THE EFFECT OF OPERATIONAL AND ENVIRONMENTAL PARAMETERS ON THE ACID-PHASE ANAEROBIC DIGESTION OF PRIMARY SLUDGE

by

PANAGIOTIS ELEFSINIOTIS

Dipl. Eng. (Civil Engineering), National Technical Univ. of Athens, Greece, 1979
M.A.Sc. (Environmental Engineering), The University of Toronto, 1982

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Department of Civil Engineering

The University of British Columbia
Vancouver, Canada

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ABSTRACT

This research explored the effect of certain operational and environmental parameters on the acid-phase anaerobic digestion of primary municipal sludge. The operational parameters included the hydraulic retention time (HRT) and the solids retention time (SRT), while pH, reactor configuration and influent characteristics were the environmental factors of interest. Moreover, an attempt was made to identify the most significant metabolic pathways involved in the conversion of the major components of primary sludge (carbohydrates, proteins and lipids) to short-chain volatile fatty acids (VFAs) and other soluble end-products.

The experiments were conducted using two continuous-flow three-liter reactors having different configurations: a completely mixed reactor (CMR) with a clarifier and sludge recycle, and an upflow anaerobic sludge blanket (UASB) reactor. Both systems were run at an ambient liquid temperature between 18 and 22 °C. The research program evolved into the following four stages: In Stage 1 the role of HRT was investigated, while Stage 2 focused on the effect of SRT. The issues of replication and the source of influent sludge were the targets in Stage 3. Finally, in Stage 4 the effect of pH was explored. During the last stage, dilute solutions (0.02N) of HCl or NaOH were continuously added through an automated pump system to keep the pH at selected values.

Favorable conditions for acidogenic digestion were established and maintained resulting, generally, in high VFA and low gas generation rates. The net VFA concentration and the specific production rate increased, in both reactors, with an

increase in HRT up to 12 hours, but decreased slightly at longer HRTs. The same pattern was followed not only by the COD concentration but also by the specific solubilization rates of COD and TOC.

Variation in SRT had a profound effect on VFA production rate only at the lower (5 day) SRT. At longer SRTs a plateau in acid production appeared to be reached.

A decrease in pH from 5.1 to 4.5 did not have an effect on the rate of VFA generation, but an increase to pH 6.1 resulted in significantly lower rates (25 to 30%) of acid production.

Acetic acid and propionic acid were the most prevalent VFAs produced and accounted for 45 and 31% (on average) of the total respectively. Butyric acid followed with an average value of 9%. The percent VFA distribution appeared to be independent of HRT, but it was a function of both SRT and pH. Besides VFAs, small amounts of formic acid, ethanol and lactic acid were regularly detected in both systems.

Results showed that the steady-state operation of the acid-phase digestion can be replicated and that the seasonal changes in the study (summer-winter) did not affect the process.

The use of a different source of influent sludge had an effect on lipid and carbohydrate utilization patterns, which was also reflected in the corresponding VFA production rates.

In general, protein degradation percentages were moderate and significantly lower than those obtained for the other two groups of organic compounds. The

utilization of all three substrates increased with an increase in HRT, but (with the exception of proteins) was essentially independent of SRT.

The reactor configuration played a role in substrate degradation as well. Although both systems showed a fairly similar behavior in protein utilization, the degradation of carbohydrates and lipids was distinctly and consistently different. Lipids were broken down more efficiently in the CMR system, while higher rates of carbohydrate dissimilation were observed in the UASB reactor.

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GLOSSARY OF TERMS

ATP:	adenosine-5'-triphosphate
CH_2O:	carbohydrates
CMR:	completely mixed reactor
CoA:	coenzyme A
COD:	chemical oxygen demand
CoV:	coefficient of variation
EMP:	Embden-Meyerhof-Parnas [glycolytic pathway]
HAc:	acetic acid
HRT:	hydraulic retention time
$NAD(H_2)$:	nicotinamide adenine nucleotide (reduced)
NAD(P):	nicotinamide adenine nucleotide (phosphate)
NH_3-N:	ammonia nitrogen
ORP:	oxidation-reduction potential
PHB:	poly-β-hydroxybutyrate
PHV:	poly-β-hydroxyvalerate
PO_4^{-3}:	orthophosphate
STD:	standard deviation
SRT:	solids retention time
TKN:	total Kjeldahl nitrogen
TOC:	total organic carbon
TP:	total phosphorus
TS:	total solids
TSS:	total suspended solids
UASB:	upfow anaerobic sludge blanket
VFAs:	volatile fatty acids
VS:	volatile solids
VSS:	volatile suspended solids
WWTP:	wastewater treatment plant

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CHAPTER 1

INTRODUCTION

Throughout recorded history humankind has continually struggled to manage the natural environment in order to improve its well-being. The ability to control many aspects of the environment is the main characteristic that has set people apart from other species on the planet.

In the last half of this century, however, environmental quality problems have surfaced at an accelerated pace. The population explosion, greater energy use, increased food production needs, changes in life-style, and numerous technological developments have created many strains on parts of the global ecosystem. As a result, an increased concern for the environment is now being witnessed in many parts of the world.

Liquid waste management has long been recognized as a necessary action in order to improve environmental quality. Collection, treatment, disposal, and reuse of the wastewater generated in urban or rural areas has become a priority, wherever the social and economic conditions permit.

Anaerobic processes have always been an integral part of the wastewater treatment scheme. In the septic tank, one of the oldest and widest applications in municipal sewage treatment, most reactions take place under anaerobic conditions. The first heyday of anaerobic digestion occurred in the period from 1920 to 1935, when it was studied and applied extensively. The popularity of the anaerobic

processes suffered largely in the 1950s and 1960s, because aerobic and physical-chemical methods became attractive alternatives with their advantage in operation and impurity removal efficiency. The energy crisis in the early 1970s and the rapid growth of biotechnology have rekindled the interest in anaerobic processes. Today the use of anaerobic microorganisms covers a wide array of applications ranging from the wastewater treatment field to the production of food, medicines and industrial chemicals, to genetic engineering and enzyme technology.

In the wastewater treatment realm, anaerobic digestion has been traditionally employed to prepare municipal sludges for ultimate disposal and provide a source of energy. Accordingly, most of the research has been focused on the methane generating phase of the process. Little attention has been paid to the acid-phase digestion, the phase in which complex organic substances, such as carbohydrates, proteins and lipids, are converted anaerobically to volatile fatty acids (VFAs) and other low molecular weight soluble carbon compounds.

Improved knowledge of the acid-phase digestion can be useful in a variety of situations, ranging from the operation of the overall digestion process itself, to its effect on subsequent treatment processes. A better understanding of digester dynamics during shock loading or digester operational stability can be obtained by exploring the acidogenic step. In addition, since the main products of this phase are soluble organic substrates, they can be used as an energy source for other processes, such as biological phosphorus removal or two-stage biological nitrogen removal.

CHAPTER 2

LITERATURE REVIEW

2.1. AN OVERVIEW OF ANAEROBIC DIGESTION

Anaerobic digestion is a response to controlled conditions of a series of reactions which occur in many circumstances in nature. It is a biological process in which organic matter is ultimately converted to methane and carbon dioxide in the absence of molecular oxygen. The overall process entails direct and indirect symbiotic associations between several distinct groups of microbial populations.

A number of investigators have attempted to elucidate the different steps and pathways involved in anaerobic metabolism (Holland et al., 1987). As many as nine recognizable steps, each mediated by a specific group of microorganisms, have been identified (Harper and Pohland, 1986). For the purpose of this research, however, the scheme proposed by Kaspar and Wuhrmann (1978a) seems to be the most appropriate, since it provides a more comprehensive insight on the initial steps involved in the degradation of biopolymers. According to this scheme, the following six processes may take place during the anaerobic digestion of a complex substrate:

1) Hydrolysis of particulate and soluble biopolymers (carbohydrates, proteins, lipids).

2) Fermentation of amino acids and sugars.

3) Anaerobic oxidation of long-chain fatty acids and alcohols.

4) Anaerobic oxidation of intermediate products such as volatile fatty acids (with the exception of acetate).

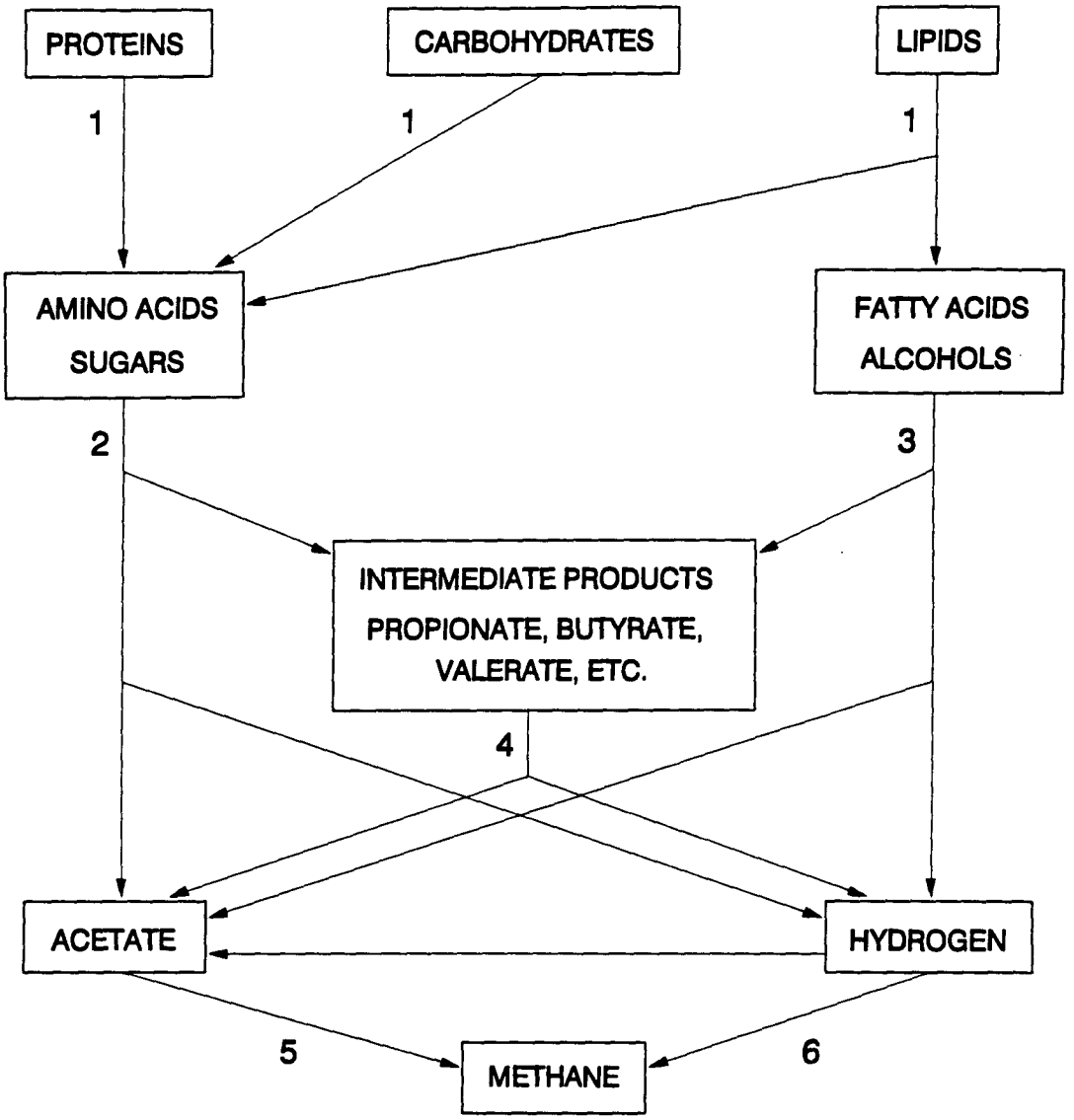
5) Conversion of acetate to methane.

6) Conversion of hydrogen and carbon dioxide to methane.

Acid-phase digestion involves the first three reactions, while methanogenesis is implied by the last three. A summary of the above sequence of reactions is depicted in Figure 2.1. Although bacteria are the main biological agents involved in anaerobic degradation of organic compounds, fermentative ciliate and flagellate protozoa, and several anaerobic fungi may also contribute in some ecosystems (McInerney and Bryant, 1981).

Hydrolysis of organic matter is a process accomplished by extracellular enzymes. The reaction rate can be greatly affected by the pH and the operating conditions of the system (Verstraete et al., 1981). Complex carbohydrates such as cellulose and starch are hydrolyzed to simple sugars, proteins to amino acids, and lipids to long-chain fatty acids.

Fermentation, in this context, can be defined as a microbial metabolic process in which organic compounds serve both as electron donors and as electron acceptors. Any hydrogen generated during fermentation originates from dehydrogenation of pyruvate. This hydrogen production mechanism is not inhibited by high partial pressures of hydrogen, up to 0.5 atm H_2 (Thauer et al., 1977). Sugars and amino acids are the substrates undergoing fermentation and they produce biomass, intermediate degradation products (propionate, butyrate, etc.), and the methane precursors acetate and hydrogen (Figure 2.1).



1) HYDROLYSIS
2) FERMENTATION
3) ANAEROBIC OXIDATION OF FATTY ACIDS
4) ANAEROBIC OXIDATION OF INTERMEDIATE PRODUCTS
5) ACETOCLASTIC METHANOGENESIS
6) REDUCTIVE METHANOGENESIS ($CO_2 + 4H_2$---> $CH_4 + 2H_2O$)

FIGURE 2.1. PATHWAYS OF ANAEROBIC METABOLISM
(Adapted from Kaspar and Wuhrmann, 1978a)

In anaerobic oxidation, molecular hydrogen serves as the main sink for electrons. The principal pathway of hydrogen formation is via oxidation (transfer of electrons to protons) of reduced pyridine dinucleotides and ferredoxin (Kaspar and Wuhrmann, 1978a). It has been demonstrated that the degradation of long-chain fatty acids under anaerobic conditions occurs by a mechanism called β-oxidation (Jeris and McCarty, 1965).

2.2. WASTEWATER COMPOSITION

Composition, in general, refers to the actual amount of physical, chemical and biological constituents in wastewater. Since the organic chemical constituents are of paramount importance in anaerobic digestion, the following discussion will revolve around these compounds.

Municipal wastewater is a principal source of organic matter entering the aquatic environment. The suspended impurities in liquid wastes from residential units, hotels, hospitals, restaurants, offices and commercial buildings are on average 70 percent organic in nature (Fair et al., 1971). Settling of wastewater, through primary sedimentation, provides raw or primary sludge, which is often used as a feed to anaerobic digesters. Primary sludge contains a great number of organic compounds, however, most of them can be grouped in three major classes: carbohydrates, proteins and lipids. Although many current research efforts have been directed towards the identification of specific organic chemicals in raw sludge (eg. aromatic hydrocarbons, chlorinated compounds etc.), the three classes mentioned here

are the key players in anaerobic processes.

The composition of primary sludge, measured by various researchers, is shown in Table 2.1. Variation in composition may not only reflect the differences in individual wastes, but also recent changes in life style, as indicated by the high carbohydrate and low lipid content of the sludge used in this study.

TABLE 2.1. ORGANIC COMPOSITION OF PRIMARY SLUDGE

REFERENCE	% VOLATILE SOLIDS				% TS
	Carbo-hydrates	Proteins	Lipids	Total	VS
Balmat	30	32	25	87	78
Buswell & Neave	18	32	41	91	61
Heukelekian	17	36	45	98	76
Heukelekian & Balmat	30	31	24	85	65
Higgins et al.	66	12	15	93	75
Hunter & Heukelekian	44	19	18	81	81
Maki	62	29	22	113	65
O' Rourke	-	22	23	-	80
AVERAGE	38	27	27	92	73
This study	58	21	17	96	75

2.2.1. CARBOHYDRATES

Carbohydrates are the most abundant organic compounds in the biosphere. They can be precisely defined as polyhydroxy aldehydes or ketones with the general

formula $(CH_2O)_n$, where $n \geq 3$. Depending on the number of carbon atoms included, carbohydrates can be classified as monosaccharides (simple sugars containing 3 to 9 carbon atoms), oligosaccharides (mainly disaccharides with 12 carbon atoms) and polysaccharides (Bailey and Ollis, 1977).

Polysaccharides are extremely large molecules. The majority of carbohydrates in nature exist as such macromolecules with molecular weights ranging from 25,000 to 15 million. They consist, for the most part, of simple and derived sugars linked together by glycosidic bonds. Polysaccharides are insoluble in water and can form colloidal suspensions (Gaudy and Gaudy, 1980). The most important polysaccharides found in municipal wastewaters include cellulose, hemicellulose, pectin and starch (Hunter and Heukelekian, 1965).

Cellulose is the most profuse source of organic carbon on earth. Structurally, it is an non-branched polymer of D-glucose units with a molecular weight span from 50,000 to over 1 million. The glycosidic linkage occurs between the 1 and 4 carbons of successive glucose units (β-1,4 bonding). Generally, cellulose is not easily biodegradable, since few microorganisms are able to break down the β-1,4 bonds (Tsao et al., 1978). The major source of cellulose in domestic wastewater is paper. Cellulose is the main constituent of non-nitrogenous, alcohol-insoluble matter (i.e. carbohydrates and lignin) in sewage, accounting for 45 to 60% of the total (Hunter and Heukelekian, 1965; Higgins et al., 1982).

Hemicellulose is a group of heteropolymers with frequent side chains. The common monomeric components of hemicellulose include hexoses such as glucose, mannose and galactose; pentoses such as xylose and arabinose; and uronic acids.

Hemicellulose is the next most significant constituent (after cellulose) of polysaccharides in wastewater, ranging from 20 to 25% (Hunter and Heukelekian, 1965).

Pectin comprises a family of complex polysaccharides containing mostly methylated poly-D-galacturonic acid, arabinose and galactose (Conn and Stumpf, 1976).

Starch has the general formula $(C_6H_{10}O_5)_x$. It occurs in two forms: amylose and amylopectin. Amylose is a linear polymer of D-glucose units linked together by α-1,4 bonds. The amylose molecule contains 100 to 1,000 glucose units and it is insoluble in water. Amylopectin is a branched polymer of glucose containing both α-1,4 bonds and α-1,6 bonds which initiate side chains. It is much larger than amylose (500 to 5,000 glucose units), is soluble in water and can form gels by absorbing water (Bailey and Ollis, 1977).

Both pectin and starch can be found in small amounts in wastewater (less than 10% of the total carbohydrates and lignin).

Lignin is a complex polymeric aromatic substance of variable structure making up a substantial portion of the woody parts of plant tissue, where it helps to "cement" cellulose fibers together (Lehninger, 1975). Both cellulose and lignin play an important structural role in plants and one of the main processes of the pulp and paper industry is to separate these two components. Lignin is considered to be a refractory compound not amenable to biodegradation. It comprises 5 to 15% of the non-nitrogenous, alcohol-insoluble matter in domestic wastewater (Hunter and Heukelekian, 1965) and in primary sludge (Higgins et al., 1982).

2.2.2. PROTEINS

Proteins constitute the most complex organic compounds in the biosphere. They all contain carbon, hydrogen, oxygen and nitrogen. Phosphorus and sulphur are present in a few. Proteins are an essential part of all living matter and a major dietary constituent. They are polymers of α-amino acids joined together by peptide bonds. These covalent bonds arise by elimination of the elements of water from the carboxyl group of one amino acid and the α-amino group of the next. The molecular weight of proteins, depending on the number of the polymers, can vary from a few thousand to several million (Gaudy and Gaudy, 1980). Proteins are divided into two major classes on the basis of their conformation: fibrous and globular. Fibrous proteins are physically tough and are insoluble in water or dilute salt solutions. On the other hand, most globular proteins are soluble in aqueous systems and they usually have a mobile or dynamic function in the cell (Lehninger, 1975).

The importance of proteins in anaerobic digestion stems from their significant buffering capacity (due to the presence of hydroxy and amino groups) as well as their ability to serve as carbon and energy sources. The nutritional value of the individual amino acids to the microorganisms is an additional asset (Tsao, 1984).

Almost all of the 20 known amino acids have been identified in untreated sewage. Alanine, aspartic acid, glutamic acid, leucine and iso-leucine are the most predominant ones (Heukelekian and Balmat, 1959; Kahn and Wayman, 1964). The former investigators have reported that the amino acids accounted for 65 to 80% of the total nitrogenous matter. According to Hunter and Heukelekian (1965), the amino

acids averaged 55% of the total organic nitrogen. Painter et al. (1961) and Hanson and Lee (1971) have reported that about 35 to 40% of the total organic nitrogen was in the amino acid form. It should be noted, however, that this diversity in amino acid content in raw sewage may be mainly the result of analytical determinations (particulate vs. soluble forms of nitrogen). Higgins et al. (1982) have found that the amino acid content of the primary sludge averaged about 65% of the total organic nitrogen.

2.2.3. LIPIDS

Lipids are organic biomolecules which are soluble in non-polar solvents such as chloroform, benzene or ether, and practically insoluble in water. Consequently, lipids are diverse in their chemical structure and biological function (Conn and Stumpf, 1976). Lipids have been classified in several different ways. The most satisfactory classification, based on their common chemical characteristics, includes simple, compound and non-saponifiable lipids (Gaudy and Gaudy, 1980).

Fats, oils and waxes are all simple lipids. Fats and oils are esters of various fatty acids and the trihydroxy alcohol glycerol. Waxes are esters of fatty acids and long-chain monohydroxy alcohols. The most common fatty acids contain 16 or 18 carbon atoms and may be saturated such as palmitic and stearic or unsaturated such as oleic, linoleic, linolenic and palmitoleic (Gurr and James, 1971).

Compound lipids are also esters of various fatty acids and alcohols. The addition of phosphorus and nitrogen compounds results in the creation of

phospholipids, and the addition of carbohydrates in that of glycolipids.

Non-saponifiable lipids do not contain fatty acids and, hence, do not yield soaps (salts of fatty acids) on alkaline hydrolysis. This subclass includes sterols, fat-soluble vitamins and plant pigments.

Lipids are contributed to domestic wastewater in butter, lard, margarine, vegetable fats and oils, and other food items (Metcalf and Eddy, 1991). The esterified fatty acids are the main lipid component (50 to 70% of total lipids) in raw sewage, followed by the unsaponifiable matter (15 to 25%). Free fatty acids and phospholipids have been found in small amounts (Hunter and Heukelekian, 1965). In primary sludge, however, free fatty acids may contribute between 40 and 60% of the total lipids, as a result of the rapid hydrolysis of the fatty acid esters to free fatty acids (Heukelekian and Mueller, 1958). Saturated fatty acids represent about 70 to 80% of the total fatty acids identified, esterified or free. Palmitic and stearic acids are the most commonly found saturated acids and oleic acid the predominant unsaturated one (Higgins et al., 1982).

2.3. PATHWAYS OF VFA FORMATION

The ability to produce volatile fatty acids under anaerobic conditions is a widespread attribute in the microbial world. A large number of bacterial species is capable of utilizing complex organic substrates such as carbohydrates, proteins and lipids to produce VFAs and other soluble carbon compounds via a variety of anaerobic metabolic pathways. In the following discussion, the metabolic pathways

of the three major organic components of the primary sludge will be reviewed.

2.3.1. CARBOHYDRATE METABOLISM

a) Hydrolysis

Bacteria are unable to take up particulate polysaccharides, because biopolymers as such cannot penetrate the cell membrane. Therefore, microorganisms excrete enzymes that are capable of degrading the complex biopolymers to small transportable molecules. These enzymes can either be set free by the organisms or remain associated with them.

Cellulose can be hydrolyzed by a number of anaerobic bacteria. *Bacteroides succinogenes* was the first one isolated from rumen (Hungate, 1949). Other common cellulose hydrolyzing organisms include *Clostridium lochheadii* and *Clostridium cellobioparum* (Hungate, 1957), *Butyrivibrio fibrisolvens* (Shane et al., 1969), and *Clostridium thermocellum* (Gottschalk, 1986). All cellulolytic bacteria excrete the enzyme complex called cellulase. It consists, in general, of three major enzyme components (Gong et al., 1979):

1) endoglucanase which cleaves the β-1,4 glycosidic bonds in the cellulose molecule,

2) exoglucanase which removes cellobiose (a disaccharide unit of cellulose) from non-reducing ends of the molecule, and

3) cellobiase which hydrolyzes cellobiose or cellotriose to two or three molecules of glucose respectively.

A detailed description of the mode of action of this exoenzyme complex is provided by Cuskey et al. (1982). Cellulose hydrolysis yields the simple sugar glucose.

Hemicellulose can be degraded by anaerobic organisms producing the exoenzyme complex hemicellulase. The complexity of this enzyme system far exceeds that of cellulose, as hemicellulose is composed of a greater variety of monomers linked together by different types of bonds. A comprehensive review of hemicellulase excreted by anaerobic microbes is presented by Dekker and Richards (1976).

Pectin hydrolysis involves bacteria found in rumen such as *Bacteroides succinogenes*, *Bacteroides ruminicola*, and *Butyrivibrio fibrisolvens*. Three types of enzymes are associated with the degradation of pectin to galacturonic acid residues. Pectinesterase demethylates pectin to produce poly-D-galacturonic acid and methanol, while hydrolase breaks down the polymer to oligomeric chains. Then, lyase depolymerizes the chains to form the final products of hydrolysis (Tsao, 1984).

Starch, as a storage material, is amenable to biodegradation. Among the many anaerobes able to hydrolyze starch are *Streptococcus bovis*, *Bacteroides amylophilus*, *Succinomonas amylolytica*, and a number of *Lactobacillus* species (Tsao, 1984). Complete hydrolysis of starch to glucose requires the synergistic action of four types of specific enzymes (Fogerty and Kelly, 1979).

b) Fermentation of Sugars

Glucose, the main simple sugar generated from polysaccharide hydrolysis, is

commonly used by fermentative microorganisms as an energy source. Most of the products formed in the fermentation of glucose originate from pyruvic acid which is produced via the glycolytic Embden-Meyerhof-Parnas (EMP) pathway. According to this pathway, two molecules of pyruvic acid are produced per molecule of glucose through a series of reactions (Figure A1, Appendix A). In addition, two molecules of adenosine-5'-triphosphate (ATP) are generated and two molecules of nicotinamide adenine dinucleotide (NAD) are reduced in the process. Since no oxygen is involved, this pathway is common in both aerobic and anaerobic metabolism (Gaudy and Gaudy, 1980). Depending on the anaerobic microbial species present, subsequent pyruvic acid fermentation can lead to the production of different VFAs.

Acetic acid is produced in a number of fermentations. There are certain bacteria, however, which form acetate as the predominant end-product. Representative genera of acetogenic organisms include *Clostridia* and *Acetobacteria*. It has been demonstrated, for example, that *Clostridium formicoaceticum* can ferment 1 mol of hexose to 3 mol of acetic acid (Ljungdahl, 1986):

$$C_6H_{12}O_6 \longrightarrow 3CH_3COOH \qquad (2.1)$$

Acetic acid is formed by the EMP pathway and by reduction of carbon dioxide to acetate (Figure A2, Appendix A). *Clostridium aceticum* and *Acetobacterium woodii* ferment hydrogen and carbon dioxide to acetate. It should be noted that carbon monoxide plays an important role as a precursor of the carboxyl group of acetate (Eden and Fuchs, 1982; Cole, 1988):

$$2CO_2 + 4H_2 \longrightarrow CH_3COOH + 2H_2O \qquad (2.2)$$

Acetic acid is also generated by mixed-acid producers. They metabolize pyruvate to acetate and other products, as will be discussed later (Section 2.4)

Propionic acid is a major end-product of fermentations carried out by many anaerobes of the *Propionibacterium* genus. *P. pentosaceum* and *P. shermanii* can degrade pyruvic acid via the succinate-propionate pathway. Lactyl-CoA and acrylyl-CoA are intermediates, while electron-transferring flavoprotein functions as hydrogen carrier. The overall reaction is as follows (Doelle, 1975):

$$3CH_3COCOOH + 3H_2 \longrightarrow 2CH_3CH_2COOH + CH_3COOH + CO_2 + H_2O \quad (2.3)$$

Lactic acid is a preferred substrate for certain bacteria such as *Clostridium propionicum* and *Megasphaera elsdenii* which produce propionic acid via the acrylate pathway (Figure A3, Appendix A). This pathway can be summarized as follows (Papoutsakis and Meyer, 1985):

$$3CH_3CHOHCOOH \longrightarrow 2CH_3CH_2COOH + CH_3COOH + CO_2 + H_2O \quad (2.4)$$

Butyric acid can be formed as a main fermentation product by many obligate anaerobes which belong to the four genera: *Clostridium*, *Butyrivibrio*, *Eubacterium*, and *Fusobacterium.* The reactions involved in the production of butyric acid are presented in Figure A4, Appendix A. In this pathway, the conversion of pyruvate to acetyl-CoA is catalyzed by the pyruvate-ferredoxin oxidoreductase enzyme system. Also, butyryl-CoA is not converted to butyric acid by simple hydrolysis, but via the formation of butyryl phosphate, which yields an additional ATP molecule (Gottschalk, 1986).

2.3.2. PROTEIN METABOLISM

a) Hydrolysis

The bacteria involved in protein metabolism have the ability to produce proteolytic enzymes which break the biopolymers into their monomeric components (i.e. amino acids) before they can enter the cell membrane and be used either as building blocks or as fermentative substrates.

Protein hydrolysis progresses in steps in reverse manner to those in which proteins are synthesized (Sawyer and McCarty, 1978):

$$\text{Protein} \longrightarrow \text{proteoses} \longrightarrow \text{peptones} \longrightarrow$$
$$\text{polypeptides} \longrightarrow \text{dipeptides} \longrightarrow \alpha\text{-amino acids} \qquad (2.5)$$

The most common anaerobic proteolytic microorganisms belong to the genus *Clostridium* (Siebert and Torein, 1969; Hobson and Shaw, 1971). *Bacteroides ruminicola* has also been found to exhibit similar activity (Hobson and Shaw, 1974).

Proteolytic enzymes are divided into two groups, according to their mode of action on a polypeptide chain: endopeptidases and exopeptidases. Pepsin, a typical endopeptidase, has very broad specificity, but preferentially attacks polypeptide chains along their length, whenever residues of aromatic amino acids occur.

On the contrary, exopeptidases can only split terminal peptide bonds. They are subdivided into: aminopeptidases, which require a free terminal amino group and are dependent on metal ions for their activity; and carboxypeptidases, which break down peptides with a free terminal carboxy group (Lehninger, 1975). The synergistic action

of both types of enzymes results in the formation of free α-amino acids.

b) Amino Acid Fermentation

Several single amino acids can serve as energy and carbon sources for strict or facultative anaerobes. Organisms possessing the enzyme dehydrogenase can convert aliphatic amino acids (containing the alkyl group, R) to the corresponding VFAs via reductive deamination. Hydrogen ions act as the hydrogen donor. A general reaction can be written as follows (Doelle, 1975):

$$R\text{-}CHNH_2COOH + 2H^+ \longrightarrow R\text{-}CH_2COOH + NH_3 \qquad (2.6)$$

Many microorganisms can specifically ferment individual amino acids to produce VFAs. A few representative cases are outlined below. *Clostridium propionicum* employs the acrylate pathway (Figure A3, Appendix A) to convert alanine, via lactic acid, to a mixture of propionic and acetic acid (Gottschalk, 1986). Glycine is a preferred substrate for *Clostridium histoliticum* and *Diplococcus glycinophilus*, with acetic acid being the main product according to the equation (Elsden and Hilton, 1978):

$$4CH_2NH_2COOH + H_2O \longrightarrow 3CH_3COOH + 4NH_3 + 2CO_2 \qquad (2.7)$$

Two different pathways have been elucidated regarding the fermentation of glutamic acid by obligate anaerobes. *Clostridium tetanomorphum* employs the methylaspartate pathway, which is rather unusual and is used only by the *Clostridium* species, for the formation of an acetic and butyric acid mixture with a 3:1 ratio

(Gottschalk, 1986). The same acids can be also produced (at a 2:1 ratio) via the hydroxyglutarate pathway followed by *Acidaminococcus fermentans*, *Clostridium microsporum* and other species (Buckel and Barker, 1974).

Not all amino acids can be fermented singly, or at least no organism capable of utilizing certain amino acids has been isolated.

The Stickland reaction is an oxidation-reduction reaction between pairs of amino acids. One amino acid acting as the hydrogen donor is oxidized, and a second one acting as the hydrogen acceptor is reduced. This allows the amino acids that cannot be fermented individually to be used as an energy source. This reaction is curried out by many proteolytic clostridia such as *C. stickandii*, *C. sporogenes*, and *C. histoliticum* (Barnard and Akhtar, 1979; Barker, 1981). The coupling of valine (hydrogen donor) and glycine (hydrogen acceptor), for example, results in the formation of iso-butyric acid and acetic acid. It was first demonstrated by Cohen-Bazire et al. (1948):

$$CH_3CHCH_3CHNH_2COOH + 2CH_2NH_2COOH + 2H_2O \longrightarrow$$
$$CH_3CHCH_3COOH + 2CH_3COOH + 3NH_3 + CO_2 \qquad (2.8)$$

In a similar fashion, iso-leucine or leucine, acting as hydrogen donors can be oxidized to the isomers of the valeric acid. In the case of iso-leucine the predominant isomer is 2-methylbutyric acid, and in that of leucine 3-methylbutyric acid (Elsden and Hilton, 1978).

2.3.3. LIPID METABOLISM

a) Hydrolysis

The hydrolysis of ester linkages in lipids requires the presence of lipolytic enzymes. Since the environment in which hydrolysis takes place involves a lipid-water interface, this is a heterogeneous enzymatic catalysis. Two common types of lipolytic enzymes include lipases and phospholipases.

Lipases catalyze the stepwise and partially reversible hydrolysis of fatty acid ester bonds in simple lipids (triglycerides), with the intermediate formation of di- and monoglycerides and the ultimate release of 3 mol of the corresponding fatty acid and 1 mol of glycerol (Ratledge, 1988):

$$\begin{aligned} \text{triglyceride} &\longleftrightarrow \text{diglyceride} + \text{fatty acid} \longleftrightarrow \\ &\text{monoglyceride} + \text{fatty acid} \longrightarrow \\ &\text{glycerol} + \text{fatty acid} \end{aligned} \tag{2.9}$$

Microbial lipases are classified into three groups according to their specificity: non-specific, 1-3 specific (catalyzing reactions at the C_1 and C_3 positions of the triglyceride), and fatty acid specific (Macrae, 1984). Lipases are widespread in nature. Under anaerobic conditions, they are excreted by microorganisms belonging mainly to the genera *Bacillus*, *Chromobacterium*, and *Serratia* (Finnerty, 1988).

Phospholipases are involved in the hydrolysis of phospholipids. Four types of phospholipases are known and are classified according to the ester bond which they hydrolyze (Waite, 1987). Phospholipid metabolism results in the production of

the corresponding fatty acids and a variety of other organic compounds, depending upon the substrate utilized. Phospholipases have been found in many spore-forming anaerobic bacteria such as *Clostridium perfrigens* and *Bacillus cereus* (Low, 1981).

b) Anaerobic Degradation of Fatty Acids

The anaerobic metabolism of long chain fatty acids occurs via a mechanism called β-oxidation, because the beta carbon (second from the carboxyl carbon) is oxidized. This pathway involves repetition of a sequence of reactions that results in the removal of two carbon atoms as acetyl-CoA with each repetition (Gaudy and Gaudy, 1980).

The first step in the β-oxidation is its activation by one of several enzymes called acyl-CoA synthetases. Since four hydrogen atoms are generated per molecule of acetyl-CoA, the overall reaction can only proceed if much of the hydrogen can be converted to H_2 gas. Many anaerobic bacteria form the enzyme hydrogenase, which catalyzes the reversible reaction of hydrogen production from a reduced high-energy electron carrier such as reduced pyridine dinucleotides and ferredoxin (Benemann and Valentine, 1971):

$$2H^+ + 2e^- \longleftrightarrow H_2 \qquad (2.10)$$

The stoichiometry of the β-oxidation reaction including oxidation of NAD(P)H or ferredoxin is as follows (Jeris and McCarty, 1965; Gujer and Zehnder, 1983):

$$(-CH_2CH_2-) + 2H_2O \longrightarrow CH_3COOH + 2H_2 \qquad (2.11)$$

The ATP yield of this reaction is not known. The oxidation of NAD(P)H, however, has a higher redox potential (-0.32 V at pH 7) than that of pyruvate dehydrogenation (-0.68 V at pH 7) (Wolin, 1976). Based on thermodynamic considerations, partial pressures of H_2 gas higher than 0.5 atm may slow down the oxidation of NAD(P)H as a result of product inhibition (Kaspar and Wuhrmann, 1978a).

Little variation has been found in the β-oxidation scheme for the various saturated fatty acids except for the activation step. The enzyme catalyzing the activation of fatty acids falls into three distinct categories depending on chain length. There is evidence that unsaturated fatty acids are first hydrogenated and then degraded by the same mechanism (Novak and Carlson, 1970; Hobson et al, 1974).

Acetyl-CoA, the main intermediate of β-oxidation can be converted to either acetic or butyric acid (Harper and Pohland, 1986). Propionic acid may also be formed as an end-product of the metabolism of fatty acids that contain odd numbers of carbon atoms. A three-carbon residue, propionyl-CoA, remains after the removal of the other carbons as acetyl-CoA, and is converted to propionic acid under anaerobic conditions (McInerney and Bryant, 1981).

2.4. OTHER PATHWAYS OF ANAEROBIC METABOLISM

A great number of microorganisms can degrade the intermediates of anaerobic metabolism alternatively to form a wide array of end-products. Two groups of anaerobes of particular interest are enterobacteria and lactic acid bacteria.

2.4.1. PRODUCTS FORMED BY ENTEROBACTERIA

Enterobacteria are classified into three categories according to the type of fermentation they carry out: mixed acid, butanediol, and propanediol producers. The mixed acid producers belong to the genera *Escherichia*, *Salmonella*, and *Shigella*. A typical member of this group, *Escherichia coli*, ferments sugars to lactic, acetic, succinic, and formic acids. Smaller amounts of ethanol, carbon dioxide, and hydrogen gas are also formed. On the other hand, species of the genera *Enterobacter*, *Serratia*, and *Erwinia* show a different metabolic activity and are called butanediol producers. *Enterobacter aerogenes*, for example, forms mainly 2,3-butanediol, ethanol, carbon dioxide and hydrogen gas. Acid generation is minimal, except for some formic acid (Wood, 1961).

Both groups of bacteria mentioned employ the EMP pathway (Figure A1, Appendix A) for glucose breakdown. All products, except succinic acid are derived from pyruvic acid. The pathway leading to succinic acid branches off at phosphoenolpyruvate. The amounts of fermentation products formed depend very much on the activity on pyruvic acid of the three enzyme systems involved (Garvie, 1980).

Members of the Enterobacteria family, such as *Citrobacter freundii*, are able to metabolize glycerol (a product of lipid hydrolysis) either to 1,3-propanediol or to glyceraldehyde-3-phosphate. This process is assumed to be independent from the carbohydrate metabolism and occurs only if glycerol is available (Doelle, 1975).

2.4.2. PRODUCTS FORMED BY LACTIC ACID BACTERIA

Lactic acid bacteria are morphologically a heterogeneous group and characterized by their main end-product, lactic acid. These microorganisms are highly saccharolytic and lack most anabolic pathways, so they exhibit very specific nutritional requirements. Most lactic acid bacteria are strictly fermentative, but are aerotolerant (Bergy's Manual, 1974).

The three following pathways can be employed for the fermentation of glucose, via pyruvate, to lactic acid and other end-products (Gottschalk, 1986):

1) The homofermentative pathway used mostly by *Lactobacillus* and *Streptococcus* species yields only lactic acid:

$$C_6H_{12}O_6 \longrightarrow 2CH_3CHOHCOOH \qquad (2.12)$$

2) The heterofermentative pathway used mainly by *Leuconostoc* species yields the following products:

$$C_6H_{12}O_6 \longrightarrow CH_3CHOHCOOH + CH_3CH_2OH + CO_2 \qquad (2.13)$$

3) The bifidum pathway employed by *Bifidobacterium* species yield lactic acid and acetic acid:

$$2C_6H_{12}O_6 \longrightarrow 2CH_3CHOHCOOH + 3CH_3COOH \qquad (2.14)$$

Besides glucose, many other saccharides can be utilized by lactic acid bacteria including fructose, galactose, lactose, and pentoses.

2.5. FACTORS AFFECTING VFA PRODUCTION

In general, the acid-phase digestion products may be markedly affected by the characteristics of the wastewater, environmental factors such as culture pH, temperature, oxidation-reduction potential (ORP), reactor configuration and available trace minerals, and operational parameters such as hydraulic retention time (HRT) and solids retention time (SRT).

The concept of optimizing VFA production by anaerobic digestion is a relatively new one in the wastewater treatment field. Traditionally, most of the research in anaerobic sludge digestion has been focused on the methanogenic phase of the process, where VFAs are used as substrate for the methane forming bacteria. Little attention has been paid, therefore, to the optimization of the acidogenic microorganisms coupled with suppression of the methanogenic ones.

Most of the valuable contributions on the acid-phase digestion have been obtained from studies using either soluble substrates such as glucose (Ghosh and Pohland, 1974; Uribelarrea and Pareilleux, 1981; Zoetemeyer et al., 1982b; and Cohen et al., 1984), a mixture of simple organics (Andrews and Pearson, 1965), lactose (Kisaalita et al., 1987; Hsu and Yang, 1991), a protein, gelatin (Breure and van Andel, 1984); or specific industrial wastewaters generated from sugar refineries (Gil-Pena et al., 1987), and ethanol distilleries (Machado and Sant'Anna, 1987). It is questionable, therefore, whether information available from these sources can be directly applied to the design and operation of anaerobic digesters treating primary sludge from municipal wastewater treatment plants.

Relatively few studies have been performed using primary sludge from municipal wastewater treatment facilities as a feed. Among them are those by O'Rourke (1968), Chynoweth and Mah (1971), Borchard (1971), Eastman and Ferguson (1981), Rabinowitz (1985), Gupta (1986), and Ghosh (1987).

Important findings from a selected number of the above mentioned studies are summarized in the following paragraphs.

Andrews and Pearson (1965) have observed that the acidogenic phase is fairly rapid, with an optimum cell residence time of 0.75 days. In addition, the type of volatile acids generated from a given substrate is greatly influenced by variation of the organism residence time.

Chynoweth and Mah (1971) have reported a high rate of lipid dissimilation in primary sludge digestion. Acetic, propionic, and butyric acids were the main products. Formic acid was also detected in smaller amounts.

On the contrary, Eastman and Ferguson (1981) have found that lipid degradation was minimal in the acid phase, but carbohydrates and proteins were extensively metabolized. The VFA production was significantly affected by pH but not by the influent solids concentration, at least up to 6% VS.

According to Zoetemeyer et al. (1982b), the relative production of individual VFAs from glucose depends on the dilution rate and more strongly on the culture pH value, with an optimum pH in the range between 5.0 and 6.0.

Rabinowitz (1985) has found that at sludge retention times ranging from 2.5 to 10 days, acetic and propionic acids made up more than 90% of the short chain VFA production, and appeared in the fermenter supernatant in a ratio of

approximately 55:45.

Gupta (1986) has reported that the net VFA generation consistently improved with increase in temperature between 10 and 30 ^{o}C, while pH control at 7.0 did not make any significant change in the total acid production.

According to Ghosh (1987), the culture pH had a strong effect on carbohydrate, protein and lipid reduction efficiencies. In addition, increase in digester hydraulic retention time increased the degradation of all the three major organic components, while higher temperatures had a more marked effect on protein reduction.

In order to optimize the acidogenic phase of anaerobic digestion, the first three reactions in Figure 2.1 need to be encouraged, with the concurrent suppression of the last three ones which are linked to methanogenic activity.

Methane formers are very sensitive to environmental factors. Their activity drops drastically at pH below 6 (Zehnder et al., 1981). They are very slow growing organisms as well. The maximum specific growth rate of methanogens can be one order of magnitude lower than that of acidogenic bacteria (Ghosh and Klass, 1978). It has been also observed that VFA conversion to methane does not occur below a critical SRT, which appears to be system specific (Ghosh, 1987). Methanogenesis can be suppressed, therefore, by operating the digester at a pH below 6 and an SRT value below the critical one.

2.6. APPLICATIONS OF THE ACID-PHASE DIGESTION

Improved knowledge of the acid-phase anaerobic digestion can be useful in a

number of situations, ranging from the operation of the overall digestion process itself to its effect on subsequent treatment processes. The increasing use of the two-phase digestion process creates an opportunity to further explore the acid-phase step. This may result to a better understanding of digester dynamics during shock loading, a greater operational stability of the system, or higher conversion rates of the organic material. Moreover, since the main products of acidogenic activity are short-chain, soluble organic substrates, they can be used as an energy and carbon source for bacteria carrying out other processes, such as biological phosphorus removal or two-stage biological denitrification. A brief description of the biological phosphorus removal process and the role of VFAs in it is outlined below.

2.6.1. THE BIOLOGICAL PHOSPHORUS REMOVAL PROCESS

Biological phosphorus removal has been a viable alternative to chemical precipitation as a means to control nutrient discharges into receiving water bodies. In this process, phosphorus is taken up by certain species of bacteria such as *Acinetobacter* beyond their need for normal cell maintenance and synthesis (Siebrietz et al., 1983). A continuous flow biological phosphorus removal scheme consists of a bioreactor in which an aerobic zone is preceded by an anaerobic one. The addition of simple soluble carbon substrates such as VFAs in the anaerobic zone results in phosphate release and carbon storage by the biomass (Nicholls and Osborn, 1979; Barnard, 1983; Comeau et al., 1986). Carbon storage occurs mainly in the form of poly-β-hydroxybutyrate (PHB) and poly-β-hydroxyvalerate (PHV) (Comeau et al.,

1988). The fact that phosphorus-removing bacteria can assimilate the acid-phase digestion products in the anaerobic zone provides them with a competitive advantage compared to other heterotrophic microorganisms occurring in activated sludge systems (U.S. EPA, 1987).

It has been observed that there is a relationship between the amount of VFAs added and the amount of phosphate released under anaerobic conditions (Fukase et al., 1982; Arvin, 1985). When the anaerobic zone is followed by an aerobic one, the phosphorus removing bacteria take phosphate from solution and store it in polyphosphate pools. The amount of phosphorus uptake in the aerobic zone can be correlated with that released under anaerobic conditions, which in turn is a function of the amount of stored VFAs (in the from of PHB or PHV) available in the aerobic zone (Wentzel, 1984). Hence, the biological phosphorus removal capacity of a plant can be improved by the presence of short chain soluble carbon compounds in the anaerobic zone. Rensick et al. (1984) have reported that acetic acid addition increased phosphorus removal from 45 to 97%. According to Rabinowitz and Oldham (1985), the incorporation of primary sludge digestion into the design of a simplified nutrient removal process resulted in an improvement of more than 100% in phosphorus removal.

In order to induce phosphorus release in the anaerobic zone, Siebritz et al. (1983) found that, in the absence of nitrates, the minimum concentration of VFAs required in this zone is 25 to 30 mg/L (as HAc). Since the VFA content of untreated domestic wastewater is usually very low (less than 10 mg/L), an external organic carbon source is needed to trigger the biological phosphorus removal mechanism.

The soluble carbon concentration in the anaerobic zone of the process can be increased either by the addition of preformed VFAs or by primary sludge digestion with return of the fermented material to the main bioreactor.

2.7. PROCESS CONFIGURATION

The basic requirement in anaerobic processes is the maintenance of a sufficient amount of active biomass in the reactor under high organic loading conditions. In order to meet this requirement, many suspended- and attached-growth process configurations have been thoroughly investigated, such as the completely mixed anaerobic digestion (conventional digester), anaerobic contact process (completely mixed reactor with clarifier and solids recycle), anaerobic filter, upflow anaerobic sludge blanket (UASB), fluidized bed, and expanded bed (Ross and Smallen, 1981; Metcalf and Eddy, 1991).

Two reactor configurations have been selected to investigate the acid-phase digestion of primary sludge: the completely mixed reactor (CMR) with clarifier and solids recycle system; and the upflow anaerobic sludge blanket (UASB) reactor. Completely mixed digesters (with or without solids recycle) have been of fundamental importance in anaerobic treatment, with a wide range of applications in municipal and industrial wastewaters (Speece, 1983; McCarty and Smith, 1986).

The upflow anaerobic sludge blanket process is a recent modification of the biolytic tank (Jewell, 1987). In the 1970s, Lettinga and co-workers developed the UASB reactor concept in the Netherlands (Lettinga et al., 1979). It is based on the

idea that anaerobic sludge has superior settling characteristics, if the physical and chemical conditions for sludge flocculation remain favorable. The sludge blanket (bed) can be considered as a separate fluid phase with its own specific properties. A well-established sludge blanket is fairly stable and can withstand relatively high mixing forces (Lettinga et al., 1980). The sludge generated in the UASB reactor (which is essentially of a vertical plug-flow type) often is in a very dense well-defined pellet or granular form. These granular particles are nearly spherical in shape with a 1 to 5 mm diameter (Hulshoff Pol et al., 1983). As such, the system acts as a biofilm in a sense that there is substrate diffusion into the conglomeration of microorganisms and product diffusion out (McCarty and Smith, 1986). Pellets have very good settleability and are readily retained in the reactor without the need of a clarifier (Sam-Soon et al., 1988). Pellet formation in UASB systems, however, depends upon the type of the wastewater used. For example, a high degree of pelletization has been achieved in systems treating carbohydrate wastes (Lettinga et al., 1980; Ross, 1984), but a limited pellet formation has been observed with acetate-propionate mixtures (de Zeeuw and Lettinga, 1980). No pellet formation has been obtained in reactors using olive oil processing wastes (Boari et al., 1984).

The UASB concept has been extensively used in laboratory-scale and pilot-scale studies. Its feasibility has been demonstrated in anaerobic treatment of low-strength wastes, acid-phase digestion, and denitrification experiments (Lettinga and Vinken, 1980). In addition, several full-scale installations have been successfully employed in Northern Europe treating a variety of industrial wastewaters (Maat and Habets, 1987; Lettinga and Hulshoff Pol, 1991).

CHAPTER 3

RESEARCH OBJECTIVES

As discussed in the previous chapter (Section 2.5), much of the information available on the acid-phase digestion has been obtained using simple, soluble carbon substrates. In certain cases, where primary sludge was used as feed, the main focus of the research was on methane production optimization (O'Rourke, 1968; Chynoweth and Mah, 1971; Ghosh, 1987), or on phase-separation techniques (Borchard, 1971), or on kinetic modelling (Eastman and Ferguson, 1981). Consequently, information regarding details on the mechanisms and pathways involved in the transformation of the organic substrates and the full spectrum of products formed was rather limited. On the other hand, Rabinowitz (1985) and Gupta (1986) have attempted to investigate the acid-phase step. Both studies, however, were of an exploratory nature, concentrating on the production of acetic, propionic and butyric acids.

In all of the above studies, however, the use of either batch reactors or conventional continuous-flow reactors without solids recycle eliminated the possibility to distinguish between the two retention times (HRT and SRT) of the system. It should be pointed out that HRT and SRT are two different operational parameters and that they may affect any biological process in a distinctly different manner. Moreover, only a few investigations included acid-phase digestion experiments with pH control (Eastman and Ferguson, 1981; Gupta, 1986). Even in these studies, no attempt was made to control the pH at values below 5.5.

It is, therefore, apparent that there is a need for an in-depth investigation of the acid-phase digestion of primary sludge. Inspired by the above observation, this research has attempted to explore the following areas:

1) Investigate independently the effect of certain **operational** parameters (i.e. HRT and SRT) on acidogenic digestion.

2) Investigate the effect of certain **environmental** parameters (i.e. pH, reactor configuration, and influent characteristics) on the process.

3) Suggest possible mechanisms and biochemical pathways involved in the conversion of carbohydrates, proteins and lipids to VFAs and other soluble end-products.

To meet the above stated objectives, a series of laboratory-scale, continuous-flow experiments has been employed. Their design allowed for separate control of reactor HRT and SRT values. Although CMR systems have long been used in environmental engineering practice for acid-phase digestion of primary sludge, the application of UASB systems, for the same purpose, is a rather novel idea.

A better understanding of the nature of the acidogenic phase can be achieved by determining the level and rate of carbohydrate, protein, and lipid utilization, and the rate and type of product formation (C_1 to C_6 VFAs, straight-chain and branched; alcohols; lactic acid and other soluble end-products; and certain gases). Additional valuable measurements included different types of solids and nitrogen forms, as well as pH and ORP.

CHAPTER 4

EXPERIMENTAL METHODS AND ANALYTICAL PROCEDURES

4.1. WASTEWATER SOURCE

The primary sludge used in this study was obtained from the Iona Island wastewater treatment plant located in Richmond, British Columbia, except for one experimental run, where the sludge was collected from the Lions' Gate treatment plant situated in North Vancouver, British Columbia. Both plants operate as primary treatment facilities, with subsequent anaerobic digestion for sludge stabilization.

The sludge was collected, usually once a week, from the underflow lines of the primary clarifiers in 25 L carboys and stored in the laboratory cold room at 4 ^{o}C. It was subsequently screened through a 0.6 cm rectangular-shaped mesh and transferred into a 60 L covered plastic container, which was kept at the same temperature (4 ^{o}C). The screening removed most of the large fibrous material and nearly all the hair and seeds that may cause major problems in pump lines.

The total solids (TS) content of the sludge was determined and then adjusted to a value of about 4,000 mg/L before feeding, by diluting with distilled water or by settling and decanting the excess liquid, in order to provide a level of comparable feed throughout the entire study. (The TS content of primary sludge, after screening, ranged from 2,400 to 10,350 mg/L, with an average value of 5,140 mg/L).

4.2. EXPERIMENTAL SET-UP AND OPERATION

4.2.1. GENERAL SYSTEM CONFIGURATION

This research involved the use of two laboratory-scale, continuous-flow units, having different configurations: a completely mixed reactor (CMR) with clarifier and sludge recycling, and an upflow anaerobic sludge blanket (UASB) reactor, as depicted in Figure 4.1.

Both reactors were made of plexiglass (internal diameter: 11.2 cm, total volume: 3.2 L, liquid volume: 3.0 L). The CMR system was equipped with a stainless steel stirrer with blades for mixing of the contents. Visually, complete horizontal and vertical mixing appeared to be achieved. The use of a clarifier (internal diameter: 11.2 cm, liquid volume: 1.0 L) was necessary to avoid a substantial loss of biomass through the effluent line. The bottoms of the clarifier and the UASB reactor were modified to an inverted cone shape (height of cone: 8.0 cm, diameter at bottom: 4.0 cm) in order to provide good settling conditions for the clarifier and a better mixing/diffusion flow pattern in the UASB system respectively.

The two reactors were hermetically sealed to avoid any air entrapment. A small, cone-shaped device (height of cone: 6.0 cm, diameter at top: 4.0 cm) was attached internally to the cover of each reactor to act as a gas collection system. The gas production was monitored by two wet gas flow meters via water trap flasks.

Spigots for sampling and wasting were placed at different heights (12.0 and 24.0 cm from the bottom in the CMR reactor; and 8.0, 16.0 and 26.0 cm from the

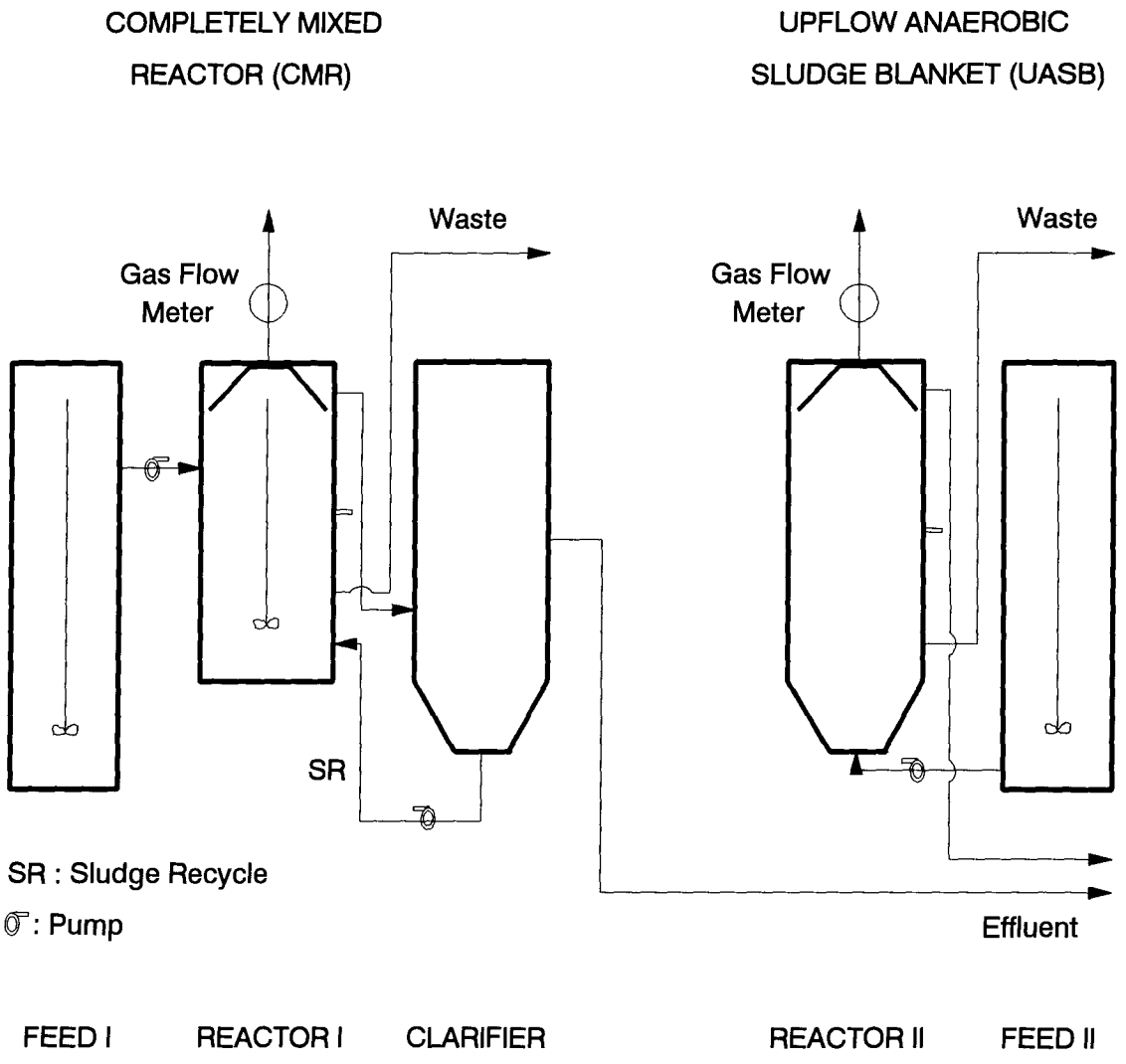


FIGURE 4.1. EXPERIMENTAL LAYOUT

bottom in the UASB unit). However, the lowest port in each reactor was exclusively used for wasting purposes. The other ports were periodically used to test the operational stability of the systems.

At two strategic diametrically opposite points, perpendicular to the feed-wasting-effluent ports, a combination oxidation-reduction potential (ORP) probe (Broadley-James Corporation) and an epoxy-body combination pH probe (Cole-Parmer Company) were inserted into each reactor. The ORP probe uses a Ag/AgCl reference electrode, with a platinum band as the noble metal, and the pH elecrode has a sealed (gel) reference electrode. Each probe was affixed to one end of a piece of rigid plastic tubing which slid inside the sleeve of another plastic tube, with minimum resistance. This latter tube opened up through a ball valve acting as a channel to allow the probe to slide into and out of the reactor. An O-ring seal inserted between the two cylinder walls prevented liquid being forced by back pressure from the interior of the reactor.

The ORP probes were used throughout the entire experimental study, while the pH probes were inserted only during the last two runs (Runs 4A and 4B), as part of the pH control strategy.

4.2.2. OPERATION

A total of 11 runs were conducted to investigate the effects of selected operational and environmental parameters on the acid-phase digestion of primary sludge. The research evolved into 4 stages, and in each stage an attempt was made

to explore the influence of a particular parameter.

In Stage 1 (Runs 1A to 1D) the role of Hydraulic Retention Time (HRT) was investigated, while Stage 2 (Runs 2A to 2C) focused on the effect of Solids Retention Time (SRT). The question of reproducibility at different conditions (summer/winter) and the source of influent sludge were the targets in Stage 3 (Runs 3A and 3B). Finally, the effect of pH was explored in Stage 4 (Runs 4A and 4B). All experiments were conducted at an ambient liquid temperature between 18 and 22 ^{o}C.

A summary of operating conditions is presented in Table 4.1. The SRT of the systems was controlled by wasting the appropriate volume from each reactor on a daily basis. The waste volume was slightly adjusted, when necessary, to compensate for the loss of biomass [measured as Volatile Suspended Solids (VSS)] through the effluent line. For the UASB system, the wastage was based on the sludge blanket volume (eg. to maintain an SRT of 10 days, one tenth of the volume of the blanket was wasted). Since the VSS content of the supernatant and the effluent was very low, usually less than 2% of that of the blanket, it was considered to have no appreciable effect.

The HRT in each system was controlled by a Cole-Parmer Company pump (Model 7015-21). The difference in liquid volume in the feed containers was calculated daily using a specially graduated stick and converted into the corresponding HRTs.

For feeding purposes, the primary sludge was transferred from the 60 L plastic container to two 10 L buckets and, after adjusting the TS content to 4,000 mg/L (as explained in Section 4.1.), it was added to the two feed tanks at the end of each

experimental day. This was done to minimize possible changes in feed characteristics due to higher temperatures in the early afternoon hours, especially during the summer months. To avoid altering the characteristics of the feed due to excess aeration, the feed tanks were covered with plastic lids and the stirrer speeds were kept as low as possible, while still keeping the particulate matter in suspension.

TABLE 4.1. OPERATING CONDITIONS (MEAN VALUES)

RUN	REACTOR TYPE	SRT (d)	WASTE (ml/d)	HRT (hr)	pH	ORP (mV)
1A	CMR	10	290	9.03	5.25	-326
	UASB	10	180	9.25	5.14	-369
1B	CMR	10	280	6.14	5.27	-284
	UASB	10	250	6.09	5.33	-362
1C	CMR	10	290	12.12	5.01	-309
	UASB	10	160	12.07	4.96	-385
1D	CMR	10	290	14.91	5.10	-325
	UASB	10	150	15.28	4.98	-370
2A	CMR	15	190	12.20	5.17	-343
	UASB	15	110	12.11	5.09	-376
2B	CMR	20	140	12.06	5.23	-364
	UASB	20	80	11.94	5.09	-391
2C	CMR	5	400	12.14	5.63	-354
	UASB	5	275	11.89	5.52	-385
3A	CMR	10	290	11.84	5.15	-296
	UASB	10	170	12.16	4.98	-371
3B	CMR	10	290	12.05	5.03	-311
	UASB	10	160	12.11	5.05	-367
4A	CMR	10	290	12.22	4.42	-278
	UASB	10	160	12.13	4.47	-333
4B	CMR	10	290	11.97	6.09	-326
	UASB	10	160	12.02	6.05	-393

Total solids (TS) were selected as the control parameter, since their analysis involves a simple, direct and readily accessible method. The TS concentration applied in this study was determined by a trial-and-error procedure, as the highest amount of solids contained in the feed without causing frequent operational problems. Two previous attempts, using 10,000 and 7,000 mg/L TS respectively, were proven to be unsuccessful due to a number of regular operational difficulties (ie. blockages of feed lines, pump failures, reactor overflows).

The recycle pump (Cole-Parmer Company, Model 7017-21) operated on a cycle of 5 minutes on and 5 minutes off. This combination was found to be adequate to clear the recycle line of blockages and to ensure a reliable volumetric throughput. The flow rate was adjusted accordingly so that the retention time in the clarifier was less than 8 hours. A scraper mechanism operating at 1 rpm was installed to prevent the sludge adhering to the clarifier walls.

During the pH control experiments (Runs 4A and 4B) a Cole-Parmer Company pH/pump system (Series 7142) was connected to each one of the pH probes which were inserted into the reactors. The pH/pump system was set at a selected pH value and the pump was activated whenever the pH was higher (in the case of acid addition) or lower (in the case of base addition) than the set value. Aqueous solutions of 0.02 N HCl and 0.02 N NaOH were used to respectively decrease or increase the pH in the reactors.

The reactors were seeded with sludge obtained from a fermenter installed at the University of British Columbia pilot plant (a biological phosphorus removal research facility) treating mostly campus wastewater, by adding 1.0 L of seed and 2.0

L of tap water. Some basic characteristics of the seed are presented in Table E1, Appendix E.

At the end of Stages 1 and 2, and afterwards, at the end of each run both systems were drained and cleaned and some of the tubing was replaced. At the same time, the ORP probes were cleaned and their responsiveness tested by immersion in a quinhydrone solution, as described by the A.S.T.M. (1989b), and discarded whenever it was considered necessary. To increase accuracy and reliability, the pH probes used in Run 4A were also replaced at the end of the run.

In every experimental run the systems were considered to be in steady-state when the volatile acid production showed approximately steady values (ie. less than 10 percent variation in concentration). This was usually achieved in less than two weeks of operation, although sporadic disturbances occurred afterwards in certain cases. To ensure that reasonable steady-state conditions were established, most experiments were operated for about 4 to 5 SRTs, as shown in Table 4.2.

4.3. ANALYTICAL PROCEDURES

Samples were obtained from three locations, in order to follow the composition changes that occurred through the process:

1) Influent sample: from the 10 L feed buckets, just before feeding.

2) Reactor sample: from the wastage of each reactor.

3) Effluent sample: from the effluent line of each system.

Sampling, handling and preservation times before analysis were kept to a

minimum. Most tests were performed regularly on a biweekly basis. The majority of tests were conducted in accordance with Standard Methods (A.P.H.A. et al., 1989). When non-standard testing procedures were performed, they are discussed in detail below.

All sample filtrations were done using Whatman No. 4 filters, with the exception of solids analysis where Whatman 934-AH glass microfiber filters were used.

TABLE 4.2. DURATION OF EXPERIMENTAL RUNS AND AMOUNT OF BIOMASS (VSS) IN THE REACTORS

RUN	SRT (d)	DAYS PER RUN	# OF SRTs	VSS IN REACTORS		
				CMR (g)	UASB (g)	% DIF.
1A	10	86	8.6	42.76	50.21	14.8
1B	10	44	4.4	52.70	66.68	21.0
1C	10	52	5.2	31.23	33.73	7.4
1D	10	47	4.7	23.58	27.27	13.5
2A	15	54	3.6	27.52	33.95	18.9
2B	20	55	2.8	30.01	35.85	15.5
2C	5	28	5.6	14.89	19.22	22.5
3A	10	38	3.8	29.65	32.03	7.4
3B	10	41	4.1	30.81	34.27	10.1
4A	10	38	3.8	28.34	33.81	16.2
4B	10	48	4.8	28.14	29.76	5.4
AVER.		48	4.7			13.9

4.3.1. CHEMICAL OXYGEN DEMAND (COD)

The filtered samples were preserved by freezing at -7 ^{o}C and analyzed in duplicate using the dichromate reflux procedure outlined in Standard Methods (A.P.H.A. et al., 1989).

4.3.2. TOTAL ORGANIC CARBON (TOC)

The filtered samples were preserved as above and analyzed in duplicate on an automatic Shimadzu Total Organic Carbon Analyzer (Model TOC-500) using a series of low and high standards, as described in the Instruction Manual (Shimadzu Corporation, 1987). The method is based on the principle that the quantity of CO_2 produced during combustion is proportional to the amount of carbon in the sample.

4.3.3. ORGANIC ACIDS

a) Volatile Fatty Acids (VFAs)

The volatile fatty acid determination was conducted using a computer-controlled Hewlett-Packard 5880A gas chromatograph, equipped with a flame ionization detector (FID). Helium was used as the carrier gas. Volatile fatty acids analyzed include: acetic, propionic, butyric, iso-butyric, valeric, 3-methylbutyric, and 2-methylbutyric.

The filtered samples were kept frozen at -7 ^{o}C in sealed plastic transfer

pipettes (Canlab No. P5214-1). At the time of analysis, the samples were thawed at room temperature and diluted 1:5 (except the influent samples) with distilled water. After being acidified with 5% phosphoric acid to bring the pH below 3, 1.0 µl aliquots were injected using microsyringes (Hamilton Model 701 N, 10 µl) and a Hewlett-Packard auto-sampler (Model 7672 A). The glass column (length: 91.0 cm, external diameter: 6.0 cm, internal diameter: 2.0 cm) was packed with 0.3% Carbowax 20M/0.1% H_3PO_4 on Supelco Carbopack C. The column was conditioned according to the procedure described in the Supelco Bulletin 751E (1989).

The operating conditions of the chromatograph were as follows:

Injector temperature:	150 °C
Detector temperature:	200 °C
Isothermal oven temperature:	120 °C
Flow rate of helium gas:	20 mL/min

Quantification of the response peaks was done by comparison with external standard methods using reagent grade standards. The detection limit of the method is 1 mg/L. At least two aliquots of each sample were injected and the mean values reported.

b) Lactic and Pyruvic Acids

The same technique used for VFA analysis was applied for lactic and pyruvic acid determination, with the following three modifications:

The samples were acidified using 0.03 M oxalic acid, the glass column was packed with 4% Carbowax 20M on Supelco Carbopack B-DA, and the isothermal

oven temperature was 175 °C (Supelco, 1990).

c) Formic Acid

Formic acid was analyzed by a colorimetric method outlined by Lang and Lang (1972). The bright yellow and green-yellow fluorescent reaction products from the formic-citric acid reaction change to raspberry red at room temperature, in the same medium. The intensity of the color is proportional to the concentration of the formic acid present. Absorbance measurements were taken at 515 nm on a Bausch & Lomb Spectronic 80 using a 1.0 cm cell. The method has a detection limit of about 5 mg/L. Detail description of the reagents used and the analytical procedure followed is provided by Kisaalita (1987).

4.3.4. SOLIDS

a) Total Solids (TS) and Volatile Solids (VS)

Total solids were determined by evaporating a known volume of well-mixed sample in a Fisher Isotemp (Model 350) forced draft oven at 104 °C. Subsequently, by igniting the residue at 550 °C in a Lindberg muffle furnace (Type 51828), the volatile solid content was measured. Both analyses were performed as outlined in Standard Methods (A.P.H.A. et al., 1989).

b) Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS)

The TSS and VSS contents of influent and effluent samples were determined

in accordance with the Standard Methods (A.P.H.A. et al., 1989). A known volume of sample was vacuum filtered through a pre-washed and oven-dried Whatman 934-AH glass microfiber filter and dried at 104 ^{o}C for TSS analysis. The VSS were determined by igniting the residue at 550 ^{o}C.

Since the suspended solids concentration in both reactors was very high, usually more than 10,000 mg/l, the Gooch crucible method was considered impractical (Anderson, 1989). Instead, a known volume of well-mixed sample was transferred into a 50 ml centrifuge tube and spun down at 2500 rpm in an IEC International Centrifuge (Model CS-CC467) for about 15 min. The supernatant was vacuum filtered through a pre-washed and oven-dried glass microfiber filter. The settled sludge at the bottom of the tube was scraped out and washed on to the filter. The filter was then placed on its aluminium storage dish and transferred into the 104 ^{o}C oven, and finally into the 550 ^{o}C furnace, as described above.

4.3.5. NITROGEN

a) Ammonia Nitrogen (NH_3-N)

Samples for ammonia determination were first filtered and preserved with concentrated sulfuric acid and then stored at 4 ^{o}C. Ammonia nitrogen was analyzed in triplicate by the automated phenate method, using a Technicon Autoanalyzer II Continuous Flow System (Industrial Method No. 98-70W). Appropriate dilutions were made prior to determining the intensity of the color complexes formed and then compared with those of a series of standards of known concentrations.

b) Total Kjeldahl Nitrogen (TKN)

Total Kjeldahl nitrogen (TKN) was measured by digesting the samples in a BD-40 Technicon Block Digester with concentrated H_2SO_4 and K_2SO_4, to liberate all organically bound nitrogen. Filtered or unfiltered samples were used to determine the soluble or total TKN respectively. Standards and samples were analyzed colorimetrically in triplicate using a Technicon Autoanalyzer II (Industrial Method No. 376-75W), according to Technicon Block Digester Instruction Manual (1974).

4.3.6. PROTEINS

The amount of protein in a sample can be estimated by measuring the nitrogen content of the organic matter present. Organic nitrogen includes the nitrogen in amino acids, amines, amides, imides, nitro-derivatives and a number of other compounds. Most of the organic nitrogen that occurs in municipal wastewater, however, is in the form of proteins or their degradation products: polypeptides and amino acids (Sawyer and McCarty, 1979). Therefore, assuming that all organic nitrogen is due to protein and that protein contains on average 16 percent nitrogen (Gaudy and Gaudy, 1980), the protein content can be calculated from the corresponding TKN value by subtracting the inorganic nitrogen concentration (in this case only the NH_3-N value) and multiplying the difference by 6.25 (100 divided by 16).

4.3.7. LIPIDS

Total lipids were determined by dry extraction (influent and reactor samples) and wet extraction methods (effluent samples).

a) Dry Extraction Method

Samples were dried overnight at 104 ^{o}C, ground in an Oster commercial blender, and weighed on Whatman 941 paper filters (9.0 cm diameter). They were then subjected to continuous extraction for 6 hours in a Soxhlet apparatus using petroleum ether as solvent, in accordance with the procedure described by Triebold and Aurand (1969). Reweighing the samples with a Mettler AC 100-52 balance (after at least 1 day in a vacuum desiccator), allowed calculation of the total lipid content as percent of the TS of the sample.

b) Wet Extraction Method

According to the Rose-Gottlieb Method (Triebold and Aurand, 1969), a known volume of the sample is treated with ethanol and ammonium hydroxide solution, and then extracted with a 1:1 mixture of ethyl and petroleum ethers. The ethers containing the dissolved lipids are decanted into a weighed flask. The extraction is repeated a second time, after which the solvents are evaporated and the weight of the extracted total lipids determined.

4.3.8. CARBOHYDRATES

Since cellulose is a major component in domestic wastewaters (Gaudy and Gaudy, 1980), a method specifically suited to measure the cellulose content (as the one described below) is considered indispensable for total carbohydrate analysis in this study.

The first step in carbohydrate determination involved an acid hydrolysis technique outlined in the A.S.T.M. (1989a). A primary hydrolysis of the samples with 72% H_2SO_4 at 30 ^oC for 1 hour was followed by a secondary hydrolysis in a preheated autoclave (Barnstead Company, Model C-0704) for 4 hours. The diluted hydrolyzates were then neutralized with a 6 N solution of NaOH.

The second step of the analysis included the post-neutralization stages of the ferricyanide method (Handbook of Micromethods, 1974). Adding the appropriate reagents (carbonate-cyanide, ferricyanide, and ferric-iron), a blue complex is formed whose intensity is proportional to the concentration of glucose. The absorbance is then measured at 690 nm and compared with that of a range of glucose standard of known concentrations.

For soluble carbohydrate determination, the ferricyanide method was followed entirely.

4.3.9. PHOSPHORUS

a) Orthophosphate (PO_4^{-3})

Samples for orthophosphate analysis were filtered and preserved as in the case of ammonia (Section 4.3.5.a). Orthophosphate was determined in triplicate by the automatic ascorbic acid reduction method on a Technicon Autoanalyzer II (Industrial Method No. 327-73W). According to this technique, a blue-colored antimony-phosphomolybdate complex is formed when ortho-phosphate reacts with ammonium molybdate and potassium antimonyl tartrate. The peak heights of standards of known concentrations are then compared to those of the samples.

b) Total Phosphorus (TP)

The samples were treated the same way as in TKN analysis (4.3.5.b). All organically bound phosphorus, liberated by acid digestion, is oxidized to ortho-phosphate, which can be measured by the ascorbic acid method mentioned above.

4.3.10. pH AND ALKALINITY

A Beckman 44 pH meter with automatic temperature compensation was used to determine the pH of the samples. The meter was calibrated daily, prior to measurements, using two standard buffer solutions of pH 4.0 and 7.0.

Total alkalinity was measured by titrating the samples to an end point pH of 4.5 with 0.02 N sulfuric acid.

4.3.11. OTHER SOLUBLE ORGANICS

In order to tentatively identify the nature of other soluble degradation products, a series of samples were analyzed on a Hewlett-Packard 5985B Gas Chromatography - Mass Spectroscopy system. The mass spectrometer was operated in the electron impact mode, using helium as carrier gas, at the following conditions:

Ion source temperature: 200 °C

Ionizing energy: 70 eV

Scan range: 34-350 amu at 1 A/D measurement.

The mass spectra were acquired with the data system and the peaks were identified with base peak probability matching using the library EPA-NIH Mass Spectra Database as described by Girard (1991).

The organic compounds analyzed included: ethanol, butanol, 2-propanol, 1,3-propanediol, 2,3-butanediol, 1,2,3-propanetriol (glycerol), ethanal (acetaldehyde), acetone, and 2,3-butanedione.

4.3.12. GAS ANALYSIS

Gas samples were extracted periodically from the head space of the reactors using an 1 ml Hamilton syringe and rapidly injected into a Fisher-Hamilton Gas Partitioner (Model 29), using helium as carrier gas and a thermal conductivity detector. The gases were identified by comparing their retention times to standard gases and concentrations were estimated by comparing the peak areas with known

standards that were used to determine response factors.

4.4. COLD STORAGE TESTING

The effects of cold storage on sludge characteristics were studied at the beginning of the experimental research and at the end of Stage 1. This was considered necessary, since the raw sludge used in this study was to be kept at 4 ^{o}C for approximately 1 to 2 weeks. In each testing, over a period of 20 days, samples were taken from the supernatant of one of the 25 L carboys and analyzed for the following parameters in duplicate: chemical oxygen demand (COD), total organic carbon (TOC), and volatile fatty acids (VFA).

4.5 STATISTICS

Averages, standard deviations, coefficients of variation and significant difference between the means (t-test) were calculated by the statistics package included in Symphony (release 1.2) of Lotus Development Corporation (Cambridge MA).

CHAPTER 5

RESULTS AND DISCUSSION

5.1. GENERAL CHARACTERISTICS

A brief description of important general issues concerning the nature of this research is presented below, preceding the detailed analysis of the four experimental stages.

5.1.1. FEED COMPOSITION

An understanding of the nature of the wastewater used as feed is essential in the design and operation of any biological treatment process. To promote this understanding, an analysis of important physical and chemical constituents of primary sludge was performed regularly and the data have been included in Appendix C. A summary of the results, along with a basic statistical evaluation, is presented in Table 5.1 (Iona Island WWTP) and Table 5.2 (Lions' Gate WWTP).

The total solids concentration of the reactor influent was continually adjusted to 4,000 mg/L, as mentioned earlier (Section 4.1), to provide a uniform feed for the entire experimental program.

Despite the fact that the range for most parameters appears to be quite wide (especially for the sludge from Iona Island), the statistical evaluation shows that both

the standard deviation (STD) and the coefficient of variation (CoV) are reasonably small. For instance, the CoV of all 4 types of solids is less than 10%, which indicates that the majority of measurements are close to the mean.

Comparing the two sources of feed, the most noteworthy difference lies in the VFA and NH_3-N content. The feed from Lions' Gate plant contains roughly 40% (for both parameters) of the amount present in the other source.

TABLE 5.1. INFLUENT SLUDGE CHARACTERISTICS (IONA ISLAND WWTP)

PARAMETER	RANGE	MEAN	STD	CoV(%)
pH	5.63 - 6.93	6.09	0.20	3.3
TS	3260 - 5235	4007	294	7.3
VS	2300 - 4205	2990	279	9.3
TSS	2625 - 5050	3613	315	8.7
VSS	2035 - 3985	2710	263	9.7
CARBOHYDRATES	1140 - 2700	1703	218	12.8
PROTEINS	473 - 834	627	64	10.2
LIPIDS	394 - 693	507	47	9.3
COD	244 - 673	427	73	17.1
TOC	71 - 208	128	25	19.5
VFA (as HAc)	46 - 150	103	19	18.4
NH_3-N	13 - 35	20	3.8	19.0
TKN	89 - 158	121	11	9.1
PO_4^{-3} (as P)	6 - 17	10	1.8	18.0
TP	14 - 27	19	2.3	12.1
ALKAL. (as $CaCO_3$)	141 - 216	184	16	8.7

Note: All values in columns RANGE, MEAN and STD are expressed in mg/L, except pH.

TABLE 5.2. INFLUENT SLUDGE CHARACTERISTICS (LIONS' GATE WWTP)

PARAMETER	RANGE	MEAN	STD	CoV(%)
pH	5.74 - 6.33	6.00	0.16	2.7
TS	3630 - 4340	4032	204	5.1
VS	2925 - 3585	3285	228	6.9
TSS	3065 - 3870	3539	219	6.2
VSS	2470 - 3310	2956	216	7.3
CARBOHYDRATES	1790 - 2360	2091	182	8.7
PROTEINS	497 - 611	559	36	6.4
LIPIDS	434 - 537	486	32	6.6
COD	359 - 522	445	50	11.2
TOC	91 - 153	128	19	14.8
VFA (as HAc)	29 - 67	44	11	25.0
NH_3-N	5 - 11	8	2.0	25.3
TKN	88 - 109	97	7	7.2
PO_4^{-3} (as P)	5 - 9	7	1.1	15.7
TP	10 - 16	13	1.8	13.8
ALKAL. (as $CaCO_3$)	153 - 197	172	16	9.3

Note: All values in columns RANGE, MEAN and STD are expressed in mg/L, except pH.

The classification of the organic composition of the influent reveals that carbohydrates are by far the most predominant group in the raw sludge from both facilities (Table 5.3). Proteins and lipids are the other two important classes of organic compounds present. The three groups together account for 95% of the volatile solids content. The sludge from Lions' Gate is richer in carbohydrates but contains less protein and lipid.

The particulate fraction of the organic matter is very high, as indicated by the VSS/VS ratio, which averages about 90%. Lipids and polysaccharides are practically insoluble in water. Analytical determination of soluble carbohydrates and proteins has shown that only 7 and 16% of the total respectively occurs in soluble form (Tables E2 and E3, Appendix E). Most of proteins in domestic wastewater are normally of globular nature and, therefore, water soluble (Gaudy and Gaudy, 1980). The low soluble protein content of primary sludge indicates that most of the proteinaceous matter is still an integral part of the suspended solids.

TABLE 5.3. ORGANIC COMPOSITION OF FEED

ORGANIC CLASS	IONA ISLAND WWTP		LIONS' GATE WWTP	
	RANGE (% of VS)	MEAN (% of VS)	RANGE (% of VS)	MEAN (% of VS)
CARBOHYDRATES	49 - 63	56	60 - 67	64
PROTEINS	18 - 25	21	15 - 19	17
LIPIDS	12 - 21	17	12 - 16	15
TOTAL		94		96

5.1.2. COLD STORAGE EXPERIMENTS

The results of both tests on stored raw sludge (at 4 ^{o}C) showed no significant variation in any of the chemical parameters tested for at least a period of 12 days (Table 5.4). The variations observed are comparable to those expected during the chemical analysis through experimental errors. Manoharan (1988) has reported that

no change in raw sewage characteristics took place within two weeks of cold storage. In this study, however, after 14 to 16 days a gradual decrease in COD and TOC and an increase in VFAs occurred, presumably as a result of bacterial activity. To avoid any alterations in feed composition, the maximum storage period was set at 10 days.

TABLE 5.4. COLD STORAGE TESTING

DAY	TEST ONE (WINTER)			TEST TWO (SUMMER)		
	COD (mg/L)	TOC (mg/L)	VFA (mg/L)	COD (mg/L)	TOC (mg/L)	VFA (mg/L)
0	420	139	98	452	137	84
2	426	128	102	440	129	82
4	411	124	96	449	125	79
6	406	122	94	431	130	88
8	415	130	101	443	120	86
10	419	122	95	435	126	80
12	414	117	103	428	125	84
14	408	120	101	402	109	86
16	370	106	113	361	99	93
18	373	102	115	347	97	97
20				298	84	106

5.1.3. ACCLIMATION AND STABILITY OF OPERATION

The original heterogeneous population in a bioreactor has to undergo biochemical acclimation and selection of the species best able to grow on the carbon

sources available in order to ensure successful and sustainable operation. In continuous-flow systems, acclimation is a time-dependent process and it can be influenced by the type of seed used, the characteristics of feed, and the chosen operational and environmental conditions.

In this study, acclimation was accomplished in a rather short period of time (6 to 10 days) in both reactors. The phenomenon was considered complete when both the increase in VFA production and the decline in pH (when it was not controlled) exhibited signs of stability. The short acclimation period observed can be attributed to the synergistic action of a number of factors such as the suitable seed used (taken from an acid-phase digester), the good digestability of the primary sludge, the favorable operating conditions and the small volume of the reactors.

It has been reported (Lettinga et al., 1979; de Zeeuw and Lettinga, 1980) that in UASB systems, long acclimation periods (sometimes up to 4 to 8 weeks) may be required, because of the slow formation of sludge blanket. The phenomenon of microbial aggregation and granulation, however, is greatly affected by various nutritional and environmental parameters such as trace metal ions (particularly calcium), temperature, the nature of the inoculum, and feed used (Mahoney et al., 1987; Guiot et al., 1988). Investigating a number of seeding and reactor loading alternatives, Fongsatitkul (1992) has found that, in most cases, the acclimation process was completed within 4 weeks. Using mesophilic granular sludge as seed material, van Lier et al. (1992) have observed that the start-up period in a UASB system was between 1 and 2 weeks. In this study, the good settling properties of the sludge resulted in a sludge blanket formation in about 3 to 6 days with minimal loss

of biomass, which in turn induced steady-state conditions within the next few days. The small volume of the reactor might have also played a critical role. Eastman and Ferguson (1981) have found that steady-state was achieved within 7 days in 2.5 L completely-mixed acidogenic reactors.

Both systems' behavior during the steady-state analysis period was stable. No significant trends were observed in any parameter over the 3 to 9 solids retention times of the experiments. The standard deviation for individual analyses was within 12% of the mean for almost all measured parameters. The higher variability observed in certain parameters in two cases (Runs 1B and 2C) is attributable to bacterial stress imposed by the short HRT and SRT respectively, of those runs.

Furthermore, the ORP values measured ranging from -270 to -400 mV (Table 4.1), suggest that good anaerobic conditions were maintained throughout this experimental investigation. The ORP values were always lower in the UASB reactor. Since the probe was inserted in the sludge blanket of this reactor, it is obvious that the environment is more reductive inside the blanket than it is in the CMR system.

5.2. THE EFFECT OF HRT - STAGE 1

5.2.1. HRT AS A CONTROL PARAMETER

The microbial population of most natural environments is usually dominated by a relatively small number of species. A few selective environmental parameters such as pH, ORP, temperature, a toxic factor, the presence or absence of a key

growth factor, etc., operate to impose a limit on the heterogeneous nature of the bacterial population, and thereby "select" one or more dominant cultures. This phenomenon of species selection has found a variety of applications in environmental engineering and related fields (Ghosh and Pohland, 1971).

In closely monitored continuous-flow bioreactors, any or all of the parameters can be controlled and maintained constant. Consequently, it is often possible to select and retain a group of microbial species which would accomplish the desired biochemical conversions at acceptable reaction rates. Survival of individual species, however, in heterogeneous cultures such as those found in wastewater treatment processes, depends upon a variety of less defined factors. Although the population in such processes tends to remain, to some degree, heterogeneous because of mutual microbial interactions (eg. competition, amensalism, parasitism, mutualism, symbiosis, predation, etc.), the relative proportion of each major species changes from one condition to another (Harrison, 1978).

An important operational variable which can be easily manipulated is the hydraulic retention time (HRT). It is the average length of time a molecule of liquid remains in the reactor and can be defined as the volume of the reactor divided by the average influent flow rate. HRT governs the amount and type of substrate being used by the cells. Since anaerobic digestion is a two-phase process, HRT can act as a selection parameter for the acidogenic phase only if it encourages the growth of acid formers and concurrently suppresses the growth of methane producers.

One of the objectives of this study has been to investigate the effect of the two operational parameters [HRT and SRT (defined in Section 5.3.1.)] independently. For

this reason, small HRT values are selected in contrast with the SRT. In Stage 1, the HRT varied from 6 to 15 hours, while SRT was kept constant at 10 days. The raw data collected during this stage are tabulated in Appendix C (Tables C1 to C20).

5.2.2. VFA PRODUCTION

Short-chain volatile fatty acids (C_2 to C_5) are normally the main products of the acidogenic digestion of primary sludge (Chynoweth and Mah, 1971). The high concentrations of total VFAs (expressed as acetic acid for comparison purposes) achieved in both bioreactors clearly support the above observation (Appendix C). For example, the profiles of influent and reactor VFA concentrations, depicted in Figure 5.1 (Runs 1C and 1D), show that a sharp increase in the reactor VFA content occurs in both runs. This suggests that favorable conditions for the growth and maintenance of a healthy population of acid-producing microorganisms have been established during the course of the experiments.

The total net VFA production (as acetic acid) at steady-state operation, as a function of HRT, is presented in Figure 5.2. In both systems, VFA concentration increases with HRT to a maximum value at 12 hours. A further increase in HRT results in a drop in concentration by about 80 mg/L. The decline in VFA generation coupled with the higher production rate of gaseous end-products (as explained in Section 5.3.4) provide strong evidence that methane-forming bacteria have been stimulated at an HRT of 15 hours.

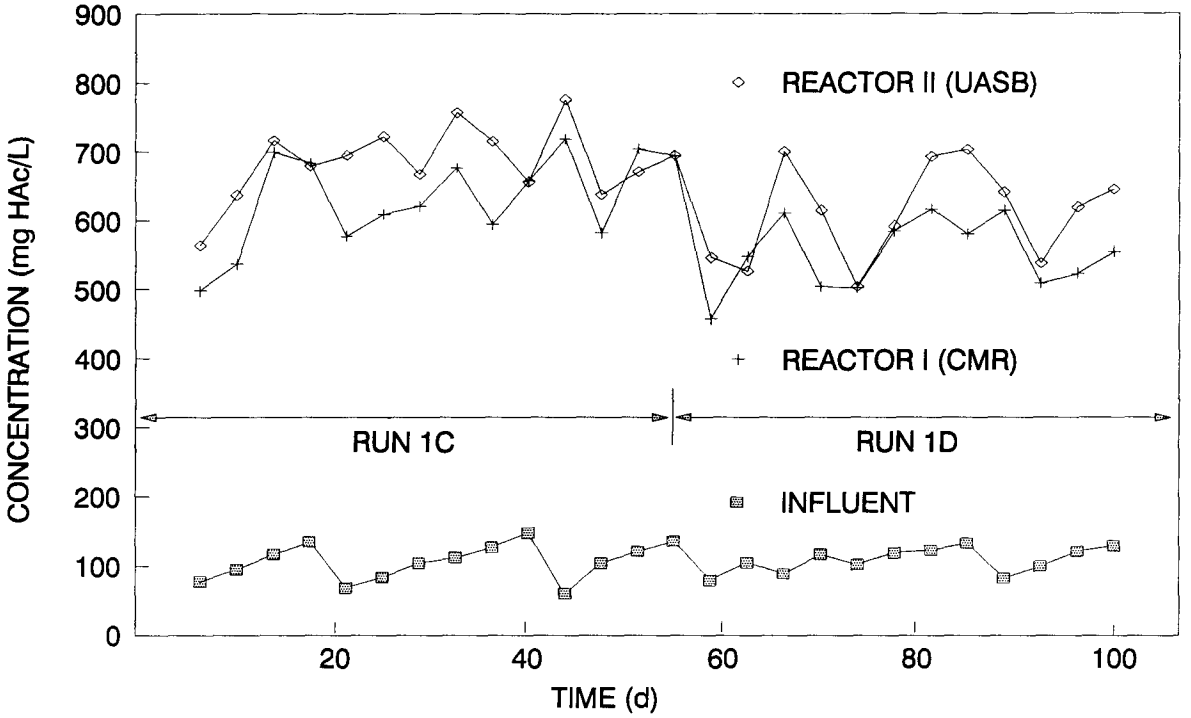


FIGURE 5.1. VFA PROFILE (RUNS 1C & 1D)

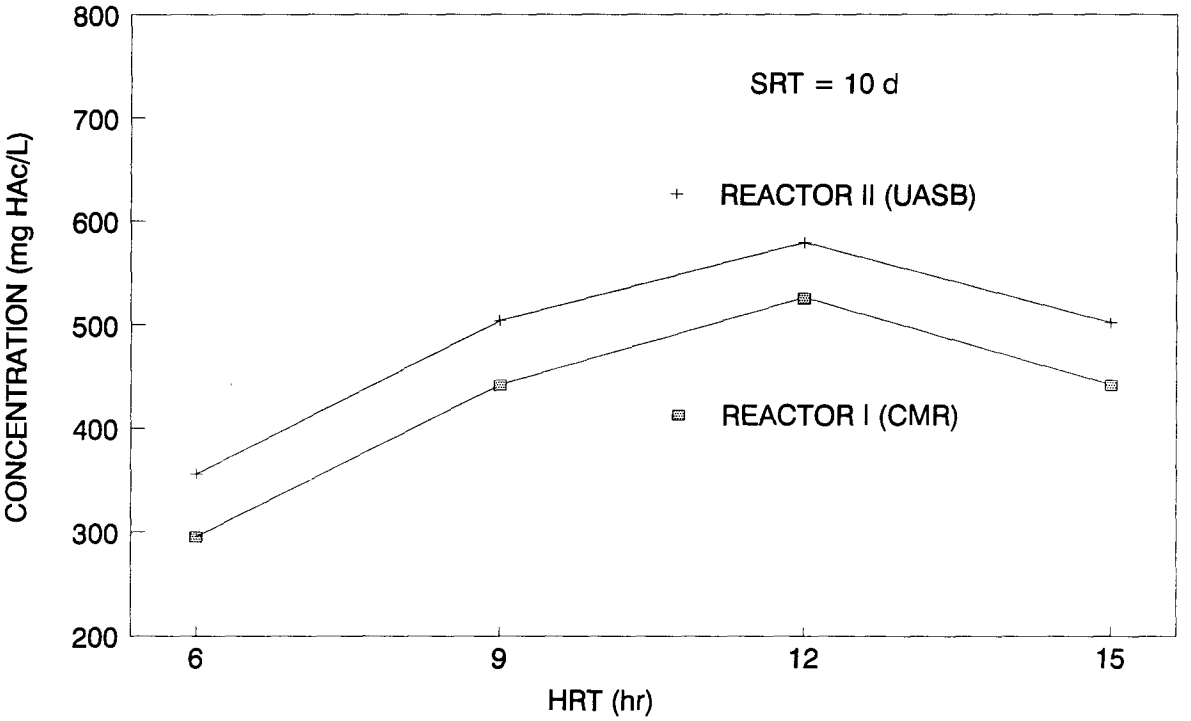


FIGURE 5.2. NET VFA PRODUCTION AS A FUNCTION OF HRT

It is obvious that the mean VFA concentration is consistently higher in the UASB reactor. As a result of the good settling properties of the sludge blanket, the amount of active biomass (measured as VSS) lost through the effluent line is considerably lower as compared to the CMR system (Appendix C). Since more bacteria are retained in the upflow reactor (the amount of VSS in the UASB reactor is on the average 14% higher than that in the CMR System - Table 4.2), they can in turn generate a greater amount of products. However, the net VFA specific production rate, expressed as mgVFA/mgVSS*d, is similar in both units (Table 5.5). This is an indication that the ability of biomass to generate VFAs appears to be independent of the reactor configuration, at least for the above mentioned conditions.

TABLE 5.5. VFA SPECIFIC PRODUCTION RATE AS A FUNCTION OF HRT

RUN	HRT (hr)	CMR (mgVFA/mgVSS*d)	UASB (mgVFA/mgVSS*d)
1B	6	0.067	0.061
1A	9	0.083	0.080
1C	12	0.101	0.103
1D	15	0.092	0.089

The specific production rate is largely affected by the change in HRT, reaching its maximum value at 12 hours. The low rate at the shortest HRT is mainly due to the limited time available for substrate assimilation, while the decline noticed at the longest HRT is probably caused by the conversion of soluble VFAs to gaseous products. Although gas generation has been detected for all HRTs (Table E4,

Appendix E), the sharp increase observed in Run 1D (HRT 15 hours) suggests that methanogenic activity was encouraged in this case. It is possible that the fraction of methane-forming bacteria in the biomass at a 10 day SRT was sufficient to affect net VFA production at the longer HRT. Based on the above results, the optimum HRT for VFA formation (for this type of wastewater) is 12 hours, with an acceptable range of more than 9 and less than 15 hours.

The VFA concentrations in the reactor and in the effluent of the CMR system are essentially the same (Table 5.6). It is possible that a dynamic equilibrium exists in the clarifier between the rates of acid formation and volatilization. In general, the rate of desorption of a volatile compound from the liquid phase is a function of pH, temperature, degree of turbulence, viscosity of the liquid, and the molecular properties of the specific compound (Loehr et al., 1973). Due to a number of synergistic reasons such as the short retention time of the liquid in the clarifier (2 to 5 hours), quiescent flow conditions, ambient temperature, small surface area (99 cm^2), and higher pH values than the corresponding pK_A values of the acids, the degree of volatilization is considered to be minimal. Similarly, no appreciable acidogenesis should be taking place, mainly because of the short retention time (6 to 8 hours) of the recyclable biomass.

On the contrary, the VFA concentration (Runs 1A and 1B) in the effluent of the UASB system is considerably lower than that in the reactor (sludge blanket), as shown in Table 5.6. The difference in VFA, which is statistically significant according to the t-test performed (Miller et al., 1990), is probably due to flow channelization in the reactor. At shorter HRTs (higher flow rates), the liquid

molecules in the middle of the reactor may move upwards faster (in a jet-like fashion) than those close to the wall and eventually leave the system earlier. This results in an even shorter HRT for part of the reactor's contents diminishing, at the same time, the opportunity for food assimilation by the bacteria, which can ultimately lead to lower VFA concentration in the effluent of the unit. At higher HRTs (12 to 15 hours), the phenomenon of flow channelization appears to be of minor importance, since the VFA values are essentially the same in the sludge blanket and the effluent of the reactor.

TABLE 5.6. COMPARISON OF REACTOR AND EFFLUENT VFA CONCENTRATIONS

RUN	CMR SYSTEM		UASB SYSTEM		
	REACTOR (mg/L)	EFFL. (mg/L)	REACTOR (mg/L)	EFFL. (mg/L)	SIGNIF. DIFFER.
1B (6 hr)	407	412	466	370	YES
1A (9 hr)	540	530	603	465	YES
1C (12 hr)	632	630	685	665	NO
1D (15 hr)	550	560	610	608	NO

5.2.3. VFA SPECIATION

Identification of the individual acids formed during the acid-phase digestion of primary sludge is important, since it may furnish valuable information on the metabolic pathways involved in the process. The VFAs identified include: acetic, propionic, butyric, iso-butyric, valeric, 3-methylbutyric and 2-methylbutyric

(Appendix D). The above VFAs are normally generated not only during the acidogenic digestion of municipal wastewaters (Perot et al., 1988), but also during the digestion of a variety of agricultural industrial wastes (Lettinga et al., 1979; Gil-Pena et al., 1986; Machado and Sant'Anna, 1987). In addition, caproic (hexanoic) acid was seldom detected and never exceeded the 3 mg/L level.

Acetic acid and propionic acid are by far the major VFAs produced, with an average value of about 46 and 32% respectively of the total (Table 5.7). In general, these two acids have been found to be the most prevalent VFAs (at an acetic to propionic acid ratio of about 1.3 to 1.5) in continuous-flow acid-phase digesters (Rabinowitz and Oldham, 1985). Butyric acid follows with 8%, while iso-butyric and the 3 isomers of valeric acid account for the remaining 14%. The distribution of the individual acids is essentially the same in both systems.

It is interesting to note that the percent VFA distribution, despite some variation in the minor acids from one run to another, is not affected by HRT (at least in the range tested), which is in contrast with the pattern followed by both the net VFA concentration and the production rate. This observation can lead to the speculation that either the majority of acid-producing bacteria is to some extent equally influenced by the variation in HRT, or possible differences in microbial activity counterbalance each other so that the final picture is basically the same.

The percent distribution also reveals that there is a shift towards the higher molecular weight VFAs (iso-butyric and the 3 isomers of valeric acid) during the digestion of primary sludge, when compared to the influent VFA distribution. The average values for Stage 1, illustrated in Figure 5.3, show that a relative reduction

TABLE 5.7. PERCENT VFA DISTRIBUTION AS A FUNCTION OF HRT

VOLATILE FATTY ACID	RUN 1B (6 hr)		RUN 1A (9 hr)		RUN 1C (12 hr)		RUN 1D (15 hr)		MEAN
	CMR	UASB	CMR	UASB	CMR	UASB	CMR	UASB	
ACETIC	43.7	45.9	48.0	45.3	47.5	46.0	50.3	43.7	46.3
PROPIONIC	36.8	34.4	33.2	32.5	29.9	30.4	28.1	33.2	32.3
BUTYRIC	7.7	8.0	7.3	7.1	9.9	10.3	7.5	6.9	8.1
ISO-BUTYRIC	3.4	3.1	3.0	2.6	3.2	2.9	4.2	4.6	3.4
VALERIC	3.7	3.9	4.2	6.3	4.4	5.6	5.2	5.7	4.9
3-METHYLBUT.	2.8	2.7	2.9	4.0	3.3	3.1	3.2	4.0	3.2
2-METHYLBUT.	1.9	2.0	1.4	2.2	1.8	1.7	1.5	1.9	1.8

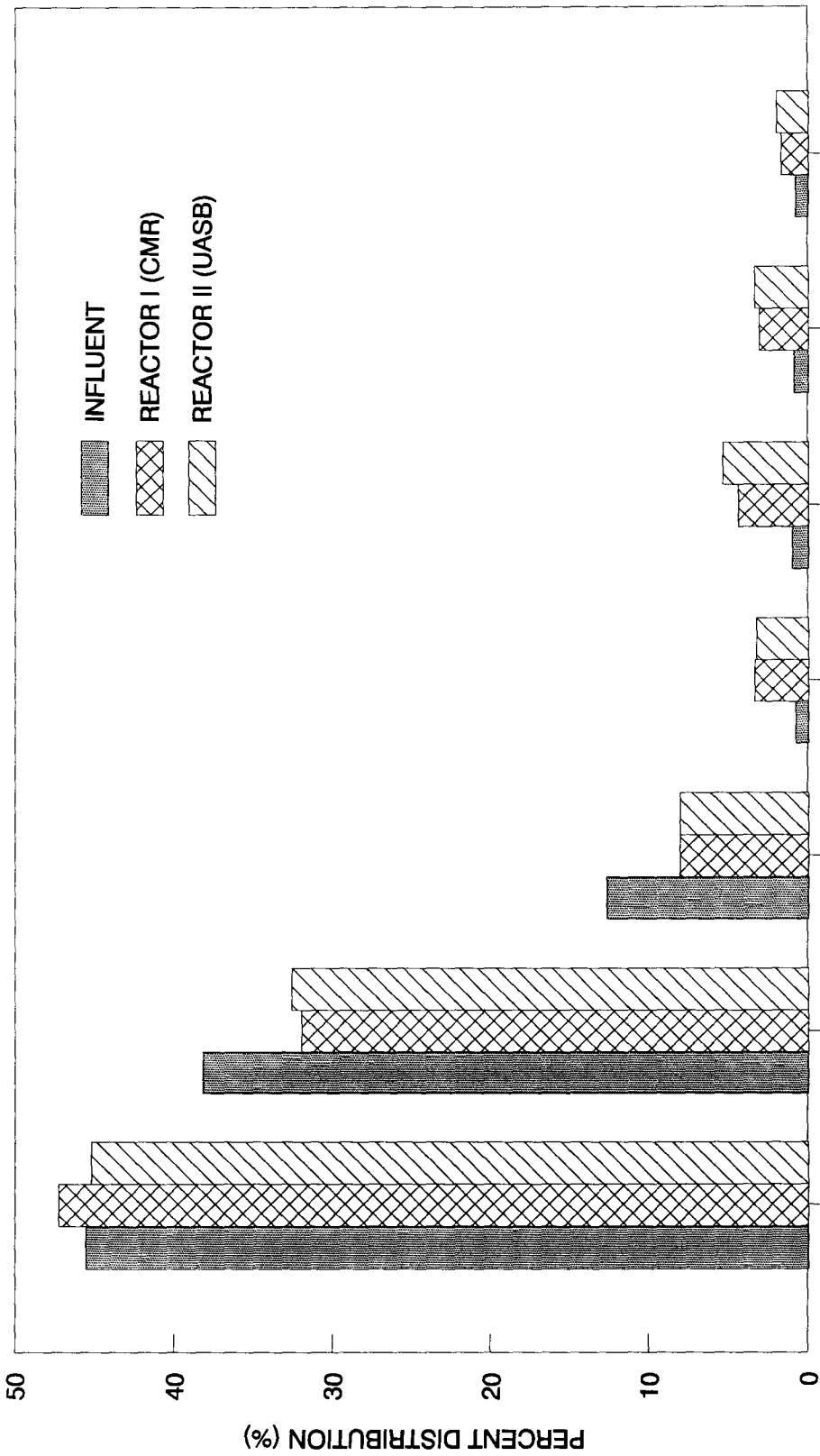


FIGURE 5.3. PERCENT VFA DISTRIBUTION (STAGE 1)

in propionic and butyric acids occurs with an increase in iso-butyric, valeric, 3-methylbutyric, and 2-methylbutyric acids. On the other hand, acetic acid percent distribution does not seem to be following any trend between the influent and the reactor contents. This shift can be primarily attributed to protein fermentation which results in the production of significant amounts of the above mentioned higher molecular weight VFAs. The rate of protein utilization is considerably higher in the bioreactors than in the environment of a sewer system or a primary clarifier, principally because of higher concentrations of biomass and longer SRTs. Moreover, greater availability of soluble extracellular proteins (enhanced by cell lysis and by-products of other biochemical reactions) and favorable environmental conditions prevailing in such treatment units can further contribute to this phenomenon.

5.2.4. PARTICULATE ORGANIC CARBON SOLUBILIZATION

Particulate organic material must first undergo liquefaction by extracellular enzymes, before being taken up by the bacteria. Since most of the substrate in primary sludge is in the particulate form (about 90% as indicated by the VSS/VS ratio), solubilization of organic matter is a crucial step in anaerobic digestion. Generally, the rate of hydrolysis depends upon the pH, temperature, the type of substrate, the nature of biomass, the size of the particles, and the remaining concentration of the biodegradable suspended matter (Eastman and Ferguson, 1981).

Substrate solubilization can be estimated from a number of non-specific parameters such as COD, TOC, TSS and VSS. These parameters were routinely

measured and the results are summarized in Appendix C.

As illustrated by the profiles of influent and reactor soluble COD concentrations depicted in Figure 5.4 (Runs 1C and 1D), a distinct increase in COD occurs in both reactors which is the result of substrate conversion from a particulate to a soluble state.

Variation in HRT has a profound effect not only on the net COD concentration (Figure 5.5), but also on the specific solubilization rates of COD and TOC, expressed as mg of net soluble COD or TOC per mg of VSS per day (Table 5.8). All three maximum values correspond to an HRT of 12 hours, which coincides with the time required for optimum VFA production. In addition, the overall trend is very similar to the one described in the previous section for VFAs.

TABLE 5.8. SPECIFIC SOLUBILIZATION RATES OF COD AND TOC AS A FUNCTION OF HRT

RUN	HRT (hr)	COD RATE (mgCOD/mgVSS*d)		TOC RATE (mgTOC/mgVSS*d)	
		CMR	UASB	CMR	UASB
1B	6	0.159	0.160	0.054	0.054
1A	9	0.163	0.168	0.057	0.060
1C	12	0.187	0.198	0.070	0.070
1D	15	0.169	0.175	0.064	0.063

The percent soluble COD in the form of VFAs (calculated by converting the VFAs to COD using the appropriate factors shown in Table E5, Appendix E) as a

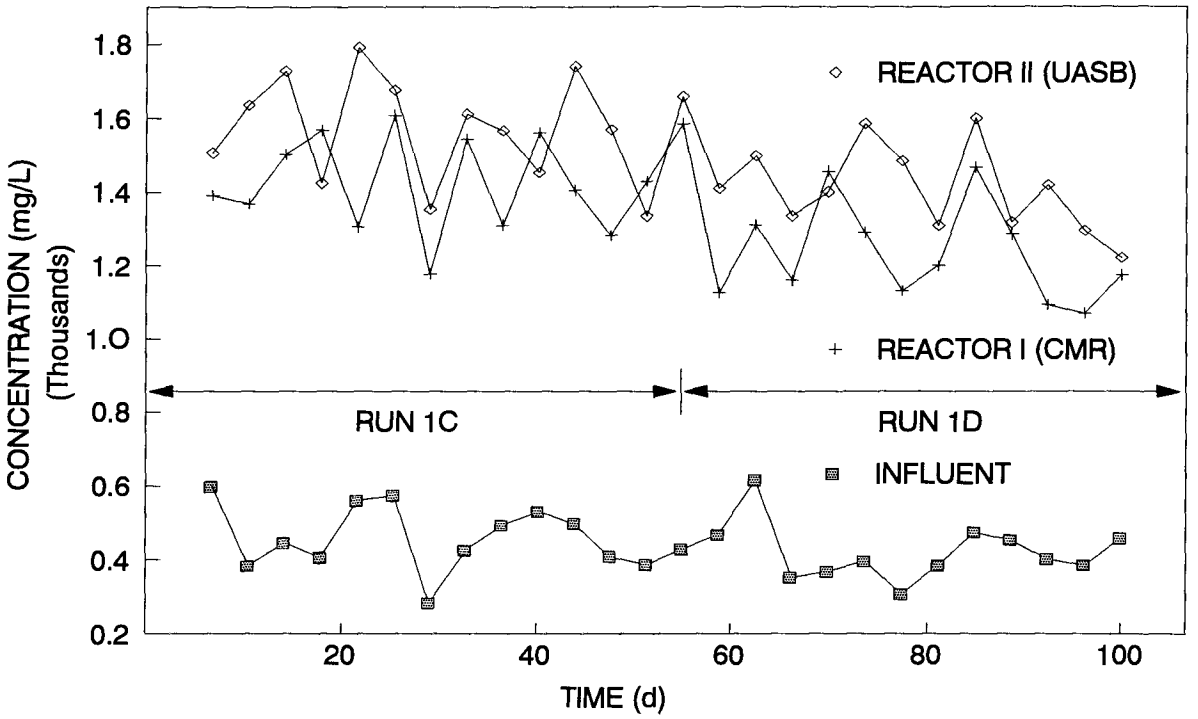


FIGURE 5.4. SOLUBLE COD PROFILE (RUNS 1C & 1D)

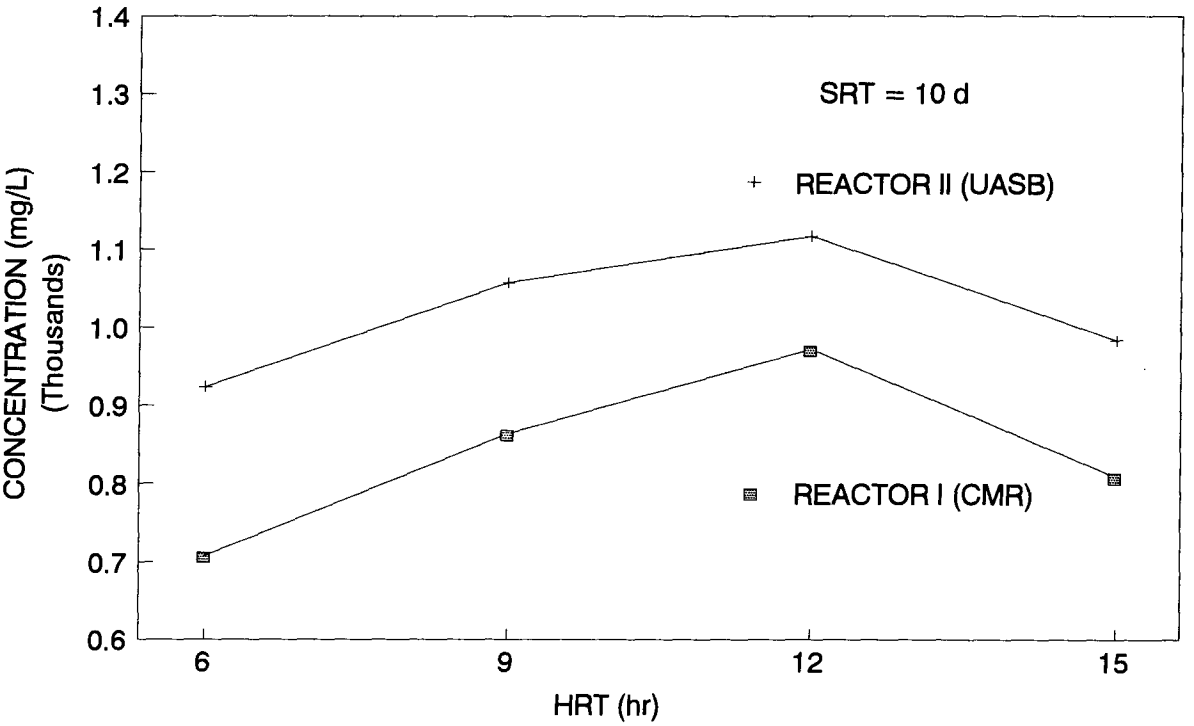


FIGURE 5.5. NET COD SOLUBILIZATION AS A FUNCTION OF HRT

function of HRT is presented in Figure 5.6. Although the percent volatile acid COD increases with a change in HRT from 6 to 9 hours, no remarkable variation is observed beyond this point. Similar percentages have been obtained in both reactors for all HRTs. The results suggest that the conversion rate of soluble substrates to VFAs may have reached a plateau. In other words, the rate of metabolism of soluble extracellular intermediate products to VFAs appears to be independent of HRT, above a certain minimum value. A smaller percent volatile acid COD, observed at 6 hours HRT, indicates that the mechanisms for acid generation are influenced by the short HRT more drastically than those involved in hydrolysis or the production of extracellular metabolic intermediates.

The extent of organic substrate solubilization can be viewed from a diametrically opposite perspective, namely from the destruction of suspended solids. The percent VSS and TSS reduction was based on a mass balance around the reactors at steady-state conditions. Mass balances were performed in two distinct manners according to the method described by Koers (1979). The "overall mass balance" refers to a summation period including the entire steady-state length of a run, while the "moving average mass balance" involves averaging the values from multiple balance periods, each equivelent to 1 SRT in length. As it is evident from the example illustrated in Table E6, Appendix E, the two methods yield similar results.

Suspended solid solubilization increases with HRT, but the percent change becomes smaller at HRTs higher than 9 hours (Table 5.9). The gradually diminishing sensitivity of the rate of hydrolysis at higher HRTs might be due to the fact that it is actually approaching a maximum value beyond which it probably becomes

independent of HRT. The relatively high percent VSS reduction obtained provides an additional evidence that the particulate complex substrates in primary sludge are amenable to solubilization.

TABLE 5.9. PERCENT VSS AND TSS REDUCTION AS A FUNCTION OF HRT

RUN	HRT (hr)	VSS (%)		TSS (%)	
		CMR	UASB	CMR	UASB
1B	6	44.2	43.8	46.1	45.5
1A	9	57.6	63.6	58.8	63.7
1C	12	63.1	70.6	64.2	69.6
1D	15	67.7	72.5	68.3	71.3

The UASB reactor shows an overall better performance (except at the shortest HRT - Run 1B) in hydrolyzing the particulate organic material. This behavior, which is also reflected in the COD solubilization rates (Table 5.8), does not result in higher VFA production rates. This is probably due to the presence of a different mix of microorganisms in the UASB reactor which generate a greater variety of intermediate products during the degradation process.

The percent TSS reduction results (Table 5.9) are essentially identical to those obtained from the VSS analysis. Since the VSS account for about 75 to 80% of the TSS in the feed, a substantial fraction of the particulate inorganics (approximately equal to that of the corresponding VSS) undergoes solubilization during digestion. This can be attributed to metabolic requirements and the low pH values in the reactors.

5.2.5. SUBSTRATE DEGRADATION

Carbohydrates, proteins and lipids in that order are the three primary sources of organic substrates in primary sludge. Since they basically occur in particulate form, they have to be first hydrolyzed by the action of specific enzymes before undergoing further degradation.

The fermentation of carbohydrates is one of the main pathways for the production of VFAs. In domestic wastewaters, carbohydrates are present in the form of polymers, principally as "designated cellulose". The term "designated cellulose" has been proposed by Hobson (1980) to denote that this is a material largely defined by the method of analysis rather than by chemical constitution. Designated cellulose mostly consists of residues of toilet and similar papers and the remains of cooked vegetables in human feces. It can be relatively easily hydrolyzed by cellulases (Ng et al., 1977). The high percentages of total carbohydrate utilization observed, ranging from 43 to 77% (based on a mass balance at steady-state operation), are in agreement with the above statement (Table 5.10). It is apparent that the percent conversion values are a function of HRT, which emphasizes the role of this parameter on the enzymatic hydrolysis of carbohydrates.

Protein and lipid utilization patterns follow a trend similar to that of carbohydrates, regarding the influence of HRT (Table 5.10). The conversion percentages, however, are remarkably different. Proteins are degraded at much lower rates than the other two organic classes. In general, proteolytic activity has been found to take place in digesters using a number of feedstocks, but the overall

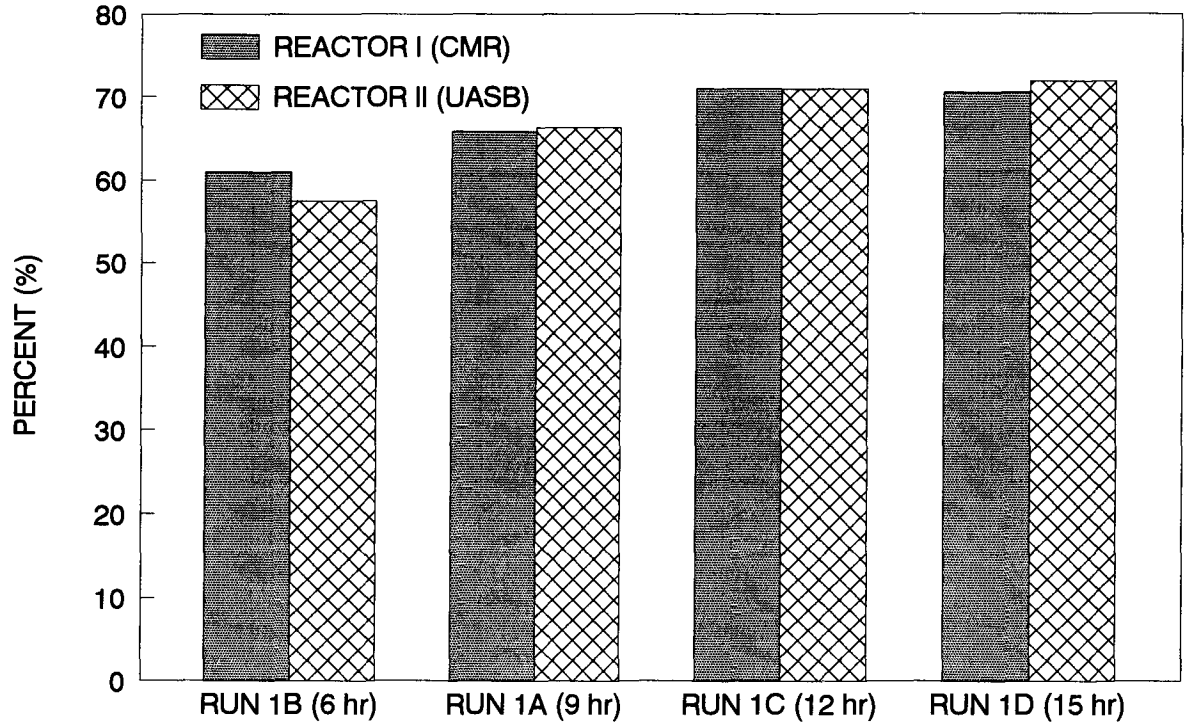


FIGURE 5.6. PERCENT SOLUBLE COD IN THE FORM OF VFAs (STAGE 1)

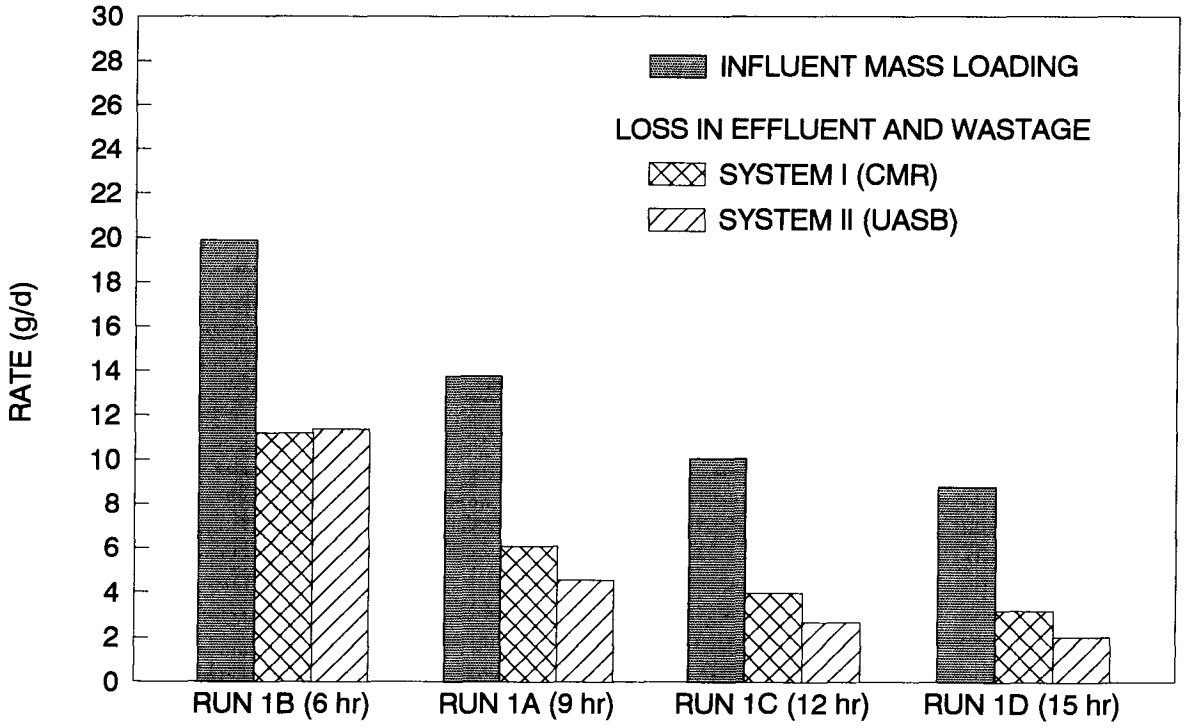


FIGURE 5.7. CARBOHYDRATE DEGRADATION AS A FUNCTION OF HRT

TABLE 5.10. PERCENT SUBSTRATE DEGRADATION AS A FUNCTION OF HRT

RUN	HRT (hr)	CARBOHYDR (%)		PROTEINS (%)		LIPIDS (%)	
		CMR	UASB	CMR	UASB	CMR	UASB
1B	6	43.5	43.1	26.4	24.5	63.4	47.5
1A	9	56.1	66.6	35.6	38.5	72.4	53.5
1C	12	60.6	73.4	42.9	45.0	80.9	62.0
1D	15	64.2	76.8	47.7	47.6	83.2	67.3

breakdown percentages are moderate (Summers and Bousfield, 1980; Gujer and Zehnder, 1983).

On the other hand, there has been a controversy regarding the extent of lipid degradation during the acid-phase process. Some investigators have reported that lipid dissimilation is minimal during the acid-phase step (Mahr, 1967; Eastman and Ferguson, 1981), while others have observed a significant utilization of lipids (Chynoweth and Mah, 1971; Ghosh, 1987). This subject will be treated in some detail in Section 5.6.5.

Concerning the effect of reactor configuration on substrate dissimilation, both systems exhibit a fairly similar behavior in protein reduction rates, but the degradation pattern of carbohydrates and lipids are distinctly and consistently different (Figures 5.7 to 5.9). Lipids are broken down more efficiently in the CMR unit, while higher rates of carbohydrate utilization are observed (except at the shortest HRT - Run 1B) in the UASB reactor.

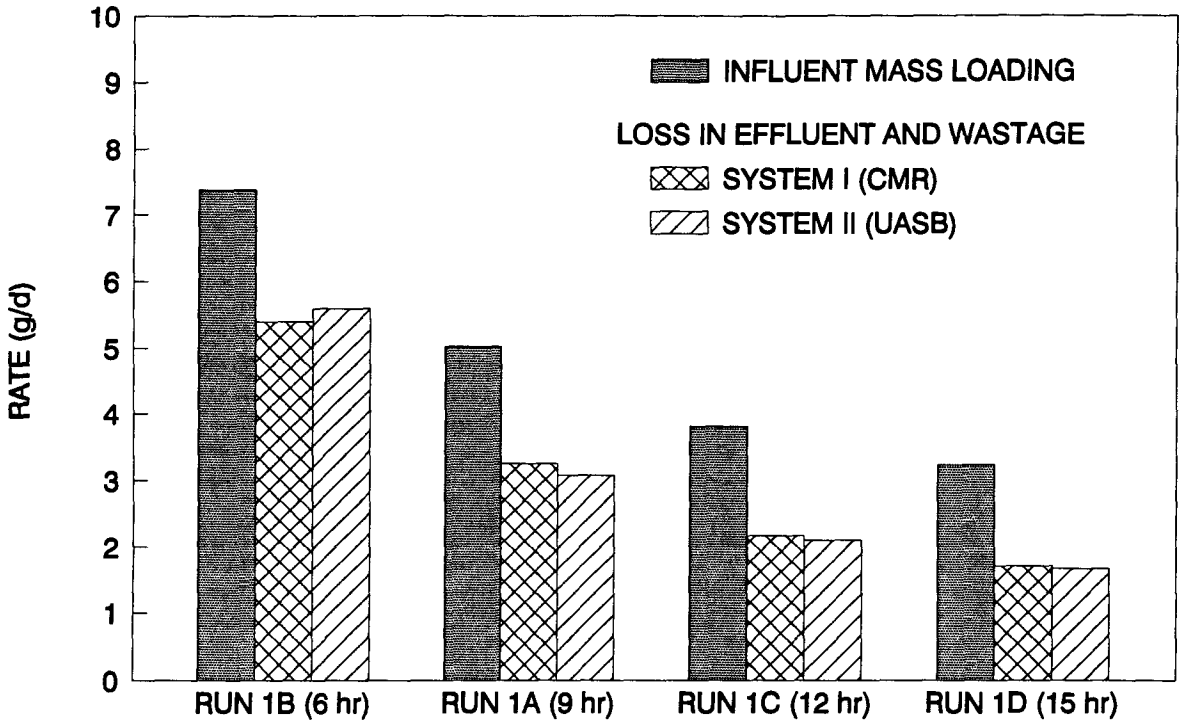


FIGURE 5.8. PROTEIN DEGRADATION AS A FUNCTION OF HRT

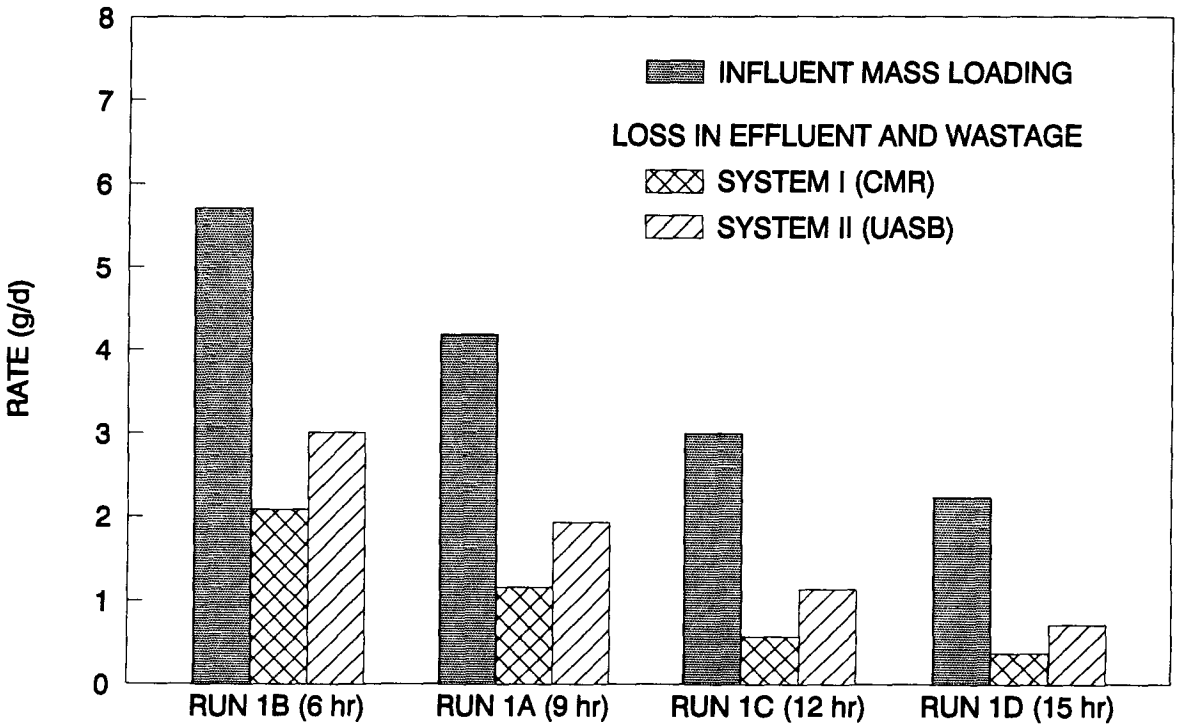


FIGURE 5.9. LIPID DEGRADATION AS A FUNCTION OF HRT

5.3. THE EFFECT OF SRT - STAGE 2

5.3.1. SRT AS A CONTROL PARAMETER

Another operational variable which can be used as a selective factor by imposing a stress on bacterial communities is the solids retention time (SRT). It is the average time allowed for a microorganism to remain in the reactor and can be defined as the amount of suspended solids in the reactor divided by the amount of suspended solids leaving the reactor per day. The SRT governs the types of organisms which eventually predominate in the system because it interferes directly with their generation time.

The physiology, environmental requirements, and growth kinetics of the acidogenic and the methanogenic groups of microbes may differ greatly from each other. It has been reported (Ghosh and Klass, 1978) that the maximum specific growth rate of the acid-producing bacteria can be up to one order of magnitude higher than that of the methane-producing organisms. This suggests that it is possible to maximize VFA production in an acid-phase digester by operating the system at an SRT below some critical value. The critical SRT (which in many cases coincides with the HRT of the system) can range from several hours to several days (Ghosh, 1987).

In most acid-phase anaerobic digestion studies found in the literature (Section 2.5) SRT and HRT are almost identical because of the use of batch reactors or conventional continuous-flow systems without solids recycle. The SRT/HRT ratio can be slightly increased to 1.5-2 as a result of withdrawal of digester supernatant (Henze

and Harremoës, 1983). Nevertheless, SRT and HRT are two different parameters and have different effects on the biological process. For this reason, no clear distinction can be made between the individual influence of the two parameters on the acidogenic phase in these previous investigations.

In this study, HRT and SRT were independently controlled through appropriate design and operational strategies. The very nature of the UASB reactor allows for individual manipulation of these two variables, while for the same reason the CMR unit was modified by adding a clarifier with a solids recycling system. The ultimate goal has been to operate at an HRT as low as possible to minimize reactor volume and associated capital costs; and concurrently to maintain a reasonably long SRT to promote growth and proliferation of the acid-generating organisms, process stability and minimal sludge production, without inducing growth of methane-forming bacteria.

Based on the results from Stage 1, the optimum HRT for VFA production in both reactors is 12 hours. The SRT in that stage was kept constant at 10 days. In Stage 2, an SRT variation from 5 to 20 days is investigated (resulting in a range of SRT/HRT ratios from 10 to 40). The chemical parameters measured during Stage 1 were also recorded for Stage 2 and the data are presented in Appendix C (Tables C21 to C35).

5.3.2. VFA PRODUCTION AND SPECIATION

Volatile fatty acids were the main soluble compounds generated during this set

of experiments as well. The net VFA concentration plotted as a function of SRT (Figure 5.10), shows that an increase in the SRT of the system, up to 20 days (at a constant HRT of 12 hours), results in higher VFA concentrations in both reactors. In general, the variation in SRT does not seem to have a profound effect on VFA production, with the exception of Run 2C (5 days SRT). The drastic drop in VFA concentration observed in this case indicates that such a short SRT may impose a strong stress on the metabolic activity of the acidogenic bacteria. The operational stability of either system also suffers, as reflected on the substantially higher standard deviation (STD) values for this run for almost all the chemical parameters analyzed (Tables C31 to C35, Appendix C).

Information presented in Table 5.11 shows that the net VFA specific production rate increases with SRT up to 15 days, but a plateau appears to be reached at this value. The influence of SRT on the VFA production rate is rather moderate (as in the previous case), except at the shortest SRT, where the production rate is reduced to almost one half of that calculated at 10 days. Overall, the CMR

TABLE 5.11. VFA SPECIFIC PRODUCTION RATE AS A FUNCTION OF SRT

RUN	SRT (d)	CMR (mgVFA/mgVSS*d)	UASB (mgVFA/mgVSS*d)
2C	5	0.053	0.056
1C	10	0.101	0.103
2A	15	0.125	0.110
2B	20	0.119	0.109

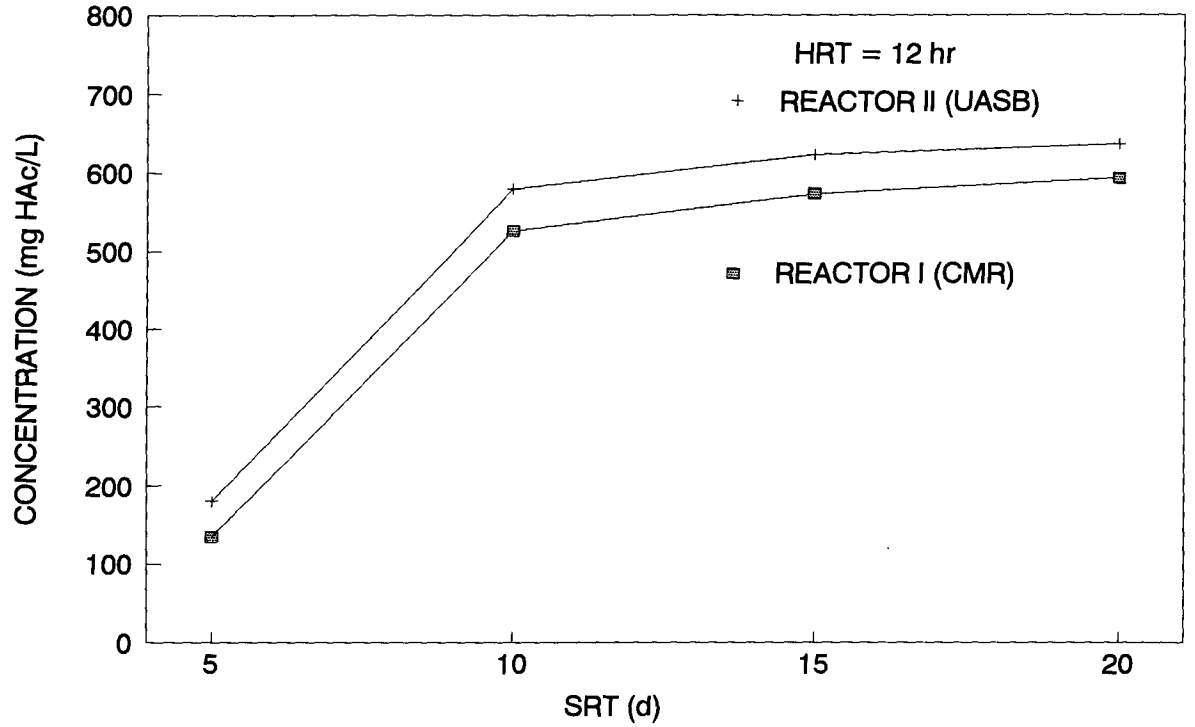


FIGURE 5.10. NET VFA PRODUCTION AS A FUNCTION OF SRT

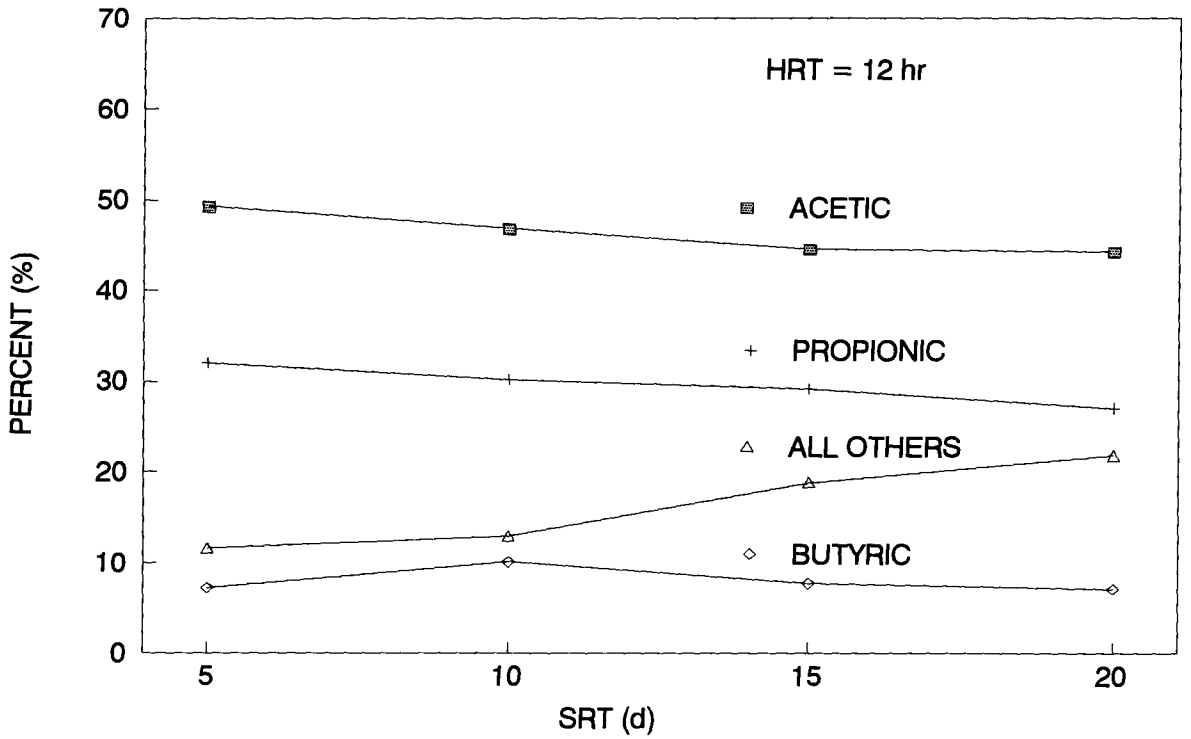


FIGURE 5.11. PERCENT VFA SPECIATION AS A FUNCTION OF SRT

system is slightly more effective in producing VFAs at SRTs of 15 and 20 days (by 14 and 9% respectively) than the other one, but at lower SRTs both systems exhibit similar rates of product formation. (The standard error of the mean for VFA specific production rates ranges from 3 to 5%).

The VFA speciation results (Table 5.12) are in agreement with many of the findings mentioned in Stage 1 (Section 5.2.3) such as those concerning the two predominant acids (acetic and propionic) or the influence of reactor configuration (CMR and UASB). It is interesting to note that the VFA distribution is, to some extent, affected by the variation in SRT, but it appears to be independent of HRT. For better illustration purposes, the average value for each run (since they are very similar in both systems) is plotted as a function of SRT in Figure 5.11. The most remarkable difference occurs in the case of the 4 "minor" acids (iso-butyric, valeric, 3-methylbutyric and 2-methylbutyric). Their percent distribution increases dramatically with SRT (almost doubles from 5 to 20 days). For both acetic and propionic acid the percent distribution declines slightly with an increase in SRT. In the case of butyric acid, a maximum is reached at 10 days. The overall picture suggests that different pathways for VFA production may predominate at various SRTs. Short SRTs seem to favor the generation of straight C_2 to C_4 VFAs, but at longer SRTs more branched C_4 and C_5 acids are formed. Although the possible presence of slower-growing microorganisms at longer SRTs cannot be excluded, the direct association of the 4 higher molecular weight VFAs with protein fermentation provides strong evidence that this phenomenon is a result of proteinaceous metabolism, as discussed in the following section.

TABLE 5.12. PERCENT VFA DISTRIBUTION AS A FUNCTION OF SRT

VOLATILE FATTY ACID	RUN 2C (5 d)		RUN 1C (10 d)		RUN 2A (15 d)		RUN 2B (20 d)	
	CMR	UASB	CMR	UASB	CMR	UASB	CMR	UASB
ACETIC	50.5	48.0	47.5	46.9	43.8	45.2	43.8	44.6
PROPIONIC	31.6	32.3	29.9	30.4	29.9	28.2	27.5	26.4
BUTYRIC	6.8	7.6	9.9	10.3	8.1	7.3	7.0	7.1
ISO-BUTYRIC	3.3	2.9	3.2	2.9	3.8	3.7	5.2	5.5
VALERIC	4.0	4.5	4.4	5.6	6.9	8.0	7.9	8.1
3-METHYLBUTYR.	2.4	2.8	3.3	3.1	5.1	5.4	6.0	5.3
2-METHYLBUTYR.	1.4	1.9	1.8	1.7	2.4	2.2	2.6	3.0
ALL 4 MINOR VFAs	11.1	12.1	12.7	12.7	18.2	19.3	21.7	21.9

5.3.3. ORGANIC CARBON SOLUBILIZATION AND SUBSTRATE DEGRADATION

The majority of observations made about the VFA data set are equally applicable to COD and TOC results. For example, the net COD concentration as a function of SRT (Figure 5.12) shows a great degree of similarity with the VFA production (Figure 5.10), dropping sharply at an SRT of 5 days and approaching a plateau at longer SRTs. However, the COD and TOC specific solubilization rates (Table 5.13) appear to be independent of SRT (i.e. no decrease at 5 days SRT). A plausible explanation for this phenomenon is that at short SRTs the biochemical pathways followed for VFA production from soluble biopolymers are much more influenced than those involved in hydrolysis. If the same microbial community is responsible for the conversion of particulate organic matter to VFAs, it can be concluded that SRTs below a certain value pose a limit on acidogenic activity, therefore intermediate soluble products accumulate.

On the contrary, the percent soluble COD in the form of VFAs increases drastically with increasing SRT, approaching the 90% level at 20 days (Figure 5.13). It is apparent that longer SRTs favor the conversion of soluble metabolic intermediates to end-products.

The percent VSS and TSS reduction results, based on a mass balance at steady-state conditions, are tabulated in Table 5.14. From the data, it is evident that the variation in SRT plays a rather minimal role in the degradation of particulate matter, at least in the range investigated. All observations made in Stage 1 about the

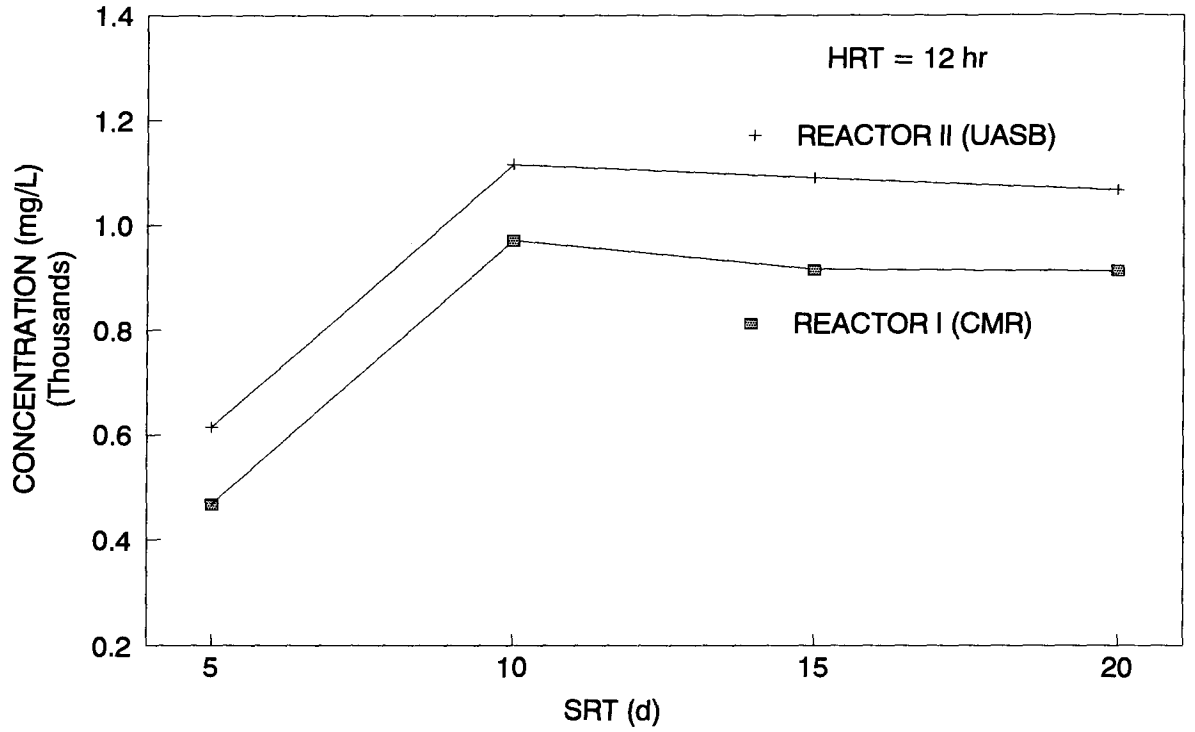


FIGURE 5.12. NET COD SOLUBILIZATION AS A FUNCTION OF SRT

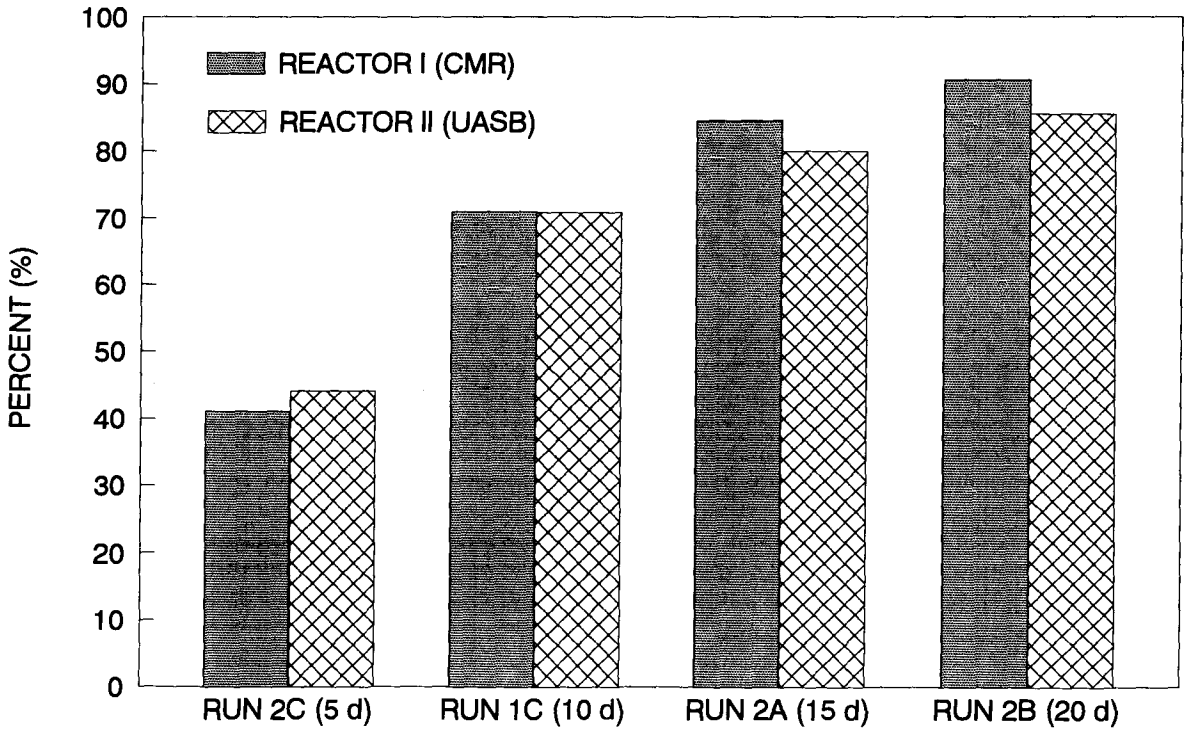


FIGURE 5.13. PERCENT SOLUBLE COD IN THE FORM OF VFAs (STAGE 2)

comparison of VSS and TSS values and the influence of reactor configuration are also valid for Stage 2.

TABLE 5.13. SPECIFIC SOLUBILIZATION RATES OF COD AND TOC AS A FUNCTION OF SRT

RUN	SRT (d)	COD RATE (mgCOD/mgVSS*d)		TOC RATE (mgTOC/mgVSS*d)	
		CMR	UASB	CMR	UASB
2C	5	0.184	0.192	0.066	0.066
1C	10	0.187	0.198	0.070	0.070
2A	15	0.200	0.193	0.078	0.072
2B	20	0.184	0.181	0.072	0.070

TABLE 5.14. PERCENT VSS AND TSS REDUCTION AS A FUNCTION OF SRT

RUN	SRT (d)	VSS (%)		TSS (%)	
		CMR	UASB	CMR	UASB
2C	5	62.8	66.2	64.6	66.9
1C	10	63.1	70.6	64.2	69.6
2A	15	67.1	75.2	68.4	75.4
2B	20	65.6	73.4	66.7	75.3

Table 5.15 shows the percent utilization of carbohydrates, proteins and lipids calculated from the respective mass balances. Considering the suspended solids behavior in the reactors as described above, the three organic classes of interest are not expected to be affected significantly by the variation in SRT. Although, this is

basically true for carbohydrates and lipids, the protein degradation pattern appears to be SRT dependent. Longer SRTs result in consistently higher protein dissimilation. Most of the protein content in primary sludge is cell protein (Section 5.1.1) and, therefore, not readily available for fermentation. In the bioreactors, however, continuous metabolic activity and cell lysis may increase the soluble protein level, especially at longer SRTs. Since the production of the 4 "minor" VFAs (iso-butyric, valeric, 3-methylbutyric and 2-methylbutyric) is mostly associated with the anaerobic metabolism of proteins (Gottschalk, 1986), the increase in protein dissimilation is in agreement with the higher production of these 4 acids at longer SRTs (Table 5.12).

TABLE 5.15. PERCENT SUBSTRATE DEGRADATION AS A FUNCTION OF SRT

RUN	SRT (d)	CARBOHYDR (%)		PROTEINS (%)		LIPIDS (%)	
		CMR	UASB	CMR	UASB	CMR	UASB
2C	5	59.0	70.4	38.7	37.4	83.1	64.5
1C	10	60.6	73.4	42.9	45.0	80.9	62.0
2A	15	62.5	78.8	51.2	48.7	84.5	69.8
2B	20	61.0	76.5	54.1	55.2	81.4	66.7

Finally, the reactor configuration affects the utilization patterns of the three organic classes in exactly the same way as outlined in Stage 1. The rate of carbohydrate degradation is significantly higher in the UASB reactor (Figure 5.14), lipids are solubilized more effectively in the CMR unit and protein dissimilation rates are similar in both systems (Figures 5.15 and 5.16).

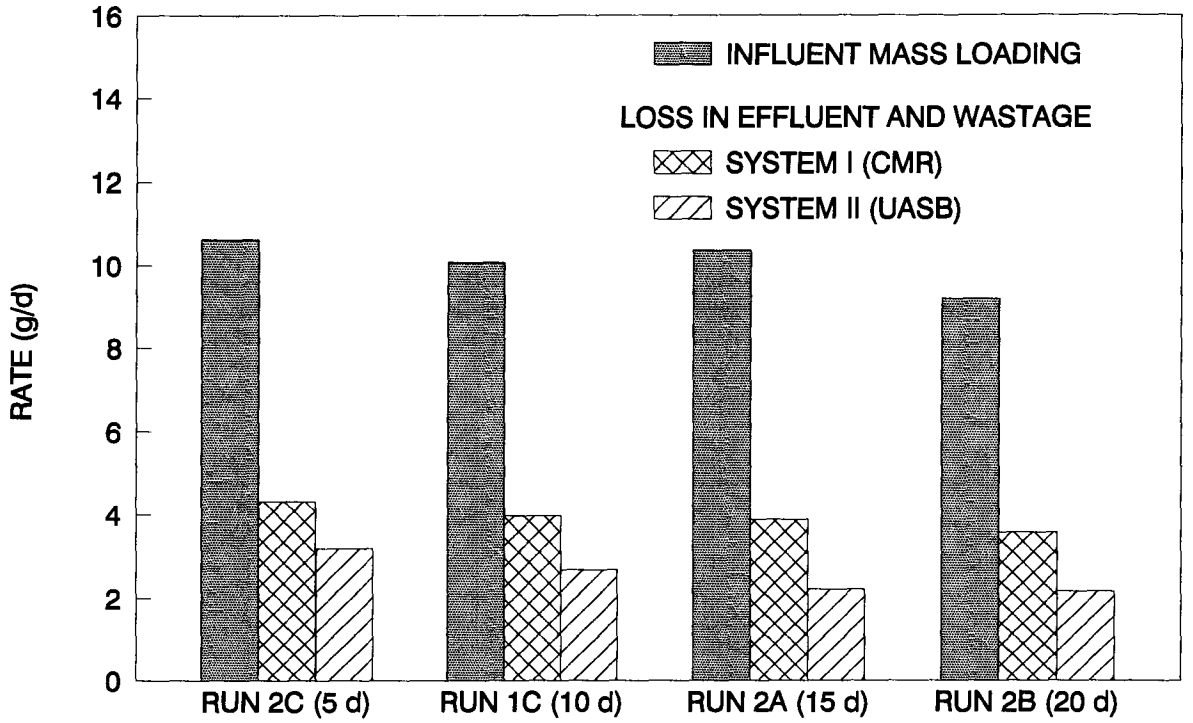


FIGURE 5.14. CARBOHYDRATE DEGRADATION AS A FUNCTION OF SRT

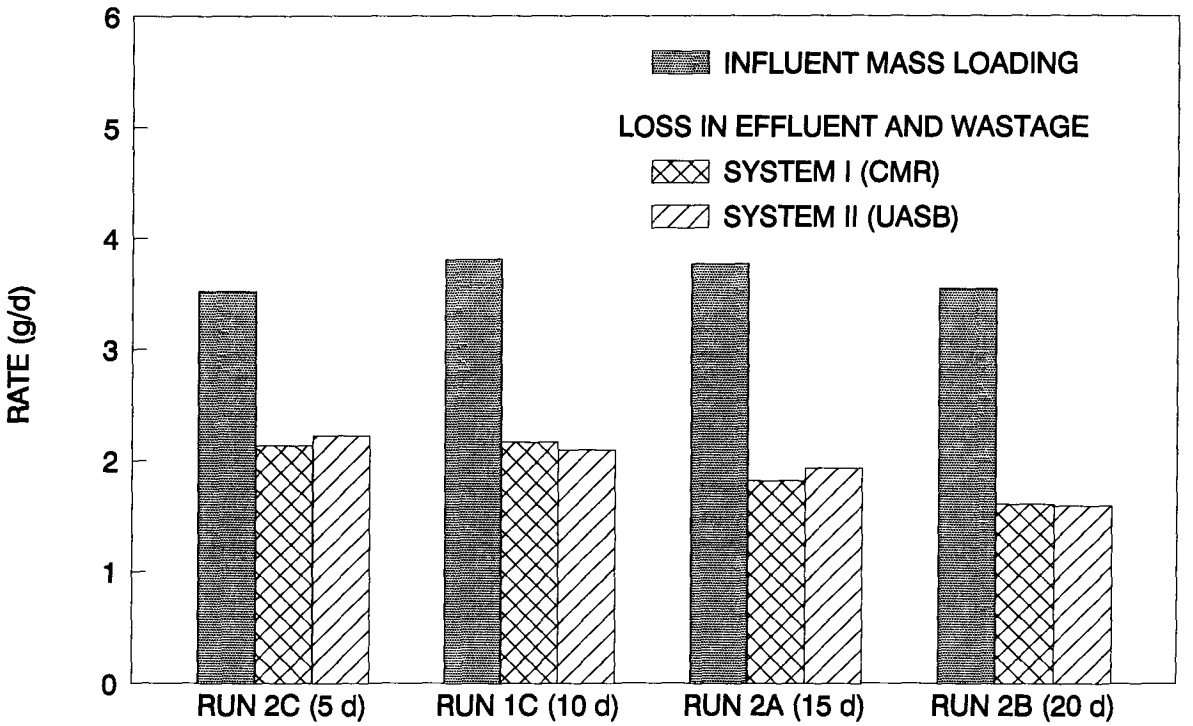


FIGURE 5.15. PROTEIN DEGRADATION AS A FUNCTION OF SRT

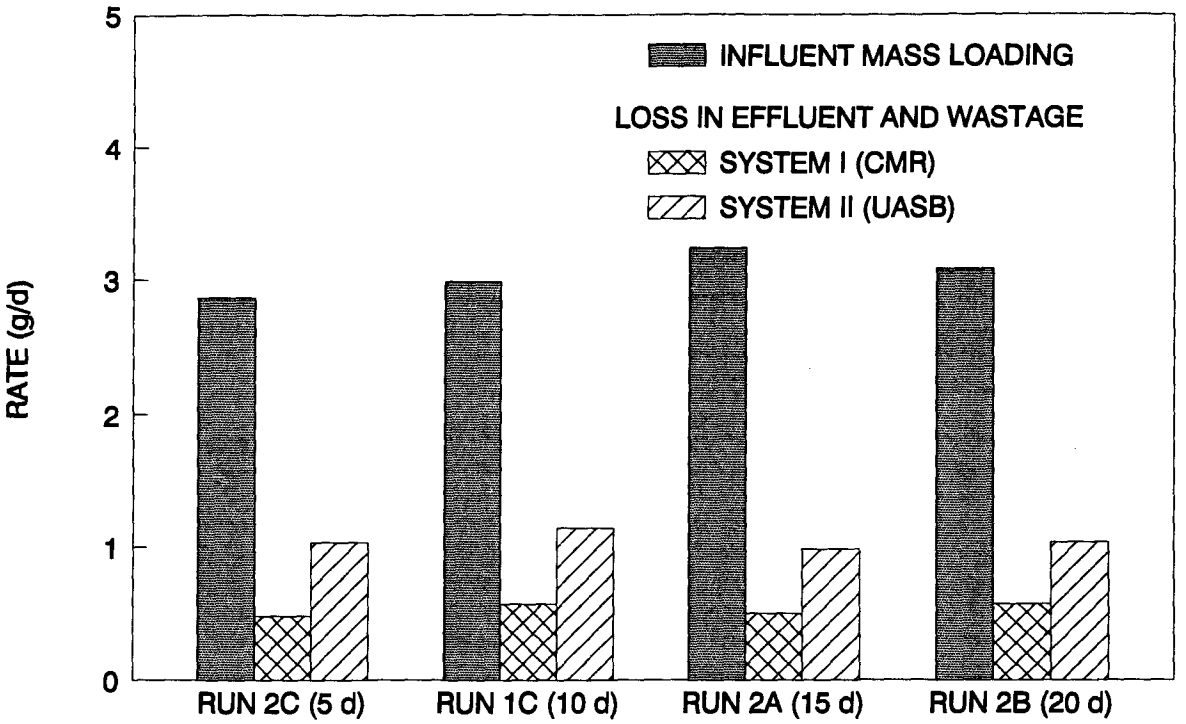


FIGURE 5.16. LIPID DEGRADATION AS A FUNCTION OF SRT

5.3.4. GAS PRODUCTION

Gas generation is the ultimate goal in the two-phase anaerobic digestion process. The acid-phase step is generally characterized by a very low gas production, mostly in the form of CO_2, N_2 and H_2, which are by-products of many pathways followed for substrate metabolism (Appendix A). Ideally, the methane content in the reactor should be negligible. In practice, however, varied amounts of methane have been detected in acid-phase digesters (Eastman and Ferguson, 1981; Ghosh, 1987). This may be due to either incomplete separation of the two phases which results in the co-existence of heterotrophic methane producers, or the presence of certain fast-

growing autotrophic methanogenic organisms such as *Methanobacterium*, or both (Novaes, 1986).

The relatively low gas production obtained (Table E4, Appendix E) indicates that methanogenesis was successfully suppressed throughout this experimental study. Despite the small volumes of gas generated, certain interesting observations can be made. Gas production appears to be independent of HRT (with the notable exception of Run 1D) but increases rather proportionally with increasing SRT in both systems. However, the two- to three-fold increase in Run 1D (HRT: 15 hours, SRT: 10 days) shows that the activity of methane-forming bacteria has been substantially encouraged during this run, as compared to any other set of experimental conditions. When the values of the two operational parameters are distinctly different (resulting in SRT/HRT ratio much higher than one), it is possible that the prolonged availability of food may trigger first the mechanism for methanogenesis. Therefore, longer HRTs may stimulate gas production by allowing better contact between the soluble substrates (i.e. VFAs) and the already present methanogens, while shorter HRTs severely limit methanogen activity without significantly affecting acidogenesis.

Several analyses of gas composition showed that CO_2 is the predominant gas in this phase. On average, the CH_4:CO_2:N_2 percentage was 32:62:6 (by volume), which is in agreement with the range reported in the literature for the acid-phase step (Ghosh et al., 1975; Fongsatitkul, 1992). This ratio is very different from the 70:25:5 ratio found in most well-operating two-phase sludge digesters (Metcalf and Eddy, 1991). Based on a rather small number of samples analyzed (2 to 4 per run), no significant changes in gas composition were observed among different runs.

5.4. REPLICATION AND THE EFFECT OF FEED SOURCE - STAGE 3

5.4.1. REPLICATION EXPERIMENTS (RUN 3A)

To determine the degree of replication possible in acid-phase digesters, two runs (1C and 3A) were operated under identical conditions, except that the first experiment took place in late spring - early summer (May - June) and the second one in winter (January - February).

The operating conditions corresponding to Run 1C (HRT: 12 hours, SRT: 10 days) were selected for the rest of the study. Although longer SRTs resulted in slightly better VFA production rates (Runs 2A and 2B), an SRT of 10 days is considered as a "reasonable" value to ensure high VFA production and at the same time to minimize the length of the experiments.

Analysis of the reactor contents during the steady-state period (Table 5.16) shows that the variation in all parameters measured is minimal between the replicate units. The distribution of the individual volatile fatty acids is about the same for both runs as well (Table 5.17). Furthermore, the variation in standard deviation of all measured values is not statistically significant, according to t-test (Table 5.18). On the basis of these data, it is concluded that the steady-state operation of the acid-phase digestion can be replicated and that the seasonal variation of influent collection (summer - winter) does not seem to play any role in the process.

TABLE 5.16. COMPARISON OF REPLICATION RESULTS AT IONA ISLAND WWTP

ORGANIC PARAMETER	CMR SYSTEM		UASB SYSTEM	
	RUN 1C-S	RUN 3A-W	RUN 1C-S	RUN 3A-W
VFA SP. PROD. RATE	0.101	0.104	0.103	0.099
COD SP. SOLUB. RATE	0.187	0.198	0.198	0.197
TOC SP. SOLUB. RATE	0.070	0.070	0.070	0.074
COD IN VFA FORM	71.0	69.5	70.9	68.5
VSS	63.1	65.5	70.6	68.7
TSS	64.2	65.9	69.6	69.9
CARBOHYDRATES	60.6	59.8	73.4	71.8
PROTEINS	42.9	43.5	45.0	43.5
LIPIDS	80.9	79.2	62.0	61.2

Note: Specific rates are expressed as mg(Parameter)/mgVSS*d, the rest of the values are (%); S=Summer, W=Winter.

TABLE 5.17. PERCENT VFA DISTRIBUTION (STAGE 3)

VOLATILE FATTY ACID	RUN 1C (I.I.)		RUN 3A (I.I.)		RUN 3B (L.G.)	
	CMR	UASB	CMR	UASB	CMR	UASB
ACETIC	47.5	46.0	47.6	45.4	45.1	46.6
PROPIONIC	29.9	30.4	30.7	32.0	35.3	33.0
BUTYRIC	9.9	10.3	9.4	9.5	8.9	8.6
ISO-BUTYRIC	3.2	2.9	2.8	2.3	4.4	4.6
VALERIC	4.4	5.6	4.9	5.4	4.1	3.8
3-METHYLBUT.	3.3	3.1	3.0	3.7	1.4	2.8
2-METHYLBUT.	1.8	1.7	1.6	1.7	0.8	0.8

Note: I.I.=Iona Island WWTP, L.G.=Lions' Gate WWTP.

TABLE 5.18. t-TEST RESULTS FOR RUNS 1C, 3A (IONA ISLAND WWTP) AND 3B (LIONS' GATE WWTP)
(Level of significance α=0.05)

ORGANIC PARAMETER	RUNS 1C and 3A |t| <2.074		RUNS 1C & 3A (comb.) and 3B, |t| <1.960	
	CMR	UASB	CMR	UASB
VFA SP. PROD. RATE	0.548	0.767	3.108	2.388
COD SP. SOLUB. RATE	0.930	0.107	0.741	0.565
TOC SP. SOLUB. RATE	0.000	0.966	0.250	1.415
% COD IN VFA FORM	0.951	1.417	4.964	5.043
% VSS REDUCTION	0.920	1.621	0.832	1.814
% TSS REDUCTION	0.441	1.459	0.567	1.411
% CH_2O DEGRAD.	0.781	1.030	1.879	1.694
% PROTEIN DEGRAD.	0.829	1.064	1.288	1.125
% LIPID DEGRAD.	1.465	0.546	1.880	0.696

5.4.2. THE EFFECT OF FEED SOURCE (RUN 3B)

A common attribute of biological treatment processes is that they are often influenced by the nature of the feed used. Primary sludges from different sources may behave in a different way during the acid-phase digestion step (Chynoweth and Mah, 1971).

To investigate the possible dependency of the process on influent characteristics, the two reactors were operated at 12 hours HRT and 10 days SRT (identical conditions with Runs 1C and 3A), using primary sludge from another source which had the composition shown in Table 5.2.

A summary of the important variables from Run 3B is presented in Table 5.19, along with the combined average values from Runs 1C and 3A for comparative purposes. It is interesting to note that all four "general" variables (COD and TOC solubilization rates, and VSS and TSS reduction percentages) are quite similar, but the "specific" parameters (with the exception of proteins) exhibit some trend of variation. For example, the VFA production rates are reduced in Run 3B by about 12% and the percent COD in the form of VFAs by about 20% in both reactors, when compared to Runs 1C and 3A. Moreover, a relatively lower rate of lipid hydrolysis and an accordingly higher rate of carbohydrate breakdown have been observed, which suggests that the lipolytic activity of lipases was to some extent adversely affected but that of carbohydrate-hydrolyzing enzymes was encouraged when the alternative feed was used. Although, as illustrated in Table 5.19, only the variation in VFA production rates and the related COD in the form of VFAs percent values can be classified as significantly different from a strictly statistical point of view (t-test; Miller et al., 1990), the variation in both carbohydrate and lipid utilization patterns are consistent and may be important especially when compared to the negligible percent changes observed during the replication experiments (Table 5.18).

The percent VFA distribution shows no appreciable changes regarding the major acids (Table 5.17). A closer examination of the minor products, however, reveals that the production of iso-butyric acid has remarkably increased and that of 3-methylbutyric and 2-methylbutyric has accordingly decreased in Run 3B. This can be better illustrated by comparing the relative ratios of the two branched C_5 VFAs to iso-butyric acid (Table 5.20). This ratio not only drops dramatically in the case

TABLE 5.19. COMPARISON OF RESULTS FROM DIFFERENT FEED SOURCES

ORGANIC PARAMETER	CMR SYSTEM				UASB SYSTEM			
	RUNS 1C & 3A	RUN 3B	(%) DIFF.	SIGN. DIFF.	RUNS 1C & 3A	RUN 3B	(%) DIFF.	SIGN. DIFF.
VFA SP. PROD. RATE	0.103	0.089	-13.6	YES	0.101	0.090	-10.9	YES
COD SP. SOLUB. RATE	0.193	0.195	+0.8	NO	0.198	0.202	+2.3	NO
TOC SP. SOLUB. RATE	0.070	0.071	+1.4	NO	0.072	0.069	-4.2	NO
COD IN VFA FORM	70.3	55.2	-21.5	YES	69.7	55.7	-20.1	YES
VSS	64.3	64.6	+0.5	NO	69.7	70.4	+1.1	NO
TSS	65.1	63.2	-2.8	NO	69.8	70.7	+1.4	NO
CARBOHYDRATES	60.2	64.1	+6.5	NO	72.6	78.7	+8.5	NO
PROTEINS	43.2	44.3	+2.6	NO	44.3	43.5	-1.8	NO
LIPIDS	80.1	72.9	-8.9	NO	61.6	57.4	-6.8	NO

Note: Specific rates are expressed as mg(Parameter)/mgVSS*d, the rest of the values are (%); Runs 1A and 3B were from Iona Island WWTP, while Run 3B was from Lions' Gate WWTP.

of the last run, but also the values calculated are the lowest values obtained in the entire study for either reactor. Since all three acids are directly related to protein metabolism, the above observation suggests a possible difference in protein (i.e. amino acid) composition between the two wastewater sources. The primary sludge from Iona Island WWTP, for example, may contain a smaller amount of valine which can produce iso-butyric acid via the Stickland reaction (Eq. 2.8), and/or higher amounts of leucine and iso-leucine which be oxidized, in a similar way, to 3-methylbyturic and 2-methylbyturic acids (Section 2.3.2.b).

TABLE 5.20. PERCENT DISTRIBUTION OF C_5 BRANCHED VFAs AND ISO-BUTYRIC ACID (STAGE 3)

RUN	REACTOR I (CMR)			REACTOR II (UASB)		
	Bran. C_5 VFAs (%)	ISO-BUT. (%)	RATIO	Bran. C_5 VFAs (%)	ISO-BUT. (%)	RATIO
1C (I.I.)	5.1	3.2	1.59	4.8	2.9	1.66
3A (I.I.)	4.6	2.8	1.64	5.0	2.3	2.17
3B (L.G.)	2.2	4.4	0.50	3.6	4.6	0.78

Note: I.I.=Iona Island WWTP, L.G.=Lions' Gate WWTP

Taking into account the spectrum of variations observed using sludge from a different source, it can be concluded that the nature of primary sludge may have an effect upon the hydrolysis of particulate organic matter and furthermore that the bacteria may use different metabolic pathways to utilize certain hydrolysis products. This behavior indicates a higher degree of sensitivity to changes in initial conditions than to changes in operational conditions.

5.5. THE EFFECT OF pH - STAGE 4

5.5.1. pH AS A SELECTIVE PARAMETER

The pH of a bioreactor determines the possibility of survival and the rate of reproduction of any microbial species present in this particular environment. In many cases, however, the primary determinants of pH are the organisms themselves (if the pH is not externally adjusted). Microorganisms are able to alter the pH of their environment through various metabolic activities. These changes might be advantageous or not to the microbes that cause them. Some species can create environments in which very few other organisms are able to survive, and if they themselves are not adversely affected by the conditions they create, they may thus eliminate competition. On the other hand, the alterations in pH may encourage the predominance of a competitor. For example, bacteria may produce acidic products that decrease the pH value in an insufficiently buffered environment and allow fungi to predominate (Gaudy and Gaudy, 1980).

The ability of microorganisms to alter pH is the basis of important interactions between species. Since pH affects growth rate, changes in pH may cause dramatic shifts in the relative numbers of different species in the population. It has been found that many aspects of microbial metabolism are greatly influenced by the variations in pH over the range within which the organisms can grow (Sakharova and Rabotnova, 1976). These aspects include utilization of carbon and energy sources, efficiency of substrate dissimilation, synthesis of protein and different types of

storage material, and release of metabolic products from the cell. Moreover, pH variations can affect cell morphology and structure and, therefore, flocculation and adhesion phenomena (Forage et al., 1985). All of the above factors play a crucial role in determining the ability of a given microbial species to compete with others in a heterogeneous environment.

5.5.2. BUFFERING CAPACITY

The buffering capacity of a biological system is manifested by the degree of its resistance to pH changes. In acid-phase digestion, many inorganic and organic buffer systems such as carbonate/bicarbonate, phosphate, borate, silicate, citrate, and proteins may be active in the pH range of interest. The resistance to acidification is a function of the total buffering capacity of the system (Powell and Archer, 1989). Throughout the uncontrolled pH experiments (Stages 1 to 3), the pH values in either reactor, after an initial drop during acclimation, were exceedingly stable during the steady-state operation (Appendix B). The coefficient of variation (CoV) was between 2 and 5% for all runs (Table 5.21). This is mainly attributed to the presence of proteins and VFAs, since the buffering capacity of the Vancouver water supply is very low (total alkalinity is usually between 100 and 150 mg/L as $CaCO_3$).

Proteins and their hydrolysis products (amino acids) act as both hydrogen donors and hydrogen acceptors since they possess the ionizable amino group ($-NH_2$) and carboxyl group (-COOH). Although the peptide bonds of proteins tie up the α-amino acid and carboxyl groups, there are both amino and carboxyl groups as well

as other ionizable groups (eg. imidazolyl, sulphide etc.) in the side chains of many acids (Gaudy and Gaudy, 1980). Thus, proteins in solution can buffer against changes in pH. Individual amino acids exert their maximum buffering potential at different pH values depending on the number of amino and carboxyl groups they possess. For example, two of the most prevalent amino acids in domestic wastewaters, aspartic acid (pK_{A1} = 3.86) and glutamic acid (pK_{A1} = 4.07) are most effective in acidic environments (CRC Handbook of Chemistry and Physics, 1981).

TABLE 5.21. pH VALUES IN BIOREACTORS (STAGES 1 TO 3)

RUN	REACTOR I (CMR)			REACTOR II (UASB)		
	MEAN	STD	CoV (%)	MEAN	STD	CoV (%)
1A	5.23	0.17	3.3	5.25	0.15	2.9
1B	5.27	0.11	2.1	5.33	0.13	2.4
1C	5.01	0.25	5.0	4.96	0.23	4.6
1D	5.06	0.14	2.8	5.10	0.13	2.5
2A	5.17	0.14	2.7	5.03	0.13	2.6
2B	5.23	0.10	1.9	5.09	0.11	2.2
2C	5.63	0.18	3.2	5.52	0.11	2.0
3A	5.15	0.17	3.3	4.98	0.13	2.6
3B	5.03	0.16	3.2	5.05	0.14	2.8

Volatile fatty acids can also act as buffers in a pH range close to their pK_A values. The two major products of acidogenic digestion, acetic acid (pK_A = 4.76) and propionic acid (pK_A = 4.87), attain their highest buffering capacity at pH of about

5 (Sawyer and McCarty, 1979).

The utilization of proteins and amino acids during the digestion process is counterbalanced by the generation of VFAs, and as a result, at steady-state conditions, the pH of the system remains fairly constant. The "equilibrium" pH range attained, however, may be a function of the relative concentrations of the reactants and the products involved. VFA concentrations below 400 mg/L resulted in an increase in pH in either reactor, but no appreciable variation in pH (less than 0.3 units) occurred at concentrations ranging from 400 to 750 mg/L (Figures 5.17 and 5.18).

To further investigate the role of pH in the process, two additional experiments were conducted at controlled conditions. Dilute solutions (0.02N) of hydrochloric acid and sodium hydroxide were used to maintain the pH at selected values. Both chemicals were specifically chosen because of their low-level interference with the metabolic pathways involved. Sodium is generally tolerated by most microorganisms, particularly in the presence of potassium. Furthermore, chloride ions are not inhibitory to bacteria at the concentrations attained (Forage et al., 1985).

5.5.3. VFA PRODUCTION AND SPECIATION

The total net VFA production (as acetic acid) at steady-state conditions is depicted in Figure 5.19. VFA concentration does not appear to be affected, in either reactor, by a drop in pH from 5.1 to 4.5 (Runs 1C and 4A), but in Run 4B an increase in pH to about 6.1 results in significantly lower (25 to 30%) total acid

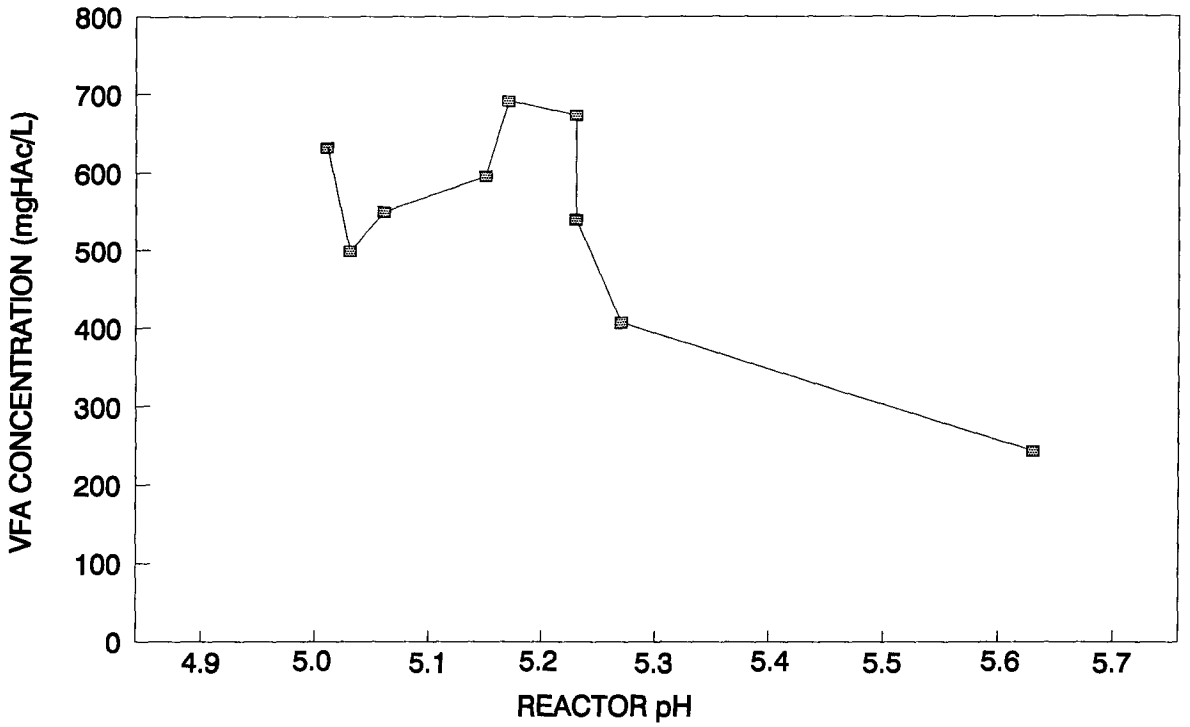


FIGURE 5.17. REACTOR pH AND VFA CONCENTRATION (CMR SYSTEM)

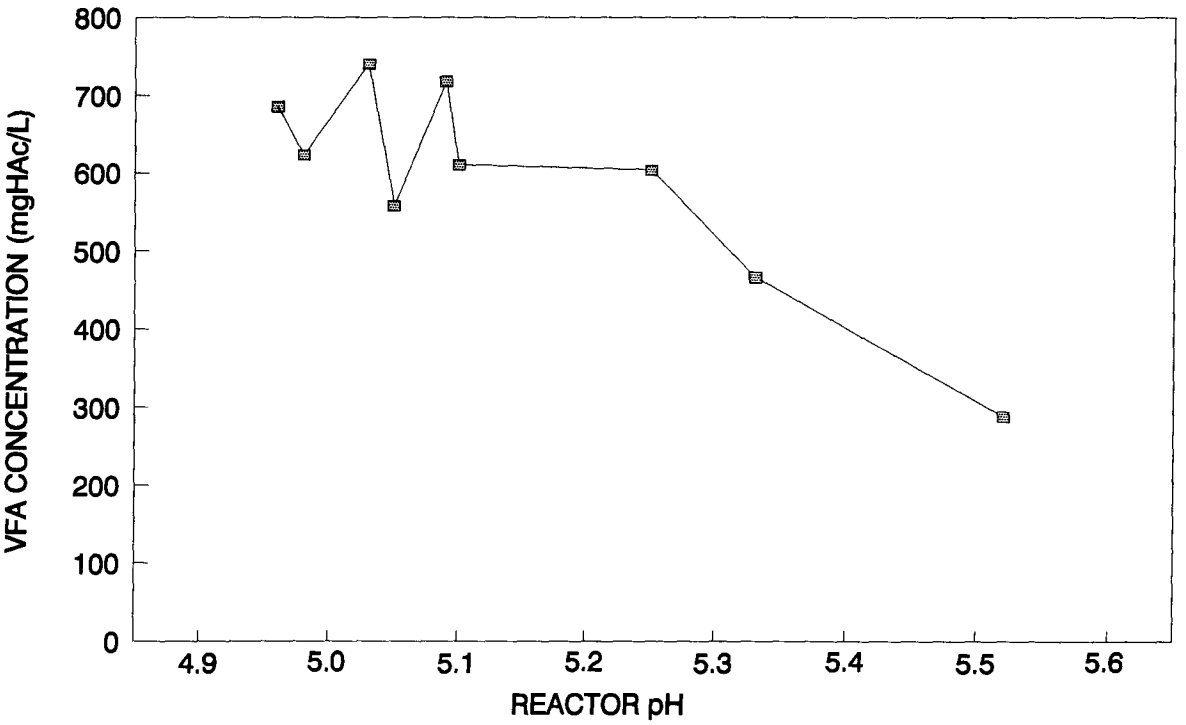


FIGURE 5.18. REACTOR pH AND VFA CONCENTRATION (UASB SYSTEM)

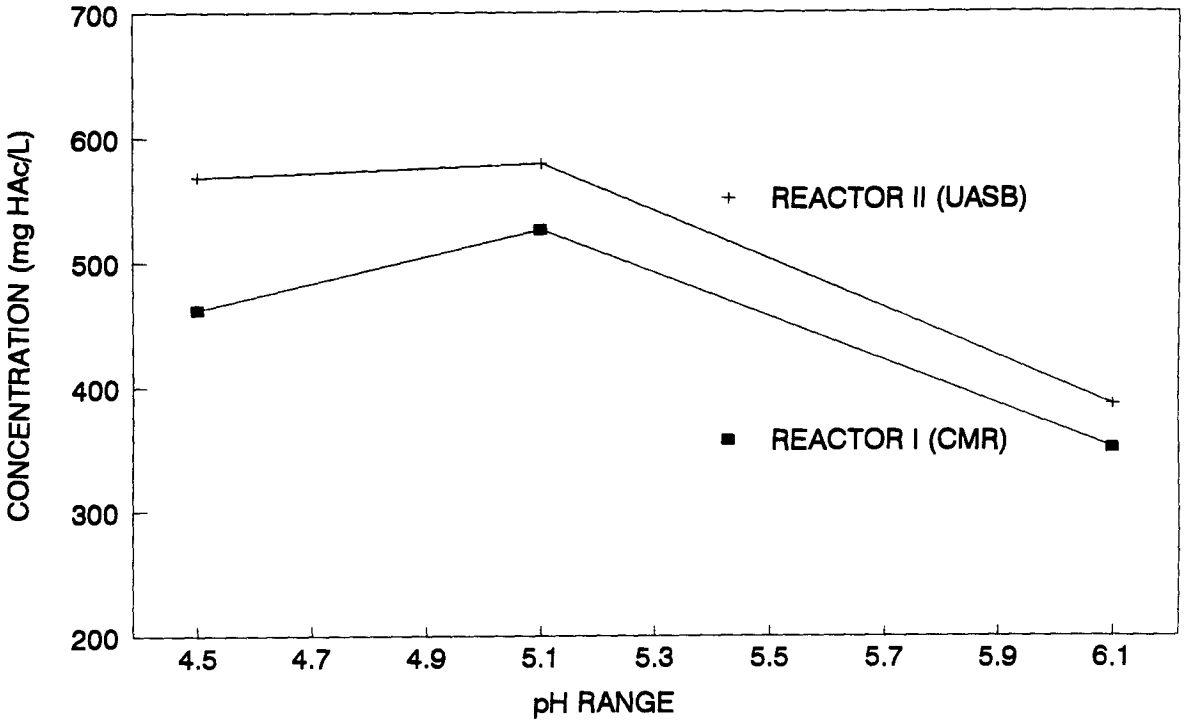


FIGURE 5.19. NET VFA PRODUCTION AS A FUNCTION OF pH

production, suggesting a sensitive response of the process at the above pH range. Since the reactor and effluent VFA concentrations of the CMR system are actually the same (Appendix C), no volatilization losses occurred at any pH value.

As in the Stage 1 results, the VFA concentration is higher in the UASB reactor, but the specific production rate is similar in both systems (Table 5.22). This is a further indication that the ability of bacteria to produce VFAs is independent of the reactor configuration, at least within the HRT and pH ranges investigated. Both the VFA production rate and concentration follow comparable trends at different pH values.

The optimum pH range for the acidogenic phase can be influenced by the characteristics of the feed and operating conditions. The results from this study show

that the runs (without pH control) associated with high VFA production were largely operated at pH values between 5.0 and 5.3, which can be considered as an "optimum" range. The same pH range has been obtained in a UASB reactor treating a synthetic sludge (Fongsatitkul, 1992). It has been frequently reported that acid-phase bioreactors were successfully operated at pH between 5.0 and 6.0 (Eastman and Ferguson, 1981; Zoetemeyer et al., 1982b; Breure et al., 1986; Kisaalita et al., 1989). In some cases, however, the optimum pH was significantly higher. Joubert and Britz (1986) and Perot et al. (1988) have found that the maximum concentration of acid-phase products was achieved at pH 6.5 and 6.8 respectively. The higher optimum pH observed in the last two studies may be due to the composition of the feed (sucrose in the former study and a mixture of primary and waste activated sludge in the latter) or the type of inoculum used.

TABLE 5.22. VFA SPECIFIC PRODUCTION RATE AS A FUNCTION OF pH

RUN	pH RANGE	CMR (mgVFA/mgVSS*d)	UASB (mgVFA/mgVSS*d)
4A	4.3 - 4.6	0.097	0.100
1C	4.9 - 5.2	0.101	0.103
4B	5.9 - 6.2	0.076	0.078

That the extracellular pH has a strong effect on the pathways of metabolism and products generated by microorganisms is a well known phenomenon in biological processes. However, the mechanism by which metabolic reactions are regulated is not

well understood. Often the response to pH in terms of product formation seems to be a logical adaptation by the microbial species (Forage et al., 1985).

As shown in Table 5.23, alterations in pH can also influence the percent VFA distribution. A relative increase in propionic acid is observed at pH 4.3-4.6 (Run 4A) and in butyric acid at pH 5.9-6.2 (Run 4B), as compared to the uncontrolled pH of 5.0-5.3 (Run 1C). In contrast, the range of pH studied (4.3-6.2) does not seem to have any appreciable effect on the percent distribution of the other VFA present. Moreover, acetic acid yield has been found by others to be independent of pH values from 4.5 to 7.0 (Hsu and Yang, 1991).

TABLE 5.23. PERCENT VFA DISTRIBUTION AS A FUNCTION OF pH

VOLATILE FATTY ACID	RUN 4A (pH=4.3-4.6)		RUN 1C (pH=4.9-5.2)		RUN 4B (pH=5.9-6.2)	
	CMR	UASB	CMR	UASB	CMR	UASB
ACETIC	45.6	43.0	47.5	46.0	43.4	42.4
PROPIONIC	38.0	39.3	29.9	30.4	20.6	22.4
BUTYRIC	5.5	6.1	9.9	10.3	21.0	19.8
ISO-BUTYRIC	3.9	3.2	3.2	2.9	4.6	3.8
VALERIC	3.7	4.1	4.4	5.6	4.8	5.2
3-METHYLBUT.	2.2	3.0	3.3	3.1	3.7	4.3
2-METHYLBUT.	1.1	1.3	1.8	1.7	1.9	2.1

There is evidence in the literature that propionic acid production is encouraged by a drop in pH (down to 4.5). Eastman and Ferguson (1981) have found that

propionic acid distribution increased steadily with the decrease in pH from 7.0 to 5.0. In another study, the highest propionic acid concentration was obtained at the lowest pH value over the range 4.5 to 8.0 (Zoetemeyer et al., 1982b). Although the optimum growth rate of most propionic-acid bacteria occurs at pH 6.0 or higher, the product yield increases significantly with decreasing pH from 6.0 to 4.5 (Hsu and Yang, 1991). In all of the above investigations the pH was externally controlled and, therefore, changes in productivity occurred as a result of pH manipulation. Since the production of propionic acid is both growth and non-growth associated, the optimum pH for cell growth is not necessarily the optimum value for propionic acid generation (Papoutsakis and Meyer, 1985).

A diametrically opposite result to the above pattern has been observed in the case of butyric acid (Table 5.23). The percent distribution increases dramatically (about 3 to 4 times) with increasing pH, especially between the Runs 4A and 4B. It has been reported that pH values of 6.0 or higher favor butyric acid production in acidogenic sewage sludge (primary and secondary) digestion (Joubert and Britz, 1986). On the other hand, the acid-phase degradation of less complex organic substrates (sucrose and lactose) resulted in either no change in the percent butyric acid distribution at pH between 4.5 and 6.5 (Zoetemeyer et al., 1982b) or even a drop in butyric acid with increasing pH (Kisaalita et al., 1987). It has not been conclusively demonstrated whether butyric acid generation is growth associated or not (Morris, 1985; Kisaalita et al., 1989). It appears that substrate composition plays, among others, a critical role in butyric acid production at different pH values.

In conclusion, the variation in product distribution as a function of pH in

steady-state, continuous-flow systems may be caused by alterations in the metabolism of the same bacterial population or by changes of the population itself, or both.

5.5.4. ORGANIC CARBON SOLUBILIZATION AND SUBSTRATE DEGRADATION

Organic carbon solubilization data, expressed as the corresponding COD and TOC rates, are shown in Table 5.24. It is apparent that a drop in pH from 5.1 to 4.5 (Runs 1C and 4A) did not induce any appreciable changes in the overall hydrolysis pattern of organic substrate. In contrast, an increase in pH from 5.1 to 6.1 (Runs 1C and 4B) resulted in remarkably higher solubilization rates. In fact, these are the highest values obtained for the entire study, in either reactor. The observed increase in substrate solubilization can be attributed to the higher rate of carbohydrate hydrolysis occurring at this pH range in both reactors (Figures 5.20 and 5.21).

TABLE 5.24. SPECIFIC SOLUBILIZATION RATES OF COD AND TOC AS A FUNCTION OF pH

RUN	pH RANGE	COD RATE (mgCOD/mgVSS*d)		TOC RATE (mgTOC/mgVSS*d)	
		CMR	UASB	CMR	UASB
4A	4.3 - 4.6	0.194	0.184	0.073	0.068
1C	4.9 - 5.2	0.187	0.198	0.070	0.070
4B	5.9 - 6.2	0.219	0.239	0.078	0.084

The percentage of COD due to VFAs, as a function of pH, is depicted in Table 5.25. Although no significant changes occur by lowering the pH to 4.5, a drastic drop in the percentage can be observed at pH of about 6.1. VFA production has been reduced at this pH range (Figure 5.19), but hydrolysis of organic matter (measured as soluble COD) is still increasing. This indicates that an increase in pH to about 6.1 adversely affects the acid-generating pathways, but on the contrary, it further stimulates the overall hydrolytic activity, which may result in higher concentration of soluble metabolic intermediate products.

These observations are further supported by the percent VSS and TSS reduction data (Table 5.26). The same trends, as above, are followed by both parameters with respect to pH alteration.

TABLE 5.25. PERCENT SOLUBLE COD IN THE FORM OF VFAs AS A FUNCTION OF pH

RUN	pH RANGE	COD IN VFA FORM (%)	
		REACTOR I (CMR)	REACTOR II(UASB)
4A	4.3 - 4.6	67.1	74.7
1C	4.9 - 5.2	71.0	70.9
4B	5.9 - 6.2	52.5	51.6

Analysis of the degradation behavior of the individual organic classes, however, reveals that certain important deviations from the previously described scheme take place, which cannot be detected in the "generic" parameters. Results presented in Figure 5.20 (CMR unit) and Figure 5.21 (UASB unit) show that none

TABLE 5.26. PERCENT VSS AND TSS REDUCTION AS A FUNCTION OF pH

RUN	pH RANGE	VSS (%)		TSS (%)	
		CMR	UASB	CMR	UASB
4A	4.3 - 4.6	62.5	67.7	64.1	69.3
1C	4.9 - 5.2	63.1	70.6	64.2	69.6
4B	5.9 - 6.2	71.3	76.0	72.9	76.1

of the utilization patterns of the three organic classes is comparable to that followed by VSS (i.e. no significant change between pH 4.5 and 5.1, a moderate increase at pH 6.1).

Lipid solubilization deviates from the above trend only at pH 6.1 (Run 4B), where a moderate drop is observed instead of an increase. This might be the result of reduced activity of the lipolytic enzymes at this pH value.

The protein degradation picture is quite different. The highest reduction percentage obtained in the entire study is observed at pH 4.5. As pH increases, a significant decrease in the protein hydrolysis rate occurs. It is interesting to note that the high protein dissimilation rate observed at pH 4.3-4.6 (Run 4A) did not induce an increase in any of the end-products associated with protein fermentation. The production of the corresponding VFAs (iso-butyric and the 3 isomers of valeric acid) and ammonia is about the same or even lower in Run 4A compared to the other two runs at higher pH values (Table 5.27). Although many proteolytic organisms usually prefer a neutral pH environment, proteolytic enzymes may exhibit their maximum activity at different pH values ranging from 2 to 10 (Bailey and Ollis, 1977). Since

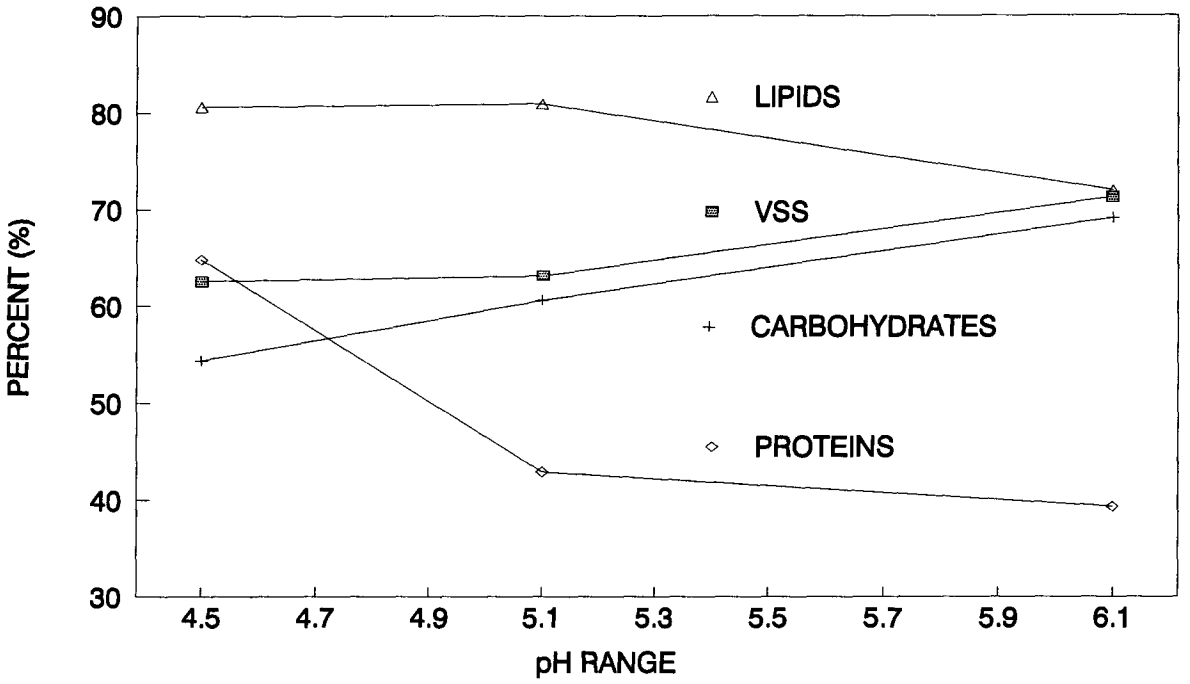


FIGURE 5.20. PERCENT SUBSTRATE DEGRADATION AS A FUNCTION OF pH IN THE CMR SYSTEM

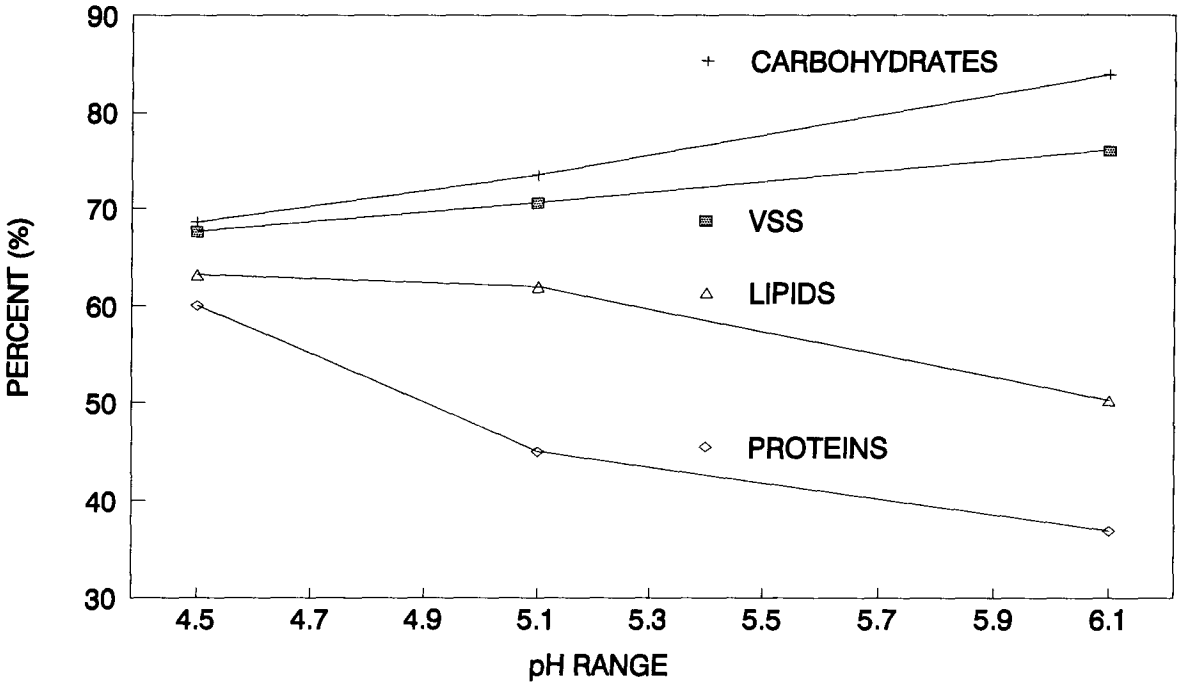


FIGURE 5.21. PERCENT SUBSTRATE DEGRADATION AS A FUNCTION OF pH IN THE UASB SYSTEM

enzymatic activity is strongly pH dependent, it is possible that an environment with an extracellular pH of about 4.5 may activate further the proteolytic enzymes without, at the same time, promoting acidogensis.

TABLE 5.27. PROTEIN DEGRADATION AND ITS END-PRODUCTS AS A FUNCTION OF pH

PARAMETER	RUN 4A (pH=4.3-4.6)		RUN 1C (pH=4.9-5.2)		RUN 4B (pH=5.9-6.2)	
	CMR	UASB	CMR	UASB	CMR	UASB
RELATED VFAs (% of total)	10.9	11.6	12.7	13.3	15.0	15.4
NH_3-N (mg/L)	30.3	29.8	29.3	35.7	30.5	28.5
PROTEIN DEGRAD. (%)	64.8	60.1	42.9	45.0	39.3	36.8

On the other hand, carbohydrate degradation increases steadily with increasing pH, in the range investigated (4.3-6.2). A similar trend has been observed by Eastman and Ferguson (1981) in continuous flow reactors treating primary sludge at pH between 5.2 and 6.5. It has been reported that hydrolysis of complex carbohydrates reaches a maximum rate at a pH value between 6.0 to 6.5 (Breure et al., 1986), which suggest that the activity of the enzymes involved increases with pH up to the optimum rate.

Regarding the effect of reactor configuration on the utilization of the three organic classes, no variation from the previously described pattern was observed.

5.6. GENERAL REVIEW

5.6.1. VFA FORMATION

A summary of the distribution of VFAs generated in the anaerobic digestion of primary sludge is presented in Table 5.28. Acetic acid is the most prevalent product, as it is formed directly from the fermentation of carbohydrates and proteins, as well as the anaerobic oxidation of lipids via a number of metabolic pathways (Sections 2.3.1 to 2.3.3). Propionic acid is formed primarily from carbohydrates, but it can be also produced in the digestion of the other two organic classes (McCarty et al., 1963). On the other hand, butyric acid is mainly generated in the digestion of proteins and lipids. It may also be formed in the fermentation of carbohydrates from pyruvate via an alternative pathway (Figure A4, Appendix A). In mixed-culture fermentations, however, this pathway is considered as a rather minor one (Gottschalk, 1986). Taking into account the relative content of the three organic components in the feed, this can provide an explanation for the remarkable difference in the formation of propionic and butyric acids (Table 5.28). The enhanced production of butyric acid at the pH range of 5.9-6.2 (which coincides with the pH for maximum carbohydrate hydrolysis) may be partially due to activation of the above mentioned biochemical pathway.

Iso-butyric acid and the three isomers of valeric acid are largely associated with the fermentation of proteins. They can be formed via reductive deamination of single amino acids (Eq. 2.6) or by an oxidation-reduction reaction between pairs of

amino acids known as the Stickland reaction (Eq. 2.8). It has been found that the production of all four acids during the digestion of non-proteinaceous substrates is minimal (Cohen et al., 1984).

It can be also observed that the percent VFA distribution is remarkably similar in both reactors (Table 5.28). Although there is a significant difference in the degradation rates of carbohydrates and lipids between the two systems, the generation of the same VFAs (i.e. acetic, propionic and butyric acids) from the metabolism of these two substrates results in an overall similar picture with respect to product distribution.

5.6.2. FORMATION OF OTHER SOLUBLE END-PRODUCTS

In acid-phase digestion, besides VFAs, a variety of simple soluble C_1 to C_4 end-products may be generated such as organic acids (formic and lactic), alcohols (ethanol, butanol, 2-propanol, 1,3-propanediol, 2,3-butanediol and glycerol), ketones (acetone and 2,3-butanedione) and aldehydes (acetaldehyde) (Doelle, 1975; Gottschalk, 1986). Chemical analyses for the above compounds plus pyruvic acid showed that only formic acid, lactic acid and ethanol were regularly detected in both reactors, at relatively low concentrations (Table 5.29). The rest of the chemicals either were not detected at all (2-propanol, 1,3-propanediol, acetone, 2,3-butanedione and acetaldehyde), or found sporadically at very low levels, usually less than 1 mg/L (butanol, 2,3-butanediol and glycerol). Moreover, pyruvic acid, the key intermediate metabolite in carbohydrate fermentation, was never detected. In general, pyruvic acid

TABLE 5.28. SUMMARY OF PERCENT VFA DISTRIBUTION

VOLATILE FATTY ACID	REACTOR I (CMR)		REACTOR II (UASB)	
	RANGE	MEAN	RANGE	MEAN
ACETIC	43.4 - 50.5	46.3	42.4 - 48.0	45.1
PROPIONIC	20.6 - 38.0	31.0	22.4 - 39.3	31.3
BUTYRIC	5.5 - 21.0	9.0	6.1 - 19.8	8.9
ISO-BUTYRIC	2.8 - 5.2	3.8	2.3 - 5.5	3.6
VALERIC	3.7 - 7.9	4.9	3.8 - 8.1	5.5
3-METHYLBUT.	1.4 - 6.0	3.3	2.6 - 5.4	3.7
2-METHYLBUT.	0.8 - 2.6	1.7	0.8 - 3.0	1.9

TABLE 5.29. OTHER SOLUBLE END-PRODUCTS (MEAN VALUES)

RUN	REACTOR I (CMR)			REACTOR II (UASB)		
	Formic Acid	Lactic Acid	Ethanol	Formic Acid	Lactic Acid	Ethanol
1A	N.A.	N.A.	6.5	N.A.	N.A.	7.7
1B	N.A.	N.A.	4.0	N.A.	N.A.	10.1
1C	15.2	1.5	6.4	6.3	<1.0	9.0
1D	23.2	<1.0	3.8	7.7	<1.0	6.7
2A	30.6	<1.0	9.2	14.5	1.6	10.5
2B	33.5	1.3	7.7	14.8	<1.0	13.4
2C	15.1	2.5	8.5	7.4	2.0	10.1
3A	21.0	<1.0	5.9	11.1	1.4	9.8
3B	16.5	<1.0	4.0	9.2	<1.0	12.7
4A	14.8	1.7	1.1	6.0	<1.0	2.8
4B	28.5	7.8	17.7	14.1	11.7	28.4

Note: N.A. =Not Analyzed; All values are expressed in mg/L.

is very rarely excreted by anaerobic microorganisms because it plays a crucial role in bacterial energy balance. The pathway leading from pyruvic acid to the end-products of fermentation may accomplish a dual purpose: oxidation of the already reduced $NADH_2$, and production of additional ATP by substrate level phosphorylation (Gaudy and Gaudy, 1980). The first result is essential for the completion of the biochemical cycle, while the second is highly desirable since anaerobic growth is directly proportional to the amount of ATP generated (Gottschalk, 1986).

It should be noted that all of the above compounds (except glycerol) are fermentation end-products of carbohydrate metabolism. Glycerol is mainly formed during lipid hydrolysis (Eq. 2.9). These results are in agreement with several studies which have found that generation of soluble non-VFA end-products is minimal in continuous flow systems using a heterogeneous particulate feed (Chynoweth and Mah, 1971; Eastman and Ferguson, 1981; Ghosh, 1987). Significant amounts of lactic acid or ethanol have been obtained in batch experiments (Uribelarrea and Pareilleux, 1981) and in studies using simple soluble substrates such as glucose (Zoetemeyer et al., 1982a), sucrose (Joubert and Britz, 1986) or lactose (Kisaalita et al., 1990).

There is no apparent trend in the production of formic acid, lactic acid and ethanol associated with the variations in the operational parameters (HRT and SRT) and the feed source, except a slight increase in formic acid at longer SRTs (Table 5.29, Runs 2A and 2B). Changes in pH, however, affect to a great extent all three compounds. At pH 4.3-4.6 (Run 4A) ethanol production is limited, but at pH 5.9-6.2 (Run 4B) the amounts of both lactic acid and ethanol are remarkably higher. Formic acid concentration increases with pH as well (Run 4B).

The pH of the environment may have a strong effect on many pathways of anaerobic metabolism. For example, a number of saccharolytic clostridia which normally ferment carbohydrates to butyric acid are able to change their metabolism when the pH is lowered to about 4.0, favoring the production of acetone, and concurrently to convert the butyric acid produced to butanol (Doelle, 1975).

It should be noted that the reactor regime appears to play a role in the production of formic acid which is 2 to 3 times higher in the CMR system. On the contrary, ethanol is generated at an almost double rate in the UASB reactor.

In carbohydrate fermentation, formic acid and ethanol are formed by decarboxylation of pyruvic acid. As mentioned earlier, the major objective of metabolic reactions that convert pyruvic acid to various products is the reoxidation of the electron carrier ($NADH_2$) that has already been reduced. Certain microorganisms can utilize a mechanism which removes two hydrogen atoms along with the C_1 fragment without reducing the electron carrier. In this case, the products of the C_1-C_2 split of pyruvic acid are formic acid and acetyl-CoA. The latter compound may be then reduced to ethanol by accepting four hydrogen atoms, which results in the simultaneous oxidation of two molecules of $NADH_2$ (Gaudy and Gaudy, 1980).

In acidic pH conditions, bacteria able to synthesize the enzyme formic dehydrogenase can degrade formic acid to H_2 and CO_2. Depending on the strain and the pH, variable amounts of formic acid may be converted, with the remainder appearing as a fermentation product. The substantially lower formic acid concentration in the UASB reactor (Table 5.29) may be due to either greater

degradation rates or lower formation rates of the acid in this particular environment, or both.

Although lactic acid is an important product in many fermentations (Section 2.4.2), it is usually present at only very low concentrations in anaerobic digestion effluents (Ueki et al., 1978; Uribelarrea and Pareilleux, 1981). It has been demonstrated that lactic acid can be converted to propionic acid and other products by anaerobic bacteria employing the acrylate pathway (Figure A3, Appendix A) or the succinate pathway (Nakamura and Takahashi, 1971). Formation and subsequent conversion of lactic acid occurs as a normal process in digesters. The interaction between lactate-generating and lactate-utilizing bacteria plays an important role in the fermentation of carbohydrates during sludge digestion (Ueki et al., 1980). Since the growth of lactate-utilizing bacteria is suppressed by high glucose concentrations, lactic acid accumulation may occur in digesters treating glucose-rich wastewaters (de la Torre and Goma, 1981; Zoetemeyer et al., 1982a). The relatively low soluble carbohydrate (i.e. glucose) levels measured in this study (Table E2, Appendix E) did not interfere with the metabolism of lactate-utilizers resulting in very small amounts of lactic acid in both reactors (Table 5.29).

5.6.3. RATE-CONTROLLING STEP AND NATURE OF SOLUBLE COMPOUNDS

As mentioned in Section 2.1, the anaerobic digestion of complex substrates is a multi-step process. In general, when a process consists of a sequence of reactions,

one step is usually much slower than the others. The last slow step in the sequence is called the rate-controlling, rate-limiting or rate-determining step (Hill, 1977). In anaerobic digestion, the rate-controlling step is related to the nature of the substrate, process configuration, loading rate, and temperature (Speece, 1983). For instance, the rate of hydrolysis of particulate organics may impose a limit on the overall digestion process if raw cellulosics (including lignin) or grease and lipids of certain industrial origin are involved (Pavlostathis and Giraldo-Gomez, 1991). The particulate organic matter in raw municipal sludge can be relatively easily solubilized (Ghosh et al., 1975). The high VSS reduction percentages obtained in this research are in agreement with the above statement. Detection of rather significant amounts of soluble substrate (carbohydrates and proteins) in the effluent of both systems (Tables E2 and E3, Appendix E) diminishes the possibility that the hydrolysis of particulate substrate is the rate-controlling step of the process. (It should be also noted that no variations in the soluble carbohydrate and protein concentrations were observed between the reactor and the effluent of each system).

Based on the analytical results and theoretical considerations (as discussed in the following paragraphs), the conversion of soluble metabolic intermediates to VFAs and other end-products of acidogenic digestion appears to play the most critical role in determining the rate-limiting step in the case of high hydraulic loading experiments (HRTs much less than 1 day).

The soluble compounds identified in the effluent of acid-phase digestion systems can be classified into three categories: soluble substrates, extracellular intermediate metabolites, and end-products of the phase. Although the main end-

products of acidogenic digestion of primary sludge are short-chain VFAs, a number of other soluble compounds can be generated in smaller amounts (Section 5.6.2). A summary of the percent soluble COD in the form of VFAs, according to various researchers, is presented in Table 5.30. The results show a great deal of variation, with mean values ranging from 40 to 90%. Only Zoetemeyer et al. (1982b) have reported significant amounts of other products such as ethanol, lactic acid and formic acid. It should be noted that this was the only study using a simple soluble substrate (glucose) instead of primary sludge. From the results illustrated in Table 5.30, it does not appear to be any obvious and clear relationship between the percent soluble COD in the form of VFAs and the prevailing operating conditions (SRT, SRT/HRT ratio, temperature). Although in the continuous-flow studies included in this summary higher VFA percentages can be associated with a low SRT/HRT ratio, other factors such as the characteristics of the feed and the type of seed used may play a more critical role in this phenomenon. It has not been possible from the information available to identify the nature of the soluble non-VFA compounds contributing to COD in most of the studies included in Table 5.30.

In this work, the soluble COD in the form of VFAs averages 66% of the total, in both reactors. Taking into account the soluble carbohydrate and protein fraction in the effluent (Tables E2 and E3, Appendix E) and using the appropriate conversion factors (Table E5, Appendix E), the average values increase to 79 and 74% for the CMR and the UASB units respectively. The minor end-products (Table 5.29) account for an additional 1 to 3% of the soluble COD in both systems. Therefore, the remaining soluble COD (approximately 20% in the CMR unit and 25% in the UASB

unit) can be principally attributed to the metabolic intermediates of the process. It is possible that in high hydraulic loading rate reactors the limited time available for food assimilation may not allow for the completion of the corresponding pathways resulting in accumulation of intermediate products.

TABLE 5.30. OPERATIONAL PARAMETERS AND PERCENT SOLUBLE COD IN THE FORM OF VFAs FROM VARIOUS ACID-PHASE ANAEROBIC DIGESTION STUDIES

REFERENCE	SRT (d)	SRT/ HRT	TEMP. (° C)	% COD as VFAs	
				RANGE	MEAN
Gupta et al. (1985) - (B)	3 - 9	1	10 - 30	31 - 48	41
Perot et al. (1988) - (B)	8 - 10	1	35 - 55	36 - 59	46
This study	5 - 20	10 - 40	20	41 - 91	66
Fongsatitkul (1992)	20 - 40	5 - 10	35	56 - 75	68
Zoetemeyer et al. (1982b)	0.2 - 0.4	1	30	59 - 88	74
Ghosh et al. (1975)	0.5 - 1.2	1	36	59 - 91	77
Eastman & Ferguson (1981)	1 - 3	1	35	83 - 95	90

Note: Studies marked with a (B) are batch studies, the rest are continuous-flow experiments.

The type and amount of the intermediates in acidogenic metabolism depend largely on substrate composition and concentration, pH, temperature, and operational parameters (Hobson et al., 1974). A few specific examples are given below.

In carbohydrate fermentation, succinic acid is an important extracellular intermediate. It is formed by certain fermentative species in the rumen and in sludge, but it cannot be converted to propionic acid by the same species (Scheifinger and Wolin, 1973).

Bacterial deamination under anaerobic conditions can also proceed without reduction (independently of reductive deamination described in Eq. 2.6) to form the corresponding unsaturated acids (Sawyer and McCarty, 1978):

$$R\text{-}CH_2CHNH_2COOH \longrightarrow R\text{-}CH{=}CHCOOH + NH_3 \qquad (5.1)$$

Aromatic amino acids are fermented by certain bacteria belonging to the genus *Clostridium* to phenylacetic acid, phenylpropionic acid, benzoic acid, indolylacetic acid, phenol, p-cresol and other products (Elsden et al., 1976). Subsequent conversion of these compounds to short-chain aliphatic acids is very slow, whenever possible (Hobson et al., 1974).

Degradation of glycolipids and phospholipids can yield galactose (a soluble C_6 aldose), in addition to glycerol (McInerney and Smith, 1981). The whole array of C_8 to C_{14} monocarboxylic acids is normally produced as intermediates during the anaerobic β-oxidation of long-chain fatty acids. Their solubility is mainly a function of the chain length and at 20 °C ranges from 680 mg/L for octanoic acid (C_8) to 20 mg/L for tetradecanoic acid (C_{14}) (Streitwieser and Heathcock, 1981). Substantial quantities of these acids have been found in anaerobic digestion systems (Novak and Carlson, 1970).

5.6.4. MASS BALANCES: SOLIDS AND PHOSPHORUS

Mass balance is a useful method to evaluate the performance of a biological treatment process with respect to a specific parameter. In addition to the mass

balances discussed previously, the overall behavior of another set of parameters (TS, VS, TP, PO_4^{-3}-P) is outlined here. The TS and VS measurements account for the dissolved and suspended solid content in the systems, thus any missing solids can be presumed to be lost in the form of gases (CH_4, CO_2). Total phosphorus (TP) is a "conservative" component in this process, since the biological mechanism for phosphorus removal is not feasible under anaerobic conditions.

Both the TS and VS mass balances (exclusive of losses in gaseous end-products) show high recovery percentages, with a range from 90 to 98% and an average value of 94% (Table 5.31), except for Run 1D where the average solids recovery is 84%. During this run, however, the gas production was considerably higher than the rest of the experiments (Table E4, Appendix E).

TABLE 5.31. PERCENT RECOVERY BASED ON MASS BALANCE

PARAMETER	CMR SYSTEM		UASB SYSTEM	
	RANGE	MEAN	RANGE	MEAN
TS (exc. Run 1D) TS (Run 1D)	90.9 - 96.1	93.6 83.8	93.2 - 98.0	94.9 84.5
VS (exc. Run 1D) VS (Run 1D)	90.6 - 95.2	92.9 83.3	92.9 - 97.5	94.7 83.0
TP	96.5 - 105.0	101.9	100.6 - 109.0	104.7
ORTHO-P	75.7 - 90.2	83.4	67.8 - 84.8	75.7

The TP mass balance shows a slight increase in phosphorus through the process, averaging about 3%. The order of magnitude of this error is typical in

analytical measurements. Other researchers have reported that similar errors may range from 5 to 9% (Jenkins and Mavinic, 1989; Wareham, 1992). The orthophosphate mass balance reveals that a considerable reduction in soluble PO_4^{3-} occurs in the process (17% in the CMR unit and 24% in the UASB unit). Orthophosphates, which are incorporated into poly-phosphates and ATP, are used by the cells to meet their energy requirements. The lower percent recovery in the UASB system may be attributed to both the higher amount of biomass retained in this reactor (Table 4.2) and differential phosphate precipitation, most likely in the form of calcium phosphate or ammonium magnesium phosphate (Snoeyink and Jenkins, 1980). Precipitation of orthophosphate in UASB reactors has been also mentioned by Fongsatitkul (1992). It is possible that the slow flow pattern in the UASB system creates certain "pockets" where the solubility-product constants of the corresponding phosphate salts are exceeded, resulting in their precipitation. It should be noted, however, that the solubilities of ammonium magnesium phosphate and calcium phosphate in water at 20 °C and neutral pH are 200 mg/L and 20 mg/L respectively (CRC Handbook of Chemistry and Physics, 1981). Since the solubility of both salts increases dramatically with decreasing pH, it can be assumed that at the pH range of this study (4.3 to 6.2) precipitation of phosphate salts was rather limited.

5.6.5. SUBSTRATE UTILIZATION PATTERNS

The degree of dissimilation of various substrates determines the types of bacteria resident in the particular environment under investigation. At any given

moment, the population of the microorganisms depends on the operational and environmental parameters applied.

As stated earlier (Section 5.2.5), the overall lipid degradation patterns observed by various researchers have been rather controversial. The conversion percentages have been either minimal or over the 60% level. It should be noted, however, that it is difficult to interpret the results of different studies on lipid degradation, as various methods of extraction of "total lipids" or "fats" have been employed by different investigators. The total lipid fraction of sludge may contain in addition to glycerides, phospholipids, free fatty acids, waxes, hydrocarbon grease and oils (Hobson et al., 1974).

Although the composition of lipids in the feed may have played a role in the above mentioned controversy, since certain fractions are more easily biodegraded than others (eg. saponifiable vs. non-saponifiable lipids), it has been demonstrated that inhibition of lipid degradation is mainly a function of SRT and the enrichment of sludge used (Chynoweth and Mah, 1971). Long SRTs permit development of organisms with long generation times, while short SRTs can eliminate such organisms. Novak and Carlson (1970) have found that rapid dissimilation of linoleic and oleic acids occurred at SRTs of 4 days or longer, but essentially no fatty acid conversion took place at an SRT shorter than 4 days. Furthermore, protein- and carbohydrate-enriched sludges suppress the degradation of lipids present (Mahr, 1969). These observations along with the "polarized" ranges of lipid conversion percentages reported suggest that lipolytic bacteria may not function at all under certain conditions, but if a viable population is established, then they can degrade the

substrate available at very high rates.

High percentages of carbohydrate degradation were also observed in this study. It has been found that the enzymatic hydrolysis of cellulose (the main carbohydrate component in primary sludge) can be enhanced by the presence of "cellulosome" particles (Lamed et al., 1983). The quaternary structure of cellulosome particles (a macromolecular complex of molecular weight of about 1.2 million produced by certain anaerobic Clostridia species) plays a dual role by binding to the surface of cellulose substrate and, at the same time, by bringing individual cellulolytic enzymes to within close proximity of one another.

Protein conversion percentages in this study are generally moderate and significantly lower than those obtained for the other two substrate fractions. Studies have illustrated that proteins can be singly fermented at high rates to VFAs (Breure and van Andel, 1984; Breure et al., 1985). In municipal sludges, however, proteins are present simultaneously with lipids and carbohydrates. Often substantial degradation of proteins cannot be achieved in anaerobic wastewater treatment (Gujer and Zehnder, 1983). It has been found that, in pure cultures, easily fermentable carbohydrates can repress the synthesis of exopeptidases, a group of enzymes involved in protein hydrolysis (Glenn, 1976; Pansare et al., 1985). There is also evidence that the degradation of a protein, gelatin, was progressively retarded with increasing concentrations of carbohydrates present in the medium as a second substrate (Breure et al., 1986). It is possible that the high carbohydrate content in the primary sludge may have reduced, to some extent, the amount of the proteolytic enzymes synthesized, which resulted in lower conversion rates.

The reactor configuration appears to influence the degradation patterns of both lipids and carbohydrates. It is believed that the observed behavior is due to the impact of the physical environment on the molecular structures of lipids and carbohydrates. In the CMR system, lipids have been dissimilated at a higher rate throughout the experimental study. Vigorous mixing conditions result in better dispersion of the lipids and may accelerate the rate of reaction of the heterogeneous catalysis by increasing contact between substrate and enzyme at the lipid-water interface (Heukelekian and Mueller, 1958). On the contrary, the slow diffusion flow regime in the UASB reactor enhances the hydrolysis of carbohydrates (mainly cellulose) which have a considerably more complex physical structure than that of lipids. Since cellulolytic enzymes need a longer time to diffuse and penetrate the macromolecular structure of the substrate (Tsao, 1984), the microenvironment provided in this type of reactor favors their activity.

In conclusion, the heterogeneous population of microorganisms engaged in the acid-phase digestion process is in a dynamic equilibrium state. Various selective pressures may encourage growth of certain bacterial species. Such changes may result in a shift in the population which is reflected in the different rates of substrate conversion and product formation.

5.6.6. POTENTIAL APPLICATION OF FINDINGS

The results obtained in this research have contributed towards a better understanding of some basic mechanisms of the acid-phase anaerobic digestion of

primary sludge. In the realm of biological process design, the findings of this study may be useful in a number of cases. Some general ideas are presented below.

Since soluble COD was found to be, on the average, significantly higher (over 50%) than the amount of VFAs generated, in biological phosphorus removal applications soluble COD may be useful as a replacement test for VFA to determine the usefulness of digester supernatant for phosphorus removal.

Furthermore, the acid-phase digestion process exhibited a remarkable degree of operational stability. It was observed that the amount of VFAs produced in most runs under "normal" operating conditions is high enough (in the range of 550 to 650 mg/L as acetic acid) to support subsequent biological P removal processes (Section 2.6.1). For example, assuming that the TSS content of raw sewage is 250 mg/L, 60% of TSS is removed during primary clarification and the TSS concentration in primary sludge is 3,600 mg/L (Table 5.1), then a 600 mg/L VFA production by acidogenic digestion transcribes into a concentration relative to influent sewage flow of about 25 mg/L. However, the amount of VFAs produced under an environmental stress (eg. short HRTs or SRTs; Runs 1B and 2C) may not be high enough to initiate the phosphorus removal mechanism. A 200 mg/L VFA concentration, for instance, transcribes into an influent concentration of 8 mg/L. This remark clearly illustrates the importance of the acid-phase digestion in biological nutrient removal processes.

The overall consistency of the lipid and carbohydrate utilization patterns suggests that a CMR system can be used to treat more effectively wastes with a high lipid content. On the other hand, for carbohydrate-rich wastes a higher degree of organic matter degradation can be achieved in UASB reactors.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

The operational and environmental parameters investigated had a distinct effect on the acid-phase anaerobic digestion process. Based on the results of this research, the following conclusions can be made:

1) A favorable environment for acidogenic digestion has been established and maintained resulting, in most cases, in high VFA production. At the same time, the methanogenic phase has been successfully suppressed, as indicated by the high TS and VS percent recovery and the low gas generation rates.

2) The net VFA concentration and specific production rate (expressed as mgVFA/mgVSS*d) increase, in either reactor, with an increase in HRT (up to 12 hours). The decrease observed at an HRT of 15 hours can be attributed to the onset of methanogenesis.

3) Variation in HRT has a profound effect not only on the net COD concentration, but also on the COD and TOC specific solubilization rates, expressed as mgCOD(or mgTOC)/mgVSS*d. All three maximum values correspond to an HRT of 12 hours, which coincides with the time required for optimum VFA production.

4) The net VFA concentration, VFA specific production rate and net COD concentration as a function of SRT follow the same pattern, showing a sharp decrease

at an SRT of 5 days and approaching a plateau at SRTs of 10 days or longer. On the contrary, the COD and TOC solubilization rates are not affected by the changes in SRT.

5) Both systems exhibit similar VFA production rates at SRTs up to 10 days, regardless of the HRT. At longer SRTs, however, the CMR unit becomes slightly more effective (by about 12 %) than the UASB reactor.

6) Although a decrease in pH from 5.1 to 4.5 does not have an effect on the specific rate of VFA generation, an increase to pH 6.1 results in significantly lower rates (25 to 30 %) of acid production.

7) Acetic acid and propionic acid are the most prevalent VFAs produced averaging about 45 and 31% of the total respectively. Butyric acid follows with an average value of 9%. The percent VFA distribution appears to be independent of HRT, but it is a function of both SRT and pH. The relative distributions of iso-butyric and the three isomers of the valeric acid increase dramatically with SRT. Moreover, a low pH range (4.3-4.6) encourages the production of propionic acid (39% of total VFAs), while at a pH range of 5.9-6.2 more butyric acid is formed (20% of total VFAs).

8) The percent solubilization of organic matter (measured by the VSS content) increases with HRT, but it is not influenced by the variation in SRT. A moderately higher VSS reduction can be also observed at pH 5.9-6.2, as compared to the other two pH ranges. In all experimental runs TSS solubilization follows a trend identical to that of the VSS.

9) The steady-state operation of the acid-phase anaerobic digestion can be

replicated and the seasonal variation of influent collection (summer-winter) does not seem to play any significant role in the process.

10) The use of a different source of influent sludge has an effect on lipid and carbohydrate utilization patterns, which is also reflected in the corresponding VFA production rates.

11) Besides VFAs, relatively small amounts of formic acid, ethanol, and lactic acid were regularly detected in both reactors. No other end-products were found at any appreciable concentration.

12) Lipids and carbohydrates are generally utilized at higher rates (expressed as g/d) than proteins, regardless of the prevailing experimental conditions. The degradation of all three organic components of primary sludge increases with an increase in HRT, but only in the case of proteins is a similar behavior observed for increases in SRT. Carbohydrate and lipid dissimilation is essentially independent of SRT. In a similar fashion, variation in pH significantly affects the protein degradation pattern, but only has a small effect upon the other two organic classes.

13) The reactor configuration has an effect on substrate dissimilation as well. Although both systems exhibit a fairly similar behavior in protein degradation, the utilization patterns of carbohydrates and lipids are distinctly different. Lipids are broken down more effectively in the CMR unit, while higher rates of carbohydrate dissimilation have been obtained in the UASB reactor. Furthermore, in the case of easily hydrolyzable wastes, UASB systems may be used to treat wastewaters that have a reasonably high particulate content (in the range of 3,000 to 4,000 mg/L TSS).

6.2 RECOMMENDATIONS

Consideration for further research should be focused on the following areas:

1) The role of temperature on the process can be investigated. Since this study was conducted at an ambient liquid temperature (18 to 22 °C), experimental work at a temperature range from 10 to 35 °C may provide useful information for many practical applications.

2) The sensitivity of the process to organic feed composition should be further explored. Using primary sludge with varying organic composition may furnish valuable knowledge on the overall substrate degradation patterns and pathways. Spiking sludge with known compounds, possibly even some radioactive compounds, and following the metabolites of degradation may also be helpful in these studies.

3) Throughout this experimental work a diluted sludge feedstock (4,000 mg/L TS) was used. In many full-scale applications, however, the solids concentration can be very high. It is, therefore, useful to investigate the performance of the process using higher total solid concentrations in the feed.

4) Research on the identification of the hydrolysis products and on other soluble metabolic intermediates of acidogenic digestion could result in a better understanding of the mechanisms and pathways involved in the process.

5) This laboratory investigation may be extended to a pilot-plant scale operation. The further research should be planned to more closely determine design criteria for full-scale design.

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APPENDIX A

BIOCHEMICAL PATHWAYS

FIGURE **PAGE**

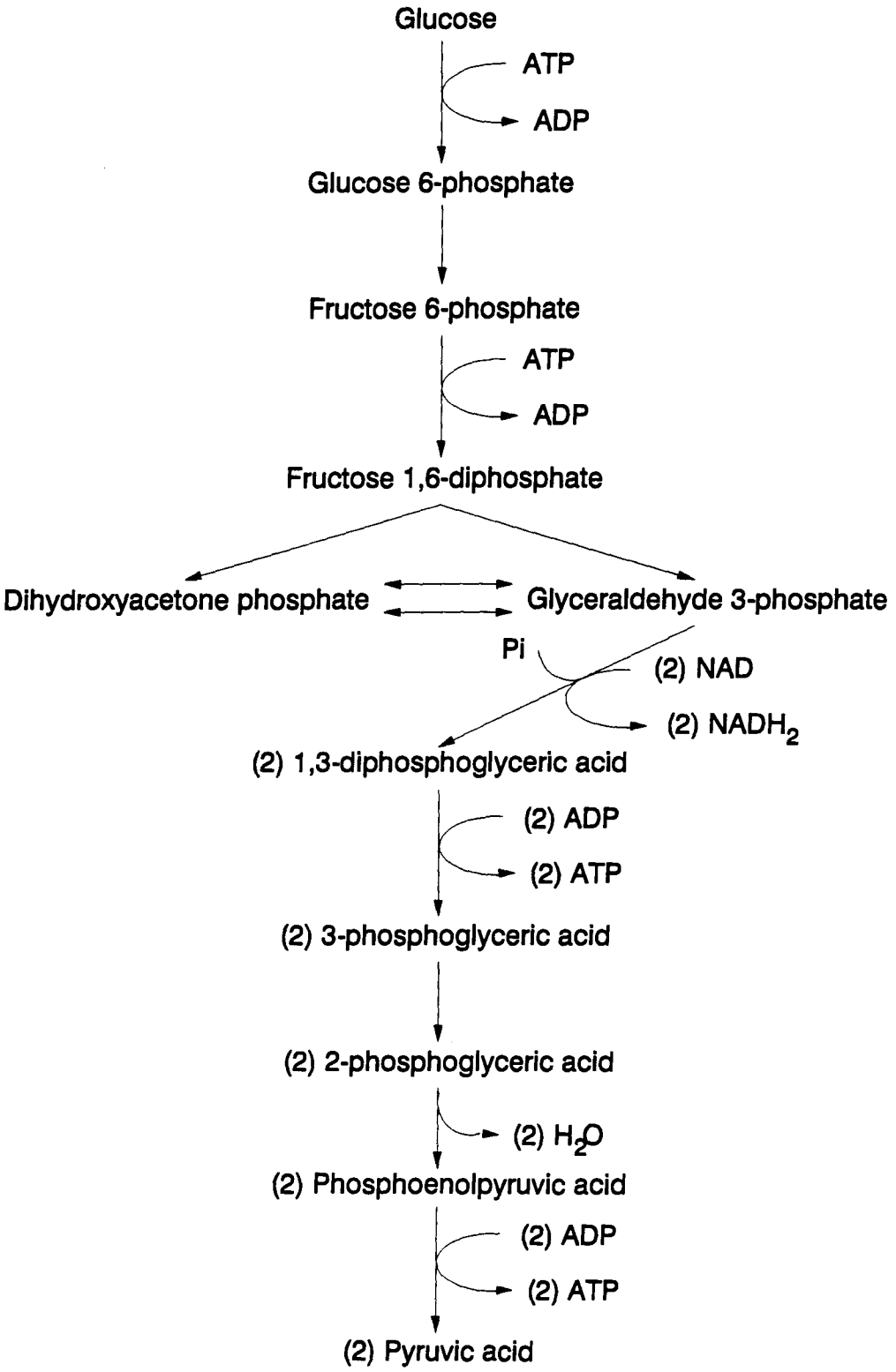

FIGURE A1. THE EMBDEN-MEYERHOF-PARNAS (EMP) PATHWAY FOR GLUCOSE CATABOLISM (Adapted from Gaudy and Gaudy, 1980)

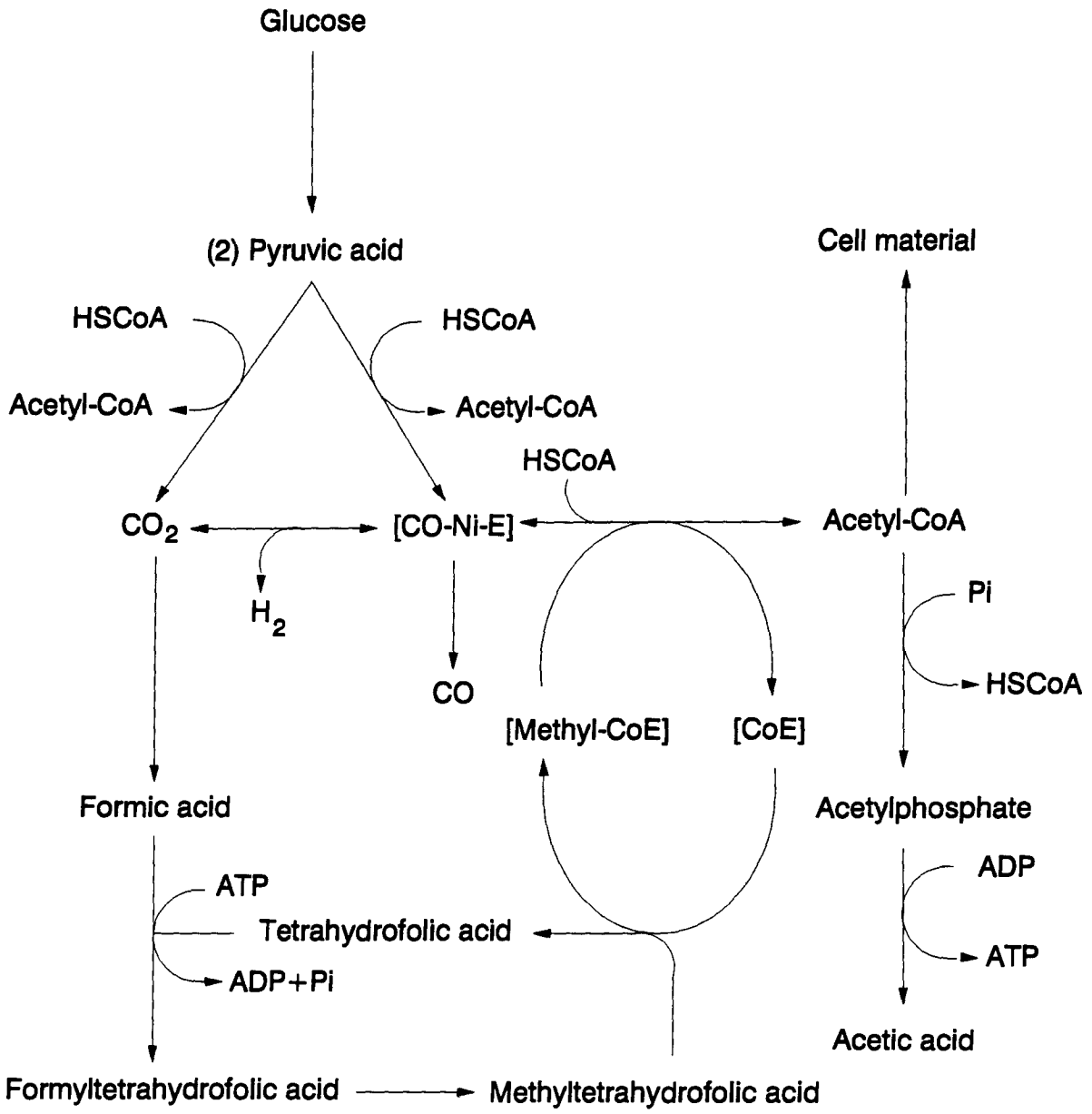

FIGURE A2. THE PATHWAY FOR AUTOTROPHIC FORMATION OF ACETIC ACID
(Adapted from Ljungdahl, 1986)

Note: CO-Ni-E is the complex between carbon monoxide and its nickel-containing dehydrogenase; CoE is the corrinoid protein.

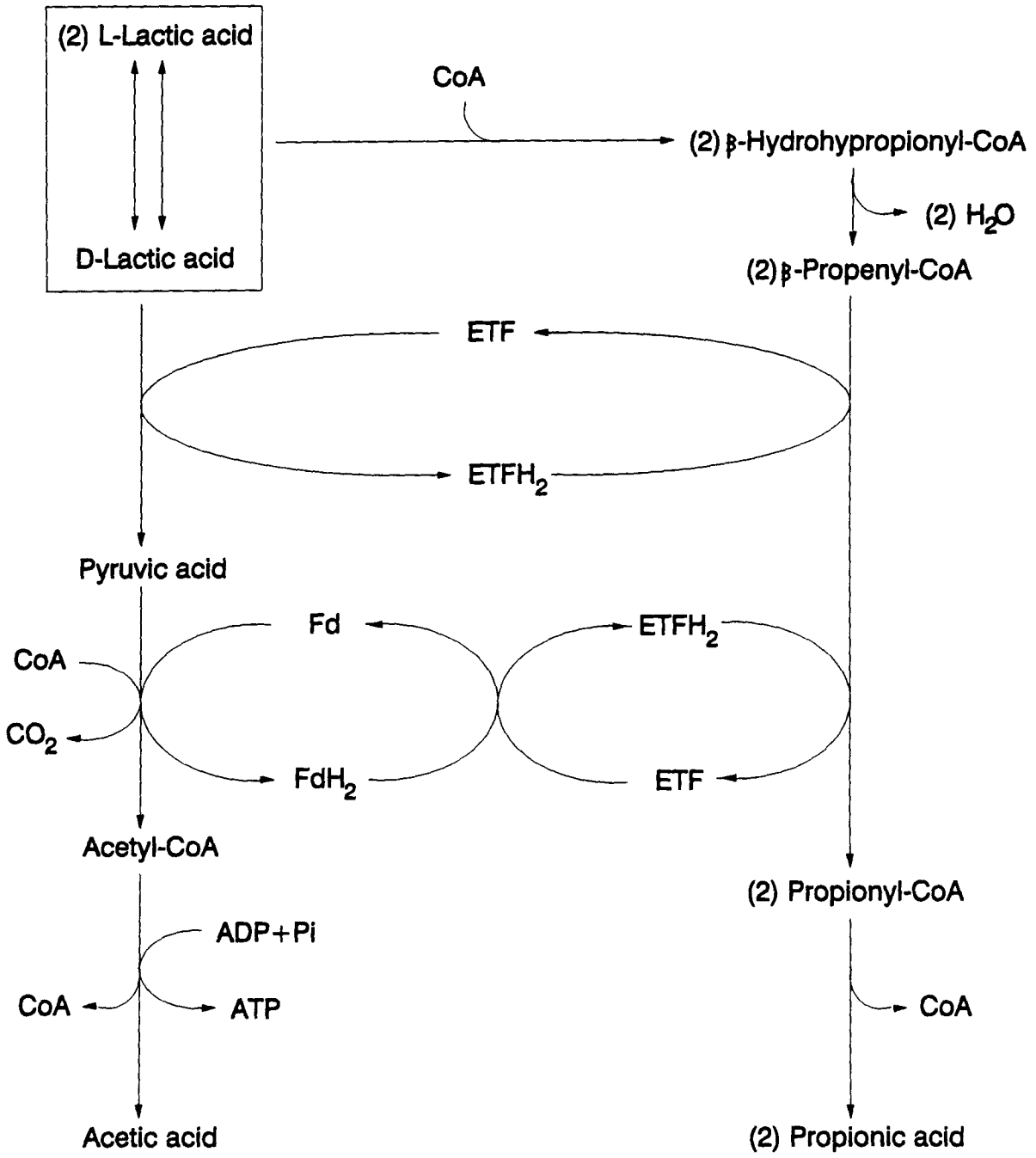

FIGURE A3. THE ACRYLATE PATHWAY FOR ACETIC ACID AND PROPIONIC ACID FORMATION (Adapted from Gottschalk, 1986)

Note: ETF is the electron-transferring flavoprotein; Fd is the ferredoxin electron carrier. CoA transferace completes the cycle in propionic acid production.

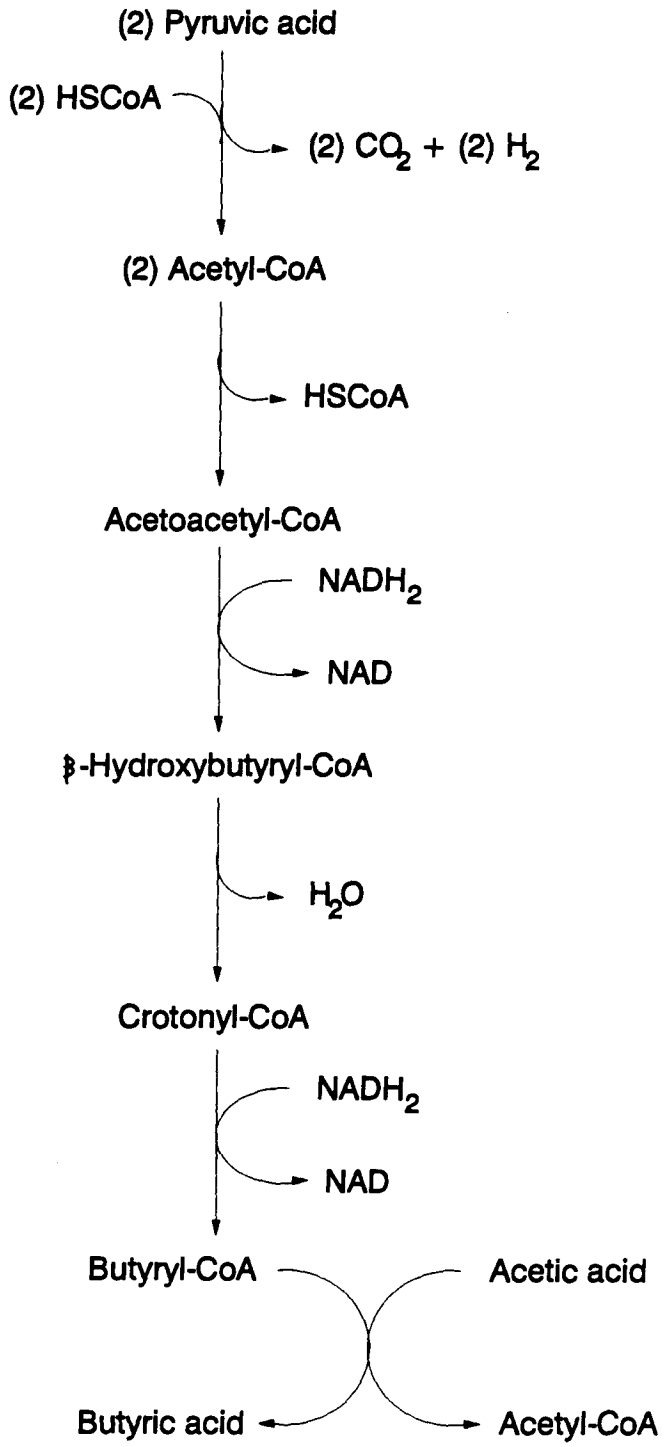

FIGURE A4. THE PATHWAY FOR BUTYRIC ACID FORMATION FROM PYRUVIC ACID
(Adapted from Gaudy and Gaudy, 1980)

APPENDIX B

REACTOR OPERATION
(HRT AND pH VALUES)

TABLE **PAGE**

TABLE B1. OPERATING CONDITIONS OF RUN 1A

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
12/13/89	1	7.90	7.65	6.32				
12/14/89	2	8.50	9.95	6.34				
12/15/89	3	9.29	10.20	6.21	5.83	5.71	5.81	5.71
12/16/89	4	9.45	8.93	6.25	5.75	5.51	5.88	5.64
12/17/89	5	7.72	9.66	6.29	5.58	5.47	5.69	5.54
12/18/89	6	8.22	8.77	6.17	5.38	5.40	5.30	5.27
12/19/89	7	8.18	9.40	6.15	5.46	5.37	5.52	5.36
12/20/89	8	9.11	8.88	6.15	5.70	5.45	5.74	5.61
12/21/89	9	9.40	9.26	6.09	5.61	5.42	5.73	5.59
12/22/89	10	8.88	9.20	6.12	5.43	5.33	5.53	5.64
12/23/89	11	8.57	8.09	6.04	5.26	5.36	5.37	5.36
12/24/89	12	8.39	8.88	6.06	5.33	5.24	5.37	5.26
12/25/89	13	10.15	9.83	5.98	5.34	5.33	5.44	5.34
12/26/89	14	9.54	9.64	5.97	5.45	5.28	5.31	5.23
12/28/89	16	9.35	8.97	5.96	5.27	5.24	5.47	5.36
12/29/89	17	8.66	9.55	5.93	5.36	5.15	5.26	5.28
12/30/89	18	8.92	8.39	6.01	5.28	5.05	5.36	4.91
12/31/89	19	9.27	9.29	6.05	5.19	5.22	5.33	5.34
01/01/90	20	8.90	8.45	5.92	5.21	5.07	5.13	5.23
01/02/90	21	9.10	9.15	5.86	5.40	5.14	5.26	5.08
01/03/90	22	9.14	9.56	6.02	5.36	5.27	5.23	5.18
01/04/90	23	9.11	9.22	6.71	5.24	5.20	5.13	5.02
01/05/90	24	8.84	9.17	6.59	5.34	5.30	5.31	5.40
01/06/90	25	8.73	8.75	6.63	5.24	5.25	5.17	5.26
01/07/90	26	9.40	9.76	6.10	5.34	5.06	5.19	5.13
01/08/90	27	9.62	9.09	6.10	5.10	5.11	5.05	5.21
01/09/90	28	7.73	9.32	6.08	5.07	5.05	4.97	5.27
01/11/90	30	8.14	8.67	6.02	5.38	5.49	5.30	5.46
01/12/90	31	8.31	9.08	6.93	5.48	5.38	5.31	5.33
01/13/90	32	8.85	8.42	6.79	5.37	5.45	5.23	5.47
01/14/90	33	8.91	9.53	6.33	5.31	5.32	5.15	5.31
01/15/90	34	9.41	8.56	6.29	5.23	5.16	5.12	5.25
01/16/90	35	8.94	9.45	6.18	4.99	4.96	4.96	5.18
01/17/90	36	9.09	9.69	6.14	5.13	4.94	5.01	5.03
01/18/90	37	9.61	8.20	6.23	5.33	5.08	5.06	5.17
01/19/90	38	8.90	8.98	5.88	5.14	5.19	5.10	5.26
01/20/90	39	8.89	9.31	5.91	5.21	5.10	5.05	5.17
01/21/90	40	9.59	8.36	6.00	5.12	5.37	5.02	5.44
01/22/90	41	8.61	9.50	6.12	5.13	5.41	5.05	5.48
01/23/90	42	9.59	8.94	6.08	5.28	5.20	5.08	5.32
01/24/90	43	9.18	8.96	6.17	5.05	5.39	4.94	5.41
01/25/90	44	10.59	8.95	5.94	5.21	5.41	5.02	5.50
01/27/90	46	9.04	9.43	5.89	5.06	5.27	4.97	5.37
01/28/90	47	9.42	9.52	5.76	5.23	5.16	5.13	5.31
01/29/90	48	8.46	9.40	5.80	5.26	5.31	5.09	5.39
01/30/90	49	8.68	8.89	5.74	5.01	5.22	4.94	5.33
01/31/90	50	8.37	9.78	5.80	5.13	5.29	4.97	5.27
02/01/90	51	9.11	9.91	5.90	5.22	5.14	5.00	5.34
02/02/90	52	9.00	8.35	5.81	5.26	5.29	5.14	5.40
02/03/90	53	8.79	9.66	6.38	5.15	5.04	5.08	5.12
02/04/90	54	9.11	9.32	6.35	5.12	5.13	4.90	5.11
02/05/90	55	8.58	8.78	6.49	5.21	5.31	5.12	5.19
02/06/90	56	9.52	9.89	6.46	5.40	5.15	5.30	5.01
02/07/90	57	10.00	9.04	6.61	5.16	5.38	5.08	5.18
02/09/90	59	8.67	10.08	6.44	5.21	5.46	5.06	5.49
02/10/90	60	8.75	9.02	6.43	5.10	5.44	5.01	5.39
02/11/90	61	8.34	9.53	6.53	5.15	5.25	4.99	5.35
02/12/90	62	9.61	8.66	6.20	5.27	5.42	5.05	5.51
02/13/90	63	8.89	8.78	6.00	5.13	5.13	4.95	5.24
02/14/90	64	9.90	9.46	5.84	5.19	5.26	4.99	5.32
02/15/90	65	9.66	8.64	5.98	5.18	5.30	5.11	5.40
02/16/90	66	9.39	9.33	6.03	5.17	5.29	5.00	5.23
02/17/90	67	8.93	8.99	5.77	5.00	5.41	4.85	5.45
02/18/90	68	9.08	8.65	5.73	5.04	5.45	4.91	5.49
02/20/90	70	8.70	9.66	5.88	5.15	5.13	5.06	5.27
02/21/90	71	9.07	9.37	5.78	5.17	5.20	4.97	5.31
02/22/90	72	9.32	9.31	5.98	5.02	5.08	4.94	5.17
02/23/90	73	10.27	8.93	6.36	5.06	5.09	4.97	5.14
02/24/90	74	9.02	8.60	6.36	5.28	5.28	4.93	5.31
02/25/90	75	8.81	9.25	6.62	5.28	4.99	5.09	5.25
02/26/90	76	8.50	8.37	6.57	5.12	5.29	5.04	5.34
02/27/90	77	9.52	9.42	6.26	5.16	5.18	4.87	5.27
02/28/90	78	8.85	9.51	6.66	5.06	5.26	4.86	5.23
03/01/90	79	9.06	8.82	6.22	5.23	5.36	5.13	5.41
03/02/90	80	9.15	9.73	6.21	5.06	5.34	5.05	5.40
03/03/90	81	9.32	9.40	6.27	5.15	5.27	5.04	5.44
03/04/90	82	8.85	8.92	6.24	5.04	5.14	4.90	5.12
03/05/90	83	9.67	8.52	6.01	5.13	5.11	4.87	5.30
03/06/90	84	8.60	9.54	6.08	5.01	5.19	4.92	5.32
03/07/90	85	8.96	9.19	6.18	4.98	5.13	4.85	5.18
03/08/90	86	9.43	9.35	5.92	5.12	5.06	4.90	5.11
	MEAN	9.03	9.15	6.16	5.23	5.25	5.14	5.31
	STD	0.53	0.49	0.27	0.17	0.15	0.23	0.15

TABLE B2. OPERATING CONDITIONS OF RUN 1B

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
03/14/90	1	6.36	6.31	6.29	5.30	5.20	5.01	5.28
03/15/90	2	6.00	6.26	6.22	5.40	5.22	5.17	5.19
03/16/90	3	5.97	6.57	6.36	5.24	5.20	5.03	5.07
03/17/90	4	6.00	5.83	6.25	5.16	5.19	5.06	5.04
03/18/90	5	6.08	6.43	6.33	5.05	5.39	5.24	5.38
03/20/90	7	5.68	6.24	6.06	5.37	5.48	5.32	5.25
03/21/90	8	6.43	6.16	6.14	5.08	5.49	5.09	5.46
03/22/90	9	6.58	6.33	6.12	5.15	5.54	5.20	5.33
03/23/90	10	6.51	6.91	5.96	5.19	5.37	5.04	5.19
03/25/90	12	6.14	5.88	5.75	5.24	5.35	5.07	5.12
03/26/90	13	5.97	5.42	5.83	5.11	5.36	5.27	5.07
03/27/90	14	6.96	6.29	5.63	5.35	5.17	5.11	5.11
03/28/90	15	5.90	6.15	6.23	5.28	5.16	4.94	5.03
03/29/90	16	5.66	6.39	6.16	5.30	5.44	5.33	5.29
03/30/90	17	6.06	6.13	5.87	5.15	5.41	5.27	5.23
03/31/90	18	5.69	5.64	5.96	5.39	5.45	5.29	5.45
04/01/90	19	6.90	6.58	5.91	5.34	5.42	5.26	5.37
04/02/90	20	6.26	5.68	5.82	5.17	5.37	5.04	5.07
04/03/90	21	6.28	6.35	5.82	5.20	5.22	5.23	5.20
04/04/90	22	6.35	6.00	5.88	5.44	5.37	5.29	5.23
04/05/90	23	6.15	6.00	5.69	5.25	5.31	5.15	5.28
04/06/90	24	6.29	5.95	6.54	5.20	5.02	5.12	4.92
04/07/90	25	6.06	5.88	6.38	5.46	5.49	5.19	5.21
04/08/90	26	5.96	5.86	5.98	5.37	5.19	5.07	5.02
04/09/90	27	6.07	5.93	6.28	5.12	5.37	5.07	5.14
04/10/90	28	5.94	5.61	6.17	5.25	5.20	5.03	5.15
04/11/90	29	5.93	6.59	5.97	5.40	5.39	5.28	5.16
04/12/90	30	6.21	5.77	5.94	5.37	5.46	5.29	5.27
04/13/90	31	6.02	6.04	6.18	5.45	5.51	5.25	5.34
04/14/90	32	5.90	6.17	6.21	5.40	5.43	5.31	5.23
04/15/90	33	6.32	6.21	6.17	5.26	5.48	5.14	5.17
04/16/90	34	5.54	5.69	6.04	5.19	5.17	5.03	5.02
04/17/90	35	6.11	6.12	6.13	5.42	5.16	5.30	5.04
04/18/90	36	6.09	6.08	5.92	5.19	5.49	4.98	5.31
04/19/90	37	6.38	5.97	5.99	5.27	5.45	5.20	5.45
04/20/90	38	6.51	5.89	5.87	5.21	5.19	5.12	5.09
04/21/90	39	6.08	6.14	6.11	5.12	5.08	5.13	4.92
04/22/90	40	5.94	6.03	6.05	5.36	5.34	5.32	5.28
04/23/90	41	6.04	5.72	6.02	5.47	5.40	5.17	5.21
04/24/90	42	5.88	6.43	6.12	5.18	5.48	5.39	5.37
04/25/90	43	6.29	6.24	5.90	5.12	5.29	4.94	5.06
04/26/90	44	6.32	5.85	5.95	5.34	5.16	5.32	5.18
	MEAN	6.14	6.09	6.05	5.27	5.33	5.17	5.19
	STD	0.29	0.30	0.20	0.11	0.13	0.12	0.14

TABLE B3. OPERATING CONDITIONS OF RUN 1C

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
04/28/90	1	11.11	11.00	6.07	5.62	5.51	5.56	5.48
04/29/90	2	11.91	13.06	6.09	5.63	5.41	5.61	5.67
04/30/90	3	11.19	11.72	6.06	5.36	5.44	5.38	5.55
05/01/90	4	12.58	12.38	6.52	5.39	5.23	5.36	5.36
05/02/90	5	13.13	12.80	6.29	5.66	5.30	5.49	5.35
05/03/90	6	10.71	11.44	5.87	5.45	5.23	5.29	5.36
05/04/90	7	12.93	10.71	5.94	5.37	5.12	5.21	5.22
05/05/90	8	11.79	12.94	5.95	5.25	5.34	5.04	5.37
05/06/90	9	12.63	12.60	5.91	5.20	5.16	5.03	5.26
05/07/90	10	12.04	12.10	5.86	5.26	5.08	5.14	5.02
05/08/90	11	11.48	12.89	5.92	5.04	4.98	5.09	5.07
05/09/90	12	11.79	11.00	5.99	4.86	5.13	4.79	5.10
05/10/90	13	12.37	12.86	5.77	4.88	4.84	4.90	4.91
05/11/90	14	12.71	12.50	5.84	4.73	4.86	4.66	4.85
05/12/90	15	11.37	11.20	5.96	4.87	4.71	4.79	4.69
05/13/90	16	12.45	12.94	5.75	4.70	4.67	4.66	4.70
05/14/90	17	12.27	11.91	5.84	4.74	4.70	4.67	4.71
05/15/90	18	12.05	12.27	5.88	4.77	4.78	4.69	4.76
05/16/90	19	12.50	11.76	5.84	4.71	4.71	4.74	4.72
05/17/90	20	11.10	11.74	5.77	4.88	4.68	4.73	4.69
05/18/90	21	12.13	11.40	5.92	4.81	4.75	4.78	4.68
05/19/90	22	12.50	12.72	6.14	4.98	4.70	4.80	4.75
05/20/90	23	12.30	12.37	6.03	4.80	4.74	4.68	4.67
05/21/90	24	12.08	12.00	5.91	4.94	4.81	4.77	4.72
05/22/90	25	13.07	12.68	5.79	4.75	4.79	4.70	4.84
05/23/90	26	12.62	11.33	6.42	4.70	4.91	4.66	4.92
05/24/90	27	12.16	13.04	6.31	4.81	4.74	4.67	4.67
05/25/90	28	11.80	11.61	6.29	4.92	4.82	4.82	4.71
05/26/90	29	11.42	11.77	6.10	4.81	4.85	4.79	4.79
05/27/90	30	12.69	12.20	6.17	4.93	4.91	4.78	4.78
05/28/90	31	12.00	11.82	6.41	5.12	4.98	5.09	4.83
05/29/90	32	11.76	11.76	6.22	5.19	5.11	4.95	5.14
05/30/90	33	12.07	12.57	6.08	5.24	5.25	5.02	5.25
05/31/90	34	11.74	11.56	5.96	5.09	5.36	4.83	5.30
06/01/90	35	11.36	11.36	5.98	4.97	5.05	4.81	5.19
06/02/90	36	11.63	11.18	6.43	5.05	4.96	4.83	5.03
06/03/90	37	12.08	12.18	6.22	4.99	5.28	4.91	5.18
06/04/90	38	12.33	11.57	6.21	5.10	5.02	4.89	4.88
06/06/90	40	12.12	12.21	6.19	5.07	4.95	4.96	4.92
06/07/90	41	12.54	12.50	6.04	4.89	4.83	4.82	4.81
06/08/90	42	11.95	11.73	6.13	4.74	4.74	4.70	4.71
06/09/90	43	12.09	12.25	5.80	5.10	4.67	5.13	4.68
06/10/90	44	12.64	12.35	5.90	5.02	4.91	4.80	4.83
06/11/90	45	12.21	12.12	5.86	4.87	4.76	4.75	4.81
06/12/90	46	12.04	12.23	6.14	4.83	5.03	4.79	5.08
06/13/90	47	12.93	11.81	6.05	4.80	4.80	4.72	4.73
06/14/90	48	11.88	11.92	6.11	4.91	4.79	4.84	4.73
06/15/90	49	12.30	12.45	5.97	5.08	4.72	5.11	4.68
06/16/90	50	12.25	12.04	5.91	4.90	4.91	4.86	4.81
06/17/90	51	12.83	12.40	5.86	4.81	4.70	4.77	4.70
06/18/90	52	12.40	12.62	5.98	5.11	5.00	5.05	4.92
	MEAN	12.12	12.07	6.03	5.01	4.96	4.92	4.95
	STD	0.53	0.58	0.19	0.25	0.23	0.24	0.27

TABLE B4. OPERATING CONDITIONS OF RUN 1D

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
06/21/90	1	14.63	16.00	6.03	5.06	5.04	4.89	5.12
06/22/90	2	14.67	15.18	6.25	5.18	5.16	5.16	4.94
06/23/90	3	15.25	15.67	5.80	5.04	5.19	4.91	5.08
06/24/90	4	13.93	13.84	5.77	4.89	5.12	4.72	4.87
06/25/90	5	14.26	15.92	5.80	4.77	5.17	4.67	5.04
06/26/90	6	15.67	15.80	5.82	4.98	5.21	4.77	5.13
06/27/90	7	16.03	14.59	5.73	5.17	5.22	5.12	5.20
06/28/90	8	15.00	16.03	5.77	5.21	5.30	5.19	5.24
06/29/90	9	14.83	14.58	5.74	4.93	5.13	4.81	4.92
07/01/90	11	14.26	15.13	6.01	5.00	5.10	4.72	5.05
07/02/90	12	16.07	15.57	6.04	5.09	5.03	4.97	4.94
07/03/90	13	14.61	15.42	5.94	4.96	5.13	4.84	5.16
07/04/90	14	15.30	15.30	5.71	5.17	5.00	5.10	4.93
07/05/90	15	14.40	15.00	5.83	5.10	5.06	4.96	5.06
07/06/90	16	15.41	15.83	6.03	5.15	5.15	4.99	5.20
07/07/90	17	15.14	14.00	6.32	5.27	5.02	5.14	5.17
07/08/90	18	14.68	15.93	6.16	5.05	4.96	4.95	5.05
07/09/90	19	14.65	14.32	6.28	4.93	5.04	4.92	5.14
07/10/90	20	14.21	15.30	6.41	5.03	4.96	5.01	5.05
07/11/90	21	15.32	14.40	6.09	5.16	5.24	5.12	5.28
07/12/90	22	14.25	14.57	6.21	5.07	5.00	5.03	5.04
07/13/90	23	16.00	15.58	6.16	5.10	5.17	5.06	5.19
07/14/90	24	14.66	14.66	5.99	5.06	5.27	5.11	5.20
07/15/90	25	15.00	14.83	5.98	5.15	5.38	5.11	5.33
07/16/90	26	14.20	15.70	6.02	5.13	5.17	5.05	5.08
07/17/90	27	14.88	15.44	6.39	5.08	5.04	5.00	4.98
07/18/90	28	15.93	14.69	6.12	5.36	5.32	5.35	5.33
07/19/90	29	14.05	15.31	6.24	5.28	5.24	5.04	5.20
07/20/90	30	15.58	15.46	6.01	5.07	4.96	4.93	4.99
07/21/90	31	15.50	15.92	5.85	4.82	4.78	4.89	4.73
07/22/90	32	14.67	14.34	5.75	4.73	4.93	4.96	4.87
07/23/90	33	15.65	15.46	5.96	5.10	5.10	5.01	4.99
07/24/90	34	15.08	16.17	5.83	5.22	5.26	5.14	5.24
07/25/90	35	14.32	15.40	5.72	5.27	5.02	5.16	4.83
07/26/90	36	14.47	15.34	5.87	4.98	4.90	4.86	4.85
07/27/90	37	14.88	14.92	5.90	4.91	4.94	4.84	4.97
07/28/90	38	14.96	15.74	6.20	4.83	4.85	4.70	4.85
07/29/90	39	15.80	15.39	6.14	4.97	5.06	4.87	5.21
07/30/90	40	14.64	14.77	6.02	5.11	5.19	5.09	5.29
07/31/90	41	14.07	15.82	6.12	5.17	5.25	5.13	5.29
08/01/90	42	14.95	15.61	5.93	4.88	5.22	4.93	5.24
08/02/90	43	15.20	15.85	5.93	4.93	5.11	4.92	5.06
08/03/90	44	14.22	15.80	5.80	4.84	5.08	4.73	5.04
08/04/90	45	14.34	14.98	5.94	5.08	4.93	5.04	4.87
08/05/90	46	15.32	15.77	5.79	5.23	4.99	5.14	4.92
08/06/90	47	15.03	15.39	5.90	5.16	5.15	5.05	5.09
	MEAN	14.91	15.28	5.98	5.06	5.10	4.98	5.07
	STD	0.58	0.57	0.19	0.14	0.13	0.15	0.15

TABLE B5. OPERATING CONDITIONS OF RUN 2A

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
08/30/90	1	11.32	10.86	6.09				
08/31/90	2	12.15	11.14	6.14	5.55	5.47	5.64	5.52
09/01/90	3	12.02	12.72	6.21	5.51	5.36	5.50	5.46
09/02/90	4	11.21	11.79	6.01	5.37	5.24	5.43	5.31
09/03/90	5	13.24	12.16	5.94	5.45	5.10	5.42	5.16
09/04/90	6	12.55	11.90	5.91	5.21	5.15	5.19	5.18
09/05/90	7	12.88	12.00	5.88	5.15	4.96	5.05	4.86
09/06/90	8	12.63	12.43	5.78	5.22	4.93	5.10	5.00
09/07/90	9	12.88	11.61	5.81	4.92	4.91	4.81	4.99
09/08/90	10	11.40	13.20	5.73	5.19	5.12	5.22	4.83
09/09/90	11	12.75	10.91	5.82	5.20	5.11	5.12	5.03
09/10/90	12	12.07	12.05	6.07	5.14	4.98	5.12	5.13
09/11/90	13	12.84	12.80	6.17	5.15	5.01	5.17	5.12
09/12/90	14	11.27	11.80	6.05	5.16	5.12	5.10	5.06
09/13/90	15	11.96	12.50	5.98	5.10	4.95	4.96	5.02
09/14/90	16	12.73	12.50	6.23	5.12	5.10	4.92	5.14
09/15/90	17	13.02	12.89	6.29	5.07	5.06	4.89	4.91
09/16/90	18	11.38	11.87	5.88	5.21	5.02	5.22	5.10
09/17/90	19	12.84	12.61	5.81	5.19	4.87	5.00	4.96
09/18/90	20	11.87	12.89	5.87	5.14	4.96	5.02	4.97
09/19/90	21	11.94	12.57	5.83	5.03	4.93	5.05	4.99
09/20/90	22	12.48	12.76	5.78	5.30	4.91	5.11	4.97
09/21/90	23	12.66	12.27	6.53	5.28	4.98	5.13	5.04
09/22/90	24	11.78	12.00	6.50	5.38	5.23	5.22	5.18
09/23/90	25	12.52	12.00	6.38	5.32	4.96	5.20	5.12
09/24/90	26	11.90	12.50	6.38	5.17	4.93	4.99	4.97
09/25/90	27	12.13	12.13	6.13	5.33	5.12	5.17	5.11
09/26/90	28	11.63	11.69	6.47	5.04	5.01	4.99	5.06
09/27/90	29	12.81	12.49	6.19	5.29	4.92	5.23	4.95
09/28/90	30	12.41	11.88	6.17	5.14	5.12	5.11	5.18
09/29/90	31	12.89	12.57	6.22	5.12	5.06	5.08	5.02
09/30/90	32	13.11	11.34	6.27	5.32	4.95	5.15	4.89
10/01/90	33	11.03	11.16	6.14	5.21	5.10	5.22	5.16
10/02/90	34	12.75	12.45	6.11	5.29	5.17	5.30	5.05
10/03/90	35	11.65	11.57	6.15	5.21	4.93	5.15	4.88
10/04/90	36	12.52	12.63	6.16	5.14	5.11	5.11	5.10
10/05/90	37	12.00	12.41	5.88	5.17	4.95	5.14	5.00
10/06/90	38	12.56	12.33	5.79	4.93	5.08	4.89	5.14
10/08/90	40	12.00	12.22	6.29	5.18	4.96	5.06	4.92
10/09/90	41	12.22	12.69	6.30	5.19	4.97	5.11	4.82
10/10/90	42	11.77	11.95	6.26	5.23	4.89	5.09	4.98
10/11/90	43	11.82	12.00	6.41	5.05	5.02	5.03	5.16
10/12/90	44	11.97	12.54	6.31	5.20	5.22	5.22	5.24
10/13/90	45	12.26	11.76	5.97	5.17	5.14	5.12	5.02
10/14/90	46	11.47	12.43	5.81	4.98	4.97	4.80	4.91
10/15/90	47	12.50	11.64	5.75	4.86	4.94	4.92	5.03
10/16/90	48	11.34	11.91	5.77	4.85	4.80	4.81	4.80
10/17/90	49	11.97	12.42	5.72	5.06	4.86	4.97	4.95
10/18/90	50	12.54	11.87	6.55	4.99	4.96	5.13	4.99
10/19/90	51	12.00	11.86	6.31	5.21	5.16	5.18	5.23
10/20/90	52	12.33	12.10	6.37	5.16	4.91	5.09	4.92
10/21/90	53	12.27	11.32	6.04	5.01	4.83	4.93	4.96
10/22/90	54	12.22	11.87	6.22	5.15	5.08	5.13	5.17
	MEAN	12.20	12.11	6.09	5.17	5.03	5.11	5.05
	STD	0.54	0.52	0.23	0.14	0.13	0.16	0.14

TABLE B6. OPERATING CONDITIONS OF RUN 2B

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
10/24/90	1	11.67	11.85	5.97	5.23	4.97	5.21	4.99
10/26/90	3	11.74	13.00	6.24	5.21	5.10	4.97	5.16
10/27/90	4	12.58	11.60	6.25	5.24	5.04	5.25	5.15
10/28/90	5	12.91	12.91	6.06	5.13	4.93	4.93	5.04
10/29/90	6	12.63	12.29	6.04	4.99	4.92	4.79	4.95
10/30/90	7	13.12	12.18	6.25	5.05	4.98	4.87	5.00
10/31/90	8	10.80	11.25	6.13	5.23	5.08	5.04	4.92
11/01/90	9	12.69	12.88	6.22	5.28	5.19	5.27	5.18
11/02/90	10	11.35	11.89	6.11	5.31	5.22	5.25	5.16
11/03/90	11	12.39	12.75	6.34	5.24	5.17	5.06	5.03
11/04/90	12	12.10	10.78	6.30	5.31	5.06	5.29	5.11
11/05/90	13	12.97	12.00	6.63	5.34	5.16	5.15	5.15
11/06/90	14	12.22	11.58	6.50	5.42	5.25	5.17	5.12
11/07/90	15	12.00	12.77	6.43	5.17	5.03	5.26	5.09
11/08/90	16	12.54	10.95	6.39	5.41	5.16	5.28	5.14
11/09/90	17	12.17	11.97	6.14	5.19	5.02	5.15	4.99
11/10/90	18	11.80	11.14	6.06	5.27	5.20	5.20	5.21
11/11/90	19	12.33	11.67	6.11	5.30	5.05	5.14	5.02
11/12/90	20	11.39	12.67	6.15	5.23	5.10	5.24	5.09
11/13/90	21	12.39	11.40	6.19	5.17	5.20	5.15	5.14
11/14/90	22	10.91	11.43	6.00	5.33	5.18	5.30	5.08
11/15/90	23	11.90	11.90	5.93	5.27	5.07	5.07	5.10
11/17/90	25	12.37	11.75	5.90	5.30	5.00	5.25	4.98
11/18/90	26	11.02	12.61	6.34	5.12	5.25	5.07	5.11
11/19/90	27	11.38	11.20	6.37	5.32	5.26	5.22	5.09
11/20/90	28	12.20	11.43	6.51	5.08	5.06	4.96	5.16
11/21/90	29	12.40	10.93	6.39	5.36	5.22	5.24	5.24
11/22/90	30	12.45	12.41	6.60	5.04	4.99	4.86	5.10
11/23/90	31	11.00	11.46	6.42	5.32	5.24	5.32	5.26
11/24/90	32	11.40	11.59	6.32	5.27	5.18	5.08	5.24
11/25/90	33	11.60	12.25	6.17	5.19	5.04	5.11	5.15
11/26/90	34	11.71	12.00	5.97	5.08	4.93	4.93	5.04
11/27/90	35	11.91	12.27	5.84	5.18	4.92	4.95	4.95
11/28/90	36	11.66	12.70	5.93	5.32	4.98	5.29	5.00
11/29/90	37	12.93	11.42	6.14	5.24	5.08	5.14	5.02
11/30/90	38	11.38	12.36	6.27	5.10	5.19	5.01	5.08
12/01/90	39	12.55	11.49	6.09	5.19	5.22	4.98	5.14
12/02/90	40	12.22	11.92	6.22	5.26	5.17	5.17	4.98
12/03/90	41	12.67	12.28	6.30	5.29	5.12	5.24	5.17
12/04/90	42	12.30	12.61	6.31	5.07	5.23	5.14	5.22
12/05/90	43	11.51	12.14	6.07	5.04	5.22	4.90	5.19
12/06/90	44	11.93	11.38	5.88	5.17	5.07	5.15	4.99
12/07/90	45	12.05	11.66	5.91	5.11	5.00	4.96	4.88
12/08/90	46	12.68	11.93	6.14	5.26	4.91	5.22	4.88
12/09/90	47	12.59	12.19	6.34	5.30	4.90	5.23	4.91
12/10/90	48	11.20	12.81	6.27	5.31	4.96	5.15	4.93
12/11/90	49	11.82	12.29	6.20	5.34	5.06	5.28	4.96
12/12/90	50	12.53	11.33	6.27	5.27	5.24	5.14	5.17
12/13/90	51	12.94	12.40	6.35	5.07	5.22	5.12	5.23
12/14/90	52	11.61	12.02	6.40	5.29	5.16	5.23	5.08
12/15/90	53	12.83	11.69	6.09	5.34	5.10	5.25	5.05
12/16/90	54	11.49	11.72	5.94	5.28	5.01	5.23	4.91
12/17/90	55	12.34	11.91	6.27	5.10	4.93	5.05	4.85
	MEAN	12.06	11.94	6.20	5.23	5.09	5.13	5.07
	STD	0.59	0.55	0.19	0.10	0.11	0.13	0.10

TABLE B7. OPERATING CONDITIONS OF RUN 2C

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
12/18/90	1	12.55	12.55	6.54	5.20	5.28	5.34	5.21
12/19/90	2	11.69	11.87	6.50	5.28	5.31	5.43	5.24
12/20/90	3	12.00	12.00	6.52	5.41	5.39	5.50	5.26
12/21/90	4	10.88	11.00	5.99	5.42	5.35	5.49	5.41
12/22/90	5	12.11	13.27	6.02	5.50	5.50	5.48	5.48
12/23/90	6	12.17	11.85	6.64	5.51	5.60	5.55	5.57
12/24/90	7	11.33	11.41	6.52	5.78	5.55	5.82	5.56
12/25/90	8	12.86	12.50	6.35	5.64	5.49	5.75	5.55
12/27/90	10	12.47	12.45	6.22	5.84	5.71	5.95	5.66
12/28/90	11	12.33	11.12	6.10	5.90	5.73	5.90	5.77
12/29/90	12	12.15	12.00	5.99	5.61	5.54	5.68	5.63
12/30/90	13	11.94	12.14	6.38	5.88	5.48	5.86	5.42
12/31/90	14	12.57	12.35	6.49	5.66	5.59	5.75	5.70
01/01/91	15	12.51	11.41	6.51	5.74	5.61	5.83	5.66
01/02/91	16	11.68	12.05	6.24	5.87	5.60	5.84	5.51
01/03/91	17	11.91	12.69	6.27	5.79	5.44	5.77	5.40
01/04/91	18	11.89	11.62	6.11	5.69	5.54	5.73	5.44
01/05/91	19	12.04	11.65	6.04	5.51	5.66	5.57	5.49
01/06/91	20	12.40	11.08	6.15	5.43	5.63	5.46	5.73
01/07/91	21	12.86	11.13	5.90	5.50	5.50	5.59	5.45
01/08/91	22	12.61	11.59	6.27	5.67	5.44	5.78	5.32
01/09/91	23	11.80	11.81	6.11	5.88	5.63	5.83	5.40
01/10/91	24	12.52	12.03	6.01	5.78	5.47	5.70	5.67
01/11/91	25	12.21	11.70	6.35	5.70	5.55	5.77	5.61
01/12/91	26	11.73	12.06	6.13	5.61	5.60	5.53	5.50
01/13/91	27	12.34	11.66	6.13	5.55	5.49	5.58	5.47
01/14/91	28	12.18	12.14	6.18	5.60	5.44	5.62	5.38
	MEAN	12.14	11.89	6.25	5.63	5.52	5.67	5.50
	STD	0.44	0.53	0.20	0.18	0.11	0.16	0.15

TABLE B8. OPERATING CONDITIONS OF RUN 3A

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
01/15/91	1	13.25	11.02	6.17	5.59	5.45	5.61	5.52
01/16/91	2	11.87	13.05	6.10	5.48	5.31	5.57	5.34
01/19/91	5	12.16	12.62	5.95	5.26	5.17	5.35	5.19
01/20/91	6	11.31	12.72	5.91	5.28	5.09	5.35	5.22
01/21/91	7	10.85	12.35	5.74	5.35	5.02	5.37	5.08
01/22/91	8	11.15	12.31	5.73	5.31	4.94	5.35	5.17
01/23/91	9	11.60	11.52	5.92	5.37	5.08	5.39	5.04
01/24/91	10	11.98	12.67	6.22	5.39	4.98	5.43	5.14
01/25/91	11	12.46	12.72	6.29	5.35	5.11	5.44	5.25
01/26/91	12	12.42	12.57	6.08	5.26	5.10	5.38	5.19
01/27/91	13	11.31	12.10	5.88	5.19	4.92	5.24	5.14
01/28/91	14	12.80	12.77	5.94	5.14	4.85	5.10	4.93
01/29/91	15	10.73	11.79	6.01	4.98	4.82	5.01	4.94
01/30/91	16	11.45	11.67	5.87	4.92	4.96	4.94	4.92
01/31/91	17	11.23	12.25	6.24	4.91	4.92	4.95	5.03
02/01/91	18	11.93	12.77	6.12	4.95	4.88	4.93	4.89
02/02/91	19	11.69	12.19	6.09	5.13	4.91	5.06	4.83
02/03/91	20	11.82	12.68	5.70	5.17	4.97	5.12	4.80
02/04/91	21	11.12	12.66	5.72	5.14	4.86	4.97	4.93
02/05/91	22	11.76	12.33	5.74	4.98	4.92	4.99	5.11
02/06/91	23	12.76	12.60	5.85	4.99	4.98	4.93	5.08
02/07/91	24	11.61	11.25	5.97	5.03	4.85	5.01	4.93
02/08/91	25	12.59	12.82	5.93	4.92	4.91	4.90	4.98
02/09/91	26	12.05	11.65	6.03	5.11	5.04	4.91	5.12
02/10/91	27	12.41	11.78	6.04	5.04	4.90	5.01	4.88
02/11/91	28	11.77	11.31	6.01	5.10	4.94	4.87	4.99
02/12/91	29	11.05	12.10	5.95	5.26	4.96	5.19	4.92
02/13/91	30	11.69	11.82	5.92	5.21	4.87	5.22	4.82
02/14/91	31	12.62	11.88	5.80	5.02	4.89	5.05	4.98
02/15/91	32	12.06	12.00	5.88	4.94	4.92	4.90	5.03
02/16/91	33	11.94	12.16	6.19	4.92	5.11	4.84	5.20
02/17/91	34	11.55	11.55	6.24	5.20	5.04	5.01	5.05
02/18/91	35	12.33	11.91	6.02	5.22	4.86	5.17	4.82
02/19/91	36	12.10	11.22	5.91	5.26	4.89	5.08	4.86
02/20/91	37	11.22	12.37	5.83	5.01	5.05	5.11	5.12
02/21/91	38	11.57	12.41	6.04	4.96	4.90	4.92	4.98
	MEAN	11.84	12.16	5.97	5.15	4.98	5.13	5.04
	STD	0.58	0.52	0.16	0.17	0.13	0.21	0.16

TABLE B9. OPERATING CONDITIONS OF RUN 3B

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
02/23/91	1	12.75	13.10	6.05	5.45	5.41	5.50	5.51
02/24/91	2	11.68	12.32	6.11	5.40	5.37	5.38	5.47
02/25/91	3	12.19	12.68	5.94	5.33	5.33	5.34	5.31
02/26/91	4	13.13	11.71	5.84	5.30	5.21	5.40	5.25
02/27/91	5	11.31	11.79	5.77	5.23	5.19	5.31	5.10
02/28/91	6	12.28	12.06	6.02	5.28	5.08	5.37	5.07
03/01/91	7	11.19	12.64	6.15	5.17	5.10	5.19	5.27
03/02/91	8	11.47	12.58	5.98	5.20	5.12	5.02	5.25
03/03/91	9	12.37	11.09	5.89	5.14	5.24	4.97	5.18
03/04/91	10	12.09	11.53	6.24	5.01	5.20	4.96	5.25
03/06/91	12	11.30	12.74	6.19	5.07	5.13	4.98	5.26
03/07/91	13	12.61	11.31	6.12	4.97	5.03	4.90	5.09
03/08/91	14	11.35	12.78	5.90	4.98	5.11	4.89	5.13
03/09/91	15	12.54	11.25	6.01	4.88	5.07	4.81	4.99
03/10/91	16	12.94	11.63	5.80	4.81	4.91	4.80	4.95
03/11/91	17	11.60	12.45	5.88	4.86	4.91	4.78	4.83
03/12/91	18	11.72	12.15	5.97	4.98	4.87	4.98	4.97
03/13/91	19	12.63	11.49	5.74	5.08	4.90	5.05	5.06
03/14/91	20	12.05	13.00	5.78	4.96	5.13	4.91	5.10
03/15/91	21	12.42	11.44	5.74	4.83	5.01	4.80	5.04
03/16/91	22	12.15	11.69	5.79	4.93	4.97	4.90	5.14
03/17/91	23	12.32	12.41	6.33	4.98	5.07	4.81	4.92
03/18/91	24	12.87	12.40	6.20	4.88	5.08	4.88	5.13
03/19/91	25	12.20	12.02	6.27	4.84	5.11	4.83	5.09
03/20/91	26	11.84	12.66	6.19	4.92	4.94	4.80	4.97
03/21/91	27	11.82	11.32	5.96	4.84	5.05	4.80	5.01
03/22/91	28	11.89	11.80	5.92	5.06	4.95	5.02	5.10
03/23/91	29	12.41	12.13	5.89	5.12	4.91	5.11	4.83
03/24/91	30	11.55	12.41	5.94	4.89	5.12	4.84	5.16
03/25/91	31	11.80	12.66	6.30	5.06	4.98	4.96	4.97
03/26/91	32	12.02	12.10	6.07	5.18	4.88	5.04	5.08
03/27/91	33	12.41	11.45	6.25	5.01	4.98	5.12	5.14
03/28/91	34	11.67	11.89	6.10	4.97	5.11	4.86	5.08
03/29/91	35	11.92	12.00	5.97	4.88	4.89	4.91	5.02
03/30/91	36	11.95	12.32	5.85	4.91	4.85	4.91	4.92
03/31/91	37	12.23	12.46	5.88	4.84	5.11	4.78	5.16
04/01/91	38	11.62	11.62	5.89	4.98	4.91	4.86	4.96
04/02/91	39	11.78	12.35	6.11	5.15	4.87	5.07	5.04
04/03/91	40	12.12	12.29	6.17	5.04	4.96	4.99	4.92
04/04/91	41	11.90	12.48	5.91	4.96	5.05	4.88	5.10
	MEAN	12.05	12.11	6.00	5.03	5.05	4.99	5.10
	STD	0.47	0.51	0.16	0.16	0.14	0.19	0.15

TABLE B10. OPERATING CONDITIONS OF RUN 4A

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
04/09/91	1	11.32	12.33	6.25	4.64	4.75	4.57	4.58
04/10/91	2	11.55	11.88	6.24	4.45	4.59	4.60	4.78
04/11/91	3	11.34	10.83	6.37	4.49	4.66	4.39	4.62
04/14/91	6	11.66	11.85	6.12	4.31	4.45	4.26	4.47
04/15/91	7	12.55	12.74	6.14	4.38	4.38	4.42	4.33
04/16/91	8	12.20	12.80	6.07	4.35	4.40	4.55	4.30
04/17/91	9	13.41	12.75	6.12	4.46	4.52	4.44	4.51
04/18/91	10	12.22	12.75	5.96	4.48	4.48	4.39	4.40
04/19/91	11	11.86	13.05	5.94	4.30	4.36	4.40	4.48
04/20/91	12	11.03	11.68	5.80	4.45	4.35	4.31	4.40
04/21/91	13	12.44	12.31	5.87	4.42	4.57	4.46	4.47
04/22/91	14	12.85	12.50	5.81	4.26	4.42	4.30	4.39
04/23/91	15	12.38	11.51	6.29	4.42	4.38	4.48	4.31
04/24/91	16	12.98	12.55	6.18	4.43	4.37	4.43	4.30
04/25/91	17	12.05	12.82	6.33	4.39	4.41	4.49	4.51
04/26/91	18	11.37	11.75	6.01	4.33	4.54	4.42	4.54
04/27/91	19	12.43	12.00	5.98	4.24	4.44	4.24	4.57
04/28/91	20	12.79	11.95	5.81	4.53	4.39	4.57	4.38
04/29/91	21	12.60	11.05	5.77	4.50	4.55	4.48	4.49
04/30/91	22	12.50	12.86	5.79	4.42	4.57	4.53	4.45
05/01/91	23	12.43	11.33	5.75	4.59	4.42	4.50	4.44
05/02/91	24	12.46	12.46	5.88	4.51	4.39	4.55	4.54
05/03/91	25	12.82	12.82	6.19	4.36	4.34	4.33	4.32
05/04/91	26	12.58	12.00	6.27	4.57	4.57	4.57	4.62
05/05/91	27	12.69	12.35	6.20	4.48	4.53	4.51	4.58
05/06/91	28	11.71	11.32	5.92	4.54	4.33	4.57	4.49
05/07/91	29	12.38	12.38	5.80	4.39	4.50	4.34	4.61
05/08/91	30	11.54	11.72	6.03	4.52	4.59	4.49	4.73
05/09/91	31	12.63	11.54	6.04	4.34	4.54	4.34	4.63
05/10/91	32	12.07	12.07	6.34	4.32	4.42	4.26	4.42
05/11/91	33	11.38	12.63	6.12	4.41	4.34	4.52	4.31
05/12/91	34	12.15	11.47	5.98	4.37	4.55	4.32	4.57
05/13/91	35	12.32	11.84	5.83	4.36	4.66	4.40	4.64
05/14/91	36	11.80	12.42	5.80	4.30	4.50	4.32	4.70
05/15/91	37	12.91	12.02	6.20	4.42	4.47	4.33	4.59
05/16/91	38	12.44	12.50	6.27	4.31	4.35	4.28	4.38
	MEAN	12.22	12.13	6.04	4.42	4.47	4.43	4.50
	STD	0.55	0.56	0.19	0.09	0.10	0.10	0.13

TABLE B11. OPERATING CONDITIONS OF RUN 4B

DATE	DAY	HRT (hr)		pH VALUES				
		Reactor I	Reactor II	Influent	Reactor I	Reactor II	Effluent I	Effluent II
05/18/91	1	12.11	11.50	6.07	5.78	5.69	6.04	5.85
05/19/91	2	11.02	11.25	6.03	6.25	6.00	6.29	6.28
05/21/91	4	11.88	12.54	6.11	6.07	5.84	6.01	5.85
05/22/91	5	12.73	11.12	6.04	6.18	6.17	5.93	6.21
05/23/91	6	11.25	12.20	6.19	6.17	5.95	6.08	6.03
05/24/91	7	12.10	12.29	6.27	6.09	6.13	6.04	6.15
05/25/91	8	12.30	12.14	6.39	6.04	5.89	6.06	5.95
05/26/91	9	12.14	12.06	6.12	5.96	5.95	5.86	6.13
05/27/91	10	12.01	11.95	5.97	6.10	6.08	6.02	6.21
05/28/91	11	11.73	12.40	5.83	6.25	6.00	5.90	5.93
05/29/91	12	11.58	11.38	5.99	6.01	6.27	5.92	5.95
05/30/91	13	11.45	11.45	6.32	5.95	5.97	5.85	5.88
05/31/91	14	11.95	11.77	6.41	6.22	6.05	5.83	6.08
06/01/91	15	12.22	12.45	6.20	6.02	5.91	5.93	6.25
06/02/91	16	12.09	12.66	6.02	5.91	6.15	5.88	6.13
06/03/91	17	11.58	11.65	5.85	6.01	6.18	6.02	6.04
06/04/91	18	12.42	12.20	5.82	6.02	5.95	6.06	6.05
06/05/91	19	11.77	11.77	5.95	6.08	6.29	5.96	6.19
06/06/91	20	11.89	11.50	6.33	6.26	6.02	6.18	6.19
06/07/91	21	12.34	12.53	6.30	6.15	5.89	6.15	6.05
06/08/91	22	12.41	11.61	5.90	6.03	6.05	6.08	6.11
06/09/91	23	12.63	12.65	6.24	6.02	5.92	5.98	5.89
06/10/91	24	11.38	12.56	6.09	6.03	6.01	6.03	6.25
06/11/91	25	12.09	12.85	6.21	6.10	6.07	6.13	6.17
06/12/91	26	12.13	11.63	6.39	6.00	6.13	6.00	6.29
06/13/91	27	12.20	12.00	6.03	6.11	5.96	5.94	6.18
06/14/91	28	12.11	11.64	6.04	5.95	6.09	6.03	6.12
06/15/91	29	12.73	12.73	6.21	6.18	6.20	6.15	6.27
06/16/91	30	11.65	11.65	5.95	6.03	5.93	5.97	5.92
06/17/91	31	11.71	12.51	5.90	6.22	5.88	6.19	6.01
06/18/91	32	12.10	12.03	6.32	6.15	6.24	5.93	6.35
06/19/91	33	12.04	11.92	6.08	5.93	6.11	5.89	6.25
06/20/91	34	11.76	11.53	5.92	6.04	6.00	6.08	6.02
06/21/91	35	11.93	12.14	6.21	6.13	5.82	6.10	5.89
06/22/91	36	12.11	12.39	6.19	6.25	6.21	6.22	6.39
06/23/91	37	11.58	11.77	6.30	6.09	6.18	5.88	6.38
06/24/91	38	11.67	12.22	6.21	6.22	6.10	6.11	6.14
06/25/91	39	11.82	12.06	6.11	6.01	6.14	6.10	6.16
06/26/91	40	12.03	11.89	6.09	6.21	6.12	6.24	5.89
06/27/91	41	12.14	11.44	5.98	6.03	6.21	5.98	6.11
06/28/91	42	12.22	11.90	5.99	5.97	5.93	6.01	5.98
06/29/91	43	11.96	12.23	6.17	6.08	6.06	6.10	6.17
06/30/91	44	11.74	12.65	6.13	6.17	6.14	6.13	6.22
07/01/91	45	11.80	12.28	6.28	6.13	6.17	6.06	6.24
07/02/91	46	12.41	12.12	6.12	6.26	6.22	6.23	6.30
07/03/91	47	12.21	11.63	6.03	6.02	5.96	6.11	6.03
07/04/91	48	11.67	11.94	6.14	6.20	6.17	6.18	6.00
	MEAN	11.97	12.02	6.12	6.09	6.05	6.04	6.11
	STD	0.36	0.43	0.15	0.11	0.13	0.11	0.15

APPENDIX C

CHEMICAL PARAMETERS

TABLE **PAGE**

TABLE **PAGE**

TABLE C1. INFLUENT CHARACTERISTICS FROM RUN 1A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/21/89	9	3920	2975	3540	2700	654	437	1825	99	430	139	131	26.5	18.4	9.2
12/24/89	12	3820	2900	3270	2495	695	588	1535	90	452	157	136	25.1	18.0	11.5
12/29/89	17	4000	3170	3600	2820	708	627	1705	93	408	139	130	16.9	17.6	9.9
01/02/90	21	5235	4205	5050	3985	844	582	2700	80	456	149	158	23.2	22.0	10.8
01/05/90	24	5170	4105	4880	3840	834	693	2420	99	468	162	155	21.3	21.2	9.8
01/09/90	28	4130	3050	3710	2745	632	465	1820	137	332	94	116	14.7	18.2	8.8
01/17/90	36	4225	3315	3990	3130	665	453	1985	73	396	105	118	11.8	18.6	9.5
01/20/90	39	3765	2605	3610	2410	640	597	1130	108	460	146	115	13.0	18.4	6.1
01/23/90	42	3805	2910	3630	2795	635	582	1625	91	466	150	119	17.6	17.9	10.4
01/27/90	46	4235	3260	3860	2950	627	539	1960	103	507	189	118	17.8	16.1	10.6
01/30/90	49	3935	2980	3215	2600	585	476	1890	116	623	201	115	21.7	17.3	11.5
02/02/90	52	3645	2750	3345	2525	531	581	1560	77	638	208	120	34.8	13.9	7.5
02/06/90	56	3550	2730	3365	2590	473	520	1650	92	367	92	89	13.4	15.6	10.0
02/09/90	59	4240	3165	3710	2830	564	554	1895	76	392	98	104	14.2	20.4	13.3
02/13/90	63	4000	3075	3190	2610	543	479	1880	89	415	137	107	20.0	18.8	12.5
02/16/90	66	3895	2580	3365	2365	557	471	1560	107	422	133	108	19.3	17.9	10.7
02/20/90	70	3835	2600	3200	2380	496	483	1520	121	501	167	103	24.1	17.6	11.4
02/24/90	74	3745	2675	3090	2460	639	405	1465	56	303	81	118	16.0	18.4	10.6
02/27/90	77	3420	2300	2990	2155	562	412	1140	85	359	89	105	15.4	15.7	7.1
03/02/90	80	4240	3240	3930	3045	710	530	1895	90	340	106	134	20.2	23.7	14.7
03/06/90	84	3500	2685	3410	2370	654	574	1345	129	398	119	124	19.6	19.6	11.6
03/08/90	86	4025	3050	3820	2830	689	555	1705	150	417	125	132	21.6	20.5	13.0
	MEAN	4015	3015	3626	2756	634	527	1737	98	434	136	121	19.5	18.4	10.5
	STD	441	442	503	436	92	72	353	22	81	35	16	5.2	2.2	2.0

TABLE C2. REACTOR I (CMR) CHARACTERISTICS FROM RUN 1A

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/21/89	9	19595	15295	14490	10800	2445	2250	7855	543	1109	380	440	49	80	9.4
12/24/89	12	22850	17950	16915	13975	2525	1900	10750	594	1379	476	454	50	92	10.8
12/29/89	17	29855	22655	20040	16470	2120	1475	12785	649	1334	524	396	57	111	10.3
01/02/90	21	20140	14980	12000	10145	1940	1680	7980	466	1374	438	353	42	82	9.2
01/05/90	24	27445	20270	18615	15360	1800	1715	12035	518	1305	501	343	55	110	8.4
01/09/90	28	23600	17705	17525	14445	1725	1600	10835	552	1149	443	325	49	99	7.7
01/17/90	36	24905	19090	16855	12910	1630	1510	10345	332	1247	460	313	52	91	10.0
01/20/90	39	24435	18820	15250	11175	1950	1665	8160	527	1173	357	341	29	84	8.2
01/23/90	42	26730	19755	16640	12680	1755	1910	10000	616	1127	385	323	43	81	9.6
01/27/90	46	26400	19405	17180	13205	2125	1675	10235	648	1397	464	399	59	97	10.3
01/30/90	49	25270	19995	18030	14910	1750	2020	11510	576	1575	552	347	67	106	11.0
02/02/90	52	31635	24770	21465	17670	1605	2300	13975	424	1481	546	300	43	114	8.6
02/06/90	56	30025	22880	19605	16040	2020	1615	13325	602	1259	400	376	52	110	8.8
02/09/90	59	23085	17075	15485	13040	1635	2090	10180	492	1373	401	306	44	85	11.2
02/13/90	63	19140	15700	14965	12450	1730	1665	9015	511	1454	536	305	28	82	11.7
02/16/90	66	29840	22870	20520	15740	1625	1890	12580	569	1293	412	299	39	100	10.3
02/20/90	70	27575	20435	18120	14915	1690	2180	11535	509	1542	515	315	45	91	12.0
02/24/90	74	26120	20405	17585	14675	2150	1925	11850	507	1213	371	379	35	93	9.8
02/27/90	77	29295	22735	20840	17255	1835	1715	13649	582	1193	360	325	32	108	8.8
03/02/90	80	28035	21900	18520	15405	1580	1540	11165	551	1292	355	282	29	98	10.6
03/06/90	84	26035	20575	19050	16160	1720	1675	13285	577	1112	382	322	47	107	10.2
03/08/90	86	24670	18515	16940	14125	1925	1855	10870	536	1178	400	347	39	91	12.3
	MEAN	25758	19717	17574	14252	1876	1811	11087	540	1298	439	345	45	96	10.0
	STD	3365	2568	2225	1986	257	234	1761	71	134	65	45	10	11	1.2

TABLE C3. EFFLUENT I CHARACTERISTICS FROM RUN 1A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/21/89	9	2428	1846	820	628	349	106	335	547	1045	387	96	40	14.3	7.3
12/24/89	12	2596	1924	1020	734	378	100	401	641	1376	447	110	50	15.7	10.2
12/29/89	17	3428	2458	1218	860	458	91	491	619	1300	463	122	48	14.9	10.4
01/02/90	21	2880	2102	874	650	327	76	372	521	1384	502	91	39	17.8	9.0
01/05/90	24	2556	1998	762	588	281	73	316	554	1341	519	98	53	15.7	7.8
01/09/90	28	3376	2464	1008	772	321	87	439	478	1221	417	103	51	15.6	7.2
01/17/90	36	2476	1770	680	532	362	68	298	327	1169	455	115	57	14.3	9.3
01/20/90	39	2580	1986	792	590	391	91	305	447	1130	399	89	27	15.0	8.2
01/23/90	42	3128	2314	838	662	365	89	361	624	1139	413	97	38	14.8	9.1
01/27/90	46	3694	2808	1400	1054	483	72	530	636	1415	531	136	59	12.5	8.3
01/30/90	49	3056	2200	1042	758	302	71	475	483	1564	575	113	65	12.7	9.6
02/02/90	52	2830	2142	886	696	275	87	384	445	1457	547	82	38	9.7	7.0
02/06/90	56	2450	1794	648	504	383	85	272	529	1207	411	114	53	13.2	7.6
02/09/90	59	2770	2066	696	522	401	66	296	487	1390	443	105	41	17.3	11.1
02/13/90	63	2476	1882	654	500	440	70	277	525	1408	519	105	35	15.7	8.3
02/16/90	66	3158	2204	676	544	289	92	273	567	1279	381	84	38	14.6	10.7
02/20/90	70	3406	2418	1056	730	438	107	396	581	1445	472	116	46	13.0	9.2
02/24/90	74	3372	2426	998	748	275	81	416	493	1235	371	79	35	15.9	9.9
02/27/90	77	2978	2114	748	576	267	101	315	549	1185	360	81	39	12.3	8.7
03/02/90	80	3428	2640	1164	934	313	80	508	510	1247	365	80	30	19.0	11.2
03/06/90	84	2502	1952	702	558	388	73	324	581	1111	401	105	43	14.2	10.3
03/08/90	86	3186	2294	836	678	286	68	412	512	1129	427	86	41	18.1	10.4
	MEAN	2943	2173	887	674	353	83	373	530	1281	446	100	44	14.8	9.1
	STD	391	273	199	141	63	12	78	71	134	62	15	10	2.1	1.3

TABLE C4. REACTOR II (UASB) CHARACTERISTICS FROM RUN 1A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/21/89	9	40530	32530	30485	22280	7170	8420	13470	487	1445	494	1208	61	281	6.8
12/24/89	12	53840	42855	40190	30269	9175	8950	18420	601	1546	544	1507	39	371	8.3
12/29/89	17	52775	42945	41715	31005	8920	9545	17570	652	1376	474	1476	48	380	7.4
01/02/90	21	55270	44660	42065	32100	7085	8680	21030	537	1561	591	1187	53	394	9.2
01/05/90	24	53885	44445	45630	34395	7825	11340	20945	526	1729	614	1308	56	375	8.6
01/09/90	28	51840	41770	39370	30415	7240	8155	20245	659	1269	445	1211	53	352	6.3
01/17/90	36	48690	38464	35540	27955	8060	9380	14960	492	1438	470	1323	34	311	6.7
01/20/90	39	47305	37325	32755	26065	6600	9415	13370	595	1664	584	1110	54	288	7.8
01/23/90	42	50455	39880	36695	29420	7170	8020	19520	733	1425	439	1209	62	324	5.3
01/27/90	46	50355	41070	39090	28650	6035	9235	18475	692	1552	529	1023	57	302	8.6
01/30/90	49	54530	44245	42785	31170	8000	10385	16035	560	1672	599	1337	57	384	8.8
02/02/90	52	45975	35860	33645	26410	5715	9990	18450	580	1732	593	964	50	293	8.2
02/06/90	56	51950	39410	34285	26110	5530	8425	15440	677	1321	482	949	64	287	7.1
02/09/90	59	49525	39455	37490	29320	8465	8260	18695	564	1399	479	1389	34	322	7.4
02/13/90	63	42220	33100	29995	23375	8220	7490	13260	532	1456	496	1360	45	276	6.6
02/16/90	66	44010	34510	31595	23105	9075	7765	13805	701	1657	524	1512	60	294	6.9
02/20/90	70	40875	32075	30810	22975	6910	9145	13060	662	1644	579	1152	46	302	7.7
02/24/90	74	51860	40865	39540	30070	6380	10215	17905	566	1191	419	1056	35	386	8.6
02/27/90	77	53515	40255	36575	28685	5975	8860	19280	584	1300	464	991	35	371	9.0
03/02/90	80	49900	41010	37075	27480	7565	7965	17525	626	1342	468	1262	51	350	8.8
03/06/90	84	46590	36340	30235	23620	6005	9650	15335	644	1520	512	1022	61	311	10.1
03/08/90	86	52295	40765	39080	28760	7730	9325	16650	589	1559	541	1279	42	358	9.5
	MEAN	49463	39265	36666	27892	7311	9028	16975	603	1491	515	1220	50	332	7.9
	STD	4341	3743	4413	3231	1073	928	2525	67	151	57	170	10	39	1.2

TABLE C5. EFFLUENT II CHARACTERISTICS FROM RUN 1A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/21/89	9	2622	1924	506	388	259	39	204	365	1166	389	102	60	10.1	7.2
12/24/89	12	2986	2146	530	436	215	47	237	505	1426	493	77	43	12.9	9.1
12/29/89	17	3572	2478	700	510	171	45	280	494	1305	419	71	44	10.5	7.0
01/02/90	21	3132	2202	578	408	151	36	226	479	1299	479	74	50	11.7	8.3
01/05/90	24	2226	1620	436	366	218	32	199	486	1561	507	91	56	13.0	9.1
01/09/90	28	2518	1854	592	380	258	53	206	475	1084	388	90	49	9.8	6.4
01/17/90	36	2358	1772	396	324	263	50	153	383	1155	451	81	39	9.6	6.7
01/20/90	39	2598	1976	406	292	298	32	147	504	1375	457	106	59	9.8	7.2
01/23/90	42	2866	2004	388	318	235	38	148	435	1334	434	99	61	9.5	6.0
01/27/90	46	3230	2268	640	510	191	31	293	511	1488	465	96	66	13.2	8.8
01/30/90	49	2240	1722	438	338	256	29	181	381	1475	551	100	59	13.0	10.0
02/02/90	52	2642	1886	422	344	216	27	178	460	1561	551	90	56	10.3	7.7
02/06/90	56	3000	2100	454	360	200	36	188	463	1239	409	95	63	11.0	7.4
02/09/90	59	2658	2034	492	328	266	43	151	420	1087	377	81	39	10.6	7.7
02/13/90	63	2242	1662	376	286	290	45	131	377	1262	390	95	49	9.2	6.1
02/16/90	66	2846	2064	540	420	241	40	217	578	1495	498	99	60	10.9	7.4
02/20/90	70	3174	2300	544	432	162	38	238	494	1340	460	70	44	12.1	8.3
02/24/90	74	3038	2142	496	482	207	29	261	477	1072	374	70	37	13.0	9.0
02/27/90	77	2586	1858	436	292	239	39	144	496	1213	453	75	37	9.8	7.6
03/02/90	80	2238	1686	418	328	274	44	152	499	1255	461	92	49	12.1	9.6
03/06/90	84	2530	1782	464	338	192	40	176	552	1414	465	93	63	13.9	10.5
03/08/90	86	2922	2100	502	364	224	45	184	400	1333	435	81	45	13.7	10.3
	MEAN	2737	1981	489	375	228	39	195	465	1315	450	88	51	11.4	8.1
	STD	362	222	83	65	40	7	45	56	146	50	11	9	1.5	1.3

TABLE C6. INFLUENT CHARACTERISTICS FROM RUN 1B

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
03/20/90	7	3810	2980	3285	2710	619	568	1715	82	244	71	115	15.8	16.8	7.9
03/23/90	10	3985	2850	3570	2630	635	498	1520	112	347	104	122	20.4	17.1	8.6
03/27/90	14	3815	2860	3695	2650	639	519	1670	120	534	171	122	19.3	16.8	9.0
03/30/90	17	4625	3300	4465	2970	627	564	1975	83	301	92	114	13.2	17.6	7.7
04/03/90	21	3600	2740	3300	2500	506	425	1660	119	321	103	96	14.8	14.0	8.5
04/06/90	24	4325	3145	4065	2905	589	441	2015	126	389	125	110	15.4	15.1	9.9
04/09/90	27	4110	3100	3830	2890	776	528	1715	110	375	110	142	17.6	26.7	12.1
04/12/90	30	3485	2545	3185	2415	647	442	1400	136	448	139	124	20.1	22.7	11.7
04/16/90	34	3820	2825	3535	2550	694	497	1510	91	401	128	130	18.5	19.5	10.3
04/19/90	37	4035	3010	3710	2755	610	500	1855	99	374	121	112	14.3	17.4	9.2
04/23/90	41	3780	2720	3440	2435	598	424	1605	118	353	109	119	22.9	17.6	8.2
04/26/90	44	3555	2625	3265	2404	569	419	1620	132	426	130	106	15.0	19.9	11.5
	MEAN	3912	2892	3612	2651	626	485	1688	111	376	117	117	17.3	18.4	9.6
	STD	315	214	358	190	63	52	177	17	71	24	11	2.9	3.3	1.5

TABLE C7. REACTOR I (CMR) CHARACTERISTICS FROM RUN 1B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
03/20/90	7	24675	18070	17425	13640	2000	2420	9820	359	942	317	349	29	126	6.2
03/23/90	10	27605	20785	19995	16445	1905	3040	11175	605	991	364	357	52	147	10.7
03/27/90	14	28955	21995	22620	18825	2200	2635	13850	502	1207	425	396	44	155	9.8
03/30/90	17	25285	19300	20150	16270	1795	2225	11735	312	1203	392	317	29	130	7.2
04/03/90	21	32970	24695	23260	19355	2080	2370	13960	371	1090	357	366	33	172	8.1
04/06/90	24	31385	23220	23285	18365	2000	2230	14100	315	1128	386	357	37	174	8.0
04/09/90	27	24910	18490	18990	15810	1615	2685	11445	341	977	319	295	37	139	9.3
04/12/90	30	25345	19445	20425	16140	1715	2740	11210	452	1045	338	322	47	148	12.0
04/16/90	34	30095	23420	24420	20375	2160	2900	14695	378	1161	380	377	32	166	7.8
04/19/90	37	32685	24730	24975	19730	2050	2464	14375	435	1098	331	360	32	176	8.7
04/23/90	41	26220	20120	19820	16650	1725	2215	12340	418	990	308	320	44	127	8.0
04/26/90	44	32900	24855	23660	19215	1860	2640	14435	397	1174	344	328	31	145	6.7
	MEAN	28586	21594	21585	17568	1925	2547	12762	407	1084	355	345	37	150	8.5
	STD	3184	2432	2304	1937	179	260	1584	80	89	34	28	7	18	1.6

TABLE C8. EFFLUENT I CHARACTERISTICS FROM RUN 1B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
03/20/90	7	2622	1872	1070	764	332	100	473	355	1067	388	88	35	11.2	5.8
03/23/90	10	2804	1964	1184	920	419	112	558	578	950	303	107	40	14.4	9.4
03/27/90	14	3680	2738	1878	1420	624	148	836	504	1161	403	139	39	19.3	9.1
03/30/90	17	3488	2602	1796	1308	447	136	768	316	1228	416	97	25	16.6	7.7
04/03/90	21	3654	2740	1816	1396	398	153	838	350	1112	364	99	35	17.0	7.0
04/06/90	24	3186	2262	1318	960	371	102	628	352	1072	361	98	39	13.9	6.2
04/09/90	27	2548	1820	1144	850	391	93	549	378	1032	356	92	29	14.4	8.2
04/12/90	30	3006	2204	1362	1032	559	105	612	463	1076	369	143	53	16.3	10.4
04/16/90	34	3688	2618	1700	1222	410	130	730	362	1195	428	96	30	15.8	7.5
04/19/90	37	2710	1986	1334	958	359	101	618	430	1088	311	92	34	14.2	6.8
04/23/90	41	3064	2206	1302	1000	415	116	627	447	1103	357	109	43	17.8	8.7
04/26/90	44	3362	2488	1648	1184	368	138	754	408	1198	372	88	29	16.4	6.1
	MEAN	3151	2292	1463	1085	424	120	666	412	1107	369	104	36	15.6	7.7
	STD	405	324	275	207	81	20	112	73	75	36	18	7	2.0	1.4

TABLE C9. REACTOR II (UASB) CHARACTERISTICS FROM RUN 1B

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
03/20/90	7	47375	35915	36620	26760	5820	8305	14985	426	1046	361	969	38	306	8.9
03/23/90	10	50825	39040	38650	29905	8025	8760	17865	569	1174	428	1328	44	338	7.4
03/27/90	14	42200	33220	32795	25715	6390	8360	13765	509	1408	472	1063	41	306	7.0
03/30/90	17	51980	40865	42180	30655	8375	9705	16975	405	1221	356	1369	29	353	6.2
04/03/90	21	41755	31410	30485	23170	5560	7780	13080	451	1328	468	922	33	274	7.9
04/06/90	24	45665	36665	38835	29005	7010	8355	16745	506	1525	487	1152	31	310	5.3
04/09/90	27	48380	36700	38325	28280	7120	9510	15095	319	1260	429	1169	29	293	5.1
04/12/90	30	41890	32475	35290	25645	6095	8795	13785	545	1454	493	1026	51	275	7.6
04/16/90	34	43445	33335	33965	24375	6760	7915	13285	488	1412	429	1128	47	298	8.0
04/19/90	37	40985	31350	33675	26140	7525	7120	15890	406	1188	371	1247	43	325	9.4
04/23/90	41	39855	30145	31380	23410	6350	8030	13280	501	1204	388	1046	30	335	6.0
04/26/90	44	46540	35355	35685	27000	8170	8365	16315	472	1390	449	1341	34	356	6.8
	MEAN	45075	34706	35657	26672	6933	8417	15089	466	1301	428	1147	37	314	7.1
	STD	3824	3141	3289	2325	898	685	1586	66	135	47	143	7	26	1.3

TABLE C10. EFFLUENT II CHARACTERISTICS FROM RUN 1B

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
03/20/90	7	2038	1426	742	628	300	64	460	349	1045	344	83	35	11.7	7.5
03/23/90	10	2492	1770	1062	758	247	75	502	460	1087	360	80	40	12.2	6.9
03/27/90	14	3006	2172	1264	942	253	77	629	419	1240	390	80	40	14.1	7.1
03/30/90	17	3636	2706	1696	1352	351	101	888	313	975	331	86	29	15.4	5.8
04/03/90	21	3240	2380	1434	1110	428	93	739	338	1215	410	97	28	13.9	5.4
04/06/90	24	2984	2140	1134	804	350	78	563	350	1287	382	91	35	12.2	6.0
04/09/90	27	3026	2200	1342	998	356	89	675	282	1085	338	87	30	12.6	5.3
04/12/90	30	3262	2346	1314	1006	267	93	709	448	1301	417	89	46	13.3	6.7
04/16/90	34	2646	1892	1100	816	358	63	604	334	1148	348	105	48	14.0	8.2
04/19/90	37	2726	2004	1202	944	416	70	696	352	1010	358	112	45	13.8	8.3
04/23/90	41	3428	2452	1388	1040	374	82	765	411	976	300	92	32	11.7	4.9
04/26/90	44	2804	2070	1206	948	310	68	652	388	1193	359	87	38	11.0	6.2
	MEAN	2941	2130	1240	946	334	79	657	370	1130	361	91	37	13.0	6.5
	STD	418	323	223	178	57	12	112	52	112	32	9	6	1.2	1.1

TABLE C11. INFLUENT CHARACTERISTICS FROM RUN 1C

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/03/90	6	3885	2795	3525	2555	656	482	1530	77	598	139	131	26.2	19.8	11.9
05/07/90	10	3975	3015	3630	2750	668	405	1745	95	384	118	122	15.2	18.3	7.3
05/10/90	13	3760	2800	3430	2560	586	540	1470	117	445	137	114	20.4	15.8	10.0
05/14/90	17	4025	3000	3660	2685	609	446	1645	135	406	131	123	26.0	17.3	10.0
05/17/90	20	3790	2695	3405	2520	512	394	1755	68	560	168	103	21.2	20.5	12.3
05/21/90	24	3570	2850	3275	2615	502	512	1645	84	574	190	107	26.6	15.4	7.6
05/24/90	27	4790	3870	4320	3625	807	545	2240	104	283	83	143	14.3	21.0	12.8
05/28/90	31	4135	3225	3845	3030	693	620	1690	112	425	135	132	21.1	21.5	12.4
05/31/90	34	3835	2915	3460	2710	640	563	1570	127	493	126	129	26.4	19.9	10.3
06/04/90	38	4350	3415	3770	3190	715	512	2005	147	531	158	142	27.3	22.2	12.7
06/07/90	41	3260	2480	2625	2200	541	452	1435	60	497	156	111	24.9	14.7	9.3
06/11/90	45	3840	2770	3340	2595	614	494	1530	104	409	128	119	20.4	16.9	9.8
06/14/90	48	4220	3150	3695	2880	719	549	1675	121	387	111	136	20.8	19.8	11.1
06/18/90	52	4045	3080	3625	2720	700	510	1740	136	428	135	136	23.5	20.2	10.6
	MEAN	3963	3004	3543	2760	640	502	1691	106	459	137	125	22.5	18.8	10.6
	STD	348	331	358	331	83	60	206	26	84	25	12	4.0	2.3	1.7

TABLE C12. REACTOR I (CMR) CHARACTERISTICS FROM RUN 1C

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/03/90	6	14315	11235	9570	7825	1455	755	5445	498	1390	463	301	69	68	11.2
05/07/90	10	16095	13190	10445	8285	1690	965	5975	537	1368	469	330	59	66	11.8
05/10/90	13	18540	14375	13095	10950	1910	1140	7615	699	1502	502	344	38	89	7.4
05/14/90	17	20630	16680	14020	11605	2150	1280	7815	684	1567	558	390	46	101	8.5
05/17/90	20	17300	13745	12645	10150	1745	1075	6750	577	1305	467	318	39	94	7.1
05/21/90	24	16465	12820	11580	9030	1695	950	6075	609	1608	562	313	42	82	9.3
05/24/90	27	21560	17205	15085	12300	1920	1230	8590	621	1177	383	359	52	103	9.8
05/28/90	31	22380	18000	16335	13360	2205	1385	9140	676	1543	540	399	46	110	7.4
05/31/90	34	20255	15690	13120	10405	1880	1120	7230	594	1310	467	366	66	87	10.3
06/04/90	38	18570	14735	12935	11010	1740	1255	7435	657	1561	482	332	54	89	10.7
06/07/90	41	17680	14360	11415	9675	1690	880	6725	719	1405	468	314	44	75	8.6
06/11/90	45	21425	17280	14055	11200	1955	1210	7670	582	1283	494	374	61	93	9.6
06/14/90	48	16730	13310	11550	9880	1810	1130	6365	704	1429	523	349	60	76	12.0
06/18/90	52	18975	15705	12540	10065	1945	1285	7350	694	1586	588	361	50	91	8.2
	MEAN	18637	14881	12742	10410	1842	1119	7156	632	1431	498	347	52	87	9.4
	STD	2287	1893	1732	1441	189	171	982	66	129	51	29	10	12	1.6

TABLE C13. EFFLUENT I CHARACTERISTICS FROM RUN 1C

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/03/90	6	2350	1664	516	418	268	37	268	490	1315	455	109	67	16.6	11.3
05/07/90	10	2452	1782	656	510	322	39	317	559	1421	476	115	64	15.7	9.6
05/10/90	13	3510	2598	1004	818	334	49	481	672	1541	511	99	46	18.5	8.0
05/14/90	17	3146	2234	716	566	318	52	356	690	1552	518	88	37	14.8	8.4
05/17/90	20	3370	2426	928	706	348	27	457	578	1223	469	101	45	18.1	7.3
05/21/90	24	3104	2298	670	514	374	53	326	648	1507	554	101	41	14.4	8.8
05/24/90	27	2628	1938	628	490	261	51	312	620	1177	391	91	49	14.9	9.7
05/28/90	31	2862	2046	622	506	255	51	303	699	1496	528	94	54	12.7	7.6
05/31/90	34	2990	2138	558	454	235	44	282	580	1324	476	106	68	15.4	10.8
06/04/90	38	3098	2292	744	562	242	34	349	623	1582	523	96	57	16.7	9.3
06/07/90	41	3086	2284	552	412	284	31	264	682	1304	489	94	49	13.9	8.1
06/11/90	45	2696	1934	582	474	236	42	298	594	1338	501	98	61	16.2	10.3
06/14/90	48	2972	2200	696	528	332	51	323	709	1296	461	115	62	17.5	11.6
06/18/90	52	3244	2320	680	544	254	48	336	681	1562	586	97	56	17.2	8.0
	MEAN	2965	2154	682	536	290	44	334	630	1403	496	100	54	15.9	9.2
	STD	323	246	133	105	45	8	61	62	131	46	8	9	1.6	1.3

TABLE C14. REACTOR II (UASB) CHARACTERISTICS FROM RUN 1C

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/03/90	6	31565	24970	23925	17870	6190	5585	9245	564	1506	573	1057	66	278	11.4
05/07/90	10	35125	27085	25750	20025	7405	6170	10150	637	1637	582	1254	69	304	12.1
05/10/90	13	41840	33155	31635	23400	7990	7770	11365	716	1729	597	1327	48	350	8.3
05/14/90	17	43720	35340	34020	26045	8910	8145	13580	679	1423	475	1473	48	363	8.8
05/17/90	20	40250	32140	28155	20580	8460	6230	11100	695	1792	586	1394	41	298	7.2
05/21/90	24	32015	25980	24260	18435	6975	5285	9620	723	1677	509	1165	49	274	8.6
05/24/90	27	39495	32535	30255	22470	8105	6750	12185	667	1353	451	1348	51	335	9.4
05/28/90	31	34270	28575	25945	20175	7370	5430	11630	757	1612	520	1246	67	314	10.9
05/31/90	34	40500	31400	27075	20830	7950	5145	11705	715	1566	497	1345	73	321	11.5
06/04/90	38	31535	26370	24405	18840	6485	5590	9490	656	1453	456	1088	50	296	8.8
06/07/90	41	40385	32045	29775	21935	8090	7065	11595	776	1740	606	1352	58	330	10.5
06/11/90	45	38695	32220	29770	21385	8665	7300	10255	638	1569	550	1455	68	331	7.6
06/14/90	48	37380	29435	27845	20860	6940	6220	10645	671	1335	482	1177	67	310	7.9
06/18/90	52	41135	31890	30040	22265	7925	7495	11680	695	1661	573	1328	60	348	10.8
	MEAN	37708	30224	28061	21080	7676	6441	11032	685	1575	533	1286	58	318	9.6
	STD	3941	3034	2911	2049	781	951	1148	52	139	53	123	10	26	1.6

TABLE C15. EFFLUENT II CHARACTERISTICS FROM RUN 1C

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/03/90	6	2616	1962	300	226	137	23	139	545	1407	510	88	66	14.5	10.7
05/07/90	10	2242	1716	268	214	128	21	134	633	1498	538	84	63	13.9	11.0
05/10/90	13	3120	2434	486	390	196	20	223	670	1690	580	82	51	13.3	8.1
05/14/90	17	2962	2280	398	298	189	22	186	694	1466	455	71	41	12.1	7.5
05/17/90	20	2700	2012	306	234	152	17	146	649	1629	554	68	44	10.4	7.4
05/21/90	24	3190	2408	378	290	188	17	184	672	1675	515	78	48	10.9	8.0
05/24/90	27	2584	1948	332	246	123	18	158	658	1385	424	73	54	11.9	7.9
05/28/90	31	2558	1996	336	270	108	17	165	772	1510	471	75	58	13.2	10.2
05/31/90	34	2354	1816	260	194	145	20	122	691	1601	528	94	70	11.7	9.6
06/04/90	38	2314	1770	238	182	111	16	116	646	1499	494	65	48	10.9	8.3
06/07/90	41	2672	1890	282	226	152	20	137	726	1661	561	84	59	12.8	9.1
06/11/90	45	3116	2430	416	308	178	19	193	605	1562	559	89	60	11.7	7.6
06/14/90	48	2946	2324	368	280	135	17	176	665	1258	468	85	64	9.8	7.3
06/18/90	52	2792	2178	310	234	145	22	144	689	1593	567	80	57	13.3	9.0
	MEAN	2726	2083	334	257	149	19	159	665	1531	516	80	56	12.2	8.7
	STD	297	245	66	52	28	2	29	51	120	46	8	8	1.3	1.2

TABLE C16. INFLUENT CHARACTERISTICS FROM RUN 1D

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
06/28/90	8	4285	3325	3795	3165	774	514	1940	79	467	150	142	18.2	23.1	12.5
07/02/90	12	3905	3140	3560	2870	647	476	2005	105	615	197	133	29.6	22.3	15.6
07/05/90	15	4195	3265	3985	3005	686	429	1955	89	352	97	129	19.3	18.9	9.3
07/09/90	19	4170	3090	3940	2840	667	442	1825	117	367	115	129	22.3	17.5	8.3
07/12/90	22	3995	2720	3590	2590	632	459	1680	102	396	130	128	26.4	18.8	8.0
07/16/90	26	3440	2670	3045	2515	524	431	1580	119	307	94	100	15.9	17.2	9.4
07/19/90	29	4130	3430	3920	3200	782	454	2065	123	385	129	146	21.1	20.7	11.8
07/23/90	33	4170	3335	3945	3025	641	480	2090	133	474	154	127	24.4	21.7	12.9
07/26/90	36	3825	2865	3540	2635	683	467	1650	82	453	128	135	25.5	18.0	10.0
07/30/90	40	4185	3130	3875	2880	688	502	1740	100	402	117	127	17.3	23.0	13.8
08/02/90	43	4090	3055	3805	2815	690	468	1855	121	386	118	127	16.2	18.4	11.1
08/06/90	47	4020	2960	3740	2755	721	482	1695	129	458	146	141	25.7	20.9	13.7
	MEAN	4034	3082	3728	2858	678	467	1840	108	422	131	130	21.8	20.0	11.4
	STD	219	232	254	207	65	25	164	17	76	27	11	4.3	2.1	2.3

TABLE C17. REACTOR I (CMR) CHARACTERISTICS FROM RUN 1D

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
06/28/90	8	15905	12120	11060	8890	1790	1070	6280	457	1127	400	349	62	101	8.7
07/02/90	12	13575	10075	8705	6815	1605	825	4900	548	1311	442	326	69	83	11.8
07/05/90	15	12880	9880	9560	7565	1420	935	5425	611	1161	389	300	72	90	12.5
07/09/90	19	13700	9970	8535	6750	1470	690	4900	504	1455	507	302	67	80	9.3
07/12/90	22	10990	8385	8755	6390	1285	885	4710	502	1290	405	263	58	79	8.0
07/16/90	26	15195	11125	10210	8515	1735	670	6240	584	1132	359	340	63	102	8.8
07/19/90	29	12170	9310	9225	7200	1610	770	5030	617	1200	441	336	78	89	10.9
07/23/90	33	14195	10785	11485	9355	1570	1005	6815	580	1466	544	319	68	114	12.6
07/26/90	36	17880	13720	12815	9885	1820	840	7245	615	1286	467	344	53	120	9.4
07/30/90	40	15015	11090	11380	8670	1595	695	6280	509	1093	416	303	47	87	7.5
08/02/90	43	11670	8630	8745	6955	1380	640	5240	523	1070	410	270	49	77	11.0
08/06/90	47	14405	10545	9730	7340	1505	715	5255	555	1174	460	296	55	84	11.4
	MEAN	13965	10486	10017	7861	1565	812	5693	550	1230	437	312	62	92	10.1
	STD	1841	1395	1323	1102	157	134	806	50	127	50	27	9	13	1.7

TABLE C18. EFFLUENT I CHARACTERISTICS FROM RUN 1D

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
06/28/90	8	2554	1974	578	456	250	30	331	464	1097	383	107	67	14.1	8.9
07/02/90	12	2408	1868	584	448	229	36	320	574	1350	421	110	74	16.6	12.4
07/05/90	15	3176	2376	808	654	344	43	431	618	1199	406	125	70	19.0	12.3
07/09/90	19	2686	1968	536	392	301	41	278	524	1369	481	109	61	12.8	8.7
07/12/90	22	2298	1814	490	388	279	28	283	490	1270	399	98	53	13.1	9.1
07/16/90	26	3274	2390	778	634	339	36	422	591	1136	353	125	71	15.5	8.2
07/19/90	29	2874	2192	734	564	315	25	399	627	1223	430	128	78	17.2	11.0
07/23/90	33	2778	2112	626	476	258	24	346	592	1443	493	114	73	16.6	12.1
07/26/90	36	2550	1980	522	380	236	37	269	621	1291	447	96	58	14.0	9.7
07/30/90	40	2582	1944	518	393	224	40	274	512	1149	397	90	54	11.8	8.8
08/02/90	43	2818	2116	688	532	301	29	365	567	1211	389	108	60	16.7	11.0
08/06/90	47	2490	2000	596	454	252	42	312	542	1169	390	105	65	15.5	11.8
	MEAN	2707	2061	622	481	277	34	336	560	1242	416	110	65	15.2	10.3
	STD	282	175	102	91	40	6	55	52	100	39	12	8	2.0	1.5

TABLE C19. REACTOR II (UASB) CHARACTERISTICS FROM RUN 1D

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
06/28/90	8	35470	27570	28855	22270	7945	5870	11705	546	1410	453	1352	81	328	11.2
07/02/90	12	38305	31010	31425	24035	8380	5550	12860	527	1498	527	1411	70	340	9.1
07/05/90	15	32145	24415	23335	16570	6225	4265	9655	700	1335	485	1056	60	271	8.0
07/09/90	19	31285	23605	23340	17435	6085	4160	10160	615	1400	481	1039	66	280	9.4
07/12/90	22	28645	21720	20815	15470	5500	3315	8650	504	1586	531	946	66	263	7.3
07/16/90	26	28080	20840	22650	16265	5660	4220	8290	592	1484	509	964	58	288	7.9
07/19/90	29	30885	23555	22710	16020	7080	3765	8655	693	1309	443	1201	68	295	9.8
07/23/90	33	28700	21660	22060	16830	7225	3980	9300	703	1600	572	1223	67	302	7.6
07/26/90	36	36710	28885	28900	20925	8315	4925	11110	641	1317	457	1383	52	317	10.7
07/30/90	40	31845	24410	25985	18740	6590	3970	10730	538	1418	512	1104	50	311	8.4
08/02/90	43	30930	25140	23950	17160	7740	4745	8625	619	1295	466	1294	56	293	10.3
08/06/90	47	28170	21950	23195	16465	6885	4330	8935	645	1222	399	1170	68	277	7.9
	MEAN	31764	24563	24768	18182	6969	4425	9890	610	1406	486	1178	63	297	9.0
	STD	3272	3011	3142	2638	948	703	1382	67	113	45	153	8	22	1.3

TABLE C20. EFFLUENT II CHARACTERISTICS FROM RUN 1D

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
06/28/90	8	2688	1962	320	246	150	14.5	133	552	1260	432	103	79	14.4	11.8
07/02/90	12	2328	1746	258	190	128	14.0	103	564	1563	510	91	70	11.7	10.0
07/05/90	15	2362	1784	280	206	126	13.6	115	678	1310	451	83	63	11.1	8.8
07/09/90	19	2770	2050	364	282	168	14.5	152	645	1252	452	96	70	11.6	9.0
07/12/90	22	2286	1692	252	186	118	13.7	104	480	1492	482	81	62	10.4	8.1
07/16/90	26	2602	1886	276	202	127	12.8	111	544	1574	522	79	58	9.8	7.4
07/19/90	29	2130	1598	228	174	100	11.4	97	714	1182	387	80	64	10.7	8.6
07/23/90	33	2890	2134	348	258	172	15.9	138	697	1510	576	91	64	12.9	9.2
07/26/90	36	2710	2006	304	224	154	14.1	121	651	1335	434	79	54	14.3	10.5
07/30/90	40	2452	1802	282	202	124	15.3	108	526	1526	544	66	46	11.8	8.1
08/02/90	43	2128	1638	256	190	112	16.8	97	597	1244	445	77	59	13.5	11.3
08/06/90	47	2364	1744	294	232	150	13.7	128	653	1217	430	92	68	12.3	9.7
	MEAN	2476	1837	289	216	136	14.2	117	608	1372	472	85	63	12.0	9.4
	STD	241	163	38	31	22	1.3	17	72	142	53	10	8	1.4	1.3

TABLE C21. INFLUENT CHARACTERISTICS FROM RUN 2A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
09/06/90	8	3925	3045	3610	2840	645	540	1615	106	434	128	119	15.4	15.7	6.8
09/10/90	12	3975	2980	3590	2725	592	564	1630	132	489	140	113	18.3	17.9	8.3
09/13/90	15	3800	2940	3365	2745	546	542	1680	89	425	118	109	21.8	14.8	10.4
09/17/90	19	3960	3035	3640	2840	596	574	1710	103	537	162	123	27.2	14.7	10.0
09/20/90	22	4380	3380	4055	3180	597	569	2020	116	560	164	124	28.9	18.4	11.8
09/24/90	26	4605	3555	4330	3405	679	580	2155	127	587	191	135	26.0	17.0	10.0
09/27/90	29	4320	3400	3920	3065	613	447	2135	134	590	201	123	25.3	15.1	9.5
10/01/90	33	4295	3130	3945	2920	623	553	1780	113	402	119	125	25.1	19.3	10.5
10/04/90	36	3605	2635	3440	2450	611	509	1340	136	373	104	127	28.8	16.9	8.3
10/09/90	41	4675	3680	4420	3340	754	579	2065	128	426	121	146	25.1	23.8	14.4
10/11/90	43	4105	3040	3870	2845	716	464	1645	150	530	136	128	13.4	19.3	11.5
10/15/90	47	3955	2965	3745	2755	630	555	1690	93	447	113	127	26.2	17.0	10.7
10/18/90	50	4045	3035	3800	2790	630	572	1525	120	331	94	129	27.7	17.0	9.3
10/22/90	54	4130	3010	3835	2805	663	591	1530	116	319	87	127	20.6	20.2	12.8
	MEAN	4127	3131	3826	2908	635	546	1751	119	461	134	125	23.6	17.7	10.3
	STD	289	267	292	248	52	42	240	17	87	33	8	4.8	2.4	1.9

TABLE C22. REACTOR I (CMR) CHARACTERISTICS FROM RUN 2A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
09/06/90	8	15275	11610	9505	7715	2600	1160	5755	550	1180	387	477	61	86	7.4
09/10/90	12	13565	10255	8365	6900	2335	1285	5035	659	1455	502	428	55	77	7.9
09/13/90	15	16440	12440	11190	8335	2670	1090	6170	695	1308	485	479	52	94	8.8
09/17/90	19	20685	15420	13535	10780	2920	1835	7380	687	1583	590	545	78	121	9.7
09/20/90	22	17915	13615	12050	9365	2665	1640	6490	703	1531	527	493	67	107	8.0
09/24/90	26	17285	12775	11080	8550	3000	1375	6335	720	1483	532	549	69	93	10.3
09/27/90	29	17440	13550	12405	10080	2795	1590	7130	684	1389	457	511	64	129	7.6
10/01/90	33	22130	16440	14345	11350	3160	1695	8205	743	1274	451	571	65	137	10.9
10/04/90	36	16480	12505	11670	9405	2610	1440	6700	654	1502	546	484	66	101	9.3
10/09/90	41	14425	10715	9980	7995	2395	1290	5875	676	1352	440	449	65	78	8.1
10/11/90	43	20815	16080	13475	10410	2935	1790	7215	726	1450	550	514	44	116	7.7
10/15/90	47	18935	13865	11760	9255	3120	1595	6605	802	1286	496	563	64	100	11.2
10/18/90	50	16980	11985	10030	8265	2560	1410	5805	677	1191	441	479	69	86	9.3
10/22/90	54	21205	15640	12955	10005	2875	1710	7015	711	1302	509	519	59	122	8.4
	MEAN	17827	13350	11596	9172	2760	1493	6551	692	1378	494	504	63	103	8.9
	STD	2527	1893	1645	1226	245	226	783	54	122	52	41	8	18	1.2

TABLE C23. EFFLUENT I CHARACTERISTICS FROM RUN 2A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
09/06/90	8	2698	2052	648	494	182	28	368	518	1229	395	100	71	12.1	6.9
09/10/90	12	3144	2376	972	788	231	44	523	609	1469	518	94	57	15.4	8.3
09/13/90	15	3552	2728	990	812	162	43	537	656	1404	454	87	61	16.1	7.8
09/17/90	19	3904	3014	1056	840	260	47	544	689	1542	549	114	72	17.8	9.5
09/20/90	22	3502	2566	874	700	219	41	475	707	1488	500	102	67	15.4	8.2
09/24/90	26	3352	2470	878	668	243	36	461	760	1592	543	112	74	16.7	10.6
09/27/90	29	3742	2732	846	668	295	32	450	724	1287	440	110	62	13.2	7.1
10/01/90	33	3036	2318	740	592	318	34	404	707	1277	445	115	64	16.0	10.3
10/04/90	36	2856	2186	680	524	243	35	378	631	1469	540	110	71	13.6	8.0
10/09/90	41	3890	2980	1008	776	211	42	510	715	1460	480	103	69	15.9	8.6
10/11/90	43	3784	2774	987	780	207	47	496	694	1337	483	82	49	14.7	7.2
10/15/90	47	3288	2400	788	606	248	41	391	781	1318	501	115	75	16.3	10.7
10/18/90	50	3098	2312	708	544	178	29	390	675	1173	454	103	75	13.1	8.4
10/22/90	54	3534	2608	962	780	215	43	512	702	1403	514	103	69	14.2	6.6
	MEAN	3384	2537	867	684	229	39	460	683	1389	487	104	67	15.0	8.4
	STD	368	276	130	112	42	6	61	63	118	44	10	7	1.6	1.3

TABLE C24. REACTOR II (UASB) CHARACTERISTICS FROM RUN 2A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
09/06/90	8	41140	30545	27400	19575	7850	7190	9335	542	1349	476	1330	74	324	8.2
09/10/90	12	43540	32640	29835	22705	9145	9015	9725	619	1599	587	1534	71	366	10.4
09/13/90	15	38635	27220	22605	16565	7580	5765	8670	697	1572	564	1271	58	307	9.3
09/17/90	19	47325	36405	33825	24705	10425	9665	10805	749	1735	585	1733	65	380	10.5
09/20/90	22	47740	36165	31375	23455	10650	8925	11005	854	1692	590	1768	64	368	10.5
09/24/90	26	48755	37030	32390	24095	10205	8040	12510	820	1707	607	1697	64	387	7.8
09/27/90	29	44920	33220	27685	20000	8955	7400	9400	687	1541	511	1489	57	339	8.7
10/01/90	33	40945	29975	25535	19340	7615	6595	9760	785	1435	478	1279	61	326	9.9
10/04/90	36	46440	33810	28990	20555	8650	6285	10655	721	1441	497	1446	62	343	7.3
10/09/90	41	49705	36300	32845	23495	10130	8340	11420	796	1536	546	1691	70	374	9.0
10/11/90	43	39850	28885	25245	18880	7845	7670	8205	745	1682	602	1301	46	313	11.7
10/15/90	47	44865	33970	27600	19720	10025	6835	10025	867	1427	512	1668	64	338	10.3
10/18/90	50	49245	37175	32590	23150	10920	6495	12665	698	1374	477	1819	72	382	8.8
10/22/90	54	43870	32495	28870	20820	8690	7700	10160	793	1636	581	1452	62	364	11.6
	MEAN	44784	33274	29056	21219	9192	7566	10310	741	1552	544	1534	64	351	9.6
	STD	3489	3078	3185	2303	1151	1098	1257	86	125	48	187	7	26	1.3

TABLE C25. EFFLUENT II CHARACTERISTICS FROM RUN 2A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
09/06/90	8	2800	2126	358	300	148	22	173	548	1368	471	92	68	10.8	7.9
09/10/90	12	3036	2262	372	284	132	26	162	633	1516	522	87	66	11.3	8.1
09/13/90	15	2670	1984	320	272	154	27	151	685	1534	553	85	60	12.4	9.5
09/17/90	19	3438	2682	574	480	214	23	256	729	1563	556	91	56	14.6	9.1
09/20/90	22	3662	2736	612	504	210	18	263	800	1663	593	98	64	14.5	8.3
09/24/90	26	2928	2220	356	280	139	19	166	797	1594	564	78	56	9.7	6.7
09/27/90	29	3116	2306	358	276	147	28	155	662	1469	461	74	50	10.9	8.3
10/01/90	33	3120	2404	380	316	175	31	172	739	1410	469	80	52	11.5	8.0
10/04/90	36	2538	1890	296	244	148	19	145	744	1469	464	88	64	9.9	6.9
10/09/90	41	3472	2642	400	328	183	32	177	731	1412	515	86	57	10.8	7.4
10/11/90	43	3294	2454	358	302	139	22	173	787	1604	584	63	41	13.6	10.2
10/15/90	47	3542	2710	494	400	178	27	220	846	1416	530	89	61	12.8	7.9
10/18/90	50	3418	2598	440	364	132	27	196	680	1319	462	92	71	10.6	6.3
10/22/90	54	3016	2360	394	314	143	29	181	765	1617	588	82	59	12.5	8.0
	MEAN	3146	2384	408	333	160	25	185	725	1497	524	85	59	11.9	8.0
	STD	328	261	89	75	26	4	35	75	100	49	8	8	1.5	1.0

TABLE C26. INFLUENT CHARACTERISTICS FROM RUN 2B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
10/29/90	6	3845	2965	3425	2580	603	515	1615	74	330	94	115	18.2	19.2	11.0
11/01/90	9	3810	2790	3515	2565	612	484	1580	80	322	88	122	24.0	19.4	10.5
11/05/90	13	4035	2740	3560	2600	610	525	1415	98	421	139	123	25.8	19.8	9.3
11/08/90	16	3710	2680	2930	2145	563	479	1530	108	453	126	109	19.4	20.4	11.5
11/12/90	20	3995	2815	3370	2460	664	528	1395	117	401	109	121	14.3	15.6	7.5
11/15/90	23	4575	3470	4065	3035	557	549	1950	46	265	73	103	14.1	18.8	7.8
11/19/90	27	3635	2620	3130	2210	494	418	1605	76	344	97	95	16.4	18.9	10.7
11/22/90	30	3710	2440	3110	2035	566	444	1315	75	272	75	108	17.3	18.9	11.1
11/26/90	34	3510	2330	3150	2160	516	491	1180	65	393	108	98	15.0	18.6	9.3
11/29/90	37	4150	2890	3560	2545	652	608	1540	55	280	80	122	17.5	22.8	12.6
12/03/90	41	4195	2890	3510	2565	648	583	1485	87	375	103	119	15.2	18.5	10.4
12/06/90	44	4025	3015	3505	2655	629	535	1630	69	334	99	115	14.8	16.1	8.0
12/10/90	48	3730	2855	3280	2490	583	488	1625	83	359	104	112	18.7	18.3	9.1
12/13/90	51	3800	2925	3345	2575	618	532	1570	91	401	116	120	21.0	17.5	6.9
12/17/90	55	3695	2700	3250	2380	563	503	1545	98	419	121	111	21.3	16.6	7.5
	MEAN	3895	2808	3380	2467	592	512	1532	81	358	102	113	18.2	18.6	9.5
	STD	263	254	259	243	48	47	166	19	56	18	9	3.4	1.7	1.7

TABLE C27. REACTOR I (CMR) CHARACTERISTICS FROM RUN 2B

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
10/29/90	6	18950	14335	12100	9415	3255	1610	7190	530	1411	502	587	66	155	10.7
11/01/90	9	23595	18200	15515	11005	3940	1965	7780	587	1126	420	686	55	198	7.4
11/05/90	13	20780	15425	13685	9780	3380	1770	7400	667	1299	450	610	69	169	9.6
11/08/90	16	22565	16935	13590	9840	4015	2125	7665	721	1217	440	693	50	184	10.1
11/12/90	20	17475	12880	11875	8590	3090	1550	6390	703	1111	411	536	42	157	8.2
11/15/90	23	22230	16890	14280	10925	3880	2220	7825	762	967	345	659	39	200	6.2
11/19/90	27	24975	18900	15225	11525	4445	2335	8340	556	1310	474	763	52	209	6.1
11/22/90	30	24535	19015	15620	12170	4515	2475	8670	649	1137	434	787	64	224	10.0
11/26/90	34	22440	16660	14180	10580	3660	2000	7685	714	1215	422	642	56	188	8.4
11/29/90	37	17990	14075	12210	9325	3470	1880	6420	646	1338	487	620	65	164	8.0
12/03/90	41	17890	13345	11480	8870	3150	1920	6240	738	1368	480	552	48	157	7.2
12/06/90	44	19375	14750	12520	9055	3235	2215	6250	745	1400	505	585	67	162	9.8
12/10/90	48	22650	16975	14065	10340	3960	2375	7085	652	1330	467	695	62	190	6.7
12/13/90	51	19630	14600	12170	9220	3280	2310	5995	698	1468	548	584	59	158	7.7
12/17/90	55	21855	16680	13420	9845	3875	1920	7530	743	1386	532	670	50	166	9.0
	MEAN	21129	15978	13462	10032	3677	2045	7231	674	1272	461	645	56	179	8.3
	STD	2369	1879	1317	1000	441	270	789	69	134	50	70	9	21	1.4

TABLE C28. EFFLUENT I CHARACTERISTICS FROM RUN 2B

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
10/29/90	6	3526	2604	988	748	234	66	496	560	1318	496	110	73	18.3	10.2
11/01/90	9	2996	2232	756	542	200	42	391	628	1127	455	93	61	14.3	7.3
11/05/90	13	3832	2882	1046	806	251	68	518	715	1228	461	102	62	17.9	8.3
11/08/90	16	3408	2488	910	684	177	56	474	673	1146	425	87	59	17.4	9.0
11/12/90	20	3112	2210	818	618	166	50	422	694	1096	435	75	49	14.8	7.8
11/15/90	23	3428	2578	964	702	134	44	481	718	1008	369	61	40	15.6	7.0
11/19/90	27	2840	2016	686	520	230	36	382	571	1225	461	85	49	13.0	6.2
11/22/90	30	3018	2120	710	554	199	39	397	638	1208	444	96	64	14.9	8.3
11/26/90	34	3060	2296	758	600	147	47	412	739	1156	431	83	59	14.7	7.4
11/29/90	37	3536	2564	962	724	177	52	495	672	1242	481	97	69	17.8	8.2
12/03/90	41	2970	2208	736	552	172	35	395	724	1273	487	76	48	14.3	7.3
12/06/90	44	3028	2180	710	538	159	41	388	748	1324	500	96	71	16.2	9.0
12/10/90	48	3616	2662	920	720	229	57	483	686	1266	485	105	68	15.8	6.4
12/13/90	51	2902	2110	776	604	213	48	430	751	1441	550	93	59	14.1	6.8
12/17/90	55	3134	2204	732	572	174	43	394	783	1451	511	84	56	16.2	8.3
	MEAN	3227	2357	831	632	191	48	437	687	1234	466	90	59	15.7	7.8
	STD	292	244	116	88	34	10	47	63	117	42	12	9	1.5	1.0

TABLE C29. REACTOR II (UASB) CHARACTERISTICS FROM RUN 2B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
10/29/90	6	48135	34480	31915	24495	9825	10885	11875	585	1492	495	1636	64	502	8.9
11/01/90	9	51065	37095	33740	25540	11940	11205	12815	663	1236	455	1964	54	526	7.3
11/05/90	13	40270	28080	24685	18800	8705	8600	9440	696	1362	489	1444	51	394	10.1
11/08/90	16	47055	34600	30945	23005	10190	10080	11250	709	1611	613	1695	65	468	6.7
11/12/90	20	44435	32535	27520	20485	9385	9285	9825	780	1472	561	1550	48	437	9.0
11/15/90	23	50290	37550	32455	24715	10975	11195	11205	821	1300	461	1801	45	484	7.8
11/19/90	27	51895	39145	33370	25300	11625	10100	13075	600	1178	388	1922	62	510	6.1
11/22/90	30	42550	30070	26970	21490	8900	9675	10630	673	1374	519	1493	69	432	7.5
11/26/90	34	44960	31965	27495	22020	8985	9860	11140	752	1453	580	1492	54	457	9.0
11/29/90	37	40945	28600	24975	19755	8395	8945	9660	704	1210	426	1391	48	404	10.2
12/03/90	41	38725	27815	23285	18995	8510	8860	9185	737	1451	539	1433	71	422	7.6
12/06/90	44	41310	30010	25325	20180	9060	9945	10260	776	1444	536	1516	67	441	11.0
12/10/90	48	46920	34420	29080	23700	9765	10190	12105	699	1517	544	1615	52	463	7.3
12/13/90	51	50360	36400	30865	25030	10425	11075	12410	768	1678	559	1716	48	507	6.5
12/17/90	55	46315	32595	27660	22595	9040	9205	10770	805	1592	529	1507	60	445	8.6
	MEAN	45682	33024	28686	22407	9715	9940	11043	718	1425	513	1612	57	459	8.2
	STD	4096	3493	3257	2282	1075	835	1192	67	143	59	170	8	39	1.4

TABLE C30. EFFLUENT II CHARACTERISTICS FROM RUN 2B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
10/29/90	6	3298	2384	506	392	154	44	232	575	1411	504	92	67	14.1	7.9
11/01/90	9	3576	2642	608	484	132	48	281	686	1287	421	71	50	13.9	5.4
11/05/90	13	2792	2150	430	348	168	36	211	702	1403	483	79	52	13.6	9.5
11/08/90	16	2800	2072	378	308	120	33	189	732	1507	551	88	68	11.0	6.2
11/12/90	20	3440	2494	526	432	114	50	249	773	1333	523	64	46	14.5	7.4
11/15/90	23	2720	2054	368	276	171	28	173	803	1212	445	83	56	11.1	6.7
11/19/90	27	2664	1958	366	266	125	29	165	601	1155	415	87	67	10.4	5.5
11/22/90	30	3066	2208	420	344	143	34	206	623	1421	524	88	65	11.2	6.0
11/26/90	34	2956	2276	456	360	96	37	216	729	1327	509	72	56	15.4	9.4
11/29/90	37	3578	2612	524	408	154	42	233	681	1251	475	70	45	12.7	6.8
12/03/90	41	3212	2404	414	336	114	44	200	756	1509	530	89	70	12.2	7.4
12/06/90	44	2838	2176	422	324	160	46	192	784	1459	510	94	68	15.5	10.1
12/10/90	48	2904	2077	460	350	149	36	211	710	1392	486	82	58	11.2	6.5
12/13/90	51	3040	2204	504	414	141	42	247	727	1590	575	67	44	11.9	5.1
12/17/90	55	3132	2294	504	398	130	37	246	759	1597	539	79	59	13.9	7.3
	MEAN	3068	2267	459	363	138	39	217	709	1390	499	80	58	12.8	7.1
	STD	290	198	67	57	21	6	30	65	127	44	9	9	1.6	1.5

TABLE C31. INFLUENT CHARACTERISTICS FROM RUN 2C

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/20/90	3	3810	2630	3490	2200	595	454	1535	87	339	91	119	24.2	13.7	6.4
12/24/90	7	4150	2890	3600	2485	564	514	1525	105	390	106	109	18.8	16.6	7.7
12/27/90	10	4195	3055	3685	2655	648	457	1795	117	412	121	125	21.4	18.5	9.3
12/31/90	14	3970	2845	3660	2420	550	500	1620	108	491	141	112	23.9	15.9	7.1
01/03/91	17	4365	3200	4005	2775	605	506	1885	122	417	119	119	22.2	20.1	10.6
01/06/91	20	4200	3285	3905	2865	592	487	2045	96	428	126	113	18.6	16.4	9.4
01/09/91	23	4075	3155	3830	2835	565	438	1990	120	463	144	110	19.6	18.7	10.1
01/12/91	26	4225	3310	3945	2805	619	506	1970	101	475	141	124	25.0	20.3	9.7
01/14/91	28	3980	2740	3560	2420	556	452	1585	120	369	100	107	17.9	15.9	6.9
	MEAN	4108	3012	3742	2607	588	479	1772	108	420	121	115	21.3	17.3	8.6
	STD	157	232	174	221	31	27	197	12	47	18	6	2.5	2.1	1.5

TABLE C32. REACTOR I (CMR) CHARACTERISTICS FROM RUN 2C

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/20/90	3	13515	10130	8805	6910	2760	885	4855	345	1090	365	501	60	76	9.5
12/24/90	7	11015	8005	6935	5375	2105	654	4015	279	919	300	378	41	63	7.4
12/27/90	10	11150	8030	6955	5125	2000	601	3880	247	884	295	366	46	56	7.4
12/31/90	14	9615	6960	5050	3920	1415	526	2760	274	798	245	269	42	46	8.9
01/03/91	17	9640	7135	5775	4535	1610	609	3380	194	780	257	295	37	52	6.3
01/06/91	20	9145	6615	5340	4170	1550	517	3015	173	842	251	295	47	41	5.5
01/09/91	23	10435	7630	6190	4710	1805	622	3550	228	905	306	320	32	55	9.6
01/12/91	26	9775	6995	5860	4565	2040	651	3255	252	835	266	361	35	57	8.2
01/14/91	28	11510	8570	7025	5360	1845	603	3990	198	954	320	345	50	67	7.8
	MEAN	10644	7786	6437	4963	1903	630	3633	243	890	289	348	43	57	7.8
	STD	1269	1019	1076	834	375	101	595	50	89	37	65	8	10	1.3

TABLE C33. EFFLUENT I CHARACTERISTICS FROM RUN 2C

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/20/90	3	3616	2622	1102	810	299	50	586	327	1100	365	113	65	15.8	8.3
12/24/90	7	2978	2096	796	552	229	34	436	247	955	302	77	41	11.6	6.3
12/27/90	10	3548	2524	1084	780	216	45	581	260	845	256	82	47	16.3	9.0
12/31/90	14	3000	2190	844	586	207	39	455	261	901	297	83	50	13.6	8.2
01/03/91	17	3516	2604	1040	744	301	51	565	203	808	249	89	41	13.3	6.6
01/06/91	20	3274	2358	962	668	270	40	517	169	927	300	99	56	12.1	5.8
01/09/91	23	3062	2120	868	612	231	38	487	217	880	277	79	42	15.5	10.2
01/12/91	26	3556	2588	1076	706	263	47	544	248	972	318	80	38	13.5	7.0
01/14/91	28	3012	2132	838	652	236	37	492	195	874	280	91	53	12.4	7.3
	MEAN	3285	2359	957	679	250	42	518	236	918	294	88	48	13.8	7.6
	STD	259	215	115	83	33	6	51	44	81	33	11	8	1.6	1.3

TABLE C34. REACTOR II (UASB) CHARACTERISTICS FROM RUN 2C

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/20/90	3	33700	24670	22925	16990	5840	3985	10135	355	1263	402	993	58	221	10.1
12/24/90	7	27865	20705	18660	13570	4820	3200	8725	334	1045	361	812	41	187	8.7
12/27/90	10	27270	19360	16730	12175	4375	2830	7840	286	940	305	746	46	172	6.6
12/31/90	14	29105	21020	18510	13220	5105	2685	8800	290	992	315	852	35	184	7.3
01/03/91	17	24505	17640	15375	11515	4255	2775	7335	253	891	284	722	41	163	5.2
01/06/91	20	29510	21635	20565	14745	5010	3265	9640	259	1058	346	854	53	192	9.0
01/09/91	23	26155	19605	19595	13900	4525	3170	8595	247	985	299	768	44	175	5.0
01/12/91	26	29710	21320	19870	14815	5105	3335	9080	308	1114	351	851	34	204	6.3
01/14/91	28	26885	20005	17955	12660	4560	2930	8385	261	1022	320	778	48	169	7.8
	MEAN	28301	20662	18909	13732	4844	3131	8726	288	1034	331	820	44	185	7.3
	STD	2484	1824	2072	1550	460	373	803	36	102	35	76	7	17	1.6

TABLE C35. EFFLUENT II CHARACTERISTICS FROM RUN 2C

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
12/20/90	3	3144	2326	488	342	176	32	161	342	1175	380	87	59	13.4	9.6
12/24/90	7	2948	2078	380	256	155	26	137	310	939	298	74	49	10.8	8.2
12/27/90	10	2442	1710	296	196	160	20	106	274	1040	327	71	45	9.7	7.0
12/31/90	14	3086	2132	490	338	136	35	160	263	974	319	65	43	11.3	7.4
01/03/91	17	2824	1954	432	304	131	31	146	237	912	290	68	47	9.5	5.9
01/06/91	20	2448	1762	388	260	180	28	125	235	1101	373	84	55	11.5	8.2
01/09/91	23	2690	1950	302	202	149	33	102	240	942	298	71	48	9.4	7.1
01/12/91	26	2492	1768	344	212	133	34	119	298	1066	348	61	40	8.9	6.0
01/14/91	28	3100	2204	440	326	174	25	151	225	963	312	84	56	10.5	6.6
	MEAN	2797	1987	396	271	155	29	134	269	1012	327	74	49	10.6	7.3
	STD	273	203	69	56	18	5	21	38	83	31	9	6	1.3	1.1

TABLE C36. INFLUENT CHARACTERISTICS FROM RUN 3A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
01/21/91	7	4050	2990	3475	2715	627	514	1715	83	420	122	116	15.3	17.4	9.9
01/24/91	10	3380	2340	2850	2115	541	483	1300	92	324	108	110	23.9	15.9	9.2
01/28/91	14	3885	2565	3390	2420	546	530	1350	109	439	118	106	18.5	18.3	12.0
01/31/91	17	3790	2710	3150	2305	639	520	1415	115	396	110	121	19.2	16.7	10.5
02/04/91	21	4610	3320	4170	2845	622	559	2005	87	506	152	121	21.4	19.4	10.9
02/07/91	24	4085	2925	3490	2650	684	465	1580	89	355	104	125	15.3	16.7	8.1
02/11/91	28	4055	2860	3615	2555	667	491	1500	114	412	129	124	16.8	17.8	10.7
02/14/91	31	3795	2755	3305	2525	590	516	1495	121	477	137	118	23.2	14.4	6.7
02/18/91	35	4130	3170	3645	2885	699	533	1785	74	511	160	131	18.7	18.2	10.8
02/21/91	38	4020	3095	3510	2780	673	520	1790	87	423	132	124	16.0	19.7	11.4
	MEAN	3980	2873	3460	2580	629	513	1594	97	426	127	119	18.8	17.5	10.0
	STD	297	278	326	234	53	26	213	15	57	18	7	3.0	1.5	1.5

TABLE C37. REACTOR I (CMR) CHARACTERISTICS FROM RUN 3A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
01/21/91	7	16320	11710	10525	7660	1645	865	5935	548	1188	391	307	44	89	5.8
01/24/91	10	19160	13915	12160	9340	1840	970	7050	594	1331	416	349	55	108	7.8
01/28/91	14	22560	15765	14635	10905	2120	1090	8245	633	1435	485	389	50	134	9.2
01/31/91	17	21705	15440	15335	11835	2065	1255	8650	677	1493	505	398	68	137	10.3
02/04/91	21	19555	13620	12170	9230	1800	910	7240	576	1595	534	326	38	111	7.1
02/07/91	24	16485	11880	10945	8490	1625	860	6325	609	1392	473	304	44	98	6.4
02/11/91	28	23745	17260	14700	10820	2200	1105	8205	648	1306	433	410	58	121	5.4
02/14/91	31	22945	16220	13505	10475	2065	950	8240	567	1423	490	386	56	126	5.7
02/18/91	35	19955	14885	12040	8760	1780	920	6345	531	1372	479	328	44	95	8.7
02/21/91	38	22650	15835	14485	11305	1930	1285	8475	581	1246	421	358	49	132	9.0
	MEAN	20508	14653	13050	9882	1907	1021	7471	596	1378	463	356	51	115	7.5
	STD	2518	1747	1616	1303	190	147	964	43	113	43	37	8	16	1.6

TABLE C38. EFFLUENT I CHARACTERISTICS FROM RUN 3A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
01/21/91	7	2576	1880	516	412	298	56	281	524	1153	393	99	51	13.8	9.2
01/24/91	10	2936	2176	596	468	323	70	309	559	1284	434	107	56	12.6	7.5
01/28/91	14	2656	1944	464	328	250	53	211	638	1400	490	88	48	14.1	10.3
01/31/91	17	3388	2438	716	556	235	76	374	655	1322	462	103	65	15.9	9.8
02/04/91	21	2836	2014	494	392	211	54	272	581	1639	579	80	47	12.2	7.8
02/07/91	24	3302	2410	754	608	268	80	397	569	1286	453	92	49	13.5	6.8
02/11/91	28	3110	2178	696	510	307	64	357	628	1301	493	102	53	12.4	7.5
02/14/91	31	2692	1992	568	406	329	56	274	536	1527	547	113	60	10.2	5.9
02/18/91	35	2584	1804	492	352	268	50	244	508	1317	485	93	50	11.8	9.2
02/21/91	38	2792	2080	530	380	293	55	268	602	1238	446	104	57	14.7	10.8
	MEAN	2887	2092	583	441	278	61	299	580	1347	478	98	54	13.1	8.5
	STD	277	200	99	87	37	10	57	48	135	51	9	6	1.5	1.5

TABLE C39. REACTOR II (UASB) CHARACTERISTICS FROM RUN 3A

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
01/21/91	7	30935	23100	20620	15770	7130	5750	8860	550	1279	426	1201	60	226	6.8
01/24/91	10	33260	23970	21435	17330	7265	5935	9315	612	1394	467	1217	55	257	9.7
01/28/91	14	36380	26755	24775	19605	8050	6560	10300	603	1604	550	1353	65	280	8.7
01/31/91	17	39715	29315	24790	18765	8750	6075	10240	662	1556	522	1448	48	265	7.6
02/04/91	21	40660	30345	27310	21920	9015	7135	11495	715	1697	569	1489	47	297	10.4
02/07/91	24	36975	27880	25120	19055	8025	6310	10450	629	1410	508	1341	57	261	8.3
02/11/91	28	42605	31030	28505	22285	9120	7020	11475	598	1326	467	1504	45	308	6.3
02/14/91	31	34450	24660	22465	17155	7480	5935	9335	686	1433	541	1239	42	242	7.0
02/18/91	35	33500	24375	21630	16520	7245	5680	9190	607	1590	591	1219	60	245	11.1
02/21/91	38	40745	29150	24820	20010	8085	6220	10805	572	1547	574	1350	56	281	9.0
	MEAN	36923	27058	24147	18842	8017	6262	10147	623	1484	522	1336	53	266	8.5
	STD	3689	2738	2453	2081	707	477	898	48	128	51	110	7	24	1.5

TABLE C40. EFFLUENT II CHARACTERISTICS FROM RUN 3A

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
01/21/91	7	2284	1606	258	184	137	19.3	108	544	1223	397	80	58	9.1	7.2
01/24/91	10	2862	1844	382	288	150	28.1	166	557	1322	417	80	56	12.4	9.3
01/28/91	14	2198	1538	294	236	104	24.8	129	626	1428	485	83	67	9.6	7.0
01/31/91	17	3026	2224	356	268	134	22.6	163	692	1511	507	70	49	10.7	7.8
02/04/91	21	2590	1890	388	288	112	27.0	183	686	1579	518	64	46	12.1	9.2
02/07/91	24	3170	2346	406	308	110	17.7	198	677	1524	539	67	49	10.2	7.0
02/11/91	28	3056	2170	334	260	117	19.8	156	628	1262	434	61	42	8.8	6.1
02/14/91	31	2830	2008	418	322	160	16.9	205	691	1485	533	64	39	9.0	5.8
02/18/91	35	2564	1794	400	302	122	17.4	191	584	1553	551	73	53	13.4	10.2
02/21/91	38	3005	2060	348	276	138	20.2	162	619	1390	502	72	50	10.3	6.8
	MEAN	2759	1948	358	273	128	21.4	166	630	1428	488	71	51	10.6	7.6
	STD	318	250	49	38	17	3.8	29	53	118	51	7	8	1.5	1.4

TABLE C41. INFLUENT CHARACTERISTICS FROM RUN 3B

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
02/28/91	6	3630	2960	3065	2470	553	450	1790	36	460	134	96	7.3	11.9	4.9
03/04/91	10	3960	2925	3485	2805	497	455	1835	43	359	91	90	10.2	12.4	6.5
03/07/91	13	4340	3585	3870	3310	608	434	2325	53	447	120	109	11.4	15.7	8.6
03/11/91	17	4160	3540	3650	3140	530	471	2360	32	476	130	91	5.8	14.0	6.5
03/14/91	20	3800	3180	3295	2880	508	468	2055	67	383	103	88	7.0	13.8	7.3
03/18/91	24	4270	3570	3750	3120	569	525	2300	53	513	153	96	5.2	10.2	6.8
03/21/91	27	4195	3365	3725	3005	611	537	2085	40	480	146	107	9.2	13.6	8.0
03/25/91	31	4150	3395	3675	3085	592	490	2195	44	398	115	102	7.7	13.9	7.1
03/28/91	34	3885	3075	3410	2820	535	492	2010	55	522	153	91	5.3	10.9	5.7
04/01/91	38	4025	3380	3495	3045	564	523	2095	29	417	120	98	8.1	11.7	6.9
04/04/91	41	3940	3155	3505	2835	577	502	1950	37	445	138	102	10.0	16.2	8.5
	MEAN	4032	3285	3539	2956	559	486	2091	44	445	128	97	7.9	13.1	7.0
	STD	204	228	219	216	36	32	182	11	50	19	7	2.0	1.8	1.1

TABLE C42. REACTOR I (CMR) CHARACTERISTICS FROM RUN 3B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
02/28/91	6	16620	12935	10330	8560	1515	945	6620	388	1311	444	294	52	77	7.0
03/04/91	10	17815	14480	12490	10245	1720	1090	7825	462	1249	424	314	38	93	5.2
03/07/91	13	19185	15610	11775	9545	1800	965	7500	477	1337	480	331	43	82	5.1
03/11/91	17	22255	17725	14330	11335	1995	1205	8855	542	1588	536	349	30	103	5.9
03/14/91	20	20500	16020	13715	10535	1950	1100	8260	512	1394	493	339	27	97	5.6
03/18/91	24	18525	14835	11500	8840	1560	1025	6870	583	1742	601	289	40	76	4.2
03/21/91	27	22310	18130	15110	12120	2080	1270	9415	592	1615	534	366	34	114	6.9
03/25/91	31	19640	15975	13425	10235	1865	1140	7930	488	1485	503	339	40	91	4.4
03/28/91	34	17060	13870	12100	9310	1735	995	7095	451	1559	516	327	50	81	7.3
04/01/91	38	22815	18055	14720	11315	2030	1165	8610	483	1273	435	362	37	105	5.0
04/04/91	41	19310	16340	14335	10950	1765	1090	8490	515	1326	447	330	48	96	4.3
	MEAN	19640	15816	13075	10272	1820	1090	7952	499	1444	492	331	40	92	5.5
	STD	2033	1630	1463	1070	176	97	835	56	156	51	23	8	12	1.1

TABLE C43. EFFLUENT I CHARACTERISTICS FROM RUN 3B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
02/28/91	6	2798	2054	624	500	252	68	337	401	1169	409	97	56	9.7	6.4
03/04/91	10	3246	2542	844	692	208	85	459	447	1232	412	84	51	10.8	4.8
03/07/91	13	3446	2726	930	764	281	96	499	478	1303	448	88	43	11.3	5.2
03/11/91	17	3012	2320	628	492	230	67	335	566	1474	506	71	35	9.0	5.6
03/14/91	20	2886	2228	682	546	196	74	366	514	1286	455	60	28	9.7	5.2
03/18/91	24	3020	2416	718	572	244	79	390	594	1687	548	84	45	9.5	4.4
03/21/91	27	2654	2134	588	474	187	73	319	597	1390	446	78	48	9.4	6.2
03/25/91	31	3152	2458	680	560	261	93	358	481	1466	481	77	35	9.1	4.7
03/28/91	34	3316	2680	756	608	275	93	404	463	1527	499	97	53	12.0	7.0
04/01/91	38	2932	2342	744	612	229	98	403	478	1191	422	76	40	11.0	4.9
04/04/91	41	2732	2090	640	520	204	72	342	526	1328	438	87	54	8.5	4.3
	MEAN	3018	2363	712	576	233	82	383	504	1368	460	82	44	10.0	5.3
	STD	239	217	98	85	31	11	53	59	151	42	10	9	1.1	0.8

TABLE C44. REACTOR II (UASB) CHARACTERISTICS FROM RUN 3B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
02/28/91	6	36870	28780	25370	21015	6865	6020	10685	474	1429	465	1140	41	231	6.6
03/04/91	10	40990	32215	27645	23465	8460	7255	11160	489	1447	486	1406	52	260	5.8
03/07/91	13	35885	29040	25730	22005	7330	6635	11145	537	1559	527	1211	38	252	4.1
03/11/91	17	42165	32690	29895	24795	8340	7570	11560	544	1500	511	1375	41	278	4.6
03/14/91	20	34240	26935	22815	19405	6715	5650	10390	639	1607	546	1108	33	211	5.9
03/18/91	24	39125	30595	27860	23125	7255	6930	11350	608	1863	602	1190	30	246	5.6
03/21/91	27	35795	27470	23610	20085	6665	5845	10030	527	1801	588	1116	50	220	3.8
03/25/91	31	42310	32295	26070	22040	8045	7035	10800	601	1618	526	1323	36	265	6.7
03/28/91	34	34380	26405	22920	19175	6685	5470	9705	626	1715	549	1096	28	209	7.1
04/01/91	38	37485	29720	25635	21280	7625	6345	11020	521	1546	491	1254	34	243	4.0
04/04/91	41	34370	26000	22545	19200	7250	5695	9970	565	1500	482	1201	41	215	4.6
	MEAN	37601	29286	25463	21417	7385	6405	10710	557	1599	525	1220	39	239	5.3
	STD	2949	2323	2257	1789	627	689	584	53	135	42	103	7	22	1.1

TABLE C45. EFFLUENT II CHARACTERISTICS FROM RUN 3B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
02/28/91	6	2758	2206	338	284	132	33	150	452	1265	418	63	42	8.9	5.8
03/04/91	10	2414	1934	270	228	154	29	115	481	1325	431	78	53	7.4	5.2
03/07/91	13	3000	2470	352	284	115	35	141	524	1450	491	63	45	6.0	3.6
03/11/91	17	3198	2638	404	340	97	44	188	521	1316	436	56	41	7.9	4.3
03/14/91	20	3194	2502	352	290	128	36	155	539	1414	496	57	36	8.6	5.3
03/18/91	24	3300	2716	460	392	93	46	217	596	1661	590	49	34	9.0	4.7
03/21/91	27	3018	2374	322	266	98	32	138	534	1576	548	69	54	6.8	4.0
03/25/91	31	2808	2292	338	276	124	34	146	610	1422	510	52	32	8.7	6.1
03/28/91	34	3112	2568	404	328	129	41	179	628	1642	559	51	30	10.1	6.3
04/01/91	38	2444	2006	356	286	148	31	159	512	1344	446	64	41	6.8	3.7
04/04/91	41	2956	2440	440	370	113	45	208	570	1418	487	65	47	8.7	4.2
	MEAN	2927	2377	367	304	121	37	163	542	1439	492	61	41	8.1	4.8
	STD	282	237	53	46	19	6	30	52	127	54	8	8	1.2	0.9

TABLE C46. INFLUENT CHARACTERISTICS FROM RUN 4A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
04/15/91	7	4295	2990	3860	2695	562	430	1870	87	571	134	106	16.1	19.3	8.3
04/18/91	10	4150	3230	3735	3025	610	538	1915	106	375	116	116	18.7	20.4	12.4
04/22/91	14	3510	2845	3210	2685	543	446	1665	126	353	102	110	22.7	20.6	9.6
04/25/91	17	4130	3325	3720	3110	684	562	1870	133	398	123	134	25.0	18.3	9.1
04/29/91	21	3675	2895	3330	2705	599	492	1685	101	419	129	116	20.3	17.2	9.4
05/02/91	24	4380	3570	4050	3360	720	591	2055	122	460	156	132	16.6	17.0	8.3
05/06/91	28	4070	3015	3745	2765	644	509	1715	135	475	128	119	15.6	20.0	12.1
05/09/91	31	3895	2975	3480	2750	625	518	1610	104	387	102	120	20.2	22.4	13.4
05/13/91	35	3955	2885	3465	2635	667	538	1520	120	418	119	129	22.0	23.7	13.5
05/16/91	38	4200	3110	3845	2850	711	531	1665	109	452	127	129	15.5	18.2	10.4
	MEAN	4026	3084	3644	2858	637	516	1757	114	431	124	121	19.3	19.7	10.7
	STD	258	218	249	222	57	47	155	15	59	15	9	3.1	2.1	1.9

TABLE C47. REACTOR I (CMR) CHARACTERISTICS FROM RUN 4A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
04/15/91	7	13975	11005	10275	8445	1310	980	6440	494	1215	427	241	31	118	6.2
04/18/91	10	17950	14250	12680	10735	1545	1055	8280	547	1153	411	293	45	141	5.5
04/22/91	14	15150	11910	10375	8740	1335	865	6705	523	1394	469	268	54	122	5.7
04/25/91	17	13170	10265	8995	7680	1200	900	5845	572	1318	449	254	62	106	7.7
04/29/91	21	19560	15560	13570	11495	1910	1285	8290	594	1515	516	361	56	164	10.8
05/02/91	24	19635	14000	12025	10055	1730	1250	7650	608	1591	563	319	42	146	11.9
05/06/91	28	16560	11975	10945	9185	1295	1125	6860	686	1425	500	261	54	128	9.3
05/09/91	31	14465	11125	9990	8285	1210	970	6480	614	1197	419	254	60	130	7.6
05/13/91	35	16850	12820	10415	8880	1750	895	6825	530	1411	484	334	54	114	7.2
05/16/91	38	20550	15580	12930	10960	1935	1235	8145	593	1373	473	349	39	155	8.4
	MEAN	16787	12849	11220	9446	1522	1056	7152	576	1359	471	293	50	132	8.0
	STD	2458	1811	1415	1220	274	151	828	53	133	45	42	9	18	2.0

TABLE C48. EFFLUENT I CHARACTERISTICS FROM RUN 4A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
04/15/91	7	2708	2018	630	572	144	43	402	514	1198	406	59	36	12.2	7.4
04/18/91	10	2580	1942	584	496	136	36	389	551	1096	388	67	45	10.6	5.5
04/22/91	14	3136	2384	846	720	162	55	493	538	1367	445	81	56	12.8	4.8
04/25/91	17	3620	2712	1026	754	197	64	558	562	1269	411	92	61	15.8	7.9
04/29/91	21	3500	2520	1010	680	170	58	557	624	1458	489	86	59	17.0	10.2
05/02/91	24	2840	2176	738	534	137	44	456	602	1572	520	66	44	17.2	12.0
05/06/91	28	2852	2164	660	520	133	40	410	686	1327	452	73	51	14.5	9.2
05/09/91	31	3470	2658	852	742	184	52	495	664	1194	417	92	62	15.5	8.1
05/13/91	35	3386	2574	914	748	170	61	516	533	1334	464	83	55	16.0	7.9
05/16/91	38	2952	2316	714	626	147	47	443	597	1265	437	67	44	13.8	8.2
	MEAN	3104	2346	797	639	158	50	472	587	1308	443	77	51	14.5	8.1
	STD	350	255	148	97	21	9	59	55	130	38	11	8	2.1	2.0

TABLE C49. REACTOR II (UASB) CHARACTERISTICS FROM RUN 4A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
04/15/91	7	36500	26490	24520	21485	6005	6370	11585	618	1297	439	999	38	330	6.3
04/18/91	10	36905	27370	25780	22635	6420	6655	12520	574	1331	442	1081	54	347	7.0
04/22/91	14	32430	23415	22095	19890	5060	5820	10735	648	1544	547	868	58	309	5.9
04/25/91	17	40440	30390	26635	23215	6815	6945	12095	684	1681	570	1141	50	365	8.0
04/29/91	21	37610	27975	24560	21025	6105	6335	11490	701	1360	475	1022	45	327	11.6
05/02/91	24	34405	25150	24325	22005	5210	6720	11835	764	1560	557	888	54	337	11.2
05/06/91	28	31875	22715	20555	18660	5105	5730	10125	748	1457	505	861	44	303	9.7
05/09/91	31	34830	24655	22455	20035	5645	6190	10345	670	1399	470	964	61	310	8.1
05/13/91	35	40210	30015	25510	22510	6200	6900	11755	691	1687	595	1033	41	347	6.8
05/16/91	38	32955	24085	22630	19855	5450	6480	10555	729	1491	524	918	46	314	8.8
	MEAN	35816	26226	23907	21132	5802	6415	11304	683	1481	512	977	49	329	8.3
	STD	2893	2541	1810	1410	569	394	768	55	131	52	90	7	19	1.9

TABLE C50. EFFLUENT II CHARACTERISTICS FROM RUN 4A

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
04/15/91	7	2490	1918	448	332	81	19	232	616	1279	438	51	38	9.8	5.8
04/18/91	10	2788	2070	420	306	98	14	207	562	1205	420	71	55	10.1	6.2
04/22/91	14	2408	1874	366	266	88	13	198	629	1577	563	75	61	9.5	6.3
04/25/91	17	3194	2412	454	346	122	18	235	680	1622	578	68	49	11.9	8.0
04/29/91	21	3322	2496	580	424	119	20	295	675	1321	462	67	48	15.2	10.3
05/02/91	24	3222	2486	468	332	108	22	214	722	1464	515	75	57	14.3	10.4
05/06/91	28	3538	2732	594	444	129	16	310	745	1477	506	65	44	12.9	7.9
05/09/91	31	2988	2208	574	418	92	21	284	698	1286	475	75	61	13.4	8.0
05/13/91	35	2700	2074	442	344	79	14	247	735	1665	578	52	40	10.8	6.4
05/16/91	38	3270	2616	552	438	87	17	308	707	1520	544	65	52	12.5	7.0
	MEAN	2992	2289	490	365	100	17	253	677	1442	508	66	50	12.0	7.6
	STD	360	285	75	58	17	3	41	55	152	55	8	8	1.9	1.6

TABLE C51. INFLUENT CHARACTERISTICS FROM RUN 4B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/23/91	6	3705	2725	3295	2525	657	472	1405	78	590	137	128	23.0	19.4	9.7
05/27/91	10	4435	3380	4035	2900	669	481	2120	102	673	201	132	25.1	25.0	14.5
05/30/91	13	3880	2910	3415	2500	575	509	1620	103	551	177	123	30.5	21.7	11.1
06/03/91	17	3795	2940	3415	2595	524	417	1760	61	316	87	105	21.0	18.1	9.3
06/06/91	20	3990	2805	3550	2445	619	524	1365	79	361	106	117	18.4	16.7	8.8
06/10/91	24	4150	3050	3610	2650	532	555	1600	112	365	132	101	15.8	20.2	12.1
06/13/91	27	4205	3085	3850	2620	517	483	1850	145	527	166	103	20.1	21.6	13.6
06/17/91	31	4085	3100	3595	2715	703	479	1895	109	503	157	139	26.1	22.8	16.1
06/20/91	34	3960	2920	3685	2545	538	518	1620	117	414	129	104	18.3	20.7	13.9
06/24/91	38	4175	3050	3590	2720	666	542	1640	106	432	120	127	20.5	20.1	11.8
06/27/91	41	4260	3230	3750	2850	679	552	1805	88	450	133	131	22.2	24.4	16.7
07/01/91	45	3985	2785	3665	2465	541	470	1555	105	504	162	104	17.8	18.3	10.3
07/04/91	48	3875	2970	3405	2545	580	475	1630	111	465	127	118	25.6	19.0	11.0
	MEAN	4038	2996	3605	2621	600	498	1682	101	473	141	118	21.9	20.6	12.2
	STD	196	175	194	136	65	38	196	20	96	29	13	3.9	2.4	2.5

TABLE C52. REACTOR I (CMR) CHARACTERISTICS FROM RUN 4B

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/23/91	6	16230	11830	10155	7795	1765	1180	5140	420	1642	542	351	68	130	6.9
05/27/91	10	20730	15080	13320	9925	2100	1565	6795	472	1730	605	376	40	165	8.2
05/30/91	13	16680	12915	11410	8550	1815	1385	5750	460	1651	567	349	59	149	10.2
06/03/91	17	20145	14895	12125	8955	2210	1625	5950	431	1456	469	417	64	145	8.6
06/06/91	20	22225	16165	13065	9740	2460	1815	6530	483	1396	459	438	44	169	11.6
06/10/91	24	17720	12830	11055	8575	1730	1280	6005	495	1360	477	322	46	153	10.5
06/13/91	27	23050	17150	14390	10355	2515	1630	7305	513	1515	508	448	45	181	6.1
06/17/91	31	21060	15390	12170	9270	1960	1390	6440	408	1328	445	374	61	150	8.3
06/20/91	34	23255	17485	14375	10740	2455	1840	7515	412	1446	487	446	53	173	10.7
06/24/91	38	19175	14390	13700	9910	1835	1375	7140	429	1390	455	342	49	160	8.1
06/27/91	41	21230	16040	14175	10615	2320	1620	6470	472	1614	538	412	41	167	7.6
07/01/91	45	18235	13885	12010	8330	1900	1265	5875	426	1377	457	357	53	141	11.5
07/04/91	48	20610	14570	11550	9195	2035	1645	7020	459	1482	508	386	60	148	10.8
	MEAN	20027	14817	12577	9381	2085	1509	6457	452	1491	501	386	52	156	9.2
	STD	2195	1614	1313	886	270	202	667	32	124	47	41	9	14	1.7

TABLE C53. EFFLUENT I CHARACTERISTICS FROM RUN 4B

DATE	DAY	PARAMETERS (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/23/91	6	2428	1866	296	236	257	60	166	430	1608	531	111	70	10.9	7.6
05/27/91	10	2524	1880	372	292	250	71	200	451	1762	625	78	38	12.9	8.8
05/30/91	13	3268	2454	486	408	305	82	271	489	1635	562	110	61	16.4	10.7
06/03/91	17	2664	1958	360	284	267	64	198	428	1447	492	108	65	13.5	9.0
06/06/91	20	2754	2108	408	328	290	76	228	501	1380	456	92	46	16.8	12.7
06/10/91	24	3078	2372	316	244	299	58	171	467	1465	508	93	45	15.4	12.0
06/13/91	27	3312	2520	440	360	328	71	255	502	1598	530	103	50	13.9	8.9
06/17/91	31	3120	2436	448	366	288	78	258	411	1412	464	110	64	13.3	8.2
06/20/91	34	2584	1938	368	286	240	62	201	401	1392	477	85	47	15.8	11.8
06/24/91	38	2732	2010	414	344	259	70	244	414	1406	495	92	50	13.8	9.0
06/27/91	41	2810	2146	368	358	300	63	262	490	1691	602	88	40	15.3	10.3
07/01/91	45	3102	2340	422	292	232	80	186	418	1330	434	82	45	16.7	12.9
07/04/91	48	2638	1980	378	296	303	64	209	439	1498	506	108	60	15.9	11.5
	MEAN	2847	2154	390	315	278	69	219	449	1510	514	97	52	14.7	10.3
	STD	282	229	51	49	28	8	35	35	130	54	11	10	2	2

TABLE C54. REACTOR II (UASB) CHARACTERISTICS FROM RUN 4B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/23/91	6	36750	26235	23450	16625	7275	7140	6940	415	1812	578	1207	43	370	7.7
05/27/91	10	32475	24180	21120	15090	6850	6775	6175	471	1903	658	1131	35	344	7.6
05/30/91	13	42015	30910	29805	21920	8200	7890	9520	512	1624	560	1366	54	482	8.8
06/03/91	17	42165	29775	27265	19450	7935	7610	8655	484	1849	651	1328	59	433	9.0
06/06/91	20	39275	28560	25335	18535	7355	7325	8055	459	1527	526	1229	52	412	10.3
06/10/91	24	42630	31695	29660	21045	8315	8030	9010	524	1453	486	1378	47	469	10.5
06/13/91	27	40005	30085	27450	19230	8160	7775	8285	547	1508	506	1363	57	428	8.7
06/17/91	31	35075	25380	24570	17515	6765	7035	7985	469	1718	549	1143	61	390	8.5
06/20/91	34	36715	25770	23715	17205	7055	6840	7415	518	1482	493	1182	53	383	11.2
06/24/91	38	41200	28355	27640	19350	7880	7795	8900	467	1618	540	1302	41	431	10.4
06/27/91	41	42015	30215	29005	20195	8405	8015	8870	455	1489	476	1387	42	450	7.8
07/01/91	45	36800	26650	24140	17440	6930	7490	6985	520	1825	641	1159	50	388	8.6
07/04/91	48	37675	27435	24855	18155	7405	6760	8365	488	1569	515	1245	60	402	9.6
	MEAN	38830	28096	26001	18597	7579	7422	8089	487	1644	552	1263	50	414	9.1
	STD	3061	2262	2573	1800	570	454	931	35	152	61	91	8	38	1.1

TABLE C55. EFFLUENT II CHARACTERISTICS FROM RUN 4B

DATE	DAY	P A R A M E T E R S (mg/L)													
		TS	VS	TSS	VSS	PROTEINS	LIPIDS	CARBOHYDR	TOT. VFA	COD	TOC	TKN	NH3-N	TP	PO4
05/23/91	6	2268	1716	150	114	162	46	49	412	1653	534	74	48	9.4	7.4
05/27/91	10	2656	1984	168	134	160	51	56	457	1832	614	62	36	9.8	7.4
05/30/91	13	2846	2248	196	160	194	57	67	503	1506	487	80	49	11.0	8.2
06/03/91	17	2968	2256	164	128	204	44	55	514	1794	566	93	60	10.5	8.2
06/06/91	20	3134	2410	222	186	189	67	76	454	1548	524	82	51	13.1	9.9
06/10/91	24	2340	1806	144	106	153	38	48	530	1461	501	75	50	12.3	10.4
06/13/91	27	2914	2264	172	134	210	43	57	537	1568	500	93	59	10.2	7.8
06/17/91	31	3240	2452	200	154	217	58	64	464	1627	566	93	59	9.8	7.0
06/20/91	34	2664	1938	142	108	157	39	50	541	1508	490	74	48	13.0	11.1
06/24/91	38	2996	2274	148	120	175	54	49	464	1586	541	70	42	11.7	9.6
06/27/91	41	3130	2432	204	162	220	58	72	443	1382	469	82	47	10.9	8.0
07/01/91	45	2602	1888	146	110	158	41	47	532	1798	603	77	52	9.5	7.4
07/04/91	48	2714	2086	162	134	169	53	57	498	1644	524	89	62	11.0	8.6
	MEAN	2806	2135	171	135	182	50	57	488	1608	532	80	51	10.9	8.5
	STD	288	238	26	24	24	8	9	40	131	43	9	7	1.2	1.3

APPENDIX D

VFA DISTRIBUTION

TABLE **PAGE**

TABLE D1. INFLUENT VFA DISTRIBUTION

RUN	PARAMETERS (mg/L)							
	Acetic	Propionic	Butyric	Iso-butyric	Valeric	3-methyl-butyric	2-methyl-butyric	Total VFAs (as HAc)
1A								
MEAN	52	44	12	0.4	0.2	1.0	1.1	98
STD	11	11	4					22
1B								
MEAN	57	50	15	1.3	1.4	0.7	0.9	111
STD	8	10	4					18
1C								
MEAN	53	46	19	1.3	1.6	0.9	1.3	106
STD	13	12	6					27
1D								
MEAN	58	45	16	0.9	1.6	1.6	0.7	108
STD	9	9	4					18
2A								
MEAN	62	52	18	1.3	1.5	1.6	0.9	119
STD	9	10	5					17
2B								
MEAN	45	34	10	0.7	0.8	1.3	0.5	81
STD	10	8	4					19
2C								
MEAN	58	45	14	0.7	1.3	1.5	1.0	108
STD	9	8	4					12
3A								
MEAN	51	41	18	0.2	1.4	0.6	0.1	97
STD	8	8	3					16
3B								
MEAN	22	20	7	0.5	0.3	0.1	0.1	44
STD	6	6	2					11
4A								
MEAN	62	44	18	1.9	2.2	1.9	1.2	114
STD	7	7	2					15
4B								
MEAN	51	41	20	2.1	1.9	1.2	0.7	101
STD	9	8	4					21

TABLE D2. REACTOR I (CMR) VFA DISTRIBUTION

RUN	PARAMETERS (mg/L)							
	Acetic	Propionic	Butyric	Iso-butyric	Valeric	3-methyl-butyric	2-methyl-butyric	Total VFAs (as HAc)
1A								
MEAN	298	206	45	19	26	18	9	540
STD	49	28	8	3	4	4	3	72
1B								
MEAN	206	174	36	16	18	14	9	407
STD	56	36	9	4	4	4	3	84
1C								
MEAN	347	218	72	23	32	25	13	632
STD	40	32	8	5	6	5	4	68
1D								
MEAN	318	177	48	26	33	20	9	550
STD	30	21	7	4	5	4	2	52
2A								
MEAN	357	245	66	31	56	41	20	692
STD	39	33	7	5	8	8	5	56
2B								
MEAN	351	220	56	42	63	48	21	674
STD	38	24	6	6	7	7	3	71
2C								
MEAN	140	87	19	9	11	7	4	243
STD	40	14	3	2	3	1	1	53
3A								
MEAN	327	212	65	20	34	21	11	596
STD	14	29	8	3	4	3	2	46
3B								
MEAN	259	202	50	26	25	8	5	499
STD	36	21	8	5	5	1	2	59
4A								
MEAN	300	251	37	26	25	15	8	576
STD	26	25	7	5	5	3	2	55
4B								
MEAN	234	111	113	25	26	20	10	452
STD	19	16	15	4	4	4	2	34

TABLE D3. EFFLUENT I (CMR) VFA DISTRIBUTION

RUN	PARAMETERS (mg/L)							
	Acetic	Propionic	Butyric	Iso-butyric	Valeric	3-methyl-butyric	2-methyl-butyric	Total VFAs (as HAc)
1A								
MEAN	287	205	48	20	24	18	7	530
STD	44	33	8	3	4	3	2	73
1B								
MEAN	214	173	34	15	19	12	10	412
STD	47	32	8	3	3	3	3	76
1C								
MEAN	341	226	69	24	35	22	13	630
STD	29	37	8	5	6	3	3	64
1D								
MEAN	317	185	50	26	35	19	13	560
STD	30	22	8	4	5	4	2	64
2A								
MEAN	346	246	63	33	59	40	20	683
STD	41	28	11	6	8	8	4	66
2B								
MEAN	355	227	57	44	63	49	20	687
STD	32	29	7	6	7	8	3	65
2C								
MEAN	132	86	20	9	12	7	5	236
STD	30	14	5	2	2	2	1	47
3A								
MEAN	321	202	65	20	31	19	12	580
STD	20	23	7	5	5	3	2	50
3B								
MEAN	262	202	54	26	22	11	5	504
STD	29	31	8	5	5	2	1	62
4A								
MEAN	309	255	45	22	21	14	8	587
STD	26	26	8	3	3	3	1	58
4B								
MEAN	231	109	117	24	25	20	11	449
STD	20	14	19	5	5	4	2	36

TABLE D4. REACTOR II (UASB) VFA DISTRIBUTION

RUN	PARAMETERS (mg/L)							
	Acetic	Propionic	Butyric	Iso-butyric	Valeric	3-methyl-butyric	2-methyl-butyric	Total VFAs (as HAc)
1A								
MEAN	318	229	50	19	44	28	15	603
STD	34	35	8	4	8	6	4	68
1B								
MEAN	248	185	43	16	21	15	11	466
STD	40	30	6	3	4	3	3	69
1C								
MEAN	366	242	83	23	44	24	14	685
STD	29	30	8	3	7	4	3	54
1D								
MEAN	312	237	49	33	41	28	14	610
STD	34	28	7	6	6	5	2	70
2A								
MEAN	394	246	63	32	70	47	19	741
STD	49	33	7	5	11	7	4	90
2B								
MEAN	379	225	60	48	68	44	26	718
STD	26	26	7	7	10	7	5	69
2C								
MEAN	159	106	25	10	15	9	7	288
STD	19	17	6	3	3	2	2	38
3A								
MEAN	328	231	69	16	40	27	13	623
STD	22	23	8	3	5	5	2	51
3B								
MEAN	299	212	56	30	24	17	5	557
STD	24	24	8	5	5	2	1	55
4A								
MEAN	339	311	49	26	33	24	10	683
STD	29	27	7	5	7	3	2	58
4B								
MEAN	247	130	116	22	30	25	12	487
STD	17	19	18	5	5	4	2	36

TABLE D5. EFFLUENT II (UASB) VFA DISTRIBUTION

RUN	PARAMETERS (mg/L)							
	Acetic	Propionic	Butyric	Iso-butyric	Valeric	3-methyl-butyric	2-methyl-butyric	Total VFAs (as HAc)
1A								
MEAN	242	180	42	12	38	22	7	465
STD	26	31	8	3	7	5	2	57
1B								
MEAN	199	144	33	14	17	11	9	370
STD	31	25	7	3	3	2	2	55
1C								
MEAN	362	233	76	24	40	21	15	665
STD	30	31	9	5	7	5	3	53
1D								
MEAN	324	215	55	30	40	29	15	608
STD	38	28	7	6	6	6	3	75
2A								
MEAN	392	236	60	31	72	43	19	725
STD	41	31	7	5	10	7	2	78
2B								
MEAN	373	219	60	50	70	46	23	709
STD	28	29	6	7	9	7	4	67
2C								
MEAN	150	98	23	9	13	8	6	269
STD	18	16	6	3	2	2	2	40
3A								
MEAN	326	233	76	19	42	25	15	630
STD	30	21	9	3	6	5	3	56
3B								
MEAN	283	208	56	30	29	17	6	542
STD	30	30	9	6	6	3	2	54
4A								
MEAN	350	294	49	26	30	19	12	677
STD	33	24	6	5	6	4	2	58
4B								
MEAN	254	121	114	25	29	25	13	488
STD	12	15	19	6	5	5	4	42

APPENDIX E

VARIOUS EXPERIMENTAL RESULTS AND CONVERSION FACTORS

TABLE **PAGE**

TABLE E1. SEED CHARACTERISTICS

PARAMETERS	MEAN VALUES (mg/L)	STD (mg/L)
pH	6.2	0.3
TS	6800	608
VS	5030	612
TSS	5890	709
VSS	4850	556
COD (soluble)	830	109
TOC	240	36
VFAs (as HAc)	35	8
NH3-N	28	4
TKN (soluble)	44	6

TABLE E2. SOLUBLE CARBOHYDRATES

RUN	INFLUENT		EFFLUENT			
			Reactor I (CMR)		Reactor II (UASB)	
	Mean (mg/L)	Percent of Total	Mean (mg/L)	STD (mg/L)	Mean (mg/L)	STD (mg/L)
1A	125	7.2	52	14	35	7
1B	96	5.7	78	19	68	11
1C	135	8.0	47	9	36	8
1D	131	7.1	53	13	29	4
2A	116	6.6	44	11	27	5
2B	112	7.3	50	8	30	5
2C	113	6.4	78	14	28	6
3A	107	6.7	66	12	29	4
3B	199	9.5	64	7	37	4
4A	130	7.4	69	10	33	6
4B	135	8.0	118	16	39	6
MEAN	127	7.3				

TABLE E3. SOLUBLE PROTEINS

RUN	INFLUENT		EFFLUENT			
			Reactor I (CMR)		Reactor II (UASB)	
	Mean (mg/L)	Percent of Total	Mean (mg/L)	STD (mg/L)	Mean (mg/L)	STD (mg/L)
1A	116	18.3	83	11	68	8
1B	89	14.2	89	13	76	10
1C	108	16.9	66	6	47	7
1D	87	12.8	71	9	45	5
2A	109	17.2	47	6	31	4
2B	82	13.8	24	4	21	3
2C	92	15.7	63	8	54	8
3A	107	17.0	69	9	46	4
3B	107	19.1	56	5	52	7
4A	94	14.8	67	8	37	4
4B	103	17.1	70	7	60	8
MEAN	99	16.1				

TABLE E4. GAS PRODUCTION (MEAN VALUES)

RUN	SRT (days)	HRT (hr)	Reactor I		Reactor II	
			Mean (mL/d)	STD (mL/d)	Mean (mL/d)	STD (mL/d)
1A	10	9	26	5	24	6
1B	10	6	33	7	31	7
1C	10	12	24	4	34	6
1D	10	15	80	10	92	11
2A	15	12	47	5	39	5
2B	20	12	45	7	52	9
2C	5	12	21	3	25	5
3A	10	12	33	5	37	6
3B	10	12	38	5	49	7
4A	10	12	21	4	31	5
4B	10	12	25	5	28	4

TABLE E5. CONVERSION FACTORS

A. CONVERSION FACTORS FOR VFAs		
PARAMETER	Mol. Weight	mgVFA/mgHAc
ACETIC	60.05	1.000
PROPIONIC	74.08	0.817
BUTYRIC	88.10	0.682
VALERIC	102.13	0.588

B. MISCELLANEOUS CONVERSION FACTORS		
PARAMETER	CONVERSION FACTOR	BASIS
ACETIC ACID COD	1.067 mg/mg Acid	Acetic Acid
PROPIONIC ACID COD	1.514 mg/mg Acid	Propionic Acid
BUTYRIC ACID COD	1.818 mg/mg Acid	Butyric Acid
VALERIC ACID COD	2.039 mg/mg Acid	Valeric Acid
NITROGENOUS COD	9.58 mg/mg Org. N	(C4 H6.1 O1.2 N)x
	or 1.533 mg/mg Protein	Org.N=16% Protein
CARBOHYDRATE COD	1.067 mg/mg	Glucose
FORMIC ACID COD	0.348 mg/mg	Formic Acid
ETHANOL COD	2.087 mg/mg	Ethanol
LACTIC ACID COD	1.066 mg/mg	Lactic Acid

TABLE E6. MASS BALANCE CALCULATION EXAMPLE (RUN 1B, CMR SYSTEM)

A. MONING AVERAGE MASS BALANCE									
DAY	Inf. Flow (L/d)	Waste (L/d)	Eff. Flow (L/d)	Inf. VSS (mg/L)	Waste VSS (mg/L)	Eff. VSS (mg/L)	Rate In (g/d)	Rate Out (g/d)	Reduction (%)
7	11.97	0.28	11.69	2710	13640	764	32.44	12.75	
10	11.07	0.28	10.79	2630	16445	920	29.11	14.53	
14	11.33	0.28	11.05	2650	18825	1420	30.02	20.96	47.3
17	12.26	0.28	11.98	2970	16270	1308	36.41	20.23	41.7
21	11.46	0.28	11.18	2500	19355	1396	28.65	21.03	34.6
24	11.50	0.28	11.22	2905	18365	960	33.41	15.91	41.9
27	11.94	0.28	11.66	2890	15810	850	34.51	14.34	46.9
30	11.95	0.28	11.67	2415	16140	1032	28.86	16.56	51.6
34	12.11	0.28	11.83	2550	20375	1222	30.88	20.16	45.8
37	11.63	0.28	11.35	2755	19370	958	32.04	16.30	42.2
41	11.72	0.28	11.44	2435	16650	1000	28.54	16.10	42.5
44	11.68	0.28	11.40	2405	19215	1184	28.09	18.88	42.2

B. OVERALL MASS BALANCE									
MEAN VAL	11.73	0.28	11.45	2651	17568	1085	31.08	17.34	44.2

MOVING AVERAGE MASS BALANCE: % VSS REDUCTION = 43.7
OVERALL MASS BALANCE: % VSS REDUCTION = 44.2