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1.0 INTRODUCTION

1.1 Purpose of the Study

The Durham County Triangle Wastewater Treatment Plant faces new wastewater effluent restrictions with the renewal of the plant's National Pollutant Discharge Elimination System (NPDES) permit. The North Carolina Department of Environment, Health and Natural Resources, Division of Environmental Management (NCDEM), that administers the enforcement of NPDES in North Carolina, imposed more stringent effluent requirements on five-day biochemical oxygen demand (BOD_5), ammonia nitrogen (NH_3-N), total phosphorus (TP), fecal coliform, residual chlorine and dissolved oxygen (DO). The new effluent TP restrictions, along with recent prohibition of wastewater sludge wasting into landfills in North Carolina and potential agricultural application of waste sludge, motivated Durham County to investigate additional nutrient removal alternatives. The Biological Nutrient Removal (BNR) approach, in contrast to chemical removal of phosphorus, demonstrates potential for lowering operation and maintenance costs and reducing sludge production. Also, BNR proves more suitable for land application of sludge because it does not employ potentially harmful chemicals.

This report describes a laboratory investigation of the feasibility of physical, operational and hydraulic modifications to the extended aeration basins of the Triangle Wastewater Treatment Plant for enhanced biological phosphorus removal, nitrification and denitrification, combined with effective

carbonaceous oxidation.

The Durham County Engineering Office funded this project to investigate the feasibility of using BNR technology at the Durham County Triangle WWTP. The focus of the study is the conversion of the existing extended aeration tanks to alternating anaerobic and aerobic sections for the purpose of facilitating BNR.

1.2 Existing Facilities

Durham County Triangle Wastewater Treatment plant is located in the southern part of Durham County just south of the point of confluence of Northeast Creek and Burden's Creek. The plant has a nominal flow capacity of 6 million gallons per day (mgd) and it currently treats 2.5 mgd average daily flow.

The sources of wastewater are approximately 53 percent flow from domestic/residential and 47 percent flow from research and industrial facilities in the Research Triangle Park. At present, twenty-one industries discharge their wastewater to the Durham County Triangle WWTP. The type of industries vary, including research and development, pharmaceutical, agricultural, electronic and a metal plating plant [1].

Preliminary treatment includes two bar screens, followed by two grit chambers. Four vertical centrifugal pumps transfer influent wastewater from the headworks to the extended aeration basins. Two parallel extended aeration basins - 392 feet long, 98 feet wide and with 12 feet of water depth - each provide a hydraulic detention time of 24 hours at the design flow of 6 mgd. Aeration is achieved by eight surface aerators, which are platform-mounted - four in each basin. Alum is added to the aeration basins for phosphorus precipitation, and caustic soda for pH control. From the aeration basins, the flow proceeds to the secondary clarifiers. Two clarifiers - center pier with siphon feed and peripheral overflow - provide a total hydraulic detention time of four hours. Activated sludge is returned to the head of the

aeration basin by six vertical, centrifugal pumps - three for each train. Activated sludge is wasted to two on-site sludge holding lagoons. Following treatment in the activated sludge basin, chlorine is added for disinfection and the effluent is then filtered. Effluent filters comprise high grade silica sand media. After filtration, wastewater effluent is discharged to Northeast Creek [2]. A flow diagram for the plant is shown in Figure 1.1. Table 1.1 shows plant performance from July 1987 to June 1989.

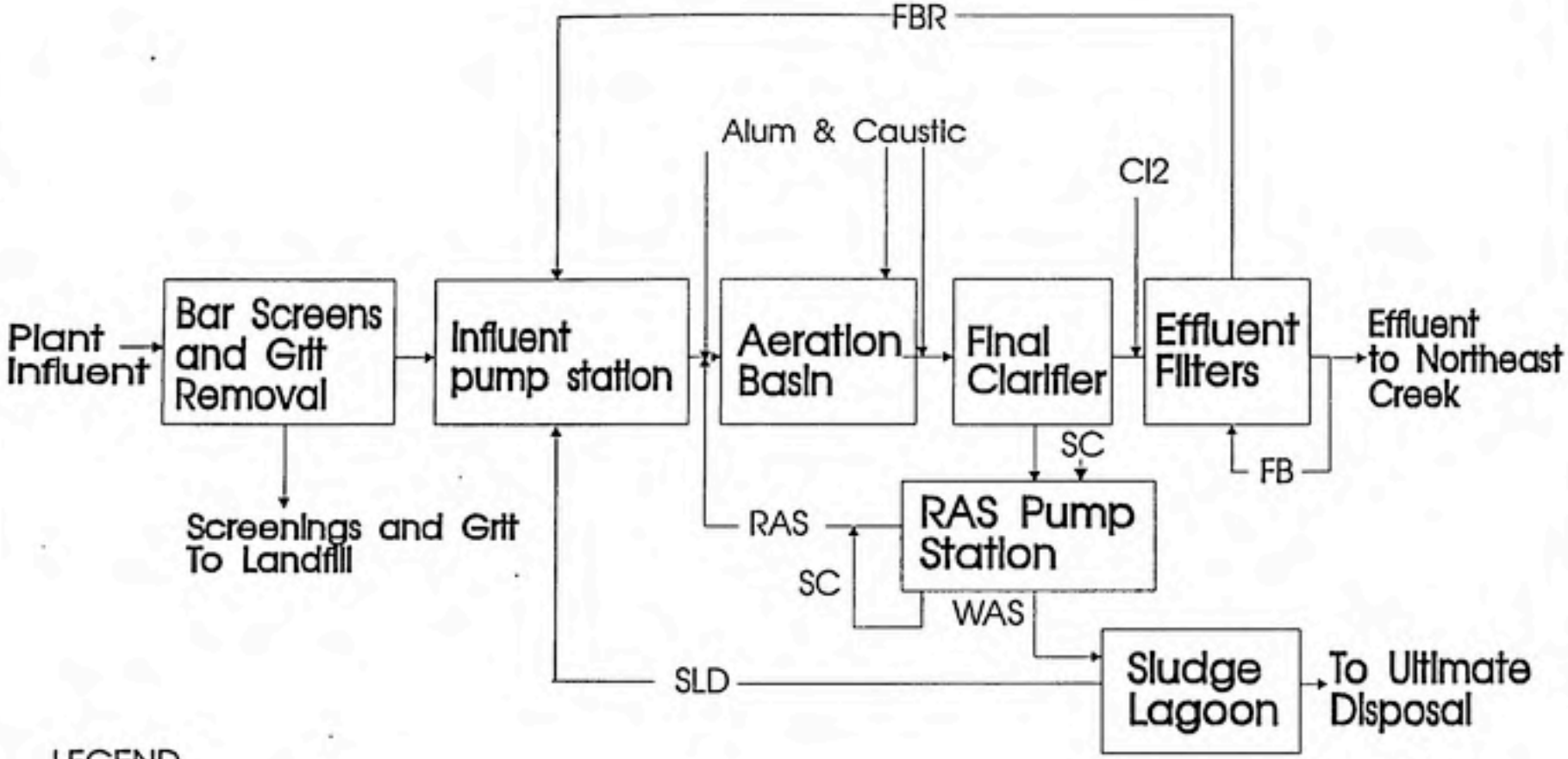
Table 1.1

Plant Performance

July 1987 TO June 1989

Durham County Triangle Plant

Yearly Averages Derived from Monthly Average Data							
parameter	unit	Influent			Effluent		
		1987	1988	1989	1987	1988	1989
Flow	mgd	2.44	2.82	2.42	2.44	2.82	2.42
BOD5	mg/L	142	130	120	2	3	2
COD	mg/L	469	401	355	17.5	26.5	30.2
TSS	mg/L	204	176	175	2	4	2
Ammonia	mg/L	14.2	13.5	14.5	0.1	0.4	0.2
Phosphorus	mg/L	6.3	5.4	5	3.2	1.5	1.1



LEGEND

FB	Filter Backwash
FBR	Filter Backwash Return
RAS	Return Activated Sludge
SC	Scum
SLD	Sludge Lagoon Decant
WAS	Waste Activated Sludge

EXISTING PLANT PROCESS FLOW SCHEMATIC

Durham County Triangle Plant.

Figure 1.1

2.0 NEW EFFLUENT LIMITS AND THEIR IMPLICATIONS

2.1 Changes to Effluent Limits

Durham County is permitted to discharge treated wastewater by NCDEM. In mid-1990, stricter summer and winter discharge requirements were stipulated in the plant's renewed NPDES permit. The new discharge requirements for the Triangle Wastewater Plant include reduction in effluent nutrient levels. Specifically, summer limits of ammonia nitrogen (NH_3-N) and total phosphorus (TP) have been reduced from 2.0 milligrams per liter (mg/L) and 2.0 mg/L to 1.0 mg/L and 0.5 mg/L, respectively. NCDEM stated that the reduction in the discharge of phosphorus is required to improve problems of localized eutrophic conditions measured by potential algal growth in the Northeast Creek arm of B. Everett Jordan Reservoir, south of the treatment plant site [1]. Table 2.1 shows changes to winter and summer discharge limits for the Triangle Wastewater Treatment Plant.

Historical operating data that appear in Table 1.1 demonstrate that NH_3-N has been removed effectively. The plant could meet the new ammonia limits with little or no changes to the current operating practices. However, phosphorus removal could be more difficult to achieve. Considerable increase in the application of chemical precipitant will be required to meet the new summer monthly average TP limit of 0.5 mg/L, if the current practice of chemical treatment for phosphorus removal continues.

Table 2.1

Old and New NPDES Effluent Limits

for Selected Parameters

Durham County Triangle Plant

Effluent Characteristics	OLD		NEW	
	MONTHLY WINTER AVERAGE	MONTHLY SUMMER AVERAGE	MONTHLY WINTER AVERAGE	MONTHLY SUMMER AVERAGE
Flow, MGD	6.0	6.0	6.0	6.0
BOD5, mg/L	16.0	8.0	10.0	5.0
TSS, mg/L	30.0	30.0	30.0	30.0
NH3-N, mg/L	4.0	2.0	1.8	1.0
DO, mg/L	5.0	5.0	6.0	6.0
TP, mg/L	2.0	2.0	2.0	0.5

Summer: April 1 to October 31

Winter: November 1 to March 31

2.2 Effect of New TP Limits on the Plant Operation

The removal of phosphorus is achieved at present by means of alum addition. Alum has been used since mid-1987. The new summer TP limit of 0.5 mg/L could be met by increasing alum precipitant feed, an option which carries an associated higher chemical cost.

However, alum feed pumps are manually operated, and the plant is staffed for only 8 hours each day. Constant rate for the chemical feed pumps is not optimal because the influent flow and strength change significantly through the day, evening and night hours (diurnal variations). Periods of low flow and high alum application could result in low pH levels, insufficient TP removal, wasting of alum and potentially greater whole effluent toxicity. The addition of higher amounts of alum, for increased phosphorus removal, would require additional alkalinity, and therefore would require application of greater amounts of sodium hydroxide.

Sodium hydroxide feed is monitored manually, so application of sodium hydroxide to match continuing variations in alkalinity could pose an operational problem. Again it would carry additional chemical cost. Automated chemical metering for alum and sodium hydroxide would require an expensive upgrade to existing chemical handling facilities.

In the future, the Triangle Plant will likely pursue sludge land application as space in the existing sludge holding lagoons is limited. The anticipated increase in alum feed would generate more sludge and increase the aluminum content in the sludge, making it less suitable for safe land application. For these reasons, biological nutrient removal technology may have greater long term advantages than chemical phosphorus removal.

3.0 WHY BIOLOGICAL NUTRIENT REMOVAL

The objective of biological phosphorus removal is to promote a net accumulation of phosphorus in sludge without the intervention of chemicals. The key to successful phosphorus removal is providing both anaerobic and aerobic conditions for selection of phosphorus removing organisms. Removal of phosphorus from the main stream system is accomplished by wasting phosphorus rich sludge from the secondary clarifiers. Up to 7% accumulation of phosphorus on a dry weight basis has been recorded for municipal systems utilizing biological phosphorus removal. Activated sludge that is a product of conventional activated sludge process typically contains 3% phosphorus by weight (3).

Many wastewater plants that utilize biological nutrient removal consistently meet removal requirements and save in operation and maintenance costs (5). Full scale conversion of an extended aeration plant to a BNR configuration was shown to have phosphorus removal potential to sub-mg/L. Modifications to the plant were done at a minimal capital cost (4). Savings in annual operation and maintenance cost of US$5-6 million have been estimated for a total of thirty-two nutrient removal plants operating in South Africa (6).

Specifically for the Triangle Plant, operation and maintenance costs associated with power requirements for aeration could be lowered using BNR technology as discussed in chapter 10.

4.0 BACKGROUND AND LITERATURE REVIEW

In this study phosphorus and nitrogen removal were addressed. The wastewater industry refers to these two constituents as the main nutrients of concern or as the "prime nutrients". In the following sections, phosphorus and nitrogen removal are discussed in greater detail.

4.1 Phosphorus In The Aquatic Environment

All living cells require phosphorus, nitrogen, sulfur and carbon. Phosphorus constitutes approximately 3% of the cell mass on a dry basis. Phosphates play a physiological role in the cell by being the constituents of nucleic acids, phospholipids and coenzymes. In most aquatic environments the most commonly found forms of phosphorus are orthophosphate, polyphosphate and organically bound phosphorus. The orthophosphates, such as, PO_4^{-3}, HPO_4^{-2}, $H_2PO_4^-$ and H_3PO_4 are available for microbial metabolism. Polyphosphates include molecules with more than one phosphorus atom. In many cases, polyphosphates are hydrolyzed and converted to orthophosphates before their metabolism can proceed. In the aquatic environment, activity of microorganisms affects solubility and mobilization of phosphorus as inorganic phosphates are assimilated into or released out of microbial cells. The phosphorus cycle represents phosphorus movement with no change to the oxidation state (6)(7). All phosphorus forms remain in the +5 oxidation state.

The main sources of phosphates in wastewater include 1)laundering

and other cleaning constituents, 2)fertilizers that include orthophosphates and are carried into the wastewater systems via surface runoff and snow melt and 3)biologically mediated release of organic phosphates.

When excess phosphorus enters a phosphate-limited aquatic habitat, a sudden increase in the bacterial and algal productivity - termed eutrophication - can be experienced, leading to substantial increase in organic matter in the body of water. The depletion of oxygen associated with such excessive growth becomes deadly to fish and other oxygen dependent biota. Concerns about eutrophication led to the tightening of national effluent limits on phosphorus [7][15] and are the reason for the newer total phosphorus limits for the Durham County Triangle Plant [1].

4.2 Biological Phosphorus Removal In Wastewater Treatment

Polyphosphate is a form of inorganic phosphate that can be used in the generation and accumulation of adenosine triphosphate (ATP), a major carrier of energy in biological systems. Internal buildup of polyphosphate reserves allows ATP production during periods of limited external food and energy sources. The buildup of polyphosphate characteristic of the polyphosphate bacteria is used in biological phosphorus removal systems.

A recent study confirmed that polyphosphate is the major form of bioaccumulated phosphorus in activated sludge. It was shown that the storage of increased levels of polyphosphate can be stimulated by providing fatty acids as carbonaceous oxygen demand (COD)

source in conjunction with elevated magnesium and potassium [9].

Polyphosphate is stored in internal cytoplasmic granules that can be detected in a laboratory by staining techniques, such as the Niesser staining, and using light microscopy. These granules are often referred to as volutin . Following the fate of phosphorus in BNR plants, polyphosphate and polyhydroxybutyrate (PHB) have been shown to exist in volutin granules from activated sludge samples. PHB molecules are common carbon reserve materials in bacterial cells [6][7][10].

In wastewater treatment plants utilizing Enhanced Biological Phosphorus Removal Systems (EBPR), the lack of terminal electron acceptors - such as oxygen or oxidized nitrogen at the head of the treatment train - provides advantages for sustaining microorganisms that can accumulate internal carbon reserves over other bacteria. Some of these bacteria, specifically heterotrophic polyphosphate bacteria, are also capable of storing polyphosphate reserves under aerobic conditions and subsequently utilizing it for ATP production. Under anaerobic conditions heterotrophic polyphosphate consuming organisms will hydrolyze internal polyphosphate for energy needed to take up and store organic carbon [7][15]. It has been suggested that during the initial anaerobic stage, fermentation of complex influent organic matter to low molecular weight compounds such as acetic acid is required for anaerobic organic carbon uptake to be achieved [10].

An anaerobic condition can cause internal hydrolysis of polyphosphates and their release from the cell into solution -

often referred to as "phosphorus release". Energy from breaking high energy polyphosphate bonds enables target organisms to extract soluble organic material from the wastewater. The result of the hydrolysis of polyphosphate is a release of orthophosphate from the cell. Organic carbon uptake in the anaerobic zone provides a mechanism for phosphorus accumulating organisms to successfully compete with microbes that are otherwise selected in a aerobic or anoxic environments [10].

When biomass is introduced into an aerobic environment following the anaerobic environment, phosphorus can be assimilated back into the cell in the form of polyphosphate by the microorganisms. Some phosphorus consuming organisms will hydrolyze organic compounds to produce new cell mass and in turn will store polyphosphate with the available energy. This stored phosphorus is in excess of usual cell concentrations. The assimilation of phosphorus under aerobic conditions is often referred to as "phosphorus uptake". As a result, a net accumulation of phosphorus is taking place and a portion of the biomass rich in phosphorus is wasted as waste activated sludge.

Data collected in field investigations of four full scale plants that use biological phosphorus removal technology revealed a clear correlation between effluent phosphorus and effluent NO_3-N [11]. This correlation demonstrated that the presence of NO_3-N in the return sludge stream inhibits EBPR. These findings suggest that organic substrate which enters the anaerobic stage is used in the presence of NO_3-N for denitrification, therefore rendering it unavailable for phosphorus release [11]. Another explanation for

the inhibiting effect of nitrate is that nitrate inhibits fermentation reactions responsible for forming acetic acid and other simple carbon sources, which are required by phosphorus removing organisms [6].

Limits in influent organic carbon can lower the extent of phosphorus release and uptake. Therefore, high influent BOD/P ratios are desirable to achieve biological phosphorus removal. Significant improvements in phosphorus removal efficiency have been experienced when easily biodegradable organic material was provided [12]. Temperature and mean cell residence time (MCRT) are two other important parameters that influence EBPR. McClintock et al. [13] reported that EBPR was not possible at MCRT values lower than 5 days and 10 degrees C, even with additional COD (as acetate) added. Higher MCRT values were considered optimal because of the associated reduced sludge production. In another laboratory bench scale experiment, EBPR functioned efficiently at MCRT higher than 2.9 days. At lower MCRT values, EBPR capabilities begun deteriorating and showed dependency on temperature [14].

4.3 Nitrogen in the Aquatic Environment

Like phosphorus, nitrogen is an essential element for growth of organisms in the environment. It constitutes 12%-13% of cell mass on a dry basis. Unlike the phosphorus cycle, the nitrogen cycle represents movement of nitrogen with a corresponding changes in its oxidation state. The forms in which nitrogen most commonly exists in the aquatic environment are organic nitrogen and ammonia nitrogen (-3 oxidation state), nitrite nitrogen (+3 oxidation

state) and nitrate nitrogen (+5 oxidation state). Organic nitrogen and ammonia nitrogen are the principal forms in untreated wastewater. The transformation of organic nitrogen to ammonia nitrogen, referred to as ammonification, takes place by bacterial decomposition of proteinaceous substrate and hydrolysis of urea (15).

Two species of ammonia nitrogen are commonly found in the aquatic environment - the protonated ammonia species, ammoniun ion (NH_4^+) and its conjugate base, ammonia (NH_3). The relative concentration of the two species depends on pH; the pK_a is 9.3. Organic materials such as protein, peptides, nucleic acids, urea and synthetic organic material are the source of organic nitrogen. The incorporation of NH4+ into nitrogen-containing material is termed amination (16)(17).

The combination of nitrite (NO_2^-) and nitrate (NO_3^-) is commonly described as total oxidized nitrogen. The pE region over which nitrite dominates is very narrow, supporting the observation that nitrite is found normally in extremely low concentrations in the aquatic environment and is readily inter-convertible to $NO3^-$ and $NH4^+$ (17).

Nitrogen enters aquatic environments from natural and manmade sources. Several factors contribute to increased amounts of nitrogen in natural waters: Increase in human activity, commercial and industrial growth, elevated levels contained in precipitation, dustfall and non-urban runoff, as well as the increase associated with discharge of human waste. The main problems with nitrogen

build-up in natural waters are: 1)oxygen demand exerted when nitrogen is discharged into the aquatic environment and 2)toxicity of ammonia nitrogen to aquatic organisms. If nitrogen is a limiting nutrient in the receiving waters, any form of nitrogen entering the system can contribute to eutrophication (15).

Nitrification and denitrification are two processes by which NH_3-N and NO_3-N ,respectively, are removed from wastewater. These two processes are discussed in the next two sections .

4.4 Nitrification

The oxidation of ammonia nitrogen to nitrate, with nitrite formation as an intermediate, is a process mediated by autotrophic bacteria and is known as nitrification. Autotrophic bacteria derive energy for growth from an inorganic source such as ammonia and use carbon dioxide (CO_2) as a carbon source for cell synthesis. Two groups of autotrophic microorganisms, Nitrosomonas sp. and Nitrobacter sp., carry out nitrification in the presence of oxygen. Nitrosomonas sp. and Nitrobacter sp. are obligate aerobes. They do not nitrify in the absence of oxygen. The reaction is acid producing as demonstrated by the following overall equation:

$$NH_4^+ + 2O_2 \text{ -----> } NO_3^- + 2H^+ + H_2O$$

Approximately 7.14 mg/L of alkalinity, expressed as $CaCO_3$, is consumed when 1 mg/L nitrogen goes through conversion from ammonia nitrogen to nitrate.

4.5 Denitrification

Denitrification is a process by which nitrate is utilized as an electron acceptor by heterotrophic bacteria to break down and utilize organic substrates in an anoxic environment. Denitrifying bacteria are facultative anaerobes that can grow under both aerobic and anaerobic conditions. In this process nitrate is reduced to nitrogen gas ($N_{2(g)}$), which is released to the atmosphere. About 3.57 mg/L of alkalinity can be recovered from conversion of 1 mg/L of nitrate as nitrogen to nitrogen gas. The availability of an organic carbon source is necessary for denitrification to proceed [15][19].

4.6 Nitrification and Denitrification in Wastewater Treatment

Nitrogen in municipal wastewater is composed of about 60% organic nitrogen and 40% ammonia nitrogen. Typical concentrations of ammonia nitrogen in municipal wastewater influents are around 25 mg/L and can be as high at times as 50 mg/L. Because ammonification of organic nitrogen occurs during aerobic wastewater treatment, complete nitrification normally requires conversion of the total influent nitrogen to nitrate. Both aerobic suspended growth and aerobic attached growth systems have been identified as successful in carrying out nitrification [8].

Combined carbon oxidation and nitrification approaches ("single sludge") or separate stage nitrification approaches have been used successfully in activated sludge systems. The two main advantages

of a separate reactor for nitrification include good protection against most toxicants and stable operation with enhanced selection of the targeted nitrifying bacteria. However, the separate tank typically carries higher capital cost.
Systems for nitrogen removal are discussed in more detail in the next chapter. The nitrification process is carried out by obligate aerobes; therefore, dissolved oxygen levels in the system must be closely monitored. The dissolved oxygen level should not fall below 1-2 mg/L for successful carbonaceous oxidation and ammonia nitrogen nitrification. Filamentous bulking can also become an operational problem with low DO levels [8].

The following conditions have been identified to encourage high rates of nitrification: low BOD_5/TKN ratios, operation in high temperatures and at pH levels in the range of 7 to 9 [8].

Some facilities combine denitrification with nitrification. Nitrate respiration in anoxic zones reduces the amount of oxygen needed for aerobic biodegradation. Nitrate as terminal electron acceptor in total nitrogen removing systems was shown to have potential for both reduction in energy for aeration and partial recovery of alkalinity lost during nitrification [18][19].

A comparison of aerobic and anoxic conditions in activated sludge applications was made by McClintock et al. [18]. The effects of nitrate respiration on microbial growth and biokinetic parameters as well as removal efficiency in the activated sludge system were explored. An anoxic system, utilizing nitrate as the terminal electron acceptor, showed lower yield and higher substrate

utilization rate. The results pointed to the potential advantages in reduction of sludge and savings in aeration energy. The reduction in required oxygen can translate to lower power cost associated with oxygen transfer.

5.0 BIOLOGICAL PHOSPHORUS AND NITROGEN REMOVAL PROCESSES

A number of processes have been proposed for biological nitrogen and phosphorus removal. Some of the nitrogen removal processes are designed for nitrification only, while others nitrify and denitrify ; i.e., remove both ammonia nitrogen and oxidized nitrogen. Biological phosphorus removal can be accomplished alone or in combination with nitrogen removal. Biological phosphorus and nitrogen removal often are combined in the same systems because the removal of oxidized nitrogen often improves enhanced biological phosphorus removal, as discussed in chapter 4.

Various commercial nutrient removal processes have been developed, and most have been given trade names. The differences among nutrient removal processes are mainly in the location of the anaerobic, anoxic and aerobic stages in the treatment train and the point of wastewater application. In addition, the origin and flow of internal recirculation and the feed mode of the return activated sludge (RAS) vary for some processes.

The use of chemicals is eliminated or reduced with the use of biological nutrient removal approaches. An exception is the "Phostrip Process" which is described below. When phosphorus removal to sub mg/L is desired, filtration of the secondary effluent can be used. Filtration can remove phosphorus associated with suspended solids following secondary clarification, but will not be effective in removing dissolved phosphorus.

A description of some of the nutrient removal processes available

is summarized below. The processes mentioned are all suspended-growth type.

5.1 Single-Stage and Separate-Stage Nitrification

In Single-Stage nitrification, both carbon oxidation and nitrification occur in the same tank. The extent of nitrification in Single-Stage systems depends on the operating mean cell residence time. In Separate-Stage nitrification, carbon oxidation and ammonia nitrification are thought to occur in separate reactors.

The Separate-Stage nitrification configuration provides the ability to optimize independently the two processes. Also, the nitrifying bacteria could be protected from shock-loading of biodegradable toxins, which are consumed prior to reaching the nitrification reactor. Adequately long sludge retention time (SRT) and dissolved oxygen (DO) above 2 mg/L are necessary to allow the slow-growing autotrophs to nitrify successfully. Figures 5.1 and 5.2 show the Single-Stage and Separate-Stage nitrification systems, respectively. Both single and separate stage processes shown in Figures 5.1 and 5.2 are referred to as Single-Sludge systems, because the same biomass is used for both carbonaceous BOD removal and nitrification. When separate clarifiers are used between processes, the system is called Separate-Sludge system.

Figure 5.3 shows a Separate-Sludge Nitrification system. The Two-sludge system is likely more effective at separating carbon oxidation from nitrification because of the ability to vary sludge

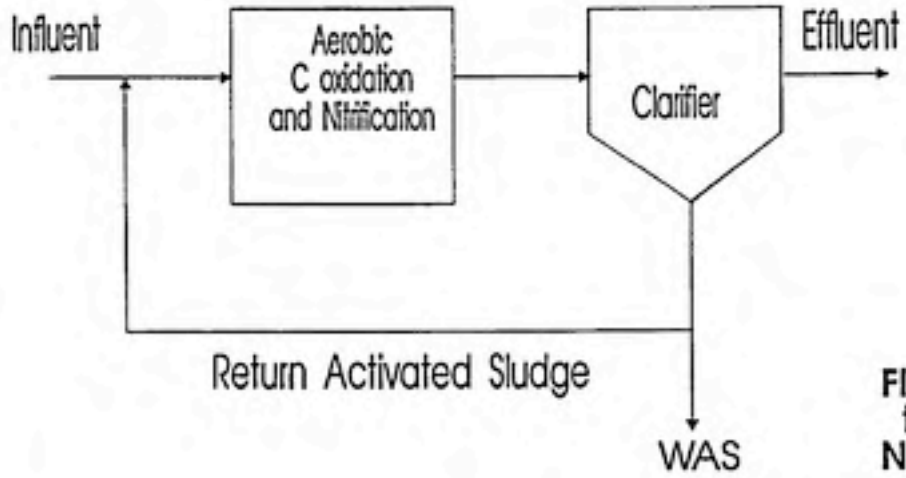


Figure 5.1
Flow Schematic of the Single-Stage Nitrification System

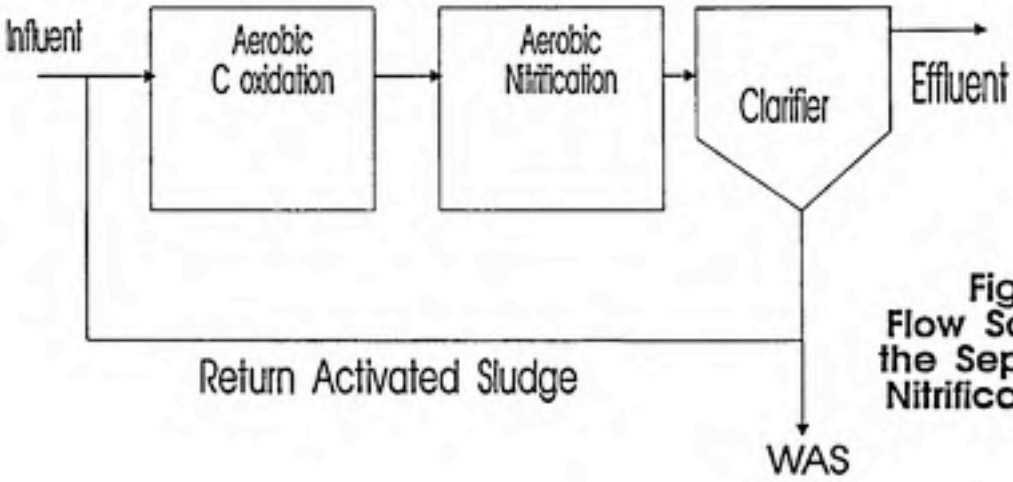


Figure 5.2
Flow Schematic of the Separate-Stage Nitrification System

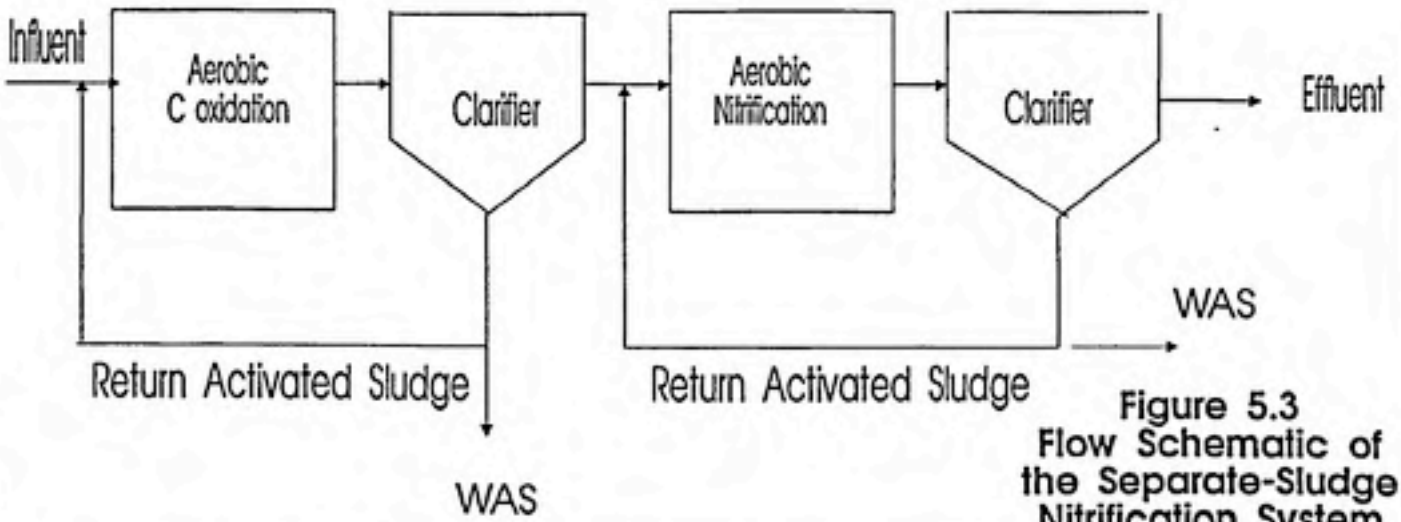


Figure 5.3
Flow Schematic of the Separate-Sludge Nitrification System

retention times (SRT) independently in each stage. Nitrification can be precluded in the first stage by operating it at low SRT. In the Single-Sludge, Separate-Stage system, nitrification is likely to overlap with carbon oxidation in the first reactor [6].

5.2 Single-Sludge, Two-stage Nitrogen Removal

The Single-Sludge, Two-stage Nitrogen Removal (nitrification plus denitrification) process features a modification to conventional activated sludge. An example is shown in Figure 5.4 for a system with an external carbon source for denitrification. An aeration stage remains at the head of the activated sludge system where most carbonaceous compounds are oxidized and nitrification takes place. Nitrified mixed liquor is then transferred to an anoxic zone with no measurable dissolved oxygen where denitrification occurs. In past applications, denitrification was slow in the anoxic stage unless the volume of the tank was increased significantly. Better total nitrogen removal results can be maintained with a continuous introduction of nitrogen-free, readily biodegradable organic carbon source (for example methanol) to the second anoxic zone. This addition provides substrate for the denitrifiers [6].

5.3 Operationally Modified Activated Sludge Process

The Operationally Modified Activated Sludge process is a process that converts part of the operating activated sludge facility to an initial anaerobic stage [15]. This process is applicable for conservatively-sized activated sludge plants.

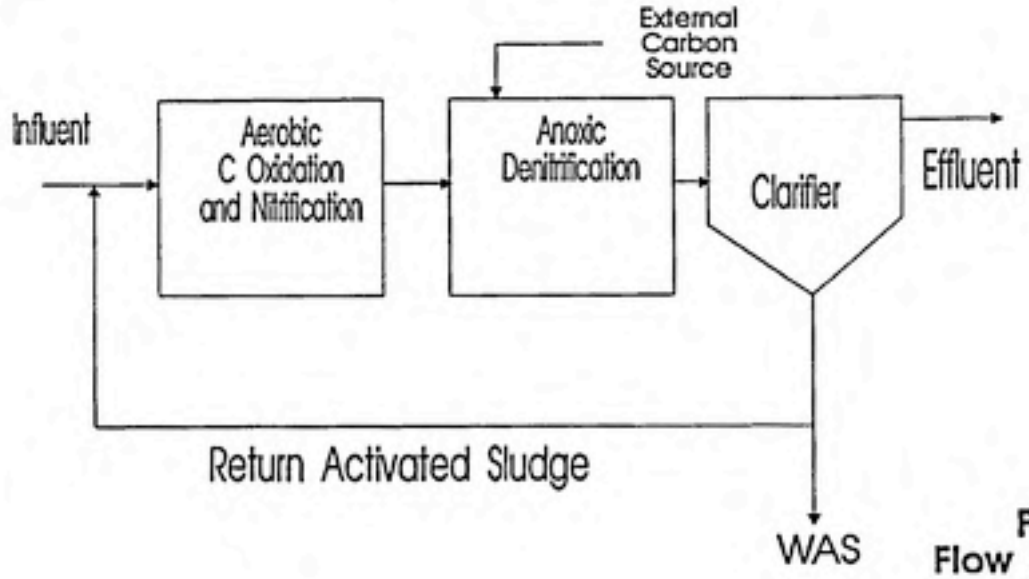


Figure 5.4
Flow Schematic of the Single-Sludge Nitrogen Removal

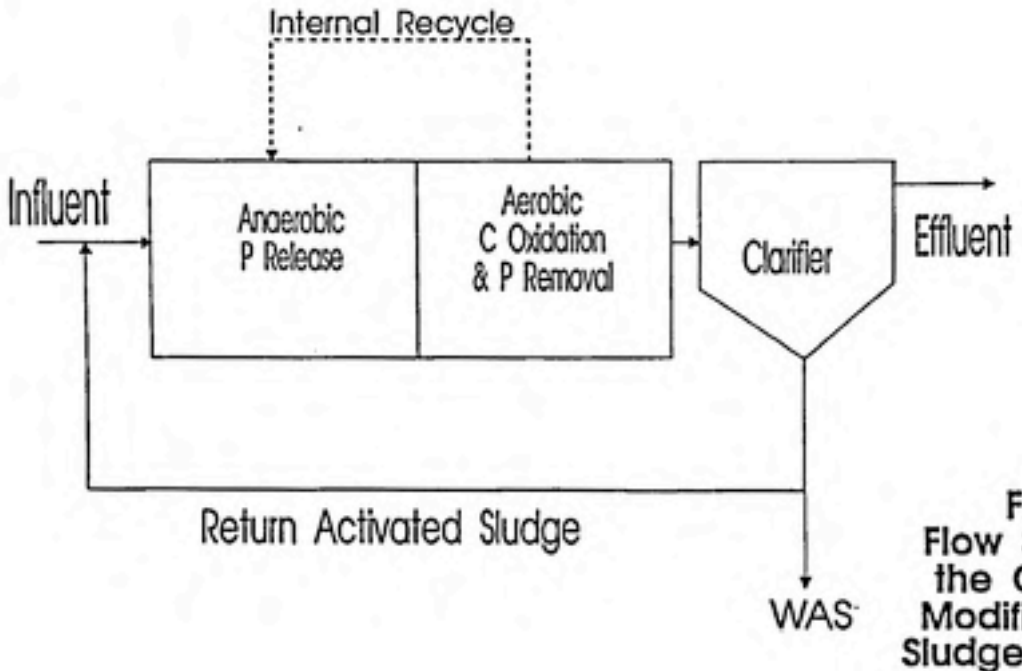


Figure 5.5
Flow Schematic of the Operationally Modified Activated Sludge Process (Also Phoredox Process)

Influent and recycled sludge are mixed in the anaerobic zone, where denitrification of nitrate in the return sludge takes place. The extent of denitrification in the overall process depends on the recycle ratios. High extents of nitrogen removal require very high recycle ratios, e.g., 3:1 or higher. Some plants use an "internal recycle" of mixed liquor from the aerobic section to the anaerobic section, instead of using high recycle ratios (see description of the A2/O process below). Figure 5.5 shows a flow schematic of this process.

5.4 Phoredox Process

Like the Operationally Modified Activated Sludge Process, the Phoredox Process is designed for carbon and phosphorus removal and is based on simple alteration of the activated sludge system as shown in Figure 5.5. Anaerobic stage for phosphorus release is followed by aerobic stage for phosphorus uptake.

A true anaerobic section i.e., no nitrate, at the head of the train is needed for efficient phosphorus removal . Therefore, the possible recirculation of nitrate-rich RAS to the anaerobic zone could reduce phosphorus removal in this system. Consequently, this system is applicable for plants that do not nitrify because nitrate and nitrite production in the aerobic compartment will otherwise be circulated to the anaerobic compartment with the RAS and constitute an undesired external electron acceptor (6).

5.5 A/O and A^2/O Processes

The A/O process represents a patented configuration for combined carbon and phosphorus removal, utilizing an anaerobic zone followed by an aerobic (oxic) zone. It was trademarked by Air Products and Chemicals, Inc., Allentown, PA. The wastewater technology and patents were transferred recently from Air Products to the Danish firm, I Kruger. The patents on the A/O process will expire in 1993. A schematic of the process is shown in Figure 5.6.

The A/O system is similar to the Phoredox Process and the Operationally Modified Activated Sludge Process. However, both aerobic and anaerobic sections are staged to provide a configuration closer to an ideal plug flow. When nitrification is needed, longer hydraulic detention time in the oxic compartment is required.

The A^2/O process includes denitrification in addition to nitrification and carbon and phosphorus removal as shown in Figure 5.7. An anoxic zone between the anaerobic and oxic section can be maintained by "internal recycle" of nitrified mixed liquor from the last oxic stage [20]. The process is useful at plants that must nitrify because nitrates are essentially eliminated from the return sludge due to "internal recycling". This minimizes the potential reduction in phosphorus removal associated with the presence of nitrates in the anaerobic stage.

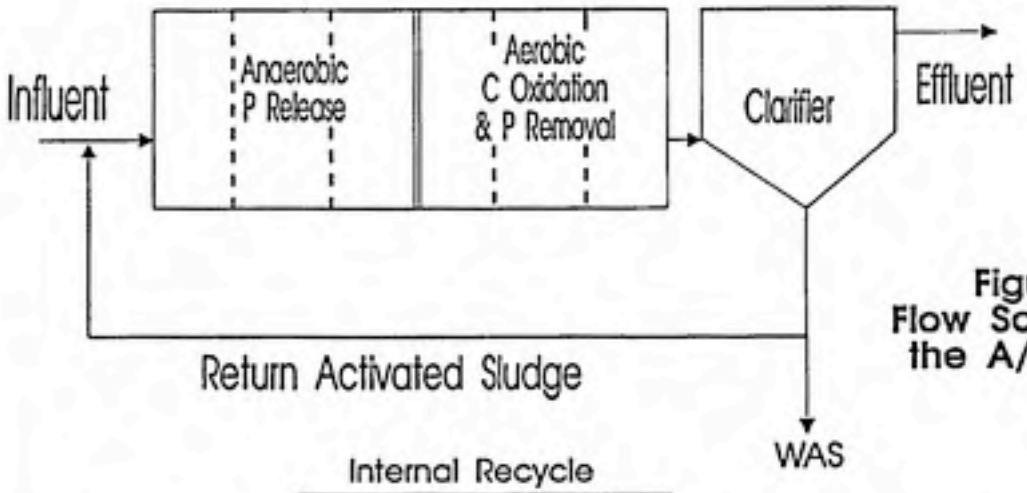


Figure 5.6
Flow Schematic of the A/O Process

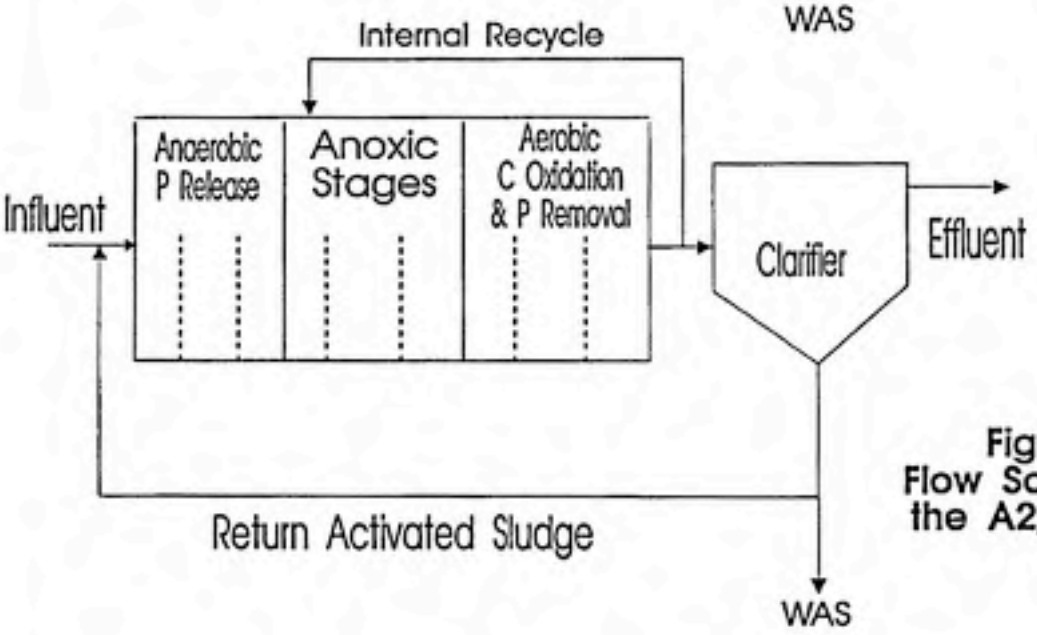


Figure 5.7
Flow Schematic of the A2/O Process

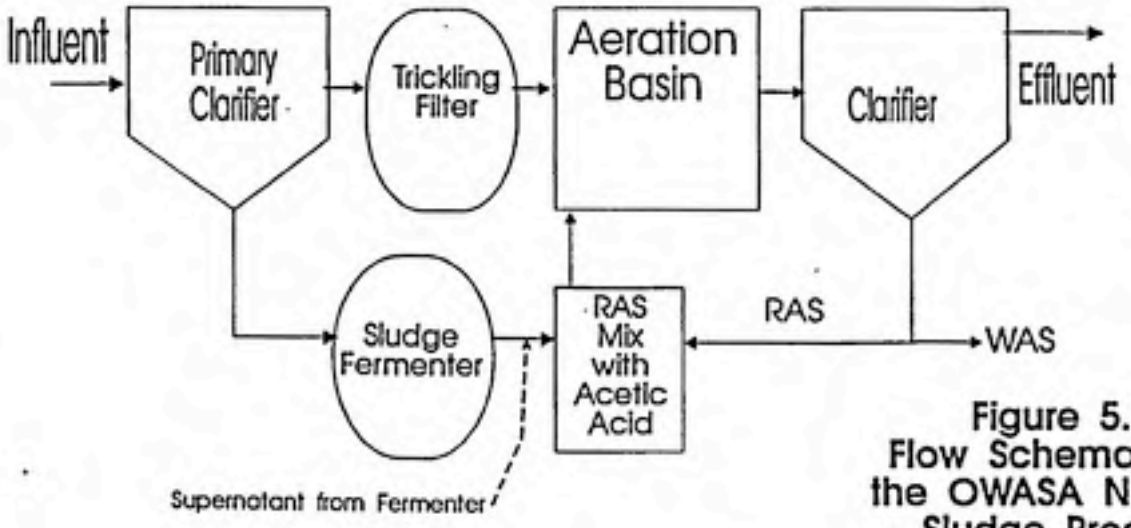


Figure 5.8
Flow Schematic of the OWASA Nutrified Sludge Process

5.6 OWASA Nutrified Sludge Process

The Orange Water and Sewer Authority (OWASA), Carrboro, North Carolina, developed a biological process identified as "Nutrified Sludge" process to reduce phosphorus discharge from trickling filter plants. Plants incorporating trickling filters experience difficulty with biological phosphorus removal in the subsequent activated sludge unit because trickling filter effluent has a very low BOD/P ratio. Therefore a supplemental carbon source must be supplied in the activated sludge system to promote biological phosphorus removal. Figure 5.8 shows a schematic of this process.

Acetic acid is fed from a side-stream sludge fermentation tank to phosphorus-consuming microorganisms in a separate environment from the mainstream treatment. The RAS is exposed to the acetic acid and then it is returned to the head of the aeration basin, where it is mixed with trickling filter effluent. Production of acetic acid is achieved in a two-stage fermentation tank - a high rate anaerobic digester - to which raw sludge is diverted from the primary clarifier. This process makes full use of existing trickling filters ahead of the aeration basin and is applicable for plants that formerly utilized trickling filters as the main secondary treatment approach. Dependable results of effluent total phosphorus below 1 mg/L without tertiary filters are reported for the full scale operation at the OWASA wastewater treatment plant in Chapel Hill, North Carolina [21].

5.7 PhoStrip

The PhoStrip process is designed to provide combined nitrification, denitrification and phosphorus removal and is demonstrated schematically in Figure 5.9. The process includes an activated sludge reactor that is fed by a combination of influent wastewater and return sludge that has been stripped of phosphorus. Return sludge is routed to an anaerobic clarifier where, in the absence of oxygen, intracellular polyphosphate is "stripped" (hydrolyzed) and separated from the sludge. The phosphorus stripped sludge is returned to the main activated sludge reactor, while the phosphate rich supernatant is precipitated with a coagulant in a separate tank.

The phosphorus stripper is normally designed for a solid detention time of 5 to 20 hours. Solid detention time is determined by the mass of solids in the stripper divided by the mass of solids leaving the reactor per day. This process has provided satisfactory phosphorus removal results in full scale applications but has rendered inadequate nitrate removal except in cases when external carbon source was provided to the anoxic zone (6)(8).

5.8 Four-Stage Bardenpho

The Bardenpho process involves alternating anoxic and aerobic stages. Originally four stages were included for carbon and nitrogen removal as shown in Figure 5.10. A modification to the Bardenpho process added a fifth stage for combined nitrogen and phosphorus removal, as discussed in Section 5.9.

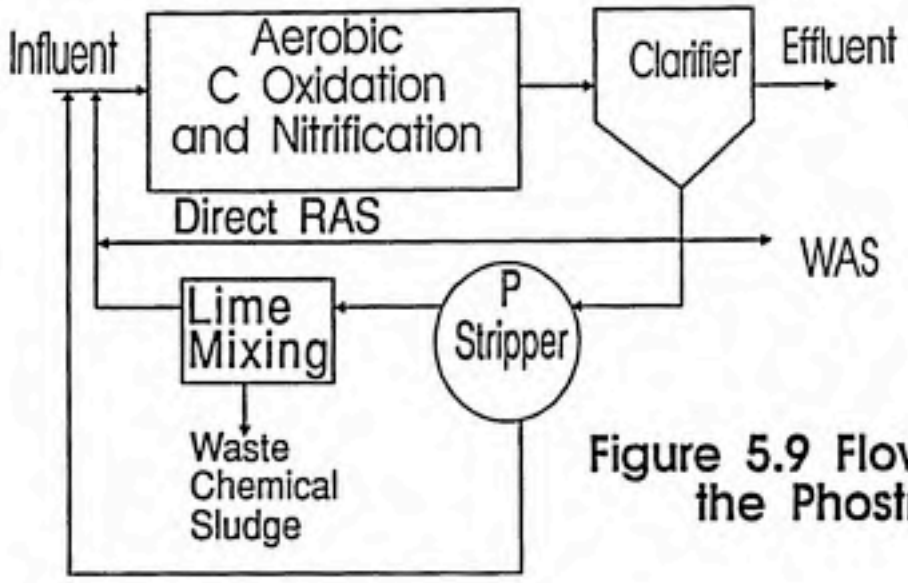


Figure 5.9 Flow Schematic of the Phostrip Process

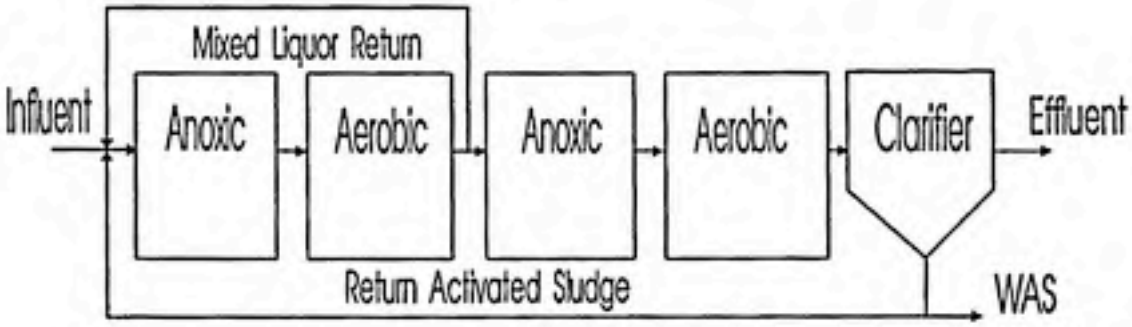


Figure 5.10 Flow Schematic of the Four-Stage Bardenpho

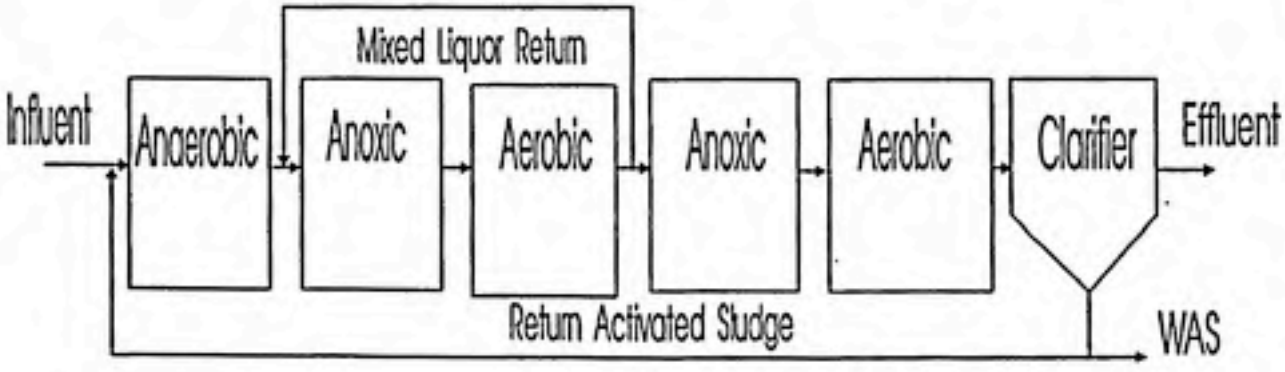


Figure 5.11 Flow Schematic of the Five-Stage Bardenpho

Denitrification takes place in the primary anoxic zone in which raw wastewater or primary effluent is mixed with MLSS rich in oxidized nitrogen from the primary aerobic zone. Nitrification and carbonaceous oxidation occur simultaneously in the primary aerobic stage. Further reduction of nitrate takes place in the secondary anoxic stage as a result of endogenous metabolism of stored reserves within the bacterial cells. A secondary aerobic zone is the fourth stage in the Bardenpho treatment train. The secondary aerobic stage is designed to stop denitrification just before secondary clarification to combat rising sludge associated with $N_2(g)$ production and to prevent phosphorus release associated with anaerobic conditions [8].

5.9 Five-Stage and Three-Stage Modified Bardenpho

The five-stage Bardenpho system is similar to the four-stage process as shown in Figure 5.11. The difference between the two is that an additional anaerobic tank is placed at the head of the treatment train in the five-stage process to promote selection of phosphorus-accumulating microorganisms. In some cases, the last two tanks of the five stage system - secondary anoxic and secondary aerobic - have been deleted because they have been observed to have little impact on total N removal. In this case the process has been referred to as the three-stage modified Bardenpho process.

5.10 Biodenipho

The Biodenipho process is a sequencing batch system proposed by

Arvin and Kristensen in 1985. The process is based on four operational phases, as illustrated in Figure 5.12. Phases A and B promote initial nitrification and phases C and D follow with denitrification. Each phase takes approximately 1 hour. Biological P release is accomplished by an anaerobic tank at the head of the facility. Advantages of this system include the elimination of recycle pumping and piping and added flexibility with allowed variation of detention time for nitrification and denitrification (6).

5.11 The University Of Cape Town Process

The University Of Cape Town (UCT) Process is designed for carbonaceous oxidation, nitrification, denitrification and phosphorus removal. A schematic of the UCT process is shown in Figure 5.13. It is similar to the three stage modified Bardenpho process. Unlike the Three-stage Bardenpho, return activated sludge and, sometimes, last stage aerobic effluent are pumped into the anoxic zone while mixed liquor is recycled from the effluent of the anoxic compartment to the first anaerobic reactor (6). One of the main goals of the UCT process is to prevent uncontrolled loading of oxidized nitrogen into the anaerobic tank.

5.12 Extended Anaerobic Sludge Contact (EASC) for Biological Phosphorus Removal

In the EASC system, both raw wastewater and return activated sludge are fed to an anaerobic basin that originally served as a primary clarifier. Mixed liquor from this anaerobic zone is

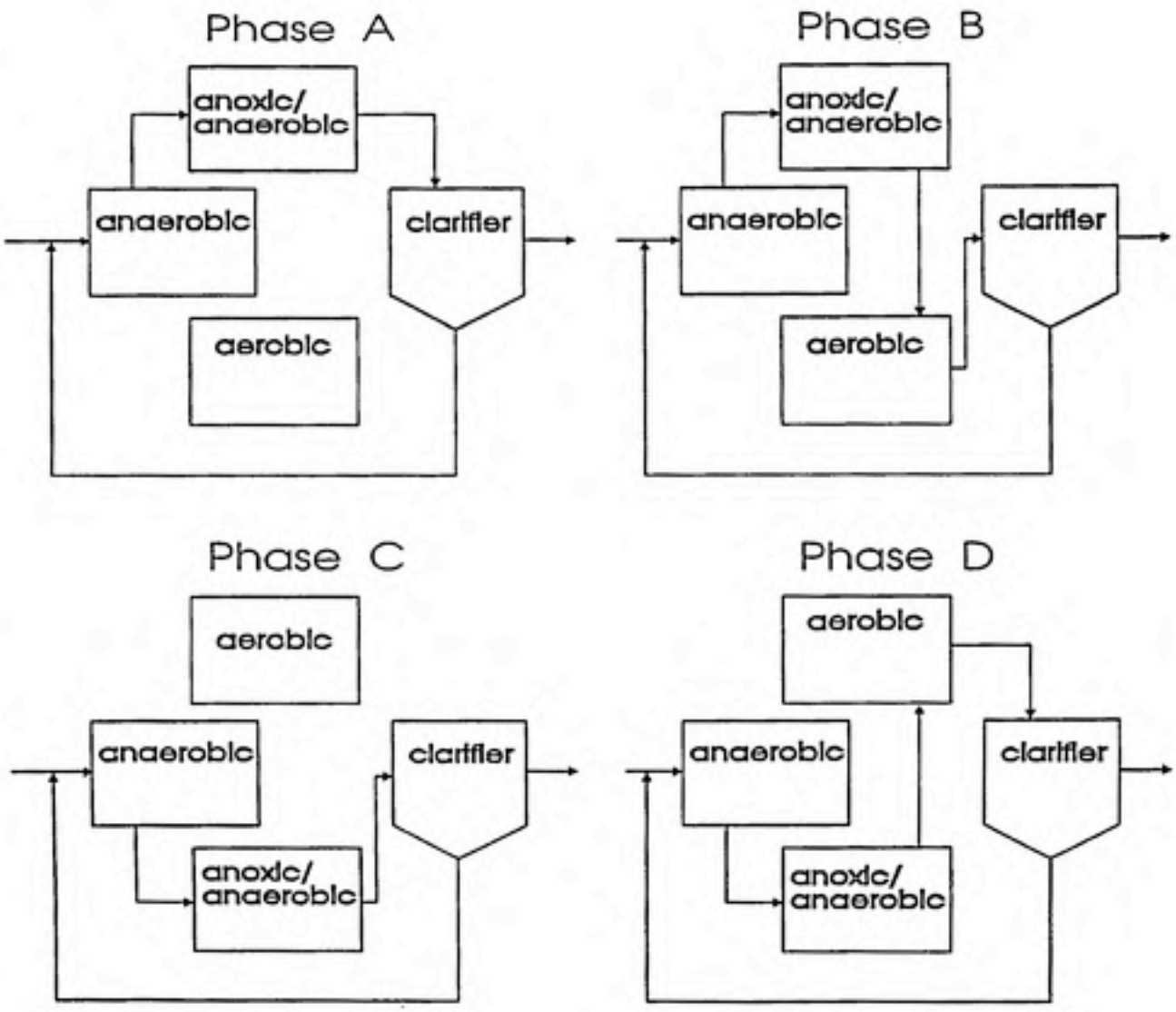


Figure 5.12
Flow Schematic of
the Biodenipho
Process

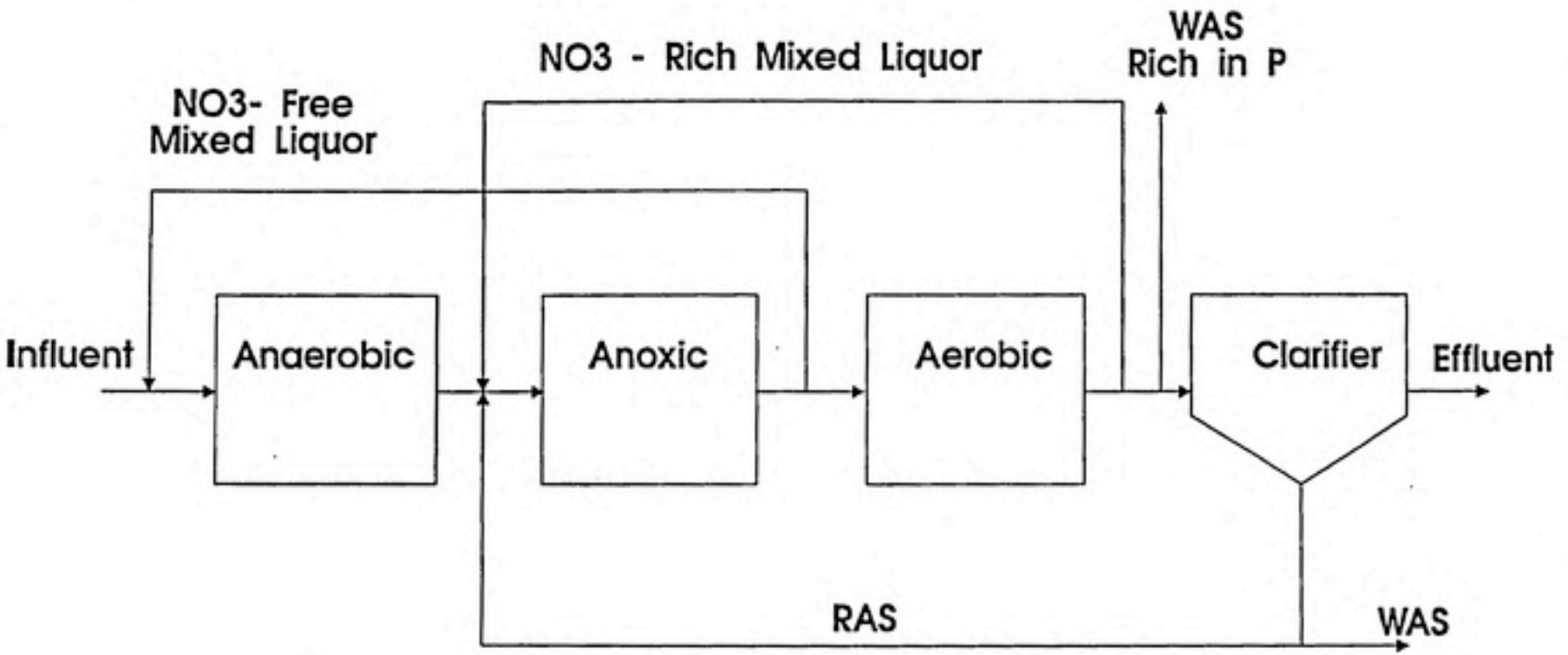


Figure 5.13
Flow Schematic of the
UCT Process

transferred to an aerobic activated sludge section and a final clarifier. The elimination or reduction of primary clarification allows for greater feed of particulate substrate ,which can enhance fermentation reactions that lead to production of acetic acid and other organic acids. As discussed above, these acids are vital in the selection of microorganisms responsible for phosphorus removal. The anaerobic stage at the head of the process train adds to the anaerobic sludge detention time essential for the relatively slow fermentation reaction. The EASC arrangement promotes stratification within the basin contents, creating anaerobic sludge blanket with anoxic supernatant (22).

5.13 Consideration of EBPR at the Durham County Trangle Plant

The Triangle Wastewater Treatment Plant is in the process of investigating additional chemical doses and chemical storage facilities needed to achieve the new NPDES nutrient limits. Hazen and Sawyer, P.C. performed a preliminary cost and technical evaluation that outlined in a report alternatives for phosphorus reduction (2). The alternatives compared were chemical phosphorus removal, the A/O Process, the Bardenpho Process, UCT (University of Capetown) Process and the Operationally Modified Activated Sludge Process. Based on a life-cycle cost comparison for a 20-year planning period, the present worth cost for the Operationally Modified Activated Sludge Process was found to be similar to the cost for chemical phosphorous removal technology. Pilot or plant-scale studies for the Triangle Plant were recommended to determine if the existing extended aeration basins were capable of accommodating phosphorus removal to the required levels and to

assess the need of additional tankage volume (2).

6.0 PROPOSED PHYSICAL AND PROCESS MODIFICATIONS

A schematic of the eight-stage alternating anaerobic and aerobic system proposed in this report is shown in Figure 6.1. This system is different from other available biological nutrient removal systems. There is no "internal recirculation" of mixed liquor from aerobic stages to anoxic stages to accomplish denitrification. Instead, nitrification and denitrification occur in incremental steps as flow proceeds downstream. The first anaerobic stage is for EBPR. The following seven aerobic and anoxic stages are for nitrification and denitrification, respectively. In addition, the proposed system does not use an external source of carbon to enhance the rate of denitrification in the anoxic stages.

The rational for eight alternating anaerobic and aerobic stages in series is that carbon oxidation and nitrification can occur in steps as wastewater makes its way through the reactor stages. In the intermediate anoxic stages 3, 5 and 7 denitrification can be made to occur.

The approach for total nitrogen removal, presented here, is similar in principal to the way in which nitrification and denitrification are carried out in sequencing batch reactors; the air is turned on and off in alternating cycles until total nitrogen is removed to a desired level [23].

Figure 6.2 shows hypothetical profiles for ammonia, nitrate and COD for an ideal eight stage alternating anaerobic and aerobic reactor. The actual profile in any given system would depend on

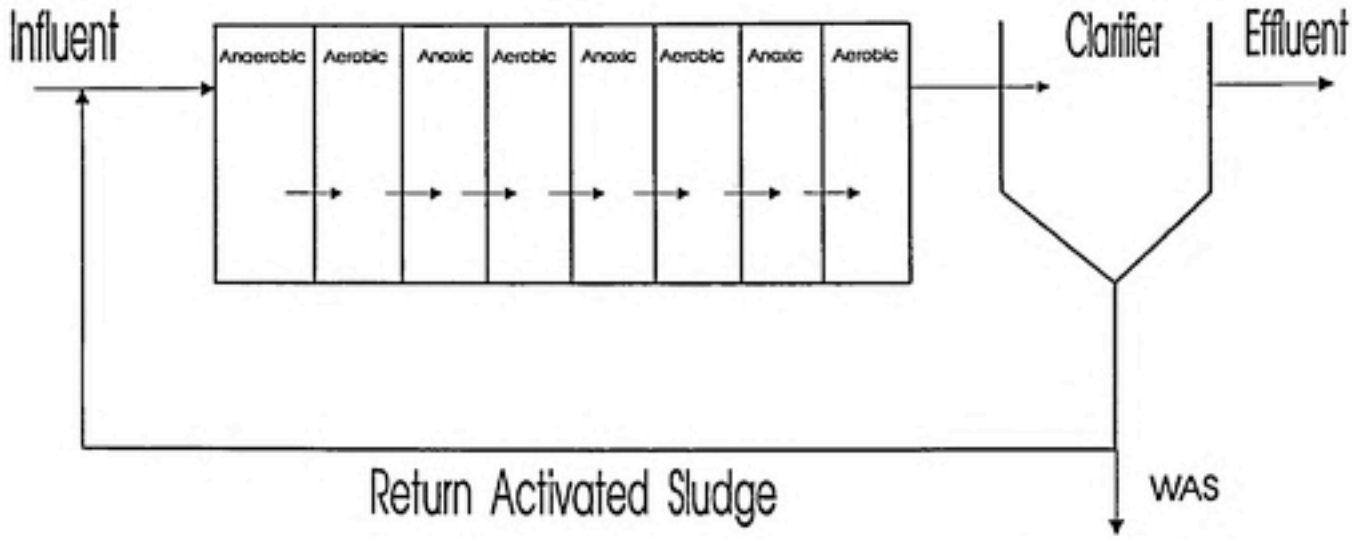


Figure 6.1

Flow Schematic of the Proposed Alternating Anaerobic/Aerobic Process

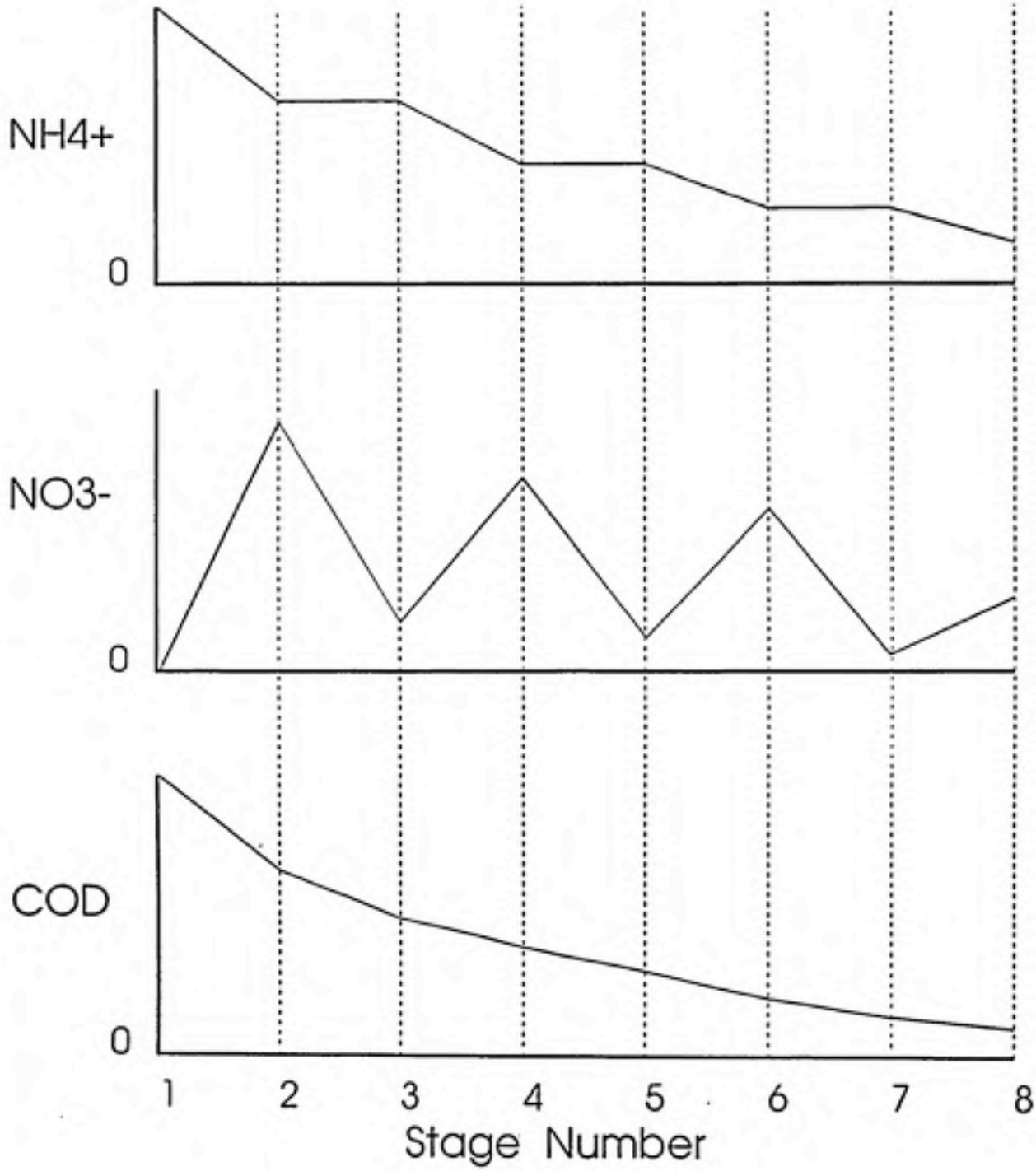


Figure 6.2
Hypothetical Profiles for COD, Nitrate and Ammonia

the size each reactor in the series.

It is important that not all of the biodegradable COD be consumed in the up-stream aerobic stages. The extent of denitrification is contingent upon the availability of some soluble biodegradable COD as a food source for denitrifiers at the latter anoxic stages. Without biodegradable COD, denitrification in reactors 5 and 7 likely to be insignificant and only due to endogenous decay.

Since there is no need for "internal recirculation" pumping, the system is a more passive nutrient removal system than the Bardenpho, UCT, A2/O or the Modified Activated Sludge Process. The proposed alternating anaerobic/aerobic system closely resembles a design for plug flow condition with eight independent compartments in series. Of the processes described, the proposed configuration is most similar to the Five-stage Bardenpho system.

The configuration of the existing extended aeration tanks at the Durham County Triangle Plant is ideal for a conversion to BNR technology. The two rectangular tanks could be retrofitted with a relatively minor capital investment to a BNR configuration by compartmentalizing the basins as shown in Figure 6.3. Baffles or concrete walls with minimum size openings for flow could be added to divide anaerobic zones from aerobic zones within the basins. The size of the interstage openings should be minimized to reduce undesired oxygen transfer from the aerobic zones to the anaerobic zones.

Currently, screened and degritted wastewater is split equally

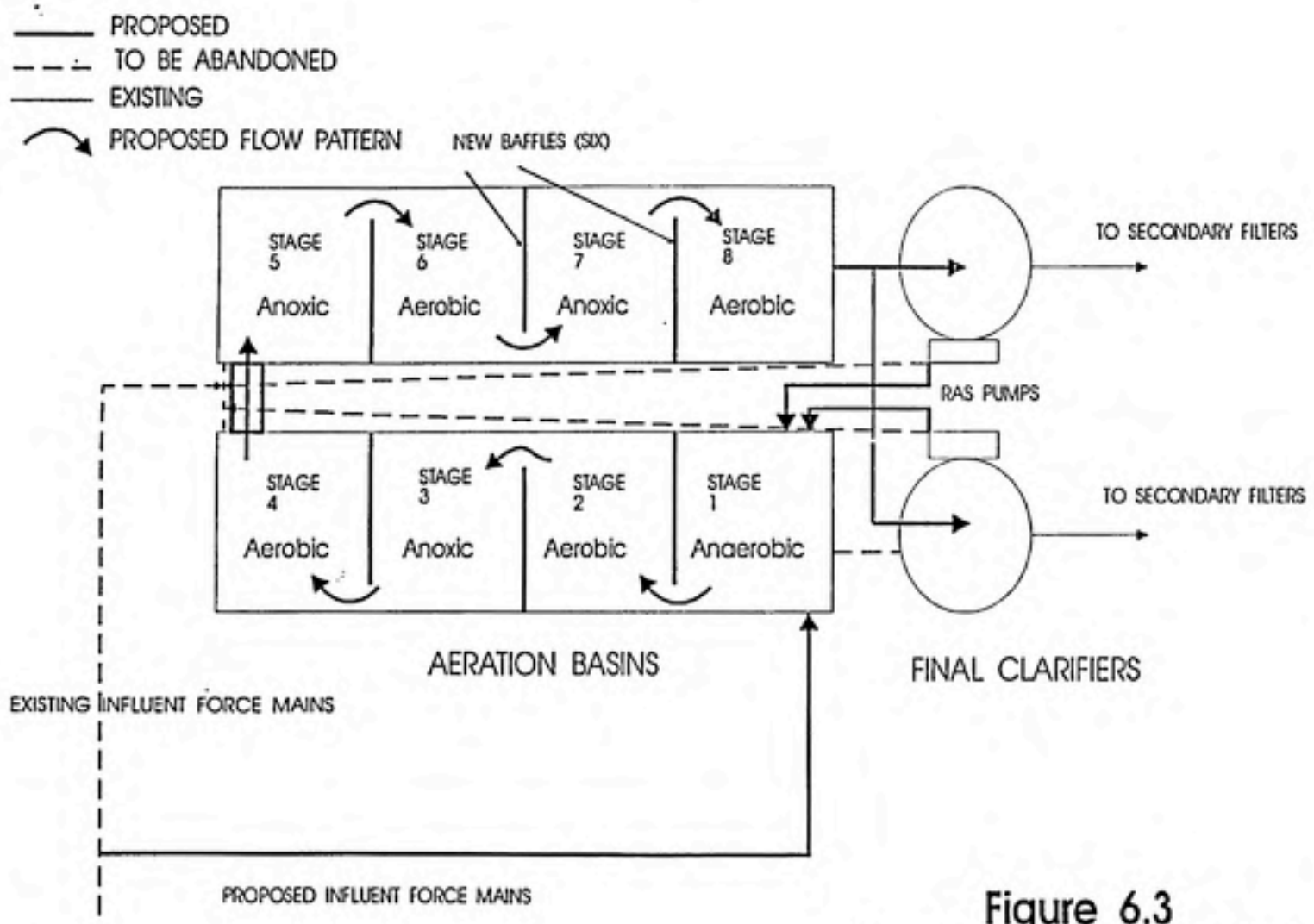


Figure 6.3
Proposed Modifications
to the Extended
Aeration Basins

between the two parallel extended aeration basins. The hydraulic configuration in the aeration tanks could be modified by relocating the aeration influent force main and reversing the flow in one of the two basins. As a result, the aeration tanks could operate in series with one flow pattern through eight stages, instead of the existing two independent flow patterns in parallel. The existing mounted surface aerator could provide mixing and dissolution of air in the aerobic stages, while lower mixing impellers could be utilized to provide mixing only at the anaerobic sections.

The goal behind the proposed modification is an accomplishment of selection of microorganisms that consume and store high levels of phosphorus in a slow rate activated sludge treatment arrangement. As discussed in chapter 4, an anaerobic zone at the beginning of the activated sludge process would select for phosphorus removing bacteria.

By definition, total nitrogen includes all ammonia forms and nitrate species. The Triangle Wastewater Plant's NPDES permit does not include total nitrogen - only NH_3-N is included in the permit. Therefore, the plant is not required to remove nitrate and nitrite. However, the proposed modifications would facilitate removal of nitrate and nitrite (denitrification) in addition to ammonia removal (nitrification), which is necessary for successful phosphorus removal. A sequential reduction in total nitrogen would result in return activated sludge (RAS) low in nitrate. With RAS low in oxidized nitrogen, anaerobic conditions in the first stage could be accomplished, benefiting biological phosphorus removal,

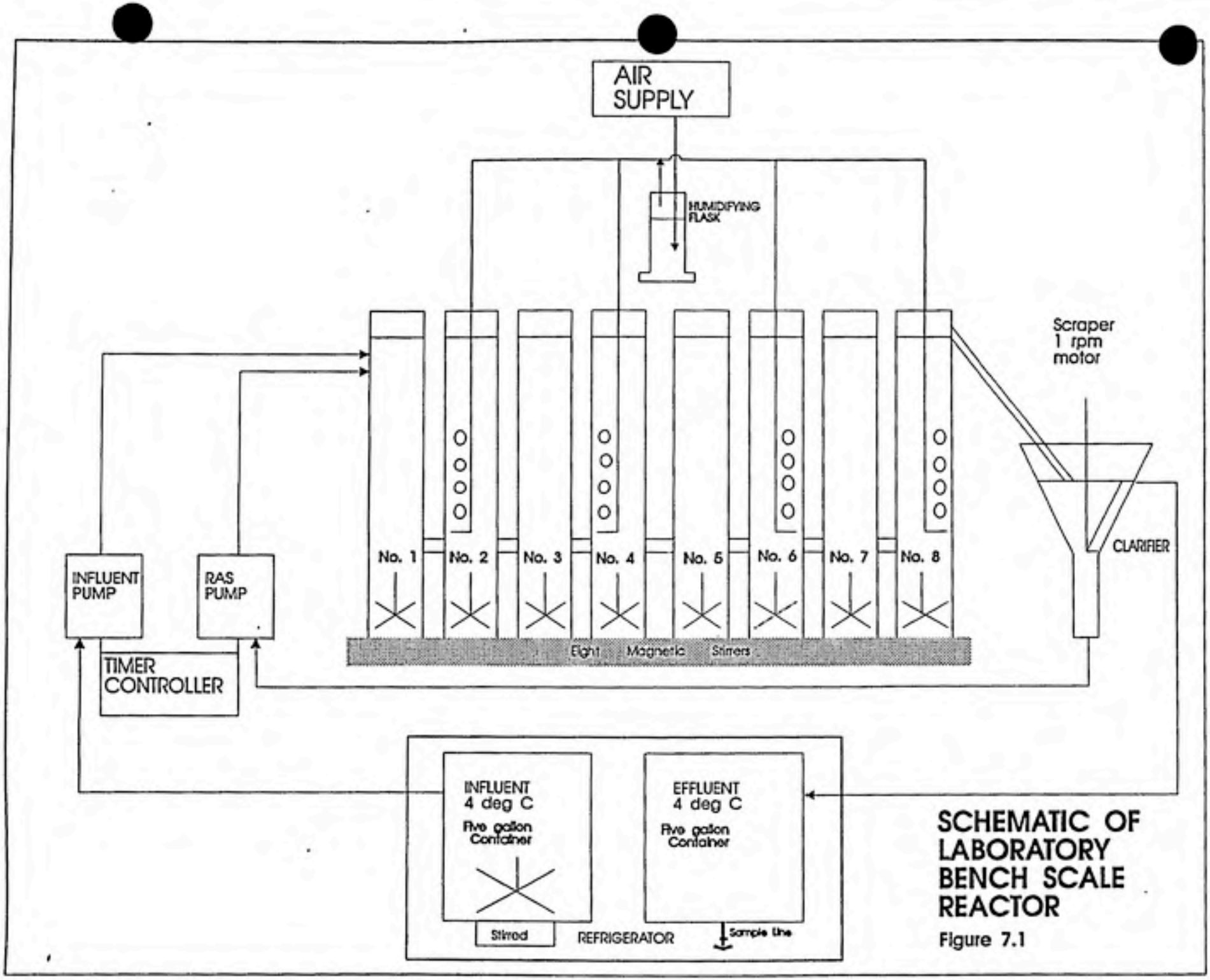
as discussed in Chapter 4.

7.0 EXPERIMENTAL SETUP

7.1 Reactor Setup

A bench scale reactor was set up and operated continuously in a laboratory within the Department of Environmental Sciences and Engineering. A schematic of the reactor is shown in Figure 7.1. The bench scale model consisted of 8 square, transparent acrylic compartments, 6.5 cm X 6.5 cm X 24 cm - and a circular secondary clarifier that measured 15 cm in diameter and was made from a plastic funnel. The reactor was operated in an alternating aerobic/anoxic configuration, as described in the previous chapter. Compartment number 1 was mixed at the bottom, in the absence of diffused air, and was followed by compartment number 2 that utilized both bottom mixing and aeration, and the alternation continued for compartments 3-8. All 8 stages were bottom mixed by magnetic stirrers. Air was supplied continuously to the oxic zones at stages number 2,4,6 and 8 after passing through a humidifying flask filled with distilled water.

The total volume of the eight compartments was 5.4 L with an operating side water depth of 16 cm. The compartments were connected in series by 1.2 cm diameter, 5 cm long transparent polyethylene tubes. An identical polyethylene tube created a gravity flow connection from stage number 8 to the secondary clarifier. Flexible Tygon tubing (R-3603) was utilized to feed raw wastewater from a refrigerated influent container to stage No. 1, and to return activated sludge from the secondary clarifier to stage No. 1. Tygon tubing also was used to convey secondary



SCHEMATIC OF LABORATORY BENCH SCALE REACTOR

Figure 7.1

clarifier effluent to a refrigerated effluent container. Return activated sludge and raw wastewater were pumped to stage 1 by two Cole-Parmer peristalic pumps (model 7520-35). Masterflex tubing was used within the head of each pump, and was connected at each end by the Tygon tubing. The peristalic pumps were turned on and off by a programmable timer/controller. Discontinuous operation of the pumps was necessary because continuous pump flow was too high to maintain a hydraulic residence time of 24 hours in the 8 compartments. The on/off cycle for the influent flow was five minutes on and five minutes off. Consequently, the influent pump was turned on six times every hour. RAS pumps were turned on three times an hour for 5 minutes, followed by 15 minute off interval.

Raw wastewater from the Durham County Triangle plant was used as feed to the reactors. Fresh sample was collected every three to four days in a 15 L plastic container and placed in a refrigerator. The container was placed on a stirrer to maintain solids in suspension.

7.2 Reactor Operation

Mean cell residence time (MCRT) was controlled by equal wasting of activated sludge from all eight stages. Maintaining a nominal MCRT of 10 days was attempted during this study. Table 7.1 summarizes the operating parameters of the reactor.

A mechanical scraper was operated continuously in the clarifier to reduce build-up of sludge on the clarifier walls and to ensure

efficient settling and collection of RAS. The scraper was made of three teflon bands attached to an aluminum wire and was continuously rotated by a one RPM motor. In addition, the side walls of the eight compartments were manually scraped daily to diminish attachment of solids to the walls. Further, daily maintenance of the bench scale model included cleaning of the interstage tubing and manual wasting of activated sludge in the form of mixed liquor.

Table 7.1

Bench Scale Model Operating Parameters

No. of Stages, total	8
No. of Anoxic Stages	4
No. of Oxic Stages	4
Stage Volume, cm^3 each	676
Influent Feed, L/day	5.4
Recycle Rate, L/day	2.7
HRT, hrs	24
MCRT, days	10
Clarifier Overflow Rate, $L/(cm^2*day)$	0.03(a)
Steady Operation Period, days	40
Nominal Temperature, ^oc	24

(a) $L/(cm^2*day) * 245.5 = gal/(ft^2*day)$

During start-up on June 1,1991 the reactor was seeded with activated sludge from the Durham County Triangle Wastewater Treatment Plant. On July 23,1991 the reactor was seeded a second

time with diluted return activated sludge from the OWASA plant in Chapel Hill, NC. The second seeding was required because operational problems in the first month created unstable conditions in the reactor that led to washout of the biomass.

The reactor was operated from June 1, 1991 to September 6, 1991 - a period of 96 days. The schedule for the laboratory study is shown in Table 7.2. The initial setup period was used to fine-tune reactor operation - correcting mixing problems in the different stages and installing a 1 RPM mechanical scraper for the clarifier. Then, continuous steady operation was achieved. Results of this study are reported for the continuous steady operation time that extended 40 days after successful setup.

Table 7.2

Laboratory Testing Schedule

Durham County Triangle Plant

June 1 - July 22, 1991	Setup
July 23 - August 30, 1991	Continuous steady Operation
August 31 - September 6, 1991	Final Lab Testing, Dismantle

8.0 METHODS OF LABORATORY ANALYSIS

Various tests were performed to determine the characteristics of the influent and effluent wastewater. Table 7.2 summarizes the laboratory tests. All tests were conducted at the UNC-CH laboratory except the phosphorus and TKN tests, which were conducted at the City of Durham Farrington Road Treatment Plant laboratory.

Table 8.1

Laboratory Testing

Durham County Triangle Plant

Test	Frequency	Process Stream(1)
Total Phosphorus	twice a week	PI,RE
Soluble Phosphorus	twice a week	PI,RE
Chemical Oxygen Demand (COD)	twice a week	PI,RE
Soluble COD	twice a week	PI,RE
Mixed Liquor Suspended Solids	twice a week	PI,RE
Nitrate	twice a week	PI,RE
Ammonia Nitrogen	twice a week	PI,RE
Kjeldahl Nitrogen	twice a week	PI,RE
Dissolved Oxygen	occasionally	stages 1-8
pH	occasionally	PI, RE & stages

(1) Plant influent (PI), grab sample prior to screening and grit removal. Reactor effluent (RE) from refrigerated effluent container.

Samples were analyzed at least once for every new five gallon grab sample of plant influent wastewater. Tests on duplicate influent and effluent samples were performed for quality assurance. Tables A1, A2 and A3 in the Appendix summarize laboratory testing reliability.

In addition, concentration profiles of various constituents in stages 1 through 8 were performed to follow the change in concentration through the reactor. The results of profiles are discussed in Chapter 9 and are summarized in Table A4 in the Appendix.

The different laboratory tests are described in further detail in the following sections.

8.1 Total Phosphorus and Total Soluble Phosphorus

General Discussion: Wastewater contains phosphorus primarily in the form of phosphates - mainly orthophosphates; condensed phosphates, such as polyphosphate; and organically bound phosphates. Each of the phosphate forms can be further categorized into soluble or particulate fractions.

The determination of total phosphorus is a two-step process aimed at conversion of various forms of phosphate into dissolved orthophosphate. This is done by digestion. Then, the resulting orthophosphate ion concentration is measured. Filtration prior to digestion and orthophosphate measurement can distinguish between soluble (dissolved) and insoluble forms of phosphorus (16).

Test Procedure: The phosphorus tests were performed using an autoanalyzer at the City of Durham Farrington Road Treatment Plant laboratory. EPA method 365.1 (Colorimetric, Automated, Ascorbic Acid) was used [24]. Two phosphorus species were analyzed: total phosphorus and total soluble phosphorus.

In the first step of the total phosphorus test a predetermined sample volume was acid hydrolyzed with sulfuric acid and digested with ammonium persulfate. This digestion step was carried out for 30-40 minutes in a boiling environment. As a result, the condensed and organically bound phosphates were converted to an orthophosphate form, which is detectable by a colorometric reading.

The second step was carried out by City of Durham Farrington Road Plant laboratory personnel. In this step, concentration of orthophosphate was determined by a colorometric approach:

1)Ammonium molybdate and antimony potassium tartrate reacted in an acid medium with soluble orthophosphate to form an antimony-phospho-molybdate complex.

2)This complex was reduced to a blue-colored complex by ascorbic acid.

3)The intensity of the blue color, which is proportional to the concentration of orthophosphate, was measured with a spectrophotometer by absorbance measurement at 650 nm.

4) Phosphorus concentration was then determined from a standard curve.

Standard phosphate solutions were prepared with anhydrous potassium dihydrogen phosphate (KH_2PO_4) in accordance with Standard Methods[16].

Similar procedures were followed to measure dissolved phosphorus, except samples were filtered through a 0.45 micron pore diameter filter before digestion.

Sample Handling & Preservation: Samples for total phosphorus and total dissolved phosphorus were differentiated by filtration shortly after collection. Samples were preserved by adding Sulfuric acid (H_2SO_4) and cooling to 4 degrees C. The phosphorus testing took place within 14 days of collecting the samples. Glassware and plastic containers used in handling samples were acid washed (H_2SO_4). Phosphorus-free detergent was used for cleaning of glassware and containers prior to acid washing.

Total phosphorus tests were run on duplicate samples to determine the repeatability and reliability of the testing method. Results of the reliability tests are presented in Table A3 in the Appendix.

8.2 Chemical Oxygen Demand

General Discussion: The chemical oxygen demand (COD) test was used to measure the amount of organic material in the wastewater samples. The COD test is widely used in the wastewater field and is approved by the Environmental Protection Agency (EPA) as an acceptable test procedure for analysis of pollutants under the Clean Water Act [25].

With the COD test, an oxygen equivalent of oxidizable organic matter is measured. Potassium dichromate serves as an oxidizing chemical for converting organic contents in the wastewater to carbon dioxide and water. The test must be performed at elevated temperatures. The results are expressed in units of equivalent oxygen mass per unit volume required for the oxidation.

Test Procedure: Dried potassium hydrogen phthalate (KHP) was used for preparing the COD standards in conformance with Standard Methods [16]. Standard solutions were prepared and digested periodically to construct a standard curve relating COD standard concentration to absorbance [26].

The following steps were taken in the COD test:

1) Two mL samples were added to vials containing pre-measured reagents.

2) The vials were mixed thoroughly and incubated for two hours at 150 degrees Celsius in a COD digester until digestion was

completed.

3) The digester was then turned off and the vials were given time to cool.

4) The COD concentration was then determined by a colorometric method using a spectrophotometer. Oxidizable organic compounds react and reduce the dichromate ion present in the vials to green chromic ion. The colorimetric method detects the amount of chromic ion produced.

Hach COD digestor reactor (model # 45600) and Hach vials containing reagents for determination of 0-1500 mg/L COD were used. The reagents in the vials included:

*potassium dichromate as the oxidizing agent
*silver sulfate as catalyst
*concentrated sulfuric acid
*mercuric sulfate that acted as suppressant of chloride ion interference.

Sample handling & preservation: Both soluble COD and total COD tests were performed. Samples were filtered through a 0.45 micrometer pore diameter glass fiber filter immediately after collection of influent or effluent samples. Samples were preserved with sulfuric acid and by cooling to 4 degrees C. The COD analysis took place within 14 days of sample collection.

Testing reliability was checked by measuring COD of duplicate

samples; see Table A1 in the Appendix.

8.3 Total Suspended Solids

General Discussion: Total Suspended Solids (TSS) testing followed Standard Methods procedure 2540 D, "Total Suspended Solids Dried at 103-105 Degrees C" [16]. This gravimetric method is approved by EPA for testing non-filterable solids (27).

Test Procedure: The test was used to capture solids from liquid samples of a known volume by running the samples through pre-rinsed, pre-dried (105 degrees C for 1 hour) and pre-weighed glass fiber filters. After the solids were captured, the glass fiber filters were dried at 105 degrees Celsius for an hour, again. The dried weight difference of pre-rinsed filters and the same pre-rinsed filters with captured solids gave the suspended solids result on mass basis [16].

Blank samples using distilled water were filtered, dried and weighed for control in every TSS testing. Duplicate samples were tested for reliability; see Table A3 in the Appendix.

Sample handling & preservation: Concentrated samples, such as that of mixed liquor were diluted before filtration. All influent and effluent samples were thoroughly mixed before testing. Total suspended solids testing took place on the same day of sample collection. In a few exceptions samples were preserved with sulfuric acid and were analyzed within seven days of sample collection.

8.4 Nitrate

General Discussion: Nitrate concentrations in samples were determined by Standard Methods, Nitrate Electrode Method, 4500-NO_3^-. The nitrate electrode is a selective electronic sensor that signals quantitatively the presence of nitrate ions. A potential develops across the nitrate electrode membrane that holds a water-immiscible liquid ion exchanger. The electrode responds to nitrate ion activity between about 10^{-5} and 10^{-1} M (.14 to 1400 mg NO_3^-/L) (16).

Test Procedure: The nitrate electrode testing followed three steps:

In the first step, a reference electrode and nitrate electrode were prepared and checked. The outer chamber of the reference electrode was filled with a dilute ionic strength adjuster (ISA) containing $(NH_4)SO_4$. The nitrate electrode was soaked initially in distilled water for 15 minutes, then in standard nitrate solution for at least an hour. Orion Model 93-07 nitrate electrode and Fisher Calomel double-junction reference electrode were used.

The reference and nitrate electrodes were checked by slope measurement. Slope measurement detected the change in millivolts (mV) readout with a tenfold change in nitrate concentration as follows: Nitrate and reference electrodes were connected to the mV meter, 100 ml of distilled water was mixed with 2 ml ISA in a beaker. One ml of 1000 ppm nitrate standard was added to the beaker and the potential was recorded. Ten ml of the same nitrate

standard was added to the same beaker and the potential recorded again. The difference between the first and the second reading was defined as the slope of the electrode. The difference was confirmed to be between -54 to -60 mV per tenfold change at a temperature of approximately 25 degrees C. Potential measurements were taken using a Fisher pH/mV meter model 610 with readability to 0.1 mV.

In the second step, calibration curves were prepared. A stock nitrate solution was diluted to make standard nitrate solutions, ranging in concentration from 0.1 mg/L NO_3^--N to 50 mg/L NO_3^--N. The different standard nitrate solutions were placed in 150 ml beakers with 2 ml of ISA and stirred thoroughly. The potential in mV, corresponding to each standard nitrate solution concentration, was measured and plotted on a semilogarithmic graph paper. The NO_3^--N concentration was plotted on the logarithmic axis and the potential in mV on the linear axis.

A calibration curve with a straight line resulted in the 1 mg/L NO_3^--N to 50 mg/L NO_3^--N range. For concentration ranging from 0.1 mg/L NO_3^--N to 1 mg/L NO_3^--N, at least four standard nitrate solutions were used because the line in that concentration range was not straight.

In the third step, concentration of samples of unknown nitrate concentration was measured. A 100 ml sample and 2 ml of ISA were mixed in a beaker and then the potential was measured. Concentration was read from the calibration curves (28).

Sample handling & preservation: Influent and effluent samples were preserved with sulfuric acid and by cooling to 4 degrees C. The nitrate electrode test took place within 14 days of sample collection.

Stock nitrate solution and all nitrate standards were prepared in accordance with Standard Methods [16]. Stock nitrate solution was preserved with chloroform ($CHCl_3$). Fresh standards were prepared from the stock nitrate solution for every new day of testing. Standards and samples of unknown nitrate concentration were kept under the same temperature during the testing procedure. All samples were stirred with teflon magnetic stirrers in the 150 ml beakers while the potential measurements were taken. Between measurements, both reference and nitrate electrodes were rinsed in distilled water. Reliability of testing method was examined by measuring nitrate levels for duplicate samples. See table A2 in the appendix for raw nitrate data, including duplicate results.

The method of standard additions was used to check accuracy of nitrate direct measurement. Results are shown in Table A11 in the Appendix. It appears from the data in Table A11 that there was a slight matrix effect in measuring nitrate. However, this effect did not appear to be significant for the low concentrations tested. Therefore, direct measurement of nitrate in wastewater samples was believed to be accurate for the purpose of this study.

8.5 Ammonia Nitrogen

General Discussion: The Ammonia-Selective Electrode Method was

used to measure concentrations of dissolved ammonia ($NH_{3(aq)}$ and NH_4^+). In the presence of a strong base at pH above 11 the ammonium ion (NH_4^+) is converted to $NH_{3(aq)}$. In the ammonia-selective electrode, a hydrophobic gas-permeable membrane separates the sample solution from the electrode internal solution. The electrode internal solution was made up of ammonium chloride. Diffusion of ammonia from the sample through the membrane was carried out until the partial pressure of ammonia was the same on both sides of the membrane. As ammonia diffused through the membrane into the internal solution, it reacted with the internal water. The partial pressure of ammonia for a given sample is proportional to its concentration. Therefore, a standard calibration curve with standards of a known NH_3-N concentration were used to determine NH_3-N concentration of a samples with unknown NH_3-N concentration.

Test Procedure: The ammonia-selective electrode test procedure can be described in three steps: electrode preparation and checking, preparation of a standard curve and sample measurement.

For ammonia-selective electrode preparation prior to analysis, the inner body of the electrode was first soaked overnight in internal filling solution. The ammonia-selective electrode was then prepared by placing a loose membrane in the electrode outer body. Internal filling solution was then poured inside the electrode outer body. For same-day or over-night storage, the electrode tip was immersed in 1000 ppm standard NH_3-N with no ISA added. For longer storage, the membrane was removed and the electrode outer body drained. The electrode was washed and dried prior to storage.

An Orion ammonia-selective electrode was used for the NH_3-N analysis [29].

To check the ammonia-selective electrode operation the electrode was rinsed in distilled water and then was connected to an electrometer. The electrode was placed in a 150 ml beaker containing 100 ml distilled water mixed with 2 ml ionic strength adjuster (ISA). First, 1 ml of a 1000 ppm NH_3-N standard solution was added to the beaker and a mV reading was taken. Then, 10 ml of the same standard solution was added to the same beaker and a new reading was recorded. The difference between the first and second reading was confirmed to be in the range of -54 to -60 mV/decade.

In the preparation of standard curves, two ammonium chloride standards with NH_3-N concentration that differed by a factor of ten were prepared. The two standards bracketed the expected ammonia level in the sample. For samples in the low ammonia range, the mV response to a ten-fold change in concentration was nonlinear. For these low concentration samples, more standards were used at smaller increments to construct the nonlinear portion of the standard curve. The more diluted standard was measured first followed by a measurement of concentrated standards. For all standards, reading in mV was taken and results plotted on a semilogarithmic graph paper. A calibration curve was prepared by plotting the mV values on the linear axis and the concentration in mg/L NH_3-N on the logarithmic axis.

The calibration curve was then used for measuring ammonia concentration in the samples. The electrode was placed in a 150 ml

beaker containing 100 ml of sample mixed with 2 ml ISA. The resulting mV reading was plotted on the calibration curve to determine the ammonia concentration.

Sample handling & preservation: Influent and effluent ammonia samples were preserved with sulfuric acid and by cooling to 4 degrees C. The Ammonia-Selective Electrode test took place within 14 days of sample collection.

Stock ammonium solution was prepared with dried anhydrous ammonium chloride (NH_4Cl) in accordance with Standard Methods.
All ammonia standards were prepared in accordance with Standard Methods. Fresh standards were prepared from the stock ammonia solution for every new day of testing. Standards and samples of unknown ammonia concentration were kept under the same temperature during the testing procedure. All samples were stirred with teflon magnetic stirrers in the 150 ml beakers while the potential measurements took place. Between measurements the ammonia-selective electrode was rinsed in distilled water.

See Table A2 in the Appendix for reliability results.

8.6 Kjeldahl Nitrogen

General Discussion: The Total Kjeldahl Nitrogen (TKN) method measures nitrogen concentrations in the -3 oxidation state, some of which undergoes conversion from organically bound nitrogen to ammonia nitrogen. The combined concentration of organic nitrogen and ammonia nitrogen is by definition the kjeldahl nitrogen (5).

EPA Method 351.4 (Micro Kjeldahl, Ion Selective Electrode) was use for TKN measurements [24].

Test Procedure: The TKN test was carried out at the City of Durham Farrington Road Treatment Plant laboratory. The first step of the TKN test was a digestion step. Well-mixed samples or standards were mixed with sulfuric acid (H_2SO_4), potassium sulfate (K_2SO_4) and mercuric sulfate ($HgSO_4$) in a digestion flask. Digestion flasks were placed on a heating manifold. The mixture was evaporated, using the Kjeldahl apparatus until SO_3 fumes were given off. Then, the solution was digested for an additional 30 minutes. Boiling chips were placed in each digestion flask to prevent blow-out. Organically bound nitrogen in the sample was converted to ammonium sulfate ($(NH4)_2SO_4$) during the digestion.

After cooling, the digestion residue was placed in a 200 ml volumetric flask and diluted to the 200 ml mark with deionized water. Ammonia concentration in the digested sample was then determined by the electrode method.

The slope of the ammonia-selective electrode was first determined by measuring the difference in mV reading for various standards of a known NH_3-N concentration. Then, the standard addition method was used to detect unknown NH_3-N concentration.

One hundred mls of well mixed digested sample was placed in a 150 ml beaker. The contents were mixed with a stirring bar and an ammonia-selective electrode was immersed in the solution. The mV reading was observed to increase in the positive direction. Five

mls of TKN Alkaline reagent was added while mixing. The reagent included sodium hydroxide, sodium iodide and ethylene diamine tetraacetic acid (NaOH-NaI-EDTA). EDTA was added to NaOH-NaI to prevent precipitation of metal hydroxides. Sodium hydroxide (NaOH) was added to the solution for pH adjustment to convert ammonium ion to NH_3.

The electrode mV reading was recorded when it became stable. An ammonia standard was then added to the beaker as follows: five ml of 10 mg/L ammonia was added to effluent samples and 5 ml of 100 mg/L was added to influent samples. Again, mV was recorded after stabilization. The TKN concentration was determined by the difference in the two readings, using the following formula:

$$\text{sample mg/L } NH_3 = \frac{\text{(standard volume*standard concentration)}}{[\text{INVlog}(\triangle \text{ mv/slope})*(\text{ml sample+ml std.added})-(\text{ml/sample})} * 6.67$$

Blanks and 1,10,and 20 mg/L standards were run with each analysis. Blanks were always subtracted from the results to account for interference from reagents [24].

Sample handling & preservation: Like the preservation of ammonia nitrogen, TKN samples were preserved by refrigeration at 4 degrees and acidification to pH levels lower than 2 with H_2SO_4. The TKN Micro procedure took place within 14 days of sample collection.

Stock ammonium solution was prepared with dried anhydrous ammonium chloride (NH_4Cl) in accordance with Standard Methods [16].

All ammonia standards were prepared in accordance with Standard Methods. See Table A2 in the Appendix for TKN testing reliability results.

8.7 Dissolved Oxygen and pH Measurements

Dissolved oxygen (DO) was measured periodically in Stages 1 through 8 of the reactor. A DO probe was first calibrated and then immersed inside the reactor stages.

A pH probe was used during the study to determine the pH of influent and effluent samples and the pH at various stages. It was calibrated by using standard buffer solutions .

DO and pH measurements were not conducted continuously. Their purpose was occasional trouble-shooting and fine-tuning of reactor operation.

9.0 RESULTS AND DISCUSSION

In general, the performance of the alternating anaerobic and aerobic reactor was successful in COD, TSS, Ammonia and TKN removal. Nitrate and phosphorus removal results were lower than expected, which was attributed to operational problems as described further below. It should be noted that, because of these problems, true "steady state" conditions were never achieved.

During the first three weeks of the reported period of operation the aerobic reactors were likely over-aerated. Excessive oxygen in the anoxic stages was detected the first time DO measurements were made. Suspected over-aeration in the reactor caused significant transfer of unwanted oxygen through the interstage tube connection to the anoxic stages. This in turn precluded significant denitrification, which may have impacted phosphorus removal as well. After DO measurements were made, the aeration rate was lowered to correct the problem.

During the reported operating period, an aeration failure also occurred in one incident. The exact length of the aeration down-time is not known. Down-time was estimated at approximately 18 to 36 hours. The time and results of this failure are discussed in the sections below. Another unanticipated operational phenomenon that could have adversely affected the reactor performance, was the continuous accumulation of mixed liquor on the reactor walls below and above the liquid level. As mentioned in Chapter 7, continuous mechanized scraping was provided only at the clarifier. Therefore, manual scraping and daily cleaning of the stage walls

was required. Sludge attachment to the reactor walls created interference with steady state operation due to occasional periods of low MLSS concentration, and uneven distribution of MLSS throughout the eight stages.

The removal results for each constituent are discussed further below. Results of eight stage profiles of the different constituents are summarized in Table A4 in the Appendix.

COD: Figures 9.1 and 9.2 show influent COD and influent soluble COD, respectively. Soluble COD concentrations were significantly lower than total COD, as expected for a plant without primary settling. Two of the measurements of influent total COD showed high COD concentrations between 800 and 900 mg/L. High COD days were not representative of composites collected independently by the City of Durham.

The values for influent soluble COD ranged between 100 and 200 mg/L which are substantially lower than typical values for untreated domestic sewage. Domestic wastewater of medium strength would typically measure around 500 mg/L COD [8].

Figures 9.1 and 9.2 also show effluent COD and effluent soluble COD data respectively. Effluent COD concentrations averaged 51 mg/L and did not exceed 92 mg/L. After the first ten days of operation, effluent soluble COD did not exceed 45 mg/L. The effluent soluble COD average was 37 mg/L. Both soluble and total COD results indicate successful performance. Table A5 in the Appendix shows the actual COD concentration values.

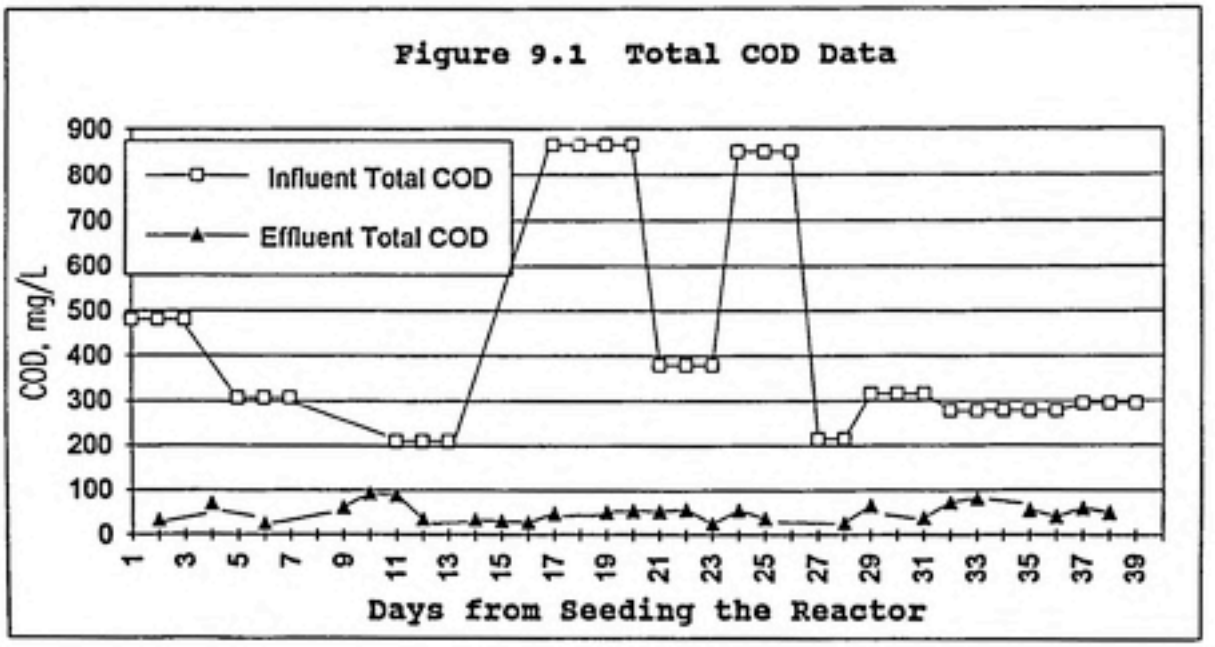


Figure 9.1 Total COD Data
900
800
700
600
500
400
300
200
100
0
COD, mg/L
Influent Total COD
Effluent Total COD
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Days from Seeding the Reactor

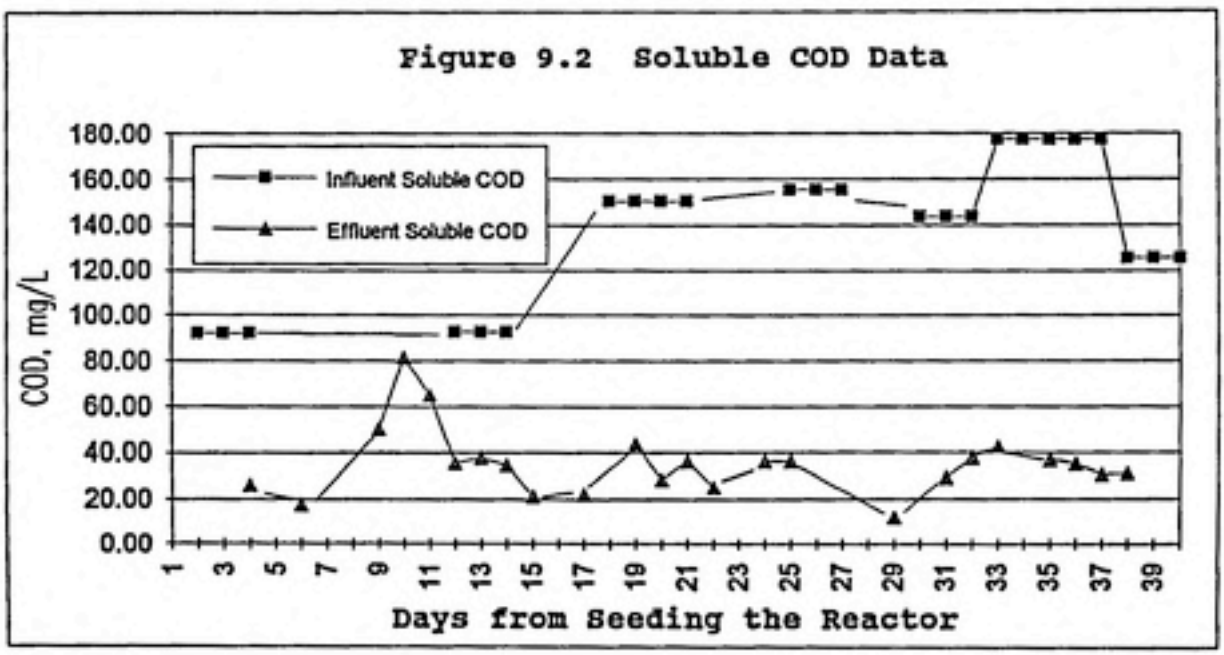


Figure 9.2 Soluble COD Data
Influent Soluble COD
Effluent Soluble COD
COD, mg/L
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Days from Seeding the Reactor

Profiles of soluble COD for the eight stages are shown in Figures 9.3, 9.4 and 9.5. The profiles indicate that most of the COD removal took place in the first two stages after which soluble COD leveled off.

Phosphorus: Phosphorus data are shown in Figure 9.6. Some phosphorus removal did occur during the study, but there was no clear indication that enhanced biological phosphorus removal took place. By comparing limited influent soluble phosphorus data to effluent soluble phosphorus data, it appears that most P removal occurred through suspended solids removal.

A profile of soluble P over the eight stages was taken on September 29, 1991. The profile result is shown in Figure 9.7 and it suggests that some phosphorus release could have been occurring in the first anaerobic stage followed by phosphorus uptake in the second stage. The level of soluble phosphorus dropped from 2.55 mg/L in Stage 1 to 2.12 mg/L in Stage 2. However, this observation could be as easily explained by normal aerobic consumption of P by cells, not specifically conditioned for enhanced P removal.

Effluent phosphorus levels were always above the summer limit of 0.5 mg/L for the Triangle Plant. Data between days 8 and 19 of operation indicate that winter limits of 2 mg/L could be met.

It is important to note that optimum operating conditions were maintained over very little of the reported operating period because of problems discussed above. Further study under optimum

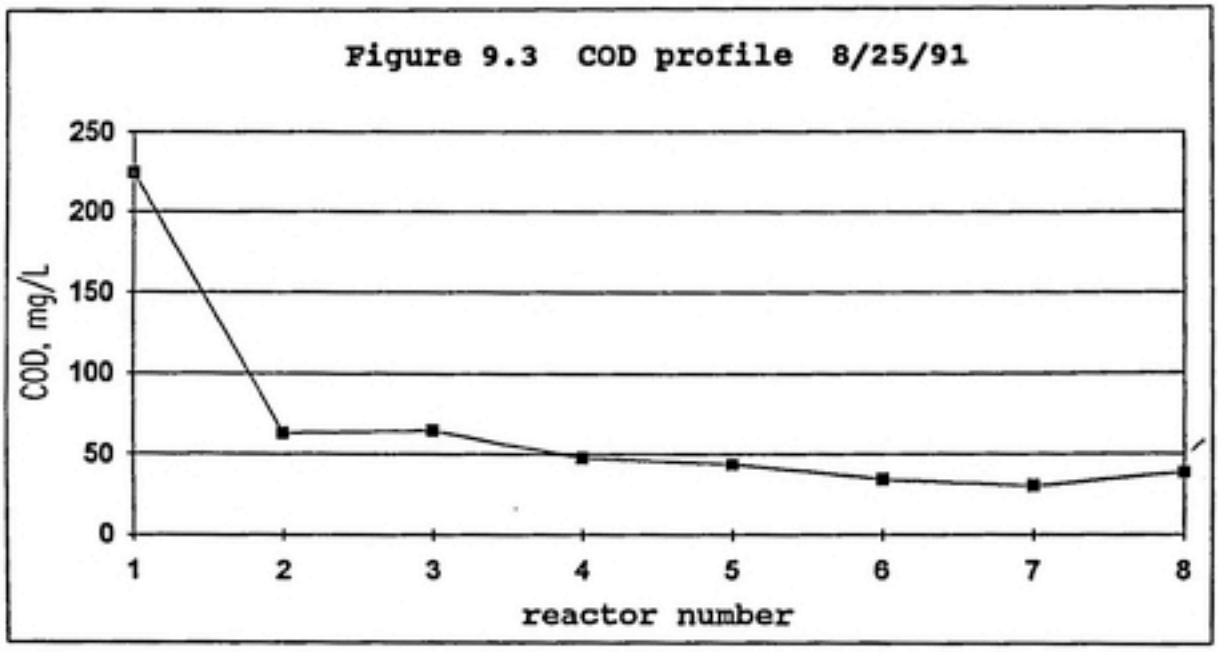


Figure 9.3 COD profile 8/25/91
250
200
150
100
50
0
COD, mg/L
1
2
3
4
5
6
7
8
reactor number

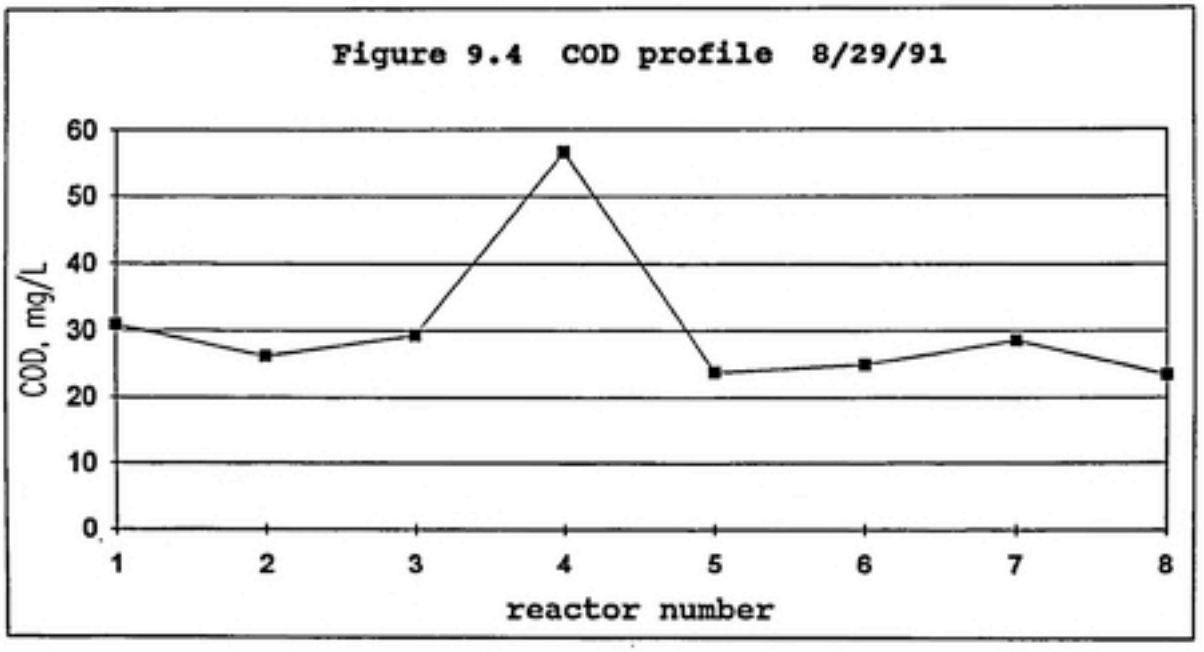


Figure 9.4 COD profile 8/29/91
COD, mg/L
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
reactor number

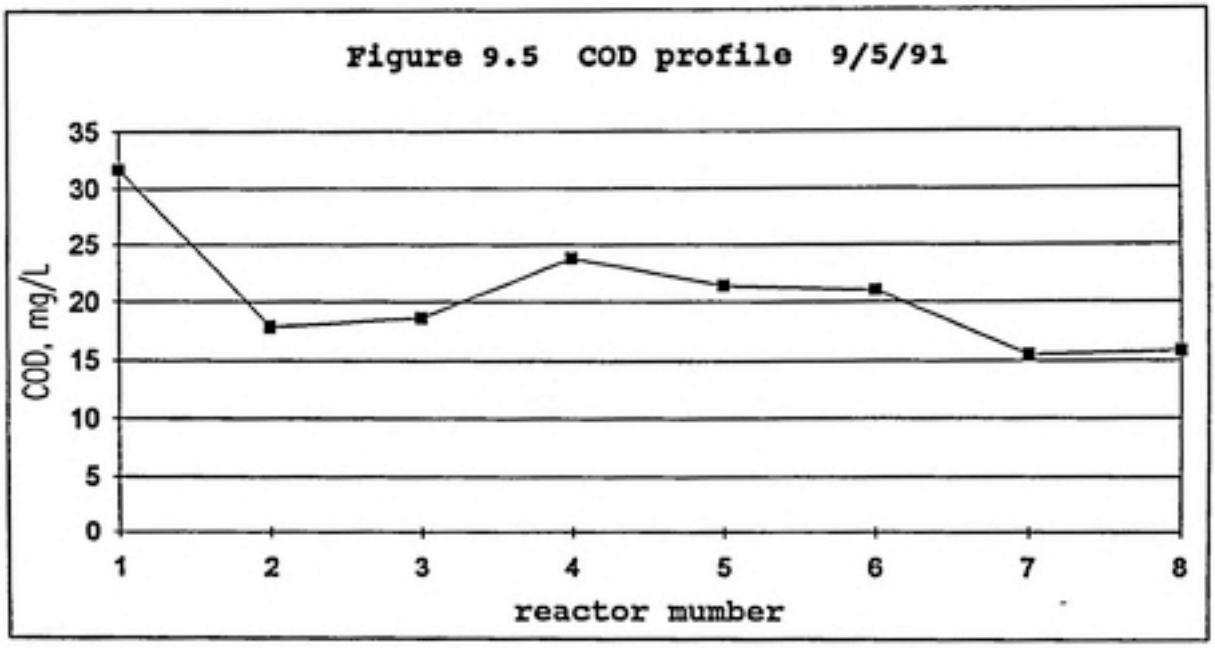


Figure 9.5 COD profile 9/5/91
COD, mg/L
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
reactor number

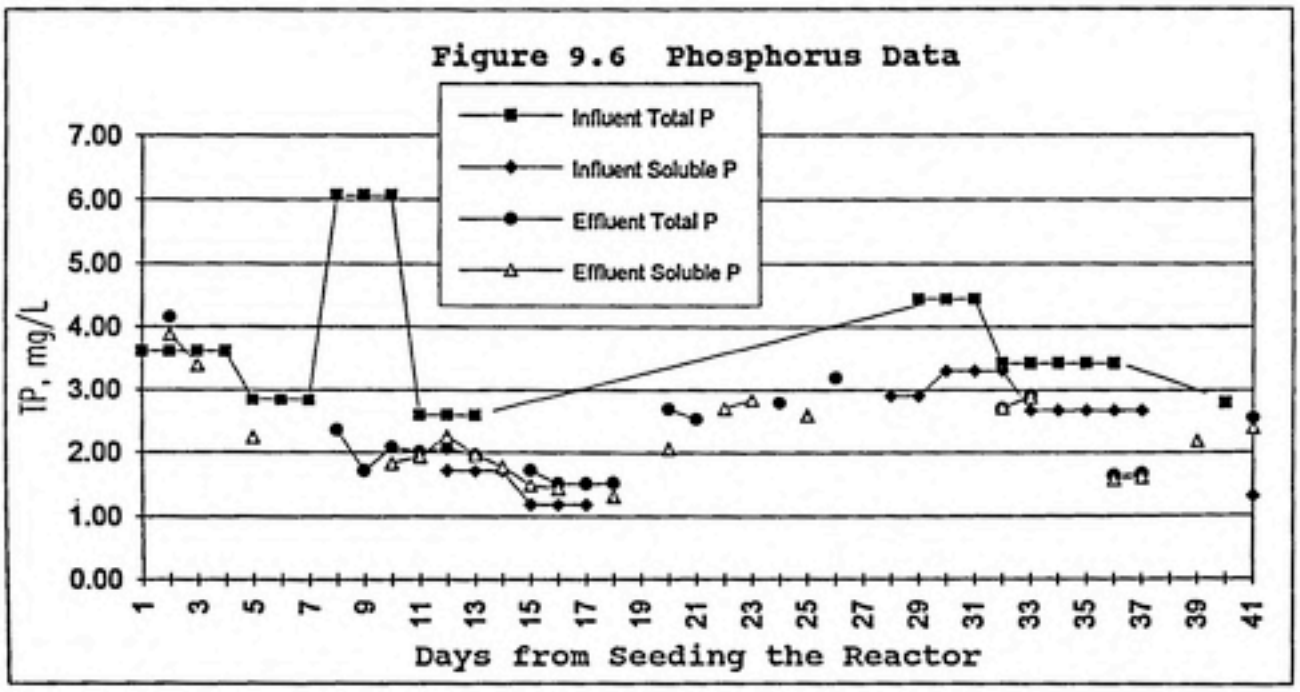


Figure 9.6 Phosphorus Data
Influent Total P
Influent Soluble P
Effluent Total P
Effluent Soluble P
TP, mg/L
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
Days from Seeding the Reactor

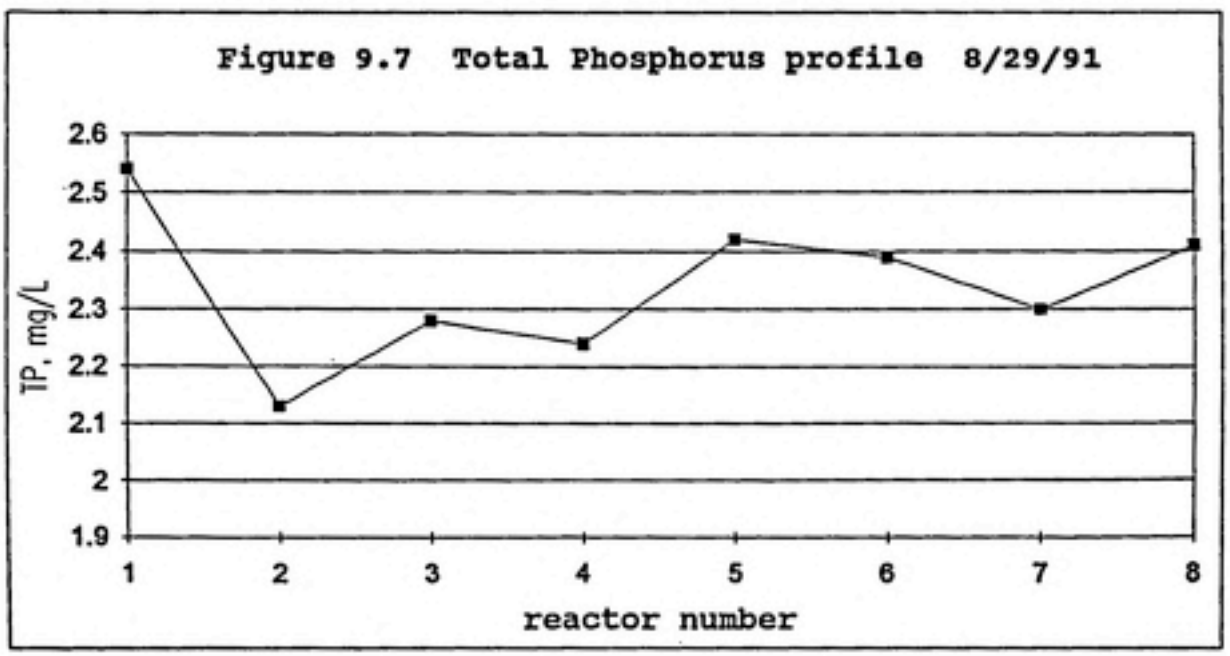


Figure 9.7 Total Phosphorus profile 8/29/91
TP, mg/L
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1
2
3
4
5
6
7
8
reactor number

conditions would be required to confirm that the 2 mg/L winter limit could be met routinely.

Only a small difference was observed between effluent total P and effluent soluble P. Most of the phosphorus in the effluent was soluble. This demonstrates the efficiency of the reactor in removal of suspended solids.

Raw phosphorus data appear in Table A6 of the Appendix.

Ammonia and TKN: The laboratory setup proved efficient in ammonia and TKN removal as shown in Figures 9.8 and 9.9. The levels of the two followed the same trend.

Ammonia was removed to levels well below the summer limit of 1 mg/L for most of the reported operating period. An exception was the period affected by aeration failure. During that period, in the absence of oxygen, nitrifying bacteria were not effective in removing ammonia as expected. An ammonia profile was performed for filtered MLSS samples from each of the eight stages and is shown in Figure 9.10. The ammonia level decreased from 4.7 mg/L to below 0.5 mg/L by Stage 4, and the level remained low in the remaining reactors. A TKN profile on the same day revealed a similar trend, as shown in Figure 9.11.

Total nitrogen is by definition the sum of TKN and nitrate concentration. Figure 9.12 demonstrates that TKN was only a minor fraction of the total nitrogen in effluent samples, which consisted mostly of nitrate.

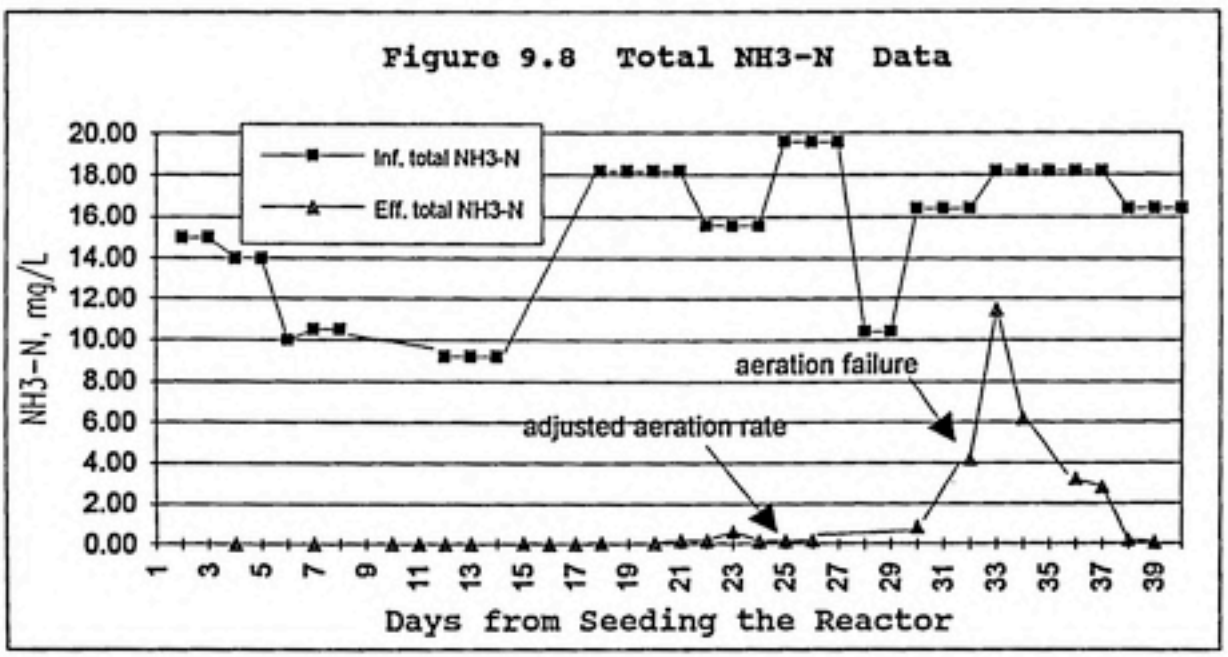


Figure 9.8 Total NH3-N Data
Inf. total NH3-N
Eff. total NH3-N
aeration failure
adjusted aeration rate
NH3-N, mg/L
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Days from Seeding the Reactor

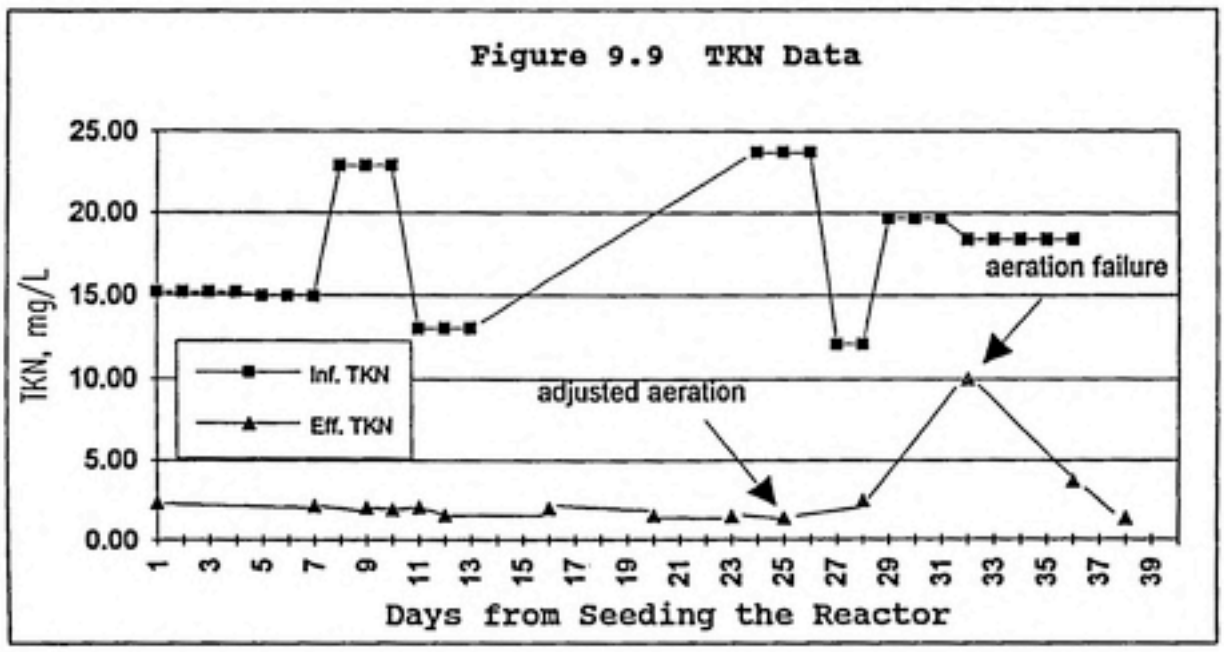


Figure 9.9 TKN Data
25.00
20.00
15.00
10.00
5.00
0.00
TKN, mg/L
Inf. TKN
Eff. TKN
aeration failure
adjusted aeration
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Days from Seeding the Reactor

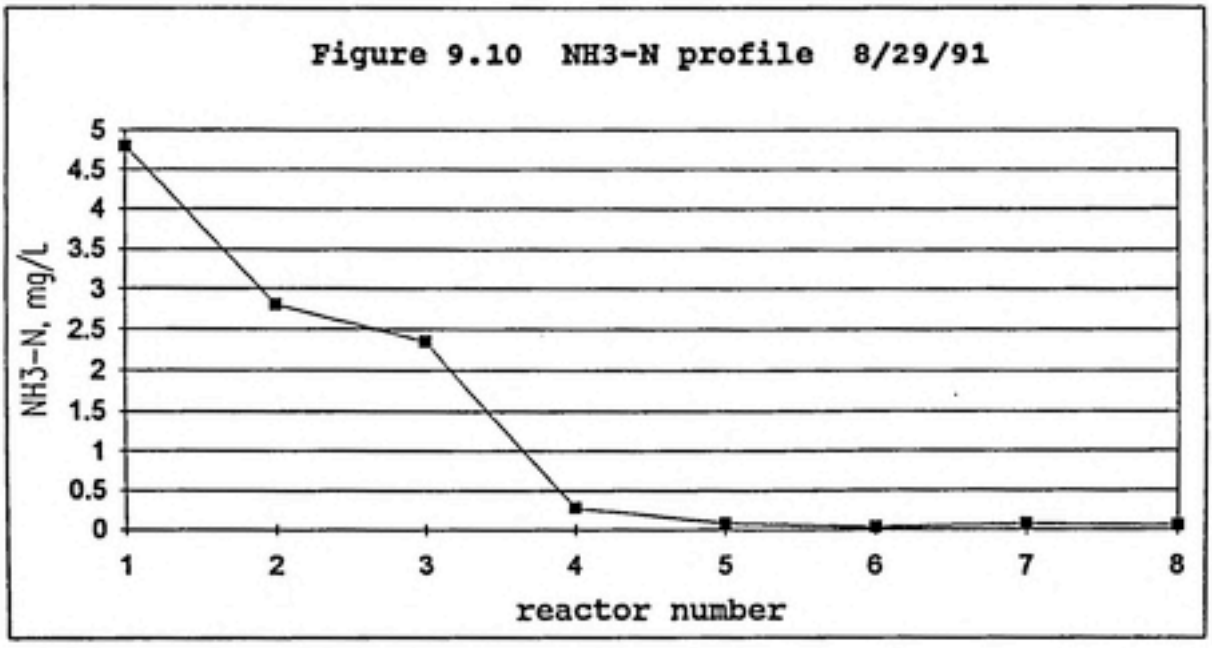


Figure 9.10 NH3-N profile 8/29/91
NH3-N, mg/L
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1
2
3
4
5
6
7
8
reactor number

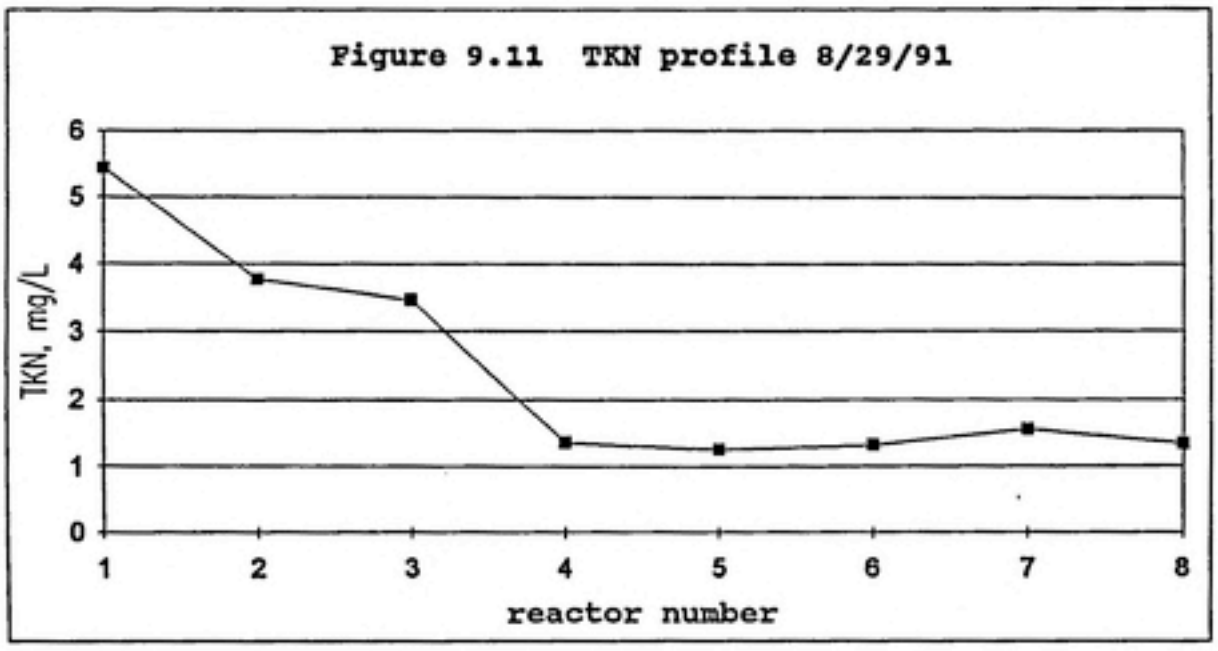


Figure 9.11 TKN profile 8/29/91
TKN, mg/L
0
1
2
3
4
5
6
1
2
3
4
5
6
7
8
reactor number

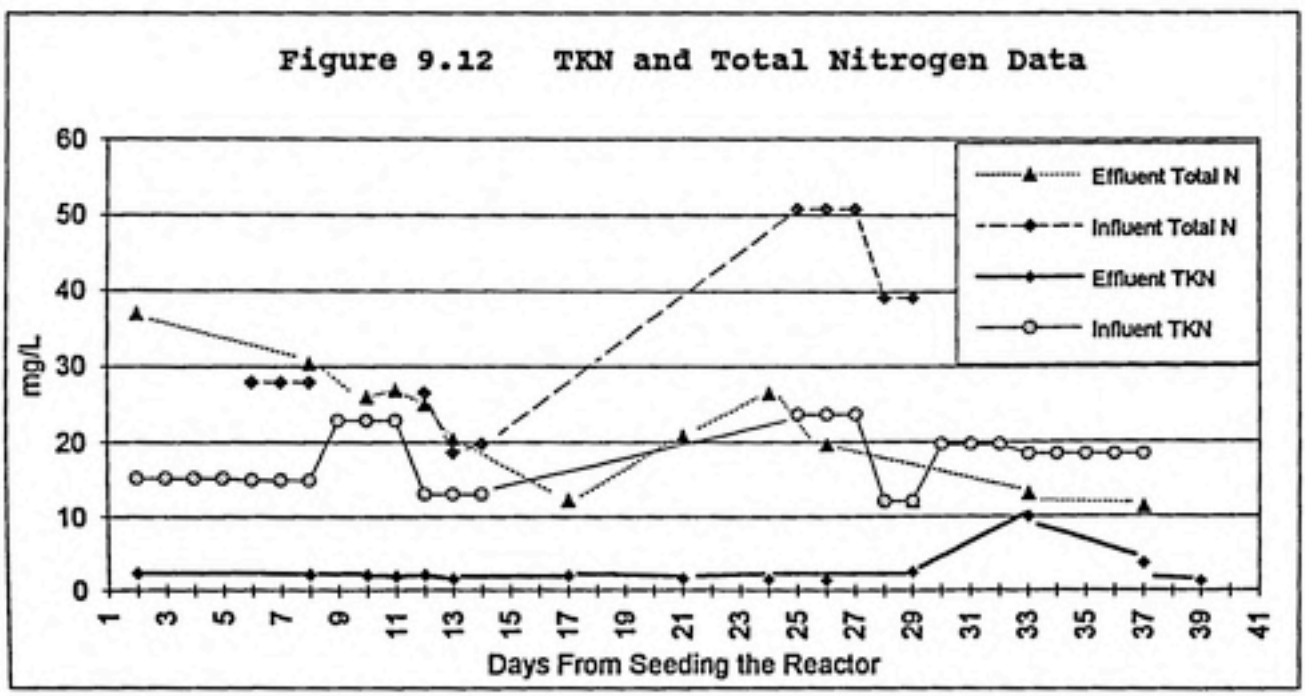


Figure 9.12 TKN and Total Nitrogen Data
60
50
40
30
20
10
0
mg/L
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
Days From Seeding the Reactor
Effluent Total N
Influent Total N
Effluent TKN
Influent TKN

Tables A7 and A8 in the Appendix present raw data of ammonia nitrogen and TKN, respectively.

Nitrate: Influent nitrate concentration fluctuated for the various influent samples; Table A9 in the Appendix shows that influent nitrate was measured as low as 1.2 mg/L and as high as 27 mg/L.

Influent and effluent nitrate data are presented in Figure 9.13. As shown, effluent nitrate concentrations closely resembled effluent total nitrogen, indicating almost complete nitrification. From the limited influent nitrate data, it appears that very little denitrification occurred over the initial operating period Effluent nitrate was equivalent to influent total nitrogen.

The influent nitrate levels were found surprisingly high. When high influent nitrate is combined with nitrate produced by nitrification, it is not surprising that significant nitrate levels were observed in the reactors and in the effluent samples. As mentioned before, the high influent nitrate concentration, combined with oxygen overdose to the first anaerobic section could explain the apparent inability to select for phosphorus accumulating bacteria. Effluent nitrate concentrations would have been reduced if denitrification was carried out. However, low COD levels in combination with high oxygen levels in anaerobic Stages 3,5 and 7 likely limited the efficiency of denitrification.

The possibility that low influent biodegradable carbon was responsible for limited success with denitrification was checked.

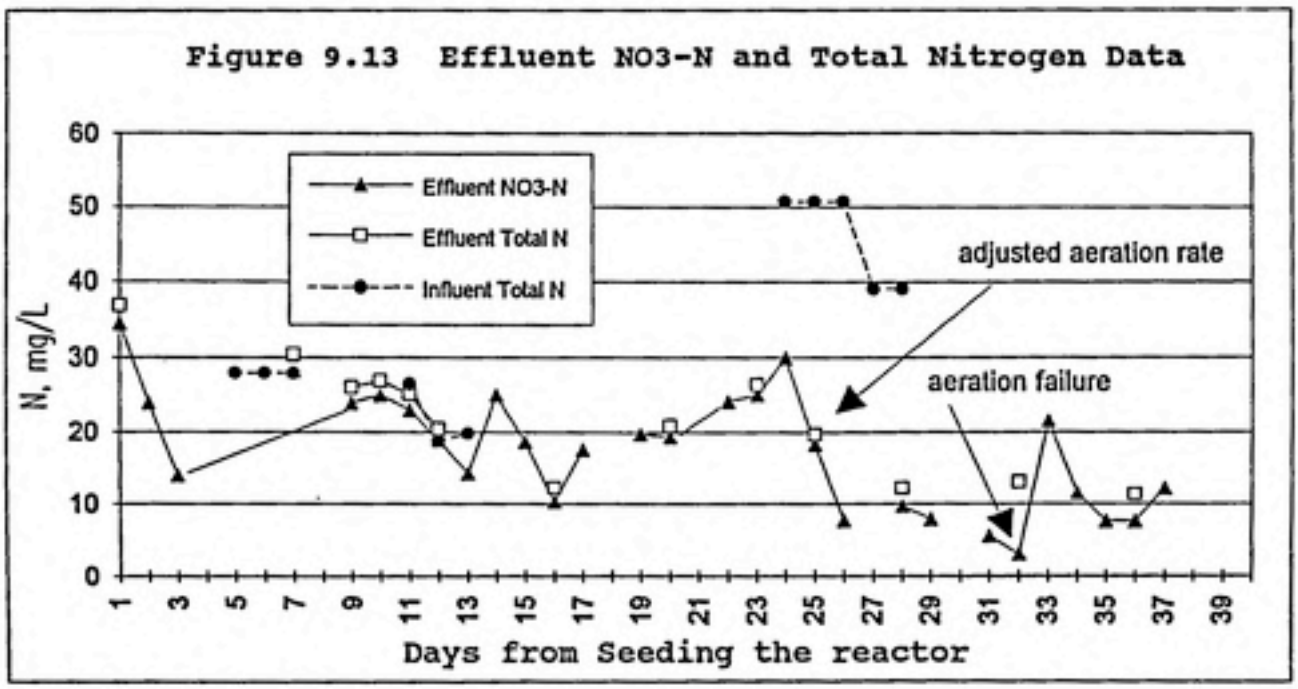


Figure 9.13 Effluent NO3-N and Total Nitrogen Data
Effluent NO3-N
Effluent Total N
Influent Total N
adjusted aeration rate
aeration failure
N, mg/L
Days from Seeding the reactor
0
10
20
30
40
50
60
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39

The theoretical amount of COD needed for complete nitrogen removal was calculated to determine if the system was COD deficient due to low influent COD. This calculation was based on the assumption that all of the TKN in the influent would undergo nitrification and be converted to nitrate. This assumption is reasonable because of the high nitrification rates achieved for the project, and provides a minimum estimate of COD required for denitrification.

The range of total nitrogen in the influent, comprising influent TKN and influent nitrate, was converted to COD equivalent using a conversion factor of 2.86 mg O_2 per mg of NO_3^--N [30]. The range of influent total nitrogen was 18.7 mg/L to 50.7 mg/L. On the basis of influent total nitrogen range, the minimum amount of influent COD needed for complete nitrogen removal is 53.5 mg/L to 145 mg/L. Of course, additional COD will be consumed for cell growth. The additional COD needed for growth is a function of the net cell yield in the system.

Actual influent COD, ranging from 214 mg/L to 865 mg/L, was well above the theoretical minimum COD required for complete nitrogen removal. Therefore COD deficiency was ruled out as a reason for unsuccessful denitrification results.

The apparent lack of denitrification was investigated by measuring DO in each stage of the reactor on the 25th day of operation. It was discovered that high DO existed in all reactors, including those intended to be anoxic. Aeration intensity was therefore lowered consequently to assure that aerobic conditions were maintained exclusively in Stages 2,4,6 and 8. After aeration

adjustment, effluent nitrate dropped below 10 mg/L. The adjustment of the aeration rates and the aeration failure event are both indicated in Figure 9.13. The lowest nitrate concentration occurred at the time of aeration failure, consistent with the inability of nitrifiers to nitrify in the absence of oxygen.

A profile of nitrate measured through the reactor stages was recorded on 8/25/91 after aeration was adjusted. No indication of nitrate reduction throughout the eight stages could be observed, as shown in Figure 9.14. Another profile recorded on 9/5/91 shows increase of nitrate downstream, as presented in Figure 9.15. This again points to effective nitrification but a lack of denitrification.

Total Suspended Solid: TSS was removed efficiently with the laboratory setup as shown in Figure 9.16. Activated sludge in the reactors had favorable settling characteristics. An SVI test was performed on MLSS from the 8th stage on 8/29/91. The results of the SVI test is shown in Table 9.1. SVI values of below 120 ml/mg are considered acceptable.

Table 9.1

SVI test, 8/29/91

TSS, mg/L	Settling Volume, ml/L	SVI, ml/gr
520	60	115
560	60	107

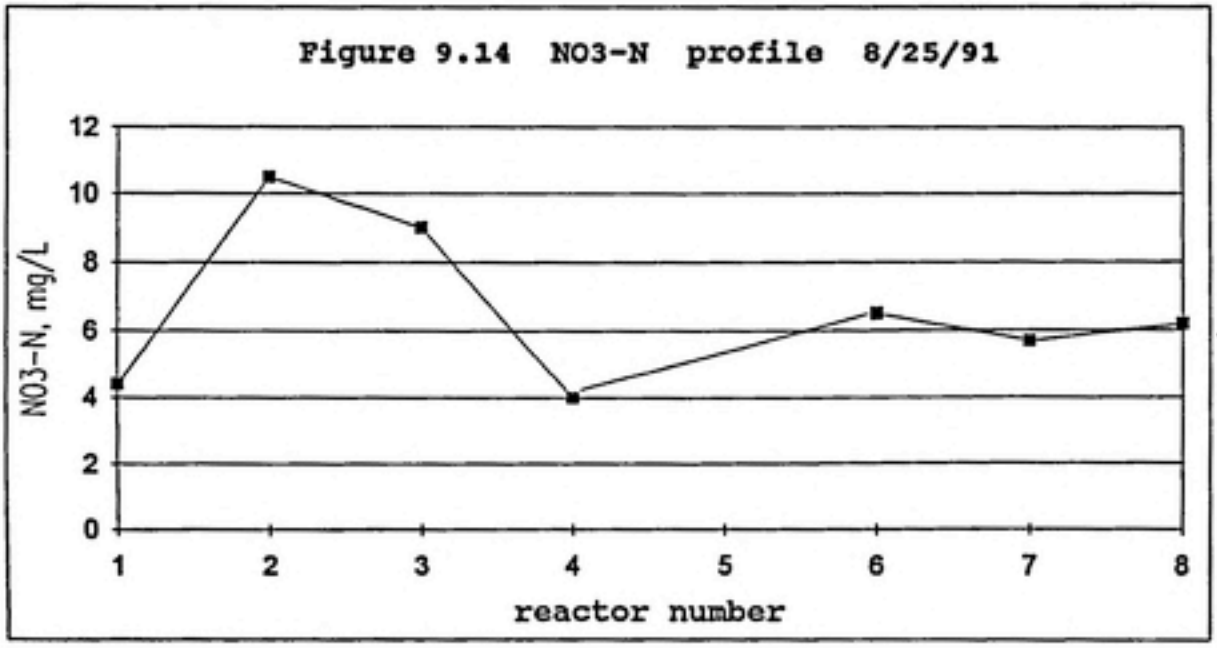


Figure 9.14 NO3-N profile 8/25/91
NO3-N, mg/L
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
reactor number

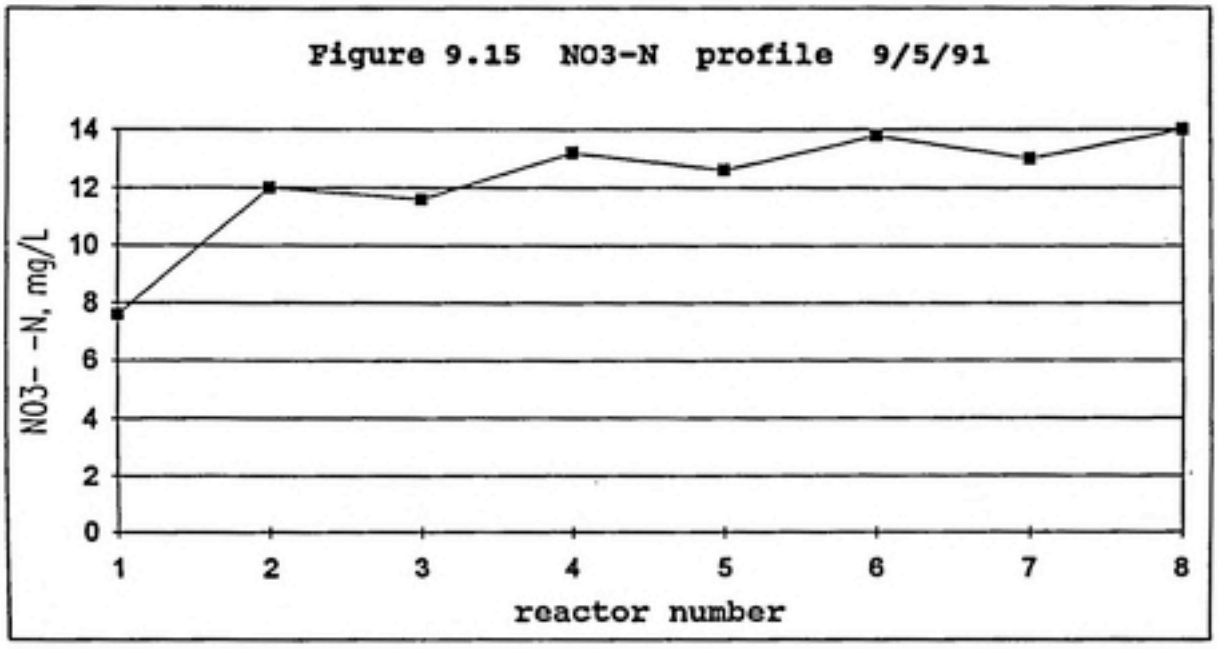


Figure 9.15 NO3-N profile 9/5/91
NO3- -N, mg/L
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
reactor number

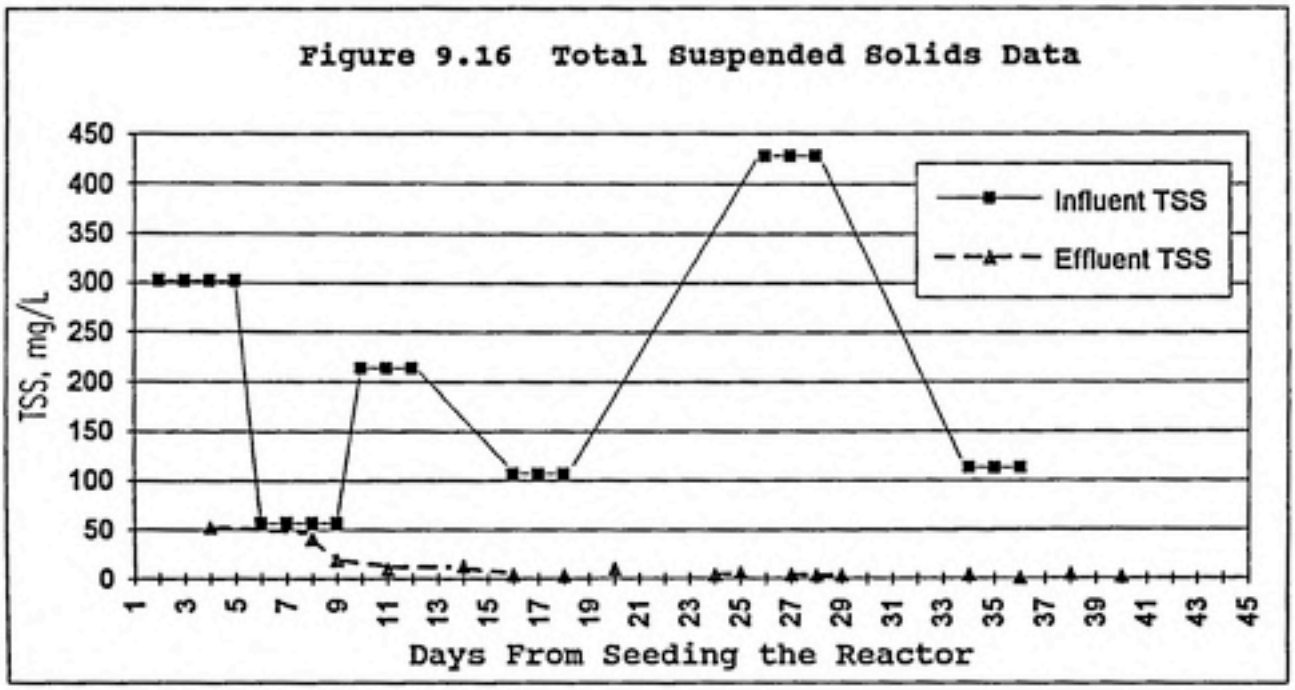


Figure 9.16 Total Suspended Solids Data
TSS, mg/L
450
400
350
300
250
200
150
100
50
0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
Days From Seeding the Reactor
Influent TSS
Effluent TSS

10.0 CONCLUSIONS AND RECOMMENDATIONS

Utilization of Biological Nutrient Removal with alternating anaerobic and aerobic stages could benefit the Durham County Triangle Plant. The treatability study described in this report gave preliminary evidence that total nitrogen removal could be accomplished at the plant. Excellent nitrification was achieved in the laboratory system. Operating problems limited the amount of data that could be used to indicate long-term denitrification performance. From the limited periods of operation under optimum conditions, denitrification appears to be feasible with the proposed reactor configuration. While the plant is not required to remove total nitrogen, using nitrification coupled with denitrification could save in operation and maintenance costs [31].

No evidence was found to support biological phosphorus removal for meeting the new summer limit of 0.5 mg/L. High influent nitrate levels and low influent COD could be the reason that results were insignificant. However, biological phosphorus removal has potential for use for meeting the winter phosphorus limits of 2 mg/L. With a possible reduction of nitrate in the return stream due to denitrification, the 2 mg/L could be met by the plant in the winter while saving in chemical cost because no alum for precipitation of P would be needed. Further work under optimum operating conditions is needed to confirm conclusions about phosphorus removal.

It is possible that, due to the infrequent influent feed

collection, the grab samples were not representative of the actual soluble COD loading to the plant. The performance of the proposed scheme could improve in the area of P and nitrate removal with higher soluble COD levels. Therefore, it is recommended that a sampling program to determine actual soluble COD loading to the plant be implemented.

The distribution of COD in the eight reactors is important for successful BNR. As mentioned in Chapter 6, some soluble COD may need to be available as a food source for denitrification in the down-stream stages. One approach for achieving this is to operate the eight stage system with smaller reactors at the up-stream end. Optimization of reactor size would require further experimental work.

The levels of nitrate in the influent were surprisingly high. Typically, nitrate is not expected to be found in untreated wastewater. Possible explanations include that nitrification is taking place upstream of the plant in the collection mains or that nitrate is discharged into the collection system from an industrial source. These possibilities could be evaluated with a nitrate monitoring program at incremental distances upstream along the collection sewers.

The City of Durham already monitors effluent nitrate once a month. In addition, grab samples from the Northeast Creek to which the plant is discharging are tested for nitrate three times a month, as part of a receiving stream nitrogen monitoring program. It is recommended that, in addition to the up-stream nitrate monitoring

program, the City continuously test influent nitrate to confirm the unusual nitrate strength and its diurnal trend.

It is recommended that Durham County further experiment with Biological Nutrient Removal by setting up a pilot plant at the Triangle Plant. A pilot plant with the same configuration of alternating anaerobic/aerobic stages could offer the following improvements to the bench scale experiment and advantages for operation of the experiment:

* A larger volume reactor would enable continuous feeding of influent into the reactor and continuous recycling of sludge back to Stage 1.

* Continuous feeding of raw wastewater would ensure that influent characteristics would be identical for the pilot system and the full scale plant. Of course influent feed would not require refrigeration prior to feed.

* A more reliable mechanical mixing would improve consistency of MLSS concentration throughout all 8 stages.

* Larger volume reactors should have greater surface to volume ratio. This would lessen the effect of attachment of MLSS to the reactor walls.

* Larger reactors would permit better control over aeration rates and consequently DO in each stage of the system.

* The bench scale laboratory reactor was operated at only one mode of operation with 10 days MCRT. Variation in MCRTs with the pilot plant could help to determine a more optimal mode of operation.

* A variation of the size of the aerobic stage 2 and possibly stage 4 could be experimented with to identify the configuration that will provide a more uniform distribution of COD throughout the eight stages. By making the front stages smaller then the remaining stages, more soluble COD is expected to be available in down-stream stages for denitrification.

If the Triangle Plant decides to employ biological phosphorus removal it should reexamine the current practice of returning decant from the sludge lagoons to the headworks. It is quite possible that significant amounts of phosphorus would be then recycled back to the headworks, overburdening the liquid treatment stream in the plant.

If the Triangle Plant continues the current practice of chemical addition, chemical metering pumps are recommended to replace the manually adjusted chemical pumps, currently used. The flow from the pumps would match diurnal variations and pH fluctuations. The chemical metering pumps should be capable of sufficient turndown by an automated electronic actuator that will vary the speed of the pump or by pump stroke adjuster. The alum flow rate could be controlled by influent flow while the sodium hydroxide flow could be controlled by set-point pH.

Finally, increasing application of biological methods for treatment would result in reducing dependence on chemical intervention. Further research along the lines of Biological Nutrient Removal are worthy of continuous support by public and private institutions.

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12.0 APPENDIX

CODRELI.XLS

Table A1
COD Test Reliability

Durham County Triangle Plant

COD UN INF

	MEASURMENT 1st	2nd	3rd	4th	AVERG.	STD. DEV	REL. S.D.(a)
8-2-91	200.6	218			209.30	8.700	0.04157
8-12-91	379	379.8			379.40	0.400	0.00105
8-15-91	841.2	857.8			849.50	8.300	0.00977
8-18-91	214.1	214.1			214.10	0.000	0.00000
8-20-91	316.2	314			315.10	1.100	0.00349
8-28-91	294.9	294.9			294.90	0.000	0.00000

COD FILT INF

	MEASUREMENT 1st	2nd	3rd	4th	AVERG.	STD. DEV	REL. S.D. (a)
8-15-91	155.4	155.4			155.40	0.000	0.00000
8-20-91	145.9	141.1	144		143.77	1.996	0.01388
8-28-91	126.1	125.3			125.70	0.400	0.00318

COD EFF UNFILT

	MEASUREMENT 1st	2nd	3rd	4th	AVERG.	STD. DEV	REL. S.D. (a)
7-28-91	25.23	27.06			26.15	0.915	0.03500
7-31-91	58.67	64.21			61.44	2.770	0.04508
8-1-91	90.38	92.76			91.57	1.190	0.01300
8-2-91	88.00	89.59			88.80	0.795	0.00895
8-7-91	26.16	30.13			28.15	1.985	0.07053
8-8-91	38.85	59.46			49.16	10.305	0.20964
8-10-91	52.32	50.74			51.53	0.790	0.01533
8-11-91	53.91	53.91			53.91	0.000	0.00000
8-12-91	26.96	77.7			52.33	25.370	0.48481
8-13-91	55.50	58.67			57.09	1.585	0.02777
8-15-91	47.57	64.21			55.89	8.320	0.14886
8-16-91	36.47	38.05			37.26	0.790	0.02120
8-20-91	66.59	65.8			66.20	0.395	0.00597
8-26-91	54.70	55.5			55.10	0.400	0.00726
8-27-91	34.88	34.09	53.9		40.96	9.163	0.22370
8-28-91	55.50	63.42			59.46	3.960	0.06660
8-29-91	46.78	99.1	33.3	21.4	50.15	29.654	0.59133

COD EFF FILT

	MEASUREMENT 1st	2nd	3rd	4th	AVERG.	STD. DEV	REL. S.D. (a)
7-28-91	17.55	17.44			17.50	0.055	0.00314
7-31-91	52.32	48.36			50.34	1.980	0.03933
8-2-91	60.25	74.52	63.4	61.8	65.01	5.605	0.08622
8-4-91	38.85	37.26			38.06	0.795	0.02089
8-8-91	24.58	19.82			22.20	2.380	0.10721
8-10-91	44.40	43.6			44.00	0.400	0.00909
8-11-91	30.92	26.16			28.54	2.380	0.08339
8-12-91	37.26	35.68			36.47	0.790	0.02166
8-15-91	36.47	36.47			36.47	0.000	0.00000
8-20-91	14.27	9.514			11.89	2.378	0.19997
8-26-91	37.26	37.26			37.26	0.000	0.00000
8-27-91	35.68	34.88			35.28	0.400	0.01134
8-28-91	32.50	30.13	29.3	30.1	30.52	1.188	0.03891
8-29-91	26.96	21.41	47.6	28.5	31.12	9.860	0.31683

(a) Relative Standard Deviation = Std. Dev./ Average

NRELIAB.XLS

Table A2
Nitrogen Test Reliability

Durham County Triangle Plant

AMMONIA FILT INF

	MEASUREMENT 1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-20-91	16.5	16.4	16.5	16.47	0.047	0.00286

AMMONIA UNFILT EFF

	MEASUREMENT 1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-29-91	0.07	0.05		0.06	0.009	0.15254

AMMONIA FILT EFF

	MEASUREMENT 1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-20-91	0.07	1.00		0.53	0.466	0.87266

TKN FILT INF

	MEASUREMENT 1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-22-91	17.10	16.30		16.70	0.400	0.02395

NO3-N UNFILT INF

	MEASUREMENT 1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-8-91	15.5	12.7		14.10	1.400	0.09929

NO3-N UNFILT EFF

	MEASUREMENT 1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-5-91	21	30		25.50	4.500	0.17647
8-19-91	8.8	10.5		9.65	0.850	0.08808
8-22-91	7.8	5.7		6.75	1.050	0.15556
8-25-91	8.5	17.8	8.2	11.50	4.456	0.38752

NO3-N FILT EFF

	MEASUREMENT 1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-5-91	26	23		24.50	1.500	0.06122
8-6-91	22.5	19		20.75	1.750	0.08434
8-20-91	8.7	7		7.85	0.850	0.10828
8-22-91	4.9	3.8		4.35	0.550	0.12644

(a) Relative Standard Deviation = Std. Dev./ Average

TPTSSREL.XLS

Table A3
PHOSPHORUS AND TSS Test Reliability

Durham County Triangle Plant

TP UNFILT INF

	MEASUREMENT					
	1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-20-91	4.47	4.42		4.45	0.025	0.00562
8-31-91*	2.71	2.88		2.80	0.085	0.03041

TP FILT INF

	MEASUREMENT					
	1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-2-91*	1.73	1.7		1.72	0.015	0.00875
8-20-91	3.30	3.36	3.26	3.31	0.041	0.01243

TP FILT EFF

	MEASUREMENT					
	1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-27-91*	1.61	1.61		1.61	0.000	0.00000
8-29-91	2.13	2.23		2.18	0.050	0.02294

TSS EFF

	MEASUREMENT					
	1st	2nd	3rd	AVERG.	STD. DEV.	REL. S.D.(a)
8-6-91	9.60	9.6	10.4	9.87	0.377	0.03822
8-11-91	6.00	6		6.00	0.000	0.00000

(a) Relative Standard Deviation = Std. Dev./ Average

PROFILES.XLS

TABLE A4
PROFILES SUMMARY

DURHAM COUNTY TRIANGLE PLANT

Test/Date	Reactor Number 1	Reactor Number 2	Reactor Number 3	Reactor Number 4	Reactor Number 5	Reactor Number 6	Reactor Number 7	Reactor Number 8
COD (mg/L)/ 8-25-91	224.4	63.42	65.01	47.57	43.6	34.09	30.13	38.05
NO3--N (mg/L)/ 8-25-91	4.4	10.5	9	4		6.5	5.7	6.2
NH3-N (mg/L)/ 8-29-91	4.8	2.8	2.35	0.275	0.075	0.03	0.067	0.052
TKN (mg/L)/ 8-29-91	5.44	3.77	3.46	1.36	1.25	1.32	1.55	1.34
COD (mg/L)/ 8-29-91	30.92	26.165	29.33	56.685	23.785	24.97	28.54	23.385
COD (mg/L)/ 9-5-91	31.71	17.84	18.635	23.785	21.41	21.005	15.505	15.855
TOTAL P (mg/L)/ 8-29-91	2.54	2.13	2.28	2.24	2.42	2.39	2.3	2.41
NO3--N (mg/L)/ 9-5-91	7.6	12	11.6	13.2	12.6	13.8	13	14
D.O. (mg/L)/								
8-15-91AM	0.25	4.5	0.3	7	0.8	7.3	1	5
8-15-91PM	<0.1	1.95	0.25	6.2	0.15	7.4	0.15	8
8-16-91pm	0.1	0.7	0.1	3.5	0.1	5.6	0.2	4.7
8-27-91am	0.1	0.1	0.1	2.6	0.2	1	0.3	1.1
8-27-91pm	0.1	0.2	0.1	3.7	0.1	1.1	0.1	2.9

TABLE A5
COD REMOVAL DATA

DURHAM COUNTY, TRIANGLE PLANT

Date	days from reactor initial seeding Days	INFLUENT: COD mg/L unfiltered Influent COD	COD mg/L filtered Soluble Influent COD	EFFLUENT: COD mg/L unfiltered Effluent COD	COD mg/L filtered Soluble Effluent COD
7-23-91*	1	481.60			
7-24-91	2	481.60	92.31	32.67	
7-25-91	3	481.60	92.31		
7-26-91	4		92.31	69.07	26.03
7-27-91*	5	306.60			
7-28-91	6	306.60		26.15	17.50
7-29-91	7	306.60			
7-30-91*	8				
7-31-91	9			61.44	50.34
8-1-91	10			91.57	81.66
8-2-91*	11	209.30		88.80	65.01
8-3-91	12	209.30	92.70	35.68	35.68
8-4-91	13	209.30	92.70		38.06
8-5-91*	14		92.70	34.09	34.88
8-6-91	15			31.71	21.41
8-7-91	16			28.15	
8-8-91*	17	864.90		49.16	22.20
8-9-91	18	864.90	150.60		
8-10-91	19	864.90	150.60	51.53	44.00
8-11-91	20	864.90	150.60	53.91	28.54
8-12-91*	21	379.40	150.60	52.33	36.47
8-13-91	22	379.40		57.09	25.37
8-14-91	23	379.40		25.37	
8-15-91*	24	849.50		55.89	36.47
8-16-91	25	849.50	155.40	37.26	36.47
8-17-91	26	849.50	155.40		
8-18-91*	27	214.10	155.40		
8-19-91	28	214.10		27.75	
8-20-91*	29	315.15		66.20	11.89
8-21-91	30	315.15	143.77		
8-22-91	31	315.15	143.77	38.05	29.33
8-23-91*	32	277.50	143.77	72.14	38.05
8-24-91	33	277.50	177.60	81.66	42.81
8-25-91	34	277.50	177.60		
8-26-91	35	277.50	177.60	55.10	37.26
8-27-91	36	277.50	177.60	40.96	35.28
8-28-91*	37	294.90	177.60	59.46	30.52
8-29-91	38	294.90	125.70	50.15	31.12
8-30-91	39	294.90	125.70		
8-31-91*	40		125.70		
Average		430.77	138.33	50.86	35.68

* date in which new effluent was fed into the influent tank

PREMOVAL.XLS

Table A6
Phosphorus Removal Data

Durham County Triangle Plant

Date	INFLUENT: Phosphorus mg/L unfiltered Influent Total P	INFLUENT: Phosphorus mg/L filtered Influent Soluble P	EFFLUENT: Phosphorus mg/L unfiltered Effluent Total P	EFFLUENT: Phosphorus mg/L filtered Effluent Soluble P	days from reactor initial seeding
7-23-91*	3.61		4.15	3.88	1
7-24-91	3.61			3.40	2
7-25-91	3.61				3
7-26-91	3.61			2.24	4
7-27-91*	2.84				5
7-28-91	2.84				6
7-29-91	2.84		2.35		7
7-30-91*	6.07		1.72		8
7-31-91	6.07		2.08	1.84	9
8-1-91	6.07		2.01	1.94	10
8-2-91*	2.60	1.72	2.07	2.26	11
8-3-91	2.60	1.72	1.96	1.97	12
8-4-91	2.60	1.72		1.78	13
8-5-91*		1.19	1.72	1.49	14
8-6-91		1.19	1.51	1.44	15
8-7-91		1.19	1.51		16
8-8-91*			1.52	1.32	17
8-9-91					18
8-10-91			2.70	2.07	19
8-11-91			2.54		20
8-12-91*				2.71	21
8-13-91				2.85	22
8-14-91			2.80		23
8-15-91*				2.60	24
8-16-91			3.20		25
8-17-91					26
8-18-91*		2.91			27
8-19-91		2.91			28
8-20-91*	4.45	3.31			29
8-21-91	4.45	3.31			30
8-22-91	4.45	3.31	2.71	2.72	31
8-23-91*	3.43	2.68	2.92	2.89	32
8-24-91	3.43	2.68			33
8-25-91	3.43	2.68			34
8-26-91	3.43	2.68	1.64	1.57	35
8-27-91	3.43	2.68	1.66	1.61	36
8-28-91*					37
8-29-91				2.18	38
8-30-91					39
8-31-91*	2.80	1.30	2.55	2.40	40
Average	3.74	2.30	2.27	2.25	

* date in which new effluent was fed into the influent tank

Table A7
Ammonia Nitrogen Removal Data

Durham County, Triangle Plant

Date	INFLUENT: Ammonia-N mg/L unfilt	INFLUENT: Ammonia-N mg/L filtered	EFFLUENT: Ammonia-N mg/L unfilt	EFFLUENT: Ammonia-N mg/L filtered	days from reactor initial seeding
7-23-91*					1
7-24-91	15.00			<0.1	2
7-25-91	15.00				3
7-26-91	14.00		<0.1	<0.1	4
7-27-91*	14.00				5
7-28-91	10.00				6
7-29-91	10.50		<0.1	<0.1	7
7-30-91*	10.50				8
7-31-91					9
8-1-91			<0.05	0.07	10
8-2-91*			<0.05		11
8-3-91	9.20	9.00	<0.05	0.05	12
8-4-91	9.20	9.00	0.03	0.03	13
8-5-91*	9.20			0.03	14
8-6-91		6.27	0.03	0.02	15
8-7-91		6.27	0.03	0.01	16
8-8-91*		6.27	0.02		17
8-9-91	18.20	18.20	0.04	0.02	18
8-10-91	18.20	18.20			19
8-11-91	18.20	18.20	0.05	0.05	20
8-12-91*	18.20	18.20	0.16	0.16	21
8-13-91	15.60	15.50	0.16	0.15	22
8-14-91	15.60	15.50	0.59	0.58	23
8-15-91*	15.60	15.50	0.14	0.14	24
8-16-91	19.60	19.50	0.13	0.15	25
8-17-91	19.60	19.50	0.16	0.13	26
8-18-91*	19.60	19.50			27
8-19-91	10.40				28
8-20-91*	10.40				29
8-21-91	16.40	16.47	0.87	0.53	30
8-22-91	16.40	16.47			31
8-23-91*	16.40	16.47	4.20	5.80	32
8-24-91	18.20	17.80	11.50	10.00	33
8-25-91	18.20	17.80	6.20	6.30	34
8-26-91	18.20	17.80			35
8-27-91	18.20	17.80	3.20	3.40	36
8-28-91*	18.20	17.80	2.80	2.80	37
8-29-91	16.40	16.00	0.21	0.21	38
8-30-91	16.40	16.00	0.06		39
8-31-91*	16.40	16.00			40
Average	15.31	15.42	1.53	1.46	

* date in which new effluent was fed into the influent tank

Table A8
TKN Removal Data

Durham County, Triangle Plant

Date	INFLUENT: TKN mg/L unfiltered	TKN mg/L filtered	EFFLUENT: TKN mg/L unfiltered	TKN mg/L filtered	days from reactor initial seeding
7-23-91*	15.22		2.38	2.05	1
7-24-91	15.22			1.03	2
7-25-91	15.22				3
7-26-91	15.22			2.19	4
7-27-91*	14.96				5
7-28-91	14.96				6
7-29-91	14.96		2.19		7
7-30-91*	22.90			1.82	8
7-31-91	22.90		2.05	1.55	9
8-1-91	22.90		1.93	1.63	10
8-2-91*	13.06	8.19	2.10	1.68	11
8-3-91	13.06	8.19	1.58	1.25	12
8-4-91	13.06	8.19			13
8-5-91*		7.12		2.25	14
8-6-91				0.96	15
8-7-91			2.01		16
8-8-91*					17
8-9-91					18
8-10-91				0.99	19
8-11-91			1.56		20
8-12-91*					21
8-13-91				1.18	22
8-14-91			1.47		23
8-15-91*	23.70	17.68		0.85	24
8-16-91	23.70	17.68	1.37		25
8-17-91	23.70	17.68			26
8-18-91*	12.10				27
8-19-91	12.10		2.50		28
8-20-91*	19.70	16.70		1.06	29
8-21-91	19.70	16.70			30
8-22-91	19.70	16.70			31
8-23-91*	18.39	15.70	10.02	8.50	32
8-24-91	18.39	15.70			33
8-25-91	18.39	15.70			34
8-26-91	18.39	15.70			35
8-27-91	18.39	15.70	3.70	3.20	36
8-28-91*					37
8-29-91			1.33	1.20	38
8-30-91					39
8-31-91*					40
Average	17.69	14.22	2.59	1.96	

* date in which new effluent was fed into the influent tank

Table A9
Nitrate Removal Data

Durham County, Triangle Plant

Date	days from reactor initial seeding Day	INFLUENT: NO3-N mg/L unfiltered Influent NO3-N Unfilt	INFLUENT: NO3-N mg/L filtered Influent NO3-N filt	EFFLUENT: NO3-N mg/L unfiltered Effluent NO3-N Unfilt	EFFLUENT: NO3-N mg/L filtered Effluent NO3-N filt
7-23-91*	1	1.20		34.50	
7-24-91	2	1.20			24.00
7-25-91	3	1.20		15.00	13.00
7-26-91	4	1.20			
7-27-91*	5	13.00			
7-28-91	6	13.00			
7-29-91	7	13.00		29.00	27.50
7-30-91*	8				
7-31-91	9			18.00	30.00
8-1-91	10			26.50	23.50
8-2-91*	11	13.50	8.50	21.50	24.50
8-3-91	12	5.70	8.50	19.80	18.00
8-4-91	13	6.80		12.80	15.70
8-5-91*	14		2.05	25.50	24.50
8-6-91	15		2.05	16.50	20.75
8-7-91	16		2.05	10.30	
8-8-91*	17	14.10	15.00	16.60	18.60
8-9-91	18	14.10	15.00		
8-10-91	19	14.10	15.00	21.00	18.50
8-11-91	20	9.00	9.00	20.00	18.60
8-12-91*	21	3.50			
8-13-91	22	3.50		26.00	22.30
8-14-91	23	3.50		24.00	26.00
8-15-91*	24	27.00	19.00	32.00	28.00
8-16-91	25	27.00	19.00	20.50	16.00
8-17-91	26	27.00	19.00	5.30	10.00
8-18-91*	27	27.00	19.00		
8-19-91	28	27.00	19.00	9.65	
8-20-91*	29				7.85
8-21-91	30				
8-22-91	31			6.75	4.35
8-23-91*	32			3.00	3.10
8-24-91	33			24.50	18.70
8-25-91	34			11.50	
8-26-91	35			7.70	7.50
8-27-91	36			7.80	7.40
8-28-91*	37			13.40	11.00
8-29-91	38				
8-30-91	39				
8-31-91*	40				
Average		12.12	12.30	17.74	17.57

* date in which new effluent was fed into the influent tank

TSSREMOV.XLS

Table A10
Total Suspended Solids Removal

Durham County, Triangle Plant

Date	days from reactor initial seeding Days	INFLUENT: TSS mg/L Influent TSS	EFFLUENT: TSS mg/L Effluent TSS
7-19-91*	1	301.60	
7-20-91	2	301.60	
7-21-91	3	301.60	52.50
7-22-91	4	301.60	
7-23-91*	5	57.00	
7-24-91	6	57.00	
7-25-91	7	57.00	41.00
7-26-91	8	57.00	19.00
7-27-91*	9	214.00	
7-28-91	10	214.00	10.00
7-29-91	11	214.00	
7-30-91*	12		
7-31-91	13		12.40
8-1-91	14		
8-2-91*	15	107.00	4.40
8-3-91	16	107.00	
8-4-91	17	107.00	3.70
8-5-91*	18		
8-6-91	19		9.87
8-7-91	20		
8-8-91*	21		
8-9-91	22		
8-10-91	23		3.80
8-11-91	24		6.00
8-12-91*	25	428.00	
8-13-91	26	428.00	4.20
8-14-91	27	428.00	3.70
8-15-91*	28		3.40
8-16-91	29		
8-17-91	30		
8-18-91*	31		
8-19-91	32		
8-20-91*	33	113.00	4.30
8-21-91	34	113.00	
8-22-91	35	113.00	0.80
8-23-91*	36		
8-24-91	37		4.60
8-25-91	38		
8-26-91	39		2.20
8-27-91	40		
8-28-91*	41		
8-29-91	42		
8-30-91	43		
8-31-91*	44		
Average		201.02	10.93

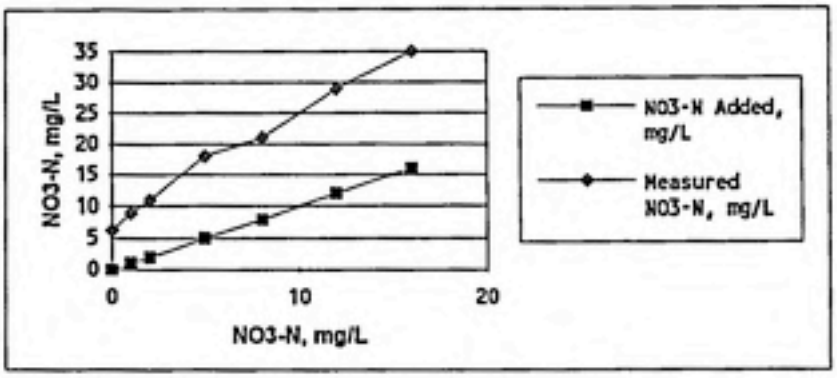
* date in which new effluent was fed into the influent tank

Table A11
The Method of Standard Additions

Durham County Triangle Plant

Standard Addition Effluent Sample 8-17-91

	NO3-N Added, mg/L	Measured NO3-N, mg/L
0	0	6.2
1	1	9
2	2	11
5	5	18
8	8	21
12	12	29
16	16	35



Standard Addition Effluent Sample 8-27-91

	NO3-N Added, mg/L	Measured NO3-N, mg/L
0	0	7.4
1	1	
5	5	17
16	16	32.4
25	25	43.5