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Laboratory studies on the temperature-phased anaerobic digestion of mixtures of primary and waste activated sludge

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Laboratory studies on the temperature-phased anaerobic digestion of mixtures of primary and waste activated sludge

by

Yue Han

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Major: Civil Engineering (Environmental Engineering)
Major Professor: Shihwu Sung

Iowa State University
Ames, Iowa
1997

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TABLE OF CONTENTS

I. INTRODUCTION

Background

Anaerobic digestion has been used successfully for stabilizing wastewater sludges for over 70 years. Because of the emphasis on energy conservation and recovery and the desirability of obtaining beneficial use of wastewater sludge, anaerobic digestion has been and will continue to be the dominant sludge stabilization process. The primary objectives of anaerobic digestion are (1) reduce pathogens, (2) eliminate offensive odors, and (3) reduce organic matter and the potential for putrefaction.

New federal regulations on wastewater sludge management were implemented in 1993 and will have an impact on virtually every biosolids disposal method, including application to agricultural land. The new regulations have restricted land use of sludge based on pathogen destruction criteria. According to the new standards for the disposal of sewage sludge [6], all Class A sludge must meet one of the following criteria at the time it is sold, given away, or used.

Either

- A fecal coliform density less than 1,000 Most Probable Number per gram of total solids (1,000 MPN/g TS).

or

- A Salmonella spp. Density less than 3 Most Probable Number per 4 grams of total solids (3 MPN/4g TS).

In general, the fecal coliform density of domestic primary wastewater sludge is in a range from 10^5 to 10^9 MPN/g TS. The conventional anaerobic digestion process can achieve some pathogen destruction, as shown in Table 1 [85]. The results in Table 1 show that the digested sludge through conventional anaerobic digester can not meet the pathogen destruction criteria of the recent 40 CFR Part 503 Standards for Class A biosolids.

Table 1. Fecal coliform destruction through conventional mesophilic anaerobic digestion

Raw sludge (MPN/g TS)	Single-stage digestion (MPN/g TS) (15 days HRT, 30-38°C)
4.3×10^8	9.3×10^5
2.3×10^8	3.5×10^6
1.6×10^8	4.1×10^6
2.4×10^8	1.4×10^6
1.0×10^8	1.8×10^6
1.1×10^9	2.9×10^6

Historically anaerobic digestion has been applied for stabilization of raw, domestic primary sludge (PS) and biological solids produced by the activated sludge or trickling filter processes. The volatile solids (VS) reduction rate is slowed by even small additions of biological solids, particularly waste activated sludge (WAS). The WAS is a dilute suspension of microbial cells and cell debris. Because the potential substrates are "membrane-enclosed"

within viable cells, WAS becomes more difficult to degrade, compared with primary sludge (PS). The presence of Nocardia spp. bacteria and foam producing organic matter in WAS can lead to serious foaming.

In summary, three problems are commonly encountered in the application of conventional mesophilic anaerobic digestion of WAS or the mixture of WAS and PS: 1) low pathogen destruction, 2) low volatile solids reduction, and 3) foaming.

Studies have been conducted to find solutions to the problems mentioned above. The important research includes: thermophilic anaerobic digestion [21, 22, 23, 42, 67, 69], two-phase anaerobic digestion [26, 42], multiple digestion (meso/thermo) [88], and temperature-phased anaerobic digestion (TPAD, thermo/meso) [29]. The comparison of these processes in terms of pathogen destruction, volatile solids reduction, foaming, and their stability is shown in Table 2. Thermophilic anaerobic digestion has been found to achieve much higher pathogen destruction and to enhance hydrolysis of the complex biological materials in WAS [29, 68]. Foaming is also reduced significantly in a thermophilic anaerobic digester [68]. However, thermophilic anaerobic digestion is thought to be sensitive to changes in some parameters, such as temperature and VS loading [12]. Also, volatile fatty acids (VFA) are high in the effluent from thermophilic anaerobic digesters, which cause offensive odors [19, 21, 23]. Two-phase anaerobic digestion has been reported to increase the VS removal rate and to reduce foaming, but the pathogen destruction rate is low for the mesophilic two-phase system due to its low operating temperature and bad odors always exist for the thermophilic two-phase system due to the high volatile fatty acids content in its effluent. Although high

Table 2. Performance of different processes

	Pathogen destruction	VS removal	Odor	Foaming	Stability
Thermophilic (single-stage)	high	high	yes	no	poor
Two-phase (thermophilic)	high	high	yes	no	poor
Two-phase (mesophilic)	low	high	no	no	good
Multiple-digestion (meso/thermo)	high	middle	yes	NA	good
TPAD (thermo/meso)	high	high	no	no	good

stability and VS removal rates were reported by using multiple-digestion (meso/thermo), this process could not fully take advantage of the thermophilic unit due to the arrangement of the thermophilic reactor as the second stage. Besides this arrangement could lead to serious foaming in the first mesophilic stage due to high VS loading rate and relatively short hydraulic retention time (HRT) on this stage.

Rationale for the Application of Temperature-Phased Anaerobic Digestion

The temperature-phased anaerobic process has been under development by Dague and coworkers at Iowa State University [29, 30, 35]. This system consists of two reactors

operated in series, with the first stage operated at a thermophilic temperature and the second stage operated at a mesophilic temperature. This arrangement allows the system to take full advantage of both thermophilic (high pathogen destruction, high VS removal rate, and foaming reduction) and mesophilic digestion (less odor effluent and high stability) and to avoid the disadvantages of each one: the odor and low stability associated with thermophilic anaerobic digestion and low pathogen destruction, low VS removal, and serious foaming associated with mesophilic anaerobic digestion. The temperature-phased process has been shown to achieve higher organic removals than is possible for single-stage systems operated at either 55°C or 35°C. In the author's previous study, temperature-phased anaerobic digestion was applied for treating primary sludge. The TPAD was able to achieve much higher VS removals than was possible with single-stage mesophilic digestion and almost complete destruction of coliforms. The VFA in the second stage of the TPAD system was as low as that from the single-stage mesophilic digester. Thus no odor problem was observed in the effluent from TPAD system.

Therefore, it is hypothesized that the TPAD system would achieve high pathogen destruction, high volatile solids removal, reduction or elimination of foaming and odors for treatment of mixtures of waste activated sludge and primary sludge. The thermo/meso arrangement would fully take advantage of both thermophilic anaerobic digestion and mesophilic anaerobic digestion.

Objectives and Scope of Study

The objectives of this research were to evaluate the performance of the TPAD system for the treatment of mixtures of primary and waste activated sludge. The main objectives were to determine:

- volatile solids removal rate;
- the degree of pathogen destruction;
- biogas production rate of the TPAD system;
- the optimum operational conditions for the TPAD system.

II. LITERATURE REVIEW

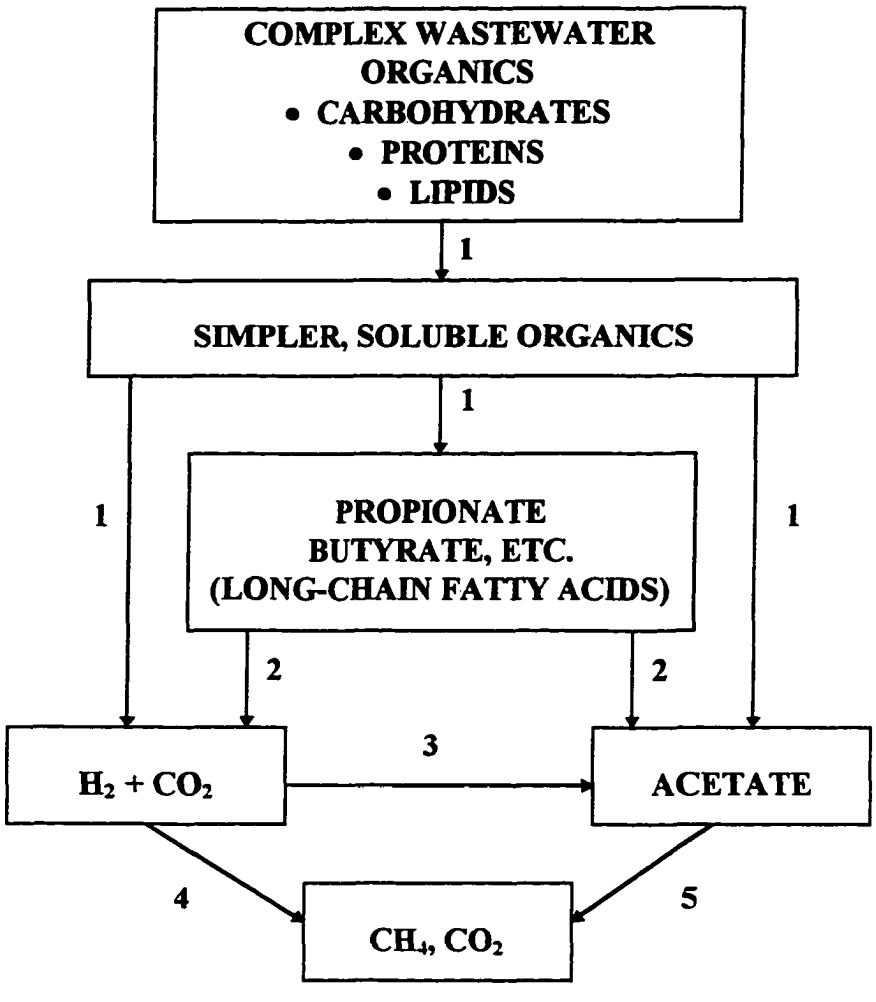
Microbiology and Biochemistry of Anaerobic Digestion

Anaerobic digestion is a microbial process. The anaerobic microbial degradation of organic matter to methane and carbon dioxide occurs naturally in a variety of anaerobic habitats. The objective of the environmental engineer has been to confine the natural organisms in a human-made system and to optimize the rates and extents of the natural reactions so that polluting substances will be destroyed.

Functional Groups of Bacteria

The microorganisms carrying out the reactions in anaerobic digestion are bacteria, and that kind of bacteria known as 'anaerobes'; bacteria that live without oxygen and may be killed by oxygen. The metabolic stages involved in the production of methane from wastes are hydrolysis, acidogenesis, acetogenesis, and methanogenesis [11, 37]. The bacteria involved are acidogenic, acetogenic, and methanogenic bacteria, respectively, which can be further specified as five groups as shown in Figure 1 [58, 91, 92].

Acidogenic Bacteria The hydrolytic and acidogenic stages may be combined in the anaerobic acidogenic bacteria. Acidogenic bacteria commonly found in digesters are species of Butyrivibrio, Propionic, Clostridium, Bacteroides, Ruminococcus,



BACTERIAL GROUPS:

1. Fermentative bacteria
2. Hydrogen-producing, acetogenic bacteria
3. Hydrogen-consuming, acetogenic bacteria
4. CO_2-reducing methanogens
5. Aceticlastic methanogens

Figure 1. Methane formation in anaerobic digestion

Acetivibrio, Eubacterium, Selenomonas, Lactobacillus, Streptococcus, and members of the Enterobacteriaceae [90]. In mesophilic sewage sludges there are in the range from 10^8 to 10^9 hydrolytic bacteria per ml.

The Acetogenic Bacteria Acetogenic species can be subdivided into two groups. One group are not obligately proton-reducing, i.e. hydrogen-producing and the other do reduce protons to hydrogen obligately during acetogenesis. The first group consists of the homoacetogens and species which may direct their metabolism to proton-reduction in the presence of an efficient hydrogen-removing system. Homoacetogenic species are known in the genera Acetobacterium [3, 4, 9, 18, 74], Acetoanaerobium [77], Acetogenium [43], Butyribacterium [90], Clostridium [63, 74], Eubacterum [75], and Pelobacter [72, 73]. In mesophilic sludges there exist approximately 10^5 homoacetogens per ml forming acetate from $H_2 + CO_2$ [9]. Obligately proton-reducing acetogenic bacteria can only grow in an efficient electron-removing environment. The simple mixed culture involving this type of interaction is a culture containing the acetogen and a hydrogen-removing bacterium, such as a methanogen. Many obligate proton-reducing acetogens have been described:
Syntrophomonas wolfei degrades benzoate [58, 59], Syntrophobacter wolinii degrades propionate [7], Syntropholomonas wolfei degrades butyrate.

The Methanogens Methanogens are present in sewage sludge at populations up to 10^8 per ml [80] and contribute up to 10% of the volatile solids. They are a morphologically

diverse group of archaebacteria unified by their ability to derive energy from methanogenesis [3]. Acetate, H_2 and CO_2 are the most important substrates for the methanogens in anaerobic digestion. Most methanogenic bacteria utilize H_2 and CO_2, but species of only two genera, Methanosarcina and Methanothrix, can produce methane from acetic acid.

Reactions in Anaerobic Digestion

Conceptually, anaerobic digestion of complex organics can be described as a three-stage process, as shown in Figure 1: (1) Hydrolysis and fermentation; (2) hydrogen and acetic acid formation; and (3) methane formation. Five groups of bacteria are thought to be involved as mentioned above, each deriving energy from a limited number of biochemical reactions.

Hydrolysis and Fermentation Most organic matter in wastewater sludge is insoluble and can not be assimilated directly by bacteria. Therefore hydrolysis and liquefaction of complex organics are necessary to convert them to soluble form that can pass through bacterial cell walls for use as energy and nutrient sources. During hydrolysis, the organic matter is simply converted into a soluble form that can be assimilated by the bacteria. Although essentially no organic waste stabilization occurs, the stabilization of complex organics can not be accomplished unless this initial hydrolysis step is functioning properly. The overall rate of stabilization and methane fermentation can be limited by this step.

Following hydrolysis, the organics are fermented to long-chain organic acids, sugars, amino acids, and eventually to smaller organic acids such as propionic, butyric, and valeric

acids [13,47, 51, 52]. This phase is called the "acid-forming", or fermentation phase. No stabilization occurs during this phase.

Hydrogen is thought to be inhibitory to many of the acid-forming bacteria and must be removed from the system as acid production continues [8, 26, 57, 92]. Fortunately, hydrogen is consumed by some methanogenic bacteria as their energy source in the reduction of CO_2 to methane [88, 90, 91, 92].

Hydrogen and Acetic Acid Formation Hydrogen is produced by the fermentative bacteria and hydrogen-producing, acetogenic bacteria (group 1 and 2 of Figure 1[92]. Acetate is also produced by these two groups in addition to hydrogen-consuming, acetogenic bacteria (group 3). It is believed that hydrogen plays a key role in regulating organic acid production and consumption [48, 49, 92]. If the partial pressure of hydrogen is higher than 10^{-4} atm, methane production is inhibited and thus results in an increase in the organic acids such as propionic and butyric acids [49, 92]. A large, stable population of CO_2-reducing methanogens (group 4 of Figure 1) will ensure maintenance of low hydrogen partial pressure.

Methane Formation Waste stabilization occurs when the conversion of the acetic and other volatile fatty acids into methane and carbon dioxide is complete. Methane is essentially insoluble in water and readily separates from the sludge. Carbon dioxide either escapes as gas or is converted to bicarbonate alkalinity. Methanogenic bacteria are strict

anaerobes and oxygen is inhibitory to them [51]. Very few substrates can act as energy sources for the methane forming bacteria. It is widely accepted that only formic acid, acetic acid, methanol, and hydrogen can be used as energy sources by the various methanogens [44, 45, 91]. Among these substrates, acetic acid and hydrogen serve as the major substrates for methane formation in the anaerobic digestion of wastewater sludges [36].

Around 72% of the methane is produced from acetate cleavage by aceticlastic bacteria [44, 81]:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad \text{..... (1)}$$

The other 28% of the methane comes from the reduction of carbon dioxide by CO_2-reducing methanogens using hydrogen as the energy source:

$$CO_2 + H_2 \rightarrow CH_4 + H_2O \quad \text{..... (2)}$$

Important Operational and Environmental Factors of Anaerobic Digestion

Both operational and environmental conditions determine the performance of an anaerobic digester. The big difference between anaerobic digestion in nature and in a digester is that the latter is controlled by human. It is therefore very important for people to fully understand the key factors involved in anaerobic digestion. Although many factors have impacts on the anaerobic digestion, they can classified as two categories: operational and environmental factors.

Operational Factors

Temperature Bacteria have three ranges of temperature at which they can grow. Three ranges for growth are from 0 to about 15°C, from 15 to 45°C, and from 50 to 65°C. In the temperature range below 45°C (the 'mesophilic' and 'psychrophilic' ranges) digestion becomes slower as temperature decreases. Normal 'mesophilic' digestion virtually ceases at about 15°C. O'Rourke [62] suggested that 20°C was the lowest practical limit for lignin breakdown, and thus the lowest practical temperature for anaerobic sludge digestion.

Anaerobic sludge digesters are most often operated in a mesophilic range: 30 to 38°C. Very few anaerobic digesters are operated in a thermophilic range from 50 to 65°C due to higher energy consumption and unsteady operation [22]. Each specific methane-forming bacterium has an optimum temperature for growth. If temperature fluctuates, no group of methane formers can achieve a stable population. This results in reduced stabilization and reduced methane formation [2]. Therefore, it is important that the temperature remain constant.

Hydraulic Retention Time (HRT) and Solids Retention Time (SRT) HRT is the average time that fluid stays in a reactor and SRT is the average time that biosolids stay in the system. In conventional digesters, HRT is equivalent to system SRT (HRT = SRT). Retention time is an important factor for bacterial growth. To ensure the conversion of complex organic matter to methane and carbon dioxide, the bacteria in the digester must be of a sufficient quantity and concentration, and retention time must be adequate for them to

metabolize substrates. From a design standpoint, this means proving sufficient reactor volume for a given operating condition, which directly affects system cost.

The use of SRT as the most important design parameter is a relatively new concept that providing insight into how changes in operating conditions affect system performance [47, 54]. SRT is defined as the mass of solids contained in the reactor divided by the mass of solids discharged and/or wasted from the system per day. For completely stirred tank reactor (CSTR) such as well mixed anaerobic digester, SRT and HRT are equal and can be calculated as follows:

$$SRT = HRT = V/Q \quad \ldots\ldots \quad (3)$$

where:

HRT = hydraulic retention time

SRT = solids retention time, day

V = volume of reactor, L

Q = flow rate of incoming sludge, L/d

Anaerobic sludge digesters have been designed empirically, usually on the basis of a specific digester volume (cubic meters or cubic feet) per capita of contributing population, or by volatile solids (VS) loading rate (kg VS/m^3-day or lb VS/cu ft-day) [40, 54, 67]. However, SRT has now become the most important parameter for the system design and operation because it really defines the relationship between the bacterial system and digester operating condition.

Loading Rate The solids retention time, hydraulic retention time, reactor volume, and solids concentration determine the solids loading rate to a digester. These factors determine the amount of sludge the bacteria must stabilize and the amount of time the bacteria have to stabilize the sludge. The maximum loading rates possible for stable operation are determined mainly by microorganism growth and stabilization rates. In general, higher temperatures are associated with higher growth and stabilization rates, and therefore could result in higher solids loading rates. For anaerobic digester at a temperature of 35°C, the typical volatile solids loading rates are 1.6 to 3.2 $kg/m^3/d$ at SRTs from 15 to 20 days [2, 54].

Mixing Application of mixing domestic sludge digesters can provide efficient utilization of the entire reactor volume, prevent short-circuiting and temperature gradients, transport sludge solids from the bulk solution to the microorganism cell wall and disperse metabolic end products from the cell wall to the bulk solution, and maintain intimate contact between the bacteria, bacterial enzymes, and their substrates [2, 78]. In short, adequate mixing provides for a uniform environment to ensure good digestion. The effect of inefficient mixing is manifested in the decrease in effective system volume and hence a decrease in SRT. Other concerns with poor mixing are foaming and scum formation, and excessive solids deposition.

Studies with full-scale digesters have shown that inefficient mixing may reduce the effective volume of a digester by as much as 70% [55, 87]. A volume reduction of 70% at 35°C results in a process efficiency of less than the desired 90%, while a volume reduction of 70% at 30°C results in near washout conditions. Thus adequate mixing is critical if digesters are to operate as designed.

Environmental Factors

The anaerobic process is essentially biochemical in nature. The proper chemical environment is required for bacteria to grow. The following environmental factors are important.

Nutrients Nutrients must be provided in sufficient quantities to ensure efficient digestion. A commonly accepted, empirical formula for bacteria is $C_5H_7O_2N$ [76], in which nitrogen comprises approximately 12% of bacterial cell mass. Nitrogen is needed in the synthesis of proteins, enzymes, ribonucleic acids (RNA), and deoxyribonucleic acids (DNA). The phosphorus requirement for bacterial growth is about 1/7-1/5 of the nitrogen requirement [82].

Other nutrients such as iron, nickel, cobalt, sulfur, calcium, and some trace organics are also required, but in smaller amount [10, 20, 32, 61, 65, 66, 82, 89]. Domestic sludge usually contains sufficient quantities of nitrogen and phosphorus for bacterial growth [50]. However, some industrial wastes may require addition of nitrogen and phosphorus. It is also thought that domestic sludge has sufficient quantities of all nutrients.

pH Maintenance of system pH in the proper range is necessary for efficient anaerobic digestion. The widely accepted range is 6.5-7.6 [14, 50]. This range is determined by methanogenic bacteria, because they are most sensitive to pH changes. When system imbalance occurs, volatile acids produced by acetogenic bacteria increase at a faster rate than can be decomposed by the methane bacteria. The accumulation of acids result in a drop of pH.

If pH maintains at unacceptably low levels, methane production will decrease and may eventually cease.

Volatile acids Volatile acids are intermediates of sludge stabilization. Accumulation of volatile acids suggests that the utilization of the volatile acids is inhibited. There are conflicting reports about the inhibitory effects of volatile acids in anaerobic digestion. McCarty and McKinney [49] had earlier found that acetic acid in high concentration did not inhibit digestion. However, the experiments conducted by Kroeker [38]. suggested that propionic acid was inhibitory to laboratory digesters and it was postulated that it is the unionized volatile acids (UVA), that are toxic to the methane bacteria. Inhibition was observed to occur at UVA levels of 30-60 mg/L. Among many volatile acids, acetic acid is the predominant one and the following equilibrium exists:

$$CH_3COOH \Leftrightarrow CH_3COO^- + H^+ \quad \text{..... (4)}$$

It is clear that the concentration of UVA is dependent on the pH in a digester. To reach a UVA concentration of 30 mg/L at pH 7.0, a total volatile acid concentration of approximately 5,500 mg/L is required, while at pH 6.5, 1,800 mg/L of total volatile acids are needed. For a UVA of 60 mg/L, approximately 11,000 and 3,600 mg/L, at pH 7.0 and 6.5, respectively, are required.

In spite of some controversy as to whether the inhibition is due to the UVA or low pH, it is clear that high concentrations of volatile acids can be tolerated so long as the pH does not fall out of the optimum range of 6.5-7.6.

Alkalinity In anaerobic digesters the major acid-base system that controls pH is the carbonate-bicarbonate acid-base system. According to McCarty [51] when total volatile acids in a well balanced digester are low, bicarbonate alkalinity is approximately equal to total alkalinity. Digesters should have a bicarbonate alkalinity of 2,500 to 5,000 mg/L to neutralize volatile acids and prevent a drop in pH.

Toxicity Whether a substance is toxic to a biological system depends on the nature of the substance, concentration, and acclimation. Many substances will stimulate the reaction in low concentrations; however, they become inhibitory to the system as their concentrations increase. Substances commonly reported as inhibitory to anaerobic digestion include inorganics such as the alkali and alkaline-earth metals, heavy metals, ammonia-nitrogen, sulfide, and a wide variety of organic compounds. Table 3 contains a summary of the concentrations of inorganics thought to be inhibitory to anaerobic digestion. Table 4 lists concentrations of a variety of organics considered to inhibit anaerobic digestion.

Ammonia-Nitrogen Ammonia-nitrogen and bicarbonate alkalinity are produced during the digestion of organics containing nitrogen. Many studies [50, 51] have been reported that concentrations of ammonia between 50 and 200 mg/L are beneficial. McCarty reported that ammonia-nitrogen was considered to be toxic depending on pH [1, 50, 83]. It may exists in the form of the ammonium ion, NH_4^+, or as dissolved ammonia gas, NH_3,

Table 3. Concentrations of inorganics reported to be inhibitory to anaerobic digestion

Substance	Concentration, mg/L	
	Moderately inhibitory	Strongly inhibitory
Na^+	3,500-5,500	8,000
K^+	2,500-4,500	12,000
Ca^+	2,500-4,500	8,000
Mg^+	1,000-1,500	3,000
Ammonia-nitrogen	1,500-3,000	3,000
Sulfide	200	200
Copper (Cu)	----	0.5 (soluble) 50-70 (total)
Chromium VI (Cr)	----	3.0 (soluble) 200-260 (total)
Chromium III	----	180-420 (total) Nickel (Ni)
	----	2.0 (soluble) 30 (total)
Zinc (Zn)	----	1.0 (soluble)

Table 4. Concentrations of various organics inhibitory to anaerobic digestion

Organic	Inhibitory concentration (mg/L)
Formaldehyde	50-200
Chloroform	0.5
Ethyl Benzene	200-1,000
Ethylene Dichloride	5
Kerosene	500
Linear ABS (detergent)	1% of dry solids

as shown by the following equilibrium:

$$NH_3 + H_2O \Leftrightarrow NH_4^+ + OH^- \quad \text{..... (5)}$$

It is widely accepted that the toxicity is associated with free ammonia (NH_3-N). Concentrations above 100 mg/L may cause severe toxicity [37, 38]. It is believed that pH control can alleviate ammonia toxicity by maintaining free ammonia concentrations below 100 mg/L [50]. Therefore, a pH near 7.0 is recommended to prevent system failure due to free ammonia.

Different studies report various levels of ammonia-N at which it becomes toxic. McCarty reported that concentrations between 1,500 and 3,000 mg/L were inhibitory at pH levels above 7.4 and those in excess of 3,000 mg/L were toxic regardless of pH. Other researchers reported inhibitory of methane fermentation at ammonia-N concentrations near 2,000 mg/L [16, 38, 53].

Recent work indicates that ammonia-N toxicity may be responsible for the increased sensitivity of thermophilic digestion of domestic sludges compared to mesophilic digestion [22]. At thermophilic temperatures more ammonia-N is released due to the more complete degradation of proteinaceous materials.

Sulfides Lawrence et al. [41] found that soluble sulfides in excess of 200 mg/L caused significant decreases in methane production. Rudolfs and Ambers [71] observed a decreased gas production of near 30% following addition of 200 mg/L sulfide.

Feed Characteristics As mentioned before, anaerobic digestion was first used for the treatment of primary sludges. Now it is more commonly applied to biological sludge (typically from activated sludge and trickling filter processes) and to mixtures of primary and biological sludge. There is an inherent difference in the biodegradability of primary sludge and waste activated sludge. Based on O'Rourke's data [62], McCarty [47] estimated that the COD contained in primary sludge is 69% biodegradable and the volatile solids of PS is also approximately 69% biodegradable. Therefore, at a very long digester SRT there would be nearly 69% reduction of COD and VS. Typical values in the literature are 40-60% reduction in COD and 40-70 reduction in VS [31, 33, 54, 84]. Reductions in BOD vary from 60 to 90% [51, 54]. The reduction in COD or VS is a function of SRT as mentioned before, and relative process efficiency can be estimated by comparing the observed reduction with the reported ultimate biodegradability.

It is generally believed that WAS is approximately "half as digestible as primary sludge." The degradable portion of WAS is comprised primarily of active bacterial cells. The estimated biodegradable fraction of WAS is 68% [27]. However, this does not mean that WAS is 68% degradable, because WAS also contains nonbiodegradable debris from dead bacterial cells and refractory organics not removed by primary sedimentation. Stuckey [84] reported the ultimate anaerobic biodegradability of WAS to be 48-53% of the COD under mesophilic conditions and 45% under thermophilic conditions. The observed COD or VS reduction reported in the literature [24, 27, 46, 54, 57, 84] varies in a range of 20-50% under mesophilic conditions (30-38°C) and 36-50% under thermophilic conditions (50-65°C). Thus,

WAS is less biodegradable than primary sludge. Even at very long SRTs, the reduction of COD or VS are generally less than 50%.

Thermophilic Anaerobic Digestion

Most wastewater treatment plants are employing anaerobic digestion systems to treat wastewater sludge, either primary sludge or waste activated sludge or mixtures of both. Almost all anaerobic digesters for sludge treatment are operated in the mesophilic range. Very few are operated at a thermophilic temperature. The reason behind this is that thermophilic anaerobic digestion system is thought to have following disadvantages:

(1) high energy requirement for heating,

(2) high volatile fatty acids in the effluent, resulting poor supernatant quality, and

(3) poor process stability.

However, thermophilic anaerobic digestion can offer several advantages over mesophilic anaerobic digestion:

(1) increased volatile solids removal,

(2) increased destruction of pathogenic organisms, and

(3) improved dewatering ability of the digested sludge.

The earlier research on thermophilic anaerobic digestion began in the 1930s. In 1930, Rudolfs and Heukelekian [70] conducted bench scale experiments using thermophilic anaerobic digestion to treat primary municipal sludge. They observed a higher yield of gas per gram of volatile matter added and a greater percentage of volatile solids destruction. There

was no significant difference in gas composition at the mesophilic and thermophilic temperatures. They operated their system at different temperatures of 45-55°C and SRTs from 11 to 15 days. They stated that the thermophilic anaerobic digestion system for the treatment of primary municipal sludge was applicable and that the SRT in this temperature range from 45 to 55°C was shorter than for the mesophilic temperature range.

The earliest plant scale study of thermophilic anaerobic digestion was conducted by Fischer and Greene [19] in 1930s. Their plant scale thermophilic anaerobic digestion system was operated at a temperature of 54°C at Aurora, Illinois in 1931. The system was fed primary sludge only. The SRT was 12.9 days, and the organic loading was 0.45 kg volatile matter/m^3/d (0.028 lb/ft^3/d). It was observed that volatile solids removal in the thermophilic anaerobic digestion (56.4%) was higher than that in the mesophilic digester (50.5%).

There were several plant scale studies in 1940s. Fischer and Greene [19] began their research on full-scale thermophilic anaerobic digestion system in 1942. They had run their thermophilic anaerobic digestion system in Jackson, Michigan for three years. Two three-stage digesters were used. Only the primary tanks were heated and operated at temperatures of 29 and 52°C, respectively. Both systems were fed with a mixture of 1 to 3 volumetric ratio of primary and waste activated sludge. The total solids content of the mixture was 5.2% with volatile part of 64% in the total solids. The primary tanks of two three-stage systems had the same SRT of 27 days and the same organic loadings of 0.53 kg volatile matter/m^3/d (0.033 lb/ft^3/d). The primary stage of the thermophilic digester achieved 44.2 % volatile solids destruction, higher than 38.0 % achieved by the primary tank of the mesophilic digester. Gas

produced from the thermophilic unit per kg of volatile matter destroyed was also a little bit higher than that from the mesophilic unit(1.08 vs 1.0 m^3). The thermophilic sludge from the primary tank had a higher solids concentration (3.8 vs 3.3%) and the supernatant from the third stage of the thermophilic unit was of higher quality than that from the third stage of the mesophilic unit.

There were more extensive plant scale studies of thermophilic anaerobic digestion in 1950s. Garber [21, 22] conducted one of the most extensive plant-scale tests of thermophilic anaerobic digestion in the U.S. The full-scale anaerobic digestion system was operated from 1953 to 1957 at the Los Angeles Hyperion Plant. The system was a simple single-stage anaerobic digester and was fed with a mixture of approximately 70% primary and 30% waste activated sludge. The total solids content of the mixture was 6.4%. The anaerobic digester were operated at three different temperatures of 29, 38 and 49°C. Two different detention times of 12 and 24 days and organic loadings of 2.1 and 3.8 kg volatile solids/m^3/d (0.13 and 0.24 lb/ft^3/d) were used. They reported a 54% of the volatile solids destruction At a thermophilic temperature of 49°C, a 54% of the volatile solids destruction was achieved for both loadings and detention times. This was the highest volatile solids removal achieved by the system compared to that obtained at other temperatures. The gas production per kg of volatile solids destroyed was approximately the same at all temperatures. Higher volatile fatty acids concentrations were observed in the thermophilic digesters, varying from 600 to 800 mg/L while concentrations of volatile acids at other temperatures varied in a range from 100 to 200 mg/L.

Popova and Bolotina [67] reported the plant scale tests on the anaerobic digestion in a 1 million m^3/d (260 MGD) treatment plant in Moscow, U.S.S.R. The test began in 1944, and in 1958 the convertion of all of the digesters from mesophilic to thermophilic was complete and they were operated at a temperature of 51°C. The digesters were fed with a mixture of primary and waste activated sludge. The total solids level varied in a range from 3 to 7% with a volatile part of 70% in the total solids. Steam injection with recirculation of the steam-sludge mixture was applied for heating and mixing. The application of the thermophilic digestion reduced the detention time from 18 to 9 days and resulted an increase in organic loading from 1.65 up to 3.5 kg volatile solids/m^3/d, with an organic solids destruction of up to 50%. The sanitery quality was improved significantly. The thermophilic digestion system achieved complete viable helminth eggs destruction, while only 80% reduction of viable helminth eggs was obtained through the mesophilic digestion system. At end of 1950s, Golueke [28] conducted bench scale tests to investigate the impacts of temperatures on the digestion of primary sludge. The same detention time of 30 days and an organic loading of 1.4 kg volatile matter/m^3/d (0.09 lb/ft^3/d) were applied to the system, but at different operating temperatures. Because of this long detention time and low solids loading, no significant difference in solids destruction for temperatures ranging from 35 to 55°C was observed. Gas production rates, gas composition, and general sludge appearance were nearly the same at temperatures ranging from 35 to 60°C. However the sludge produced at 50 °C and 60 °C showed significant difference in their dewatering characteristics, as measured by the amount of coagulant required. Higher coagulant dosage was required for the sludge produced at 50 °C

than at 60 °C. They also observed that sludges produced at the higher temperatures had higher volatile acids concentrations.

Another similar study on the effects of temperature on the performance of anaerobic digestion was conducted by Malina. The substrate he used was waste activated sludge. The system was operated at the same SRT of 6 days and the same organic loading of 4.8 kg volatile matter per cubic meter per day. At a temperature of 52.5°C, the system achieved 42% volatile solids destruction. At temperatures of 42.5 and 32.5°C the volatile solids destruction was a little bit low, 41 and 39%, respectively, which were not significantly low. Higher volatile acids concentrations were also observed at the higher temperatures.

Since 1972, Garber et al. [22] continued their research on thermophilic anaerobic digestion. Their plant-scale thermophilic anaerobic digester was operated at 46-51°C. They reported that the operation of a thermophilic anaerobic digester is similar to that of a mesophilic anaerobic digester. However the thermophilic anaerobic digestion system is more sensitive to temperature change. High volatile acids concentrations were observed when the digester temperature was raised to 52°C. Garber [22, 23] further reported that thermophilic operation was able to achieve much higher destruction of pathogenic bacteria.

At the end of 1970s, Rimkus [69] conducted another extensive plant-scale test at the West-Southwest Sewage Treatment Works, Chicago, Illinois. The system was fed with a mixture of WAS and PS with 90% of WAS and 10% of PS. The thermophilic anaerobic digester was operated at a temperature of 52.7°C and an SRT of 7 days. They reported an increase in volatile solids destruction (34.0%) compared to mesophilic anaerobic digester

(31.3%). The higher concentration of volatile acids were observed and hence the thermophilically digested sludge had a greater odor intensity than mesophilically digested sludge. A remarkable reduction in foaming in the thermophilic anaerobic digester was observed and no adverse effects due to temperature change (3°C) were experienced in the thermophilic digester in a 24-hour period. They concluded that operation of the thermophilic anaerobic process did not require any greater knowledge or skills by the operating personnel than that required for the mesophilic process.

In the 1980s, there was not much research on thermophilic anaerobic digestion. Instead, some modification was made to overcome the disadvantages of the thermophilic anaerobic digestion. Torpey [88] studied the multiple digestion (mesophilic/thermophilic) in New York City at the Rockaway Wastewater Treatment Plant. A two-stage digestion system, consisting of a mesophilic stage, followed by a thermophilic stage, was used. He observed a volatile solids destruction of 60%, improved dewatering characteristics, and high stability of the system.

At the end of 1980s, Lee et al. [42] conducted a lab-scale study to investigate the pathogen destruction through thermophilic anaerobic digestion. A two-phase system at a thermophilic temperature of 53°C was operated and a mixture of WAS and PS with a 2:1 volumetric ratio was used as substrate. They reported a significant increase in volatile solids removal in the thermophilic acid-phase digester and much higher fecal coliform destruction in all thermophilic units than that in mesophilic units.

Most recently Dague et al. [29, 30, 35] developed an innovative process, temperature

phased anaerobic process (TPAP). They reported that the new system was able to combine the advantages of both thermophilic and mesophilic anaerobic reactors and avoid the disadvantages of both. Han and Dague [29] investigated the temperature-phased anaerobic digestion (TPAD) system for treating primary sludge. They found 18% higher volatile solids removal and much higher total and fecal coliform destruction achieved by TPAD compared to conventional mesophilic anaerobic digesters and volatile acids level in the effluent from TPAD was the same as that from conventional mesophilic digester.

Development of Temperature-Phased Anaerobic Digestion

In 1992, Harris conducted a comparative study of mesophilic and thermophilic anaerobic filters under Dr. Dague at Iowa State University. At first the filters were operated in parallel at 35 and 55°C and non-fat dry milk was used as the substrate. The thermophilic filters produced a lower quality effluent than the mesophilic filters at high organic loading rates. At the end of the study, it was decided to run the filters in series with the thermophilic filter as the first stage and the mesophilic filter as the second stage. This temperature-phased anaerobic filter system was able to achieve over 90% total COD removal at system loadings up to 20 g/L/d. Further research on this system was conducted by Kaiser (35). In her study three sets of filter system with a thermophilic first stage and mesophilic second stage were tested. The system were operated at HRTs of 24, 36, and 48 hours and achieved soluble COD removals from 96.9 to 99.5% and total COD removals from 89.8 to 98.5%. In 1993, Steinbach and Dague applied the concept of temperature phase to Anaerobic Sequencing Batch Reactor

(ASBR). Similarly to the previous research, two ASBRs were operated in series, with the first stage at a thermophilic temperature of 55°C and the second stage at a mesophilic temperature of 35°C. Non-fat dry milk was used as substrate. The system was able to achieve soluble COD removals greater than 97% and total COD removals greater than 90% at system HRTs of 54 and 18 hours.

Han and Dague (1994) conducted a lab-scale study on the application of thermophilic anaerobic digestion for treatment of domestic wastewater sludge (primary sludge). Two completely stirred tank reactors (CSTRs) were applied as the temperature-phased anaerobic digestion system with the thermophilic unit (55°C) as the first stage and mesophilic unit as the second stage. They observed 18% higher VS removal for the TPAD system over conventional mesophilic anaerobic digester and a 5 to 6 log reduction of total and fecal coliforms through TPAD compared to less than one log reduction by conventional single-stage anaerobic digestion system. The biogas composition was similar at thermophilic and mesophilic unit.

III. EXPERIMENTAL STUDY

This study was conducted from August 1994 to July 1996. Lab-scale reactor system were set-up and operated under different conditions. Data were collected at various SRTs after the system reached the steady-state.

Experimental Set-Up

Two TPAD systems were designed with different volume ratios of the first stage to the second stage. For comparison, a single-stage system was set-up and run simultaneously with the TPAD system. The volume and dimensions of the reactor system was designed according to the goal of the study. The whole system consisted of feeding tank, reactor, and biogas measurement unit.

Design and Dimensions of Reactors

The laboratory set-up consisted of three systems. One is a conventional, single-stage system, operated at a temperature of 35°C. The other two systems were temperature-phase anaerobic digesters (TPAD). The first stage was operated at a thermophilic temperature of 55°C and the second stage operated at a mesophilic temperature of 35°C.

Five Plexiglas reactors were used, one for the single-stage system and the other four (4) for the two TPAD systems. All five (5) reactors were fabricated by the Engineering Research Institute (ERI) Machine Shop at Iowa State University. Reactor 1 (R1) for the

single-stage system, shown in Figure 2, had a working volume of 14 liters. The reactor height was 45 cm and the inside diameter was 21.6 cm. The wall thickness was 0.64 cm. The top flange had a diameter of 26 cm and a thickness of 1 cm. It was attached to the reactor flange by 8 hex-head bolts. The flanges were sealed by a 0.32 cm O-ring which fits into a groove in the reactor flange. Mechanical mixing was applied to all five reactors. The mixer of R1 had a shaft length of 37 cm. The diameter of the paddle was 8 cm.

The two-stage system A consisted of two reactors (R2 and R3) with R2 as the first stage and R3 as the second stage. The working volumes of R2 and R3 were 4 and 10 liters, respectively. The total working volume of the two-stage system A therefore was 14 liters, the same as the volume of the single-stage system. The volume ratio of the first stage to the second stage was 2:5. Two-stage system B consisted of two reactors (R4 and R5) with R4 as the first stage and R5 as the second stage. The working volume of R4 was only 2 liters while R5 had the same working volume as R3, 10 liters. Thus the total working volume of two-stage system B was 12 liters and the volume ratio of the first stage to the second stage was 1:5. The structure of all five reactors was similar. The dimensions of R2, R3, R4, and R5 are shown in Figures 3, 4, 5, and 6, respectively.

Each of five reactors had four ports on the top flange. The center port was for instillation of the mixer and the other three were for influent, effluent, and gas tubings, respectively. All the ports had the same diameter of 1 cm.

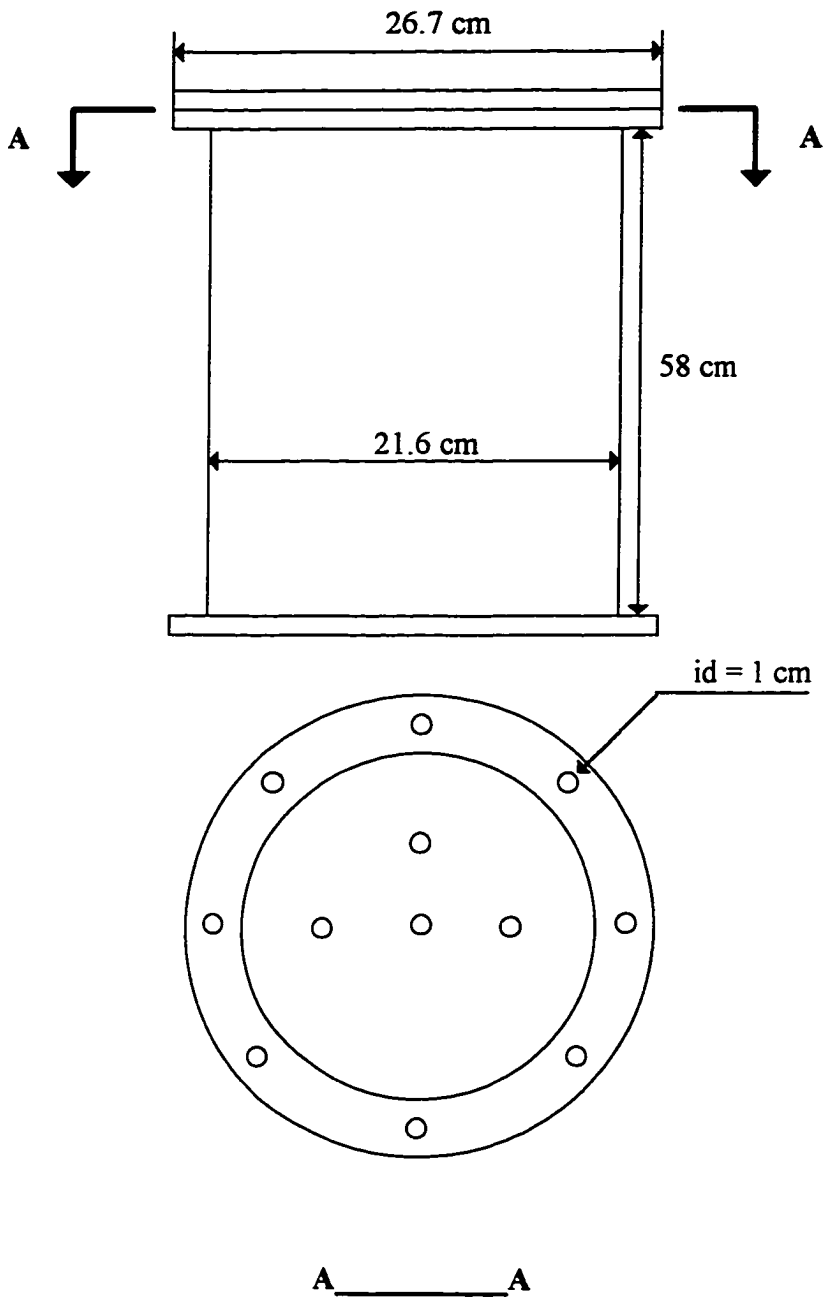


Figure 2. Dimensions of Reactor 1 (R1)

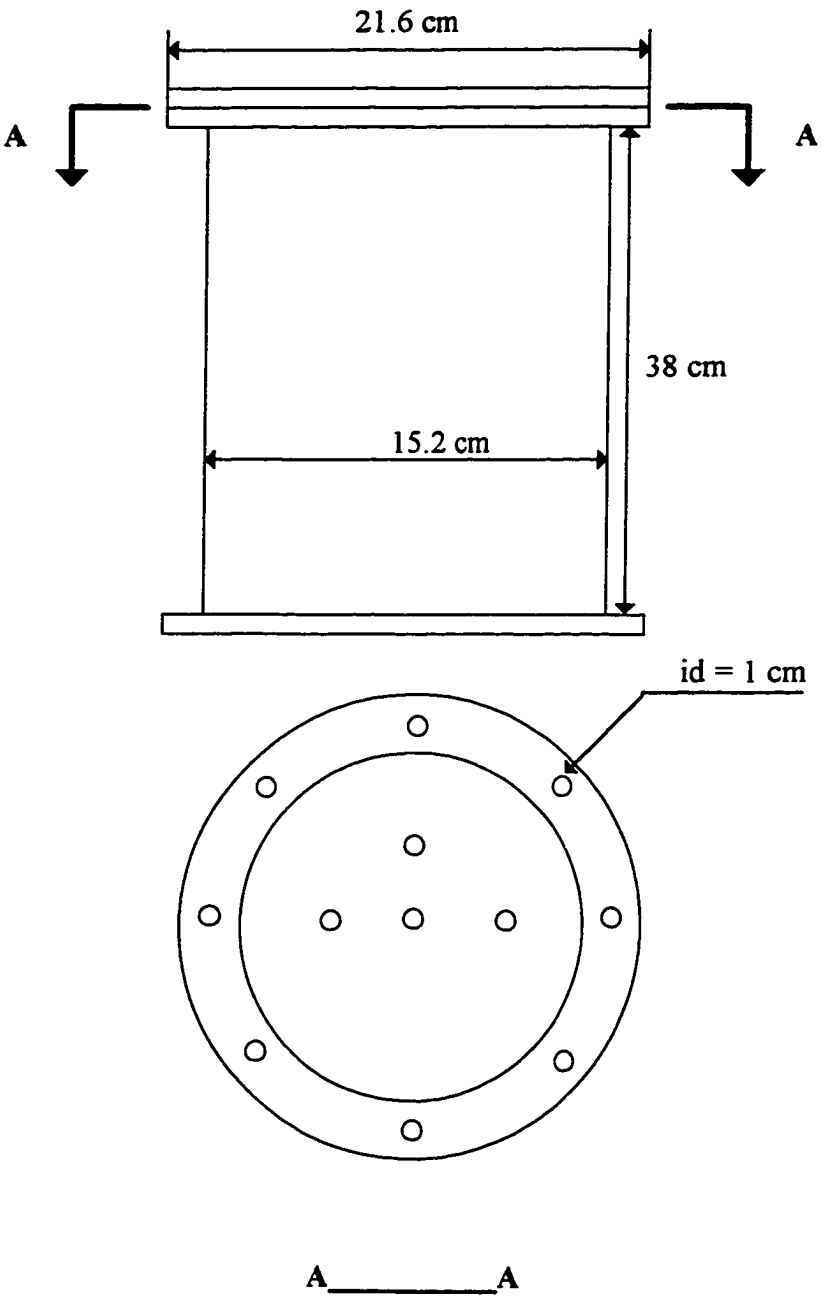


Figure 3. Dimensions of Reactor 2 (R2)

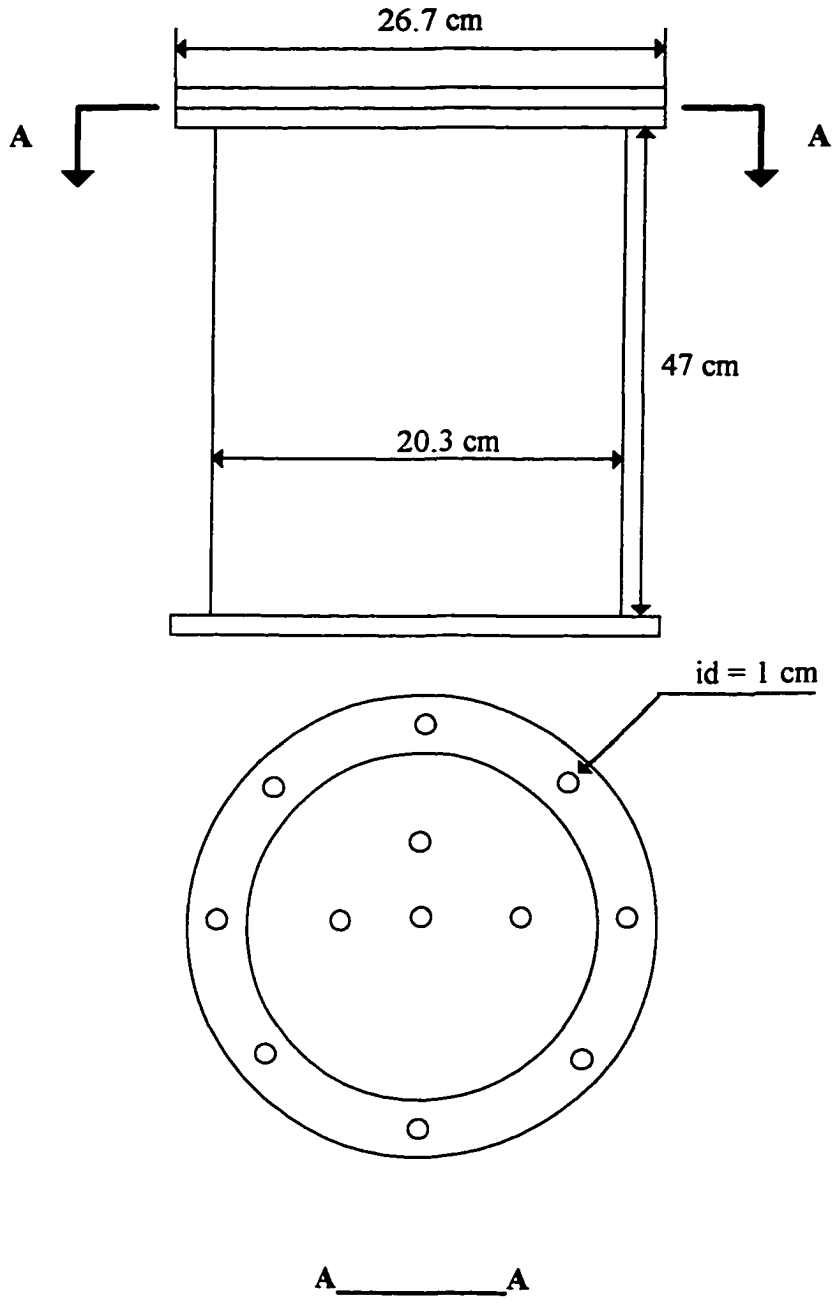


Figure 4. Dimensions of Reactor 3 (R3)

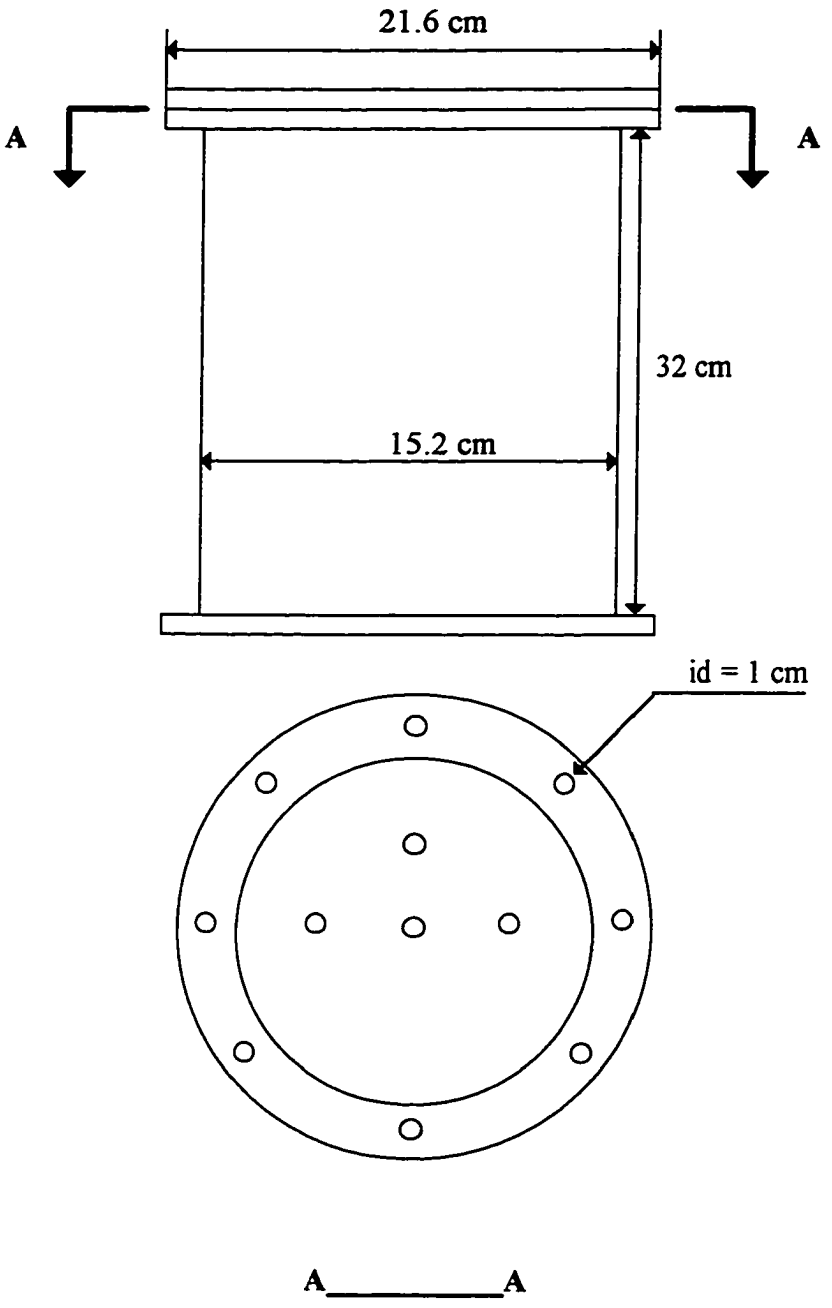


Figure 5. Dimensions of Reactor 4 (R4)

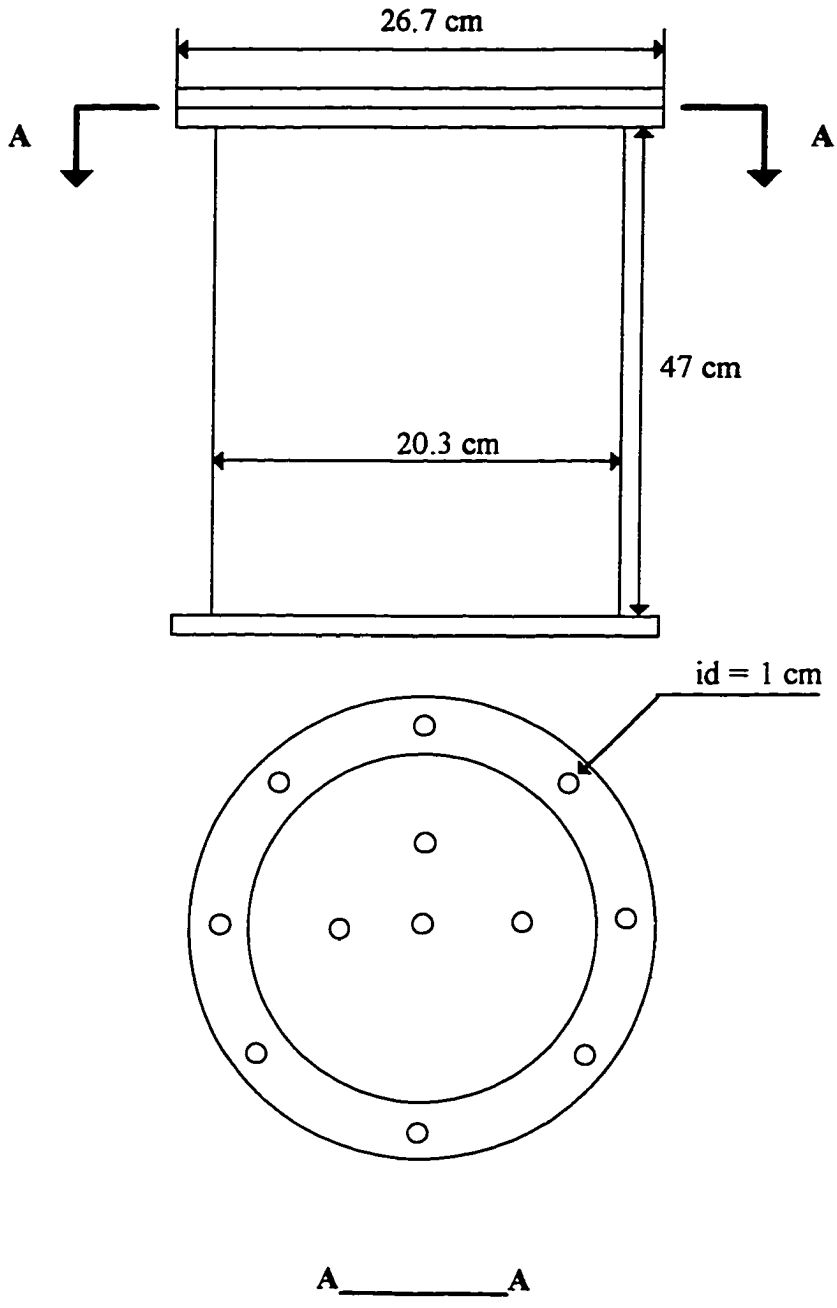


Figure 6. Dimensions of Reactor 5 (R5)

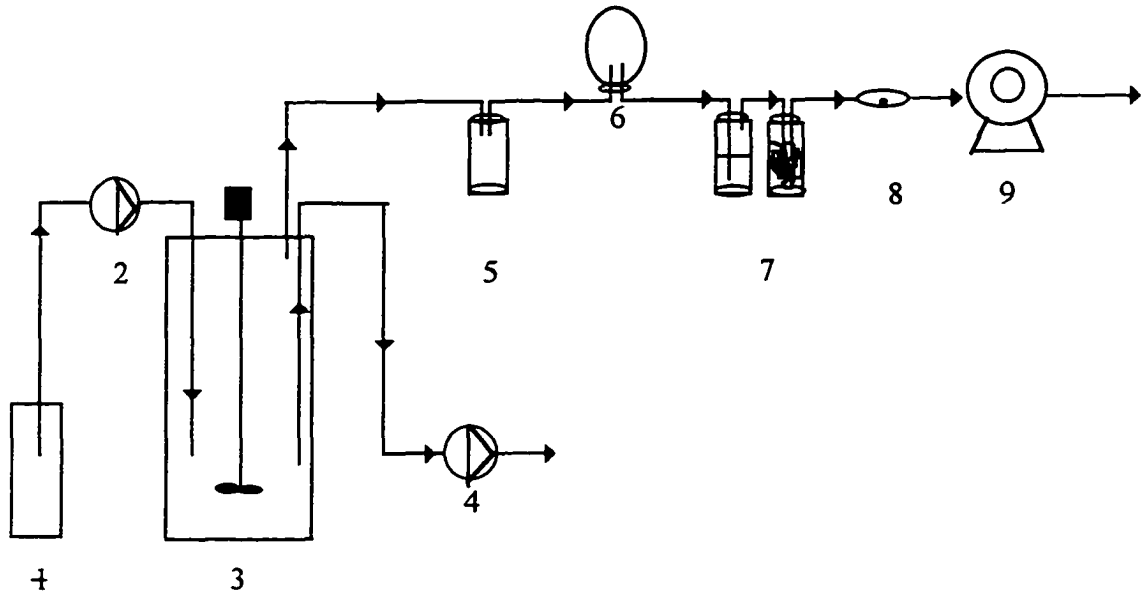
Reactor Configuration and Equipment

The single- and two-stage systems were set-up in a constant temperature room maintained at a temperature of 35°C. The first stage of the two-stage system A and B were heated to 55°C using a water bath maintained at a constant temperature of 55°C.

The configurations and the relative equipment of the single-stage and the two-stage systems are shown in Figures 7 and 8, respectively.

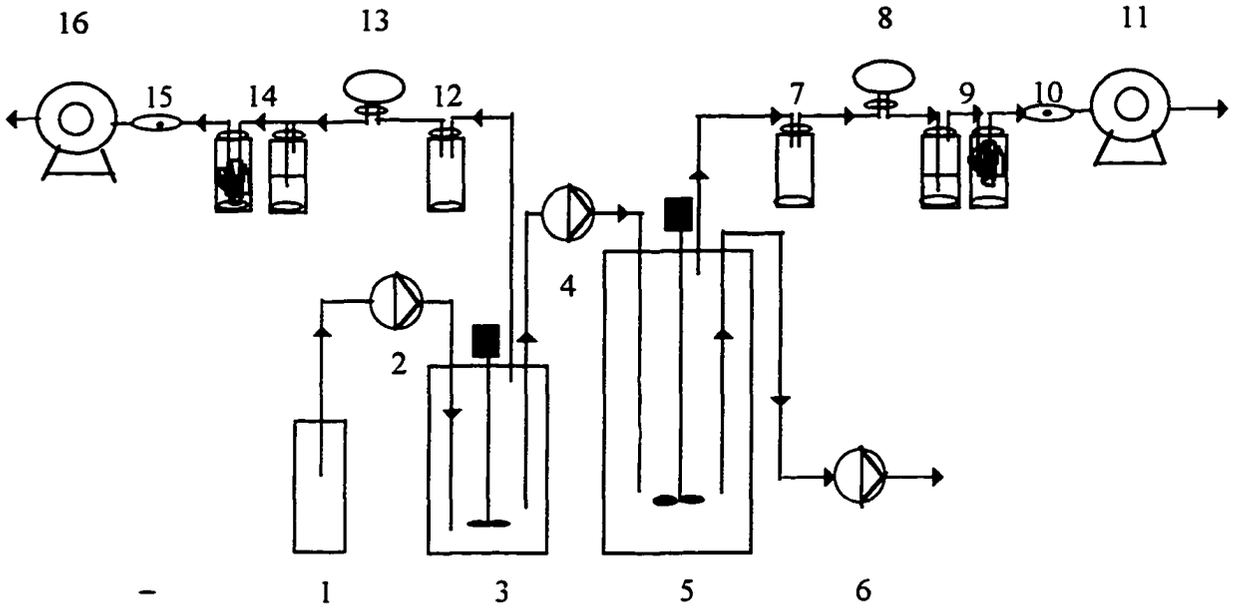
The single-stage system consisted mainly of three parts: a feeding tank, a reactor, and a gas measuring unit. The substrate was stored in the feeding tank in a refrigerator at a temperature of 4°C. The reactor was fed semicontinuously (24 times/day) by a masterflex pump. All pump heads were masterflex size 18. Tygon tubings with an inside diameter of 3/8" (0.95 cm) were used to connect various components. The moving direction of the substrate and biogas through the system are indicated by arrows in Figure 7.

The substrate was pumped into the reactor and was digested in it. The reactor was fully mixed by a mixer driven by T-Line Laboratory Stirrer (Talboys, Engineering Corp., Emerson, NJ). The operating temperature of the reactor was 35°C. The digested sludge was pumped out by a masterflex pump and discharged to the sewer. The biogas produced passed through the gas measuring unit into a vent. Foam was separated in the foam separation bottle. A gas bag was used to avoid pulling a vacuum when the digested sludge was withdrawn from the reactor. The gas was cleaned by a sulfide scrubber and measured by a Wet-Tip Gas Meter produced by Rebel Point Wet-Tip Gas Meter Co. (5840 Robert E. Lee Dr., Nashville, TN 37215). Gas samples were taken from the sample port.



1. Feeding tank 2. Feeding pump 3. Single-stage digester (R1) 4. Effluent pump
5. Foam separation bottle 6. Gas bag 7. Sulfide scrubbers 8. Gas sample port
9. Gas meter

Figure 7. Diagram of the single-stage digestion system



1. Feeding tank 2. Feeding pump 3. First stage digester 4. Pump
5. Second stage digester 6. Effluent pump 7, 12. Foam separation bottles
8, 13. Gas bags 9, 14. Sulfide scrubbers 10, 15. Gas sampling ports 11, 16. Gas meters

Figure 8. Diagram of the two-stage digestion system

The two-stage system was arranged with two reactors in series. The substrate was fed from the feeding tank into the first stage by a masterflex pump. The effluent from the first stage was pumped into the second stage. The first stages, R2 and R4, were set in a water bath held at a constant temperature of 55°C. An Isotemp Immersion Circulator was used to heat the water bath (Fisher Scientific). The gas measuring units for R2, R3, R4, and R5 were the same as that for R1. The same kind of mixers were used for all five reactors.

Experimental Procedure

After all systems were set-up, each reactor was seeded and fed with substrate. Following successful start-up of the system, reactors were operated under various conditions and daily monitoring work was done to maintain their normal operations.

Substrate

The substrate fed to the system was a mixture of primary and waste activated sludge. In order to study the impact of WAS on the mixture and to get information over a range of different ratios of PS and WAS, two typical ratios were chosen, 1:1 and 1:3 (volume ratio of PS to WAS). Both the PS and WAS were obtained from Marshalltown, Iowa, Water Pollution Control Plant (WPCP). The WAS had an approximate total solids (TS) content of 4%. The TS content of the PS varied in a range from 3 to 5%, but was adjusted to 4% by either dewatering or dilution. Each batch was used for 2-4 weeks and was stored in a refrigerator at 4°C before feeding to the system. Because of the low temperature and short

storage time, the composition of the PS and WAS maintained nearly the same for each batch. The primary sludge was screened with a No. 5 (opening 4.00 mm) sieve to avoid clogging of the tubing system. The mixture was made according to the desired volume ratio, 1:1 or 1:3 (PS : WAS). The characteristics of the Marshalltown primary sludge and waste activated sludge are shown in Table 7.

Table 7. Characteristics of Marshalltown Primary and Waste Activated Sludges

	Primary Sludge	Waste Activated Sludge
Total Solids, %	3.0-5.0	3.7-4.2
Volatile Solids, %	2.9-3.2	3.0-3.3
Chemical Oxygen Demand, g/L	50-70	45-65
Total Coliforms, MPN/gTS	10^7-10^9	10^5-10^8
Fecal Coliforms, MPN/gTS	10^6-10^8	10^5-10^7
Alkalinity, mg/L as $CaCO_3$	800-1500	1000-1700
pH	5.0-6.5	5.5-6.5

Reactor Start-Up

The single-stage and the second stage of the TPAD system were seeded initially with digesting sludge from the mesophilic anaerobic digester at the Marshalltown, Iowa, WPCP. The first stages of TPAD systems were thermophilic and therefore seeded with thermophilic digesting sludge available from ongoing research. Start-up of the temperature-phased anaerobic digesters A and B took one month while holding the SRT/HRT for these two systems at 14 and 12 days, respectively. The start-up of the single-stage system at an SRT of

20 days suffered serious foaming and the system eventually failed. It was then decided to start it at an SRT of 24 days. This time the system did not fail, however foaming was still severe.

Operation of the System and Daily Maintenance

Both single and TPAD system were operated in a semicontinuous manner by feeding and withdrawing sludge from them 24 times per day. Each reactor was fully mixed intermittently by a mechanical mixer, on a 4-minutes mixing of 5-minute cycle. The reactor was withdrawn first and then fed with the substrate. For the two-stage system, the second stage was withdrawn first and then the first stage. The effluent from the first stage was fed to the second stage, while the first stage was fed last with substrate from the feeding tank. Before each feeding, the sludge in the feeding tank was mixed completely by a mechanical mixer to ensure the TS content was consistent all times.

In addition to data collection, some routine maintenance work was done often to keep each system running normally. This kind of work included (1) recording the gas meter reading for all five reactors at the same time every day; (2) recording the temperature and pressure in the laboratory; (3) adding substrate to the feeding tank; (4) checking the temperature in the constant temperature room and of the water bath, and (5) maintaining all equipment at normal operating conditions.

Experimental Testing

Several tests were conducted on the systems. These included (1) influent and effluent total solids and total volatile solids, (2) influent and effluent COD, (3) influent and effluent total coliform and fecal coliform, (4) effluent volatile fatty acids, (5) effluent alkalinity, (6) influent and effluent pH, and (7) biogas composition.

Total Solids (TS) and Total Volatile Solids (TVS)

The TS and TVS tests were conducted according to Standard Methods [24]. Evaporating dishes were used for these tests. The evaporating dishes were dried in a 530°C muffle furnace for 1 hour and weighed just before use. A sample volume of 10 to 20 mL was added to the dishes and they were dried in a 103°C oven for 1 hour. After drying, the dishes were cooled in a desiccator for not less than one hour and then weighed. The total solids in the samples were then calculated as:

$$TS = \frac{(B - A)}{V} * 1{,}000 \quad \text{..... (6)}$$

where:

TS = total solids concentration in the sample, g/L

B = the weight of evaporating dish with dried residue, grams

A = the weight of evaporating dish, grams

V = the volume of the sample, mL

To determine TVS, the dishes with residue were placed in the 550°C muffle furnace for 20 minutes for volatilization of the non-inert material in the samples. After burning, the dishes were cooled for one hour in a desiccator and then weighed again. The TVS was calculated as:

$$TVS = \frac{(B - C)}{V} * 1{,}000 \quad \text{..... (7)}$$

where:

TVS = total volatile solids concentration in the sample, g/L

B = the weight of the dish after drying, grams

C = the weight of the dish after burning, grams

V = the volume of the sample, mL

Chemical Oxygen Demand (COD)

The COD test was conducted according to Standard Methods [24]. Test tubes with Teflon-line screw caps were used for this test. A sample volume of 5 mL was put in the tube and then 3 mL of 0.1 normal $K_2Cr_2O_7$ containing 33.3 mg/L $HgSO_4$, and 7 mL concentrated H_2SO_4 containing 10.0 mg/L $AgSO_4$, were added to the sample. The prepared samples were placed in a 150°C oven for 2 hours, after which they were titrated to the ferrous endpoint with 0.1 normal ferrous ammonium sulfate (FAS). Two blanks and two standards, which used 5 mL of distilled water instead of sample, were used to standardize the $K_2Cr_2O_7$ and FAS, respectively. They were treated exactly the same as the samples, except that the standards were not placed in the oven. The COD of a sample was calculated as:

$$COD = \frac{(A - B) * M * 8{,}000 * DF}{V} \quad \text{..... (8)}$$

where:

COD = chemical oxygen demand of the sample, mg/L

A = volume of FAS required to titrate a sample to the ferrion endpoint, mL

B = volume of FAS required to titrate a sample to the ferrion endpoint, mL

M = molarity of the FAS solution, mol/L

DF = dilution factor of the sample

V = sample volume, mL

8,000 converts mol FAS to mg O_2

Coliform and Fecal Coliform Tests

Since human fecal pathogens vary in kind (bacteria, protozoa, viruses) and in number, it would be impossible to test each sample for each pathogen. Instead, an indicator organism is generally used to suggest the possible presence of pathogens by indicating the presence of fecal material. Coliform and fecal coliforms are such indicators.

The coliform group is comprised of Gram-negative, nonspore-forming, aerobic to facultatively anaerobic rods, which ferment lactose to acid and gas at 35°C in 48 hours. The major organisms in the coliform group are E. coli, Enterobacter aerogens, and Klebsiella pneumoniae. A subgroup of the coliforms, the fecal coliforms, consists of Gram-negative, nonspore-forming, facultative anaerobic rods, which ferment lactose to acid and gas at 44.5°C in 48 hours.

These tests were conducted according to the standard procedure [83]. Durham tubes were used for these tests. Lactose Lauryl Tryptose Broth was used as incubation solution, which had a composition as follows:

Tryptose	20.0 g
Lactose	5.0 g
K_2HPO_4	2.75 g
KH_2PO_4	2.75 g
NaCl	5.0 g
Na lauryl sulfate	0.1 g
Distilled Water	1000 mL

After the lactose broth was added in Durham tubes, they were placed in an autoclave at a temperature of 121°C and a pressure of 15 psi for 20 minutes. After sterilization by the autoclave, they were cooled at room temperatures. Two series of tubes were prepared, one series of tubes for coliform and the other for fecal coliform. The samples were diluted by different amounts: 10, 100, 1000, ..., depending on the coliform concentrations to be analyzed. For each dilution, six tubes were inoculated each with one mL of the diluted sample. They were incubated for 48 hours at 35°C and 44.5°C, respectively. The tubes with gas production were recorded as a positive reaction and those without gas production as negative. The Most Probable Number (MPN) Table [61], shown in Table 6, was used to calculate the MPN of coliforms and fecal coliforms in each sample. This table represents a statistical evaluation of the probability of finding a given number of organisms in a sample for any given series of results. For example, the number of tubes showing gas was 3 out of the 3 inoculated with the undiluted sample, 2 out of 3 inoculated with the 10^{-1} dilution, 1 out of 3 inoculated

with the 10^{-2} dilution, and 0 out of 3 inoculated with the 10^{-3} dilution. Listing the positive results in order, gives 3-2-1-0. Choosing the three numbers in this series which just reach 0 (2-1-0), use Table 6 to determine the MPN of coliforms in the original sample. Note that 2-1-0 gives an MPN of 0.15 coliforms per inoculum (which was 1 mL for this dilution) of the middle dilution in that series, or 0.15 coliforms per mL at $1/10^{-2}$ dilution which equals 15 coliforms MPN/mL of the sample.

Volatile Fatty Acids (VFA)

VFA tests were conducted using a modified distillation approach [24]. A sample of 100 mL volume was taken from the reactor effluent and added to 100 mL of distilled water and 5 mL of concentrated sulfuric acid. This solution was distilled on electric heating plate and condenser with 150 mL of the distillate collected and titrated to a pH value of 8.3 using 0.1 N NaOH. The VFA of the sample was calculated as:

$$VFA = \frac{V_{NaOH} * (0.1) * (60{,}000)}{V_{sample} * (0.7)} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

where:

VFA = volatile fatty acid concentration in the sample, mg/L as acetic acid

V_{NaOH} = volume of 0.1 N NaOH used to titrate the sample to pH of 8.3, mL

0.1 = normality of NaOH solution, equivalents/L

60,000 = milliequivalent weight of acetic acid, mg/equivalent

V_{sample} = volume of the sample taken from a reactor, 100 mL

0.7 = assumption that 70% of the VFA's are accounted for by this method

Table 6. Three-tube most probable number (MPN) table [61]

Combination of positives	MPN per inoculum of the middle dilution	Combination of positives	MPN per inoculum of the middle dilution
0-0-0	<0.03	2-3-0	0.29
0-1-0	0.03	3-0-0	0.23
0-2-0	0.062	3-0-1	0.39
1-0-0	0.036	3-0-2	0.64
1-0-1	0.072	3-1-0	0.43
1-1-0	0.11	3-1-1	0.75
1-1-1	0.11	3-1-2	1.20
1-2-0	0.11	3-2-0	0.93
2-0-0	0.09	3-2-1	1.50
2-0-1	0.14	3-2-2	2.10
2-1-0	0.15	3-3-0	2.40
2-1-1	0.20	3-3-1	4.60
2-2-0	0.21	3-3-2	11.00
2-2-1	0.28	3-3-3	>24.00

Alkalinity

Alkalinity was measured by a titration method. A certain volume of the sample was titrated to pH 4.5 using 0.1 N H_2SO_4. The alkalinity was calculated as:

$$Alk = \frac{V_a * (0.1) * (50{,}000)}{V_s} \quad \text{..... (10)}$$

where:

Alk = alkalinity of the sample, mg/L expressed as $CaCO_3$

V_a = volume of H_2SO_4 used to titrate sample to pH 4.5, mL

0.1 = normality of H_2SO_4, equivalents/L

50,000 = milliequivalent weight of $CaCO_3$, mg/equivalent

V_s = volume of the sample, mL

pH

The effluent pH was measured every three days. The influent pH was measured whenever a new batch of feed was prepared. All pH measurements were made using a pH meter, which was calibrated before each measurement using standard pH solutions of 7.00 and 10.00.

Biogas Composition Analysis

The composition of the biogas produced from each reactor was determined by gas chromatography (GC) once every week. Samples were collected using a 1-mL syringe

(Hamilton Company, Reno, NY) equipped with metal hub needles (Alltech Associates, Inc., Deerfield, IL). A biogas sample of 0.9 mL was withdrawn from the gas sampling ports and the gas was then injected into the GC. The GC column used for the analysis detected relative proportions of nitrogen, methane, and carbon dioxide. The GC was calibrated using a custom-made gas standard (Union Carbide Industrial Gases, Inc., Specialty Gas, East Chicago, IN) which contained 5% nitrogen, 70% methane, and 25% carbon dioxide. The characteristics of the GC are shown in Table 7.

Table 7. GC parameters for biogas analysis

Item	Specification
Gas chromatography	Hewlett Packard 5730A
Column	6 ft*0.125 in, stainless steel
Packing	Porapak Q, 80/100 mesh size
Temperature	Ambient
Carrier gas	Helium
Flow rate	30 mL/minute
Detector	Thermal Conductivity
Temperature	200°C
Injection block temperature	100°C
Data station	Maxima Data Station

Experimental Plan

General Background

The experiments in this study were designed to evaluate the effects of the temperature-phased digestion system on volatile solids removal, pathogen destruction, and other operational features. The ultimate goal of the study was to operate the TPAD system at a range of SRTs and corresponding VS loadings, thus to determine the design and operating parameters.

For comparison, a single-stage system was operated simultaneously. To determine the optimum volume ratio of the first stage to the second stage, two TPAD systems A and B were used, with volume ratios 2:5 and 1:5, respectively.

The TS content of the feed sludge was adjusted to constant as 4%. Since the reactors used were CSTRs, the SRT was equal to the HRT. Thus, the different SRTs to the system were achieved by changing flow rate. The data were taken at each SRT when the system's performance was stable. The steady-state in this study is defined as a condition under which every parameter does not change significantly (+/- 10%) with time for a period of at least one week. Testing for steady-state performance was not conducted until two SRTs had passed after a change in SRT and VS loading.

System Operation

After accomplishment of start-up, each system was operated at its first designated SRT. For the two TPAD systems, a flow rate of 1.0 liter per day was used. The

corresponding SRTs for system A and B were 14 and 12 days, respectively. For the single-stage system, an SRT of 24 days was operated and the corresponding flow rate was therefore 0.58 liters per day. Each system was operated at an SRT until it reached steady-state. After data collection of each steady state performance, each system was applied to other SRTs by changing its flow rate. The working volume of each reactor maintained constant except for the two stage system B at an SRT of 11 days. In this run, the working volume of its first stage (R4) was adjusted from 2 to 1 liter.

A mixture (mixture 1) of 1:1 (volume ratio) of PS to WAS was used for first set of runs at various SRTs. Then the WAS content was raised to 75%, i.e. 3:1 volume ratio of WAS to PS. For this mixture (mixture 2), only two systems: two-stage system A and single-stage system, were used.

VI. RESULTS AND DISCUSSION

Results

VS Loading Rates at Different SRTs

By definition, VS loading is the mass flow rate of volatile solids per unit volume of the reactor. The corresponding mathematical formula is as following:

$$\text{VS loading rate} = \frac{Q * C_o}{V} \quad \text{..... (11)}$$

where:

Q = flow rate, L/d

C_o = volatile solids concentration in influent, g/L

V = volume of reactor, L

In most cases, volume of reactor (V) is constant. Volatile solids loading rate is proportional to the flow rate and VS content in the feed sludge. In this study, the TS content of the feed sludge was adjusted to 4% and VS content varied only slightly from batch to batch in a range from 2.9 to 3.1%. Thus, as flow rate was raised and the SRT was reduced correspondingly, VS loading rate increased. The VS loading rates of each reactor at different SRTs are shown in Tables 8 and 9 for mixture 1 (1:1 volume ratio of PS to WAS) and mixture 2 (1:3 volume ratio of PS to WAS), respectively. The variations of VS loading vs. SRTs for mixture 1 and mixture 2 are also shown in Figures 9, 10, and 11, respectively.

Table 8. Volatile solids loadings at various SRTs for mixture 1

SRT or HRT (days)	Volatile solids loadings, g VS/L/day				
	Single-stage	Two-stage A		Two-stage B	
		1st stage	2nd stage	1st stage	2nd stage
11				29(1)*	2.7(10)
12				15(2)	2.5(10)
14		7.3(4)	2.1(10)		
17				10.5(2.7)	2.2(14.3)
20		5.3(5.7)	1.9(14.3)		
24	1.2			7.3(4)	1.9(20)
28	1.1	3.8(8)	1.8(20)		
34	0.9				
40	0.8				

* The SRT or HRT for each stage of the two-stage systems are shown in parentheses.

Table 9. Volatile solids loadings at various SRTs for mixture 2

SRT or HRT (days)	Volatile solids loadings, g VS/L/day		
	Single-stage (meso)	Two-stage A	
		1st stage	2nd stage
14		7.4(4)	2.2(10)
20		5.2(5.7)	2.1(14.3)
24	1.3		
28	1.1	3.9(8)	1.9(20)
34	0.9		
40	0.8		

* The SRT or HRT for each stage of the two-stage system A are shown in parentheses.

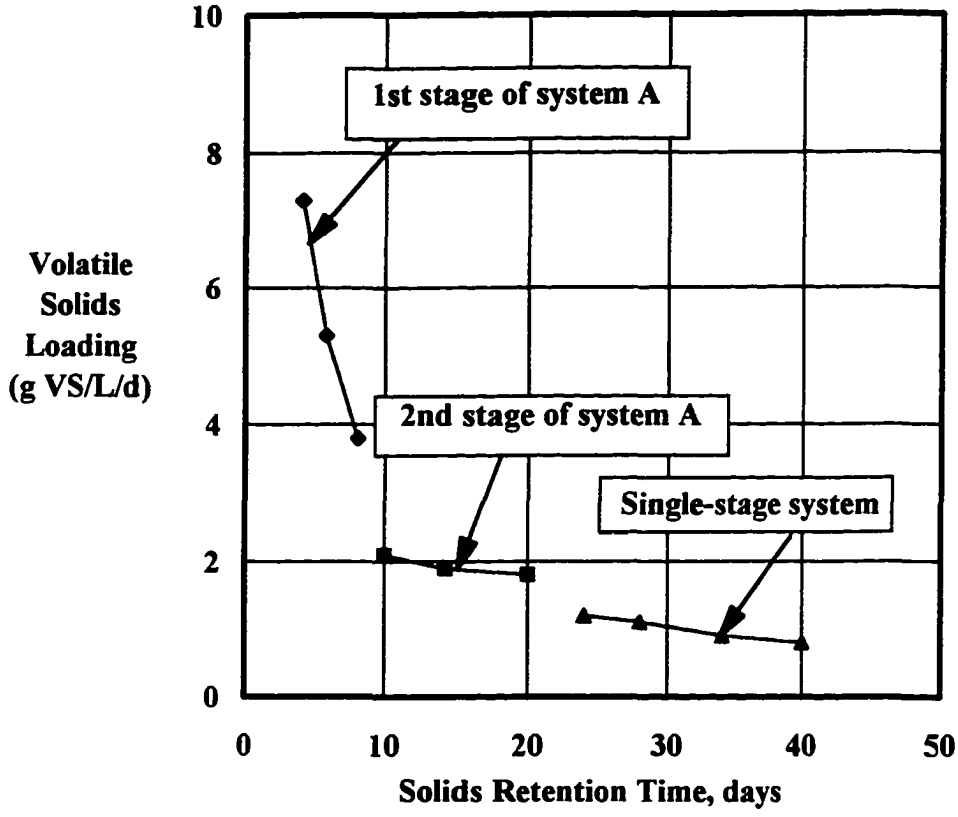


Figure 9. VS loading of single-stage and two-stage system A at different SRTs for mixture 1

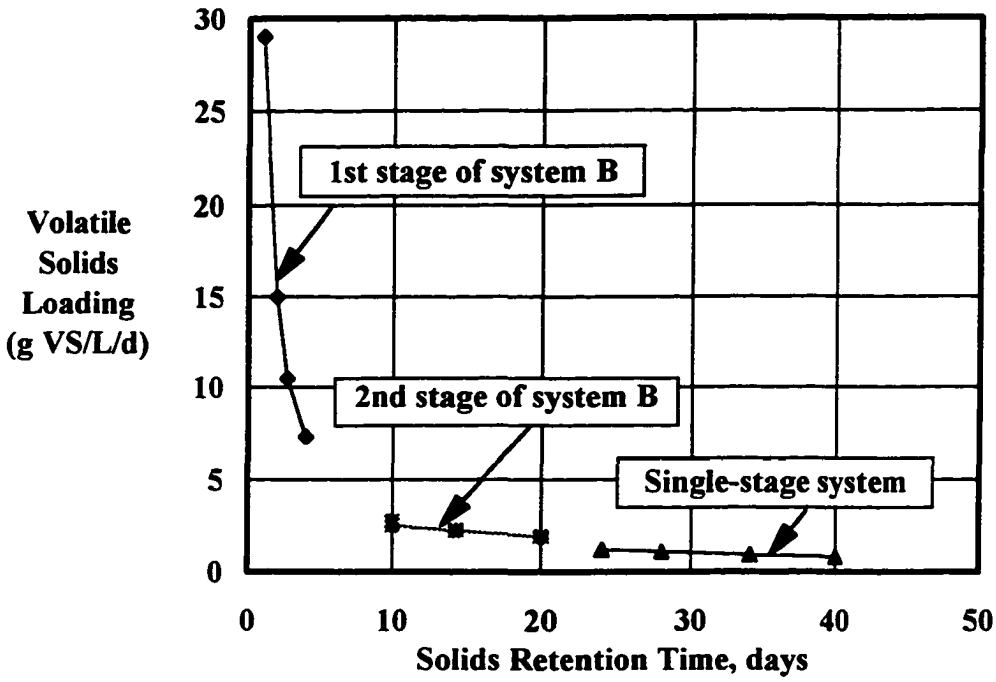


Figure 10. VS loading of single-stage and two-stage system B at different SRTs for mixture 1

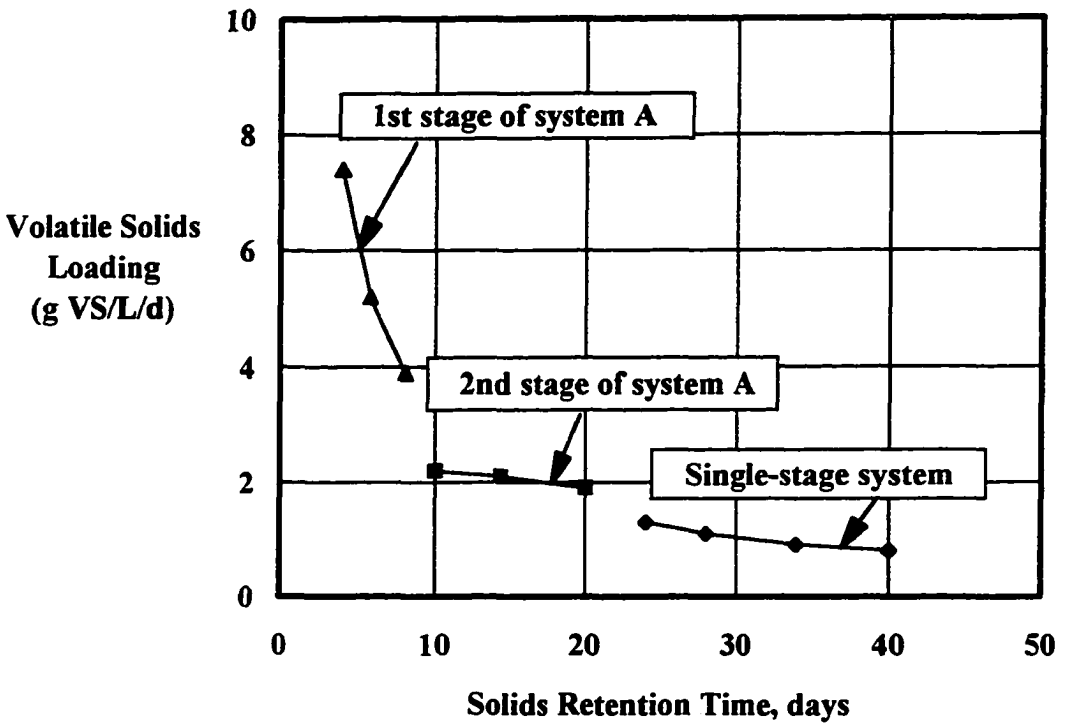


Figure 11. VS loading of single stage and two-stage system A at different SRTs for mixture 2

Volatile Solids Removal

One of the main goals of anaerobic digestion is to destroy volatile solids in the incoming sludge. The percentage of volatile solids removal is most commonly used, which indicates the performance of the system. It can be calculated as following:

$$\text{VS removal (\%)} = \frac{S_o - S_e}{S_o} * 100 \quad \text{..... (12)}$$

where:

S_o = volatile solids concentration in the influent, g/L

S_e = volatile solids concentration in the effluent, g/L

In general, VS removal depends on VS loading rate, SRT, bacterial concentration, temperature, and other factors. In most cases, SRT and VS loading are most important. For a certain VS loading, a longer SRT usually leads to an increase of VS removal. In this study, the SRTs applied varied from the shortest time of 1 day to the longest time of 40 days. Since higher SRTs were achieved by reducing flow rates, the VS loading rates were decreased corresponding to the flow rates. The relationships between volatile solids loading rates and SRTs in various operating conditions are shown in Figures 9, 10, and 11.

Table 10 shows volatile solids removal of all three systems for mixture 1. For all of them, VS removal increases as SRT is extended. The VS removal of the conventional single-stage system varied from 32.5 to 47.3% as the SRT increases from 24 to 40 days. Although VS destruction of both two-stage system A and B were a little bit higher than or as the same as those for single-stage system, the SRT required was much shorter than that used for single-stage system. For two-stage system A, 45% VS removal was achieved at an SRT of 14 days.

Table 10. Volatile solids removal of each system at different SRTs for mixture 1

System		Q (L/d)	SRT (day)	Volatile solids (g/L)		VS removal (%)	
				Influent	Effluent	Stage	System
Single-stage system		0.580	24	29.2	19.7	32.5	32.5
		0.500	28	30.1	18.0	40.2	40.2
		0.412	34	30.3	16.8	44.6	44.6
		0.350	40	29.8	15.7	47.3	47.3
Two-stage system A	1st stage	1.000	4.0	29.2	20.1	31.2	
	2nd stage	1.000	10.0	20.1	16.1	19.9	44.9
	1st stage	0.700	5.7	30.2	18.7	38.1	
	2nd stage	0.700	14.3	18.7	15.7	16.0	48.0
	1st stage	0.500	8.0	30.3	17.6	41.9	
	2nd stage	0.500	20.0	17.6	15.0	14.8	50.5
Two-stage system B	1st stage	1.000	1.0	29.2	25.8	11.6	
	2nd stage	1.000	10.0	25.8	19.3	25.2	33.9
	1st stage	1.000	2.0	29.5	23.6	20.0	
	2nd stage	1.000	10.0	23.6	18.1	23.3	38.6
	1st stage	0.700	2.8	30.0	20.7	31.0	
	2nd stage	0.700	14.2	20.7	17.4	15.9	42.0
	1st stage	0.580	4.0	30.5	19.1	37.4	
	2nd stage	0.580	20.0	19.1	16.4	14.1	46.2

As SRTs were from 14 to 28 days, the corresponding VS destruction was increased to 50%. Similar relationship between VS removal and SRT in two-stage system B was observed. The lowest SRT of 10 days was studied in system B. At this SRT, the VS removal was 34%. The VS removal rose to 46% as the SRT increased from 10 to 24 days. The variation of VS removal with respect to system SRT is shown in Figure 12. The individual performance in terms of VS removal of each stage of the two-stage system is shown in Figures 13 and 14. As the WAS content increased from 50% to 75% in mixture 2, the volatile solids removal of all systems went down, but the similar relationship between VS removal and SRT still maintained as shown in Table 11 and Figure 15.

COD Removal

Besides VS removal, COD removal is also widely used to show the degree of reduction of organic matter. For wastewater sludge, Volatile solids can be well measured than COD. The COD measurement is not so accurate as the VS measurement because the dilution is needed for COD analysis. However, COD data is still important. The main reason for measuring COD is that there is a clear relationship between COD removed and methane produced. The theoretical value is 0.35 liters of methane per gram of COD destroyed. In this study, when ever VS was measured, COD was also measured. The VS to COD ratios (VS/COD) of sludge samples from reactor effluent and influent were consistent in a range

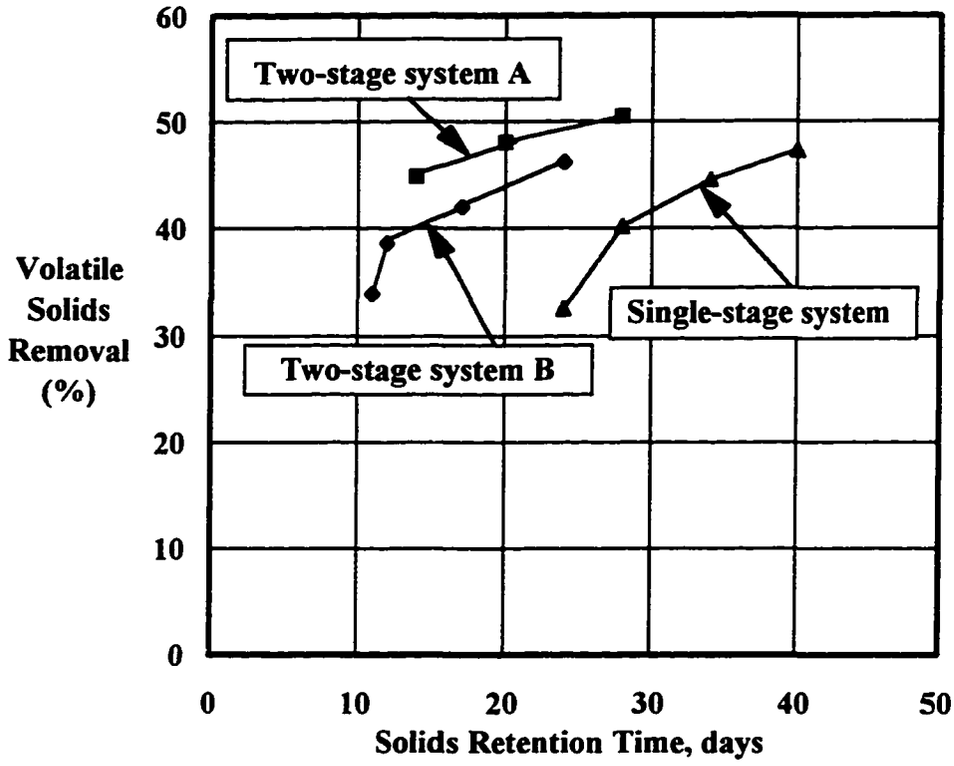


Figure 12. Volatile solids removal of single-stage and two-stage systems at different SRTs for mixture 1

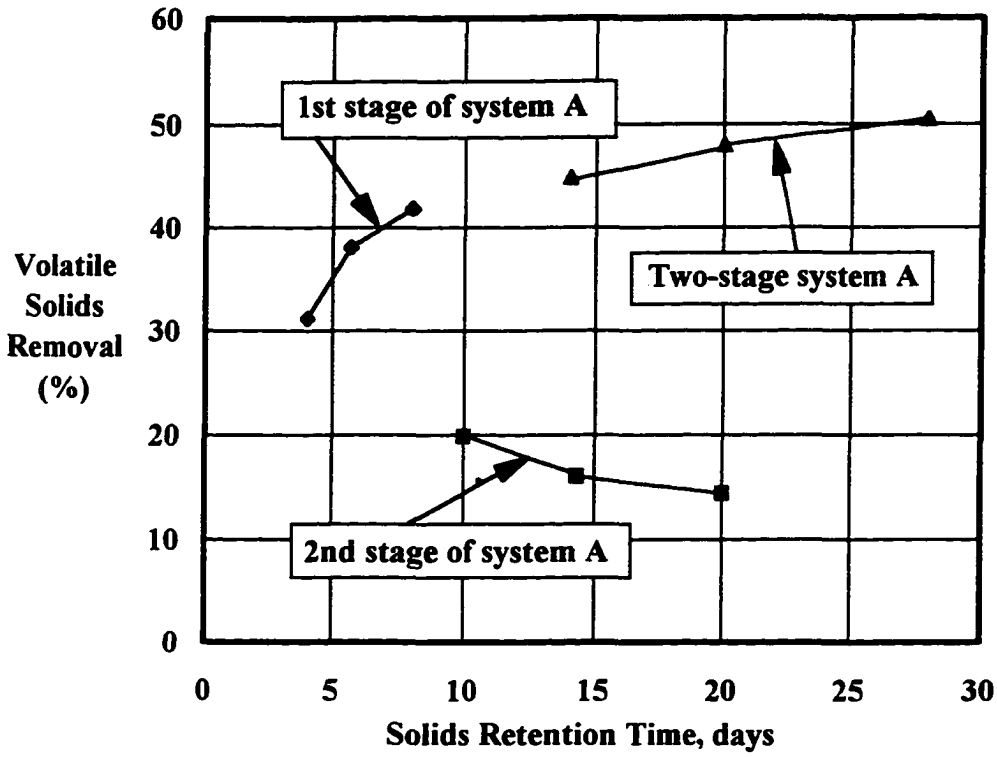


Figure 13. Volatile solids removal of each stage of two-stage system A at different SRTs for mixture 1

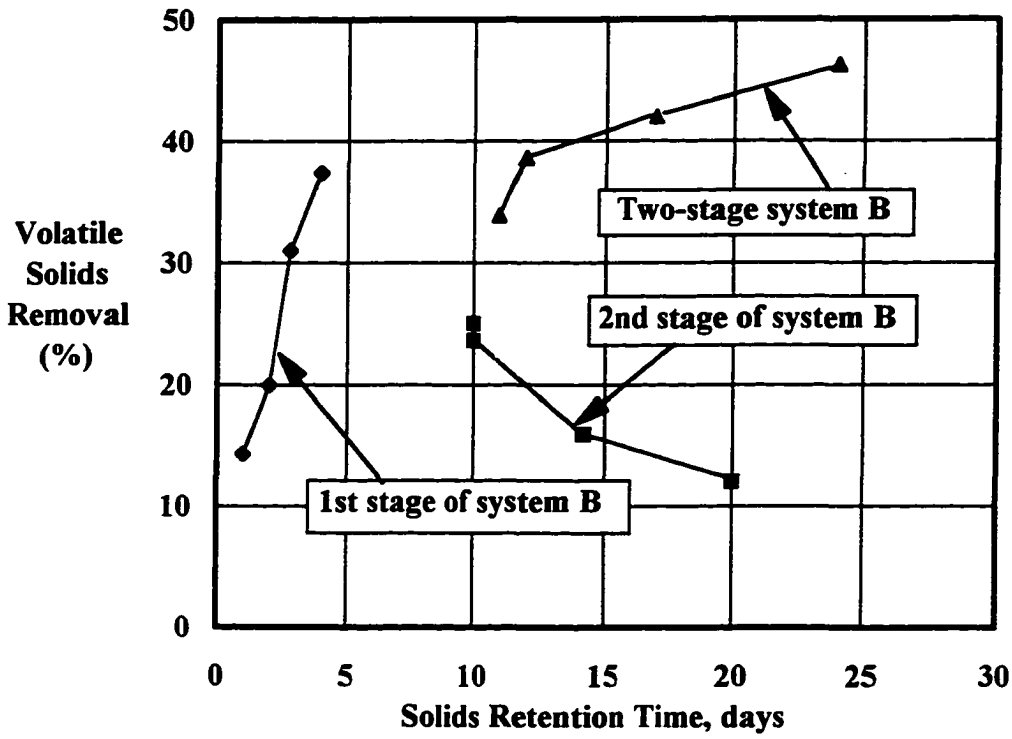


Figure 14. Volatile solids removal of each stage of system B at different SRTs for mixture 1

Table 11. Volatile solids removal of each system at different SRTs for mixture 2

System		Q (L/d)	SRT (day)	Volatile solids (g/L)		VS removal (%)	
				Influent	Effluent	Stage	System
Single-stage system		0.580	24	29.6	20.8	29.7	29.7
		0.500	28	30.2	18.8	37.7	37.7
		0.412	34	29.8	17.5	41.3	41.3
		0.350	40	30.1	16.5	45.2	45.2
Two-stage system A	1st stage	1.000	4.0	29.2	21.3	27.1	
	2nd stage	1.000	10.0	21.3	17.1	19.7	41.4
	1st stage	0.700	5.7	29.8	20.1	32.6	
	2nd stage	0.700	14.3	20.1	16.3	18.9	45.3
	1st stage	0.500	8.0	30.2	18.9	37.4	
	2nd stage	0.500	20.0	18.9	15.8	16.4	47.7

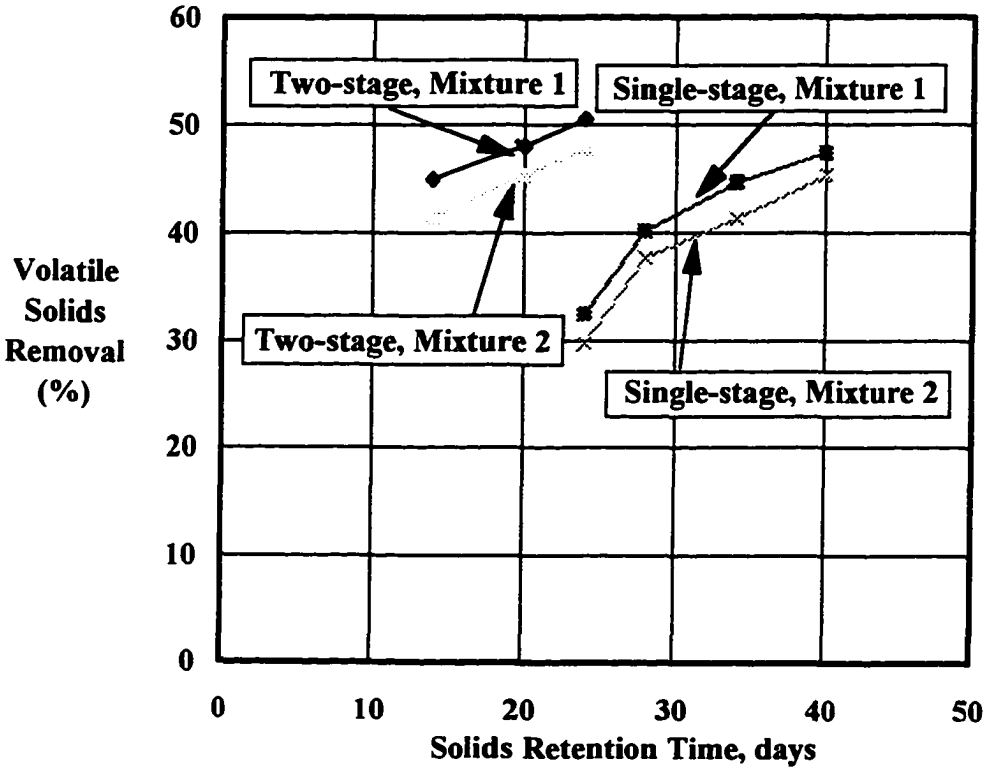


Figure 15. Volatile solids removal of single-stage and two-stage systems at different SRTs for mixture 1 and mixture 2

of 1.3 to 1.5. COD removal can be calculated in a similar way as VS removal as following:

$$\text{COD removal \%} = \frac{C_o - C_e}{C_o} * 100 \quad \ldots\ldots\ldots\ldots \quad (13)$$

where:

C_o = influent COD concentration, g/L

C_e = effluent COD concentration, g/L

The COD performance data are summerised in Tables 12 and 13 for mixture 1 and mixture 2, respectively. The variation of COD removal vs. SRT for each system was quite similar to result of VS removal vs. SRT. The results of COD removal at various SRTs at single vs. Two stage system A and B are shown in Figures 16, 17, and 18, respectively.

Coliform and Fecal Coliform Destruction

Both total and fecal coliform concentrations were measured at each SRT when the system reached steady-state. The destruction rate of total and fecal coliforms is calculated as following:

$$\text{Coliform Destruction Rate (\%)} = \frac{P_o - P_e}{P_o} * 100 \quad \ldots\ldots\ldots\ldots \quad (14)$$

where:

P_o = influent total or fecal coliform concentration, MPN/g TS

P_e = effluent total or fecal coliform concentration, MPN/g TS

Table 12. COD removal of each system at different SRTs for mixture 1

System		Q (L/d)	SRT (day)	COD (g/L)		COD removal (%)	
				Influent	Effluent	Stage	System
Single-stage system		0.580	24.0	41.6	27.6	33.7	33.7
		0.500	28.0	39.6	23.9	39.6	39.6
		0.412	34.0	40.1	22.8	43.1	43.1
		0.350	40.0	41.2	22.6	45.1	45.1
Two-stage system A	1st stage	1.000	4.0	40.3	28.9	28.3	
	2nd stage	1.000	10.0	28.9	22.1	23.5	45.2
	1st stage	0.700	5.7	42.3	27.1	35.9	
	2nd stage	0.700	14.3	27.1	21.8	19.6	48.5
	1st stage	0.500	8.0	41.8	25.3	39.5	
	2nd stage	0.500	20.0	25.3	20.6	18.6	50.7
Two-stage system B	1st stage	1.000	1.0	41.8	36.8	12.0	
	2nd stage	1.000	10.0	36.8	27.6	25.0	34.0
	1st stage	1.000	2.0	40.6	33.7	17.0	
	2nd stage	1.000	10.0	33.7	24.8	26.4	38.9
	1st stage	0.700	2.8	40.3	28.3	29.8	
	2nd stage	0.700	14.2	28.3	22.7	19.8	43.7
	1st stage	0.580	4.0	41.5	26.1	37.1	
	2nd stage	0.580	20.0	26.1	22.7	13.0	45.3

Table 13. COD removal of each system at different SRTs for mixture 2

System		Q (L/d)	SRT (day)	COD (g/L)		COD removal (%)	
				Influent	Effluent	Stage	System
Single-stage system		0.580	24	41.8	29.7	28.9	28.9
		0.500	28	42.9	26.5	38.2	38.2
		0.412	34	40.6	24.1	40.6	40.6
		0.350	40	42.7	23.8	44.4	44.4
Two-stage system A	1st stage	1.000	4.0	41.5	30.2	27.2	
	2nd stage	1.000	10.0	30.2	24.1	20.2	41.9
	1st stage	0.700	5.7	41.6	28.0	32.7	
	2nd stage	0.700	14.3	28.0	22.8	18.6	45.2
	1st stage	0.500	8.0	42.2	26.8	36.5	
	2nd stage	0.500	20.0	26.8	22.3	16.8	47.2

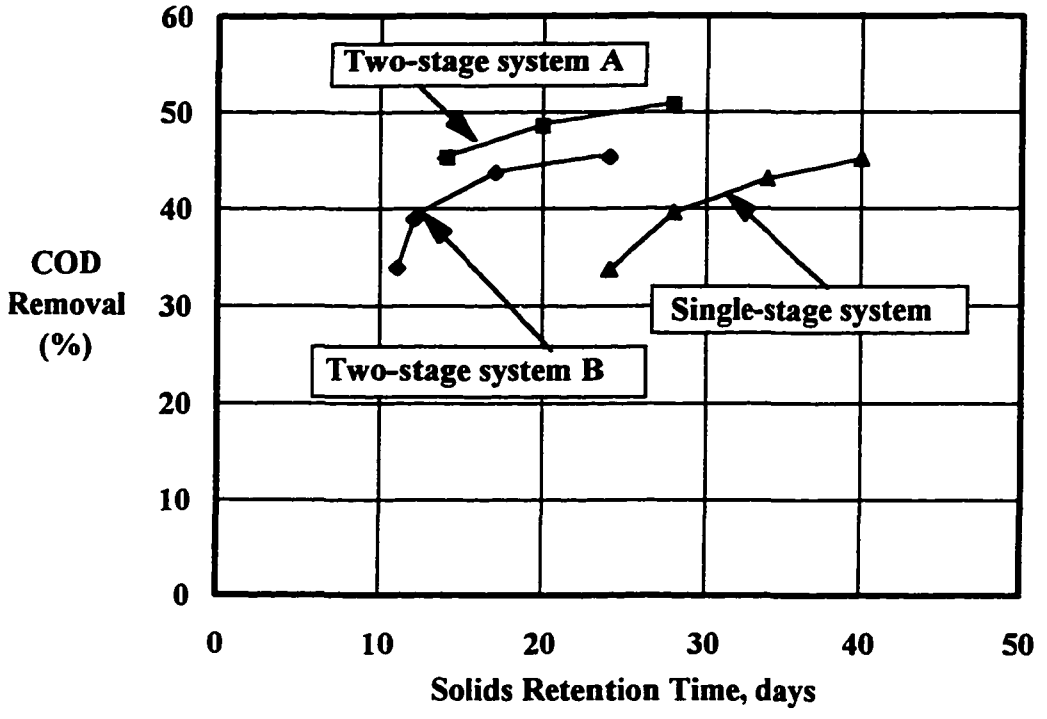


Figure 16. COD removal of single-stage and two-stage systems at different SRTs for mixture 1

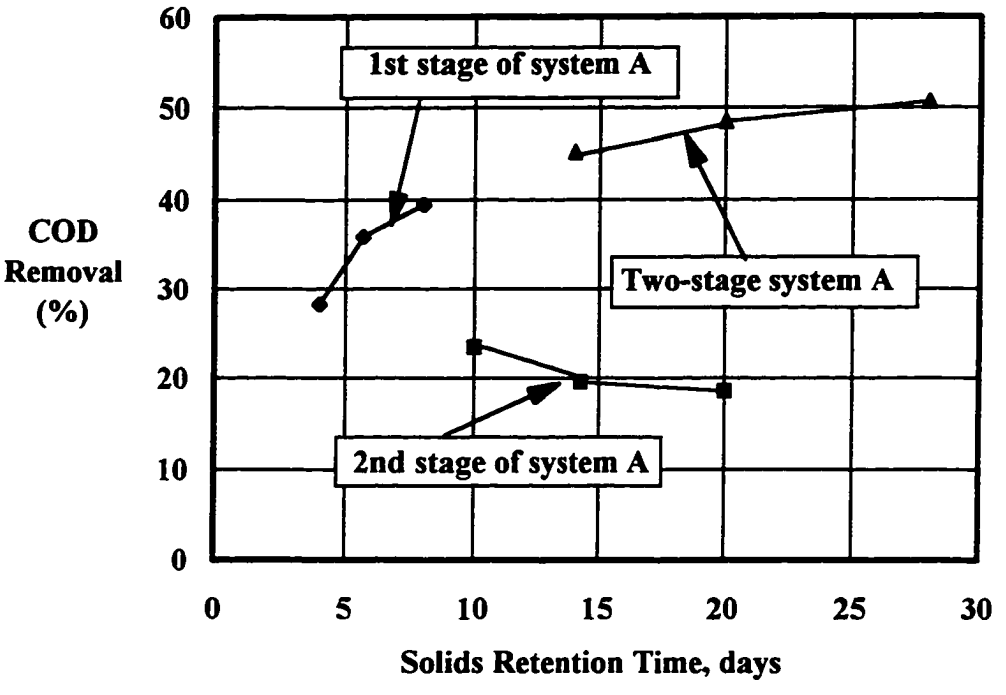


Figure 17. COD removal of each stage of two-stage system A at different SRTs for mixture 1

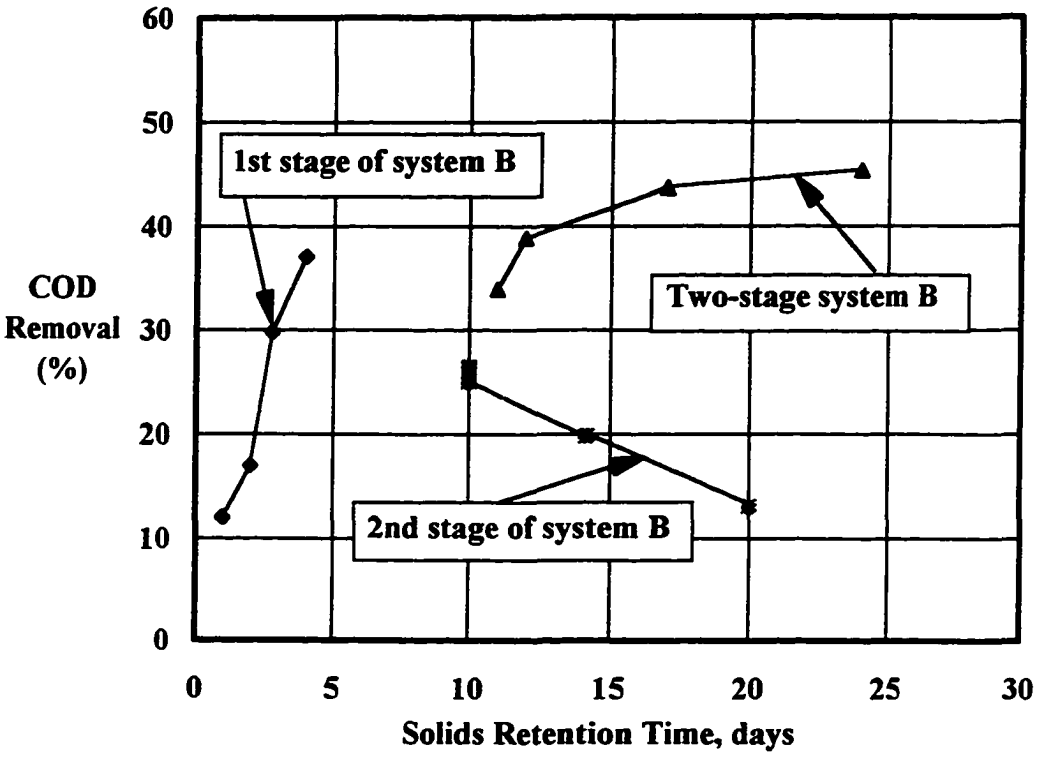


Figure 18. COD removal of each stage of two-stage system B at different SRTs for mixture 1

The data of total coliform destruction for the single-stage and the two-stage systems are shown in Tables 14 and 15. For the single-stage system the total coliform destruction varied from 92.2 to 84.5% in an SRT range of 24 to 40 days. In contrast to the single-stage system, a much higher coliform destruction was achieved by the two-stage system. For two-stage system A, total coliform destruction rates were 99.999% or above for all SRTs tested. Similar result was also obtained for two-stage system B. The single-stage was able to only achieve around a one log or less reduction, i.e. 90% or less, of total coliforms. The mesophilic second-stage of the two-stage system achieved also only one log or less destruction of total coliforms. The significantly high reduction up to 99.999% (5 log) was achieved by the thermophilic first-stage. The total coliform concentrations and the destruction data of all three systems, two-stage system A, and two-stage system B are shown in Figures 19, 20, and 21, respectively. At a system SRT of 14 days, as shown in Table 14, system A achieved a coliform destruction of 99.9996%, with a destruction of 99.999% in the first-stage. The lowest SRT used in the study was 11 days for the two-stage system B. At the system B, although the first-stage had only an SRT of one day, the total coliform destruction still maintained as high as 99.9996%. Table 15 presents the total coliform destruction rates for mixture 2. They are quite similar to those shown in Table 14. There is no significant difference between mixture 1 and mixture 2 regarding total coliform destruction.

The corresponding fecal coliform destruction rates are shown in Tables 16, 17, and Figures 22, 23, 24, 25, and 26 for the single-stage system, the system A, and the system B, respectively. The single-stage system achieved only 90% (one log) or less fecal coliform.

Table 14. Total coliform destruction of each system at different SRTs for mixture 1

System		Q (L/d)	SRT (day)	Coliform (MPN/g TS)		Coliform destruction (%)	
				Influent	Effluent	Stage	System
Single-stage system		0.580	24.0	1.62E+08	1.26E+07	92.20	92.20
		0.500	28.0	6.49E+07	1.96E+07	69.73	69.73
		0.412	34.0	2.48E+08	5.32E+07	78.57	78.57
		0.350	40.0	1.57E+08	2.44E+07	84.47	84.47
Two-stage system A	1st stage	1.000	4.0	4.02E+07	4.02E+02	99.99900	
	2nd stage	1.000	10.0	4.02E+02	1.56E+02	61.1	99.99961
	1st stage	0.700	5.7	8.07E+07	1.60E+02	99.99980	
	2nd stage	0.700	14.3	1.60E+02	7.74E+01	51.5	99.99990
	1st stage	0.500	8.0	3.66E+07	2.44E+02	99.99933	
	2nd stage	0.500	20.0	2.44E+02	9.51E+01	61.0	99.99974
Two-stage system B	1st stage	1.000	1.0	1.27E+08	5.30E+02	99.99958	
	2nd stage	1.000	10.0	5.30E+02	1.55E+02	70.82	99.99988
	1st stage	1.000	2.0	6.56E+07	2.82E+02	99.99957	
	2nd stage	1.000	10.0	2.82E+02	1.97E+02	30.17	99.99970
	1st stage	0.700	2.8	3.94E+08	4.01E+02	99.99990	
	2nd stage	0.700	14.2	4.01E+02	1.24E+02	69.1	99.99997
	1st stage	0.580	4.0	1.63E+08	1.98E+02	99.99988	
	2nd stage	0.580	20.0	1.98E+02	6.52E+01	67.0	99.99996

Table 15. Total coliform destruction of each system at different SRTs for mixture 2

System		Q (L/d)	SRT (day)	Coliform (MPN/g TS)		Coliform destruction (%)	
				Influent	Effluent	Stage	System
Single-stage system		0.580	24.0	1.02E+08	2.26E+07	77.84	77.84
		0.500	28.0	2.49E+07	9.63E+06	61.25	61.25
		0.412	34.0	9.83E+07	4.32E+07	56.05	56.05
		0.350	40.0	5.70E+07	3.44E+07	39.73	39.73
Two-stage system A	1st stage	1.000	4.0	.02E+07	5.02E+02	99.99751	
	2nd stage	1.000	10.0	5.02E+02	2.56E+02	48.92	99.99873
	1st stage	0.700	5.7	8.01E+06	3.60E+02	99.99551	
	2nd stage	0.700	14.3	3.60E+02	1.20E+02	66.50	99.99850
	1st stage	0.500	8.0	1.66E+07	4.44E+02	99.99733	
	2nd stage	0.500	20.0	4.44E+02	9.71E+01	78.13	99.99942

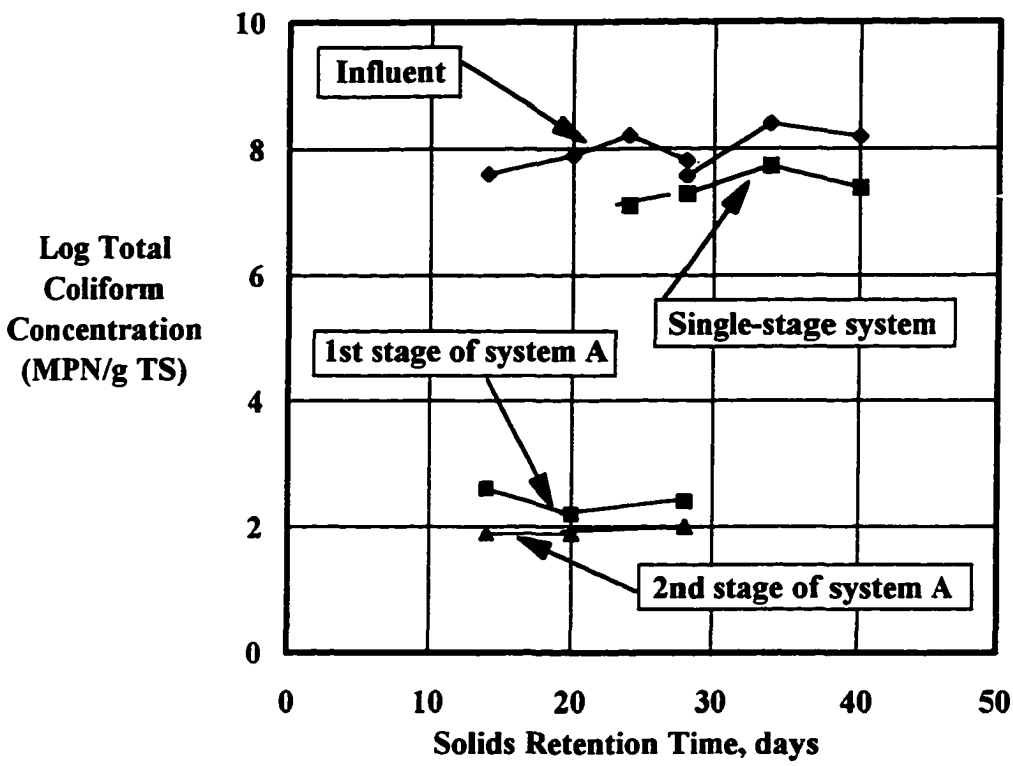


Figure 19. Total coliform destruction of two-stage system A at different SRTs for mixture 1

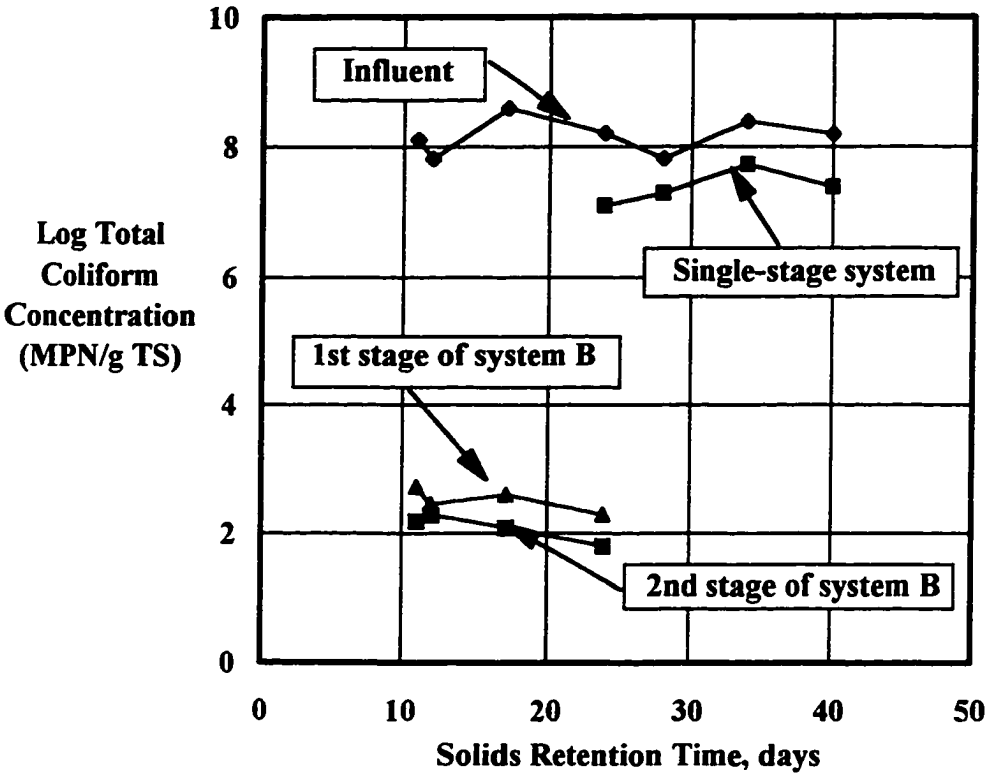


Figure 20. Total coliform destruction of two-stage system B at different SRTs for mixture 1

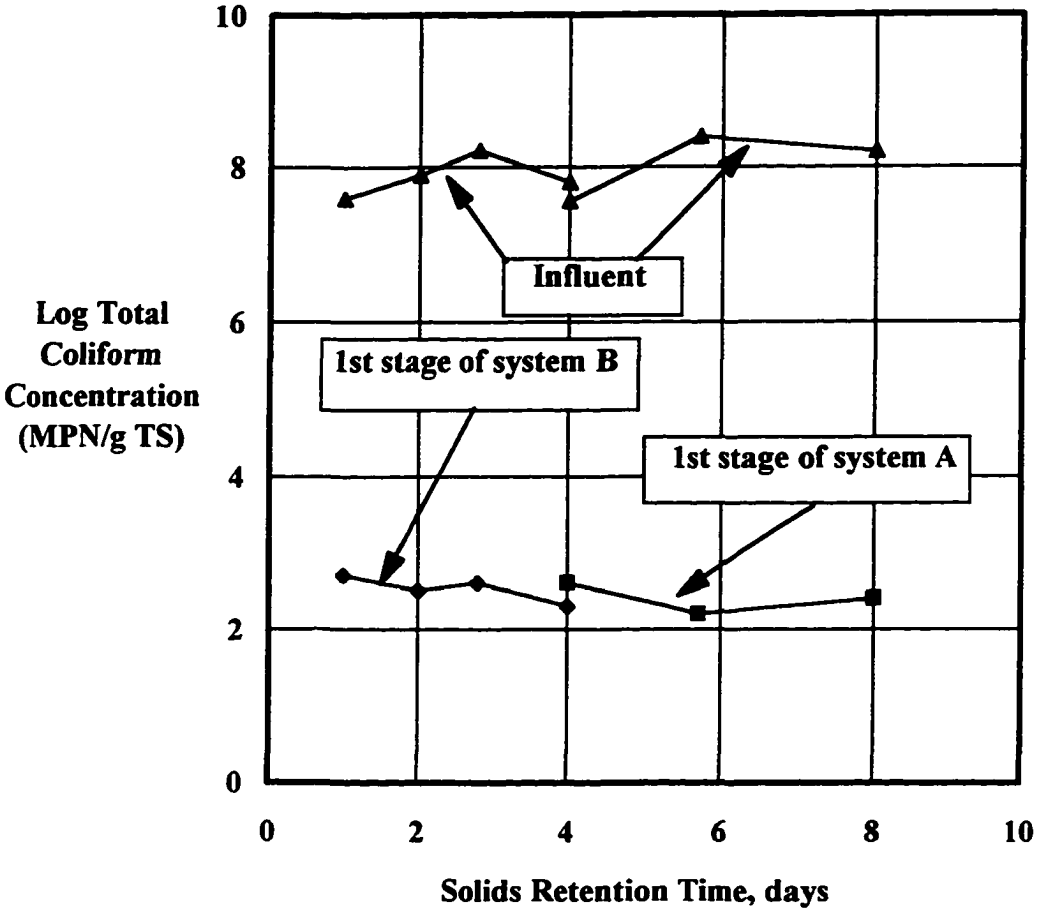


Figure 21. Total coliform destruction of the first stages of two-stage system A and B at different SRTs for mixture 1

Table 16. Fecal coliform destruction of each system at different SRTs for mixture 1

System		Q (L/d)	SRT (day)	Fecal coliform (MPN/g TS)		Fecal coliform destruction (%)	
				Influent	Effluent	Stage	System
Single-stage system		0.580	24.0	1.07E+07	1.26E+06	88.25	88.25*
		0.500	28.0	7.85E+06	7.94E+05	89.88	89.88*
		0.412	34.0	6.03E+07	7.94E+06	86.82	86.82*
		0.350	40.0	7.89E+06	8.51E+05	89.21	89.21*
Two-stage system A	1st stage	1.000	4.0	6.22E+07	7.94E+01	99.99987	
	2nd stage	1.000	10.0	7.94E+01	6.31E+01	20.57	99.99990**
	1st stage	0.700	5.7	3.08E+07	1.26E+02	99.99959	
	2nd stage	0.700	14.3	1.26E+02	3.98E+01	68.38	99.99987**
	1st stage	0.500	8.0	2.09E+07	5.01E+01	99.99976	
	2nd stage	0.500	20.0	5.01E+01	3.16E+01	36.90	99.99985**
Two-stage system B	1st stage	1.000	1.0	3.98E+07	3.98E+02	99.99900	
	2nd stage	1.000	10.0	3.98E+02	7.94E+01	80.05	99.99980**
	1st stage	1.000	2.0	6.31E+06	2.51E+02	99.99602	
	2nd stage	1.000	10.0	2.51E+02	2.00E+01	92.05672	99.99968**
	1st stage	0.700	2.8	1.02E+08	2.00E+02	99.99981	
	2nd stage	0.700	14.2	2.00E+02	2.51E+01	87.41	99.99998**
	1st stage	0.580	4.0	1.00E+07	1.58E+02	99.99842	
	2nd stage	0.580	20.0	1.58E+02	1.26E+01	92.06	99.99987**

* Do not meet 40 CFR Part 503 pathogen destruction criteria for Class A sludge

** Meet 40 CFR Part 503 pathogen destruction criteria for Class A sludge

Table 17. Fecal coliform destruction of each system at different SRTs for mixture 2

System		Q (L/d)	SRT (day)	Fecal coliform (MPN/g TS)		Fecal coliform destruction (%)	
				Influent	Effluent	Stage	System
Single-stage system		0.580	24.0	2.07E+07	4.26E+06	79.44	79.44*
		0.500	28.0	5.78E+06	9.14E+05	84.19	84.19*
		0.412	34.0	3.03E+07	8.74E+06	71.10	71.10*
		0.350	40.0	2.89E+06	9.51E+05	67.07	67.07*
Two-stage system A	1st stage	1.000	4.0	3.22E+07	1.79E+02	99.99944	
	2nd stage	1.000	10.0	1.79E+02	1.10E+02	38.64	99.99966**
	1st stage	0.700	5.7	2.08E+07	2.26E+02	99.99892	
	2nd stage	0.700	14.3	2.26E+02	8.58E+01	62.01	99.99959**
	1st stage	0.500	8.0	1.09E+07	1.45E+02	99.99867	
	2nd stage	0.500	20.0	1.45E+02	1.21E+02	16.88	99.99889**

* Do not meet 40 CFR Part 503 pathogen destruction criteria for Class A sludge

** Meet 40 CFR Part 503 pathogen destruction criteria for Class A sludge

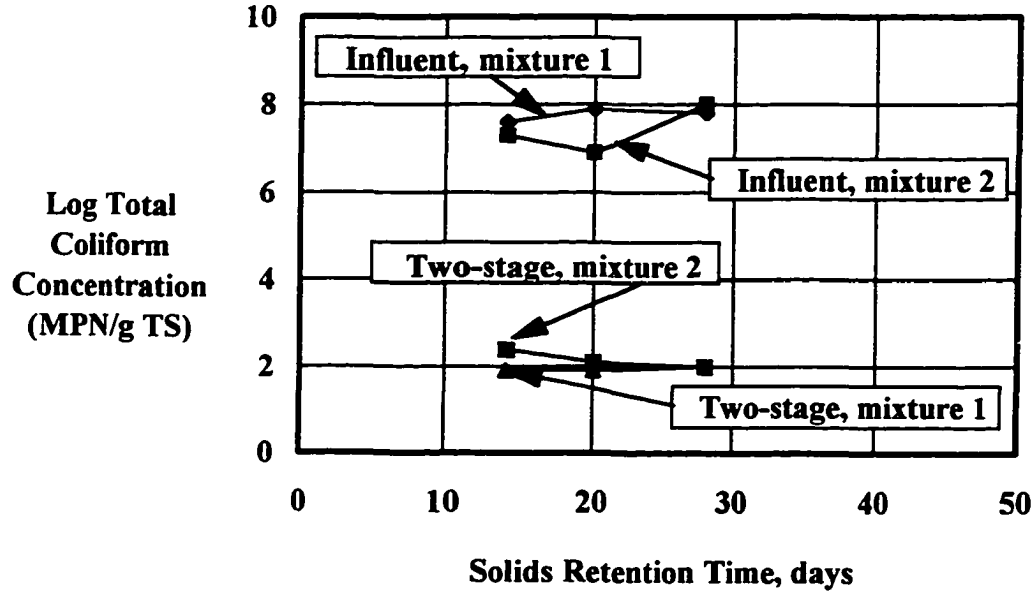


Figure 22. Total coliform destruction of the two-stage system at different SRTs for mixture 1 and mixture 2

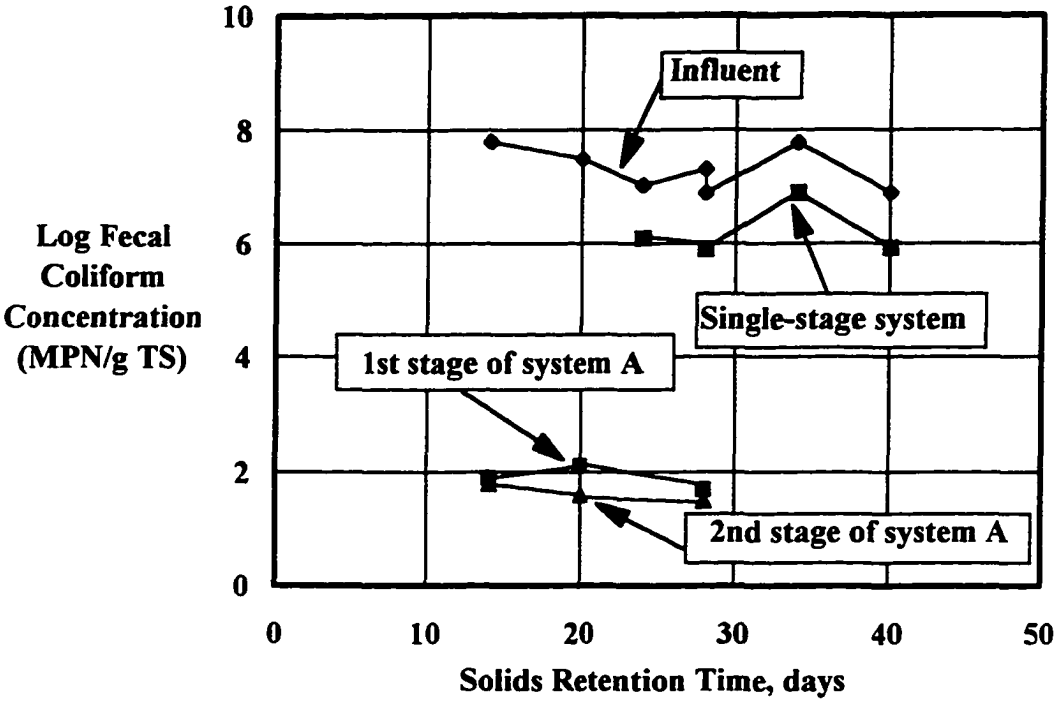


Figure 23. Fecal coliform destruction of two-stage system A at different SRTs for mixture 1

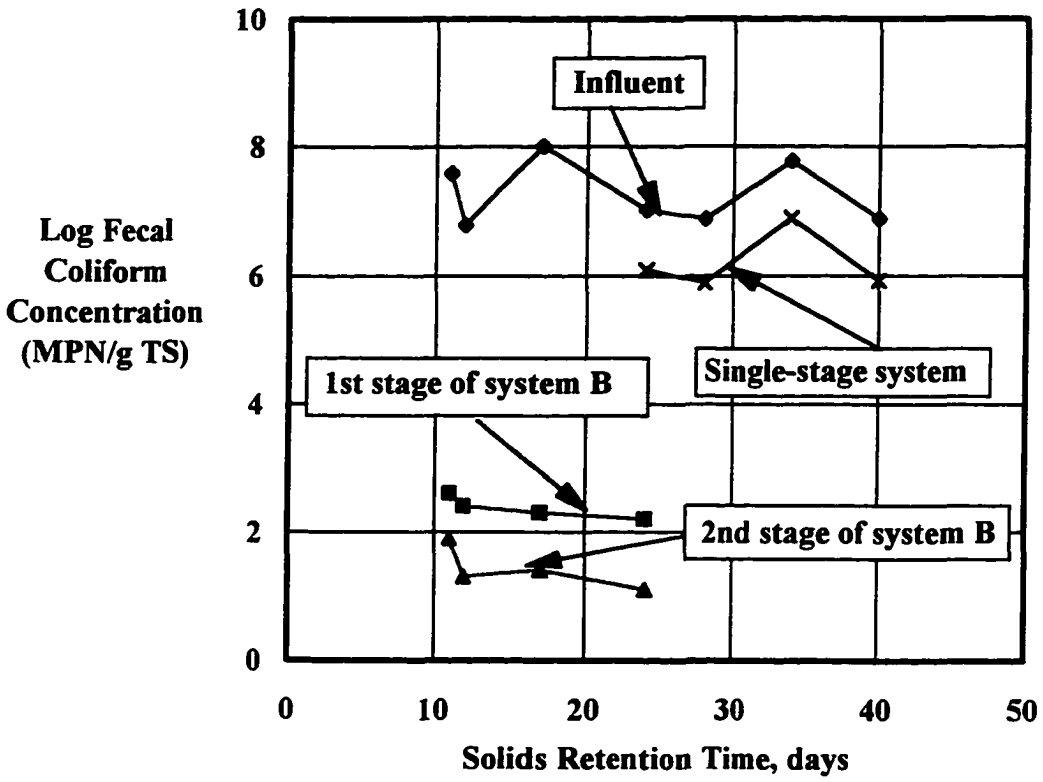


Figure 24. Fecal coliform destruction of two-stage system B at different SRTs for mixture 1

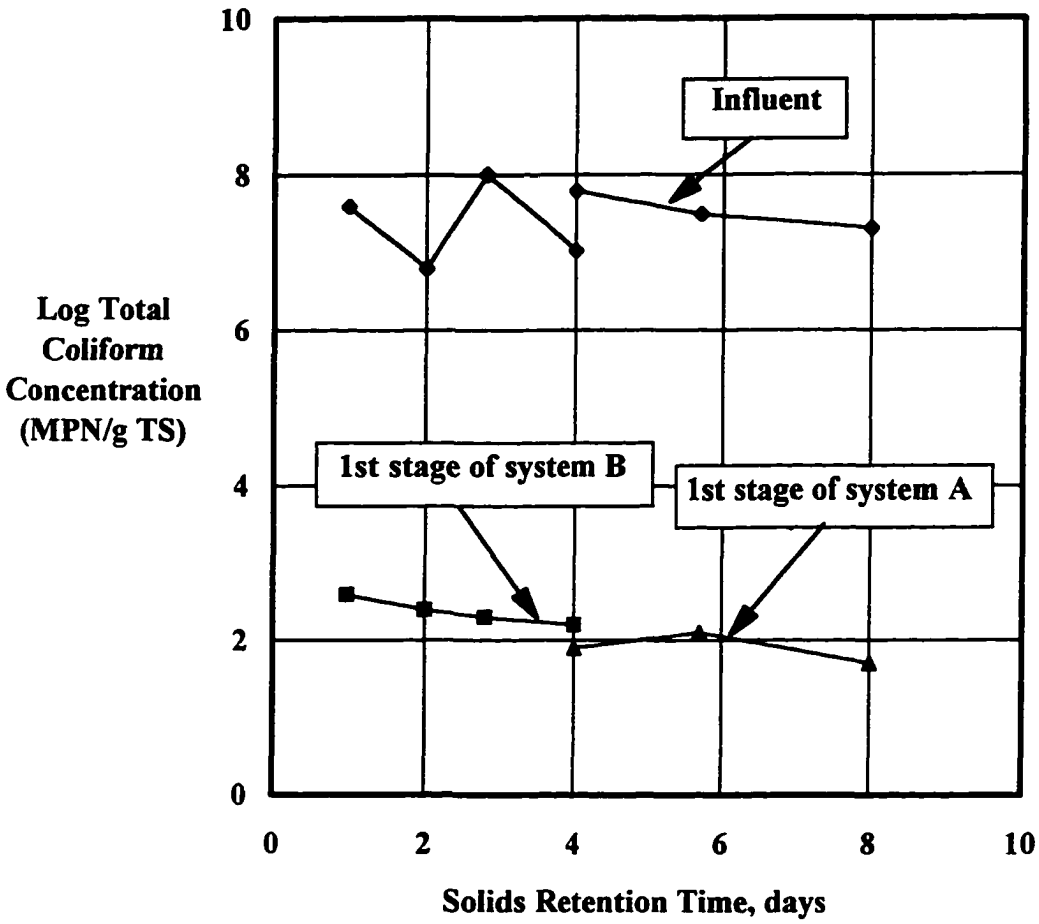


Figure 25. Fecal coliform destruction of the first stages of two-stage system A and B at different SRTs for mixture 1

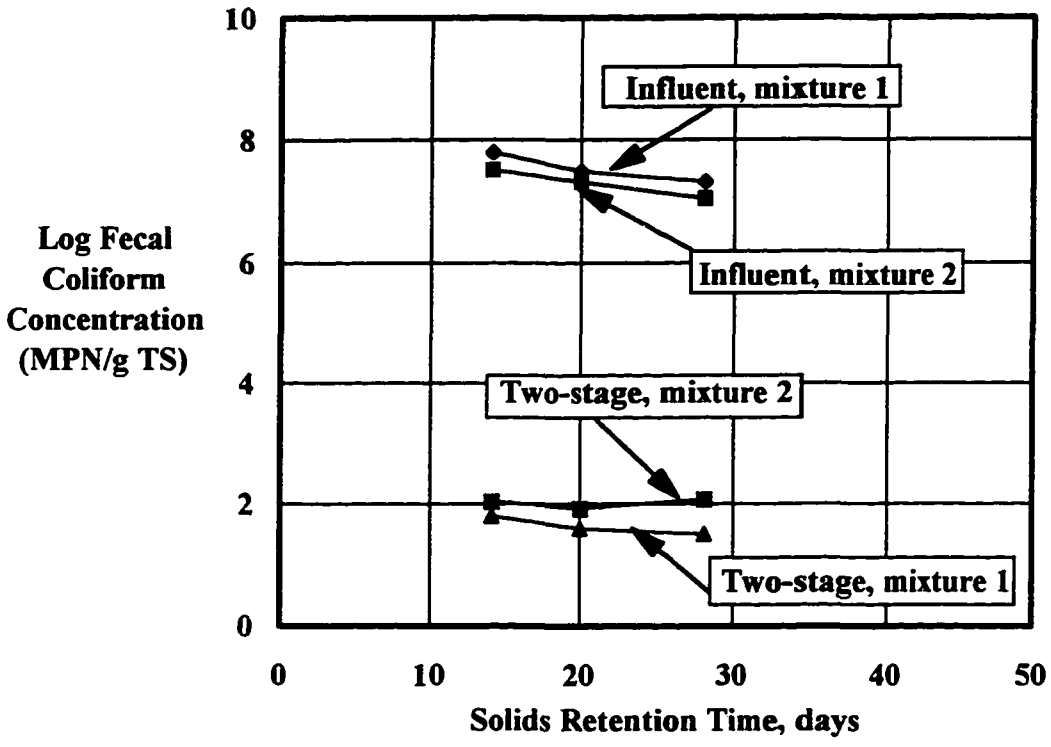


Figure 26. Fecal coliform destruction of the two-stage system at different SRTs for mixture 1 and mixture 2

destruction, while the temperature-phased anaerobic digestion systems were able to achieve fecal coliform destruction up to 99.99998% (6 log). The lowest fecal coliform removal rate of the two-stage system was 99.99968%. The highest fecal coliform density in the effluent from the two-stage system, as shown in Table 16, was only 79 MPN/g TS, which occurred at an SRT of 11 days, with one day SRT for the first-stage. No significant difference in fecal coliform destruction was observed at different SRTs used in this study. Although the SRT for the first-stage of two-stage system B was as low as one day, the destruction rate for both total and fecal coliform did not drop as shown in Figures 21 and 25. Again no significant difference was observed for mixture 1 and 2 in terms of fecal coliform destruction. Not a single circumstance, did fecal coliform count in the effluents from the two-stage system exceed 1,000 MPN/g TS.

Methane Content and Daily Production Rate

The biogas composition data are listed in Tables 18 and 19 for mixture 1 and mixture 2, respectively. For single-stage system (mesophilic) the CH_4 concentration of biogas varied in a range of 67 to 72% at SRTs from 24 to 40 days. The second stage (mesophilic) of the two-stage system showed similar results for methane content, as shown in Figure 27. The methane content of the first stage (thermophilic) of the two-stage system was a little bit lower than that in the mesophilic units. It varied from 58 to 69% as shown in Table 18. The lowest methane content occured at a system SRT of 11 days, with one day SRT for the first stage, as shown in both Table 18 and Figure 27.

Daily methane production was shown in Tables 20 and 21 for mixture 1 and 2, respectively. The two-stage system showed higher methane production rate compared to the single-stage system. The higher methane production rate was caused by the higher volatile solids removal rate of the two-stage system. An optimum range of SRT of the two-stage system can be determined in terms of daily methane production rate and volatile solids removal rate. As shown in Figure 28, the optimum SRTs for the two-stage system was in a range from 11 to 17 days. In contrast, no clear peak of daily methane rate was observed for the single-stage system. Although the daily methane production rates showed significant variation between the single and two-stage systems and among different SRTs for each system, the methane production per gram of volatile solids destroyed are quite constant, 0.32 to 0.35 STP liters/g COD destroyed for both single- and two-stage systems and at all SRTs employed in the study.

pH, Volatile Fatty Acids, and Alkalinity

The pH, volatile fatty acids (VFA), and alkalinity of each system are shown in Tables 22 and 23 for mixtures 1 and 2, respectively. For single-stage system pH varied from 7.3 to 7.6, VFA varied from 170 to 200 mg/L as acetic acid, and alkalinity varied from 4,500 to 5,500 mg/L as $CaCO_3$. The lowest pH and alkalinity occurred at the shortest SRT of 24 days. The pH and alkalinity for the two-stage system showed a similar variation compared to the single-stage system. However, the VFA in the first stage of the two-stage system were much higher than that in either the single-stage system or the second stage of the two-stage systems.

Table 18. Biogas composition of each system at different SRTs for mixture 1

System		Q (L/d)	SRT (day)	CH_4 (%)	CO_2 (%)	N_2 (%)
Single-stage system		0.580	24.0	69.0	26	4
		0.500	28.0	71.0	24	5
		0.412	34.0	67.0	29	4
		0.350	40.0	72.0	25	3
Two-stage system A	1st stage	1.000	4.0	65.0	30	5
	2nd stage	1.000	10.0	70.0	28	2
	1st stage	0.700	5.7	69.0	29	3
	2nd stage	0.700	14.3	71.0	26	3
	1st stage	0.500	8.0	68.0	28	4
	2nd stage	0.500	20.0	71.0	25	4
Two-stage system B	1st stage	1.000	1.0	58.0	37	5
	2nd stage	1.000	10.0	68.0	28	4
	1st stage	1.000	2.0	63.0	32	5
	2nd stage	1.000	10.0	67.0	29	4
	1st stage	0.700	2.8	64.0	31	5
	2nd stage	0.700	14.2	70.0	27	3
	1st stage	0.580	4.0	67.0	29	4
	2nd stage	0.580	20.0	71.0	26	3

Table 19. Biogas composition of each system at different SRTs for mixture 2

		Q (L/d)	SRT (day)	CH_4 (%)	CO_2 (%)	N_2 (%)
Single-stage system		0.580	24.0	71	25	4
		0.500	28.0	72	23	5
		0.412	34.0	71	26	3
		0.350	40.0	74	23	3
Two-stage system A	1st stage	1.000	4.0	66	29	5
	2nd stage	1.000	10.0	70	27	3
	1st stage	0.700	5.7	69	28	3
	2nd stage	0.700	14.3	71	26	3
	1st stage	0.500	8.0	70	26	4
	2nd stage	0.500	20.0	72	24	4

Table 20. Daily methane production of each system at different SRTs for mixture 1

System		Q (L/d)	SRT (day)	Daily Methane (STP L/d)	System Daily Methane (STP L/d)
Single-stage system		0.580	24.0	2.75	2.75
		0.500	28.0	2.85	2.85
		0.412	34.0	2.57	2.57
		0.350	40.0	2.45	2.45
Two-stage system A	1st stage	1.000	4.0	3.95	6.35
	2nd stage	1.000	10.0	2.40	
	1st stage	0.700	5.7	3.68	4.75
	2nd stage	0.700	14.3	1.07	
	1st stage	0.500	8.0	2.86	3.60
	2nd stage	0.500	20.0	0.74	
Two-stage system B	1st stage	1.000	1.0	1.70	4.80
	2nd stage	1.000	10.0	3.10	
	1st stage	1.000	2.0	2.50	5.50
	2nd stage	1.000	10.0	3.00	
	1st stage	0.700	2.8	2.90	4.05
	2nd stage	0.700	14.2	1.15	
	1st stage	0.580	4.0	2.75	3.40
	2nd stage	0.580	20.0	0.65	

Table 21. Daily methane production of each system at different SRTs for mixture 2

System		Q (L/d)	SRT (day)	Daily Methane (STP L/d)	System Daily Methane (STP L/d)
Single-stage system		0.580	24.0	2.41	2.41
		0.500	28.0	2.83	2.83
		0.412	34.0	2.32	2.32
		0.350	40.0	2.25	2.25
Two-stage system A	1st stage	1.000	4.0	3.89	6.00
	2nd stage	1.000	10.0	2.11	
	1st stage	0.700	5.7	3.28	4.53
	2nd stage	0.700	14.3	1.25	
	1st stage	0.500	8.0	2.64	3.39
	2nd stage	0.500	20.0	0.75	

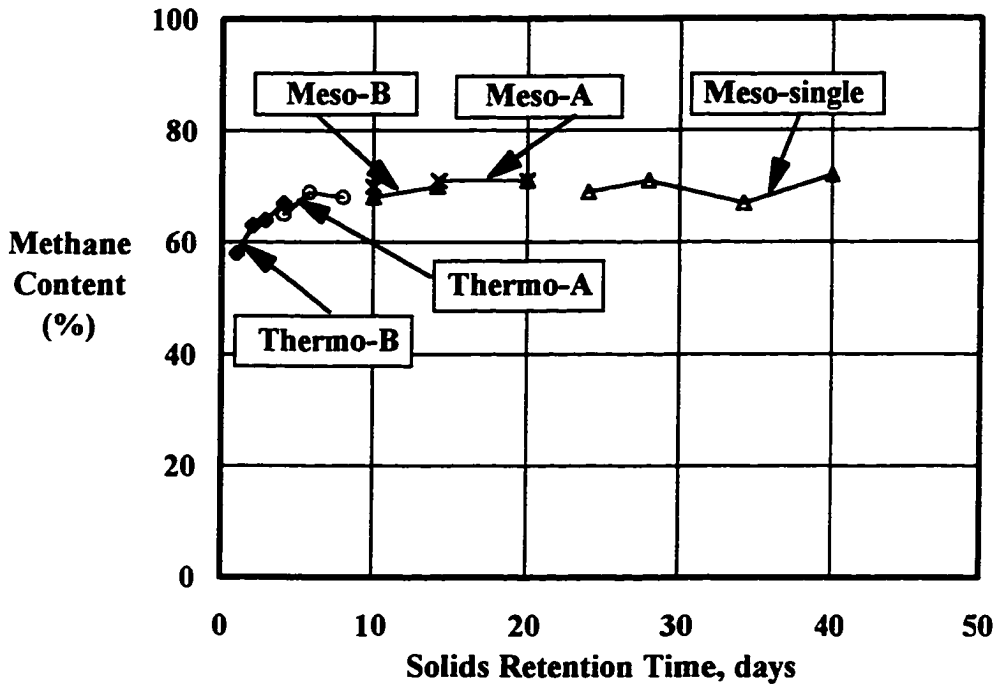


Figure 27. Methane content of the biogas from each stage of the system at different SRTs for mixture 1

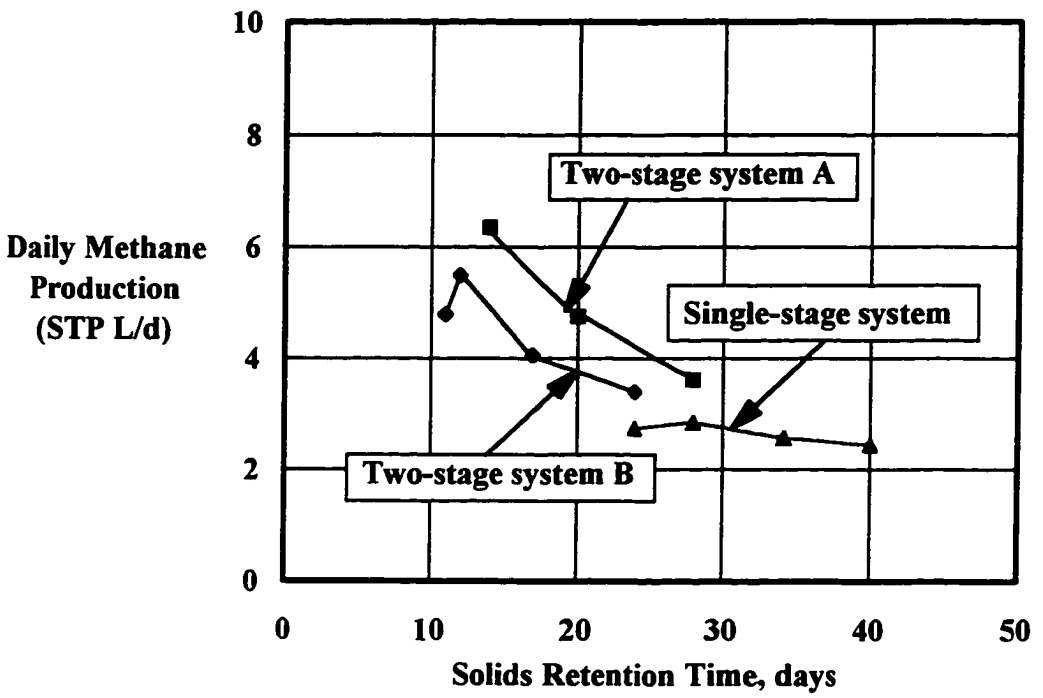


Figure 28. Daily methane production of single-stage and two-stage system at different SRTs for mixture 1

Table 22. pH, VFA, and Alkalinity of each system at different SRTs for mixture 1

System		Q (L/d)	SRT (day)	pH	VFA, as acetic (mg/L)	Alkalinity, as $CaCO_3$ (mg/L)
Single-stage system		0.580	24.0	7.3	180	4500
		0.500	28.0	7.4	200	4800
		0.412	34.0	7.4	195	5100
		0.350	40.0	7.6	170	5500
Two-stage system A	1st stage	1.000	4.0	7.2	1360	4700
	2nd stage	1.000	10.0	7.4	210	5000
	1st stage	0.700	5.7	7.3	1010	5100
	2nd stage	0.700	14.3	7.4	200	5300
	1st stage	0.500	8.0	7.4	800	5000
	2nd stage	0.500	20.0	7.5	190	5300
Two-stage system B	1st stage	1.000	1.0	7.1	2150	4200
	2nd stage	1.000	10.0	7.3	230	4800
	1st stage	1.000	2.0	7.2	1730	4500
	2nd stage	1.000	10.0	7.3	180	5100
	1st stage	0.700	2.8	7.2	1350	4500
	2nd stage	0.700	14.2	7.4	190	5300
	1st stage	0.580	4.0	7.3	1080	4800
	2nd stage	0.580	20.0	7.5	160	5600

Table 23. pH, VFA, and Alkalinity of each system at different SRTs for mixture 2

System		Q (L/d)	SRT (day)	pH	VFA, as acetic (mg/L)	Alkalinity, as $CaCO_3$ (mg/L)
Single-stage system		0.580	24.0	7.4	190	5100
		0.500	28.0	7.5	170	5600
		0.412	34.0	7.6	150	5800
		0.350	40.0	7.6	160	6100
Two-stage system A	1st stage	1.000	4.0	7.3	1200	5000
	2nd stage	1.000	10.0	7.6	190	5200
	1st stage	0.700	5.7	7.4	910	5200
	2nd stage	0.700	14.3	7.5	170	5400
	1st stage	0.500	8.0	7.5	700	5100
	2nd stage	0.500	20.0	7.6	150	5600

At the shortest SRT of one day for the first stage of two-stage system B, as shown in both Table 22 and Figure 29, VFA level reached 1,360 mg/L as acetic acid. As the SRT was longer, the VFA concentration decreased. The lowest VFA of mg/L 800 for mixture 1 and 700 mg/L for mixture 2 was observed at the same SRT of 8 days in the first stage of the two-stage system A, as shown in Table 22, Table 23, and Figure 30, respectively. Although the VFA in the first stage of the two-stage system were several times higher than that in the single-stage system, the VFA in the second stage of the two-stage system were as low as that in the single-stage system. PH values in each reactor varied in a range from 7.0 to 7.6, as shown in Figure 31. Even when SRT of the first stage of the two-stage system B was as low as one day, the pH was still above 7.0. The relatively high alkalinity in the system helped the system maintain its pH values above 7.0. The alkalinity concentrations in all the systems varied from 4200 to 5600 mg/L as $CaCO_3$, as shown in Table 22 and Figure 32. In general, alkalinity went down as the SRT became short. At an SRT of one day, the first stage of two-stage system B reached the lowest alkalinity in this study (4200 mg/L as $CaCO_3$).

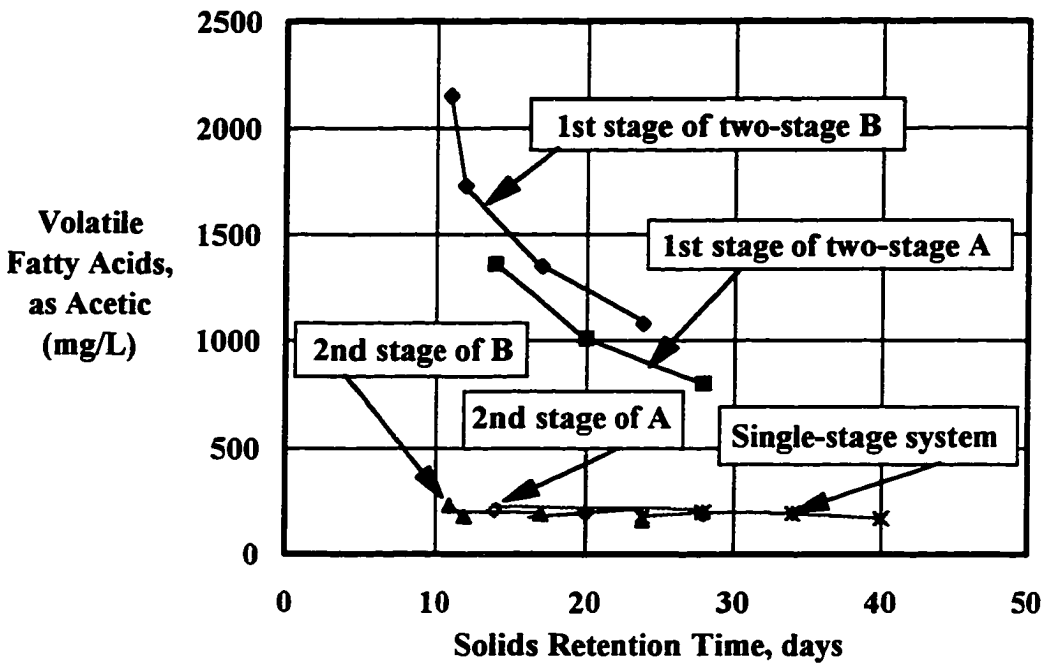


Figure 29. Volatile fatty acids concentrations in each stage of single-stage and two-stage systems at different SRTs for mixture 1

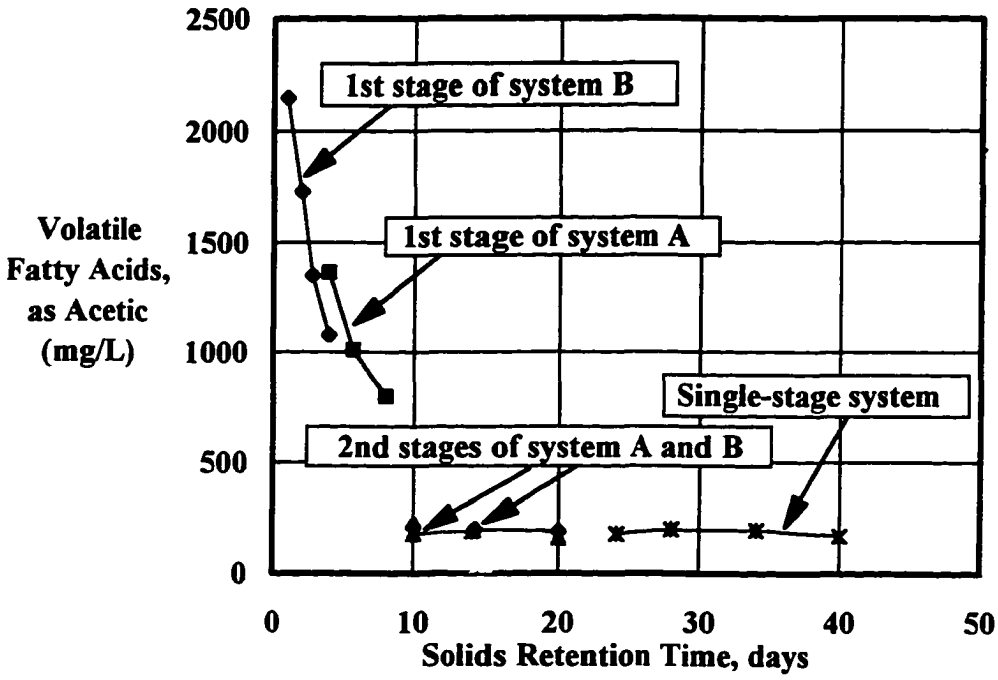


Figure 30. Volatile fatty acids concentrations in each stage of single-stage and two-stage systems at different SRTs for mixture 1

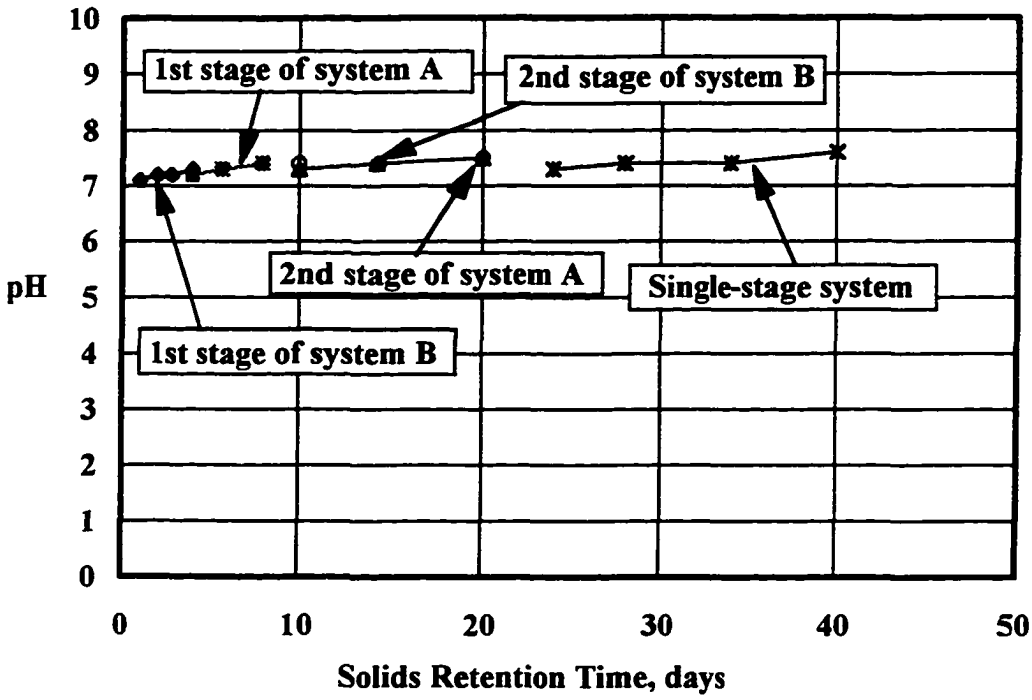


Figure 31. pH in each stage of single-stage and two-stage systems at different SRTs for mixture 1

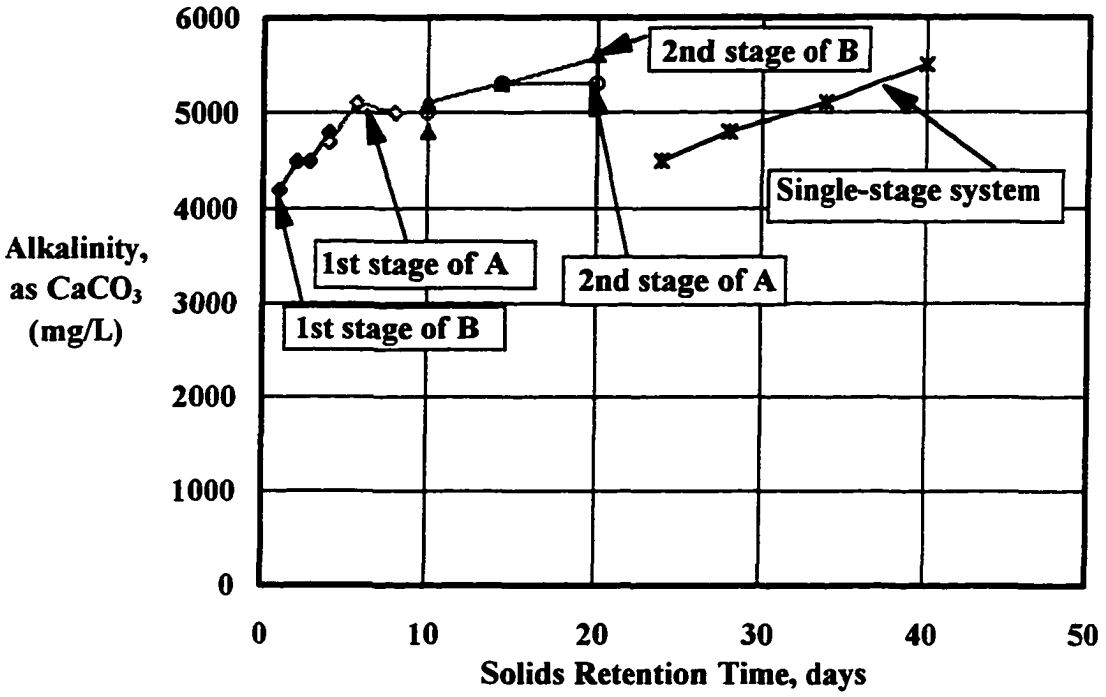


Figure 32. Alkalinity in each stage of single-stage and two-stage systems at different SRTs for mixture 1

Discussion

In this study, the results show that for the same volatile solids removal, SRTs required for conventional single-stage system are much longer than those for two-stage systems. The main reason of shorter SRTs required for the two-stage system is that the thermophilic first stage of the two-stage system was able to enhance the hydrolysis of waste activated sludge, which made waste activated sludge available for acidogenic and methanogenic bacteria. The arrangement of two reactors in series, with the thermophilic unit as the first stage and the mesophilic unit as the second stage, can fully take advantages of both thermophilic and mesophilic digesters. The thermophilic unit has a higher temperature and higher VS loading, and therefore a higher VS destruction rate. Since the volume of the first stage is not large and the HRT is not long, the effluent from the first stage contains high VFAs. The second mesophilic stage was able to convert those acids to methane and carbon dioxide. This phenomenon is illustrated in Figure 29. Although the VFAs are as high as 2,150 mg/L as acetic acid in the thermophilic first stage, they reduced to approximately 200 mg/L as acetic, in the second stage of the two-stage systems. Also the thermophilic stage played a main role in the high destruction of both total and fecal coliforms, as shown in Figures 19, 20, 21, 22, 23, 24, 25, and 26. The single-stage and the second stage of the temperature-phased system (both mesophilic) achieved only less than one log (90%) reduction in both total and fecal coliforms. In contrast, the first stage of the temperature-phased system (thermophilic) achieved a 5-6 log (99.999-99.9999%) reduction of both total and fecal coliforms. No significant difference was observed in terms of coliform destruction under all SRTs applied in this study. This implies

that coliform destruction is mainly a function of temperature. In previous research, SRTs equal to or greater than 10 days have been reported for thermophilic digestion (Garber, 1975 and Lee, 1989). In this study, the SRT of the thermophilic unit was reduced to only one day, when the total system SRT was 11 days. Data presented in Figures 24 and 25 showed that coliform destruction can be maintained to the same degree at this low SRT. The highest fecal coliform concentration in the effluent from the temperature-phased system was only 121 MPN/g TS, as shown in Table 17.

A possible shortcoming of the temperature-phased anaerobic digestion system is the potentially higher energy requirements for heating thermophilic stage. However, for equal VS destruction, the volume of the temperature-phased system can be as low as 50%, or less, of a comparable single-stage mesophilic system, as shown in Figure 9. Heat losses through the reactor surfaces can be minimized by smaller reactor volume required by a two-stage system. Also, as illustrated in Figure 28, the two-stage system can achieve a significant increase in methane production, compared to the single-stage system. More energy can be recovered from the two-stage system, which compensates for any added energy requirements of thermophilic digestion. The reduction of foaming by using two-stage system can also reduce operating problems.

Many conventional digesters now operating in the U.S. can not meet Class A fecal coliform requirements for biosolids disposal. Temperature-phased anaerobic digestion (two-stage) system can meet the Class A biosolids fecal coliform requirement. Foaming is also a problem when treating waste activated sludge. This study suggests that a two-stage system

may be a good alternative for solving these problems. Conventional single-stage systems could be modified to two-stage systems by putting a thermophilic anaerobic digester in front of an existing digester. In practice, it would appear advisable to place an effluent heat exchanger on the first-stage thermophilic reactor. This approach will reduce the temperature of the thermophilic effluent to the optimum mesophilic level and recover a portion of the energy used in raising the temperature of the incoming sludge to the thermophilic level.

V. CONCLUSIONS

Based on this research, the following conclusions are evident:

1. The temperature-phased anaerobic digestion process is capable of achieving almost complete destruction of fecal coliforms over a range of SRTs from 11 to 28 days producing a digested sludge that meets 40 CFR, Part 503 coliform requirements for Class A sludge.
2. Although SRTs could be longer, the optimal SRT of the temperature-phased system exists in the range from 11 to 17 days. At those SRTs the capacity of VS removal of the temperature-phased anaerobic digestion system was more than double that of the conventional single-stage system.
3. For equal volatile solids destruction when treating 50-50 mixtures of PS and WAS, the volume of the temperature-phased anaerobic digestion system (two-phase system) is approximately 40% of that required for single-stage mesophilic digesters.
4. The temperature-phased anaerobic digestion system applied to waste activated sludge digestion offers the advantages of each of the thermophilic and mesophilic processes while avoiding the disadvantages of each process, such as the odors and instability associated with thermophilic digestion and the lower rates of VS and pathogen destruction and serious foaming associated with mesophilic digestion.

APPENDIX A.

TIME PERIOD AND DAILY BIOGAS PRODUCTION FOR 50:50 PS AND WAS

Table 24. Time period of the first run test for mixture 1

System	Q (L/d)	SRT (days)	Time period		
Single-stage system	0.580	24	2/16/95	to	4/4/95
	0.500	28	4/5/95	to	5/30/95
	0.412	34	5/31/95	to	8/6/95
	0.350	40	8/7/95	to	10/25/95
Two-stage system A	1.000	14	2/16/95	to	4/12/95
	0.700	20	4/13/95	to	7/1/95
	0.500	28	7/2/95	to	10/25/95
Two-stage system B	1.000	11	2/16/95	to	3/31/95
	1.000	12	4/1/95	to	5/18/95
	0.700	17	5/19/95	to	7/25/95
	0.580	24	7/26/95	to	10/25/95

Table 25. Daily biogas production of single-stage system at different SRTs for mixture 1

Date	SRT (days)	Biogas (STP L/d)
2/16/95	24	3.8
2/17/95	24	3.7
2/18/95	24	3.8
2/19/95	24	3.5
2/20/95	24	3.6
2/21/95	24	3.8
2/22/95	24	3.8
2/23/95	24	3.8
2/24/95	24	3.7
2/25/95	24	3.8
2/26/95	24	3.8
2/27/95	24	3.8
2/28/95	24	3.5
3/1/95	24	3.9
3/2/95	24	4.0
3/3/95	24	4.0
3/4/95	24	4.1
3/5/95	24	4.0
3/6/95	24	4.2
3/7/95	24	3.9
3/8/95	24	4.0
3/9/95	24	4.0
3/10/95	24	4.1
3/11/95	24	3.8
3/12/95	24	4.0
3/13/95	24	4.0
3/14/95	24	4.0
3/15/95	24	4.0
3/16/95	24	4.1
3/17/95	24	3.9
3/18/95	24	4.0
3/19/95	24	4.0
3/20/95	24	4.0
3/21/95	24	4.0
3/22/95	24	4.0
3/23/95	24	4.0
3/24/95	24	4.0

3/25/95	24	4.0
3/26/95	24	4.0
3/27/95	24	4.0
3/28/95	24	4.0
3/29/95	24	4.0
3/30/95	24	4.0
3/31/95	24	4.0
4/1/95	24	4.0
4/2/95	24	4.0
4/3/95	24	4.0
4/4/95	24	4.0
4/5/95	28	4.1
4/6/95	28	4.1
4/7/95	28	4.1
4/8/95	28	4.2
4/9/95	28	4.3
4/10/95	28	4.1
4/11/95	28	4.2
4/12/95	28	4.1
4/13/95	28	4.1
4/14/95	28	4.2
4/15/95	28	4.3
4/16/95	28	4.1
4/17/95	28	4.1
4/18/95	28	4.2
4/19/95	28	4.1
4/20/95	28	4.1
4/21/95	28	4.2
4/22/95	28	4.2
4/23/95	28	4.3
4/24/95	28	4.2
4/25/95	28	4.1
4/26/95	28	4.1
4/27/95	28	4.2
4/28/95	28	4.2
4/29/95	28	4.1
4/30/95	28	4.3
5/1/95	28	4.3
5/2/95	28	4.1
5/3/95	28	4.2

5/4/95	28	4.3
5/5/95	28	4.2
5/6/95	28	4.1
5/7/95	28	4.2
5/8/95	28	4.1
5/9/95	28	4.3
5/10/95	28	4.4
5/11/95	28	4.2
5/12/95	28	4.1
5/13/95	28	4.1
5/14/95	28	4.2
5/15/95	28	4.3
5/16/95	28	4.2
5/17/95	28	4.1
5/18/95	28	4.2
5/19/95	28	4.3
5/20/95	28	4.2
5/21/95	28	4.3
5/22/95	28	4.1
5/23/95	28	4.1
5/24/95	28	4.2
5/25/95	28	4.3
5/26/95	28	4.3
5/27/95	28	4.2
5/28/95	28	4.2
5/29/95	28	4.3
5/30/95	28	4.2
5/31/95	34	3.9
6/1/95	34	3.9
6/2/95	34	3.9
6/3/95	34	3.8
6/4/95	34	3.9
6/5/95	34	3.9
6/6/95	34	3.7
6/7/95	34	3.9
6/8/95	34	3.7
6/9/95	34	3.8
6/10/95	34	3.6
6/11/95	34	3.8
6/12/95	34	3.8

6/13/95	34	3.8
6/14/95	34	3.8
6/15/95	34	3.7
6/16/95	34	3.6
6/17/95	34	3.9
6/18/95	34	3.8
6/19/95	34	3.8
6/20/95	34	3.8
6/21/95	34	3.8
6/22/95	34	3.7
6/23/95	34	3.7
6/24/95	34	3.8
6/25/95	34	3.8
6/26/95	34	3.7
6/27/95	34	3.7
6/28/95	34	3.8
6/29/95	34	3.8
6/30/95	34	3.7
7/1/95	34	3.6
7/2/95	34	3.8
7/3/95	34	3.8
7/4/95	34	3.8
7/5/95	34	3.7
7/6/95	34	3.8
7/7/95	34	3.7
7/8/95	34	3.8
7/9/95	34	3.8
7/10/95	34	3.8
7/11/95	34	3.8
7/12/95	34	3.8
7/13/95	34	3.7
7/14/95	34	3.7
7/15/95	34	3.8
7/16/95	34	3.8
7/17/95	34	3.8
7/18/95	34	3.8
7/19/95	34	3.8
7/20/95	34	3.7
7/21/95	34	3.7
7/22/95	34	3.7

7/23/95	34	3.7
7/24/95	34	3.8
7/25/95	34	3.7
7/26/95	34	3.7
7/27/95	34	3.7
7/28/95	34	3.7
7/29/95	34	3.8
7/30/95	34	3.7
7/31/95	34	3.7
8/1/95	34	3.7
8/2/95	34	3.7
8/3/95	34	3.8
8/4/95	34	3.6
8/5/95	34	3.7
8/6/95	34	3.7
8/7/95	40	3.7
8/8/95	40	3.7
8/9/95	40	3.7
8/10/95	40	3.7
8/11/95	40	3.7
8/12/95	40	3.7
8/13/95	40	3.7
8/14/95	40	3.7
8/15/95	40	3.7
8/16/95	40	3.8
8/17/95	40	3.7
8/18/95	40	3.6
8/19/95	40	3.6
8/20/95	40	3.5
8/21/95	40	3.6
8/22/95	40	3.6
8/23/95	40	3.6
8/24/95	40	3.5
8/25/95	40	3.6
8/26/95	40	3.6
8/27/95	40	3.6
8/28/95	40	3.7
8/29/95	40	3.6
8/30/95	40	3.6
8/31/95	40	3.5

9/1/95	40	3.6
9/2/95	40	3.6
9/3/95	40	3.6
9/4/95	40	3.5
9/5/95	40	3.6
9/6/95	40	3.6
9/7/95	40	3.7
9/8/95	40	3.6
9/9/95	40	3.6
9/10/95	40	3.6
9/11/95	40	3.5
9/12/95	40	3.6
9/13/95	40	3.6
9/14/95	40	3.8
9/15/95	40	3.6
9/16/95	40	3.6
9/17/95	40	3.6
9/18/95	40	3.6
9/19/95	40	3.6
9/20/95	40	3.7
9/21/95	40	3.6
9/22/95	40	3.6
9/23/95	40	3.5
9/24/95	40	3.6
9/25/95	40	3.6
9/26/95	40	3.6
9/27/95	40	3.6
9/28/95	40	3.6
9/29/95	40	3.6
9/30/95	40	3.6
10/1/95	40	3.6
10/2/95	40	3.5
10/3/95	40	3.6
10/4/95	40	3.6
10/5/95	40	3.6
10/6/95	40	3.5
10/7/95	40	3.6
10/8/95	40	3.6
10/9/95	40	3.6
10/10/95	40	3.7

10/11/95	40	3.6
10/12/95	40	3.6
10/13/95	40	3.6
10/14/95	40	3.6
10/15/95	40	3.6
10/16/95	40	3.5
10/17/95	40	3.6
10/18/95	40	3.6
10/19/95	40	3.6
10/20/95	40	3.6
10/21/95	40	3.4
10/22/95	40	3.6
10/23/95	40	3.6
10/24/95	40	3.6
10/25/95	40	3.6

Table 26. Daily biogas production of two-stage system A at different SRTs for mixture 1

Date	First-stage		Second-stage		System	
	SRT (days)	Biogas (STP L/d)	SRT (days)	Biogas (STP L/d)	SRT (days)	Biogas (STP L/d)
2/16/95	4	5.7	10	3.4	14	9.1
2/17/95	4	5.7	10	3.4	14	9.1
2/18/95	4	5.7	10	3.4	14	9.1
2/19/95	4	5.7	10	3.4	14	9.1
2/20/95	4	5.7	10	3.4	14	9.1
2/21/95	4	5.6	10	3.4	14	9.0
2/22/95	4	5.7	10	3.4	14	9.1
2/23/95	4	5.6	10	3.4	14	9.0
2/24/95	4	5.7	10	3.4	14	9.1
2/25/95	4	5.7	10	3.5	14	9.2
2/26/95	4	5.7	10	3.5	14	9.2
2/27/95	4	5.7	10	3.5	14	9.2
2/28/95	4	5.7	10	3.5	14	9.2
3/1/95	4	5.5	10	3.5	14	9.0
3/2/95	4	5.7	10	3.5	14	9.2
3/3/95	4	5.7	10	3.5	14	9.2
3/4/95	4	5.7	10	3.5	14	9.2
3/5/95	4	5.8	10	3.5	14	9.3
3/6/95	4	5.7	10	3.5	14	9.2
3/7/95	4	5.8	10	3.5	14	9.3
3/8/95	4	5.8	10	3.5	14	9.3
3/9/95	4	5.8	10	3.5	14	9.3
3/10/95	4	5.8	10	3.5	14	9.3
3/11/95	4	5.8	10	3.5	14	9.3
3/12/95	4	5.7	10	3.5	14	9.2
3/13/95	4	5.8	10	3.5	14	9.3
3/14/95	4	5.8	10	3.5	14	9.3
3/15/95	4	5.8	10	3.5	14	9.3
3/16/95	4	5.8	10	3.5	14	9.3
3/17/95	4	5.6	10	3.5	14	9.1
3/18/95	4	5.8	10	3.5	14	9.3
3/19/95	4	5.7	10	3.5	14	9.2
3/20/95	4	5.8	10	3.5	14	9.3
3/21/95	4	5.8	10	3.5	14	9.3
3/22/95	4	5.8	10	3.5	14	9.3
3/23/95	4	5.8	10	3.5	14	9.3

3/24/95	4	5.8	10	3.5	14	9.3
3/25/95	4	5.8	10	3.5	14	9.3
3/26/95	4	5.7	10	3.5	14	9.2
3/27/95	4	5.7	10	3.5	14	9.2
3/28/95	4	5.7	10	3.5	14	9.2
3/29/95	4	5.7	10	3.5	14	9.2
3/30/95	4	5.8	10	3.5	14	9.3
3/31/95	4	5.7	10	3.5	14	9.2
4/1/95	4	5.7	10	3.5	14	9.2
4/2/95	4	5.9	10	3.5	14	9.4
4/3/95	4	5.7	10	3.5	14	9.2
4/4/95	4	5.7	10	3.5	14	9.2
4/5/95	4	5.8	10	3.5	14	9.3
4/6/95	4	5.7	10	3.5	14	9.2
4/7/95	4	5.8	10	3.5	14	9.3
4/8/95	4	5.8	10	3.5	14	9.3
4/9/95	4	5.8	10	3.5	14	9.3
4/10/95	4	5.8	10	3.5	14	9.3
4/11/95	4	5.8	10	3.5	14	9.3
4/12/95	4	5.8	10	3.5	14	9.3
4/13/95	5.7	5.6	14.3	3.3	20	8.9
4/14/95	5.7	5.6	14.3	3.3	20	8.9
4/15/95	5.7	5.6	14.3	3.3	20	8.9
4/16/95	5.7	5.6	14.3	3.3	20	8.9
4/17/95	5.7	5.6	14.3	3.2	20	8.8
4/18/95	5.7	5.5	14.3	3.2	20	8.7
4/19/95	5.7	5.5	14.3	3.2	20	8.7
4/20/95	5.7	5.5	14.3	2.8	20	8.3
4/21/95	5.7	5.5	14.3	2.5	20	8.0
4/22/95	5.7	5.5	14.3	2.4	20	7.9
4/23/95	5.7	5.4	14.3	2.4	20	7.8
4/24/95	5.7	5.4	14.3	2.1	20	7.5
4/25/95	5.7	5.4	14.3	2.1	20	7.5
4/26/95	5.7	5.4	14.3	2.1	20	7.5
4/27/95	5.7	5.4	14.3	2.0	20	7.4
4/28/95	5.7	5.4	14.3	2.0	20	7.4
4/29/95	5.7	5.4	14.3	1.8	20	7.2
4/30/95	5.7	5.4	14.3	1.8	20	7.2
5/1/95	5.7	5.3	14.3	1.8	20	7.1
5/2/95	5.7	5.3	14.3	1.8	20	7.1

5/3/95	5.7	5.3	14.3	1.7	20	7.0
5/4/95	5.7	5.3	14.3	1.7	20	7.0
5/5/95	5.7	5.3	14.3	1.7	20	7.0
5/6/95	5.7	5.3	14.3	1.7	20	7.0
5/7/95	5.7	5.3	14.3	1.6	20	6.9
5/8/95	5.7	5.3	14.3	1.6	20	6.9
5/9/95	5.7	5.3	14.3	1.6	20	6.9
5/10/95	5.7	5.3	14.3	1.6	20	6.9
5/11/95	5.7	5.3	14.3	1.6	20	6.9
5/12/95	5.7	5.3	14.3	1.6	20	6.9
5/13/95	5.7	5.3	14.3	1.6	20	6.9
5/14/95	5.7	5.3	14.3	1.7	20	7.0
5/15/95	5.7	5.3	14.3	1.7	20	7.0
5/16/95	5.7	5.3	14.3	1.7	20	7.0
5/17/95	5.7	5.3	14.3	1.7	20	7.0
5/18/95	5.7	5.3	14.3	1.7	20	7.0
5/19/95	5.7	5.3	14.3	1.6	20	6.9
5/20/95	5.7	5.3	14.3	1.6	20	6.9
5/21/95	5.7	5.3	14.3	1.6	20	6.9
5/22/95	5.7	5.3	14.3	1.6	20	6.9
5/23/95	5.7	5.3	14.3	1.6	20	6.9
5/24/95	5.7	5.3	14.3	1.6	20	6.9
5/25/95	5.7	5.3	14.3	1.6	20	6.9
5/26/95	5.7	5.3	14.3	1.6	20	6.9
5/27/95	5.7	5.3	14.3	1.6	20	6.9
5/28/95	5.7	5.3	14.3	1.6	20	6.9
5/29/95	5.7	5.3	14.3	1.6	20	6.9
5/30/95	5.7	5.3	14.3	1.6	20	6.9
5/31/95	5.7	5.3	14.3	1.6	20	6.9
6/1/95	5.7	5.3	14.3	1.6	20	6.9
6/2/95	5.7	5.3	14.3	1.6	20	6.9
6/3/95	5.7	5.3	14.3	1.6	20	6.9
6/4/95	5.7	5.3	14.3	1.6	20	6.9
6/5/95	5.7	5.3	14.3	1.6	20	6.9
6/6/95	5.7	5.3	14.3	1.5	20	6.8
6/7/95	5.7	5.3	14.3	1.6	20	6.9
6/8/95	5.7	5.3	14.3	1.6	20	6.9
6/9/95	5.7	5.3	14.3	1.6	20	6.9
6/10/95	5.7	5.3	14.3	1.7	20	7.0
6/11/95	5.7	5.3	14.3	1.6	20	6.9

6/12/95	5.7	5.3	14.3	1.6	20	6.9
6/13/95	5.7	5.3	14.3	1.6	20	6.9
6/14/95	5.7	5.3	14.3	1.6	20	6.9
6/15/95	5.7	5.3	14.3	1.6	20	6.9
6/16/95	5.7	5.3	14.3	1.5	20	6.8
6/17/95	5.7	5.3	14.3	1.6	20	6.9
6/18/95	5.7	5.3	14.3	1.6	20	6.9
6/19/95	5.7	5.3	14.3	1.6	20	6.9
6/20/95	5.7	5.3	14.3	1.7	20	7.0
6/21/95	5.7	5.3	14.3	1.6	20	6.9
6/22/95	5.7	5.3	14.3	1.6	20	6.9
6/23/95	5.7	5.3	14.3	1.6	20	6.9
6/24/95	5.7	5.3	14.3	1.6	20	6.9
6/25/95	5.7	5.3	14.3	1.5	20	6.8
6/26/95	5.7	5.3	14.3	1.6	20	6.9
6/27/95	5.7	5.3	14.3	1.6	20	6.9
6/28/95	5.7	5.3	14.3	1.5	20	6.8
6/29/95	5.7	5.3	14.3	1.6	20	6.9
6/30/95	5.7	5.3	14.3	1.6	20	6.9
7/1/95	5.7	5.3	14.3	1.6	20	6.9
7/2/95	8	4.8	20	1.4	28	6.2
7/3/95	8	4.7	20	1.3	28	6.0
7/4/95	8	4.6	20	1.2	28	5.8
7/5/95	8	4.3	20	1.1	28	5.4
7/6/95	8	4.2	20	1.1	28	5.3
7/7/95	8	4.2	20	1.1	28	5.3
7/8/95	8	4.2	20	1.1	28	5.3
7/9/95	8	4.2	20	1.1	28	5.3
7/10/95	8	4.2	20	1.1	28	5.3
7/11/95	8	4.2	20	1.1	28	5.3
7/12/95	8	4.2	20	1.1	28	5.3
7/13/95	8	4.2	20	1.1	28	5.3
7/14/95	8	4.2	20	1.1	28	5.3
7/15/95	8	4.2	20	1.1	28	5.3
7/16/95	8	4.2	20	1.1	28	5.3
7/17/95	8	4.2	20	1.1	28	5.3
7/18/95	8	4.2	20	1.1	28	5.3
7/19/95	8	4.2	20	1.1	28	5.3
7/20/95	8	4.2	20	1.1	28	5.3
7/21/95	8	4.2	20	1.1	28	5.3

7/22/95	8	4.2	20	1.1	28	5.3
7/23/95	8	4.2	20	1.2	28	5.4
7/24/95	8	4.1	20	1.1	28	5.2
7/25/95	8	4.1	20	1.1	28	5.2
7/26/95	8	4.1	20	1.1	28	5.2
7/27/95	8	4.1	20	1.2	28	5.3
7/28/95	8	4.1	20	1.1	28	5.2
7/29/95	8	4.1	20	1.1	28	5.2
7/30/95	8	4.1	20	1.1	28	5.2
7/31/95	8	4.1	20	1.3	28	5.4
8/1/95	8	4.1	20	1.1	28	5.2
8/2/95	8	4.2	20	1.1	28	5.3
8/3/95	8	4.2	20	1.2	28	5.4
8/4/95	8	4.2	20	1.1	28	5.3
8/5/95	8	4.2	20	1.1	28	5.3
8/6/95	8	4.2	20	1.1	28	5.3
8/7/95	8	4.2	20	1.2	28	5.4
8/8/95	8	4.2	20	1.1	28	5.3
8/9/95	8	4.2	20	1.1	28	5.3
8/10/95	8	4.2	20	1.3	28	5.5
8/11/95	8	4.2	20	1.1	28	5.3
8/12/95	8	4.2	20	1.1	28	5.3
8/13/95	8	4.2	20	1.0	28	5.2
8/14/95	8	4.2	20	1.1	28	5.3
8/15/95	8	4.2	20	1.1	28	5.3
8/16/95	8	4.2	20	1.1	28	5.3
8/17/95	8	4.2	20	1.2	28	5.4
8/18/95	8	4.2	20	1.1	28	5.3
8/19/95	8	4.2	20	1.1	28	5.3
8/20/95	8	4.2	20	1.3	28	5.5
8/21/95	8	4.2	20	1.1	28	5.3
8/22/95	8	4.2	20	1.1	28	5.3
8/23/95	8	4.2	20	1.2	28	5.4
8/24/95	8	4.2	20	1.1	28	5.3
8/25/95	8	4.2	20	1.2	28	5.4
8/26/95	8	4.2	20	1.1	28	5.3
8/27/95	8	4.2	20	1.1	28	5.3
8/28/95	8	4.2	20	1.1	28	5.3
8/29/95	8	4.2	20	1.1	28	5.3
8/30/95	8	4.2	20	1.2	28	5.4

8/31/95	8	4.2	20	1.1	28	5.3
9/1/95	8	4.2	20	1.2	28	5.4
9/2/95	8	4.2	20	1.1	28	5.3
9/3/95	8	4.2	20	1.1	28	5.3
9/4/95	8	4.2	20	1.3	28	5.5
9/5/95	8	4.2	20	1.1	28	5.3
9/6/95	8	4.2	20	1.1	28	5.3
9/7/95	8	4.2	20	1.1	28	5.3
9/8/95	8	4.2	20	1.2	28	5.4
9/9/95	8	4.2	20	1.1	28	5.3
9/10/95	8	4.2	20	1.1	28	5.3
9/11/95	8	4.2	20	1.1	28	5.3
9/12/95	8	4.2	20	1.1	28	5.3
9/13/95	8	4.2	20	1.1	28	5.3
9/14/95	8	4.2	20	1.2	28	5.4
9/15/95	8	4.2	20	1.1	28	5.3
9/16/95	8	4.2	20	1.1	28	5.3
9/17/95	8	4.2	20	1.1	28	5.3
9/18/95	8	4.2	20	1.3	28	5.5
9/19/95	8	4.2	20	1.1	28	5.3
9/20/95	8	4.2	20	1.1	28	5.3
9/21/95	8	4.2	20	1.1	28	5.3
9/22/95	8	4.2	20	1.1	28	5.3
9/23/95	8	4.2	20	1.2	28	5.4
9/24/95	8	4.2	20	1.1	28	5.3
9/25/95	8	4.2	20	1.2	28	5.4
9/26/95	8	4.2	20	1.1	28	5.3
9/27/95	8	4.2	20	1.1	28	5.3
9/28/95	8	4.2	20	1.2	28	5.4
9/29/95	8	4.2	20	1.2	28	5.4
9/30/95	8	4.2	20	1.2	28	5.4
10/1/95	8	4.2	20	1.2	28	5.4
10/2/95	8	4.2	20	1.2	28	5.4
10/3/95	8	4.2	20	1.1	28	5.3
10/4/95	8	4.2	20	1.1	28	5.3
10/5/95	8	4.2	20	1.3	28	5.5
10/6/95	8	4.2	20	1.1	28	5.3
10/7/95	8	4.2	20	1.1	28	5.3
10/8/95	8	4.2	20	1.1	28	5.3
10/9/95	8	4.2	20	1.1	28	5.3

10/10/95	8	4.2	20	1.3	28	5.5
10/11/95	8	4.2	20	1.1	28	5.3
10/12/95	8	4.2	20	1.1	28	5.3
10/13/95	8	4.2	20	1.2	28	5.4
10/14/95	8	4.2	20	1.1	28	5.3
10/15/95	8	4.2	20	1.1	28	5.3
10/16/95	8	4.2	20	1.1	28	5.3
10/17/95	8	4.2	20	1.0	28	5.2
10/18/95	8	4.2	20	1.1	28	5.3
10/19/95	8	4.2	20	1.1	28	5.3
10/20/95	8	4.2	20	1.1	28	5.3
10/21/95	8	4.2	20	1.1	28	5.3
10/22/95	8	4.2	20	1.2	28	5.4
10/23/95	8	4.2	20	1.1	28	5.3
10/24/95	8	4.2	20	1.1	28	5.3
10/25/95	8	4.2	20	1.1	28	5.3

Table 27. Daily biogas production of two-stage system B at different SRTs for mixture 1

Date	First-stage		Second-stage		System	
	SRT (days)	Biogas (STP L/d)	SRT (days)	Biogas (STP L/d)	SRT (days)	Biogas (STP L/d)
2/16/95	1	2.3	10	4.3	11	6.6
2/17/95	1	2.3	10	4.3	11	6.6
2/18/95	1	2.3	10	4.3	11	6.6
2/19/95	1	2.3	10	4.3	11	6.6
2/20/95	1	2.3	10	4.3	11	6.6
2/21/95	1	2.4	10	4.3	11	6.7
2/22/95	1	2.4	10	4.4	11	6.8
2/23/95	1	2.4	10	4.4	11	6.8
2/24/95	1	2.4	10	4.4	11	6.8
2/25/95	1	2.4	10	4.4	11	6.8
2/26/95	1	2.4	10	4.5	11	6.9
2/27/95	1	2.4	10	4.4	11	6.8
2/28/95	1	2.4	10	4.4	11	6.8
3/1/95	1	2.4	10	4.5	11	6.9
3/2/95	1	2.4	10	4.4	11	6.8
3/3/95	1	2.5	10	4.4	11	6.9
3/4/95	1	2.5	10	4.4	11	6.9
3/5/95	1	2.5	10	4.4	11	6.9
3/6/95	1	2.5	10	4.4	11	6.9
3/7/95	1	2.5	10	4.4	11	6.9
3/8/95	1	2.5	10	4.5	11	7.0
3/9/95	1	2.5	10	4.5	11	7.0
3/10/95	1	2.5	10	4.5	11	7.0
3/11/95	1	2.5	10	4.6	11	7.1
3/12/95	1	2.5	10	4.5	11	7.0
3/13/95	1	2.5	10	4.5	11	7.0
3/14/95	1	2.5	10	4.5	11	7.0
3/15/95	1	2.5	10	4.6	11	7.1
3/16/95	1	2.5	10	4.5	11	7.0
3/17/95	1	2.5	10	4.5	11	7.0
3/18/95	1	2.5	10	4.5	11	7.0
3/19/95	1	2.5	10	4.6	11	7.1
3/20/95	1	2.5	10	4.5	11	7.0
3/21/95	1	2.5	10	4.5	11	7.0
3/22/95	1	2.5	10	4.5	11	7.0
3/23/95	1	2.5	10	4.5	11	7.0

3/24/95	1	2.5	10	4.4	11	6.9
3/25/95	1	2.5	10	4.5	11	7.0
3/26/95	1	2.5	10	4.5	11	7.0
3/27/95	1	2.5	10	4.3	11	6.8
3/28/95	1	2.5	10	4.5	11	7.0
3/29/95	1	2.5	10	4.5	11	7.0
3/30/95	1	2.5	10	4.6	11	7.1
3/31/95	1	2.5	10	4.5	11	7.0
4/1/95	2	2.9	10	4.4	12	7.3
4/2/95	2	2.9	10	4.4	12	7.3
4/3/95	2	2.9	10	4.4	12	7.3
4/4/95	2	3.0	10	4.4	12	7.4
4/5/95	2	3.0	10	4.4	12	7.4
4/6/95	2	3.0	10	4.4	12	7.4
4/7/95	2	3.0	10	4.4	12	7.4
4/8/95	2	3.1	10	4.4	12	7.5
4/9/95	2	3.1	10	4.4	12	7.5
4/10/95	2	3.1	10	4.4	12	7.5
4/11/95	2	3.1	10	4.4	12	7.5
4/12/95	2	3.3	10	4.3	12	7.6
4/13/95	2	3.3	10	4.3	12	7.6
4/14/95	2	3.3	10	4.3	12	7.6
4/15/95	2	3.3	10	4.3	12	7.6
4/16/95	2	3.4	10	4.3	12	7.7
4/17/95	2	3.4	10	4.5	12	7.9
4/18/95	2	3.4	10	4.5	12	7.9
4/19/95	2	3.4	10	4.5	12	7.9
4/20/95	2	3.5	10	4.5	12	8.0
4/21/95	2	3.6	10	4.5	12	8.1
4/22/95	2	3.5	10	4.5	12	8.0
4/23/95	2	3.5	10	4.4	12	7.9
4/24/95	2	3.5	10	4.4	12	7.9
4/25/95	2	3.6	10	4.4	12	8.0
4/26/95	2	3.6	10	4.2	12	7.8
4/27/95	2	3.6	10	4.4	12	8.0
4/28/95	2	3.6	10	4.4	12	8.0
4/29/95	2	3.6	10	4.4	12	8.0
4/30/95	2	3.6	10	4.4	12	8.0
5/1/95	2	3.6	10	4.4	12	8.0
5/2/95	2	3.6	10	4.4	12	8.0

5/3/95	2	3.6	10	4.3	12	7.9
5/4/95	2	3.6	10	4.4	12	8.0
5/5/95	2	3.6	10	4.4	12	8.0
5/6/95	2	3.6	10	4.4	12	8.0
5/7/95	2	3.6	10	4.3	12	7.9
5/8/95	2	3.6	10	4.4	12	8.0
5/9/95	2	3.5	10	4.4	12	7.9
5/10/95	2	3.6	10	4.4	12	8.0
5/11/95	2	3.6	10	4.4	12	8.0
5/12/95	2	3.6	10	4.4	12	8.0
5/13/95	2	3.4	10	4.4	12	7.8
5/14/95	2	3.6	10	4.4	12	8.0
5/15/95	2	3.5	10	4.4	12	7.9
5/16/95	2	3.6	10	4.4	12	8.0
5/17/95	2	3.7	10	4.4	12	8.1
5/18/95	2	3.6	10	4.4	12	8.0
5/19/95	2.8	3.9	14.2	4.0	17	7.9
5/20/95	2.8	3.9	14.2	3.8	17	7.7
5/21/95	2.8	3.9	14.2	3.7	17	7.6
5/22/95	2.8	3.9	14.2	3.4	17	7.3
5/23/95	2.8	4.1	14.2	3.2	17	7.3
5/24/95	2.8	4.1	14.2	3.1	17	7.2
5/25/95	2.8	4.2	14.2	2.7	17	6.9
5/26/95	2.8	4.1	14.2	2.5	17	6.6
5/27/95	2.8	4.1	14.2	2.3	17	6.4
5/28/95	2.8	4.2	14.2	2.0	17	6.2
5/29/95	2.8	4.2	14.2	1.9	17	6.1
5/30/95	2.8	4.2	14.2	1.8	17	6.0
5/31/95	2.8	4.2	14.2	1.8	17	6.0
6/1/95	2.8	4.3	14.2	1.8	17	6.1
6/2/95	2.8	4.3	14.2	1.8	17	6.1
6/3/95	2.8	4.3	14.2	1.8	17	6.1
6/4/95	2.8	4.3	14.2	1.8	17	6.1
6/5/95	2.8	4.2	14.2	1.8	17	6.0
6/6/95	2.8	4.3	14.2	1.8	17	6.1
6/7/95	2.8	4.3	14.2	1.7	17	6.0
6/8/95	2.8	4.2	14.2	1.7	17	5.9
6/9/95	2.8	4.3	14.2	1.7	17	6.0
6/10/95	2.8	4.4	14.2	1.7	17	6.1
6/11/95	2.8	4.3	14.2	1.6	17	5.9

6/12/95	2.8	4.4	14.2	1.7	17	6.1
6/13/95	2.8	4.3	14.2	1.8	17	6.1
6/14/95	2.8	4.2	14.2	1.4	17	5.6
6/15/95	2.8	4.3	14.2	1.9	17	6.2
6/16/95	2.8	4.4	14.2	1.7	17	6.1
6/17/95	2.8	4.3	14.2	1.7	17	6.0
6/18/95	2.8	4.3	14.2	1.6	17	5.9
6/19/95	2.8	4.5	14.2	1.7	17	6.2
6/20/95	2.8	4.3	14.2	1.7	17	6.0
6/21/95	2.8	4.1	14.2	1.8	17	5.9
6/22/95	2.8	4.3	14.2	1.7	17	6.0
6/23/95	2.8	4.3	14.2	1.7	17	6.0
6/24/95	2.8	4.3	14.2	1.7	17	6.0
6/25/95	2.8	4.2	14.2	1.7	17	5.9
6/26/95	2.8	4.3	14.2	1.6	17	5.9
6/27/95	2.8	4.3	14.2	1.7	17	6.0
6/28/95	2.8	4.5	14.2	1.7	17	6.2
6/29/95	2.8	4.3	14.2	1.5	17	5.8
6/30/95	2.8	4.3	14.2	1.7	17	6.0
7/1/95	2.8	4.2	14.2	1.7	17	5.9
7/2/95	2.8	4.3	14.2	1.7	17	6.0
7/3/95	2.8	4.2	14.2	1.7	17	5.9
7/4/95	2.8	4.2	14.2	1.7	17	5.9
7/5/95	2.8	4.3	14.2	1.8	17	6.1
7/6/95	2.8	4.3	14.2	1.7	17	6.0
7/7/95	2.8	4.4	14.2	1.7	17	6.1
7/8/95	2.8	4.3	14.2	1.7	17	6.0
7/9/95	2.8	4.5	14.2	1.7	17	6.2
7/10/95	2.8	4.3	14.2	1.7	17	6.0
7/11/95	2.8	4.3	14.2	1.9	17	6.2
7/12/95	2.8	4.3	14.2	1.5	17	5.8
7/13/95	2.8	4.3	14.2	1.7	17	6.0
7/14/95	2.8	4.3	14.2	1.7	17	6.0
7/15/95	2.8	4.3	14.2	1.7	17	6.0
7/16/95	2.8	4.2	14.2	1.8	17	6.0
7/17/95	2.8	4.3	14.2	1.7	17	6.0
7/18/95	2.8	4.3	14.2	1.7	17	6.0
7/19/95	2.8	4.1	14.2	1.8	17	5.9
7/20/95	2.8	4.3	14.2	1.7	17	6.0
7/21/95	2.8	4.3	14.2	1.7	17	6.0

7/22/95	2.8	4.3	14.2	1.9	17	6.2
7/23/95	2.8	4.3	14.2	1.7	17	6.0
7/24/95	2.8	4.2	14.2	1.7	17	5.9
7/25/95	2.8	4.3	14.2	1.7	17	6.0
7/26/95	4	3.9	20	1.0	24	4.9
7/27/95	4	3.9	20	1.0	24	4.9
7/28/95	4	3.9	20	1.0	24	4.9
7/29/95	4	3.9	20	1.0	24	4.9
7/30/95	4	3.9	20	1.0	24	4.9
7/31/95	4	3.9	20	1.0	24	4.9
8/1/95	4	3.8	20	1.0	24	4.8
8/2/95	4	3.9	20	1.0	24	4.9
8/3/95	4	3.7	20	1.0	24	4.7
8/4/95	4	3.9	20	1.0	24	4.9
8/5/95	4	3.9	20	1.0	24	4.9
8/6/95	4	3.9	20	1.0	24	4.9
8/7/95	4	3.9	20	0.9	24	4.8
8/8/95	4	3.9	20	0.9	24	4.8
8/9/95	4	3.9	20	0.9	24	4.8
8/10/95	4	3.7	20	0.9	24	4.6
8/11/95	4	3.9	20	0.9	24	4.8
8/12/95	4	3.9	20	1.0	24	4.9
8/13/95	4	3.7	20	1.0	24	4.7
8/14/95	4	3.7	20	1.0	24	4.7
8/15/95	4	3.9	20	1.1	24	5.0
8/16/95	4	3.8	20	1.0	24	4.8
8/17/95	4	3.9	20	1.0	24	4.9
8/18/95	4	3.9	20	1.0	24	4.9
8/19/95	4	3.9	20	1.0	24	4.9
8/20/95	4	3.8	20	1.0	24	4.8
8/21/95	4	3.9	20	1.0	24	4.9
8/22/95	4	3.8	20	0.9	24	4.7
8/23/95	4	3.9	20	1.0	24	4.9
8/24/95	4	3.9	20	1.0	24	4.9
8/25/95	4	3.9	20	1.0	24	4.9
8/26/95	4	4.0	20	0.9	24	4.9
8/27/95	4	3.6	20	1.0	24	4.6
8/28/95	4	3.9	20	1.0	24	4.9
8/29/95	4	3.9	20	1.0	24	4.9
8/30/95	4	3.9	20	0.9	24	4.8

8/31/95	4	3.9	20	0.9	24	4.8
9/1/95	4	3.9	20	0.9	24	4.8
9/2/95	4	3.9	20	1.0	24	4.9
9/3/95	4	3.9	20	1.0	24	4.9
9/4/95	4	3.9	20	0.9	24	4.8
9/5/95	4	3.9	20	1.0	24	4.9
9/6/95	4	3.9	20	1.0	24	4.9
9/7/95	4	3.9	20	1.1	24	5.0
9/8/95	4	3.9	20	1.0	24	4.9
9/9/95	4	3.9	20	1.0	24	4.9
9/10/95	4	3.8	20	1.1	24	4.9
9/11/95	4	3.7	20	1.0	24	4.7
9/12/95	4	3.9	20	1.0	24	4.9
9/13/95	4	3.9	20	1.1	24	5.0
9/14/95	4	3.9	20	1.0	24	4.9
9/15/95	4	3.9	20	1.0	24	4.9
9/16/95	4	3.8	20	1.1	24	4.9
9/17/95	4	3.9	20	1.1	24	5.0
9/18/95	4	3.7	20	0.9	24	4.6
9/19/95	4	3.9	20	0.9	24	4.8
9/20/95	4	3.9	20	1.0	24	4.9
9/21/95	4	3.9	20	1.0	24	4.9
9/22/95	4	3.9	20	1.0	24	4.9
9/23/95	4	3.9	20	1.0	24	4.9
9/24/95	4	3.9	20	1.1	24	5.0
9/25/95	4	3.8	20	1.0	24	4.8
9/26/95	4	3.9	20	1.0	24	4.9
9/27/95	4	3.9	20	0.9	24	4.8
9/28/95	4	3.8	20	1.0	24	4.8
9/29/95	4	3.9	20	1.0	24	4.9
9/30/95	4	3.9	20	1.1	24	5.0
10/1/95	4	3.8	20	1.0	24	4.8
10/2/95	4	3.8	20	0.9	24	4.7
10/3/95	4	3.9	20	1.0	24	4.9
10/4/95	4	3.9	20	1.0	24	4.9
10/5/95	4	3.9	20	1.0	24	4.9
10/6/95	4	3.9	20	1.0	24	4.9
10/7/95	4	3.9	20	1.1	24	5.0
10/8/95	4	3.9	20	1.0	24	4.9
10/9/95	4	3.9	20	1.0	24	4.9

10/10/95	4	3.9	20	1.1	24	5.0
10/11/95	4	3.9	20	1.0	24	4.9
10/12/95	4	3.9	20	1.1	24	5.0
10/13/95	4	3.9	20	1.0	24	4.9
10/14/95	4	3.9	20	1.0	24	4.9
10/15/95	4	3.9	20	1.0	24	4.9
10/16/95	4	3.8	20	0.9	24	4.7
10/17/95	4	3.9	20	1.0	24	4.9
10/18/95	4	3.9	20	1.0	24	4.9
10/19/95	4	3.9	20	1.0	24	4.9
10/20/95	4	3.7	20	1.0	24	4.7
10/21/95	4	3.9	20	1.0	24	4.9
10/22/95	4	3.9	20	1.0	24	4.9
10/23/95	4	3.9	20	1.0	24	4.9
10/24/95	4	3.9	20	1.1	24	5.0
10/25/95	4	3.8	20	1.0	24	4.8

APPENDIX B.

TIME PERIOD AND DAILY BIOGAS PRODUCTION FOR 25:75 PS AND WAS

Table 28. Time period of the second run test for mixture 2

System	Q (L/d)	SRT (days)	Time period
Single-stage system	0.580	24	11/1/95 to 12/18/95
	0.500	28	12/19/95 to 2/12/96
	0.412	34	2/13/96 to 4/20/96
	0.350	40	4/21/96 to 7/9/96
Two-stage system A	1.000	14	11/1/95 to 12/26/95
	0.700	20	12/27/95 to 3/15/96
	0.500	28	3/16/96 to 7/9/96

Table 29. Daily biogas production of single-stage system at different SRTs for mixture 2

Date	SRT (days)	Biogas (STP L/d)
11/1/95	24	3.4
11/2/95	24	3.4
11/3/95	24	3.4
11/4/95	24	3.5
11/5/95	24	3.4
11/6/95	24	3.5
11/7/95	24	3.4
11/8/95	24	3.4
11/9/95	24	3.5
11/10/95	24	3.4
11/11/95	24	3.4
11/12/95	24	3.4
11/13/95	24	3.5
11/14/95	24	3.4
11/15/95	24	3.6
11/16/95	24	3.4
11/17/95	24	3.4
11/18/95	24	3.5
11/19/95	24	3.4
11/20/95	24	3.4
11/21/95	24	3.5
11/22/95	24	3.4
11/23/95	24	3.6
11/24/95	24	3.6
11/25/95	24	3.5
11/26/95	24	3.6
11/27/95	24	3.5
11/28/95	24	3.6
11/29/95	24	3.4
11/30/95	24	3.6
12/1/95	24	3.6
12/2/95	24	3.5
12/3/95	24	3.6
12/4/95	24	3.5
12/5/95	24	3.6
12/6/95	24	3.6
12/7/95	24	3.6

12/8/95	24	3.6
12/9/95	24	3.6
12/10/95	24	3.5
12/11/95	24	3.6
12/12/95	24	3.6
12/13/95	24	3.5
12/14/95	24	3.6
12/15/95	24	3.5
12/16/95	24	3.6
12/17/95	24	3.4
12/18/95	24	3.6
12/19/95	28	3.7
12/20/95	28	3.7
12/21/95	28	3.7
12/22/95	28	3.8
12/23/95	28	3.8
12/24/95	28	3.7
12/25/95	28	3.9
12/26/95	28	3.7
12/27/95	28	3.8
12/28/95	28	3.7
12/29/95	28	3.8
12/30/95	28	3.9
12/31/95	28	3.9
1/1/96	28	3.9
1/2/96	28	4.0
1/3/96	28	3.9
1/4/96	28	3.9
1/5/96	28	3.9
1/6/96	28	3.9
1/7/96	28	3.9
1/8/96	28	3.9
1/9/96	28	4.0
1/10/96	28	4.0
1/11/96	28	3.8
1/12/96	28	4.0
1/13/96	28	4.1
1/14/96	28	4.0
1/15/96	28	4.2
1/16/96	28	4.0

1/17/96	28	3.8
1/18/96	28	4.0
1/19/96	28	4.0
1/20/96	28	4.1
1/21/96	28	3.9
1/22/96	28	3.9
1/23/96	28	4.2
1/24/96	28	4.0
1/25/96	28	4.0
1/26/96	28	4.1
1/27/96	28	4.1
1/28/96	28	4.1
1/29/96	28	3.9
1/30/96	28	4.2
1/31/96	28	3.9
2/1/96	28	4.1
2/2/96	28	4.1
2/3/96	28	4.0
2/4/96	28	4.0
2/5/96	28	3.9
2/6/96	28	4.2
2/7/96	28	4.0
2/8/96	28	4.1
2/9/96	28	4.1
2/10/96	28	3.9
2/11/96	28	4.1
2/12/96	28	4.0
2/13/96	34	3.8
2/14/96	34	3.8
2/15/96	34	3.6
2/16/96	34	3.6
2/17/96	34	3.6
2/18/96	34	3.5
2/19/96	34	3.5
2/20/96	34	3.4
2/21/96	34	3.4
2/22/96	34	3.4
2/23/96	34	3.5
2/24/96	34	3.4
2/25/96	34	3.5

2/26/96	34	3.5
2/27/96	34	3.5
2/28/96	34	3.5
2/29/96	34	3.3
3/1/96	34	3.5
3/2/96	34	3.4
3/3/96	34	3.5
3/4/96	34	3.4
3/5/96	34	3.4
3/6/96	34	3.5
3/7/96	34	3.6
3/8/96	34	3.5
3/9/96	34	3.3
3/10/96	34	3.4
3/11/96	34	3.4
3/12/96	34	3.2
3/13/96	34	3.5
3/14/96	34	3.5
3/15/96	34	3.4
3/16/96	34	3.3
3/17/96	34	3.4
3/18/96	34	3.4
3/19/96	34	3.5
3/20/96	34	3.4
3/21/96	34	3.6
3/22/96	34	3.2
3/23/96	34	3.5
3/24/96	34	3.5
3/25/96	34	3.4
3/26/96	34	3.4
3/27/96	34	3.3
3/28/96	34	3.4
3/29/96	34	3.5
3/30/96	34	3.4
3/31/96	34	3.4
4/1/96	34	3.4
4/2/96	34	3.4
4/3/96	34	3.3
4/4/96	34	3.5
4/5/96	34	3.4

4/6/96	34	3.4
4/7/96	34	3.4
4/8/96	34	3.3
4/9/96	34	3.4
4/10/96	34	3.4
4/11/96	34	3.2
4/12/96	34	3.4
4/13/96	34	3.4
4/14/96	34	3.3
4/15/96	34	3.4
4/16/96	34	3.4
4/17/96	34	3.5
4/18/96	34	3.4
4/19/96	34	3.3
4/20/96	34	3.4
4/21/96	40	3.3
4/22/96	40	3.3
4/23/96	40	3.2
4/24/96	40	3.3
4/25/96	40	3.3
4/26/96	40	3.4
4/27/96	40	3.2
4/28/96	40	3.1
4/29/96	40	3.2
4/30/96	40	3.2
5/1/96	40	3.3
5/2/96	40	3.2
5/3/96	40	3.2
5/4/96	40	3.4
5/5/96	40	3.2
5/6/96	40	3.1
5/7/96	40	3.2
5/8/96	40	3.3
5/9/96	40	3.0
5/10/96	40	3.3
5/11/96	40	3.2
5/12/96	40	3.3
5/13/96	40	3.5
5/14/96	40	3.3
5/15/96	40	3.0

5/16/96	40	3.3
5/17/96	40	3.3
5/18/96	40	3.3
5/19/96	40	3.2
5/20/96	40	3.2
5/21/96	40	3.4
5/22/96	40	3.2
5/23/96	40	3.3
5/24/96	40	3.1
5/25/96	40	3.3
5/26/96	40	3.3
5/27/96	40	3.2
5/28/96	40	3.3
5/29/96	40	3.4
5/30/96	40	3.3
5/31/96	40	3.5
6/1/96	40	3.2
6/2/96	40	3.1
6/3/96	40	3.2
6/4/96	40	3.3
6/5/96	40	3.3
6/6/96	40	3.4
6/7/96	40	3.3
6/8/96	40	3.5
6/9/96	40	3.3
6/10/96	40	3.1
6/11/96	40	3.3
6/12/96	40	3.2
6/13/96	40	3.2
6/14/96	40	3.4
6/15/96	40	3.1
6/16/96	40	3.3
6/17/96	40	3.4
6/18/96	40	3.3
6/19/96	40	3.2
6/20/96	40	3.3
6/21/96	40	3.1
6/22/96	40	3.3
6/23/96	40	3.2
6/24/96	40	3.2

6/25/96	40	3.3
6/26/96	40	3.3
6/27/96	40	3.1
6/28/96	40	3.3
6/29/96	40	3.2
6/30/96	40	3.2
7/1/96	40	3.3
7/2/96	40	3.3
7/3/96	40	3.1
7/4/96	40	3.3
7/5/96	40	3.2
7/6/96	40	3.3
7/7/96	40	3.4
7/8/96	40	3.3
7/9/96	40	3.3

Table 30. Daily biogas production of two-stage system A at different SRTs for mixture 2

Date	First-stage		Second-stage		System	
	SRT (days)	Biogas (STP L/d)	SRT (days)	Biogas (STP L/d)	SRT (days)	Biogas (STP L/d)
11/1/95	4	5.4	10	2.8	14	8.2
11/2/95	4	5.4	10	3.0	14	8.4
11/3/95	4	5.3	10	3.0	14	8.3
11/4/95	4	5.4	10	3.0	14	8.4
11/5/95	4	5.4	10	2.9	14	8.3
11/6/95	4	5.4	10	2.9	14	8.3
11/7/95	4	5.5	10	2.9	14	8.4
11/8/95	4	5.6	10	3.1	14	8.7
11/9/95	4	5.5	10	3.1	14	8.6
11/10/95	4	5.4	10	3.0	14	8.4
11/11/95	4	5.5	10	3.1	14	8.6
11/12/95	4	5.3	10	3.1	14	8.4
11/13/95	4	5.5	10	3.0	14	8.5
11/14/95	4	5.6	10	3.0	14	8.6
11/15/95	4	5.5	10	3.2	14	8.7
11/16/95	4	5.3	10	3.0	14	8.3
11/17/95	4	5.5	10	2.9	14	8.4
11/18/95	4	5.6	10	3.0	14	8.6
11/19/95	4	5.6	10	3.1	14	8.7
11/20/95	4	5.4	10	3.1	14	8.5
11/21/95	4	5.6	10	3.2	14	8.8
11/22/95	4	5.3	10	3.1	14	8.4
11/23/95	4	5.6	10	3.1	14	8.7
11/24/95	4	5.4	10	3.0	14	8.4
11/25/95	4	5.6	10	3.1	14	8.7
11/26/95	4	5.5	10	3.2	14	8.7
11/27/95	4	5.6	10	3.2	14	8.8
11/28/95	4	5.3	10	3.1	14	8.4
11/29/95	4	5.6	10	3.2	14	8.8
11/30/95	4	5.5	10	3.2	14	8.7
12/1/95	4	5.6	10	3.0	14	8.6
12/2/95	4	5.4	10	3.1	14	8.5
12/3/95	4	5.4	10	3.1	14	8.5
12/4/95	4	5.6	10	2.9	14	8.5
12/5/95	4	5.5	10	3.1	14	8.6
12/6/95	4	5.5	10	3.2	14	8.7

12/7/95	4	5.4	10	3.1	14	8.5
12/8/95	4	5.5	10	3.3	14	8.8
12/9/95	4	5.5	10	2.9	14	8.4
12/10/95	4	5.6	10	3.1	14	8.7
12/11/95	4	5.6	10	3.1	14	8.7
12/12/95	4	5.5	10	3.0	14	8.5
12/13/95	4	5.4	10	3.1	14	8.5
12/14/95	4	5.6	10	3.1	14	8.7
12/15/95	4	5.3	10	3.2	14	8.5
12/16/95	4	5.6	10	3.1	14	8.7
12/17/95	4	5.4	10	3.1	14	8.5
12/18/95	4	5.6	10	3.1	14	8.7
12/19/95	4	5.3	10	3.1	14	8.4
12/20/95	4	5.6	10	3.1	14	8.7
12/21/95	4	5.5	10	3.1	14	8.6
12/22/95	4	5.6	10	3.1	14	8.7
12/23/95	4	5.3	10	3.1	14	8.4
12/24/95	4	5.7	10	3.1	14	8.8
12/25/95	4	5.6	10	3.1	14	8.7
12/26/95	4	5.6	10	3.1	14	8.7
12/27/95	5.7	5.3	14.3	2.8	20	8.1
12/28/95	5.7	5.1	14.3	2.6	20	7.7
12/29/95	5.7	4.8	14.3	2.5	20	7.3
12/30/95	5.7	4.8	14.3	2.2	20	7.0
12/31/95	5.7	4.8	14.3	2.1	20	6.9
1/1/96	5.7	4.8	14.3	2.0	20	6.8
1/2/96	5.7	4.7	14.3	1.9	20	6.6
1/3/96	5.7	4.7	14.3	1.8	20	6.5
1/4/96	5.7	4.6	14.3	1.8	20	6.4
1/5/96	5.7	4.8	14.3	1.8	20	6.6
1/6/96	5.7	4.7	14.3	1.8	20	6.5
1/7/96	5.7	4.7	14.3	1.9	20	6.6
1/8/96	5.7	4.9	14.3	1.9	20	6.8
1/9/96	5.7	4.7	14.3	1.9	20	6.6
1/10/96	5.7	4.6	14.3	1.9	20	6.5
1/11/96	5.7	4.7	14.3	1.7	20	6.4
1/12/96	5.7	4.8	14.3	1.8	20	6.6
1/13/96	5.7	4.6	14.3	1.9	20	6.5
1/14/96	5.7	4.7	14.3	1.8	20	6.5
1/15/96	5.7	4.6	14.3	1.8	20	6.4

1/16/96	5.7	4.8	14.3	1.8	20	6.6
1/17/96	5.7	4.6	14.3	1.9	20	6.5
1/18/96	5.7	4.5	14.3	1.9	20	6.4
1/19/96	5.7	4.8	14.3	1.8	20	6.6
1/20/96	5.7	4.8	14.3	1.9	20	6.7
1/21/96	5.7	4.7	14.3	1.9	20	6.6
1/22/96	5.7	4.8	14.3	1.7	20	6.5
1/23/96	5.7	4.6	14.3	1.9	20	6.5
1/24/96	5.7	4.8	14.3	1.9	20	6.7
1/25/96	5.7	4.8	14.3	1.7	20	6.5
1/26/96	5.7	4.5	14.3	1.9	20	6.4
1/27/96	5.7	4.8	14.3	1.8	20	6.6
1/28/96	5.7	4.7	14.3	1.9	20	6.6
1/29/96	5.7	4.6	14.3	1.9	20	6.5
1/30/96	5.7	4.7	14.3	1.7	20	6.4
1/31/96	5.7	4.7	14.3	1.8	20	6.5
2/1/96	5.7	4.8	14.3	1.8	20	6.6
2/2/96	5.7	4.7	14.3	1.9	20	6.6
2/3/96	5.7	4.6	14.3	1.8	20	6.4
2/4/96	5.7	4.7	14.3	1.9	20	6.6
2/5/96	5.7	4.7	14.3	1.8	20	6.5
2/6/96	5.7	4.8	14.3	1.9	20	6.7
2/7/96	5.7	4.7	14.3	1.9	20	6.6
2/8/96	5.7	4.7	14.3	1.9	20	6.6
2/9/96	5.7	4.6	14.3	1.9	20	6.5
2/10/96	5.7	4.7	14.3	1.7	20	6.4
2/11/96	5.7	4.7	14.3	1.9	20	6.6
2/12/96	5.7	4.8	14.3	1.8	20	6.6
2/13/96	5.7	4.7	14.3	1.8	20	6.5
2/14/96	5.7	4.6	14.3	1.7	20	6.3
2/15/96	5.7	4.7	14.3	1.8	20	6.5
2/16/96	5.7	4.6	14.3	1.9	20	6.5
2/17/96	5.7	4.7	14.3	1.9	20	6.6
2/18/96	5.7	4.7	14.3	1.7	20	6.4
2/19/96	5.7	4.5	14.3	1.9	20	6.4
2/20/96	5.7	4.9	14.3	1.9	20	6.8
2/21/96	5.7	4.7	14.3	1.8	20	6.5
2/22/96	5.7	4.7	14.3	1.9	20	6.6
2/23/96	5.7	4.8	14.3	1.9	20	6.7
2/24/96	5.7	4.5	14.3	1.8	20	6.3

2/25/96	5.7	4.7	14.3	1.9	20	6.6
2/26/96	5.7	4.6	14.3	1.9	20	6.5
2/27/96	5.7	4.7	14.3	1.7	20	6.4
2/28/96	5.7	4.5	14.3	1.9	20	6.4
2/29/96	5.7	4.9	14.3	1.8	20	6.7
3/1/96	5.7	4.7	14.3	1.9	20	6.6
3/2/96	5.7	4.7	14.3	1.7	20	6.4
3/3/96	5.7	4.8	14.3	1.9	20	6.7
3/4/96	5.7	4.7	14.3	1.8	20	6.5
3/5/96	5.7	4.9	14.3	1.9	20	6.8
3/6/96	5.7	4.7	14.3	1.7	20	6.4
3/7/96	5.7	4.7	14.3	1.9	20	6.6
3/8/96	5.7	4.8	14.3	1.9	20	6.7
3/9/96	5.7	4.7	14.3	1.8	20	6.5
3/10/96	5.7	4.6	14.3	1.9	20	6.5
3/11/96	5.7	4.8	14.3	1.8	20	6.6
3/12/96	5.7	4.7	14.3	1.9	20	6.6
3/13/96	5.7	4.8	14.3	1.9	20	6.7
3/14/96	5.7	4.7	14.3	1.8	20	6.5
3/15/96	5.7	4.7	14.3	1.9	20	6.6
3/16/96	8	4.3	20	1.6	28	5.9
3/17/96	8	4.1	20	1.5	28	5.6
3/18/96	8	3.9	20	1.4	28	5.3
3/19/96	8	3.9	20	1.3	28	5.2
3/20/96	8	3.9	20	1.2	28	5.1
3/21/96	8	3.9	20	1.2	28	5.1
3/22/96	8	3.8	20	1.1	28	4.9
3/23/96	8	3.7	20	1.2	28	4.9
3/24/96	8	3.8	20	1.1	28	4.9
3/25/96	8	3.8	20	1.1	28	4.9
3/26/96	8	3.9	20	1.2	28	5.1
3/27/96	8	3.8	20	1.1	28	4.9
3/28/96	8	4.0	20	1.1	28	5.1
3/29/96	8	3.8	20	3.0	28	6.8
3/30/96	8	3.8	20	1.0	28	4.8
3/31/96	8	3.7	20	1.0	28	4.7
4/1/96	8	3.9	20	1.1	28	5.0
4/2/96	8	3.9	20	1.0	28	4.9
4/3/96	8	3.8	20	1.0	28	4.8
4/4/96	8	3.9	20	1.2	28	5.1

4/5/96	8	3.7	20	1.1	28	4.8
4/6/96	8	3.9	20	1.1	28	5.0
4/7/96	8	3.9	20	1.1	28	5.0
4/8/96	8	3.7	20	1.1	28	4.8
4/9/96	8	3.9	20	1.2	28	5.1
4/10/96	8	3.8	20	1.1	28	4.9
4/11/96	8	3.8	20	1.0	28	4.8
4/12/96	8	3.8	20	1.1	28	4.9
4/13/96	8	3.9	20	1.1	28	5.0
4/14/96	8	3.8	20	1.1	28	4.9
4/15/96	8	3.8	20	1.1	28	4.9
4/16/96	8	4.0	20	1.2	28	5.2
4/17/96	8	3.8	20	1.1	28	4.9
4/18/96	8	3.8	20	1.2	28	5.0
4/19/96	8	3.9	20	1.2	28	5.1
4/20/96	8	3.8	20	1.2	28	5.0
4/21/96	8	3.8	20	1.0	28	4.8
4/22/96	8	3.7	20	1.2	28	4.9
4/23/96	8	3.8	20	1.2	28	5.0
4/24/96	8	3.9	20	1.2	28	5.1
4/25/96	8	3.9	20	1.1	28	5.0
4/26/96	8	3.9	20	1.2	28	5.1
4/27/96	8	3.8	20	1.1	28	4.9
4/28/96	8	3.9	20	1.2	28	5.1
4/29/96	8	3.7	20	1.1	28	4.8
4/30/96	8	3.9	20	1.2	28	5.1
5/1/96	8	3.9	20	1.2	28	5.1
5/2/96	8	3.8	20	1.1	28	4.9
5/3/96	8	3.9	20	1.2	28	5.1
5/4/96	8	3.9	20	1.2	28	5.1
5/5/96	8	3.7	20	1.1	28	4.8
5/6/96	8	3.8	20	1.2	28	5.0
5/7/96	8	3.9	20	1.0	28	4.9
5/8/96	8	3.8	20	1.2	28	5.0
5/9/96	8	3.9	20	1.2	28	5.1
5/10/96	8	3.8	20	1.0	28	4.8
5/11/96	8	3.7	20	1.1	28	4.8
5/12/96	8	3.8	20	1.0	28	4.8
5/13/96	8	3.9	20	1.2	28	5.1
5/14/96	8	3.8	20	1.2	28	5.0

5/15/96	8	3.9	20	1.1	28	5.0
5/16/96	8	3.8	20	1.2	28	5.0
5/17/96	8	3.7	20	1.1	28	4.8
5/18/96	8	3.8	20	1.0	28	4.8
5/19/96	8	3.8	20	1.2	28	5.0
5/20/96	8	3.9	20	1.1	28	5.0
5/21/96	8	3.8	20	1.2	28	5.0
5/22/96	8	3.8	20	1.1	28	4.9
5/23/96	8	3.9	20	1.2	28	5.1
5/24/96	8	3.8	20	1.2	28	5.0
5/25/96	8	3.7	20	1.0	28	4.7
5/26/96	8	3.8	20	1.2	28	5.0
5/27/96	8	4.0	20	1.1	28	5.1
5/28/96	8	3.8	20	1.0	28	4.8
5/29/96	8	3.8	20	1.1	28	4.9
5/30/96	8	3.7	20	1.2	28	4.9
5/31/96	8	3.8	20	1.3	28	5.1
6/1/96	8	3.9	20	1.1	28	5.0
6/2/96	8	3.8	20	1.1	28	4.9
6/3/96	8	3.7	20	1.2	28	4.9
6/4/96	8	3.8	20	1.2	28	5.0
6/5/96	8	3.9	20	1.1	28	5.0
6/6/96	8	3.8	20	1.2	28	5.0
6/7/96	8	3.8	20	1.1	28	4.9
6/8/96	8	3.7	20	1.2	28	4.9
6/9/96	8	3.8	20	1.2	28	5.0
6/10/96	8	3.8	20	1.1	28	4.9
6/11/96	8	3.9	20	1.1	28	5.0
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6/13/96	8	3.8	20	1.1	28	4.9
6/14/96	8	3.7	20	1.1	28	4.8
6/15/96	8	3.8	20	1.1	28	4.9
6/16/96	8	3.6	20	1.2	28	4.8
6/17/96	8	3.8	20	1.1	28	4.9
6/18/96	8	3.9	20	1.2	28	5.1
6/19/96	8	3.8	20	1.1	28	4.9
6/20/96	8	3.9	20	1.2	28	5.1
6/21/96	8	3.8	20	1.2	28	5.0
6/22/96	8	3.8	20	1.1	28	4.9
6/23/96	8	3.7	20	1.2	28	4.9

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6/25/96	8	3.9	20	1.2	28	5.1
6/26/96	8	3.8	20	1.1	28	4.9
6/27/96	8	3.9	20	1.2	28	5.1
6/28/96	8	3.7	20	1.0	28	4.7
6/29/96	8	3.9	20	1.2	28	5.1
6/30/96	8	3.8	20	1.2	28	5.0
7/1/96	8	3.8	20	1.2	28	5.0
7/2/96	8	3.7	20	1.1	28	4.8
7/3/96	8	3.8	20	1.2	28	5.0
7/4/96	8	3.8	20	1.1	28	4.9
7/5/96	8	3.9	20	1.0	28	4.9
7/6/96	8	3.8	20	1.2	28	5.0
7/7/96	8	3.7	20	1.0	28	4.7
7/8/96	8	3.9	20	1.1	28	5.0
7/9/96	8	3.8	20	1.2	28	5.0

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