THE EFFECTIVENESS OF MULTIPLE REDOX TREATMENT STRATEGIES ON THE TREATABILITY OF A HIGH STRENGTH INDUSTRIAL WASTEWATER

by

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(ABSTRACT)

The treatability of a high strength industrial wastewater, 9,000 mg/L as chemical oxygen demand (COD), by three sequencing batch reactor (SBRs) systems operated under alternating redox environments: anaerobic/aerobic (ANA), anoxic/aerobic (ANX), and aerobic was investigated. A synthetic wastewater was modeled after a wastewater from an existing chemical processing facility. The largest component, hydroxypivaldehyde, was unavailable for the use in this research and was substituted by pivalic acid, both of which have a tertiary carbon. No significant degradation occurred in the anaerobic phase of operation; however, 55-65% of the COD was removed during anoxic operation. Simultaneous removal of pivalic acid and acetic acid was seen in both the anoxic and aerobic reaction phases. The anoxic/aerobic SBR provided the best overall treatability of the synthetic wastewater based on: effluent quality, sludge characteristics and settling properties. The results suggested that anoxic/aerobic treatment schemes are a viable treatment alternative for industrial wastewaters containing high concentrations of organic acids, including acids with tertiary carbons. The treatability of the three alternating redox environments on the Industry's wastewater was also investigated. Again, no significant degradation of the industrial wastewater occurred during the anaerobic reaction phase. During the anoxic reaction phase, 15-20% of the COD was removed from the industrial wastewater in contrast to the high removals seen with the synthetic wastewater. The aerobic SBR provided the best COD removal for the industrial wastewater. The performance differences between the synthetic and industrial wastewaters stress the importance of treatability studies on the actual industrial wastewater. Biological treatment of the synthetic and Industry wastewaters was unable to achieve the effluent goal of 100 mg/L as COD. Sand filtration followed by granular activated carbon adsorption treatment of the effluent from the synthetic wastewater-fed ANA SBR provided the COD removal necessary to achieve the effluent goal.

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CHAPTER I. INTRODUCTION

Removal of chemical oxygen demand (COD) from highly concentrated wastewaters prior to discharge into receiving waters or municipal treatment plants is a challenge for many industrial treatment systems. As more information becomes available on the ecological impacts of wastewater discharge, permit limitations are becoming more stringent.

A chemical processing company, hereafter referred to as the Industry, currently operates a chemical processing facility in the United States and will be building an additional facility in Asia. The U.S. wastewater treatment plant utilizes conventional activated sludge treatment to meet mass based BOD limitations. Typical effluent COD concentrations at the wastewater treatment plant range from 250 - 350 mg/L as COD. The Asian wastewater treatment plant will be required to meet an effluent limitation of 100 mg/L as COD. The Industry believed enhanced wastewater treatment would be necessary to meet the stricter discharge limitation.

At the U.S. facility, several chemical production lines are used to produce organic chemicals. Separate waste streams are generated from the individual chemical production lines. The waste streams are collected and combined to form a concentrated wastewater with a COD between 24,000 - 30,000 mg/L. Prior to biological treatment, the concentrated wastewater is diluted 1:3 with additional water. The wastewater is composed primarily of: aldehydes, long chain alcohols, and highly branched compounds.

In 1996, degradation studies were conducted on the individual waste streams, as well as the combined wastewater (Young *et al.*, 1996). The studies showed that anaerobic treatment could provide substantial COD removal for the wastewater and 2 of

the 3 waste streams tested. The researchers suggested that certain compounds in the third waste stream were toxic to the anaerobic microorganisms; therefore, the stream could not be substantially treated under an anaerobic environment. At the Asian facility the toxic stream will not be sent to the wastewater treatment plant but will be routed to a syngas unit. The aerobic treatability of the waste streams was also investigated by the researchers. The study showed that the individual waste streams tested and the combination of the waste streams were significantly degraded under aerobic conditions. The results suggested that anaerobic treatment would not provide sufficient COD removal to meet effluent limitations. However, a combination of anaerobic and aerobic treatment would enhance treatability and provide economic savings to the Industry.

Several enhanced treatment options including high-rate systems, both fixed-film and suspended growth, and multiple redox treatment strategies were considered to provide the necessary increase in COD removal. Sequencing batch reactors (SBR) operated with multiple redox treatment environments were chosen. The treatment environments selected for this research were anaerobic/aerobic, anoxic/aerobic and aerobic only. Because of the unavailability of the actual industrial wastewater at the beginning of this study, a synthetic wastewater was modeled after the concentrated wastewater for laboratory use. In composing the synthetic wastewater, substitutions were made for compounds that were unavailable or unknown at the beginning of the research. Wastewater from the U.S. chemical facility was obtained towards the end of the study, and treatability studies were conducted for comparison with the results of the synthetic wastewater studies.

Results from the biological treatment studies indicated that tertiary treatment would be necessary to consistently meet the effluent COD limitation of 100 mg/L. Therefore, granular activated carbon was chosen to remove the remaining soluble COD. Several types of GAC were tested to determine isotherm parameters.

The specific objectives for this research include:

1) compare the overall treatability of 3: anaerobic/aerobic, anoxic/aerobic and aerobic multiple redox treatment strategies on a synthetic industrial wastewater based on the following criteria: a) effluent quality, b) sludge characteristics/system handling, c) settling properties and d) degradation patterns across the reaction phases.
2) compare overall treatability of the 3 multiple redox treatment strategies on the actual industrial wastewater based on: effluent quality and degradation patterns across the reaction phases.
3) determine isotherm parameters for several types of granular activated carbon for the removal of soluble COD remaining after anaerobic/aerobic treatment.
4) determine if an effluent COD of 100 mg/L can be met after biological treatment, sand filtration and adsorption to granular activated carbon.

CHAPTER II. LITERATURE REVIEW

Introduction

The sponsoring Industry currently operates a chemical processing plant in the United States that generates a wastewater with a chemical oxygen demand (COD) of approximately 30,000 mg/L. The concentrated waste stream is a combination of several chemical waste streams (see Table 2-1) that is diluted 1:3 with additional water before treatment. The wastewater contains some additional intermediate compounds which contribute to increased COD concentrations: C10 acetal, C10 ester, and 2,2,4-trimethyl-3-hydroxy-pentanal. The U.S. plant uses conventional activated sludge treatment to remove BOD/COD from the wastewater. The existing treatment plant produces typical effluent COD concentrations ranging from 250 - 350 mg/L as COD. The Industry will be building a new chemical processing plant in Asia similar to the existing U.S. facility; however, the effluent limitation imposed on the wastewater treatment plant is 100 mg/L as COD.

Researchers at Pennsylvania State University conducted studies to determine the anaerobic and aerobic treatability of the NPG, TXOL and Copolymer waste streams (see Table 2-1), both individually and in combination (Young *et al.*, 1996). Semi-continuous anaerobic studies were conducted initially with a solids retention time (SRT) of 20 days. After several weeks, the SRT was increased to 40 days in an effort to enhance removal efficiencies for all studies; however, no improvement in COD removal was observed. The study concluded that the NPG and Copolymer waste streams were partially treatable by anaerobic means. The remaining stream, TXOL, was unable to be treated anaerobically and the researchers suggested that compounds found in the stream were toxic to the biomass. At the new facility, this waste stream will not be fed to the wastewater treatment

Table 2-1: Industrial wastewater components (kg/hr)

	NPG				TXOL	2EH	BuOH	Copolymer
Stream Numbers	23	26D	31	Total	232	303	29	
C9 acetal			1	1				
Ethylhexanediol						5.5		
Ethylene glycol								17
Formaldehyde		0.9	2.3	3.2				
Hydroxypivaldehyde	98.7			98.7				
i-butanol		2.4	41.8	44.2	0.8	0.2		
i-butyraldehyde		1.9	0.8	2.7	6.8			
Methanol	11.2	0.3	4.9	16.4				
n-butyraldehyde				0			7	
n-butanol				0			11.8	
n-propanol				0			0.9	
Neopentylglycol	14.5			14.5				
Neopentylgycol-MI	1.1			1.1				
Trimethylpentanediol				0	3.4			
Organic Salts								
Sodium Hydroxide	3.5			3.5	1.1	25.57		
Sodium Formate	95.84			95.84				
Sodium Hydroxypivalate	4.34			4.34				
Sodium Butyrate				0	0.6			
Sodium 2-ethyl Hexanoate				0		12.43		
Sodium Carbonate	5.68			5.68				
Acetic acid								17
Water	4124	2.2	529	4655	713.4	1165.4	188.9	

plant but instead routed to a syngas unit. The combination of all three waste streams showed a 55 - 65% reduction in COD based on cumulative methane gas production and biomass generation.

The aerobic tests produced significantly different degradation results from the anaerobic tests. Two of the waste streams, NPG and TXOL, were tested under aerobic conditions, as well as the combination of all three waste streams. Under aerobic conditions, significant COD removal occurred in all cases with 79%, 95%, and 89% COD removal for NPG, TXOL, and the mixture, respectively. The studies indicated that biosolids production for aerobic treatment was approximately 5 times greater than biosolids production for anaerobic treatment.

Although complete degradation in an anaerobic environment was not achieved, the results showed a low but stable removal efficiency for the anaerobic environment. The results clearly showed that anaerobic treatment may be used to degrade only a fraction of the waste stream but could be coupled with an aerobic downstream process for enhanced COD removal. The researchers suggested that anaerobic treatment with a COD removal efficiency of at least 80% could be justified as the first step in a treatment process due to the savings in sludge handling and disposal. The researchers also suggested that additional exposure to the waste streams could generate an acclimated biomass and may lead to higher removal levels. It is unlikely that 100% removal could be achieved with anaerobic treatment alone; however, significant cost savings in reduced aeration and sludge production could justify use of an anaerobic-aerobic process with anaerobic removal efficiencies less than 80%.

Several options existed for achieving the increased degree of COD removal necessary for the Asian wastewater treatment plant. High rate systems, including fixed film or specialized suspended growth systems, provide high organic removal upstream of conventional activated sludge systems. Several different high rate systems can provide organic removal: anaerobic contact reactors (AC), upflow anaerobic sludge blanket reactors (UASB), anaerobic filters (AF), hybrid UASB/AF, downflow stationary fixed film (DSFF) and fluidized bed/expanded bed (FB/EB) (Grady and Daigger, 1997). The high rate systems maintain extremely high biomass concentrations which results in long SRTs. The long SRTs help provide the systems with increased stability. The high biomass concentrations allow for high organic loading rates and provide high organic removal rates (Grady and Daigger, 1997).

Although high rate systems have proven to be effective at removing high organic loads, there are several disadvantages to these systems (Grady and Daigger, 1997). The high rate systems, listed above, cannot tolerate high influent suspended solids concentrations. Additionally, the systems allow for little process control during operation. The systems operate with low HRTs that decrease the dilution of toxic compounds and also reduce equalization of the wastewater. The AF, UASB/AF, EB, and FB systems have high costs associated with the filter media and the necessary support systems. The upflow systems listed above also have high pumping cost associated with operation because of the large volumes of water pumped through the systems.

Another alternative to the high rate processes listed above are selectors. Selectors are activated sludge reactors with concentrated biomass that can be operated under anaerobic, anoxic, or aerobic environments. High biomass concentrations are maintained

by recirculating the concentrated sludge from the clarifier into the selector. Selectors are most often used to control the growth of filamentous organisms; however, the high biomass concentrations provide large organic removals in a relatively small reactor volume. Smets *et al.* (1994) compared kinetic parameters of two activated sludge systems: one with a selector and one without. The results indicated that the system with selectors promoted growth of organisms with high organic removal capabilities and selected against those that did not.

An alternative to the high rate systems discussed above is to use multiple redox environments for treating a high strength wastewater. Alternating between two or more redox environments can provide nutrient removal capabilities as well as enhanced organic carbon removal. Multiple redox environments may also provide a more diverse culture of microorganisms that can work together to degrade a broader range of compounds (Zitomer and Speece, 1993).

Sequencing batch reactors (SBRs) are a popular treatment option for many industries, and provide many cost advantages to the high rate systems discussed above. All processes are carried out in one reactor, eliminating the need for separate clarifiers or multiple reactors. Additionally, pumping costs are significantly reduced by treating the wastewater in a single reactor. Multiple redox environments (anaerobic, anoxic or aerobic) can easily be incorporated into treatment strategies involving SBRs. An additional benefit of SBRs can be improved settling properties; because the sludge is not pumped to a clarifier, deflocculation or shearing due to pumping is eliminated. Improved settling can also be achieved with SBRs relative to completely mixed systems because bacterial population structure is influenced by substrate concentration gradients. For this

study, SBRs were used and operated with multiple redox environments: 1) anaerobic/aerobic, 2) anoxic/aerobic and 3) aerobic only to treat the industrial wastewater.

Sequencing Batch Reactors

SBRs have 5 distinct phases of operation (see Figure 2-1): fill, react, settle, decant and idle. During the fill phase, wastewater is added to the reactor over a specific time interval with the mixers and aeration on, if desired. Across the reaction phase, there can be several different environments as is the case with the experimental reactors used during this study (see Figure 2-2). After the reaction phase, the mixers and air are turned off and the biomass is allowed to settle to the bottom of the reactor. After the allotted settling time, the supernatant is removed from the reactor during the decant time. The final idle phase provides downtime when nothing is being added, removed or stirred in the reactor.

One advantage of SBRs is the ease of operation of the systems. All processes: reaction, clarification, treated effluent removal, and wastewater addition occur in one reactor, eliminating the need for extra pumps, piping, reactors and settling basins. Orhon *et al.* (1986) studied the operation of several SBRs and concluded that advantages of SBRs were due primarily to the "flexible nature of the operating parameters". Several operational and treatment adjustments can be made with a fixed reactor volume simply by changing the operational times of the different phases. Additionally, carbon oxidation, nitrification, denitrification, and phosphorous removal can occur within one reactor as opposed to tanks in series, saving money and space. Another advantage of SBRs is that they provide a concentration gradient across time in a completely mixed reactor, exposing biomass to a similar condition as that provided by plug flow reactors (Grady and Daigger, 1997). Orhon *et al.* (1986) also found that soluble substrate removal rates were faster in

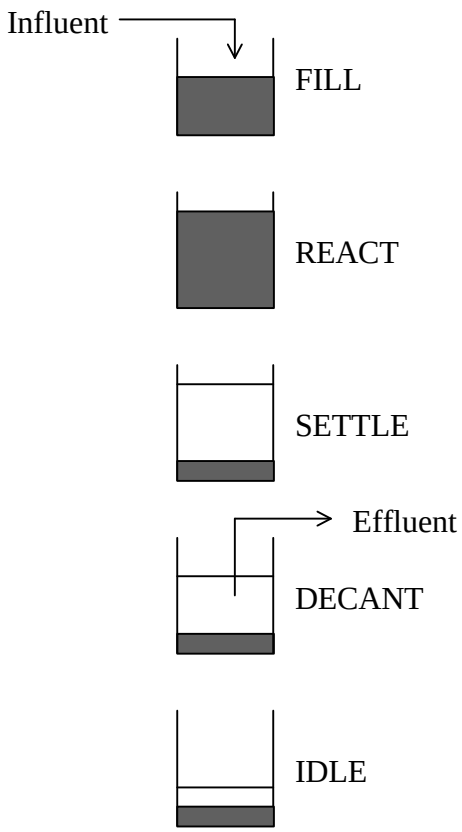

Figure 2-1: Operational steps for Sequencing Batch Reactor

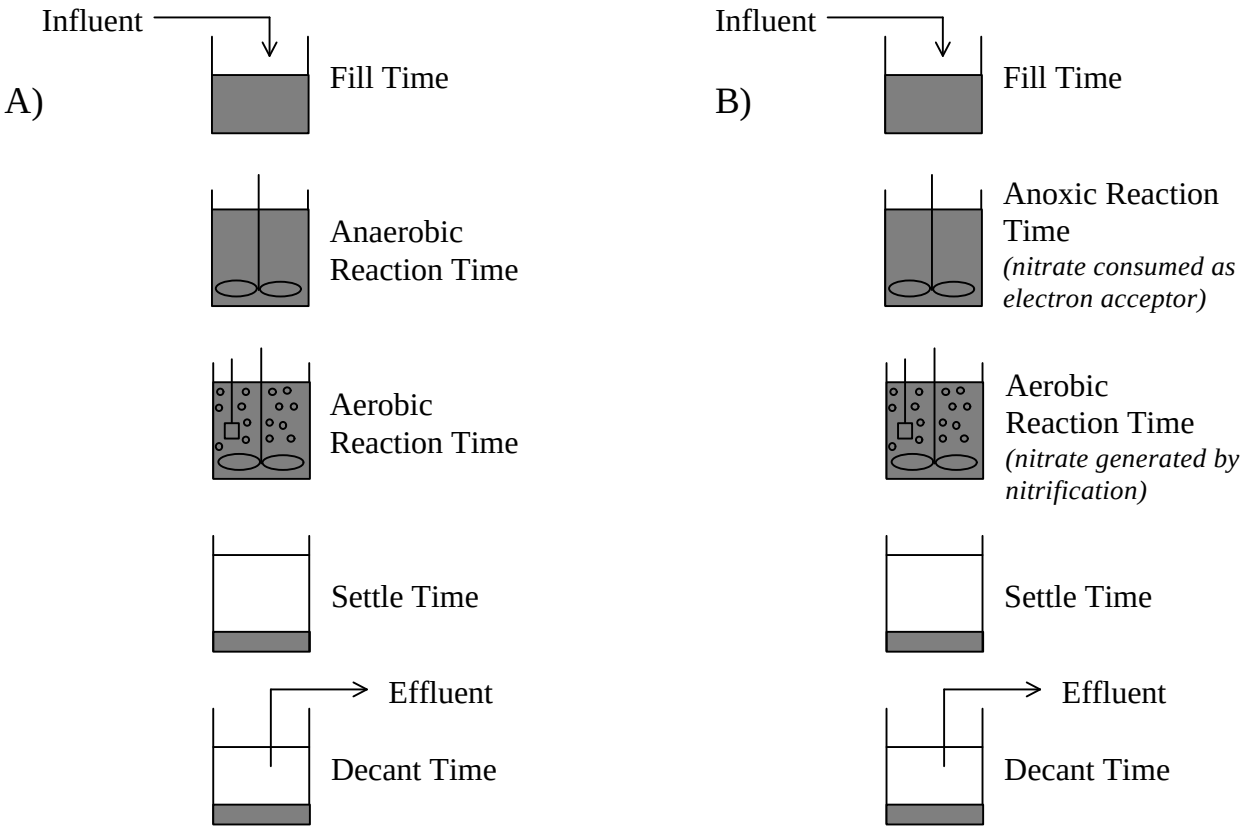

Figure 2-2: Operation of SBRs with sequential environments
A) Anaerobic/aerobic SBR B) Anoxic/aerobic SBR

SBRs than rates reported for conventional systems, supporting the concept that SBRs may be considered high rate systems relative to conventional designs.

An existing nightsoil treatment plant was modified from a conventional activated sludge system to a SBR to accomplish nutrient removal (Choi *et al*., 1997). The SBR was operated under anaerobic, aerobic and then anoxic environments. The researchers found that over a 10 month study both organic and nutrient removal efficiencies improved dramatically. Although capital expenditures for installing timers and modifying piping had to be made, organic and nutrient removal efficiencies improved without having to increase the tank volumes or the blower capacities. Oxygen requirements were reduced 40 - 53% providing additional O&M cost savings. The heat released by the degradation of the organic components caused an increase in temperature allowing for increased nitrification, especially in the winter months. The authors also predicted that additional cost savings would occur at the plant due to improved effluent quality.

Chin (1989) investigated the use of an aerobic SBR after anaerobic fixed film treatment of a edible oil refinery. The effluent from the anaerobic fixed film reactor was highly variable in organic quantity and quality mainly due to large variations in the refinery wastewater. Chin found that stable operation of the SBR could be achieved under variable organic loading rates and operating conditions. Biomass yields from the aerobic SBR were lower than other reported yield values. High COD removal efficiencies suggested that the low yield values were not due to nutrient limitations, but due to operation of the SBR with a long anoxic fill time and low dissolved oxygen concentrations in the aerobic reaction time. The researchers also looked at field operation of an SBR and found that removal efficiencies for COD were lower and more variable than the

laboratory SBR; however, the authors reported that oxygen transfer problems may have occurred due to a poorly designed aeration system and suggested that it may have led to poorer effluent quality in the field SBR.

Rim *et al*. (1997) operated a pilot scale SBR fed wastewater from a recreational facility. The recreational facility wastewater was extremely variable in quality and quantity. The researchers found that the effluent quality could be maintained by controlling the decant volumes and operating cycles of the SBRs. Removal efficiencies for BOD, suspended solids, total nitrogen and total phosphorous were equivalent to those reported in the literature for other nutrient removal systems. The researchers supported SBRs as a viable alternative to conventional treatment, especially for wastewaters with highly variable quality and quantity.

Environmental Conditions

Anaerobic Operation : There are a variety of degradation mechanisms in anaerobic zones, such as fermentation or methanogenesis. Fermentation is the conversion of organic compounds from one form to another with no significant loss in COD. In fermentation, organic compounds serve as the electron acceptor as well as the electron donor. Two groups of methanogens carry out methanogenesis: aceticlastic methanogens and hydrogen-utilizing methanogens. Aceticlastic methanogens split acetic acid, typically produced by fermentation reactions, into methane and carbon dioxide (Grady and Daigger, 1997). The hydrogen-utilizing methanogens reduce carbon dioxide to methane. It is generally accepted that 2/3 of the methane produced during anaerobic digestion operations come from the acetoclastic methanogens and the remaining 1/3 comes from the hydrogen-utilizing methanogens. Methanogens are very sensitive to temperature and pH changes in

the reactor. Care must be taken to avoid upsetting the balance of the anaerobic reactions. Another common anaerobic reaction that occurs in nature, sulfate reduction, is typically discouraged in wastewater treatment due to the hazardous and odorous nature of the reduced product, hydrogen sulfide (H_2S).

Anoxic Operation: Nitrate reduction can occur by two pathways: assimilatory reduction and dissimilatory reduction (Madigan *et al.*, 1997). Assimilatory reduction (see Figure 2-3) reduces nitrate to ammonia to be used in cell synthesis. Although assimilatory reduction can occur in the presence or absence of oxygen, it will occur only in the absence of ammonia. Dissimilative reduction consists of two possible routes for nitrate reduction (see Figure 2-4): nitrate reduction to nitrogen gas or nitrate reduction to ammonia. Dissimilative reduction of nitrate to ammonia will occur only in the absence of oxygen and is believed to be uncommon. Denitrification utilizes the dissimilative reduction of nitrate to nitrous oxide or nitrogen gas. In denitrification, nitrate (NO_3^-) serves as the electron acceptor for microbial degradation of the organic compounds. Although an anaerobic reaction, because it occurs in the absence of oxygen, nitrate reduction is referred to as an anoxic operation by the wastewater treatment industry.

Denitrification is most often utilized in conjunction with nitrification for biological nitrogen removal from domestic and industrial wastewaters. Nitrification involves the conversion of ammonia to nitrate by aerobic autotrophic nitrifying bacteria, and is then denitrified to nitrogen gas by heterotrophic bacteria, resulting in the removal of nitrogen from the wastewater. McClintock *et al*. (1988) ran experiments to determine the benefits of operating an anoxic environment versus an aerobic environment. The results showed that greater than 25% cost savings can occur due to operating under anoxic conditions as

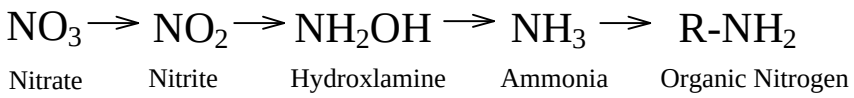

Figure 2-3: Assimilative Pathway for nitrate reduction

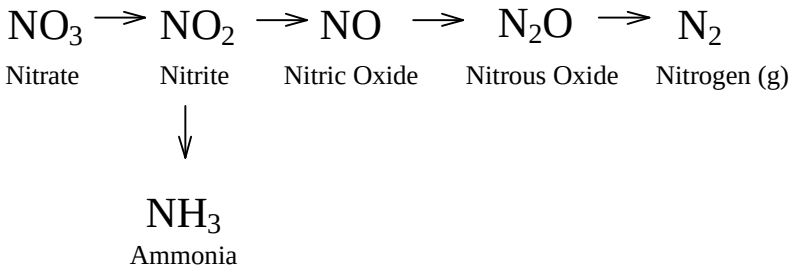

Figure 2-4: Dissimilative Pathways for nitrate reduction

opposed to aerobic conditions. McClintock *et al*. suggested the cost savings from reduced aeration and sludge handling and disposal would far exceed the cost requirements for nitrate chemicals and mixing requirements. Operation of an anoxic environment can be an economical advantage even when nitrogen removal is not the primary objective. If, however, ammonia is present the operation of a nitrification/denitrification sequence would provide nitrogen removal, as well as additional cost savings.

Aerobic Operation: In an aerobic environment, oxygen is utilized as the electron acceptor for carbon oxidation. Aerobic respiration provides the greatest amount of energy to the microorganisms. During aerobic degradation, organic compounds are oxidized to carbon dioxide and oxygen is reduced to water. Many xenobiotic compounds can readily be degraded in aerobic environments, including: phenol, acetonitrile, and diethanolamine, while many are not, including: 1,3-dichlorobenzene, 1,2,4-trichlorobenzene, and trichloroacetic acid (Zitomer and Speece, 1993).

Multiple Redox Treatment Strategies

Sequential treatment strategies have been utilized for nutrient (nitrogen and phosphorous) removal from both domestic and industrial wastewaters. Zitomer and Speece (1993) suggested that exposure of microorganisms to multiple redox environments to remove nutrients could also allow for more effective removal efficiencies for a wide range of organic chemicals. Anaerobic, anoxic and aerobic environments all have degradation limitations, but when combined could enhance degradation to include a wide variety of compounds in a single treatment system.

There are several benefits to the use of anaerobic treatment : decrease in electrical power requirements, production of methane which can be recovered and converted to

power, and lower sludge production by the anaerobic organisms (Zitomer and Speece, 1993). In this research, a single sludge system with alternating anaerobic/aerobic environments was studied to determine the effects on COD removal and settling properties. Several studies have looked at the performance enhancement of anaerobic treatment prior to aerobic treatment; however, the studies discussed below did not use single sludge systems.

Rintala and Vuoriranta (1988) compared the performance of a single sludge activated sludge system to a UASB reactor followed by aerobic treatment on a white water waste from a pulp and paper mill. They found the anaerobic removal of COD and BOD_7 to be 50-75% and 70-85%, respectively, and overall process removal was 80-85% of COD and over 90% of BOD_7. The performance of the anaerobic/aerobic system was comparable to a single stage activated sludge system based on COD and BOD_7 removals; however, the anaerobic/aerobic systems produced 67% less sludge than the conventional system. The reduction in sludge handling would provide great economical savings to a full scale plant. The authors also found that nutrient augmentation was not needed for the anaerobic/aerobic system, leading to additional cost savings.

Zaloum and Abbott (1997) compared three systems on their ability to treat a landfill leachate: 1) an existing system consisting of 3 lagoons in series: an anaerobic lagoon, aerobic stabilization pond, and mechanically aerated lagoon, 2) an aerobic SBR receiving raw leachate, and 3) an anaerobic lagoon followed by an aerobic SBR. The results indicated that the (#3) anaerobic/aerobic system was superior to the other systems because it required less reactor volume, eliminated the need for a clarifier and reduced the sludge handling requirements. The aerobic SBR following anaerobic pretreatment

maintained effluent suspended solids concentrations less than 80 mg/L while the aerobic SBR treating the raw leachate generated effluent suspended solids concentrations ranging from 150 - 350 mg/L. However, the aerobic SBR following anaerobic pretreatment produced effluent suspended solids concentrations greater than the permit limitation during upset or transitional periods.

Mehner *et al*. (1988) compared the ability of 3 different systems to treat a forest industry effluent: two-stage activated sludge treatment, anaerobic-aerobic treatment, and conventional treatment and their ability to treat a forest industry effluent. The authors found several advantages for all systems. The anaerobic-aerobic system allowed for higher volumetric loadings than the other systems. Additionally, the authors found that nutrient addition to the wastewater was not necessary for the anaerobic-aerobic system. The anaerobic-aerobic system produced sludge with enhanced settling properties. Finally, the system produced 67% less sludge than the conventional system which would provide a significant reduction in O&M costs. Zitomer and Speece (1993) reported on a study by Flammino *et al*. concerning a pulp and paper treatment plant that used an anaerobic mixing zone upstream of conventional treatment. The system provided the biosolids with enhanced flocculation characteristics compared to a system without anaerobic pretreatment. .

Several studies have shown that anaerobic pretreatment can produce an effluent more amenable to aerobic treatment as well as provide the removal efficiencies required by typical U.S. permit limitations. Zalhoum and Abbott (1997) reported the BOD_7/COD ratio of a leachate increased from 0.4 to 0.5 after anaerobic lagoon treatment, resulting in a greater fraction of the wastewater that could be degraded aerobically. Zaoyan *et al*.

(1992) investigated the use of an anaerobic rotating biological contactor (RBC) followed by an aerobic RBC on the treatment of a textile dye wastewater. The authors found that the anaerobic zone was able to breakdown recalcitrant compounds into more easily degradable compounds prior to aerobic treatment. Rintala and Lepistö (1993) compared performance of 3 systems: anaerobic, anaerobic-aerobic and aerobic thermophilic activated sludge processes in removing COD and AOX (a generic term for organic compounds containing a halogen) from a Kraft bleaching effluent. The results showed that the anaerobic-aerobic process produced slightly lower effluent COD and AOX concentrations. However, the aerobic treatment provided some COD removal during regular operation and removed the remaining BOD, resulting in greater that 95% removal of BOD. In addition to BOD removal, the aerobic zone provided the necessary removal during short increases in COD loadings to the system.

Bode (1988) compared anaerobic-aerobic treatment with aerobic treatment on several industrial wastewaters: pectin wastewater, sugar wastewater, and animal wastewater. Aerobic treatment produced slightly better effluent quality for the pectin and sugar wastewaters. The authors suggested that performance differences were only minor and could be neglected when comparing the two systems. The decrease in energy requirements and large reduction in sludge production, provided by the anaerobic treatment, would provide great economical advantages to a wastewater treatment plant. The authors suggested that the anaerobic-aerobic process would provide the most economical treatment for the pectin and sugar wastewaters because of these savings listed. The animal wastewater results indicated that anaerobic-aerobic system would not provide adequate or economical treatment. The hydrolysis of proteinaceous COD uptake in the

anaerobic zone left behind more ammonium than aerobic degradation. The excess ammonium could cause severe operational problems. The results from the study stressed the importance of treatability studies before design of a wastewater treatment facility.

In summary, anaerobic/aerobic treatment can provide several economical and operational advantages. The decrease in sludge production can significantly reduce O&M costs. The enhanced performance of such systems in BOD and COD removal and improved settling characteristics are both beneficial to operation. There are also cost saving advantages in reduced aeration costs and potential decrease in nutrient addition.

As mentioned previously, anoxic (denitrification) and aerobic treatment are often combined for biological nitrogen removal in single sludge processes. The use of anoxic/aerobic environments can also provide benefits in COD removal, settling and system stability. Huang and Drew (1985) looked at the treatability of a wastewater, from a diet drink manufacturer supplemented with ammonium and carbonate buffer compounds, by a sequencing anoxic/aerobic oxidation ditch. The study found that the anoxic/aerobic system provided stable treatment even with highly variable influent loadings. Bell and Hardcastle (1984) looked at a continuously fed, intermittently operated activated sludge system, operated with alternating anoxic and aerobic environments, that received wastewater from a munitions plant. The influent was fed continuously to the reactor and the reactor was periodically allowed to settle after which effluent was removed. The researchers concluded they had an extremely stable system that was also very tolerant of operational problems. They also found that, with the exception of two runs where high food/microorganism ratios caused deflocculation, the settling characteristics of the system were excellent.

In addition to system stability , enhanced COD removal has been seen with sequential anoxic/aerobic systems. Cheng *et* al. (1996) compared the treatment of a resin wastewater stream between a conventional activated sludge process with extended aeration to a single sludge system with an anoxic denitrification unit followed by aerobic treatment. As expected, the anoxic/aerobic system was far superior in removing organic nitrogen, 69%, compared to 39% for the conventional system. The anoxic/aerobic system also promoted better removal efficiencies for COD, TKN and TN.

An interesting study by Oleszkiewicz (1991), looked at removal of orthochlorophenol (OCP) in the presence of phenol, casein, and dextrose. Oleszkiewicz *et al.* compared anoxic/aerobic treatment conditions to results from strictly aerobic conditions. Removal of OCP did not occur in the anoxic zone of the anoxic/aerobic reactor; however, removal of OCP in the aerobic zone occurred at a significantly higher rate than in the solely aerobic reactor . Phenol removal in the aerobic zone in the anoxic/aerobic reactor was approximately 3 times greater than removal in the solely aerobic reactor.

Zitomer and Speece (1993) suggest multiple redox environments as an alternative for detoxifying wastewaters. Beccari *et al*. (1984) used an anoxic zone to prevent the inhibition of nitrification due to high concentrations of ammonium nitrogen and phenols. Denitrification reactions used phenol as the electron donor. The removal of phenol from the wastewater prevented nitrification inhibition. They found that they were able to accomplish high removal efficiencies of both the phenol (95%) through denitrification and ammonium (98%) by nitrification. Lubkowitz (1996) investigated methyl ethyl ketoxime (MEKO) inhibition of nitrification by operating a SBR under several environmental

treatment strategies. MEKO concentrations of 2 mg/L significantly reduce nitrification in an activated sludge system. Aerobic degradation of MEKO is quite slow; therefore alternative environments were investigated for MEKO degradation. She found that an anoxic/anaerobic/aerobic SBR could effectively reduce the MEKO concentration and allow for nitrification during the aerobic phase. MEKO degradation occurred under nitrate-limiting conditions.

Granular Activated Carbon

Granular activated carbon (GAC) can be made from several different materials including the following: almond, coconut, walnut hulls, wood, peat, lignite, subbituminous coal and bituminous coal (Ponitus, 1990; Metcalf and Eddy, 1991). According to Eckenfelder, bituminous coal will typically produced GAC with small pore sizes, large surface area, and the highest bulking density while lignite coal will produce GAC with large pore size, the least surface area and the lowest bulking density (Eckenfelder, 1989).

Many factors affect the adsorptive capabilities of GAC including: carbon preparation, particle size, starting material for GAC, surface area, pore size distribution and surface chemistry (Peel and Benedek, 1980; Ponitus, 1990; Yonge et al., 1985). For crushed GAC the typical United States sizes are 12 X 40 and 8 X 30 which represent sizes of 1.68 to 0.42 mm and 2.38 to 0.59 mm, respectively (Ponitus, 1991). In addition to the GAC properties, solute properties can also influence the adsorptive capabilities of GAC. Some properties of solutes that can increase or decrease adsorption are: size of the molecules, charge of the molecules, solubility, and the presence of hydrophilic or hydrophobic groups (Ponitus, 1990). Additional studies have shown that the presence of molecular oxygen can increase the adsorptive capacity of GAC on such compounds as o-

cresol and p-chlorophenol (Vidic and Suidan, 1992; Sorial *et al*., 1993). Mass transport mechanisms will affect the rate of adsorption. These mechanisms include: 1) the movement of the solute from solution to the boundary later surrounding the GAC, 2) diffusion of the solute from solution through the boundary later, 3) diffusion of the solute into the capillaries of pores of the GAC and 4) adsorption of the solute on the activated sites (Reynolds and Richards, 1996). The diffusion of solutes into the capillaries of the GAC and the adsorption of the solute onto the activated sites most significantly impact the kinetics of GAC adsorption.

The adsorptive capacity of GAC refers to the ability of the carbon to remove the desired constituents (color, COD, TOC, phenol, etc.). Several equations exist for predicting the adsorptive ability of GAC; however, the Freundlich and Langmuir isotherms are most commonly used. The isotherms are used to predict the constant temperature equilibrium relationship between the mass of sorbate sorbed per unit sorbent, q_e, and the equilibrium concentration, C_e (Ponitus, 1990).

Equation 1 shows the empirically derived Freundlich isotherm (Richards and Reynolds, 1996). Several important considerations should be noted when applying the Freundlich isotherm. The Freundlich isotherm is empirically fit and may be better for heterogeneous surfaces, such as GAC. Care should be taken when extending the experimentally determined parameters outside the concentration range tested. K and n can be determined by plotting the q_e versus C_e data on a log-log plot. The result should be a line with K as the intercept and 1/n as the slope.

$$x / m = q_e = Kc_e^{1/n} \qquad (1)$$

x = mass of solute adsorbed (mass)

m = mass of adsorbent (mass)

q_e = mass ratio of the solid phase

C_e = equilibrium concentrations of solute (mass/volume)

K, n = experimental constants

The Langmuir isotherm is theoretically based upon several assumptions: homogeneous surface, monolayer formation on surface (no interaction between solute molecules), fixed number of sites with homogeneous energy, adsorption is reversible and assumes a maximum capacity, q_{max} (Ponitus, 1990; Metcalf and Eddy, 1991). The Langmuir equation is shown by equation 2.

$$q_e = (q_{max} b C_e)/(1 + bC_e) \qquad (2)$$

q_e = mass ratio of the solid phase (same as above)

q_{max} = maximum value of q_e that can be achieved with increasing C_e

C_e = equilibrium concentration (mass/volume)

b = constant relating to energy of adsorption

Values for q_{max} and b can be determined by plotting $1/q_e$ versus $1/C_e$. The resulting line will have an intercept of 1/b and a slope of $1/(q_{max} b)$.

Activated carbon has many application in the wastewater treatment industry including: powdered activated carbon (PAC) addition to activated sludge reactors, biological activated carbon filters for both removal of inhibitory compounds and treatment of wastewater, and adsorption of pollutants from biological treatment effluents.

Schultz and Keinath (1984) investigated the benefits of PAC addition to activated sludge treatment of synthetic wastewater containing phenol as the organic source. They used radiolabeled phenol as a substrate for acclimated PACT biomass (powdered activated carbon addition to activated sludge) and biomass cultures. The results indicated that the

addition of PAC did not enhance the degradation of phenol, measured by ^{14}C radiolabeled carbon dioxide captured during the reaction phase. Çeçen (1994) studied the performance of an activated sludge system with PAC addition receiving a Kraft pulp bleaching effluent. The pulp bleaching effluent contained large quantities of nonbiodegradable compounds which contributed to high color units. Çeçen (1994) found no improvement in substrate degradation with the addition of PAC, supporting results found by Schultz and Keinath (1984); however, PAC addition lead to enhanced color removal efficiencies. The results indicated that PAC addition would be a viable treatment for wastewaters where color removal is desired.

Lee *et al.* (1989) compared the treatment performance of a conventional activated sludge system with an activated sludge system supplemented with PAC on a Cr(VI)-containing wastewater. The results showed a much greater adsorption of Cr(VI) to activated carbon than to the activated sludge. They found that the adsorption data for the Cr(VI) on to activated carbon was best modeled by the Freundlich isotherm. Both systems were able to maintain high COD removal efficiencies; however, the PAC system produced greater removal efficiencies. Cr(VI) removal efficiencies were significantly greater for the PAC system than the conventional system with efficiencies of 41% and 9%, respectively. Additionally, they studied the recovery time required for activated sludge stressed by Cr(VI), measured by oxygen uptake rates. The PAC system was able to recover from increased Cr(VI) loading in 1 day while the conventional system required 7 days to recover.

GAC can also be used to removal inhibitory compounds from wastewaters prior to conventional activated sludge treatment. Suidan *et al.* (1983) compared the performance

of two anaerobic filters: one using packed saddles and the other utilizing GAC prior to a nitrification aeration reactor. The filters received a coal gasification waste stream which included cresol and phenol based compounds. The anaerobic filter with the packed saddles showed little COD or dissolved organic carbon (DOC) removal and was eventually removed from the treatment scheme. The completely mixed, expanded bed anaerobic GAC filter was able to adsorb the compounds from the waste stream and significantly reduce the COD; however, there was a steady increase in effluent strength from the filter. The increasing strength suggested that GAC replacement would be necessary for continued reduction of toxicity and adsorption of the compounds. The activated sludge unit was able to polish the wastewater and achieve nitrification.

Another study, involving a synthetic goal gasification wastewater, utilized anaerobic filters for removal of cresol and phenol compounds (Fox *et al.*, 1988). Only 70.5% of the wastewater constituents were biologically degradable. Analysis of methane generation showed that nearly complete wastewater degradation, measured by methane production, occurred during operation of the anaerobic filter. The results indicated that the GAC sorbed the inhibitory compounds allowing for biodegradation of the more readily degradable compounds. The data indicate that 90% of the COD sorbed to the GAC was from nonbiodegradable substances. Continuous replacement of GAC would be necessary to prevent breakthrough of the nonbiodegradable compounds.

Cooper *et al*. (1992) evaluated several treatment systems for a complex chemical wastewater. Three treatment schemes were compared: 1) biological treatment followed by sand filtration and GAC treatment to be discharged to a POTW, 2) sand filtration and GAC to be discharged to a POTW and 3) biological treatment followed by sand filtration

and GAC treatment for discharge directly into a river. Biological treatment alone was unable to meet the organic removal requirements for either discharge site. However, biological treatment combined with sand filtration and GAC treatment was able to meet the organic removal efficiencies required by both discharge sites. The biological treatment and followed by sand filtration and GAC treatment was able to meet metal removal requirements for the POTW but not for discharging to the river. The GAC treatment was able to meet both the organic removal and metal requirements for the POTW. Once the POTW was chosen as the discharge site, sand filtration and GAC treatment were determined to be the most cost effective methods for treating the chemical wastewater.

Microtox Toxicity

Several methods have been developed for testing the toxicity of water samples. These methods include various fish, protozoa, algae and other organisms. Qureshi *et al.* (1984) listed several reasons for using bacteria for toxicity testing: 1) bacteria have many of the same biochemical processes as other organisms, 2) bacteria have organization in the membrane structure, 3) bacteria have similar responses to toxic effects as higher organisms and 4) bacteria are the lowest organisms in both freshwater and marine systems. Microtox toxicity tests require the rehydration of the freeze-dried photoluminescing bacteria, *Vibrio fischeri,* (formerly known as *Photobacterium phosphoreum*). Toxicity effects are determined by monitoring the light produced by the bacteria. Decreased light generation indicated toxicity in a quantitative manner,

Several studies have been conducted to compare the Microtox toxicity results to other toxicity tests. Chang *et al.* (1981) compared the performance of the Microtox test with rat and fish toxicity values. The results showed high correlation between the rat and

fish toxicity for selected compounds (ethanol, 1-butanol, benzene, toluene, phenol, m-cresol and formaldehyde) as well as some respiratory inhibitors. However, the results showed little correlation between LD_{50} for rat toxicity and the EC_{50} from the Microtox for selected pesticides. They pointed out the comfort of using 10^5 bacteria to determine toxicity as opposed to a few small organisms.

Sanchez *et al*. (1988) conducted toxicity measurements of industrial effluents using the Microtox, *Spirillum volutans* and the conventional bioassay *Daphnia similis*. The authors reported that good agreement was found between all three indicators; however, better agreement existed between the *D. similis* and the Microtox than with the *S. volutans*. *S. volutans* tended to be more sensitive than the other two organisms. The authors concluded that the Microtox and *S. volutans* microbial bioassays could be used to monitor toxic effects to receiving streams by industrial effluents.

Kahru *et al.* (1996) compared the toxicity of a phenolic wastewater as well as the individual components of the wastewater using the Biotox and Microtox systems. Biotox is a bioassay test used for short-term toxicity testing, also based on *V. fischeri*. They found a log-log correlation of 0.87 for the 14 phenolic compounds tested. However, the Microtox system was found to be 7.5 times more sensitive than the Biotox system. Results from the toxicity of the wastewater suggested that analysis of individuals compound could not be used to determine the toxicity of a complex mixture.

Several factors need to be considered when choosing a toxicity test: 1) cost, 2) reproducibility, 3) speed and 4) biological representation (Bulich, 1982). Conventional acute and chronic toxicity tests are very labor intensive and can require 24 hours to several days to complete. Microtox results can be obtained in as short as 30 - 40 minutes.

Although purchase of the equipment, photoluminescent organism, and reagents are expensive, time reduction and reduced labor hours may justify the costs.

Several uses for Microtox have been suggested by researchers. Dutka and Kwan (1981) suggested using Microtox for monitoring the performance of a consistent wastewater effluent. The authors suggested that the real-time results from the Microtox could target problems which could be corrected before discharging a toxic effluent. Microtox could also be used to monitor leachate and alert officials when toxic compounds begin leaching from landfills (Bulich, 1982). Bulich (1982) suggested that Microtox is a "cost effective, reproducible and fast" test that could be used as a primary test to determine which samples are significantly toxic. Variability exists for all toxicity values; therefore, care should be taken when evaluating which bioassay to use.

CHAPTER III. MATERIALS AND METHODS

The purpose of the research was to investigate the effectiveness of three multiple redox treatment strategies: anaerobic/aerobic, anoxic/aerobic and aerobic on the treatability of a synthetic high strength industrial wastewater and an actual industrial wastewater. This section describes the methods used to obtain the goal. The first section describes the experimental approach used in conducting the research. The second section describes operation of three main SBRs fed synthetic wastewater; three industry SBRs fed industrial wastewater, a gravity sand filter and GAC adsorption studies. Additionally, sampling and analysis procedures are described for the different experiments.

Experimental Approach

Specific objectives, described in the introductory chapter, were achieved by operating SBRs and performing GAC isotherm studies. SBRs were designed to operate with two multiple redox environments: anaerobic/aerobic and anoxic/aerobic, and a solely aerobic SBR, which served as a single redox environment control. The SBRs received a synthetic industrial wastewater that was modeled after an industrial wastewater generated at a chemical processing plant in the United States. To allow the biomass to acclimate to the synthetic wastewater, the wastewater strength was increased over time to a maximum of 9,000 mg/L as COD. In addition, the SBR total cycle time was gradually increased to enhance the degradation of the wastewater.

Industry SBRs were designed to operate under similar conditions as the main SBRs. However, the industry SBRs were fed the actual industrial wastewater supplemented with nutrients required by the biomass. Performance differences were evaluated to determine the effect of the substitutions made in the synthetic wastewater.

The final objective was to determine isotherm parameters of the adsorption of the COD remaining after anaerobic/aerobic biological treatment. To emulate the actual plant operations, a gravity sand filter was designed to filter the ANA effluent prior to use in the isotherm experiments. Batch GAC experiments were performed to determine the isotherm parameters.

Materials

Initial Biomass Inocula

The main SBRs were seeded in April, 1996 with sludge obtained from the activated sludge basins at Eastman Chemical Company, Kinsgport, Tennessee. The industrial sludge contained a diverse culture of microorganisms previously exposed to xenobiotic compounds. Due to filamentous bulking problems in May of 1996, the SBRs were reseeded with new sludge from the Eastman activated sludge basin.

Organic Compounds for the Synthetic Wastewater

The synthetic wastewater used during this research was modeled after the wastewater shown in Table 2-1. Several substitutions were made for compounds that were unavailable or unknown at the start of the research. Hydroxypivaldehyde (HOHPv), the largest component based on COD, was unavailable for purchase from the chemical suppliers. Pivaldehyde was first considered as the substitution for HOHPv; however, the cost of pivaldehyde was prohibitive and another alternative was chosen. Pivalic acid (trimethylacetic acid) was chosen as the substitution for HOHPv because it was assumed to be a degradation intermediate. In order to minimize odor problems within the laboratory, additional neopentylglycol (NPG) was added to the wastewater in place of

neopentylglycol-monoisobutyrate (NPG-MI). Organic salts constitute a large fraction of the total wastewater COD. The exact composition of the organic salts was unknown at the beginning of the research. After discussions with the Industry's representative, potassium acetate was selected to make up the total COD contributed by the organic salts to the wastewater. The compounds in the synthetic wastewater are listed in Table 3-1.

All compounds listed in Table 3-1, except 2-ethylhexanol, were added to tap water to make the wastewater. Figure A-1 in Appendix A shows the structures for the organic compounds listed in Table 3-1. 2-Ethylhexanol (2EH) would not dissolve into the tap water at the concentration required in the stock solution; therefore, 2EH was added directly to the SBRs. The Industry's wastewater maintains a pH between 8 - 8.5, therefore, 23 mL 1 N sodium hydroxide was added to each liter of organic feed. To make wastewater, the organic feed was diluted 1:3.5 with the mineral salt medium (MSM). After dilution, the pH of the wastewater was between 8 - 8.5.

Table 3-1 - Organic Compounds in the Synthetic Industrial Wastewater

Organic Compound	Final Wastewater Concentration (mg/L) at COD = 5,500 mg/L	Final Wastewater Concentration (mg/L) at COD = 9000 mg/L
Methanol	206	387
Acetal	12.6	23.6
Neopentylglycol (NPG)	189	354
2,2,4-Trimethylpentandiol (TMPD)	55	103
2-Ethylhexanol (2EH)	51.4	84.4
2-Ethylhexandiol (EHD)	103	193
Potassium Acetate	3160	5925
Trimethylacetic Acid (Pivalic Acid)	1126	2109

Mineral Salt Medium and Nitrate Stock

Mineral salt medium (MSM) modified from Porter (1993) was used to supply the microorganisms with essential macro and micro nutrients. In addition to the nutrients, several vitamins were added to the wastewater. The mineral salt concentrations and the vitamin concentrations can be found in Tables 3-2 and 3-4, respectively. Concentrated stock solutions were made of chloride, sulfate, phosphate, ammonium and calcium chloride. The stocks were made from minerals and vitamins purchased from Fisher Scientific. All compounds were reagent grade or higher.

The chloride stock was acidified with concentrated hydrochloric acid to minimize precipitation in the stock solution. In addition, a separate stock was made of calcium chloride to minimize precipitate formation in the chloride stock. A carbonate buffer was added to the MSM to maintain reactor pH values between 8 - 8.5. At a wastewater COD of 5,500 mg/L, 5 mL of each mineral stock and 2.5 mL of the vitamin stock were added to 1 liter of tap water to make the MSM. When the COD was increased to 9000 mg/L, the stock volumes were increase to 8 mL of each mineral stock and 4.5 mL of the vitamin stock. 1.25 L of MSM was diluted with 0.5 L of organic feed to make the wastewater.

The MSM for ANA and AER SBRs was made using all stocks; however, the MSM for the ANX SBR did not receive the ammonium chloride stock. The ammonium source for the ANX SBR was the nitrate stock, which was added to maintain anoxic conditions. The nitrate stock (see Table 3-2) was made of ammonium and potassium nitrate and was pumped directly into the ANX reactor.

On February 6, 1997, a nutrient deficiency was discovered in the MSM which was responsible for incomplete treatment in the ANA and AER SBRs, and may have influenced treatment performance to some degree in the ANX system. Calculations were

Table 3-2: Composition of mineral salt stocks and modified mineral salt medium after increase in nutrient loading (after 2/6/97)

Compounds	Stock Concentration g/L	Concentration in Wastewater at COD = 5500 mg/L mg/L	Concentration in Wastewater at COD = 9000 mg/L mg/L
Chlorides[a]			
$FeCl_3$	4.50	16.7	25.7
$CoCl_2 \cdot 2H_2O$	0.30	1.1	1.7
$ZnCl_2$	0.35	1.3	2.0
$CuCl_2 \cdot 2H_2O$	0.10	0.36	0.57
H_3BO_3	0.03	0.11	0.17
$MgCl_2 \cdot 6H_2O$	25.90	92.5	148.0
Calcium Chloride[b]			
$CaCl_2$	21.30	76.1	121.7
Sulfate			
$MnSO_4$	16.73	59.8	95.6
$MnSO_4 \cdot H_2O$	0.90	3.2	5.14
$NaMoO_4 \cdot 2H_2O$	0.10	0.36	0.57
Phosphate			
KH_2PO_4	136.07	486.0	777.5
Carbonate Buffer			
$NaHCO_3$	26.38	94.2	150.7
$NaCO_3$	11.20	40.0	64.0
Ammonium Chloride[c]			
NH_4Cl	285.0	266.4 as N added to ANA & AER only	426.0 as N added to ANA & AER only
Nitrate Stock (ANX only)			
NH_4NO_3	40.79	326 as NH_4-N 326 as NO_3-N	612 as NH_4-N 612 as NO_3-N
KNO_3	96.78	613 as NO_3-N	1149 as NO_3-N

a = Chloride stock acidified with 6 mL concentrated hydrochloric acid
b = Calcium Chloride kept separate to prevent precipitation in chloride stock
c = ANX MSM didn't get ammonium chloride; ammonium came from nitrate stock

Table 3-3: Composition of mineral salt stocks and modified mineral salt medium before increase in nutrient loading (before 2/6/97)

Compounds	Stock Concentration g/L	Concentration in Wastewater at COD = 5500 mg/L mg/L
Chlorides[a]		
$FeCl_3$	3	10.7
$CoCl_2 \cdot 2H_2O$	0.30	1.1
$ZnCl_2$[d]	0.35	1.1
$CuCl_2 \cdot 2H_2O$	0.10	0.36
H_3BO_3	0.03	0.11
$MgCl_2 \cdot 6H_2O$[d]	25.90	92.5
Calcium Chloride[b]		
$CaCl_2$[d]	5.3	76.1
Sulfate		
$MnSO_4 \cdot H_2O$[d]	0.90	3.2
$NaMoO_4 \cdot 2H_2O$	0.10	0.36
Phosphate		
KH_2PO_4	136.07	486.0
Carbonate Buffer		
$NaHCO_3$	26.38	94.2
$NaCO_3$	11.20	40.0
Ammonium Chloride[c]		
NH_4Cl[d]	40.5	145 as N added to ANA & AER only
Nitrate Stock (ANX only)		
NH_4NO_3[d]	18.69	150 as NH_4-N 150 as NO_3-N
KNO_3	117.28	742 as NO_3-N

a = Chloride stock acidified with 6 mL concentrated hydrochloric acid
b = Calcium Chloride kept separate to prevent precipitation in chloride stock
c = ANX MSM didn't get ammonium chloride; ammonium came from nitrate stock
d = nutrient limiting for COD of 5,500 mg/L

made to determine which nutrients were limiting in the reactor. Nutrient requirements were calculated based on reported data presented in Table A-1 in Appendix A. Several nutrients were found to be limiting: calcium, zinc, magnesium, sulfur and most importantly a severe ammonium limitation existed in the SBRs. The nutrient concentrations before and after the increase can be found in Tables 3-3 and 3-2, respectively.

Table 3-4: Vitamin Stock Concentrations used in Mineral Salt Medium

Vitamin	Stock Concentration mg/L	Concentration in Wastewater at COD = 5500 mg/L µ/L	Concentration in Wastewater at COD = 9000 mg/L µ/L
Biotin	6	10.7	19.3
Riboflavin	15	26.8	48.2
Nicotinic Acid	15	26.8	48.2
B12	0.4	0.71	1.29
Thioctic Acid	15	26.8	48.2
Folic Acid	6	10.7	19.3
Thiamin	15	26.8	48.2
p-Aminobenzoic Acid	15	26.8	48.2
Pantothenic	15	26.8	48.2

Granular Activated Carbon

Several types of granular activated carbon (GAC) were tested in the isot herm studies. The manufacturing method and general description for each GAC is listed in Table 3-5. Prior to use in the isotherm studies, each GAC was rinsed several times with distilled water and placed in a drying oven at 105°C for 24 hours. After drying, a mortar and pestle were used to pulverize each GAC. Once the GAC was pulverized, it was stored in a dessicator until used in the isotherm studies. The Calgon carbon received was pulverized by the manufacturer.

Table 3-5: Description of the GAC used in isotherm studies
(Source: manufacturer's literature)

GAC	Manufacturing Method	Description
Unisorb AGL 12 X 40	steam activation of bituminous coal under strictly controlled conditions	highly developed pore structure and high resistance to attrition
Unisorb AC 10 X 30	steam activation of coconut shells under strictly controlled conditions	highly developed pore structure, excellent resistance to attrition and low resistance to flow
Norit GAC 830	steam activation of select grades of coal	superior adsorption properties
Hydrodarco 3000	high temperature steam activation of lignite coal	wide pore size distribution and large pore volume
Calgon Activated Carbon - WPH Pulv.	high temperature steam activation of bituminous coal and then pulverized to a powder form	virgin, powdered activated carbon designed for treating potable water

Methods

Operation of MainSBRs

Three SBRs: anaerobic/aerobic (ANA), anoxic/aerobic (ANX) and aerobic (AER) were operated throughout this research. All three were operated according to the following cycle: feed, react, settle, and decant. Throughout the research, there were several changes in reactor operation that are summarized in Table 3-6. Although data were collected over the entire research period, the data presented in the results and discussion chapter come from the time period after the increase in nutrient loading

(2/6/97). Operational parameters and conditions shown in this chapter are for the time period following the increase in nutrient loading. The operational parameters and conditions for the time prior to the nutrient increase are listed in Tables A-2 through A-5 in Appendix A.

The SBRs were operated in 4 L Pyrex ® beakers (10 in. x 6 1/4 in. diameter) that were modified to have a sample/wastage port. The sample port was a piece of bent glass

Table 3-6: SBR operation changes for ANA, ANX, and AER SBRs

Date	Major Change
4/8/96	Start up: 12 hr cycle time; feed COD = 2000 mg/L
5/29/96	Filamentous bulking problems reseed w/ Eastman sludge; 18 hr cycle time; feed COD = 2000 mg/L
7/15/96	Wastewater COD increased to 4000 mg/L
11/8/96	Increased cycle time to 24 hr
11/24/96	Increased cycle time to 48 hr
2/6/97	Increased nutrient loading to reactors
3/26/97	Wastewater COD increased to 9000 mg/L

tubing (5 1/2 in. x 3/4 in. diameter) with one end in the mixed liquor and the other end through the side of the beaker. Plastic tubing was then attached to the outside of the sample port. Samples and wastage were taken by creating a siphon on the sample port. The SBRs were covered with a square piece of plexi-glass (8 in. x 8 in. x 3/8 in) to

minimize evaporation and potential odor problems. Diagrams for the ANA, ANX and AER SBRs are shown in Figures 3-1 through 3-3.

The operation of the SBRs was controlled by ChonTrol® XT-4 timers (San Diego, California) using several single step programs. The operational parameters for the SBRs are shown in Table 3-7. Descriptions of the cycles for the ANA, ANX, and AER SBRs are shown in Tables 3-8, 3-9 and 3-10, respectively. At the end of each cycle, 1.75L of supernatant was removed from the reactor and replaced with the wastewater. Organic feed (500 mL) was pumped into the reactor at a rate of 33 mL/min for 15 minutes. The organic feed was diluted by a ratio of 1:7 as it entered the 3.5 L SBRs. The organic feed was typically remade every 4 - 6 cycles. The MSM was made in 9.5 L Pyrex® jars: one for the ANA and AER SBRs and a separate jar for the ANX SBR. Due to the high concentration of salts and the tendency for precipitate formation, the MSM was kept stirring with a stir bar and magnetic stir plate. In addition to the organic feed, 1.25 L of MSM was pumped into the reactors at a rate of 83 mL/min. for 15 minutes.

At the start of a cycle, nitrogen gas, controlled by a solenoid valve, was used to purge ANA and ANX for 20 minutes to remove any residual oxygen from the mixed liquor. Mixing was accomplished by 100 rpm motors, mounted above the reactors, that were attached to stainless steel paddles (3 in x 1 in). The bottom of the paddles were 3 inches above the bottom of the SBR. To maintain an anoxic environment in the ANX SBR, nitrate stock was added at 6.67 mL/min for 12 and 22.5 minutes when the feed COD was 5,500 mg/L and 9,000 mg/L, respectively.

In order to control filamentous bulking problems, chlorine was added to the SBRs in the form of bleach. ANA and AER received a chlorine dose of 3 g HOCl/kg of MLSS-

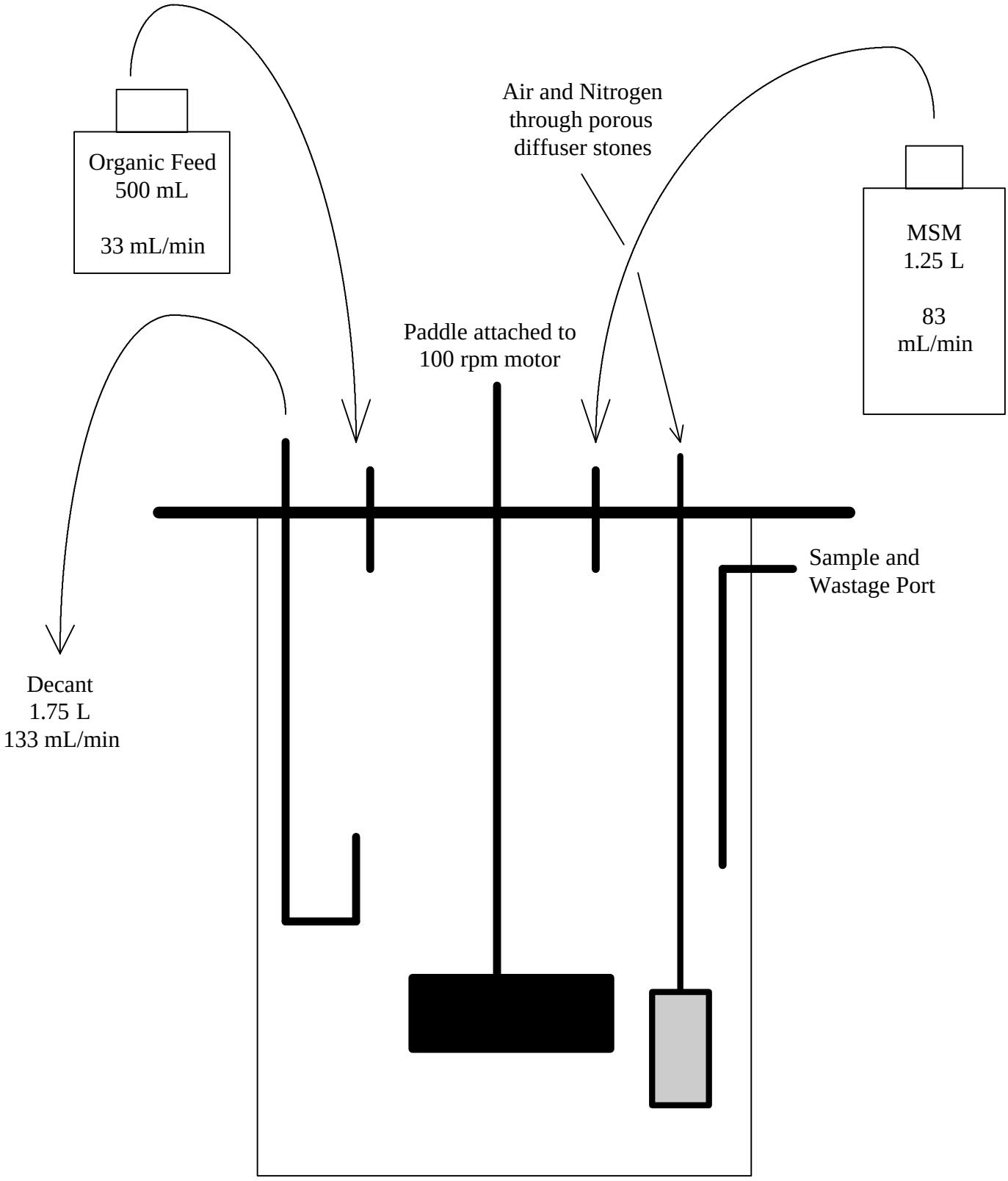

Figure 3-1: ANA Sequencing Batch Reactor

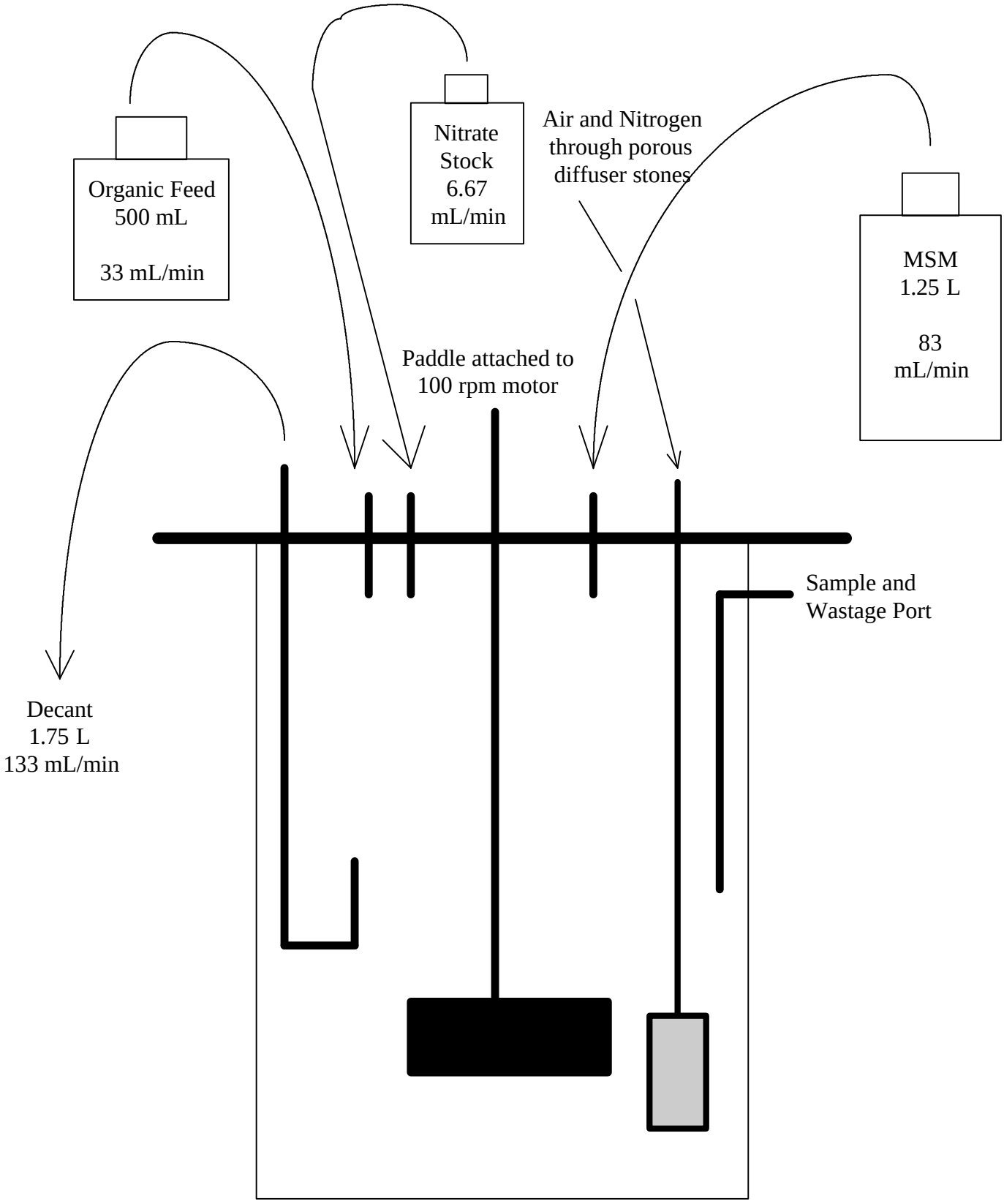

Figure 3-2: ANX Sequencing Batch Reactor

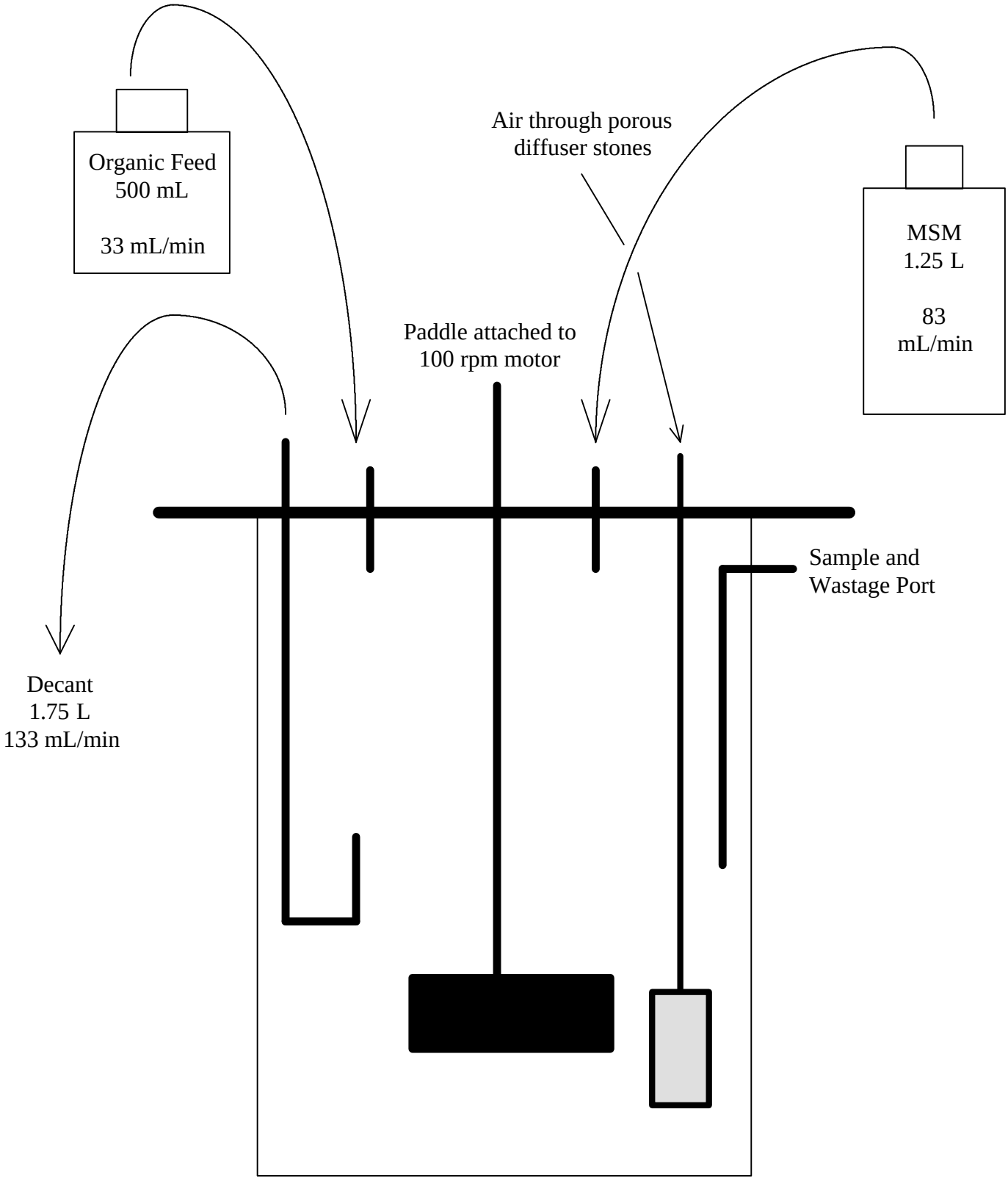

Figure 3-3: AER Sequencing Batch Reactor

Table 3-7: Operational parameters for ANA, ANX and AER SBRs

1 cycle/ 2 day: 46 hr. reaction time 1 1/2 hr. settle time 0.25 hr. decant 0.25 hr. feed
Reactor Volume: 3.5 L Influent COD: 5,500 mg/L (3/26/97 increased to 9,000 mg/L) Solids Residence Time: 15 days Effective Hydraulic Residence Time: 96 hr. At time = 0 pH between 8 - 8.5 Temperature 29 - 32 °C using Digital Circulating Water Bath

Table 3-8: Description of ANA SBR cycle

Operation	Time (hr:min)
Decant Off	0:00
Motors On	0:00
Nitrogen Purge On	0:00
MSM On	0:00
Organics Feed On	0:00
MSM Off	0:15
Organic Feed Off	0:15
Nitrogen Purge Off	0:20
Air On	8:15
Motors Off	46:15
Air Off	46:15
Decant On	47:45

Table 3-9: Description of ANX SBR cycle

Operation	Time (hr:min)
Decant Off	0:00
Motors On	0:00
Nitrogen Purge On	0:00
MSM On	0:00
Organic Feed On	0:00
Nitrate On[a]	0:03 (0:00)
MSM Off	0:15
Organic Feed Off	0:15
Nitrate Off[a]	0:15 (0:22.5)
Nitrogen Purge Off	0:20
Air On	8:15
Motors Off	46:15
Air Off	46:15
Decant On	47:45

a = ( ) time required for wastewater COD = 9,000 mg/L

Table 3-10: Description of AER SBR cycle

Operation	Time (hr:min)
Decant Off	0:00
Motors On	0:00
MSM On	0:00
Organic Feed On	0:00
Air On	0:00
MSM Off	0:15
Organic Feed Off	0:15
Motors Off	46:15
Air Off	46:15
Decant On	47:45

cycle and ANX received a chlorine dose of 1.5 g HOCl/kg of MLSS-cycle. Chlorine volumes were calculated each time the MLSS values were determined. Chlorination continued for the duration of the research to prevent filamentous bulking problems. When chlorination was discontinued for several days, filamentous organisms increased in concentration. The ANX sludge did not develop the filamentous bulking problems; however, chlorine was added to the reactors. The ANX reactor received less chlorine than the ANA and AER because the solids concentration began to decrease with the addition of 3 g of HOCl/ kg of MLSS.

Whisper® 600 Air pumps were used to provide the reactors with dissolved oxygen concentrations greater than 2 mg/L during aerobic operation. Air entered the reactor through diffuser stones that were checked weekly and replaced when clogged. During operation at a wastewater COD of 5,500 mg/L, two air pumps were used for each SBR. An additional air pump was added to each SBR when the influent COD concentration was increased to 9,000 mg/L. Air for the AER SBR was turned on at the start of the feed cycle. ANA and ANX operated under nonaerobic conditions for 8 hours; consequently, the air for ANA and ANX was turned on after 8 hours of reaction time. After 46 hours of reaction time, all motors and air pumps were turned off and the SBRs were allowed to settle for 1 1/2 hours. At the end of the 1 1/2 hours, 1.75 liters of supernatant was pumped off the settled mixed liquor at a rate of 117 mL/min for 15 minutes. The supernatant was removed through a J-tube to prevent the removal of settled suspended solids. The effluent from each SBR was collected in a 2L plastic beaker.

Due to expected temperatures of the Industry's wastewater, the temperature of the SBRs was maintained at 29 - 31 °C. The temperature of the SBRs was controlled by a

circulating water bath (Fisher Circulating Water Bath) which pumped heated water, at 15 L/min, through a 3/4 inch tubing wrapped around the SBRs.

Due to solids accumulation on the beakers, the SBRs were scraped daily with a metal spatula. After the sides were scraped, the appropriate wastage volumes were removed by siphoning mixed liquor out the sample port. Wasting and scraping were done prior to the settling phase of the SBR. A 15 day solids residence time (SRT) was maintained by calculating wastage volumes on a mass basis. The wastage volumes were recalculated each time the MLSS and effluent suspended solids were determined.

Sampling and Monitoring of SBRs

Effluent samples and completely mixed samples were taken from the SBRs. Effluent samples were taken upon completion of the 15 minute decant phase. The completely mixed samples were taken either by siphoning a sample through the sample port or by drawing a sample into a pipette through an opening in the plexi-glass lid. Both types of samples were centrifuged at 8,000 rpm for 8 minutes. The samples were then passed through a 55 mm 0.45 µm filter (Supor® - 450, Gelman Science, Ann Arbor, MI) using a vacuum pump, and collected in acid washed; distilled water rinsed glass flasks. The filtrate was then filtered through a 0.2 µm filter (Supor® - 200, Gelman Science, Ann Arbor, MI). Two samples were taken for each reactor: one was acidified to a pH of less than 2 with concentrated phosphoric acid and the other was stored with no pH adjustment. Samples were analyzed for any combination of the following: TOC, COD, nitrate, nitrite, pivalic acid and acetic acid.

Operation of Reactors fed Industry's Wastewater

Three industry SBRs were set up to operate under the same conditions as the main SBRs: anaerobic/aerobic (ANA-T), anoxic/aerobic (ANX-T) and aerobic (AER-T). However, the industry SBRs were fed the Industry's wastewater, from an U.S. operation, which is similar to the new facility, instead of the synthetic wastewater.

The industry SBRs were operated in 1 liter glass jars with rubber stopper lids which had an outlet for gas exchange. Each industry SBR was seeded with 500 mL of sludge from the corresponding main SBR. The operation of the industry SBRs was controlled both manually and by a ChonTrol® XT-4 Timer (San Diego, California). Feeding, decanting, nitrate addition (ANX-T only) and wastage were done manually while mixing and aeration were under automated control. The operational parameters and a description of the timing cycle for the industry SBRs can be found in Tables 3-11 and 3-12, respectively.

Table 3-11: Operational parameters for ANA-T, ANX-T and AER-T SBRs

1 cycle/ 2 day: 46 hr. reaction time 1 1/2 hr. settle time 0.5 hr for feeding and decant
Reactor Volume: 0.5 L
Influent COD: approx. 7800 mg/L
Solids Residence Time: 15 days
Effective Hydraulic Residence Time: 96 hr.
At time = 0 pH between 8 - 8.5
Temperature 29 - 32 °C

The wastewater obtained from the Industry was concentrated and had a strength of approximately 90,000 mg/L as COD. The concentrated stream during wastewater treatment would be diluted with waste cooling water; therefore, the goal was to dilute the Industry's wastewater to approximately the same concentration, based on COD, as the

synthetic feed. To make the Industry's organic feed stock, the actual Industry wastewater was diluted 1:3.2 (150 mL of wastewater added to 350 mL of tap water).

Table 3-12: Description of timing cycle for ANA-T, ANX-T and AER-TSBRs

Operation	Time (hrs:min) for ANA-T & ANX-T	Time (hrs:min)for AER-T
Mixing On	0:00	0:00
Air On	8:00	0:00
Mixing Off	46:00	46:00
Air Off	46:00	46:00

At the end of each cycle, 250 mL of supernatant was removed from each SBR. 72 mL of the Industry's diluted organic feed was added with 178 mL of the appropriate MSM to the SBRs. As with the main SBRs, the MSM for ANA-T and AER-T contained ammonium chloride and the MSM for ANX-T did not. The ANX-T SBR received ammonium and nitrate from the ANX nitrate stock solution that was pumped in for 3 minutes and 12 seconds at the start of each cycle.

Mixing for the industry SBRs was provided by magnetic stir plates and stir bars. Due to accumulation of solids, the industry SBRs were scraped daily with a metal spatula. The reactors were scraped and 33 mL MLSS was wasted from each SBR prior to settling. The temperature of the SBRs remained between 29 - 31 °C, although no temperature control was provided.

Whisper® 600 air pumps were used to provide dissolved oxygen concentrations greater than 2 mg/L to the industry SBRs during aerobic operation. The AER-T received air at the start of the cycle while the ANA-T and ANX-T operated under nonaerobic conditions for the first 8 hours of the cycle. Air entered through diffuser stones that were checked weekly and replaced when clogged. As with the main SBRs, after 46 hours of

reaction time, the mixing and air were turned off and the SBRs were allowed to settle for 1 1/2 hours. The removal of supernatant and addition of the wastewater occurred within the allotted 1/2 hour prior to the start of the reaction time.

Sampling of Side Industry Reactors

Effluent and completely mixed samples were take from the industry reactors. Effluent samples were taken during the 30 minutes allotted for removal of the supernatant and addition of the wastewater. Completely mixed samples were taken with a pipette through the top of the reactors. Both types of samples were centrifuged at 8,000 rpm for 8 minutes. After being centrifuged, the samples were filtered through a 0.2 μm filter (Supor® - 200) and the filtrate was used for analysis. The samples collected were analyzed for TOC or nitrate.

Sand Filter Operation

After biological treatment at the Industry's wastewater treatment system, the wastewater will pass through a sand filter and then into a GAC column. To emulate the operation of the Industry's wastewater treatment facility, it was necessary to construct a gravity operated sand filter. The effluent from the ANA SBR was passed through the filter prior to use in the isotherm studies. Figure 3-4 shows a diagram of the filter and Table 3-13 contains the filter characteristics.

A 2 L graduated cylinder (19 1/2 inches x 3 1/8 in. diameter) was used as the filter apparatus. The cylinder was packed with the large gravel (3 in.), followed by the small gravel (2 in.), and topped with the sand (5 in.). The ANA effluent was collected in a 2 L plastic beaker. Due to the presence of suspended solids in the effluent, a magnetic stir plate and stir bar were used to keep the solids suspended and uniformly distributed. The

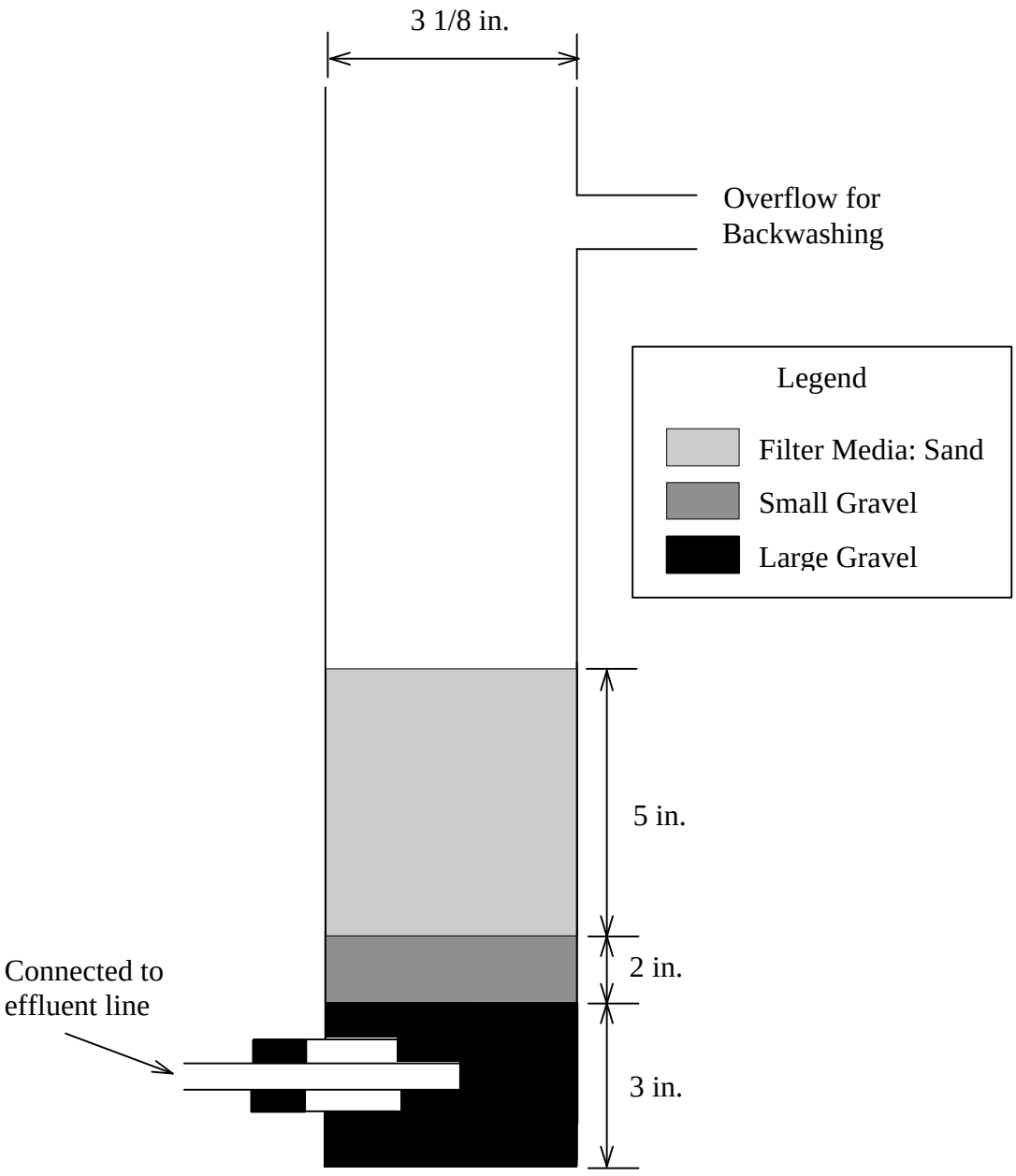

Figure 3-4: Sand filter

effluent, while stirring, was pumped into the top of the graduated cylinder. A flow of 1 - 2 gpm/ft^2 (200 - 400 mL/min) was maintained by gravity flow through the filter. To help maintain the proper flow, a water head of 5 inches was maintained on top of the sand for as long as possible. The effluent, from the sand filter, was collected in graduated cylinders and measured to ensure the proper flow through the column. The filtered ANA effluent was stored at 4 °C prior to use in the isotherm experiments. If the flow through the column fell below the desired rate or at the end of a filter run, the filter was backwashed with at least 6 L of clean tap water. To backwash, the effluent line was attached to a faucet and flow was reversed through the column and out the overflow port.

Table 3-13: Sand filter characteristics

Total Height	19 1/2 inches
Inner Diameter	3 1/8 inches
Effluent Diameter	3/8 inches
Height of Large Gravel	3 inches
Height of Small Gravel	2 inches
Height of Sand	5 inches
Effective Size of Sand[a]	0.50 mm
Uniformity Coefficient[a]	1.8
Target Flow	1 - 2 gpm/ft^2

a = sand analysis shown in Table A-7 and Figure A-2 in Appendix

GAC Isotherm Experiments

As mentioned previously, the GAC was rinsed with distilled water and pulverized and the ANA effluent was sand filtered and refrigerated prior to use in the isotherm experiments. A preliminary GAC study was done to determine an appropriate COD/GAC ratio for the isotherm experiments. Another preliminary study was done to determine the time required to reach equilibrium. From the preliminary experiments, TOC/GAC ratios were targeted between 30 - 350 mg TOC/g GAC and a 12 hour contact time were

determined to be sufficient to achieve equilibrium and minimize the effects of biodegradation during incubation. To determine isotherm parameters, a series of batch 20 mL vials were set up with various masses of GAC and a constant TOC/COD value.

Several experiments were conducted to collect the data required to determine the isotherm parameters. For the isotherm experiments, GAC masses between 0.00 g - 2.50 g, were used. Table A-6, in Appendix A, lists the exact masses used during the isotherm experiments. The first experiment was run with Unisorb AC, Unisorb AGL and Calgon. The GAC was put into 20 mL scintillation vials with 15 mL of the filtered ANA effluent. All experiments were performed in duplicate. After the addition of the effluent and carbon, the vials were placed on a shaker table and kept at a constant temperature of 20°C for 12 hours. A control with no GAC was run with each experiment to determine loss of TOC/COD from factors other than sorption to the GAC. At the end of 12 hours, the samples were removed from the shaker table and filtered through a 0.2 μm filter (Supor® - 200, Gelman Science, Ann Arbor, MI). After analyzing the data from the first experiment, an adjustment was made to the amounts of GAC added to the vials. The second experiment was run with Norit 830 and Norit HD 3000. A final experiment, #3, was run to supplement the data collected in the first experiment. The final experiment was run with the Unisorb AC, Unisorb AGL and Calgon.

Analytical Methods

This section describes the methods used for analyzing samples throughout the research. Procedures listed in *Standard Methods for the Analysis of Water and Wastewater*(1992) were used, if applicable.

Chemical Oxygen Demand : Chemical Oxygen Demand (COD) was determined using Standard Method 5220C, the closed reflux, titrimetric method. This method was used for analyzing organic feed jar concentrations and effluent samples prior to the nutrient increase. Potassium phthalate standards were run with the effluent samples. Known COD concentrations were added to MSM solution and effluent samples to determine the recovery of COD. Once the nutrient concentrations were increased, the high chloride and salt concentrations in the samples caused an interference with the COD measurements that prevented direct measurements of COD from that point forward.

Dissolved Organic Carbon : Dissolved organic carbon was used to measure the organic concentrations in the effluent samples. The samples were analyzed using a Dohrmann® DC-80 TOC Analyzer (Santa Clara, CA) according to Standard Method 5310C, persulfate-ultraviolet oxidation. For samples containing greater than 400 mg/L DOC, greater than 20 mg/L DOC and less than 400 mg/L, and less than 20 mg/L DOC, the 2000 mg/L, 400 mg/L and 10 mg/L output ranges were utilized, respectively. Standard DOC solutions were used to standardize the machine prior to sample analysis. Standards were run periodically while running samples to make certain the analyzer held the calibration. A standard curve was also run between 20 - 50 mg/L DOC on the 400 mg/L setting to ensure accurate readings.

Total and Volatile Suspended Solids : The total suspended solids (TSS) and volatile suspended solids (VSS) were determined in accordance with Standard Methods 2540D and 2540E. Total suspended solids analysis were performed on all reactors, both the mixed liquor and effluent samples, every 3 - 7 days to determine wastage rates. Volatile suspended solids were determined every third TSS sample to determine a

TSS/VSS ratio. Volatile suspended solids were also measured during all kinetic experiments so that data could be normalized to mass of VSS.

Anion Analysis: Phosphate (PO_4^{3-}) and sulfate ($SO_4^{=}$) were analyzed by ion chromatography (I.C.) in accordance with Standard Methods 4110B. A Dionex 2010I Ion Chromatograph with a Dionex 4270 Integrator was used with an eleunt of 1.8 mM sodium carbonate (Na_2CO_3) and 1.7 mM sodium bicarbonate ($NaHCO_3$) at a flow of 2 mL/min. Samples taken from the anoxic cycle had high enough anion concentrations to be analyzed on the I.C. with no chloride interference; however, effluent samples did not. High chloride concentrations prevented the use of the I.C. on effluent nitrite and nitrate samples. Therefore, nitrate analysis for effluent samples was performed in accordance with Standard Methods 4500-NO_3^- E, Cadmium Reduction Method. In addition to nitrate interference, high chloride concentrations caused interference with nitrite analysis on the I.C. Therefore, nitrite was analyzed according to Standard Methods 4500-NO_2^- B, colorometric method. For both the cadmium reduction and the colorometric methods, standards were made in the MSM solution to minimize ionic strength differences in the samples.

Ammonium Analysis: Samples analyzed for ammonia were analyzed according to Standard Methods 4500-NH_3 C, Titrimetric Method. Ammonia analyses were performed on effluent samples to confirm that sufficient ammonia was added to the SBRs. TKN analysis was run to determine the total organic nitrogen in the samples. Insignificant amounts of organic nitrogen were found in the effluent samples; therefore, ammonia analysis was considered to be sufficient.

Pivalic Acid Analysis: Pivalic acid was analyzed using a high pressure liquid chromatograph (HPLC). A Hewlett Packard 1090 Liquid Chromatograph with and a diode array detector and a Zorbax ODS C-17 column (4.6 mm X 25 cm) was used for pivalic acid analysis. The operational parameters used in the analysis are contained in Table 3-14. Note that the eluent for pivalic acid analysis is composed of 70% 25 mM solution of pH 2.4 phosphate buffer and 30% acetonitrile. Analysis of the chromatographs produced showed that peak heights produced a better standard curve than peak areas.

Table 3-14: HPLC parameters for pivalic acid analysis

Parameters	Values
Flow of eluent	1.00 mL/min
Eluent Constituents	70% 25 mM pH 2.4 phosphate buffer 30 % acetonitrile
Oven Temperature	40.0 °C
Max Pressure	400
Injection Volume	20 microL
Detector Wavelength	210 nm

Acetic Acid Analysis: Acetic acid analysis was accomplished using gas chromatography (G.C.). Analysis was performed by a Hewlett Packard 5880A Series Gas Chromatograph with a FID detector. The operating conditions for the analysis are listed in Table 3-15. All samples, standards and distilled water were acidified with formic acid, 10µL/1 mL of sample, prior to injection. After lighting the flame, the column was rinsed with distilled water and formic acid. Ten water injections were made at 2 minute increments to clean any residuals off the column. Peak areas were used to determine standard curves and for sample analysis.

Table 3-15: GC parameters for acetic acid analysis

Parameter	Value
Carrier Gas (Nitrogen) Flow Rate	50 mL/min
Hydrogen Flow	40 psi
Air Flow	40 psi
Injector Port Initial Temperature	200 °C
Initial Oven Temperature	120 °C
Detector Temperature	200 °C
Initial hold time	3 min.
Temperature rise	1 °C/min
Final Oven Temperature	130 °C
Final Temperature Hold	1 min
Injection Size	1 μL
Packed Column	30 % carbowax 20 M 10% H_3PO_4 60/80 carbopack C
Detector	FID

Microtox: Toxicity analysis was performed with a Microtox® Model 500 (Azure Environmental, formerly Microbics Corporation, Carlsbad, CA). The active reagent was a freeze-dried marine bacterium *Vibrio fischeri* (formerly known as *Photobacterium phosphoreum)*, NRRL numberB-11177, purchased from Microbics Corporation. The diluent (2% sodium chloride, 98% water) was purchased from the Microbics Corporation. Samples did not require osmotic requirement because the MSM provided sufficient ionic strength. The Microtox Acute Toxicity Basic Test Procedure was used for the preparation of assays. Serial dilutions of 1:2 were made with effluent and the diluent 7 times to determine light production at different effluent percentages. The reconstitued *Vibrio fischeri* was then added to the cuvettes. The cuvettes were then allowed to incubate at 15°C for 15 minutes after which the light production was measured. Microtox software was used to determine the gamma value, the ratio of light lost to diluted effluent in the

sample. The EC_{50} values have a log-log relationship with the gamma values. EC_{50} values represent the percent dilution required for a 50% reduction in light production.

Color and pH can cause interferences with toxicity analysis. From preliminary experiments, it was determined that effluent color would not cause an interference with the toxicity analysis. Samples collected for toxicity analysis were initially a pH between 8.5 - 9; therefore, hydrochloric acid was used to adjust the pH to 7 - 7.5, as stated in the Microtox® manual.

CHAPTER IV. RESULTS AND DISCUSSION

In this chapter, results from the operation of the main SBRs, the industry SBRs, and the GAC isotherm studies are presented and discussed.

Data collected from the operation of the ANA, ANX and AER SBRs will show performance differences in terms of: average effluent quality, settling characteristics, sludge characteristics, and degradation across the reaction phases. Total organic carbon, COD and effluent toxicity were used to compare the effluent quality of the SBRs. Settling characteristics for the SBRs were compared on the basis of sludge volume index (SVI) and effluent suspended solids.

Operation of the industry SBRs fed the industrial wastewater will be compared on the basis of effluent DOC and degradation patterns during the reaction phase. Performance differences between the industry SBRs and the main SBRs will be discussed, as well as the effect of the compound substitutions made in the synthetic wastewater.

The results from the GAC isotherm experiments will also be presented and discussed. The performance of the different types of GAC will be compared and problems with the adsorption will be discussed. Isotherm parameters will be presented for the data collected from the batch isotherm GAC experiments.

ANA, ANX, and AER SBR Performance

Performance Overview : The ANA, ANX and AER SBRs were routinely monitored during the time period from April, 1996 to June, 1997. The data collected for the SBRs are presented in Table B-1 in Appendix B.

Several major operational changes occurred throughout the operation of the SBRs. The major changes are listed in Table 3-6 and are shown in Figure 4-1. An initial

wastewater concentration of 2000 mg/L was used with the intention of gradually increasing the strength of the wastewater until the reactors received the full strength, 12,000 mg/L as COD. Additionally, a total cycle time of 12 hours was arbitrarily chosen with the intention of increasing the cycle time as necessary to achieve complete degradation. The reactors were seeded with the industrial sludge and after one month of operation, excessive growth of filamentous organisms caused bulking and settling problems for the ANA and AER reactors. The ANX SBR did not experience excessive filamentous growth. In an attempt to control the filaments, chlorine was added to the ANA and AER reactors at the beginning of each cycle. Unfortunately, the ANA and AER SBRs were unable to recover from the filamentous organisms and the reactors were reseeded with new industrial sludge on May 29, 1996.

Performance of the SBRs, in terms of effluent DOC concentrations, for the duration of the project is shown in Figure 4-1. Degradation of the wastewater was not being achieved prior to the reseed; therefore, the cycle time was increased to 18 hours (5/29/96). After several months of operation, degradation of the wastewater, at a concentration of 2,000 mg/L as COD, began to occur and the wastewater concentration was increased to 5,500 mg/L as COD (7/15/96). Several months passed with no improvement in degradation. The cycle time was increased to 24 hours (11/8/96) and then a few weeks later increased to 48 hours (11/24/96) to try and increase the extent of degradation.

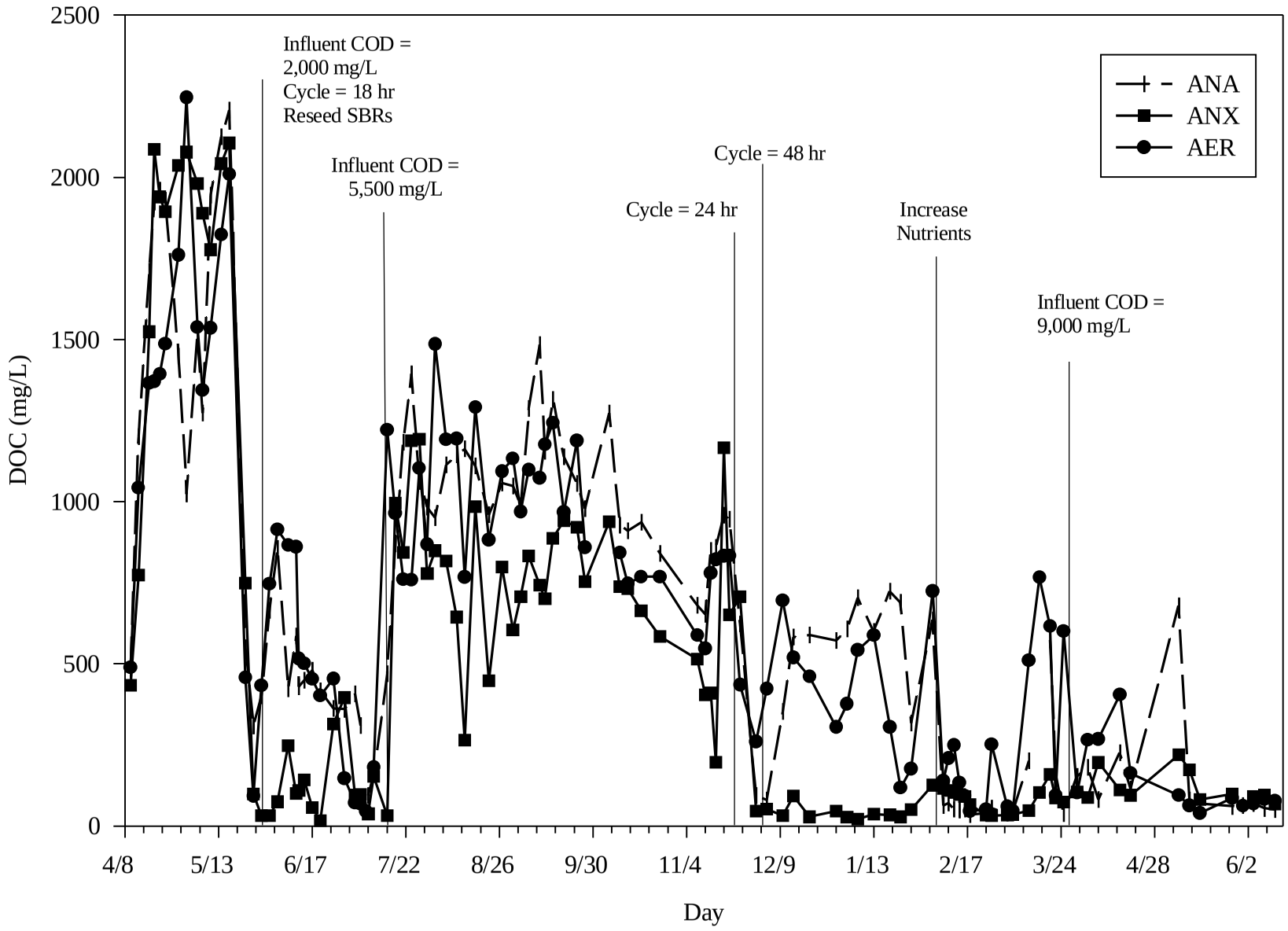

Figure 4-1: Effluent DOC concentrations (mg/L) for ANA, ANX, and AER SBRs.

As previously discussed, on February 6, 1997, several nutrient deficiencies were discovered in the synthetic wastewater. The concentrations of limiting nutrients were increased to ensure adequate levels to support complete COD degradation. Increased degradation was observed almost immediately after correcting the nutrient loading to the SBRs (see Figure 4-1). After two months of operation, the wastewater strength was increased to 9,000 mg/L as COD (3/26/97). Although the original intent was to increase the COD to 12,000 mg/L, the decision was made to discontinue operation of the SBRs after being fed the 9,000 mg/L COD wastewater for 2 ½ months due to difficulties associated with operating the ANA and AER systems at this loading.

Mixed Liquor Suspended Solids: All three SBRs operated with extremely high mixed liquor suspended solids (MLSS) concentrations. MLSS data collected for the ANA, ANX and AER SBRs are presented in Table B-2 in Appendix B. The MLSS data collected during the entire operation of the three SBRs are shown in Figure 4-2. Due to the nutrient limitations, discussion and conclusions drawn between the three reactors will be based on data collected after the nutrient increase on February 6, 1997. MLSS data collected after the increase in nutrient loading are shown in Figure 4-3.

The influent wastewater concentration was increased on March, 26, 1997; therefore, average values were calculated for different time periods. Averages and standard error of the mean values were calculated for three different time periods: 1) from 2/6/97 - end of operation, 2) for operation at a wastewater COD of 5,500 mg/L (2/6 - 3/26/97) and 3) for operation at a wastewater COD of 9,000 mg/L (3/26 - 6/12/97) and are listed in Table 4-1. Average values are plotted with the MLSS data on Figure 4-3. As

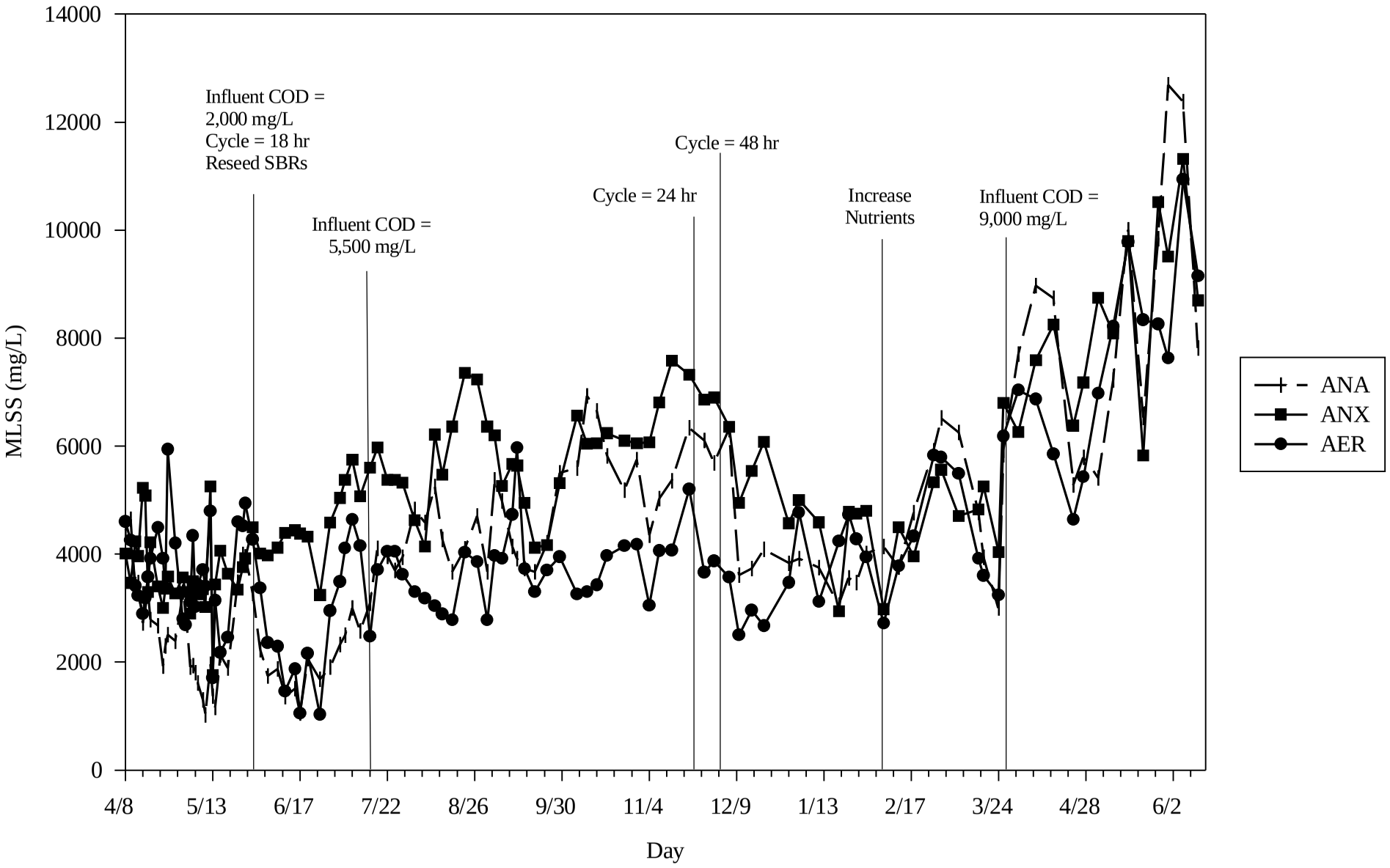

Figure 4-2: Mixed liquor suspended solids concentrations (mg/L) for ANA, ANX, and AER SBRs.

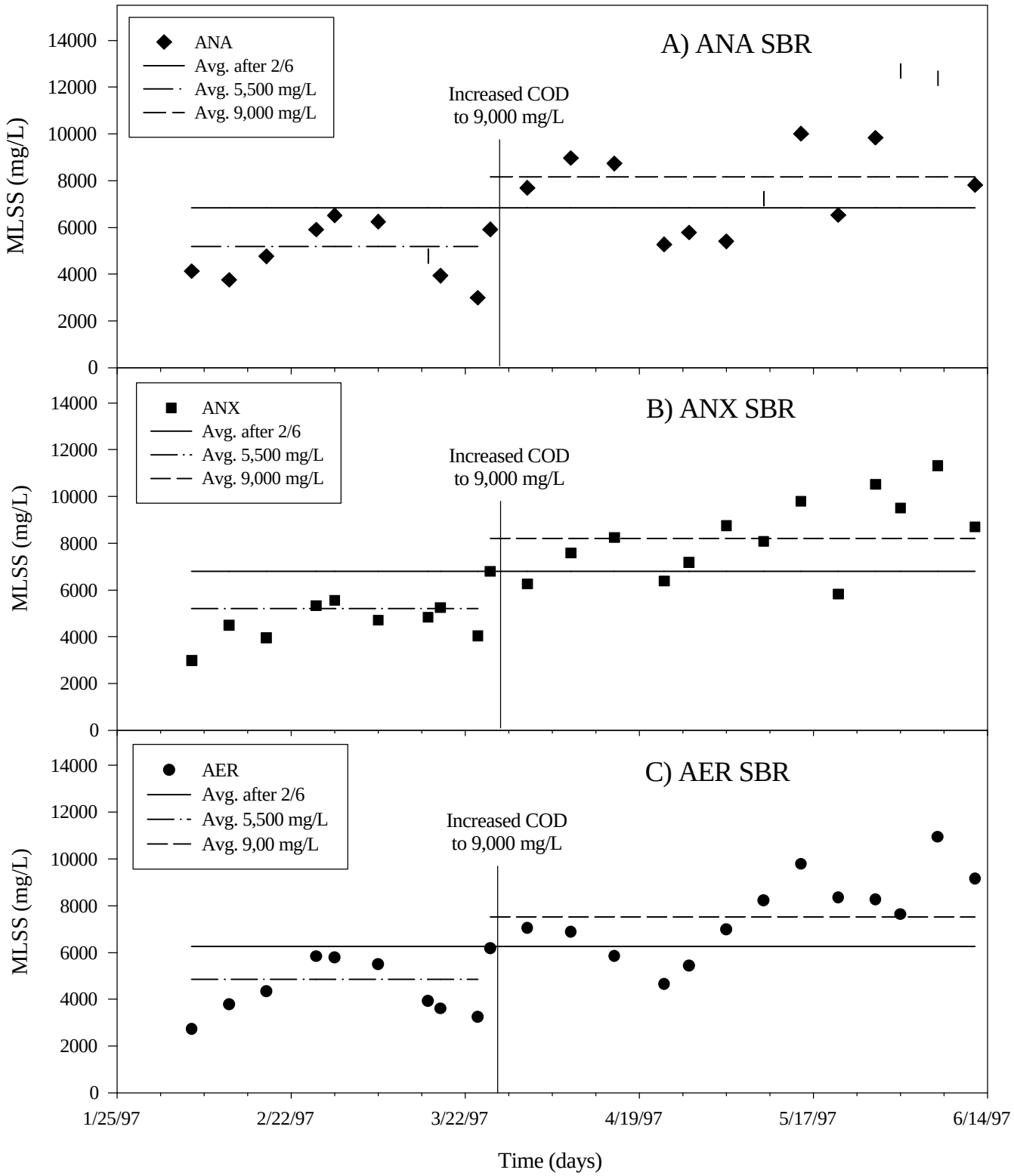

Figure 4-3: Mixed liqour suspended solids concentrations for ANA, ANX, and AER SBRs after nutrient increase on 2/6/97.

was expected, the average MLSS concentrations increased for all SBRs after the influent wastewater COD was increased to 9,000 mg/L as COD. The MLSS concentrations have an increasing trend during the operation at the increased COD concentration.

Table 4-1: Mixed liquor suspended solids concentrations for ANA, ANX and AERSBRs after nutrient increase on 2/6/97[a].

	ANA	ANX	AER
Avg. 2/6 - 6/12/97	6843 ± 114[b]	6789 ± 99	6261 ± 96
# of data	23	23	23
Avg. 2/6 - 3/26/97	5189 ± 189	5217 ± 123	4864 ± 84
# of data	7	7	7
Avg. 3/26 - 6/12/97	8165 ± 173	8213 ± 119	7522 ± 124
# of data	14	14	14

a = increased influent COD concentrations from 5,000 mg/L to 9,000 mg/L on 3/26/97
b = standard error of the mean

To determine whether any significant difference existed in MLSS concentrations between the 3 SBRs, box plots were constructed. The box plots for MLSS concentrations are shown in Figure 4-4. The box plots show little difference in MLSS concentration between the ANA, ANX and AER SBRs. Typically anaerobic and anoxic environments produce less sludge than aerobic systems; however, the long aeration time for all SBRs seems to eliminate the benefit of reduced sludge production and provides ample opportunity for aerobic biomass decay to occur in all cases. Although the single sludge system provided no noticeable reduction in sludge produced, the use of separate anaerobic and aerobic systems could substantially reduce the sludge production if significant degradation occurs in the anaerobic zone.

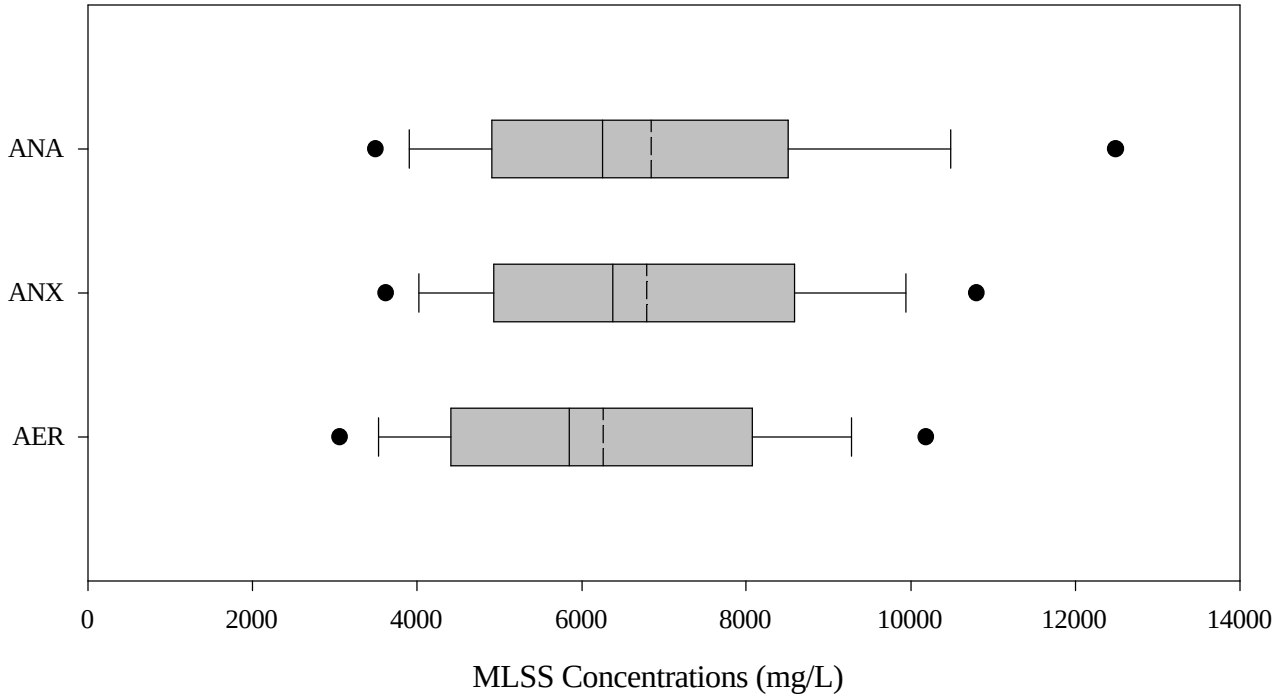

Figure 4-4: Box Plot for ANA, ANX and AER SBRs for MLSS concentrations (mg/L) after increase in nutrient loading (2/6/97). $5^{th}/95^{th}$ confidence intervals shown with the black circles, 10^{th} and 90^{th} percentiles shown with lines, box represents $25^{th}/75^{th}$ percentiles, and median and mean values are represented by the solid and dashed lines, respectively.

Effluent Quality: Effluent organic concentrations were measured as total organic carbon (DOC) and chemical oxygen demand (COD). The permit for the new wastewater treatment plant limits the effluent to 100 mg/L as COD. As mentioned previously, problems existed measuring the COD of the effluent samples after the increase in nutrient loading. High chloride concentrations, as well as high dissolved salt concentrations in general, caused severe interferences with COD recoveries. Phthalate spikes, 100 mg/L as COD, in distilled water produced recoveries ranging from 94 - 101 mg/L as COD. Known concentrations of potassium phthalate, 100 mg/L as COD, were prepared in solution with the same salt concentrations as the wastewater. Effluent samples were also spiked with known concentrations of potassium phthalate. COD recoveries in the salt solution and effluent samples were low and extremely variable, and ranged from 26 - 86 mg/L and 35 - 85, respectively.

Table 4-2: COD:DOC ratios for ANA, ANX and AER SBRs.

	ANA	ANX	AER
COD:DOC	3.12	3.02	3.07
Standard Deviation	0.22	0.49	0.49
# of data points	35	36	36

To determine whether the effluent limitation could be met by the SBRs, a COD:DOC ratio was established based on data collected during the time periods when COD could be reliably measured. Six months of data (7/15/96 - 2/6/97) were used to determine the COD:DOC ratios presented in Table 4-2. The six month time period was chosen because the reactors were receiving a constant influent COD concentration of 5,500 mg/L. The COD and DOC data used to determine the COD:DOC ratios are presented in Tables B-3 - B-5 and Figure B-1 in Appendix B. DOC concentrations were

used to indicate organic concentrations in effluent samples after the increase in nutrient loading. The effluent DOC values were converted to COD values using the ratios determined for each SBR from data collected prior to the nutrient change.

Effluent DOC concentrations were monitored throughout the duration of the research. The DOC data are listed in Table B-6 in Appendix B. As seen in Figure 4-1, the effluent DOC values were variable for all SBRs but variations were most severe for the ANA and AER SBRs. Average effluent DOC concentrations, as well as the standard error of the means were calculated for three time periods: 1) from 2/6/97 - end of operation, 2) for operation at a wastewater COD of 5,500 mg/L (2/6 - 3/26/97) and 3) for operation at a wastewater COD of 9,000 mg/L (3/26 - 6/13/97) and are listed in Table 4-3. Effluent DOC data collected after the increase in nutrient loading are shown with the average values in Figure 4-5 for each SBR.

Table 4-3: Effluent total organic carbon values (mg/L) for ANA, ANX and AER after increase in nutrient loading (2/6/97[a].)

	ANA	ANX	AER
Avg. 2/6 - 6/12/97	127 $\pm$ 6[b]	98 $\pm$ 2	206 $\pm$ 8
# of data points	26	26	26
Avg. 2/6 - 3/26/97	106 $\pm$ 10	79 $\pm$ 3	258 $\pm$ 29
# of data points	14	15	15
Avg. 3/26 - 6/12/97	152 $\pm$ 15	123 $\pm$ 4	142 $\pm$ 9
# of data points	12	11	12

a = Increased influent COD concentration from 5,500 mg/L to 9,000 mg/L on 3/26/97
b = standard error of the mean

Box plots, Figure 4-6, were constructed to evaluate the performance of the 3 SBRs based on effluent DOC concentrations. The lowest average value was clearly achieved by the ANX SBR; however the lowest median value was achieved by the ANA SBR. The

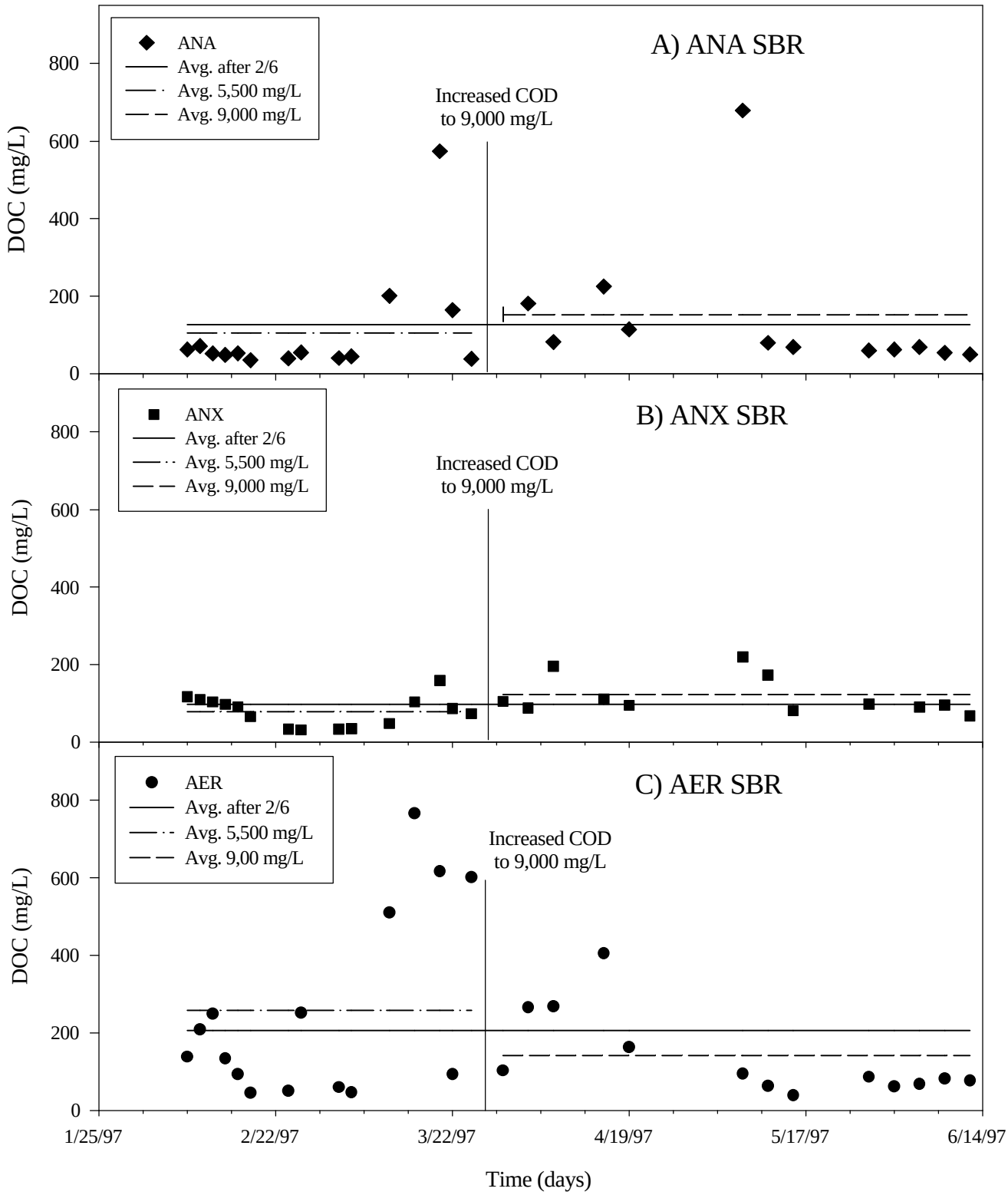

Figure 4-5: Effluent dissolved organic carbon concentrations (mg/L) for ANA, ANX, and AER SBRs after increase in nutrient loading (2/6/97).

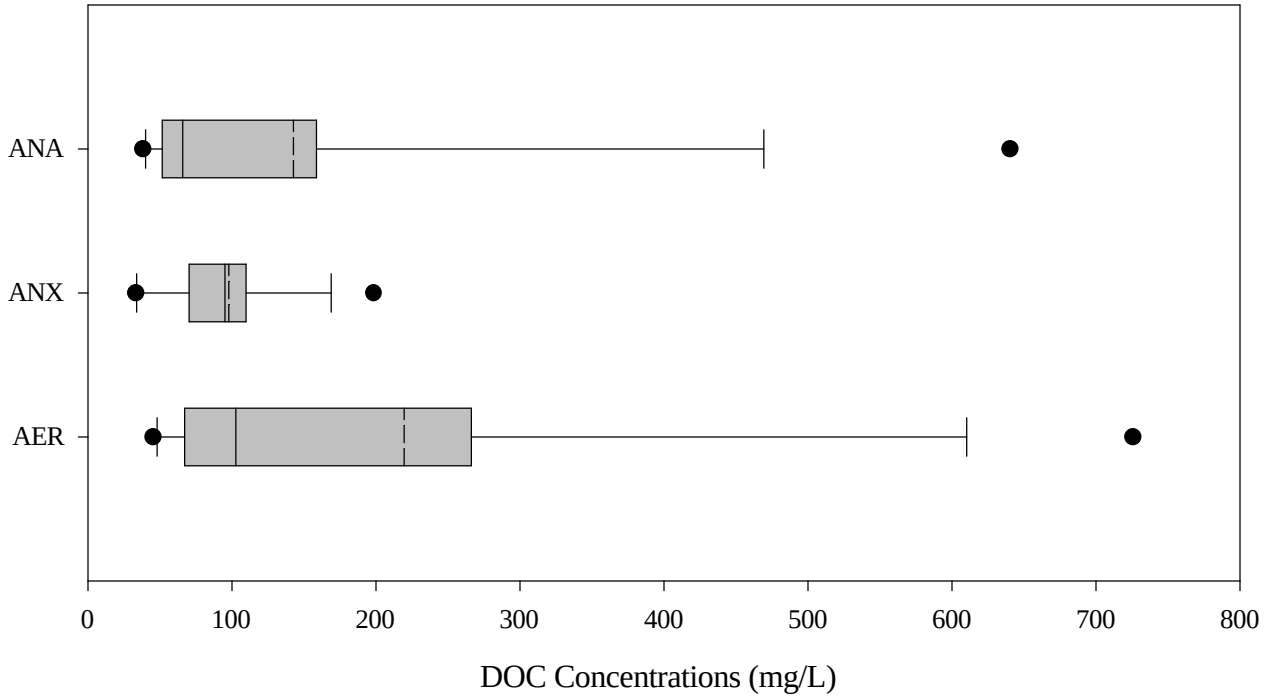

Figure 4-6: Box plot for ANA, ANX and AER for effluent DOC concentrations (mg/L) after increase in nutrient loading (2/6/97). 5th/95th confidence intervals are shown with the black circles, 10th and 90th percentiles shown with lines, box represents 25th/75th percentiles, and median and mean values are represented by the solid and dashed lines, respectively.

effluent DOC data from the ANA SBR varied greatly resulting in a low median value and high average value. The 25 th and 75th percentiles show that the ANX SBR produced the most stable effluent DOC concentrations while the ANA and AER SBRs varied tremendously. The box plots show that 95% confidence intervals for the ANA and AER SBRs are approximately three times greater than the interval for the ANX SBR.

Measured COD concentrations for the time period prior to the nutrient increase are listed in Table B-7 in Appendix B. COD values determined from the COD:DOC ratios (see Table 4-2) and the effluent DOC concentrations are listed in Table B-8 in Appendix B. COD values, both experimental and calculated, for the ANA, ANX, and AER are presented in Figure 4-7. As was expected, the effluent COD concentrations for the three SBRs are highly variable.

Some variability may be associated with long time periods of instability after correcting for the long term nutrient deficiencies, since the effluent DOC for the ANA and AER SBRs stabilized approximately 14 weeks after nutrient adjustments were made. The ANX SBR received an additional nitrogen source in the form of nitrate; however, nitrate was completely consumed during the anoxic reaction phase. Therefore, the ANX SBR was also nitrogen limited and performed better than the ANA and AER under the nutrient limiting conditions.

As shown in Figure 4-8, the effluent COD limitation was met only briefly by the ANX SBR (2/24 - 3/6/97). The effluent limitation was met when the influent COD concentration was 5,500 mg/L as COD or 40% of full strength. The ANA and AER SBRs were never able to achieve the 100 mg/L as COD limitation.

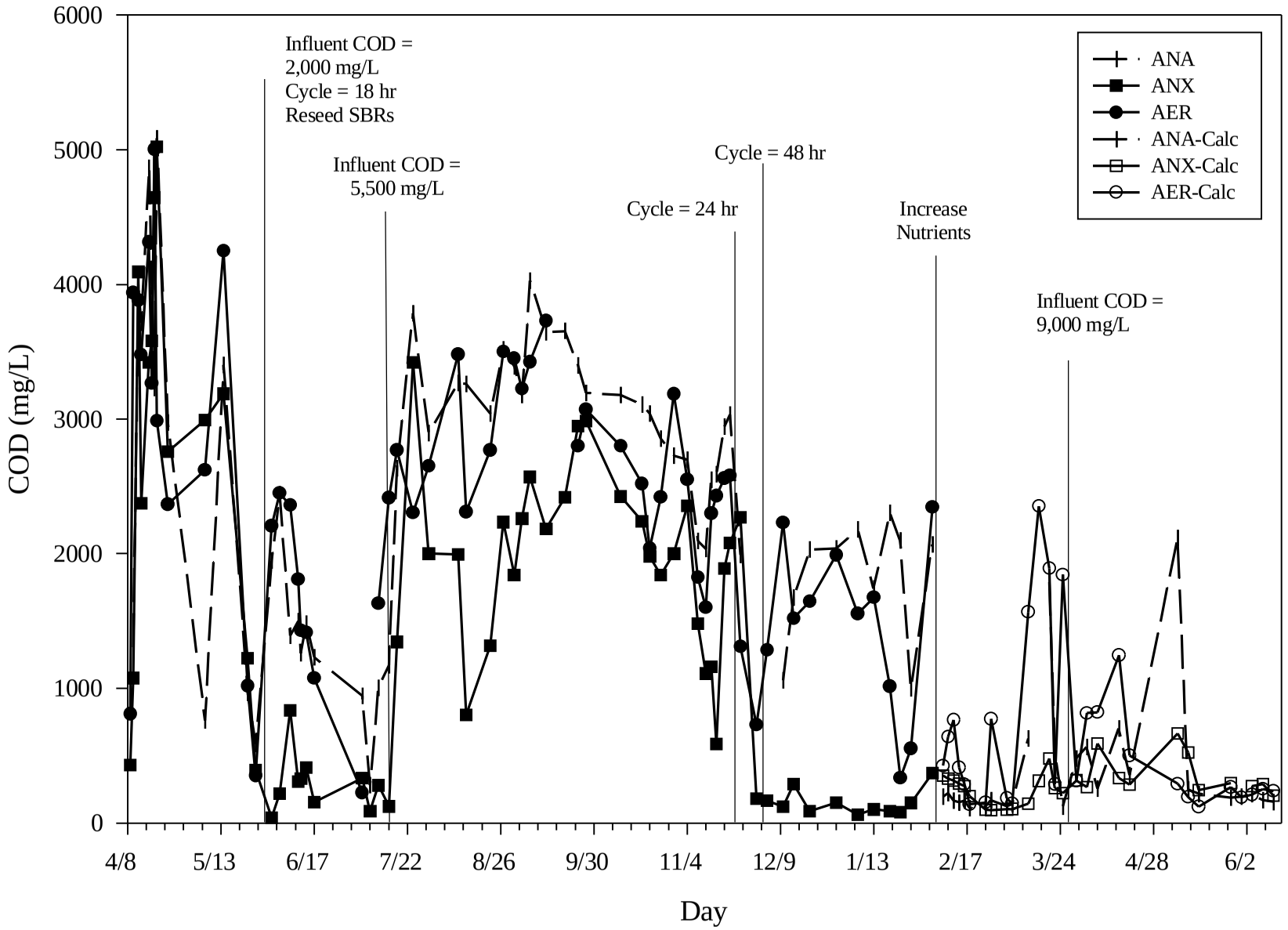

Figure 4-7: Experimentally determined and calculated COD concentrations (mg/L) for ANA, ANX, and AER SBRs.

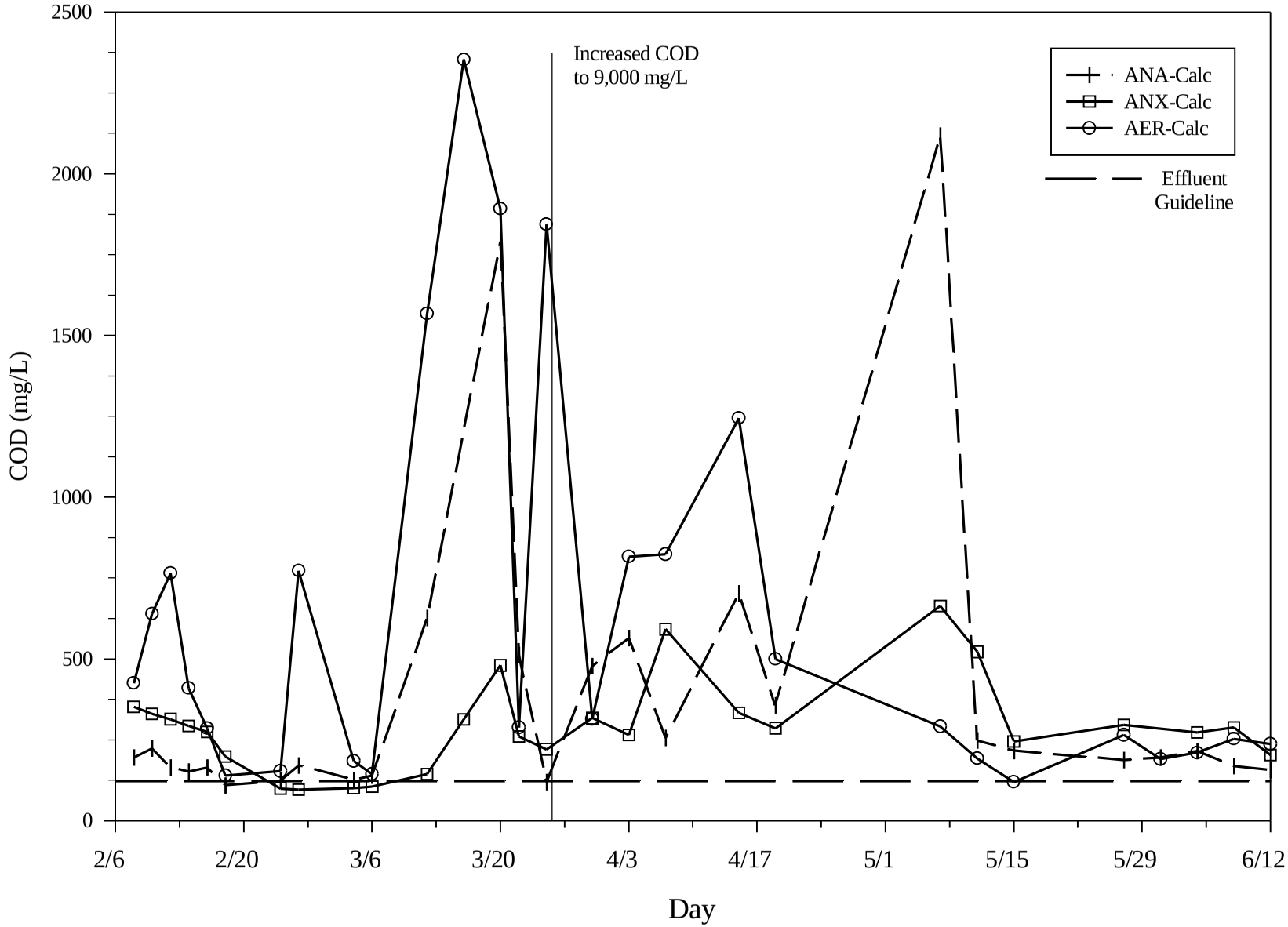

Figure 4-8: Calculated COD values (mg/L) for AnA, ANX, and AER SBRs.
100 mg/L COD target is designated with dashed line

Effluent Toxicity: Microtox EC_{50} values were determined for several effluents. Table 4-4 shows the EC_{50} values (% dilution) and 95% confidence intervals for the effluent samples. Note that the EC_{50} values represent % of effluent concentration required for a 50% reduction in light produced by the *V. fischeri* bacteria; therefore, a lower EC_{50} represents a more toxic effluent. The 95% confidence intervals suggest no significant difference in effluent toxicity between the three SBRs for any given day. The influent wastewater concentration was 5,500 mg/L as COD for the February and March data and 9,000 mg/L as COD for the April data. Again, the 95% confidence intervals suggest that the increase in influent concentration had no negative impact of the effluent toxicity values.

Hao *et al.* (1996) described effluents from various industrial plants by their toxicity units. The results showed that several tannery wastewaters as well as a pulp and paper plant produced effluent toxicity units of less than 1. The average toxicity units for the ANA, ANX and AER effluents range from 1.5 - 2.5 (see Table 4-4) which indicated similar toxicity levels to those tested by Hao. As shown by Hao *et al.*(1996), no correlation existed between the toxicity unit values and the effluent COD for the ANA, ANX, and AER SBRs. The lack of correlation between toxicity and COD indicates that COD is not a good measure of effluent toxicity.

Several different ranking systems are available for determining the toxicity of a complex effluent based on the EC_{50} values. Coleman and Quershi (1985) described the following percent ranking method (PRM) system based on Bulich (1982): 1 - very toxic EC_{50} < 25%, 2 - moderately toxic EC_{50} 25 - 50%, 3 - toxic EC_{50} 51-75%, 4 - slightly toxic EC_{50} > 75%, and 5 - nontoxic EC_{50} can't be determined. Vasseur (1984) tested

Table 4-4: Microtox EC $_{50}$ (% dilution), 15 minute exposure times, effluent COD values (mg/L), and toxicity units (Hao, 1996) for ANA, ANX, and AER SBRs.

Date	EC_{50} (% dilution)			COD (mg/L)			Toxicity Units		
	ANA	ANX	AER	ANA	ANX	AER	ANA	ANX	AER
2/20/1997[b]	58 (22-148)[a]	42 (37-48)	58 (42-82)	51 (20-131)	77 (68-88)	62 (45-88)	1.7 (4.5-0.7)	2.4 (2.7-2.0)	1.7 (2.1-1.2)
3/20/1997[b]	48 (37-62)	55 (45-57)	55 (46-67)	860 (663-1110)	264 (216-312)	1040 (870-1267)	2.1 (2.7-1.6)	1.8 (2.2-1.5)	1.8 (2.1-1.5)
4/15/1997[c]	66 (54-82)	48 (37-63)	55 (50-61)	464 (380-576)	160 (124-211)	685 (622-759)	1.5 (1.9-1.2)	2.1 (2.7-1.6)	1.8 (2.0-1.6)

a = 95% confidence intervals
b = influent wastewater COD = 5,500 mg/L
c = influent wastewater COD = 9,000 mg/L

several industrial effluents for toxicity including but not limited to the following effluents: drugs and phenols, pharmaceutical, organic dyes and other various compounds. According to the PRM, the organic dye waste would be classified as very toxic to moderately toxic with toxicity values between 3 - 40% while the drugs and phenols, pharmaceutical and various compound effluents would be slightly toxic. Oanh (1995) found that the Bai Bang Paper Company (BAPCO) had an average EC_{50} of 45% with a 95% confidence interval of 38 - 53%. The BAPCO effluent would be classified as moderately toxic to toxic. Although the BAPCO effluent was classified as moderately toxic, samples taken from the river 100 meters downstream of the discharge point indicated EC_{50} values greater than 100% or non-toxic. According to the PRM, the ANA, ANX and AER effluents would be classified as moderately toxic to toxic effluents.

Sludge Characteristics : Microscopic analysis of the ANA, ANX and AER SBRs indicated the generation of biosolids with different characteristics. As discussed previously, excessive filamentous organisms dominated the microorganism population in the ANA and AER SBRs after one month of operation. The filamentous organisms were identified as *Sphaerotilis natans*, a common filament found in laboratory systems (Scruggs, 1996). *S. natans* is commonly found in reactors with low dissolved oxygen and readily degradable substrates over a wide range of SRT values (Jenkins *et al.* 1993). According to Jenkins *et al.*, *S. natans* tends to proliferate in completely mixed, continuously fed aeration basins as well as in feed jars on feed lines. Filamentous growth in the ANA and AER SBRs cannot be explained by the availability of readily degradable substrate or by growth in the feed jar or lines because all three systems received the same wastewater from the same stock jars. A possible explanation for *S. natans* growth in the

ANA and AER SBRs was the extremely high organic loading to the aerobic phases of the reaction cycle. The anoxic phase significantly reduced the organic loading to the aerobic phase, thereby reducing the high initial oxygen demand seen at the beginning of the aerobic phase. The anaerobic phase was unable to reduce the organic concentrations; therefore, low dissolved oxygen concentrations during the aerobic phases of the ANA and AER SBRs could have led to the growth of *S. natans*.

Chlorine addition was not effective at significantly reducing the *S. natans* population and the reactors were reseeded. Chlorination was stopped after the SBRs were reseeded; however, filamentous organisms began to proliferate in the ANA and AER SBRs again. Chlorination was restarted and continued for the duration of the SBR operation. The ANX SBR did not develop a filamentous bulking problem; nevertheless, chlorine was added at half the dosing rates of the ANA and AER SBRs to ensure that contamination from these systems did not cause bulking problems in the ANX SBR.

At a wastewater concentration of 5,500 mg/L as COD, the ANA and ANX SBRs produced biosolids with similar characteristics. The ANA and ANX biosolids were very granular with large solids visible in the reactor. The AER biomass did not contain the large granules. The ANA and ANX biomass contained greater than 50% higher life organisms with very dense flocs seen under the microscope. However, ANA sludge had a significant number of filamentous organisms that often dictated the shape of the flocs while the ANX SBR did not. The ANA flocs were dense but often had filamentous organisms as backbones. There were few individual bacteria or free-swimming higher life organisms seen in either the ANA or ANX biosolids. However, the AER sludge contained

very thin flocs and the majority of biosolids existed as dispersed, individual cells. The AER biomass contained approximately 25% higher life organisms.

Wanner (1992) operated a two-step completely mixed activated sludge system (anaerobic followed by aerobic) and an SBR operated with anaerobic and aerobic reaction phases fed a synthetic wastewater containing: ethanol, peptone, glucose and acetic acid with a total COD of 1000 mg/L. The two systems were operated with multiple redox environments, anaerobic/aerobic, to accomplish phosphorous removal. The conventional activated sludge system had few filamentous organisms while the SBR system contained filamentous populations that were able to accomplish carbon storage. Wanner found the SBR system promoted the formation of large, compact flocs unlike the conventional system. The results indicated the filamentous organisms did not adversely affect settling properties primarily because of the formation of the large, compact flocs.

In addition to the differences in microorganisms, the color of each reactor was different. The ANA reactor tended to be blackish-green and sometimes would occasionally turn a yellowish-green. The ANX reactor generally was tan and often looked slightly orange. Finally, the AER reactor remained yellowish/brown with very little change in appearance until the increase in wastewater COD. The biosolids produced at the U.S. facility are yellowish brown to brown.

After the increase in COD, the biomass characteristics for all three reactors became quite similar. All three reactors contained large, dense masses of biosolids that accumulated within the reactors. Large, granular flocs were clearly visible in all three SBRs. Under the microscope, dense flocs were seen for all three and all contained large populations of higher life organisms. The AER reactor continued to have large

populations of free swimming bacteria and higher life organisms while the ANA and ANX reactors did not. None of the biosolids contained any significant filamentous populations. Note that the lack of filaments could be due to chlorine addition which continued throughout the research.

Settling Properties/System Handling : In addition to effluent quality, settling characteristics were monitored based on: sludge volume index (SVI) and effluent suspended solids (ESS). Additionally, general system handling was compared for the three SBRs.

Effluent suspended solids concentrations were measured every 3 - 7 days and were used to monitor SBR performance and determine wastage volumes for the SBRs. ESS data are listed in Table B-9 in Appendix B. As with the MLSS and effluent DOC data, averages and standard error of the mean were calculated for the ESS data for three time periods: 1) after increasing nutrient loading (2/6/97), 2) at an influent wastewater of 5,500 mg/L as COD (2/6 - 3/26/97) and 2) at an influent wastewater of 9,000 mg/L as COD (3/36 - 6/12/97). The results are listed in Table 4-5.

Table 4-5: Effluent suspended solids (mg/L) for ANA, ANX and AER SBRs after the increase in nutrient loading (2/6/97)[a].

	ANA	ANX	AER
Avg. 2/6 - 6/12/97	594 ± 43[b]	218 ± 9	419 ± 35
# of data points	20	20	20
Avg. 2/6 - 3/26/97	200 ± 12	84 ± 12	284 ± 45
# of data points	6	6	6
Avg. 3/26 - 6/12/97	763 ± 71	276 ± 13	477 ± 58
# of data points	14	14	14

a = increased the influent wastewater concentration from 5,500 mg/L to 9,000 mg/L as COD on 3/26/97
b = standard error of the mean

As shown in Figure 4-9, all SBRs maintained high effluent solids concentrations. As mentioned previously, the synthetic wastewater contained high salt concentrations which may have contributed to the high effluent solids concentrations (Novak *et al.*, 1997). Box plots were constructed to compare the ESS concentrations for the three different systems. As shown in Figure 4-10, the 10/90 th percentiles show the ANX SBR had the most stable ESS profiles relative to the AER and ANA SBRs, and the latter varied most extensively. The three SBRs had similar median values for effluent suspended solids. The ANA and AER SBRs had a significant number of low ESS as well as high ESS concentrations. The extreme variability resulted in low median values with significantly greater average ESS values.

The high ESS for the AER reactor can partly be explained by the nature of the biomass generated in the reactor. As discussed previously, the AER sludge contained large quantities of dispersed cells while the ANA or ANX SBRs did not. The AER effluent generally had high concentrations of smaller flocs and dispersed cells. The ANA SBR often had larger, more granular flocs in the effluent which can partly explain the extreme variability in ESS concentrations. Although all three effluents were a yellowish-tan color, the ANX was generally clearer with some smaller flocs present in the effluent.

In addition to the ESS determinations, SVI values were monitored to evaluate SBR settling performance. In order to have the reactors operating at similar conditions, SVIs were determined for each SBR within the 2 hour time period just prior to the settling time in the SBR cycle. The SVI data collected are shown in Table B-10 in Appendix B. Table 4-6 contains SVI averages and standard error of the mean values for three time periods: 1) after nutrient increase (2/6/97) to the end of operation, 2) operation

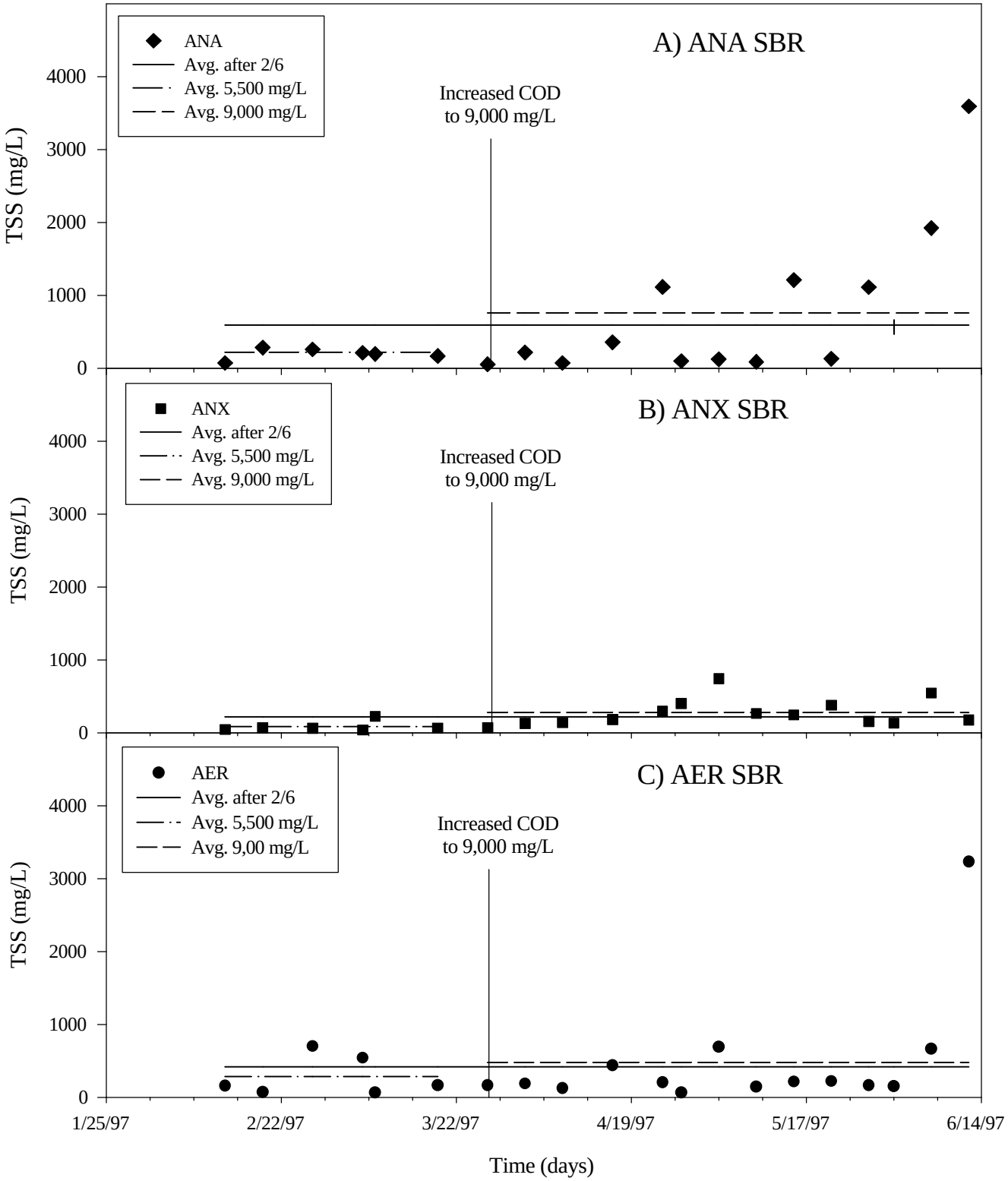

Figure 4-9: Effluent suspended solids concentrations (mg/L) for ANA, ANX, and AER SBRs after increase in nutrient loading (2/6/97).

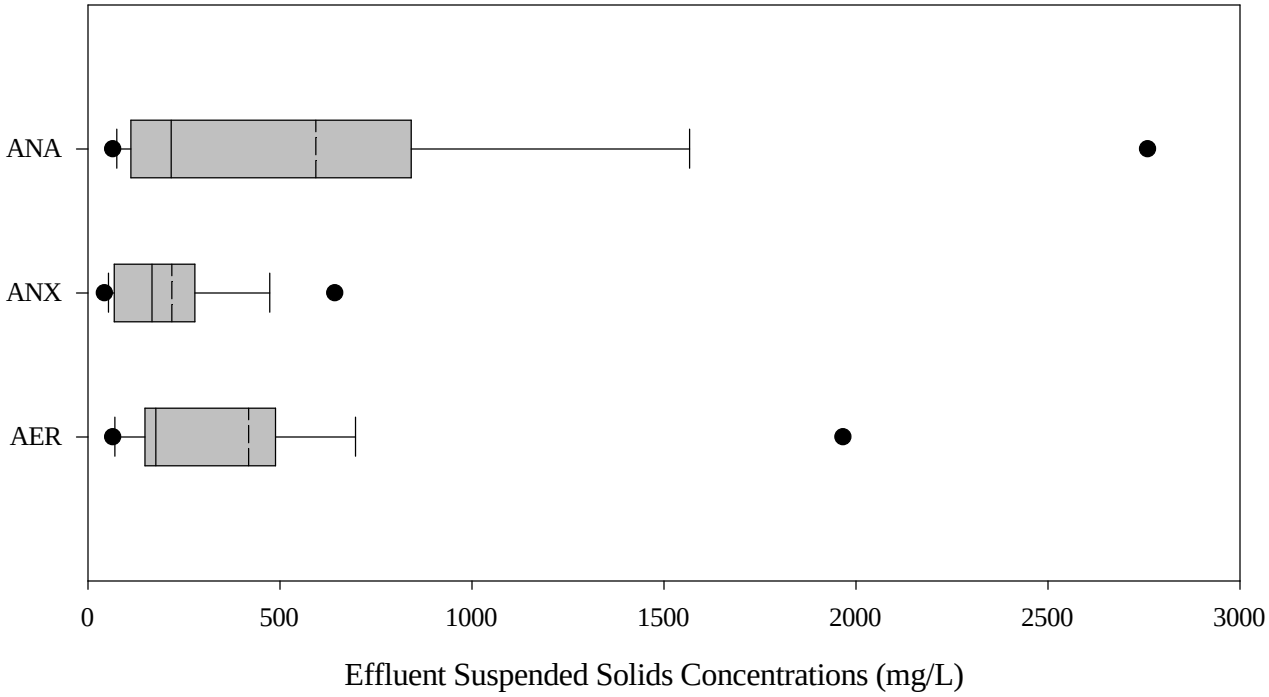

Figure 4-10: Box plots for ANA, ANX, and AER SBRs for effluent suspended solids concentrations (mg/L) after increase in nutrient loading (2/6/97). $5^{th}/95^{th}$ confidence intervals are shown with the black circles, 10^{th} and 90^{th} percentiles shown with lines, box represents $25^{th}/75^{th}$ percentiles, and median and mean values are represented by the solid and dashed lines, respectively.

at 5,500 mg/L COD (2/6 - 3/26/97) and 3) operation at 9,000 mg/L COD (3/26 - 6/12/97). The SVI values for all reactors are very low partly because of the high solids concentrations maintained in the SBRs. As seen in Figure 4-11, all three reactors would be classified as good settling systems because all three generally maintain SVI values below 150 mL/g.

Table 4-6: Sludge volume index averages for ANA, ANX, and AER SBRs after increasing nutrient loading (2/6/97)[a].

	ANA	ANX	AER
Avg. 2/6 - 6/12/97	72 ± 22[b]	39 ± 14	87 ± 26
# of data points	18	18	18
Avg. 2/6 - 3/26/97	91 ± 16	45 ± 15	109 ± 28
# of data points	7	7	7
Avg. 3/26 - 6/12/97	60 ± 15	34 ± 11	72 ± 10
# of data points	11	11	11

a = increased influent wastewater concentration from 5,500 mg/L to 9,000 mg/L as COD on 3/26/97
b = standard deviation

Lee *et al*. (1983) conducted several experiments using diluted SVI, SVI, stirred SVI and total extended filament length (TEFL) to determine the most effective parameters for evaluating sludge settleability. The authors state several reasons why diluted SVIs would be better than an SVI test. The SVI results have no consistent maximum value because the denominator constantly changes. Diluted SVIs would consistently use a given solids concentration which would allow the data to be collected on the same scale with a maximum value. Diluted sludges would have reduced time to reach the compression phase of settling (Lee *et al.*, 1987). The authors found the best correlation between diluted SVIs and TEFL. Although diluted SVIs were not performed during this study, SVI values were collected and are considered a legitimate basis for comparing the relative settling performance of the three SBRs.

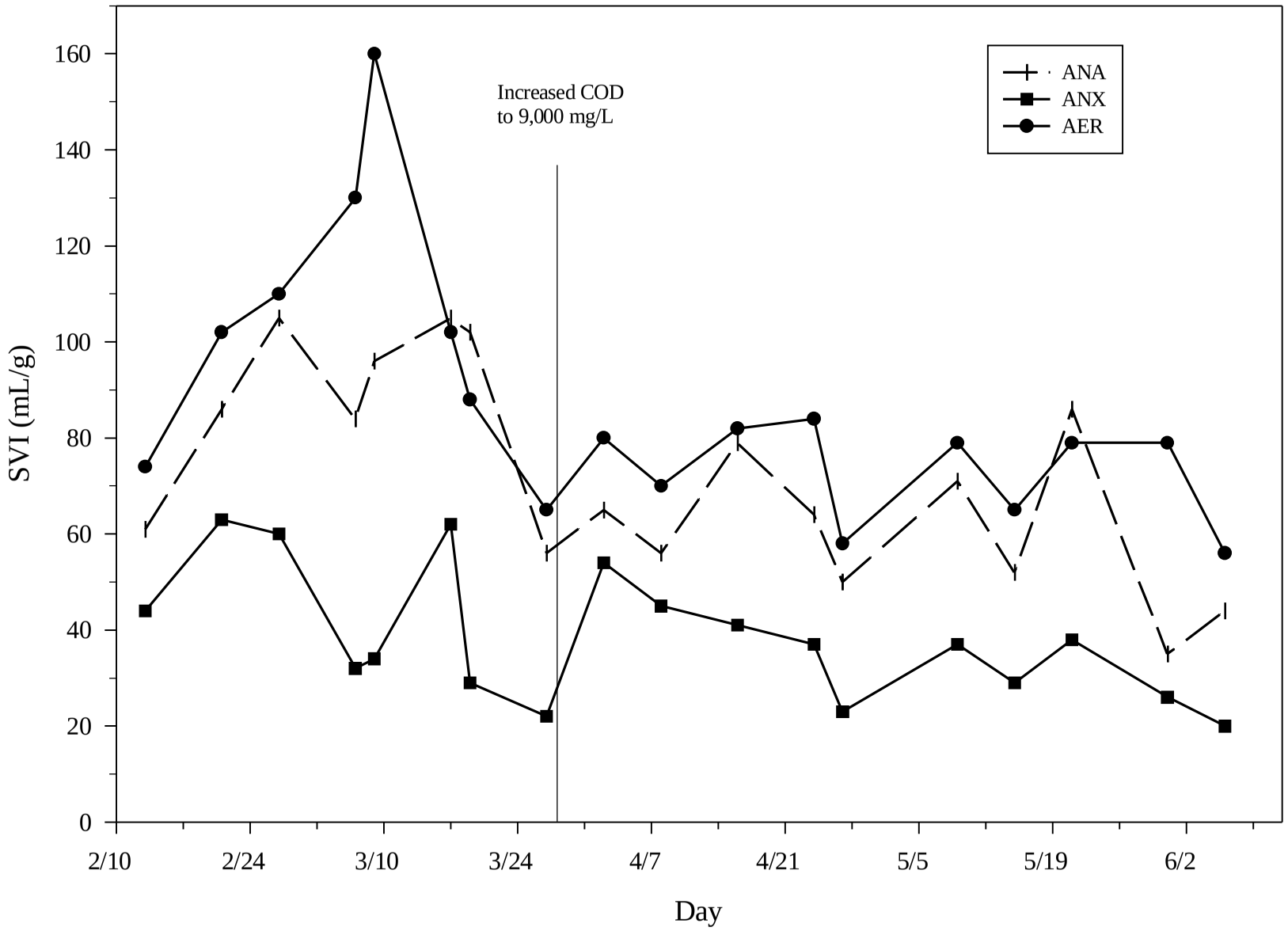

Figure 4-11: Sludge volume index data for ANA, ANX, and AER SBRs after nutrient increase (2/6/97).

Box plots, Figure 4-12, were made to compare the relative performance of the three SBRs based on SVI data. The 5 th and 95th confidence intervals for the ANX SBR showed that the ANX SBR generally produced lower SVI values than the ANA or AER SBRs. Wanner (1992) compared completely mixed activated sludge systems (anaerobic followed by aerobic) and an SBR operated with anaerobic and aerobic zones. Although both systems would be classified as good settling systems, the SVI values from the SBR were less than 100 mL/g and more stable than the conventional system, which produced SVI values between 100 - 200 mL/g and were significantly more variable.

Observations made during the SVI determination indicated that the ANA and ANX biosolids were able to settle more quickly than the AER sludge. The rapid settling of the ANA and ANX biosolids was due to the formation of large, granular solids which were able to settle more quickly than the dispersed AER sludge. Wanner (1992) ran zone settling velocities for the conventional activated sludge system, and the SBR and found that the SBR sludge was able to settle 2 - 5 times better than the sludge from the conventional system. Tanaka *et al*. (1991) studied the differences in operation between two parallel systems: a conventional activated system and one modified to operate anaerobically then aerobically. The SVI data for the two systems showed that the anaerobic/aerobic process not only improved setteability but also produced more consistent SVI values. The data indicated that a single sludge system operated with multiple redox environments produced sludge with enhanced settling properties.

As discussed previously, the SBRs did not contain significant populations of filamentous organisms after being reseeded. Sporadic foaming occurred for the SBRs prior to the increase in nutrient loading; however, significant foaming problems existed

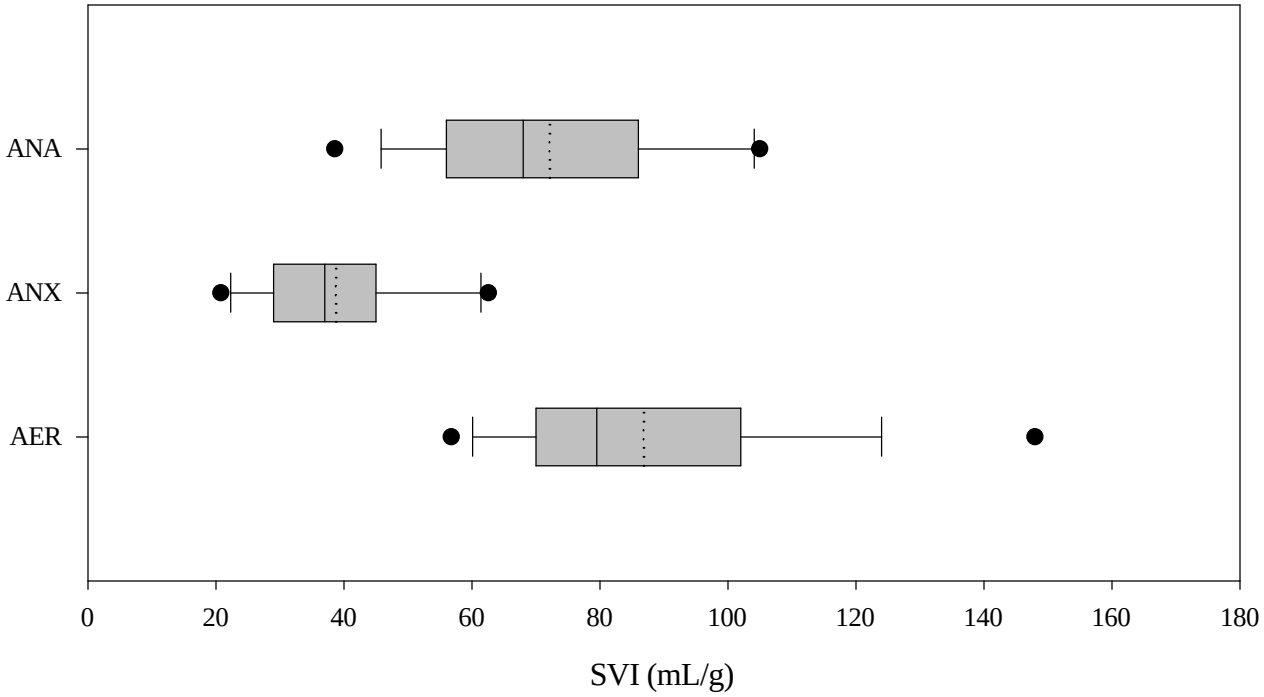

Figure 4-12: Box plots for ANA, ANX and AER SBRs for SVI (mL/g) after increase in nutrient loading (2/6/97).
5th/95th confidence intervals are shown with the black circles, 10th and 90th percentiles are shown with lines, box represents 25th/75th percentiles, and median and mean values are represented by the solid and dashed lines, respectively.

for both the ANA and AER reactors after the increase. Foaming did not occur during the anaerobic operation in the ANA SBR. The foaming began for both ANA and AER after several hours of operation under aerobic conditions. Large quantities of foam would bubble out of the top and sides of the ANA and AER SBRs. The foaming caused significant solids losses for both the ANA and AER SBRs. Unfortunately, monitoring the solids lost to foaming was very difficult. Every effort was made collect lost solids and return them to the SBRs. At no point did the ANX reactor experience foaming problems.

Degradation across reaction phases: Several reactor cycles were analyzed to determine the wastewater degradation patterns across the reaction phases. Under normal operating conditions, the wastewater was fed to the SBRs over a 15 minute time interval. In an attempt to get an accurate time zero concentration for the cycle, the wastewater was added manually to the SBRs. Wastewater addition occurred in approximately 2 minutes and the SBRs were allowed to mix for an additional 3 minutes prior to taking the first sample to ensure uniform initial concentrations.

Samples were taken over the entire 48 hour cycle. The two largest organic components in the synthetic wastewater, pivalic acid and acetic acid (42% and 34% of influent COD, respectively), were analyzed for each sample, as well as DOC. Nitrate was analyzed for the anoxic phase in the ANX SBR. Data collected during the cycle analyses are listed in Tables B-11, B-12 and B-13 in Appendix B. DOC, nitrate, pivalic acid and acetic acid concentration profiles are shown for one 48 hour cycle during the months of February, March and April in Figures 4-13, 4-14, and 4-15, respectively. During the February and March cycles the influent wastewater COD was 5,500 mg/L while the influent wastewater COD was 9,000 mg/L for the April cycle.

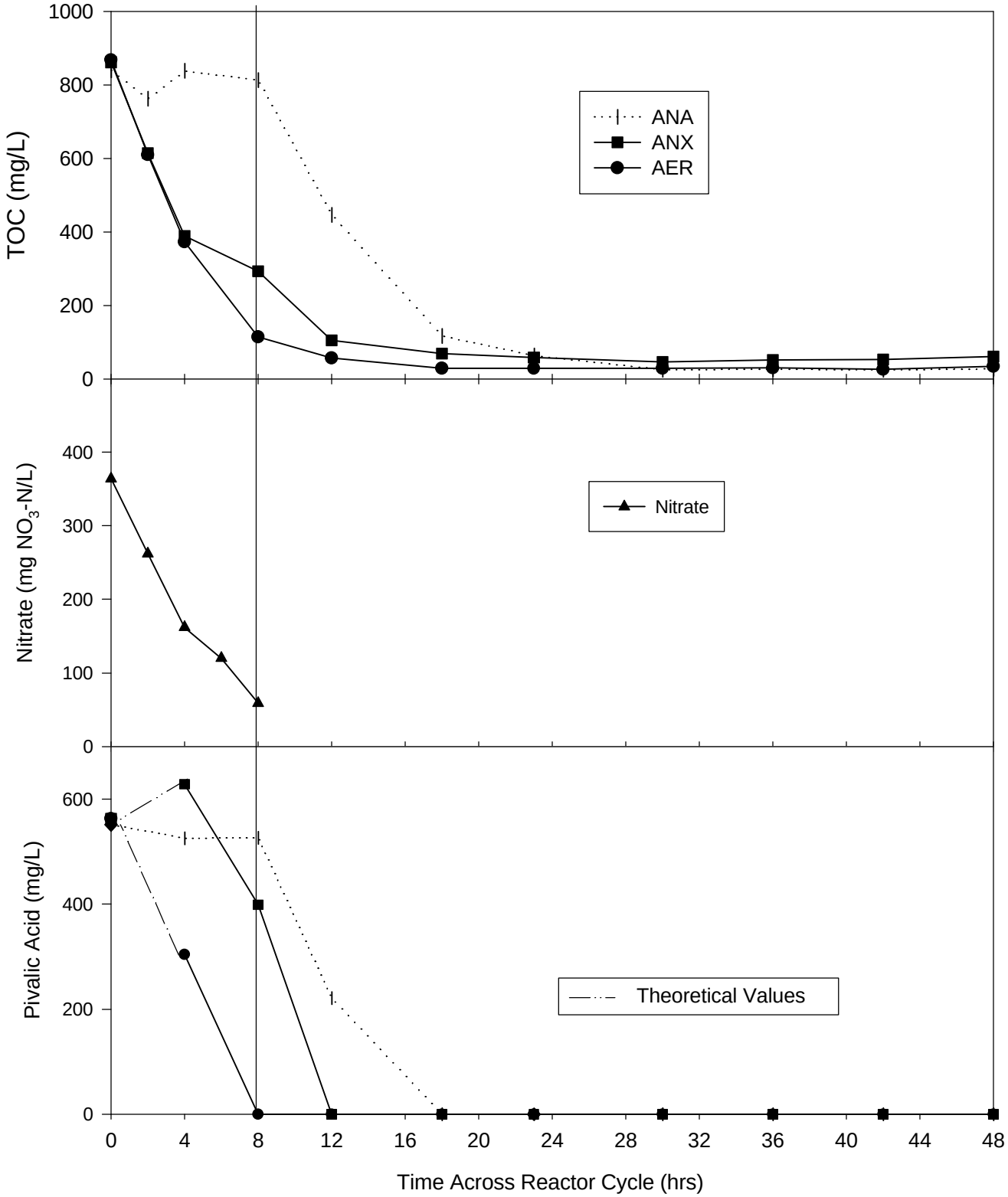

Figure 4-13: Analysis for ANA, ANX and AER SBRs across reaction phase for February 18-20, 1997 Influent Wastewater COD = 5,500 mg/L.

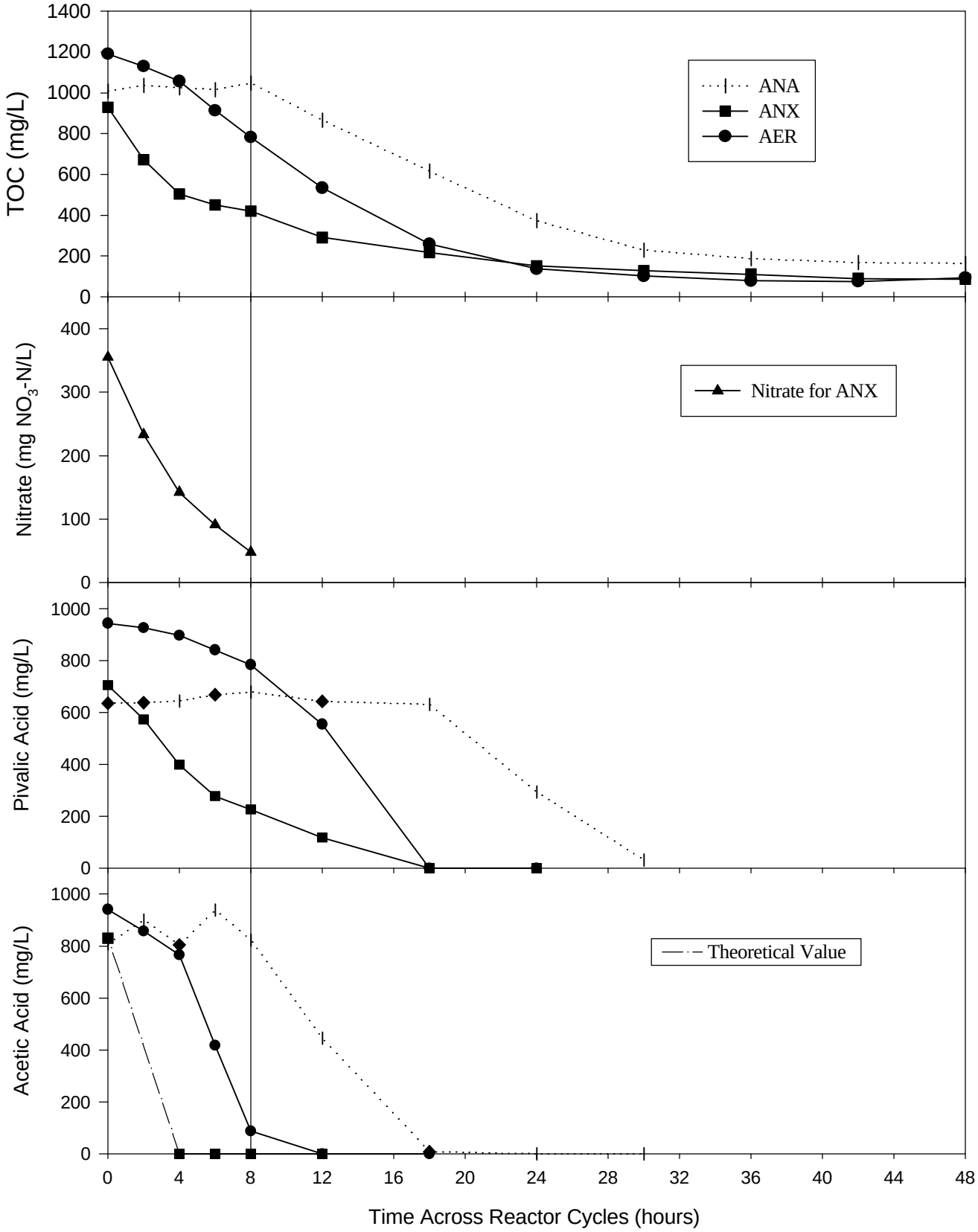

Figure 4-14: Analysis for ANA, ANX and AER SBRs across reaction phase for March 20-22, 1997 Influent Wastewater COD = 5,500 mg/L.

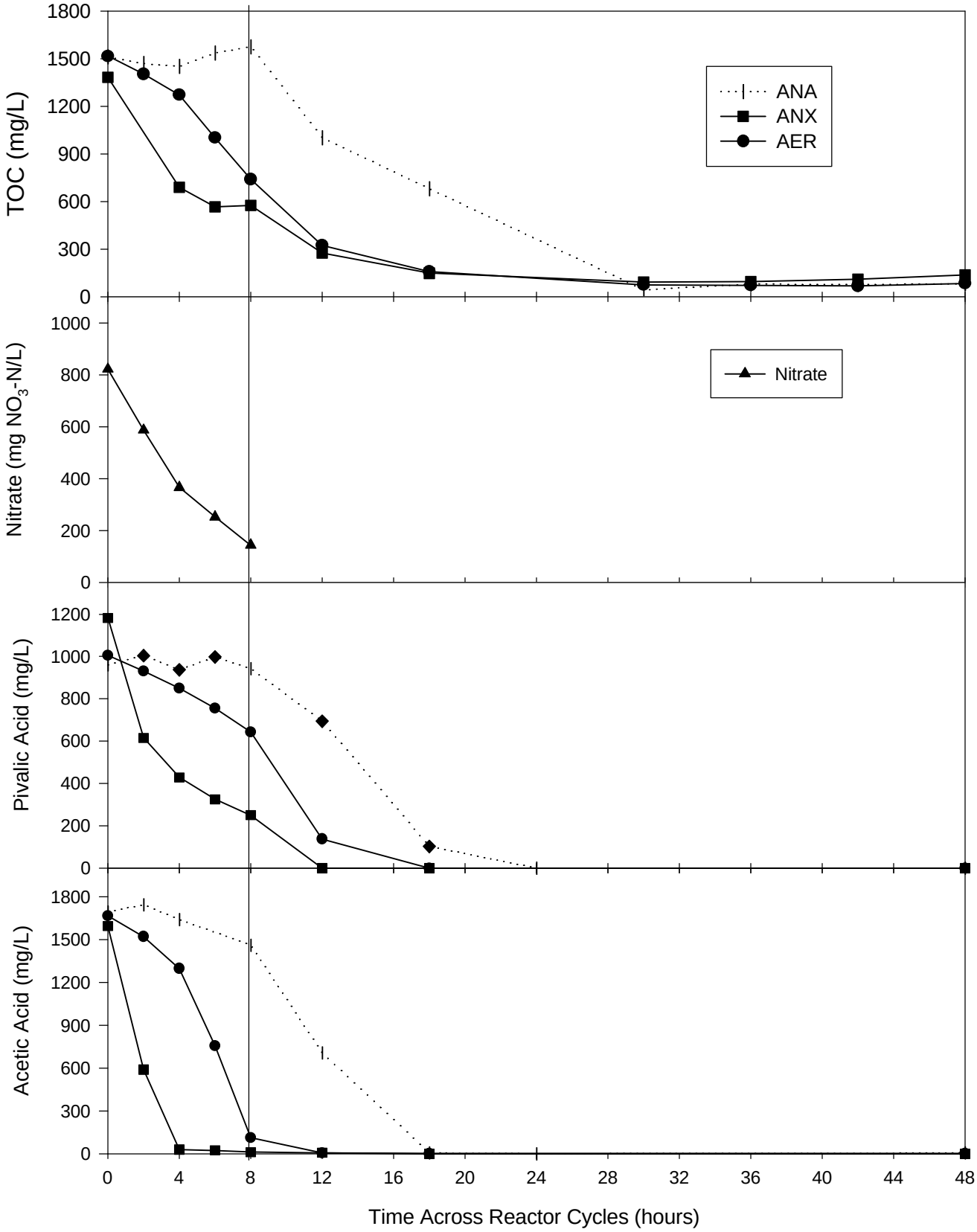

Figure 4-15: Analysis for ANA, ANX and AER SBRs across reaction phase for April 27-29, 1997 Influent Wastewater COD = 9,000 mg/L.

As shown in Figures 4-13, 4-14 and 4-15, no significant degradation of DOC occurred during anaerobic operation in the ANA SBR. Analysis of pivalic acid and acetic acid concentrations show little change for either compound across the anaerobic reaction time. The data indicated that fermentation of the COD was not occurring in the anaerobic zone. Although the anaerobic phase of treatment was unable to remove the COD, the ANA SBR was able to significantly degrade the wastewater. All degradation for the ANA SBR occurred during aerobic operation.

Under anoxic conditions, the ANX SBR degraded a significant fraction of the synthetic wastewater. The ANX SBR was consistently able to remove between 55 - 65 % of the DOC, with an average of 59%, while the AER SBR removals during the first 8 hours of operation ranged from 34 - 87%, with an average of 58%. One possible explanation for the difference in removals is the availability of the electron acceptor. Adequate nitrate was present throughout the initial 8 hours of operation while in the aerobic zone sufficient oxygen levels were difficult to maintain given the high level of MLSS. High front end organic loading during operation is a typical problem for aerobic SBRs. An initial anoxic phase would eliminate the oxygen limitation during the high initial organic loading.

Individual compound analysis showed that acetic and pivalic acids were degraded simultaneously under anoxic conditions, as shown in Figures 4-14 and 4-15. Acetic acid was completely degraded after 4 hours of anoxic reaction time with no significant lag prior to degradation. In the ANX SBR, pivalic acid degradation occurred more quickly while acetic acid was present with a significant decrease in the rate of consumption after acetic

acid was completely consumed. Additionally, the rate of pivalic acid degradation increased when the ANX SBR changed to aerobic operation.

Degradation of DOC in the AER SBR was generally slower during the first four hours of operation but increased after the initial lag time. As shown in Figures 4-14 and 4-15, pivalic acid and acetic acid degradation occurred simultaneously as it did in the anoxic phase; however, unlike the anoxic reactions, the degradation of pivalic acid increased after the acetic acid was completely consumed. Additionally, a 4 hour lag time existed before the degradation of DOC increased during 2 of the 3 cycles monitored. The lag prior to degradation could be due to low oxygen concentrations at the beginning of the cycle due to high organic loadings combined with high MLSS concentrations.

Substantial nitrification did not occur in any of the three SBRs as shown in Table B-43 in Appendix B. Several factors may contribute to nitrification inhibition: dissolved oxygen levels, temperature, pH, free ammonia, presence of inhibitory compounds (Yang and Alleman, 1992; Painter and Loveless, 1983). During this research, dissolved oxygen concentrations and temperature were satisfactory for nitrification. Due to pH values typically between 8.0 - 9.5, the free ammonia concentration in the SBRs may have inhibited nitrification. Additionally, compounds present in the wastewater may cause nitrification inhibition. Further studies would have to be done to determine the most critical inhibition effects of the wastewater. The synthetic wastewater contained high concentrations of organic acids which has been shown to cause nitrification inhibition (Eilerson *et al.*, 1994).

In all cases, complete degradation in the ANX and AER reactors took approximately the same amount of reaction time. The COD removed during anoxic

operation reduced the required aeration time for the ANX SBR. Although nitrate addition would be required, the reduced aeration demand could provide significant cost savings for a wastewater treatment plant (McClintock *et al*, 1988). When comparing the ANA and AER reactors, degradation appeared to take the same amount of aerobic time for both systems. The anaerobic environment did not enhance or adversely impact the degree of degradation that occurred in the aerobic zone. No benefit can be found for the anaerobic zone in terms of degradation capabilities of the ANA sludge compared to the ANX or AER SBRs fed the synthetic wastewater.

In order to look at the degradation patterns of pivalic acid and acetic acid, th e concentrations were converted to DOC based on 0.588 mg C/mg pivalic acid and 0.407 mg C/mg acetic acid, respectively. Pivalic acid and acetic acid concentrations as DOC are listed in Tables B-14 and B-15 in Appendix B for the March 20 - 22, 1997 and April 27 - 29, 1997 cycles, respectively. Figures 4-16 through 4-21 show the DOC concentrations for the March and April reactor cycles.

As seen in Figures 4-16 through 4-21, degradation patterns across the reaction phases did not change with an increase in wastewater COD for each SBR system. Additionally, the time required to complete degradation did not significantly change for any SBR with the increase in wastewater COD. Under both wastewater conditions and in all SBRs, there was a significant fraction of DOC that could not be degraded. The DOC remaining at the end of each cycle was generally less that the DOC provided by the wastewater constituents other than pivalic acid and acetic acid. Consequently, it is unclear whether the remaining DOC consisted of: original compounds that were not degraded, intermediates that were not degraded further, soluble microbial products produced by the

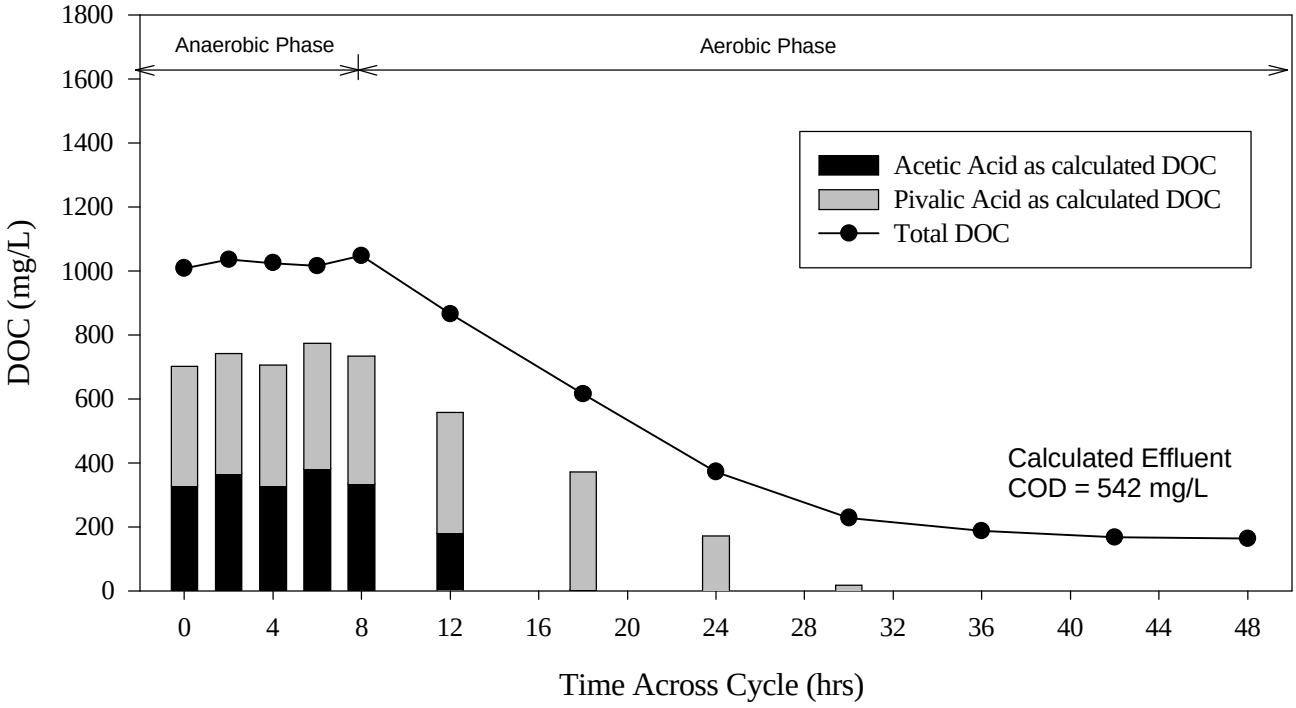

Figure 4-16: Analysis for ANA SBR across reaction phase on March 20-22, 1997 Influent Wastewater COD = 5,500 mg/L.

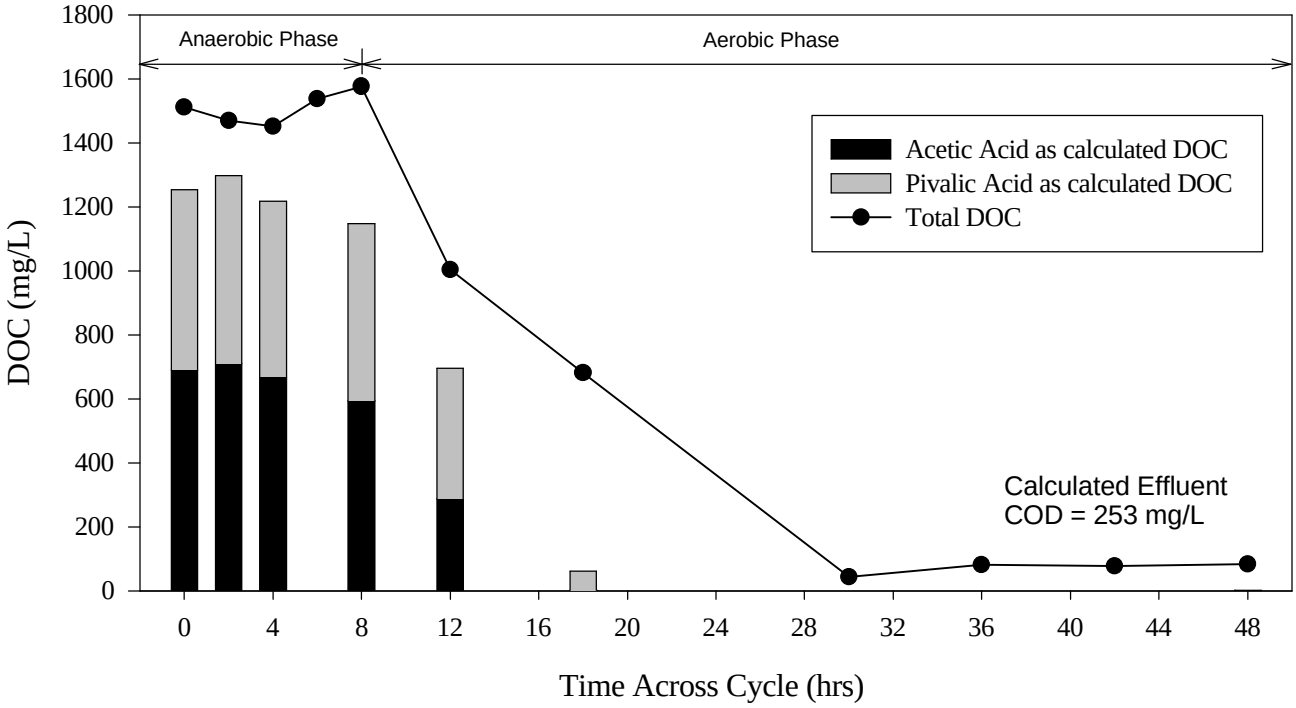

Figure 4-17: Analysis for ANA SBR across reaction phase on April 27-29, 1997 Influent Wastewater COD = 9,000 mg/L.

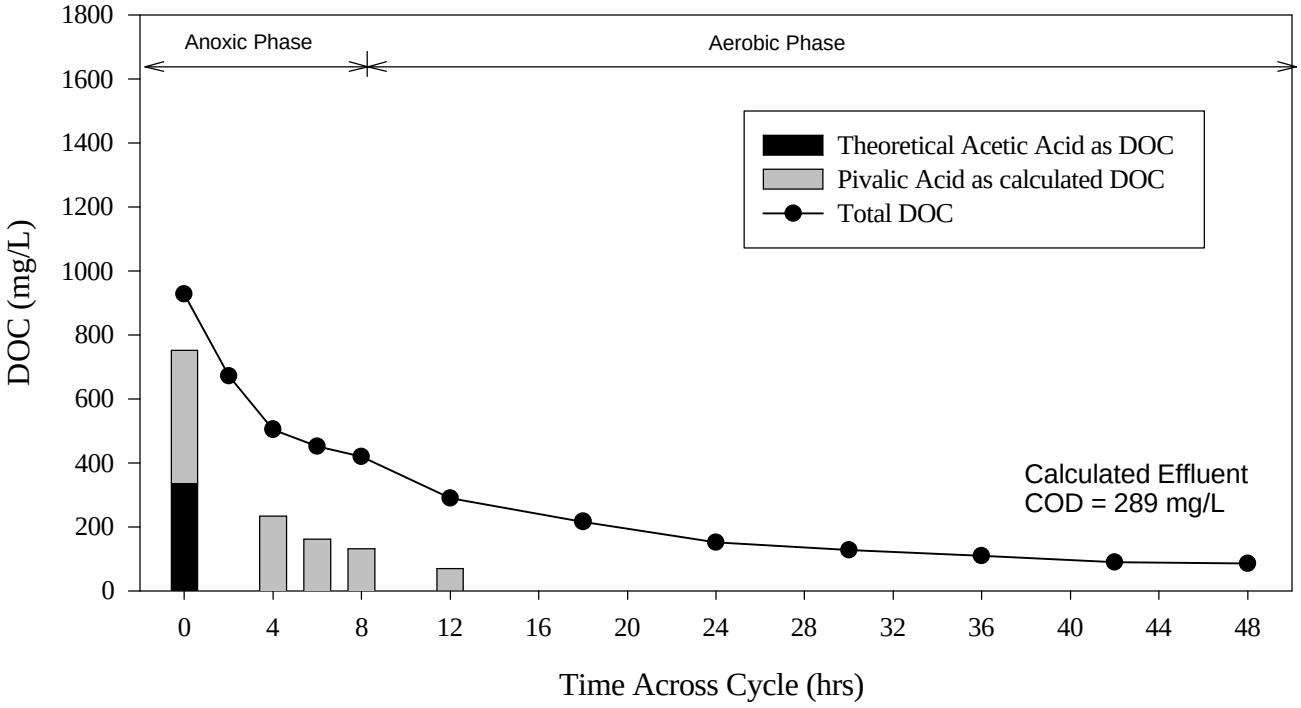

Figure 4-18: Analysis for ANX SBR across reaction phase on March 20-22, 1997 Influent Wastewater COD = 5,500 mg/L.

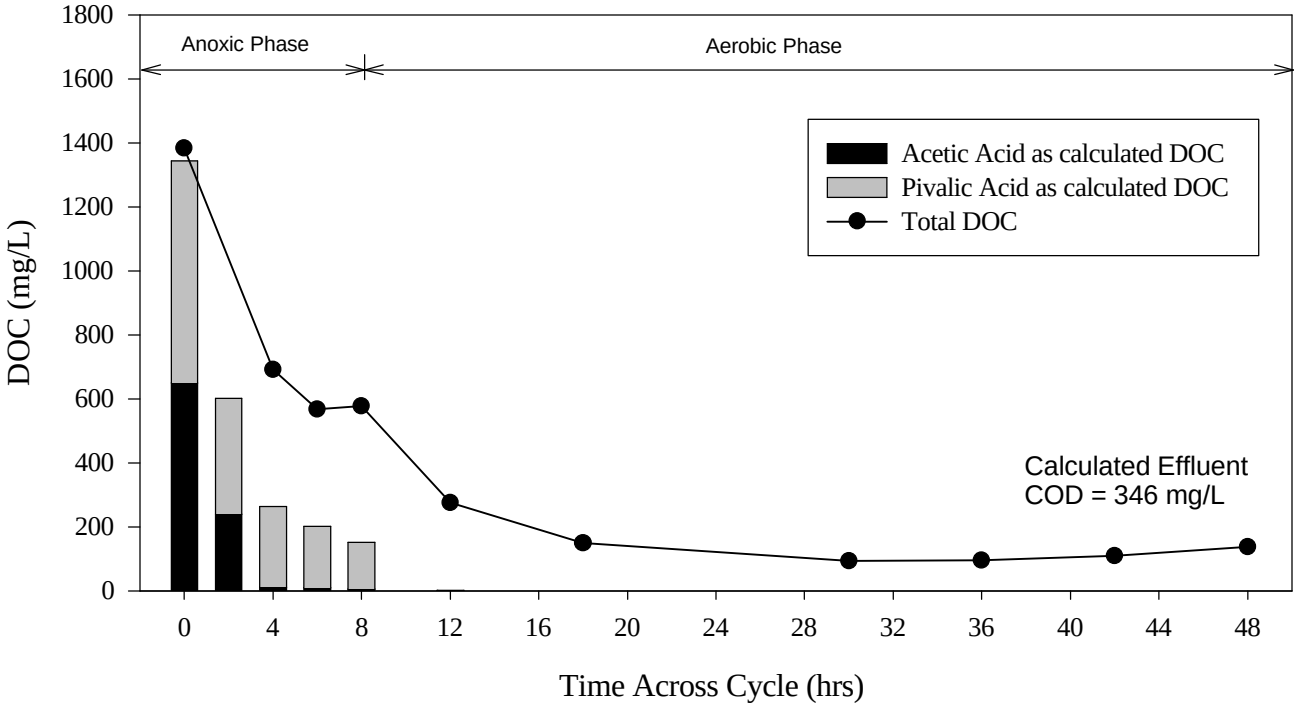

Figure 4-19: Analysis for ANX SBR across reaction phase on April 27-29, 1997 Influent Wastewater COD = 9,000 mg/L.

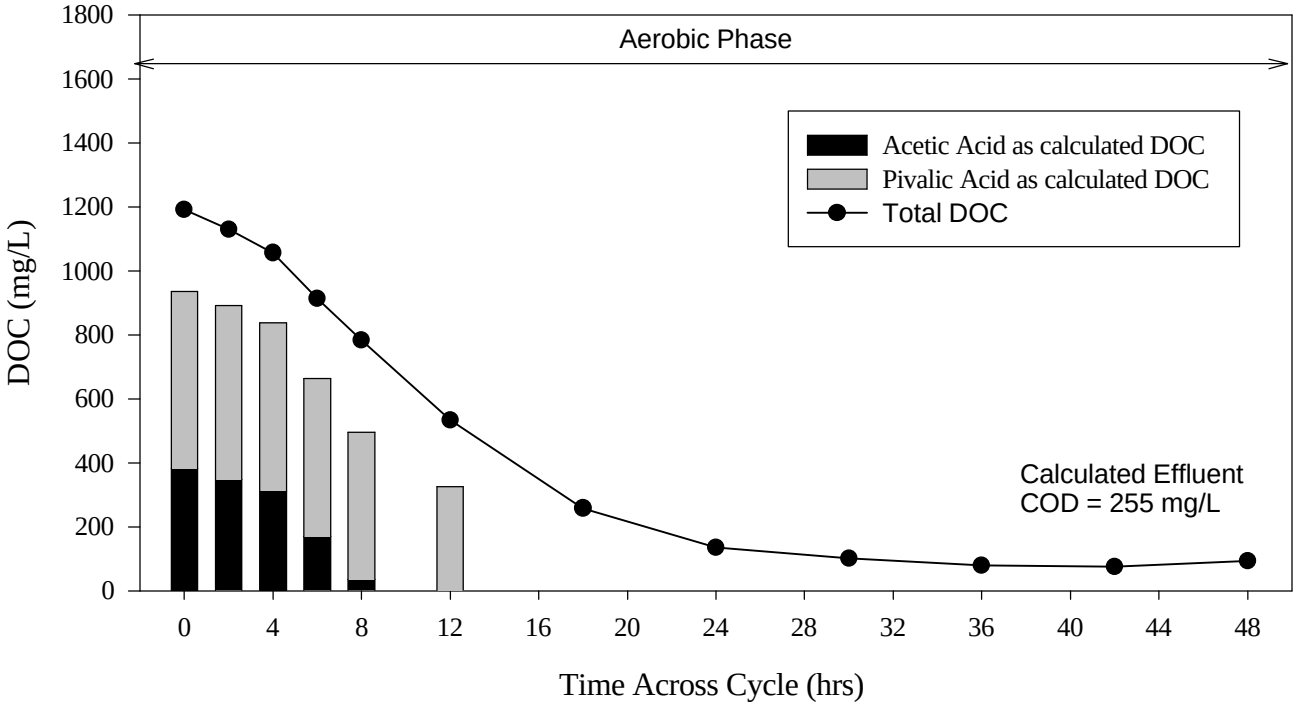

Figure 4-20: Analysis for AER SBR across reaction phase on March 20-22, 1997 Influent Wastewater COD = 5,500 mg/L.

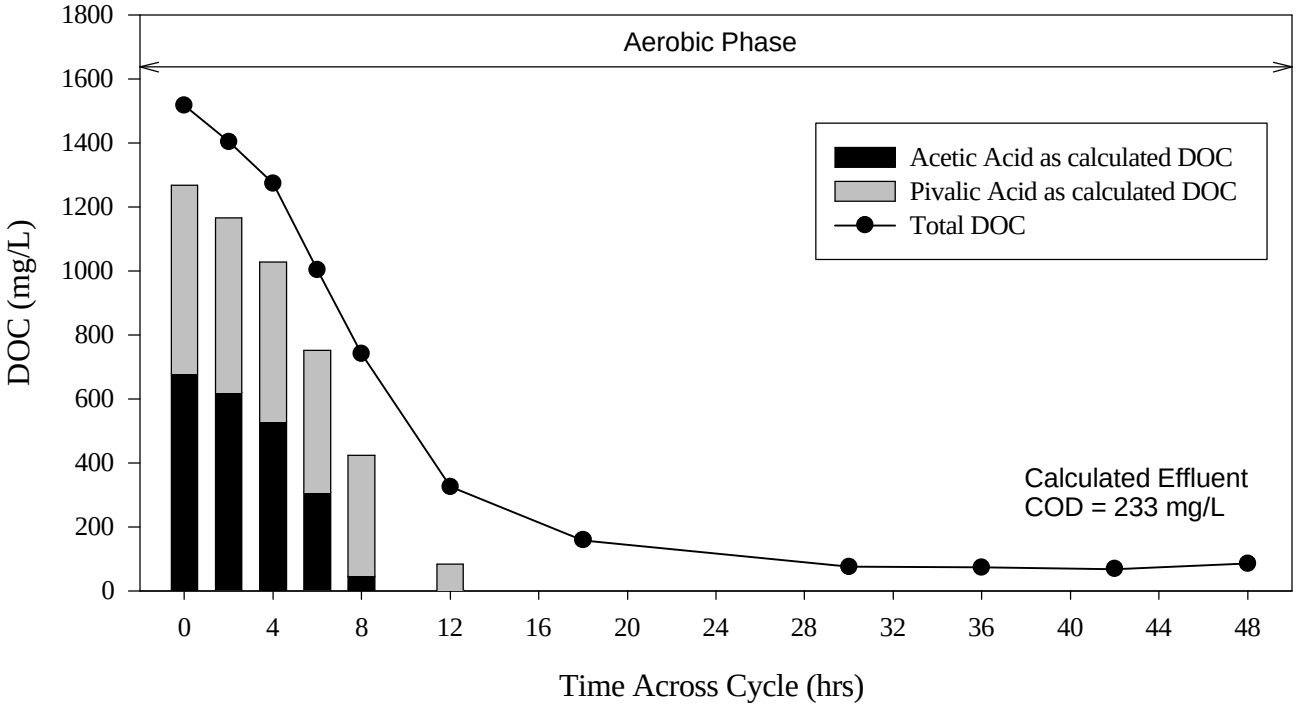

Figure 4-21: Analysis for AER SBR across reaction cycle on April 27-29, 1997 Influent Wastewater COD = 9,000 mg/L.

bacteria or some combination of these options. The data suggest that an increase in reaction time would not increase the degree of degradation for any of the SBR systems. The systems did not achieve the effluent limitation of 100 mg/L as COD (see Figures 4-8 and 4-16 through 4-21).

ANA-T, ANX-T, and AER-T Performance

Routine Monitoring: Routine monitoring for ANA-T, ANX-T and AER-T occurred from April, 1997 to June, 1997. Tables B-16 and B-17 in Appendix B contain data collected for these reactors.

Several differences existed between the synthetic wastewater and the Industry's wastewater. The Industry wastewater used during this research was collected from the NPG waste stream (see Table 2-1). As discussed in the Materials and Methods chapter, pivalic acid was substituted in the synthetic wastewater for hydroxypivaldehyde. Additionally, at the beginning of the research the exact composition of the organic salts present in the wastewater was unknown. Potassium acetate was chosen to represent all COD constituted by the organic salts. Later it was determined that sodium formate, sodium hydroxypivalate, and sodium butyrate constitute most of the organic salts in the industrial wastewater. Several additional compounds are present in the Industry's wastewater that were not included in the synthetic wastewater: formaldehyde, i-butanol, i-butyraldehyde, n-butyraldyhyde, n-butanol, and n-propanol (see Table 2-1). The additional compounds make up approximately 30% of the total COD in the Industry's wastewater. Several intermediate compounds that have been identified may also be present in the wastewater including: C10 acetal, C10 ester, and 2,2,4-trimethyl-3-hydroxypentanal. The differences in performance between the SBRs fed synthetic and

industrial wastewaters were significant in the extent of degradation and degradation patterns in the SBRs.

Effluent Quality: The industry SBRs were seeded with sludge exposed to the multiple redox environments and the synthetic wastewater. Because the industrial wastewater was also diluted with the MSM, to provide the essential nutrients, the high chloride and salt concentrations interfered with COD measurements as they did with the main SBRs. Effluent analysis for the side SBRs was based on DOC concentrations. The effluent DOC data collected for the ANA-T, ANX-T, and AER-T SBRs are presented in Table B-18 in Appendix B. The influent wastewater had a COD:DOC ratio of 2.88; however, no attempt was made to convert effluent DOC concentrations to COD values.

Table 4-7: Average effluent DOC concentrations (mg/L) for ANA-T, ANX-T and AER-T SBRs[a].

	ANA	ANX	AER
Average DOC	215	265	207
Standard error of the mean	5	2	7
# of data	12	12	12

a = values calculated for DOC data after 5/19/97

As shown in Figure 4-22, ANA-T and ANX-T accumulated significant DOC concentrations during the first few weeks of operation. However, the AER-T SBR was able to degrade the wastewater with no significant lag time and no accumulation of DOC. After several weeks, the ANA-T and ANX-T were also able to significantly degrade the wastewater. However, unlike the main SBRs, fed the synthetic wastewater, the ANA-T and AER-T SBRs were able to degrade the industrial wastewater to a greater extent than the ANX-T SBR. The effluent DOC concentrations from the industry SBRs were much less variable than the effluent DOC values from the main SBRs, even though both systems were fed constant COD wastewaters. Average effluent DOC values and standard

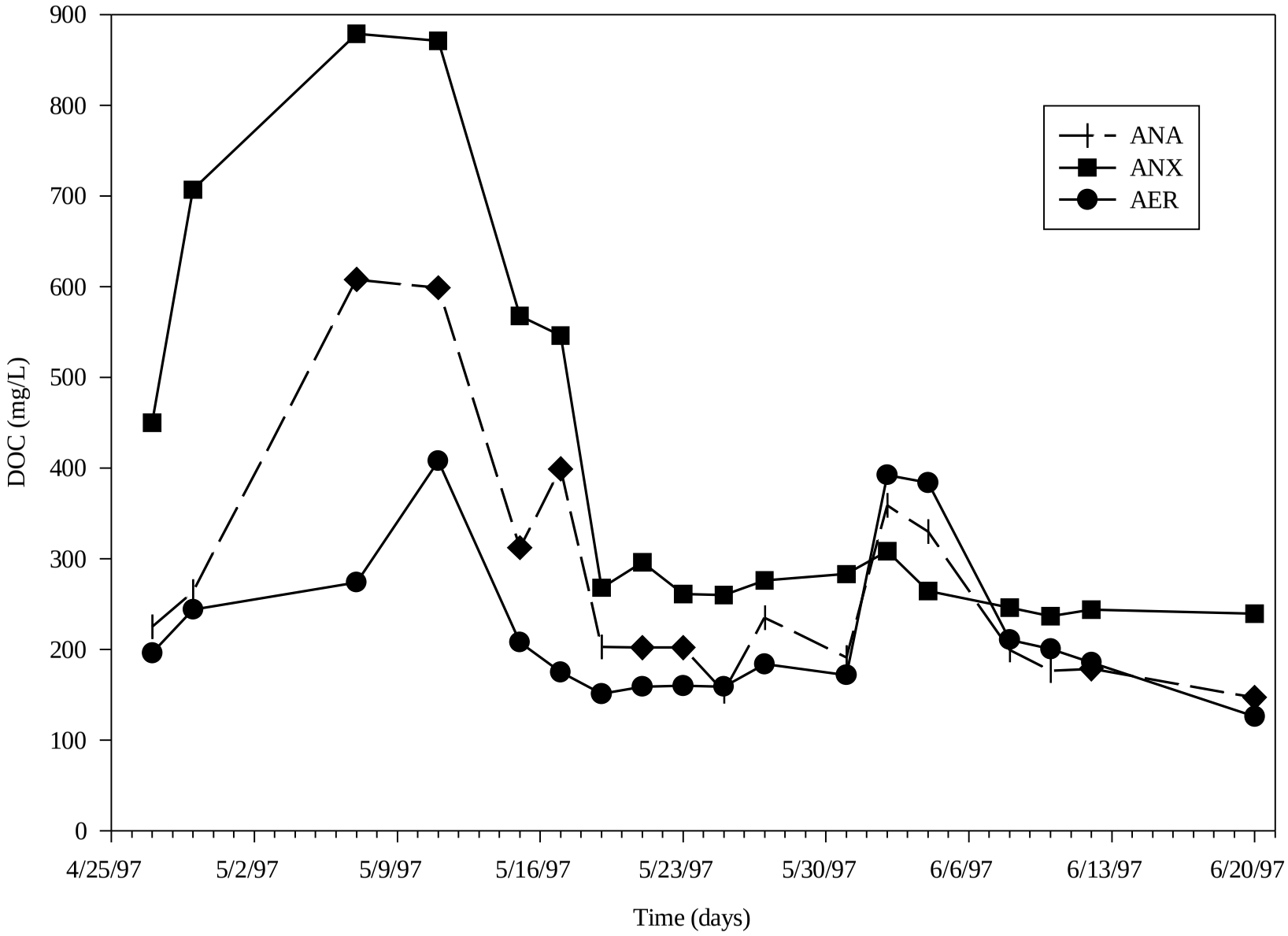

Figure 4-22: Effluent dissolved organic carbon concentrations (mg/L) for ANA-T, ANX-T, and AER-T SBRs.

error of the means were calculated for the industry SBRs after reduction of the accumulated DOC (5/19/97). The average and standard error of the mean values are listed in Table 4-7. Although substantial degradation occurred for the ANA-T and AER-T SBRs, the effluent limit of 100 mg/L as COD was not achieved for any system.

Degradation across reaction phases : Analysis of the degradation patterns for the side SBRs provided interesting results when compared to the main SBRs. Two analyses were done across the cycle for the industry SBRs. The data collected, DOC and nitrate (ANX-T only) for the April 27-29, 1997 and May 17-19, 1997 cycles, are presented in Tables B-19 and B-20 in Appendix B, respectively.

As shown in Figures 4 -23 and 4-24, no degradation occurred during anaerobic operation of the ANA-T which is similar to results observed for the ANA SBR fed the synthetic wastewater. The substitutions in the wastewater did not seem to influence the degradation of the wastewater in the anaerobic zone. Because analysis of individual compounds could not be done, fermentation cannot be eliminated as a possible degradation pathway during anaerobic operation. Young *et al.* (1996) operated their reactors for several weeks with a 20 day SRT and then increased to a 40 day SRT for the remaining test period. The increase in SRT did not increase the degradation of the individual waste streams or the mixture of the three streams. Young *et al.*(1996) found that the NPG waste stream was 55% degradable under anaerobic conditions shown by cumulative methane production and solids determinations; however, the anaerobic reactors operated with an HRT equal to the SRT which was 10-20 times greater than the HRT for the industry SBRs. Unlike Young's work, anaerobic degradation was not achieved with the ANA-T SBR over the time period studied. Performance differences

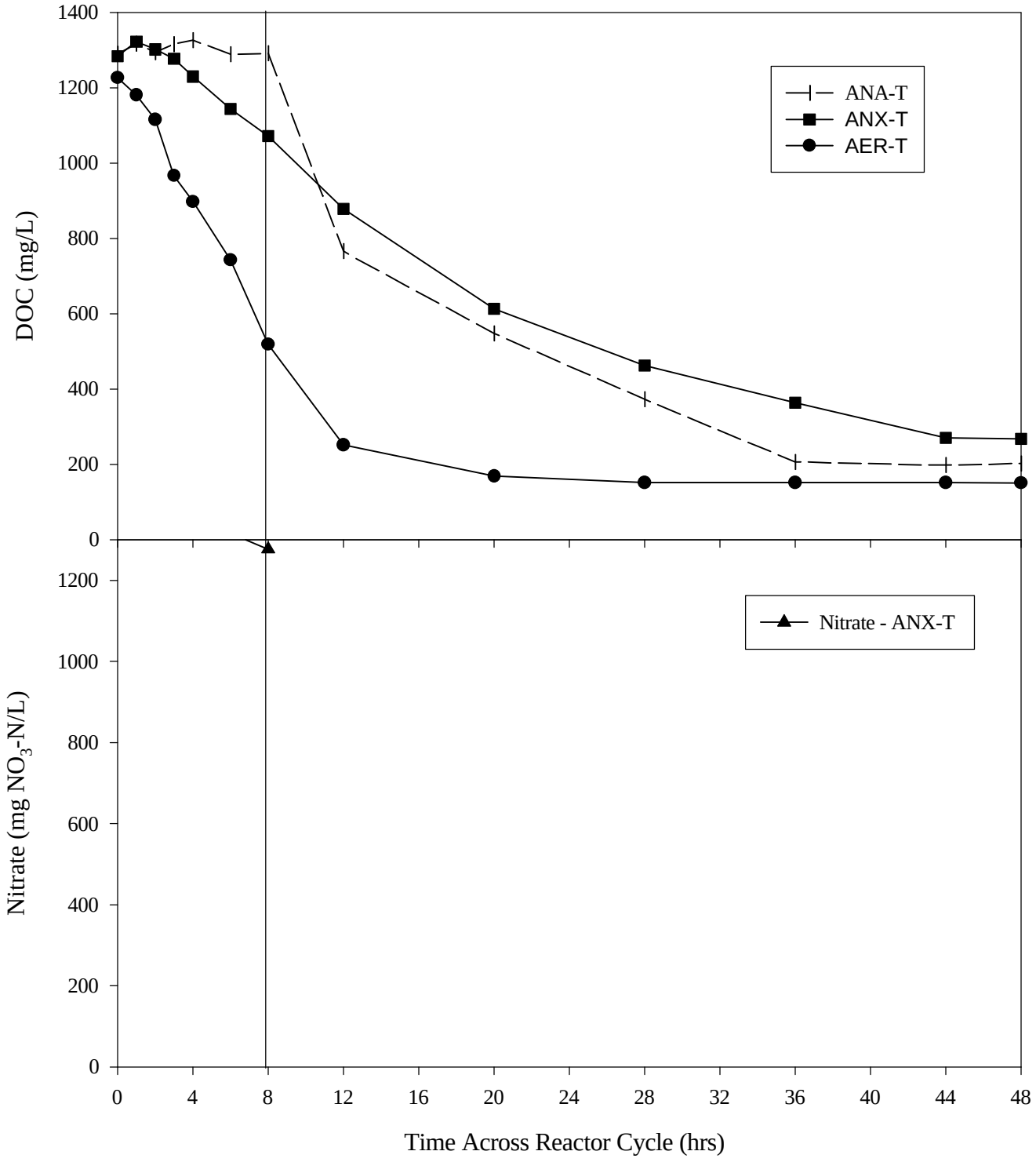

Figure 4-23: Analysis for ANA-T, ANX-T, and AER-T SBRs for April 27 - 29, 1997.

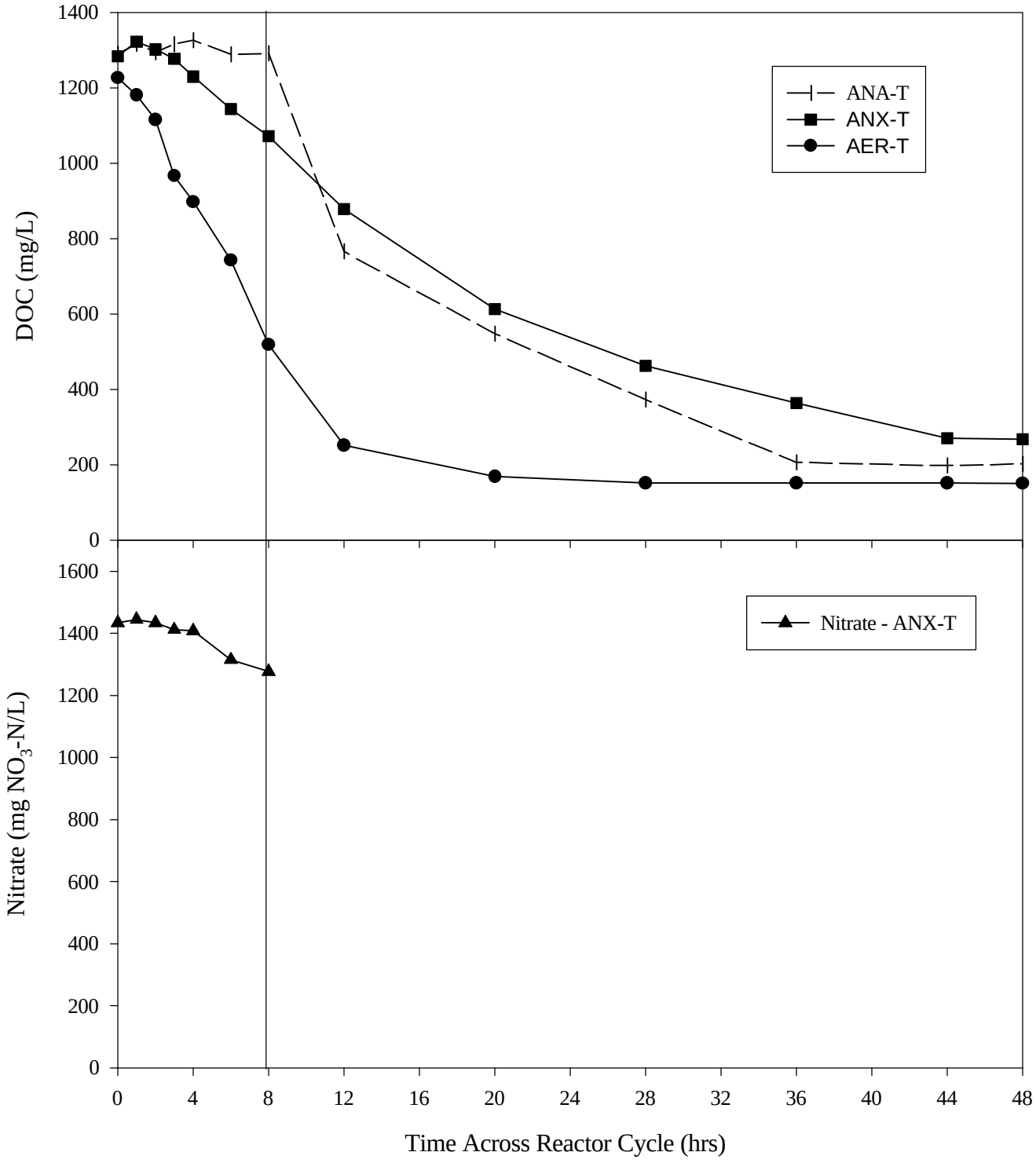

Figure 4-24: Analysis for ANA-T, ANX-T, and AER-T SBRs for May 17 - 19, 1997.

between these two studies could relate to the fact that the reactors maintained by Young and coworkers were strictly anaerobic and probably achieved lower redox potentials than the alternating anaerobic/aerobic single sludge SBRs maintained in this study.

Although anaerobic degradation pathways were not significantly affected by the substitutions made in the synthetic wastewater, the anoxic treatment was significantly different. Degradation during anoxic operation for the ANX-T was limited to approximately 15% removal while nearly 60% removal could consistently be achieved in the main SBRs fed the synthetic wastewater. The industrial wastewater contained nearly 44% and 28% of aldehyde and butanol compounds as COD, respectively. Neither of these classes of compounds were represented in the synthetic wastewater. Aldehyde degradation requires a conversion of the aldehyde to a carboxylic acid (Gottschalk, 1986). The results suggest the anoxic zone was unable to degrade the aldehyde compounds. Nitrate consumption was limited during anoxic operation and nitrate accumulated in the ANX-T SBR, as shown in Figures 4-23 and 4-24. During the last 3 cycles, nitrate addition was stopped and no significant effect was seen on the effluent DOC. The May reaction phase profile was analyzed after the SBRs had been exposed to the industrial wastewater for approximately 5 weeks. The overall degradation of the ANX-T SBR improved dramatically compared to the April analysis, but DOC removal during anoxic operation did not improve.

Aerobic operation provided substantial degradation of the industrial wastewater for all SBRs. The improvement in degradation after prolonged exposure to the industrial wastewater increased degradation in the AER-T only slightly but provided dramatic improvement in the aerobic operation of the ANX-T SBR. Degradation continued in

both ANA-T and ANX-T for nearly 44 hours of total reaction time while in the AER-T SBR degradation stopped after 12 - 20 hours.

The AER-T provided between 80-85% removal of the COD which coincides with the 79% COD removal Young (1996) reported for the NPG waste stream under aerobic conditions with a 10 day SRT and HRT. The data from the industry SBRs suggested that aerobic treatment would provide the most complete and cost effective removal of COD from the industrial wastewater.

The Asian facility has incorporated several modifications to the manufacturing area which have significantly impacted the composition of the waste streams. With these changes, the synthetic wastewater more closely mimics the Industrial wastewater at the Asian facility than the U.S. industry wastewater, with the exception of the HOHPv and the organic salts. However, as noted earlier, the substitution of pivalic acid for HOHPv and acetic acid for a more complex mixture of organic salts had a significant effect on the outcome of this study, especially for the ANX and ANX-T SBRs.

Kinetic parameters were determined for DOC uptake in the ANA-T, ANX-T, and AER-T. The data used to determine the kinetic parameters are listed in Tables B-19 and B-20. Zero and first order kinetics were analyzed for the different operational conditions: 1)ANA-T: aerobic uptake, 2) ANX-T: aerobic uptake and 3) AER-T: aerobic uptake. The experimental data, zero order equation and first order equation for each case are shown in Figures B-2 through B-7; parameters determined using linearization methods. Mean sum of squares of errors (MSSE) was used to determine the best model fit to the raw data.

Table 4-8: Zero Order and First Order Kinetic Parameters for ANA-T, ANX-T, and AER-T SBRs from April and May reaction cycles.

	April		May	
	Zero[a]	First[b]	Zero[a]	First[b]
ANA-T: aerobic uptake	**	0.014	**	0.013
ANX-T: aerobic uptake	**	0.0046	**	0.0073
AER-T: aerobic uptake	16.1	**	17.0	**

a = units mg DOC/g MLVSS-day b = units: L/g MLVSS-day
** = model fit not reported because alternate model MSSE lower

Kinetic parameters determined for the ANA-T, ANX-T, and AER-T SBRs are listed in Table 4-8. Note the parameters were normalized to mixed liquor volatile suspended solids to eliminate rate differences due to changes in biomass concentration. An example of first order degradation is shown in Figure 4-25 for ANA-T aerobic degradation. The wastewater degradation for the aerobic phases of ANA-T and ANX-T were modeled by first order kinetic model while the AER-T degradation followed the zero order model. An example of zero order degradation is shown for the AER-T SBR in Figure 4-26. The first order parameters for the ANA-T SBR were 2-3 times greater than those for the ANX-T SBR. While fermentation was shown to be minimal during the anaerobic phase of degradation of the synthetic wastewater studies, it cannot be ruled out here because specific compounds were not monitored. Although DOC concentrations were stable during the anaerobic phase of the industry SBR studies, higher aerobic rates of DOC degradation may have resulted from anaerobic fermentation. Zero order DOC degradation kinetics in the AER-T SBR resulted in faster DOC degradation overall for the three industry SBRs. In order for the AER-T SBR to demonstrate zero order kinetics in the presence of the same wastewater fed to the ANX-T and ANA-T SBRs, the AER-T

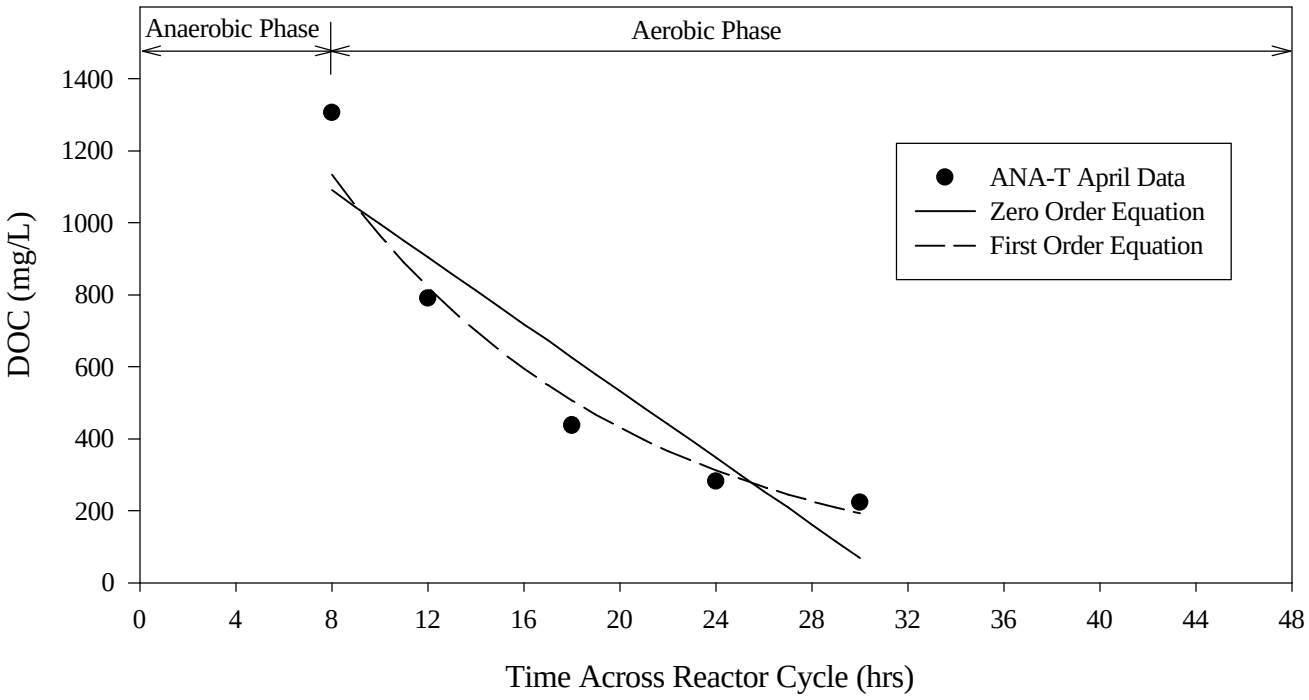

Figure 4-25: An example of ANA-T first order wastewater degradation. Data are from ANA-T April 27 - 29,1997 reactor cycle. Note the equations predict degradation during the aerobic phase of ANA-T operation.

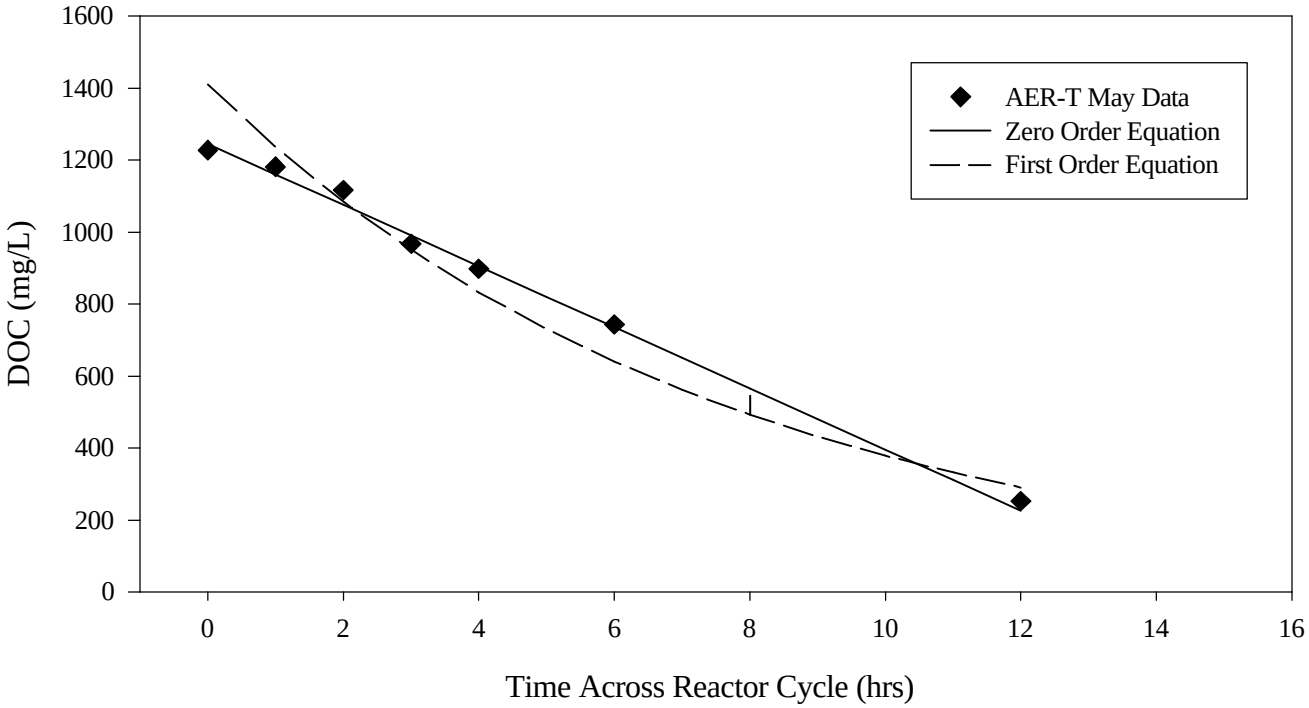

Figure 4-26: An example for AER-T zero order wastewater degradation. Data are from the AER-T May 17 - 19, 1997 reactor cycle.

biosolids must have a lover half saturation constant (K_s) overall if Monod kinetics hold. The reason for the shift is unclear.

The anoxic phase of the ANX-T SBR appears to have a biphasic DOC uptake as shown in Figures 4-23 and 4-24. The change in degradation seen in the ANX-T SBR is similar to that seen in the ANX SBR. For the synthetic wastewater, the individual compounds were analyzed to explain the shift in degradation rates. The compounds for the ANX-T SBR were unknown; however, the change in degradation rate could be due changes in the compounds being degraded.

GAC Isotherm Studies

Sand Filter Performance : Effluent from the ANA SBR was collected at the end of each cycle beginning 5/21/97 and filtered through the sand filter. Flow of 1 -2 gpm/ft^2 was maintained through the sand filter. The flow data collected from the filter operation is listed in Tables B-21 - B-26 in Appendix B. For 5 filter runs, effluent suspended solids were measured prior to filtration and again after filtration. The average suspended solids concentrations in the ANA effluent were 1380 mg/L prior to filtration and 25 mg/L ESS after filtration. After filtration the effluent was then stored at 4° C until use in the isotherm studies. The average DOC concentrations of the ANA effluent prior to filtration was 59 mg/L and combined effluent from the filter had an average DOC concentration of 50 mg/L.

GAC Studies : As discussed in the materials and methods chapter, several different batch experiments were run to collect the GAC data. The data collected from the experiments are presented in Tables B-27 - B-42 in Appendix B.

Experiments were conduct ed in three batches in an attempt to find the correct range of GAC masses and guarantee that enough data were collected to estimate isotherm parameters. Several experiments were run to collect GAC isotherm data. In the first experiment, the GAC ranged from 2.5 g - 0.1 g. The data collected from experiment #1 showed there was a level at which no additional DOC was sorbed with additional GAC suggesting that a nonsorbable fraction existed in the effluent. A second experiment was run using GAC masses ranging from 1.5 g - 0.1 g. The data collected from the second experiments also showed a nonsorbable fraction. A final experiment (#3) was run to supplement the data collected from experiment #1. The Calgon data that was collected could not be used to determine isotherm parameters because the Calgon GAC sorbed all measurable DOC in every assay vial leaving only a nonsorbable fraction. Calgon GAC was the only carbon used during this study that was pulverized by the manufacturer and was more fine than the hand pulverized GAC: Unisorb AGL, Unisorb AC, Norit 830 and Norit 3000. The GAC was pulverized prior to use in the isotherm studies to minimize the effect of transport and diffusion mechanisms during adsorption of the compounds onto the GAC. This may have influenced the results by providing more available sites for adsorption per mass of carbon; consequently the Calgon data are not comparable and are not presented here.

As discussed in the literature review, some compounds are highly sorbed and will dictate the isotherm parameters causing incorrect parameter determination. Ponitus (1990) suggests eliminating the nonsorbable fraction and the highly sorbable fraction and using the remaining data to estimate the isotherm parameters. Use of the nonsorbable fraction will increase the amount of GAC required with no increase in effluent quality. The

highly sorbable fraction can sorb very quickly and can change surface characteristics of the GAC. The isotherm data collected from the experiments showed that a highly sorbable fraction as well as a nonsorbable fraction existed in the ANA effluent after filtration (see Figures 4-27 and 4-28).

Ng *et al.* (1987) conducted isotherm studies on a refinery wastewater treated with biological treatment. The authors suggested the formation of metabolic end products (MEP, also called soluble microbial products, SMP) composed of metabolites and cellular components of lysed cells could have caused abnormal isotherm results. Studies by Shultz (cited in Ng *et al.*, 1987) suggested that up to 75% of the MEP could be irreversibly sorbed to the carbon and that MEP could severely influence the adsorption parameters, especially when the wastewater contains low amounts of adsorbable compounds. As shown in Figures 4-27 and 4-28, the isotherms generated from this study were representative of MEP-influenced isotherms reported by others (Ng *et al,* 1987), suggesting that MEP may have influenced the isotherm parameters estimated during this study. Schultz and Keinath (1984) tested the ability of PAC added to activated sludge to remove ^{14}C MEP obtained from degradation of phenol. They were able to show 50% MEP removal by the PAC. These studies support the use of activated carbon to remove MEP remaining in effluent from biological treatment plants.

The Freundlich and Langmuir isotherms were fit to data collected for the Unisorb AC, Unisorb AGL, Norit 830 and Norit 3000 granular activated carbon (hand pulverized). The masses of GAC that sorbed everything but the nonsorbable fraction were not used to determine the isotherm fits. GAC data that resulted in sorption of only the highly sorbable fraction were not used in the parameter determination. Additionally, GAC data which

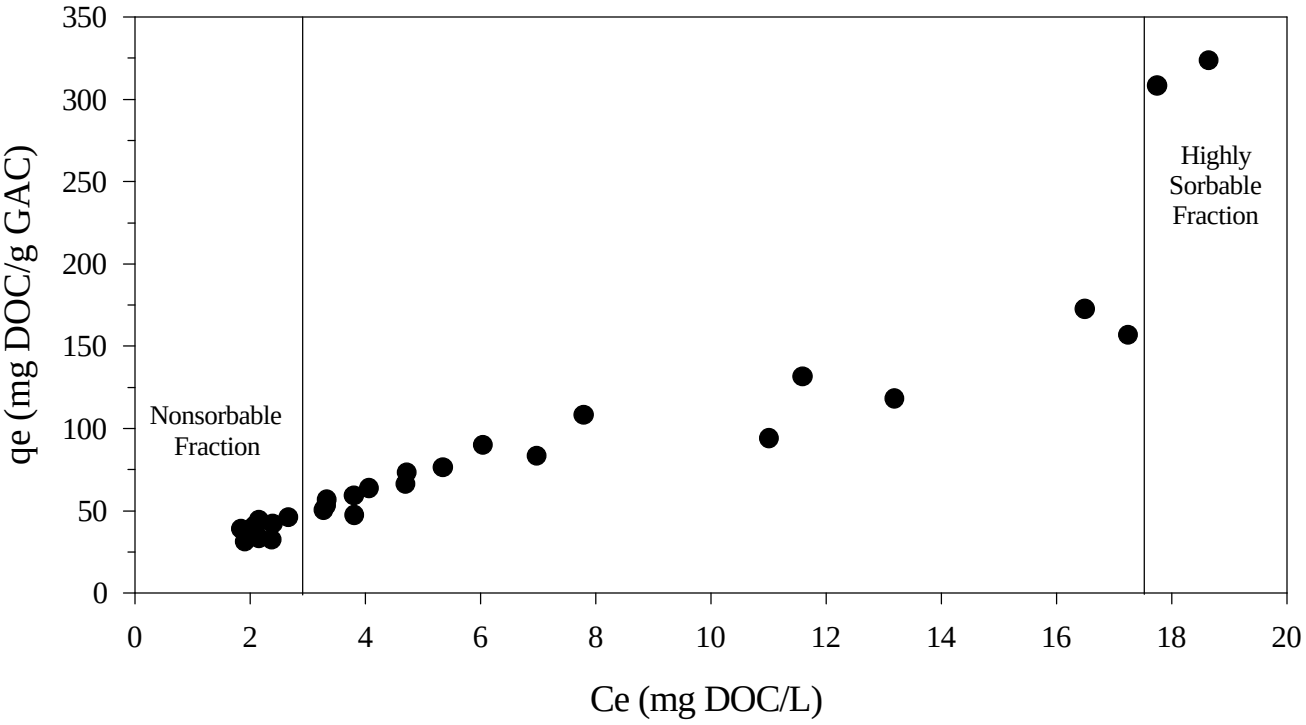

Figure 4-27: GAC isotherm data for Norit 830.

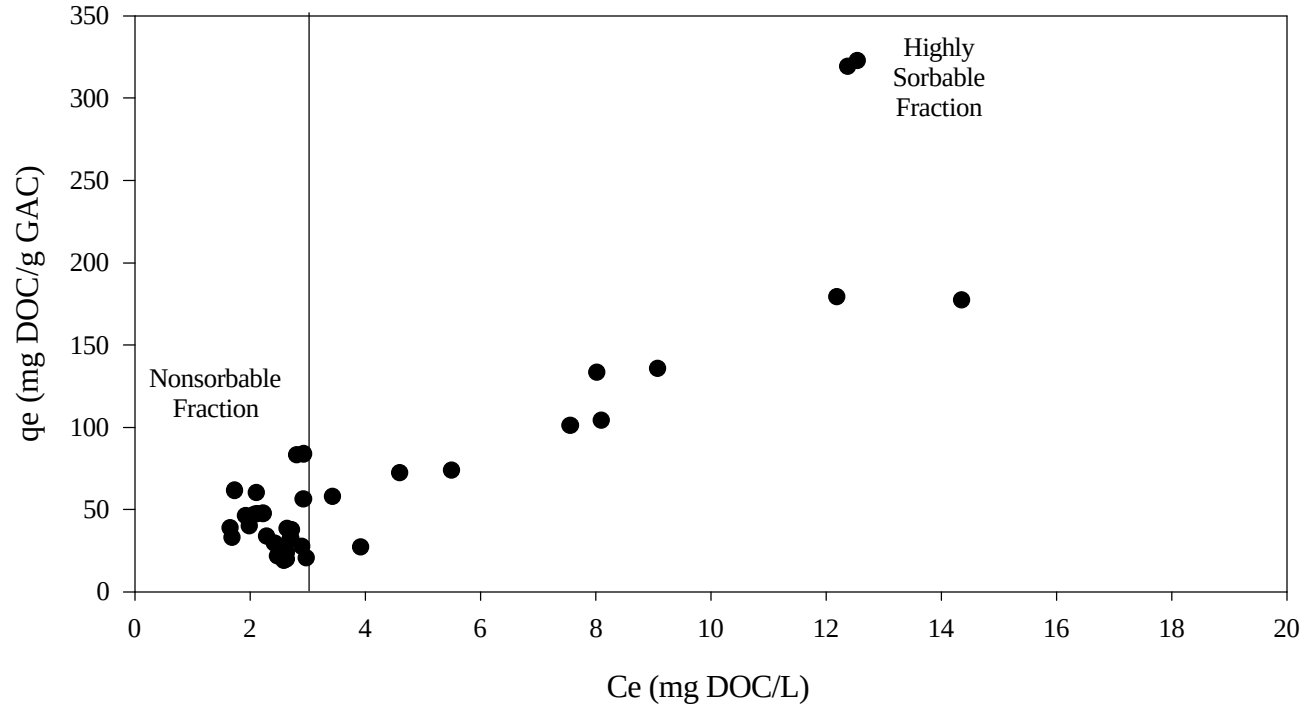

Figure 4-28: GAC isotherm data for Unisorb AGL.

showed no improvement in DOC removal with increased GAC mass (leaving only the nonsorbable fraction) were not used to determine the isotherm parameters. The Freundlich (equation 1) and Langmuir (equation 2) isotherm parameters were determined for the GAC and are listed in Table 4-9. The mean sum of squared errors (MSSE) were determined for each parameter fit.

Table 4-9: Freundlich and Langmuir parameters for Unisorb AC, Unisorb AGL, Norit 830 and Norit 3000.

	Freundlich		Langmuir	
	n	K_f	b	q_{max}
Unisorb AC	1.15 (62)[a]	13.3	0.018 (64)	606
Unisorb AGL	1.38 (117)	25.5	0.11 (345)	235
Norit 830	1.51 (98)	24.1	0.079 (122)	253
Norit 3000	1.93 (275)	72.1	0.45 (361)	221

a = mean sum of squared errors

The raw data, Freundlich isotherm, Langmuir isotherm and the MSSE values for each carbon are shown in Figure 4-29. Although the MSSE values were calculated, it is difficult to determine which isotherm more accurately predicts DOC adsorption to GAC. In all cases, the MSSE values are lower for the Freundlich isotherm fits than for the Langmuir model. The Langmuir isotherm asymptotically approaches a maximum (mg DOC/g GAC) which typically does not represent GAC adsorption data well.

Parameters determined for the Norit 3000 GAC suggest it has the best removal capabilities compared to all GAC tested. The K_f value determined for the Norit 3000 is greater than twice the value for the other GAC. The increased K_f value indicates a greater capacity for the COD remaining in the effluent (Ponitus, 1991). In addition, the 1/n value for the Norit 3000 was the lowest 1/n value suggesting the strongest bond between the COD and GAC (Ponitus, 1991).

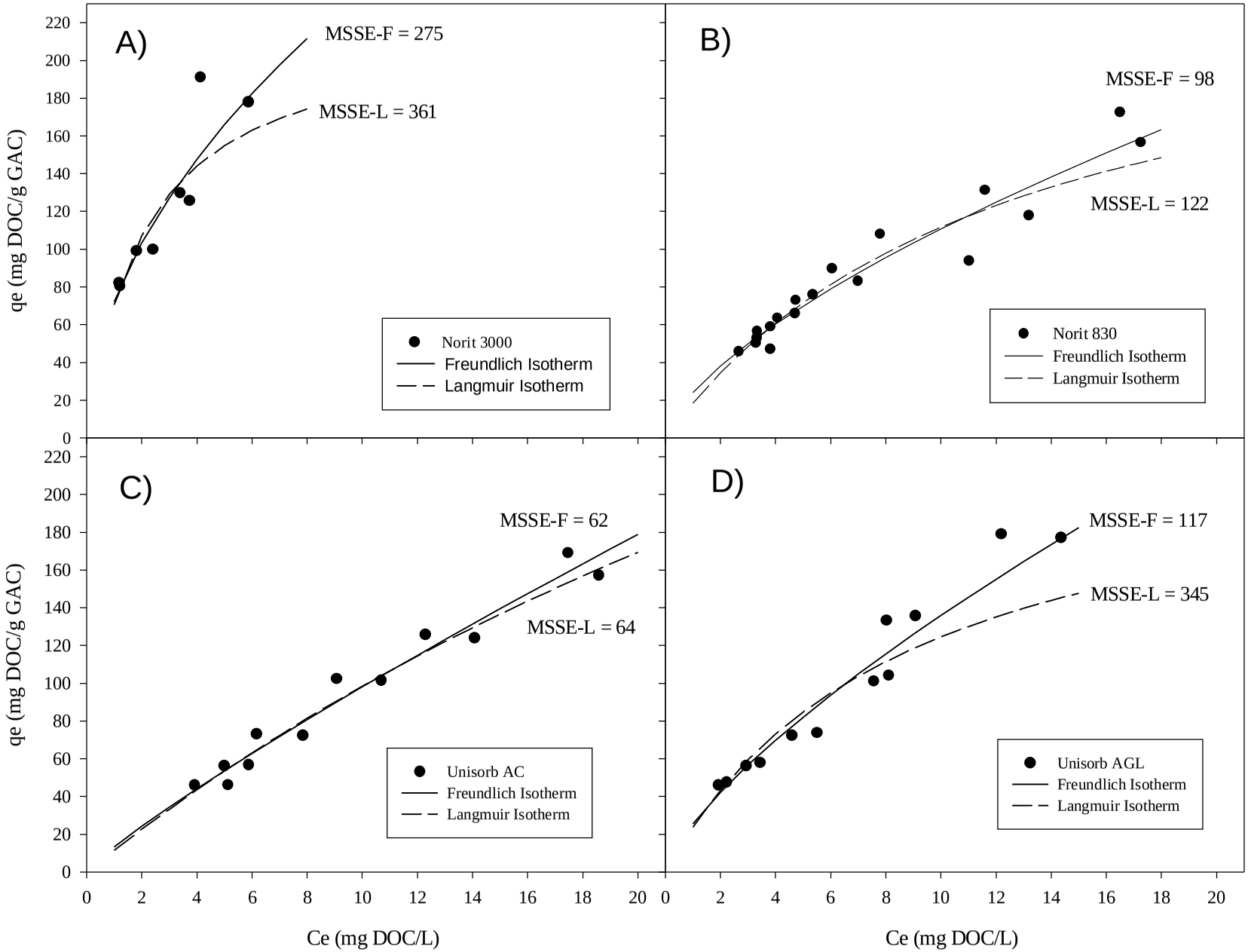

Figure 4-29: Freundlich and Langmuir isotherms for: A) Norit 3000, B) Norit 830, C) Unisorb AC and D) Unisorb AGL. MSSE-F = mean sum of squared errors for Freundlich isotherm, MSSE-L = mean sum of square errors for Langmuir isotherm

Çeçen *et al*. (1992) evaluated biological treatment followed by GAC treatment for a spent bleaching effluent from a sulfate pulp mill. Initial concentrations for 1,1,1-trichloroethane, trichloroethene and tetrachloroethane were 9.9, 0.2 and 0.1 µg/L. The concentration of 1,1,1-trichloroethane was substantially reduced by biological treatment to 0.5 µg/L while trichloroethene was reduced to 0.1 µg/L. GAC treatment provided additional removal and all three compounds were reduced to below the detection limit of 0.1 µg/L. GAC doses of 20 - 2,000 mg/L were only able to remove up to 45% of the COD, DOC, color and AOX remaining in the effluent. However, GAC doses of 20 g/L were able to resulted in greater than 90% removal for COD, DOC, color and AOX. These results indicate that GAC treatment can effectively remove residual pollutants after biological treatment of a wastewater.

Although no color measurements were made, the GAC removed the existing color from the wastewater. Ng *et al*. (1987) found color removal from refinery wastewater by GAC during adsorption studies. As discussed earlier, Cooper *et al*. (1992) evaluated biological treatment followed by sand filtration and GAC treatment for removal of organics and metals. The three component treatment scheme was consistently able to reduce organic concentrations below the required effluent limitations while biological treatment alone was unable to meet the limits. The data collected from the ANA SBR indicated that the new wastewater treatment plant should be able to meet the effluent limitation of 100 mg/L as COD with biological treatment followed by sand filtration and GAC adsorption.

CHAPTER V. SUMMARY AND CONCLUSIONS

The purpose of the research was to investigate the treatability of a high strength synthetic and a high strength industrial wastewater using sequential treatment strategies: anaerobic/aerobic, anoxic/aerobic and aerobic. Each system had an effluent goal of 100 mg/L as COD. Effluent quality was monitored to evaluate and compare the performance of the three systems. Samples across the reaction phase were monitored to determine the fate of the industrial compounds under the anaerobic, anoxic and aerobic environments over several cycles. The systems were operated with a 48 hour cycle time and fed a wastewater with a strength up to 9,000 mg/L as COD. No system was able to consistently meet the 100 mg/L effluent COD limitation. The effluent from the anaerobic/aerobic reactor was filtered through a gravity sand filter and then used to determine GAC isotherm parameters. The use of a sand filter followed by GAC sorption would allow the effluent to reach the 100 mg/L COD effluent limitation.

Summary

From the results of the effluent quality evaluation, reaction phase analysis, operation of the reactors fed the industrial wastewater and the GAC studies, the following observations were made:

Effluent Quality

1) ANX SBR produced a more stable effluent with consistently lower TOC/COD values and effluent solids. The SBR does not significantly nitrify. Nitrification alone cannot sustain the anoxic environment; however, other researchers have also shown advantages in operating an anoxic environment for COD removal using supplemental nitrate addition (McClintock, 1988).

2) No significant difference in effluent toxicity existed between the ANA, ANX and AER SBRs. Additionally, the increase in influent COD concentrations did not increase the effluent toxicity for any system.

3) Effluent TOC and COD concentrations were extremely variable despite a constant influent concentration.

4) The ANA, ANX and AER SBRs were unable to meet the effluent limit of 100 mg/L as COD.

Settling Properties

1) ANX and AER SBRs had consistently lower effluent suspended solids concentrations than the ANA SBR which also demonstrated the greatest degree of variability in effluent TSS concentrations. All SBRs maintained high solids concentrations believed to be due in part to the high salt concentration added to the synthetic wastewater (Novak *et al*., 1997).

2) SVI values suggested that all three SBRs had good settling properties. The ANX SBR consistently had lower SVI values than the ANA and AER SBRs.

3) The ANA and AER SBRs had foaming problems during aerobic operations. The foam did not appear to be related to filamentous organisms; the ANA SBR had few filamentous organisms and the AER had even less. At no time during the operation did the ANX SBR experience foaming problems.

Biosolids Properties

1) At an influent COD of 5,500 mg/L, the SBRs had different biomass characteristics. The ANA and ANX SBRs had very large, granular biosolids with solid flocs visible in the SBRs. Under the microscope, the ANA and ANX contained greater than 50% higher life organisms with very dense flocs and few individual cells. The AER biomass had few

granules and had very thin flocs with very dispersed cells. The AER biosolids contained approximately 25% free swimming higher life organisms.

2) At an influent COD of 9,000 mg/L, all three SBRs contained biomass with very similar characteristics. The SBRs had large masses of solids that would accumulated in the reactors. The biosolids contained high percentages of higher life organisms and very large, dense flocs. The AER SBR continued to have a large population of free swimming organisms. Filamentous organisms were minimal in all three SBRs at this loading.

SBR Cycle Analysis:

1) The anaerobic zone did not degrade any significant fraction of the total COD. Analysis of the two most significant substrate sources in the wastewater along with DOC values indicated that fermentation was not occurring during anaerobic operation.

2) During anoxic operation, the ANX SBR was able to degrade between 55 - 65% of the total TOC. Pivalic acid and acetic acid were degraded simultaneously. A significant shift in nitrate uptake occurred in the middle of the anoxic phase and the change appeared to be related to the concentrations of the compounds being consumed.

3) The rate of pivalic acid consumption changed three times during anoxic/aerobic cycling. Pivalic acid was consumed rapidly during anoxic operation while acetic acid was present. The pivalic acid consumption slowed when acetic acid was completely degraded and increased again once aerobic operation began.

4) Aerobic consumption of pivalic acid and acetic acid occurred simultaneously in the ANA and AER SBRs as in the anoxic phase of the ANX SBR; however, pivalic acid consumption increased once the acetic acid was completely consumed. Additionally, a 4

hour lag time existed before a significant increase in consumption of acetic acid occurred while it was much more rapid with the ANX SBR.

5) Degradation patterns across the three systems did not change significantly with the increases in wastewater COD.

Industry SBR operation:

1) As with the ANA SBR, no significant degradation occurred during anaerobic operation of the ANA-T SBR.

2) During the anoxic phase of the ANX-T SBR, the reactor was able to consume 20% of the influent TOC. The anoxic phase consumed significantly less of the industrial wastewater than the synthetic wastewater which was composed of 70% organic acids.

3) AER-T SBR achieved the lowest effluent TOC concentration. Degradation of the wastewater occurred more rapidly than for the ANA-T and ANX-T SBRs.

4) During aerobic operation all SBRs were able to degrade a significant fraction of the total COD; however, no SBR was able to reach the effluent limitation of 100 mg/L as COD.

GAC Isotherm Studies

1) The ANA effluent contained a nonsorbable fraction that remained for each GAC tested.

2) All GAC types tested were able to remove a large fraction of the COD remaining in the effluent after sand filtration.

3) The effluent contained a mixture of compounds which made isotherm parameter estimation more difficult.

4) The parameters for the Norit 3000 GAC suggest it has the best removal capabilities for the ANA effluent; however, column studies should be conducted to determine design information.

5) The effluent limitation of 100 mg/L can be met with biological treatment followed by GAC adsorption.

Conclusions

1) The anoxic/aerobic SBR proved to be an effective treatment strategy for industrial wastewaters containing high concentrations of organic acids including compounds containing tertiary carbons. Compounds with tertiary carbons are often difficult to degrade because of the compact arrangement of the carbons. Anoxic/aerobic treatment may require nitrate addition; however, anoxic/aerobic can still provide substantial O&M economic savings.
2) Anaerobic conditions imposed on the wastewater during this research did not provide significant degradation of the wastewater, additionally, the conditions did not enhance the aerobic degradation. Although anaerobic treatment is often considered for treating high strength wastewater, its effectiveness will be controlled by the operating conditions and wastewater characteristics. An anaerobic environment with a lower redox potential can provide significant removal as was shown by Young *et al.* (1996).
3) Performance differences between the SBRs treating the synthetic and industrial wastewater stress the importance of conducting treatability studies with the actual industrial wastewater. Compound substitutions can cause dramatic differences in reactor performance as was seen in the ANX and ANX-T SBRs.

4) As was seen in this research, SMP formation and effluent containing complex mixtures complicate the determination of isotherm parameters. Granular activated carbon adsorption is an effective method for removing COD remaining after biological treatment.

5) Although biological treatment was unable to achieve the effluent limitation of 100 mg/L as COD imposed on the new wastewater treatment plant, biological treatment followed by sand filtration and GAC adsorption will provide the necessary means for meeting the effluent limitation.

Engineering Significance

Many treatment plants have incorporated multiple redox treatment strategies: anaerobic/aerobic, anoxic/aerobic, and anaerobic/anoxic/aerobic systems, for the removal of phosphorous and nitrogen from industrial and municipal wastewaters. The use of multiple redox treatment strategies has the potential to enhance degradation of COD as well as xenobiotic compounds (Zitomer and Speece, 1993). Results from this research provide evidence of enhanced wastewater treatment for multiple redox treatment strategies.

Single sludge SBRs can provide several advantages over multi-sludge multiple redox environments. The utilization of SBRs reduces the construction costs by eliminating clarifiers between different treatment phases. Additionally, pumping costs are reduced because all processes: anaerobic, anoxic and aerobic reaction phases as well as clarfication occur in the same reactor. Simply by changing the time allotted for each operation: fill, react, settle and decant the system performance can potentially be enhanced (Rim *et al.*, 1997; Chin, 1989). During the SBR operation, changes in HRT and anaerobic, anoxic, and aerobic reaction times were easily made by modifying timer programs.

At the beginning of an aerobic cycle, SBRs and conventional systems have high oxygen demand requirements; however, the use of an anaerobic or anoxic environment prior to aerobic treatment minimizes or eliminates this problem. *S. natans* growth in the ANA and AER SBRs may have been evidence of low dissolved oxygen concentrations at the beginning of the aerobic reaction phase due to a high oxygen demand. Significant degradation of COD reduced the organic load to the ANX SBR, thereby reducing the

oxygen demand. This reduction in oxygen demand could have prevented growth of *S. natans*. Because SBRs do not use separate clarifiers, a poor settling sludge would provide serious operational problems for a wastewater treatment plant. The SBR relies on good settling sludge to provide a quality effluent. Another potential problem for multiple redox treatment strategies within an SBR are pH and temperature fluctuations which can severely affect performance of bothmethanogens and nitrifiers.

The ANX SBR provided superior treatment of the synthetic wastewater compared to the ANA and AER SBRs. The performance of the ANX SBR demonstrated the potential degradation capabilities of an anoxic/aerobic system on a wastewater containing high organic acid concentrations. Pivalic acid contains a quaternary carbon which was completely degraded during anoxic treatment. Compounds containing tertiary carbons are often difficult to degrade because of the compact nature of the carbons.

Unlike SBRs fed the synthetic wastewater, the AER-T SBR provided the greatest degradation for the industrial wastewater containing high concentrations of aldehydes, alcohols and organic acids. Operation of a completely aerobic activated sludge system will require increased blower capacities and energy requirements. No significant degradation was seen during the anaerobic reaction phase of the ANA-T; however, alternate anaerobic studies showed significant (55-65%) COD removal from the wastewater. Treatability studies should be conducted utilizing reactor configuration similar to those designed for the wastewater treatment plant.

Performance differences between SBRs receiving the synthetic and industrial wastewaters illustrate the potential problems with compound substitutions. The substitution of a carboxylic acid for a hydroxylated aldehyde significantly enhanced the

degradation of the synthetic wastewater during the anoxic reaction phase. In addition to substitution differences, a high degree of variability exists between different industrial wastewater; therefore, treatability studies should be conducted on the actual industrial wastewater to determine the applicability of the multipleredox treatment schemes.

Finally, results from the isotherm studies show the effectiveness of GAC in removing nonbiodegradable compounds from the effluent of biological treatment. The nonbiodegradable fraction can consist of original compounds present in the wastewater, degradation intermediates that can not be degraded or MEP. As was evident in the GAC adsorption data, adsorbance differences between compounds in a complex effluent can make isotherm parameters fits more complicated.

Recommendations

The results from this study and the work performed by Young *et al.* (1996) conflict regarding the anaerobic treatability of the wastewater. Young *et al.* (1996) were able to maintain anaerobic conditions with a lower redox potential because the systems were operated under strictly anaerobic conditions while the SBRs in this research alternated between anaerobic and aerobic environments. This certainly could have influenced the difference in results between the two studies. The Industry has decided to use a UASB prior to conventional activated sludge treatment at the new wastewater plant in Asia. Additional treatability studies should be conducted to determine the performance of the UASB on COD removal from the wastewater.

Nitrification studies should be conducted with a wastewater containing high concentrations of organic acids to determine if nitrification could support an anoxic

treatment system. Potential problems with volatile fatty acids and ammonia inhibition of nitrification should be investigated.

Batch studies were performed using a sand filtered effluent to determine the isotherm parameters for several types of GAC. Additional GAC isotherm studies should be conducted using the biological treatment effluent from the U.S. facility. The compound substitutions caused significant performance differences by the biological treatment and also may have effected the composition of the COD remaining in the effluent. Differences in COD composition could alter the isotherm parameters for each carbon. At the minimum, continuous flow column studies should be performed to monitor the performance of the GAC. Additional isotherm studies and column studies should be performed if concentrations from the biological treatment are much greater than the initial values used in the GAC studies. Measurements were made of the toxicity of the effluent prior to GAC treatment; however, no toxicity measurements were determined after GAC treatment. GAC was an effective method for removal of COD and studies should be done to determine its effectiveness at removing toxicity from the effluent.

Studies should be done to determine the nature and amount of SMP formed during biological treatment of industrial wastewaters. The SMP may produce a nontoxic source of COD; however, toxic compounds may adhere to the macromolecules. If significant SMP is produced during biological treatment many plant will have difficulty reaching low effluent COD limitations.

The biosolids formed during the SBR operations contained large granules. The formation of this type of biomass may have allowed from simultaneous aerobic respiration and denitrification for carbon removal. Studies should be conducted to determine the

effectiveness of simultaneous denitrification and aerobic respiration treatment on both municipal and industrial wastewaters.

This research has shown the potential for multiple redox treatment strategies on both a synthetic and an industrial wastewater. The use of multiple redox treatment strategies can be an effective method for modifying an existing facility that needs to increase carbon removal or nutrient removal.

BIBLIOGRAPHY

Beccari, M., Di Pinto, A. C., Passina, R., Ramadori, R., and Tandoi, V. (1984) "Single Sludge Anoxic-Aerobic Systems for Biological Treatment of Coke Plant Wastewater" *Water Science and Technology,* Vol. 17, pp. 421-432

Bell, B. A. and Hardcastle, G. J. (1984) "Treatment of a High-Strength Industrial Waste in a Continuously Fed, Intermittently Operated, Activated Sludge System" *Journal of the Water Pollution Control Federation,* Vol. 56, No. 11, pp. 1160-1164

Bode, H. (1988) "Anaerobic-Aerobic Treatment of Industrial Wastewater" *Water Science and Technology,* Vol. 20, No. 4/5, pp. 189-198

Bulich, A. A. (1982) "A Practical and Reliable Method for Monitoring the Toxicity of Aquatic Samples" *Process Biochemistry,* Vol. 2, pp. 45-47

Cecen, Ferhan. (1994) "Activated Carbon Addition to Activated Sludge in the Treatment of Kraft Pulp Bleaching Wastes" *Water Science and Technology*, Vol. #30, No. 3, pp. 183-192

Cecen, F., Urban, W., and Haberl, R. (1992) "Biological and Advanced Treatment of Sulfate Pulp Bleaching Effluents" *Water Science and Technology,* Vol. 26, No. 1-2, pp. 435-444

Chang, J. C., Taylor, P. B., and Leach, F. R. (1981) "Use of Microtox Assay System for Environmental Samples" *Bulletin of Environmental Contamination and Toxicology,* Vol. 26, pp. 150-156

Cheng, S., Yin, Y., and Chen, S. (1996) "Enhanced Biodegradation of Organic Nitrogenous Compounds in Resin Manufacturing Wastewater By Anoxic Denitrification and Oxic Nitrification Process" *Water Science and Technology,* Vol. 34, No. 10, pp. 35-41

Chin, Kee Kean (1989) "Post Treatment of Anaerobic Effluent Using Sequencing Batch Reactors" *Water Science and Technology,* Vol. 21, pp. 23-28

Choi, E., Oa, S. W., and Lee, J. J. (1997) "Nightsoil Treatment Plant Converted Into A Sequencing Batch Reactor to Improve Removal of Pollutants and Nutrients" *Water Science and Technology,* Vol. 35, No. 1, pp. 233-240

Coleman, R. N. and Qureshi, A. A. (1985) "Microtox and *Sprillum volutans* Tests for Assessing Toxicity of Environmental Samples" *Bulletin of Environmental Contamination and Toxicology,* Vol. 35, pp. 443-451

Cooper, A. M., Torrens, K. D., and Musterman, J. L. (1992) “On-site Evaluation of Treatment System Requirements to Satisfy Direct and Indirect Discharge Limits for a Complex Industrial Wastewater: A Case Study” *Environmental Progress,* Vol. 11, No. 1, pp. 18-26

Dutka, B. J. and Kwan, K. K. (1981) “Comparison of Three Microbial Toxicity Screeening Tests with the Microtox Test” *Bulletin of Environmental Contamination and Toxicology,* Vol. 27, pp. 753-757

Eckenfelder, W. W. Jr. (1989) *Industrial Wastewater Pollution Control Second Edition*, McGraw-Hill Book Company. New York

Eilersen, A. M., Henze, M. and Klíft, L. (1994) ”Effect of Volatile Fatty Acids and Trimethlyamine on Nitrification in Activated Sludge” *Water Research,* Vol. 28, No. 6, pp. 1329-1336

Flammino, A., Bellanca, M. A., and Tracy, K. D. (1989) In *Proceedings TAPPI Environmental Conference*; TAPPI: Atlanta, GA pg. 305-320

Fox, P., Suidan, M. T., and Pfeffer, J. T. (1988) “Anaerobic Treatment of a Biologically Inhibitory Wastewater” *Journal of the Water Pollution Control Federation,* Vol. 60, No. 1, pp. 87-92

Gottschalk, Gerhard. (1986) *Bacterial Metabolism*, Springer-Verlag New York, Inc., New York, NY

Grady, C. P. L. and Daigger, G. T. (1997) *Biological Wastewater Treatment, Theory, and Application,* Marcel Dekker, Inc. New York, NY.

Hao, O. J., Shin, C., Lin, C., Jeng, F., and Chen, Z. (1996) “Use of Microtox Tests for Screening Industrial Wastewater Toxicity” *Water Science and Technology,* Vol. 34, No. 10, pp. 43 - 50

Huang, J. Y. and Drew, D. M. (1985) “Investigation of the Removal of Organics and Nitrogen in an Oxidation Ditch” *Journal of the Water Pollution Control Federation,* Vol. 57, No. 2, pp. 151-156

Jenkins, D., Richard, M. G., and Daigger, G. T. (1993) *Manual on the Causes and Control of Activated Sludge Bulking and Foaming*, Lewis Publishers, Chelsea, M.I.

Kahru, A., Kurvet, M., and Kulm, I. (1996) “Toxicity of Phenolic Wastewater to Luminescent Bacteria *Photobacterium phosphoreum* and Activated Sludges” *Water Science and Technology,* Vol. 33, No. 6, pp. 139-146

Lee, E. L., Shin, H. S., and Byeong, C. P. (1989) "Treatment of Cr(VI)-Containing Wastewater by the Addition of Powdered Activated Carbon to the Activated Sludge Process" *Water Research,* Vol. 23, No. 1, pp. 67-72

Lee, S., Koopman, B, Bode, H., and Jenkins, D. (1993) "Evaluation of Alternative Sludge Setteability Indices" *Water Science and Technology,* Vol. 17, No. 10, pp. 1421-1426

Lubkowitz, E. M. (1996) "Biological Treatment Schemes for Preventing Oxime Inhibition of Nitrification" M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA

Madigan, M. T., Martinko, J. M., and Parker, J. (1997) *Brock: Biology of Microorganisms Eighth Edition,* Prentice Hall, Upper Saddle River, NJ

McClintock, S. A., Sherrard, J. H., Novak, J. T., and Randall, C. W. (1988) "Nitrate versus Oxygen Respiration in the Activated Sludge Process" *Journal of the Water Pollution Control Federation,* Vol. 60, No. 3, pp. 342-350

Mehner, A., Morange, H., Rintala, J., Silvo, R., Vitasaari, M., and Vuoriranta, P. (1988) "Process Alternatives for Enhanced Biological Treatment Efficiency of Forest Industry Effluents" *Water Science and Technology,* Vol. 20, No. 1, pp. 241-250

Metcalf & Eddy, Inc. (1995) *Wastewater Engineering: Treatment, Disposal and Reuse,* McGraw-Hill, Inc., New York, NY.

Ng, A., Stenstrom, M. K. and Marrs, D. R. (1987) "Nitrification Enhancement in the Powdered Activated Carbon-activated Sludge Process for the Treatment of Petroleum Refinery Wastewaters" *Journal of the Water Pollution Control Federation,* Vol. 59, No. 4, pp. 199 - 211

Novak, J. T., Love, N. G., Smith, M. L., and Wheeler, E. R. "The Impact of Cationic Salt Addition on the Settling and Dewatering Properties of an Industrial Activated Sludge", accepted for publication in *Water Environment Research*, July, 1997

Oanh, N. T. K. and Bengtsson, B. (1995) "Toxicity to Microtox, Micro-Algae and Duckweed of Effluents from the Bai Bang Paper Company (BAPACO), A Vietnamese Bleached Kraft Pulp and Paper Mill" *Environmental Pollution,* Vol. 90, No. 3, pp. 391-399

Oleszkiewicz, J. A., Janeczko, A., and Trebacz, W. (1991) "Removal of Simple Phenolics in Aerobic and Denitrifying Sequencing Batch Reactors" *Environmental Technology,* Vol. 12 pp. 1017-1026

Orhon, D., Cimsit, Y., and Tunay, O. (1986) "Substrate Removal Mechanisms for Sequencing Batch Reactors" *Water Science and Technology,* Vol. 18, pp. 21-33

Painter, H. A. and Loveless, J. E. (1983) “Effect of Temperature and pH on the Growth Rate Constants of Nitrifying Bacteria in the Activated Sludge Process” *Water Research,* Vol. 17, pp. 237-248

Peel, R. G., and Benedek, A. (1980) “Attainment of Equilibrium in Activated Carbon Isotherm Studies” *Environmental Science and Technology,* Vol. 14, pp. 66

Ponitus, F. W., ed. (1990) *Water Quality and Treatment,* McGraw-Hill, Inc., New York, NY.

Porter, R. S. (1993) “Effects of the Nature of the Electron Acceptor on the Kinetics and Stoichiometry of Microbial Growth on Aromatic Compounds” Ph.D. Dissertation, Clemson University, Clemson, SC.

Qureshi, A. A., Coleman, R. N., and Paran, J. H. (1984) “Evaluation and refinement of Microtox test for Use in Bacterial Toxicity Screening” P.1-22 *In* D. Liu and B. Dutka, (eds) Toxicity Procedures Using Bacterial Screening, Marcel Dekker, New York.

Reynolds, T. D. and Richards, P. A. (1996) *Unit Operations and Processes in Environmental Engineering,* PWS Publishing, Boston, Mass.

Rim, Y. T., Yang, H. J., Yoon, C. H., Kim, Y. S., Seo, J. B., Ryu, J. K., and Shin, E. B. (1997) “A Full-Scale Test of a Biological Nutrients Removal System Using the Sequencing Batch Reactor Activated Sludge Process” *Water Science and Technology*, Vol. 35, No. 1, pp. 241-247

Rintala, J. and Lepistö, R. (1993) “Thermophilic Anaerobic-Aerobic and Aerobic Treatment of Kraft Bleaching Effluents” *Water Science and Technology,* Vol. 28, No. 2, pp. 11-16

Rintala, J. and Vuoriranta, P. (1988) “Anaerobic-aerobic treatment of thermomechanical puling effluents” *Tappi Journal*, Sept. 1988 pp. 201-207

Sanchez, P. S., Sato, M. I., Paschoal, C. M., Alves, M. N., and Furlan, E. V. (1988) “Toxicity Assessment of Industrial Effluents from S. Paulo State, Brazil, Using Short-Term Microbial Assays” *Toxicity Assessment,* Vol. 3, pp. 55-80

Schultz, J. R. (1982) “PACT Process Mechanisms.” Ph.D. Dissertation, Environmental Systems Engineering, Clemson University, Clemson, S.C.

Schultz, J. R. and Keinath, T. M. (1984) “Powdered Activated Carbon Treatment Process Mechanisms” *Journal of the Water Pollution Control Federation,* Vol. 56, No. 2, pp. 143-151

Scruggs, Caroline. Personal communication. May, 1996

Smets, B. F., Ellis, T. G., Brau, S., Sanders II, R. W., and Grady, L. G. Jr. (1994) "Quantification of the Kinetic Differences Between Communities Isolated From Completely Mixed Activated Sludge Systems Operated With or Without a Selector Using a Novel Respirometric Method" *Water Science and Technology,* Vol. 30, No. 11, pp. 255-261

Sorial, G. A., Suidan, M. T., Vidic, R. D., and Brenner, R. C. (1993). "Effect of GAC characteristics on adosrption of organic pollutants" *Water Environment Research,* Vol. 65, No. 1, pp. 53 - 57

Standard Methods for the Examination of Water and Wastewater, (1995) American Public Health Association, Washington, D.C.

Suidan, M. T., Strubler, C. E., Kao, S. and Pfeffer, J. T. (1983) "Treatment of Coal Gasification Wastewater with Anaerobic Filter Technology" *Journal of the Water Pollution Control Federation,* Vol. 55, No. 10, pp. 1263-1270

Tanaka, T., Kitagwa, M. and Ohkubo, E. (1991) "Energy Saving, High Biological Phosphorous Removal and Improvement of Sludge Setteability on Full-Scale Anaerobic-Aerobic Activated Sludge Process" *Water Science and Technology*, Vol. 23, pp. 810-810

Vasseur, P., Ferard, J. F., Rast, C., and Larbaight, G. (1984) "Luminescent Marine Bacteria in Ecotoxicity Screening Test of Complex Effluents" P.23-35 *In* D. Liu and B. Dutka, (eds) Toxicity Procedures Using Bacterial Screening, Marcel Dekker, New York.

Vidic, R. D. and Suidan, M. T. (1992). "Operating Capacity of GAC adsorbers - dissolved oxygen and extended service life" *Water Environment Research,* Vol. 64, No. 6, pp. 798 - 804

Wanner, J. (1992) "Comparison of Biocenoses from Continuous and Sequencing Batch Reactors" *Water Science Technology,* Vol. 25, No. 6, pp. 239-249

Yang, L. and Alleman, J. E. (1992) "Investigation of Batchwise Nitrite Build-Up by an Activated Enriched Nitrification Culture" *Water Science and Technology,* Vol. 26, No. 5/6, pp. 997-1005

Yonge, D.R., Keinath, T. M. and Poznanska, K. (1985) "Single-Solute Irreversible Adsorption on Granular Activated Carbon" *Environmental Science and Technology,* Vol 55, pp. 329

Young, J. C., Khandaker, N., and Boothanth, R. (1996) "Final report for Treatability Studies for Industry" Pennsylvania State University

Zaloum, R. and Abbott, M. (1997) “Anaerobic Pretreatment Improves Single Sequencing Batch Reactor Treatment of Landfill Leachates” *Water Science and Technology*, Vol. 35, No. 1, pp. 207-214

Zaoyan, Y., Ke, S., Guangliang, S., Fan, Y., Jinshan, D., and Huanian, M. (1992) “Anaerobic-Aerobic Treatment of A Dye Wastewater By Combination of RBC with Activated Sludge” *Water Science and Technology*, Vol. 26, No. 9, pp. 2093-2096

Zitomer, D. H. and Speece, R. E. (1993) “Sequential Environments for Enhanced Biotransformation of Aqueous Contaminants” *Environmental Science and Technology,* Vol. 27, No. 2, pp. 227-244

APPENDIX A

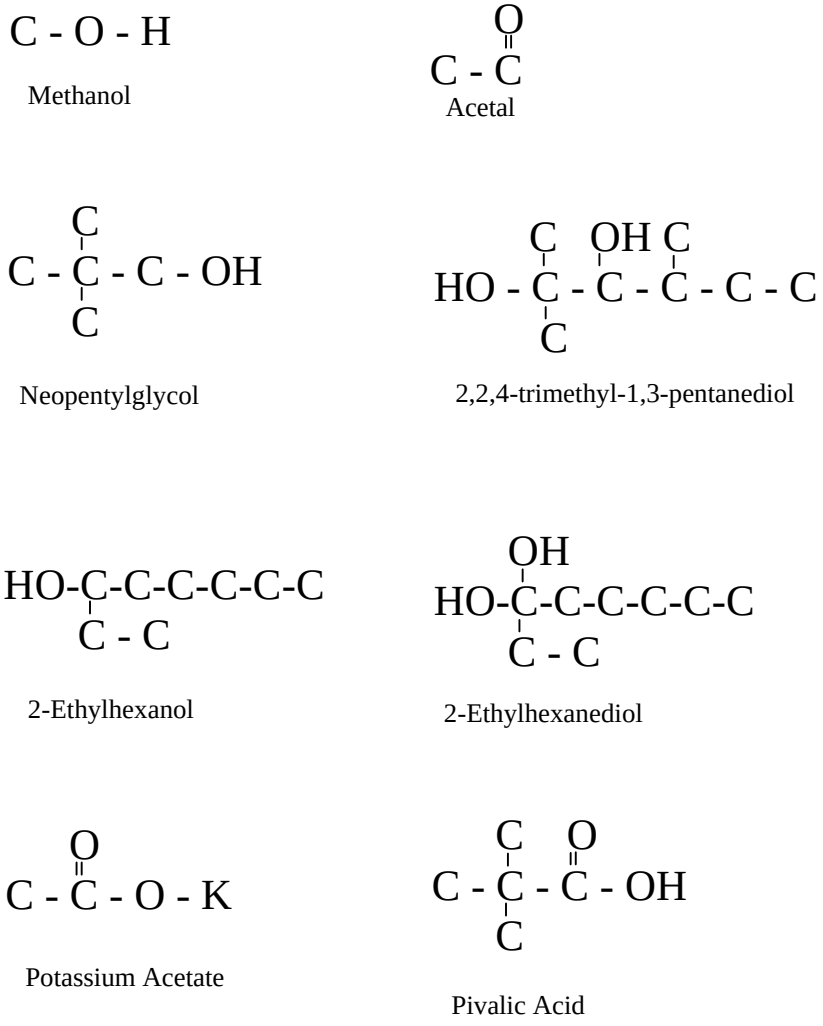

Figure A-1: Diagrams of the compounds contained in the synthetic wastewater

Table A-1: Approximate Micronutrient requirements for Bacterial Growth (source:Grady and Daigger, 1997)

Micronutrient	Approximate Requirement μg/mg Biomass COD formed
Potassium	10
Calcium	10
Magnesium	7
Sulfur	6
Sodium	3
Chloride	3
Iron	2
Zinc	0.2
Manganese	0.1
Copper	0.02
Molybdenum	0.004
Cobalt	<0.0004

Table A-2: Description of ANA Cycle for 12 hr, 18 hr, and 24 hr cycle times

Operation	12 hr CycleTime (hr)	18 hr Cycle Time (hr)	24 hr Cycle Time (hr)
Decant Off	0:00	0:00	0:00
Motors On	0:00	0:00	0:00
Nitrogen Purge On	0:00	0:00	0:00
MSM On	0:00	0:00	0:00
Organics Feed On	0:00	0:00	0:00
MSM Off	0:15	0:15	0:15
Organic Feed Off	0:15	0:15	0:15
Nitrogen Purge Off	0:20	0:20	0:20
Air On	4:00	6:00	8:00
Motors Off	10:15	16:15	22:15
Air Off	10:15	16:15	22:15
Decant On	11:45	17:45	23:45

Table A-3: Description of ANX Cycle for 12 hr, 18 hr, and 24 hr cycle times

Operation	12 hr CycleTime (hr)	18 hr Cycle Time (hr)	24 hr Cycle Time (hr)
Decant Off	0:00	0:00	0:00
Motors On	0:00	0:00	0:00
Nitrogen Purge On	0:00	0:00	0:00
MSM On	0:00	0:00	0:00
Organics Feed On	0:00	0:00	0:00
Nitrate On	0:00	0:00	0:00
MSM Off	0:15	0:15	0:15
Organic Feed Off	0:15	0:15	0:15
Nitrate Off	0:15	0:15	0:15
Nitrogen Purge Off	0:20	0:20	0:20
Air On	4:00	6:00	8:00
Motors Off	10:15	16:15	22:15
Air Off	10:15	16:15	22:15
Decant On	11:45	17:45	23:45

Table A-4: Description of AER Cycle for 12 hr, 18 hr, and 24 hr cycle times

Operation	12 hr CycleTime (hr)	18 hr Cycle Time (hr)	24 hr Cycle Time (hr)
Decant Off	0:00	0:00	0:00
Motors On	0:00	0:00	0:00
MSM On	0:00	0:00	0:00
Organics Feed On	0:00	0:00	0:00
Air On	0:00	0:00	0:00
MSM Off	0:15	0:15	0:15
Organic Feed Off	0:15	0:15	0:15
Motors Off	10:15	16:15	22:15
Air Off	10:15	16:15	22:15
Decant On	11:45	17:45	23:45

Table A-5: Operational Paramters for ANA, ANX and AER SBRs prior to 2/6/97

Operation	Time Period of Operation			
	4/8 - 5/29/96	5/29 - 4/15/96	11/8 - 11/24/96	11/24 - 2/6/97
Reaction Time (hr)	10	16	22	46
Settle Time (hr)	1.5	1.5	1.5	1.5
Decant Time (hr)	0.25	0.25	0.25	0.25
Fill Time (hr)	0.25	0.25	0.25	0.25
Reactor Volume (L)	3.5	3.5	3.5	3.5
Influent COD (mg/L)	2000	2000	5500	5500
SRT (days)	15	15	15	15
Effective HRT (hrs)	24	32	48	96
Initial pH	8 - 8.5	8 - 8.5	8 - 8.5	8 - 8.5

Table A-6: GAC masses (g) used in isotherm experiments

Experiment #1	Experiment #2	Experiment #3
2.50	1.50	1.50
2.40	1.40	1.30
2.30	1.30	1.10
2.20	1.20	0.90
2.00	1.10	0.70
1.80	1.00	0.50
1.60	0.90	0.10
1.40	0.80	0.00
1.20	0.70	-
1.00	0.60	-
0.80	0.50	-
0.60	0.40	-
0.40	0.30	-
0.30	0.20	-
0.20	0.10	-
0.00	0.00	-

Table A-7: Sieve Analysis for Sand Filter Media

Run 1

Sieve #	Sieve Opening (in)	Sieve Opening (mm)	Tare (g)	Tare + Mass Retained (g)	Mass Retained (g)	% Retained	Cumulative % Passing	Cumulative % Passing
10	0.0787	2.000	469.71	470.69	0.98	0.1	0.1	99.9
20	0.0328	0.840	445.76	564.72	118.96	10.4	10.5	89.5
60	0.0098	0.250	442.59	1443.88	1001.29	87.6	98.1	1.9
100	0.0059	0.149	335.93	353.21	17.28	1.5	99.6	0.4
200	0.0029	0.075	332.01	335.99	3.98	0.3	100.0	0.0
Pan	0.0000	0.000	377.17	377.49	0.32	0.0	100.0	0.0
				Total =	1142.81			

Run 2

Sieve #	Sieve Opening (in)	Sieve Opening (mm)	Tare (g)	Tare + Mass Retained (g)	Mass Retained (g)	% Retained	Cumulative % Retained	Cumulative % Passing
10	0.0787	2.000	469.74	470.76	1.02	0.1	0.1	99.9
20	0.0328	0.840	445.87	551.69	105.82	9.4	9.4	90.6
60	0.0098	0.250	443.68	1452.11	1008.43	89.1	98.6	1.4
100	0.0059	0.149	335.97	349.45	13.48	1.2	99.8	0.2
200	0.0029	0.075	332.11	334.42	2.31	0.2	100.0	0.0
Pan	0.0000	0.000	377.17	377.32	0.15	0.0	100.0	0.0
				Total =	1131.21			

Average

Sieve #	Sieve Opening (in)	Sieve Opening (mm)	Cumulative % Passing
10	0.0787	2.000	99.9
20	0.0328	0.840	90.0
60	0.0098	0.250	1.6
100	0.0059	0.149	0.3
200	0.0029	0.075	0.0
Pan	0.0000	0.000	0.0

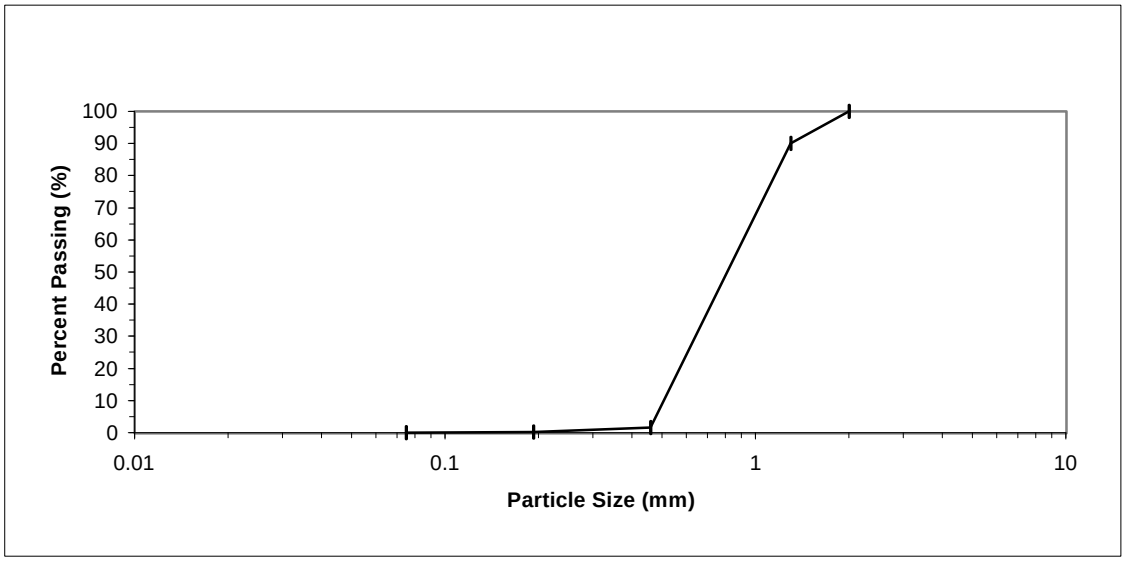

Figure A-2: Particle size distribution for filter media

APPENDIX B

Table B-1: Routine Monitoring for ANA, ANX and AER June 4, 1996 - June 12, 1997

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
4/10/96	N/A		8.44		233	N/A		8.80		233	N/A		8.53		233
4/11/96	N/A		8.40		233	N/A		8.50		233	N/A		8.20		233
4/12/96	N/A		5.04		233	N/A		7.25		233	N/A		5.04		233
4/13/96	N/A		5.27		233	N/A		8.17		233	N/A		5.53		233
4/14/96	N/A		8.65		233	N/A		8.43		233	N/A		8.52		233
4/15/96	N/A					N/A					N/A				
4/16/96	N/A		7.33		200	N/A		8.31		200	N/A		8.46		200
4/17/96	N/A		6.98		213	N/A		7.57		213	N/A		7.42		213
4/18/96	N/A		6.91		233	N/A		7.92		233	N/A		8.24		233
4/19/96	N/A		6.89		233	N/A		7.55		233	N/A		8.05		233
4/20/96	N/A		7.69		233	N/A		7.81		233	N/A		8.65		233
4/21/96	N/A		6.95		233	N/A		7.82		233	N/A		8.28		233
4/22/96	N/A		6.82		233	N/A		7.75		233	N/A		8.24		233
4/23/96	N/A		7.04		213	N/A		7.51		213	N/A		7.77		213
4/24/96	N/A		6.82		233	N/A		7.58		233	N/A		7.87		233
4/25/96	N/A		6.90		233	N/A		7.36		233	N/A		7.60		233
4/26/96	N/A		6.87		233	N/A		7.01		233	N/A		7.17		233
4/27/96	N/A		6.80		233	N/A		7.42		233	N/A		7.38		233
4/28/96	N/A		7.45		233	N/A		7.48		233	N/A		7.36		233
4/29/96	N/A		7.50		233	N/A		7.62		233	N/A		7.40		233
4/30/96	N/A				-	N/A				-	N/A				-
5/1/96	N/A		8.54		-	N/A		8.13		233	N/A		6.72		-
5/2/96	N/A		8.36		-	N/A		9.24		233	N/A		9.24		-
5/3/96	N/A					N/A					N/A				
5/4/96	N/A				-	N/A				169	N/A				160
5/5/96	N/A		8.00		-	N/A		7.93		170	N/A		8.06		160
5/6/96	0.66		8.45		-	N/A		7.88		-	0.38		7.59		-
5/7/96	0.38		7.43		-	N/A		7.54		147	0.66		7.81		-
5/8/96	0.38				-	N/A				140	0.72				140
5/9/96	0.38		7.18		-	N/A		8.19		140	0.77		8.43		140
5/10/96	0.38		8.30		-	N/A		8.59		140			8.80		-
5/11/96	0.24				-	N/A				140	0.78				-
5/12/96	0.21		7.02		-	N/A		8.25		160	0.71		8.09		-
5/13/96	0.21		6.75		-	N/A		7.43		174	0.71		7.78		-
5/14/96	0.29				-	N/A				178	0.36				-
5/15/96	0.24				-	N/A				186	0.58				-
5/16/96	0.24				-	N/A				200	0.29				-
5/17/96	0.45				-	N/A					0.67				
5/18/96	0.41				-	N/A				196	0.67				-
5/19/96	0.41				-	N/A				196	0.67				-
5/20/96	0.41				-	N/A				196	0.67				-
5/21/96	0.41				-	N/A				196	0.67				-

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
5/22/96	0.83				-	N/A				200	1.34				-
5/23/96	0.83				-	N/A				200	1.34				-
5/24/96	0.83				-	N/A				-	1.34				-
5/25/96		5.5			RESEED	N/A	6.6			RESEED		6.4			RESEED
5/26/96	1.67				200	N/A				200	1.90				200
5/27/96		6.4			-	N/A	5.5			-		2.4			-
5/28/96	1.90				200	N/A				200	2.07				-
5/29/96	1.90				200	N/A				200	2.07				200
5/30/96	1.37				168	N/A				300	1.79				200
5/31/96	1.37				200	N/A				-	1.79				200
6/1/96	1.37		8.00		-	N/A		8.05		-	1.79		7.85		-
6/2/96	0.94					N/A				-	1.41				-
6/3/96	0.94		8.08		-	N/A		8.11		-	1.41		7.80		-
6/4/96	0.94		8.62		200	N/A		8.96		200	1.41		8.78		200
	0.71					N/A					0.99				
6/5/96	0.71	6.0	7.60	31.0	155	N/A	0.1	8.05	31.0	213	0.99	6.6	7.58	31.0	140
6/6/96	0.71		7.29	29.0	155	N/A		7.54	29.0	210	0.99		6.89	29.0	140
6/7/96	0.71		7.40	29.0	155	N/A		8.01	29.0	210	0.99		7.98	29.0	140
6/8/96	0.79	6.2	8.10	30.0	120	N/A	1.2	8.36	30.0	201	0.97	7.6	8.40	30.0	144
6/9/96	0.79	3.9	8.04	30.5	N/A	N/A	5.2	8.65	30.5	402	N/A	7.0	7.60	30.5	N/A
6/10/96	0.79	6.5	8.24	30.0	340	N/A	6.0	8.80	30.0	402	0.97	6.7	7.58	30.0	228
6/11/96	0.57	3.2	7.96	30.0	120	N/A	6.2	9.06	30.0	N/A	0.61	6.6	7.68	30.0	N/A
6/12/96	0.57	0.1	7.51	29.0	495	N/A	0.1	9.18	29.0	495	0.61	7.9	7.40	29.0	495
6/13/96	0.57	6.2	8.44	30.0	N/A	N/A	5.7	8.85	30.0	N/A	0.61	6.5	8.86	30.0	N/A
6/14/96	0.57				N/A	N/A				N/A	0.61				N/A
6/15/96	0.57		7.59	31.5	N/A	N/A		9.08	31.5	N/A	0.61		8.22	31.5	N/A
6/16/96	0.64	4.4	8.36	30.0	N/A	N/A	6.1	8.76	30.0	200	0.79	6.5	8.80	30.0	120
6/17/96	0.64		7.72	31.0	N/A	N/A		8.80	31.0	215	0.79		8.80	31.0	50
6/18/96	0.45		7.80	31.0	200	N/A		9.11	31.0	215	0.45		8.17	31.0	60
6/19/96	0.45	5.1	7.79	31.0	N/A	N/A	5.5	9.12	31.0	215	0.45	6.1	8.34	31.0	60
6/20/96	0.45		7.67	31.0	N/A	N/A		9.04	31.0	215	0.45		8.26	31.0	60
6/21/96	0.87		7.56	30.8	187	N/A		8.98	30.8	45	0.91		8.40	30.8	165
6/22/96	0.87		7.60	31.2	187	N/A		8.24	31.4	45	0.91		7.99	31.4	165
6/23/96	0.87		7.54	31.8	187	N/A		7.60	31.8	45	0.91		7.87	31.8	165
6/24/96	0.87		7.76	31.2	187	N/A		8.08	31.2	45	0.91		7.69	31.0	165
6/25/96	0.87				187	N/A				N/A	0.91				165
6/26/96	0.71	6.0	8.51	30.5	N/A	N/A	2.8	8.07	30.8	N/A	0.44	2.9	8.16	31.0	N/A
6/27/96	0.71				N/A	N/A				N/A	0.44				N/A
6/28/96	0.71	6.0	8.49	31.0	189	N/A	2.1	8.06	31.0	N/A	0.44	5.6	8.12	30.5	N/A
6/29/96	N/A	6.0	8.42	31.0	N/A	N/A	2.0	8.16	31.0	N/A	N/A	5.4	8.24	31.0	N/A
6/30/96	N/A	0.6	8.05	30.5	235	N/A	3.5	8.66	30.5	N/A	N/A	2.6	8.12	31.0	220
7/1/96	N/A		7.64	31.5	172	N/A		8.33	30.5	N/A	N/A		7.66	30.5	220
7/2/96	N/A			30.5	N/A	N/A			30.0	N/A	N/A			30.0	N/A

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
7/3/96	N/A	0.1	7.64		490	N/A	0.1	8.81		490	N/A	0.1	8.01		490
7/4/96	N/A	4.1	8.20		N/A	N/A	6.2	8.96		N/A	N/A	5.7	8.62		N/A
7/5/96	N/A	1.5	8.66	30.5	200	N/A	6.3	9.01	29.8	233	N/A	5.8	8.05	30.5	215
7/6/96	N/A		7.94	30.0	200	N/A		8.86	30.0	233	N/A		7.98	29.5	215
7/7/96	N/A	3.4	8.31	30.8	200	N/A	4.9	8.81	31.5	233	N/A	5.4	8.70	31.5	215
7/8/96	N/A	2.5	8.41	30.8	200	N/A	4.9	8.84	31.5	233	N/A	5.8	8.73	32.0	215
7/9/96	N/A		7.59	31.8	187	N/A		8.94	31.5	233	N/A		8.48	32.0	223
7/10/96	N/A		7.57		600	N/A		7.67		600	N/A		7.53		900
7/11/96	1.25		7.52	31.8	N/A	N/A		9.19	31.0	N/A	1.95		8.53	31.8	N/A
7/12/96	1.10		7.59	28.0	N/A	N/A		9.02	28.8	N/A	1.75		8.47	28.5	N/A
7/13/96	1.10		7.53	29.0	N/A	N/A		8.26	29.0	N/A	1.75		8.33	29.0	N/A
7/14/96	1.10		7.62	31.5	187	N/A		8.91	30.8	223	1.75		8.37	31.0	233
7/15/96	1.10				187	N/A				233	1.75				176
7/16/96	1.10		7.96	31.0	176	N/A		8.80	30.8	233	1.75		8.80	30.8	167
7/17/96	1.30	4.1	8.50	30.5	176	N/A	3.3	8.67	31.0	233	1.04	5.3	8.73	30.8	167
7/18/96	1.30		8.41	31.5	176	N/A		8.41	31.5	233	1.04		8.69	30.8	167
7/19/96	1.30	3.7	8.37	30.5	176	N/A	3.6	8.68	31.5	233	1.04	5.5	8.77	31.0	N/A
7/20/96	1.30	1.0	8.55	30.5	213	N/A	2.8	8.68	29.5	233	1.10	5.7	8.72	29.5	203
7/21/96	1.30		8.46	30.5	213	N/A		8.72	30.0	233	1.10		8.81	30.0	203
7/22/96	1.67				233	N/A				233	1.86				222
7/23/96	1.67		7.98	31.0	215	N/A		8.72	30.8	233	1.86		8.18	30.5	220
7/24/96	N/A		8.41	31.0	215	N/A		8.68	30.8	233	N/A		8.32	30.8	220
7/25/96	1.67	0.5	8.28	30.8	173	N/A	0.8	8.61	30.8	233	1.86	2.5	8.54	30.5	200
7/26/96	1.67		8.49	29.5	173	N/A		8.27	29.5	233	1.86		8.23	30.0	200
7/27/96	1.67		8.25	30.0	173	N/A		8.33	30.0	233	1.86		8.05	30.0	200
7/28/96	1.67		7.89	30.5	173	N/A		8.77	30.0	200	1.86		8.46	30.0	200
7/29/96	1.64	4.8	8.60	30.5	185	N/A	3.4	8.61	31.0	233	1.52	1.2	8.22	31.0	N/A
7/30/96	1.64		8.40	30.5	185	N/A		8.92	30.5	N/A	1.52		8.28	30.0	N/A
7/31/96	1.64		7.15	30.5	185	N/A		8.86	30.0	N/A	1.52		7.82	30.0	N/A
8/1/96	1.64				185	N/A				N/A	1.52				N/A
8/2/96	1.64	1.0	8.50	30.5	185	N/A	1.5	8.82	30.5	N/A	1.52	6.4	6.93	30.0	N/A
8/3/96	2.03				215	N/A				N/A	1.39				181
8/4/96	2.03				215	N/A				N/A	1.39				181
8/5/96	2.03	4.8	8.38	31.0	215	N/A	0.5	9.06	31.5	N/A	1.39	6.2	8.67	31.0	181
8/6/96	2.03	1.4	8.38	30.5	215	N/A	6.0	8.81	30.5	N/A	1.38	6.5	8.21	30.5	181
8/7/96	1.93	5.2	8.47	30.5	215	N/A	6.1	8.68	30.0	N/A	1.34	6.4	8.17	29.5	181
8/8/96	1.93	5.4	8.39	30.5	215	N/A	5.1	8.75	30.5	N/A	1.34	4.6	8.26	30.0	181
8/9/96	1.93		8.41	30.5	215	N/A		8.76	30.0	233	1.34		8.21	30.0	180
8/10/96	1.93	5.4	8.41	30.5	215	N/A	4.2	8.72	30.5	233	1.34	3.6	8.28	30.0	185
8/11/96	2.21				215	N/A				233	1.34				185
8/12/96	2.21	4.1	8.36	30.0	215	N/A	4.5	8.68	30.5	215	1.28	5.2	8.41	30.0	185
8/13/96	2.21				207	N/A				215	1.30				185
8/14/96	2.10	4.1	7.77	31.0	207	N/A	3.8	8.64	31.0	215	1.30	4.5	8.27	31.0	185

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
8/15/96	1.80		7.07	31.0	207	N/A		8.90	30.5	215	1.22		8.46	31.0	185
8/16/96	1.80		6.98	31.5	207	N/A		8.94	31.8	215	1.22		8.58	31.5	185
8/17/96	1.80	3.1	7.82	30.8	159	N/A	3.0	8.84	31.2	203	1.22	3.0	8.37	31.0	144
8/18/96	1.54	6.2	8.28	30.8	159	N/A	1.3	8.93	30.5	203	1.17	2.6	8.52	30.5	144
8/19/96	1.54		7.13	31.8	159	N/A		8.69	31.4	203	1.17		8.45	31.4	144
8/20/96	1.54		7.21	31.8	159	N/A		7.61	31.4	203	1.17		8.56	31.0	144
8/21/96	1.54				159	N/A				203	1.17				144
8/22/96	1.54	0.5	8.05	31.8	159	N/A	2.5	8.53	31.8	203	1.17	3.5	8.52	31.8	144
8/23/96	1.73	4.2	8.49	31.8	N/A	N/A	1.0	8.48	31.8	N/A	1.70	3.2	8.48	31.6	N/A
8/24/96	1.73	5.9	8.98		660	N/A	3.5	8.72		660	1.70	5.9	8.96		660
8/25/96	1.73				N/A	N/A				N/A	1.70				N/A
8/26/96	1.73	3.0	8.08	31.8	N/A	N/A	3.5	8.42	31.8	N/A	1.70	3.5	8.37	31.8	N/A
8/27/96	1.73	5.9	8.90	31.6	N/A	N/A	1.0	8.61	31.8	N/A	1.70	6.3	9.83	31.6	N/A
8/28/96	1.98				188	N/A				N/A	1.62				208
8/29/96	1.98	4.5	8.48	31.6	180	N/A	1.0	8.57	31.6	N/A	1.62	5.8	8.46	31.6	208
8/30/96	1.98		8.47	31.8	180	N/A		8.21	31.8	N/A	1.62		8.30	31.4	208
8/31/96	1.98	4.3	8.61	31.6	180	N/A	3.2	8.80	31.8	117	1.62	4.4	8.43	31.6	208
9/1/96	1.98		7.26	31.0	180	N/A		9.08	31.4	N/A	1.62		8.45	29.4	208
9/2/96			8.54	31.6	212	N/A		8.89	31.8	117			8.42	31.6	201
9/3/96	2.12		7.72	29.2	212	N/A		8.62	31.0	N/A	1.81		8.12	29.2	201
9/4/96	2.26		7.54	30.6	212	N/A		9.12	30.8	N/A	1.67		8.32	30.4	201
9/5/96	2.26	4.3	8.54	30.8	212	N/A	4.2	8.88	30.8	N/A	1.67	5.7	8.76	30.5	201
9/6/96	2.26		8.46	30.8	212	N/A		8.71	30.8	N/A	1.67		8.42	30.8	201
9/7/96	2.26				212	N/A				N/A	1.67				201
9/8/96	2.10	4.3	8.42	30.8	200	N/A	2.3	8.78	30.8	N/A	1.65	5.7	8.69	30.8	190
9/9/96	2.10	5.7	8.61	30.6	200	N/A	5.5	8.82	30.8	N/A	1.65	5.8	8.47	30.8	190
9/10/96	1.74				230	N/A				60	1.99				230
9/11/96	1.74		6.83	30.8	N/A	N/A		7.99	30.6	30	1.99		7.63	30.6	N/A
9/12/96	1.74	5.9	7.41	30.8	N/A	N/A	5.8	8.46	30.6	20	1.99	5.3	8.01	30.8	N/A
9/13/96	1.65	5.9	8.91		N/A	2.37	4.0	8.71		N/A	2.51	6.4	8.95		N/A
9/14/96	1.65		8.42		N/A	2.37		8.76		186	2.51		8.47		N/A
9/15/96	1.65	7.0	8.68		75	2.37	7.2	9.03		N/A	2.51	5.7	8.34		203
9/16/96	1.53		8.56		N/A	2.08		8.78		N/A	1.57		8.42		N/A
9/17/96	1.53	5.6	7.12	30.8	N/A	2.08	5.8	7.69	30.8	N/A	1.57	5.9	7.38	30.6	N/A
9/18/96	1.53				100	2.08				N/A	1.57				100
9/19/96	1.53	5.5	7.81	30.6	191	2.08	5.5	7.51	30.5	146	1.57	5.1	7.51	30.5	180
9/20/96	2.04		8.06	29.6	214	2.43		9.05	29.8	194	2.08		8.50	29.8	210
9/21/96	2.04		7.01	29.4	214	2.43		8.63	29.6	194	2.08		8.20	29.0	210
9/22/96	2.04				214	2.43				194	2.08				210
9/23/96	2.04		7.47	29.8	214	2.43		8.78	29.8	194	2.08		8.42	29.8	210
9/24/96	2.04	5.4	7.18	29.4	214	2.43	3.2	8.94	29.6	194	2.08	5.8	8.69	29.0	210
9/25/96	1.76		8.81	29.0	204	1.75		8.81	29.4	197	1.55		8.88	29.6	175
9/26/96	1.76	5.4	8.78	30.0	204	1.75	3.2	8.81	30.5	197	1.55	5.7	8.89	30.0	175

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
9/27/96	1.76		7.15	30.4	204	1.75		8.98	30.8	197	1.55		8.78	30.5	175
9/28/96	1.76		7.48	30.5	204	1.75		8.68	30.0	197	1.55		8.42	30.5	175
9/29/96	2.31		8.51	30.0	203	2.23		9.15	29.5	168	1.66		8.52	28.8	187
9/30/96	2.31				N/A	2.23				N/A	1.66				N/A
10/1/96	2.31				400	2.23				340	1.66				380
10/2/96	2.31		8.68	30.0	203	2.23		8.42	29.5	168	1.66		8.49	29.0	187
10/3/96	2.31		8.52	29.5	N/A	2.23		8.89	29.0	168	1.66		8.37	29.0	187
10/4/96	2.31		8.61	30.0	203	2.23		8.47	29.0	168	1.66		8.29	29.0	187
10/5/96	2.31	5.4	8.89	29.0	N/A	2.23	5.6	9.27	28.5	168	1.66	4.9	8.84	28.5	187
10/6/96	2.31		7.11	29.0	N/A	2.23		9.21	29.5	169	1.66		8.72	29.5	187
10/7/96	2.31	4.8	8.80	29.5	N/A	1.38	5.6	9.00	29.5	214	1.37	4.8	8.72	29.5	N/A
10/8/96	2.31		8.37	29.5	N/A	1.38		9.04	30.0	214	1.37		8.71	30.2	N/A
10/9/96	1.70		6.91	28.0	195	1.38		8.50	28.0	214	1.37		8.13	28.5	N/A
10/10/96	1.70		7.27	29.5	195	1.38		9.16	29.0	202	1.37		8.67	29.5	N/A
10/11/96	2.91	5.4			195	1.27	5.8			202	1.39	6.2			N/A
10/12/96	2.90		7.17		195	1.27		8.99		202	1.39		8.60		145
10/13/96	2.91		8.40	29.5	195	1.27		8.83	30.0	202	1.39		8.59	29.5	145
10/14/96	2.91	3.8	8.27	30.0	195	1.27	4.5	8.68	30.0	202	1.39	5.2	8.78	29.5	145
10/15/96	2.79	5.2	7.98	29.5	200	1.27	3.9	8.68	29.0	195	1.44	5.3	8.42	29.5	156
10/16/96	2.79		8.47	29.5	209	1.27		8.65	29.5	204	1.44		8.75	29.5	156
10/17/96	2.79	4.2	8.56	30.5	209	1.27	2.7	8.56	31.0	204	1.44	5.8	8.75	31.0	156
10/18/96	2.44	3.5	8.42	29.5	207	1.31	4.6	8.68	29.0	186	1.59	5.1	8.61	30.0	162
10/19/96	2.44				207	1.31				186	1.59				162
10/20/96	2.44		8.48	29.5	207	1.31		8.36	29.5	186	1.59		8.51	29.5	162
10/21/96	2.44		8.32	29.5	207	1.31		8.56	30.0	186	1.59		8.72	29.5	162
10/22/96	2.73				N/A	1.40				N/A	1.76				N/A
10/23/96	2.73	5.4	8.17	29.5	N/A	1.40	5.2	8.72	30.0	N/A	1.76	4.6	8.48	29.5	N/A
10/24/96	2.73		7.02	29.5	N/A	1.40		9.16	30.5	N/A	1.76		8.28	29.5	N/A
10/25/96	2.73	6.5	7.44		495	1.40	6.2	8.14		495	1.76	5.8	8.04		495
10/26/96	2.18		8.81		197	1.28		9.01		1.99	2.00		8.67		180
10/27/96	2.18		7.18		N/A	1.28		8.55		199	2.00		7.85		180
10/28/96	2.18				197	1.28				199	2.00				180
10/29/96	2.18		8.72		197	1.28		8.81		199	2.00		8.45		180
10/30/96	2.42	5.6	8.54	31.0	211	1.27	4.7	8.75	31.5	217	1.76	3.6	8.36	31.0	197
10/31/96	2.42				211	1.27				217	1.76				197
11/1/96	2.42		8.41	30.5	211	1.27		8.68	30.0	217	1.76		8.48	29.5	197
11/2/96	2.42		7.98		211	1.27		8.68		217	1.76		8.37		197
11/3/96	2.42				211	1.27				217	1.76				197
11/4/96	2.42		8.42	29.5	220	1.27		8.78	29.5	209	1.76		8.59	29.5	166
11/5/96	2.24				220	1.47				209	1.69				166
11/6/96	2.24				220	1.47				209	1.69				166
11/7/96	2.24	5.4	8.36		220	1.47	4.8	8.83		209	1.69	4.9	8.42		1.66
11/8/96	2.11		8.24		210	1.43		8.72		222	1.71		8.63		160

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
11/9/96	2.11		8.17		210	1.43		8.89		222	1.71		8.52		160
11/10/96	2.11		8.30		210	1.43		9.00		222	1.71		8.61		160
11/11/96	2.11		7.18	29.0	210	1.43		9.12	28.5	220	1.71		8.29	28.0	N/A
11/12/96	2.11				210	1.43				220	1.71				160
11/13/96	2.11		8.16		202	1.43		8.74		222	1.71		8.58		126
11/14/96	2.25				202	1.60				222	1.71				126
11/15/96	2.25		8.41	29.5	202	1.60		8.81	30.0	222	1.71		8.61	29.5	N/A
11/16/96	2.25				202	1.60				222	1.71				N/A
11/17/96	2.25		8.01	29.5	202	1.60		8.61	30.0	222	1.71		8.32	29.0	N/A
11/18/96	2.25		8.41	30.5	202	1.60		8.78	30.5	222	1.71		8.62	30.0	126
11/19/96	2.25				195	1.71				217	1.61				50
11/20/96	2.25		8.41	29.5	195	1.71		8.78	30.0	217	1.61		8.53	30.0	50
11/21/96	2.66		8.18	29.5	195	1.54		8.62	29.5	217	2.18		8.43	29.0	50
11/22/96	2.66		7.78		195	1.54		8.41		217	2.18		8.21		N/A
11/23/96					195					217					50
11/24/96	2.66		8.01	30.0	195	1.54		8.28	30.5	217	2.18		8.14	30.0	N/A
11/25/96			8.43		195			8.81		217			8.51		50
11/26/96	2.66		8.17	29.5	195	1.54		8.34	30.0	217	2.18		8.21	30.0	N/A
11/27/96					195					217					N/A
11/28/96					N/A					N/A					N/A
11/29/96	2.66				390	1.54				434	2.18				N/A
11/30/96	2.66		8.32		200	1.54		8.51		204	2.18		8.42		N/A
12/1/96		4.6	8.84	29.0	200		4.4	8.98	29.5	204		6.0	9.06	30.0	N/A
12/2/96	2.39				200	1.45				204	1.63				N/A
12/3/96			8.56	30.0	200			8.68	29.5	204			8.62	30.0	-
12/4/96	2.39		7.89		200	1.45		8.21		204	1.63		8.10		-
12/5/96		4.8	8.79	30.0	200		5.6	8.87	30.5	204		6.7	9.03	30.5	-
12/6/96	2.65				203	1.34				218	1.50				185
12/7/96			8.69	28.5	203			8.70	29.0	218			8.70	29.0	185
12/8/96	2.65				203	1.34				218	1.50				185
12/9/96					203					218					-
12/10/96	2.65		8.54	29.5	202	1.34		8.61	30.5	219	1.50		8.62	30.0	-
12/11/96					202					219					-
12/12/96	2.65		8.20	30.5	202	1.34		8.50	31.0	219	1.50		8.54	31.0	196
12/13/96			8.93	30.5	202			8.51	31.0	219			8.85		196
12/14/96	2.65		8.33	29.5	203	1.34		8.71	30.0	218	1.50		8.37	30.0	184
12/15/96		4.6	8.84	29.0	200		4.4	8.98	29.5	204		6.0	9.06	30.0	N/A
12/16/96	2.39				200	1.45				204	1.63				N/A
12/17/96					208					228					210
12/18/96	1.57		7.98	30.0	208	1.16		8.12	29.5	228	1.24		8.00	29.0	210
12/19/96					208					228					210
12/20/96	1.72		7.92	28.0	208	1.28		8.21	27.5	228	1.12		8.06	27.0	210
12/21/96					194					224					173

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
12/22/96	1.72		7.02	26.1	194	1.28		8.05	26.1	224	1.21		7.70	25.9	173
12/23/96					194					224					173
12/24/96	1.72		7.15		194	1.28		8.83		224	1.12		8.27		173
12/25/96					194					224					173
12/26/96	1.72		7.20		N/A	1.28		8.59		N/A	1.12		8.22		N/A
12/27/96					388					448					346
12/28/96	1.72		7.20		194	1.28		8.78		224	1.12				173
12/29/96					194					224					173
12/30/96	1.61				210	0.96				N/A	1.46				166
12/31/96		5.8	8.94	30.5	210		5.8	8.98	30.2	N/A		6.0	9.08	30.0	166
1/1/97	1.61				210	0.96				N/A	1.46				166
1/2/97			8.82	30.5	210			8.88	30.8	220			8.60	31.0	166
1/3/97	1.61				210	0.96				220	1.46				166
1/4/97			9.12	30.5	212			9.00	30.8	213			9.10	30.5	88
1/5/97	1.64		8.42	30.8	212	1.05		9.08	31.0	240	2.00		8.90	31.0	88
1/6/97					212					240					88
1/7/97	1.64				212	1.05				240	2.00				88
1/8/97			9.06	31.0	212			8.98	30.5	240			9.02	30.8	88
1/9/97	1.64		8.01	30.0	N/A	1.05		8.52	29.5	N/A	2.00		8.48	30.0	N/A
1/10/97					N/A					N/A					N/A
1/11/97	1.64	0.1	7.36		135	1.05	0.1	7.57		195	2.05	0.1	7.31		135
1/12/97		5.8	8.93		180		5.9	9.13		180		5.9	8.98		180
1/13/97	1.64				160	105.00				270	2.05				94
1/14/97					170					215					135
1/15/97	1.58		7.70	28.0	170	0.96		8.43	27.5	215	1.31		8.46	28.0	135
1/16/97			8.62		170			9.20		215			9.12		135
1/17/97	1.58		7.77	28.0	170	0.96		8.49	29.0	215	1.31		8.38	28.5	135
1/18/97					-					-					-
1/19/97	1.58		7.41	29.0	377	0.96		7.68	29.5	-	1.31		7.33	29.0	351
1/20/97			8.91	28.0	207			9.18	28.0	-			9.01	28.5	216
1/21/97	1.28				-	0.62				-	1.78				-
1/22/97			8.81	29.5	-			8.98	29.5	-			8.92	29.5	-
1/23/97	1.28		7.63		450	0.62		7.87		600	1.78		7.71		450
1/24/97		4.4			-		5.2			-		4.6			-
1/25/97	1.50				-	1.00				217	1.99				-
1/26/97			8.36	29.0	-			9.01	29.5	217			8.57	29.0	-
1/27/97	1.50		7.62	29.5	171	1.00		7.98	29.0	217	2.00		7.75	30.0	196
1/28/97					171					217					196
1/29/97	1.50		7.67	29.5	171	1.00		8.22	30.0	217	1.99		8.01	29.5	196
1/30/97			8.62	30.0	171			8.79	30.0	217			8.53	30.5	196
1/31/97	1.68				400	1.00				440	1.66				214
2/1/97					-					-					-
2/2/97	1.68				200	1.00				220	1.66				107

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
2/3/97					200					220					107
2/4/97	1.68		7.63	29.5	200	1.00		8.20	29.5	218	1.66		7.89	29.5	107
2/5/97					-					-					-
2/6/97	1.74		7.52	29.5	400	0.63		8.01	29.5	436	1.14		7.82	30.0	214
2/7/97		4.7	8.27	29.5	219		5.2	8.78	29.5	211		4.4	8.43	29.0	185
2/8/97	1.74				219	0.63				211	1.14				185
2/9/97			8.61	29.5	219			8.96	30.0	211			8.59	29.5	185
2/10/97	1.76		7.46		219	0.63		7.99		211	1.14		7.65		185
2/11/97					219					211					185
2/12/97	1.58		7.33	30.0	198	0.95		9.21	29.5	216	1.59		8.51	30.0	161
2/13/97			8.27	29.5	198			9.16	29.5	216			8.71	29.5	161
2/14/97	1.58				198	0.95				216	1.59				161
2/15/97					198					216					161
2/16/97	1.58		7.46	29.5	198	0.95		9.12	29.5	216	1.59		8.37	30.0	161
2/17/97			8.31	29.5	198			8.98	29.5	216			8.42	30.0	161
2/18/97	1.58		7.12		180	0.95		8.73		240	1.59		7.46		180
2/19/97		4.7	8.39		180		6.5	9.16		210		6.0	8.80		180
2/20/97	2.00	6.2	8.64		90	0.83	5.6	9.09		105	1.82	6.1	8.67		90
2/21/97					129					203					204
2/22/97	2.00				-	0.83				-	1.82				-
2/23/97					-					-					-
2/24/97	2.00		7.48		-	0.83				-	1.82				-
2/25/97					600					600					600
2/26/97	2.48		7.23	29.5	156	1.12		8.67	30.5	213	2.45		8.23	30.0	23
2/27/97					156					-					23
2/28/97	2.48		7.47	29.5	-	1.12		8.52	30.0	-	2.45		8.31	29.5	-
3/1/97					156					213					-
3/2/97	2.48		7.53	29.5	156	1.12		8.67	30.0	213	2.45		8.44	30.0	-
3/3/97					156					213					-
3/4/97	2.48		7.94	31.0	156	1.12		9.24	31.5	213	2.45		8.24	31.5	23
3/5/97					156					213					23
3/6/97	2.48		7.42	31.0	176	1.12		9.01	31.0	225	2.45		8.41	31.5	70
3/7/97					176					-					-
3/8/97	2.74		7.28	31.0	156	1.17		8.89	31.5	550	2.43		8.04	31.5	550
3/9/97					-					90					-
3/10/97	2.63				420	0.99				224	2.31				-
3/11/97					198					-					-
3/12/97	2.63		7.28	29.5	198	0.99		8.68	30.5	550	2.31		8.01	30.5	550
3/13/97		4.3	8.54	29.5	-		3.9	9.26	30.0	-		3.6	8.79	30.5	-
3/14/97	2.63		7.35	29.5	198	0.99		8.91	29.5	224	2.31		8.04	30.0	66
3/15/97					198					224					66
3/16/97	2.63		7.41	29.0	198	0.99		8.77	29.5	224	2.31		8.12	29.0	66
3/17/97					198					224					66

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
3/18/97	1.65		7.39	29.5	159	1.10		8.74	30.0	212	1.53		7.85	30.0	150
3/19/97			8.01		159			9.15		212			8.48		150
3/20/97	1.65		7.17	29.0	225	1.10		8.60		225	1.53		7.45	29.5	225
3/21/97			8.28		180			8.99		180			8.49		180
3/22/97	1.65		7.61	29.5	159	1.10		9.10	30.0	212	1.53		8.10	30.0	150
3/23/97					159					212					150
3/24/97	1.65		7.57	29.5	159	1.10		9.05	30.0	212	1.53		8.31	30.0	150
3/2597		4.0			159		3.9			212		4.2			150
3/26/97	1.65		7.46	29.5	159	1.10		8.28	30.0	212	1.53		7.68	30.0	150
3/27/97			8.60		-			9.17		212			8.58		150
3/28/97	1.65		7.62		159	1.10		8.31		212	1.53		7.68		150
3/29/97					217					216					187
3/30/97	2.49		7.47	30.0	217	1.43		8.37	30.5	216	2.60		7.62	30.0	187
3/31/97					-					216					187
4/1/97	2.49		7.71		217	1.43		8.52		216	2.60		8.01		187
4/2/97			8.49		184			9.13		198			8.68		187
4/3/97	3.23				184	1.32				198	2.96				187
4/4/97			8.61		184			9.10		198			8.78		187
4/5/97	3.23		7.47	29.5	-	1.32		8.98	30.0	198	2.96		7.90	30.0	187
4/6/97					184					198					187
4/7/97	3.23		7.62		184	1.32		8.91		198	2.96		7.86		187
4/8/97					215					201					201
4/9/97	3.77		7.47	29.5	219	1.59		8.78	30.0	201	2.89		7.72	30.5	201
4/10/97			8.05	29.5	219			9.08	30.5	201			8.71	30.5	201
4/11/97	3.77				215	1.59				200	2.89				200
4/12/97					215					200					200
4/13/97	3.77				215	1.59				200	2.89				200
4/14/97					219					201					201
4/15/97	3.77		7.62	29.5	219	1.59		8.68	30.0	201	2.89		8.14	30.0	201
4/16/97					162					195					102
4/17/97	3.67		7.42	29.5	162	1.74		8.73	30.0	195	2.46		8.20	30.5	102
4/18/97			8.43		162			9.12		195			8.53		102
4/19/97	3.67		7.63		162	1.74		8.71		195	2.46		8.15		102
4/20/97			8.42		162			9.01		195			8.47		-
4/21/97	3.67		7.92	30.5	-	1.74		8.79	30.5	-	2.46		8.46	30.0	-
4/22/97		<1			-		4+			-		3+			-
4/23/97	3.67		7.53	29.0	500	4.74		8.69	29.5	500	2.46		7.90	29.5	500
4/24/97					-					195					102
4/25/97	3.27		7.46	30.0	-	1.84		8.72	30.5	175	2.86		7.78	30.5	181
4/26/97			8.46	30.5	-			9.26	30.5	181			8.47	31.5	181
4/27/97	3.27		7.49	30.0	-	1.84		8.76	30.5	119	2.86		7.84	30.0	-
4/28/97					-					119					-
4/29/97	3.36		7.24	31.0	199	2.05		8.68	30.5	119	3.28		7.72	30.5	211

	ANA/AER					ANX/AER					AER				
Date	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage	Chlorine	D.O. mg/L	pH	Temp. (°C)	Wastage
4/30/97					-					119					-
5/1/97	3.36		7.36	31.0	-	2.05		8.78	30.5	119	3.28		7.83	30.5	-
5/2/97			8.96		-			9.24		119			8.97		-
5/3/97	3.36		7.42	30.5	193	2.05		8.89	31.0	85	3.28		7.89	30.5	-
5/4/97					-					85					60
5/5/97	2.27		7.32	30.5	193	1.84		8.81	31.0	85	2.93		7.94	30.5	60
5/6/97					193					85					60
5/7/97	2.27		7.93	31.0	-	1.84		9.15	31.0	85	2.93		8.16	30.5	-
5/8/97			8.97		-			9.40		85			8.98		-
5/9/97	2.27		7.15	31.0	193	1.84		9.20	31.5	85	2.93		8.09	30.5	60
5/10/97					-					85					-
5/11/97	3.04		7.23	31.0	-	1.70		9.27	31.5	176	3.45		8.21	31.0	-
5/12/97					212					176					203
5/13/97	3.04		7.47	31.5	-	1.70		8.42	31.0	176	3.45		7.98	31.0	-
5/14/97			8.46	31.0	-			8.98	31.0	176			8.52	31.0	-
5/15/97	3.04				212	1.70				176	3.46				203
5/16/97			9.01	29.0	-			9.55	29.5	190			8.68	29.5	196
5/17/97	4.11		7.14		17	2.06		8.23		190	4.20		8.41		1.96
5/18/97			8.89		-			9.44		190			8.87		196
5/19/97	4.11		8.16		-	2.06		9.13		190	4.20		7.11		196
5/20/97					-					190					-
5/21/97	4.11		7.52	31.0	-	2.06		9.44	31.0	190	4.20		8.47	31.0	-
5/22/97		4.3			-		4.2			131		3.6			-
5/23/97	2.45		7.46	30.5	-	1.27		9.36	30.5	131	3.51		8.52	31.0	-
5/24/97					-					-					-
5/25/97	2.45		7.52	30.5	194	1.37		9.41	31.0	-	3.51		8.33	31.0	187
5/26/97			8.47		-			9.43		-			8.72		-
5/27/97	2.45		7.56	31.0	500	1.37		9.28	30.5	900	3.51		8.49	31.0	225
5/28/97					-					-					-
5/29/97	4.13		7.61	31.0	-	2.21		9.36	31.0	-	3.48		8.42	31.0	-
5/30/97					-					205					-
5/31/97	4.13		7.49	31.0	-	2.21		9.28	30.5	205	3.48		8.48	30.5	500
6/1/97					-					209					-
6/2/97	5.33		7.60	30.0	-	2.00		9.23	30.0	209	3.20		8.41	30.0	198
6/3/97			8.55		-			9.07		209			8.49		198
6/4/97	5.33		7.42	30.0	155	2.00		9.18	30.5	209	3.20		8.32	30.0	198
6/5/97					-					209					100
6/6/97	5.33		7.46	30.0	155	2.00		9.31	31.0	209	3.20		8.41	30.5	198
6/7/97					-					209					198
6/8/97	5.20		7.52	30.0	-	2.38		9.28	31.0	209	4.59		9.28	31.0	127
6/9/97					-					149					127
6/10/97	5.20		7.46	30.0	-	2.38		8.38	30.5	149	4.59		8.01	30.5	127
6/11/97					-					149					127

TableB-2: Mixed liquor suspended solids concentrations (mg/L) for ANA, ANX and AER SBRs

Date	ANA (mg/L)	ANX (mg/L)	AER (mg/L)
4/8/96	4440	4010	4600
4/10/96	4640	3469	4255
4/12/96	3335	4235	3410
4/13/96	3473	3963	3230
4/15/96	2725	5230	2895
4/16/96	2980	5085	3185
4/17/96	3340	3295	3575
4/18/96	2785	4217	3920
4/21/96	2675	3405	4490
4/23/96	1925	3005	3920
4/24/96	2295	3365	3370
4/25/96	2505	3585	5940
4/28/96	2390	3275	4200
5/1/96	3300	3571	2795
5/2/96	2900	3300	2690
5/4/96	1910	2900	3120
5/5/96	1930	3500	4340
5/6/96	1800	3420	3025
5/7/96	1615	3260	3430
5/9/96	1300	3350	3710
5/10/96	1020	3020	3405
5/12/96	1965	5250	4795
5/13/96	1370	1760	1705
5/14/96	1165	3440	3140
5/16/96	2130	4060	2175
5/19/96	1890	3640	2460
5/23/96	3485	3340	4595
5/25/96	3990	3760	4520
5/26/96	3950	3920	4940
5/29/96	3270	4500	4270
6/1/96	2230	4010	3370
6/4/96	1740	3980	2360
6/8/96	1870	4120	2290
6/11/96	1360	4390	1460
6/15/96	1510	4440	1870
6/17/96	1058	4380	1050
6/20/96	2067	4320	2160
6/25/96	1683	3240	1030
6/29/96	1910	4580	2950
7/3/96	2320	5040	3490
7/5/96	2500	5375	4110
7/8/96	3000	5750	4641
7/11/96	2575	5070	4150
7/15/96	3090	5600	2475
7/18/96	4110	5975	3710
7/22/96	3960	5375	4050
7/25/96	3700	5375	4050
7/28/96	3940	5325	3625
8/2/96	4830	4625	3300
8/6/96	4580	4137	3180
8/10/96	5250	6213	3040
8/13/96	4270	5470	2890
8/17/96	3670	6365	2780
8/22/96	4100	7360	4030
8/27/96	4710	7237	3860

Date	ANA (mg/L)	ANX (mg/L)	AER (mg/L)
8/31/96	3670	6365	2780
9/3/96	5380	6200	3970
9/6/96	4980	5260	3920
9/10/96	4140	5670	4730
9/12/96	3917	5640	5970
9/15/96	3730	4950	3730
9/19/96	3670	4120	3300
9/24/96	4210	4170	3700
9/29/96	5500	5310	3950
10/6/96	5590	6570	3260
10/10/96	6930	6040	3300
10/14/96	6650	6050	3430
10/18/96	5820	6240	3970
10/25/96	5180	6100	4150
10/30/96	5750	6050	4180
11/4/96	4350	6070	3050
11/8/96	5030	6810	4060
11/13/96	5360	7580	4070
11/20/96	6340	7320	5200
11/26/96	6100	6860	3662
11/30/96	5690	6900	3870
12/6/96	6310	6360	3570
12/10/96	3610	4950	2500
12/15/96	3730	5540	2960
12/20/96	4090	6080	2670
12/30/96	3830	4570	3470
1/3/97	3910	5000	4770
1/11/97	3750	4590	3120
1/19/97	3050	2940	4240
1/23/97	3560	4780	4730
1/26/97	3470	4750	4280
1/30/97	4010	4800	3942
2/6/97	4140	2980	2720
2/12/97	3760	4500	3780
2/18/97	4770	3960	4330
2/26/97	5910	5330	5830
3/1/97	6520	5560	5790
3/8/97	6250	4710	5490
3/16/97	4780	4830	3920
3/18/97	3940	5250	3600
3/24/97	3000	4040	3240
3/26/97	5920	6800	6180
4/1/97	7700	6260	7040
4/8/97	8970	7590	6870
4/15/97	8740	8250	5850
4/23/97	5280	6380	4640
4/27/97	5790	7180	5430
5/3/97	5410	8750	6980
5/9/97	7230	8090	8220
5/15/97	10010	9800	9780
5/21/97	6530	5830	8340
5/27/97	9840	10520	8260
5/31/97	12690	9510	7630
6/6/97	12380	11320	10940
6/12/97	7820	8700	9150

Table B-3: COD:TOC Ratio for ANA SBR

Date	COD (mg/L)	TOC (mg/L)	COD:TOC
7/15/96	1170	470	2.49
7/18/96	2635	870	3.03
7/24/96	3785	1394.5	2.71
7/30/96	2895	983	2.95
8/10/96	3270	1145	2.86
8/13/96	3260	1163	2.80
8/22/96	3040	960	3.17
8/27/96	3520	1058	3.33
8/31/96	3390	1048	3.23
9/3/96	3180	987	3.22
9/6/96	4030	1287	3.13
9/12/96	3645	1156	3.15
9/19/96	3655	1139	3.21
9/24/96	3400	1056	3.22
9/27/96	3195	979	3.26
10/10/96	3180	927.7	3.43
10/18/96	3110	936.7	3.32
10/25/96	2855	840.1	3.40
11/8/96	2095	680.3	3.08
11/11/96	2035	651.7	3.12
11/13/96	2550	849.3	3.00
11/15/96	2590	858.8	3.02
11/18/96	2945	957.9	3.07
11/20/96	3035	945.7	3.21
11/24/96	1990	622.7	3.20
12/10/96	1060	352.6	3.01
12/14/96	1675	582	2.88
12/20/96	2030	589	3.45
12/30/96	2040	571.8	3.57
1/7/97	2180	704.1	3.10
1/13/97	1740	599.1	2.90
1/19/97	2305	723.9	3.18
1/23/97	2100	690.15	3.04
1/27/97	1000	317.6	3.15
2/4/97	2071	636	3.26

Table B-4: COD:TOC Ratio for ANX SBR

Date	COD (mg/L)	TOC (mg/L)	COD:TOC
7/15/96	123	31.5	3.90
7/18/96	1345	996	1.35
7/30/96	2000	778	2.57
8/10/96	1995	644	3.10
8/13/96	803	264	3.04
8/22/96	1315	447.5	2.94
8/27/96	2235	799	2.80
8/31/96	1840	604.4	3.04
9/3/96	2260	707	3.20
9/6/96	2570	832	3.09
9/12/96	2185	701	3.12
9/19/96	2420	942	2.57
9/24/96	2950	920.6	3.20
9/27/96	2985	752.8	3.97
10/10/96	2425	737.8	3.29
10/18/96	2240	663	3.38
10/25/96	1840	584.4	3.15
11/8/96	1480	515.2	2.87
11/11/96	1110	404.4	2.74
11/13/96	1160	409.7	2.83
11/15/96	588	196.4	2.99
11/18/96	1890	1166	1.62
11/20/96	2080	650.5	3.20
11/24/96	2270	707.2	3.21
11/30/96	181	46.49	3.89
12/4/96	167	52.21	3.20
12/10/96	121	32.33	3.74
12/14/96	288	92.52	3.11
12/20/96	88	27.93	3.15
12/30/96	151	45.58	3.31
1/7/97	61	20.57	2.97
1/13/97	101	36.5	2.77
1/19/97	88	34.335	2.56
1/23/97	80	28.12	2.84
1/27/97	149	50.77	2.93
2/4/97	370	125.7	2.94

Table B-5: COD:TOC Ratio for AER SBR

Date	COD (mg/L)	TOC (mg/L)	COD:TOC
7/15/96	2415	1221	1.98
7/18/96	2770	964	2.87
7/24/96	2305	758.7	3.04
7/30/96	2650	868	3.05
8/10/96	3480	1194	2.91
8/13/96	2310	767	3.01
8/22/96	2770	882.4	3.14
8/27/96	3500	1093	3.20
8/31/96	3450	1133	3.05
9/3/96	3225	969	3.33
9/6/96	3425	1098	3.12
9/12/96	3730	1176	3.17
9/24/96	2800	1188	2.36
9/27/96	3070	858.5	3.58
10/10/96	2800	842.3	3.32
10/18/96	2520	768.3	3.28
10/25/96	2420	768.3	3.15
11/8/96	1825	587.6	3.11
11/11/96	1600	546.5	2.93
11/13/96	2300	780	2.95
11/15/96	2430	821.7	2.96
11/18/96	2560	832.4	3.08
11/20/96	2580	833.6	3.10
11/24/96	1310	435.6	3.01
11/30/96	730	259.3	2.82
12/4/96	1285	422.9	3.04
12/10/96	2230	695.2	3.21
12/14/96	1520	518.9	2.93
12/20/96	1645	460.4	3.57
12/30/96	995	305.2	3.26
1/7/97	1555	542.7	2.87
1/13/97	1675	587.9	2.85
1/19/97	1015	304.5	3.33
1/23/97	335	118	2.84
1/27/97	553	175.9	3.14
2/4/97	2345	723.7	3.24

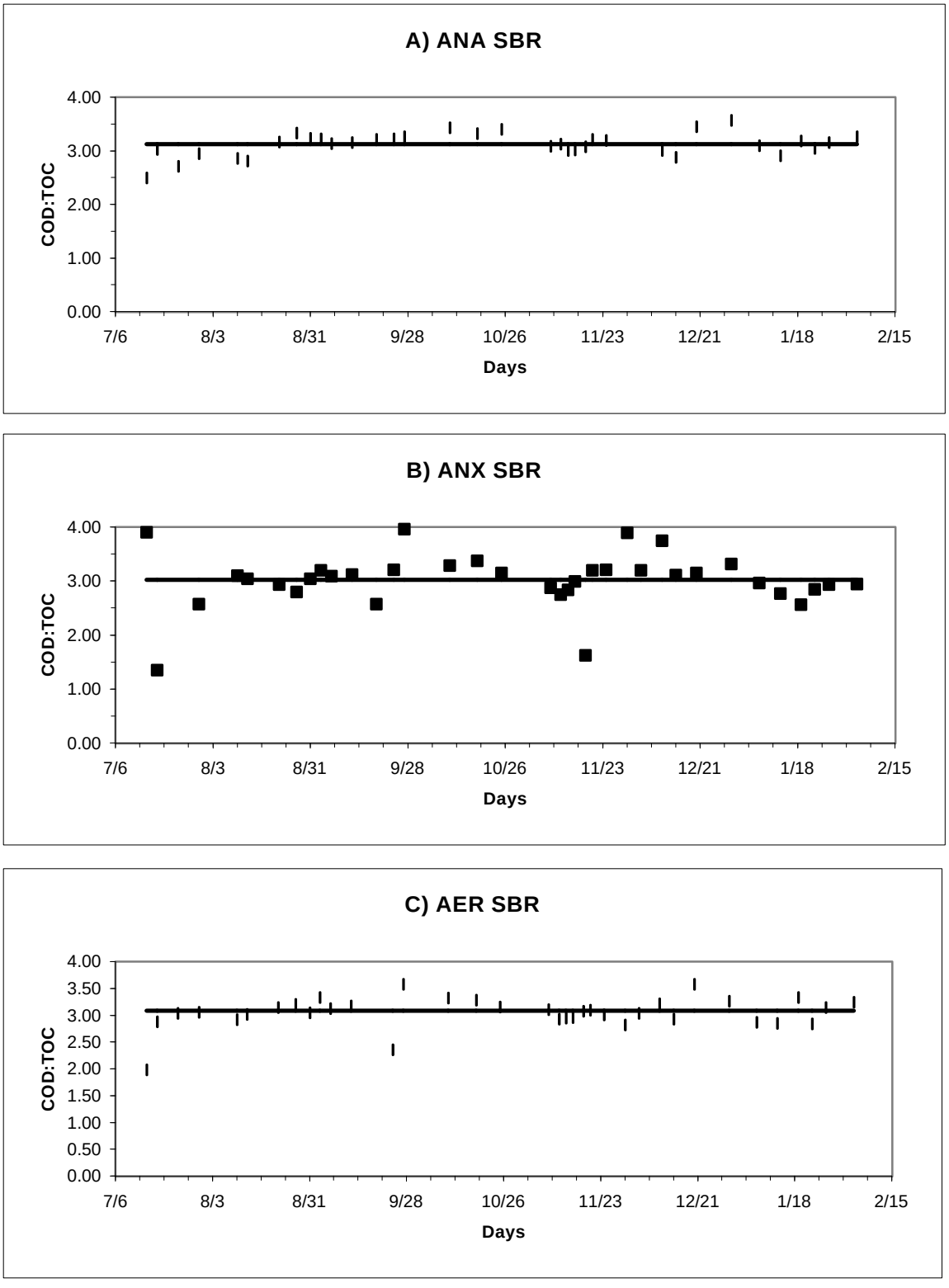

Figure B-1: COD:TOC ratios for ANA, ANX and AER SBRs for data collected from 7/15/96 - 2/4/97

Table B-6: Effluent TOC Concentrations (mg/L) for ANA, ANX and AER SBRs

Date	ANA (mg/L)	ANX (mg/L)	AER (mg/L)
4/10/96	480	434	489
4/13/96	1201	774	1043
4/17/96	1711	1524	1366
4/19/96	1924	2087	1371
4/21/96	1961	1940	1394
4/23/96	1929	1894	1487
4/28/96	1449	2037	1760
5/1/96	1023	2078	2246
5/5/96	1520	1981	1538
5/7/96	1274	1890	1344
5/10/96	1946	1777	1536
5/14/96	2125	2042	1823
5/17/96	2207	2106	2009
5/23/96	549	748	458
5/26/96	308	99	92
5/29/96	402	32.5	433
6/1/96	665	31.5	746
6/4/96	856	74.7	914
6/8/96	423	248	866
6/11/96	586	100	860
6/12/96	430	110	516
6/14/96	450	142	501
6/17/96	481	57	453
6/20/96	417	16.1	402
6/25/96	362	315	454
6/29/96	360	396	147
7/3/96	407	94.6	71.5
7/5/96	310	97.2	68.78
7/7/96			45.33
7/8/96	93.6	37.69	
7/10/96	160	153	181
7/15/96	470	31.5	1221
7/18/96	870	996	964
7/21/96	1184	843	760
7/24/96	1394.5	1188	758.65
7/27/96	1062	1193	1103
7/30/96	983	778	868
8/2/96	951	849	1486
8/6/96	1113	817	1192
8/10/96	1145	644	1194
8/13/96	1163	264	767
8/17/96	1111	984	1291
8/22/96	960	447.5	882.4
8/27/96	1058	799	1093
8/31/96	1048	604.4	1133
9/3/96	987	707	969
9/6/96	1287	832	1098
9/10/96	1484	743	1073
9/12/96	1156	701	1176
9/15/96	1316	887.4	1243
9/19/96	1139	942	967
9/24/96	1056	920.6	1188
9/27/96	979	752.8	858.5

Date	ANA (mg/L)	ANX (mg/L)	AER (mg/L)
10/6/96	1273	938	
10/10/96	927.7	737.8	842.3
10/13/96	910.3	732.3	747
10/18/96	936.7	663	768.3
10/25/96	840.1	584.4	768.3
11/8/96	680.3	515.2	587.6
11/11/96	651.7	404.4	546.5
11/13/96	849.3	409.7	780
11/15/96	858.8	196.4	821.7
11/18/96	957.9	1166	832.4
11/20/96	945.7	650.5	833.6
11/24/96	622.7	707.2	435.6
11/30/96	94.6	46.49	259.3
12/4/96	79.81	52.21	422.9
12/10/96	352.6	32.33	695.2
12/14/96	582	92.52	518.9
12/20/96	589	27.93	460.4
12/30/96	571.8	45.58	305.2
1/3/97	607.3	27.82	376.5
1/7/97	704.1	20.57	542.7
1/13/97	599.1	36.5	587.9
1/19/97	723.9	34.335	304.45
1/23/97	690.15	28.12	117.95
1/27/97	317.6	50.77	175.9
2/4/97	636	125.7	723.7
2/8/97	62.51	116.7	138.4
2/10/97	71.53	109.2	208.5
2/12/97	52.73	104.1	249.1
2/14/97	48.65	97.03	133.55
2/16/97	52.93	91.22	93.11
2/18/97	34.96	65.69	45.39
2/24/97	39.72	33.25	49.88
2/26/97	54.87	31.76	251.7
3/4/97	40.48	33.32	60.03
3/6/97	44.89	34.8	46.8
3/12/97	201.05	47.84	510.6
3/16/97		103.7	766.45
3/20/97	573.95	159	616.15
3/22/97	164.2	86.49	93.85
3/25/97	38.45	73.29	600.8
3/30/97	153.3	105.1	102.7
4/3/97	181	87.81	265.7
4/7/97	81.9	195.9	268
4/15/97	225.3	110.7	405.4
4/19/97	114.4	94.83	162.8
5/7/97	678.9	219.8	94.7
5/11/97	79.95	172.9	62.91
5/15/97	69.09	81.2	39.2
5/27/97	60.34	98.12	86.29
5/31/97	62.56		61.95
6/4/97	68.9	90.49	68.26
6/8/97	54.18	95.6	82.43
6/12/97	50	67.38	77.1

Table B-7: COD Concentrations (mg/L) for ANA, ANX and AER SBRs before increase in nutrient loading (2/6/9

Date	**ANA** (mg/L)	**ANX** (mg/L)	**AER** (mg/L)
4/9/96	-	432	810
4/10/96	1306	1076	3938
4/12/96	3938	4094	3882
4/13/96	3717	2374	3478
4/16/96	4867	3420	4315
4/17/96	3987	3582	3267
4/18/96	3231	4644	5004
4/19/96	5085	5022	2988
4/23/96	2973	2758	2367
5/7/96	763	2992	2621
5/14/96	3402	3189	4250
5/23/96	968	1223	1018
5/26/96	587	391	352
6/1/96	1949	38	2206
6/4/96	2440	217	2450
6/8/96	1390	837	2360
6/11/96	1500	307	1810
6/12/96	1260	330	1430
6/14/96	1480	411	1415
6/17/96	1230	155	1075
7/5/96	945	335	225
7/8/96	280	89.2	
7/11/96	1005	280	1630
7/15/96	1170	123	2415
7/18/96	2635	1345	2770
7/24/96	3785	3420	2305
7/30/96	2895	2000	2650
8/10/96	3270	1995	3480
8/13/96	3260	803	2310
8/22/96	3040	1315	2770
8/27/96	3520	2235	3500
8/31/96	3390	1840	3450
9/3/96	3180	2260	3225
9/6/96	4030	2570	3425
9/12/96	3645	2185	3730
9/19/96	3655	2420	
9/24/96	3400	2950	2800
9/27/96	3195	2985	3070

Date	**ANA** (mg/L)	**ANX** (mg/L)	**AER** (mg/L)
10/10/96	3180	2425	2800
10/18/96	3110	2240	2520
10/21/96	3040	1980	2040
10/25/96	2855	1840	2420
10/30/96	2730	2000	3185
11/4/96	2700	2355	2550
11/8/96	2095	1480	1825
11/11/96	2035	1110	1600
11/13/96	2550	1160	2300
11/15/96	2590	588	2430
11/18/96	2945	1890	2560
11/20/96	3035	2080	2580
11/24/96	1990	2270	1310
11/30/96		181	730
12/4/96		167	1285
12/10/96	1060	121	2230
12/14/96	1675	288	1520
12/20/96	2030	88	1645
12/30/96	2040	151	1990
1/7/97	2180	61	1555
1/13/97	1740	101	1675
1/19/97	2305	88	1015
1/23/97	2100	80	335
1/27/97	1000	149	553
2/4/97	2071	370	2345

Table B-8: COD values (mg/L) calculated from TOC concentrations for ANA, ANX and AER SBRs after nutrient increase on 2/6/97

Date	ANA (mg/L)	ANX (mg/L)	AER (mg/L)
2/8/97	195	352	425
2/10/97	223	330	640
2/12/97	165	314	765
2/14/97	152	293	410
2/16/97	165	275	286
2/18/97	109	198	139
2/24/97	124	100	153
2/26/97	171	96	773
3/4/97	126	101	184
3/6/97	140	105	144
3/12/97	627	144	1568
3/16/97		313	2353
3/20/97	1791	480	1892
3/22/97	512	261	288
3/25/97	120	221	1844
3/30/97	478	317	315
4/3/97	565	265	816
4/7/97	256	592	823
4/15/97	703	334	1245
4/19/97	357	286	500
5/7/97	2118	664	291
5/11/97	249	522	193
5/15/97	216	245	120
5/27/97	188	296	265
5/31/97	195		190
6/4/97	215	273	210
6/8/97	169	289	253
6/12/97	156	203	237

Table B-9: Effluent suspended solids concentrations for ANA, ANX and AER SBRs

Date	ANA (mg/L)	ANX (mg/L)	AER (mg/L)
2/13/97	75	46	156
2/19/97	284	69	73
2/27/97	260	62	700
3/7/97	213	39	540
3/9/97	198	224	66
3/19/97	168	64	167
3/27/97	56	68	165
4/2/97	219	128	188
4/8/97	74	140	126
4/16/97	358	182	436
4/24/97	1117	294	203
4/27/97	101	403	64
5/3/97	124	743	693
5/9/97	89	264	145
5/15/97	1210	247	215
5/21/97	130	380	221
5/27/97	1115	156	166
5/31/97	567	133	153
6/6/97	1925	544	665
6/12/97	3593	177	3233

Table B-10: Sludge Volume Index values for ANA ANX, and AER SBRs

Date	ANA (mL/g)	ANX (mL/g)	AER (mL/g)
2/13/97	61	44	74
2/21/97	86	63	102
2/27/97	105	60	110
3/7/97	84	32	130
3/9/97	96	34	160
3/17/97	105	62	102
3/19/97	102	29	88
3/27/97	56	22	65
4/2/97	65	54	80
4/8/97	56	45	70
4/16/97	79	41	82
4/24/97	64	37	84
4/27/97	50	23	58
5/9/97	71	37	79
5/15/97	52	29	65
5/21/97	86	38	79
5/31/97	35	26	79
6/6/97	44	20	56

Table B-11: TOC, Pivalic Acid, and Nitrate Concentrations for ANA, ANX, and AER SBRs February 18-20, 1997 Cycle
Influent Wastewater = 5,500 mg/L

	ANA		ANX			AER	
Time	TOC	Pivalic Acid	TOC	Pivalic Acid	Nitrate	TOC	Pivalic Acid
(hrs)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	mg-N/L	(mg/L)	(mg/L)
0	840.1	551[a]	862.2	551[a]	364	868.7	1021
2	762.3		614.5		262	610.3	
4	838.2	526	389.3	628	162	373.4	304
8	813.7	526	293.9	399	120	114.4	0
12	446.6	221	105.3	0	59	57.42	0
18	117.2	0	69.53	0		29.05	0
23	64.02	0	58.67	0		29.48	0
30	25.55	0	46.81	0		29.49	0
36	26.83	0	51.67	0		30.23	0
42	25	0	52.98	0		26.24	0
48	28.3	0	60.88	0		34.76	0

a = theoretical value

Table B-12: TOC, Pivalic Acid, Acetic Acid, and Nitrate Concentrations for ANA, ANX and AER SBRs March 20-22, 1997 Cycle
Influent Wastewater = 9,000 mg/L

	ANA			ANX				AER		
Time	TOC	Pivalic Acid	Acetic Acid	TOC	Nitrate	Pivalic Acid	Acetic Acid	TOC	Pivalic Acid	Acetic Acid
(hours)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mgN/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0	1009	635	808	928.3	355	704	831[a]	1191	943	941
2	1036	637	900	672.4	233	573		1130	926	858
4	1025	643	804	504.9	142	398	0	1057	896	766
6	1016	668	938	451.2	91	277		913.9	840	417
8	1048	678	823	420.2	48	226		783.1	783	88
12	866.4	642	445	290.7		118		534.5	554	0
18	616.5	630	8	216.7		0		259.1	0	0
24	372.7	293	0	151.9		0		136.6	0	
30	229.1	31	0	127.6				102.2		
36	188			110.8				79.54		
42	168.4			89.8				75.57		
48	164.2			86.49				93.85		

a = theoretical value

Table B-13: TOC, Pivalic Acid, Acetic Acid, and Nitrate Concentrations for ANA, ANX and AER SBRs April 27-29, 1997 Cycle
Influent Wastewater COD = 9,000 mg/L

	ANA			ANX				AER		
Time	TOC	Pivalic Acid	Acetic Acid	TOC	Nitrate	Pivalic Acid	Acetic Acid	TOC	Pivalic Acid	Acetic Acid
(hours)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mgN/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0	1511.5	961	1693	1383.5	822	1183	1594	1517	1005	1666
2	1470	1004	1742		587	615	589	1404.5	931	1520
4	1452.5	937	1639	691	366	429	29	1273	850	1297
6	1537.5	998		568	253	326	24	1003	755	756
8	1576.5	942	1459	576.75	144	250	12	741.35	643	112
12	1003.05	694	705	275.45		0	7	325.25	138	5
18	681.85	102	5	148.9		0	0	158.65	0	1
24		0	0							
30	44.285			94.16				76.07		
36	81.525			95.125				73.42		
42	78.475			110				68.965		
48	82.92	0	5	138.1		0	0	84.905	0	2

Table B-14: Pivalic acid and Acetic acid concentrations as TOC for ANA, ANX and AER SBRs for March 20-22, 1997 Influent Wastewater COD = 5,500 mg/L

	ANA		ANX		AER	
Time (hours)	Pivalic Acid (mg C/L)	Acetic Acid (mg C/L)	Pivalic Acid (mgC/L)	Acetic Acid (mg C/L)	Pivalic Acid (mg C/L)	Acetic Acid (mg C/L)
0	373	329	414	338[a]	554	383
2	375	366	337		544	349
4	378	327	234	0	527	312
6	393	382	163		494	170
8	399	335	133		460	36
12	377	181	70		326	0
18	370	3	0		0	0
24	172	0	0		0	
30	18	0				
36						
42						
48						

a = theoretical value

Table B-15: Pivalic acid and Acetic acid concentrations as TOC for ANA, ANX and AER SBRs for April 27 - 29, 1997 Influent Wastewater COD = 9,000 mg/L

	ANA		ANX		AER	
Time (hours)	Pivalic Acid (mg C/L)	Acetic Acid (mg C/L)	Pivalic Acid (mg C/L)	Acetic Acid (mg C/L)	Pivalic Acid (mg C/L)	Acetic Acid (mg C/L)
0	565	689	695	649	591	678
2	590	709	362	240	548	619
4	551	667	252	12	500	528
6	587		192	10	444	308
8	554	594	147	5	378	46
12	408	287	0	3	81	2
18	60	2	0	0	0	0
24	0	0				
30						
36						
42						
48	0	2	0	0	0	1

Table B-16: Routine Monitoring for ANA-T, ANX-T, and AER-T SBR from April, 1997 to June, 1997

	ANA/AER			ANX/AER			AER		
Date	pH	Temp (°C)	DO (mg/L)	pH	Temp. (°C)	DO (mg/L)	pH	Temp. (°C)	DO (mg/L)
4/23/97	7.53	29		8.69	29.5		7.9	29.5	
4/26/97	8.95	30		9.1	30		9.07	29.5	
4/27/97	9.01			8.92			8.93		
4/28/97	9.18		7.4	9.29		7	9.04		6.4
4/29/97	9.24			9.34			9.1		
5/2/97	9.32	29		9.3	29.5		9.08	29	
5/3/97	7.49	29.5		8.41	29		7.88	29	
5/5/97	7.67			8.61			7.91		
5/9/97	9.03	29.5		8.83	30		8.94	29	
5/12/97	9.12			9.33			9.21		
5/16/97	8.97			9.13			8.79		
5/17/97	8.89			8.94			8.75		
5/18/97	9.05		7.2	9.24		7.3	8.85		6.9
5/19/97	9.05	29		9.32	29.5		9.04	29.5	
5/21/97	8.81			8.96			8.64		
5/23/97	8.78			8.81			8.73		
5/25/97	8.68	29		8.83	29.5		8.72	30	
5/29/97	8.78	29.5		8.98	29.5		8.72	29.5	
5/31/97	8.67			8.91			8.69		
6/2/97	8.62	29		8.88	29		8.74	29.5	
6/4/97	8.67			8.91			8.78		
6/6/97	8.81			8.97			8.68		
6/8/97	8.78	29.5		8.99	30		8.79	29.5	
6/10/97	8.71	29.5		8.98	29		8.76	29.5	

Table B-17: Mixed liquor suspended solids concentrations (mg/L) and mixed liquor volatile suspended solids concentrations (mg/L) for ANA-T, ANX-T and AER-T SBRs

	MLSS (mg/L)			MLVSS (mg/L)		
Date	ANA-T	ANX-T	AER-T	ANA-T	ANX-T	AER-T
4/23/97	7780	8750	6800	5280	6380	4640
4/27/97	7900	8060	7470	5590	5770	5340
5/9/97	5350	6920	5770			
5/17/97	5590	6270	6490	4470	4820	5000
5/31/97	4800	4780	4430			
6/6/09	8720	6080	7900			
6/18/97	6610	6410	6280	4910	4800	4590

Table B-18: Effluent TOC Concentrations for ANA-T, ANX-T, and AER-T SBRs

Date	ANA-T (mg/L)	ANX-T (mg/L)	AER-T (mg/L)
4/27/97	225	450	196
4/29/97	264	707	244
5/7/97	608	879	274
5/11/97	599	871	408
5/15/97	312	568	208
5/17/97	399	546	175
5/19/97	203	268	151
5/21/97	202	296	159
5/23/97	202	261	160
5/25/97	154	260	159
5/27/97	234.8	275.85	183.7
5/31/97	190.9	283.1	171.75
6/2/97	358.75	308.35	392.4
6/4/97	329.75	264.3	383.8
6/8/97	199.5	245.95	210.75
6/10/97	176.6	236.75	200.5
6/12/97	178.6	243.85	185.75
6/20/97	147	239.45	126

Table B-19: TOC and Nitrate Samples for ANA-T, ANX-T and AER-T SBRs for April 18-20, 1997 Cycle

Time (hours)	ANA-T TOC (mg/L)	ANX-T TOC (mg/L)	ANX-T Nitrate (mgN/L)	AER-T TOC (mg/L)
0	1369	1313	1052	1256
2	1268	1282	1049	981
4	1264	1251	1017	799
6	1284	1189	944	649
8	1305	1111	878	438
12	790	992		214
18	438	893		212
24	282	657		217
30	224	645		208
36	239	640		226
42	227	636		225
48	264	708		244

Table B-20: TOC and Nitrate Concentrations for ANA-T, ANX-T and AER-T SBRs for May 17-19, 1997 Cycle

Time (hours)	ANA-T TOC (mg/L)	ANX-T TOC (mg/L)	ANX-T Nitrate (mg-N/L)	AER-T TOC (mg/L)
0	1291	1284	1434	1227
1	1317	1323	1445	1181
2	1295	1302	1434	1116
3	1316	1277	1412	967
4	1327	1230	1408	898
6	1289	1144	1315	743
8	1292	1072	1277	519
12	766	879		252
20	548	613		169
28	373	463		152
36	207	364		152
44	198	271		152
48	203	268		151

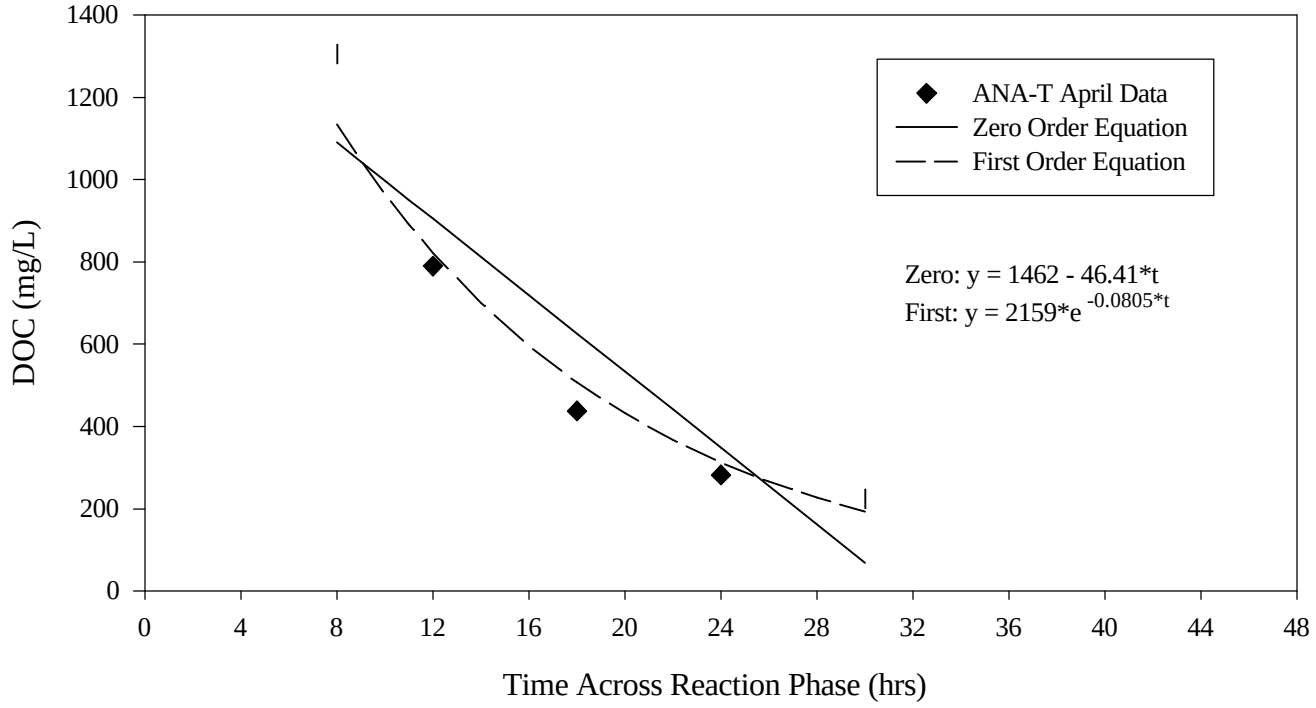

Figure B-2: ANA-T data from April 27 - 29, 1997 reaction cycle with zero and first order equations. Note equations predict degradation during the aerobic phase of the ANA-T operation.

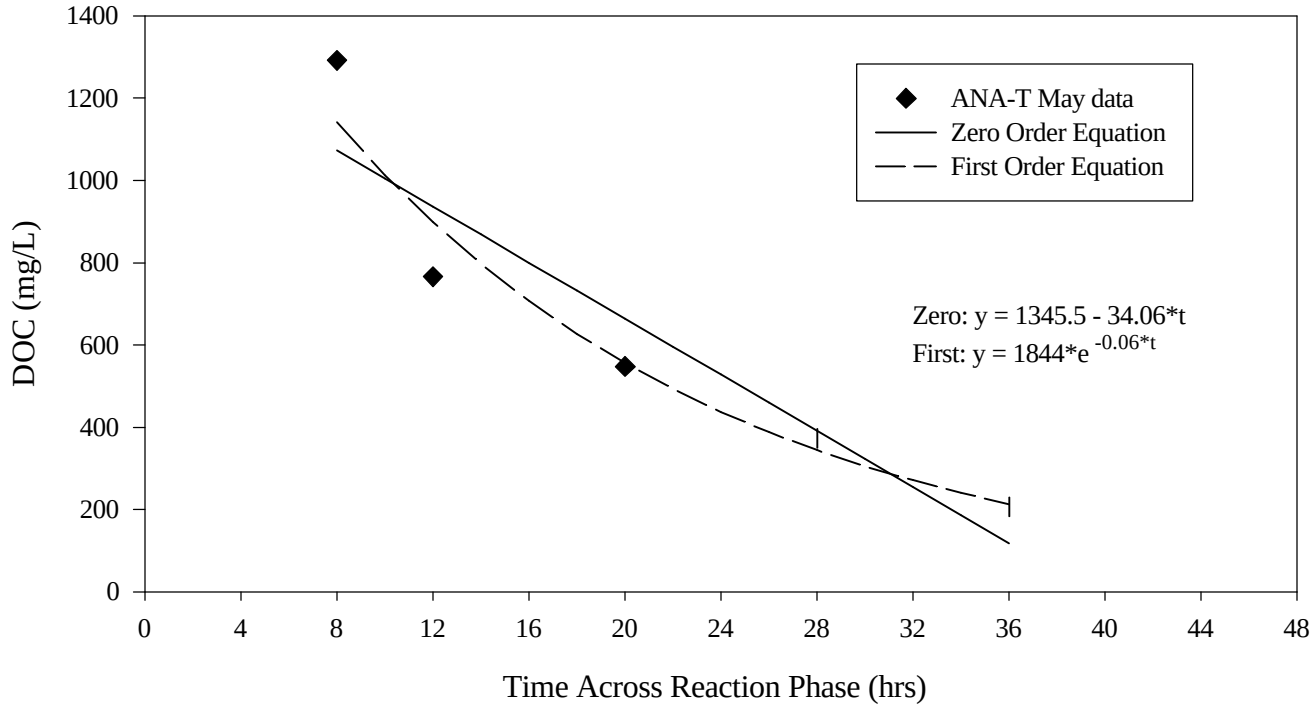

Figure B-3: ANA-T data from May 17 - 19, 1997 reaction cycle with zero and first order equations. Note equation predict degradation during the aerobic phase of the ANA-T operation.

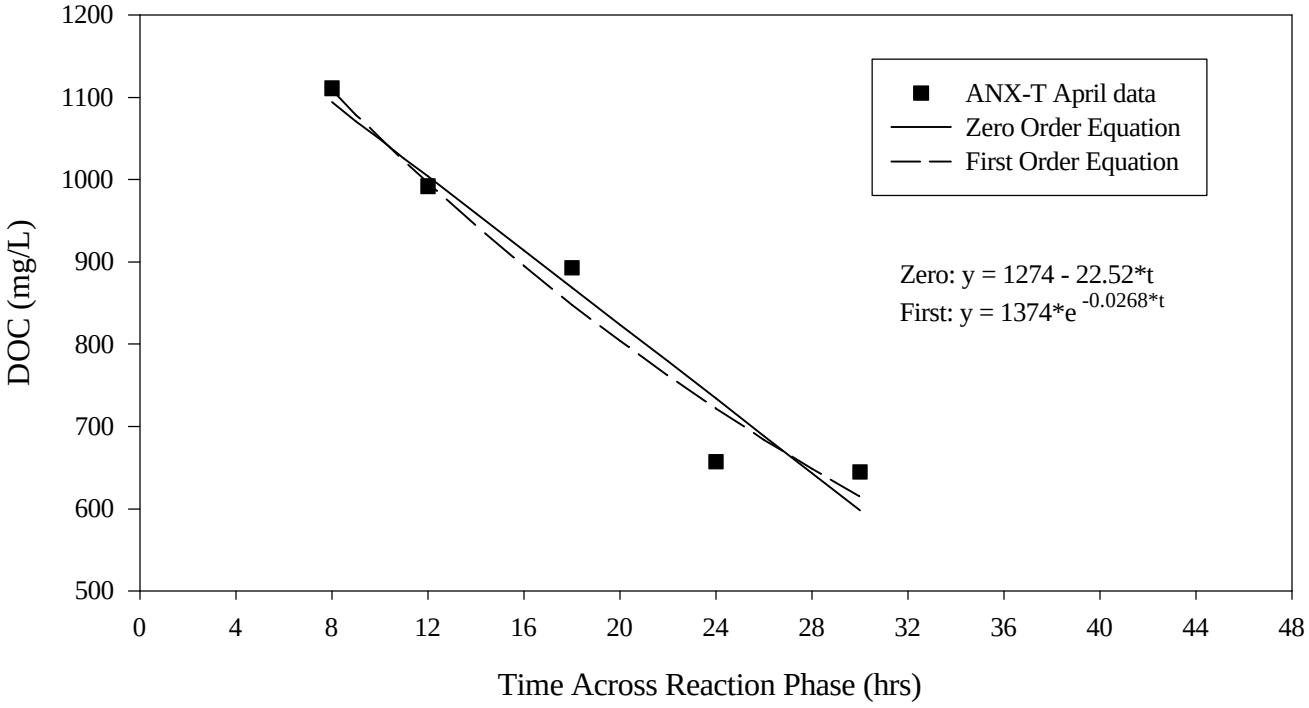

Figure B-4: ANX-T data from April 27 - 29, 1997 reaction cycle with zero and first order equations. Note equations predict degradation during the aerobic phase of the ANX-T operation.

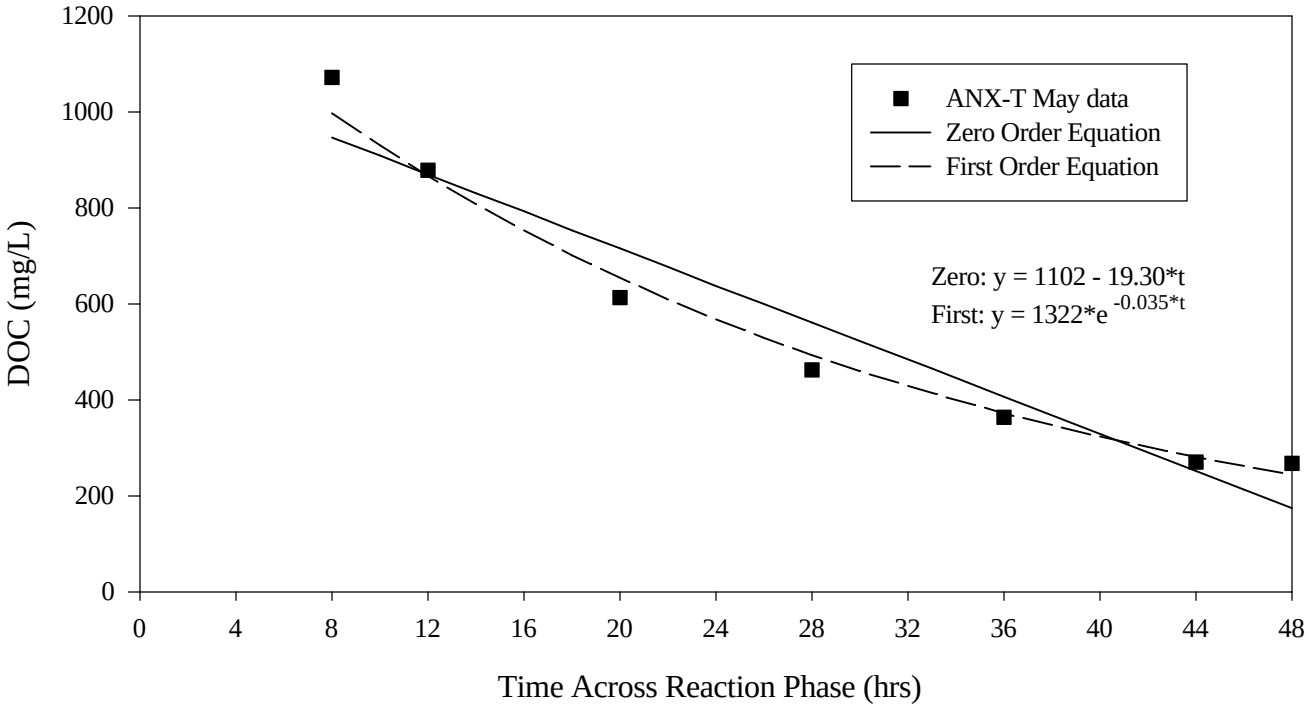

Figure B-5: ANX-T data from May 17 - 19, 1997 reaction cycle with zero and first order equations. Note equation predict degradation during the aerobic phase of the ANX-T operation.

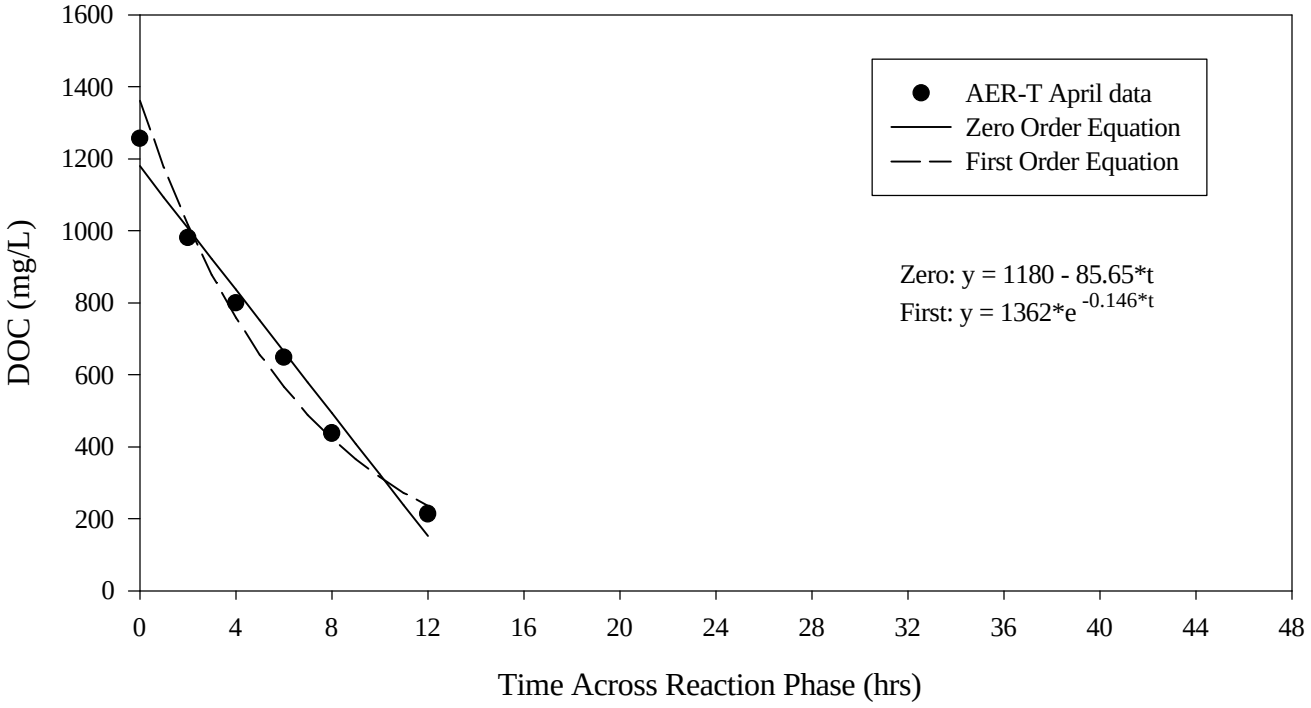

Figure B-6: AER-T data from April 27 - 29, 1997 reaction cycle with zero and first order equations.

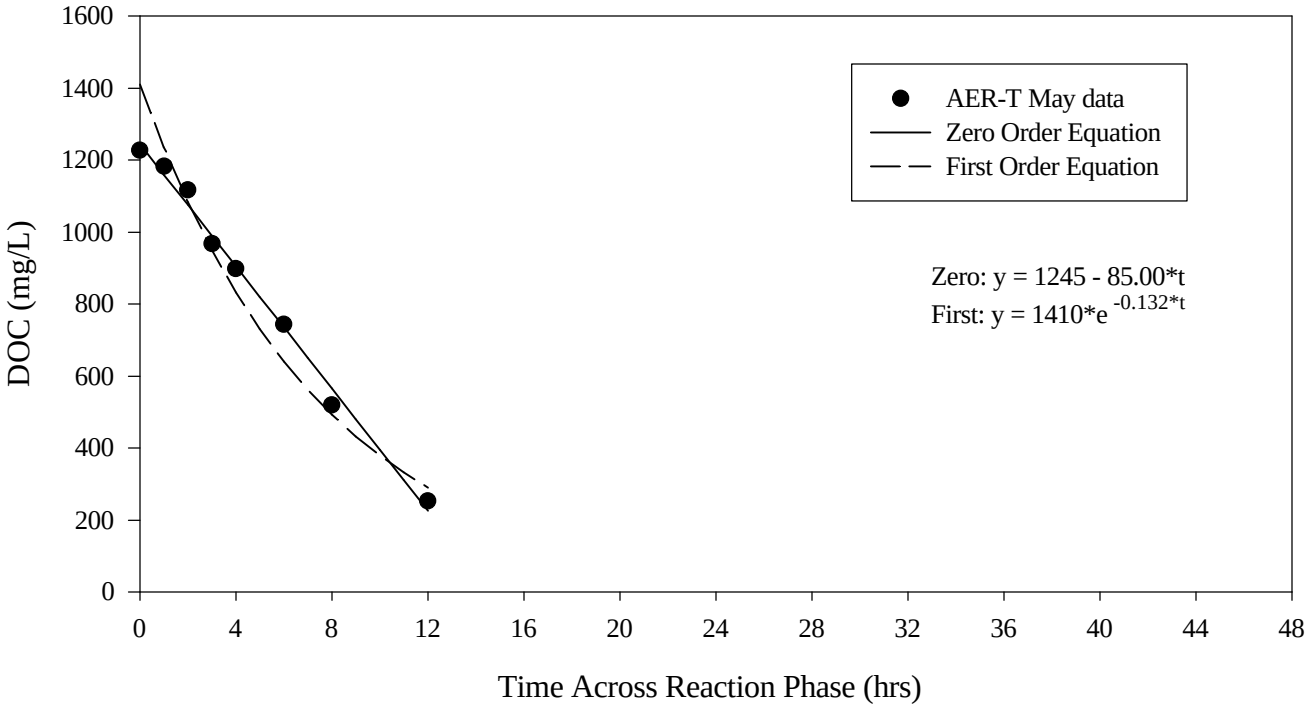

Figure B-7: AER-T data from May 17 - 19, 1997 reaction cycle with zero and first order equations.

Table B-21: Filter Run for 5/21/97

Time (min)	Volume (mL)
0.0	-
0.5	250
1.0	420
1.5	650
1.8	800

Table B-22: Filter Run for 5/23/97

Time (min)	Volume (mL)
0.0	-
0.5	250
1.0	450
1.5	670
2.0	880
2.5	1050
3.0	1150

Table B-23: Filter Run for 5/25/97

Time (min)	Volume (mL)
0.0	-
0.5	250
1.0	500
1.5	700
1.8	800

Table B-24: Filter Run for 5/31/97

Time (min)	Volume (mL)
0.0	-
0.5	250
1.0	500
1.5	700
2.0	900
2.5	1000

Table B-25: Filter Run for 6/5/97

Time (min)	Volume (mL)
0.0	-
0.5	220
1.0	500
1.5	700
2.0	850
2.5	1000

Table B-26: Filter Run for 6/12/97

Time (min)	Volume (mL)
0.0	-
0.5	200
1.0	450
1.5	700
2.0	800
2.5	900
3.0	950

Table B-27: GAC Data Set #1 for Unisorb AC, Experiment #1

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	51.29		
2.50	5.786	45.50	18.20
2.40	5.142	46.15	19.23
2.30	5.549	45.74	19.89
2.20	5.649	45.64	20.75
2.00	4.694	46.60	23.30
1.80	4.720	46.57	25.87
1.60	4.066	47.22	29.52
1.40	3.696	47.59	34.00
1.20	4.253	47.04	39.20
1.00	5.124	46.17	46.17
0.80	5.874	45.42	56.77
0.60	7.840	43.45	72.42
0.40	10.690	40.60	101.50
0.30	14.080	37.21	124.03
0.20	17.465	33.83	169.13

Table B-28: GAC Data Set #2 for Unisorb AC, Experiment #1

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	50.03		
2.50	6.568	43.46	17.38
2.40	5.320	44.71	18.63
2.30	5.001	45.02	19.58
2.20	4.727	45.30	20.59
2.00	4.308	45.72	22.86
1.80	4.027	46.00	25.55
1.60	3.826	46.20	28.87
1.40	3.643	46.38	33.13
1.20	3.563	46.46	38.72
1.00	3.914	46.11	46.11
0.80	4.989	45.04	56.30
0.60	6.159	43.87	73.11
0.40	9.071	40.95	102.39
0.30	12.290	37.74	125.78
0.20	18.580	31.45	157.23

Table B-29: GAC Data Set #1 for Unisorb AGL, Experiment #1

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	49.79		
2.50	2.583	47.21	18.88
2.40	2.626	47.16	19.65
2.30	2.978	46.81	20.35
2.20	2.473	47.32	21.51
2.00	2.625	47.17	23.58
1.80	2.593	47.20	26.22
1.60	2.425	47.37	29.60
1.40	2.281	47.51	33.94
1.20	1.982	47.81	39.84
1.00	2.224	47.57	47.57
0.80	3.435	46.36	57.94
0.60	5.499	44.29	73.82
0.40	8.097	41.69	104.23
0.30	9.073	40.72	135.72
0.20	14.360	35.43	177.15

Table B-30: GAC Data Set #2 for Unisorb AGL, Experiment #1

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	48.01		
1.40	1.684	46.32	33.09
1.20	1.652	46.35	38.63
1.00	1.924	46.08	46.08
0.80	2.926	45.08	56.35
0.60	4.596	43.41	72.35
0.40	7.559	40.45	101.12
0.30	8.022	39.98	133.28
0.20	12.190	35.82	179.08

Table B-31: GAC Data Set #1 for Calgon, Experiment #1

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	50.27		
1.40	2.267	48.00	34.29
1.20	2.228	48.04	40.04
1.00	2.088	48.18	48.18
0.80	2.235	48.04	60.04
0.60	1.608	48.66	81.10
0.40	1.480	48.79	121.98
0.30	1.716	48.55	161.85
0.20	3.677	46.59	232.97

Table B-32: GAC Data Set #2 for Calgon, Experiment #1

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	49.33		
1.40	2.226	47.10	33.64
1.20	2.521	46.80	39.00
1.00	1.721	47.60	47.60
0.80	1.875	47.45	59.31
0.60	1.161	48.16	80.27
0.40	1.630	47.70	119.24
0.30	1.817	47.51	158.36
0.20	3.685	45.64	228.20

Table B-33: GAC Data Set #1 for Norit 3000, Experiment #2

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	41.47		
1.50	2.589	38.88	25.92
1.40	1.327	40.14	28.67
1.30	1.553	39.92	30.71
1.20	1.436	40.03	33.36
1.10	1.081	40.39	36.72
1.00	1.813	39.66	39.66
0.90	1.241	40.23	44.70
0.80	1.593	39.88	49.85
0.70	1.118	40.35	57.65
0.60	1.848	39.62	66.04
0.50	1.203	40.27	80.54
0.40	1.809	39.66	99.15
0.30	3.732	37.74	125.80
0.20	5.868	35.60	178.01
0.10	8.638	32.83	328.33

Table B-34: GAC Data Set #2 for Norit 3000, Experiment #2

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	42.34		
1.50	0.953	41.38	27.59
1.40	1.008	41.33	29.52
1.30	0.847	41.49	31.91
1.20	0.699	41.64	34.70
1.10	1.062	41.27	37.52
1.00	1.028	41.31	41.31
0.90	1.168	41.17	45.74
0.80	1.204	41.13	51.41
0.70	0.941	41.39	59.14
0.60	0.996	41.34	68.90
0.50	1.180	41.16	82.31
0.40	2.401	39.93	99.84
0.30	3.394	38.94	129.81
0.20	4.123	38.21	191.06
0.10	10.305	32.03	320.30

Table B-35: GAC Data Set #1 for Norit 830, Experiment #2

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	51.00		
1.50	2.375	48.63	32.42
1.40	2.112	48.89	34.92
1.30	2.073	48.93	37.64
1.20	2.082	48.92	40.77
1.10	2.153	48.85	44.41
1.00	3.809	47.19	47.19
0.90	3.319	47.68	52.98
0.80	3.802	47.20	59.00
0.70	4.698	46.30	66.15
0.60	5.348	45.65	76.09
0.50	6.040	44.96	89.92
0.40	7.790	43.21	108.03
0.30	11.595	39.41	131.35
0.20	16.495	34.51	172.53
0.10	18.640	32.36	323.60

Table B-36: GAC Data Set #2 for Norit 830, Experiment #2

g of GAC	Avg. 0.5 day Ce	TOC cons.	mg TOC/gGAC qe
Control	48.57		
1.50	1.905	46.67	31.11
1.40	2.151	46.42	33.16
1.30	2.028	46.54	35.80
1.20	1.843	46.73	38.94
1.10	2.392	46.18	41.98
1.00	2.661	45.91	45.91
0.90	3.279	45.29	50.32
0.80	3.328	45.24	56.55
0.70	4.063	44.51	63.58
0.60	4.723	43.85	73.08
0.50	6.979	41.59	83.18
0.40	11.010	37.56	93.90
0.30	13.185	35.39	117.95
0.20	17.245	31.33	156.63
0.10	17.750	30.82	308.20

Table B-37: GAC Data Set #1 for Unisorb AC, Experiment #3

g of GAC	Avg. 0.5 day	TOC cons.	mg TOC/gGAC
	Ce		qe
Control	43.42		
1.50	8.866	34.55	23.04
1.30	7.164	36.26	27.89
1.10	6.745	36.68	33.34
0.90	6.297	37.12	41.25
0.70	6.964	36.46	52.08
0.50	6.893	36.53	73.06
0.10	14.300	29.12	291.20

Table B-38: GAC Data Set #2 for Unisorb AC, Experiment #3

g of GAC	Avg. 0.5 day	TOC cons.	mg TOC/gGAC
	Ce		qe
Control	44.97		
1.50	7.527	37.44	24.96
1.30	6.518	38.45	29.58
1.10	6.282	38.69	35.17
0.90	6.337	38.63	42.93
0.70	6.186	38.78	55.41
0.50	6.782	38.19	76.38
0.10	17.170	27.80	278.00

Table B-39: GAC Data Set #1 for Unisorb AGL, Experiment #3

g of GAC	Avg. 0.5 day	TOC cons.	mg TOC/gGAC
	Ce		qe
Control	44.80		
1.50	3.914	40.88	27.25
1.30	2.708	42.09	32.37
1.10	2.644	42.15	38.32
0.90	2.116	42.68	47.42
0.70	1.728	43.07	61.53
0.50	2.930	41.87	83.73
0.10	12.540	32.26	322.55

Table B-40: GAC Data Set #2 for Unisorb AGL, Experiment #3

g of GAC	Avg. 0.5 day	TOC cons.	mg TOC/gGAC
	Ce		qe
Control	44.30		
1.50	2.899	41.40	27.60
1.30	2.702	41.60	32.00
1.10	2.722	41.58	37.80
0.90	2.073	42.23	46.92
0.70	2.113	42.19	60.27
0.50	2.809	41.49	82.98
0.10	12.380	31.92	319.20

Table B-41: GAC Data Set #1 for Calgon, Experiment #3

g of GAC	Avg. 0.5 day	TOC cons.	mg TOC/gGAC
	Ce		qe
Control	44.22		
1.50	2.641	41.58	27.72
1.30	1.654	42.57	32.74
1.10	1.476	42.74	38.86
0.90	1.396	42.82	47.58
0.70	1.255	42.97	61.38
0.50	1.296	42.92	85.85
0.10	8.117	36.10	361.04

Table B-42: GAC Data Set #2 for Calgon, Experiment #3

g of GAC	Avg. 0.5 day	TOC cons.	mg TOC/gGAC
	Ce		qe
Control	45.17		
1.50	1.856	43.31	28.87
1.30	1.634	43.53	33.49
1.10	1.400	43.77	39.79
0.90	1.340	43.83	48.69
0.70	1.618	43.55	62.21
0.50	0.962	44.20	88.41
0.10	5.636	39.53	395.30

Table B-43: Nitrogen Species for ANX cycle and ANA
and AER effluent on 5/31 - 6/2/97

	Nitrate 6/2/97 mg-NO_3-N/L	Nitrite 6/2/97 mg-NO_2-N/L	Total Ammonia 6/2/97 mg-N/L	Total Ammonia 4/20/97 mg-N/L	Total Ammonia 3/6/97 mg-N/L	Total Ammonia 3/4/97 mg-N/L	Total Ammonia 2/26/97 mg-N/L
Influent	a	-	440	440	270	270	270
11:45 am X	7.0	0.041	-	1	-	-	-
12 pm X	650.0	0.034	-	-	-	-	-
8 pm X	87.0	0.12	-	-	-	-	-
ANX	2.0	0.028	191	>200	10	1	0.8
Influent			403	403	252	252	252
ANA	11.5	0	1.3	32.5	-	70.9	67.2
AER	26.0	9.64	82.9	78.2	73.5	-	-

a = used 80 mL of stock at 14.49 mg-NO_3-N/L

VITA

Kristina L. Perri was born on August 26, 1973 in Fairfax, Virginia. She attended Thomas Jefferson High School for Science and Technology and graduated in June, 1991. After high school, she pursued her Bachelors of Science in Civil Engineering from Virginia Polytechnic Institute and State University and completed her degree with an environmental option in May, 1995. Upon completion of her bachelors degree, she continued at Virginia Polytechnic Institute and State University were she completed her Master of Science in Environmental Engineering in September, 1997.