of a minimum of three MCRT's was allowed to pass after any MCRT adjustments were made. Due to the constant exchange of biomass between the fixed film and suspended mixed liquor, and the different ratios of heterotrophic and autotrophic growth in each aerobic cell, six weeks became the standard acclimation period. In this time, the bacterial populations within the fixed film could reestablish a proper balance with the substrate concentrations under the given operating conditions.

System performance analysis under steady state conditions involved sampling from some or all the sections of the treatment trains, as well as the collection of influent and effluent samples. Analysis of a system was called a "profile", and data consisting of a mixture of long, medium and short profiles would be taken over the steady state period. Data for the first phase of operation were analyzed on May 28, 1993. Data for the second phase were analyzed between September 14, 1993 and December 29, 1993. Data for the third phase were analyzed between February 23, 1994 and April 4, 1994. Data for the fourth phase were analyzes between June 2, 1994 and June 28, 1994. Appendix B contains all raw data and indicates the dates each profile was taken. Table 3-3 summarizes the sampling procedures for each type of profile, as well as the information gained from each.

Samples collected for analysis were either taken as total samples (not filtered) or as soluble samples, which were filtered on site through Whatman 934 AH glass microfiber filters with a pore size of 1.5 μm. All samples were then taken directly to the laboratory on the Virginia Tech campus for immediate analysis. Periodically, all samples could not be analyzed on the day they were taken; in this case they were preserved in accordance with recommended procedures found in Standard Methods.

Table 3-3. Sampling Procedures for Profile Analysis

Sample	Long, Med, Short (L,M,S)	NH_3-N	TKN, SKN	NO_2^--N, NO_3^-N, OP	COD, SCOD	TP	MLSS, MLVSS
Influent	L,M,S	Yes	TKN	No	COD	Yes	No
Anaerobic 1	L	Yes	No	Yes	SCOD	No	Yes
Anaerobic 2	L,M	Yes	No	Yes	SCOD	No	Yes
Anoxic 1	L	Yes	No	Yes	SCOD	No	Yes
Anoxic 2	L,M,S	Yes	SKN	Yes	SCOD	No	Yes
Aerobic 1	L,M	Yes	SKN	Yes	SCOD	No	Yes
Aerobic 2	L,M	Yes	SKN	Yes	SCOD	No	Yes
Aerobic 3	L,M,S	Yes	SKN, TKN	Yes	COD, SCOD	Yes	Yes
Effluent	L,M,S	Yes	SKN	Yes	SCOD	Yes	Yes

Key: Mixed Liquor Suspended Solids (MLSS)
Mixed Liquor Volatile Suspended Solids (MLVSS)
Ammonia-nitrogen (NH_3-N)
Nitrite-nitrogen (NO_2^--N)
Nitrate-nitrogen (NO_3^--N)
Total Kjeldahl Nitrogen (TKN)
Soluble Kjeldahl Nitrogen (SKN)
Chemical Oxygen Demand (COD)
Soluble COD (SCOD)
Total Phosphorus (TP)
Orthophosphorus (OP)

ANALYTICAL PROCEDURES

Samples taken during a profile run were analyzed for Mixed Liquor Suspended Solids (MLSS), Mixed Liquor Volatile Suspended Solids (MLVSS), Ammonia-nitrogen (NH_3-N), Nitrite-nitrogen (NO_2^--N), Nitrate-nitrogen (NO_3^--N), Total Kjeldahl Nitrogen (TKN), Soluble Kjeldahl Nitrogen (SKN), Chemical Oxygen Demand (COD), Soluble COD (SCOD), Total Phosphorus (TP), and Orthophosphorus (OP). Oxygen uptake rates were also measured during long and medium profiles for both mixed liquor and mixed liquor containing specified quantities of media. Table 3-4 summarizes the analytical tests performed, and notes the reference in which they can be found.

Biomass growth on the media was also an important factor which was measured in each aerobic cell. This was done for both the Ringlace and Captor sponges by taking a representative strand (Ringlace) or four sponges (Captor) and drying them in a 103° C oven for 24 hours. The total weight of biomass was then determined by subtracting the tare weight of an identical oven dried piece of media having no growth. The amount of growth was then determined per unit length or piece of media. In order to account for the wear and tear on the Captor sponges, the sponges having no growth used to calculate the tare weight were simply the actual sponges analyzed after they had been thoroughly soaked and cleaned of growth. This was found to be more accurate than using a new, clean sponge that had not lost any of its mass to wear and tear.

STATISTICAL ANALYSIS

A simple paired t-test was used to compare IFAS performance to that of the control system. This test was chosen because all treatment systems were fed the same influent wastewater, thus direct comparisons were simplified.

Table 3-4. Analytical Procedures

Test	Procedure and Reference Number (Standard Methods*)
TKN, SKN	Semi-micro Kjeldahl Method, (4500-N_{org} C) followed by Titration (4500-NH_3 E)
NH_3-N	Ammonia Selective Electrode Method (4500-NH_3 F)
NO_2^--N, OP, NO_3^--N	Ion Chromatography with Chemical Suppression of Eluant Conductivity using Dionex 2010i (4110 B)
COD	Closed Reflux, Titrametric Method (5220 C)
MLSS	Total Suspended Solids Dried at 103°-105°C (2540 D)
MLVSS	Fixed and Volatile Solids Ignited a 550°C (2540 E)
TP	Persulfate Digestion (4500-P B.5) followed by Ascorbic Acid Method (4500-P E)
Temperature	On-site Measurement with a Mercury Filled Celsius Thermometer (2550 B)
DO	Measured using YSI Model 54A Membrane Electrode Oxygen Meter (4500-O G)

*Standard Methods for the Examination of Water and Wastewater (1992)

CHAPTER FOUR: RESULTS

INTRODUCTION

As noted in the Materials and Methods chapter, fixed film media was installed in three separate activated sludge BNR treatment trains, Train 1 (20% Captor), Train 2 (30% Captor) and Train 3 (Ringlace). A fourth train, designated as Control, contained no media and was used as a reference with which to compare the IFAS trains. The experiments conducted were divided into four phases, each having different operating conditions. These phases were:

Phase 1. Total Aerobic Suspended Growth MCRT = 3.4 days, temperature: 12°C. Comparison of 30% Captor sponges and Ringlace in the aerobic zone (Trains 2, 3, and Control).

Phase 2. Total Aerobic Suspended Growth MCRT = 3.1 days, temperature: 12°C. Comparison of 20% and 30% Captor sponges and Ringlace in the aerobic zone (Trains 1, 2, 3, and Control).

Phase 3. Total Aerobic Suspended Growth MCRT = 2.4 days, temperature: 12°C. Comparison of 30% Captor sponges in the aerobic zone (Train 2 and Control).

Phase 4. Total Aerobic Suspended Growth MCRT = 1.7 days, temperature: 12°C. Comparison of 30% Captor sponges in the aerobic zone (Train 2 and Control).

Table 3-2 summarizes the various parameters associated with each phase.

The terms 20%Cap, 30%Cap, Ringlace and Control will be used to denote the 20% Captor system, the 30% Captor system, the Ringlace system and the non-IFAS system throughout this chapter. The results of each of the four phases are presented in this chapter, with an emphasis on meeting the major objectives of evaluating media effects on nitrification and denitrification. Sludge production, sludge yield, and COD uptake data are presented to compare process performance. A detailed description of all calculations used is presented in Appendix A.

NITRIFICATION

Nitrification in each system was studied very carefully, and many parameters were measured. The following determinations were made to describe performance: (1) System Nitrification, i.e. total oxidation of organic nitrogen and ammonium to NO_2^--N, (2) Ammonia oxidation in each aerobic cell, and (3) Nitratification, i.e. oxidation of NO_2^--N to NO_3^--N. Each experiment was further classified as either "normal" (normal Influent TKN) or urea "spiked" (high Influent TKN). Raw data collected during each experimental phase are presented in Appendix B, tables B-1 through B-4.

System Nitrification

Nitrification in each system was calculated using mass balance techniques. The quantity of organic nitrogen and ammonia oxidized to nitrite under normal conditions during each phase is given in Table 4-1a. The quantity oxidized to nitrite under spiked conditions during each phase is given in Table 4-1b. It should be noted that during phase two (3.1 day MCRT), the ability of the air compressor to supply air to all four trains was strained. Diffusers leading to the 20%Cap treatment train were rerouted to the 30%Cap train to ensure it received proper aeration. As a result, the quantity of air supplied to the 20%Cap train was most likely too low for the train to consistently nitrify to its utmost ability. After five profiles of 20%Cap were run, it was decided that experiments on it would be discontinued in order to concentrate research efforts on 30%Cap and Ringlace. 20%Cap data presented in this chapter is for rough comparison only, and no statistical analysis was performed on it.

Figures 4-1 through 4-8 depict the ammonia profiles of each train during each phase. Table 4-2 summarizes the results of paired t-tests done on calculated nitrification rates for each train during each phase under normal conditions. Table 4-3 summarizes the results of paired t-tests done on calculated nitrification rates for each train during each phase under spiked conditions.

Phase One. Figure 4-1 indicates that near complete nitrification took place in all trains during phase 1 (normal), because the effluent ammonia levels were less than 1 mg/L. Table 4-1a indicates that roughly the same quantity of nitrification occurred in all trains during phase 1 (normal). Figure 4-2 indicates that during phase 1 (spiked) each of the effluents contained greater than 10 mg/L ammonia, with the control having nitrified less than Ringlace which nitrified less than

Table 4-1a. Effect of IFAS on System Nitrification Under Normal Conditions Ammonium to Nitrite

Aerobic MCRT (days)	20%Cap	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	7.9	7.9	6.4
Δ Control	N/A	1.5	1.5	N/A
3.1	8.0	11.8	11.4	10.3
Δ Control	(2.3)	1.5	1.1	N/A
2.4	ND	8.2	ND	3.8
Δ Control	N/A	4.4	N/A	N/A
1.7	ND	8	ND	1.3
Δ Control	N/A	6.7	N/A	N/A

Table 4-1b. Effect of IFAS on System Nitrification Under Spiked Conditions Ammonium to Nitrite

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	9.5	7.1	6.5
Δ Control	N/A	3.0	0.6	N/A
3.1	9.9	13.7	11.6	11.7
Δ Control	(1.8)	2.0	(0.1)	N/A
2.4	ND	11.1	ND	4.2
Δ Control	N/A	6.9	N/A	
1.7	ND	9.5	ND	2.6
Δ Control	N/A	6.9	N/A	N/A

20%Cap values are the sums of aerobic cell ammonium oxidation rates
ND indicates that no data points were taken.
N/A indicates that the analysis is not applicable

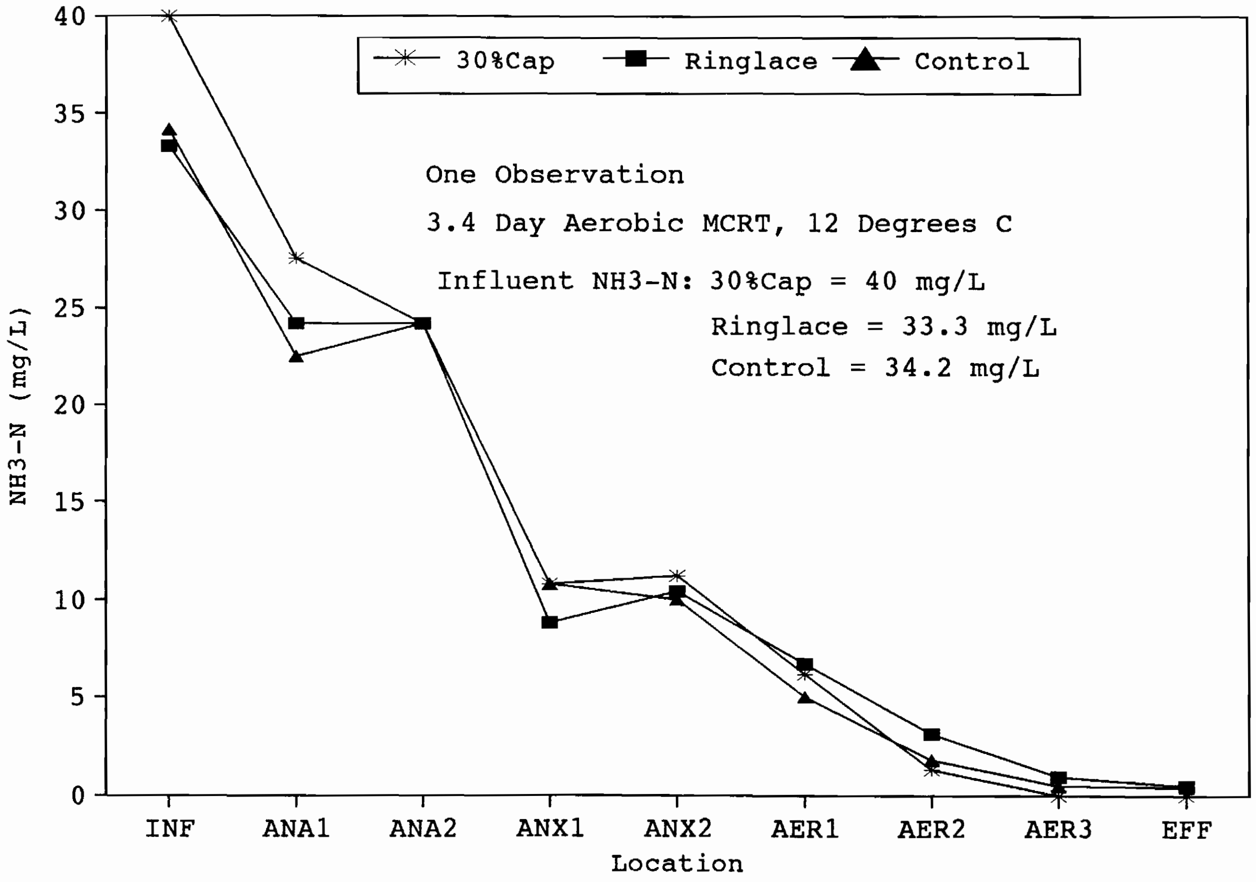


Figure 4-1. Ammonia Profile of Phase One Experiments Under Normal Conditions

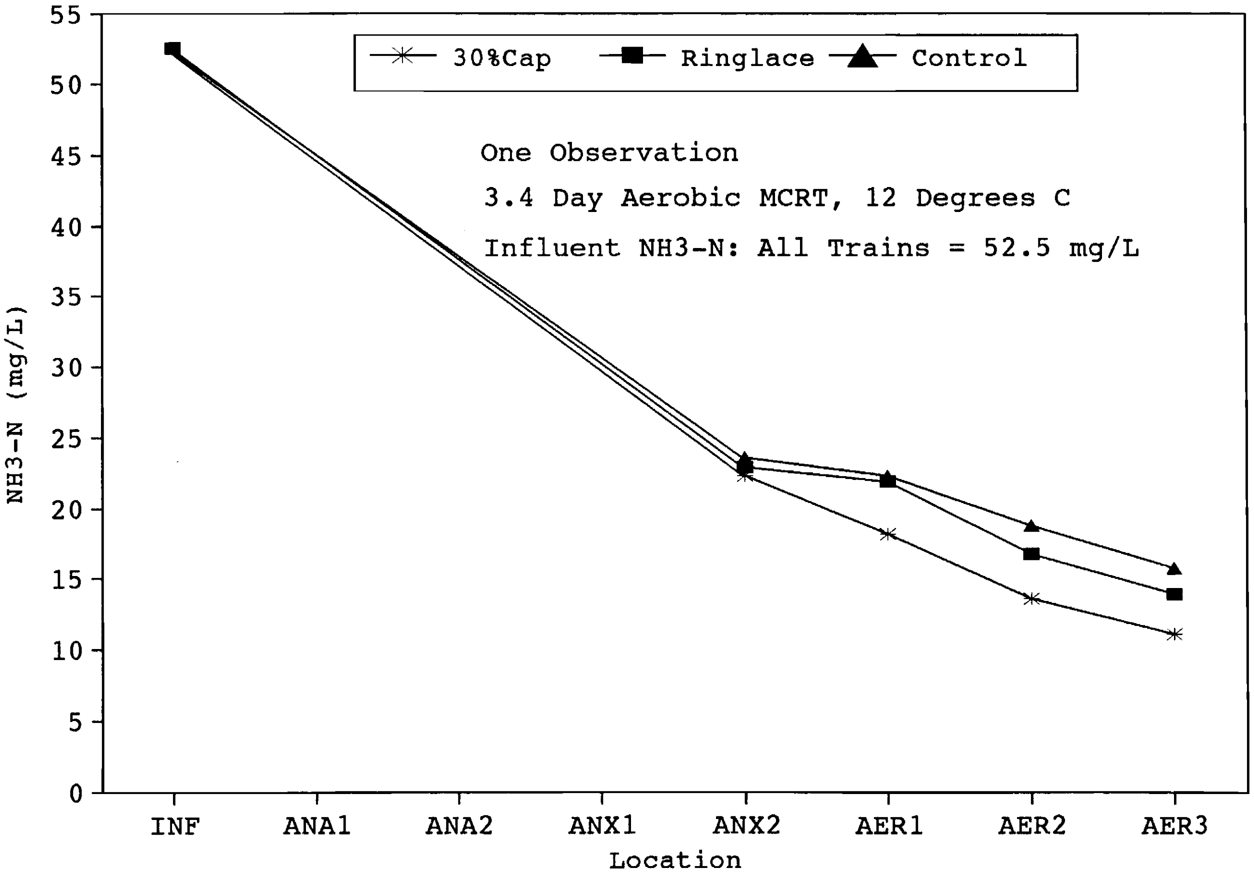


Figure 4-2. Ammonia Profile of Phase One Experiments Under Spiked Conditions

30%Cap. Table 4-1b also indicates that during phase 1 (spiked), 30%Cap nitrified to a greater extent than Ringlace and the Control. A paired t-test was not conducted for either condition because during this phase only one data set was taken.

Phase Two. Figure 4-3 shows that during phase 2 (normal), 30%Cap and Ringlace reached a lower effluent ammonia concentration than 20%Cap, which reached a lower concentration than the Control. However, the influent ammonia concentrations for 30%Cap and the Control were higher than those of 20%Cap and Ringlace. Table 4-1a indicates that during phase 2 (normal) 30%Cap and Ringlace nitrified to a greater extent than the Control, which nitrified more than 20%Cap. A paired t-test (Table 4-2) demonstrated that nitrification rates in 30%Cap and Ringlace were statistically higher than the Control, at 99% and 90% confidence levels, respectively. A t-test was not conducted on 20%Cap because problems with the air supply to the system led to low dissolved oxygen levels in the mixed liquor, potentially limiting the amount of nitrification which could occur.

During phase 2 (spiked), Figure 4-4 indicates that 30%Cap discharged less than 10 mg/L ammonia-N into the effluent, while 20%Cap discharged greater than 10 mg/L and Ringlace and the Control discharged greater than 30 mg/L. In this case, the influent ammonia levels for 20%Cap and 30%Cap were lower than those for Ringlace and the Control. Table 4-1b clarifies the situation for phase 2 (spiked) by showing that 30%Cap nitrified to a greater extent than Ringlace and the Control, which nitrified more than 20%Cap. Table 4-3 demonstrates that during phase 2 (spiked), nitrification in 30%Cap was statistically higher than the Control at a 99% confidence level, while nitrification in Ringlace was not statistically higher than the Control, even at a 60% confidence level.

Phase Three. Figure 4-5 depicts the ammonia profile of phase 3 (normal), and shows that under the given conditions, 30%Cap nitrified almost completely as evidenced by the effluent ammonia level of approximately 1 mg/L. However, the Control discharged approximately 24 mg/L of ammonia into the effluent. Table 4-1a supports this observation by showing that 30%Cap nitrified more than twice as much nitrogen as the Control. The paired t-test (Table 4-2) conducted indicates that 30%Cap nitrified at a statistically higher level with 99% confidence.

During phase 3 (spiked), Figure 4-6 indicates both trains discharged significantly higher levels of ammonia into the effluent than during phase 3 (normal), with 30%Cap nearing 15 mg/L and the Control approaching 50 mg/L. Again, 30%Cap nitrified at greater than twice the rate of the

Table 4-2. Paired t-test Results for Total Nitrification Under Normal Conditions: Compared to Control
Ammonium to Nitrite

Aerobic MCRT (days)	Parameter	30%Cap (g/d)	Ringlace (g/d)
3.1 Phase 2	t_{obs}	5.61	1.75
	DF	5	5
	t_{crit}	3.365	1.476
	Different?	Yes	Yes
	Conf. Level of t_{crit}	99%	90%
2.4 Phase 3	t_{obs}	7.54	ND
	DF	4	ND
	t_{crit}	3.747	ND
	Different?	Yes	ND
	Conf. Level of t_{crit}	99%	ND
1.7 Phase 4	t_{obs}	31.33	ND
	DF	4	ND
	t_{crit}	3.747	ND
	Different?	Yes	ND
	Conf. Level of t_{crit}	99%	ND

ND indicates that no data points were taken.

Table 4-3. Paired t-test Results for Total Nitrification Under Spiked Conditions: Compared to Control
Ammonium to Nitrite

Aerobic MCRT (days)	Parameter	30%Cap (g/d)	Ringlace (g/d)
3.1 Phase 2	t_{obs}	18.43	-0.84
	DF	2	3
	t_{crit}	6.965	0.277
	Different?	Yes	No
	Conf. Level of t_{crit}	99%	60%
2.4 Phase 3	t_{obs}	16.61	ND
	DF	4	ND
	t_{crit}	3.747	ND
	Different?	Yes	ND
	Conf. Level of t_{crit}	99%	ND
1.7 Phase 4	t_{obs}	19.33	ND
	DF	4	ND
	t_{crit}	3.737	ND
	Different?	Yes	ND
	Conf. Level of t_{crit}	99%	ND

ND indicates that no data points were taken.

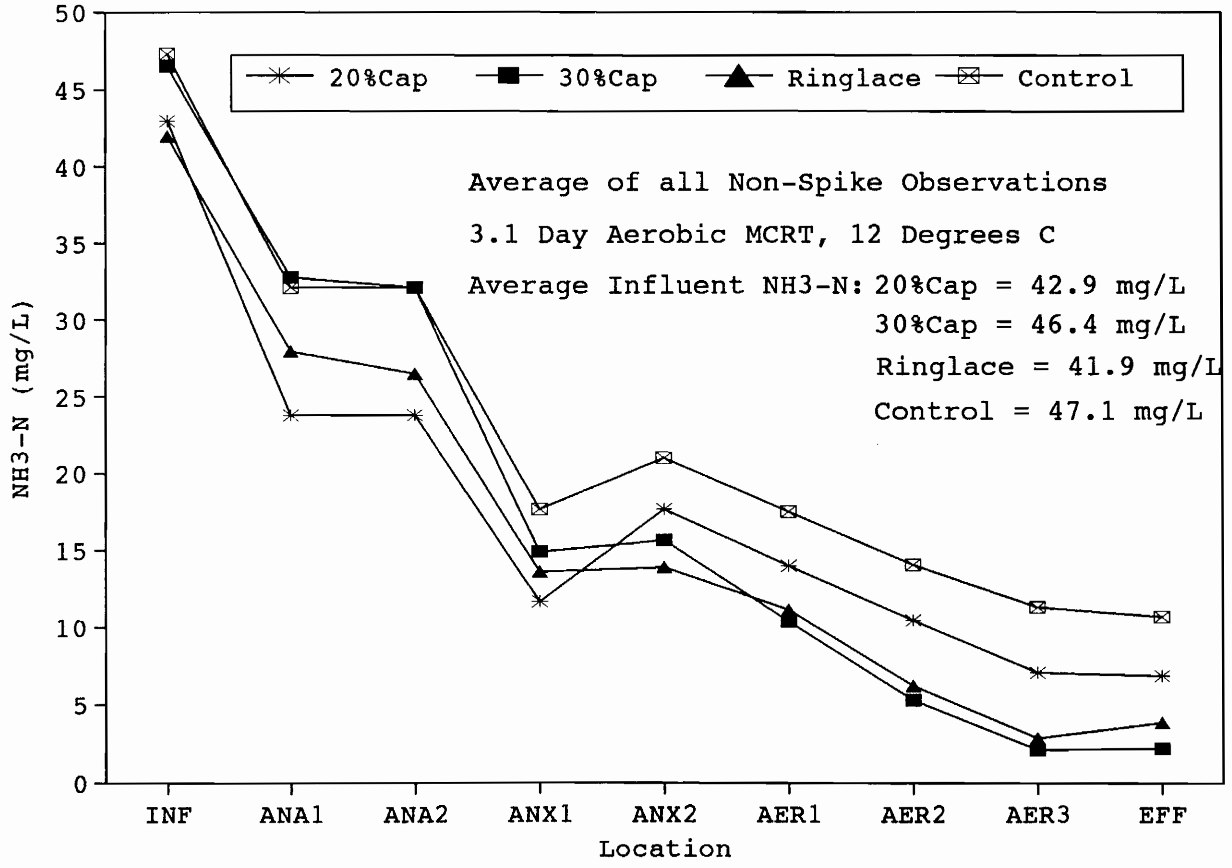


Figure 4-3. Ammonia Profile of Phase Two Experiments Under Normal Conditions

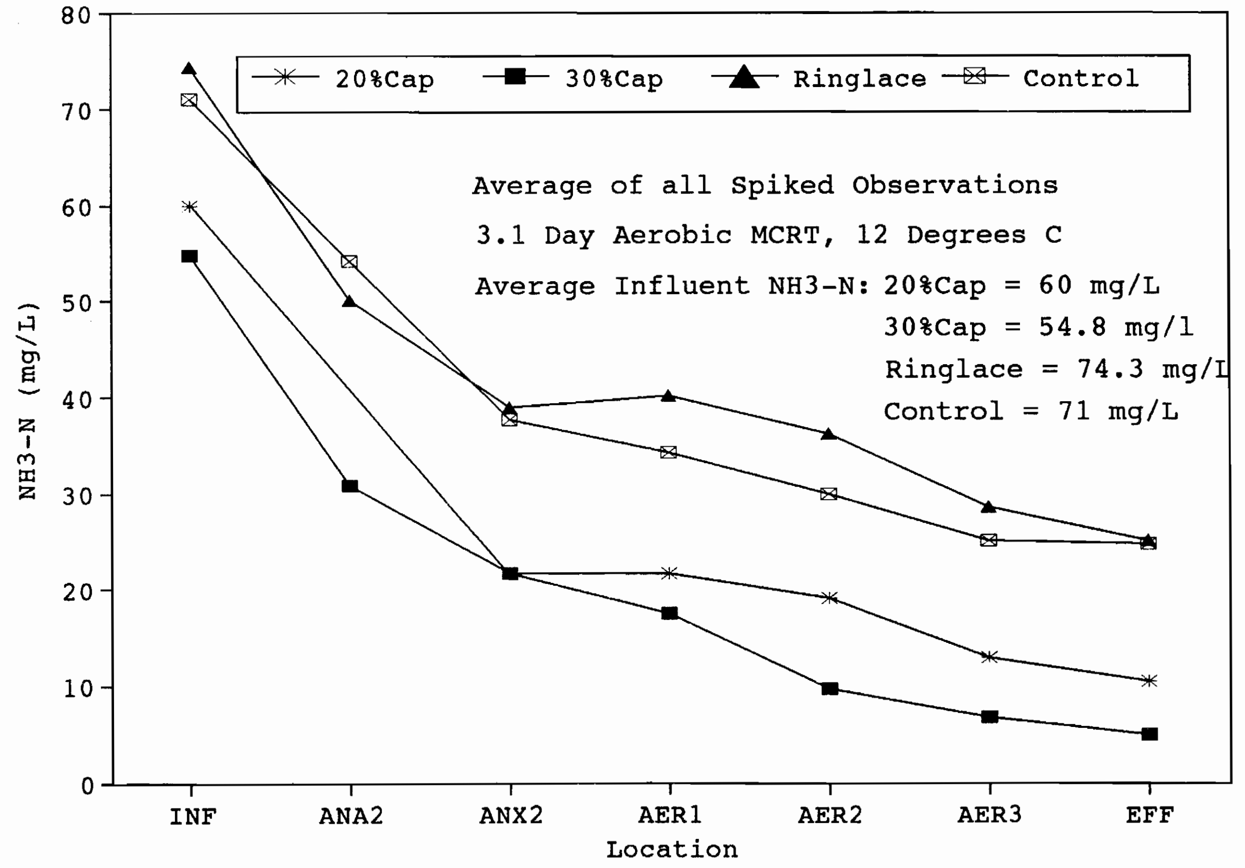


Figure 4-4. Ammonia Profile of Phase Two Experiments Under Spiked Conditions

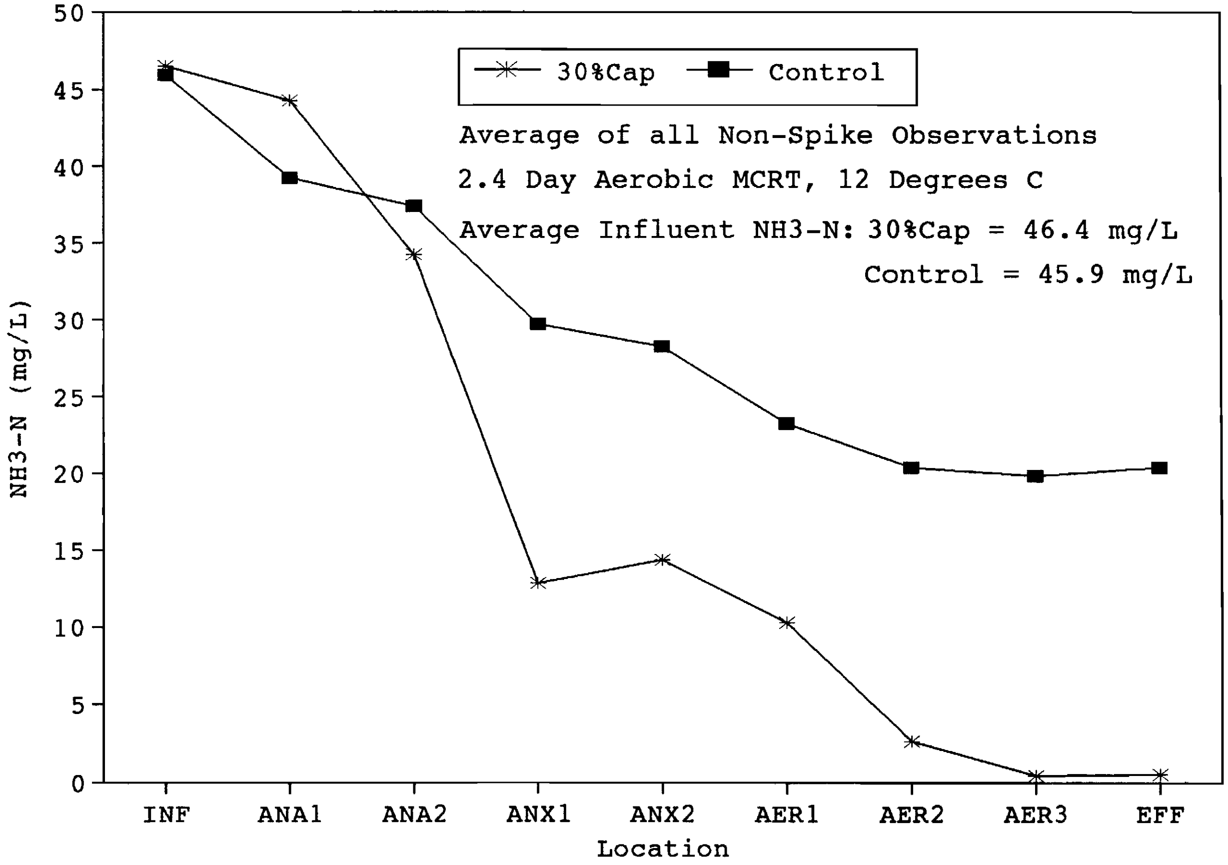


Figure 4-5. Ammonia Profile of Phase Three Experiments Under Normal Conditions

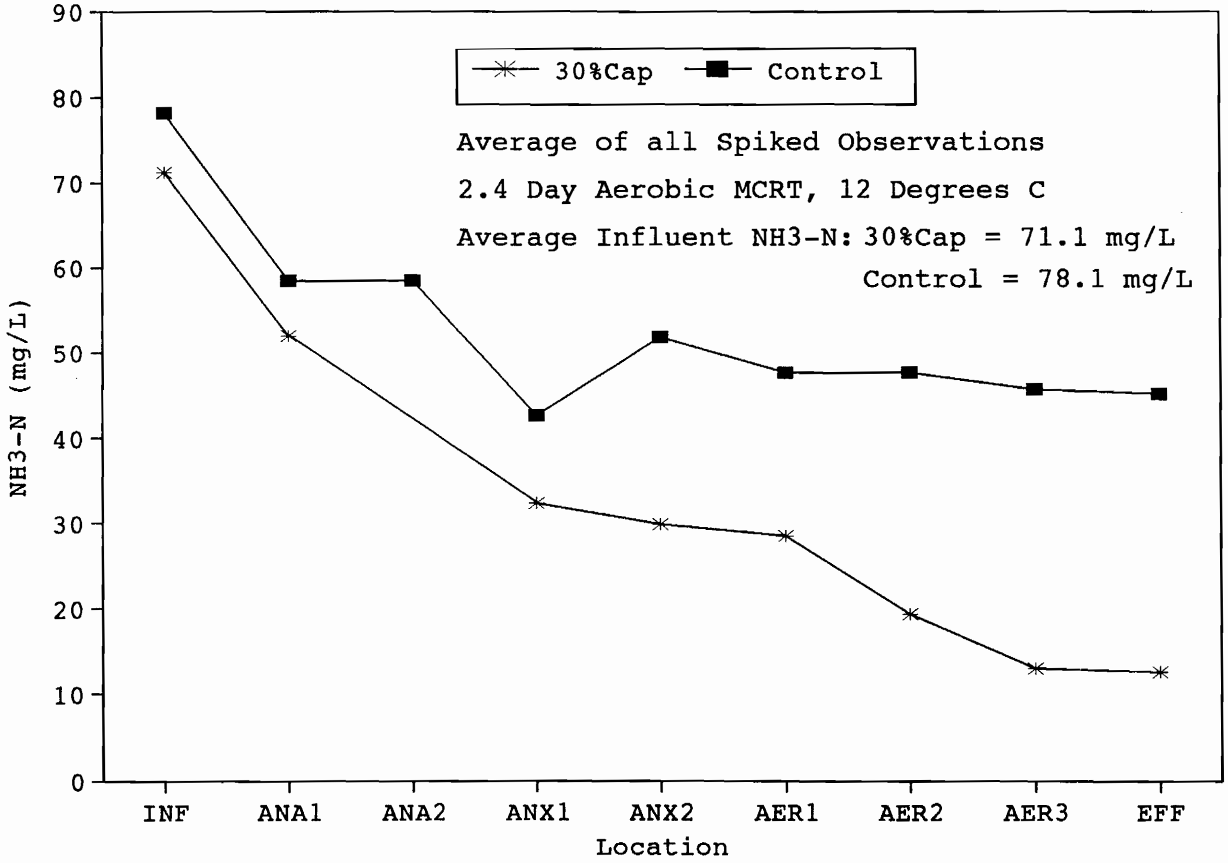


Figure 4-6. Ammonia Profile of Phase Three Experiments Under Spiked Conditions

Control, as can be seen in Table 4-1b. This result is reiterated in Table 4-3, where the paired t-test again shows that 30%Cap nitrified at a greater rate than the Control, with a 99% confidence level.

Phase Four. Figure 4-7 indicates that during phase 4 (normal), 30%Cap discharged less than 10 mg/L ammonia into the effluent while the Control discharged greater than 30 mg/L. Table 4-1a shows that under normal conditions, 30%Cap nitrified at a rate greater than four times that of the control. Table 4-2 demonstrates that, statistically, 30%Cap again nitrified at a greater rate than the Control, at a 99% confidence level.

Figure 4-8 shows that in phase 4 (spiked), both trains discharged even higher levels of ammonia, with 30%Cap effluent being greater than 20 mg/L and the Control's effluent being greater than 50 mg/L. Table 4-1b indicates that during phase 4 (spiked), 30%Cap nitrified nearly four times as much nitrogen as did the Control. This result is supported by Table 4-3 which notes that nitrification in 30%Cap was statistically higher than in the Control, at a 99% confidence level.

Looking at Tables 4-1a and 4-1b, throughout all phases the greatest and least amounts of nitrification in 30%Cap differed by only 33% and 31% for normal and spiked conditions, respectively. The greatest and least nitrification amounts for the Control differed by 87% and 78% for normal and spiked conditions, respectively. This quantifies the sharp drop in efficiency that the control experienced. The differences for both trains were greatest between phase 2 (3.1 day MCRT) and phase 4 (1.7 day MCRT). Ringlace also performed best during the 3.1 day MCRT.

Aerobic Cell Ammonia Oxidation

Another way of quantifying nitrification within the systems is depicted in Tables 4-4 and 4-5, where the ammonia oxidation rates, calculated as described in Appendix A, achieved in each aerobic cell under normal and spiked conditions are tabulated. The data for the 3.4 day (spiked) MCRT were obtained from Mitta (1994). On average, the percentage of ammonia oxidized under normal conditions in 20%Cap was 35%, 34% and 31% for cells one, two and three respectively. In 30%Cap, the percentages were 37%, 44% and 19%. In Ringlace, the percentages were 32%, 41% and 27%. In the Control, the percentages were 40%, 34% and 26%.

Table 4-4. Aerobic Cell Ammonia Oxidation Rates Under Normal Conditions

Aerobic MCRT	Location	Aerobic Cell 1	Aerobic Cell 2	Aerobic Cell 3
3.4 days	30%Cap (g/d)	3.6	3.4	0.9
	Ringlace (g/d)	3.1	2.9	1.9
	Control (g/d)	3.3	2.2	0.9
3.1 days	20%Cap (g/d)	2.8	2.7	2.5
	30%Cap (g/d)	4.7	4.6	2.5
	Ringlace (g/d)	2.9	5.1	3.4
	Control (g/d)	3.8	3.5	3.0
2.4 days	30%Cap (g/d)	3.1	4.0	1.1
	Control (g/d)	1.3	1.1	1.4
1.7 days	30%Cap (g/d)	2.0	3.5	2.5
	Control (g/d)	0.5	0.5	0.3

Table 4-5. Aerobic Cell Ammonia Oxidation Rates Under Spiked Conditions

Aerobic MCRT	Location	Aerobic Cell 1	Aerobic Cell 2	Aerobic Cell 3
3.4 days	30%Cap (g/d)	3.8	3.7	2.0
	Ringlace (g/d)	1.4	3.6	2.1
	Control (g/d)	2.1	2.6	1.8
3.1 days	20%Cap (g/d)	0	2.9	7.0
	30%Cap (g/d)	1.9	7.6	4.2
	Ringlace (g/d)	2.7	4.4	4.5
	Control (g/d)	3.7	3.7	4.3
2.4 days	30%Cap (g/d)	3.0	3.9	4.2
	Control (g/d)	ND	ND	ND
1.7 days	30%Cap (g/d)	2.9	3.7	2.9
	Control (g/d)	0.9	0.9	0.8

ND indicates that no data points were taken.

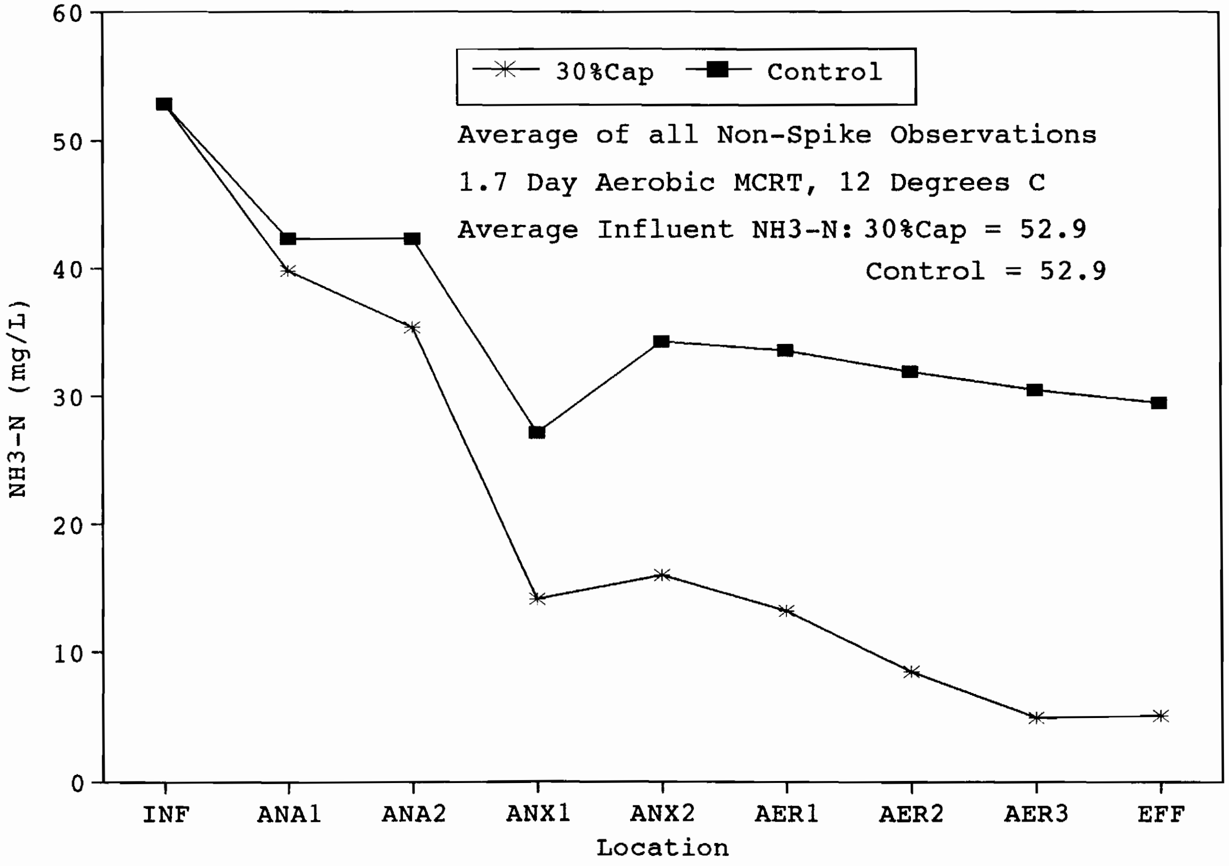


Figure 4-7. Ammonia Profile of Phase Four Experiments Under Normal Conditions

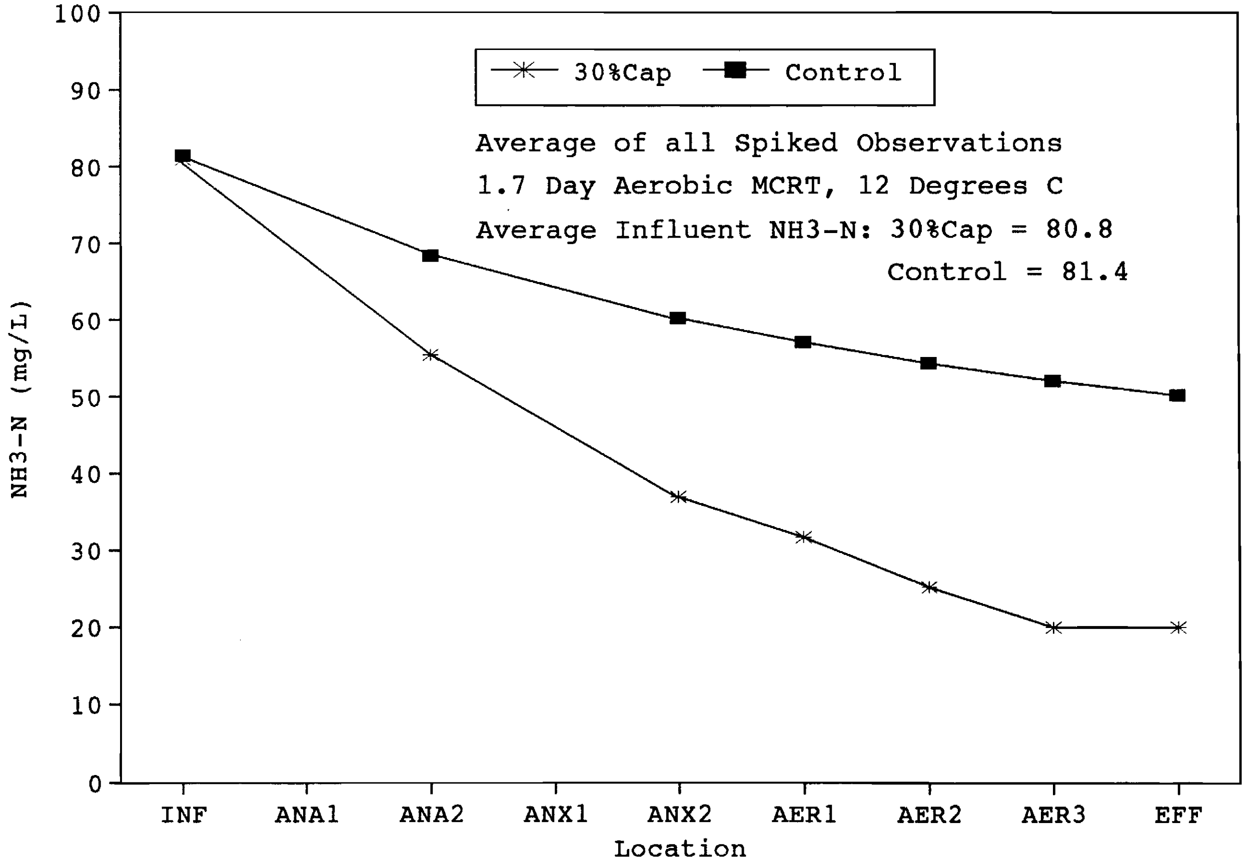


Figure 4-8. Ammonia Profile of Phase Four Experiments Under Spiked Conditions

Under spiked conditions for 20%Cap, the percentages were 0%, 30% and 70%, in 30%Cap the percentages were 28%, 42% and 30%, in Ringlace the percentages were 21%, 45% and 34%, and in the Control, the percentages were 33%, 36% and 31%. Again, as seen in Tables 4-1a and 4-1b, the greatest amount of total nitrification took place in 30%Cap in all phases.

Nitratification

Nitratification, or the oxidation of NO_2^--N to NO_3^--N, also was determined through mass balance calculations. Table 4-6a presents the calculated nitratification values for each MCRT under normal conditions. Table 4-6b presents nitratification values under spiked conditions. 30%Cap achieved the greatest degree of nitratification and, as was the case for nitrification, the largest difference between the greatest and least nitratification values occurs between the 3.1 and 1.7 day MCRT's. The average drop in nitratification in 30%Cap was 32% under normal conditions, and 30% under spiked conditions. In the Control, the drops were 88% and 78%, respectively. These values are nearly identical to those calculated for nitrification, as shown in Tables 4-1a and 4-1b. Ringlace also performed best at the 3.1 day MCRT.

DENITRIFICATION

Denitrification was also studied extensively, and mass balance calculations were performed to determine values for System Denitrification, Denitrification in the Anoxic Zone, Denitrification in the Aerobic Zone, and Denitrification in each Aerobic Cell.

System Denitrification

Mass Balance. Tables 4-7a and 4-7b summarize the values calculated for system denitrification under normal and spiked conditions. The results are similar to those seen for nitrification and nitratification, with 30%Cap achieving greater levels of denitrification throughout the system. An exception occured during the 3.4 day MCRT experiment, where Ringlace outperformed 30%Cap and the Control by a slight margin under normal conditions. Also, the greatest difference in denitrification occurred between the 3.1 and 1.7 day MCRT's under both conditions. Denitrification decreased 37% and 36% under normal and spiked conditions in 30%Cap, while in the Control it dropped 88% and 79% respectively. Ringlace also performed best at the 3.1

Table 4-6a. Effect of IFAS on Nitratification Under Normal Conditions
Nitrite to Nitrate

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	7.8	7.9	6.4
ΔControl	N/A	1.4	1.5	N/A
3.1	7.9	11.8	11.2	9.9
ΔControl	(2.0)	1.9	1.3	N/A
2.4	ND	8.2	ND	3.6
ΔControl	N/A	4.6	N/A	N/A
1.7	ND	8.0	ND	1.2
ΔControl	N/A	6.8	N/A	N/A

Table 4-6b. Effect of IFAS on Nitratification Under Spiked Conditions
Nitrite to Nitrate

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	ND	ND	ND
ΔControl	N/A	N/A	N/A	N/A
3.1	8.9	13.5	11.5	11.4
ΔControl	(2.5)	2.1	0.1	N/A
2.4	ND	11.0	ND	4.0
ΔControl	N/A	7.0	N/A	N/A
1.7	ND	9.4	ND	2.5
ΔControl	N/A	6.9	N/A	N/A

ND indicates that no data points were taken.
N/A indicates that the analysis is not applicable

Table 4-7a. Effect of IFAS on System Denitrification Under Normal Conditions

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	5.8	6.1	4.5
ΔControl	N/A	1.3	1.6	N/A
3.1	6.6	10.0	9.2	8.4
ΔControl	(1.8)	1.6	0.8	N/A
2.4	ND	6.2	ND	3.0
ΔControl	N/A	3.2	N/A	N/A
1.7	ND	6.3	ND	1.0
ΔControl	N/A	5.3	N/A	N/A

Table 4-7b. Effect of IFAS on System Denitrification Under Spiked Conditions

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	ND	ND	ND
ΔControl	N/A	N/A	N/A	N/A
3.1	7.0	10.9	10.0	9.8
ΔControl	(2.8)	1.1	0.2	N/A
2.4	ND	7.9	ND	3.4
ΔControl	N/A	4.5	N/A	N/A
1.7	ND	7.0	ND	2.1
ΔControl	N/A	4.9	N/A	N/A

ND indicates that no data points were taken.
N/A indicates that the analysis is not applicable

day MCRT. The difference in denitrification between 30%Cap and the Control increased as the aerobic MCRT decreased because of limited nitrification.

NO$_x$-N Profiles. Figures 4-9 through 4-15 show the concentration of NO_2^--N and NO_3^--N throughout each system during the four phases for both normal and spiked conditions. The quantity of NO_x in a given cell was indicative of the net result of a series of biological reactions which occurred in that cell, and the drop in NO_x seen in the profile was a measure of the ability of a system to denitrify.

As seen in Figure 4-9, 30%Cap maintained a higher quantity (as much as 3 mg/L) of NO_x-N than did Ringlace and the Control. However, the influent NH_3-N for 30%Cap, which is a measure of how much nitrogen is available for nitrification and subsequently denitrification, was approximately 6 mg/L higher than Ringlace and the Control. NO_x-N data for Phase One under spiked conditions was not available.

Figure 4-10 shows the NO_x-N profile of Phase two (normal). 20%Cap achieved a lower quantity of NO_x-N than did the other trains, but the influent NH_3-N was also lower. 30%Cap and the Control achieved the same levels of NO_x-N, and had approximately the same influent NH_3-N levels. Ringlace had the lowest influent NH_3-N, but had the highest effluent NO_x-N levels.

Figure 4-11 shows the NO_x-N profile of Phase Two (spiked). In this instance, 20%Cap and 30%Cap had the lowest influent NH_3-N, but had the highest effluent NO_x-N. Ringlace achieved the lowest level of NO_x-N even though it had the highest influent ammonia level. The Control, with a higher influent NH_3-N level, also achieved a lower NO_x-N concentration than 30%Cap (approximately 5 mg/L lower).

As can be seen in Figures 4-12 and 4-13, despite the fact that influent ammonia levels for both trains in phase three were approximately equal, 30%Cap had a significantly higher level of NO_x-N in the effluent than did the Control during normal and spiked conditions. The effect was the greatest under spiked conditions. The possible reasons for these differences will be discussed in the next chapter.

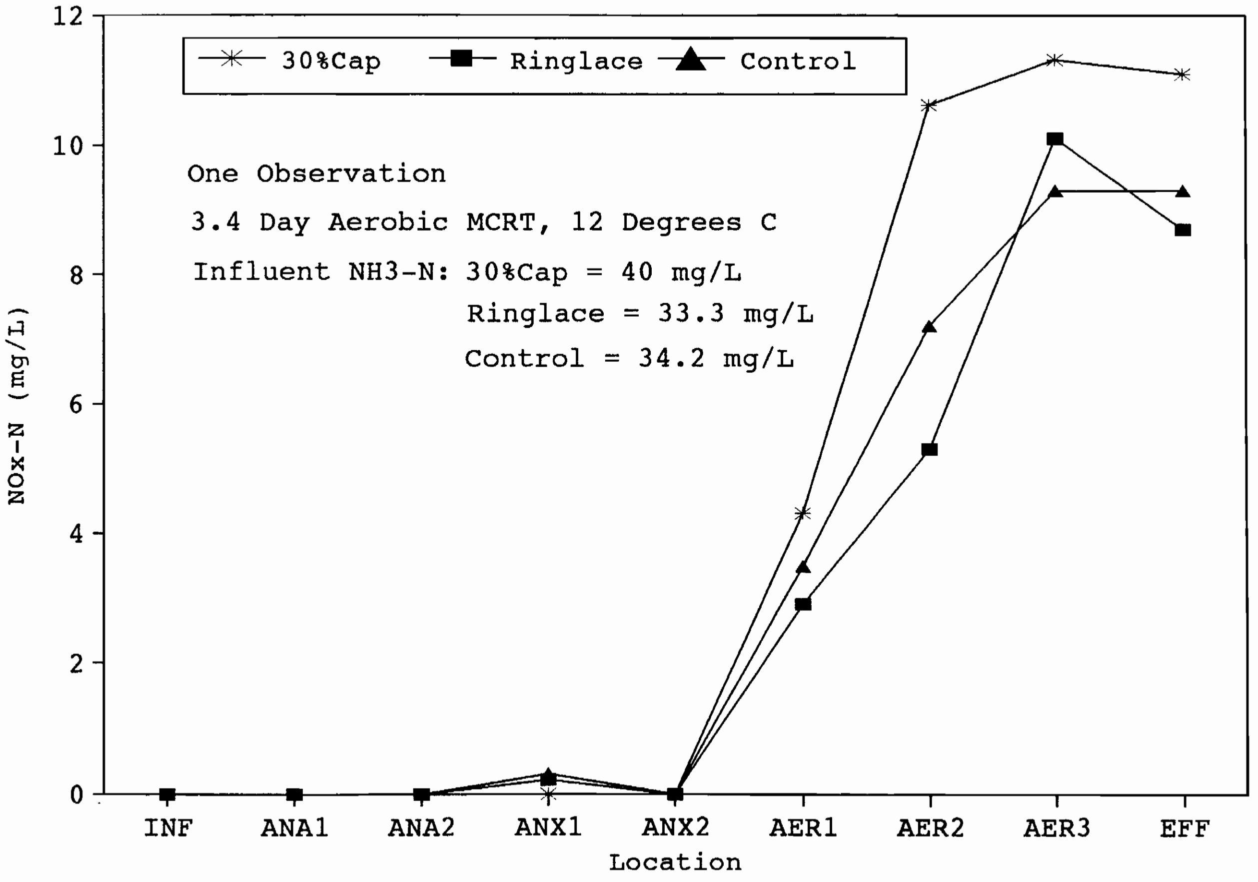


Figure 4-9. NOx-N Profile of Phase One Experiments Under Normal Conditions

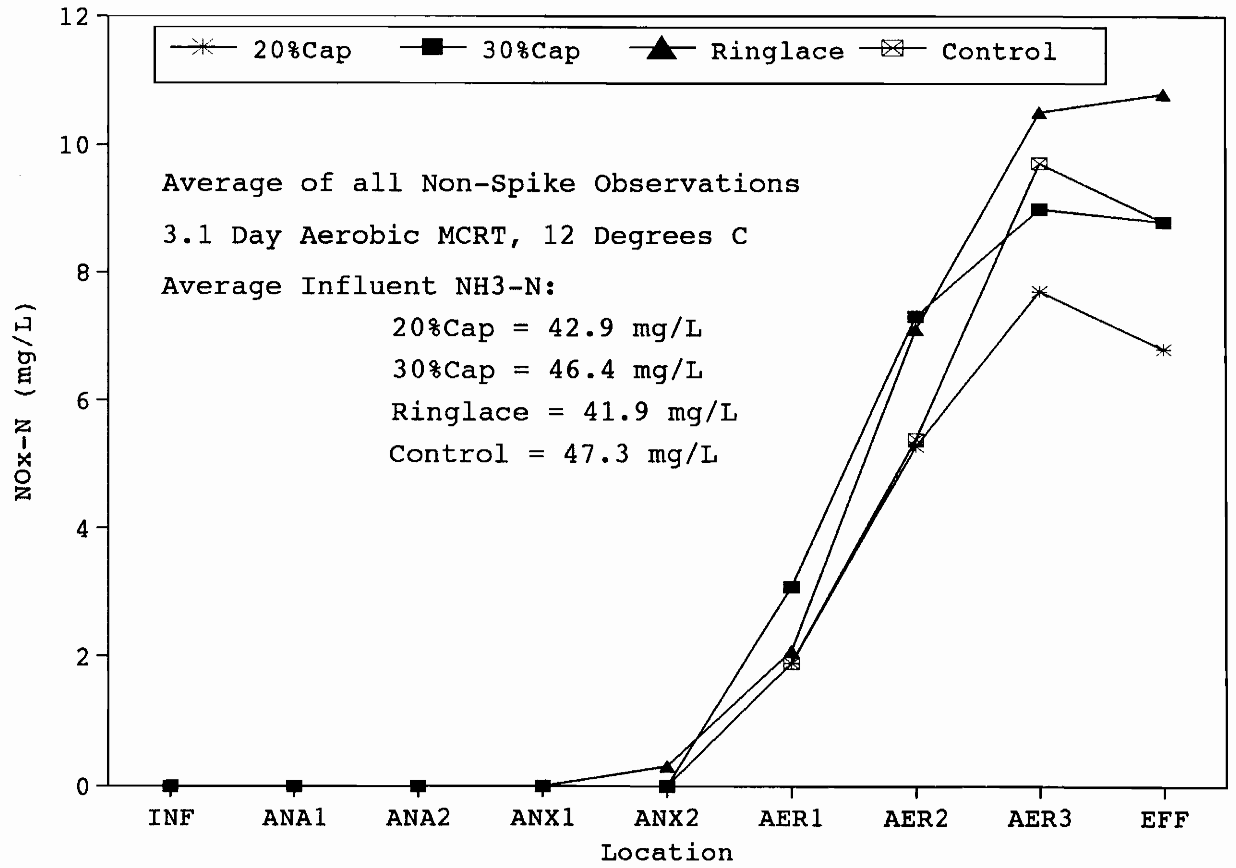


Figure 4-10. NOx-N Profile of Phase Two Experiments Under Normal Conditions

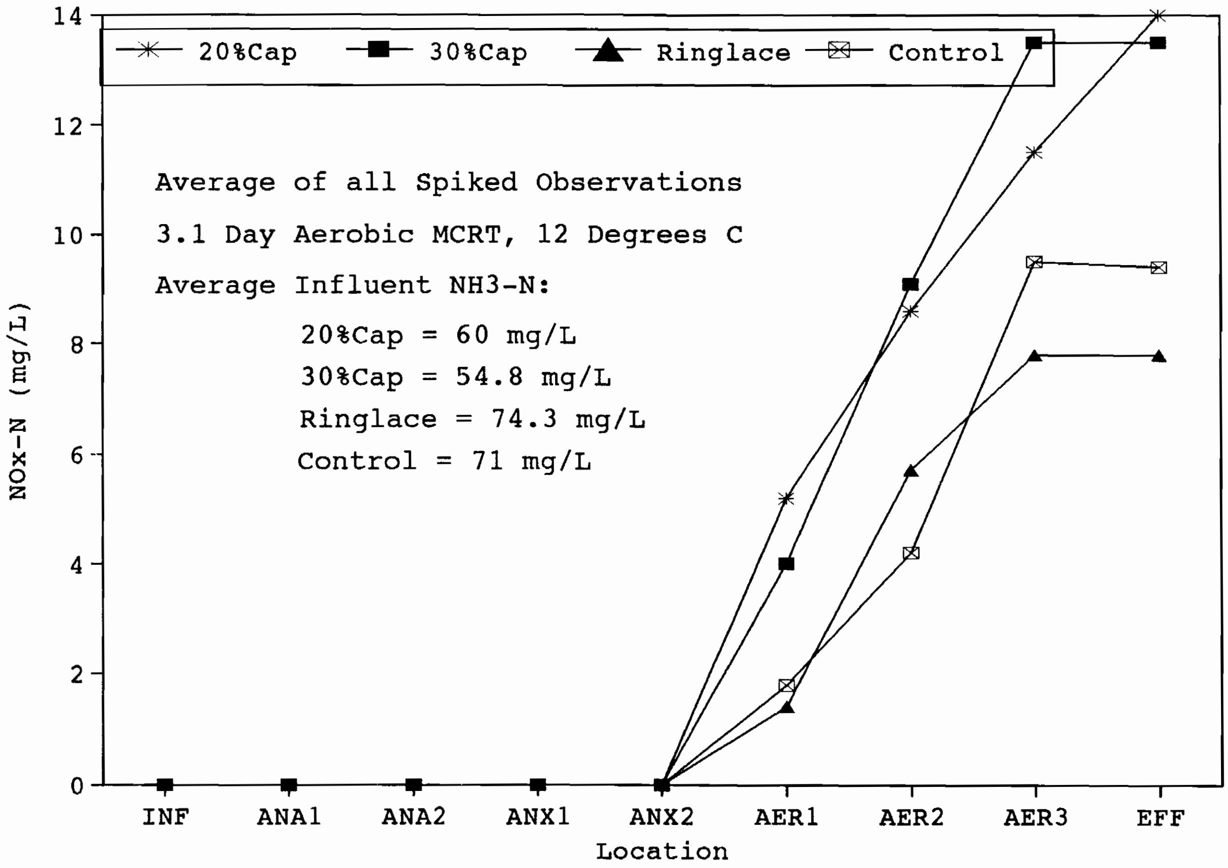


Figure 4-11. NOx-N Profile of Phase Two Experiments Under Spiked Conditions

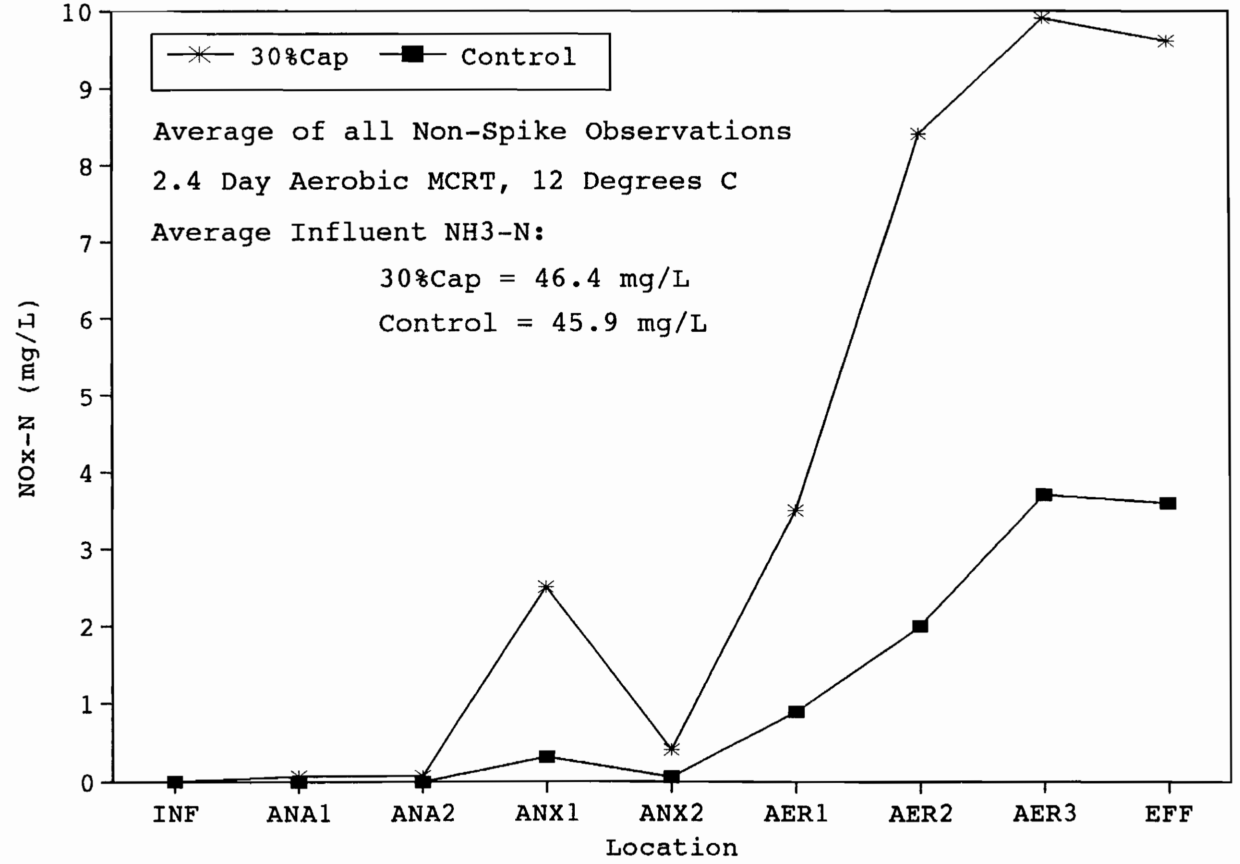


Figure 4-12. NOx-N Profile of Phase Three Experiments Under Normal Conditions

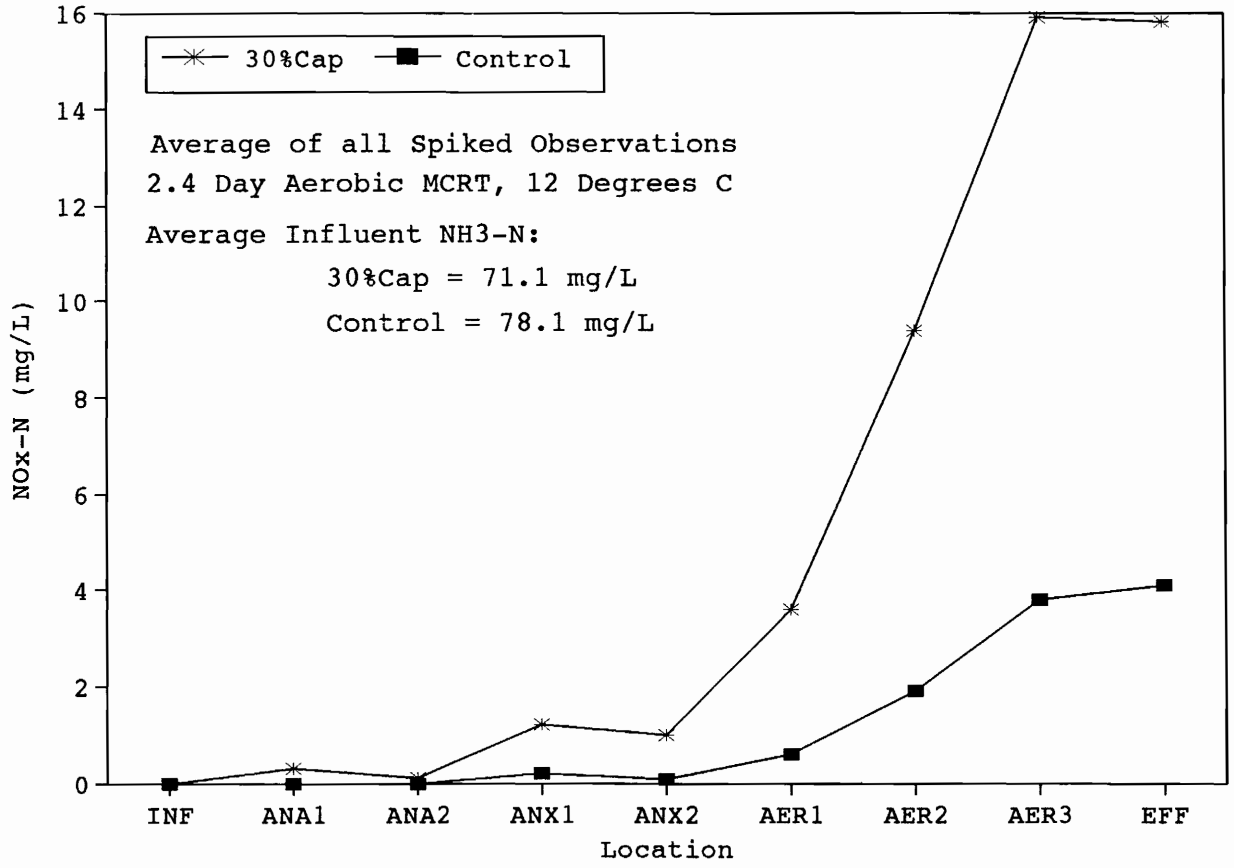


Figure 4-13. NOx-N Profile of Phase Three Experiments Under Spiked Conditions

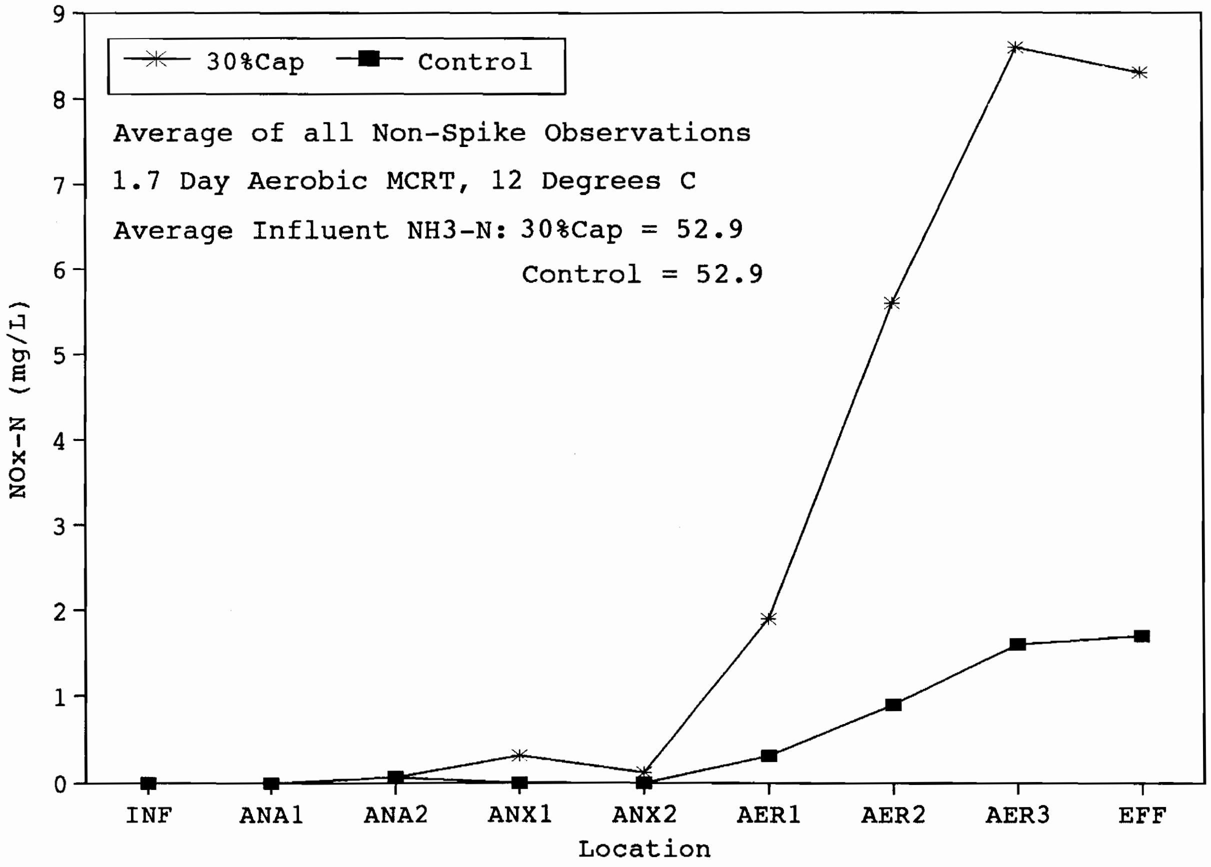


Figure 4-14. NOx-N Profile of Phase Four Experiments Under Normal Conditions

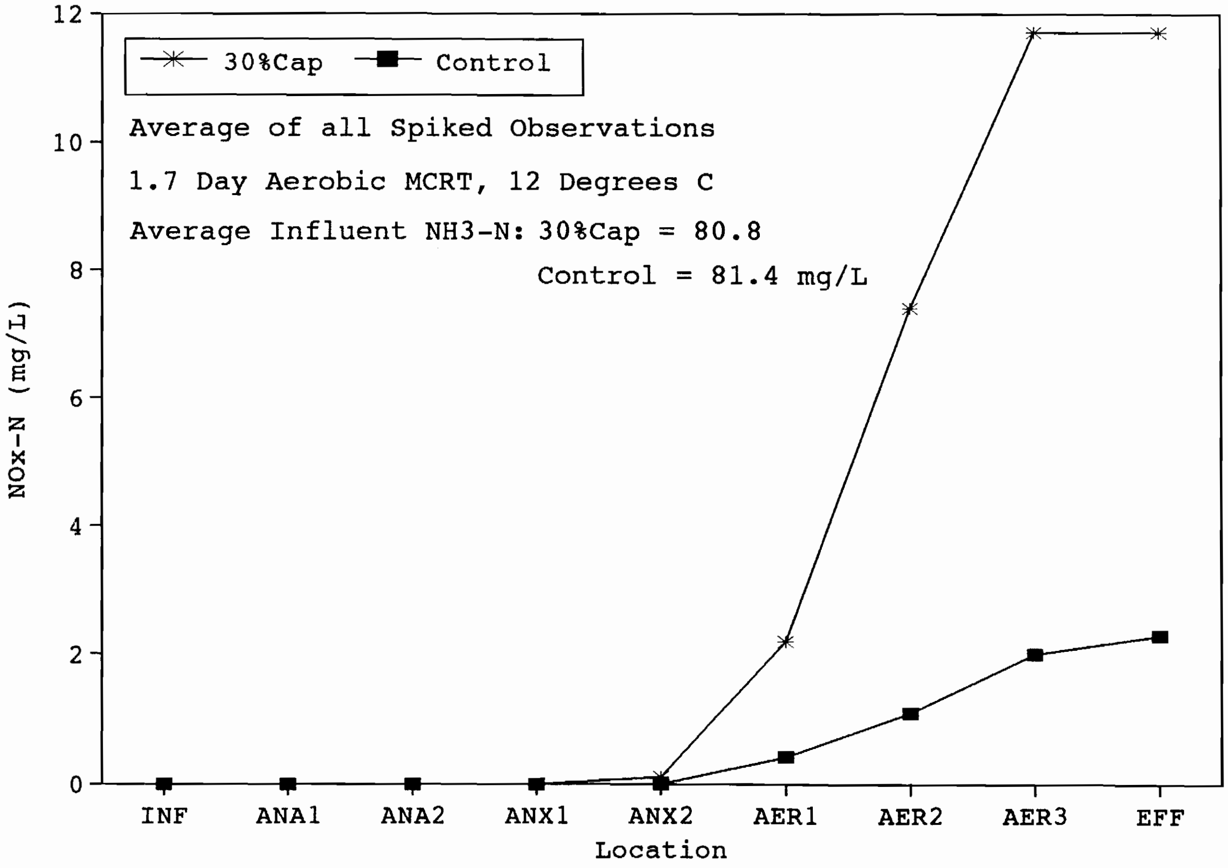


Figure 4-15. NOx-N Profile of Phase Four Experiments Under Spiked Conditions

Figures 4-14 and 4-15 show the NO_x-N profiles for phase 4 during normal and spiked conditions, respectively. They also show the trend seen during phase 3, where 30%Cap has a greater amount of effluent NO_x-N than the Control. Again, this was despite the fact that the influent NH_3-N levels were nearly equal, and the effect was greatest under spiked conditions. Reasons for this difference will be discussed in the following chapter.

Denitrification in the Anoxic Zone

A mass balance approach was again used to calculate the amounts of denitrification occurring in the anoxic zones of each system. Table 4-8a summarizes the effects of IFAS on denitrification in the anoxic zone under normal conditions. During phase 1, 30%Cap denitrified to a greater extent than Ringlace and the Control, but only by an amount less than 1 g/d. During phase 2, 30%Cap denitrified to a lesser extent than Ringlace and the Control, but more than 20%Cap. During phase 3, 30%Cap maintained a high level of denitrification while the Control did not; the difference being 2.6 g/d. The same trend is magnified during phase 4 when the difference between 30%Cap and the Control is 3.7 g/d.

Table 4-8b shows denitrification during spiked conditions. Phase 1 did not have a spiked condition. Phase 2 shows that 30%Cap denitrified more than 20%Cap, which denitrified more than the Control and Ringlace. Phases 3 and 4 show that 30%Cap maintained its high level of denitrification while the Control steadily lost its ability to denitrify, almost completely.

In all trains during both normal and spiked conditions, denitrification in the anoxic zone was greater than 99% complete, indicating that denitrification was limited by the amount of nitrification which occured in the aerobic cells. The amount of nitrification in the aerobic cells controled the NO_x concentration in the recycle flows to the anoxic zones, and thus was the limiting factor in anoxic denitrification.

Denitrification in the Aerobic Zone

The effects that IFAS had on denitrification in the aerobic zone are shown in Tables 4-9a, 4-9b, 4-10a and 4-10b. A mass balance approach was used to calculate the values in Tables 4-9a and 4-9b; a detailed description of the method is available in Appendix A. Tables 4-10a and 4-10b were calculated by dividing denitrification the aerobic zone by system nitrification. As can be seen

Table 4-8a. Effect of IFAS on Denitrification in the Anoxic Zone Under Normal Conditions

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	4.7	4.2	3.9
ΔControl	N/A	0.8	0.3	N/A
3.1	3.2	3.7	3.9	4.0
ΔControl	(0.8)	(0.3)	(0.1)	N/A
2.4	ND	3.8	ND	1.2
ΔControl	N/A	2.6	N/A	N/A
1.7	ND	4.5	ND	0.8
ΔControl	N/A	3.7	N/A	N/A

Table 4-8b. Effect of IFAS on Denitrification in the Anoxic Zone Under Spiked Conditions

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	ND	ND	ND
ΔControl	N/A	N/A	N/A	N/A
3.1	4.8	5.6	3.2	3.9
ΔControl	0.9	1.7	(0.7)	N/A
2.4	ND	5.6	ND	1.5
ΔControl	N/A	4.1	N/A	N/A
1.7	ND	5.7	ND	0.9
ΔControl	N/A	4.8	N/A	N/A

ND indicates that no data points were taken.
N/A indicates that the analysis is not applicable

Table 4-9a. Effect of IFAS on Denitrification in the Aerobic Zone Under Normal Conditions

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	1.1	2.0	0.7
ΔControl	N/A	0.4	1.3	N/A
3.1	3.4	6.2	5.3	4.4
ΔControl	(1.0)	1.8	0.9	N/A
2.4	ND	2.4	ND	1.8
ΔControl	N/A	0.6	N/A	N/A
1.7	ND	1.7	ND	0.1
ΔControl	N/A	1.6	N/A	N/A

Table 4-9b. Effect of IFAS on Denitrification in the Aerobic Zone Under Spiked Conditions

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	ND	ND	ND
ΔControl	N/A	N/A	N/A	N/A
3.1	2.2	5.4	6.7	5.9
ΔControl	(3.7)	(0.5)	0.8	N/A
2.4	ND	2.3	ND	1.9
ΔControl	N/A	0.4	N/A	N/A
1.7	ND	1.4	ND	1.2
ΔControl	N/A	0.2	N/A	N/A

ND indicates that no data points were taken.
N/A indicates that the analysis is not applicable

Table 4-10a. Percentage of Nitrate Denitrified in Aerobic Zone Under Normal Conditions

Aerobic MCRT (days)	20%Cap	30%Cap	Ringlace	Control
3.4	ND	14%	25%	11%
ΔControl	N/A	3%	14%	N/A
3.1	43%	53%	46%	43%
ΔControl	0%	10%	3%	N/A
2.4	ND	29%	ND	47%
ΔControl	N/A	(18%)	N/A	N/A
1.7	ND	21%	ND	8%
ΔControl	N/A	13%	N/A	N/A

Table 4-10b. Percentage of Nitrate Denitrified in Aerobic Zone Under Spiked Conditions

Aerobic MCRT (days)	20%Cap	30%Cap	Ringlace	Control
3.4	ND	ND	ND	ND
ΔControl	N/A	N/A	N/A	N/A
3.1	22%	39%	58%	50%
ΔControl	(28%)	(11%)	8%	N/A
2.4	ND	21%	ND	45%
ΔControl	N/A	(24%)	N/A	N/A
1.7	ND	15%	ND	46%
ΔControl	N/A	(31%)	N/A	N/A

ND indicates that no data points were taken.
N/A indicates that the analysis is not applicable

from Table 4-9a, Ringlace denitrified more in the aerobic zone during phase 1 (normal) than did 30%Cap or the Control. During phase 1 the data points were nearly all lower than during any other Phase. The lack of data points does lend a high uncertainty to these numbers, however. During phase 2, 30%Cap clearly denitrified more than the other trains, the value being 0.9 g/d higher than Ringlace, which denitrified more than the Control and 20%Cap. 20%Cap did not denitrify nearly as well as the others, being 1 g/d lower than the Control. During phases 3 and 4, denitrification decreased in both 30%Cap and the Control as the MCRT was lowered. 30%Cap, however, seemed to be able to maintain its ability to denitrify under these conditions better than the Control. 30%Cap denitrified 0.6 g/d more than the Control during Phase 3, and 1.6 g/d more than the Control during phase 4.

Table 4-9b sets forth the same type of information as 4-9a, but for the spiked experiments. During phase 1 there were no spiked experiments. During phase 2, Ringlace denitrified a greater quantity (0.8 g/d) than the Control and 1.3 g/d more than 30%Cap. 20%Cap denitrified to a much lesser extent. As during the normal conditions, phases 3 and 4 had decreases in overall denitrification in the aerobic zones the changes being 0.9 g/d in 30%Cap and 0.7 g/d in the Control.

Table 4-10a shows that the percentages of denitrification that took place in the aerobic zone generally followed the same trends seen when studying mass quantities of denitrification as discussed in previous paragraphs, with some exceptions. These exceptions occurred during the 2.4 and 1.7 day MCRTs during both normal and spiked conditions, where the Control achieved limited nitrification. As a result, the denitrification that occurred in the aerobic zone of the Control was a larger percentage of the total nitrification.

Denitrification in each Aerobic Cell

Tables 4-11a and 4-11b summarize the denitrification which occurred in each of the aerobic cells during all phases, calculated as described in Appendix A. Table 4-11a shows that during phase 1 (normal), 30%Cap had 55% of the denitrification taking place in cell 1, 0% in cell 2, and 45% in cell 3, while Ringlace had 40%, 60% and 0% and the Control had 100%, 0% and 0% respectively. During phase 2, 20%Cap had 38% denitrification in cell 1, 41% in cell 2 and 21% in cell 3, 30%Cap had 63%, 24% and 13%, Ringlace had 55%, 30% and 15% while the Control had 68%, 32% and 0% respectively. During phase 3, the percentages were, for 30%Cap, 42%, 42% and 16%, and for the

Table 4-11a. Aerobic Cell Denitrification Rates Under Normal Conditions

Aerobic MCRT	Location	Aerobic Cell 1	Aerobic Cell 2	Aerobic Cell 3
3.4 days	30%Cap (g/d)	0.6	0	0.5
	Ringlace (g/d)	0.8	1.2	0
	Control (g/d)	0.7	0	0
3.1 days	20%Cap (g/d)	1.3	1.4	0.7
	30%Cap (g/d)	3.9	1.5	0.8
	Ringlace (g/d)	2.9	1.6	0.8
	Control (g/d)	3.0	1.9	0
2.4 days	30%Cap (g/d)	1	1	0.4
	Control (g/d)	0.7	0.5	0.6
1.7 days	30%Cap (g/d)	0.6	0.7	0.4
	Control (g/d)	0.04	0.03	0.03

Table 4-11b. Aerobic Cell Denitrification Rates Under Spiked Conditions

Aerobic MCRT	Location	Aerobic Cell 1	Aerobic Cell 2	Aerobic Cell 3
3.1 days	20%Cap (g/d)	ND	ND	2.2
	30%Cap (g/d)	1.3	1.1	3.0
	Ringlace (g/d)	2.8	2.0	1.9
	Control (g/d)	2.5	1.7	1.7
2.4 days	30%Cap (g/d)	1.7	0.2	0.4
	Control (g/d)	ND	ND	ND
1.7 days	30%Cap (g/d)	0.8	0.4	0.2
	Control (g/d)	0.4	0.4	0.4

ND indicates that no data points were taken.

Control, 39%, 28% and 33%. During phase 4, 30%Cap had values of 35%, 41% and 24% and the Control had 40%, 30% and 30%. These numbers indicated a slight trend toward increased denitrification in aerobic cells 2 and 3 at lower MCRT's.

Under spiked conditions, the trend seen under normal conditions did not repeat. Table 4-11b shows that during phase 2, 30%Cap denitrified an average of 24% in cell 1, 20% in cell 2 and 56% in cell 3 while Ringlace had 42%, 30% and 28% and the Control denitrified 42%, 29% and 29%, respectively. During phase 3, the percentages were, for 30%Cap, 73%, 11% and 16%. There was no data for the Control under spiked conditions. During phase 4, 30%Cap denitrified 57%, 28% and 15% while the Control denitrified 34%, 33% and 33%.

SLUDGE PRODUCTION AND YIELD

Also of concern during this research was the effect, if any, that IFAS would have on sludge production and sludge yield. Tables 4-12a summarizes the values of sludge production while Table 4-12b shows the calculated values of sludge yield. The equations used to calculate both values are described in detail in Appendix A.

As can be seen in Table 4-12a, during phase 1, both 30%Cap and Ringlace produced less sludge than the Control - 4.2 g/d and 2.0 g/d respectively. Again, the lack of data points in Phase 1 increases the uncertainty of these numbers. During phase 2 the situation was reversed, with 30%Cap producing 1.3 g/d more sludge than the Control, while 20%Cap and Ringlace produced slightly less than the Control. During phase 3, 30%Cap produced an average of 9.1 g/d less sludge than the Control, and during Phase 4, it produced 4.4 g/d less than the Control. This seems to indicate that at lower MCRT's, the effect of IFAS on sludge production becomes more pronounced. However, as can be seen, the values calculated for 30%Cap are quite variable; the possible reasons for this are discussed in the following chapter.

Table 4-12b shows the effects of IFAS on sludge yield, and gives another perspective on the sludge production values. During phase 1, the value calculated for 30%Cap was 0.3 mg Biomass/mg COD lower than that of the Control, while Ringlace was 0.2 lower. In phase 2, the Control was only exceeded by 20%Cap; the value for 30%Cap was 0.6 lower than the Control and the value for Ringlace was 0.4 lower. The lower value for 30%Cap is in contrast to the sludge production values presented in the previous paragraph. In phase 3, 30%Cap again had a calculated yield 0.4 below that

Table 4-12a. Effect of IFAS on Sludge Production

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	26.5	28.7	30.7
ΔControl	N/A	(4.2)	(2.0)	N/A
3.1	33.4	34.9	32.3	33.6
ΔControl	(0.2)	1.3	(1.3)	N/A
2.4	ND	(26.5)	ND	35.6
ΔControl	N/A	9.1	N/A	N/A
1.7	ND	(34.8)	ND	39.2
ΔControl	N/A	4.4	N/A	N/A

Table 4-12b. Effect of IFAS Sludge Yield

Aerobic MCRT (days)	20%Cap (g/d)	30%Cap (g/d)	Ringlace (g/d)	Control (g/d)
3.4	ND	0.31	0.32	0.34
ΔControl	N/A	(0.03)	(0.02)	N/A
3.1	0.41	0.34	0.36	0.40
ΔControl	0.1	(0.06)	(0.04)	N/A
2.4	ND	0.31	ND	0.35
ΔControl	N/A	(0.04)	N/A	N/A
1.7	ND	0.36	ND	0.44
ΔControl	N/A	(0.08)	N/A	N/A

ND indicates that no data points were taken.
N/A indicates that the analysis is not applicable

of the Control, and in phase 4, it was 0.8 mg/mg less than the Control. These values generally support the sludge production values of the previous paragraph.

COD UPTAKE

Figures 4-16 through 4-19 show the average COD profiles through all trains during Phases 1-4. Because COD spikes were not applied with the urea spikes, only "normal" conditions are considered. Figure 4-16 indicates that there was essentially no difference in COD removal capacities between the three trains during phase 1. Although 30%Cap had a higher influent COD level than Ringlace or the Control, the profile suggests that during the anoxic and aerobic zones (where almost all of the COD was stabilized) the COD uptakes were almost identical. Since only one data set was available, this result should be considered as preliminary.

Figure 4-17 indicates that during phase 2 there was very little difference in COD uptake ability of the four trains. 30%Cap seemed to show a slight advantage, with its influent COD being second highest of the four but its effluent COD being third highest.

Figure 4-18 shows a very small difference. 30%Cap has the higher influent COD level of the two, yet managed to attain a lower effluent COD level. This trend is seen in Figure 4-19 as well. 30%Cap achieved a lower effluent COD value despite the fact that the influent levels were virtually equal.

When comparing all four figures side by side it can be seen that the effluent COD level attained by all trains during all phases seems to be in the range of 40 to 50 mg/L. This is despite the fact that the influent COD values ranged from 300 to 500 mg/L through the different phases. This indicates that during each phase, the trains were all COD limited and removal was virtually complete.

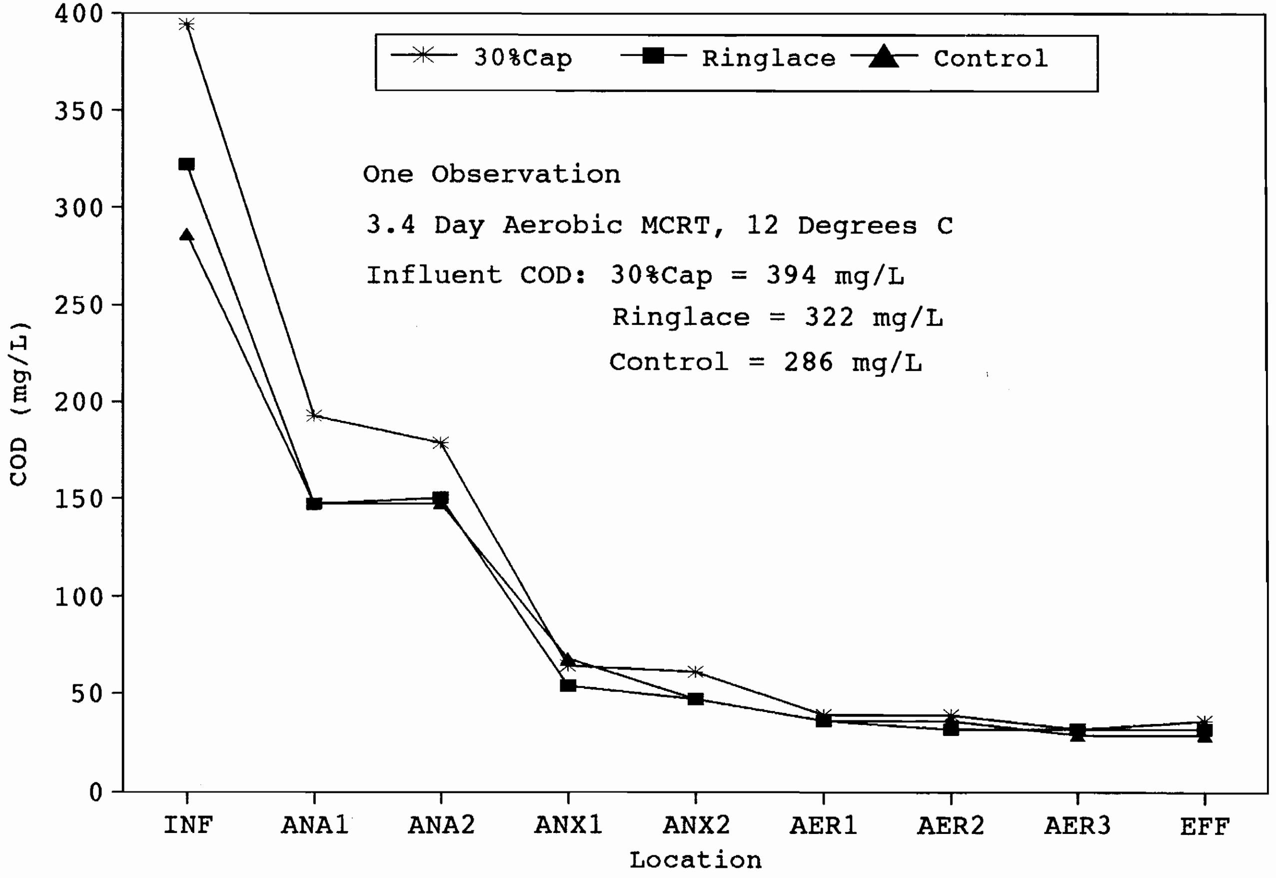


Figure 4-16. COD Profile of Phase One Experiments

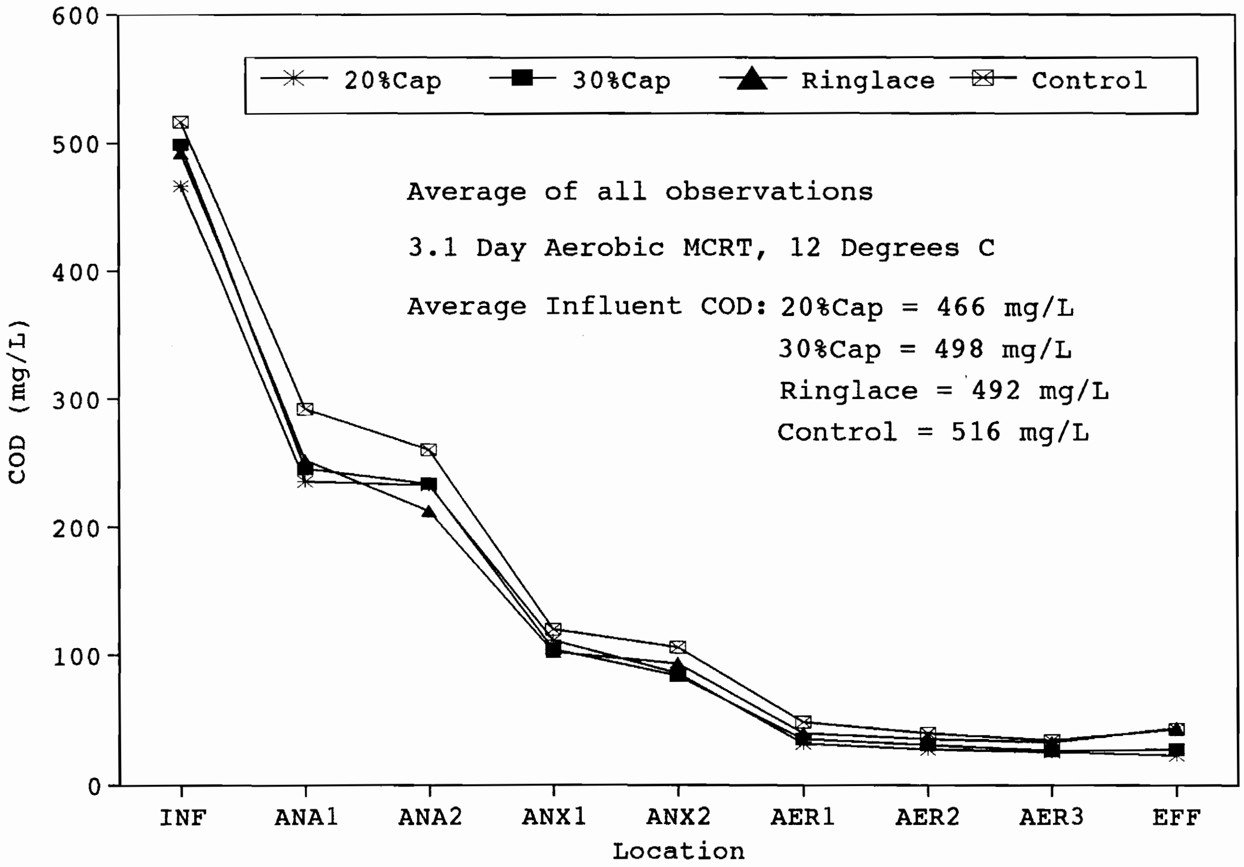


Figure 4-17. COD Profile of Phase Two Experiments

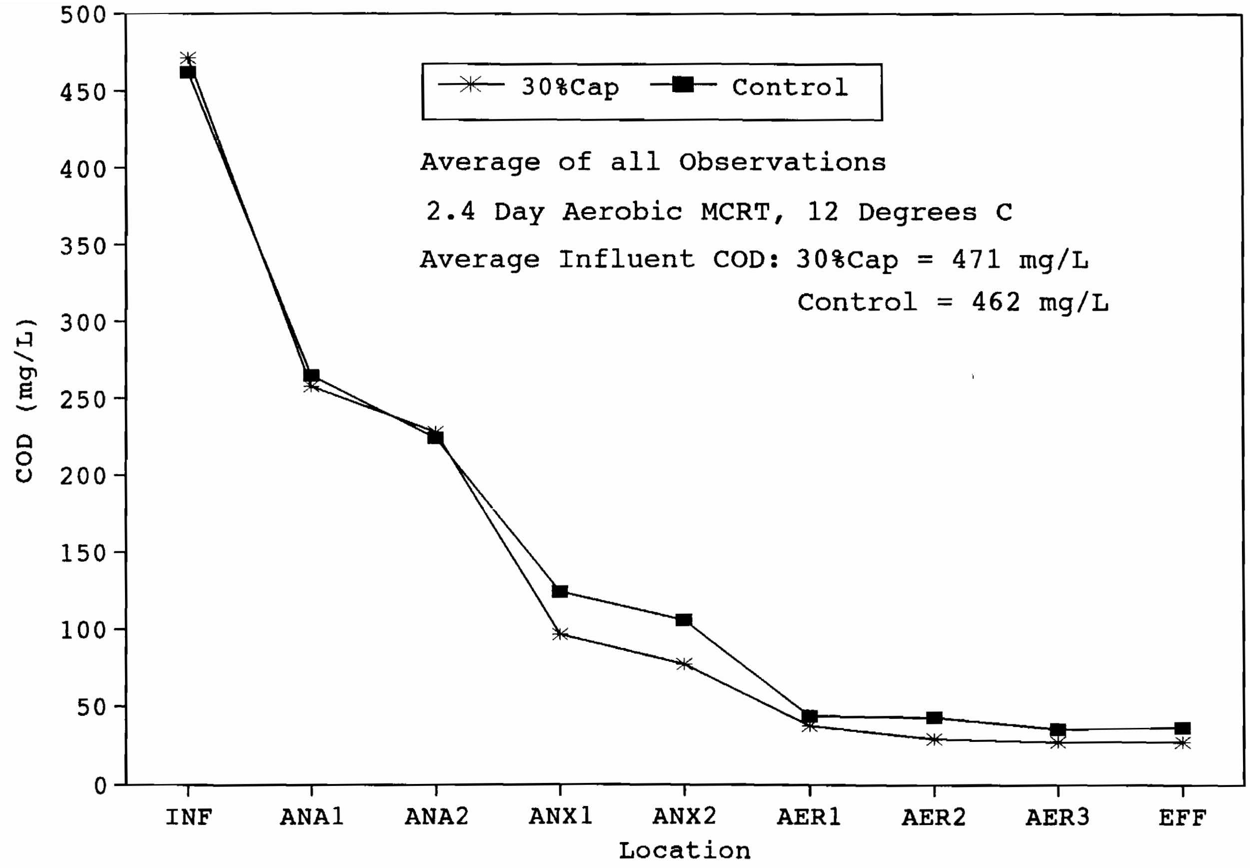


Figure 4-18. COD Profile of Phase Three Experiments

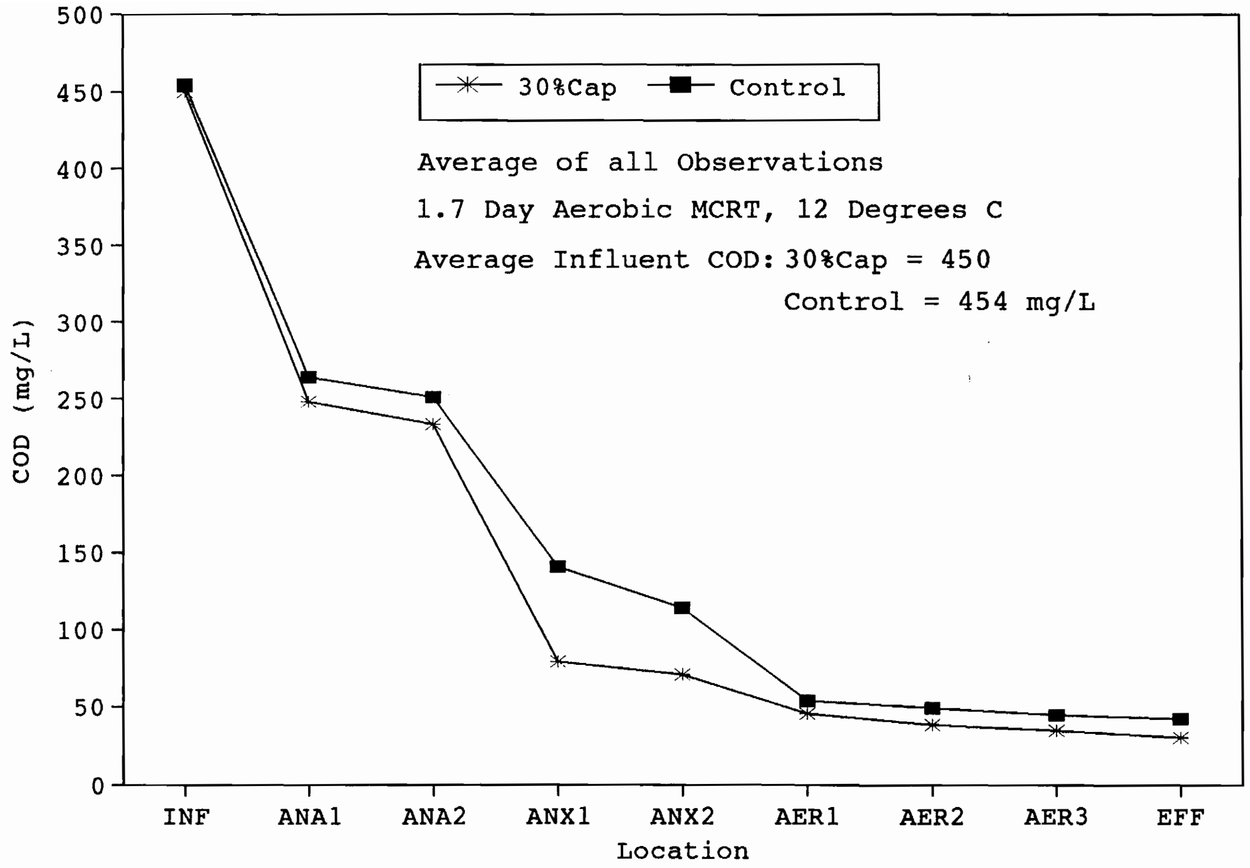


Figure 4-19. COD Profile of Phase Four Experiments

CHAPTER FIVE: DISCUSSION

INTRODUCTION

The results presented in Chapter Four clearly indicate that the integration of Fixed Film media enhanced the ability of all activated sludge systems in which it was placed to maintain a population of nitrifying bacteria. This population allowed the treatment system to maintain nitrification at short aerobic MCRTs. Statistical analysis of 30%Cap indicated that this was true with a 99% confidence level. In addition increased denitrification in the anoxic zone resulted from the use of Captor media. The results also tended to indicate that lower sludge production and sludge yields could be accomplished by using Captor, but the data was too scattered for a definitive conclusion to be reached. The combination of increased treatment efficiency under low MCRT conditions, the decreased sludge production and the increase in denitrification has the potential to result in tremendous savings in tankage, aeration costs and sludge handling. However, further review of the data was required in order to quantify more specific and less obvious differences that may have been present. The purpose of this chapter is to present and discuss the results of further analysis of the data.

The chapter includes discussion pertaining to normalization of influent TKN for equal comparison of results, comparisons of the performance of IFAS to the Control, comparison of the performance of Captor to that of Ringlace, the analysis of nitrogen removal throughout each system, and the determination of optimum placement of IFAS to maximize nitrification.

AMMONIA ASSIMILATION AND HYDROLYSIS

In Chapter Four, ammonia profiles depicting the ammonia-nitrogen concentrations within each cell of the treatment trains were shown in an effort to indicate which trains were most effective in removing ammonia. A limited range of information was gained from this type of plot due to the dilution factors caused by recycle flows. To nullify these dilution factors, the concentration of ammonia in each cell was multiplied by the total flow through that cell (including all recycle flows) to plot ammonia mass load profiles. This was done for both normal and spiked conditions. This type of plot illustrated well the actual effect an individual cell had on ammonia removal, in grams per day of ammonia-nitrogen removal. These plots are included in Appendix C, and are discussed briefly in the following paragraphs.

Immediately apparent in these plots was the elimination of the dilution factor caused by the introduction of recycle flows into the anaerobic and anoxic sections. Ammonia concentrations had generally decreased from section to section, as seen in Chapter Four, but the mass loads of ammonia were actually greater in the anaerobic and anoxic sections than the influent due to the high volume of flows passing through them. Refer to Figure 3-1 for an illustration of the origin and terminus of the recycle flows.

Influencing Factors

Each cell was subject to varying factors influencing both the rate of ammonia reduction and ammonia addition. Factors which affected ammonia removal were nitrification and ammonia assimilation into biomass during reproduction. Factors which affected ammonia addition were recycle flows and hydrolysis of organic nitrogen into ammonia, referred to as deamination. Each cell had its own unique set of circumstances that dictated which, if any, of these factors dominated.

Ammonia Removals from Cells

Ammonia removal in each of the systems occurred via two routes - the biological nitrification of ammonia to NO_x and the assimilation of ammonia-nitrogen into cell matter during cell growth. Biological nitrification only occurs under aerobic conditions, whereas assimilation of ammonia into cell growth can, and did, occur in the absence of dissolved oxygen.

During both normal and spiked conditions, all trains during all phases showed a dramatic decrease in ammonia mass loads throughout the aerobic zone. The absence of recycle flows entering the aerobic zones led to the conclusion that no factors other than nitrification and assimilation of ammonia into biomass growth were responsible for these decreases. Nitrification in the aerobic zone was expected to occur in all trains, and quantification of it is undertaken in subsequent paragraphs.

Assimilation of ammonia-nitrogen into cell growth will occur under any conditions which allow cell growth. These conditions can be anaerobic, anoxic or aerobic. In this experiment, anaerobic cell yields - the amount of cell growth observed in an anaerobic zone divided by the amount of substrate which was consumed - was assumed to be zero or nearly zero. This assumption was confirmed by Sen, 1994, (who had measured anaerobic cell yields in the treatment trains used in these experiments) in private conversation. Thus, assimilation due to anaerobic growth was assumed to be zero. Assimilation also occurred due to denitrification which occurred in both the anoxic and the aerobic cells. Denitrification in the anoxic zone was directly related to the concentrations of NO_x introduced into the anoxic zone by recycle flows. This in turn was affected by the ability of the treatment train to nitrify ammonia, thus producing the NO_x which was recycled. It was noted that during all phases, all trains were able to reduce NO_x levels to essentially zero in the second anoxic zone. Assimilation also occurred as a result of denitrification in the aerobic zone. This "aerobic denitrification" was attributed to the presence of anoxic zones within biological flocs where denitrification could, and did, take place. Quantification and comparison of the denitrification which occurred in the aerobic zone is undertaken in subsequent paragraphs.

The largest affect of assimilation occurred in the aerobic zone. Sufficient COD and ammonia was available which allowed heterotrophic growth, as well as autotrophic nitrifying bacteria, to thrive. The rapid reproduction and growth of these bacteria subsequently resulted in large quantities of ammonia being assimilated into that growth. This quantity of ammonia removed was not quantified except when nitrification mass balances were performed, where it was subtracted from values representing total nitrogen removal to determine system nitrification values.

Ammonia Addition to Cells

As stated previously, ammonia additions to cells in the treatment trains could occur via two mechanisms - deamination of organic nitrogen and the introduction into the cell of recycle flows containing ammonia. Deamination, which is essentially the transformation of organic nitrogen in the form of amines into ammonia, can occur in the presence of and in the absence of dissolved oxygen. During all phases, it was noted that ammonia concentrations sometimes increased through the anaerobic and anoxic zones. The absence of recycle flows into the second anaerobic and second anoxic cells lead to the conclusion that deamination had occurred. In many cases, the addition of ammonia into the anoxic cells was overshadowed by the assimilation which occurred there due to denitrification, and the ammonia mass loads were seen to decrease. The end result of these two factors was dependent upon the concentration of NO_x in the recycle flows, which controlled the quantity of denitrification which could occur. Figures C-1 through C-7 illustrate the varying effects of these factors. Deamination of organic nitrogen was considered to be negligible in the aerobic cells based on comparisons of SKN and ammonia-nitrogen test results. Both tests resulted in nearly identical values throughout the aerobic zones.

Ammonia contained in recycle flows played a dominant role in the first anaerobic cell and the first anoxic cell. The Mixed Liquor Return (MLR) transported ammonia from the second anoxic cell to the first anaerobic cell, thus increasing the mass loading of ammonia seen in that cell dramatically. This effect was also dependent upon the ability of the system to nitrify in the aerobic zone, since the concentration of ammonia in the second anoxic zone was affected by the Return Activated Sludge (RAS) and Nitrate Return (NR) recycle flows which originate in the clarifier and aerobic zone respectively, and enter the first anoxic zone. These recycle flows were also the cause of increased ammonia mass loads noted in the anoxic zones.

EFFECTS OF IFAS

In order to determine the effects that IFAS had upon treatment effectiveness, comparisons of calculated values for various parameters in the IFAS trains and the control were undertaken. Similar comparisons were made between the Captor and Ringlace trains. As stated in Chapter Four, both the 30%Cap and Ringlace trains achieved a statistically significant (99% and 90% confidence, respectively) higher rate of nitrification when compared to the control. These comparisons were carried out on system nitrification which included the measured conversion of ammonia-nitrogen to nitrite nitrogen. This step was considered the total nitrification step; once this conversion occurred, ammonia was effectively removed from solution. Ammonia removal also occurred in the anoxic zones as a result of assimilation during denitrification.

This section presents comparisons of anoxic ammonia uptake, nitrification in the aerobic cells, nitrification in the clarifiers, system denitrification, denitrification in the anoxic zone, and denitrification occurring in the aerobic zone.

Anoxic Ammonia Uptake

Ammonia removals in the anoxic zone occurred due to assimilation into cell growth during denitrification, and were calculated by converting the anoxic denitrification observed in a train into cell growth. This calculation included terms for the yield coefficient of denitrifying bacteria taken from ongoing research by Sen (personal communication). The anoxic denitrification was itself a direct function of NO_x levels in the Mixed Liquor Recycle and Nitrate Recycle flows originating in the aerobic zone and effluent.

NO_x levels in the aerobic zone and effluent were influenced by two primary factors. Higher nitrification rates in a train would result in higher NO_x, while high denitrification levels in the aerobic zone (a process described in following paragraphs) would reduce NO_x levels. If the net result of these two factors was high NO_x levels in the recycle flows, high ammonia uptake in the anoxic zone was noted. Lower NO_x likewise resulted in lower ammonia uptake in the anoxic zone.

Nitrification in the Aerobic Zone

Analysis of nitrification in the aerobic zone of each train was carried out using ammonia removal values for the aerobic cells calculated in Section Four. This was done under the assumption that essentially all organic nitrogen present in the influent would have been solubilized to ammonia prior to reaching the aerobic cells. This assumption was based upon the nearly identical results obtained from SKN and ammonia-nitrogen tests on the aerobic cells. The following paragraphs present an analysis of nitrification within each train.

<u>Ringlace vs. Control, Phase 1, Aerobic MCRT 3.4 Days</u>. Figure 5-1 represents the ammonia removals observed in the anoxic zone (ANX1 and ANX2), the aerobic cells, and the clarifier in phase one. During phase one, both Ringlace and the Control removed nearly all ammonia, with both average effluents being less than 0.5 mg/L. This indicated that as a whole, each train nitrified completely. Careful examination of Figure 5-1 revealed that each train nitrified varying amounts in different cells. It was found that each train removed less ammonia in AER2 than AER1, and less in AER3 than AER2. This high level of nitrification in AER1 and AER2 was attributed to the sufficient cell residence time available in the trains to decrease available COD levels in these cells to low enough values for autotrophic nitrifying bacteria to successfully compete with heterotrophic bacteria for the available oxygen. This allowed a population of nitrifiers to become established in each of these cells.

It was apparent that the Ringlace allowed a population of nitrifiers to maintain their position in aerobic cell two rather than moving freely as the mixed liquor moved between cells. When the

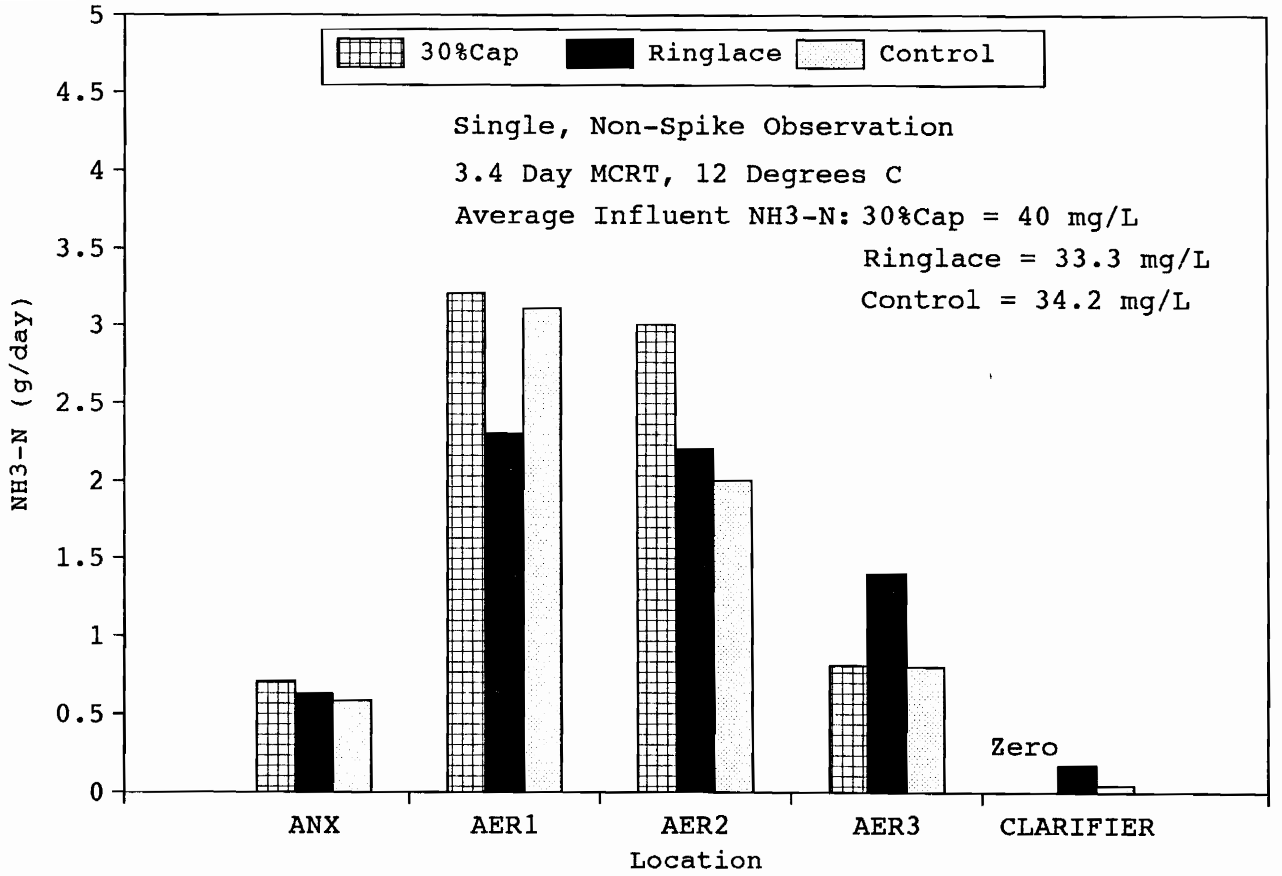


Figure 5-1. Ammonia Removals by Cell, Phase One, Normal Conditions.

phase one ammonia profile was studied, slightly lower ammonia levels in aerobic cell two of the Ringlace train did not result in proportionally lower ammonia removal rates. The higher than expected nitrification in aerobic cell two led to lower concentrations of ammonia in aerobic cell three; the result being a significantly smaller population of nitrifying bacteria on this Ringlace and a sharp drop in nitrification.

A more detailed evaluation of this data could not be accomplished because only one set of data points was analyzed during this phase. Spiked data was not available for phase one.

Captor vs. Control, Phase 1, Aerobic MCRT 3.4 Days. Ammonia uptake in the aerobic cells of 30%Cap followed the same patterns observed with Ringlace and the Control. The highest uptake occurred in aerobic cell one, followed by cell two and cell three. Again, this was indicative of low available COD levels in aerobic cell one which allowed a large population of nitrifiers to become established. As ammonia levels decreased from cell one to cell two, the corresponding population of nitrifiers also decreased.

The Captor sponges also allowed a population of nitrifiers to maintain their position in aerobic cell two rather than moving freely as the mixed liquor moved between cells. When the phase one ammonia profile was compared to the nitrification values, it was again noticed that the slightly lower ammonia levels in aerobic cell two of the 30%Cap train did not result in proportionally lower ammonia removal rates. Aerobic cell three received lower concentrations of ammonia as was the case in the Ringlace train; the result being a significantly smaller population of nitrifying bacteria and a sharp drop in nitrification.

Due to the free movement of nitrifiers within the mixed liquor of the Control, the ammonia removals in each aerobic cell decrease in a more step-like incremental manner.

Captor vs. Ringlace, Phase 1, Aerobic MCRT 3.4 Days. Figure 5-1 illustrates the effectiveness of Captor and Ringlace under similar conditions. 30%Cap nitrified to a greater extent in both aerobic cell one and aerobic cell two, while Ringlace nitrified more in aerobic cell three. However, the influent ammonia-nitrogen levels for the two trains were not equal. The difference of approximately 7 mg/L in influent ammonia concentrations corresponds to nearly 1.4 g/day of nitrogen. The difference in aerobic nitrification between 30%Cap and Ringlace was approximately 1.4 g/d, indicating that both trains nitrified completely. Based upon the variance in influent ammonia levels and the single set of data, it was not possible to determine if one form of IFAS was able to perform more efficiently than the other.

Ringlace vs. Control, Phase 2, Aerobic MCRT 3.1 Days In the aerobic cells under normal conditions, the Ringlace train exhibited a different trend than observed at aerobic MCRT 3.4 days, and the trend was likewise different from that of the Control. Figures 5-2 and 5-3 illustrate these trends. Ammonia removal peaked in cell two at 3.1 grams per day, while it was lowest in cell one, at 1.8 grams per day. The observed limitation of nitrification in the first aerobic cell was attributed to the increased available COD loading which the first cell received due to the lower MCRT. As seen on the SCOD profiles shown in Chapter Four, it was apparent that the first cell received much greater concentrations of SCOD from the second anoxic cell, on the order of 80 - 90 mg/L during phase one and roughly 50 mg/L during phase two. This increased available COD load resulted in increased growth of rapidly reproducing heterotrophic bacteria. This growth reduced growth of the slow growing autotrophic nitrifying bacteria by out-competing them for the available dissolved oxygen. Aerobic cell three, with its lower available COD concentration, was able to nitrify much of the remaining ammonia.

The shift in which the aerobic cells dominated denitrification was also seen in the Control. Although aerobic cell one nitrified to a greater extent that aerobic cell two, the difference was far less than that seen during phase one. SCOD levels similar to those found in the Ringlace train were noted, and the cause of the shift was attributed to the same factors.

These trends were magnified under spiked conditions, where higher ammonia levels ensured that nitrification rate limitations (caused by ammonia concentrations of less than 2 mg/L) would not occur and each cell would nitrify to its maximum capability. Both the Ringlace and Control trains nitrified more in aerobic cell three than cell two, and more in cell two than cell one. SCOD levels were the same as non-spike conditions, so nitrification in cell two was higher than cell one as expected. The reason that nitrification was highest in cell three was attributed to the fact that ammonia limiting conditions affected the non-spike results, and a larger population of nitrifiers accumulated in cell three due to a "right" combination of available COD and ammonia.

Captor vs. Control, Phase 2, Aerobic MCRT 3.1 Days Ammonia removal in the aerobic cells of 30%Cap under normal conditions followed the same pattern set in phase one.

Figure 5-2 illustrates the pattern. Aerobic cells one and two had only slightly different removal rates, while cell three had a significantly lower rate. Again, this was thought to be a result

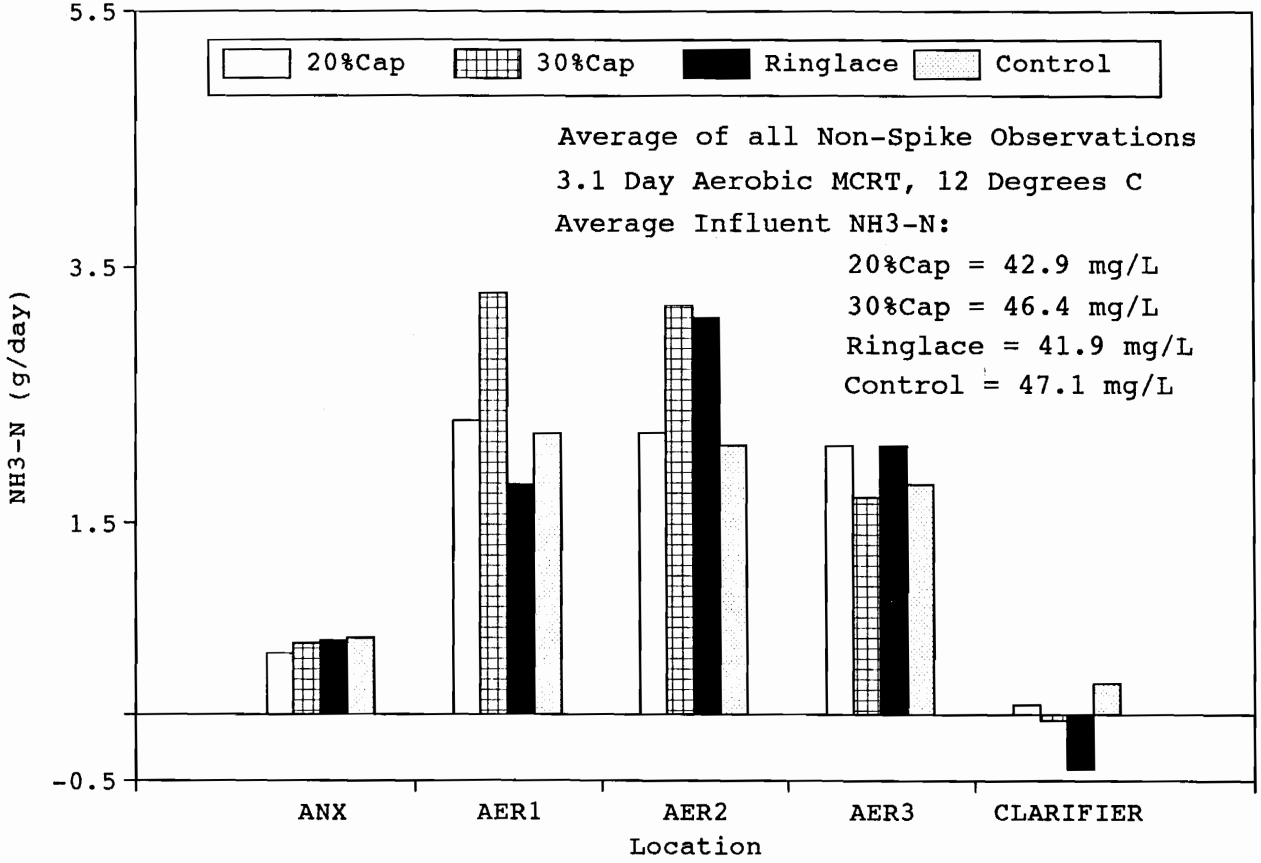
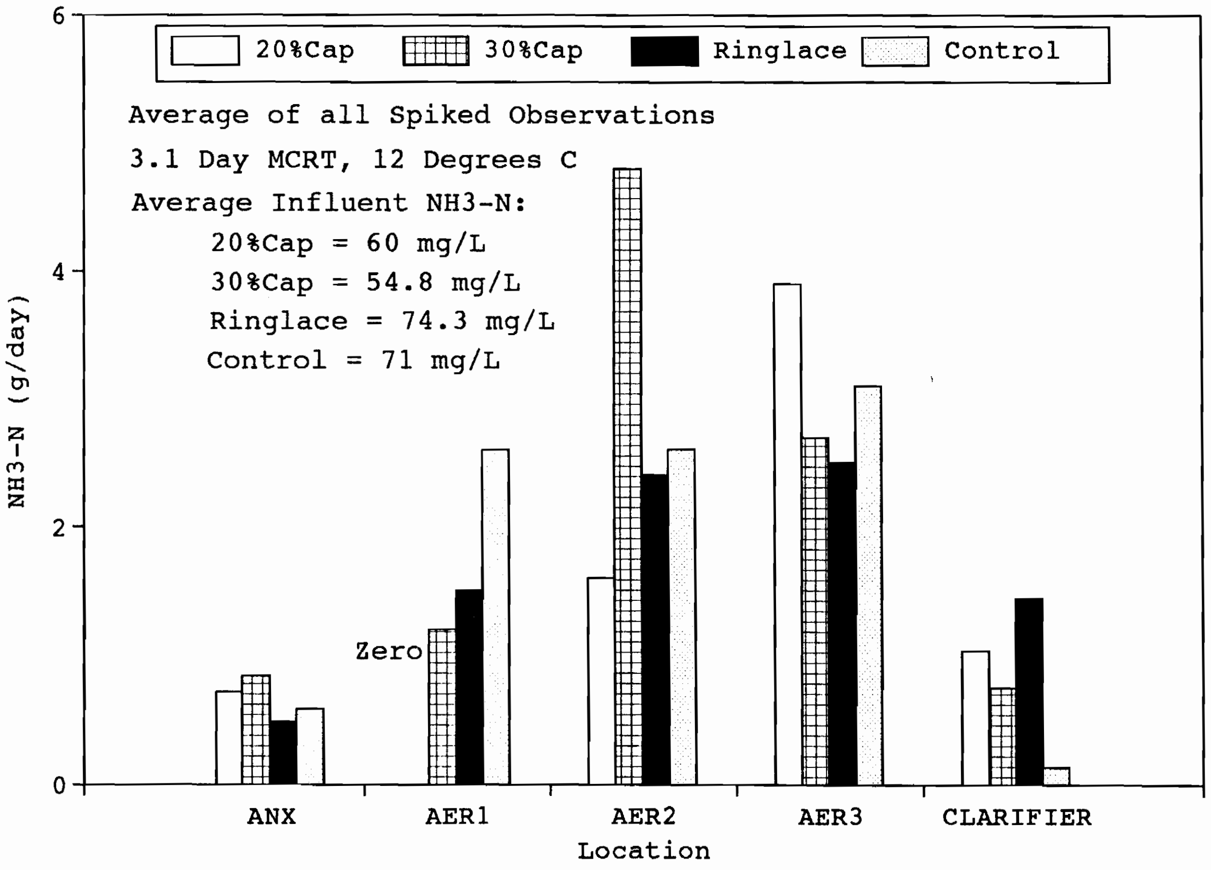


Figure 5-2. Ammonia Removals by Cell, Phase Two, Normal Conditions



Fugure 5-3. Ammonia Removals by Cell, Phase Two, Spiked Conditions

of nitrifiers attaching themselves to the Captor and thus not being washed into the third aerobic cell and possibly out of the system. 20%Cap, however, seemed to follow the pattern set by the Control, where ammonia removals decreased in nearly incremental amounts from cell one through cell three. The smaller percentage of media allowed less of a population of nitrifiers to adhere to the sponges, and thus a greater amount of nitrifiers were free floating and flowed into the following cells with the mixed liquor.

Under spiked conditions, large changes in aerobic cell ammonia removals occurred when compared to normal conditions. All trains showed increased removals as flow progressed from cell one to cell three. This phenomenon indicated that greater populations of nitrifiers had accumulated in aerobic cells two and three than in cell one, and that under conditions where ammonia limitations were absent, the majority of nitrification would take place in these two cells. Comparison of the two Captor trains to the Control indicated that the cell with the greatest population of nitrifiers varied between trains, with cell two being dominant in 30%Cap and cell three dominating in 20%Cap and the Control. A reason for this variation was found in the ammonia profile for phase two, normal conditions. It was noted that both 20%Cap and the Control had significantly higher average ammonia-nitrogen concentrations in the third aerobic cell, which allowed greater populations of nitrifiers to accumulate there. This in turn led to the higher ammonia removals under spiked conditions when ammonia levels were not limited.

Captor vs. Ringlace, Phase 2, Aerobic MCRT 3.1 Days Under normal conditions, both trains nitrified completely and ammonia limiting conditions were present. Figure 5-2 illustrates that the differences in nitrification values of the entire aerobic zone were approximately equal to the differences in influent ammonia concentrations. It was apparent that the distribution of nitrification was different between the two trains. 30%Cap maintained high nitrification rates in the first aerobic cell, while Ringlace did not. This was attributed to the greater average SCOD removal capability of the 30%Cap train. The SCOD profile of phase two confirms that average SCOD levels entering the first aerobic cell were slightly lower in 30%Cap than in the Ringlace train. In addition, biomass in the Ringlace train may have had higher levels of stored COD within their cell structure. The effect of higher COD levels was to encourage heterotrophic growth and inhibit autotrophic nitrifier growth.

Under spiked conditions it became apparent that the 30%Cap train was able to nitrify a significantly greater amount of ammonia than Ringlace. The Ringlace train had a much higher average influent ammonia concentration, yet was able to nitrify only slightly more ammonia in cell one, and much less than 30%Cap in cells two and three. The high nitrification levels in cell two of 30%Cap indicated that the levels of SCOD and ammonia-nitrogen were optimum for growth of nitrifiers. The Captor sponge matrix allowed the nitrifiers to attach and maintain their presence in the cell. From the data taken during spiked conditions, it was apparent that 30%Cap was more able to maintain nitrification within the aerobic zone, and experiments with Ringlace and 20%Cap were discontinued at this point.

Captor vs. Control, Phase 3, Aerobic MCRT 2.4 Days Figures 5-4 and 5-5 indicate that ammonia removals in the aerobic zones of the 30%Cap train shifted when compared to phase two results. The highest nitrification values were seen in cell two whereas they were seen in cell one during phase two. This was indicative of higher available COD levels present in cell one which promoted growth of heterotrophic bacteria which outcompeted the nitrifiers for available oxygen. The lowest ammonia removals were seen in cell three where ammonia limiting conditions dominated (effluent ammonia levels of less than 0.2 mg/L), slowing nitrification rates. High ammonia levels throughout the aerobic zone in the Control resulted in relatively linear ammonia removals in each cell, with slightly lower removals in cell two than cell one and higher removals in cell three than cell one. Average SCOD levels in the Control were slightly higher in aerobic cell two than cell one which accounted for the lower ammonia removals in cell two.

During spiked conditions, another notable shift was seen, where ammonia removals in the aerobic cells increased from cell one through cell three. The peak ammonia removal seen in cell two during phase two had shifted to cell three. Again, this was indicative of higher available COD levels in aerobic cell one as a result of the lower MCRT. The high ammonia removal seen in aerobic cell three indicated that conditions had allowed a larger population of nitrifying organisms to acclimate and grow, so that under conditions where ammonia was not limited the greatest amount of nitrification would take place.

The Control, under spiked conditions, was sampled only once and as such, data presented should not be used for analysis. The data was included in Figure 5-5 for informational purposes only.

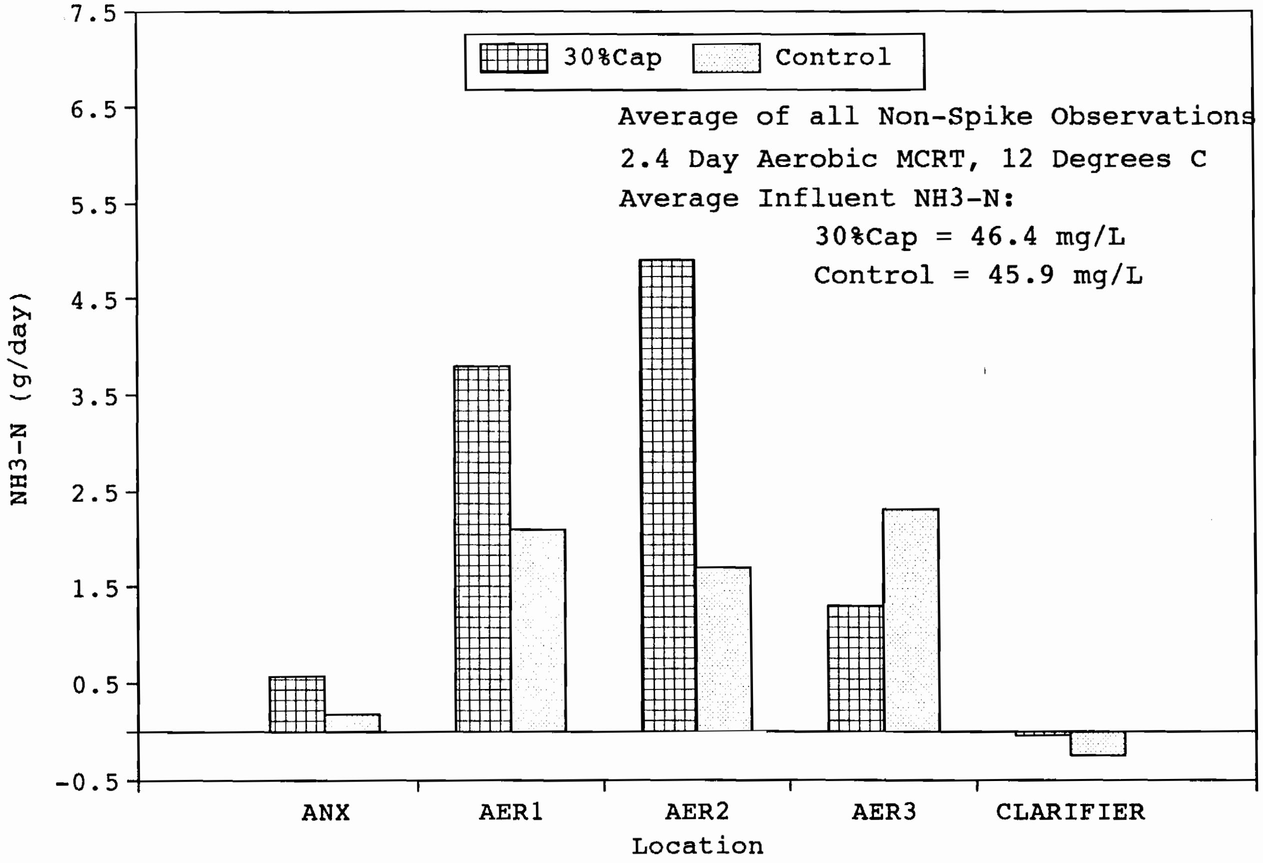


Figure 5-4. Ammonia Removals by Cell, Phase Three, Normal Conditions

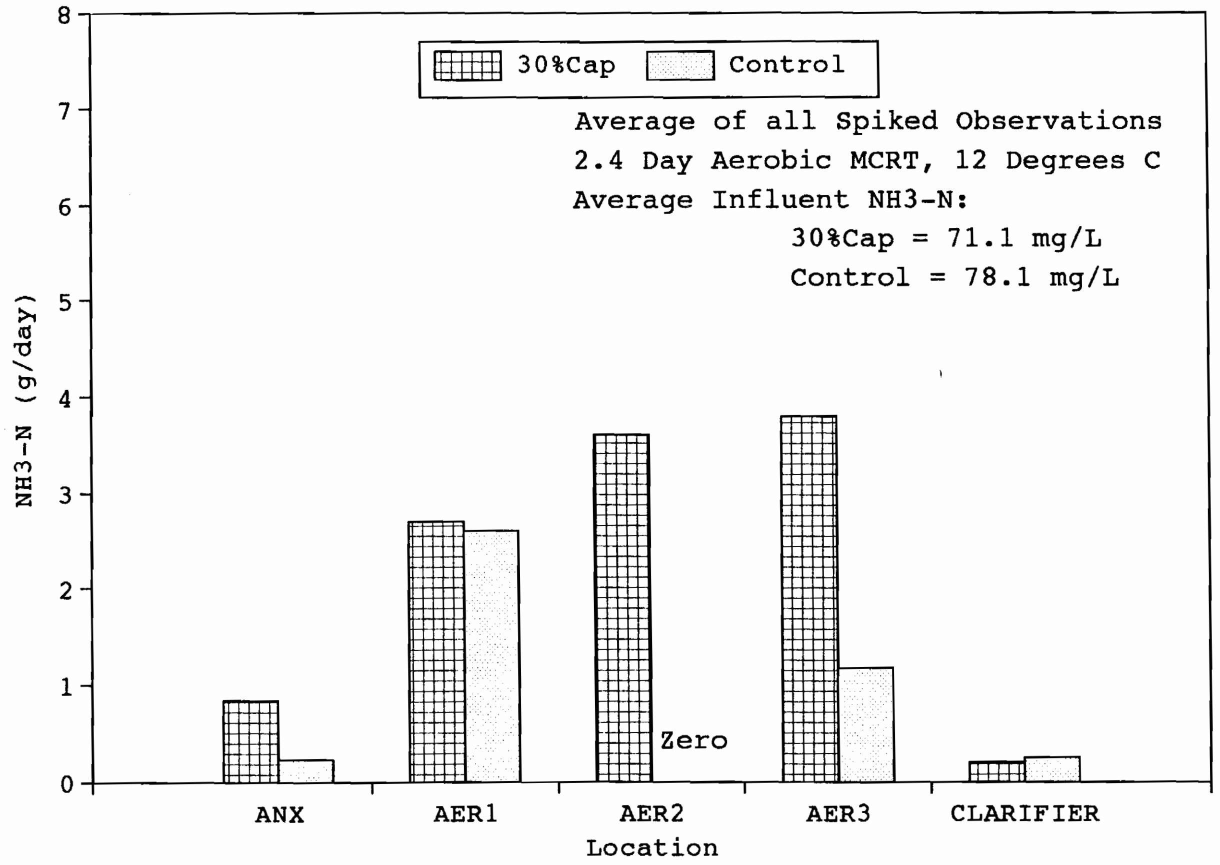


Figure 5-5. Ammonia Removals by Cell, Phase Three, Spiked Conditions

Captor vs. Control, Phase 4, Aerobic MCRT 1.7 Days As noted in Figures 5-6 and 5-7, ammonia removals during normal and spiked conditions were nearly identical. The lack of ammonia limiting conditions during normal conditions made running analyses on spiked conditions redundant. Discussions which follow apply to both conditions.

Figure 5-6 also illustrates how closely ammonia removal in the aerobic zone resembled the results seen during phase three, with one small difference. Peak removals were noted in aerobic cell two, while cell three achieved removals greater than cell one. This was indicative of the continuing inability of the system to remove COD early in treatment, and the shift of available COD toward cell three as the MCRT decreased. The control continued to exhibit a relatively linear ammonia removal from cell one through cell three. This seemed to indicate that the entire aerobic zone was essentially acting as a single completely mixed reactor instead of three individual reactors. With a lack of a fixed media for nitrifiers to attach, they would more easily transfer from cell to cell. In addition, the increase in the Nitrate Return (NR) and Return Activated Sludge (RAS) flow rates from 1.0 Q to 1.3 Q during this phase served to transfer the mixed liquor and its associated nitrifiers to the head of the facility much more rapidly. These two facts effectively eliminated the effect of the baffles within the aerobic zone. This effect was not noted in 30%Cap, where the media "fixed" the nitrifiers in place.

Ammonia Removal in the Clarifiers

Ammonia removals did occur in the clarifiers. This removal was inconsistent and it was difficult to attribute it to a given factor. It was thought that a combination of nitrification, denitrification, assimilation and solubilization contributed to the observed removals, with one or two of these factors being dominant at any one time. Nitrification could occur if sufficient ammonia and dissolved oxygen were present in the clarifier. Those conditions could be made more advantageous to nitrification if settling of the biomass was not effective, leaving the bacteria suspended in the liquid phase and thus exposed to greater quantities of ammonia and oxygen. Denitrification could occur in the absence of oxygen and the presence of NO_x. When settling of biological growth was efficient, anoxic conditions were easily attainable in the sludge blanket, leading to denitrification. Both nitrification and denitrification lead to ammonia uptake by assimilation. Solubilization of organic ammonia was possible due to endogenous decay which may have occurred in the sludge

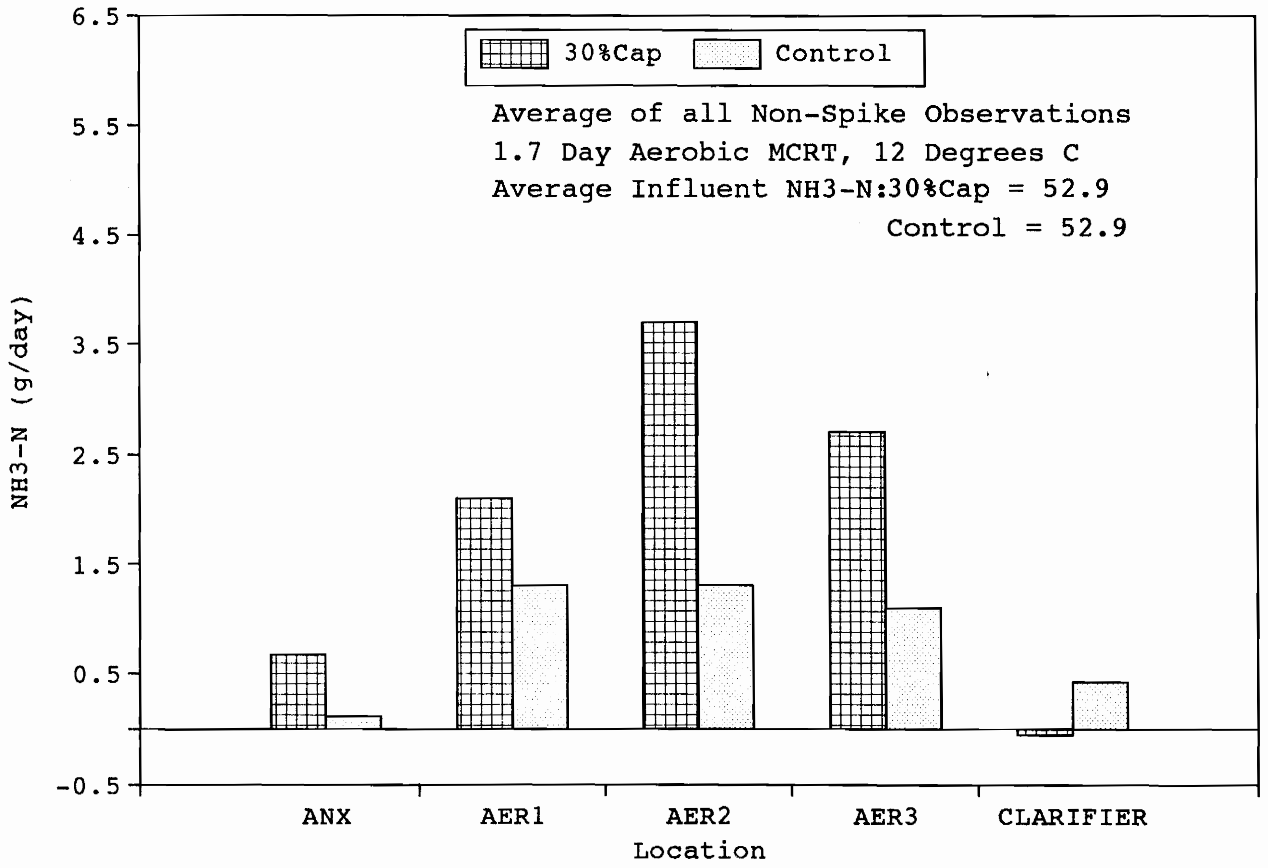


Figure 5-6. Ammonia Removals by Cell, Phase Four, Normal Conditions

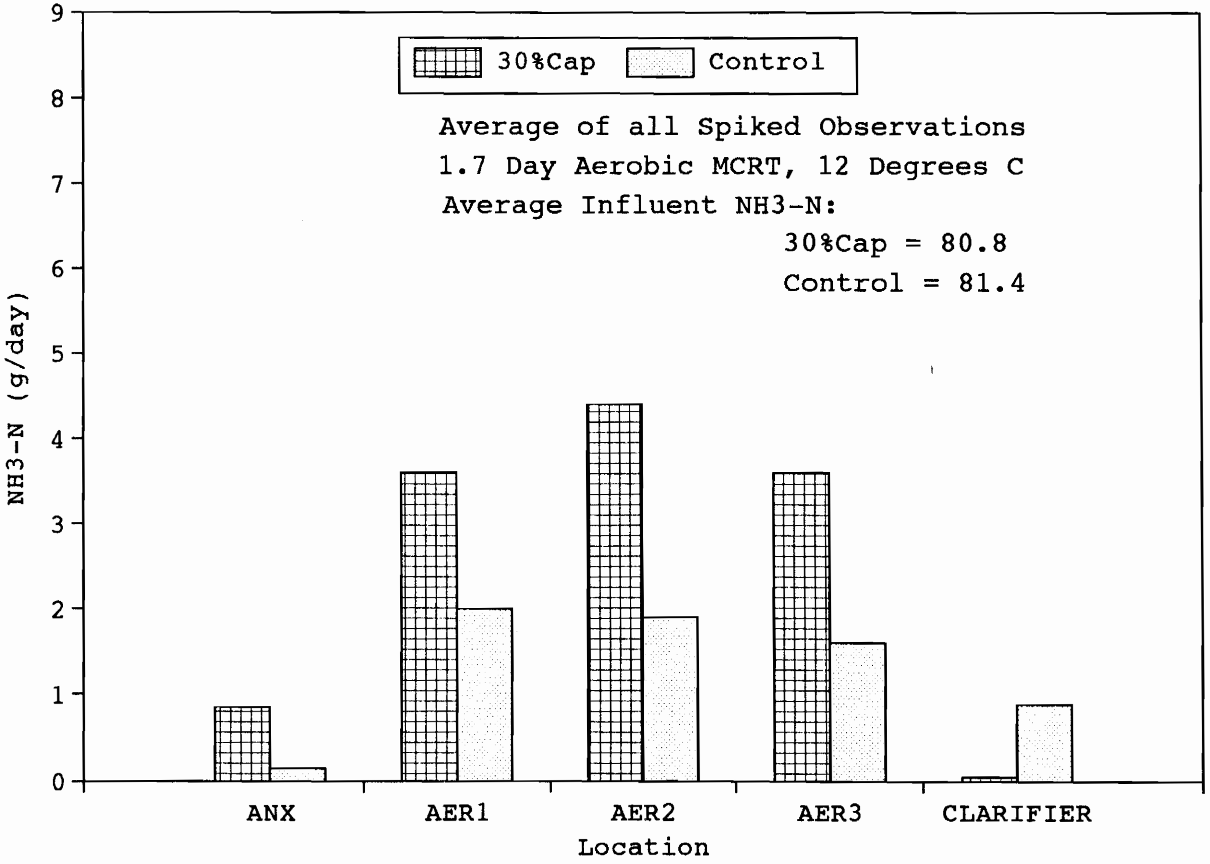


Figure 5-7. Ammonia Removals by Cell, Phase Four, Spiked Conditions

blanket. The scarcity of nutrients in the sludge blanket would lead the bacterial to use cell protoplasm (present as a result of dead cell lysis) as a food source. The lysis of cells results in an addition of organic nitrogen into the liquid phase. Solids separation efficiency, oxygen uptake rates in aerobic cell three and the clarifier, bulking due to filamentous bacteria and a host of other factors may also have contributed to the variation.

Precise measurements of the factors thought to have contributed to ammonia uptake in the clarifiers were not undertaken. Information on ammonia uptakes is presented for informational purposes and should not be used as a basis for drawing conclusions regarding the use of IFAS.

Specific Nitrification Rates

Once the comparison of ammonia uptake in each zone of the treatment trains was conducted, it was desired to determine the advantage in nitrification which occurred as a result of using IFAS within the system, and to represent it in such a way as to clearly demonstrate the effect over the range of MCRTs studied. This was accomplished by dividing the difference in system nitrification rates of the IFAS trains and the Control by the aerobic volume, and by dividing the nitrification attributed to both the fixed and suspended growth in the IFAS trains by the quantity of fixed and suspended growth present in the aerobic zone respectively (30%Cap only). Figure 5-8 illustrates the effect IFAS had upon system nitrification rates per liter of aerobic volume, as well as the percent increase in nitrification due to Captor. This data can potentially be used to size aerobic basins to achieve a desired degree of nitrification given an MCRT. Figure 5-9 shows the changing effect that the range of MCRTs had on the specific nitrification rates of both fixed and suspended growth . This data can potentially be used to determine mixed liquor concentrations and solids loadings to a sedimentation basin given a desired nitrification rate. An assumption was made in both cases that all nitrification occurred in the aerobic cells.

Figure 5-8 clearly indicates that the advantage of IFAS per unit aerobic volume was magnified dramatically at shorter MCRTs. As the MCRT decreased, the "assistance" given to system nitrification by the IFAS increased under both normal and spiked conditions. The fact that the nitrification advantage decreased slightly or did not change when the MCRT was decreased from 3.4 days to 3.1 days indicated that nitrification in the suspended growth was maintained at a high level at these two MCRTs.

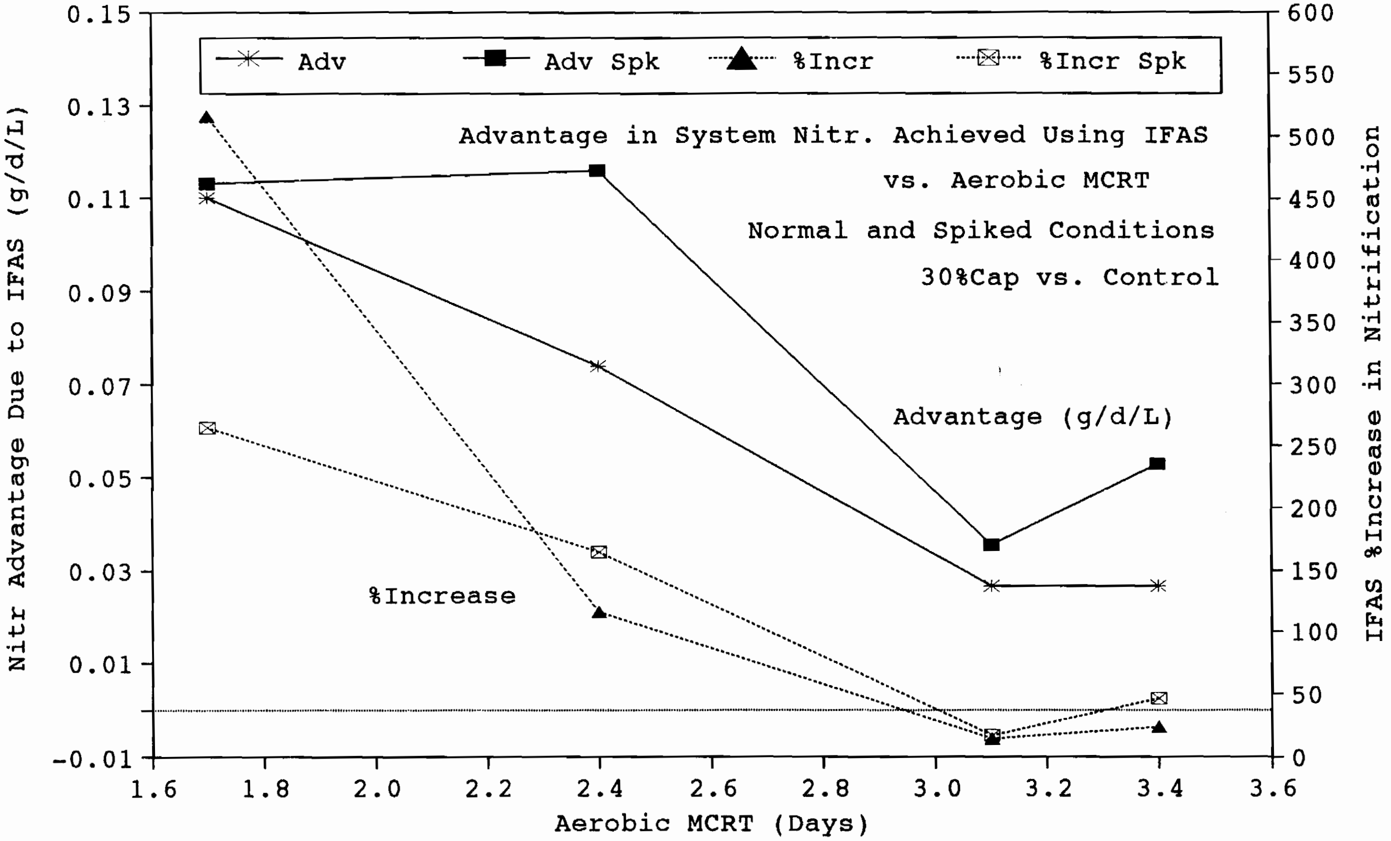


Figure 5-8. Nitrification Advantage of IFAS With Respect To Volume

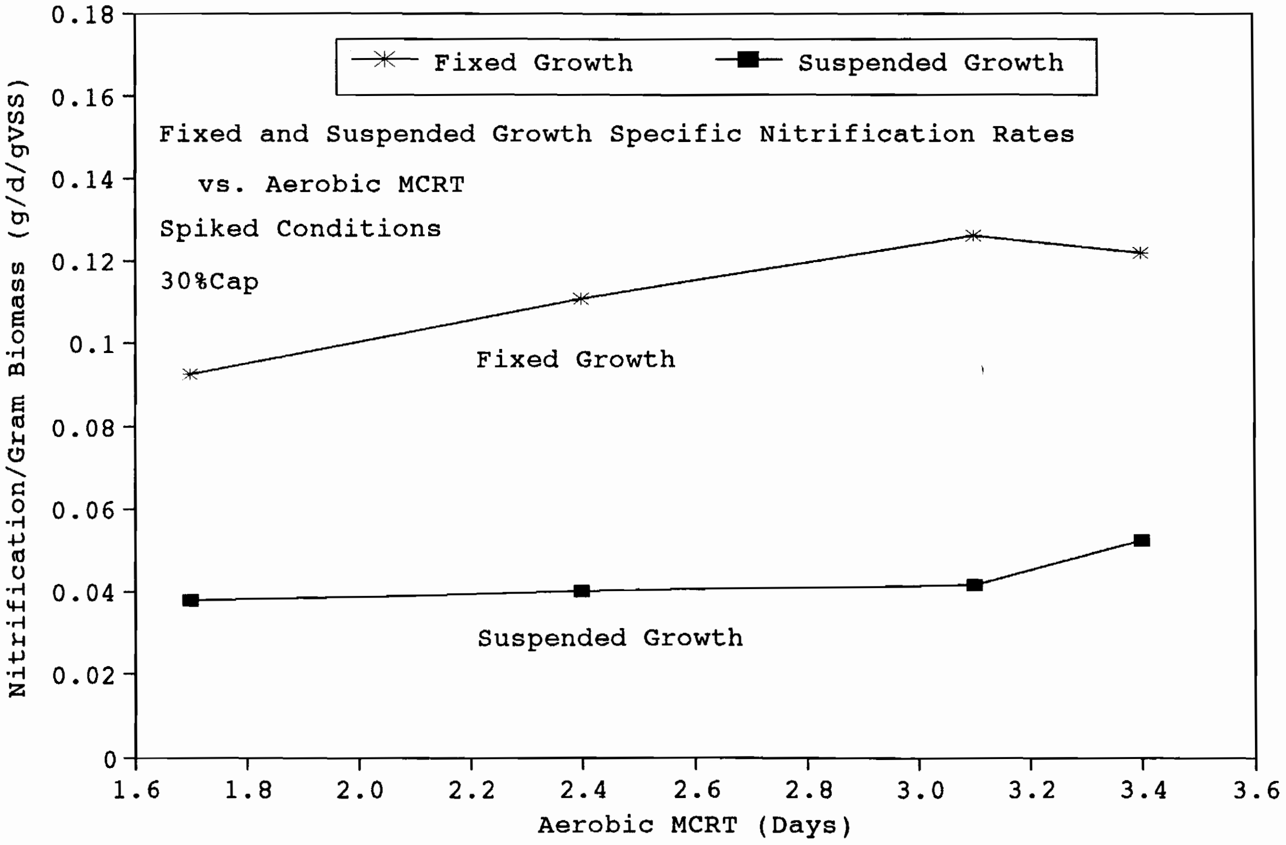


Figure 5-9. Fixed and Suspended Growth Specific Nitrification Rates

The large jump in IFAS nitrification which occurred between 3.1 days and 2.4 days seems to indicate a "break point" at which the fixed growth nitrification ability begins to dominate, accomplishing the majority of system nitrification. This "break point" corresponds to the MCRT where "washout" of nitrifiers was expected to occur, at approximately 2.5 days. Washout occurs because the specifica growth rate of nitrifying bacteria in wastewater treatment plants is approximately 0.4/day at 25 degrees celsius, and decreases as the temperature decreases (Randall et al., 1992). Thus, when the aerobic MCRT drops below the "washout" MCRT established for a given population and temperature, the removal rate (through wasting, decay etc.) of the organisms is greater than the growth rate and a population cannot become established or be maintained.

A slight decrease in the nitrification advantage was noted in the spiked data when the MCRT was decreased from 2.4 days to 1.7 days. The cause of this decrease was unknown, but may be related to the washout of fixed growth nitrifiers from the system after sloughing had occurred. Further study of lower MCRTs is being conducted by Sen and Liu at VPI&SU; data collected during their studies should be incorporated into this data to determine both if a trend exists and why it exists. The normal and spiked conditions resulted in nearly identical values at the 1.7 day MCRT; this was thought to be a representation of the decreased ability of the suspended growth to nitrify at low MCRTs while the fixed growth maintained its ability to nitrify.

Ringlace consistently resulted in lower specific nitrification rates (not shown on graph), and use of Ringlace was halted after concluding data collection for the 3.1 day MCRT.

In an effort to determine more accurately the shift in the fixed growth's ability to nitrify as the MCRT decreased, the 30%Cap suspended growth nitrification per gram of suspended growth and the fixed growth nitrification per gram of fixed growth (calculated as per Appendix A) was plotted against aerobic MCRT. Figure 5-9 illustrates well the consistent advantage in nitrifying ability which the fixed growth showed throughout the range of MCRTs studied.

The average quantity of growth that attached itself to the Captor sponges was fairly consistent throughout the range of MCRTs studied. This, along with the fact that the specific nitrification rate of the fixed growth decreased at slightly faster rate than did the suspended growth specific nitrification rate indicated that the population of nitrifiers attached to the Captor was dependent upon MCRT. This is thought to be a result of sloughing of biomass off of the sponges and into the mixed liquor, where it is subsequently washed out of the system. The largest drops in fixed growth specific nitrification rates occurred at MCRTs of less than 2.5 days (the "washout" MCRT). This also supports the hypothesis that a combination of sloughing/washout had occurred.

The suspended growth specific nitrification rate remained nearly constant between 3.1 and 1.7 days. It was originally thought that this rate would decrease steadily as the MCRT decreased due to washout of suspended growth nitrifying bacteria. The MLVSS concentrations decreased only slightly as the MCRT decreased from 3.1 to 1.7 days, indicating that for the ratio of suspended growth nitrification : MLVSS to remain nearly constant, the nitrification rate must have also decreased only slightly. This near constant nitrification rate in the suspended growth is thought to be a result of an equilibrium that had been reached in which the sloughing rate of nitrifiers off the Captor sponges was sufficient to maintain a population of nitrifiers in the suspended phase. A decrease in MCRT resulted in an increased sloughing rate which caused a decrease in the specific nitrification rate of the fixed growth and the maintenance of the specific nitrification rate of the suspended growth.

Further quantification of the advantage in nitrification achieved by the IFAS is represented in Figure 5-10. In this figure, the difference in nitrification rates of 30%Cap and the Control was divided by the MLVSS concentration in the 30%Cap train in order to illustrate the specific nitrification rate advantage directly attributable to IFAS. This was done for data from spiked conditions, where nitrification rates were maximized for each treatment system. Again, it was seen that the advantage in nitrification achieved by IFAS was greatly magnified at low MCRTs. Additionally, a "break point" was again seen, as in Figure 5-8, between the 3.1 day and 2.4 day MCRTs. This can be attributed to washout of nitrifiers in the suspended growth.

Denitrification

The effect which IFAS may have had on denitrification was also studied. Results of system denitrification, anoxic denitrification, and denitrification which occurred in the aerobic zone of the IFAS trains were compared to the same results for the Control. Since denitrification was a function of nitrification, i.e. denitrification could not occur unless nitrification occurred first, system nitrification values were frequently made reference to.

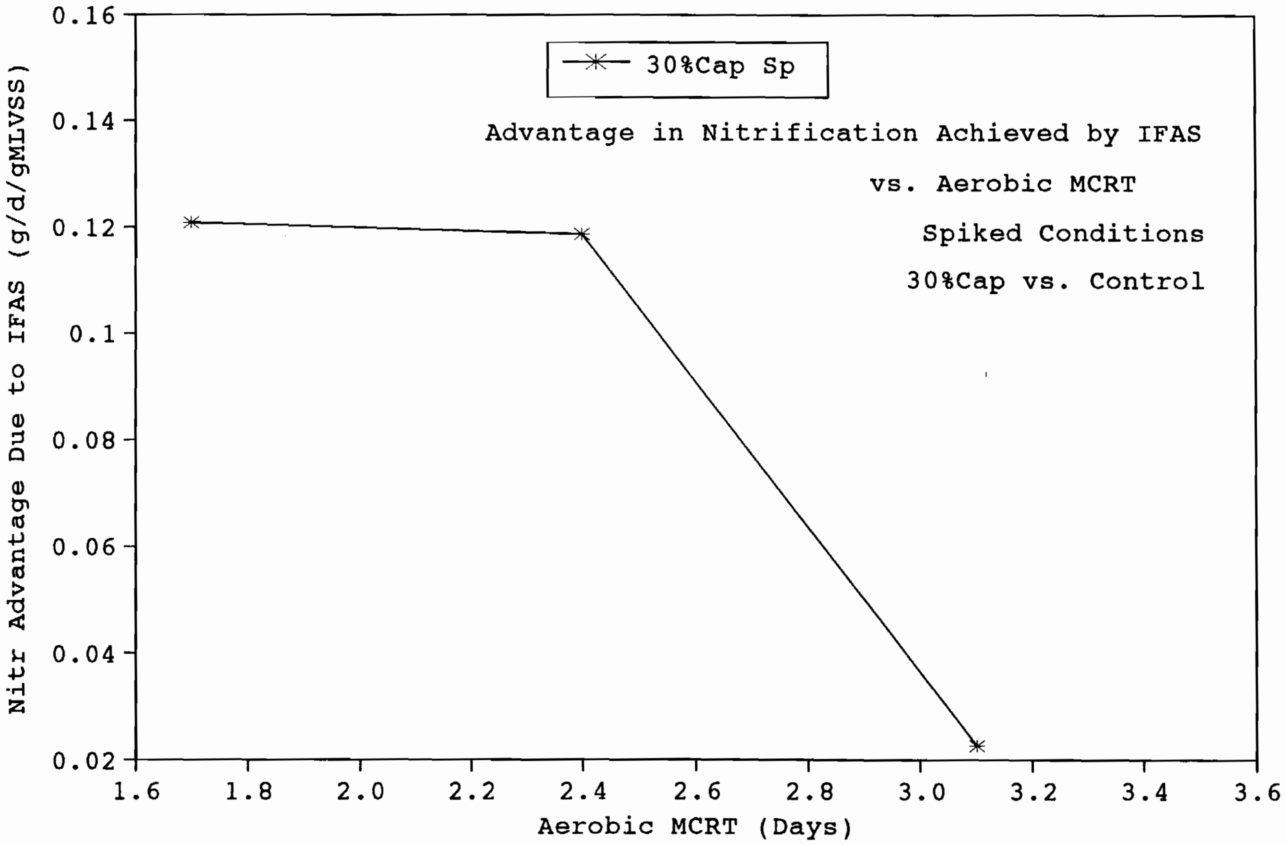


Figure 5-10. Nitrification Advantage of IFAS with Respect to Volume

Ringlace vs. Control, Phase 1, Aerobic MCRT 3.4 Days Figure 5-11 indicates that Ringlace denitrified 1.6 g/d more than did the Control. Since all trains nitrified completely (i.e. nearly equal NO_x levels) and influent ammonia levels were nearly identical, the difference in denitrification was attributed to the maintenance of a greater population of denitrifying bacteria within the Ringlace train. Possible reasons for this were investigated while studying denitrification which occurred in the anoxic and aerobic zones.

Denitrification in the anoxic zone in the Ringlace train was only higher by 0.3 g/day than anoxic denitrification in the Control. Slightly higher NO_x levels in the recycle flows to the anoxic zone of the Ringlace train should, and did, result in only slightly higher anoxic denitrification values. The remaining 1.3 g/day difference in denitrification occurred in the aerobic zone.

Denitrification in aerobic zones is not an unusual occurrence. Many researchers have noted the phenomenon, particularly Ryhiner et al. (1993), Lessel (1991 and 1993), Watanabe et al. (1992), Sen et al. (1993), Louis (1993) and Mitta (1994). All noticed the occurrence of simultaneous nitrification and denitrification within biofilms as a result of high oxygen uptake rates on the surface of the biofilm, which prevented oxygen from diffusing into the center of the biofilm. This created an anoxic (if NO_x was present) or anaerobic region. In the case of Ringlace, thick dark masses of growth were attached to the media throughout both phases, suggesting a lack of oxygen penetration into the growth. This same type of growth on Ringlace was noted by Mitta (1994). At the same time, nitrification was taking place producing NO_x, which, diffused into the center of the biomass where anoxic denitrification took place. A small amount of denitrification undoubtedly took place in the suspended growth as described in the following paragraph. This quantity was not measured during these experiments.

The Control also showed a significant quantity of denitrification in the aerobic zone, though much less than Ringlace. The cause of the denitrification was similar to that of Ringlace, however, the smaller size of suspended flocs dictated a high surface area exposed to dissolved oxygen and a corresponding small anoxic region in the center of the flocs. The result was lower denitrification rates.

No further detailed analysis of this data was possible as only one data set was studied. No data relating to spiked conditions was taken.

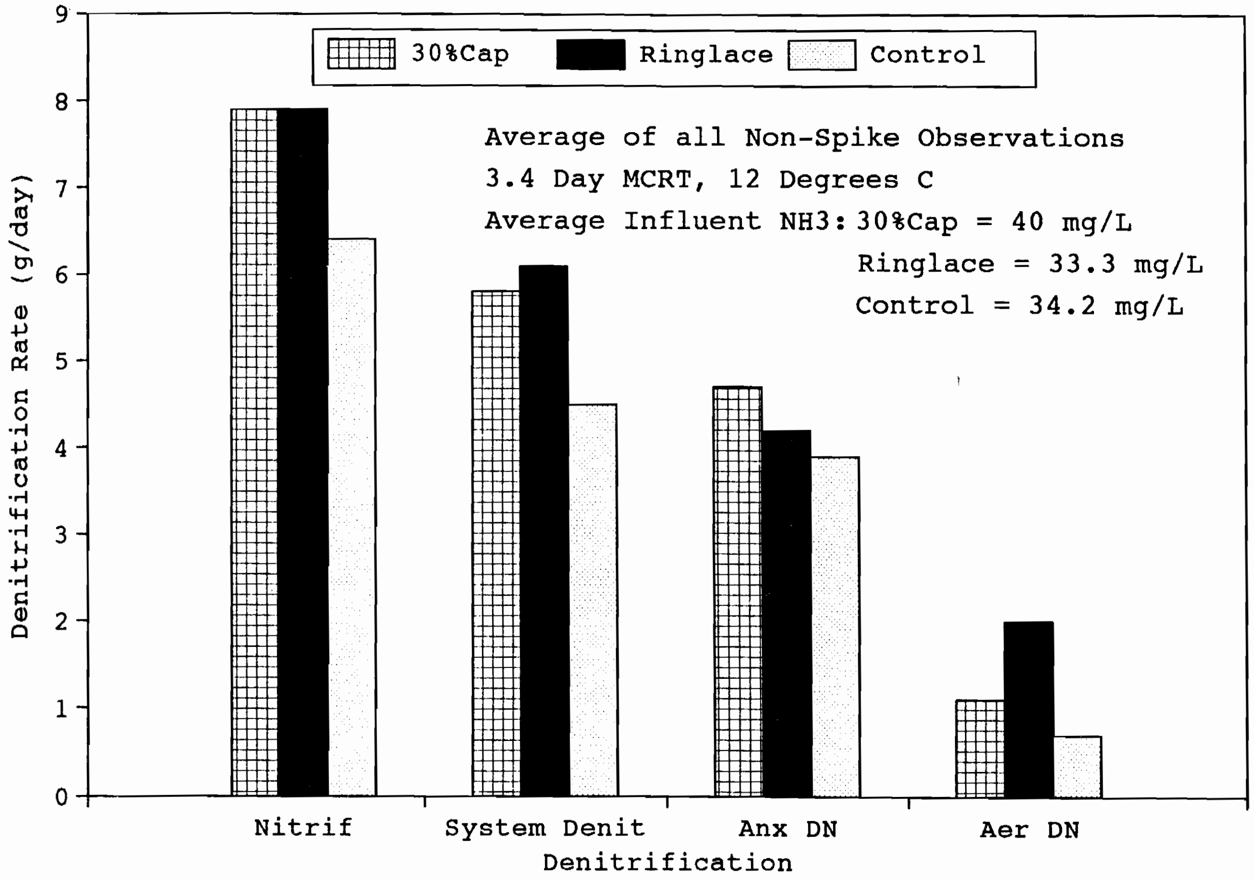


Figure 5-11. Denitrification under Normal Conditions, Phase One

Captor vs. Control, Phase 1, Aerobic MCRT 3.4 Days. Figure 5-11 shows the relationship of system and anoxic denitrification, and denitrification occurring in the aerobic zone of the 30%Cap train. System denitrification in the 30%Cap train was 1.3 g/day greater than in the Control. This difference was spread between the anoxic denitrification, at 0.8 g/day more than the Control, and the aerobic zone, at 0.5 g/day more than the Control. Greater overall nitrification due to the higher influent ammonia levels resulted in greater NO_x levels recycled into the anoxic zone, and thus a greater rate of denitrification. When aerobic zone denitrification was studied, it was apparent that the sponges, while not maintaining as large of an anoxic region as the Ringlace train, still had significantly more anoxic volume than the suspended flocs of the Control. The result was greater denitrification in the aerobic zone of 30%Cap than the Control.

No further detailed analysis was possible on this data as only one data set was studied. No spiked condition data sets were taken during this phase.

Captor vs. Ringlace, Phase 1, Aerobic MCRT 3.4 Days Figure 5-11 indicates that while system nitrification achieved by 30%Cap and Ringlace was nearly equal, the system denitrification rate was 0.3 g/day greater in Ringlace than 30%Cap. Examination of denitrification rates in the anoxic and aerobic zones was required to determine the cause of this difference.

Anoxic denitrification was a function of NO_x levels in the recycle flows. 30%Cap had NO_x concentrations 1 - 2 mg/L greater in the third aerobic cell and the effluent than did Ringlace. As seen in previous paragraphs, this translated into greater denitrification in the anoxic zone in 30%Cap because of the higher NO_x concentrations seen there.

Analysis of aerobic zone denitrification revealed that the lower NO_x levels seen in the Ringlace train were a result of the greater denitrification achieved by the Ringlace. The thick, dark, cylindrical mass of growth noted on the Ringlace resulted in a relatively small biomass surface area exposed to the liquid phase containing dissolved oxygen. This small surface area made it difficult for oxygen to diffuse into the inner layers of the biomass, creating either anoxic or anaerobic regions. The presence of NO_x as a result of nitrification and the oxygen deficient inner regions made it possible for the greater amounts of denitrification to occur.

Only one data set was taken for each train during phase one, so a statistical analysis could not be performed. No data was taken under spiked conditions.

Ringlace vs. Control, Phase 2, Aerobic MCRT 3.1 Days Figures 5-12 and 5-13 indicate that during normal conditions, denitrification results during phase two were very similar to phase one. Ringlace again denitrified to a greater extent (0.8 g/day) than did the Control. As was seen in the ammonia profiles presented in Chapter Four, Ringlace achieved much lower ammonia levels in the effluent, indicating that nitrification was more complete. Greater nitrification led to greater NO_x production, which in turn led to greater denitrification.

Nitrification in Ringlace and Control trains was nearly equal as evidenced by the nitrification column in Figure 5-13 and as noted in the ammonia profiles. This resulted in nearly identical system denitrification values, as expected.

Denitrification under normal conditions in the anoxic zone was again related to NO_x levels in the recycle flows. The Ringlace train achieved slightly higher NO_x levels in aerobic cell three and the effluent, which were recycled back to the anoxic zone. There, it did not translate into slightly higher denitrification values. This indicated that a smaller population of denitrifying bacteria were present in the anoxic zone of the Ringlace train than the Control. This indication was supported byhigher measured NO_x levels in the second anoxic cell of the Ringlace train. Under spiked conditions, greater NO_x levels in the recycle flows resulted in higher anoxic denitrification values for the Control, as was expected.

Denitrification in the aerobic zone was greater than denitrification in the anoxic zone in both trains, most notably for Ringlace. This fact was attributed to the high concentration of NO_x available for denitrifying bacteria, the large anoxic zones present in the interior regions of the Ringlace and suspended flocs, and the larger hydraulic detention time of the aerobic cells (0.9 hours each) compared to the anoxic cells (0.25 hours each). These factors combined to allow for greater denitrification to take place despite the presence of aerators. Ringlace, as it did in phase one, denitrified to a greater extent (0.9 g/day) than did the Control.

Under spiked conditions, denitrification in the aerobic zone of Ringlace was again higher, in this case, 0.8 g/day. Greater regions of anoxic conditions within the Ringlace compared to suspended flocs in the Control was the cause. As a result of the greater amount of denitrification, NO_x levels in the third aerobic cell of the Ringlace train were significantly lower than the Control.

Captor vs. Control, Phase 2, Aerobic MCRT 3.1 Days Figure 5-12 indicates that 30%Cap system denitrification rates under normal conditions were 1.6 g/day greater than the Control, and

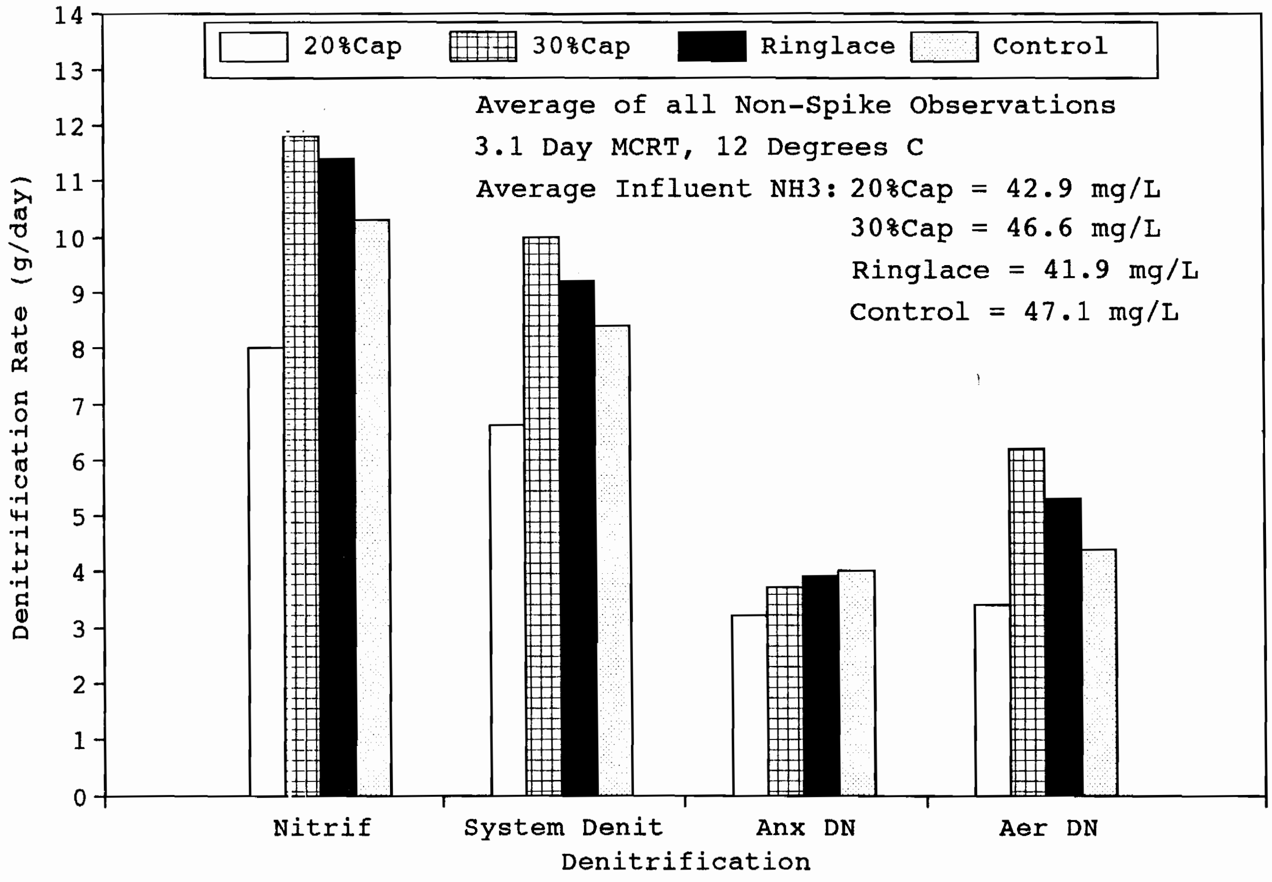


Figure 5-12. Denitrification under Normal Conditions, Phase Two

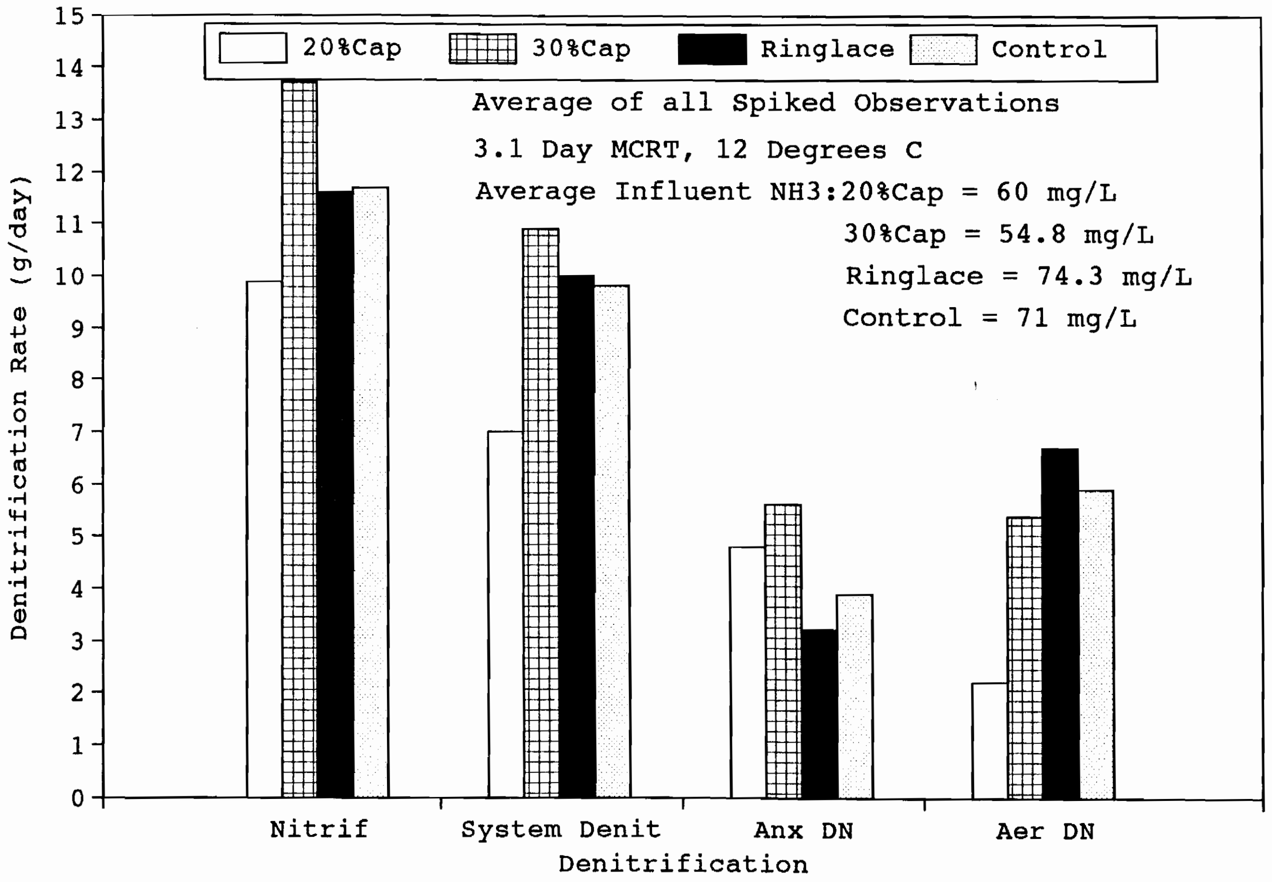


Figure 5-13.Denitrification under Spiked Conditions, Phase Two

were the highest seen during this phase. 20%Cap achieved the lowest system denitrification, 1.8 g/day less than the Control. Again, this was thought to be a result of inadequate oxygenation of the 20%Cap treatment train, as explained in Section Four. These rates were directly proportional to system nitrification, which is shown in Figure 5-12 as well. Under spiked conditions, the system nitrification and denitrification ratios were very similar to those seen under normal conditions, with 30%Cap denitrifying 1.1 g/day more than the Control, and 20%Cap denitrifying 2.8 g/day less than the Control.

Anoxic denitrification during normal and spiked conditions was directly proportional to NO_x levels in the recycle flows, as expected. However, under normal conditions, the Control achieved greater denitrification rates than both Captor trains, while under spiked conditions it did not. The increase in system denitrification in 30%Cap and 20%Cap observed under spiked conditions versus normal conditions (0.9 g/day and 0.4 g/day) resulted in an even greater increase in anoxic denitrification (1.9 g/day and 1.6 g/day). The corresponding increase in system denitrification in the Control (1.4 g/day) did not result in an increase in anoxic denitrification; in fact, the result was a decrease of 0.1 g/day. Denitrification in the aerobic zone was studied in order to determine the cause of this phenomenon.

Denitrification in the aerobic zone did not correspond to the observed NO_x levels seen in the aerobic zone, and appeared to be inversely proportional. 30%Cap, while having slightly lower NO_x levels, denitrified 1.8 g/day more than the Control. This was indicative of anoxic regions within the sponges where denitrifying bacteria had fixed themselves. 20%Cap also showed signs of having anoxic regions within the sponges. The fact that the average NO_x mass in the aerobic zone of 20%Cap was approximately 2 g/d less than the Control, and the fact that denitrification in the aerobic zone of 20%Cap was only 1.0 g/day less than the Control indicated that denitrification in 20%Cap was much more efficient. The higher rates of denitrification seen in the Captor trains was the cause of the lower NO_x levels in the aerobic zones of those trains.

Under spiked conditions, denitrification in the aerobic zone followed the same trend seen under normal conditions with respect to NO_x, but the Control denitrified to a greater extent than both 20%Cap and 30%Cap. The following rationale describes the cause of this performance reversal. During the week of October 14, 1993, prior to sampling of a majority of the spiked runs, the 20%Cap train was taken out of service. In an effort to maintain the sponges in suspension in the

30%Cap train, diffusers from the 20%Cap train were inserted into the aerobic cells of 30%Cap. The heavier turbulence achieved was effective in keeping the sponges from sinking and accumulating at the bottom of the aerobic cells. The turbulence also had an effect on the denitrification levels observed in the aerobic zones during spiked conditions. Higher aeration resulted in higher dissolved oxygen levels in the liquid surrounding the sponges. This in turn resulted in higher dissolved oxygen diffusion into the center of the sponges, decreasing the anoxic zone within the sponges. The ultimate result was a decrease in denitrification in the aerobic zone of the 30%Cap train.

The previous explanation is supported by the analytical results. The increase in system nitrification under spiked conditions seen in the Control directly corresponded to the increased nitrification in the aerobic zone. Aerobic zone denitrification in the Captor trains decreased under spiked conditions, as would be expected due to the higher oxygen transfer rate. The NO_x levels of the aerobic zones of the Control were nearly equal under normal and spiked conditions, but were also lower than levels observed for the Captor trains. The higher NO_x levels seen in the aerobic zone of 30%Cap directly impacted the anoxic denitrification rates, but not the aerobic zone denitrification because of the increased oxygen diffusion into to the centers of the sponges.

Captor vs. Ringlace, Phase 2, Aerobic MCRT 3.1 Days Figures 5-12 and 5-13 depict the denitrification values for each train during phase two. In this phase, both system nitrification and system denitrification in the 30%Cap train were greater than that achieved by Ringlace, and 20%Cap nitrified and denitrified approximately 3.5 g/day less than 30%Cap. The same was true under spiked conditions.

Anoxic denitrification again was a function of recycle NO_x levels under both normal and spiked conditions. Under normal conditions, Ringlace had the greatest anoxic denitrification and the greatest NO_x levels. The 30%Cap and 20%Cap had the middle and lowest denitrification and NO_x levels. Under spiked conditions, the denitrification / NO_x trend was 30%Cap (highest), 20%Cap (middle) and Ringlace (lowest).

Analysis of denitrification in the aerobic zone revealed that 20%Cap achieved the lowest denitrification rate under both normal and spiked conditions as a result of the lower system nitrification rates it achieved. When 30%Cap and Ringlace were studied, the inverse relationship between NO_x and denitrification was noted. Under normal conditions, 30%Cap outperformed Ringlace by 0.9 g/day, and 20%Cap by 2.8 g/day, while having lower NO_x levels than Ringlace and higher levels than 20%Cap. 20%Cap NO_x levels were low not because of high denitrification rates but because of low nitrification rates. Under spiked conditions, Ringlace outperformed both 20%Cap and 30%Cap, and had significantly lower NO_x levels as a result. It was thought that 30%Cap did not perform well because of an increased air supply to the aerobic zone which took effect the week of October 14, 1993 following the removal of the 20%Cap train from service. This change in aeration method was described in previous paragraphs when 30%Cap was compared to the Control.

Captor vs. Control, Phase 3, Aerobic MCRT 2.4 Days. Figures 5-14 and 5-15 depict the denitrification values calculated during phase three. As seen during phase two, the system nitrification to system denitrification ratios for 30%Cap and the Control observed during normal and spiked conditions were nearly identical because of the lack of ammonia limiting conditions. Denitrification under spiked conditions was 1.7 g/day greater in 30%Cap and only 0.4 g/day greater in the Control. The fact that 30%Cap nitrified nearly completely while the Control did not accounts for the difference.

Anoxic denitrification was again a function of aerobic zone NO_x levels. Aerobic zone denitrification rates decreased slightly in 30%Cap under spiked conditions, and increased slightly for the Control, although the values were virtually identical. Though increased air supply rates initiated during phase two were still being applied to 30%Cap, no other changes were made to the system. It was thus believed that the aerobic zone denitrification rates observed were indicative of the populations of denitrifiers present in the flocs and the interior of the sponges. Despite the increased air supply, 30%Cap apparently maintained a larger population of denitrifying bacteria in their anoxic center sections. The increased nitrification noted in the 30%Cap train helped increase denitrification in two ways, one being to cause increased NO_x levels in the recycle flows and the other being increased NO_x levels surrounding the anoxic portions of the sponges.

Captor vs. Control, Phase 4, Aerobic MCRT 1.7 Days. Figures 5-16 and 5-17 indicate that 30%Cap denitrified to a much greater extent in all zones, and that trends seen during phase three were repeated. The difference being the lower overall system nitrification and denitrification rates of the Control. Though ammonia limiting conditions did not occur under either condition, the increased influent ammonia levels seen under spiked conditions resulted in higher denitrification rates.

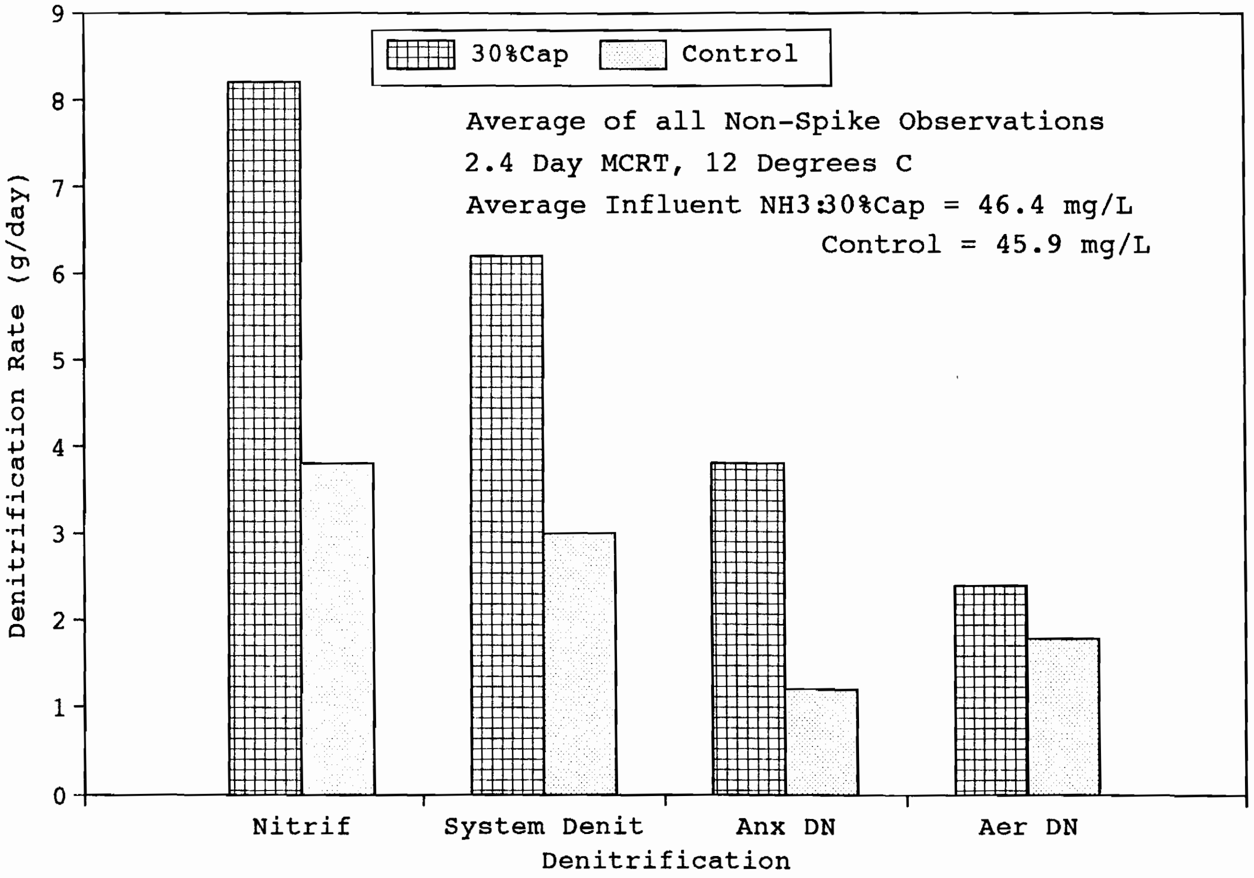


Figure 5-14. Denitrification under Normal Conditions, Phase Three

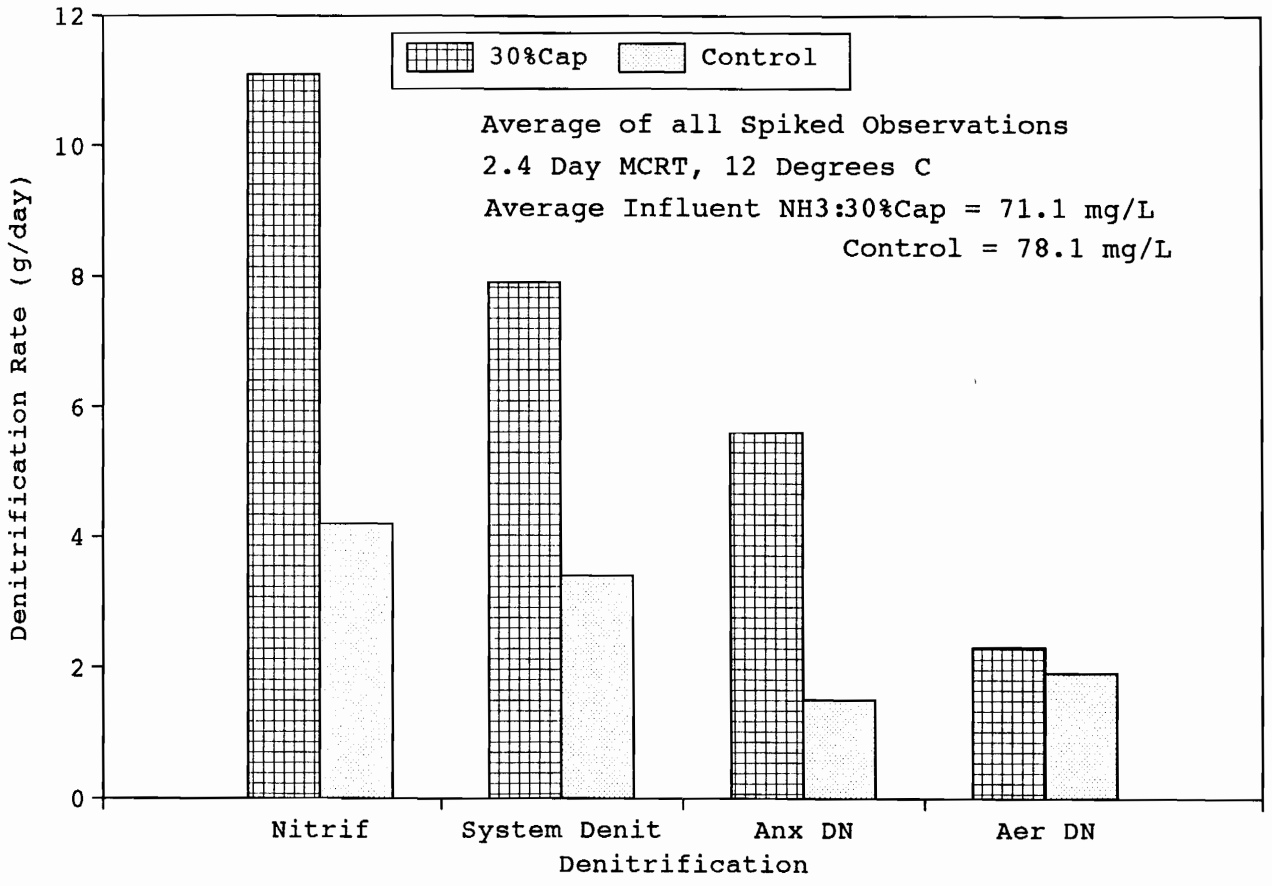


Figure 5-15.Denitrification under Spiked Conditions, Phase Three

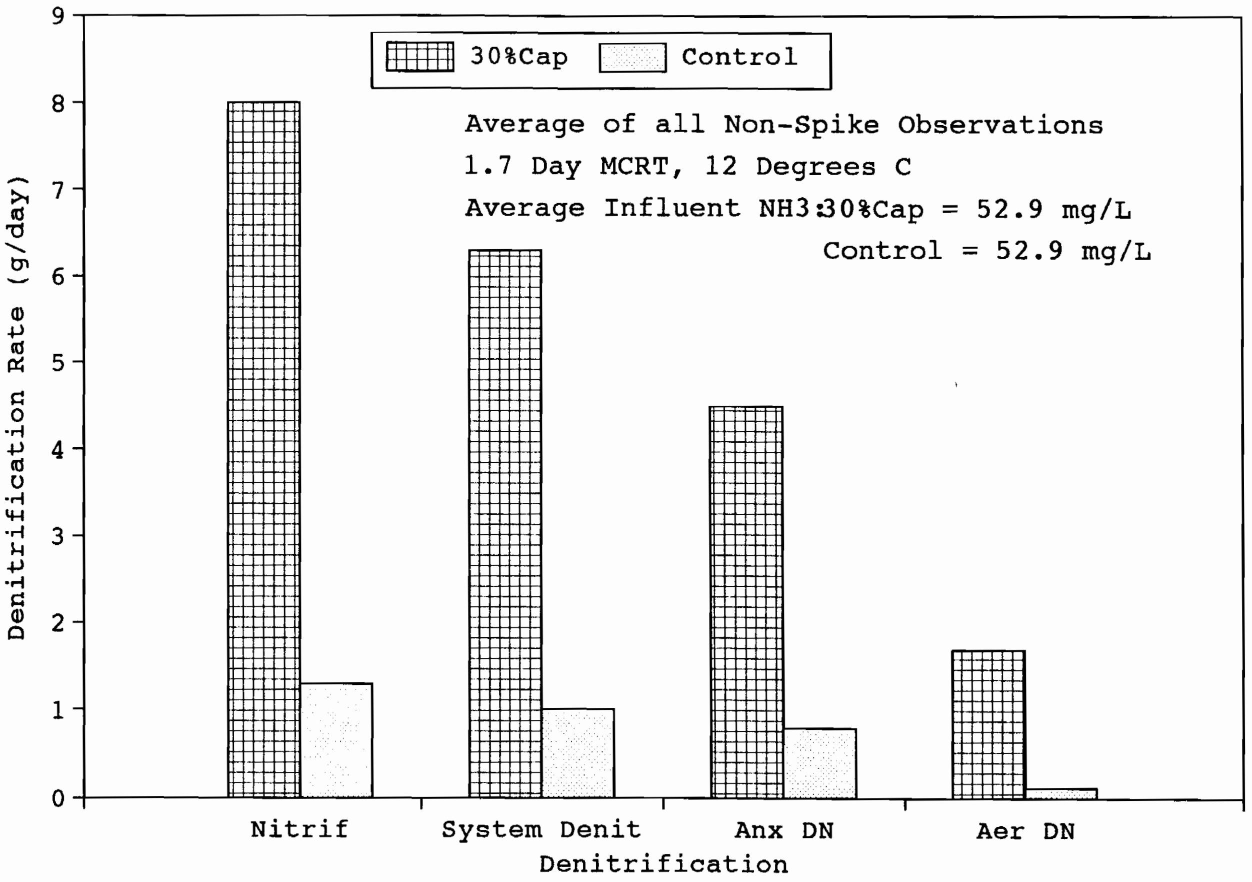


Figure 5-16. Denitrification under Normal Conditions, Phase Four

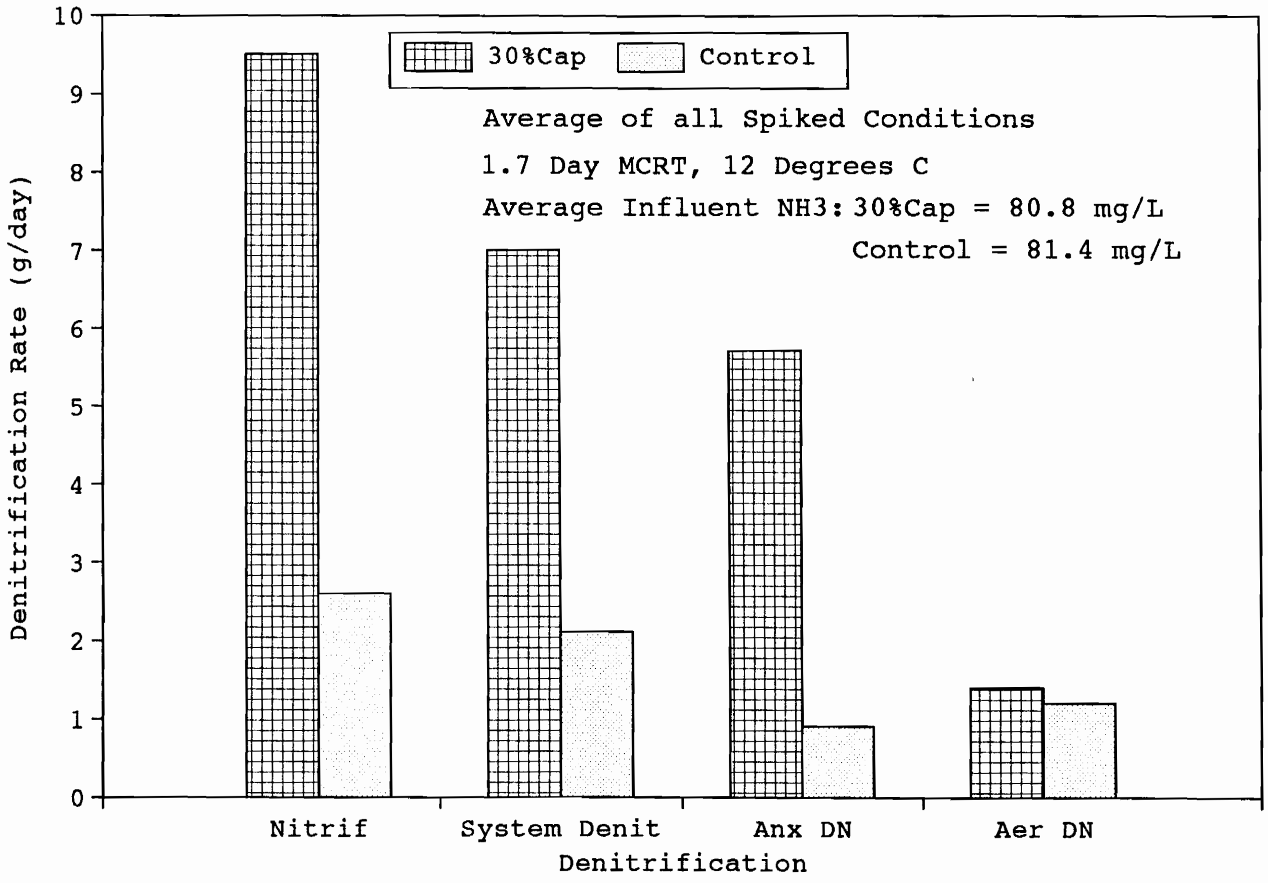


Figure 5-17. Denitrification under Spiked Conditions, Phase Four

Anoxic denitrification was directly related to NO_x levels in the recycle flows. Aerobic zone denitrification rates decreased in 30%Cap (by 0.3 g/day) under spiked conditions, but increased for the Control (by 1.1 g/day). This trend was noted in phase three as well, but not to such a great extent. This suggests an NO_x diffusion limitation into the center of the sponges or COD limitations such that denitrification was limited. It was suspected that, although SCOD levels during phase four were nearly identical to the levels noted during phase three, that COD stored within the organisms themselves had been depleted. This lack of stored COD available for the denitrifying organisms, combined with COD diffusion limitations caused by organisms on the surface of the sponges consuming SCOD before it could diffuse into the sponge, resulted in the inhibition of denitrification.

Specific Denitrification Rates

As it was with the nitrification rates, it was desired to determine the advantage in denitrification which occurred in the aerobic zone as a result of placing IFAS within the system, and to demonstrate that effect over the range of MCRTs studied. Differences in denitrification which occurred in the aerobic zone of the IFAS trains compared to the Control were divided by the aerobic volume, and system aerobic zone denitrification was divided by the quantity of suspended growth present in the aerobic zone and by the quantity of fixed growth present in the aerobic zone. Figure 5-18 depicts the effect of IFAS upon denitrification in the aerobic zone with respect to volume, as well as the percent increase in aerobic zone denitrification which IFAS produced. While denitrification in the aerobic zone is normally not a primary factor in sizing basins, quantification of denitrification which may occur in a given size basin can be very helpful to the design engineer attempting to remove nitrogen from a wastewater. Figure 5-19 illustrates the changing effect that both suspended growth and fixed growth had on the denitrification in the aerobic zone over the range of MCRTs studied.

Figure 5-18 indicates that the advantage of greater denitrification in the aerobic zone of the IFAS trains noted during analysis of each MCRT does not change appreciably when studied over the range of MCRTs studied. Although a slight increase in specific denitrification can be inferred during both normal and spiked conditions, the variation in the data makes it difficult to identify a trend. The nearly constant level at which aerobic zone denitrification was enhanced also indicated that specific denitrification was not affected appreciably by changes in MCRT. The lone data point

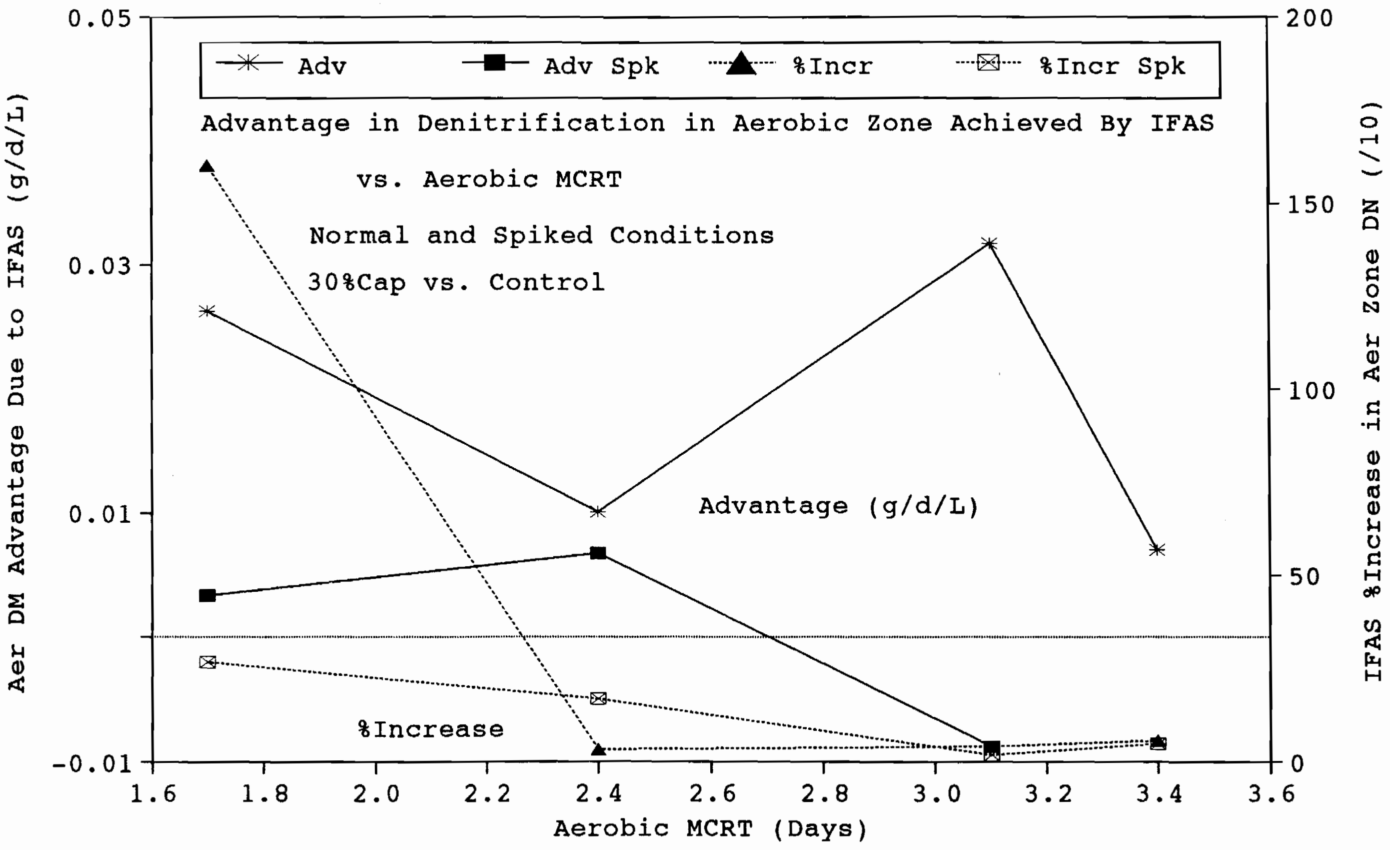


Figure 5-18. IFAS Denitrification Adv. in Aer Zone per Unit Volume.

at 1.7 days, normal conditions, where the percent increase in denitrification increases by nearly 160 times was a result of a very low denitrification rate in the Control. This low denitrification rate served as the denominator in the equation used to determine the percent increase, thus magnifying its effect. These results indicated that during all phases, sufficient COD sources and anoxic regions existed in the aerobic zone of both the 30%Cap train and the Control to accomplish denitrification.

Figure 5-19 depicts the changes in aerobic zone denitrification over the range of MCRTs studied with respect to the quantities of fixed and suspended growth in the aerobic zone. These rates varied in similar manners, decreasing as the MCRT decreased. The fact that the MLVSS concentrations and the aerobic zone denitrification rate dropped in similar manners led to the conclusion that the denitrification rate dropped at a greater rate that the loss of MLVSS alone would dictate. Thus both the fixed growth and the suspended growth aerobic zone denitrification rates were adversely affected by decreases in MCRT.

OPTIMUM PLACEMENT OF IFAS

Based upon the results of analysis undertaken during the experimental phase of this project, it was decided that 20%Cap would be taken out of service during the second phase. The problems with supplying air caused it to not perform well compared to 30%Cap in terms of both nitrification and denitrification, and the redundancy of having two Captor trains was no longer required. It was also decided that the Ringlace train would be taken out of service following phase two. This decision was made as a result of the preliminary analysis of system nitrification and denitrification during phase two, where it appeared that 30%Cap outperformed Ringlace in both nitrification and denitrification ability. Further experimentation on the use of Ringlace was expected to take place after Captor testing had been completed.

The decision to concentrate the analysis on 30%Cap and the Control appeared to have been justified during the detailed analysis performed in this section. The objective of determining the optimum placement of IFAS in and activated sludge treatment facility was fulfilled using extensive data for 30%Cap and Control performance. The results of that analysis are presented in the following paragraphs.

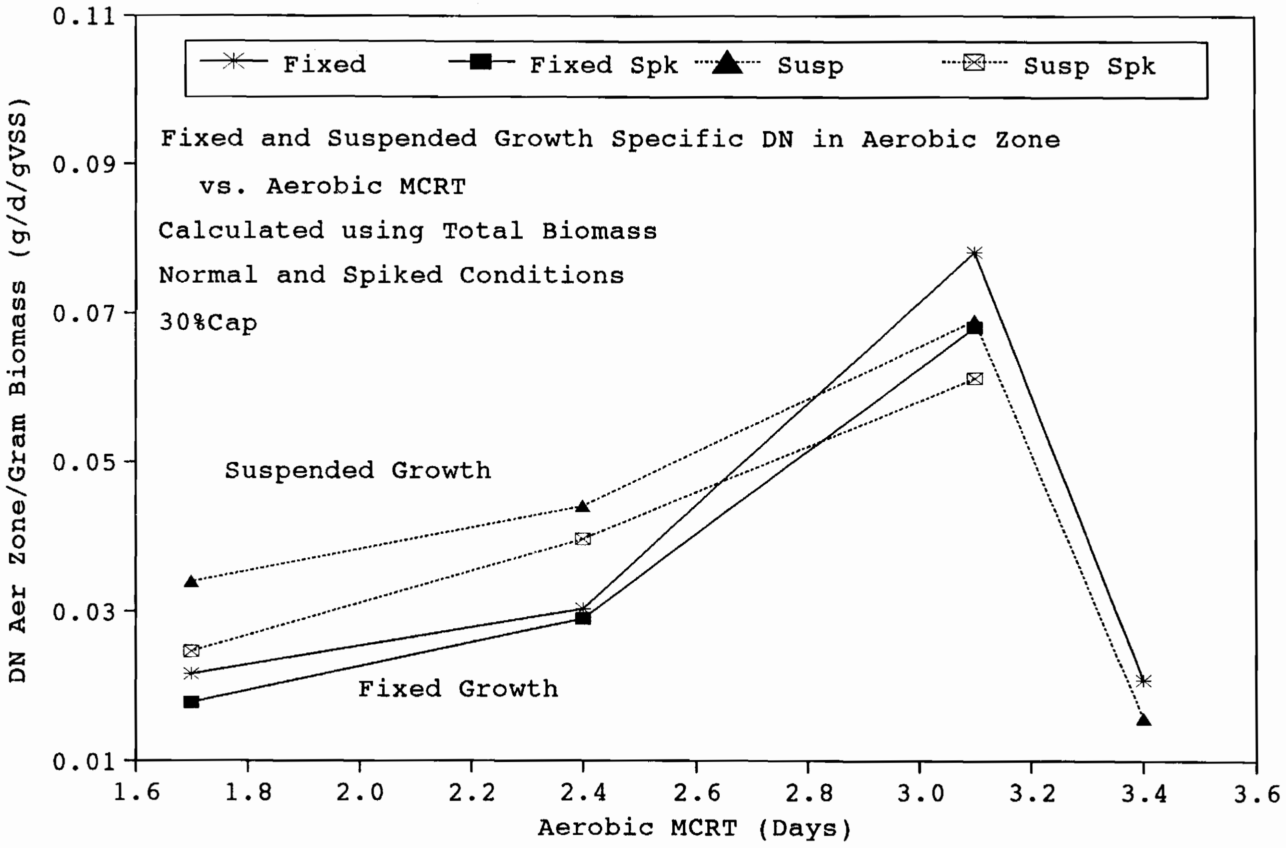


Figure 5-19. Fixed & Suspended Growth Specific Denitrification in Aer Zo

Nitrification / SCOD Relationship

In many of the preceding paragraphs reference was made to the effects of soluble COD on nitrification. In order to study those effects, average nitrification which occurred in the media in each of the aerobic cells was plotted, as were the average SCOD values. The relationship of SCOD to nitrification was then studied. COD stored within the bacterial cells was not analyzed.

The procedure to determine the nitrification which occurred in each aerobic cell involved the normalization of observed ammonia removals in each cell to the system nitrification rate. An assumption was made that all of the system nitrification occurred in the aerobic zones. The ratio of ammonia removal in a given cell divided by the total ammonia removal was applied to the system nitrification number to get the aerobic cell nitrification rate. The nitrification rate for the suspended growth, calculated using rates obtained from Sen (1994), was then subtracted. The remaining nitrification was attributed to growth on the IFAS. Details on the calculations are given in App. A.

Figure 5-20 depicts the nitrification / SCOD profile of the 30%Cap train at aerobic MCRT 3.4 days. Data for aerobic cell one was not taken. The nitrification rates and SCOD levels between aerobic cells two and three both declined simultaneously, though the SCOD concentrations declined at a faster rate. The rationale that higher SCOD concentrations inhibit nitrification cannot be confirmed, however, because of the limited data available for analysis.

All three aerobic cells were analyzed at aerobic MCRT 3.1 days, and the results are depicted in Figure 5-21. A dramatic increase in nitrification rate was observed between cell one and cell two. The simultaneous drop in SCOD levels indicated that SCOD had indeed limited the amount of nitrification that could take place in aerobic cell one. The higher SCOD levels allowed a greater population of heterotrophic bacteria to become established; these heterotrophs, having a much greater rate of growth than the nitrifying bacteria, effectively out-competed the nitrifiers for the available oxygen which further limited nitrifier growth. The decrease in nitrification noted between cell two and cell three can be attributed to a smaller population of nitrifiers that had been established in that cell. This smaller population was a result of consistently low ammonia concentrations which did not allow a large population to flourish. The fact that SCOD levels decreased at a greater rate than did nitrification values indicated that SCOD concentrations and nitrification were not interdependent. Nitrification attributed to the Captor sponges achieved its highest efficiency in aerobic cell two.

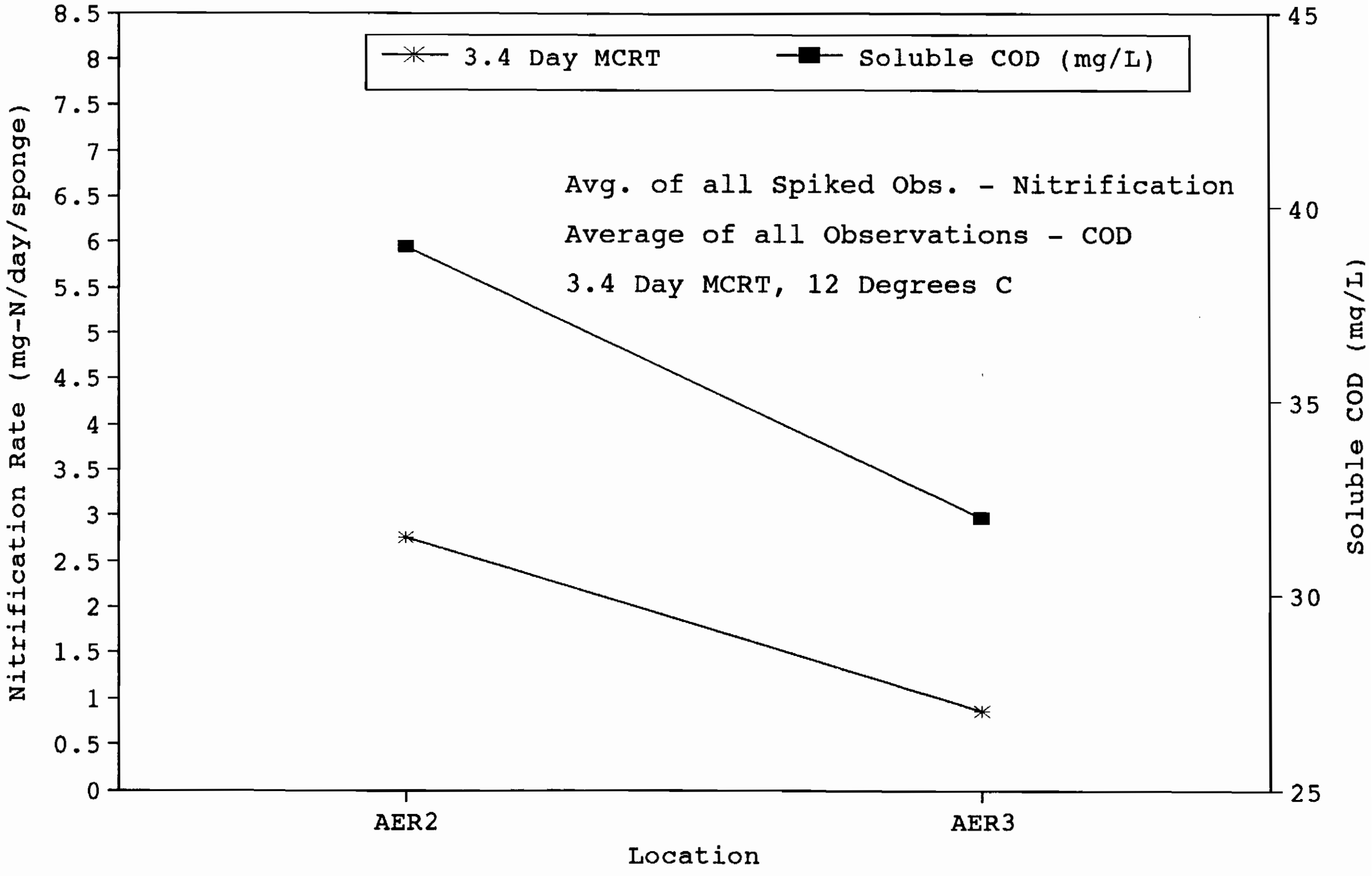


Figure 5-20. Nitr. Rates per Sponge vs COD Levels, Aer Zone, Phase One

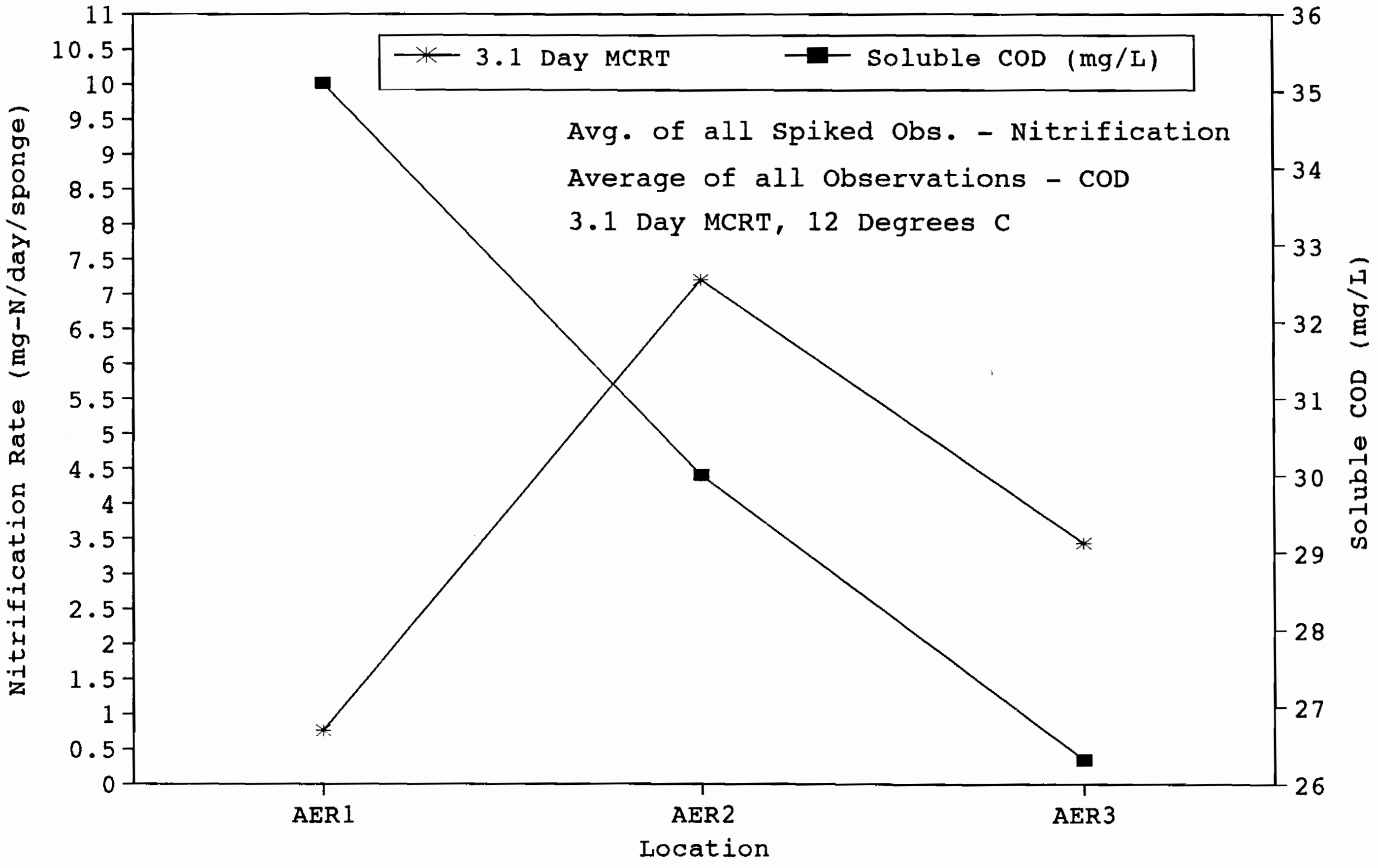


Figure 5-21. Nitr. Rates per Sponge vs COD Levels, Aer Zone, Phase Two

Figure 5-22 depicts the nitrification / SCOD profile of phase three. As was seen in phase two, an increase in nitrification was noted between cell one and cell two. An accompanying drop in SCOD levels, very similar to that seen in phase two, was also noted. Higher SCOD levels in aerobic cell one again appeared to limit the nitrification which could be achieved by the IFAS. When nitrification changes between cell two and cell three were studied, an increase in nitrification and a decrease in SCOD levels was again noted, indicating the effects of SCOD hindrances. The high level of nitrification achieved in cell three was due to a combination of higher ammonia levels in the cell than were present in phase two, and the decrease in SCOD. The decrease in SCOD allowed the nitrifying bacteria to establish a population that was dependent upon the ammonia concentration alone. Nitrification attributed to the Captor sponges achieved its highest efficiency in aerobic cell two.

Figure 5-23 depicts the nitrification / SCOD profile of phase four. A familiar pattern was noted in cells one and two, where a sharp decline in SCOD levels coincided with an increase in nitrification. The increase in nitrification was slightly smaller than that seen in phase three. Between cell two and cell three, SCOD levels dropped even further, but nitrification rates decreased. As stated in the discussion for phase two, the nitrification rate of the IFAS in cell three was more dependent upon the average ammonia concentrations seen in that cell than it was on SCOD levels. Average ammonia concentrations in aerobic cell three during normal conditions (where the population became established) were approximately 4 mg/L less than concentrations seen during phase three. This accounted for the smaller population, and thus the lesser nitrification. Nitrification attributed to Captor sponges again achieved its highest efficiency in aerobic cell two.

Stored COD

Although COD which was stored in the bacterial cells was not measured, the effects of stored COD may be inferred by studying the nitrification / SCOD profiles. It would be expected that SCOD levels would decrease as the hydraulic flow moved from cell one to cell two to cell three. This was not what happened. During each phase, SCOD levels were nearly constant between each of the cells. The increase in MLVSS values between the three cells indicated that cell growth was going on in these cells. The constant SCOD values and the presence of cell growth implied that stored COD was being utilized to achieve that growth. It would also be expected that the zones

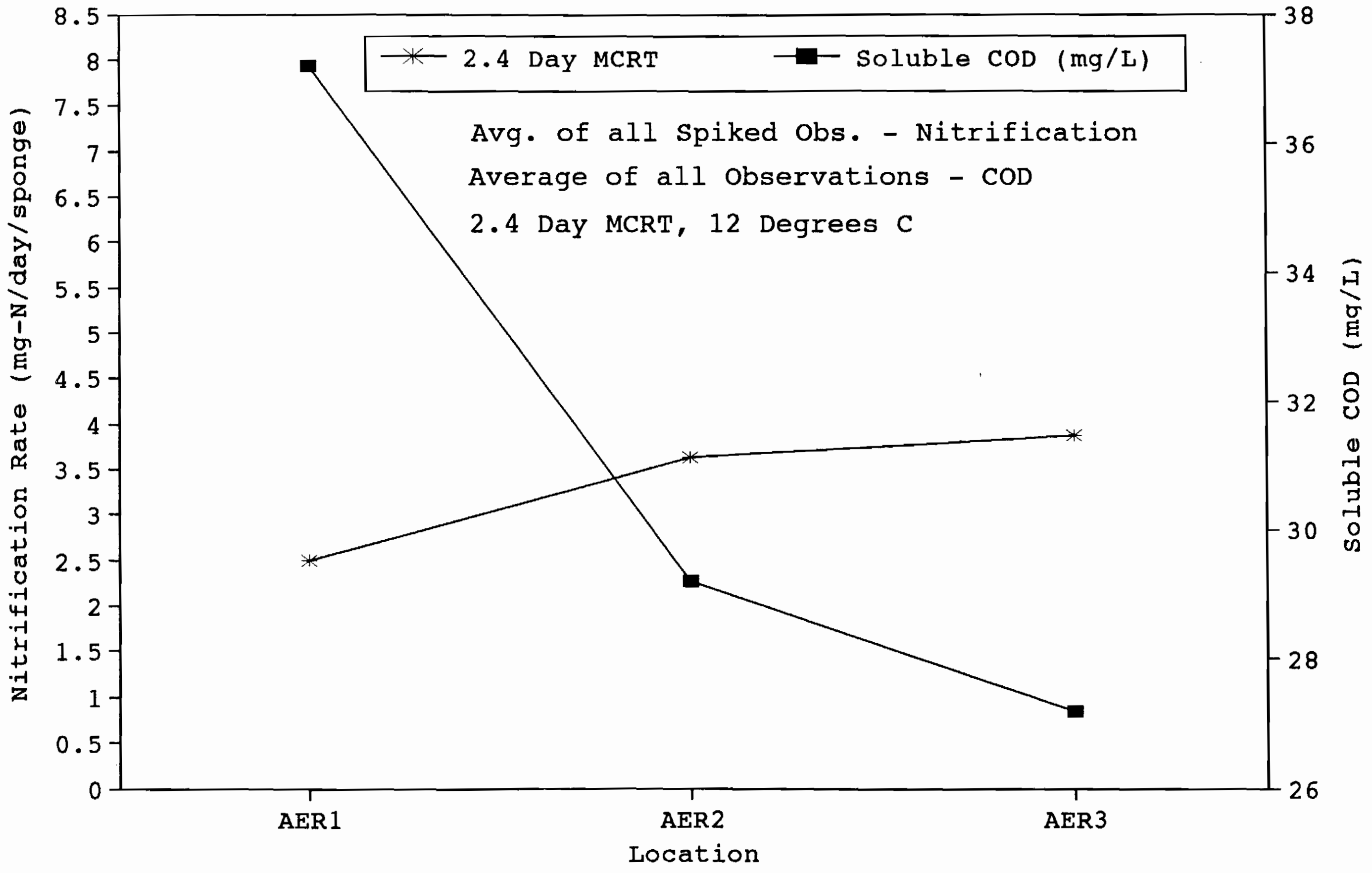


Figure 5-22. Nitr. Rates per Sponge vs COD Levels, Aer Zone, Phase Three

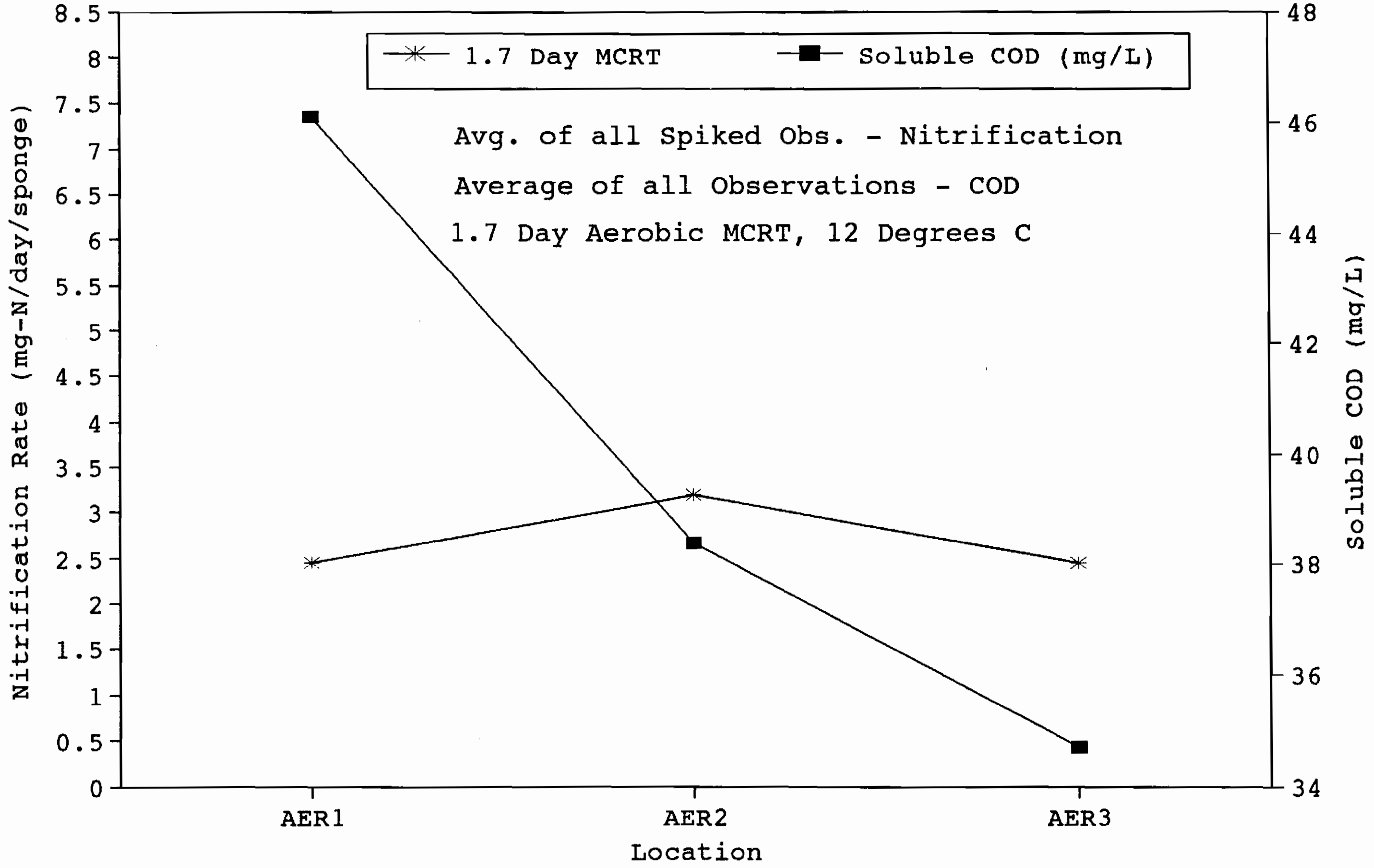


Figure 5-23. Nitr. Rates per Sponge vs COD Levels, Aer Zone, Phase Four

within the treatment trains where SCOD removal occurred would shift toward the third aerobic zone as the MCRT decreased. This would occur because at low MCRTs, the amount of time which a given bacterial cell is in contact with substrate diminished as the MCRT decreases. This would tend to limit COD uptake, particularly in the anoxic zone and the first aerobic zone, thus shifting higher COD loads (both SCOD and stored COD) to the second and third aerobic zones. Higher COD loads in the second and third cells would in turn tend to limit nitrification by increasing the heterotroph population in those cells.

When the nitrification / SCOD profiles for phases two, three and four were studied, it was apparent that stored COD was affecting the nitrification occurring in aerobic cell two. The sharp rise in nitrification noted in cell two during phase two was indicative of low stored COD. The low stored COD and SCOD levels produced conditions that were right for nitrification to occur. In phase three, a very similar drop in SCOD levels only produced a modest increase in nitrification in aerobic cell two. COD levels, in this case, stored COD levels, were apparently higher in cell two during phase three than phase two, limiting the amount of nitrification which could occur. The stored COD may have been used for bacterial growth prior to reaching cell three, allowing increased nitrification to occur in cell three. Similar results were noted in phase four. A sharp drop in SCOD levels produced only a small increase in nitrification in aerobic cell two. Continued decreases in the SCOD level in cell three did not correspond to another increase in nitrification. The small increase in nitrification in cell two can be attributed to the presence of stored COD, as was the case in phase three. The drop in nitrification in cell three, attributed to lower ammonia levels leading to a smaller population of nitrifiers, was also undoubtedly affected by the shift of stored COD in the cell mass to cell three as a result of the low 1.7 day MCRT. Further study must be done on SCOD, stored COD and nitrification rates to confirm the relationship postulated here.

SLUDGE YIELD

Figure 5-24 illustrates the effect that decreasing MCRTs had on the observed sludge yield coefficients of the suspended growth in both the 30%Cap and Control trains. Though an increase in sludge yield as the MCRT decreased seemed to be the case in both trains, the data was far too varied and the number of data points too few to realistically conclude that observed sludge yield increased as the MCRT decreased.

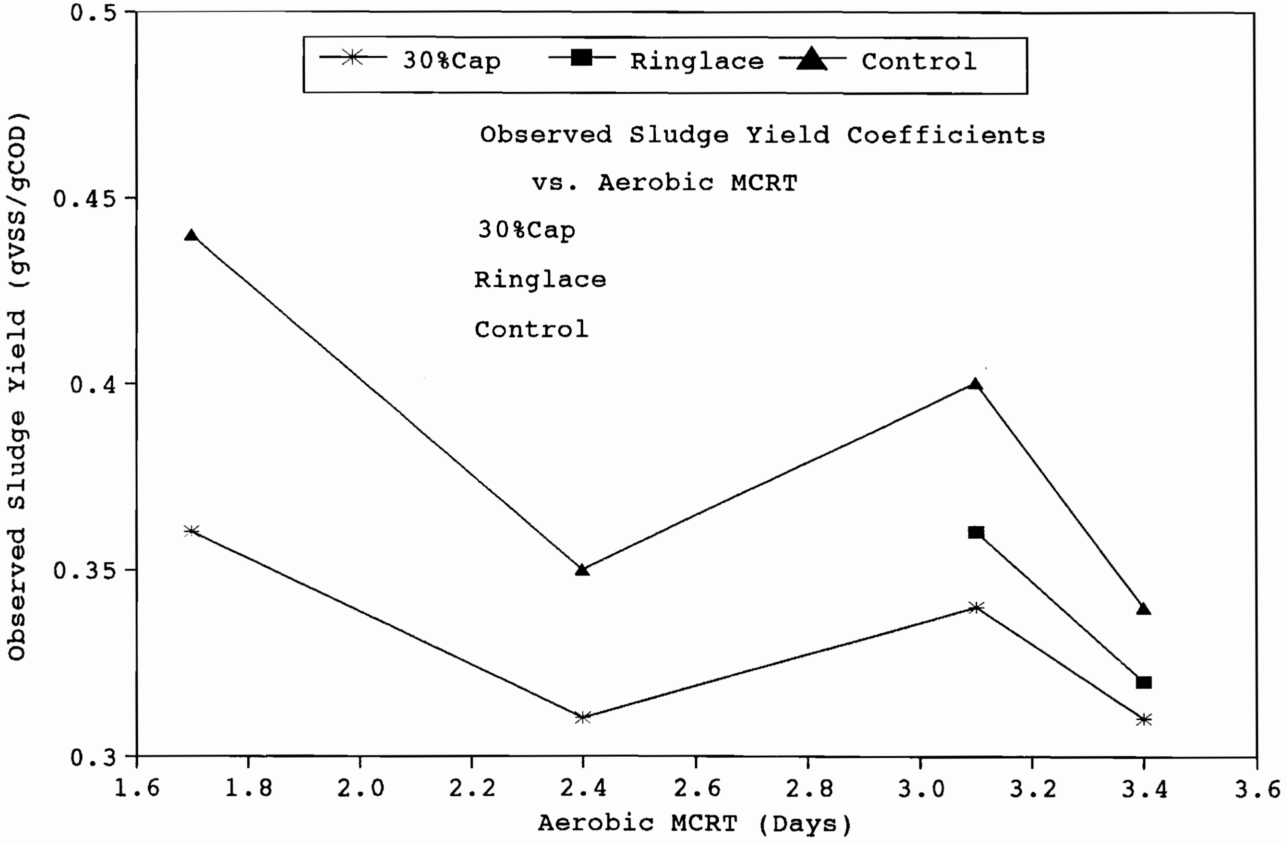


Figure 5-24. Observed Sludge Yield Coefficients

CHAPTER SIX: CONCLUSIONS

The following conclusions were drawn from the experiments.

1. Integration of fixed film media into a biological nutrient removal activated sludge system enhances its ability to maintain a population of nitrifying bacteria. Captor media, in a 30% by volume quantity, enhances this ability to a greater degree than does Ringlace media.

2. The enhanced ability of fixed film media to maintain a population of nitrifying bacteria results in a statistically verified increase in nitrogen removal at low temperatures and low aerobic MCRTs.

3. Integration of fixed film media into a biological nutrient removal activated sludge system could not be proven to enhance its ability to achieve denitrification in the aerobic zone.

4. The optimal placement of fixed film media within the aerobic zone is a function of total COD (soluble, stored, and suspended) concentrations within each cell of the aerobic zone. In the range of MCRTs studied, the optimum placement was aerobic cell two, followed by aerobic cell three.

5. The use of IFAS could not be proven to result in lower total sludge production when compared to the Control. The use of IFAS does result in consistently lower sludge yields.

Further study is required to further quantify the effects of total COD levels on the most effective placement of fixed film media for enhancement of both nitrification and denitrification.

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APPENDIX A: DESCRIPTION OF CALCULATIONS

A-1 Derivation of Formula used in Phase One to Calculate Suspended Growth Mean Cell Residence Time

The definition of Mean Cell Residence Time is:

$$MCRT = \text{Mass of cells in total reactor volume/Mass of cells wasted per day} \quad \textbf{(1)}$$

Put in terms of operating parameters, it can be stated as:

$$MCRT = \Theta_c = V * X / Q_w * X + (Q - Q_w) * X_e \quad \textbf{(2)}$$

where:

MCRT = suspended growth mean cell residence time (d)
V = volume of reactor (106 L)
X = MLSS concentration in reactor, aerobic cell three (mg/L)
Q_w = sludge wasting rate (L/d)
Q = flow rate of the influent (L/d)
X_e = effluent suspended solids concentration (mg/L)

Equation (2) can also be written as:

$$\Theta_c * [Q_w * X + (Q - Q_w) * X_e] = V * X \quad \textbf{(3)}$$

Which can be simplified to:

$$(\Theta_c * Q_w * X) + (\Theta_c * Q * X_e) - (\Theta_c * Q_w * X_e) = V * X \quad \textbf{(4)}$$

or:

$$Q_w * [(\Theta_c * X) - (\Theta_c * X_e)] = (V * X) - (\Theta_c * Q * X_e) \quad \textbf{(5)}$$

Which can be further simplified to:

$$Q_w = (V * X) - (\Theta_c * Q * X_e) / [(\Theta_c * X) - (\Theta_c * X_e)] \quad \textbf{(6)}$$

For example, if X = 1220 mg/L, Θ_c = 4.2 days, Q = 207.4 L/d and X_e = 30 mg/L, the sludge wasting rate would be:

$$Q_w = [(106 * 1220) - (4.2 * 207.4 * 30)] / [(4.2 * 1220) - (4.2 * 30)] = 20.6\ L/d$$

A-2 Derivation of Formula used in Phases 2, 3, and 4 to Calculate Suspended Growth MCRT

Equation (2) can also be written as:

$$\theta_{cAER} = (V_{AER} * X * AVF) / [(Q_{INF} - Q_w) * X_e + (Q_w * X)] \qquad \textbf{(7)}$$

where:

θ_{cAER} = aerobic suspended growth MCRT (d)
V_{AER} = volume of aerobic zone (69.2 L)
X = MLSS concentration in reactor, aerobic cell three (mg/L)
AVF = aerobic volume factor, calculated as described in chapter 3
Q_{INF} = influent flow rate (L/d)
X_e = effluent suspended solids concentration (mg/L)
Q_w = sludge wasting rate (L/d)

Rearranging the expression:

$$\theta_{cAER} * [(Q_{INF} - Q_w) * X_e + (Q_w * X)] = V_{AER} * X * AVF \qquad \textbf{(8)}$$

Equation (8) can also be written as:

$$(\theta_{cAER} * Q_{INF} * X_e) - (\theta_{cAER} * Q_w * X_e) + (\theta_{cAER} * Q_w * X) = V_{AER} * X * AVF \qquad \textbf{(9)}$$

Further simplified:

$$\theta_{cAER} * (Q_{INF} * X_e) + [(\theta_{cAER} * Q_w) * (X - X_e)] = V_{AER} * X * AVF \qquad \textbf{(10)}$$

This reduces to:

$$Q_w = [(V_{AER} * X * AVF) - (\theta_{cAER} * Q_{INF} * X_e)] / [\theta_{cAER} * (X - X_e)] \qquad \textbf{(11)}$$

For example, if θ_{cAER} = 2.4 days, AVF = 0.88, X = 1220 mg/L, X_e = 30 mg/L, V_{AER} = 69.2 L and Q_{INF} = 207.4 L/d, then the sludge wasting rate is:

$$Q_w = [(69.2 * 1220 * 0.88) - (2.4 * 207.4 * 30) / [2.4 * (1220 - 30)] = 20.8 \text{ L/d}$$

A-3 Procedure for Calculating Percentage of Nitrogen in Sludge

The equation used was:

$$\% N_{sludge} = [(AER3_{TKN} - AER3_{SKN})/MLSS] * 100 \qquad \textbf{(12)}$$

where:

$\% N_{sludge}$ = percent nitrogen in sludge
$AER3_{TKN}$ = TKN measured in aerobic cell three; includes soluble organic nitrogen and ammonia as well as N bound in sludge (mg/L)
$AER3_{SKN}$ = SKN measured in aerobic cell three; includes soluble organic nitrogen and ammonia (mg/L)
MLSS = mixed liquor suspended solids, aerobic cell three (mg/L)

For example, if $AER3_{TKN}$ = 151 mg/L, $AER3_{SKN}$ = 10 mg/L and the MLSS was 1220 mg/L, then the percent nitrogen in the sludge would be:

$$\% N_{sludge} = [(151 - 10) / 1220] * 100 = 11.6\%$$

A-4 Procedure for Calculating Percentage of Phosphorus in Sludge

The equation used was:

$$\% P_{sludge} = [(AER3_{TP} - AER3_{OP})/MLSS] * 100 \qquad \textbf{(13)}$$

where:

% P = percent phosphorus in sludge
$AER3_{TP}$ = total phosphorus measured in aerobic cell three; includes soluble P and P bound in sludge (mg/L)
$AER3_{OP}$ = ortho-phosphorus measured in aerobic cell three; includes soluble OP (mg/L)
MLSS = mixed liquor suspended solids, aerobic cell three (mg/L)

For example, if $AER3_{TP}$ = 26.4 mg/L, $AER3_{OP}$ = 5.4 mg/L and the MLSS was 1220 mg/L, then the percent phosphorus in the sludge would be:

$$\% P_{sludge} = [(26.4 - 5.4) / 1220] * 100 = 1.7\%$$

A-5 Procedure for Calculating the Nitrification (NH_3 to NO_2^--N) Mass Balance

The equation used was:

$$Nitrification = [Q_{INF} * (INF_{TKN} - EFF_{SKN})/1000] - (\% N_{sludge} * Q_w) \qquad \textbf{(14)}$$

where:

Nitrification = organic nitrogen and ammonia oxidized to NO_2^--N (g/d)
Q_{INF} = influent flow rate (L/d)
INF_{TKN} = influent TKN; includes all organic nitrogen and ammonia (mg/L)
EFF_{SKN} = SKN measured in effluent; includes soluble organic N and ammonia (mg/L)
% N_{sludge} = percent nitrogen in sludge, stated as decimal
Q_w = average sludge wasting rate (L/d)

The term involving Q_w and % N denotes the amount of nitrogen assimilated by bacteria. This equation assumes that all organic nitrogen and ammonia not assimilated by bacteria or discharged in the effluent has been oxidized. For example, if influent TKN = 55 mg/L, effluent SKN = 3.2, average sludge wasting rate = 31 L/d, % N = 10.5% and Q_{INF} = 207.4 L/d, the oxidation of nitrogen to nitrite would be:

$$Nitrification = [207.4 * (55 - 3.2)/1000] - (0.105 * 31) = 7.49\ g/d$$

A-6 Procedure for Calculating the Nitratification (NO_2^--N to NO_3^--N) Mass Balance

The equation used was:

$$Nitratification = Nitrification - [(Q_{EFF} * EFF_{NO2\text{-}N})/1000] \qquad \textbf{(15)}$$

where:

Nitratification = quantity of NO_2^--N generated which has been oxidized to NO_3^--N (g/d)
Nitrification = organic nitrogen and ammonia oxidized to NO_2^--N (g/d)
Q_{EFF} = effluent flow rate; equal to influent flow rate (L/d)
$EFF_{NO2\text{-}N}$ = concentration of NO_2^--N measured in effluent (mg/L)

For example, if Nitrification = 7.49 g/d, Q_{EFF} = 207.4 L/d and $EFF_{NO2\text{-}N}$ = 2.1 mg/L, the oxidation of NO_2^--N to NO_3^--N would be:

$$Nitratification = 7.49 - [(207.4 * 2.1)/1000] = 7.05\ g/d$$

A-7 Procedure for Calculating the System Denitrification Mass Balance

The equation used was:

$$DN_{system} = Nitrification - [(Q_{EFF} \backslash 1000) * (EFF_{NO2\text{-}N} + EFF_{NO3\text{-}N})] \tag{16}$$

where:

DN_{system} = quantity of oxidized nitrogen reduced to N_2 gas (g/d)
Nitrification = organic nitrogen and ammonia oxidized to NO_2^--N (g/d)
Q_{EFF} = effluent flow rate; equal to influent flow rate (L/d)
$EFF_{NO2\text{-}N}$ = concentration of NO_2^--N measured in effluent (mg/L)
$EFF_{NO3\text{-}N}$ = concentration of NO_3^--N measured in effluent (mg/L)

For example, if Nitrification = 7.49 g/d, Q_{EFF} = 207.4 L/d, $EFF_{NO2\text{-}N}$ = 2.1 mg/L and $EFF_{NO3\text{-}N}$ = 7.4 mg/L, the amount of denitrification throughout the system would be:

$$DN_{system} = 7.49 - [(207.4/1000) * (2.1 + 7.4)] = 5.52 \text{ g/d}$$

A-8 Procedure for Calculating Denitrification Occurring in the Anoxic Zone

The equation used was:

$$ANX\,DN = [(Q_{NR} + Q_{RAS}) * (AER3_{NO2\text{-}N} + AER3_{NO3\text{-}N})$$

$$- (Q_{INF} + Q_{MLR} + Q_{NR} + Q_{RAS}) * (ANX2_{NO2\text{-}N} + ANX2_{NO3\text{-}N})]/1000 \tag{17}$$

where:

ANX DN = denitrification occurring in the anoxic zone (g/d)
Q_{INF} = influent flow rate (L/d)
Q_{MLR} = mixed liquor return rate
Q_{NR} = nitrate recycle flow rate (L/d)
Q_{RAS} = return activated sludge flow rate (L/d)
$AER3_{NO2\text{-}N}$ = concentration of NO_2^--N measured in aerobic cell three
$AER3_{NO3\text{-}N}$ = concentration of NO_3^--N measured in aerobic cell three
$ANX2_{NO2\text{-}N}$ = concentration of NO_2^--N measured in anoxic cell two
$ANX2_{NO3\text{-}N}$ = concentration of NO_3^--N measured in anoxic cell two

This equation assumes that the only oxidized nitrogen available for denitrification in the anoxic zone comes from the nitrate recycle and the return activated sludge. In other words, no oxidized nitrogen enters the anoxic zone from the anaerobic zone. Also, any denitrification which may occur in the recycle lines or in the deoxygenation zone is considered to have occurred in the anoxic zone. For example, if $Q_{INF} = Q_{MLR} = Q_{NR} = Q_{RAS} = 207.4$ L/d, $AER3_{NO2\text{-}N} = 2.1$ mg/L, $AER3_{NO3\text{-}N} = 7.4$ mg/L, $ANX2_{NO2\text{-}N} = 0.1$ mg/L, and $ANX2_{NO3\text{-}N} = 0.2$ mg/L, then the system denitrification would be:

$$ANX\ DN = [(207.4 + 207.4) * (2.1 + 7.4) - (4 * 207.4) * (0.1 + 0.2)]/1000 = 0.17\ g/d$$

A-9 Procedure for Calculating Denitrification Occurring in the Aerobic Zone

The equation used was:

$$AER\ DN = DN_{system} - ANX\ DN \tag{18}$$

where:

AER DN = denitrification occurring in the aerobic zone (g/d)
DN_{system} = quantity of oxidized nitrogen reduced to N_2 gas in the entire system (g/d)
ANX DN = denitrification occurring in the anoxic zone (g/d)

Any denitrification which may occur in the secondary clarifier (as noted by different nitrite and nitrate concentrations measured in the third aerobic zone and in the effluent) is considered to have occurred in the aerobic zone. For example, if $DN_{system} = 5.52$ g/d and ANX DN = 3.69 g/d, then the denitrification occurring in the aerobic zone would be:

$$AER\ DN = 5.52 - 3.69 = 1.83\ g/d$$

A-10 Procedure for Calculating the Percentage of Denitrification Occurring in the Aerobic Zone

The equation used was:

$$\%\ AER\ DN = (AER\ DN / DN_{system}) * 100 \tag{19}$$

where:

% AER DN = percentage of denitrification occurring in aerobic zone
AER DN = denitrification occurring in the aerobic zone (g/d)
DN_{system} = quantity of oxidized nitrogen reduced to N_2 gas in the entire system (g/d)

For example, if AER DN was 1.83 g/d and DN_{system} was 5.52 g/d, the percentage of denitrification occurring in the aerobic zone would be:

$$\% \, AER \, DN = (1.83/5.52) * 100 = 33\%$$

A-11 Procedure for Calculating the Percentage of System Nitrification

The equation used was:

$$\% \, Nitrif = Nitrification \, / \, [(Q_{INF} * INF_{TKN}/1000) - (\% \, N_{sludge} * Q_w)] \qquad \textbf{(20)}$$

where:

% Nitrif = amount of available nitrogen which has been oxidized; available nitrogen includes all organic nitrogen and ammonia in influent minus the amount of nitrogen assimilated into bacteria
Nitrification = organic nitrogen and ammonia oxidized to NO_2^--N (g/d)
Q_{INF} = influent flow rate (L/d)
INF_{TKN} = influent TKN; includes all organic nitrogen and ammonia (mg/L)
$\% \, N_{sludge}$ = percent nitrogen in sludge; expressed as decimal
Q_w = sludge wasting rate (L/d)

This equation represents the amount of organic nitrogen and ammonia that is removed by bacterial oxidation, whether it is to NO_2^--N or NO_3^--N. For example, if nitrification = 7.49 g/d, Q_{INF} = 207.4 L/d, INF_{TKN} = 55 mg/L, $\% \, N_{sludge}$ = 0.105 and Q_w = 31 L/d, the percentage of system nitrification would be:

$$\% \, Nitrif = 7.49 \, / \, [(207.4 * 55/1000) - (0.105 * 31)] = 92\%$$

A-12 Procedure for Calculating Nitrification Occurring in Individual Aerobic Cells

First, the ammonia removal in each cell was calculted; the equation used was:

$$NH_{3rem} \, AER1 = (Q_{INF} + NR + RAS)/1000 * [ANX2_{NH3\text{-}N} - AER1_{NH3\text{-}N}] + Nitr \, AER1 \qquad \textbf{(21)}$$

where:

NH_{3rem} AER1 = ammonia removal (NH_3 to NO_2^--N and NO_3^--N) occurring in aerobic cell one (g/d)
Q_{INF} = influent flow rate (L/d)
NR = nitrate return flow rate (L/d)
RAS = return activated sludge flow rate (L/d)
$ANX2_{NH3-N}$ = NH_3-N concentration measured in anoxic cell two (mg/L), taken to be the concentration entering the first aerobic cell
$AER1_{NH3-N}$ = NH_3-N concentration measured in aerobic cell one (mg/L), taken to be the concentration leaving the first aerobic cell

This equation does not take into account the increased amount of nitrogen assimilated in the biomass due to the higher mixed liquor of aerobic cell one. However, for the purpose of this research, the effect of that increased assimilation is considered to by negligible. For example, if Q_{INF} = 207.4 L/d, NR = RAS = 207.4 L/d, $ANX2_{NH3-N}$ = 16 mg/L, and $AER1_{NH3-N}$ = 12.5 mg/L, then the ammonia removal occurring in aerobic cell one is:

$$NH_{3rem}\ AER1 = (207.4 + 207.4 + 207.4) / 1000 * (16 - 12.5) = 2.17\ g/d$$

Similar calculations were carried out for aerobic cells two and three using ammonia-N concentrations for each cell. For example, to calculate Nitr AER2, the ammonia levels in cells AER1 and AER2 would be used instead of cells ANX2 and AER1.

Next, the ammonia removals were normalized to reflect the system nitrification values. The equation used was:

$$Cell\ Nitr = Nitr/Sum\ NH_{3REM}\ Aer\ Cells * NH_{3REM}\ Cell\ (1,2\ or\ 3) \qquad \textbf{(22)}$$

where:

Cell Nitr = nitrification in an aerobic cell (g/d)
Nitr = system nitrification as calculated in section A-5 (g/d)
Sum NH_{3REM} Aer Cells = sum of NH_3-N removals in aerobic cells (g/d)
NH_{3REM} Cell (12 or 3) = NH_3-N removal in an aerobic cell (g/d)

For example, if NH_{3REM} for aerobic cells 1, 2, and 3 are 1.4, 2.4, and 1.7 g/d each, and Nitr = 5.3 g/d, the nitrification occurring in aerobic cell 2 would be:

$$Cell\ Nitr\ AER2 = [5.3 / (1.4 + 2.4 + 1.7)] * 2.4 = 2.3\ g/d \qquad \textbf{(23)}$$

A-13 Procedure for Calculating Denitrification Occurring in Individual Aerobic Cells

First, denitrification in each cell was calculated using NO_x values. The equation used was:

$$AER1\ DN = (Q_{INF} + NR + RAS)/1000 * [ANX2_{(Nox)} - AER1_{(Nox)}] + Nitr\ AER1 \qquad \textbf{(24)}$$

where:

AER1 DN = denitrification occurring (NH_3 to NO_2^--N and NO_3^--N) in aerobic cell one (g/d)
Q_{INF} = influent flow rate (L/d)
NR = nitrate return flow rate (L/d)
RAS = return activated sludge flow rate (L/d)
$ANX2_{(Nox)}$ = concentration of NO_2^--N and NO_3^--N measured in anoxic cell two (mg/L), taken to be the oxidized nitrogen entering aerobic cell one
$AER1_{(Nox)}$ = concentration of NO_2^--N and NO_3^--N measured in aerobic cell one (mg/L), taken to be the oxidized nitrogen leaving aerobic cell one
Nitr AER1 = nitrogen oxidation occurring in aerobic cell one (g/d)

For example, if Q_{INF} = NR = RAS = 207.4 L/d, $ANX2_{(NO2\text{-}N+NO3\text{-}N)}$ = 0.3 mg/L, $AER1_{(NO2\text{-}N+NO3\text{-}N)}$ = 3.5 mg/L and Nitr AER1 = 2.11 g/d, then the denitrification occurring in aerobic cell one is:

$$AER1\ DN = (207.4 + 207.4 + 207.4)/1000 * (0.3 - 3.5) + 2.11 = 0.12\ g/d$$

Similar calculation were carried out for aerobic cells two and three using NO_2^--N and NO_3^--N concentrations for the respective cells, and the calculated values of Nitr AER2 and Nitr AER3.

The cell denitrification values were then normalized to the total aerobic denitrification values, as was done for the aerobic cell nitrification values. The equation used was:

$$Cell\ Denitr = Aer\ DN/Sum\ DN\ Aer\ Cells * DN\ Cell\ (1,2\ or\ 3) \qquad \textbf{(25)}$$

For example, if the aerobic zone denitrification was 0.5 g/d, AER1 DN = 0.1 g/d, AER2 DN = 0.2 g/d, AER3 DN = 0.1 g/d, and the DN cell from above = 0.12 g/d, then the Cell Denitr would be:

$$Cell\ Denitr = 0.5 / (0.1 + 0.2 + 0.1) * 0.12 = 0.15\ g/d$$

A-14 Procedure for Calculating System Sludge Production

The equation used was:

$$Sludge\ Prod = (V_{AER} * AVF) / MCRT_{AER} * (MLSS/1000) \quad \textbf{(26)}$$

where:

Sludge Prod = amount of sludge produced (g/d)
V_{AER} = volume of aerobic zone (69.2 L)
AVF = aerobic volume factor, calculated as described in chapter 3
$MCRT_{AER}$ = operating aerobic MCRT (d)
MLSS = mixed liquor suspended solids, aerobic cell three (mg/L)

Since $MCRT_{AER}$ is a function of the total volume to aerobic volume ratio, this equation would yield the same answer if total volume and total MCRT were used. The equation also accounts for the effluent suspended solids in the $MCRT_{AER}$ term. For example, if $MCRT_{AER}$ = 3.1 days, MLSS = 1220 mg/L, AVF = 0.88 and V_{AER} = 69.2 L, the sludge production would be:

$$Sludge\ Prod = (69.2 * 0.88) / 3.1 * (1220/1000) = 24.0\ g/d$$

A-15 Procedure for Calculating Sludge Yield

The equation used was:

$$Y = (Sludge\ Prod * 1000) / [(INF_{CODav} - EFF_{CODav}) * Q_{INF} * (1 - \{HW / Weighted\ Vol\})] \quad \textbf{(27)}$$

where:

Y = observed sludge yield (mg MLSS / mg COD)
Sludge Prod = amount of sludge produced (g/d)
INF_{CODav} = average influent COD concentration (mg/L)
EFF_{CODav} = average effluent COD concentration (mg/L)
Q_{INF} = influent flow rate (L/d)
HW = amount of Q_w wasted by hand (L)
Weighted Vol = system volume weighted for average MLSS in each zone; i.e. the aerobic volume + the anoxic volume + one half of the anaerobic volume (69.2 + 17.4 + 17.4/2 = 95.3 L). The anaerobic volume is weighted by 1/2 because its average MLSS is approximately one half that of the aerobic and anoxic zones.

This equation takes into account the drop in MLSS due to the sudden removal of mixed liquor while hand wasting the amount not pumped out using the waste pump. For example, if Sludge Prod = 31 g/d, INF_{CODav} = 450 mg/L, EFF_{CODav} = 25 mg/L, Q_{INF} = 207.4 L/d, HW = 7 L and Weighted Vol = 95.3 L, the observed sludge yield would be:

$$Y = (31 * 1000) / [(450 - 25) * 207.4 * (1-\{7/95.3\})] = 0.38 \text{ mg MLSS/mg COD}$$

A-16 Procedure for Calculating the Statistical Paired t-Test for Comparison of Fixed Film Trains to the Control

The equation used was:

$$t_{obs} = [(\{X_1-Y_1\} + \{X_2-Y_2\} \ldots + \{X_n-Y_n\}) / DF] / [SD * \sqrt{(1/n)}] \qquad \textbf{(28)}$$

where:

X_1 = average data point in IFAS train during observation 1
Y_1 = average data point in Control train during observation 1
X_2 = average data point in IFAS train during observation 2
Y_2 = average data point in Control train during observation 2
DF = degrees of freedom
SD = standard deviation
n = number of observations

The value of t_{obs} is compared to a published value called $t_{critical}$ corresponding to a two sided test with n degrees of freedom and for a certain confidence level. If t_{obs} is greater than $t_{critical}$, the conclusion is that the observed data point in the IFAS train is statistically different (for the given confidence level) than the data point of the control. For example, if X_1 = 5.4, X_2 = 5.3, X_3 = 5.7, X_4 = 5.5, Y_1 = 3.1, Y_2 = 3.5, Y_3 = 2.9, Y_4 = 3.2, and SD = 0.2, then the degrees of freedom would be 3 leading to a t_{obs} of:

$$t_{obs} = [(\{5.4-3.1\} + \{5.3-3.5\} + \{5.7-2.9\} + \{5.5-3.2\}) / 3] / [0.2 * \sqrt{(1/4)}] = 30.7$$

The published value of $t_{critical}$ for a two sided test with three degrees of freedom and a 95% confidence level (i.e. the percentage of certainty that can be claimed) is 3.182. Since $t_{critical}$ is smaller than t_{obs}, the data from group X is statistically different than the data from group Y, and this can be stated with 95% confidence. This test can be performed using various $t_{critical}$ values based on the confidence level desired.

A-17 Procedure for Calculating IFAS Nitrification Rates

The IFAS nitrification rates are based upon ammonia removal data for each of the aerobic cells. The initial step in this procedure is to compute the nitrification rate for each aerobic cell by normalizing the ammonia removal data to the overall nitrification rates. This calculation is described in section A-5.

Next, the contribution that the mixed liquor in each cell makes to the Cell Nitr value must be computed. The equation used is:

$$ML\ Nitr = Rate\ (Sen\ et\ al,\ 1994) * AVF * V_{AER} \quad \textbf{(29)}$$

where:

ML Nitr = nitrification due to the mixed liquor (g/d)
Rate = rate of nitrification due to mixed liquor, from Sen et al, 1994 (g/L/d)
AVF = aerobic volume factor, calculated as described in chapter 3
V_{AER} = volume of aerobic cell

For example, if the Rate = 0.039, the AVF = 0.88 and V_{AER} = 69.2L/3, the nitrification rate would be:

$$ML\ Nitr = 0.039 * 0.88 * 69.2/3 = 0.79\ g/d$$

The contribution that the IFAS makes to the Cell Nitr value is calculated using the equation:

$$IFAS\ Nitr = Cell\ Nitr - ML\ Nitr \quad \textbf{(31)}$$

where:

IFAS Nitr = nitrification in cell due to presence of IFAS (g/d)
Cell Nitr = nitrification in an aerobic cell (g/d)
ML Nitr = nitrification due to the mixed liquor (g/d)

The IFAS Nitr value can be further manipulated to calculate the contribution of a unit value of the IFAS, i.e. as a per sponge or per inch basis. For example, if Cell Nitr = 2.3 g/d, ML Nitr = 0.79 g/d, and there are 880 sponges in a particular aerobic cell, then the IFAS Nitr value per sponge would be:

$$IFAS\ Nitr\ per\ Sponge = (2.3 - 0.79)\ /\ 880 = 0.0017\ g/d/sponge$$

Table B-1

Raw Data of Phase One Experiments
30% Captor Media in Train Two, Aerobic Cells 1 and 2
14 Loops Ringlace Media in Train Three, Aerobic Cells 1, 2, and 3
Aerobic Suspended Growth MCRT = 3.4 days
Liquid Temperature = 12 degrees C

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 10 Spng/L mg/L/min	OUR No Media mg/L/min
28 May 93	2 INF			358	394	50.4		40	10.2	N/D	N/D	9.8		
	2 ANA1			193				27.5		N/D	N/D	13		
	2 ANA2	860	740	179				24.2		N/D	N/D	13.4		
	2 ANX1			64				10.8		N/D	N/D	10.2		
	2 ANX2	1440	1230	61				11.3		N/D	N/D	16.7		
	2 AER1	1370	1220	39				6.2		0.2	4.1	9.3		
	2 AER2	1530	1290	39				1.3		0.3	10.3	9.1		
	2 AER3	1480	1230	32		148		N/D	56	N/D	11.3	5.1		
	2 EFF	31	10.4	36	75			N/D	9.2	0.2	9.9	7.9		
	3 INF			258	322	52.4		33.3	11.2	N/D	N/D	6		
	3 ANA1			147				24.2		N/D	N/D	11		
	3 ANA2	1020	950	150				24.2		N/D	N/D	13.7		
	3 ANX1			54				9.2		0.1	0.1	8.8		
	3 ANX2	1560	1330	47				10.4		N/D	N/D	9.6		
	3 AER1	1590	1310	36				6.7		0.2	2.7	8.1		
	3 AER2	1550	1310	32				3.1		0.2	5.1	7.5		
	3 AER3	1500	1260	32		146		0.9	58	0.2	9.9	6.5		
	3 EFF	21	6.4	32	50.4	6.2		0.5	7.6	N/D	8.7	4.3		
	4 INF			272	286	46		34.2	9.2	N/D	N/D	8.3		
	4 ANA1			147				22.5		N/D	N/D	12.5		
	4 ANA2	770	690	147				24.2		N/D	N/D	10.5		
	4 ANX1			68				10.8		N/D	0.3	9.8		
	4 ANX2	1340	1170	47				10		N/D	N/D	16.4		
	4 AER1	1390	1160	36				5		0.3	3.2	8.4		
	4 AER2	1470	1270	36				1.8		0.4	6.8	7.7		
	4 AER3	1510	1240	29		148		0.5	56	N/D	9.3	6.1		
	4 EFF	15	5.6	29	54	3.4		0.4	6.5	N/D	9.4	6		

Table B-2

Raw Data of Phase Two Experiments
20% Captor Media in Train One, Aerobic Cells 1, 2, and 3
30% Captor Media in Train Two, Aerobic Cells 1, 2, and 3
Fourteen Loops Ringlace in Train 3, Aerobic Cells 1, 2, and 3
Aerobic Suspended Growth MCRT = 3.1 days
Liquid Temperature = 12 degrees C

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
14 Sep 93	2 INF				425	538	58.5		48.6		N/D	N/D	12		
	2 ANA1				259				30.8		N/D	N/D	16.7		
	2 ANA2	940	810	86	260				30.8		N/D	N/D	18.6		
	2 ANX1				126				15.2		N/D	N/D	14.8		
	2 ANX2	1670	1460	87	120			16.8	14.6		N/D	N/D	17		
	2 AER1	1690	1430	85	25.7			14	8.2		N/D	3.3	12.2		
	2 AER2	1740	1520	87	24.9			4.2	2.9		N/D	7.7	9.1		
	2 AER3	1780	1540	87	20.7		165		0.4		N/D	9.9	7.7		
	2 EFF	16	16	100	19.3	45	4.5	0.9	0.4		N/D	9.6	6.4		
	3 INF				366	500	59.4		30.8		N/D	N/D	10.9		
	3 ANA1				268				23.0		N/D	N/D	15.4		
	3 ANA2	830	730	88	240				23.0		N/D	N/D	17.5		
	3 ANX1				106				9.7		N/D	N/D	13.9		
	3 ANX2	1440	1270	88	93.4			19.6	10.1		N/D	N/D	16.3		
	3 AER1	1370	1190	87	37			16.8	8.3		N/D	1.5	13.2		
	3 AER2	1630	1420	87	34.6			5.6	3.8		N/D	5.5	10.5		
	3 AER3	1510	1300	86	31.4		213	2.8	0.8		N/D	9.1	7.2		
	3 EFF	76	65	86	30.5	121	12.1	2.2	0.6		N/D	9.3	7.3		

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
20 Sep 93	2 INF				456	576	61.6		44.2		N/D	N/D	12.7		
	2 ANA1				232				34.8		N/D	N/D	14		
	2 ANA2	1200	1070		232				33.4		N/D	N/D	23.8		
	2 ANX1				84.5				14.5		N/D	N/D	20.6		
	2 ANX2	2110	1840	87	72			25.2	16.3		N/D	N/D	21.4		
	2 AER1	1830	1610	88	35.7			16.8	12.8		N/D	3.4	15.2		
	2 AER2	1930	1600	83	29.2			21	7.7		N/D	8	12.1		
	2 AER3	1850	1630	88	22.7		188	5.6	5.4		N/D	10.3	9.8		
	2 EFF	22	22	100	25.9	42.2	9.5	5.6	5.6		N/D	9.7	9.3		
	4 INF				384	424	65.8		39.3		N/D	N/D	12.5		
	4 ANA1				292				32.1		N/D	N/D	20.3		
	4 ANA2	760	710	93	248				32.1		N/D	N/D	12		
	4 ANX1				120				17.7		N/D	N/D	13.5		
	4 ANX2	1850	1640	89	92			29.2	18.3		0.03	N/D	19.4		
	4 AER1	1190	1110	93	57			23.8	14.5		N/D	1.8	13.3		
	4 AER2	1250	1150	92	43.8			19.6	11.4		2	4.4	11		
	4 AER3	1230	1170	95	43.8		148.4	15.4	9		2.4	7.8	10		
	4 EFF	3	3	100	45.5	48.7	13.4	11.8	8.7		2.3	7.5	10.2		

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
24 Sep 93	1 INF				432	488	57.4		35.8		N/D	N/D	10.3		
	1 ANA1				236				23.8		N/D	N/D	14		
	1 ANA2	1220	1050	86	232				23.8		N/D	N/D	15.4		
	1 ANX1				112				11.7		N/D	N/D	14.2		
	1 ANX2	1950	1700	87	94			16.8	11.7		N/D	N/D	15.5		
	1 AER1	1600	1430	89	29			14	7.8		N/D	2	12.9		
	1 AER2	1550	1380	89	26			6.2	4.1		1.8	4.3	11.2		
	1 AER3	1700	1470	86	23		129	3.4	1.3		1.7	6.5	9.5		
	1 EFF	29	24	83	30	39		4.2	1.7		0	6.5	9.8		
	3 INF				408	464	60.2		43.3		N/D	N/D	12.2		
	3 ANA1				236				32.9		N/D	N/D	16.9		
	3 ANA2	850	770	91	228				27.9		N/D	N/D	18.6		
	3 ANX1				100				17.5		N/D	N/D	16.5		
	3 ANX2	1540	1340	87	97			19.6	17.5		N/D	N/D	18.7		
	3 AER1	1640	1410	86	29			10.3	15.4		N/D	1.3	16.3		
	3 AER2	1920	1660	86	26				10.4		N/D	5.6	13.9		
	3 AER3	1910	1730	91	24		160		5.7		N/D	9.8	11.9		
	3 EFF	12	10	83	34	36		10.6	5.7		N/D	9.9	11.7		
	2 AER3	1850													
	2 EFF	26			23			1.7	0.34		N/D	7.4	8.5		
	4 AER3	1380													
	4 EFF	23			49			14.6	12.1		N/D	8.8	12.2		

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
25 Sep 93	1 INF						60								
	1 ANX2				102				20.5		N/D	N/D	12.2		
	1 AER1				10				15.5		N/D	1.8	9.3		
	1 AER2				17.8				12.3		1.8	4.3	8.5		
	1 AER3	1700			18.7				8.6		2.1	6.5	7.1		
	1 EFF				11.5				7.6		2	5.7	6.6		
	2 INF						60								
	2 ANX2				87.3				16.1		N/D	N/D	10.5		
	2 AER1				28.1				10.1		N/D	2.8	7.6		
	2 AER2				14.6				5.3		N/D	6.1	7.6		
	2 AER3	1850			14.6				2.1		N/D	8.2	7.2		
	2 EFF				5.3				2.4		N/D	8.3	7.5		
	3 INF						60								
	3 ANX2				88.5				21.3		N/D	N/D	11.4		
	3 AER1				37.4				18.2		N/D	1	10.4		
	3 AER2				25.6				12.8		N/D	4.9	8.5		
	3 AER3	1752			25.6				7.9		1.7	9.1	7.3		
	3 EFF				10				8.6		1.6	8.9	6.7		
	4 INF						60								
	4 ANX2				119				24.9		N/D	0.04	6.7		
	4 AER1				34.9				20.4		N/D	1.6	6.9		
	4 AER2				27.1				16.2		2.3	4.5	6.5		
	4 AER3	1380			20.9				11.8		2.8	8.6	4.9		
	4 EFF				24				12.3		2.7	8	7.9		

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
26 Sep 93	1 INF				400		70		50		N/D	N/D	6.5		
	1 ANX2				86				20.8		N/D	N/D	12.3		
	1 AER1				32.8				18.3		N/D	1.9	8.7		
	1 AER2				21.9				15		N/D	3.8	7.8		
	1 AER3	1700			18.8				11.3		N/D	6.2	6.2		
	2 INF				400		70		50		N/D	N/D	10.7		
	2 ANX2				64.1			28.7	21.7		N/D	N/D	11.7		
	2 AER1				26.6				17.5		N/D	3.2	8.7		
	2 AER2				23.5				12.9		N/D	7	9		
	2 AER3	1850			18.8			11.8	9.2		N/D	8.4	6.8		
	3 INF				400				42.5		N/D	N/D	10.2		
	3 ANX2				102			17.5	14.2		N/D	N/D	13.3		
	3 AER1				21.9				10.8		N/D	1.5	10.1		
	3 AER2				15.6				5.3		N/D	5.8	7.1		
	3 AER3	1752			15.6			1.7	1.3		0.22	8.8	4.7		
	4 INF				400		57.4		42.5		N/D	N/D	10.2		
	4 ANX2				120			30.8	23.3		N/D	N/D	11.4		
	4 AER1								22.5		N/D	0.4	9.7		
	4 AER2				42.2				19.2		N/D	0.7	10.2		
	4 AER3	1380			32.8			19.6	17.1		N/D	3.2	9.2		

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
30 Sep 93	1 INF				550				60.0						
	1 ANX2				103				21.7		N/D	N/D	8.6		
	1 AER1				56				21.7		2.9	2.3	7.5		
	1 AER2				44				19.2		3.8	4.8	7.4		
	1 AER3	1700			41				12.9		4	7.5	4.4		
	1 EFF				41				10.4		4.7	9.3	4.1		
	2 INF				530		74.2		51.7						
	2 ANX2				94			23.8	20.8		N/D	0.03	8.3		
	2 AER1				47				21.7		N/D	4.1	7.5		
	2 AER2				42				10.0		N/D	8.2	6.1		
	2 AER3	1850			33				5.2		2.4	10.4	4.2		
	2 EFF				30			5.6	4.8		2.2	10.1	4.3		
	3 INF				541		63		45.8						
	3 ANX2				115			23.8	15.8		N/D	N/D	14.8		
	3 AER1				50				11.3		N/D	1.3	10.2		
	3 AER2				47				5.7		2.3	5.7	7.1		
	3 AER3	1752			47				2.7		0.83	11.2	5.8		
	3 EFF				44			4.5	2.9		2.66	10.4	5.5		
	4 INF				560				45.8						
	4 ANX2				109			28.9	17.5		N/D	N/D	13.2		
	4 AER1				62				12.5		2.5	1.5	8.9		
	4 AER2				47				9.6		3.1	4.3	8		
	4 AER3	1380			44				7.2		3.7	7.9	7		
	4 EFF				44			7.8	7.2		3.5	7.3	7.5		

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
2 Oct 93	1 INF				430			51.8	39.2						
	1 ANX2				46				9.2		N/D	0.07	8.2		
	1 EFF								0.8		0.12	2.9	2.8		
	2 INF				430			51.8	37.1						
	2 ANX2				67			17.5	12.9		N/D	N/D	7.3		
	2 EFF				38			2.2	N/D		N/D	9.4	6		
	3 INF				384			52	49.2						
	3 ANX2				132			30.8	14.6		N/D	N/D	12		
	3 EFF				52			10.1	6.8		0.23	4	4.9		
	4 INF				368			52	49.2						
	4 ANX2				52			26.6	20.8		N/D	N/D	10.4		
	4 EFF				40			9.5	8.8		1.4	3.9	4.5		
14 Oct 93	3 INF				531		95		95						
	3 ANX2				145			58.1	55.7		N/D	N/D	15.4		
	3 AER1				61.5				52.6		N/D	0.8	13.1		
	3 AER2				58.5				50.6		2	3.1	12.2		
	3 AER3	1490			50.8				46.8		N/D	5.9	11.3		
	3 EFF				49.2			44.8	43.4		N/D	5.8	11.3		
	4 INF				577		83		83						
	4 ANX2				155			53.2	43.4		N/D	N/D	17.4		
	4 AER1				46.2				40.2		N/D	0.2	16.3		
	4 AER2				43.1				35.8		N/D	1.4	15.6		
	4 AER3	1500			40				30.8		N/D	3	14.4		
	4 EFF				40			35.3	29.6		N/D	3	15.1		

Note: May have had low DO which limited nitrification

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
19 Oct 93	2 INF				570		70		59						
	2 ANX2														
	2 AER3	2100													
	2 EFF	35			38			1.7	2.3		N/D	14	8.2		
	3 INF				650		78.4		69						
	3 ANX2														
	3 AER3	1290													
	3 EFF	13			48			24.1	18.6		N/D	4.8	12.6		
	4 INF				650		75.6		67						
	4 ANX2														
	4 AER3	1630													
	4 EFF	31			51			16.2	14		2.9	9.7	18.9		
20 Oct 93	2 INF				445		67.2		59						
	2 ANX2														
	2 EFF	2095			43			1.1	0.75		N/D	13.1	7.1		
	3 INF				520		61.6		62						
	3 ANX2														
	3 EFF	1375			49			10.1	10		0.8	2.5	2.2		
	4 INF				510		67.2		67						
	4 ANX2														
	4 EFF	1720			51			9	9		2.8	10	5.4		

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
22 Dec 93	2 INF				487		75.6		63.1		N/D	N/D	6.9		
	2 ANA2	820	740	90											
	2 ANX2				88.9			30.8	28.5		N/D	N/D	12.2		
	2 AER3	1690	1440	85	40.6		230		11.0		1.1	14.1	6.4		
	2 EFF	32	32	100	39			11.2	11.0		1.1	14	6		
	3 INF				452		81.2		68.3		N/D	N/D	7.7		
	3 ANA2	770	730	95											
	3 ANX2				101				32.2		N/D	N/D	8.1		
	3 AER3	1480	1350	91	42.1		168		21.6		1.1	8.7	7.1		
	3 EFF	62	56	90	73.3			23.5	20.8		1.2	8.7	6.7		
	4 INF				446		84		68.3		N/D	N/D	7.9		
	4 ANA2	810	740	91											
	4 ANX2				101			40.6	36.2		N/D	N/D	8.9		
	4 AER3	1750	1540	88	26.5		216		25.3		1.8	8.5	6.9		
	4 EFF	31	31	100	46.8			26.3	24.3		1.8	8.3	7.2		

Table B-2 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	VSS\SS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR w/Media mg/L/min	OUR no Media mg/L/min
29 Dec 93	2 INF				406	438	73.4		50.0		N/D	N/D	8.9		
	2 ANA2				208				30.8		N/D	N/D	13.6		
	2 ANX2				61.1			21.3	15.8		N/D	N/D	12.6		
	2 AER1				47.5				13.3		0.2	4.5	9.4		
	2 AER2				46				6.3		0.9	11.2	7.1		
	2 AER3	2140	1880	87.9	36.8	2560	225		1.9		0.9	16	5.2		
	2 EFF	26	21	80.8	21.8			2.2	1.8		0.9	16.5	5		
	3 INF				464	557	83.3		54.2		N/D	N/D	8.2		
	3 ANA2				266				50.0		N/D	N/D	9.1		
	3 ANX2				91.2			35.3	29.2		N/D	N/D	8.6		
	3 AER1				55				27.5		0.9	1.1	8.3		
	3 AER2				49				21.7		0.3	5.9	7.9		
	3 AER3	1670	1500	89.8	40	1856	178		17.5		1.1	9.4	7.5		
	3 EFF	18	14	77.8	22.4			22.4	17.5		1.1	9.6	7.5		
	4 INF				557		83.3		65.0		N/D	N/D	8.2		
	4 ANA2				272				54.2		N/D	N/D	8.2		
	4 ANX2				101			37.4	33.3		N/D	N/D	7.7		
	4 AER1				40				28.3		1.2	2.1	7.2		
	4 AER2				32				24.2		1.4	5.6	8.8		
	4 AER3	1720	1560	90.7	25.6	1584	183		19.2		1.5	10.5	7.1		
	4 EFF	30	28	93.3	32			21.5	18.3		1.6	10.1	7.2		

Table B-3

Raw Data of Phase Three Experiments
30% Captor Media in Train Two, Aerobic Cells 1,2, and 3
Aerobic Suspended Growth MCRT = 2.4 days
Liquid Temperature = 12 degrees C

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 20 Spng/L mg/L/min	OUR No Media mg/L/min
23 Feb 94	2 INF			418	475	59.6		39.3	6.6	N/D	N/D	5		
	2 ANX2			54.8				8.9		0.04	N/D	4.4		
	2 AER1													
	2 AER2	1270	1150											
	2 AER3	1250	1160	20		130	0.41	0.41	16.1	10.9	3.5			
	2 EFF	28	27	23.1			0.2	0.2		0.3	10.7	4.1		
	4 INF			418	480	51.5		40.9	6.3	N/D	N/D	5.2		
	4 ANX2			102				28.3		0.04	N/D	4.9		
	4 AER1													
	4 AER2	1590	1450											
	4 AER3	1550	1450	30.8		170	23	23	21	0.9	N/D	4.1		
	4 EFF	15	15	33.8			25	25		0.9	1.7	4.7		
26 Feb 94	2 INF				423	50.8		39.3	6.1					
	2 ANA2			192				35.5		0.02	N/D	6.7		
	2 ANX2	1210	1070	76.8			13.8	20.5		0.05	0.02	6.8		
	2 AER1	1010	880	21.2			8.2	13.2		0.5	3.6	6.4	0.51	0.35
	2 AER2	990	870	20.9			2	3.2		0.3	7.8	6.3	0.39	0.23
	2 AER3	1070	920	18.9		119	0.7	0.7		0.1	8.3	6.3	0.23	0.16
	2 EFF	34	31	23.7			1.2	1.2		0.08	6.5	6.2		
	4 INF				460	52.2		41.4	7.2					
	4 ANA2			180				33.9		N/D	N/D	6.2		
	4 ANX2	1400	1230	97.7			35.6	24.7		0.05	0.02			
	4 AER1	1910	1640	32.3			20.5	20.8		0.5	0.4	5.5		0.35
	4 AER2	1720	1480	39.9			23.3	17.7		0.7	1.1	5.4		0.3
	4 AER3	1740	1500	32.3		139	22	13.3	19.1	0.9	2.5	5.5		0.26
	4 EFF	55	45	39.9			12.4	12.4		0.8	2.3	6.1		

Table B-3 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 20 Spng/L mg/L/min	OUR No Media mg/L/min
1 Mar 94	2 INF				503	48.9		47.8	4.2					
	2 ANA2			261			33.2	34.8		0.04	0.07	6.9		
	2 ANX2	1020	940	107			15	15.8		0.01	0.01	6.3		
	2 AER1	980	900	21.1			8.3	8.7		0.6	2.6	5.9	0.49	0.3
	2 AER2	1030	930	27.3			1.5	1.8		0.4	8	5.6	0.36	0.25
	2 AER3	1030	950	24.8		109	N/D	0.3	9.9	0.1	9	5.3	0.25	0.15
	2 EFF	36	35	26.3			0.3	0.3		0.1	9	5.6		
	4 INF				450	52.5		47.8	4.9					
	4 ANA2						40.3	39.2		N/D	N/D	6.2		
	4 ANX2	1230	1130	138			26.9	26.3		N/D	N/D	5.6		
	4 AER1	1240	1120	56.7			20.4	23.4		0.6	0.5	5.2		0.35
	4 AER2	1290	1180	48.7			19.4	20		0.9	1.6	5		0.3
	4 AER3	1270	1150	31		150	17.9	15.8	9	1	3.4	4.9		0.28
	4 EFF	71	64	42			15.6	15.8		1	3.6	4.9		
7 Mar 94	2 INF				476	56.7		47.6	7.9					
	2 ANX2	1010		64.2				14.3		0.2	0.3	6.6		
	2 AER3	950		18		101	0.4	0.4	20.9	0.1	10.2	6.1		
	2 EFF	27		7.9			0.4	0.4		0.1	10.4	6.1		
	4 INF				421	67.2		47.6	7.8					
	4 ANX2	1000		77.2				33.2		0.04	0.08	6.2		
	4 AER3	1070		49.6		151	26.1	26.1	23.8	1	2.9	5.6		
	4 EFF	24	23	8.5			27.2	27.2		1	3.4	5.9		

Table B-3 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 20 Spng/L mg/L/min	OUR No Media mg/L/min
19 Mar 94	2 INF				529	55.3		56	9.2					
	2 ANA1			271				44.2		0.04	0.02	7.1		
	2 ANA2	460	410	249				32.2		0.01	0.06	7.3		
	2 ANX1			93.6				12.9		0.04	2.5	6.8		
	2 ANX2	880	770	78.1			14	12.4		0.5	0.6	6.7		
	2 AER1	840	810	49.9			28.3	27.7		0.4	1.7	6.8	0.4	0.3
	2 AER2	780	700	36			3.6	2.7		0.5	8.2	6.8	0.35	0.16
	2 AER3	760	680	29.6			0.6	0.4		0.2	10.4	6.6	0.975	0.2
	2 EFF	36	29	37.6			0.6	0.35		0.2	10.5	6.7		
	4 INF				517	56.7		51.8	8.6					
	4 ANA1			288				39.2		N/D	N/D	7.3		
	4 ANA2	500	480	251				39.2		N/D	0.02	7		
	4 ANX1			117				29.7		0.2	0.1	6.1		
	4 ANX2	990	870	106			30.8	28.5		0.04	0.01	6.3		
	4 AER1	930	830	39.5			26.9	25.3		0.4	0.2	5.9		0.27
	4 AER2	970	840	36.7			26.3	23.4		0.7	0.9	5.8		0.2
	4 AER3	910	800	33.1		115	24.6	20.8	20.2	0.9	2.1	5.9		0.2
	4 EFF	21	15	41.5			24.6	21.6		0.9	2.3	19.2		
21 Mar 94	2 INF				502	89.6		68.4	10					
	2 ANA1			243				52		N/D	0.3	6.3		
	2 ANA2	540	490	248				52		N/D	N/D	7		
	2 ANX1			99.1				32.4		N/D	1.2	7.1		
	2 ANX2	950	880	97.5			32.5	32.4		0.1	N/D	7.5		
	2 AER1	840	810	49.9			28.3	27.7		0.4	1.7	6.8	0.4	0.3
	2 AER2	910	840	38.9			21.8	21.9		0.5	7.1	7.1	0.41	0.22
	2 AER3	1250	1140	34.3		155	17.9	14.2	26.1	0.5	13.3	7	0.5	0.19
	2 EFF	35	30	36.6			17.9	13.6		0.8	12.6	7.2		
	4 INF				483	80.1		68.4	9					
	4 ANA1			242				58.5		N/D	N/D	7.3		
	4 ANA2	620	570	242				58.5		N/D	N/D	7.4		
	4 ANX1			130				42.7		0.2	N/D	6.6		
	4 ANX2	1050	950	119			51.5	41		N/D	N/D	6.8		
	4 AER1	1120	1020	47.9			47.6	41		0.4	0.2	6.9		0.3
	4 AER2	1130	1020	47.6			46.7	42.7		0.9	1	6.7		0.275
	4 AER3	1140	1040	40.5		166	44.2	39.4	27.6	1	2.2	6.8		0.25
	4 EFF	17	15	43.7			37.9	37.9		1	2.3	7.3		

Table B-3 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 20 Spng/L mg/L/min	OUR No Media mg/L/min
24 Mar 94	2 INF				530	91.5		50	7.7					
	2 ANA2	600	570	264				28.8		0.1	0.1	5.7		
	2 ANX2	1130	1020	109				25.6		N/D	0.1	5.4		
	2 AER1	1100	1020	37.1			33.6	21.9		0.4	1.6	5.1		
	2 AER2	1100	1020	32			23.5	16		0.5	6.8	4.8		
	2 AER3	1190	1060	32		140	18.7	13.1	24.8	0.6	11.9	5		
	2 EFF	26	24	28.8			17.4	13.1		0.7	11.7	5.2		
	4 INF				523	87.7		63.3	8					
	4 ANA2													
	4 ANX2	1200	1080	136				56.2		N/D	N/D	5.8		
	4 AER1													
	4 AER2													
	4 AER3	1220	1110	34.6		179	52.4	54	27.3	1.1	1.8	4.9		
	4 EFF	17	16	41.6			51.5	52		1.1	2.2	5.6		
28 Mar 94	2 INF				541	87.2			9.9					
	2 ANA2	620	550	252				58		0.01	0.08	8.6		
	2 ANX2	1550	1380	62.4			29.8	27.6		0.1	0.2	7.9		
	2 AER1	1150	1050	39.7			26.1	23.6		0.4	3.5	7.6		
	2 AER2	1140	1030	23			18.8	17.3		0.6	10.2	7.5		
	2 AER3	1220	1070	33.3		151	12.1	10.8	28.5	0.6	16.5	7.3		
	2 EFF	200	180	36.5			11.8	10.4		0.9	16.3	7.5		
	4 INF				538	93.5		92.8	9.6					
	4 ANA2													
	4 ANX2	1410	1280	121			59.9	62.4		0.06	0.07	7.6		
	4 AER1													
	4 AER2													
	4 AER3	1230	1110	44.8		172	51.3	53.4	23.8	1.5	2.6	7		
	4 EFF	18	16	50.9			55.6	55.6		1.6	2.5	7.2		

Table B-3 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 20 Spng/L mg/L/min	OUR No Media mg/L/min
31 Mar 94	2 INF				354	76.4		76.4						
	2 ANA2	550	510	145						N/D	0.2	4.4		
	2 ANX2	1050	950	37.3			27.7	27.7		1.1	0.6	3.5		
	2 AER1	1070	950	34.4			21.4	21.9		0.7	5.7	3.4	0.8	0.55
	2 AER2	1030	950	20.7			13	14.8		0.6	12.6	2.9	0.63	0.4
	2 AER3	1010	940			122	6.7	6.8		0.6	20.2	3	0.65	0.4
	2 EFF	39	38	30			16.8	19.8		0.7	14.3	5.5		
	4 INF				360	78.9		76.4						
	4 ANA2													
	4 ANX2	1130	1040	55.1			44.4	47.9		0.04	0.08	4.4		
	4 AER1													0.55
	4 AER2													0.45
	4 AER3	1060	980	26.4		161	36.1	37.9		1.2	4.5	4.5		
	4 EFF	18	18	24.5			36.1	37.9		1.4	4.7	5.9		
4 Apr 94	2 INF				380	74.7		89.4						
	2 ANA2			210				53.4		0.02	0.15	8.4		
	2 ANX2	1000	940	85			38.3	35.9		1	1.8	5.8		
	2 AER1	780	630	42			33.6	31.9		0.8	3	5.4	0.63	0.33
	2 AER2	810	730	35			29.7	27.2		0.5	7.9	5.6	0.63	0.25
	2 AER3	948	910	34		92.4	20.7	20.6		0.5	14.7	5.6	0.6	0.24
	2 EFF	152	89	30			16.8	19.8		0.7	14.3	5.5		
	4 INF				390	81.2		89.5						
	4 ANA2													
	4 ANX2	980	830	110			57.4	51.3		0.04	0.05	5.7		
	4 AER1													
	4 AER2													
	4 AER3	1160	960	35			50.4	43.8		0.7	2.5	5.2		
	4 EFF	61	38	40			49.3	42.1		0.7	2.7	5.3		

Table B-4

Raw Data of Phase Four Experiments
30% Captor Media in Train Two, Aerobic Cells 1,2, and 3
Aerobic Suspended Growth MCRT = 1.7 days
Liquid Temperature = 12 degrees C

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 10 Spng/L mg/L/min	OUR No Media mg/L/min
2 Jun 94	2 INF				404	66.8		60.5						
	2 ANX2	1150	1080	70.2			13.8	19.4		0.1	0.1	7		
	2 AER1			40.6				17.3		0.3	1.9	7.1		
	2 AER2			39				11.7		0.4	4.9	7.2		
	2 AER3	1120	1050	31.2	1365			6.8		0.3	9.3	6.8		
	2 EFF	42	40	34.3			7.7	6.3		0.5	8.6	6.7		
	4 INF				437	68.4		62.6						
	4 ANX2	1190	1090	119			29			N/D	N/D	7.6		
	4 AER1			45.2				40.8		0.3	0.02	7.2		
	4 AER2			45				39.2		0.5	0.5	6.8		
	4 AER3	790	740	44	983	120		37.7		0.7	0.9	6.7		
	4 EFF	30	30	37			37.4	36.3		0.7	1.3	6.8		
5 Jun 94	2 INF				440	67.6		46.3						
	2 ANX2	710	630	85.6			15.1	20.7		0.08	0.09	6.3		
	2 AER1			48.9				17.7		0.3	1.4	6.2		
	2 AER2			48.9	1039	99.8		14.7		0.4	4.1	6.4		
	2 AER3	780	700	35.2			14.5			0.4	6.2	6.1		
	2 EFF													
	4 INF				440	67.6		48.1						
	4 ANX2	870	770	101			25.8	34.1		N/D	0.03	6.3		
	4 AER1			51.9				32.8		0.2	0.1	6.5		
	4 AER2			44.3				31.6		0.5	0.4	5.8		
	4 AER3	930	820	43.6	1116	77.3		31.6		0.7	0.7	5.7		
	4 EFF	24	20	44.3			39.9	31.6		0.7	1	5.9		

Table B-4 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 10 Spng/L mg/L/min	OUR No Media mg/L/min
7 Jun 94	2 INF				435	63.6		54.8						
	2 ANA2	660	600	221				35		0.01	0.05	7.2		
	2 ANX2	1100	1000	74.1			20.9	14.9		N/D	N/D	6		
	2 AER1	1100	980	46.3				11.6		0.3	1.7	5.7		
	2 AER2	1020	930	44.8				6.7		0.3	5.9	6.2		
	2 AER3	1020	950	38.6	1435	129		3.4		0.4	8.9	5.6		
	2 EFF	38	33	34			5.2	3.6		0.5	8.6	5.6		
	4 INF				438	65.2		52.6						
	4 ANA2	560	510	236				44.7		N/D	0.1	7.4		
	4 ANX2	1220	1135	106			41.9	36.4		0.04	0.02	6		
	4 AER1	950	900	50.9				43.3		0.2	0.1	5.7		
	4 AER2	880	800	47.8				32.3		0.5	0.4	5.5		
	4 AER3	830	740	44.8	1103	93.4	38.6	29.7		0.7	0.8	5.9		
	4 EFF	23	23	38.6			34.7	29.7		0.6	0.9	5.5		
9 Jun 94	2 INF				417	62		52.8						
	2 ANA2			216				32.5		0.01	0.1	6.7		
	2 ANX2			70.6				13.4		0.02	0.04	6.1		
	2 AER1	900	840	39.2			12.7	9.7		0.3	1.8	5.8		
	2 AER2	890	800	34.5			5.1	4.5		0.4	6.7	5.8		
	2 AER3	910	810	26.7		103	3.2	1.8		0.4	9.5	5.8		
	2 EFF	37	34	26.7			3.2	1.6		0.4	8.8	5.8		
	4 INF				411	62		55						
	4 ANA2			224				46.8		N/D	0.02	6.7		
	4 ANX2			72			44.3	37.5		N/D	0.02	5.9		
	4 AER1	910	830	39.2				35.2		0.2	0.1	5.6		
	4 AER2	940	860	36.1				33.9		0.5	0.3	5.6		
	4 AER3	930	850	29.8	1145			32.5		0.7	0.8	5.6		
	4 EFF	27	23	36.1				30		0.6	0.8	5.6		

Table B-4 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 10 Spng/L mg/L/min	OUR No Media mg/L/min
12 Jun 94	2 INF				402	55.5		53.2						
	2 ANX2			139			40.3	38.7		N/D	0.04	6.1		
	2 AER1			56.6				35.8		0.3	0.3	6.1		
	2 AER2	1170	1110	53.7				30.5		0.4	2.6	5.9		
	2 AER3	1140	1100	47.7	1416	132		25		0.4	5	5.7		
	2 EFF	55	52.5	32.7			25.8	25		0.4	4.8	5.7		
	4 INF				400	54.7		55.3						
	4 ANX2			95.4			45.1	49.1		0.02	0.05	5.7		
	4 AER1			56.6				47.2		0.2	0.05	5.9		
	4 AER2	1200	1060	55.2				45.4		0.4	0.2	5.8		
	4 AER3	1070	1020	41				43.6		0.6	0.5	5.6		
	4 EFF	49	46	40.2			43.1	42.2		0.5	0.6	5.7		
	Note: Influent flow was 2Q this day													
17 Jun 94	2 INF				495	55.1		50.2						
	2 ANA1			255				39.8		N/D	0.02	5.6		
	2 ANA2	450	410	249				38.3		N/D	0.02	5.6		
	2 ANX1			90.8				14.1		0.1	0.2	5		
	2 ANX2	830	770	72.3			14	11.6		N/D	0.01	5.2		
	2 AER1	730	670	44.6			15.3	10		0.2	1.3	5.8		
	2 AER2	720	660	41.5			6.1	4.8		0.3	4.7	5		
	2 AER3	730	670	38.4	919	108	3.2	1.5		0.2	7.2	4.4		
	2 EFF	40	35	32.3			1.5	0.8		0.3	7.3	4.9		
	4 INF				495	55.4		46.4						
	4 ANA1			278				36.9		N/D	0.01	5.6		
	4 ANA2	540	510	272				35.5		N/D	0.02	6.2		
	4 ANX1			142				27.1		N/D	0.02	4.7		
	4 ANX2	970	880	95.3			29.8	26.1		N/D	0.01	5		
	4 AER1	1090	1000	47.6			30.1	25.1		0.2	0.1	4.6		
	4 AER2	1060	980	43.9			27.3	22.4		0.5	0.4	4.3		
	4 AER3	1020	960	41.5		134	28.6	20.7		0.7	1.1	5.3		
	4 EFF	21	17	40			27	20		0.7	1.3	4.5		

Table B-4 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 10 Spng/L mg/L/min	OUR No Media mg/L/min
22 Jun 94	2 INF				463	82.9		82.5						
	2 ANA2			267				62.9		N/D	N/D	7.5		
	2 ANX2			135			45.9	44.4		0.02	0.08	7		
	2 AER1	1140	1121	62			41.4	39.5		0.4	2	6.5	0.42	0.35
	2 AER2			55.6			38.1	31.3		0.4	9.9	6.5	0.33	0.24
	2 AER3	1240	1220	49.3	1399	163	25.8	24.8		0.3	14.8	6.5	0.26	0.2
	2 EFF	65	46	45.3			23.2	23.9		0.5	15.1	6.5		
	4 INF				451	84		85.7						
	4 ANA2			275				76.3		N/D	N/D	7.4		
	4 ANX2			175			62.7	65.4		N/D	N/D	6.9		
	4 AER1	1090	1071	81			57.1	60.5		0.3	0.1	6.2		0.35
	4 AER2			71.5			54.9	56		0.6	0.7	6		0.26
	4 AER3	1140	1119	65.2	1438	179	46.5	53.8		0.8	1.6	5.8		0.18
	4 EFF	39	24	58.8			54.8	51.3		0.7	2.2	5.8		
	Note: Nitrate Return = 0 for this day													
25 Jun 94	2 INF				491	82		76.2						
	2 ANA2			242			59.6	52		N/D	N/D	7		
	2 ANX2			86.8			42.7	30.3		0.04	0.05	6.3		
	2 AER1			47.4			40	27.1		0.3	2	6	0.4	0.36
	2 AER2	1120	1105	42.6			29.4	21.5		0.4	7.2	5.9	0.34	0.27
	2 AER3	1060	1047	37.9	1382	151	25.2	16.4		0.3	12.4	5.9	0.38	0.2
	2 EFF			30			22	15.2		0.4	12.3	5.9		
	4 INF				499	85.2		73.4						
	4 ANA2			265			71	60.6		N/D	N/D	7.1		
	4 ANX2			128			62	52.1		N/D	0.01	6.5		
	4 AER1			69.5			59	50		0.3	0.2	6.1		0.325
	4 AER2	1000	989	66.3			56	48.1		0.5	1	6.1		0.29
	4 AER3	1110	1097	60	1255	192	54.6	46.3		0.7	1.5	5.9		0.225
	4 EFF			53.7			56	44.6		0.7	1.8	6.1		

Table B-4 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 20 Spng/L mg/L/min	OUR No Media mg/L/min
28 Jun 94	2 INF				463	94.9		82.6						
	2 ANX2	890	780	33			38.7	36.7		0.3	1.6	5.5		
	2 AER1			63			38.2	36.7		0.08	0.1	5.7		
	2 AER2			29.9			28.3	27.9		0.4	5.7	5.5		
	2 AER3	910	800	37.8	1306	131	24.7	22.1		0.3	10.8	5.5		
	2 EFF	40	27.5	23.6			22.9	21.3		0.6	10.2	5.5		
	4 INF				460	94.9		82.6						
	4 ANX2	870	780	91.3			65.3	58.3		N/D	N/D	5.4		
	4 AER1			39.3			62.8	56.1		0.3	0.1	5		
	4 AER2			40.9			61.2	54		0.5	0.5	4.9		
	4 AER3	980	910	36.2	1243	167	49.6	50		0.7	1.2	4.9		
	4 EFF	32.5	22.5	36.2			43.1	50		0.7	1.4	5.3		
5 Jul 94	2 INF				441	82.9		79.2						
	2 ANA2			233				58.1		0.01	0.04	2.1		
	2 ANX2	890	890	78			39.5	36.6		0.06	0.05	4.2		
	2 AER1			37.5			34.6	33.8		0.3	1.6	3.8		
	2 AER2			31.5			30.4	29		0.4	5.4	3.8		
	2 AER3	900	880	28.5	1118		23.5	23.9		0.4	9.1	3.9		
	2 EFF	50	50	27			20.7	22.1		0.6	7.9	3.9		
	4 INF				450	83.3		82.4						
	4 ANA2			257				73.3		0.06	0.01	4.6		
	4 ANX2	770	730	116			62	62.8		0.2	0.01	4.3		
	4 AER1			45			59.1	60.4		0.2	0.1	4		
	4 AER2			42			57.7	55.9		0.5	0.4	4.1		
	4 AER3	920	860	37.5	1073		56	55.9		0.6	0.9	3.8		
	4 EFF	38	38	34.5			54	53.8		0.6	1.5	4		

Table B-4 cont.

Sample Date	Sample Location	MLSS mg/l	MLVSS mg/l	SCOD mg/l	COD mg/l	TKN mg/l	SKN mg/l	NH3-N mg/l	TP mg/l	NO2 mg/l	NO3 mg/l	OP mg/l	OUR 20 Spng/L mg/L/min	OUR No Media mg/L/min
28 Jun 94	2 INF				463	94.9		82.6						
	2 ANX2	890	780	33			38.7	36.7		0.3	1.6	5.5		
	2 AER1			63			38.2	36.7		0.08	0.1	5.7		
	2 AER2			29.9			28.3	27.9		0.4	5.7	5.5		
	2 AER3	910	800	37.8	1306	131	24.7	22.1		0.3	10.8	5.5		
	2 EFF	40	27.5	23.6			22.9	21.3		0.6	10.2	5.5		
	4 INF				460	94.9		82.6						
	4 ANX2	870	780	91.3			65.3	58.3		N/D	N/D	5.4		
	4 AER1			39.3			62.8	56.1		0.3	0.1	5		
	4 AER2			40.9			61.2	54		0.5	0.5	4.9		
	4 AER3	980	910	36.2	1243	167	49.6	50		0.7	1.2	4.9		
	4 EFF	32.5	22.5	36.2			43.1	50		0.7	1.4	5.3		
	2 INF													
	2 ANA2													
	2 ANX2													
	2 AER1													
	2 AER2													
	2 AER3													
	2 EFF													
	4 INF													
	4 ANA2													
	4 ANX2													
	4 AER1													
	4 AER2													
	4 AER3													
	4 EFF													

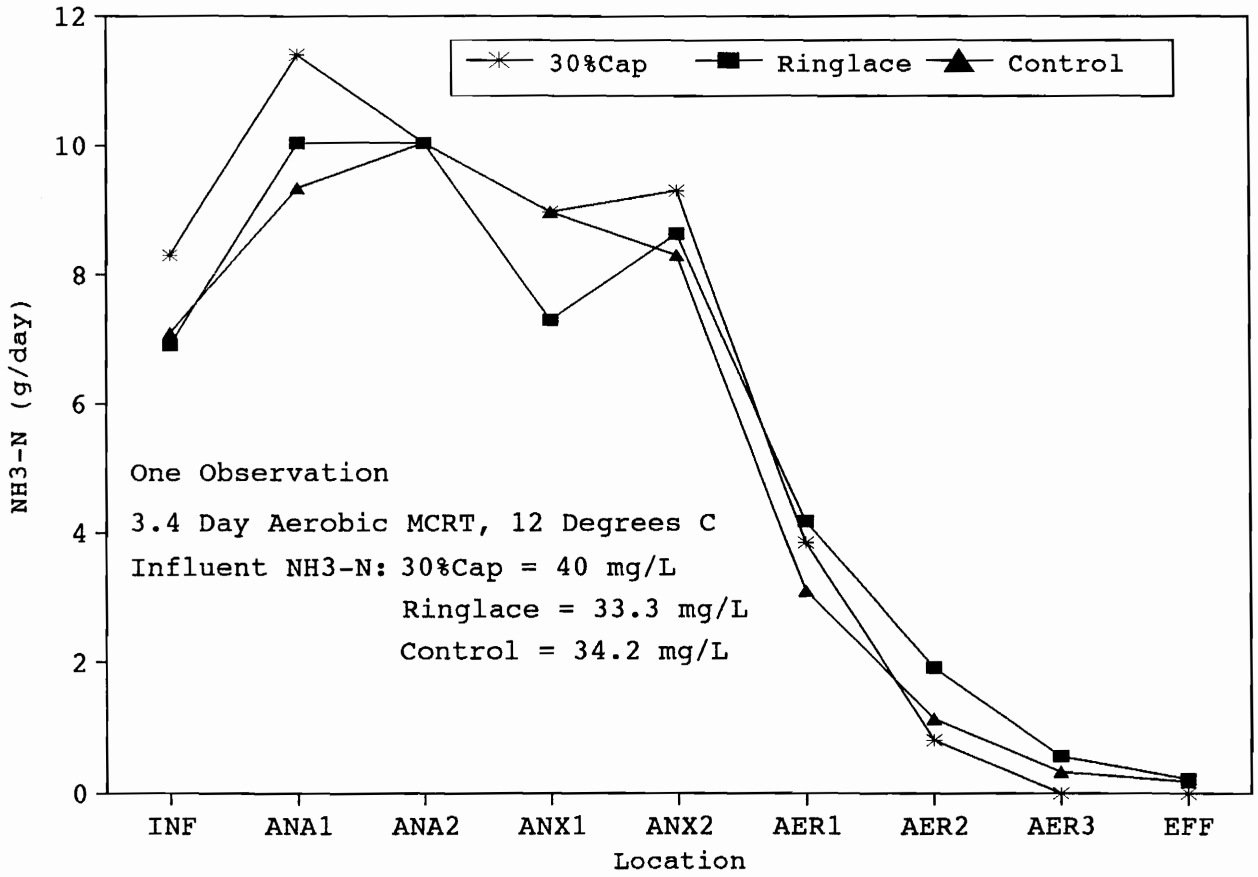

Figure C-1. Ammonia Mass Load Profile, Phase One, Normal Conditions

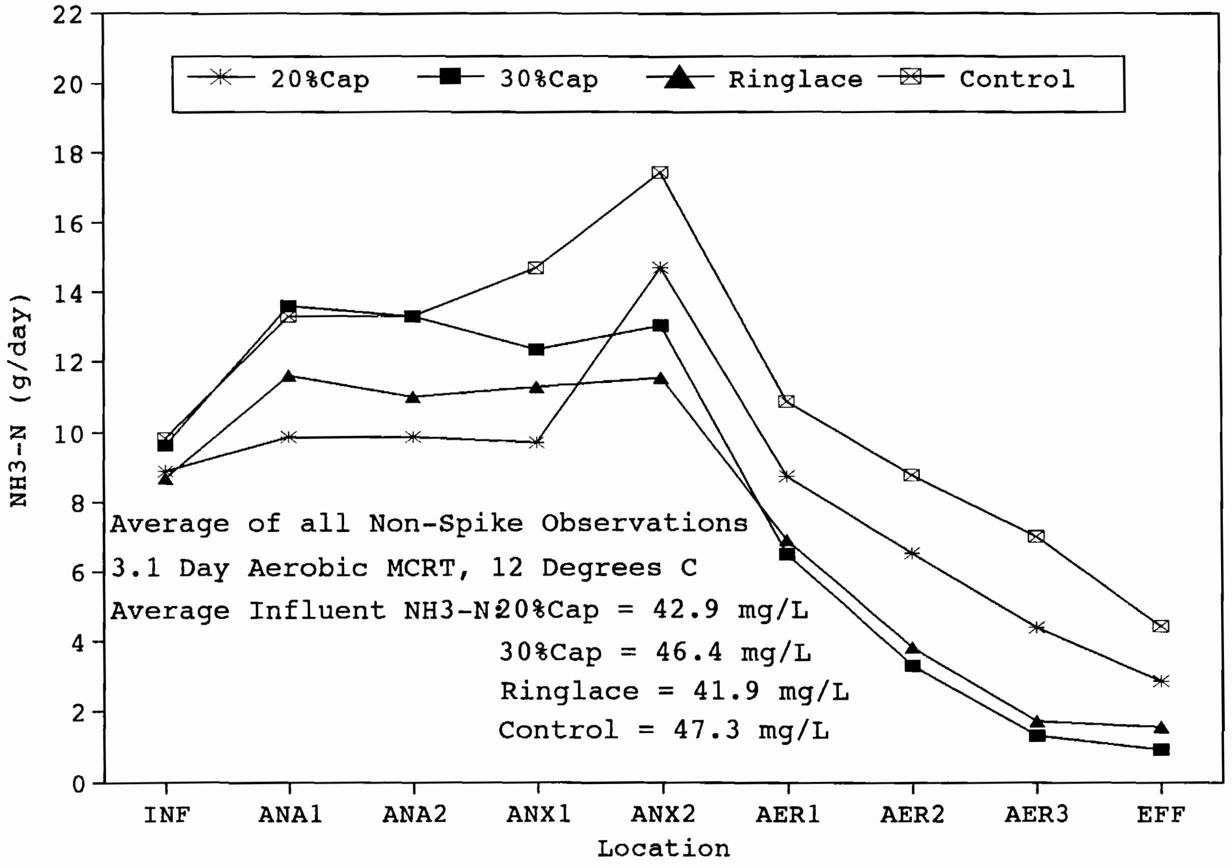

Figure C-2. Ammonia Mass Load Profile, Phase Two, Normal Conditions.

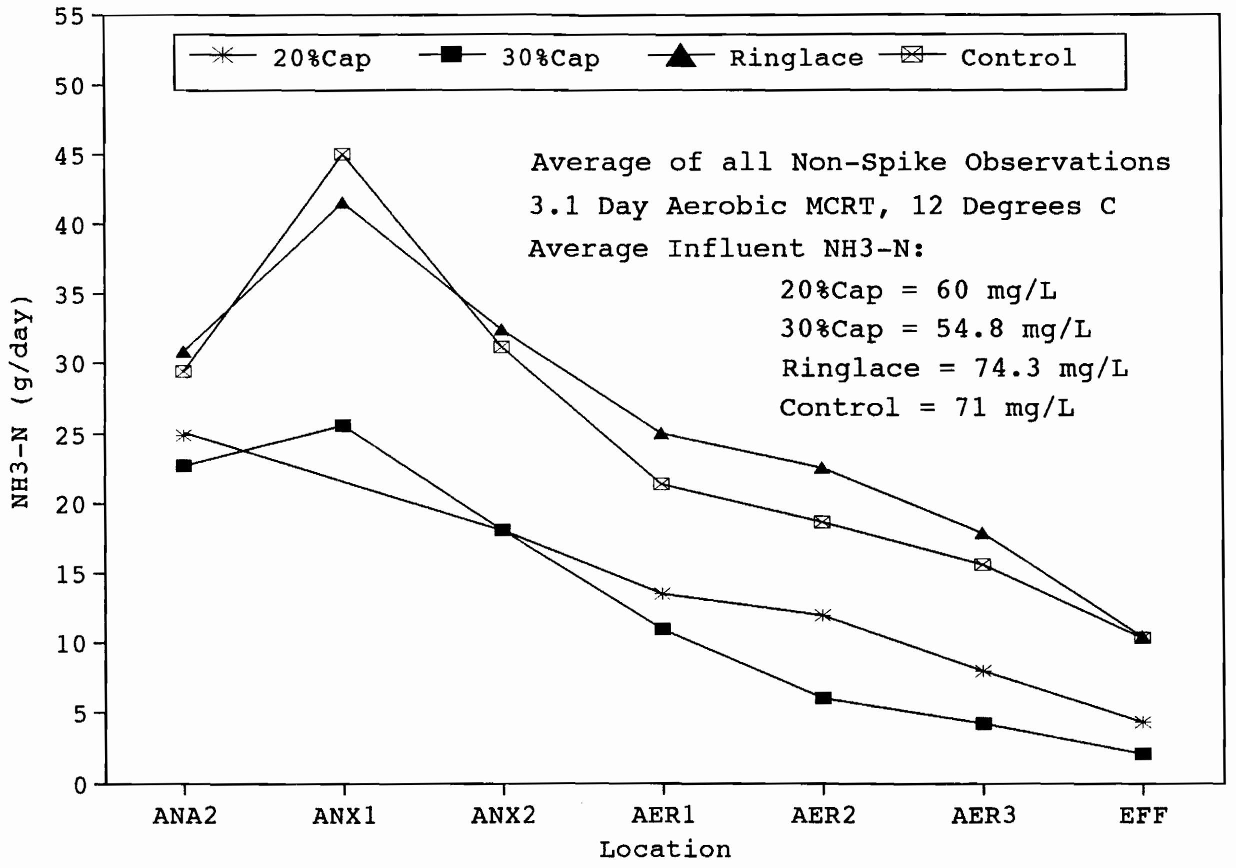

Figure C-3. Ammonia Mass Load Profile, Phase Two, Spiked Conditions.

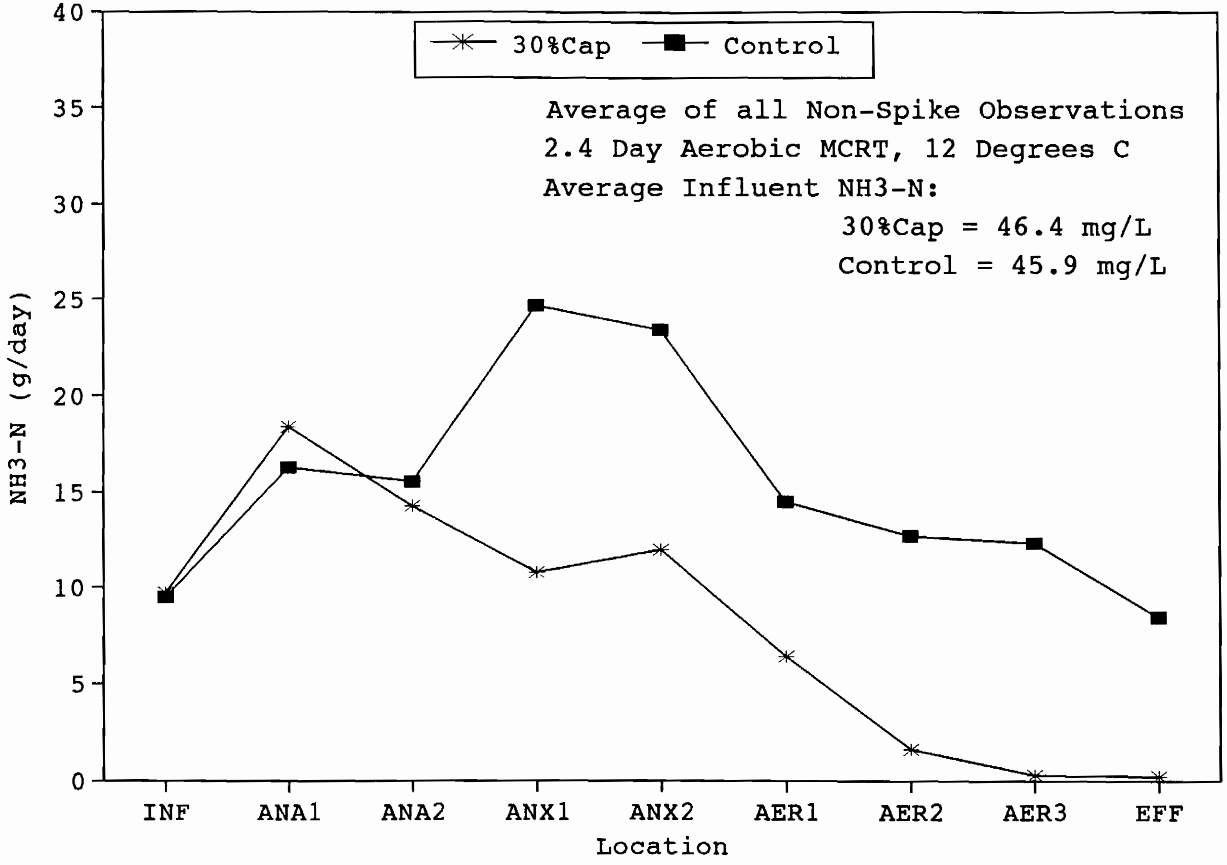

Figure C-4. Ammonia Mass Load Profile, Phase Three, Normal Conditions.

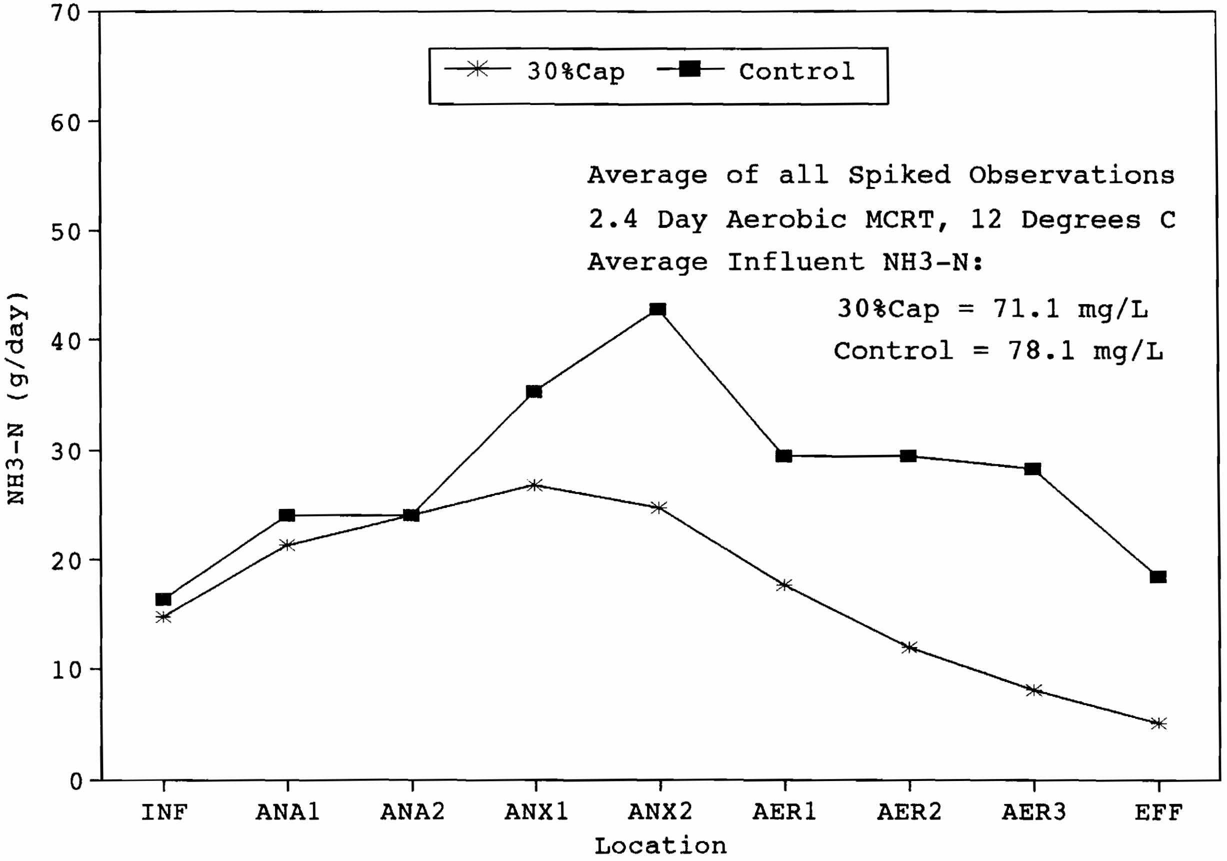

Figure C-5. Ammonia Mass Load Profile, Phase Three, Spiked Conditions.

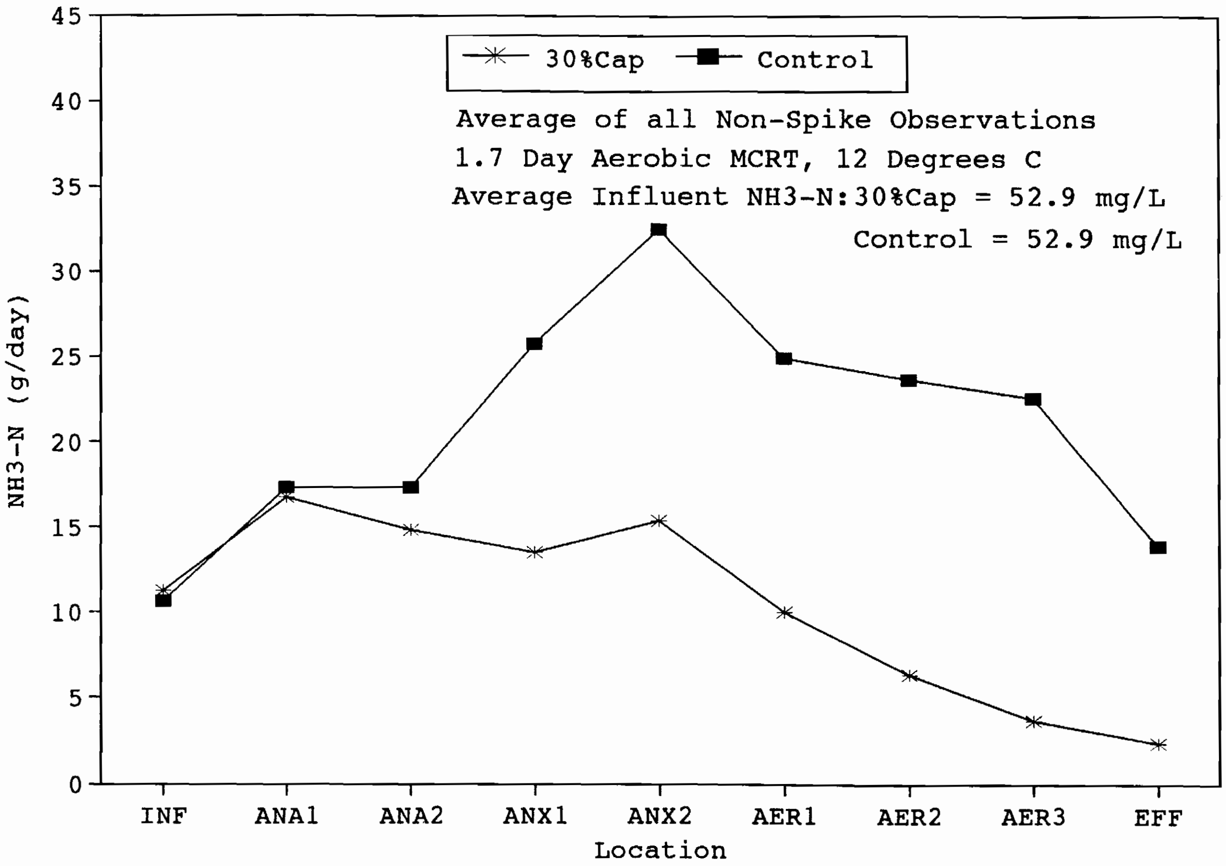

Figure C-6. Ammonia Mass Load Profile, Phase Four, Normal Conditions.

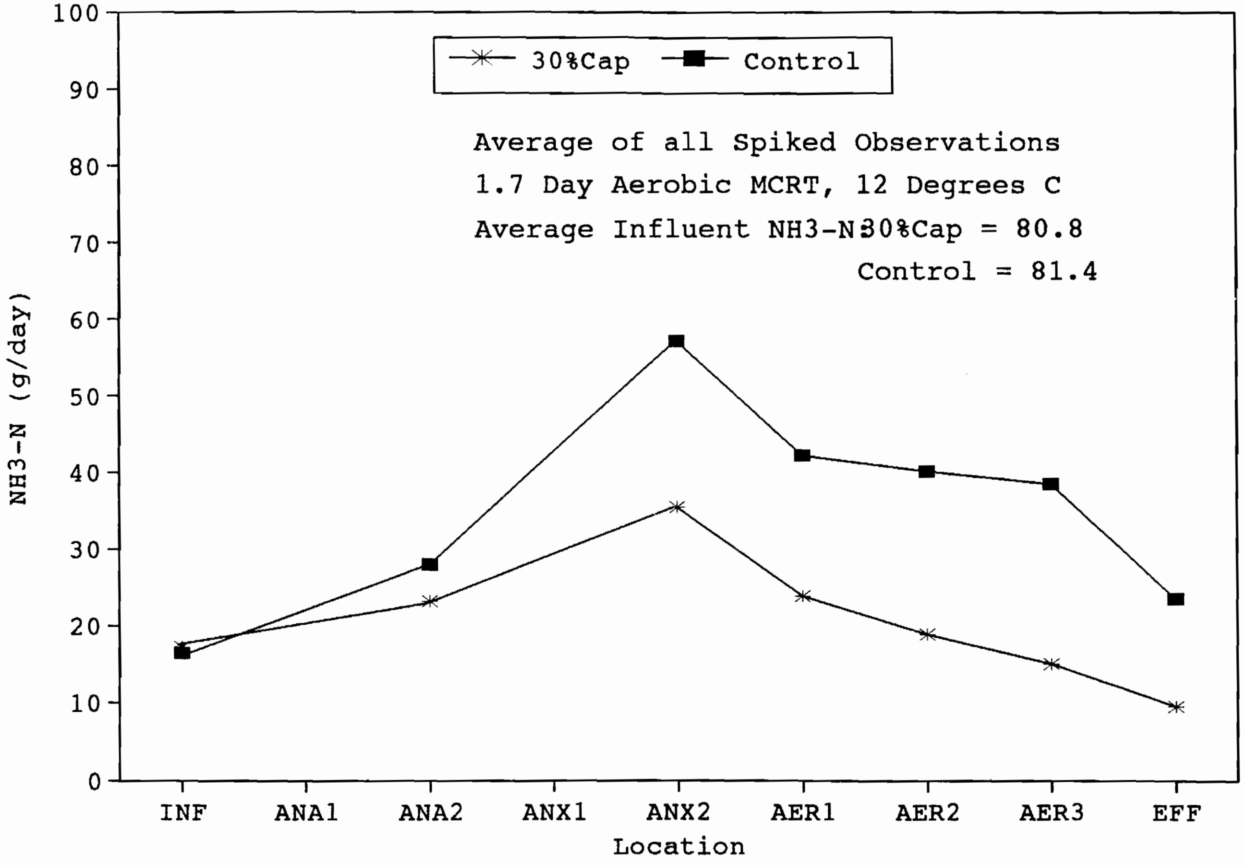

Figure C-7. Ammonia Mass Load Profile, Phase Four, Spiked Conditions.

VITA

Keith R. Jensen was born on June 26, 1965 in Mountain Home, Idaho and grew up near Bremerton, Washington. He attended Washington State University and graduated with a BS in Chemistry in May, 1987. After serving in the Navy four years and working for one year, he began work in 1992 on a Masters Degree in Environmental Engineering at Virginia Polytechnic Institute & State University. He graduated from Virginia Tech in 1994.

He has been working as a consulting engineer in the Pittsburgh, PA area since August 1994, and is actively involved in various projects aimed at improving the quality of water in the western Pennsylvania area.