THE UNIVERSITY OF CALGARY

Optimization of Volatile Fatty Acids Production in Full-Scale Fermenters

by

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ABSTRACT

This research project consisted of two separate experimental themes. First, the full-scale experiment was designed to test a total of three runs to investigate the effect of Hydraulic Retention Time (HRT) on Volatile Fatty Acid (VFA) production. The experiment was conducted using parallel identical control and experimental trains. Optimum conditions for maximum VFA production were established at an HRT of 18.4 hours. Measured VFA concentrations also increased with an increase in outside air temperature.

Second, the batch-scale experiment was intended to determine the effect solids concentration, various substrates and inhibitors had on the production of VFAs.

Combinations of 60% thickened primary sludge, 40% complete mix sludge up to 100% thickened primary sludge realized the greatest VFA production among all combinations tested.

Peptone (a protein) used as a substrate maximized VFA production when compared to different classes of macromolecules (i.e. fats and sugars).

Chemical and antibiotic inhibitors tested had a negative effect on VFA production.

ACKNOWLEDGEMENTS

I would like to express my most sincere thanks to my supervisor, Dr. Angus Chu, for his knowledge, guidance, and insight throughout the course of this research.

I would like to extend thanks to; Paul Do, John Barrett, and Dennis Johnson for all their help in the operation of the fermentation system; to the laboratory staff for making room for my smelly experiment; to Doug Neilands and Kieran McGarrigle for their electrical assistance; to the carpenters for my experimental platform; and to each and every operator who helped out with my sampling. I extend special thanks to Ken Russell and Rav Saini for all their analytical assistance and to Gary Shoults for his encouragement and advice.

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NOMENCLATURE

ATP	adneosine triphosphate
CM	complete mix tank
CoV	coefficient of variation
EBPR	enhanced biological phosphorus removal
EPA	environmental protection agency
GT	gravity thickener
HRT	hydraulic retention time
M_{CM}	mass of solids in the complete mix tank
$M_{GT,Poly}$	mass of solids in the gravity thickener using a polynomial curve
$M_{GT,Exp}$	mass of solids in the gravity thickener using an exponential curve
PHA	poly-β-hydroxy alkanoates
Poly-P	poly-phosphate
PS	primary sludge
Q_{PC}	primary clarifier effluent flow rate
Q_{PS}	primary sludge flow rate
Q_R	recycle flow rate
Q_S	supernatant flow rate
Q_W	wasting flow rate
RO Water	reverse osmosis water
RPM	revolutions per minute
SN	supernatant
SRT	solids retention time
STD	standard deviation
TPS	thickened primary sludge
TS	total solids
TSS	total suspended solids
VFA	volatile fatty acid
VFD	variable frequency drive
V_{CM}	volume of solids in the complete mix tank
V_{GT}	volume of solids in the gravity thickener
WWTP	wastewater treatment plant
W_F	final weight
W_I	initial weight
V_S	sample volume

CHAPTER 1

INTRODUCTION

The use of Enhanced Biological Phosphorus Removal (EBPR) over the past decade has been on the rise and the focus of numerous studies. The ability to control nutrient removal solely by a biological process has become a key focus of the environmental community. Wastewater Treatment Plants (WWTP) across North America have begun to rely considerably less on the tried and true chemical processes of the past and explore the newer EBPR processes which significantly aid in cutting high operational costs while also providing improved environmental protection.

Nutrient removal has been a part of wastewater treatment since the early nineteen hundreds. However, as our society concentrates more on the threats to our environment, the limitations imposed on Wastewater Treatment Plants have become increasingly more stringent. In Canada, the Environmental Protection and Enhancement Act, which replaced the Clean Water Act (1993) is the governing legislative document that addresses effluent discharges from wastewater treatment facilities. The Environmental Protection Agency (EPA) issues site-specific approvals for wastewater treatment plants expressing limits for allowable phosphorus concentrations in the effluent discharge. These limits are based on the plants' existing treatment technology and on the water quality of the receiving body.

James Barnard, a pioneer in the field of EBPR, noted in the early 1960s that during wastewater treatment, more phosphorus was removed from the wastewater than

what was required for normal bacterial growth. This phenomenon was coupled by Shapiro's discovery of a release of phosphorus into the wastewater, circa 1967, which initially he thought should be avoided. However, by the late 1960s, early 1970s, the release and subsequent uptake of phosphorus was linked to a process known as EBPR that was gaining popularity. These discoveries led to the unfolding of the importance of an anaerobic environment. Anaerobic processes, without oxygen, have been a part of wastewater treatment since the 1920s. The importance of anaerobic conditions, more specifically the process of acid phase anaerobic digestion in EBPR, is key to the development of more efficient wastewater treatment plants for the 20^{th} century.

To successfully remove phosphorus biologically depends on the ability of Bio-P bacteria to accumulate phosphorus in excess of normal metabolic requirements (Randall, 1992). The key to the biological removal of phosphorus however, is its dependence on the availability of readily biodegradable substrate in the influent stream (Piteman *et. al.*, 1992). Complex substrates, found in influent wastewater, are broken down anaerobically with the end result being short chain volatile fatty acids (VFAs). The greater the amount of VFAs present in the anaerobic zone, the greater the potential to increase the amount of phosphorus removed from the wastewater. In order to maximize phosphorus removal, VFA production must also be maximized. VFAs are intermediate end products of acid-phase anaerobic digestion, better known as fermentation. In wastewater treatment, a pre-fermenter is used to produce the required VFAs to feed into the anaerobic zone of an EBPR activated sludge process.

The fermentation process is not new to the scientific community. However, variables that affect the fermentation process in a full-scale treatment facility are only

recently being examined. Solids retention time (SRT) and hydraulic retention time (HRT) both are perceived to play a major role in the fermentation process. To better understand how changes in these variables affect acid phase digestion, experiments must be developed at both the bench and full-scale levels.

Increased knowledge in the area of acid phase anaerobic digestion will enable optimization of fermenter operation and, in turn, improve the overall operation of the EBPR processes.

CHAPTER 2

LITERATURE REVIEW

2.1 AN OVERVIEW OF BIOLOGICAL PHOSPHORUS REMOVAL

Water quality impacts the world's population. Contaminated water directly affects not only human health and wildlife, but also the many systems and services dependent on the use of the water. Natural water systems are impacted by the wastewater discharged into them. Wastewater is defined by its physical, chemical, and biological constituents. These properties vary in each wastewater stream. The Alberta guidelines for water quality and effluent discharge are set forth in the Water Quality Based Effluent Limits Procedures Manual. The stated goal of these guidelines is to establish effluent limits to ensure suitable pollution prevention, control technologies, and that receiving streams are protected accordingly (Water Quality Based Effluent Limits Procedures Manual, 1995).

Eutrophication is the enrichment of the environment with nutrients, mainly nitrogen (N) and phosphorus (P) (Internet Source D). While natural eutrophication is impossible to control, the majority of nutrient loading comes from man made sources (Internet Source B). Phosphorus is contained in sewage, detergents, shampoos, and feedlot processing waste. The primary reason for the removal of phosphorus is eutrophication. Eutrophication may result in low stream flow, taste and odor problems,

and the creation of algae blooms (Internet Source C). Conventional activated sludge treatment systems can remove up to 30-40% of the phosphorus content of municipal wastewater whereas EBPR removes close to 90% of the phosphorus content. The phosphorus concentration remaining in the wastewater after EBPR is approximately 0.5 - 1 mg/l. The required effluent concentration in order to control eutrophication is within this range (Jones and Stephenson, 1996). In addition, blue-green algae blooms are toxic and may cause death in fish stock and wildlife or illness in human's (Internet Source C).

When dealing with eutrophication, the problem is not in the amount of algae produced but the shift in the species present. Green algae, common in rivers, are beneficial to many waterways. However, the availability of N and P shifts the production of green algae to blue-green algae. Once the N level in the H_2O is depleted, blue-green algae dominates since it has the ability to fix nitrogen (National Academy of Sciences, 1969). Algae blooms clog filters in water supply systems, causes shifts in economically beneficial fish species (e.g. trout being replaced by carp), and causes the development of unappealing slimes (Internet Source A).

Two types of limits are defined by Alberta Environmental Protection (AEP); technology-based and water-quality based standards. Water quality limits are based on worst case conditions for a specific facility discharging into a specific body of water. They use a triad approach that incorporates limits for whole effluent toxicity, chemical specific toxicity, and biological monitoring. Together, compliance in these areas is said to maximize environmental protection. Technology-based limits, on the other hand, are preset by the AEP prior to the start-up of an operation and are governed by a minimum level of treatment using the Best Practicable Technology (BPT). Upon comparing the

technology-based and water-quality based limits, it is evident that the water-quality based limits are much more complex, require more expenditures, and are more difficult to enforce. For this reason, technology-based limits are readily adopted and generally preferred by the AEP. They are less complicated, less costly, and easier to enforce. They may have a tendency however, to inhibit technological advancement since it is easier for an industry or a corporation to demonstrate they are compliant with the best practicable technology when using a commonly accepted method of treatment. The problem with technology-based limits and the standards that govern them is that there is no precise definition of Best Practicable Technology. Given this fact, discretionary interpretation of AEP guidelines by AEP regulators can occur. (Technology-based limits are outlined in the Standards and Guidelines for Municipal Waterworks, Wastewater, and Storm Drainage Systems documents. These standards dictate the required sampling procedures and acceptable discharge time frames. They have strict legal requirements for the allowable phosphorus effluent discharge concentrations from wastewater treatment facilities in North America (Scheer and Seyfried, 1997). In Alberta, this limit, and many others, are defined in a facility-operating permit. The Bonnybrook Wastewater Treatment Facility located in Calgary, Alberta operates under Permit #: 001-17531. The imposed limit on phosphorus discharge for this facility is set at $\leq$1.0 mg/L which is a monthly arithmetic mean of the samples taken and is outlined in the Approval Permit issued to the City of Calgary.

Enhanced Biological Phosphorus Removal (EBPR) is a result of the response of Bio-P bacteria to the presence of readily biodegradable substrate when exposed to sequential, alternating anaerobic and aerobic zones. These zones coupled with the

presence of VFAs in the anaerobic zone drive the EBPR process. The biological removal of phosphorus depends solely on the ability of the Bio-P bacteria to accumulate phosphorus within the cell (Pitman *et. al.*, 1992) providing that sufficient substrate is available.

In 1974 James Barnard published an article entitled "Cut N and P without Chemicals". Within the scope of this article he introduced the Bardenpho process (see Figure 2.1). This process consisted of four activated sludge cells followed by a clarifier. The first and third cells were stirred to keep solids in suspension. The second and fourth cells were aerated. Wastewater entered the first cell where denitrification occurred via the conversion of nitrate to nitrogen gas.

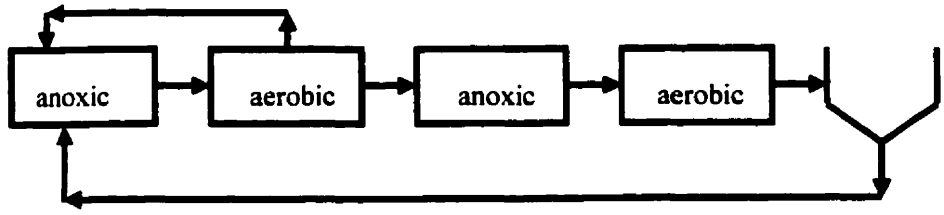


Figure 2.1 - Bardenpho Process

In the second cell, nitrification was achieved through the conversion of ammonia, NH_4, into nitrate. The nitrate rich sludge was then returned to the first basin where the nitrates were reduced by denitrification using influent carbon compounds as an energy source. The non-recycled sludge from the second cell then entered the third cell where the nitrates, again, were reduced. The wastewater then was re-aerated in the fourth cell prior to discharge. The original process focused more on the removal of nitrogen rather than phosphorus. Barnard speculated that it was difficult to design for phosphorus removal

when so little was understood about the process. The impact and influence that nitrate directly had on phosphorus removal was unknown at that time. It was noted however, that to ensure good phosphorus removal, the nitrate concentration should be low. Barnard noted that the presence of an anaerobic zone seemed to increase phosphate stripping. Other researchers including Milbury (Milbury, 1970), Shapiro, and Vacker (Shapiro *et. al.*, 1967) also noted that an anaerobic stage, separate from the anoxic cell, was needed prior to discharge to ensure that phosphates could be released and then collected in a subsequent aerobic zone.

2.2 WHY CHOOSE BIOLOGICAL PHOSPHORUS REMOVAL?

Plants across North America, Europe, and Australia are now abandoning the tried and true practices of chemical addition as a means of nutrient removal in favor of biological phosphorus removal. The EBPR process is an economically and ecologically beneficial alternative to the costly chemical-physical phosphate precipitation in use today (Hartwig and Seyfried, 1992). Conventional activated sludge typically contains only 1-2% phosphorus on a dry weight basis. Biomass from an EBPR system is able to accumulate phosphorus in excess of 3% (Randall, 1992).

2.3 BIOLOGICAL MODEL FOR PHOSPHORUS REMOVAL

There are two essential characteristics of Bio-P bacteria; the ability to store carbon as Polyβ-hydroxy alkanoates (PHA), and the ability to store polyphosphate in

excess of normal metabolic requirements. Once the supernatant rich in VFA is released into the anaerobic zone of the treatment process, the phosphorus removal cycle begins (Gerber, 1986). Under anaerobic conditions, acetic acids, along with other VFAs, are transported into the cell with a simultaneous decrease of one hydrogen ion. The acetate, once transported, disassociates and results in the accumulation of PHA in the cell (see **Figure 2.2**). The Bio-P bacteria then degrade their polyphosphate (poly-P) reserves to re-establish the pH gradient and provide energy for PHA synthesis (Daigger *et. al.*, 1993).

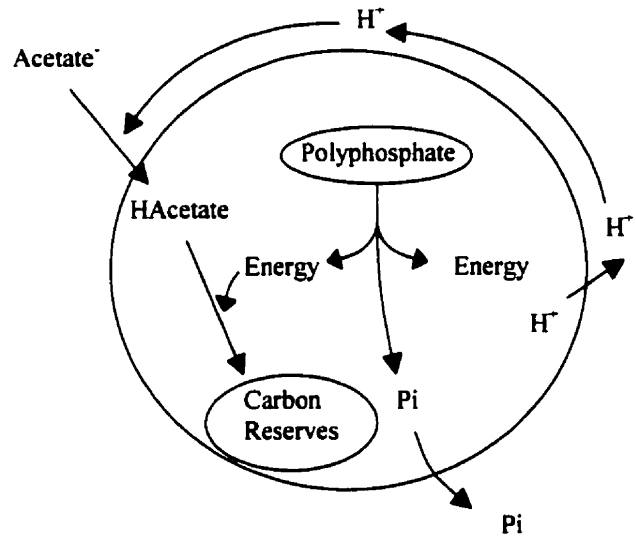


Figure 2.2 - Bio-P Bacteria Under Anaerobic Conditions
(adapted from Comeau *et. al.*, 1986)

In order for continual VFA transport and simultaneous PHA storage, the cell must regenerate the pH gradient. The rate of hydrogen ions entering the cell must be near equivalent to the rate of hydrogen ions exiting the cell. A drop in pH within the cell prevents the adequate storage of PHA (Comeau *et. al.*, 1986). A pH sensitive carrier releases phosphate from the degraded poly-P reserve into solution and subsequently re-

establishes the pH level (Randall, 1992). The anaerobic zone must be free of nitrates since they serve as a terminal electron acceptor and would allow the bacteria to utilize the energy from oxidative pathways instead of energy from the hydrolysis of the poly-phosphate store (Williams and Wilson, 1994).

Under aerobic condition, Bio-P bacteria initially have increased PHA stores and a decreased concentration of poly-P. In the presence of oxygen, the Bio-P bacteria degrade their PHA carbon reserves to provide energy for growth and to rebuild their poly-P stores (Williams and Wilson, 1994). The bacteria uptake extracellular soluble phosphorus and accumulates it as poly-P (see Figure 2.3).

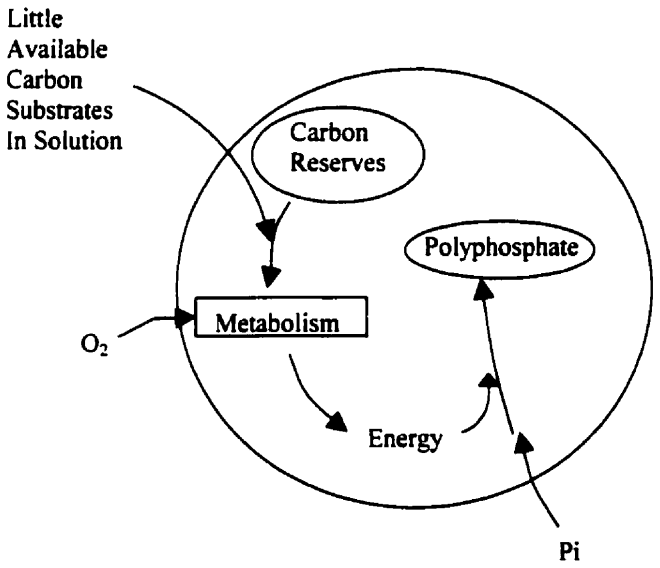


Figure 2.3 - Bio-P Bacteria Under Aerobic Conditions
(adapted from Comeau *et. al.*, 1986)

Bio-P bacteria accumulate a greater proportion of soluble phosphorus than that which is required for cell growth. This feature enables them to function as an effective means of phosphorus removal. The phosphorus rich cells settle out during secondary clarification and ultimately are removed from the wastewater when the sludge is wasted. It is

important to note that during the biological phosphorus removal process, there is the potential for the secondary release of phosphorus. Secondary release is defined as the release of orthophosphate from the cell without concomitant carbon storage. This release occurs with no energy uptake, implying that there will not be sufficient energy for the uptake of phosphate once the cell reaches the aerobic zone (Barnard, 1998). To reduce the possibility of secondary release, it is important to avoid the occurrence of fermentative processes within the anaerobic zone. Therefore, pre- fermenter units need to produce sufficient VFA to drive the entire EBPR process.

A genus of Bio-P bacteria, commonly referred to in literature, as Acinetobacter (Randall, 1992), have demonstrated the ability of Acinetobacter to accumulate phosphorus. However, many phosphate-accumulating organisms are taxonomically still unknown. These organisms are known only to be present, but not active, in operational activated sludge plants (Water Quality International, 1996). The qualitative importance of Acinetobacter in the EBPR process is still not entirely clear (Kortstee *et. al.*, 1994). The identification and speciation of Bio-P bacteria has been the focus of numerous studies. Attempts to isolate pure cultures in order to determine the genera responsible for EBPR are on going (Ubukata, 1994). Auling (Auling *et. al.*, 1991) identified 22 isolates that contribute to EBPR. Ten of these were identified to belong to the genus, Acinetobacter.

Bio-P bacteria are unique. Unlike heterotrophic species, which are able to denitrify using numerous different carbon sources, Bio-P bacteria are limited in the number of carbon sources that induce anaerobic phosphorus release. In addition, Bio-P bacteria are capable of storing substrate for future use. They have a competitive

advantage in that they are not affected by the absence of external substrate (Van Loosdrecht *et. al.*, 1997).

The operation of EBPR systems and the characteristics of wastewater entering the anaerobic zone may be affected by competition between Bio-P and non-Bio-P bacteria, specifically G bacteria (Cech *et al*, 1993). Bio-P bacteria are only capable of utilizing the short chain VFAs as substrate. The ability of G bacteria to use substrates before the occurrence of acidogenesis arrives in for competition between the two groups of organisms (Tasli *et al*, 1997). When acetate is the sole substrate present in the anaerobic zone, Bio-P bacteria have the competitive advantage (Cech *et al*, 1993). However, the presence of glucose in influent wastewater was believed by some researchers to cause a shift in the distribution of microorganisms and, in turn, slow the growth of poly-P bacteria in favor of other species. Using 3 different feed streams, the effect of a glucose-rich influent was tested (Carucci *et. al.*, 1997). When an influent containing glucose only was tested, the phosphorus release and PHA storage in the anaerobic zone ceased. Influent containing both glucose and acetate showed no affect on the phosphorus removal system. The release and uptake of phosphorus was thought to be related only to the presence of acetate and appeared unaffected by the presence of G bacteria. Further research is needed to clarify if EBPR is due solely to Bio-P bacteria activity, in spite of G-bacteria competition, or to the bacteria activity itself (Carucci *et al*, 1997).

2.4 VFA PRODUCTION

The nature of influent wastewater is ever changing. The bacteria present in influent wastewater assume responsibility for the breakdown of organic material throughout the treatment process. These bacteria however, are affected by environmental factors such as pH, temperature, and the presence of toxins. To optimize the EBPR process it is important to first understand the mechanisms driving the EBPR process itself as well as the effect of external factors such as diurnal and seasonal variations in wastewater characteristics (Merseth, 1995) in order to achieve increased treatment reliability.

Volatile fatty acids, and more commonly acetic acid, are the driving force behind EBPR process (Randall and Chapin, 1997). In order for successful phosphorus removal, sufficient quantities of VFAs are necessary in the feed stream to the anaerobic zone (Cooper *et. al.*, 1995). Typical influent wastewater contains only 15-40 mg/L VFA. Greater quantities however, are required for EBPR. A fermentative process incorporated prior to the anaerobic zone, allows for the generation of VFAs (see Figure 2.4). The production of VFAs comes predominantly from the first phase of anaerobic digestion otherwise known as acidogenesis. The anaerobic digestion process is comprised of a series of complex biological reactions where the products of one phase feeds the next. The process begins with the hydrolysis of complex organic substances into more soluble intermediates. Through the process of acidogenesis these intermediates are broken down primarily into VFAs and other monomer species. At this point, it is crucial to prevent the next stage of anaerobic digestion, namely methanogenesis, from occurring. The bacteria

driving methanogenic reactions, if present, would consume the much-desired VFAs within the fermenter more rapidly than the Bio-P bacteria. This could lead to the production of methane gas and carbon dioxide (Tchobanoglous *et al*, 1991). Two operational strategies are available to halt this process. The fermenter may be sparged at regular intervals with oxygen-rich air to destroy the oxygen-sensitive methanogens. The SRT may also be set below the growth rate of methanogens to encourage washout.

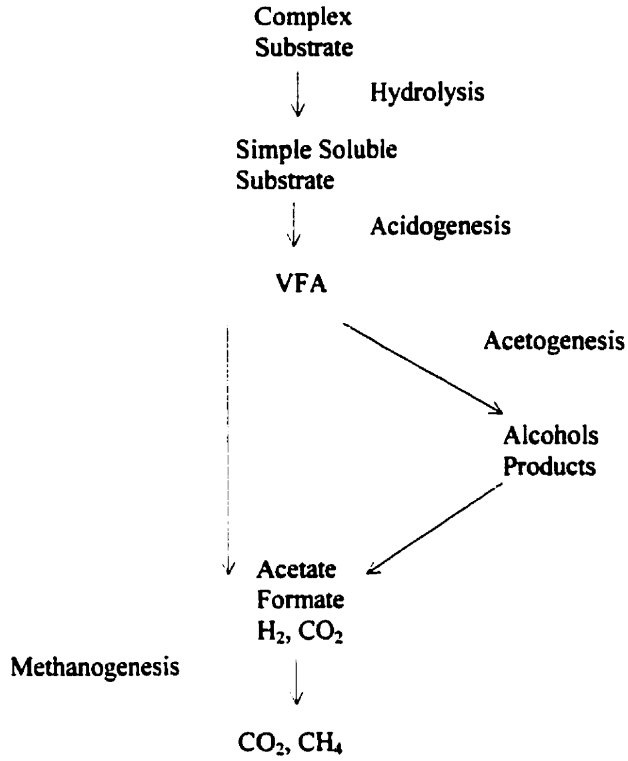


Figure 2.4 - Anaerobic Digestion
(adapted from Fox and Fredrick, 1994)

A number of different design configurations of the fermentation system has been incorporated into EBPR processes (Kerrn-Jespersen and Henze, 1993). A variety of these configurations have been examined for their ability to produce VFAs. The optimum

production was found using a complete mix tank, gravity thickener combination. The primary feed sludge entering the complete mix tank is mixed to keep substrates suspended and allow the bacteria maximum surface area for interaction. Within the confines of this tank, the conversion from complex substrate to VFA occurs. After a set period of time, the sludge leaves the complete mix tank and enters the gravity thickener. The absence of mixing allows the sludge to settle into stratified layers. From the surface to a depth of 1 to 2 meters is a layer that contains few solids. This layer, call supernatant, is rich in VFA and is the actual feed stream for the aforementioned anaerobic zone.

CHAPTER 3

METHODS AND MATERIALS

3.1 WASTEWATER SOURCE

This research project was conducted at the Bonnybrook Wastewater Treatment Plant located in Calgary, Alberta. The plant has a design capacity of 500 ML/d and currently services a sewered population of 755,000 persons (Reid Crowther and Stanley Associates Engineering Ltd., 1991). The Bonnybrook facility collects and treats wastewater from all areas within city limits, in the Northwest, Southwest, Northeast, and Southeast up to 50th Avenue and Hubalta Road. The drainage area is approximately 435 km^2. Wastewater collected from the area south and east of 50th Avenue S.E. and Hubalta Road is treated at the Fish Creek Wastewater Treatment Plant. The Fish Creek Plant has a design capacity of 72.7 ML/d and treats a drainage area of approximately 264 km^2. All samples collected for this research project were taken from the Bonnybrook Plant.

3.2 EXPERIMENTAL SET-UP

3.2.1 FULL-SCALE SYSTEM CONFIGURATION

The fermentation system at the Bonnybrook Wastewater Treatment Facility in Calgary, Alberta is shown in Figure 3.1. The fermentation system consists of two

identical process trains in terms of size and layout. In each case, the complete mix tank, fed by primary clarified sludge, is followed by a gravity thickener, which discharges its effluent into the anaerobic zone of a given bioreactor cell.

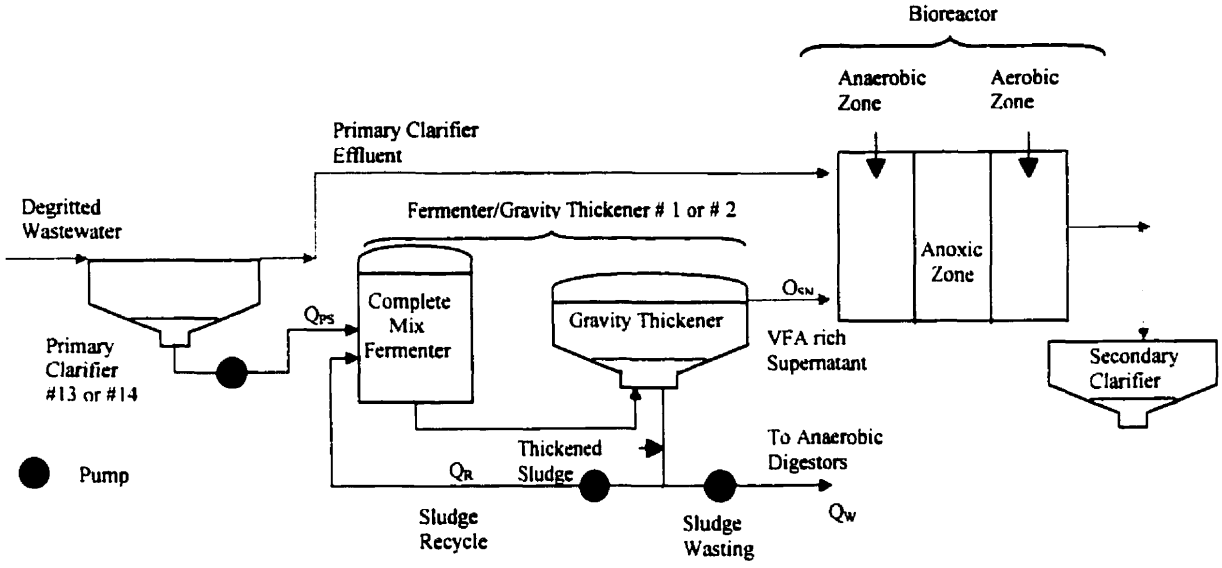


Figure 3.1 - Full-Scale Fermentation System Configuration

Primary sludge from clarifier # 13 feeds fermenter-gravity thickener # 1, and primary sludge from clarifier # 14 feeds fermenter-gravity thickener # 2. When only one fermenter train, east or west, is operational, it is fed by both clarifiers. Only 1/3 of the entire wastewater flow entering the plant was directed to primary clarifiers 13 and 14.

Each of the tanks shown in Figure 3.1 was constructed with high strength concrete and is situated in-ground. They all have conical bottoms with varying degrees of basal slope. Both the complete mix tank and gravity thickener have an aluminum cover which serves as a method of both odor control and heat retention. Figures 3.2 and 3.3 shows the inside of both the complete mix tank and gravity thickener. The

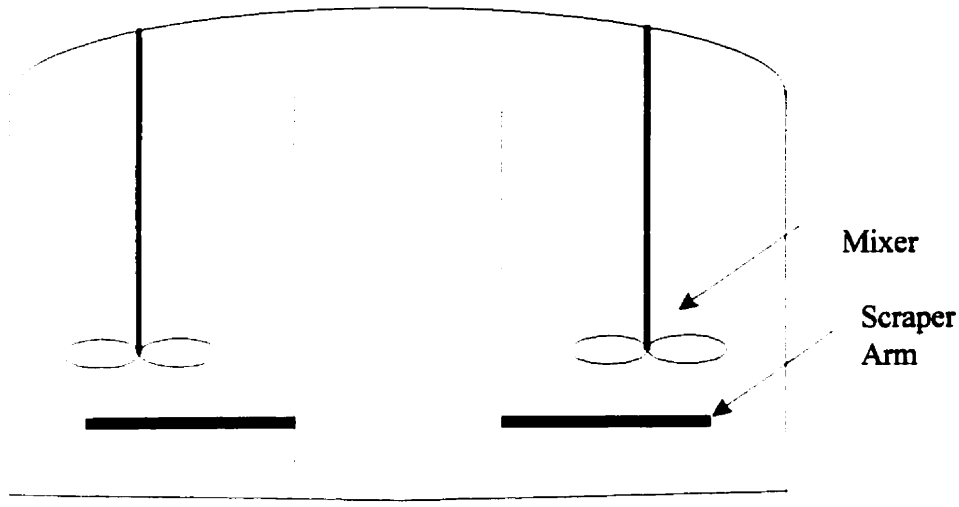


Figure 3.2 – Complete Mix Tank

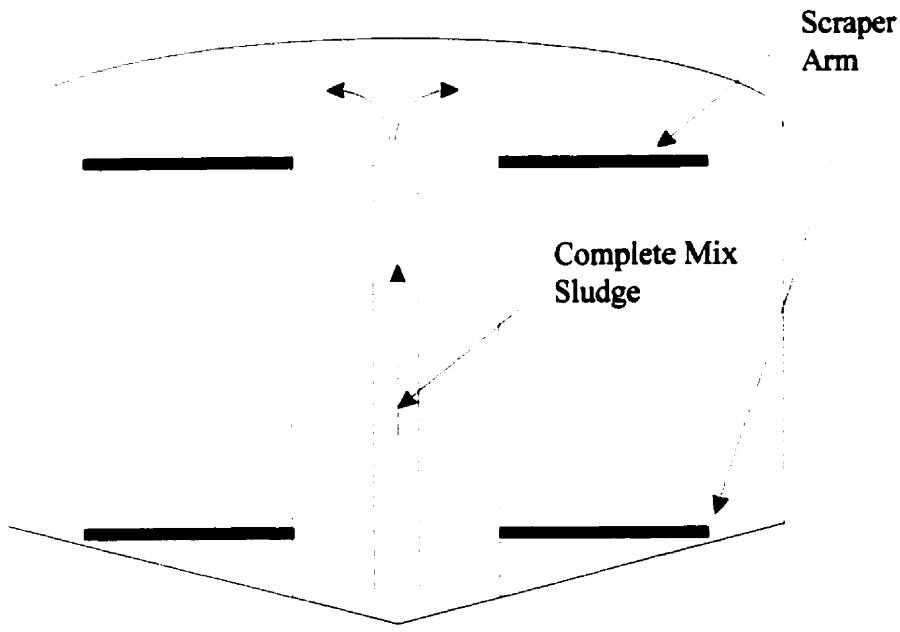


Figure 3.3 – Gravity Thickener

The dimensions of the primary clarifier, complete mix tank, and gravity thickener units are as follows.

Primary Clarifier: Side Wall Depth (SWD): 3.8 m (maximum liquid height)

Base Slope: 4.8 °

Diameter: 38m

Volume: 4906.9 m^3

Complete Mix Tank: Side Wall Depth (SWD): 4.8 – 5.35 m (depending on liquid depth)

Base Slope: 1.04 °

Diameter: 16m

Volume: 995.25 m^3

Gravity Thickener: SWD: 3.4 – 4.1 m (depending on liquid depth)

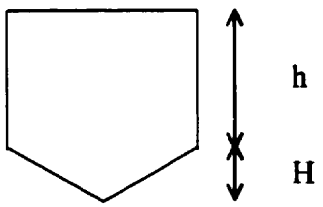
Base Slope: 14.4 °

Diameter: 16m

Volume: 841.11 m^3

The formula used for the calculation of the three tank volumes is:

$$V = \pi r^2 h + \frac{1}{3}\pi r^2 H$$



where h is the side wall depth of the wastewater.

3.2.1.1 SYSTEM CONTROL

The system is controlled by a mainframe computer, which uses the Bailey DCI System Six software. The entire plant is detailed on-line. Performance characteristics of any pump, valve, or tank can be observed and/or updated by the click of a mouse. Daily trends were plotted for the fermenter-gravity thickener trains outlining tank depths, and sludge flows. The system data however, was not archived. Generally data was kept for a preset number of days and then discarded. Any desired trends were printed out as a hardcopy.

3.2.1.2 SAMPLING PROTOCOL

Samples at each of the sampling locations described in Table 3.1 were taken in one-litre bottles as required and stored in a refrigerator at 4°C until further detailed analysis could be conducted.

Table 3.1 – Sample Name and Locations

Sample Name	Abbreviation	Sample location
Primary Sludge	PS	Primary clarifier pump house, primary sludge pumps 262A, 272A
Gravity Thickener Supernatant	GTS	Fermenter pump house, small pipeline from fermenter
Complete Mix Sludge	CM	Fermenter pump house, enters 12 inch pipe from bottom of fermenter
Recycle/Waste Sludge	R/W	Fermenter pump house, enters 12 inch pipe from bottom of gravity thickener to recycle pumps

Infrequently used lines were drained for a period of 2 – 5 minutes to ensure that a fresh sample was obtained. When sampling from a pipeline in constant use, a 30-second drain period was allowed to elapse before collection. Sampling of waste and recycle sludge individually was not required since sludge leaving the thickener was split into the recycle sludge line, and the waste sludge line. Samples representative of both waste/recycle sludge were therefore taken from the recycle pumps that are in constant operation. All bottles were rinsed twice with the sample before collection.

3.2.2 BENCH-SCALE SYSTEM CONFIGURATION

This bench-scale apparatus consisted of 6-1000ml Erlemeyer flasks with magnetic stirring platforms and stir bars, 1water bath and, 2 plastic rectangular tanks. Each flask was a small-scale batch fermenter. When in use, the unsealed flasks were filled to two centimetres below the rim, roughly 1150ml, to induce anaerobic operating conditions within each batch reactor. The water bath served as a means to control the temperature that was predetermined based on the temperature measure in the full-scale complete mix tank at the start date of each experimental run. Throughout each test run, the magnetic stir bars spun at a constant rate. Each run lasted between fifty to sixty-five hours.

Figure 3.4 shows the setup of the six individually-controlled batch reactors.

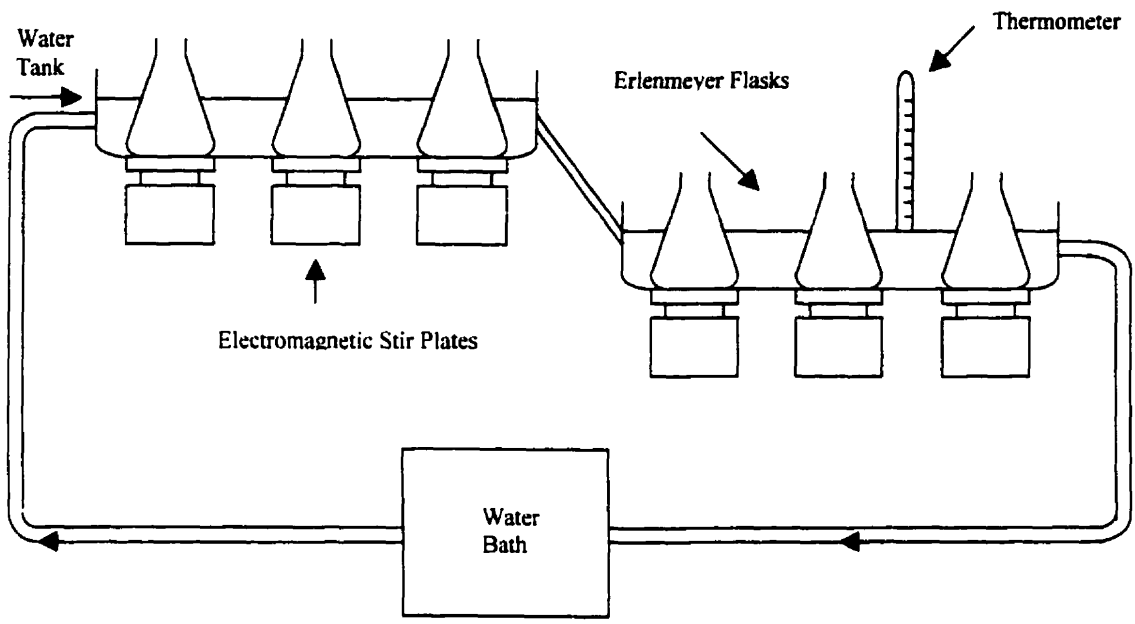


Figure 3.4 - Bench-Scale Batch Reactors Configuration

3.2.2.1 SYSTEM CONTROL

The bench-scale system was manually controlled and monitored. The flow of water through the two tanks was controlled by a pressure valve on the water bath. Flow was increased or decreased manually to adjust the water depth in the plastic tanks. Water temperature in the plastic tanks was preset to reflect the same temperature measured in the full-scale reactors at the time of sampling. Magnetic stirrers were set at the lowest possible rpm that would keep all solids in suspension. The system was monitored constantly to ensure smooth operation.

3.2.2.2 SAMPLING PROCEDURE

Samples from both the full-scale east primary clarifier and east complete mix tank were taken one to two hours prior to the start of each bench-scale batch run.

For each run, samples were drawn off the top of each flask using a 2ml plastic pipette, approximately every eight-hours starting at time zero.

3.3 OPERATION

3.3.1 FULL-SCALE SYSTEM OPERATION

The experimental matrix consisted of three runs to investigate the effect of HRT on VFA production. A summary of operating conditions is outlined in Table 3.2. The calculation of SRT and HRT is found in Appendix C.

Table 3.2 - Full-Scale Operating Conditions

	HRT (hr)		SRT (d)
	Control	Experimental	
Run 1	24.5	24.5 (medium)	4.3
Run 2	24.5	18.4 (low)	4.3
Run 3	24.5	36.7 (high)	4.3

Experimental runs were conducted using three separate HRT values, low, medium, and high, for a total of three runs. The control train was run solely using the medium HRT value while the HRT matrix was applied to the experimental train.

A Hayward primary sludge pump controlled the HRT of the system. This centrifugal pump responded by projecting wastewater to the outer wall of the pipe and pushing it through the system. The HRT values were calculated using the volumes of both the complete mix tank and gravity thickener. The total volume of the two tanks was divided by the primary sludge feed rate to determine a value for HRT (See Appendix C). The operational range of the primary sludge pumps was limited which, in turn, limited the actual range of HRT available for testing. This operational range was determined by various plant operators and subsequently confirmed by Systems Engineer, Paul Do, and Operations Manager, John Barrett.

Throughout this project, other key variables, such as, SRT and the primary clarifier influent flow rate were held constant. The SRT was selected based on previous trial and error experiments conducted prior to the start of the first full-scale run. These experiments established the amount of sludge capable of travelling though the fermentation system with minimal operational difficulties (i.e. blockage of feed lines and reactor overflow) by adjusting the Q_W from the gravity thickener. A Wemco Torque Flow waste sludge pump, also centrifical in nature, controlled the SRT. The SRT value was calculated by summing the volumes of both the complete mix tank and gravity thickener and then dividing by Q_W (see Appendix C for the calculation of SRT). The value for Q_W was set at 2.4 m^3/h. Throughout the HRT study, the SRT was established and held constant at 4.3 days using the predetermined value for Q_W of 2.4 m^3/h. The

sludge recycle rate was held constant at 1/2 of the primary sludge feed rate. The thickener supernatant flow rate was held equal to the primary sludge feed rate.

Each full-scale run lasted a period of 25-30 days, or 5-7 SRTs. When establishing the appropriate HRT value, a period of one SRT elapsed before sampling began. This was to allow the system to acclimatize. Each run consisted of a stabilization period of 4 SRTs and an experimental period of 2 SRTs. Throughout each run, the operating conditions within the tanks were monitored. The incoming and outgoing flow rates were monitored using the trends given by the Bailey Mainframe software. In addition, the mixing within the complete mix tanks was visually observed daily. Previous mixer problems had caused difficulties in maintaining the system operational. The constant monitoring was therefore a preventative measure to avoid unnecessary shutdowns. Over the duration of each run, grab samples were taken at least on alternate days throughout the stabilization period and daily during the experimental period. For each sample, measurements were taken for pH, temperature, total solids, and concentration VFAs. In addition, the sludge blanket in the gravity thickener was also measured on each sampling day. Data collected was recorded and reported on a weekly basis.

3.3.2 BENCH-SCALE SYSTEM OPERATION

The bench-scale batch experiments were designed to determine the effect solids concentration, various substrates, and inhibitors had on the production of VFAs. A summary of the operating conditions is found in Table 3.3. Experimental runs were conducted using the apparatus shown in Figure 3.4. Control flasks were used in each run

to provide a basis for comparison. Doses of inhibitors added in Runs #4 and #5 are based on LD50 values (see Section 4.2.4).

Complete mix and primary sludge samples used in each of the batch tests were taken from the East control train. Samples were taken approximately one to two hours prior to the start of the batch run. The primary sludge samples were taken when the wastewater contained the greatest amount of solids. A mechanical arm, on the bottom of the clarifier, collected and deposited settled solids from the bottom of the clarifier, in to the sample line, approximately every 20 minutes. When these solids were evident, the sample was collected. The complete mix sample was taken directly off a line in constant use.

Some runs required thickened primary sludge. This was achieved by allowing the sample collected to settle for approximately 10-15 minutes. About half the supernatant was then poured off the top of the sample and then shaken to re-suspend the solids. This process was repeated until the primary sludge sample appeared to be the same thickness as the complete mix sludge sample. All samples were diluted by 50 percent to facilitate the rotation of the magnetic stir bars.

Each bench-scale batch run lasted between 50-65 hours. Over the course of each run, the system was regularly monitored. This ensured that a) the stir bars were in constant motion; b) the water bath and tank temperatures remained constant and identical; c) the plastic tanks water level remained constant; and d) the water circulation was unimpeded. Throughout each run, seven 2-mL samples were collected approximately

Run #	Purpose	Flask						Temp. °C	Length of Run hours
		1	2	3	4	5	6		
1	Test the effect of an increased solids concentration on VFA production (Section 4.2.1)	100 PS[1] (Control)	80[4]PS/20[5]CM[2]	60PS/40CM	40PS/60CM	20PS/80CM	100 CM	16	65
2	Test the effect proportions of substrate, represented by thickened primary sludge, have on VFA production (Section 4.2.2)	100 TPS[3] (Control)	80TPS/20CM	60TPS/40CM	40TPS/60CM	20TPS/80CM	100 CM	16.8	55
3	Test the effect of different substrates on VFA production (Section 4.2.3)	100 CM (Control)	60TPS/40CM (Positive Control)	100CM + 1000mg Sodium Acetate	100CM + 1000mg Peptone	100CM + 1000mg Starch	100CM + 1000mg Linoleic Acid	17.3	53.15
4	Test the effect of different chemical inhibitors of VFA production, and re-test of peptone (Section 4.2.4)	60TPS/40CM (Positive Control)	60TPS/40CM+ 100mg Potassium Cyanide	60TPS/40CM+ 3mg Sodium Citrate	60TPS/40CM+ 1000mg Sodium Bisulphate	100 CM (Control)	100CM + 1000mg Peptone	19.4	59
5	Test the effect of different antibiotic inhibitors of VFA production (Section 4.2.5)	60TPS/40CM (Control)	60TPS/40CM+ 9 mg Tobramycin	60TPS/40CM+ 10 mg Penicillin G	60TPS/40CM+ 244 mg Sulfapyridine	60TPS/40CM+ 9 mg Imipenem	60TPS/40CM+ 246 mg Sulfapyridine	18.3	56

[1] PS - Primary Sludge [2] CM - Complete Mix Reactor Sludge [3] TPS - Thickened Primary Sludge [4] 80 - 80% volume per volume
[5] 20 - 20% volume per volume

Table 3.3 - Bench-Scale Operating Conditions

every eight hours. These samples were then prepared for VFA analysis. Data collected was graphed at the completion of each run. In addition, the total suspended solids (TSS) was measured at time zero and at the time of completion of each batch run.

3.4 ANALYTICAL PROCEDURES

The following analyses were run over the course of this study.

3.4.1 SUSPENDED SOLIDS

This measurement was used in the bench-scale experiment only. A known volume of sample was centrifuged for 10 minutes at 4000 rpm. The supernatant was suctioned through a two-micron size cut-off filter paper of known weight. The solid material, collected at the bottom of the centrifuge tube, was scraped from the tube onto a filter paper of known weight. Suction was applied to remove any excess liquid. RO water was used to rinse the centrifuge tube to ensure all the solid material was removed. The centrifuge tube contents was then poured through the same filter as the supernatant. The suspended material collected on both filter papers was dried at 103°C for 20-25 hours and then cooled in a desiccator. The filter papers were re-weighed and the TSS calculated (see Appendix B). If the final weight of the filter papers was not consistent, the drying process was repeated (Standard Methods for the Examination of Wastewater, 1996).

3.4.2 TOTAL SOLIDS

The measurement of Total Solids (TS) was used to determine the sum of the total dissolved and suspended solids present in a given volume of sample. This measurement was used in the full-scale experiment only. TS were determined by pouring a specific volume of sample into a pre-weighed aluminum dish. This dish was then re-weighed, dried at 103°C for approximately 24 hours, and then cooled in a desiccator. The dish was weighed once again, and the TS calculated (see Appendix A). If the final dish weight was not consistent, the drying process was repeated.

3.4.3 VOLATILE FATTY ACIDS

The measurement of VFAs was used to determine the concentration of short chain fatty acids, specifically, acetic, propionic, and butyric present in samples. The VFA measurements were performed using a Perkin Elmer 8500 Gas Chromatograph (GC) equipped with a Flame Ionization Detector (FID). The column used was a Nukol column with 0.5-micron film. The carrier gas used was helium. The operating parameters were as follows: (i) spitless injector temperature, 200 °C; (ii) FID temperature, 200 °C; (iii) oven temperature of 105 °C for 2 minutes and them ramped up to 140 °C at a rate of 5 °C per minute; (iv) column head pressure of helium @ 15 psig. The calibration curve had five levels for each VFA component measured. Calibrations were done daily. The data was collected, peaks quantified and concentrations calculated, based on the default

parameters entered by the user (Saini, 1997). VFAs measured in this study were acetic, proprionic, and butyric acids.

3.4.3.1 FULL-SCALE SYSTEM

Fifty (50) ml of each sample was centrifuged for 10 minutes at 70oo rpm and the supernatant poured through a 0.2-micron filter. Approximately 10-12 ml of the respective filtrates were collected and preserved by adding 2 drops of phosphoric acid, 0.1N, and stored in a 4 °C refrigerator, in screw cap glass vials, until analysis. Approximately two hours prior to analysis, VFA samples were warmed to room temperature, diluted ten-fold, and placed in small 1.5 ml glass vials sealed with teflon caps.

3.4.3.2 BENCH-SCALE SYSTEM

To determine the VFA concentration of each flask, at a series of specific points in time, 2 ml samples were drawn from each flask. The samples were placed in a micro-centrifuge for 5 minutes at 7000 rpm. Approximately 1.5 ml of the respective supernatants were collected in 10ml plastic syringes with attached plastic tubing. The tubing was removed from each syringe and a 0.2-micron filter was attached. The respective supernatants were pushed through the filter and the filtrates were collected in a series of plastic test tubes. The filtrates were diluted five-fold using an auto-diluter, placed in 1.5 ml glass vials sealed with teflon caps, preserved by adding 2 drops of ten-

fold diluted phosphoric acid, 0.1N, and stored at 4 °C until analysis. The phosphoric acid was diluted to represent the same concentration used in the full-scale experiment. Approximately two hours prior to analysis, samples were first warmed to room temperature.

3.5 TEMPERATURE AND pH

The pH and temperature of all samples taken from the full-scale system were analysed using a Hanna Instruments portable pH/Temperature Meter. The equipment was not used however, when the oily nature of the samples caused clogging in the electrode junctions. Following this, an Accumat pH/temperature metre, located in the lab facility, was used.

3.6 SLUDGE BLANKET

The sludge blanket in the gravity thickener, the point at which the supernatant layer ends, was measured using a Marklin Sludge Gun. This device was lowered into the tank to the surface of the wastewater with this being depth noted, and then lowered to the depth of the blanket where the depth of the actual blanket to the rim of the tank was again noted. To calculate the depth of the blanket, the two depth measurements were subtracted from each other. The gun functions using a laser beam between two points. When the laser beam is cut in half, a noise sounds, indicating the start of the sludge blanket.

3.7 STATISTICS

All statistical calculations (see Appendix C) were performed using MS Excel 8.0 (Office 97).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 FULL-SCALE EXPERIMENT

4.1.1 THE EFFECT OF HRT

HRT is defined as the average amount of time a water molecule spends in a reactor. It is measured by taking the total volume of that reactor and dividing by the influent flow rate. The duration of contact time between the organisms and dissolved substrate within the reactor is governed by HRT. The two-stage anaerobic digestion process, defined in Section 2.4, is easily controlled by HRT. As one operational parameter HRT affects the production of VFAs.

The range of testable HRT values is dependent on the operational range of the primary sludge pumps. This examinable range (see Section 3.3.1) for the pumps located at the Bonnybrook Wastewater Treatment Plant is between 50 m^3/hr - 100 m^3/hr. In actuality, the pumps are able to operate at a lower rate however; past experiences by the plant have shown that below 50m^3/h plugging may become an issue. Using the formula detailed in Appendix C, the testable range of HRT is 18.4hr to 36.7hr . Prior to start-up of this experiment, the accuracy of the pumping rate, as measured by flow meters, was calibrated to ensure pump accuracy (See Appendix C).

4.1.2 VFA PRODUCTION

The production of VFAs is directly from the acidogenic phase of anaerobic digestion. Short chain volatile fatty acids are produced from the hydrolysis of complex substrates found in the primary sludge feeding the complete mix reactor. The change in concentration of VFA present in the primary sludge to the concentration found in the gravity thickener supernatant is shown in Figure 4.1.

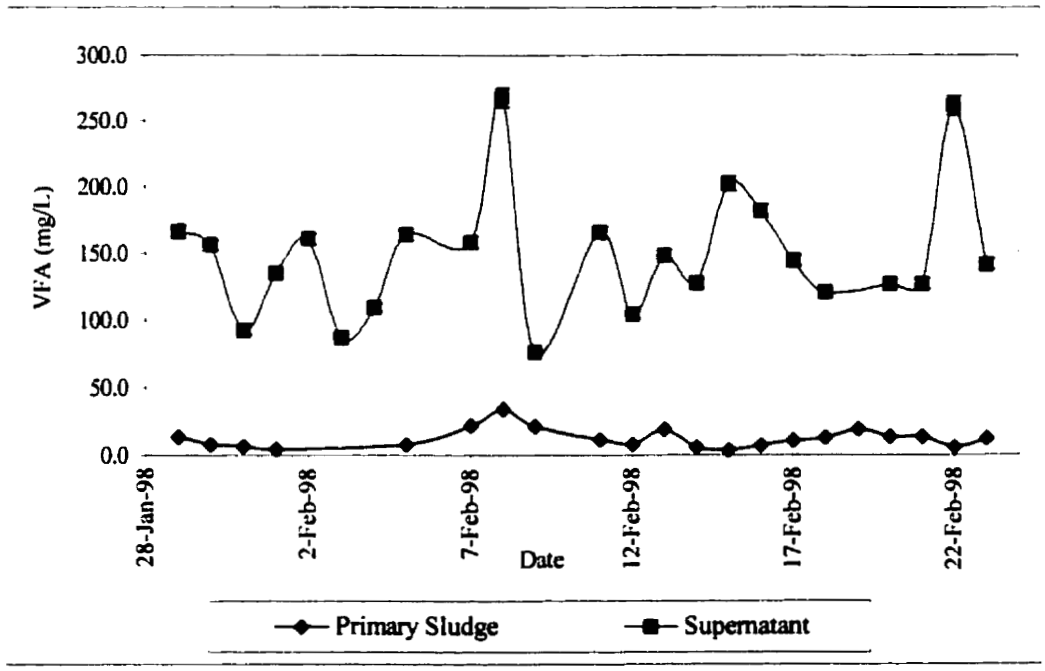


Figure 4.1 – Comparison of VFA Concentration in the Primary Sludge and Gravity Thickener Supernatant

Under the operational conditions of the fermenter and gravity thickener, the above figure demonstrates the increase in the concentration of VFAs present in influent wastewater

after the fermentation process. The purpose of the full-scale experiment is to determine the HRT value that maximizes the VFA production of the fermentation system.

4.1.2.1 Run #1: HRT_{EXP} = 24.5 hours (Medium), HRT_{CON} = 24.5 hours (Medium)

In Run 1 both the control and experimental trains were set at identical HRTs of 24.5 hours. Figure 4.2 and Figure 4.3 demonstrate the VFA production of the control train and the experimental train, respectively. The complete mix tanks for both trains were fed with primary sludge at a rate of 75 m^3/hr. Under these operational conditions, Figures 4.2 and 4.3 demonstrate that both the control and experimental train exhibit very similar VFA concentrations. Setting both trains at identical conditions examines the reproducibility of this system and enables the data of future runs to account for the difference between daily fluctuations and true variances in production due to changes in operational conditions (i.e. changes to HRT). Figure 4.4 shows the concentration of total VFAs in the gravity thickener supernatant, for both the control and the experimental trains throughout Run # 1. This figure illustrates a comparison of the concentration of VFA measured in the supernatant of the experimental train, when set to the identical HRT as the control train. Figure 4.4 also shows both the experimental and control trends are in an upward direction. This indicates that both the control and experimental train are responding to the influence of some variable in the same manner.

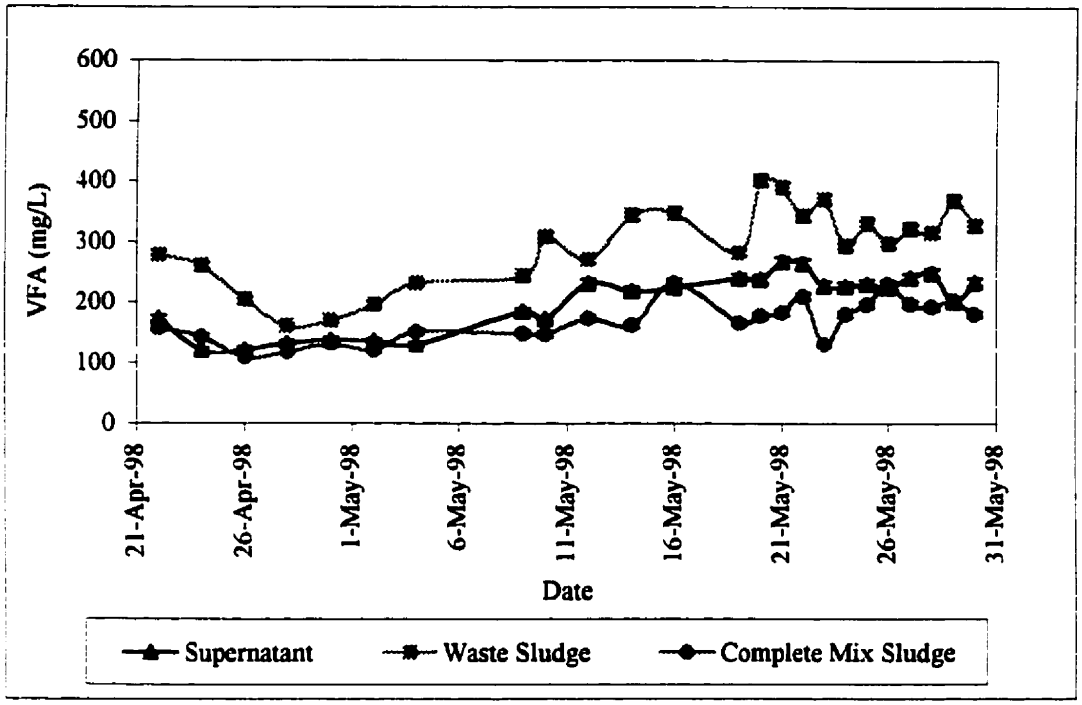


Figure 4.2 - VFA Concentrations in the Supernatant, Complete Mix Sludge, and Gravity Thickener Waste Sludge inthe Control Train for Run #1

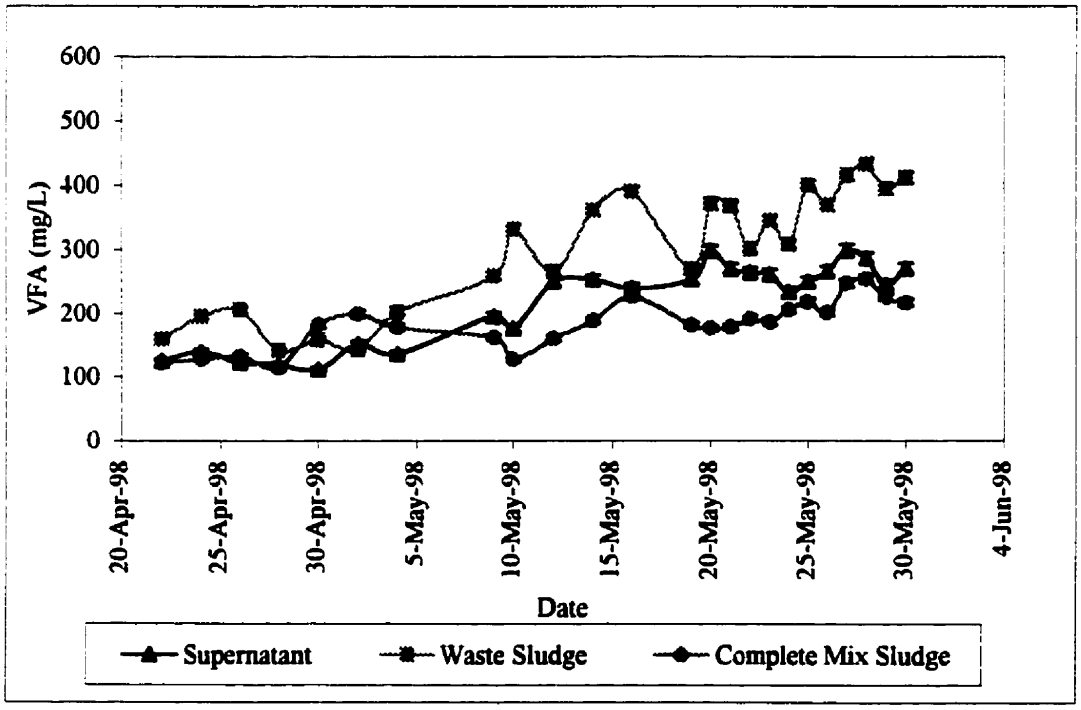


Figure 4.3 - VFA Concentrations in the Supernatant, Complete Mix Sludge, and Gravity Thickener Waste Sludge in the Experimental Train for Run #1

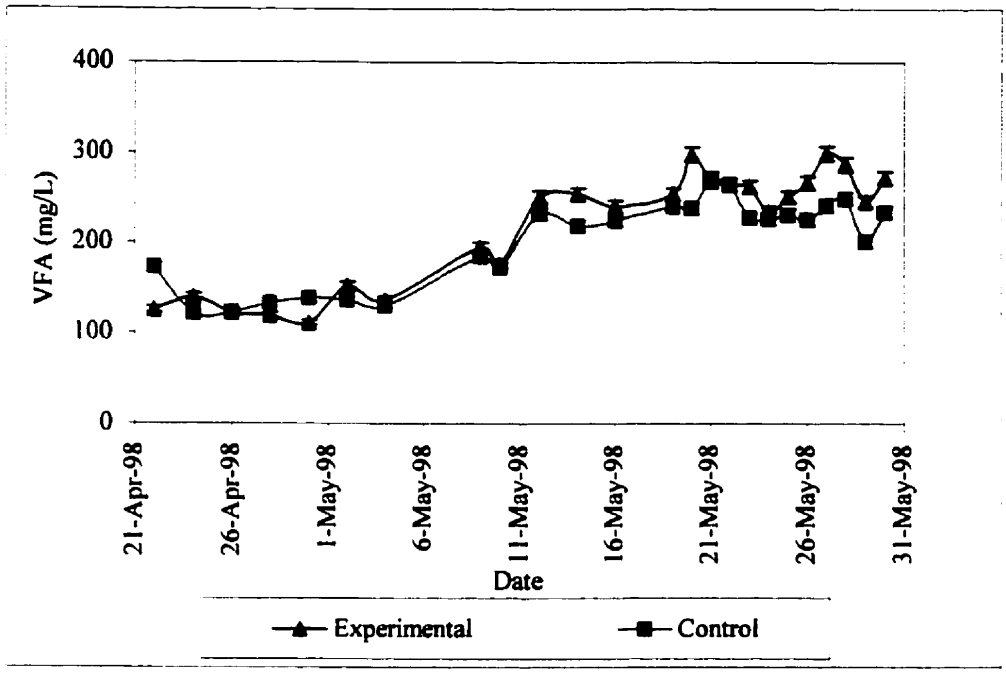


Figure 4.4 - Comparison of VFA Concentrations in the Supernatant of the Control and Experimental Train for Run #1

The purpose of this experimental run, in this instance, is to collect 'baseline data' (i.e. trends which have no imposed stresses but illustrate changes due to uncontrollable variables that causes stresses and fluctuations).

4.1.2.2 Run #2: HRT_{EXP} = 18.7 hours (Low), HRT_{CON} = 24.5 hours (Medium)

In Run #2 the HRT for the experimental train was lowered from 24.5 to 18.7 hours by increasing the primary sludge flow rate from 75 m^3/h to 100 m^3/h on June 10, 1998. Figure 4.5 and Figure 4.6 show the results of Run # 2.

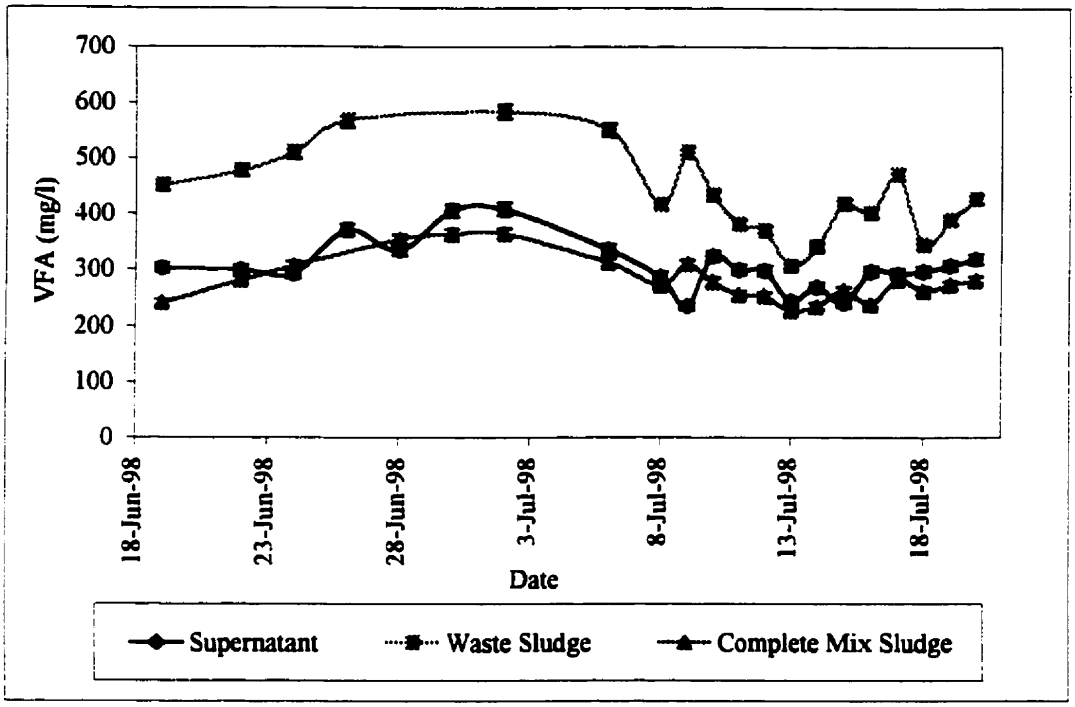


Figure 4.5 - VFA Concentrations in the Supernatant, Complete Mix Sludge, and Gravity Thickener Waste Sludge in the Control Train for Run #2

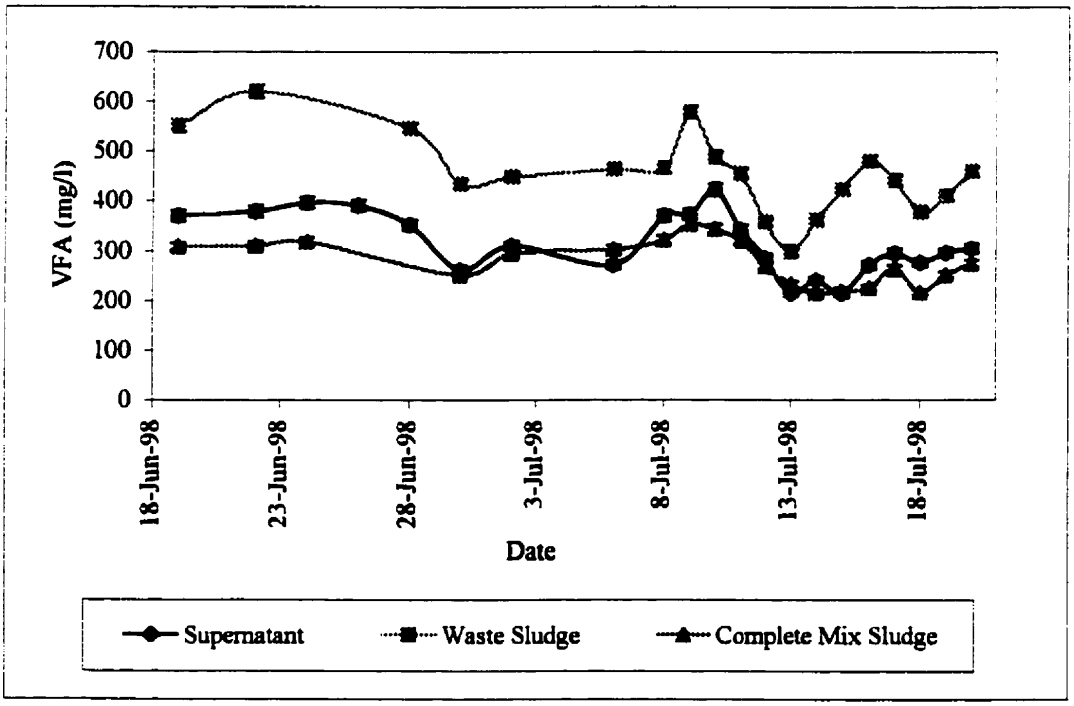


Figure 4.6 - VFA Concentrations in the Supernatant, Complete Mix Sludge, and Gravity Thickener Waste Sludge in the Experimental Train for Run #2

Under the operational stress of a change in feed flow rate, the experimental train showed larger fluctuations in VFA production during the first two SRTs when compared to the last two SRTs. However, the control train also exhibited substantial fluctuations in VFA production for this same time period suggesting the cause was due to some external stress rather than due to the change in feed rates. Figure 4.7 below shows the comparison of the VFA concentrations in the supernatant when comparing the effect of lowering the HRT.

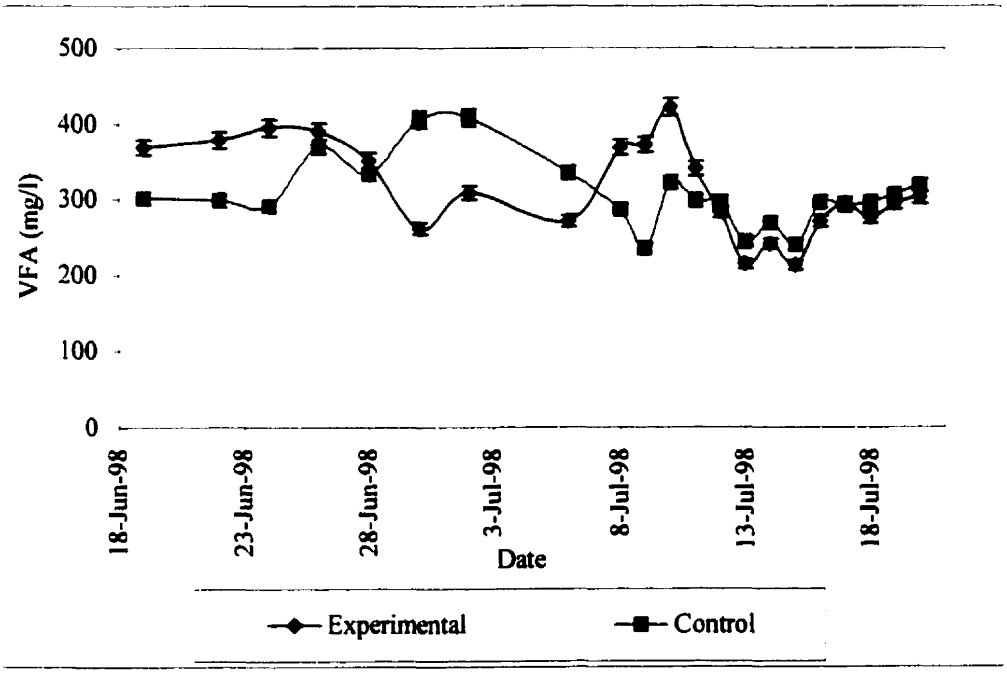


Figure 4.7 - Comparison of VFA Concentrations in the Supernatant of the Control and Experimental Train for Run #2

As Figure 4.7 demonstrates the experimental train, again, had slightly higher VFA concentrations in the supernatant by an average of 27.1 mg/l than the control train. The establishment of a low HRT of 18.7 hours for the experimental train when compared to

24.5 hour HRT applied to the control train appears to have little impact on the measured concentration of VFA.

4.1.2.3 Run #3: HRT_{EXP} = 36.7 hours (High), HRT_{CON} = 24.5 hours (Medium)

For Run # 3 the HRT for the experimental train was increased from 18.7 to 36.7 hours by decreasing the primary sludge flow rate to 50 m^3/h from 100m^3/h on July 20, 1998. Figure 4.8 and Figure 4.9 show the VFA concentrations of both control and experimental trains of Run #3.

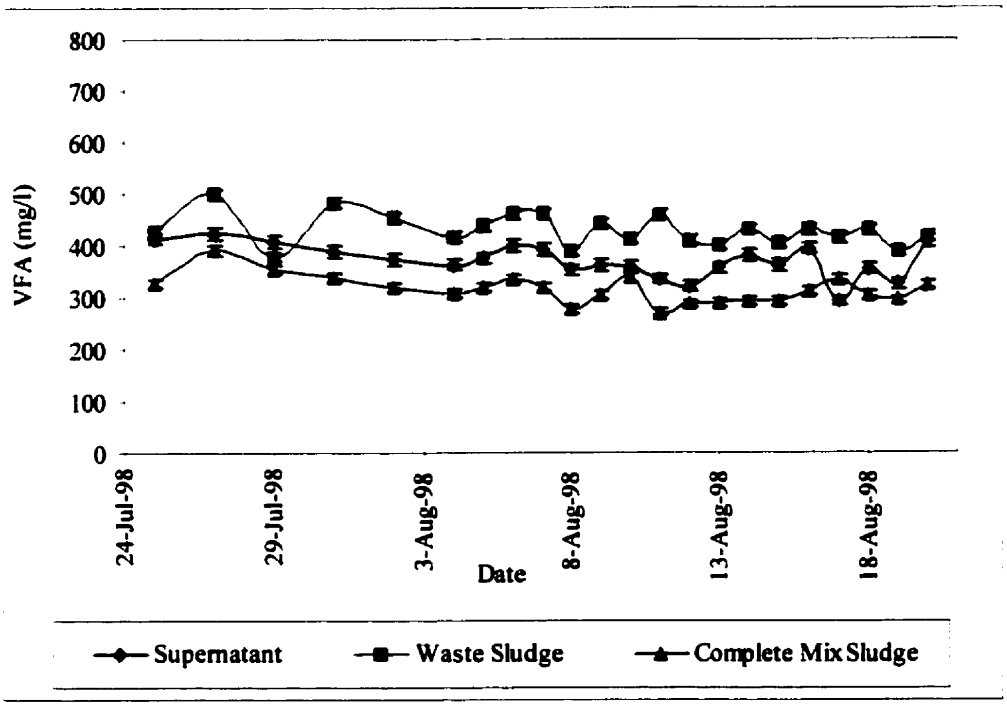


Figure 4.8 - VFA Concentrations in the Supernatant, Complete Mix Sludge, and Gravity Thickener Waste Sludge in the Control Train for Run #3

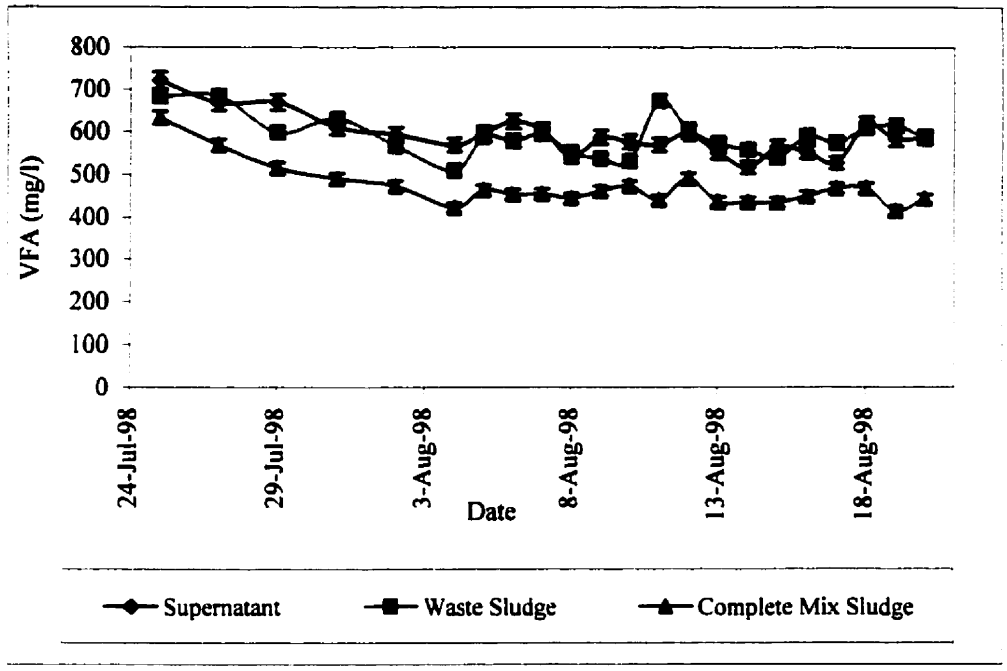


Figure 4.9 - VFA Concentrations in the Supernatant, Complete Mix Sludge, and Gravity Thickener Waste Sludge in the Experimental Train for Run #3

The data in Figure 4.9 above shows a significant increase in VFA concentrations for the experimental train when compared to the data shown in Figure 4.8 for the control train. A comparison of the total VFA concentration in the supernatant (Figure 4.10) for the control and experimental trains, further corroborates the above conclusions that the VFAs concentration in the experimental train is significantly greater than that of the control train.

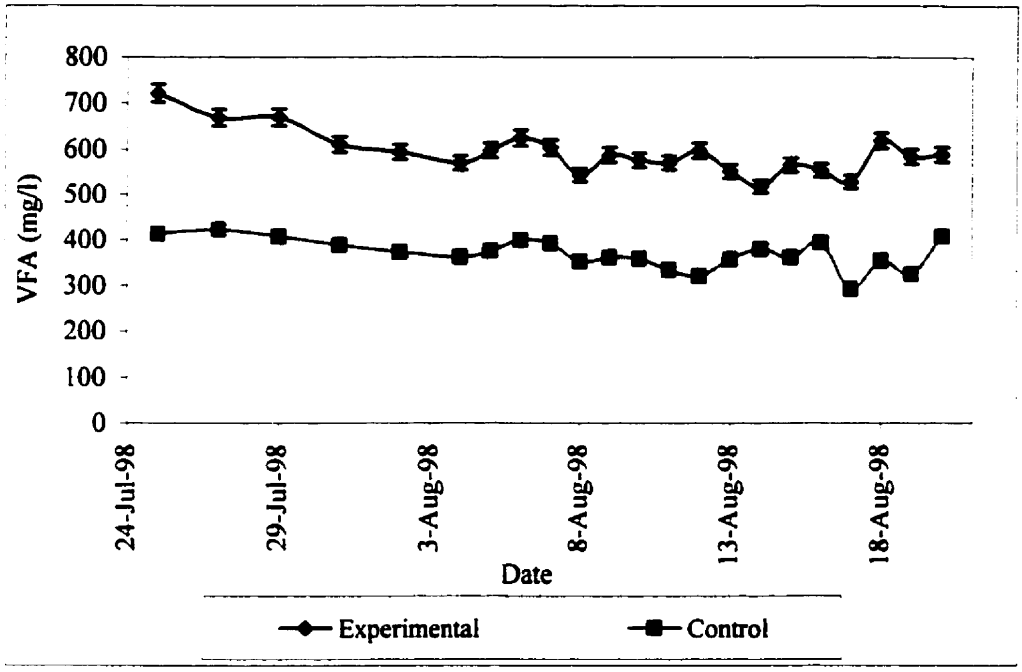


Figure 4.10 - Comparison of VFA Concentrations in the Supernatant of the Control and Experimental Train for Run #3

The concentration of VFAs in the supernatant for the experimental train contains approximately 223.2 mg/l more VFA, on average, than the control train. Although the data comparison is not shown for the complete mix and waste sludges, greater concentrations of VFAs on average were recorded, 155.9 mg/l and 156.2 mg/l, respectively, for the experimental train compared to the control train. The establishment of a high HRT of 36.7 hours showed a significant increase in the measured VFA concentrations when compared with an HRT of 24.5 hours and 18.4 hours.

4.1.2.4 NET VFA CONCENTRATIONS

The net concentrations of VFAs measured for each run is detailed in Table 4.1.

Table 4.1 – Net VFA Concentrations Measured for Runs 1 through 3

Run #	HRT		Average VFA Concentration (mg/L)					
	(Hours)		Complete Mix		Supernatant		Waste	
	Control	Exp	Control	Exp	Control	Exp	Control	Exp
1	24.5	24.5	168	183.4	200.8	217.5	293.5	300.4
2	24.5	18.4	282.1	278.1	307.1	315.6	439.6	455.3
3	24.5	36.7	428.9	590.6	369.8	593	314.9	470.7

(Exp = Experimental)

Despite the fact there was no change in HRT, the VFA concentrations of the control train were not constant over the course of all three runs. In addition, the experimental train revealed an increase in VFA concentrations paralleled by an increase in HRT as would be expected from research by Elefsiniotis (Elefsiniotis, 1992). However, increases in VFA production rates were not concomitant with increases in HRT as will be seen in Section 4.1.2.5. Elefsiniotis' research on the effect of operational and environmental parameters that effect the acidogenesis of primary sludge examined HRT as a control parameter. These experiments were conducted on a bench-scale system. Figure 4.11 and Figure 4.12 illustrate the change in net VFAs concentration from runs #1 to #3. The trends for both the control and experimental trains showed a consistent increase in measured VFAs concentration with the exception of the waste sludge from Run #1 to Run #3. This increase however, does not correspond to a steady increase in HRT given that the HRT of Run #2 is less than the HRT of both Run #1 and Run #3. This indicates that an increase in HRT does not reflect an increase in measured VFAs concentration. It is important to note that the increase in VFAs concentration from Run #2 to Run #3 of the experimental train is significantly greater than the increase of the control train over the same period.

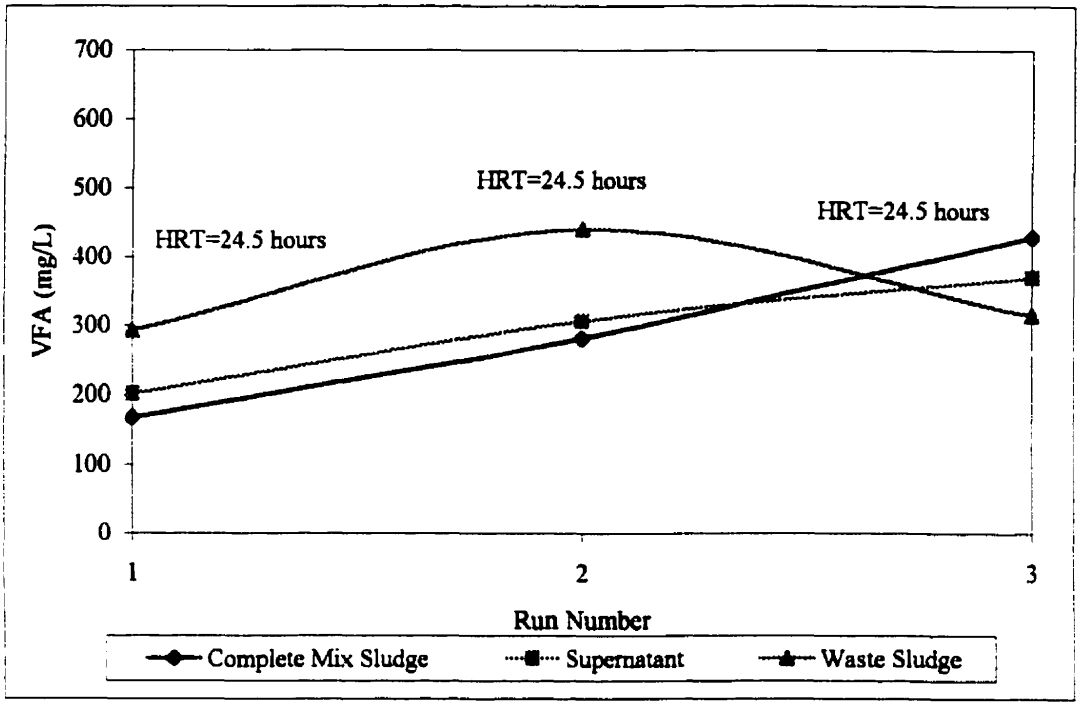


Figure 4.11 - VFA Concentration as a Function of HRT in the Control Train

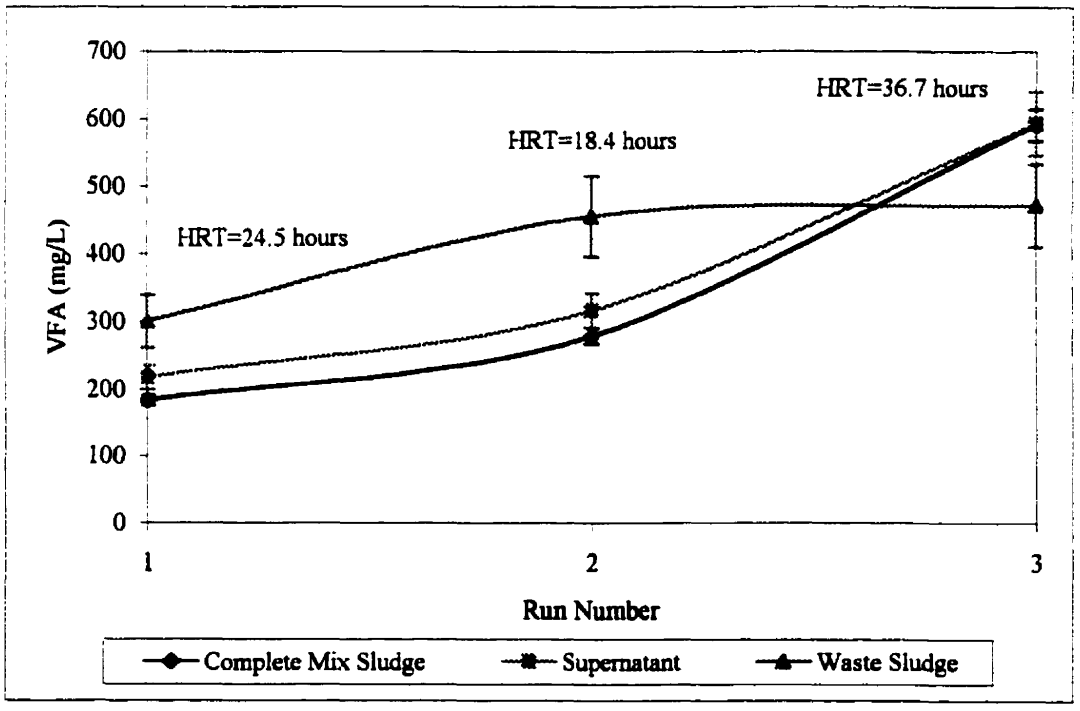


Figure 4.12 - VFA Concentration as a Function of HRT in the Experimental Train

The data in Figure 4.13 shows a comparison of VFAs concentration in the control and experimental trains for the complete mixed sludge and supernatant.

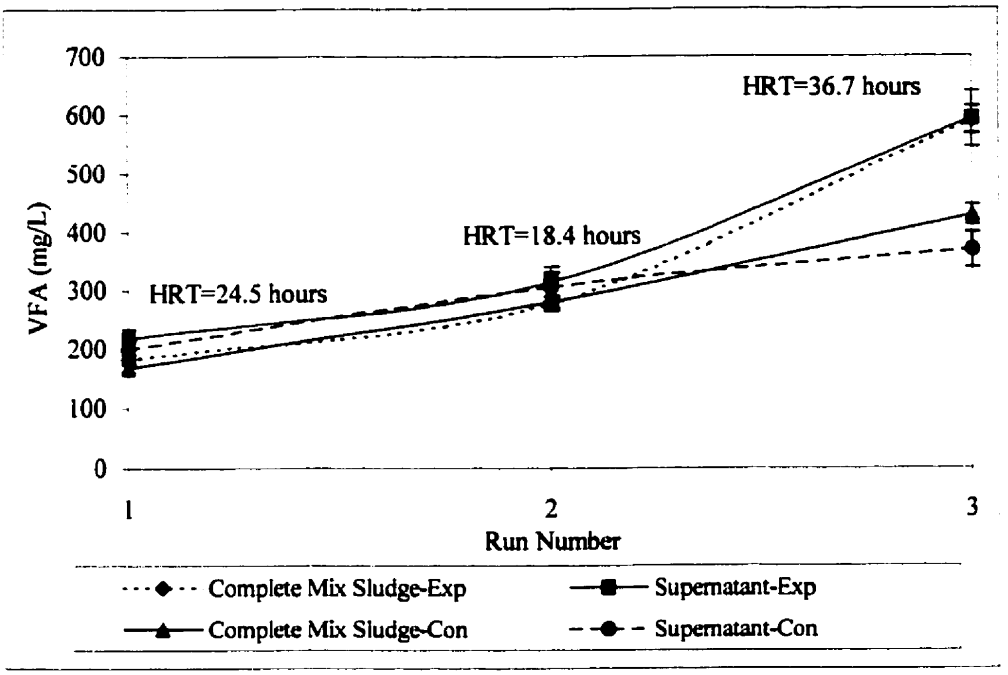


Figure 4.13 – Comparison of the Control and Experimental Trains VFAs Concentration as a Function of HRT

If HRT had no effect on measured VFAs concentration, the control and experimental trains should be almost identical. The increase in VFAs concentration, as seen in Figure 4.13, from Run 1 (HRT=24.5 hours) to Run 2 (HRT=18.4 hours), is similar in both the control and experimental trains. However, from Run #2 to Run #3 (HRT=36.7 hours), the experimental train showed a significantly greater increase in VFAs concentration than the control train. The control train showed an increase in VFAs concentration of 62 mg/L in the supernatant from Run #2 to Run #3, the experimental train showed an increase of 278 mg/L. This demonstrates that the change in the HRT from Run #2 to Run #3 does affect the measured VFAs concentration, however, given that the control train also

exhibited an increase in VFAs concentration for the same period, it is not the only factor. A discussion on temperature effects follows in Section 4.1.3.

4.1.2.5 NORMALIZED VFA PRODUCTION

In order to properly compare between the differing HRTs and their corresponding primary sludge flow rates, the measurement of VFAs must be normalized. By normalizing VFA data, the difference in solids concentration associated with the use of different primary sludge flow rates, is accounted for. Multiplying by the primary sludge flow rate normalizes the production of VFAs to a time factor thereby generating the units of measure, kilograms per day. Assessing the data in kg/day enabled the opportunity to establish proper and effective measures for comparison of VFA production. To establish a rough method for data comparison to other WWTPs and compare the VFAs concentration of the fermentation system effluent to that of the plant influent, the calculated VFA production (kg/d) is divided by the plants sewage flow in the units million litres per day.

Figure 4.14 illustrates the VFA concentrations for all three runs and Figure 4.15 illustrates the normalized production rates of VFAs in all three runs. On comparing the data in Figure 4.14 and Figure 4.15, the effect of normalizing HRT is shown. The data in Figure 4.14 illustrates that Run #3 has the highest measured concentration of VFA. However, the data in Figure 4.15 shows that, on average, production of VFAs in the supernatant, when the control train is compared to the experimental train, is highest in Run #2. Table 4.2 below, shows the average VFAs production for each run in both the experimental and control trains.

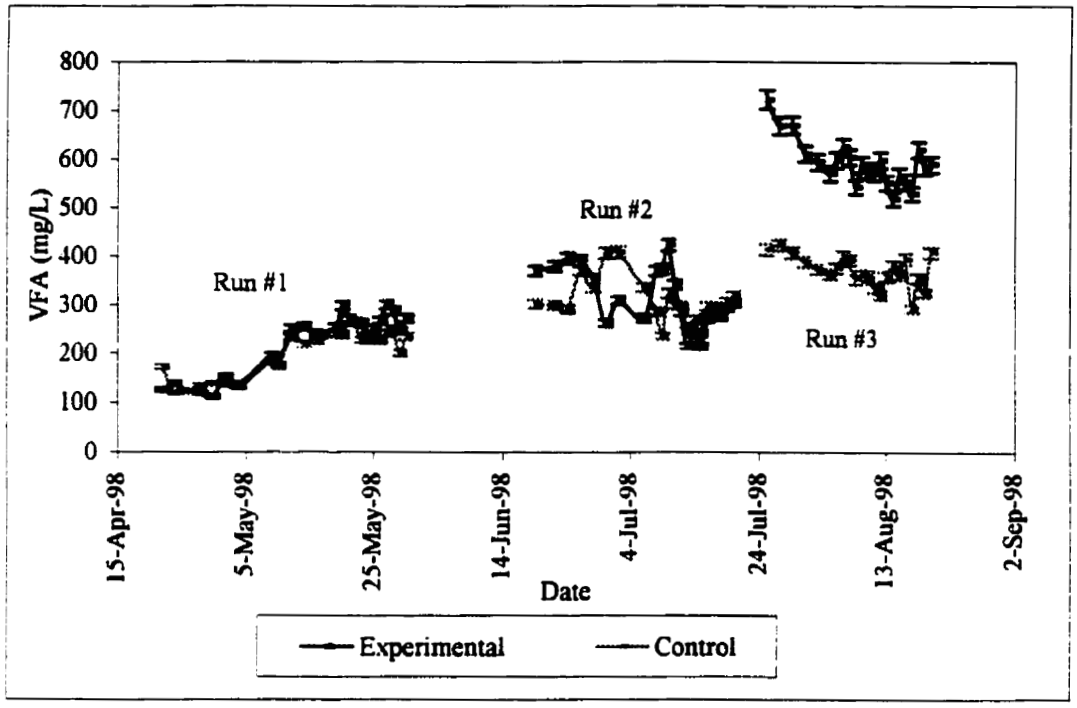


Figure 4.14 - Comparison of VFA Concentrations in the Supernatant

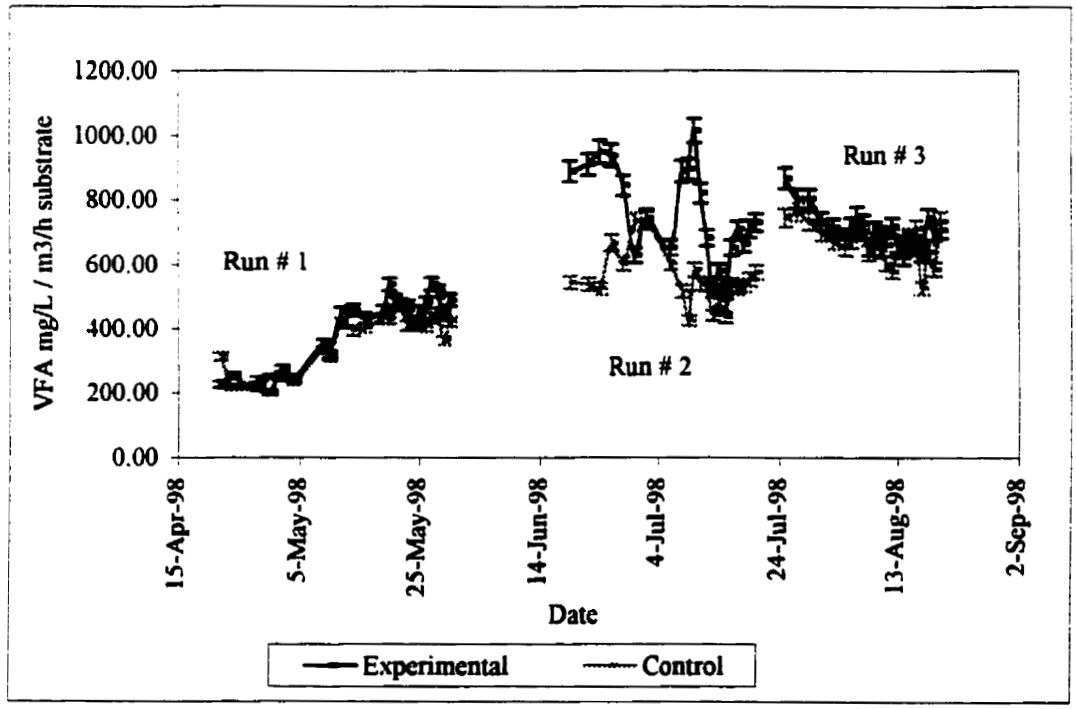


Figure 4.15 - Comparison of Normalized VFA Production in the Supernatant

Table 4.2 – Average VFAs Production in the Experimental and Control Trains

Run #	HRT		Average VFA Production in kg/day		Ratio of VFA Production
	(Hours)		Supernatant		Supernatant
	Control	Experimental	Control	Experimental	Experimental:Control
1	24.5	24.5	361 ± 13	391 ± 14	1.08
2	24.5	18.4	552 ± 20	757 ± 28	1.37
3	24.5	36.7	665 ± 25	711 ± 26	1.07

The data in Table 4.2 averages the data in Figure 4.15 and demonstrates that run #2 exhibits the highest rate of VFA production. Figure 4.15 also shows that while Run 1 and Run 3 have reasonably smooth trendlines, Run 2 appears to have large fluctuations in both the control and experimental trains (see Section 4.1.2.2). In addition, the control train, when set at identical conditions throughout this experiment, showed an increase in VFA production from one run to the next. This further demonstrates that while HRT has an effect on VFA production, it is not sole factor. A discussion of temperature effect follows in Section 4.1.3.

4.1.3 TEMPERATURE AND pH

In order for biological phosphorus removal processes to be accepted as an acceptable means of nutrient removal, it must function successfully in both warm and cold climates. The success of this process has been shown over temperatures ranging from 5 °C to 30 °C (Mamais and Jenkins, 1992). The affect of temperature is immaterial on the actual stoichiometry of the anaerobic fermentation process defined in Section 2.4.

Temperature (oC)	January	February	March	April	May	June	July	August	September	October	November	December
Daily Maximum	-3.6	-0.5	3.3	10.6	16.4	20.6	23.2	22.7	17.4	12.6	2.9	-2.3
Daily Minimum	-15.7	-12.3	-8.4	-2.4	3	7.4	9.5	8.6	3.8	-1.2	-9	-14.4
Daily Mean	-9.6	-6.3	-2.5	4.1	9.7	14	16.4	15.7	10.6	5.7	-3	-8.3
Date	893/31	893/04	951/09+	954/02	954/01	904/08+	884/05	886/30	926/24	984/31	893/30	924/17

Temperature Data from Calgary, University of Calgary, 1881 to 1990
(A publication of the Canadian Climate Program, Environment Canada, 1993)

Table 4.3 - Average Temperature History in Calgary from the years 1881 through 1990

Instead, temperature influences both the kinetics and biochemical rates of reaction of anaerobic and aerobic processes that occur in biological phosphorus removal systems (Brdjanovic et al, 1997) (Jones and Stephenson, 1996).

The Bonnybrook Wastewater Treatment Plant, located in Calgary, Alberta, operates in a cold climate. Table 4.3 illustrates the average air temperature for each month of the year. The temperature data in Table 4.3 reveals that the Bonnybrook plant operates, on average, in air temperatures below 10 °C for eight months of the year.

The full-scale system experiment comprised of three runs, described in Section 3.3.1, began April 22, 1998 and was completed on August 20, 1998. Over the course of

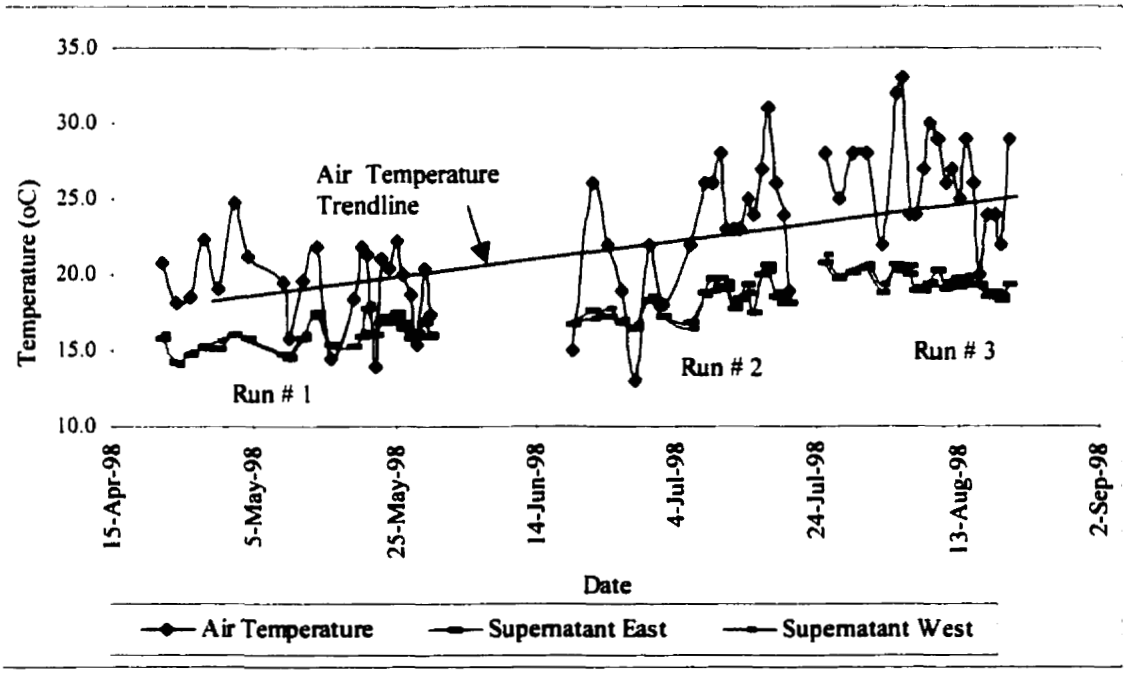


Figure 4.16 – Comparison of Air Temperature with Supernatant Temperature in both the Control and Experimental Trains

this experiment, the air temperature and the temperature of samples taken were recorded. Figure 4.16 shows the air temperature and the temperature of the supernatant in both the control and experimental train. A trendline plotted in Figure 4.16 shows the average air temperature over the course of this experiment. From this trendline, a temperature increase from Run 1 through Run 3 is evident. However, as the air temperature increases, a similar increase in temperature is apparent in both the experimental and control supernatant samples. Similar data for complete mix and waste sludge is found in Appendix A. Figure 4.16 shows that an increase in air temperature results in an increase in the temperature within the complete mix and gravity thickener tanks. Given that temperature influences the rate of biochemical reactions, the temperature increase from Run 1 through Run 3 should affect VFA concentrations. Figure 4.17 and Figure 4.18 illustrate the VFAs concentration in the supernatant as a function of temperature for both the control and experimental trains. Correlation coefficients are shown for each train.

The data in Figure 4.17 shows that as the temperature increases, from April to August, there is a concomitant increase in VFA concentration. Since the control train is held at constant HRT over each of the three runs, the increase in VFA production seems primarily caused by an increase in temperature. Data in Figure 4.18 also reflects an increase in VFA concentration as the air temperature increases from Run 1 through Run 3. Given that section 4.1.2.4 concluded that HRT is only one variable affecting VFA concentrations, and that section 4.1.2.5 further corroborates the above, it is evident from Figure 4.18 that temperature is an additional factor contributing to the increase in measured concentration of VFAs. However, correlation coefficients shown in Figure 4.17 and Figure 4.18 show an unclear effect of temperature on VFA production. A

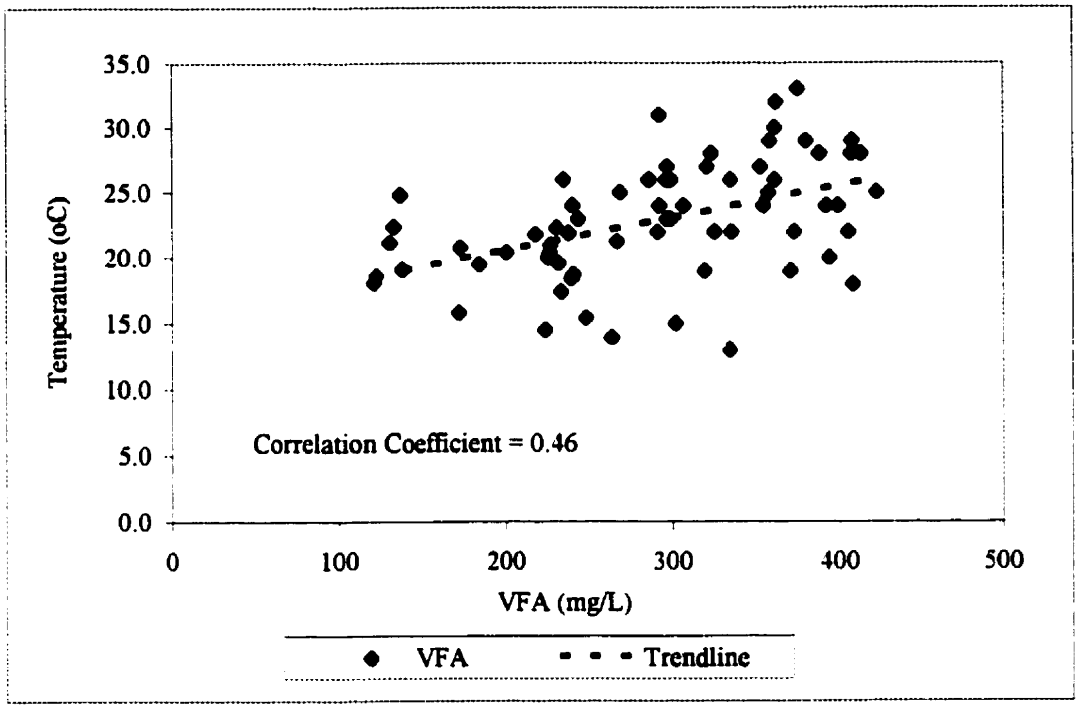


Figure 4.17 - VFA Concentration as a Function of Temperature in the Control Train

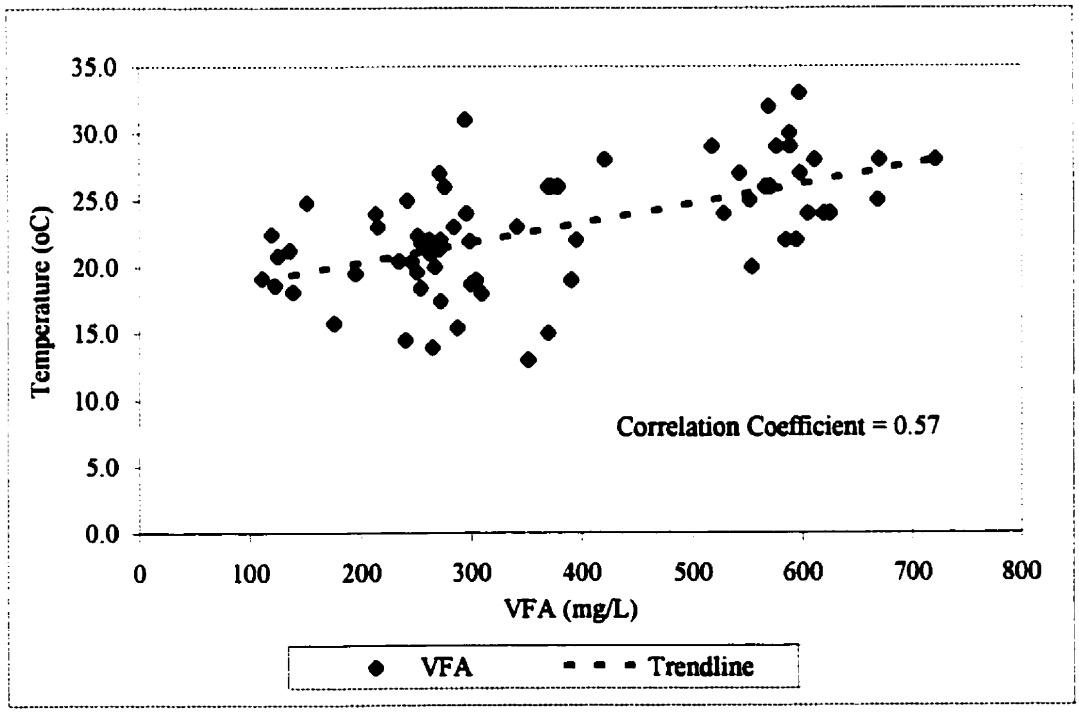


Figure 4.18 - VFA Concentration as a Function of Temperature in the Experimental Train

good correlation coefficient is around 0.8, thus the calculated values of 0.46 for the control train and 0.57 for the experimental train indicate that there are additional factors affecting VFA production.

The pH of the fermentation system can also effect the metabolism of the organisms present. The pH can affect the growth rate of bacteria. Changes in pH may cause a shift in the type of species present. Figure 4.19 illustrates the comparison of the pH in the supernatant of the experimental and control trains throughout this study period.

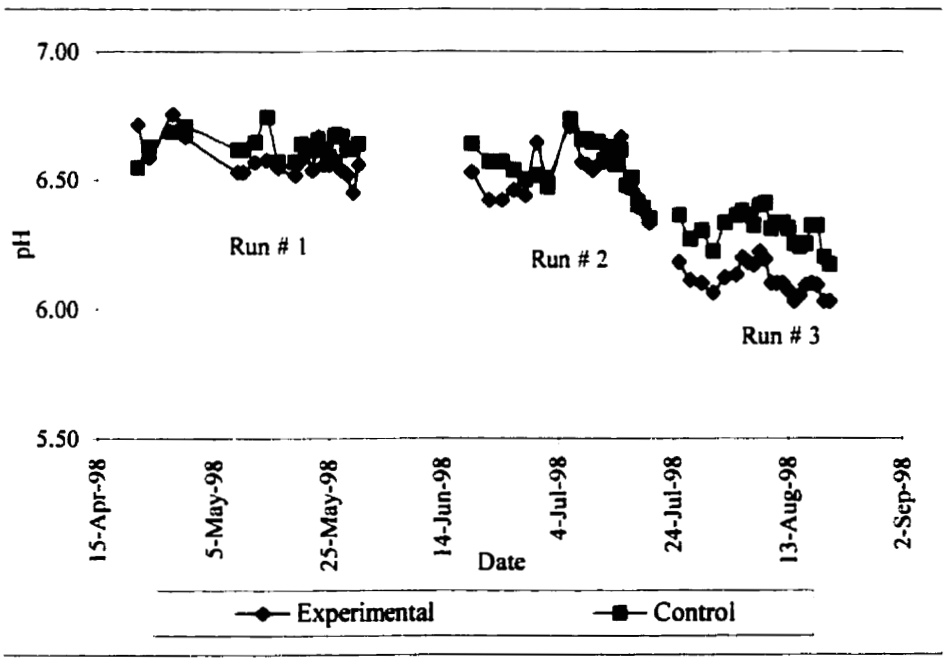


Figure 4.19 – pH Comparison of the Supernatant through Run #1 - 3

Data in Figure 4.19 shows that the pH remained between 6.0 and 7.0 for the duration of this study in each of the experimental and control trains. The pH of both trains was very similar throughout Run #1 and Run #2. Both trains had an average pH of 6.6 for Run #1 and 6.5 for Run #2. However, during Run #3, when the flow rate was decreased from 100 m^3/hr to 50 m^3/hr on July 20, the average pH of the control and experimental trains

decreased. The pH of the experimental train however, showed a much greater decrease in pH dropping to an average value of 6.1 whereas the pH of the control train had an average value of 6.3. This decrease in pH of the experimental train reflects the presence of a greater concentration of acid. Therefore, the measured concentration of VFAs in the experimental train should be higher than the concentration measured in the control train, on average. Evidence of this increased concentration in VFAs may be found in Table 4.1.

4.1.4 TOTAL SOLIDS

The solids present in the fermentation system are an indirect measure of the quantity of biomass present. Changes in HRT, due to changes in the primary sludge flow rate, are coupled by a change in the flow rate of dissolved primary substrate entering and supernatant exiting the fermentation system. As the primary sludge flow rate decreases, the amount of time solids spend in the primary clarifier increases. However, regardless of the primary sludge flow rate, the total mass of solids exiting the clarifier remains constant. This is primarily because there is no build up of a sludge blanket in the primary clarifier.

When the primary sludge flow rate is increased, reflecting a decrease in HRT, the volume of raw wastewater treated by the fermentation system per day increases. Given the entire fermentation system is gravity driven, to account for the increased flow of primary sludge entering the fermentation system, the flow rate of gravity thickener supernatant exiting the system also increases. While the actual wastewater volume present in the fermenter itself remains unchanged, the volume of raw wastewater treated

by the fermentation system per unit time increases. Given this fact, although the mass of solids present in the wastewater throughout this process is constant, there is a greater volume of dissolved organics. These dissolved organics are substrate for the fermenter bacteria, and provide more substrate available for conversion to VFAs. Therefore, in terms of flow rates, the greater the primary sludge flow rate, the greater the volume of dissolved organics available for conversion to VFAs per day.

Throughout this experiment the solids concentration in both the control and experimental trains was expected to remain constant. This is because the total mass of solids in the fermentation system should be unaffected by changes in HRT. Fluctuations in measured total solids were expected due to the ever-changing nature of the influent wastewater as well as external stresses acting on the system. Figure 4.20 shows the

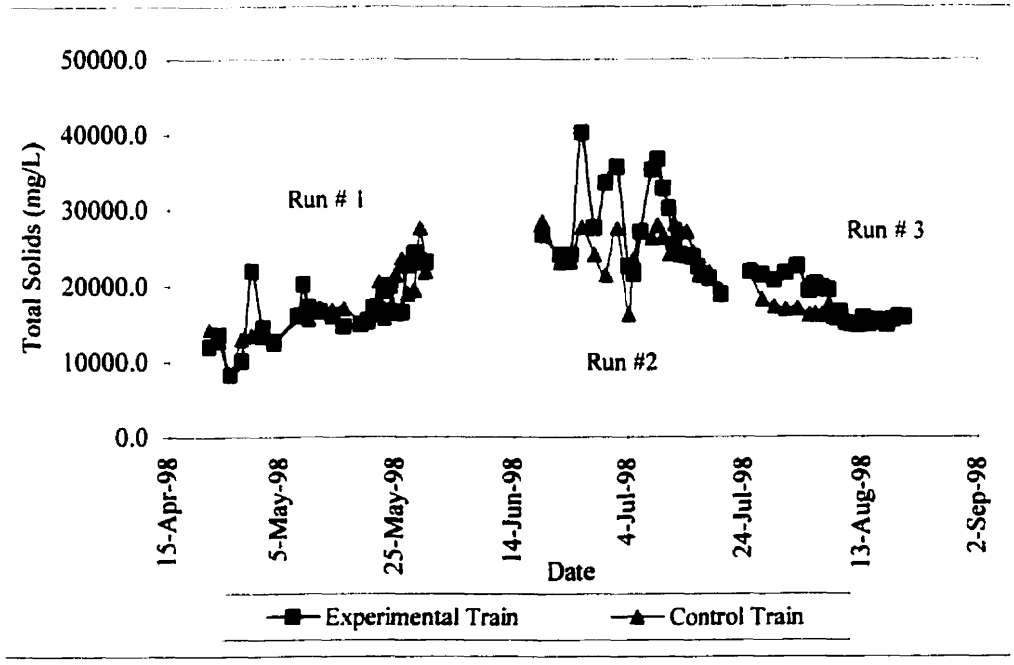


Figure 4.20 – Comparison of Complete Mix Total Solids in the Experimental and Control Trains

comparison of total solids in the complete mix tank in both the control and experimental trains. The data in Figure 4.20 shows that the solids concentration in the complete mix tank is similar during Run #1 where both trains were set at identical HRT values. Run #2 showed an increase in the measured total solids concentration in both trains from Run #1. However, while both trains show similar increases and decreases in total solids concentration at the same points in time, the experimental train increases and decreases are magnified. The solids concentration in the experimental train appears to fluctuate between 20000mg/L and 40000mg/L over a period of 6 days, from June 24 through June30. During this period, it is possible that the tank was not completely mixed. This possibility stems from problems with debris and hair build-up on the mixer blades. Run #3 shows a decrease in both the control and experimental trains total solids concentration to a similar to the measured values in Run #1. To examine the possibility that the measured total solids concentration in the complete mix reactor affects VFA production, VFA production was normalized to biomass. To calculate the normalized data, the VFA production is divided by the total biomass present in the complete mix tank. The biomass value is the product of measured total solids in the complete mix tank and the volume of the complete mix tank. The VFA production value is the product of measured VFA concentration and primary sludge flow rate. This calculation produces a measure of mg VFA production normalized to kg biomass per day. Figure 4.21 illustrates VFA production normalized to biomass for the control and experimental trains.

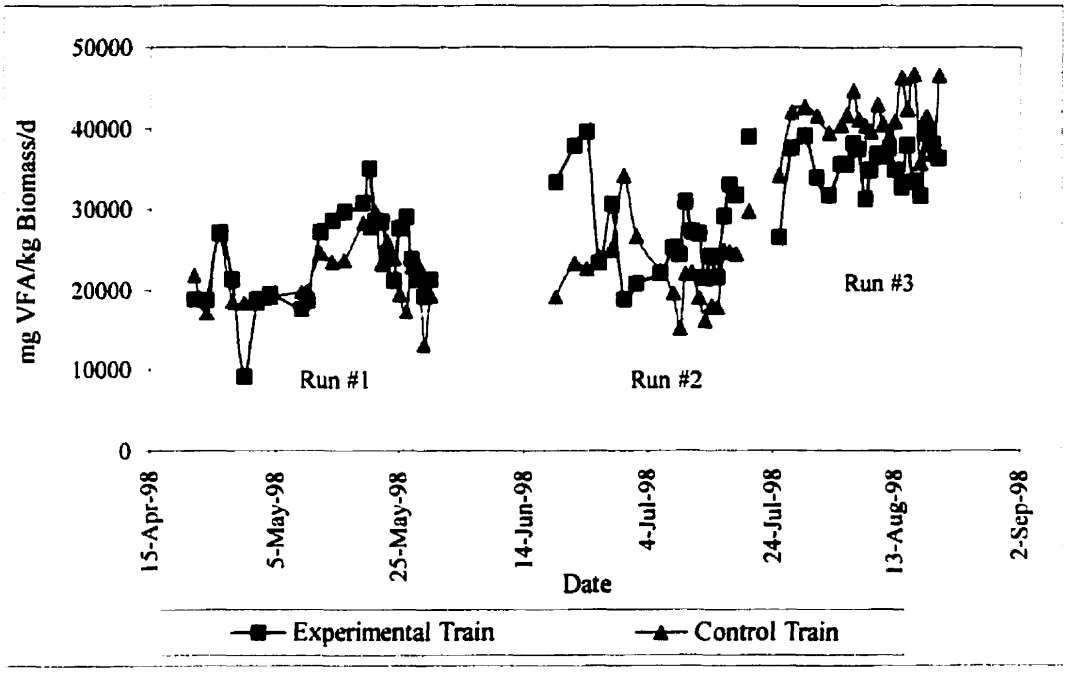


Figure 4.21 – Comparison of VFA Production Normalized to Biomass in the Control and Experimental Trains

The data in Figure 4.21 shows that the VFA production normalized to biomass in Run #1 is similar in both the control and experimental trains. In Run #2 both the control and experimental trains show an increase in VFA production normalized to biomass. However, the experimental train exhibits a greater increase in VFA production per kg of biomass than the control train. This indicates that, at a lower HRT the VFA production rate increases. Further, Run #3 shows the control train having greater VFA production normalized to biomass than the experimental train. In this case the experimental train has a higher HRT value than the control train. This confirms the previous statement wherein, at a lower HRT VFA production increases.

4.2 BENCH-SCALE EXPERIMENT

Examination of various substrates and inhibitors in bench-scale batch tests result in better understanding of parameters that influence fermentation. This series of experiments, defined in Table 3.2 of Section 3.3.2, test the effect of a) solids concentration; b) proportions of thickened primary sludge; c) typical substrates found in wastewater; d) chemical inhibitors; and e) antibiotic inhibitors; on the production of VFA. Table 3.3 illustrates the operating conditions for each run and is keyed to each bench-scale experiment section. Data collected for all runs is found in Appendix B. Error bars shown on the graphs in the following sections are an indication of machine error.

4.2.1 THE EFFECT OF SOLIDS CONCENTRATION ON VFA PRODUCTION

This run examined the effect of solids concentration on VFA production. The batch reactors each contained a combination of primary and complete mix fermenter sludge starting at 100% primary and ending with 100% complete mix (see Table 3.3). In general, complete mix fermenter sludge contains an approximate solids concentration of 20000mg/L, a significantly greater concentration of solids than the typical 1500-2000mg/L of primary sludge. Being that the fermentation process begins in the complete mix tank, the primary sludge typically contains considerably less solids than the complete mix fermenter sludge. Figure 4.22 illustrates the results of Run 1.

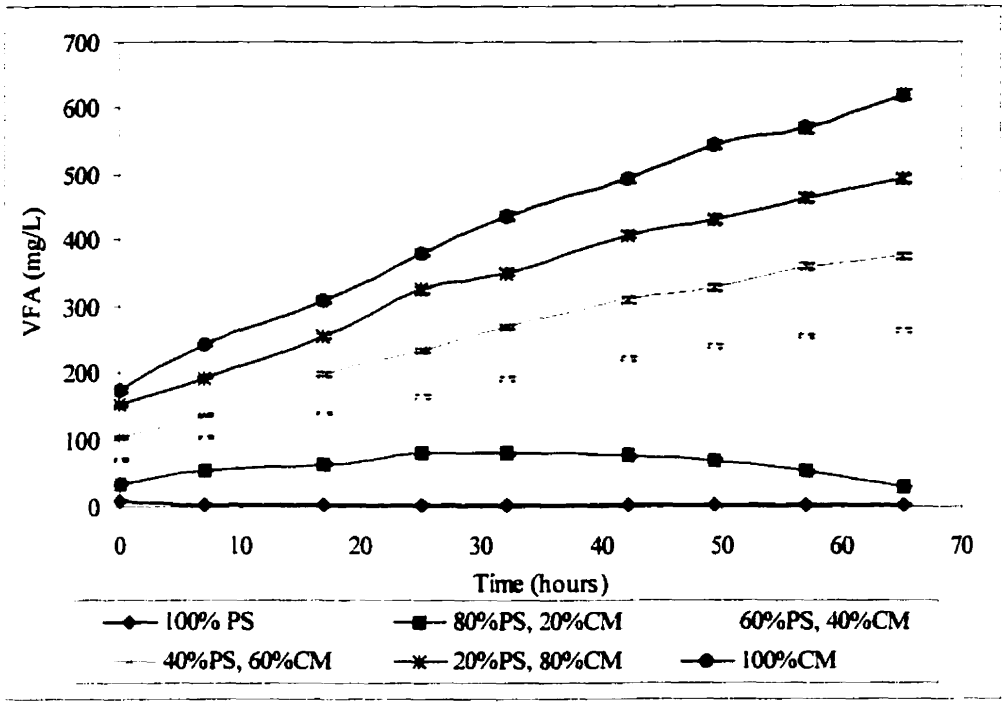


Figure 4.22 – Effect of Solids Concentration on VFA Production in Batch Experiments

As expected, Figure 4.22 shows that as the percentage of complete mix fermenter sludge in batch reactors 1 through 6 increases, so does the production of VFAs in the respective batch reactors. Thus, batch reactors containing 100% complete mix fermenter sludge produces a considerably greater concentration of VFAs than the batch reactor containing 100% primary sludge. It is important to note that the concentration of TSS, from batch reactor 1 through batch reactor 6, increases by 10-fold (see Appendix B). However, one possible method to roughly account for the different solids concentration in each batch reactor is to normalize VFA production to solids concentration. The solids concentration for each batch reactor is calculated by multiplying the measured suspended solids of a particular batch reactor by the volume of the batch reactor. Figure 4.23 shows the normalized trends.

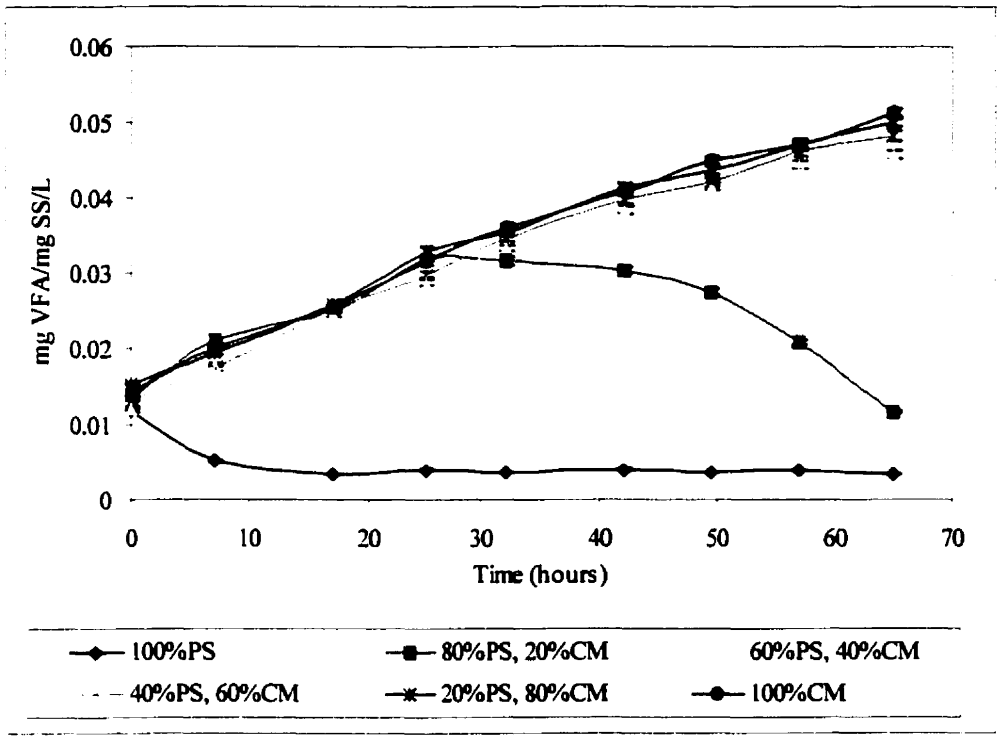


Figure 4.23 – VFA Production Normalized to Biomass in Batch Experiments

Figure 4.23 shows the VFA production in each batch reactor as normalized to total solids concentrations. This graph shows that batch reactors containing combination of 40%PS and 60%CM up to 100% CM exhibit similar VFA production. This suggests that when a certain volume of substrate is present and a minimum amount of biomass is provided to a batch reactor, the VFA production remains consistent even if the level of biomass is increased.

4.2.2 THE EFFECT OF COMBINATIONS OF THICKENED PRIMARY AND COMPLETE MIX FERMENTER SLUDGE ON VFA PRODUCTION

This experiment tested the effect relative proportions of substrate, in the form of thickened primary sludge had on VFA production with all batch reactors being of similar

solids concentration. The batch reactors contained different combinations of thickened primary sludge and complete mix fermenter sludge. The thickened primary sludge was assumed to be a food source and complete mix fermenter sludge was thought of as biomass. The contents of the batch reactors ranged from 100% thickened primary sludge to 100% complete mix fermenter sludge. The results of Run 2 are detailed in Figure 4.24.

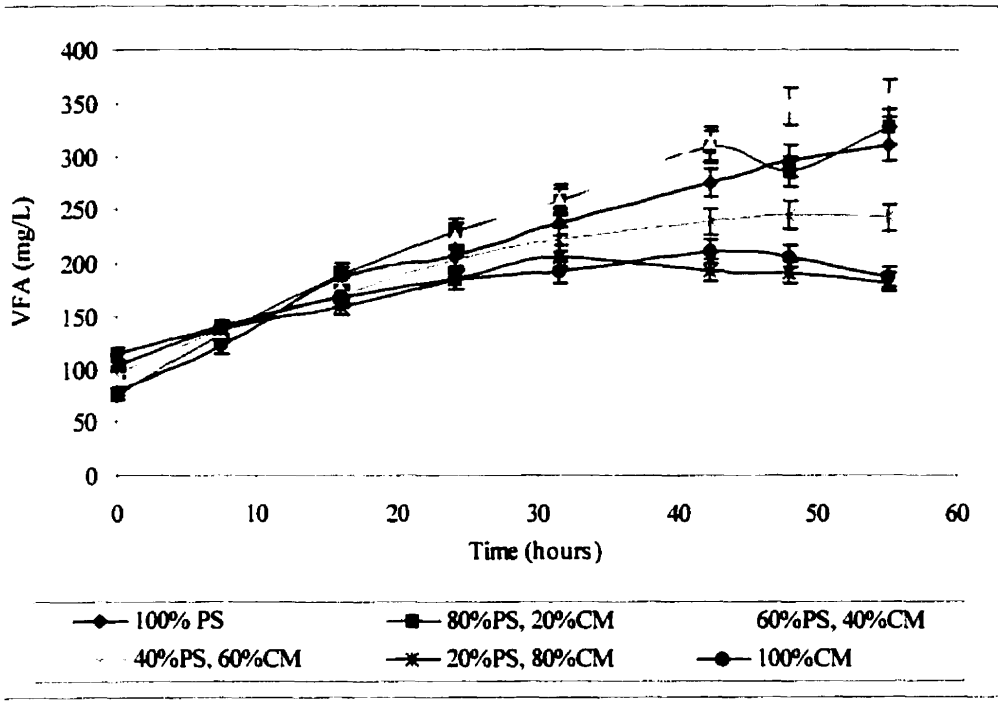


Figure 4.24 - Effect of Combinations of Thickened Primary and Complete Mix Fermenter Sludge on VFA Production in Batch Experiments

As Figure 4.24 demonstrates, combinations of 60% TPS and 40% CM, 80%TPS and 20% CM and 100% TPS yielded the greatest production of VFAs. Figure 4.24 also reveals that using less than 60% thickened primary sludge significantly reduces the production of VFAs. This run suggests that to optimize VFA production in the full-scale system, at least 60% of the complete mix reactor total volume should be TPS.

4.2.3 THE EFFECT OF DIFFERENT SUBSTRATES ON VFA PRODUCTION

This run examined the effect of different substrates on VFA production. All batch reactors were assumed to have similar solids concentrations. The control was a batch reactor of 100% complete mix fermenter sludge. As stated above in Section 4.2.2 complete mix fermenter sludge is thought to contain primarily biomass. A pure substrate representative of each of the basic chemical building blocks, proteins, carbohydrates, lipids, in the form of peptone, starch, linoleic acid respectively, were tested. In addition, sodium acetate was also tested. Sodium acetate, when dissolved in water, disassociates into acetate and a sodium ion. Acetic acid is the primary substrate that stimulates the enhanced biological phosphorus removal process.

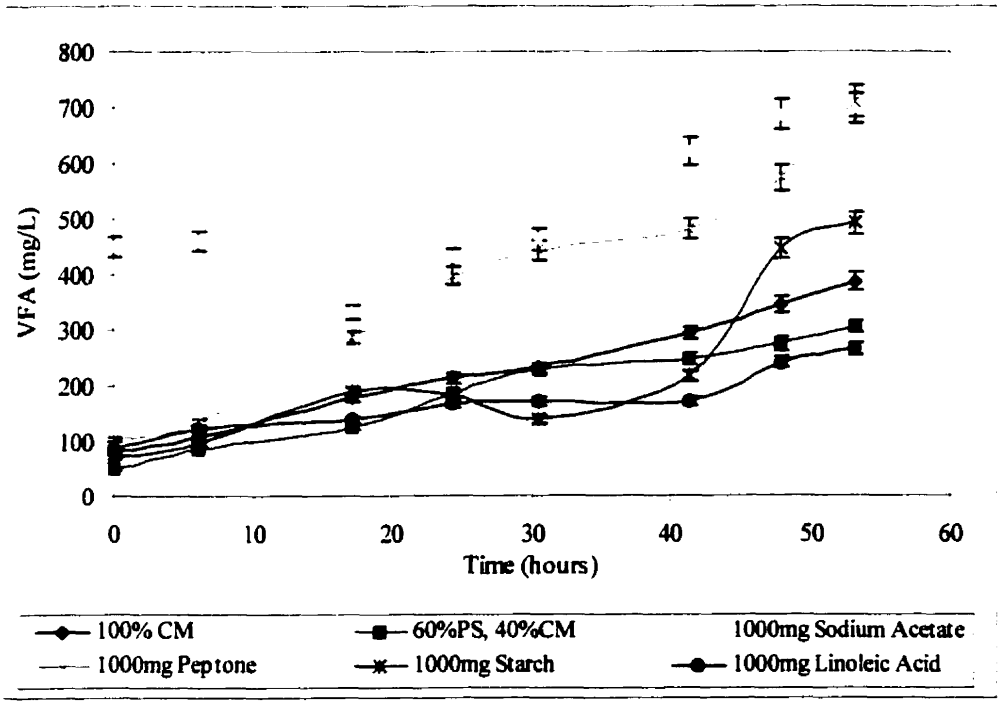


Figure 4.25 – Effect of Different Substrates on VFA Production in Batch Experiment

Figure 4.25 depicts the results of Run 3. Of the three substrates tested, Figure 4.25 shows that the addition of 1000mg of peptone to a sample of 100% complete mix sludge doubled the production rate of VFAs produced when compared to the positive control batch reactor. The addition of 1000mg of starch also enhanced the production of VFAs when compared to the control, however to a lesser extent than the peptone. Given that peptone stimulated the production of VFA in the batch system this would suggest that a high proteins content in influent wastewater to a full-scale system should stimulate VFA production.

The sodium acetate aided batch reactor was expected to closely parallel the

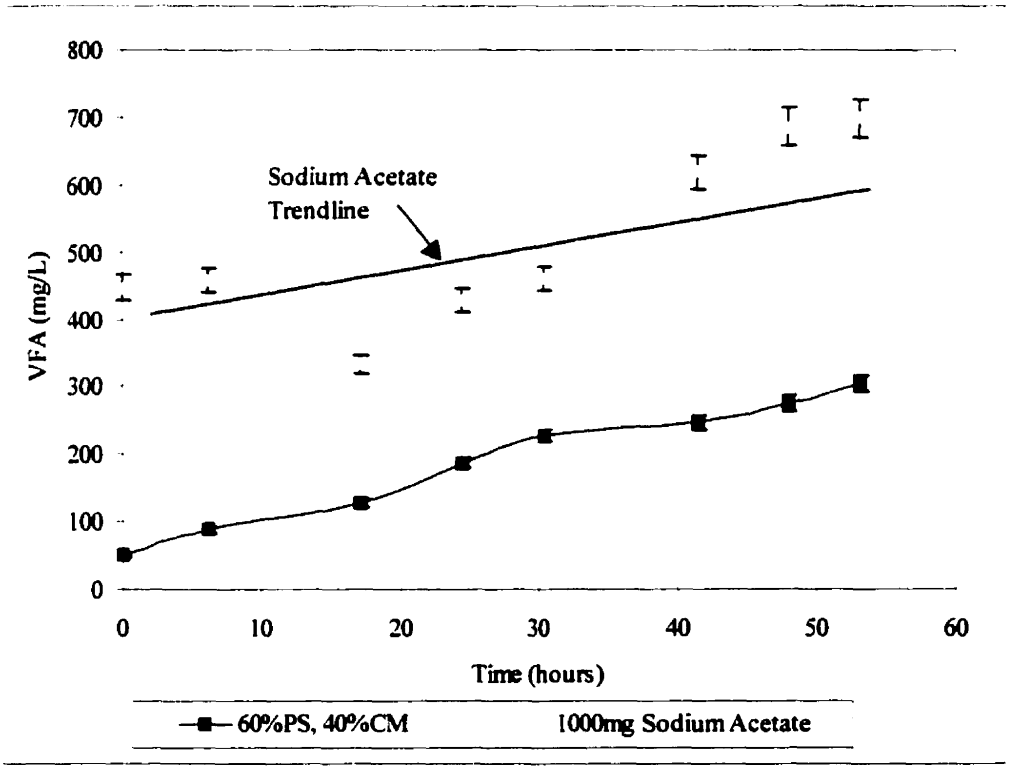


Figure 4.26 – Comparison of the Control Batch Reactor with the Sodium Acetate added Batch Reactor

production of VFAs in the control batch reactor although starting at a higher initial concentration of VFAs. Adding 1000mg of sodium acetate to a batch reactor of volume 1150ml should produce approximately 377mg/L of VFA. This concentration of VFAs is in addition to the VFAs already present in the batch reactor. This measured concentration is assumed to be similar to the amount measured in the control batch reactor, 74 mg/L. The initial concentration of VFAs in the sodium acetate added batch reactor should be near 458mg/L (74+377 mg/L), this is comparable to a measured value of 439 mg/L. However, the drop in the VFAs concentration at a time of 20 hours was inconsistent with the expected results. Figure 4.26 shows a comparison of the VFA production in the control and sodium acetate enhanced batch reactors. Figure 4.26 shows the expected sodium acetate batch reactor trendline drawn through the sodium acetate aided batch reactor data points. This trendline parallels the production of VFAs in the control batch reactor. However, this trendline does not represent the true conditions in the batch reactor. Adding 1000mg of sodium acetate to a batch reactor containing 100% CM sludge resulted in the measured concentration of VFA initially decreasing until the 20-hour mark. Given that acetic acid or acetate is a fermentative end-product of acidogenesis (see Figure 2.4), if it is present at a high level it may act to inhibit the production of VFAs. This process is known as catabolite repression. The initial concentration of acetate present inhibits further production of acetic acid. At the 20-hour mark a quantity of the acetate has been consumed, catabolite repression ceases, and the production of acetic acid begins.

Given the results of Run #2, the batch reactor containing 60% TPS and 40% CM was expected to produce a greater concentration of VFAs than the control batch reactor

containing 100% CM. Figure 4.25 demonstrates that this was not the case. One possible explanation is that a change in the composition of substrate in the primary sludge, given that fermenter bacteria are capable of using only specific substrates, may have caused anomalous results. Table 4.4 illustrates the initial and final measured VFA concentrations of the 60%TPS, 40%CM batch reactors and the 100%CM batch reactors in both Run #2 and Run #3.

Table 4.4 – Comparison of Initial and Final VFA Concentrations in Complete Mix and 60%TPS, 40% CM Sludge for Run #2 and 3

VFA Concentration	Run # 2		Run # 3	
mg/L	Initial	Final	Initial	Final
60%TPS/40%CM	98	353	49.1	305
100% CM	113	187.5	81.6	385.6

The above table shows the production of VFA in the batch reactors containing 60%TPS, 40%CM was similar for Run #2 and Run #3. However, the final measured VFA concentration for the 100% CM batch reactor in Run #3 is double the concentration measured in Run #2. This suggests that a substantial volume of substrate may have been present in the complete mix fermenter sludge sample taken from the full-scale system. In Run #2 and #3 the initial VFA concentrations are similar for both 100% CM batch reactors. However, in the 60%TPS, 40%CM batch reactor, Run #2 contained close to double the concentration of VFAs present in Run #3. This suggests a change in the composition of the thickened primary sludge. The production of VFAs in both the 100% CM and 60% TPS, 40% CM batch reactors was re-tested in Run #4.

4.2.4 THE EFFECT OF DIFFERENT CHEMICAL INHIBITORS

This run tested the effect of different chemical inhibitors on VFA production. . All batch reactors were assumed to have similar solids concentrations. The positive control batch reactor contained a 60%TPS, 40%CM sludge combination. The remaining batch reactors contained a 60%TPS, 40%CM sludge combination and the specified dose of the inhibitor being tested (see Table 3.3). It was important that the positive control be a known producer of substantial quantities of VFAs. Two inhibitors of anaerobic metabolism, Sodium Citrate and Sodium Bisulphite, and one inhibitor of aerobic metabolism, Potassium Cyanide, were tested (Cruegar and Cruegar, 1990) (Stanbury, 1995) (Lehninger, 1982). In addition, the substrate addition peptone was re-tested. An important feature of this run was the calculation of the dose of inhibitor to be added. This dose was calculated based on the published lethal dose that is capable of killing 50% of the organisms (LD_{50}). This number is generally based on a population of rats or mice. However, to translate the LD_{50} from rats to bacteria the LD_{50} value was doubled to compensate for the high biomass present in the fermentation system (see Table 3.3 for doses added). The results of this run are shown in Figure 4.27. As Figure 4.27 shows, each of the three chemical inhibitors tested slowed the VFA production rates. Each of the four batch reactors was initially at similar VFA concentrations. However, the last measurement taken in each of the four batch reactors shows that the positive control has produced at least 100mg/L more VFAs than the inhibited batch reactors.

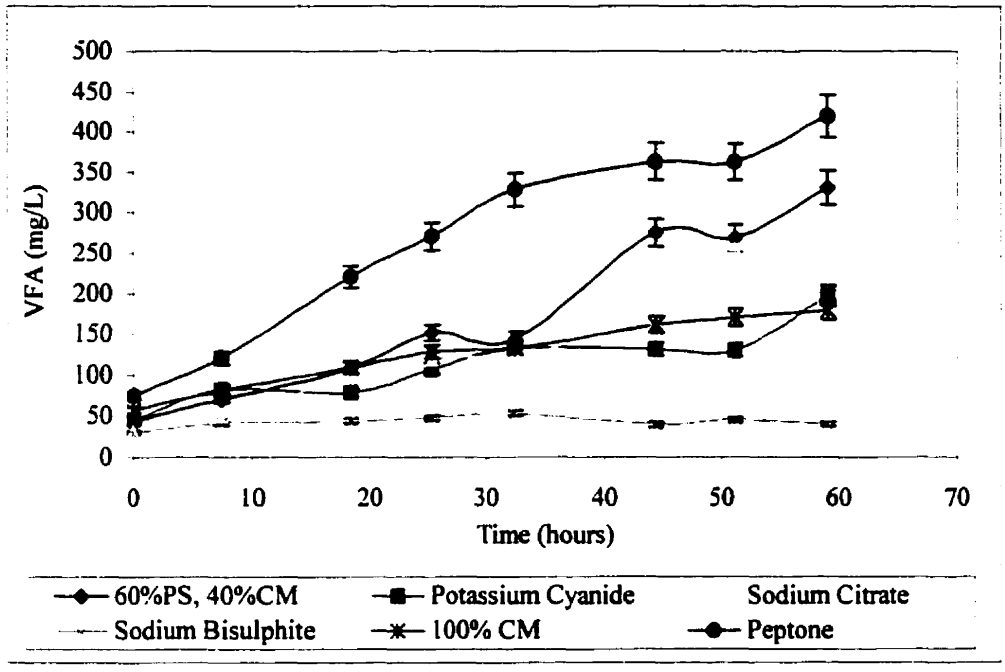


Figure 4.27 - Effect of Different Chemical Inhibitors on VFA Production in Batch Experiments

Sodium bisulphite completely inhibits VFA production. The initial and final values for the measured VFA concentration were 29.8 and 39.9 mg/L respectively. The batch reactors containing the aerobic inhibitor, potassium cyanide, and the anaerobic inhibitor, sodium citrate, exhibited similar VFA production to that of the positive control batch reactor until the 32-hour mark. At this point, the VFA production in each of these batch reactors containing potassium cyanide and sodium citrate slowed considerably when compared to the positive control batch reactor. This suggests that these inhibitors were effectively blocking a step in a required metabolic pathway in the VFA production process. The final measured VFA concentration of the control was 331 mg/L, compared to a final concentration of 196 mg/L in the potassium cyanide added batch reactor and

220 mg/L in the sodium citrate added batch reactor. It is also interesting to note that both of the aforementioned inhibitors slowed the VFA production process to the same level of VFA production produced by the batch reactor containing 100% biomass or complete mix sludge. Given that both the aerobic and anaerobic inhibitors tested had a negative effect on VFA production, wastewater effluent from industrial plants that utilize these or similar chemicals in their treatment processes should be avoided.

The addition of peptone to a sample of 100% CM sludge doubled the rate of VFA production when compared to the 100% CM control batch reactor. This confirms the results of Run #3.

4.2.5 THE EFFECT OF DIFFERENT ANTIBIOTIC INHIBITORS

This run tested the effect of different antibiotics on VFA production with all batch reactors being of equal solids concentration. The antibiotics were added to batch reactors containing a 60% TPS, 40% CM sludge combination. Again, as in Section 4.2.4, it was important that the control be a known producer of substantial quantities of VFAs. Several groups of antimicrobial agents were tested: from the group β-Lactams, enicillin G and from the sub-group Carbapenems, imipenem; from the group Sulfonamides, sulfapyridine; and from the group Aminoglycosides, tobramycin. Each of the antimicrobial agents tested were known inhibitors of anaerobic metabolism in microorangims. The quantity or dose added to each batch reactor was twice the published LD_{50} value (see Section 4.2.4 for a definition of LD_{50}). Actual dosage values are shown in Table 3.3. The results of this run are shown in Figure 4.28.

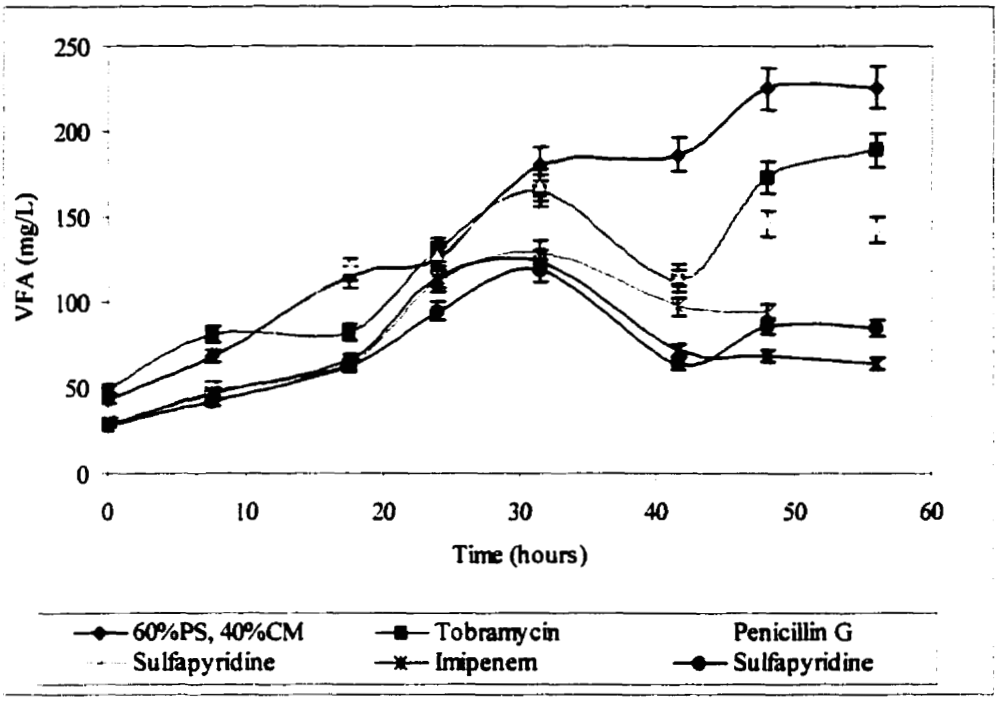


Figure 4.28 - Effect of Different Antibiotic Inhibitors on VFA Production in Batch Experiments

As Figure 4.28 shows, each of the antibiotic batch reactors exhibits a slower rate of VFA production than the control. Therefore, each of the inhibitors impedes the VFA production process by one or more means. The addition of imipenem caused the most significant reduction in VFA production. While this trend initially showed a reasonable rate of VFA production, similar to the control, at 30 hours, VFA production ceased and instead large quantities VFAs were consumed. Imipenem acts by binding to the penicillin binding proteins, and disrupts bacterial cell wall synthesis. In some cases, it causes death in susceptible bacteria.

The addition of sulfapyridine was tested using two different doses (see Table 3.3) in order to account for discrepancies in published LD_{50} values. Regardless however of

the quantity added, the degree of inhibited VFA production was nearly identical. Again, like imipenem, the trend initially showed a reasonable rate of VFA production that ceased at the 30-hour mark and from herein VFAs were depleted. Sulfonamides, the group to which sulfapyridine belongs, are structural analogs and competitors of para-aminobenzoic acid (PABA). PABA is a important link in the synthesis of folic acid. The presence of sulfonamides prevent normal bacterial utilization of PABA. Susceptible organisms are those which synthesize their own folic acid.

When Penicillin G was added to the 60% TPS, 40% CM the VFA production rate was reduced however, this did not occur until the 30 hour mark. At this point the production rate, when compared to the control, was retarded. Penicillin G acts by inhibiting cell wall synthesis, more specifically the formation of peptidoglycan that is a key component in cell walls. The addition of Penicillin G may also result in the death of susceptible bacteria. The synthesis of peptidoglycan is a three-stage process. It is the last phase of this process that is inhibited by the action of Penicillin G. Specifically, Penicillin G targets the transpeptidase and incorporates itself into the penicilloyl enzyme. However, Penicillin G also targets penicillin-binding proteins. In this case, inhibition is similar to the process described by the addition of imipenem.

Having the least affect on VFA production was the addition of Tobramycin. The production of VFAs in the batch reactor containing Tobramycin was slowed to a much lesser degree and, was only notable at the 40-hour mark. Tobramycin, like all aminoglycosides, acts by inhibiting or disrupting protein synthesis. It causes the misreading and potentially early termination of translation of mRNA. (Compendium of Pharmaceuticals and Specialties, 1998) (Stedmens Medical Dictionary, 1995).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The operational and environmental parameters studied over the course of this research demonstrated a clear effect on VFA production. Based on the results of this research project the following conclusions can be drawn:

1. Variations in HRT have a precise effect on VFA production. The production of VFAs at the Bonnybrook Wastewater Treatment Plant is maximized at an HRT of 18.4 hr. VFA production at Bonnybrook was lower at higher HRTs. The measured concentration of VFAs was highest at an HRT of 36.7 hr.
2. The external air temperature affects the sample temperature, which in turn affects the rate of VFA production. As air temperature increased, from 15 °C to 30 °C, there was a concomitant increase in VFA production.
3. The measurement of pH may be used as an indicator of either an increase or decrease in the concentration of acids present in the fermentation system. A decrease in pH is indicative of a greater concentration of VFAs. The decrease in pH in the experimental train from Run #2 to Run #3, 6.60 to 6.11 respectively, indicates a greater concentration of acids.
4. While the solids concentration of the fermentation system was constant throughout this full-scale experiment, a decrease in HRT resulted in a greater

volume of dissolved organics. Given that it is these organics that serve as substrate for the fermenter bacteria, the VFA production normalized to biomass was shown to be greatest at an HRT of 18.4 hours.

5. Protein is the best substrate for VFA production compared to lipids and carbohydrates.
6. The optimum level of VFA production in the bench-scale system, with no external substrates added, was found using combinations of 60%TPS and 40% CM up to 100% TPS.
7. All chemical and antibiotic inhibitors tested had a negative effect on VFA production to varying degrees. The addition of Sodium Bisulphite had the most significant negative effect on VFA production. The batch reactor containing Sodium Bisulphite showed no VFA production over a 50-hour test period. Imipenem showed the most significant reduction in VFA production of the antibiotics examined.

5.2 RECOMMENDATIONS

Consideration for further research is suggested to focus on the following subject areas:

1. The effect of SRT on the VFA production process in a full-scale fermentation system should be investigated. The SRT variable was held constant throughout this experiment. A study on the role SRTs plays in the VFA production may provide significant information on the optimal operating conditions to maximize VFA production.
2. This full-scale investigation should be extended in terms of the length of each run and the range of HRTs tested. A period of one month was used as a basis for this study however, given the external stresses placed on a full-scale system, an extended run time may provide additional information. In addition, testing of a greater range of HRT values will help further optimize VFA production.
3. The sensitivity of the EBPR process to various substrates and feed composition needs to be examined. In addition, the composition of influent wastewater should be explored in terms of the variety of substrates and inhibitors that may be present.
4. Further research is required to examine the method by which inhibitors effect VFA production.

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APPENDIX A

FULL-SCALE EXPERIMENT
RAW DATA

TABLE A1 - Measured VFA Concentrations of Run #1

	VFA Concentration						VFA Production	
	Supernatant		Recycle/Waste		Complete Mix		Supernatant	
	East	West	East	West	East	West	East	West
Date	Total mg/L	Total mg/L	Total mg/L	Total mg/L	Total mg/L	Acetic mg/L	Total kg/d	Total kg/d
22-Apr-98	172.5	125	277.7	159.1	157	122.2	310.5	225
24-Apr-98	120.6	139.2	259.4	194.7	142.8	127.5	217.08	250.56
26-Apr-98	121.9	122.6	203.7	205.3	109.2	132.6	219.42	220.68
28-Apr-98	132.4	119.3	160.7	141.1	117.8	114.5	238.32	214.74
30-Apr-98	137.5	111	169.3	158.2	131.4	181.5	247.5	199.8
2-May-98	136.1	151.9	195.3	142	120.2	198.4	244.98	273.42
4-May-98	129.9	136.2	231.7	201.9	151.2	178.1	233.82	245.16
9-May-98	183.9	195.2	243	259.5	148.1	162	331.02	351.36
10-May-98	171.8	175.9	308.2	332.2	146.2	127.2	309.24	316.62
12-May-98	231.7	250	269.8	265.6	172.8	159.8	417.06	450
14-May-98	218.1	253.6	343.2	361.7	161.1	189.2	392.58	456.48
16-May-98	223.9	239.6	346.6	390.1	231.9	226.7	403.02	431.28
19-May-98	239.6	253.2	282.1	269.7	165.5	180.9	431.28	455.76
20-May-98	237.8	298.1	401.4	371.5	176.8	176	428.04	536.58
21-May-98	267	270.4	389.8	368.1	182.6	178.3	480.6	486.72
22-May-98	263.8	263.9	342.2	301.3	209.2	191.2	474.84	475.02
23-May-98	226.9	261.7	369.8	345.2	130	185.9	408.42	471.06
24-May-98	226.5	233.7	292.9	308	179.6	205.4	407.7	420.66
25-May-98	230.6	250.5	330.2	399.9	196.1	217.8	415.08	450.9
26-May-98	225.2	266.5	297	369.8	230.4	200.7	405.36	479.7
27-May-98	240.6	299.4	321.8	416.6	196.9	247.6	433.08	538.92
28-May-98	248.3	287	314.7	433.2	192.3	254.8	446.94	516.6
29-May-98	200.6	245.4	367.3	395	202.6	225.47	361.08	441.72
30-May-98	233.4	271.5	326.7	412.6	180.14	216.95	420.12	488.7

TABLE A2 - Measured VFA Concentrations of Run #2

	VFA Concentration						VFA Production	
	Supernatant		Recycle/Waste		Complete Mix		Supernatant	
	East	West	East	West	East	West	East	West
Date	Total mg/L	Total mg/L	Total mg/L	Total mg/L	Total mg/L	Acetic mg/L	Total kg/d	Total kg/d
19-Jun-98	301.93	369.84	451.85	550.92	240.2	307.98	543.47	887.62
22-Jun-98	298.6	378.9	478.13	620.56	280.6	310.2	537.48	909.36
24-Jun-98	291.3	395.23	510.62		306.05	317.03	524.34	948.55
26-Jun-98	370.51	390.35	567.19				666.92	936.84
28-Jun-98	334.38	351.77		544.97	352.96		601.88	844.25
30-Jun-98	405.56	261.41		434.27	362.64	251.46	730.01	627.38
2-Jul-98	408.04	309.16	583.67	447.74	363.56	294.43	734.47	741.98
6-Jul-98	335.69	271.46	550.94	462.98	311.4	301.87	604.24	651.50
8-Jul-98	286.25	369.7	416	465.52	271.7	320.88	515.25	887.28
9-Jul-98	234.77	372.59	510.68	578.67	308.5	353.37	422.59	894.22
10-Jul-98	323.4	421.8	433.4	487.3	276.7	343.4	582.12	1012.32
11-Jul-98	298.8	341.4	380.7	454.7	255.1	319.7	537.84	819.36
12-Jul-98	297	283.9	369.8	356.7	252.8	268.5	534.60	681.36
13-Jul-98	243.7	214.3	306	296.8	226.4	232.4	438.66	514.32
14-Jul-98	268.8	241	340.8	360.5	235.2	215.2	483.84	578.40
15-Jul-98	240.1	213.1	418.1	422.5	261.7	218.5	432.18	511.44
16-Jul-98	296.7	271.3	401.7	479.9	238.7	225.1	534.06	651.12
17-Jul-98	292.1	294.7	471.8	441	281.8	263.5	525.78	707.28
18-Jul-98	296.4	275.9	344.5	377.1	261.9	216.3	533.52	662.16
19-Jul-98	306.5	295.43	389.21	409.3	272.14	251.4	551.70	709.03
20-Jul-98	318.98	303.9	427	459.36	280.96	273.35	574.16	729.36

TABLE A3 - Measured VFA Concentrations of Run #3

	VFA Concentration						VFA Production	
	Supernatant		Recycle/Waste		Complete Mix		Supernatant	
	East	West	East	West	East	West	East	West
Date	Total mg/L	Total mg/L	Total mg/L	Total mg/L	Total mg/L	Acetic mg/L	Total kg/d	Total kg/d
25-Jul-98	413.3	721.8	425.4	682.8	325.7	632.8	743.94	866.16
27-Jul-98	422.8	668.2	499.1	685	390.9	569.4	761.04	801.84
29-Jul-98	407.37	669.47	378.51	599.06	353.81	515.62	733.27	803.36
31-Jul-98	388.3	610.75	482	630.71	339.56	491	698.94	732.90
2-Aug-98	373.14	594.28	452.62	567.29	320.66	473.97	671.65	713.14
4-Aug-98	362.41	569.76	416.43	509.37	307.25	423.12	652.34	683.71
5-Aug-98	375.28	597.68	436.6	590.01	319.72	464.48	675.50	717.22
6-Aug-98	399.41	624.57	461.09	578.91	333.19	454.5	718.94	749.48
7-Aug-98	392.17	604.32	460.12	596.03	320.54	455.68	705.91	725.18
8-Aug-98	352.6	542.86	387.91	552.12	277.48	445.76	634.68	651.43
9-Aug-98	361.66	588.22	441.72	538.36	303.53	462.47	650.99	705.86
10-Aug-98	358.6	576.82	411.86	532.08	336.65	474.27	645.48	692.18
11-Aug-98	334.82	570.76	459.4	673.77	270.76	441.5	602.68	684.91
12-Aug-98	320.69	597.61	408.84	605.74	286.67	492.16	577.24	717.13
13-Aug-98	357.6	551.9	399.5	573	289.5	437.4	643.68	662.28
14-Aug-98	380.4	517.9	431.3	559.2	293.3	436.5	684.72	621.48
15-Aug-98	361.6	566.06	403.5	540.5	291.34	435.4	650.88	679.27
16-Aug-98	394	553.6	429	590.9	311.8	450.7	709.20	664.32
17-Aug-98	292.1	528.1	413.5	575.4	333.1	468.9	525.78	633.72
18-Aug-98	354.7	619	429.8	610.2	302.5	469.7	638.46	742.80
19-Aug-98	325.1	584.1	389.7	615.8	294.5	416.3	585.18	700.92
20-Aug-98	407.7	589	416.8	586.1	324.4	444.4	733.86	706.80

TABLE A4 - Measured Supernatant Line Total Solids of Run #1

	Supernatant Line					
Date	Locale	Dish	Wet	Dry	%Solids	Solids
		g	g	g		mg/L
22-Apr-98	East	2.3040	40.09	2.3908	0.2297	2170.0
	West	2.3040	39.64	2.3526	0.1302	1215.0
24-Apr-98	East	2.3465	39.83	2.3963	0.1329	1245.0
	West	2.3087	39.64	2.3559	0.1264	1180.0
26-Apr-98	East	2.2979	40.05	2.3435	0.1208	1140.0
	West	2.2921	40.05	2.3826	0.2397	2262.5
28-Apr-98	East	2.2952	40.36	2.3438	0.1277	1215.0
	West	2.2806	40.33	2.3239	0.1138	1082.5
30-Apr-98	East	2.2926	40.35	2.3435	0.1337	1272.5
	West	2.3024	40.09	2.3506	0.1276	1205.0
2-May-98	East	2.2982	40.53	2.3470	0.1276	1220.0
	West	2.2963	40.40	2.3469	0.1328	1265.0
4-May-98	East	2.3350	41.29	2.3958	0.1561	1520.0
	West	2.3542	41.15	2.4063	0.1343	1302.5
8-May-98	East	2.3386	41.56	2.3905	0.1323	1297.5
	West	2.3394	41.08	2.3959	0.1458	1412.5
9-May-98	East	2.3474	40.52	2.4006	0.1394	1330.0
	West	2.3515	40.51	2.4099	0.1530	1460.0
10-May-98	East	2.3367	40.77	2.3896	0.1376	1322.5
	West	2.3412	40.88	2.4088	0.1754	1690.0
12-May-98	East	2.3198	40.19	2.3719	0.1376	1302.5
	West	2.3361	39.99	2.3925	0.1498	1410.0
14-May-98	East	2.3085	40.11	2.3615	0.1402	1325.0
	West	2.3593	40.13	2.4173	0.1536	1450.0
16-May-98	East	2.3000	39.94	2.3585	0.1554	1462.5
	West	2.3436	39.55	2.4018	0.1564	1455.0
19-May-98	East	2.3501	40.95	2.4061	0.1451	1400.0
	West	2.3446	40.67	2.4050	0.1576	1510.0
20-May-98	East	2.3252	40.56	2.3803	0.1441	1377.5
	West	2.3492	40.01	2.4043	0.1463	1377.5
21-May-98	East	2.3460	40.78	2.3997	0.1397	1342.5
	West	2.3252	40.79	2.3809	0.1448	1392.5
22-May-98	East	2.3403	40.56	2.4029	0.1638	1565.0
	West	2.3156	40.13	2.3691	0.1415	1337.5
23-May-98	East	2.3119	40.92	2.3677	0.1445	1395.0
	West	2.3051	40.89	2.3646	0.1542	1487.5
24-May-98	East	2.2824	40.50	2.3378	0.1450	1385.0
	West	2.3385	40.65	2.3963	0.1509	1445.0
25-May-98	East	2.3408	40.80	2.4024	0.1602	1540.0
	West	2.3501	40.45	2.4106	0.1588	1512.5
26-May-98	East	2.2833	40.66	2.3390	0.1451	1392.5
	West	2.2857	40.41	2.3452	0.1561	1487.5
27-May-98	East	2.2923	40.60	2.3613	0.1801	1725.0
	West	2.3478	40.86	2.4101	0.1618	1557.5
28-May-98	East	2.3466	41.13	2.4025	0.1441	1397.5
	West	2.3494	40.83	2.4122	0.1632	1570.0
29-May-98	East	2.3368	41.37	2.3942	0.1471	1435.0
	West	2.3494	40.83	2.4122	0.1632	1570.0
30-May-98	East	2.2714	40.82	2.3350	0.1650	1590.0
	West	2.3125	40.95	2.3781	0.1698	1640.0

TABLE A5 - Measured Supernatant Line Total Solids of Run #2

	Supernatant Line					
Date	Locale	Dish g	Wet g	Dry g	%Solids	Solids mg/L
19-Jun-98	East	2.3657	40.62	2.4218	0.1467	1402.5
	West	2.3509	40.92	2.4079	0.1478	1425.0
22-Jun-98	East	2.3623	40.93	2.4206	0.1512	1457.5
	West	2.3231	40.87	2.3809	0.1499	1445.0
24-Jun-98	East	2.3573	41.00	2.4283	0.1837	1775.0
	West	2.3517	41.13	2.4091	0.1480	1435.0
26-Jun-98	East	2.3046	40.87	2.4683	0.4245	4092.5
	West	2.3338	41.16	2.3905	0.1460	1417.5
28-Jun-98	East	2.3604	41.50	2.4370	0.1957	1915.0
	West	2.3475	41.10	2.3998	0.1350	1307.5
30-Jun-98	East	2.3551	41.41	2.4276	0.1856	1812.5
	West	2.3677	41.59	2.4168	0.1252	1227.5
2-Jul-98	East	2.3333	40.83	2.4325	0.2577	2480.0
	West	2.3256	41.36	2.3791	0.1371	1337.5
4-Jul-98	East	2.3224	40.99	2.4047	0.2128	2057.5
	West	2.3250	41.57	2.3810	0.1427	1400.0
5-Jul-98	East	2.3264	41.34	2.4071	0.2069	2017.5
	West	2.3236	41.20	2.3805	0.1464	1422.5
6-Jul-98	East	2.3203	41.33	2.3826	0.1597	1557.5
	West	2.3250	41.68	2.3817	0.1441	1417.5
8-Jul-98	East	2.3396	40.82	2.4725	0.3454	3322.5
	West	2.3296	40.90	2.4026	0.1893	1825.0
9-Jul-98	East	2.3274	41.08	2.3854	0.1497	1450.0
	West	2.3255	41.03	2.3890	0.1641	1587.5
10-Jul-98	East	2.3148	41.34	2.4216	0.2737	2670.0
	West	2.3301	40.82	2.3983	0.1772	1705.0
11-Jul-98	East	2.3059	41.04	2.4585	0.3940	3815.0
	West	2.3180	41.10	2.3915	0.1895	1837.5
12-Jul-98	East	2.3282	41.09	2.4742	0.3767	3650.0
	West	2.3375	41.56	2.3971	0.1520	1490.0
13-Jul-98	East	2.3311	41.00	2.4316	0.2599	2512.5
	West	2.3287	41.25	2.3852	0.1452	1412.5
14-Jul-98	East	2.3291	40.72	2.4292	0.2607	2502.5
	West	2.3413	41.02	2.3967	0.1432	1385.0
15-Jul-98	East	2.3155	41.38	2.3912	0.1938	1892.5
	West	2.3274	40.89	2.3821	0.1418	1367.5
16-Jul-98	East	2.3502	41.23	2.4586	0.2788	2710.0
	West	2.3329	42.16	2.3896	0.1424	1417.5
17-Jul-98	East	2.3112	41.62	2.4027	0.2328	2287.5
	West	2.3306	41.63	2.3854	0.1394	1370.0
18-Jul-98	East	2.3197	41.60	2.3944	0.1902	1867.5
	West	2.3365	41.36	2.3904	0.1381	1347.5
20-Jul-98	East	2.3290	41.54	2.3974	0.1744	1710.0
	West	2.3215	41.27	2.3704	0.1256	1222.5

TABLE A6 - Measured Supernatant Line Total Solids of Run #3

	Supernatant Line					
Date	Locale	Dish g	Wet g	Dry g	%Solids	Solids mg/L
25-Jul-98	East	2.3077	41.19	2.4088	0.2600	2527.5
	West	2.3030	41.16	2.4273	0.3199	3107.5
27-Jul-98	East	2.3291	41.22	2.4000	0.1822	1771.5
	West	2.3130	40.94	2.3898	0.1988	1920.0
29-Jul-98	East	2.3369	40.65	2.4116	0.1950	1867.5
	West	2.3475	41.22	2.4186	0.1829	1777.5
31-Jul-98	East	2.3355	41.40	2.3961	0.1551	1515.0
	West	2.3482	41.44	2.4291	0.2069	2022.5
2-Aug-98	East	2.3519	41.24	2.4253	0.1887	1835.0
	West	2.3311	41.30	2.4149	0.2150	2095.0
4-Aug-98	East	2.3159	41.30	2.4073	0.2345	2285.0
	West	2.3218	40.86	2.3846	0.1630	1570.0
5-Aug-98	East	2.3276	41.04	2.3973	0.1800	1742.5
	West	2.3176	40.78	2.3888	0.1851	1780.0
6-Aug-98	East	2.3296	41.61	2.3947	0.1657	1627.5
	West	2.3304	41.23	2.3987	0.1756	1707.5
7-Aug-98	East	2.3208	40.79	2.3745	0.1396	1342.5
	West	2.3313	40.46	2.4028	0.1875	1787.5
8-Aug-98	East	2.3371	40.70	2.3843	0.1230	1180.0
	West	2.3313	41.21	2.3984	0.1726	1677.5
9-Aug-98	East	2.3376	41.06	2.3979	0.1557	1507.5
	West	2.3469	40.71	2.4189	0.1877	1800.0
10-Aug-98	East	2.3331	40.86	2.3875	0.1412	1360.0
	West	2.3393	40.53	2.4027	0.1660	1585.0
11-Aug-98	East	2.3438	41.47	2.3908	0.1201	1175.0
	West	2.3450	40.76	2.4127	0.1762	1692.5
12-Aug-98	East	2.3270	41.25	2.3778	0.1305	1270.0
	West	2.3300	41.15	2.3951	0.1677	1627.5
13-Aug-98	East	2.2907	41.10	2.3372	0.1198	1162.5
	West	2.3159	41.14	2.3815	0.1690	1640.0
14-Aug-98	East	2.3346	41.36	2.3810	0.1189	1160.0
	West	2.3213	40.79	2.4021	0.2100	2020.0
15-Aug-98	East	2.3208	40.77	2.3920	0.1852	1780.0
	West	2.3291	40.98	2.4026	0.1902	1837.5
16-Aug-98	East	2.3424	40.90	2.3991	0.1471	1417.5
	West	2.3267	40.74	2.4000	0.1908	1832.5
17-Aug-98	East	2.3421	41.40	2.3886	0.1191	1162.5
	West	2.3279	40.83	2.4010	0.1899	1827.5
18-Aug-98	East	2.3142	41.06	2.3594	0.1167	1130.0
	West	2.3155	41.16	2.3885	0.1879	1825.0
19-Aug-98	East	2.3252	41.04	2.3889	0.1645	1592.5
	West	2.3134	41.46	2.3637	0.1285	1257.5
20-Aug-98	East	2.3208	42.00	2.3759	0.1389	1377.5
	West	2.3291	40.70	2.3981	0.1798	1725.0

TABLE A7 - Measured Complete Mix Line Total Solids of Run #1

	Complete Mix Line					
Date	Locale	Dish g	Wet g	Dry g	%Solids	Solids mg/L
22-Apr-98	East	2.3259	43.92	2.8971	1.5440	14280.0
	West	2.3058	44.12	2.7875	1.2943	12042.5
24-Apr-98	East	2.3583	44.14	2.8706	1.3778	12807.5
	West	2.3498	44.22	2.8901	1.4496	13507.5
26-Apr-98	East	2.3524	44.40	2.6790	0.8721	8165.0
	West	2.3030	44.00	2.6309	0.8839	8197.5
28-Apr-98	East	2.2835	44.60	2.8015	1.3733	12950.0
	West	2.3652	44.54	2.7713	1.0807	10152.5
30-Apr-98	East	2.3525	44.95	2.8948	1.4271	13557.5
	West	2.3270	44.98	3.2042	2.3051	21930.0
2-May-98	East	2.3067	44.66	2.8436	1.4221	13422.5
	West	2.3421	44.95	2.9253	1.5344	14580.0
4-May-98	East	2.3421	45.80	2.8350	1.2684	12322.5
	West	2.3302	45.80	2.8350	1.2986	12620.0
8-May-98	East	2.3277	45.39	2.9798	1.6954	16302.5
	West	2.3076	45.85	2.9484	1.6454	16020.0
9-May-98	East	2.3559	44.57	3.0296	1.7910	16842.5
	West	2.2976	44.58	3.1033	2.1380	20142.5
10-May-98	East	2.3563	45.14	2.9807	1.6352	15610.0
	West	2.3251	45.39	3.0105	1.7818	17135.0
12-May-98	East	2.3270	44.77	3.0087	1.8013	17042.5
	West	2.3666	44.42	3.0319	1.7763	16632.5
14-May-98	East	2.3526	44.77	3.0243	1.7761	16792.5
	West	2.3040	43.31	2.9466	1.7650	16065.0
16-May-98	East	2.3540	44.47	3.0345	1.8138	17012.5
	West	2.3221	43.68	2.9060	1.5884	14597.5
19-May-98	East	2.3220	45.16	2.9337	1.5997	15292.5
	West	2.3432	44.89	2.9390	1.5700	14895.0
20-May-98	East	2.3675	44.32	2.9878	1.6606	15507.5
	West	2.3476	44.41	2.9632	1.6432	15390.0
21-May-98	East	2.3207	44.91	2.9714	1.7128	16267.5
	West	2.3112	44.90	2.9963	1.8034	17127.5
22-May-98	East	2.3425	44.01	3.1636	2.2151	20527.5
	West	2.2970	44.34	2.9672	1.7898	16755.0
23-May-98	East	2.3068	45.11	2.9394	1.6558	15815.0
	West	2.3148	45.16	3.0872	2.0195	19310.0
24-May-98	East	2.3282	45.04	3.0104	1.7899	17055.0
	West	2.2831	45.18	3.0835	2.0899	20010.0
25-May-98	East	2.3094	44.62	3.1698	2.2815	21510.0
	West	2.3407	44.95	2.9964	1.7250	16392.5
26-May-98	East	2.3511	45.05	3.2976	2.4842	23662.5
	West	2.3037	44.89	2.9676	1.7477	16597.5
27-May-98	East	2.3294	45.08	3.0892	1.9915	18995.0
	West	2.3126	45.47	3.2207	2.3551	22702.5
28-May-98	East	2.3532	45.57	3.1319	2.0164	19467.5
	West	2.3224	45.48	3.2969	2.5273	24362.5
29-May-98	East	2.3238	45.77	3.4307	2.8493	27672.5
	West	2.3448	44.60	3.2721	2.4625	23182.5
30-May-98	East	2.3036	44.55	3.1795	2.3266	21897.5
	West	2.2775	45.57	3.2005	2.3854	23075.0

TABLE A8 - Measured Complete Mix Line Total Solids of Run #2

	Complete Mix Line					
Date	Locale	Dish	Wet	Dry	%Solids	Solids
		g	g	g		mg/L
19-Jun-98	East	2.3614	45.81	3.5018	2.9354	28510.0
	West	2.3593	45.73	3.4286	2.7579	26732.5
22-Jun-98	East	2.3630	44.97	3.2882	2.4342	23130.0
	West	2.3603	45.42	3.3263	2.5116	24150.0
24-Jun-98	East	2.3456	45.79	3.2729	2.3871	23182.5
	West	2.3620	45.51	3.3255	2.4994	24087.5
26-Jun-98	East	2.2933	46.14	3.4045	2.8312	27780.0
	West	2.3456	44.62	3.9571	4.2773	40287.5
28-Jun-98	East	2.3262	45.93	3.2914	2.4745	24130.0
	West	2.3223	45.78	3.4286	2.8469	27657.5
30-Jun-98	East	2.2941	46.42	3.1515	2.1691	21435.0
	West	2.3547	45.85	3.6984	3.4545	33592.5
2-Jul-98	East	2.3242	44.68	3.4306	2.9303	27660.0
	West	2.3302	45.99	3.7605	3.6617	35757.5
4-Jul-98	East	2.3341	45.33	2.9862	1.6983	16302.5
	West	2.3484	45.86	3.2537	2.3265	22632.5
5-Jul-98	East	2.3187	45.87	3.2609	2.4188	23555.0
	West	2.3387	45.65	3.2022	2.2305	21587.5
6-Jul-98	East	2.3453	45.90	3.4313	2.7877	27150.0
	West	2.3450	45.45	3.5271	3.0699	29552.5
8-Jul-98	East	2.3539	44.92	3.4097	2.7808	26395.0
	West	2.3117	45.49	3.7243	3.6615	35315.0
9-Jul-98	East	2.3359	41.14	3.4573	3.2784	28035.0
	West	2.3349	46.00	3.8066	3.7671	36792.5
10-Jul-98	East	2.3195	45.56	3.3788	2.7413	26482.5
	West	2.3042	45.74	3.6166	3.3792	32810.0
11-Jul-98	East	2.3307	45.58	3.3014	2.5115	24267.5
	West	2.3154	45.98	3.5219	3.0883	30162.5
12-Jul-98	East	2.3386	46.05	3.4661	2.8827	28187.5
	West	2.3251	45.84	3.3389	2.6051	25345.0
13-Jul-98	East	2.3460	45.90	3.4400	2.8083	27350.0
	West	2.3311	46.04	3.2943	2.4628	24080.0
14-Jul-98	East	2.3194	45.85	3.4042	2.7864	27120.0
	West	2.3262	45.23	3.2841	2.5007	23947.5
15-Jul-98	East	2.3383	45.54	3.3156	2.5316	24432.5
	West	2.3127	44.98	3.2649	2.5013	23805.0
16-Jul-98	East	2.3322	46.49	3.1916	2.1724	21485.0
	West	2.3380	46.28	3.2356	2.2814	22440.0
17-Jul-98	East	2.3282	45.95	3.1806	2.1843	21310.0
	West	2.3438	45.87	3.2028	2.2066	21475.0
18-Jul-98	East	2.3414	45.69	3.2139	2.2516	21812.5
	West	2.3307	45.86	3.1667	2.1474	20900.0
20-Jul-98	East	2.3164	45.78	3.0924	1.9966	19400.0
	West	2.3379	46.24	3.0890	1.9110	18777.5

TABLE A9 - Measured Complete Mix Line Total Solids of Run #3

	Complete Mix Line					
Date	Locale	Dish g	Wet g	Dry g	%Solids	Solids mg/L
25-Jul-98	East	2.3077	46.00	3.1815	2.2351	21845.0
	West	2.3005	45.53	3.6068	3.3815	32657.5
27-Jul-98	East	2.3330	45.61	3.0605	1.8809	18187.5
	West	2.3507	46.01	3.2072	2.1927	21412.5
29-Jul-98	East	2.3395	45.18	3.0308	1.8077	17282.5
	West	2.3392	46.20	3.1656	2.1048	20660.0
31-Jul-98	East	2.2817	45.54	2.9561	1.7444	16860.0
	West	2.3280	45.27	3.1975	2.2677	21737.5
2-Aug-98	East	2.3133	45.97	2.9975	1.7517	17105.0
	West	2.3166	46.09	3.2190	2.3035	22560.0
4-Aug-98	East	2.3108	45.43	2.9595	1.6840	16217.5
	West	2.3221	45.76	3.0951	1.9902	19325.0
5-Aug-98	East	2.3379	44.98	2.9884	1.7099	16262.5
	West	2.3163	46.25	3.1265	2.0597	20255.0
6-Aug-98	East	2.3294	46.43	2.9754	1.6354	16150.0
	West	2.3542	46.06	3.1427	2.0162	19712.5
7-Aug-98	East	2.3129	45.34	3.0030	1.7958	17252.5
	West	2.3121	44.99	3.0894	2.0413	19432.5
8-Aug-98	East	2.3399	45.36	2.9721	1.6454	15805.0
	West	2.3482	45.76	3.1839	2.1531	20892.5
9-Aug-98	East	2.3090	45.77	2.9706	1.7024	16540.0
	West	2.3215	45.47	3.1337	2.1069	20305.0
10-Aug-98	East	2.3316	45.28	2.9346	1.5724	15075.0
	West	2.3327	46.05	3.0867	1.9275	18850.0
11-Aug-98	East	2.3211	45.98	2.9193	1.5315	14955.0
	West	2.3345	45.47	3.0884	1.9563	18847.5
12-Aug-98	East	2.3175	45.27	2.9096	1.5438	14802.5
	West	2.3074	45.68	3.0742	1.9776	19170.0
13-Aug-98	East	2.3091	46.01	2.9413	1.6168	15805.0
	West	2.3151	45.71	3.0782	1.9669	19077.5
14-Aug-98	East	2.3414	45.57	2.9349	1.5364	14837.5
	West	2.3402	45.44	3.1024	1.9797	19055.0
15-Aug-98	East	2.3298	45.56	2.9456	1.5940	15395.0
	West	2.3336	45.70	3.0542	1.8587	18015.0
16-Aug-98	East	2.3224	45.34	2.9326	1.5883	15255.0
	West	2.3345	46.05	3.1326	2.0403	19952.5
17-Aug-98	East	2.3103	45.68	2.9026	1.5277	14807.5
	West	2.3346	45.64	3.1384	2.0766	20095.0
18-Aug-98	East	2.3195	45.45	2.9386	1.6067	15477.5
	West	2.3176	45.50	3.0748	1.9625	18930.0
19-Aug-98	East	2.3335	46.26	2.9704	1.6195	15922.5
	West	2.3445	45.26	3.0838	1.9294	18482.5
20-Aug-98	East	2.3298	45.86	2.9638	1.6285	15850.0
	West	2.3336	46.44	3.1172	1.9834	19590.0

TABLE A10 - Measured Recycle Line Total Solids of Run #1

	Recycle Line					
Date	Locale	Dish g	Wet g	Dry g	%Solids	Solids mg/L
22-Apr-98	East	2.3265	44.35	4.2760	5.2091	48737.5
	West	2.3187	44.27	3.8607	4.1282	38550.0
24-Apr-98	East	2.2993	44.68	3.9806	4.4500	42032.5
	West	2.3473	44.19	3.5369	3.1940	29740.0
26-Apr-98	East	2.2877	44.00	2.7670	1.2914	11982.5
	West	2.2944	44.49	2.7480	1.2065	11340.0
28-Apr-98	East	2.3373	44.96	3.8852	4.0708	38697.5
	West	2.2828	44.67	3.3648	2.8633	27050.0
30-Apr-98	East	2.2843	44.92	4.1013	4.7769	45425.0
	West	2.3275	44.91	3.9330	4.2268	40137.5
2-May-98	East	2.2772	45.33	3.6326	3.5247	33885.0
	West	2.2706	45.01	3.9414	4.3806	41770.0
4-May-98	East	2.3457	45.45	4.1728	4.7450	45677.5
	West	2.3403	45.43	4.3496	5.2201	50232.5
8-May-98	East				0.0000	0.0
	West	2.3598	46.15	4.4216	5.2608	51545.0
9-May-98	East	2.3204	44.74	4.3495	5.3650	50727.5
	West	2.3222	45.29	4.3532	5.2933	50775.0
10-May-98	East	2.3119	45.58	3.9584	4.2579	41162.5
	West	2.3219	45.64	4.4071	5.3854	52130.0
12-May-98	East	2.3224	44.97	4.2358	5.0288	47835.0
	West	2.3036	45.39	4.3150	5.2260	50285.0
14-May-98	East	2.2981	45.15	4.0514	4.5834	43832.5
	West	2.2916	44.05	4.2706	5.3256	49475.0
16-May-98	East	2.3253	44.59	4.4743	5.7054	53725.0
	West	2.3536	45.20	4.7845	6.3556	60772.5
19-May-98	East	2.3295	45.92	4.4335	5.3960	52600.0
	West	2.3316	45.86	3.9477	4.1513	40402.5
20-May-98	East	2.3448	44.67	4.0890	4.6232	43605.0
	West	2.3361	44.27	4.0193	4.5083	42080.0
21-May-98	East	2.3320	45.70	4.6717	6.0349	58492.5
	West	2.3372	45.98	4.5908	5.7719	56340.0
22-May-98	East	2.2913	45.82	4.5849	5.8916	57340.0
	West	2.3439	44.82	4.5601	5.8509	55405.0
23-May-98	East	2.3072	46.30	4.7977	6.3220	62262.5
	West	2.3166	45.68	4.6923	6.1285	59392.5
24-May-98	East	2.3366	46.16	4.7058	6.0400	59230.0
	West	2.3388	45.91	4.1979	4.7703	46477.5
25-May-98	East	2.3276	44.64	4.7183	6.3390	59767.5
	West	2.3638	45.51	4.3356	5.1152	49295.0
26-May-98	East	2.3038	45.70	4.5471	5.7820	56082.5
	West	2.3534	45.57	4.9004	6.5953	63675.0
27-May-98	East	2.3366	45.01	4.4364	5.5149	52495.0
	West	2.2984	45.40	4.7283	6.3109	60747.5
28-May-98	East	2.3164	45.66	4.8656	6.5794	63730.0
	West	2.3136	45.87	4.9167	6.6818	65077.5
29-May-98	East	2.3164	45.66	4.8656	6.5794	63730.0
	West	2.3136	45.87	4.9167	6.6818	65077.5
30-May-98	East	2.2787	46.45	4.5247	5.6756	56150.0
	West	2.3457	46.27	4.9892	6.7220	66087.5

TABLE A11 - Measured Recycle Line Total Solids of Run #2

	Recycle Line					
Date	Locale	Dish g	Wet g	Dry g	%Solids	Solids mg/L
19-Jun-98	East	2.3421	46.58	5.2094	7.2334	71682.5
	West	2.3778	45.06	5.4045	7.9475	75667.5
22-Jun-98	East	2.3414	46.30	4.7736	6.1793	60805.0
	West	2.3372	45.34	5.5120	8.2668	79370.0
24-Jun-98	East	2.3620	46.12	5.0428	6.8458	67020.0
	West	2.3313	45.77	5.4807	8.1086	78735.0
26-Jun-98	East	2.3030	45.37	4.7702	6.4135	61680.0
	West	2.3003	45.64	5.2906	7.7186	74757.5
28-Jun-98	East	2.3114	45.70	4.7257	6.2240	60357.5
	West	2.3142	45.60	5.2740	7.6506	73995.0
30-Jun-98	East	2.3056	46.52	5.1388	7.1517	70830.0
	West	2.3579	47.05	5.5420	7.9416	79602.5
2-Jul-98	East	2.3246	46.15	5.5658	8.2627	81030.0
	West	2.3444	46.74	5.5890	8.1528	81115.0
4-Jul-98	East	2.3287	46.92	4.5797	5.6285	56275.0
	West	2.3209	45.95	5.4571	8.0352	78405.0
5-Jul-98	East	2.3078	46.65	5.4327	7.8626	78122.5
	West	2.3194	47.22	5.5178	7.9360	79960.0
6-Jul-98	East	2.2973	46.66	6.0440	9.4223	93667.5
	West	2.3440	45.14	5.9231	9.3700	89477.5
8-Jul-98	East	2.3191	46.09	5.3989	7.8621	76995.0
	West	2.3189	46.23	5.2545	7.4673	73390.0
9-Jul-98	East	2.3500	50.40	5.6190	7.5233	81725.0
	West	2.3362	46.02	5.9156	9.1579	89485.0
10-Jul-98	East	2.3268	46.21	5.3491	7.6933	75557.5
	West	2.3156	46.38	5.5010	8.0713	79635.0
11-Jul-98	East	2.3118	45.98	5.0863	7.1014	69362.5
	West	2.3149	46.01	5.2101	7.4052	72380.0
12-Jul-98	East	2.3280	46.15	5.1239	7.1281	69897.5
	West	2.3238	46.43	5.7837	8.7575	86497.5
13-Jul-98	East	2.3240	46.17	5.0458	6.9349	68045.0
	West	2.3246	46.29	4.9569	6.6866	65807.5
14-Jul-98	East	2.3237	46.01	5.0437	6.9587	68000.0
	West	2.3267	47.11	5.2169	7.1923	72255.0
15-Jul-98	East	2.3049	45.18	4.9009	6.7822	64900.0
	West	2.3337	46.17	5.2341	7.3918	72510.0
16-Jul-98	East	2.3379	46.04	4.7520	6.1736	60352.5
	West	2.3400	46.06	5.2911	7.5434	73777.5
17-Jul-98	East	2.3338	44.14	4.0964	4.7372	44065.0
	West	2.3435	46.48	4.6354	5.7967	57297.5
18-Jul-98	East	2.3149	46.00	4.4534	5.4712	53462.5
	West	2.2971	47.60	5.0600	6.7877	69072.5
20-Jul-98	East	2.3344	46.09	4.7309	6.1202	59912.5
	West	2.3319	46.07	4.7328	6.1342	60022.5

TABLE A12 - Measured Recycle Line Total Solids of Run #3

	Recycle Line					
Date	Locale	Dish g	Wet g	Dry g	%Solids	Solids mg/L
25-Jul-98	East	2.3482	45.54	4.4438	5.4299	52390.0
	West	2.3406	45.10	4.3147	4.6168	49352.5
27-Jul-98	East	2.3334	46.61	4.3897	5.1824	51407.5
	West	2.3415	44.38	4.0660	4.6060	43112.5
29-Jul-98	East	2.3359	46.48	4.2505	4.8415	47865.0
	West	2.3253	46.51	3.9628	4.1365	40937.5
31-Jul-98	East	2.3156	46.51	4.4344	5.3510	52970.0
	West	2.3422	45.13	4.1813	4.8157	45977.5
2-Aug-98	East	2.3060	45.86	4.1859	4.8258	46997.5
	West	2.3110	46.28	4.1017	4.5483	44767.5
4-Aug-98	East	2.3291	45.60	3.8952	4.0496	39152.5
	West	2.3270	45.52	3.9398	4.1788	40320.0
5-Aug-98	East	2.3481	45.92	4.1981	4.7468	46250.0
	West	2.3435	44.71	3.9555	4.2682	40300.0
6-Aug-98	East	2.3166	45.94	4.0494	4.4402	43320.0
	West	2.3264	46.21	3.9654	4.1721	40975.0
7-Aug-98	East	2.3371	45.73	4.2804	5.0092	48582.5
	West	2.3432	45.56	3.9757	4.2273	40812.5
8-Aug-98	East	2.3359	45.77	4.1590	4.6944	45577.5
	West	2.3369	45.65	3.9635	4.2015	40665.0
9-Aug-98	East	2.3329	46.00	4.1086	4.5451	44392.5
	West	2.3312	45.44	3.9405	4.1789	40232.5
10-Aug-98	East	2.3455	45.20	4.0712	4.5109	43142.5
	West	2.3142	45.44	3.7042	3.6078	34750.0
11-Aug-98	East	2.3318	45.97	4.2582	4.9345	48160.0
	West	2.3439	45.63	3.8969	4.0142	38825.0
12-Aug-98	East	2.3244	45.29	4.1858	4.8515	46535.0
	West	2.3150	45.73	3.8420	3.9339	38175.0
13-Aug-98	East	2.3184	45.67	4.1523	4.7323	45847.5
	West	2.3301	45.30	3.8026	3.8375	36812.5
14-Aug-98	East	2.3360	45.56	4.2035	4.8349	46687.5
	West	2.3475	45.56	3.8486	3.8874	37527.5
15-Aug-98	East	2.3171	45.74	4.1952	4.8374	46952.5
	West	2.3345	45.65	3.8924	4.0238	38947.5
16-Aug-98	East	2.3412	45.44	4.1224	4.6264	44530.0
	West	2.3294	45.25	4.0381	4.4588	42717.5
17-Aug-98	East	2.3279	45.45	4.0950	4.5870	44177.5
	West	2.3328	45.68	3.9169	4.0881	39602.5
18-Aug-98	East	2.3342	45.76	4.1149	4.5862	44517.5
	West	2.3345	45.68	3.9482	4.1647	40342.5
19-Aug-98	East	2.3263	45.48	3.9458	4.2005	40487.5
	West	2.3519	45.58	3.9243	4.0704	39310.0
20-Aug-98	East	2.3170	46.34	3.8608	3.9158	38595.0
	West	2.3345	46.68	3.9188	3.9860	39607.5

TABLE A13 - Measured Temperatures of Run #1

Date	Air Temp High °C	Complete Mix Temperature East Temperature (°C) Tank	Complete Mix Temperature East Temperature (°C) Air-Tank	Complete Mix Temperature West Temperature (°C) Tank	Complete Mix Temperature West Temperature (°C) Air-Tank	Recycle Temperature East Temperature (°C) Tank	Recycle Temperature East Temperature (°C) Air-Tank	Recycle Temperature West Temperature (°C) Tank	Recycle Temperature West Temperature (°C) Air-Tank	Supernatant Temperature East Temperature (°C) Tank	Supernatant Temperature East Temperature (°C) Air-Tank	Supernatant Temperature West Temperature (°C) Tank	Supernatant Temperature West Temperature (°C) Air-Tank
22-Apr-98	20.8	16.5	4.3	15.3	5.5	14.1	6.7	14.3	6.5	15.8	5.0	16.0	4.8
24-Apr-98	18.1	14.3	3.8	14.1	4.0	14.2	3.9	14.1	4.0	14.2	3.9	14.1	4.0
26-Apr-98	18.6	14.4	4.2	14.0	4.6	14.2	4.4	14.4	4.2	14.8	3.8	14.9	3.7
28-Apr-98	22.4	14.8	7.6	14.5	7.9	14.4	8.0	14.9	7.5	15.3	7.1	15.1	7.3
30-Apr-98	19.1	16.3	2.8	16.1	3.0	14.6	4.5	15.1	4.0	15.1	4.0	15.6	3.5
2-May-98	24.8	16.8	8.0	17.1	7.7	15.3	9.5	16.1	8.7	16.1	8.7	16.0	8.8
4-May-98	21.2	16.5	4.7	16.3	4.9	15.0	6.2	15.8	5.4	15.8	5.4	15.7	5.5
9-May-98	19.5	16.5	3.0	15.3	4.2	14.9	4.6	14.8	4.7	14.8	4.7	14.7	4.8
10-May-98	15.8	15.1	0.7	15.6	0.2	15.7	0.1	14.8	1.0	14.5	1.3	14.6	1.2
12-May-98	19.6	16.1	3.5	16.1	3.5	15.1	4.5	15.5	4.1	15.8	3.8	16.0	3.6
14-May-98	21.8	17.5	4.3	17.7	4.1	16.3	5.5	16.3	5.5	17.5	4.3	17.3	4.5
16-May-98	14.5	15.6	1.1	15.1	0.6	16.0	1.5	15.9	1.4	15.4	0.9	15.2	0.7
19-May-98	18.4	15.6	2.8	15.6	2.8	15.1	3.3	15.3	3.1	15.3	3.1	15.3	3.1
20-May-98	21.9	16.1	5.8	16.3	5.6	15.5	6.4	15.6	6.3	15.9	6.0	16.2	5.7
21-May-98	21.3	17.9	3.4	18.1	3.2	17.1	4.2	17.5	3.8	17.8	3.5	18.0	3 3
22-May-98	13.9	15.9	2.0	16.1	2.2	15.8	1.9	16.0	2.1	16.1	2.2	16.1	2.2
23-May-98	21.0	17.4	3.6	16.8	4.2	17.4	3.6	17.2	3.8	16.9	4.1	17.3	3.7
24-May-98	20.4	16.2	4.2	15.9	4.5	17.4	3.0	17.2	3.2	16.9	3.5	17.3	3.1
25-May-98	22.3	17.7	4.6	17.5	4.8	16.6	5.7	17.4	4.9	17.5	4.8	17.3	5.0
26-May-98	20.0	16.9	3.1	17.4	2.6	16.7	3.3	17.2	2.8	16.5	3.5	16.9	3.1
27-May-98	18.7	16.0	2.7	16.3	2.4	15.9	2.8	15.8	2.9	15.8	2.9	16.0	2.7
28-May-98	15.4	16.2	0.8	16.0	0.6	15.8	0.4	16.2	0.8	15.9	0.5	16.2	0.8
29-May-98	20.4	16.6	3.8	17.3	3.1	17.2	3.2	17.4	3.0	16.9	3.5	17.3	3.1
30-May-98	17.4	16.3	1.1	16.2	1 2	16.4	1.0	16.1	1.3	15.9	1.5	16.0	1.4

TABLE A14 - Measured Temperatures of Run #2

Date	Air Temp High °C	Complete Mix Temperature East Temperature (°C) Tank	Complete Mix Temperature East Temperature (°C) Air-Tank	Complete Mix Temperature West Temperature (°C) Tank	Complete Mix Temperature West Temperature (°C) Air-Tank	Recycle Temperature East Temperature (°C) Tank	Recycle Temperature East Temperature (°C) Air-Tank	Recycle Temperature West Temperature (°C) Tank	Recycle Temperature West Temperature (°C) Air-Tank	Supernatant Temperature East Temperature (°C) Tank	Supernatant Temperature East Temperature (°C) Air-Tank	Supernatant Temperature West Temperature (°C) Tank	Supernatant Temperature West Temperature (°C) Air-Tank
19-Jun-98	15.0	16.9	1.9	16.8	1.8	16.1	1.1	16.7	1.7	16.7	1.7	16.8	1.8
22-Jun-98	26.0	17.4	8.6	17.3	8.7	16.6	9.4	16.9	9.1	17.6	8.4	17.1	8.9
24-Jun-98	22.0	17.9	4.1	17.8	4.2	17.9	4.1	18.0	4.0	17.3	4.7	17.8	4.2
26-Jun-98	19.0	17.2	1.8	17.1	1.9	17.0	2.0	17.3	1.7	16.8	2.2	17.0	2.0
28-Jun-98	13.0	16.3	3.3	16.5	3.5	16.6	3.6	16.9	3.9	16.5	3.5	16.7	3.7
30-Jun-98	22.0	18.3	3.7	18.6	3.4	18.7	3.3	18.3	3.7	18.3	3.7	18.6	3.4
2-Jul-98	18.0	17.8	0.2	17.5	0.5	17.7	0.3	17.1	0.9	17.3	0.7	17.2	0.8
6-Jul-98	22.0	16.2	5.8	16.7	5.3	16.3	5.7	16.4	5.6	16.8	5.2	16.4	5.6
8-Jul-98	26.0	18.8	7.2	18.8	7.2	18.8	7.2	18.5	7.5	18.8	7.2	18.7	7.3
9-Jul-98	26.0	18.9	7.1	19.1	6.9	19.0	7.0	18.4	7.6	19.8	6.2	19.0	7.0
10-Jul-98	28.0	19.5	8.5	19.6	8.4	19.7	8.3	19.1	8.9	19.2	8.8	19.8	8.2
11-Jul-98	23.0	19.0	4.0	18.8	4.2	18.8	4.2	19.3	3.7	19.1	3.9	19.5	3.5
12-Jul-98	23.0	18.0	5.0	17.9	5.1	18.3	4.7	18.1	4.9	17.8	5.2	18.0	5.0
13-Jul-98	23.0	18.0	5.0	18.0	5.0	18.0	5.0	18.1	4.9	18.4	4.6	18.5	4.5
14-Jul-98	25.0	18.9	6.1	19.5	5.5	18.8	6.2	19.0	6.0	19.4	5.6	18.8	6.2
15-Jul-98	24.0	17.5	6.5	17.3	6.7	17.5	6.5	17.6	6.4	17.5	6.5	17.5	6.5
16-Jul-98	27.0	19.1	7.9	20.0	7.0	19.3	7.7	19.9	7.1	20.0	7.0	20.0	7.0
17-Jul-98	31.0	20.5	10.5	20.0	11.0	20.7	10.3	21.5	9.5	20.7	10.3	20.3	10.7
18-Jul-98	26.0	18.8	7.2	19.0	7.0	19.2	6.8	19.3	6.7	18.6	7.4	18.8	7.2
19-Jul-98	24.0	18.7	5.3	19.0	5.0	19.1	4.9	19.0	5.0	18.2	5.8	18.4	5.6
20-Jul-98	19.0	18.3	0.7	18.6	0.4	18.1	0.9	17.8	1.2	18.1	0.9	18.2	0.8

TABLE A15 - Measured Temperatures of Run #3

Date	Air Temp High	Complete Mix Temperature				Recycle Temperature				Supernatant Temperature			
		East		West		East		West		East		West	
		Temperature				Temperature				Temperature			
		Tank	Air-Tank	Tank	Air-Tank	Tank	Air-Tank	Tank	Air-Tank	Tank	Air-Tank	Tank	Air-Tank
25-Jul-98	28.0	20.6	7.4	21.0	7.0	20.1	7.9	21.4	6.6	20.8	7.2	21.3	6.7
27-Jul-98	25.0	19.8	5.2	20.0	5.0	19.3	5.7	19.5	5.5	19.7	5.3	19.9	5.1
29-Jul-98	28.0	20.2	7.8	20.3	7.7	20.1	7.9	19.9	8.1	20.1	7.9	20.3	7.7
31-Jul-98	28.0	20.9	7.1	20.5	7.5	20.0	8.0	20.8	7.2	20.4	7.6	20.7	7.3
2-Aug-98	22.0	19.3	2.7	19.4	2.6	19.3	2.7	19.3	2.7	18.8	3.2	19.3	2.7
4-Aug-98	32.0	20.3	11.7	20.4	11.6	19.9	12.1	20.6	11.4	20.6	11.4	20.6	11.4
5-Aug-98	33.0	20.8	12.2	20.6	12.4	20.4	12.6	20.8	12.2	20.3	12.7	20.5	12.5
6-Aug-98	24.0	20.3	3.7	20.4	3.6	20.9	3.1	20.8	3.2	20.0	4.0	20.5	3.5
7-Aug-98	24.0	19.0	5.0	19.4	4.6	19.2	4.8	19.4	4.6	18.9	5.1	19.1	4.9
8-Aug-98	27.0	19.3	7.7	19.3	7.7	19.3	7.7	19.5	7.5	19.0	8.0	19.3	7.7
9-Aug-98	30.0	19.5	10.5	19.4	10.6	19.5	10.5	19.5	10.5	19.4	10.6	19.5	10.5
10-Aug-98	29.0	20.3	8.7	20.7	8.3	20.6	8.4	20.7	8.3	20.3	8.7	20.3	8.7
11-Aug-98	26.0	19.1	6.9	19.4	6.6	19.2	6.8	19.5	6.5	19.1	6.9	19.3	6.7
12-Aug-98	27.0	19.7	7.3	19.5	7.5	19.9	7.1	19.9	7.1	19.5	7.5	19.8	7.2
13-Aug-98	25.0	19.3	5.7	19.3	5.7	19.1	5.9	19.1	5.9	19.2	5.8	19.2	5.8
14-Aug-98	29.0	19.6	9.4	19.6	9.4	20.0	9.0	19.5	9.5	19.7	9.3	19.9	9.1
15-Aug-98	26.0	19.2	6.8	19.4	6.6	19.7	6.3	19.5	6.5	19.4	6.6	19.3	6.7
16-Aug-98	20.0	19.3	0.7	19.4	0.6	19.6	0.4	19.5	0.5	19.3	0.7	19.2	0.8
17-Aug-98	24.0	18.7	5.3	18.5	5.5	18.9	5.1	18.7	5.3	18.5	5.5	18.8	5.2
18-Aug-98	24.0	18.3	5.7	18.5	5.5	18.4	5.6	18.6	5.4	18.8	5.2	18.8	5.2
19-Aug-98	22.0	18.5	3.5	18.6	3.4	18.9	3.1	19.0	3.0	18.3	3.7	18.5	3.5
20-Aug-98	29.0	19.2	9.8	19.3	9.7	19.4	9.6	19.5	9.5	19.3	9.7	19.4	9.6

TABLE A16 - Measured pH of Run #1

	pH					
	Complete Mix		Recycle		Supernatant	
Date	E	W	E	W	E	W
	pH		pH		pH	
22-Apr-98	6.60	6.75	6.42	6.62	6.55	6.72
24-Apr-98	6.68	6.67	6.42	6.51	6.63	6.59
28-Apr-98	6.71	6.82	6.51	6.71	6.69	6.76
30-Apr-98	6.44	6.49	6.63	6.55	6.71	6.67
9-May-98	6.33	6.58	6.29	6.42	6.62	6.53
10-May-98	6.55	6.56	6.27	6.58	6.62	6.53
12-May-98	6.63	6.61	6.54	6.46	6.65	6.57
14-May-98	6.70	6.68	6.48	6.41	6.75	6.58
16-May-98	6.64	6.63	6.43	6.49	6.57	6.55
19-May-98	6.63	6.65	6.57	6.38	6.57	6.52
20-May-98	6.72	6.67	6.43	6.44	6.64	6.58
21-May-98	6.65	6.67	6.43	6.38	6.62	6.61
22-May-98	6.61	6.66	6.39	6.42	6 63	6.54
23-May-98	6.71	6.67	6.42	6.43	6.66	6.67
24-May-98	6.68	6.61	6.48	6.46	6.62	6.56
25-May-98	6.62	6.63	6.58	6.37	6.59	6.56
26-May-98	6.56	6.63	6.44	6.26	6.68	6.58
27-May-98	6.65	6.56	6.39	6.43	6.67	6.54
28-May-98	6.68	6.61	6.38	6.22	6.62	6.52
29-May-98	6.53	6.47	6.22	6.2	6.62	6.45
30-May-98	6.54	6.49	6.3	6.32	6.64	6.56

TABLE A17 - Measured pH of Run #2

	pH					
	Complete Mix		Recycle		Supernatant	
Date	E	W	E	W	E	W
	pH		pH		pH	
19-Jun-98	6.59	6.53	6.35	6.33	6.64	6.53
22-Jun-98	6.51	6.43	6.32	6.12	6.57	6.42
24-Jun-98	6.52	6.43	6.33	6.08	6.57	6.42
26-Jun-98	6.40	6.52	6.34	6.38	6.54	6.46
28-Jun-98	6.34	5.82	6.38	6.48	6.50	6.44
30-Jun-98	6.41	6.64	6.27	6.41	6.52	6.65
2-Jul-98	6.43	6.50	6.33	6.29	6.47	6.51
6-Jul-98	6.65	6.11	6.44	6.46	6.74	6.71
8-Jul-98	6.64	6.54	6.61	6.48	6.66	6.57
9-Jul-98	6.62	6.65	6.51	6.46	6.66	6.56
10-Jul-98	6.63	6.58	6.53	6.48	6.65	6.54
11-Jul-98	6.61	6.57	6.60	6.47	6.65	6.56
12-Jul-98	6.64	6.66	6.52	6.49	6.58	6.57
13-Jul-98	6.59	6.66	6.54	6.52	6.63	6.62
14-Jul-98	6.60	6.62	6.45	6.44	6.56	6.58
15-Jul-98	6.68	6.72	6.51	6.49	6.62	6.67
16-Jul-98	6.50	6.52	6.58	6.38	6.48	6.47
17-Jul-98	6.44	6.44	6.27	6.24	6.51	6.46
18-Jul-98	6.43	6.47	6.28	6.25	6.40	6.43
19-Jul-98	6.40	6.45	6.24	6.22	6.39	6.38
20-Jul-98	6.36	6.38	6.18	6.21	6.35	6.33

TABLE A18 - Measured pH of Run #3

	pH					
	Complete Mix		Recycle		Supernatant	
Date	E	W	E	W	E	W
	pH		pH		pH	
25-Jul-98	6.47	6.11	6.19	6.74	6.36	6.18
27-Jul-98	6.32	6.20	6.20	6.35	6.27	6.11
29-Jul-98	6.31	6.12	6.11	6.05	6.30	6.10
31-Jul-98	6.28	6.15	6.08	5.98	6.22	6.06
2-Aug-98	6.40	6.17	6.10	6.06	6.33	6.12
4-Aug-98	6.33	6.16	6.14	6.03	6.36	6.13
5-Aug-98	6.41	6.29	6.29	6.14	6.38	6.20
6-Aug-98	6.37	6.24	6.21	6.11	6.36	6.18
7-Aug-98	6.35	6.21	6.21	6.13	6.32	6.17
8-Aug-98	6.47	6.27	6.28	6.16	6.40	6.22
9-Aug-98	6.39	6.21	6.25	6.11	6.41	6.19
10-Aug-98	6.28	6.19	6.11	6.02	6.31	6.10
11-Aug-98	6.32	6.13	6.12	6.00	6.33	6.10
12-Aug-98	6.33	6.22	6.12	6.01	6.33	6.10
13-Aug-98	6.31	6.10	6.11	6.00	6.31	6.07
14-Aug-98	6.25	6.09	6.10	5.99	6.25	6.03
15-Aug-98	6.29	6.14	6.11	6.00	6.24	6.05
16-Aug-98	6.36	6.20	6.15	6.03	6.25	6.09
17-Aug-98	6.32	6.13	6.15	6.01	6.32	6.10
18-Aug-98	6.31	6.14	6.14	5.98	6.32	6.09
19-Aug-98	6.25	6.17	6.10	5.97	6.20	6.03
20-Aug-98	6.20	6.10	6.09	5.94	6.17	6.03

APPENDIX B

BENCH-SCALE EXPERIMENT
RAW DATA

TABLE B1 - Measured VFA Concentrations of Run #1

Date: May 28/1998
Start Time: 3:15:00 PM
Temperature: 16°C

	VFA Concentration											
	100 % PS				80% PS, 20% CM				60% PS, 40% CM			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	8.5	0	0	8.5	26.4	5.2	2.6	34.2	50.9	9.5	4.4	70.1
7	3.7	0	0	3.7	44.4	2.2	2.6	53.7	80.7	6.4	5.3	103.2
17	2.5	0	0	2.5	54	0	0	63.6	119.8	0	5.3	140
25	2.9	0	0	2.9	71	0	0	81.1	134.5	8	6.4	164.9
32.15	2.7	0	0	2.7	74.4	0	0	80.2	149.9	16.3	7.8	190.9
42.15	2.9	0	0	2.9	71.8	0	0	77.1	166.4	26.6	9.5	220.7
49.45	2.7	0	0	2.7	64.5	0	0	69.7	177.5	32.7	10.3	238.4
57	2.8	0	0	2.8	49.9	0	0	52.5	187.9	36.5	10.8	254.5
65	2.5	0	0	2.5	29.5	0	0	29.5	195.1	37.4	10.7	262.3
	40% PS, 60% CM				20% PS, 80% CM				100% CM			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	74.8	14	6.3	104.4	98.9	18.7	8.3	151.5	122.1	24.1	9.9	172.8
7	109.9	7.6	7.3	135.6	135	27.5	11.8	192.5	153.7	51.3	16	242.1
17	143	24.2	11.6	197.6	156.5	56.7	17.6	253.6	176.5	84.8	22.4	309.2
25	158	39.2	14.5	232.5	191.5	82.6	23.8	324.6	210.5	110.8	29.9	380.9
32.15	177.2	52.7	17.2	269.5	200.8	95	26.7	350.9	238.7	130.7	35.7	436.6
42.15	197.8	68.6	20.1	310.1	224.2	120.8	32.1	408.1	264.9	150.5	41.8	493.5
49.45	203.9	77.3	21.3	327.6	230.7	133.2	34.4	431.2	289.1	168.9	47.3	544.3
57	221.4	88.2	23.5	359.8	243.4	149	37.9	464.2	301.1	178.5	50	570.4
65	229.8	93.7	24.2	375.5	258	160.6	40.4	493.7	325.9	195.3	55.2	620.3

TABLE B2 - Measured VFA Concentrations of Run #2

Date: June 24/1998
Start Time: 3:45:00 PM
Temperature: 16.8 °C

	VFA Concentration											
	100 % PS				80% PS, 20% CM				60% PS, 40% CM			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	35.12	12	3.04	78.88	45.11	11.89	4.02	74.17	58.78	12.69	5.27	98.01
7.5	70.68	29.91	4.83	120.7	88.26	23.34	6.04	132.3	94.15	19.16	7.4	134.44
16	115.2	37.54	5.86	186.88	140.99	25.14	7.09	189.66	137.3	16.29	8.63	177.52
24	146.68	36.94	5.92	207.26	183.91	20.02	7.06	229	160.88	36.81	12.86	226.43
31.5	179.09	33.73	5.75	237.99	210.11	20.68	7.57	257.04	175.07	52.24	15.6	259.36
42.25	219.91	27.95	5.28	274.67	248.5	29.3	9.29	308.16	199.14	73.97	20.06	311.64
48	235.28	32.06	5.83	296.07	228.58	28.35	9.13	285.25	220.92	83.87	23.02	346.93
55	245.62	36.37	6.42	311.02	266.4	30.3	9.9	327.4	220.26	89.11	24.34	353.37
	40% PS, 60% CM				20% PS, 80% CM				100% CM			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	66.61	11.48	6.16	96.25	74.67	10.33	6.97	102.6	85.33	9.7	7.68	113.22
7.5	107.62	7.72	6.95	136.26	115.49	2.39	5.83	137.73	109.89	10.02	8.76	139.54
16	146.14	3.23	6.12	170.37	141.12	0	2.87	158.91	130.68	12.69	9.06	168.05
24	170.91	8.74	7.02	203.03	163.79	2.63	2.24	184.45	146.43	13.67	8.61	184.99
31.5	188.12	9.72	6.45	221.86	168.12	2.4	0	206.48	156.57	11.54	7	191.79
42.25	207.5	8.28	4.64	238.75	179.84	0	0	193.21	179.41	8.46	4.48	211.16
48	217.8	7.77	4.26	244.91	183.8	0	0	191.5	183.26	6.2	3.12	206.48
55	219.1	5.6	2.9	242.1	174.37	0	0	182.15	176.56	2.3	0	187.46

TABLE B3 - Measured VFA Concentrations of Run #3

Date: July 9/1998
Start Time: 4:30:00 PM
Temperature: 17.3 °C

	VFA Concentration											
	100 % CM				60% PS, 40% CM				CM + 1000mg Acetate			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	74.29	0	7.28	81.57	37.87	6.11	5.14	49.12	439.55	0	7.6	447.15
6.15	97.94	0	8.43	106.36	72.48	7.29	7.56	87.33	448.35	0	9.62	457.97
17.15	138.78	25.72	13.72	178.22	114.44	5.3	7.26	127	301.24	20.44	11.1	332.8
24.45	156.2	40.8	16.8	213.8	173	0	8	186.4	368	42.4	18.6	428.8
30.45	161.6	51.8	18.6	232	201.2	0	7.2	228.4	406.4	37.8	17	461.2
41.45	193.4	78	22.6	294	229.8	0	5	247	517.6	70.8	25.8	619.2
48	219.8	97.6	26.4	343.8	251.4	5.4	5.2	274.6	561.6	83.6	29.6	686.2
53.15	240.4	106.8	27.6	385.6	272.6	5	5.2	305	573.6	83.6	29.6	698.4
	CM + 1000mg Peptone				CM + 1000mg Starch				CM + 1000mg Linoleic Acid			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	74.07	4.02	7.53	105.02	64.48	0	6.7	71.19	70.12	0	7.12	85.92
6.15	110.74	13.26	10.58	134.58	89.26	0	7.42	96.68	113.84	0	8.31	122.15
17.15	188.94	50.54	23.04	287.92	148	28.8	11.4	189.2	109.6	10.6	8.4	139.4
24.45	265.4	67.4	28.2	395	133.6	38.8	10.4	182.8	131.4	15	9.8	169.2
30.45	253.2	92.2	34.8	441	95.4	36.6	7.8	139.8	133.4	16.6	9.6	173.4
41.45	280.2	98.8	32.6	481.2	139.2	67.6	10.4	217.2	137.6	15.4	7.6	173.4
48	333.4	118.4	35.6	573.4	269.8	138	17.8	443.6	193.4	20.2	9	241.8
53.15	405	136.6	40	710.2	292.8	150.6	18.6	491	207.6	20.2	8.6	267

TABLE B4 - Measured VFA Concentrations of Run #4

Start Date: July 28/1998
Start Time: 3:00:00 PM
Temperature: 19.3 ^{0}C

	VFA Concentration											
	60% PS, 40% CM				60%PS/40%CM+Potassium Cyanide				60%PS/40%CM+Sodium Citrate			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	32.08	6.91	3.93	42.92	34.15	6.82	3.99	44.96	23.62	5.06	2.99	31.67
7.45	56.07	9.47	5.27	70.81	56.74	16.57	6.56	82.64	41.1	6.89	3.82	51.8
18.3	89.57	9.67	6.82	108.48	50.64	16.06	5.87	78.43	84.48	4.86	5.15	97.04
25.3	113.45	22.64	9.97	151.75	68.97	23.43	7.28	107.11	96.76	9.63	6.24	118.29
32.45	102.25	25.77	10.26	143.92	83.43	29.27	9.91	133.11	98.18	16.09	7.03	127
44.3	180.79	59.29	17.27	275.34	86.5	26.11	7.35	131.98	109.9	30.33	9.93	164.41
51.15	172.1	63.77	17.7	268.37	87.17	26.27	7.41	129.88	170.08	54.58	15.97	258.79
59	201.84	82.59	21.58	331.13	131.34	36.38	8.91	196.59	138.07	49.46	13.39	219.7
	60%PS/40%CM+Sodium Bisulphite				100% CM				CM + 1000mg Peptone			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	21.48	5.24	3.08	29.8	43.63	8.5	5.27	57.4	58.15	10.62	6.38	75.16
7.45	30.16	6.72	4.19	41.07	58.8	15.37	7	81.17	73.88	28.2	9.96	120.72
18.3	33.09	6.78	3.95	43.82	72.64	27.39	9.24	109.28	126.86	55.52	18.76	220.24
25.3	37.88	6.73	3.24	47.85	81.7	30.82	9.54	127.75	149.39	68.94	22.27	270.99
32.45	42.88	7.7	2.81	53.38	84.54	30.27	8.9	132.46	185.23	77.83	23.51	328.55
44.3	31.5	5.89	2.03	39.41	105.14	35.26	9.73	161.08	217.38	79.05	19.29	363.1
51.15	36.48	6.86	2.03	45.37	112.17	36.55	9.97	170.39	216.03	75.91	16.62	362.74
59	32.8	7.09	0	39.89	118.87	37.03	9.5	178.86	253.83	86.33	18.65	419.98

TABLE B5 - Measured VFA Concentrations of Run #5

Date: August 18/1998
Time Started: 3:30:00 PM
Temperature: 18.3 °C

	VFA Concentration											
	60% PS, 40% CM				60PS /40CM Tobramycin				60PS /40CM Penicillin G			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	30.48	8.7	3.91	43.08	34.81	9.85	4.28	48.94	21.45	6.21	2.94	30.61
7.5	53.99	9.74	4.61	68.34	63.39	12.27	5.48	81.13	38.89	7.93	3.66	50.49
17.5	87.3	19.9	7.4	114.6	67.5	5.8	3.7	82.4	88.2	15.9	6	119.2
24	95.9	14.7	6.8	125.6	115.7	3.2	4.4	130.4	103.5	10	5.5	127.9
31.5	134.1	23.1	8.9	180.8	132	12.1	6	165.2	134.6	12.7	6.1	169
41.5	135.3	30	9.1	186.6	93	7.6	3.4	112.3	87	16.2	5.3	115.4
48	160.5	38.7	10.7	225.2	141.7	13.6	4.6	172.8	103.5	24	6.6	146.1
56	154	40.4	9.7	225.8	151.5	16.9	4.1	189.2	99.6	22.6	5.4	142.5
	60PS /40CM Sulfapyridine				60PS /40CM Imipenem				60PS /40CM Sulfapyridine			
Time hr	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L	Acetic mg/L	Proprionic mg/L	Butyric mg/L	Total mg/L
0	20.59	6.12	3.02	29.73	19.75	5.87	2.8	28.42	19.33	5.7	2.83	27.86
7.5	38.27	6.14	3.3	47.71	38.8	4.87	2.43	46.09	35.04	4.34	2.58	41.96
17.5	58.6	2.7	2.3	63.6	59.2	5	2.4	66.6	63.2	0	0	63.2
24	104.3	0	2.3	112.1	98.1	7.2	3.1	114.4	87.6	1.9	0	94.5
31.5	122.7	0	0	128.7	110.6	6.5	0	123.7	112.5	0	0	118.3
41.5	91.4	0	0	97.6	64	2.8	0	72.2	63.8	0	0	63.8
48	87.2	0	0	94.1	63.5	0	0	68.8	80.2	0	0	86.1
56					56.9	0	0	64.4	78	0	0	85.1

TABLE B6 - Measured Suspended Solids of Run #1

	Suspended Solids						
	Volume mL	100 % PS mg/L	80% PS, 20%CM mg/L	60% PS, 40% CM mg/L	40% PS, 60% CM mg/L	20% PS, 80% CM mg/L	100% CM mg/L
Before	25	624	2208	4984	6772	8584	10516
After	25	556	2584	4864	6680	7352	8264

TABLE B7 - Measured Suspended Solids of Run #2

	Suspended Solids						
	Volume mL	100 % PS mg/L	80% PS, 20%CM mg/L	60% PS, 40% CM mg/L	40% PS, 60% CM mg/L	20% PS, 80% CM mg/L	100% CM mg/L
Before	25	5332	4608	5072	4140	3608	3876
After	25	4244	4544	4524	4712	4588	4476

TABLE B8 - Measured Suspended Solids of Run #3

	Suspended Solids						
	Volume mL	100 % CM mg/L	60% PS, 40%CM mg/L	100 % CM + 1000mg Acetate mg/L	100 % CM + 1000mg Peptone mg/L	100 % CM + 1000mg Starch mg/L	100 % CM + 1000mg Linoleic Acid mg/L
Before	25	5792	6608	6032	6136	5868	7624
After	25	5608	5588	5636	5764	6336	5332

TABLE B9 - Measured Suspended Solids of Run #4

	Suspended Solids						
	Volume	60%PS, 40%CM	60%PS, 40%CM + Potassium Cyanide	60% PS, 40%CM + Sodium Citrate	60%PS, 40%CM + Sodium Bisulphite	100% CM	100% CM + Peptone
	mL	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Before	25	3044	3188	2764	3328	3108	3472
After	25	2860	3024	2948	2920	3040	3668

TABLE B10 - Measured Suspended Solids of Run #5

	Suspended Solids						
	Volume	60%PS, 40%CM	60%PS, 40%CM + Tobramycin	60% PS, 40%CM + Penicillin G	60%PS, 40%CM + Sulfapyridine	60%PS, 40%CM + Imipenem	60%PS, 40%CM + Sulfapyridine
	mL	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Before	25	2120	2260	2792	2180	2092	1916
After	25	2160	2344	2276	2004	2008	2152

APPENDIX C

SOURCES OF ERROR, SRT FORMULA, & RAW DATA

SOURCES OF ERROR

HRT

The system HRT is a measure of the total volume of the system divided by the influent flow rate.

$$HRT = \frac{V_{CM} + V_{GT}}{Q_{PC}}$$

The volume measurements were assumed to have no error. Values were taken from blueprint drawings. The only contributing source of error is associated with the primary sludge flow rate. The percent error associated with the flow rate was determined using the Doppler flow meter. The flow rates, Q_{SN}, Q_W, Q_{PC}, are set using electronic flow meters. The pumps are set to certain hourly flow rates and the computer monitors their activity. Pump speeds will increase or decrease to maintain preset flow rates. The accuracy of the electronic flow meters was evaluated using a Doppler Flow Meter. This piece of equipment measured the flow rate of the fluid within the pipe. This flow rate was then compared with those read by the electronic flow meters at the same instant. The primary sludge and supernatant flow rates were determined by strapping two clamps on either side of the pipe, exactly 180 degrees apart. This is called a Double Traverse. The recycle flow rates were determined by strapping two clamps on the pipe, 90 degrees apart. This is called a single traverse. A single traverse is used when the fluid in the pipe contains more viscous flow. A conductive gel was placed on the face of each clamp to facilitate the clarity of the signal. The clamps were plugged into the flow meter and the following data was input: type (glass, stainless steel) and thickness of the pipe liner, class

of pipe, and its wall thickness. These tests were carried out in the presence of Amy VanWieran and myself. The following Table C-1 shows the data collected.

Table C1: Doppler Flow Rate Measurements

Location	Signal Strength	Sound Speed	ΔT ns	Re #	Quality	Amplitude	Signal Correlation	Doppler Flow Rate m3/h	Electronic Flow Rate m3/h	Error %
PS West	64.5	1476	145	200000	good	good	0.986	84.46	90.13	6.71
PS East	66	1480	149	200000	good	good	0.98	84.82	89.88	5.97
SN West	60.9	1478	107	144000	good	good	0.99	82.8	86.2	4.11
SN East	63.7	1486	114	158000	good	good	0.997	88	91.64	4.14
R West	62	1501	33	70000	good	good	0.978	46	41.5	9.78
R East	63.9	1444	39	96000	good	good	0.94	46	42.11	8.46
	Over 40 is very good						Over 0.90 is good	Double Traverse Error +/- 1% Single Traverse Error +/- 2%		

The above table describes the various measurement used to determine the wastewater flow rates. A signal correlation of 0.9 or greater is indicative of an accurate measurement. The fluctuation of the electronic flow meter at the time of the Doppler measurements was approximately $\pm 1 m^3/h$ for the double traverse and ± 5 m^3/h for the single traverse. Table C-1 illustrates the primary sludge (PS) error for both east and west lines. Averaging the two error values yields a percent error of 6.34%. This value was then applied in the calculation of HRT to ensure that there was no overlap, in terms of standard deviations, between the high, medium, and low set points. The middle HRT was

selected first. The mid-point of the primary sludge pumps operational range was selected and the appropriate error applied. The high and low HRT values must be outside the range of 19.3 ± 1.22 (20.5/18.1) hours. The high point was selected as 36.7 hours and the low point as 18.4 hours.

VFA

The error associated with the measurement of VFAs stems from the reproducibility of each measured value. In order to account for natural variation in the sample a series of duplicates were run. Samples taken from each regular sampling point analysis followed the procedures outlined in Section 3.4.3.1. To test the natural variation in each sample, 5-1.5 ml glass vials were prepared for random samples from September 16, 1997 through October 1, 1997. Additional error measurements were also taken on Jun 22, 1998. However, in this case, five separate samples were taken approximately 2 minutes apart from each sampling point in the control train as well as one sample from each sampling point in the experimental train. Again, 5-1.5 ml glass vial were prepared for each sample taken on this day. The percent error values calculated are shown below in Table C-2. Raw data is found at the end of this Appendix.

Table C2: Percent Error Associated with Measurement of VFAs

	Error Associated with Measured VFA Concentrations					
	SN-E	SN-W	CM-E	CM-W	R/W-E	R/W-W
Percent Error	2.4	2.8	2.2	1.8	1.4	2.6

12-HOUR ANALYSIS

In order to show the variability in VFA and total solids over the course of a day samples were taken every 1.5 hours over the course of a 12 hour period. Tables C3 and C4 show measured values of the 12-hour sampling period. The mean and standard deviation are shown for each sample taken in the control train.

SRT FORMULA

Solids Retention Time (SRT) or mean cell residence time as it is sometimes called, is a measure of the length of time a specific volume of solids remains in the system. The current formula used for the determination of System SRT is given in Equation (4) and was developed by Process Engineer Paul Do. The following demonstrates how the formula is derived.

$$SRT = \frac{(V_{CM} + V_{GT}) \times TSS_{CM}}{Q_W \times TSS_{R/W}} \qquad (1)$$

$$Since\ TSS_{R/W} = (\frac{Q_{PC} + Q_R}{Q_R}) \times TSS_{CM} \qquad (2)$$

$$and\ we\ assume\ Q_R = 0.5Q_{PC} \qquad (3)$$

Substituting in (1) *with* (2) in (3), *yields*

$$SRT = \frac{(V_{CM} + V_{GT})}{3 \times Q_W} \qquad (4)$$

Note: Equation (2) is derived from a mass balance around the gravity thickener neglecting the solids concentration in the supernatant and in the waste sludge.

However, the above formula makes two key assumptions. The impacts of these assumptions on the system are unknown.

1. **The total suspended solids in the gravity thickener and the complete mix tank are assumed to be equal.**
2. **The solids in the gravity thickener supernatant are neglected.**

TABLE C3: Variablility over 12 hours in Measured VFA in the Control Train

	East Train		
	Complete Mix	Waste/ Recycle	Supernatant
Time	Total VFA mg/L	Total VFA mg/L	Total VFA mg/L
10:00 AM	307.8	444.3	389.1
11:30 AM	323.1	382.0	317.1
1:00 PM	294.5	389.7	325.1
2:30 PM	320.5	425.1	362.0
4:00 PM	320.1	407.3	342.6
5:30 PM	333.9	410.7	352.7
7:00 PM	346.4	328.4	363.7
8:30 PM	331.5	425.9	355.1
10:00 PM	372.2	387.6	348.1
Mean	327.8	400.1	350.6
Std Dev	22.4	33.8	21.4

TABLE C4: Variablility over 12 hours in Measured Total Solids in the Control Train

	East Train					
	Complete Mix		Supernatant		Waste/Recycle	
Time	%Solids	Solids mg/L	%Solids	Solids mg/L	%Solids	Solids mg/L
10:00 AM	1.63	15758	0.09	915	4.62	44335
11:30 AM	1.65	16383	0.11	1055	4.48	43700
1:00 PM	1.60	15923	0.16	1593	4.15	40488
2:30 PM	1.62	15923	0.15	1403	4.30	42043
4:00 PM	1.63	15940	0.14	1403	4.08	39290
5:30 PM	1.66	15748	0.10	1020	4.31	43128
7:00 PM	1.68	16340	0.11	1100	4.38	43148
8:30 PM	1.67	16280	0.14	1340	4.49	44488
10:00 PM	1.84	15868	0.13	1268	4.07	39888
Mean		16018		1233		42278
Std Dev		248		222		1953

TABLE C5: Statistical Analyses of VFA Sampling Error

Sample No.	DATE	Location	Single Sample	Mean	STD	CoV (%)
			mg/L	mg/L	mg/L	mg/L
1	16-Sep-97	CM-W	176.4			
2		CM-E		120.04	7.55	6.29
3	20-Sep-97	CM-W	156.4			
4		CM-E		68.48	2.48	3.62
5	22-Sep-97	CM-W		243.12	2.01	0.83
6		CM-E		263.98	2.83	1.07
7	1-Oct-97	CM-W		149.52	4.90	3.28
8		CM-E	144			
1	16-Sep-97	R/W-W		309.42	10.58	3.42
2		R/W-E	261			
3	20-Sep-97	R/W-W	176.5			
4		R/W-E		149.64	3.28	2.19
5	22-Sep-97	R/W-W		351.68	6.60	1.88
6		R/W-E		315.88	5.79	1.83
7	1-Oct-97	R/W-W	254.7			
8		R/W-E		266.52	4.13	1.55
1	16-Sep-97	PCU-W		5.86	1.05	17.92
2		PCU-E	0.9			
3	20-Sep-97	PCU-W	6.3			
4		PCU-E		288.22	10.02	3.48
5	22-Sep-97	PCU-W	17.3			
6		PCU-E		4.92	1.71	34.71
7	1-Oct-97	PCU-W		3.78	0.58	15.36
8		PCU-E	1.6			
1	16-Sep-97	SN-W		62.38	9.34	14.97
2		SN-E	115.8			
3	20-Sep-97	SN-W		145.93	2.24	1.53
4		SN-E	154.1			
5	22-Sep-97	SN-W	258.5			
6		SN-E		271.76	8.03	2.95
7	1-Oct-97	SN-W		88.86	3.75	4.22
8		SN-E	229.6			

TABLE C6: Statistical Analyses of VFA Sampling Error in the Supernatant on June 22, 1998

Bottle #	Sample #	Location	Total	Average	Standard Deviation	%CoVar
2	1	Supernatant-E	384.6			
	2		358.21			
	3		347.86			
	4		341.38			
	5		352.64	356.94	16.66	4.67
3	1	Supernatant-E	360.4			
	2		358.87			
	3		356.21			
	4		351.48			
	5		349.4	355.27	4.72	1.33
4	1	Supernatant-E	288.38			
	2		294.02			
	3		290.54			
	4		286.53			
	5		292.71	290.44	3.06	1.05
5	1	Supernatant-E	289.18			
	2		282.9			
	3		286.2			
	4		283.92			
	5		294.31	287.30	4.60	1.60
6	1	Supernatant-E	315.58			
	2		323.91			
	3		329.28			
	4		333.07			
	5		311.61	322.69	9.03	2.80
				322.53	7.61	2.29
7	1	Supernatant-W	315.32			
	2		303.93	309.63	8.05	2.60
	3		Vial Broke			
	4		Vial Broke			
	5		Vial Broke			

TABLE C7: Statistical Analyses of VFA Sampling Error in the Complete Mix Sludge on June 22, 1998

Bottle #	Sample #	Location	Total	Average	Standard Deviation	%CoVar
8	1	Complete Mix-E	287.23			
	2		293.88			
	3		293.04			
	4		294.09			
	5		296.72	292.99	3.50	1.20
9	1	Complete Mix-E	274.47			
	2		278.3			
	3		281.38			
	4		283.15			
	5		272.38	277.94	4.53	1.63
10	1	Complete Mix-E	323.79			
	2		324.38			
	3		324.29			
	4		324.91			
	5		323.16	324.11	0.66	0.20
11	1	Complete Mix-E	309.29			
	2		314.47			
	3		306.73			
	4		311.94			
	5		319.93	312.47	5.07	1.62
12	1	Complete Mix-E	291.26			
	2		287.06			
	3		296.17			
	4		300.92			
	5		295.3	294.14	5.24	1.78
				300.33	3.80	1.29
13	1	Complete Mix-W	333.46			
	2		337.56			
	3		343.78			
	4		333.29			
	5		335.11	336.64	4.34	1.29

TABLE C8: Statistical Analyses of VFA Sampling Error in the Recycle/Waste Sludge on June 22, 1998

Bottle #	Sample #	Location	Total	Average	Standard Deviation	%CoVar
14	1	Waste-E	531.91			
	2		535.57			
	3		531.63			
	4		539.08			
	5		528.25	533.29	4.15	0.78
15	1	Waste-E	536.13			
	2		544.21			
	3		519.26			
	4		542.41			
	5		542.79	536.96	10.37	1.93
16	1	Waste-E	596.12			
	2		585.25			
	3		583.04			
	4		594.21	589.66	6.47	1.10
	5					
17	1	Waste-E	544.65			
	2		548.6			
	3		538.85			
	4		556.4			
	5		548.73	547.45	6.42	1.17
18	1	Waste-E	582.66			
	2		576			
	3		569.9			
	4		569.77			
	5		576.23	574.91	5.35	0.93
				556.45	6.55	1.18
19	1	Waste-W	860			
	2		841.21			
	3		856.71			
	4		816.57			
	5		814.49	837.80	21.54	2.57