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Michael S. Switzenbaum
Associate Professor of Civil Engineering

Kevin C. Sheehan
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Graduate Research Assistant

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UNIVERSITY OF MASSACHUSETTS
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Technical Report

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Assistant Professor of Civil Engineering

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Department of Civil Engineering
Environmental Engineering Program
University of Massachusetts
Amherst, MA 01003

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ABSTRACT

The anaerobic fluidized bed was tested over a five month period for the treatment of primary settled domestic wastewater. Over a range a hydraulic loading rates (HRT from 1.67-6.67 hours), mean BOD_5 concentrations and suspended solids concentrations of 47.2 mgL^{-1} and 30.5 mgL^{-1} were achieved over an influent temperature range of 10-23°C. Solids were never wasted over the entire study. The system was found to compare favorably with other pilot scale anaerobic processes.

Statistical analyses of the data indicated that influent substrate concentration and organic volumetric loading rate had the most influence on effluent BOD_5 concentrations and $\%BOD_5$ removal. Excellent correlations existed between effluent BOD_5 concentration and influent BOD_5 concentration, and organic loading rate. The $\%BOD_5$ removed correlated very well with the same independent variables.

In terms of design implications, it appears that optimal design of the anaerobic fluidized bed system would be achieved with a high rate (low residence time) anaerobic reactor followed by a post-treatment operation such as a gravity filter, or microscreen. Various research needs are also listed.

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INTRODUCTION

The anaerobic fermentation process converts organic waste material to methane and carbon dioxide in the absence of molecular oxygen. It has been used in waste treatment for over 100 years (1). It is known to have several important advantages over aerobic waste treatment systems such as: 1) a higher degree of stabilization; 2) a lower sludge volume; 3) lower nutrient requirements; 4) no oxygen requirement; and 5) methane, a valuable by-product is produced.

On the other hand, anaerobic treatment has several disadvantages associated with the process. These include: 1) the slow growth rate of the methanogens; 2) the sensitive nature of the methanogens; 3) the long solids retention time requirement; 4) the need for auxiliary heating (to maintain the digester at 35^{o}C); and 5) the general feeling of unreliability associated with the process.

In the past, broad scale application of the anaerobic treatment process has been largely with the treatment of municipal sewage sludges to achieve waste stabilization and solids destruction. Over the past decade, significant advances in both the fundamental understanding of the anaerobic fermentation process and the engineering application of this process have taken place. These new developments show a great deal of promise in overcoming many of the limitations associated with anaerobic treatment for the processing of both municipal and industrial wastewaters.

One of the newer developments has been the anaerobic attached film expanded bed process (2,3) or the anaerobic fluidized bed. This process has been demonstrated in the laboratory to be capable of achieving high degrees of organic removal at reduced temperatures with concomitant low detention times when treating low strength wastes.

This report will describe pilot scale testing of the anaerobic fluidized bed reactor treating primary municipal wastewater effluent. This testing was performed at the University of Massachusetts' pilot wastewater treatment plant. In addition, the potential for full scale anaerobic treatment of municipal wastewater will be discussed.

BACKGROUND INFORMATION

1. Introduction

Broad scale application of the anaerobic treatment process has been largely in the treatment of municipal sewage sludge and animal residues to achieve waste stabilization and solids reduction. Anaerobic processes can also be used for the treatment of liquid wastewaters (rather than particulate residues such as sludges and animal residues) although it is seldom done in engineering practice. This lack of application is most likely due to the general feeling of unreliability that is often associated with anaerobic digestion among Environmental Engineers. This perception is probably due to the basic lack of understanding of the fundamental concepts associated with anaerobic methane fermentation. Other disadvantages historically associated with methane fermentation include: 1) poor process stability; 2) a temperature requirement of 35^{o}C; 3) the inability to degrade various substrates; and 4) large reactor volume requirements because of slow reaction rates.

More recently, advances in the basic understanding of the microbiology and biochemistry along with advances in the hardware technology have helped to overcome many of the problems associated with anaerobic fermentation. This section reviews and briefly discusses these recent developments and applications, from the point of view of an Environmental Engineer.

2. Recent Developments

a. Microbiological

The microbiology and biochemistry of the anaerobic fermentation process have been covered in several excellent recent review papers (4,5,6). Several of the applicable highlights will be discussed here. The conversion of a complex organic waste to methane and carbon dioxide involves three stages, or metabolic groups of bacteria - the fermentative, acetogenic, and methanogenic bacteria. The fermentative bacteria (first stage) produce mainly short chain organic acids, and CO_2 and H_2. The second group takes these fatty acids or several other compounds such as lactate and methanol and produces acetate, CO_2 and H_2. The methanogens are able to use few compounds and mainly get energy for growth by using electrons generated in their oxidation of H_2. Several of the methanogenic species can use acetate (7). From the viewpoint of kinetic control of anaerobic reactors, this third group of organisms represents the rate limiting step. In particular, the acetate utilizing methanogens, which are important in anaerobic digesters, are quite slow growing. One species has been shown to have a doubling time of nine days (7). Because of this, long solids retention times are necessary in anaerobic reactors to insure good efficiency and stability of operation.

The role of H_2 has been demonstrated to be that of an extremely important regulator in the control of the overall process (8,9). The partial pressure of hydrogen must be kept low for oxidation to occur. This is accomplished by the oxidation of hydrogen in the formation of methane by the methane bacteria. Mosey (10) recently pointed out the possible value of monitoring hydrogen partial-pressure for digester control, by a relatively simple commercial instrument.

It has only recently been learned that the methanogens represent a unique phylogenic and physiological group of organisms (4). Along with the halobacteria and some thermo-acidophilic bacteria, the methanogens are proposed to represent their own kingdom of organisms called the archaebacteria (11). Woese (11) suggested that the archaebacteria kingdom was equivalent to the remaining kingdoms of eucaryotes and eubacteria.

Among the unique features of the methanogens are a series of coenzymes and metallic activators not found in nonmethanogens. For example, methanogens are dependent on nickel-an unusual growth requirement (12). Nickel is a component of factor F_{430}, an oxygen-stable nonfluorescent chromophore. Coenzyme M has been uniquely associated with methanogens as a co-factor required for the reduction of methyl vitamin B_{12} to methane (13). Another coenzyme with important electron transfer functions, and not widely found elsewhere, is factor F_{420} which exhibits a blue-green fluorescence in ultraviolet light and has a strong absorption maximum at 420 nm. The fluorescence has been used as a technique for identifying methanogens (14) and for assessing their potential activities in reactors (15). F_{420} has a high sulfur content (16).

These nutritional requirements, particulary nickel, represent important discoveries, since the development of anaerobic wastewater treatment processes has been greatly delayed due to inadequate information concerning nutrient requirements. Recently, it has been shown that kinetic rates much higher than previously reported could be achieved using nickel stimulation (12).

A related phenomenon is the effect of inhibitors on the process. Despite their reputation as sensitive organisms it seems that methanogenic cultures are quite hardy and tolerant to environmental stresses (17). Fixed films seem to offer greater protection against toxicants.

One other area of recent progress involves anaerobic degradation of compounds which had previously been thought to be non-degradable under anaerobic conditions. Aromatic compounds (18) and a range of halogenated aliphatic compounds (19,20) can be mineralized under anaerobic conditions. McCarty (21) has pointed out that the latter group is generally considered to be biologically refractory under aerobic conditions, and that anaerobic treatment therefore has

potential for application to the treatment of contaminated groundwaters as well as to industrial wastewater treatment.

b. Technological

The principal objective of any biological reactor configuration is to bring the substrate and enzymes into intimate contact for a sufficient period of time to allow the reactions to occur. For anaerobic methane fermentation processes, long microbial residence times are necessary due to the slow growth rate of the methane producing bacteria.

Anaerobic reactors have primarily been developed for sludge digestion. Typically, sludges are digested in large holding tanks, which are usually maintained at retention times on the order of 15 days. This can be referred to as the conventional digestion design (see Figure 1). The conventional digestor is usually heated and mixed. Because of the temperature requirement, high strength wastes are more suitable as the methane produced is used to heat the reactors. In addition, the high solids retention times, which dictate large reactor volumes, preclude the processing of large waste flows. In general, the conventional digester is usually more suitable for solids processing than for liquid waste streams.

While a high solids retention time (SRT) is necessary for efficient methane fermentation, a low hydraulic retention time (HRT) is desirable for system economy. The conventional system is not able to separate SRT and HRT, and thus large reactor volumes are required. The anaerobic contact process was developed from the concept of recycling biological solids to obtain a larger biomass for a longer retention time. It was initially developed in the 1950's by Schroepfer (22). Currently, several modifications of this concept are being marketed (23,24).

The process is basically an anaerobic activated sludge process (see Figure 2). The effluent from the bioreactor is pumped to a settling unit where a portion of the settled sludge is returned to the reactor, enabling the contact unit to maintain a high concentration of active mass. Thus, solids concentrations can be maintained independently of waste flow using the method of biomass solids recycle.

Another type of contact process is the upflow anaerobic sludge blanket (UASB). A sludge blanket is basically a dense layer of granular or flocculated sludge placed in a reactor which is designed to allow the upward movement of liquid waste through the blanket. Various types of sludge blankets have been used in wastewater treatment for years.

Another means of providing an anaerobic process with a high solids retention time for the methane producing bacteria with a short

hydraulic retention time for system economy is with fixed film reactors. In these systems, microorganisms grow attached to a solid support while organic matter is removed from the liquid flowing past them.

The UASB was developed in the Netherlands by Lettinga and his co-workers (25). It is similar to the basic sludge blanket process except that the reactor is equipped with a gas-solids separator in the upper part of the reactor, as shown in Figure 3. The separator acts to separate the gas provided by the methane reaction, and to separate dispersed sludge particles from the liquid flow. This is very important for the retention of sludge in the reactor. In addition, mixing and recirculation are kept at a minimum.

Several types of fixed film systems have been developed for anaerobic treatment. These includes the anaerobic filter, expanded bed, fluidized bed, and anaerobic baffled reactors. The reader is referred to two recent reviews for a more complete consideration of anaerobic fixed-film reactors (26,27). This paper will discuss only the anaerobic filter and expanded/fluidized beds.

The anaerobic filter is an upflow fixed bed (or static bed) configuration (see Figure 4). It was first developed by Young and McCarty (28). The filter is composed of one or more vertical beds containing some inert material such as rocks or plastic media which acts as a stationary support surface for microbial film attachment. Wastewaters are pumped upward through the support media, allowing contact between the attached microorganisms and wastewater. Microbial growth also takes place in the voids between the support media. There are some filter designs with downflow direction.

The anaerobic fluidized bed, another fixed-film system, will be discussed in the next section.

3. The Anaerobic Fluidized Bed

The anaerobic fluidized bed consists of inert sand sized particles in a column which expand with the upward flow of waste through the column. A schematic of the process is shown in Figure 5. The inert particles act as a support surface for the growth of attached microorganisms. The system, because of its large surface area to volume ratio, is able to support a large population of bacterial biomass. In addition the nature of the bioreactor insures excellent contact between the biomass (catalyst) and the substrate (reactant). It has been shown that the fluidized or expanded bed represents the optimal biological reactor in terms of efficiency (29,30).

Expanded and fluidized beds are similar in concept. Both resemble systems which have been commonly used in chemical engineering

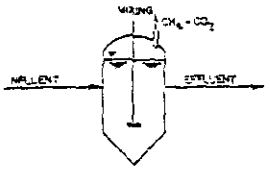


Figure 1. Conventional anaerobic digester

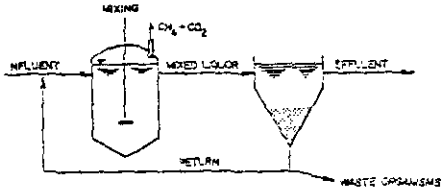


Figure 2. Anaerobic activated sludge process

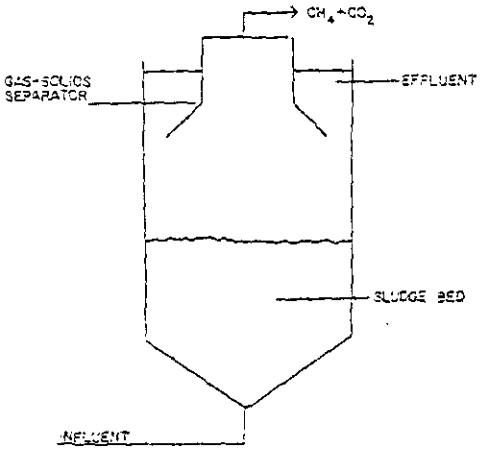


Figure 3. Upflow anaerobic sludge blanket

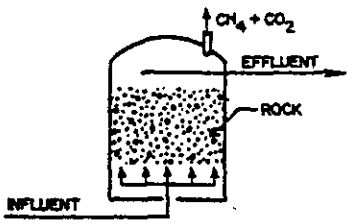


Figure 4. Anaerobic filter

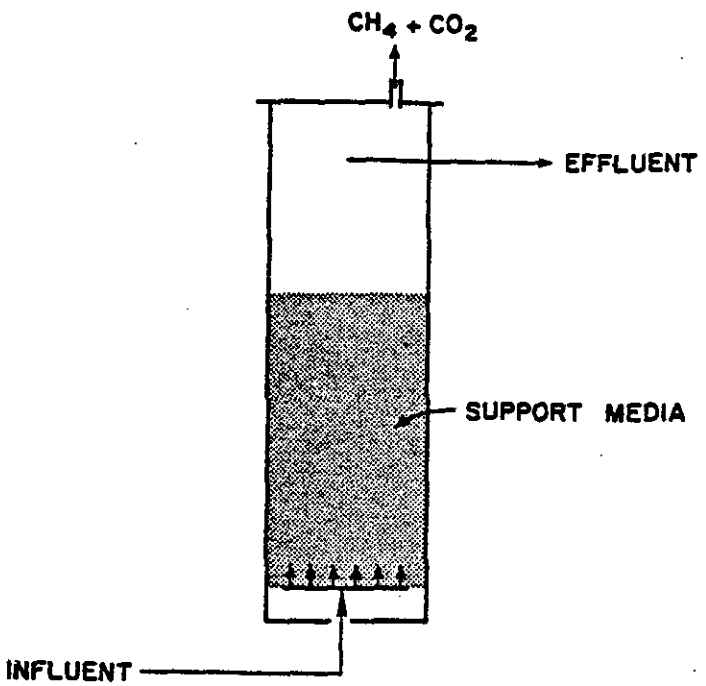


Figure 5. Anaerobic expanded/fluidized bed

process technology. Generally they have been applied to gas-solids-contacting mainly for combustion. In most cases fluidization refers to more than doubling in the reactor volume caused by the high flow rate of gas through the filter composed of small particles. The term 'expanded bed' has been used to designate reactors that have a smaller degree of expansion of the static volume.

The degree of expansion in biological systems is dependent on the type of biological reaction owing to the fact that biomass grows on the media, and thus decreases the overall density of the particles. Thus higher yielding systems such as aerobic respiration would have a higher degree of expansion (due to thicker biofilm developed) than would an anaerobic fermentation system for a given media size and superficial approach velocity. In this discussion, only anaerobic expanded beds and anaerobic fluidized beds are considered. Both of these systems operate at less than full fluidization or doubling of the reactor volume. Thus the terms expanded bed and fluidized bed are synonymous in this application.

For anaerobic fermentation, only a few studies using expanded/fluidized beds have been reported. Besides the low strength studies previously reported, these systems have been used to treat a variety of high strength industrial wastes such as cheese whey (31,32,33), and for sludge heat treatment liquor (31).

At the present time there are several full scale anaerobic fluidized beds which have been constructed. Owens et al. (34) described the use of an anaerobic fluidized bed for the treatment of a soft drink bottling plant waste. Two four meter diameter by 10.4 meter high reactors were designed to treat approximately 420 Kg COD per day. Sutton et al. (35) described the design and construction of an anaerobic fluidized bed for soy processing waste. The full scale plant consists of four 6.1 meter diameter by 12.5 meter high reactors with a design capacity of removing 8165 KG BOD_5 per day.

4. Development of the Process

The development of both the expanded and fluidized beds for wastewater treatment has been reviewed by Cooper and Wheeldon (36). These systems have been used for denitrification of water and wastewater, aerobic oxidation for BOD removal and nitrification as well as anaerobic fermentation of wastewater.

The application of this technology for anaerobic treatment was developed in the laboratory of Dr. William J. Jewell of Cornell University (37). Jewell originally was looking at a means of optimizing aerobic systems. Work by Jewell and Mackenzie (38) demonstrated that attached films had twice the organic removal capacity of suspended growth systems under comparable conditions. In a subsequent study, Jewell (39) proposed the attached film expanded bed process as a means of optimizing aerobic systems. This was based

on the assumption that large biomass concentrations could be achieved on the large surface area provided by the small sand sized particles. The small particles, which would be fluidized, would minimize diffusional limitations and eliminate clogging problems.

Beginning in 1974, the major focus on expanded bed development shifted to anaerobic treatment. Leuschner (40) demonstrated in a short study that the expanded bed was able to treat synthetic sewage at 20°C, with effluent concentrations reaching 20 mgL^{-1}. Jewell, et al. (3) conducted a preliminary study with primary effluent from the Ithaca, New York treatment plant. Greater than 70 percent COD removal efficiencies were obtained at retention times of one hour and greater at 20°C. A subsequent study (2) was carried out using a synthetic substrate to define the effect of temperature, flow rate, organic volumetric loading rate and influent substrate concentration on process efficiency. The expanded bed was found to be able to achieve high organic removal percentages at low temperatures (10°C, 20°C), treating low strength wastes (COD<600 mgL^{-1}) at short detention times (several hours) and at high organic loading rates (up to 500 lbs COD/1000 ft^3/day). A subsequent study (3) demonstrated that shock loadings (in terms of temperature and loading strength) had relatively little influence on the process. Morris and Jewell (41) investigated the efficiency of the expanded bed treating particulate wastes and found it to act also as an efficient filter. At the same time, numerous investigations examined the fluidized bed for the treatment of higher strength industrial wastes (31,32,33).

5. Anaerobic Treatment of Wastewater

If anaerobic processes were able to treat dilute wastewater, it would be a highly significant development in wastewater treatment. Since the anaerobic fermentation results in a lower cellular yield, less sludge is generated and hence lower sludge handling costs would be possible. In addition, lower energy requirements would result since aeration would not be necessary and methane would be produced as a by-product. In fact, the treatment of wastewater might be a net energy producer (rather than consumer) (42).

In general, the anaerobic fermentation process has not been considered practical for treating low strength wastes (BOD<500-1000 mgL^{-1}). Various studies in the literature report that wastes should be more concentrated and warmer than domestic wastewater in order for the anaerobic treatment process to be considered.

The work of Jewell and Switzenbaum (2,3) may be considered to be an advancement in this area (42). Working with the anaerobic expanded bed process, dilute organic wastes were efficiency converted to methane at reduced temperatures, and at high organic and hydraulic loading rates. Several other reports of low strength wastes treated anaerobically are listed in Table 1. In particular, the upflow anaerobic sludge blanket (UASB) process (46) and the anaerobic filter

Table 1. Anaerobic Processes - Treatment of Low Strength Wastes

Waste	Process	Percent Removed	Reference
Raw Sewage	Unstirred digester, upflow filter	53-78 BOD[1]	Coulter, et al. (43)
Raw Sewage	Stirred digester, upflow filter	49 SCOD[2] 90 TCOD[3]	Pretorius (44)
Raw Sewage	Contact process	80 BOD	Simpson (45)
Raw Sewage	Upflow anaerobic sludge blanket (USAB)	60-80 TCOD	Lettinga, et al. (46)
Raw Sewage	Anaerobic filter (ANFLOW)	40-85 TCOD	Davis and Koon (47)
Primary Settled Sewage	Anaerobic expanded bed	0-85 TCOD	Jewell and Switzenbaum (3)
Model Domestic Sewage	UASB	79.7-87.5 TCOD	Van der Meer, et al. (48)
Settled Sewage	Floating filter	56 TCOD	Matsche (49)
Raw Sewage	Anaerobic filter	79 BOD 73 TCOD	Kobayashi, et al. (50)

1. BOD - Biochemical Oxygen Demand
2. SCOD - Soluble Chemical Oxygen Demand
3. TCOD - Total Chemical Oxygen Demand

process (ANFLOW) (47) also show some potential for the anaerobic treatment of municipal wastewater.

6. Economic Analysis

Recently, a preliminary design for the expanded bed system was developed for evaluating the relative merits of this process in greater detail (42). This design was set for the attainment of secondary treatment standards. By doing so, costs and energy consumption estimates can be evaluated in relation to conventional secondary treatment methods such as the activated sludge and trickling filter processes for producing effluent and dewatered sludges of comparable quality. A schematic of the expanded bed system (the term SMAR, submerged media anaerobic reactor, was used by the author) is shown in Figure 6.

The three treatment alternatives were compared on the basis of residual solids handling, cost, and energy requirements. These are shown in Figures 7, 8, and 9. In terms of sludge processing the anaerobic expanded bed will produce less sludge than aerobic systems, and more stable sludge because of the high SRT. Thus, these differences in sludge quantity and quality account for the lower costs shown in Figure 7. Overall costs, shown in Figure 8, show the expanded bed to be cost effective. Most significant however, is the energy savings able to be achieved with the expanded bed as shown in Figure 9. The expanded bed was estimated to consume 20 to 48 percent less energy than comparable aerobic systems. This is due to lesser sludge handling, elimination of aeration and the generation of methane gas. Figure 9 demonstrates the possibility that the expanded bed could be a net producer of energy.

It should be kept in mind that this preliminary design was for estimating costs only. There are many unanswered questions concerning expanded/fluidized bed technology. Yet, this independent analysis is encouraging for the development of the anaerobic fluidized/expanded bed for domestic wastewater treatment.

Economic analyses have also been made for the ANFLOW process (51). An early conceptual design study estimated the total annual costs for a one million gallon per day ANFLOW system would be comparable to the costs for an activated sludge plant (approximately $\$3 \times 10^6$ in August 1978 dollars). It was noted, however, that approximately 60 percent of the battery-limit capital costs were associated with the packing material, and based on later studies, this cost could be greatly reduced by a less expensive packing material. Thus, the authors (51) expect that total annual costs for ANFLOW will be less than for conventional systems.

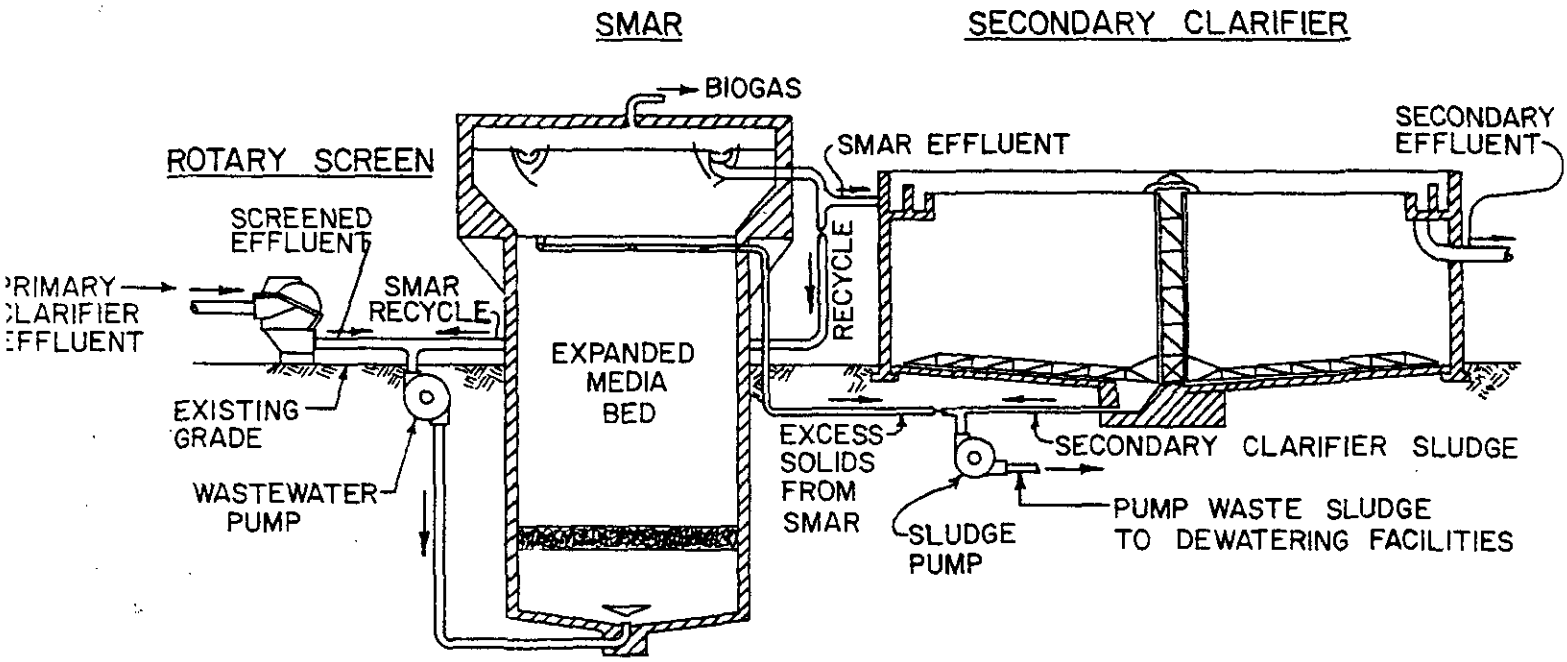


Figure 6. SMAR System for Secondary Treatment of Municipal Wastewater.

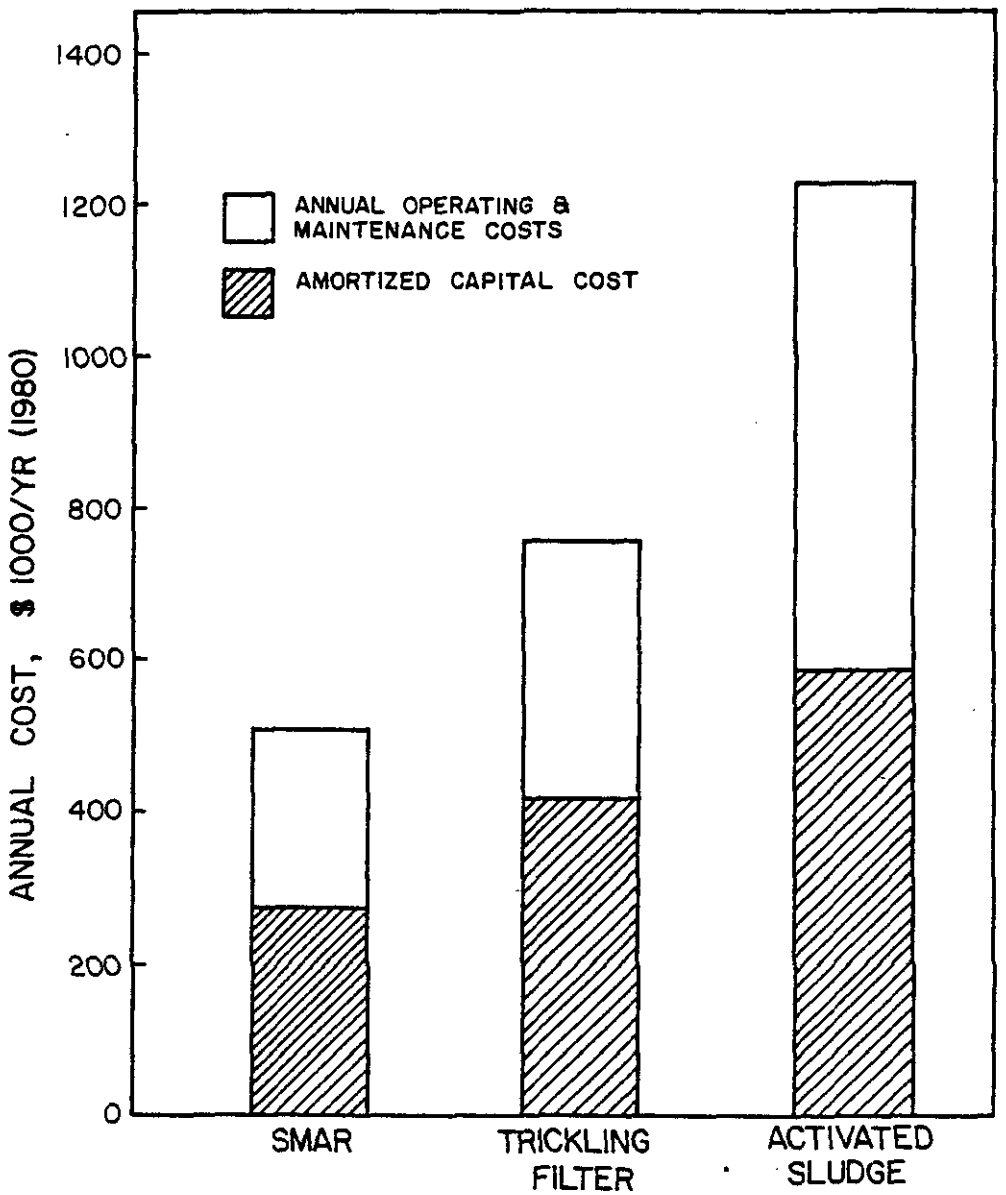


Figure 7. Residual Solids Handling Costs for 25 MGD Plant.

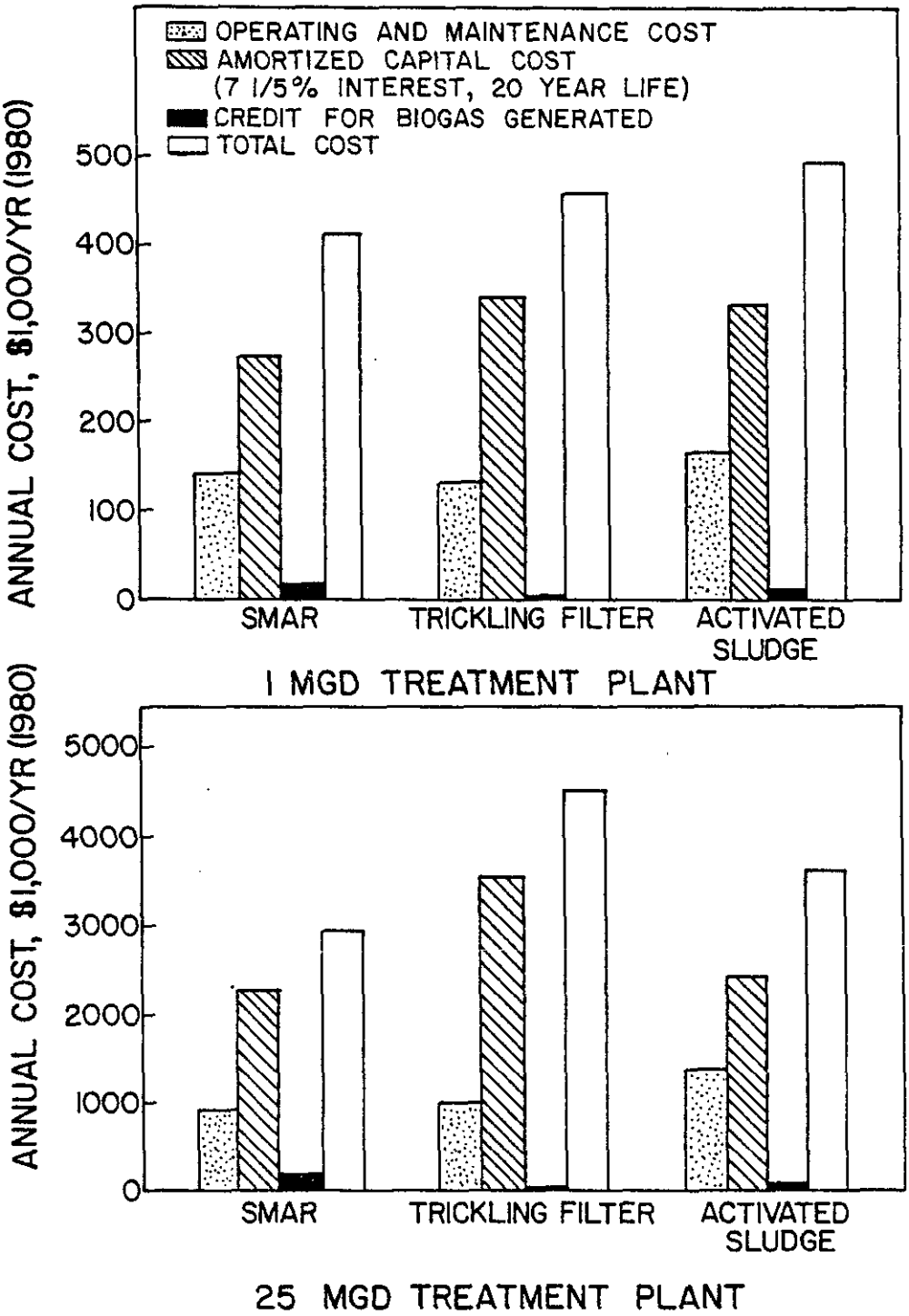


Figure 8. Summary Cost Comparison.

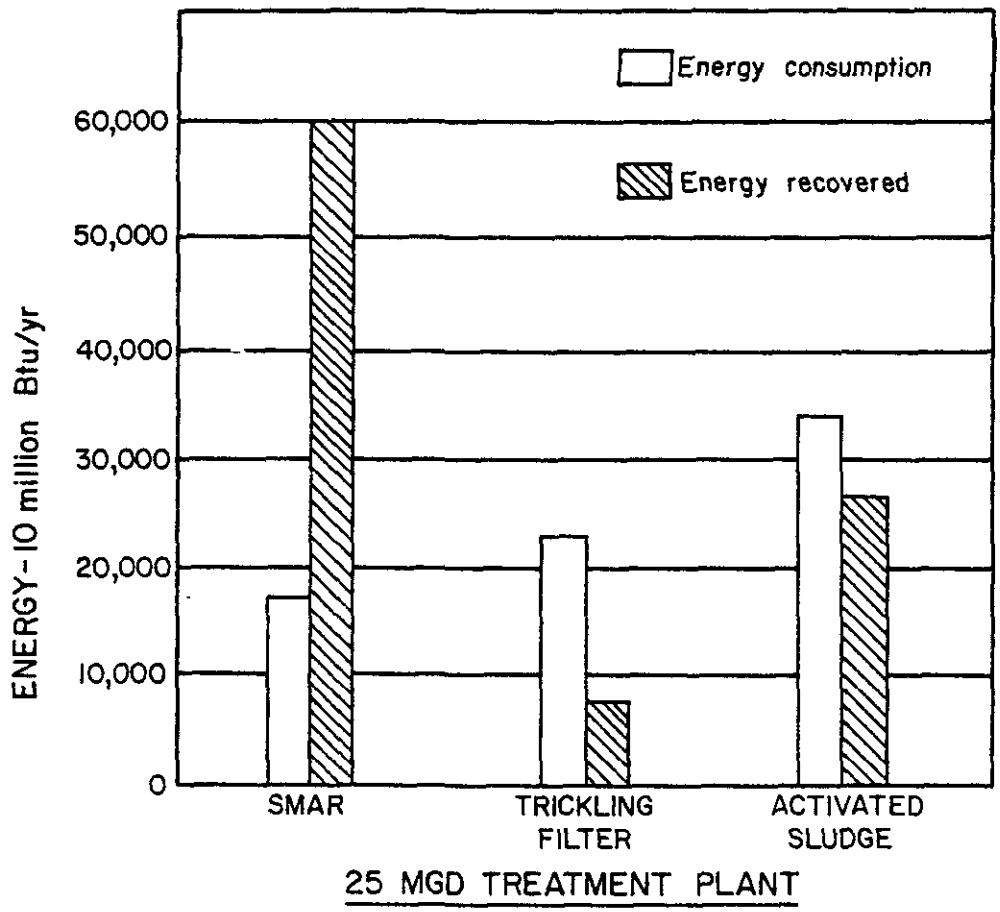


Figure 9. Comparison of Energy Balances for Alternative Secondary Processes

Caption for photograph

Scanning electron photomicrograph of a film segment from a laboratory scale anaerobic filter treating a synthetic wastewater. It shows a morphological diverse group of organisms. This photomicrograph was taken by Erika Musante in the laboratory of Stanley C. Holt, Department of Microbiology, University of Massachusetts/Amherst.

METHODS AND MATERIALS

1. Scope of Study

In order to further demonstrate the potential of the anaerobic fluidized bed for municipal wastewater treatment, and to collect design information, the process was operated on a pilot scale. Prior to this study, only bench scale testing had been performed. This pilot testing took place at the pilot wastewater treatment plant at the University of Massachusetts in Amherst.

2. Pilot-Scale Setup

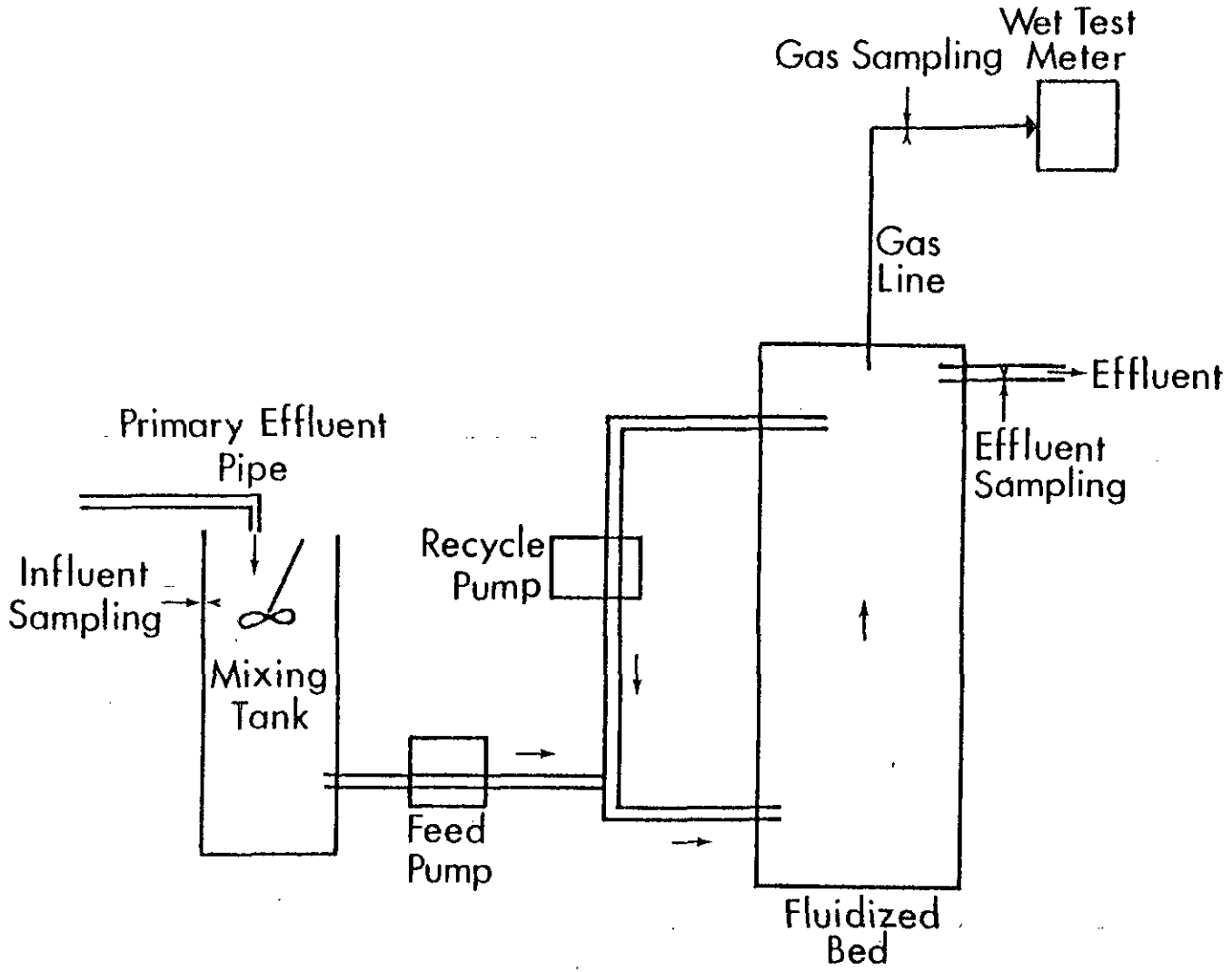
A schematic diagram of the fluidized bed reactor system used in this study is shown in Figure 10.

The pilot testing of the anaerobic fluidized bed was conducted with a standard skid mounted Hy-Flo™ fluidized bed pilot. The pilot consists of a nominal six inch diameter by ten foot high clear PVC bioreactor equipped with gas separation and measurement chambers, temperature controller and the necessary feed, recycle and chemical addition pumps. The unit was supplied to the University of Massachusetts by Ecolotrol, Inc., for use during this project. Sand was used as the support material.

Primary effluent from the Amherst treatment plant was used as the substrate for the reactor. It was continuously pumped to a holding tank, with an overflow valve. The primary effluent was pumped from the tank to the inlet of the reactor by a Masterflex pump with a variable speed control. Neither chemical controls nor heat were added to the primary effluent. The bed was kept expanded by a closed-loop recycle. The effluent from the reactor overflowed at the top and was collected in a trough where it was pumped out back to the Amherst plant.

Gas and liquid effluent left the reactor in separate lines. Gas production was measured from the top of the reactor by a Wet-Test Meter. In the line from the reactor to the gas meter, a sampling tube was placed which was used for gas composition analysis.

For liquid analysis of the influent wastewater, a composite sampling device was used. This device consisted of a Masterflex pump which was connected to a 24 hour timer. The sample contents was pumped directly into a refrigerator for storage. Usually, samples were made on an hourly basis for a 24 hour period. Influent composite samples were taken from the holding tank, while effluent grab samples were taken from the effluent line.



Fgiure 10. Schematic Diagram of Fluidized Bed Reactor System.

3. Monitoring and Sampling

During the start-up phase of this project which lasted from April, 1982 to March, 1983 the anaerobic fluidized bed was monitored daily. Usually, temperature, effluent pH and gas production were recorded. COD removal and effluent solids were measured occasionally.

Once actual testing was started, from March, 1983 to August, 1983 the reactor was monitored daily. In addition, on a schedule of approximately two times per week, several different parameters were measured. These are listed in Table 2.

During the intensive testing period, four different sets of data were taken. These correspond to four different retention times.

4. Analytical Methods

a. Gas production.

Gas production was measured by means of a Precision Scientific Wet Test Meter. This meter operates on a water displacement method and was calibrated at the beginning of the study.

b. Biochemical oxygen demand.

Five day BOD values were evaluated according to Standard Methods (15th Edition, 1980). The procedure is outlined on page 483 (52).

c. Alkalinity.

The potentiometric titration method to a pH of 4.5 was used in this study.

d. Protein.

Total protein was measured using the Biuret method (53).

e. Gas composition.

A GOW-MAC 550 thermal conductivity gas chromatograph coupled to a Fisher Recordall-Series 5000 strip chart recorder was used to determine gas composition. the separating column was stainless steel, six feet long by one-fourth inch in diameter, and packed with 80/100 mesh Porapak Q packing. Gas samples were collected and injected into the gas chromatograph with disposable 1 cm^3 tuberculin syringes. Instrument conditions are given in Table 3.

Table 2

Parameters Measured During Anaerobic Fluidized Bed Testing

Influent	Effluent
BOD_5	BOD_5
Total COD	Total COD
Soluble COD	Soluble COD
pH	pH
Alkalinity	Alkalinity
Temperature	Temperature
Total Protein	Flow rate
Soluble Protein	Total Protein
Suspended Solids	Soluble Protein
Gas	Suspended Solids
Production rate	
Composition (not on a regular basis)	
Other	
Air temperature	

Table 3

Gas Chromatograph Conditions

Carrier Gas:	Helium
Flow rate:	30 ml/min
Injection Port Temperature:	110°C
Column Temperature:	80°C
Detector Temperature:	70°C
Bridge Current:	6 ma
Attenuator Setting:	16
Recorder Setting:	10 mv full scale
Recorder speed:	0.5 in/min

f. pH.

A Fisher Accumet pH Meter Model 320 equipped with a combination electrode was used to determine pH values. The sensitivity of the pH meter was 0.1 pH units.

g. Chemical oxygen demand.

Chemical oxygen demand (COD) measurements were determined by using a modification of the Jirka and Carter method (54). A Bausch and Lomb Spectronic 20 was used for the spectrophotometric measurements. A 10,000 mgL^{-1} standard stock COD solution was prepared by dissolving 8.500 g of potassium acid pthalate in distilled water and diluting to one liter.

The digestion solution was prepared by adding 167 ml of concentrated sulfuric acid to 500 ml of distilled water. Subsequently, 17.00 g of mercuric sulfate and 10.216 g of potassium dichromate were added into the solution which was then cooled and diluted to one liter.

The catalyst solution was prepared by adding 22.00 g of silver sulfate to a 4 Kg bottle of concentrated sulfuric acid.

Kimax culture tubes (25 x 150 mm) with teflon lined screw caps were used as both digestion tubes and cuvettes for the spectrophotometric analysis. An appropriate sample volume (usually 2 ml) was introduced into the culture tube, then an appropriate amount of distilled water was added to bring the diluted volume to 10 ml. Next 6 ml of digestion solution and 14 ml of catalyst solution were added. The tubes were capped and inverted at least three times to mix contents. At least two blanks and a set of standards from 100 to 1000 mg COD/L were prepared for each set of samples.

After the addition of the digestion and catalyst solutions, samples and standards were heated in a forced air oven at 150°C for two hours. Then the tubes were cooled, rinsed with distilled water, wiped dry, and absorbance was measured at 600 nm. A calibration curve was prepared from the standards and the COD of each sample calculated.

h. Suspended solids.

Suspended solids were determined according to the procedure outline on page 94 of Standard Methods (52). Whatman GF/A (4.25 cm) glass microfiber filters (Whatman Ltd., England) were used. Filters were prewashed with three 20 ml washings to distilled water, dried at 103°C for at least one hour, and dessicated for at least one hour before use. The filtering apparatus used was a pyrex glass Millipore Filter Holder (Millipore Corporation, Bedford, Massachusetts).

Filtrate from the suspended solids test was used for soluble COD determinations.

i. Scanning electron photomicrographs.

Scanning electron photomicrographs were made by Professor Stanley Holt and his assistant, Ms. Erika Musante, in the Microbiology Department at the University of Massachusetts/Amherst. A JOEL Model JSM 25 S scanning electron microscope and Polaroid Type 665 film were used.

RESULTS

1. Start-up Period

Preparation for this study began in the Fall of 1981. During that time, the pilot plant was rehabilitated, and an agreement with Ecolotrol was made for use of the reactor employed in this study. During the winter of 1981-82, the reactor was packed with Ottawa Sawing Sand, approximately 1 mm in apparent diameter, and seeded with anaerobic digested sewage sludge from the Ware, MA treatment plant. Then, the unit began operation. It was initially fed primary effluent from the Amherst treatment plant at a very low loading rate, which was gradually increased.

During April, May and June the unit was monitored for gas production and COD removal. However, minimal amounts of each were observed. Also during this period, leakage problems in the reactor slowed any progress. During July, the reactor had to be unpacked to repair a leak. An examination of the sand showed that no growth had occurred. It was decided to use a smaller diameter sand and to restart the reactor with a more viable seed.

In September, 1982 the reactor was repacked with Banding Sand, approximately 0.2 mm in diameter. This sand resulting in less shear stress in the reactor, and provided a greater surface area to volume ratio for film attachment. The unit was then seeded with anaerobic digested dairy manure from the Sunny Valley Farm in New Milford, Connecticut.

During the period of October, 1982-February, 1983 the reactor seemed to be making better progress. The primary effluent was fed to the reactor at a rate of 80 liters per day. Increases in gas production and COD removal were noted. In December, 1982 a series of Scanning Electron Photomicrographs were taken of the sand particles by Dr. Stanley C. Holt of the Department of Microbiology, UMASS/Amherst. The photos showed that the particles were well coated after four months of operation. However, during this period, many operational problems were encountered which caused frequent shut-downs. Problems with both the influent pumping station and effluent pumping station were encountered, and then fixed over a period of several days each. However, a major problem occurred in January when the distributor in the bottom of the reactor plugged with sand due to frequent shut-down for pump repair. A new distributor was obtained from Ecolotrol which greatly improved this problem after it was installed. This, however, delayed the project as it took time to ship and install the new distributor.

Finally, in March, 1983, all the operational problems were under control, and intensive testing began. This period lasted until August, 1983 when the reactor was shut down, and the project terminated.

2. Testing Period March - August, 1983.

Four sets of data were collected over the reactor testing period. Each set corresponds to a difference average retention time, as follows: Set #1, 3/11-5/27, average HRT = 6.67 hours; Set #2 6/1-6/21, average HRT = 3.34 hours; Set #3, 6/23-7/14, average HRT = 1.67 hours; and Set #4, 7/19-8/12, average HRT = 5.00 hours. These detention times are computed based on the fluidized bed reactor volume of 30 liters. (The total reactor volume was approximately 55.6 liters).

The data, covering the four sets are presented in Tables 4, 5 and 6. Table 4 presents data for physical characteristics (flow rate, loading rate, temperatures) and pH and alkalinity. Table 5 presents operational data such as total and soluble COD, BOD_5, suspended solids (SS) and gas production. Gas composition is listed in Table 6.

Since this project deals with municipal wastewater treatment, the two most important operational parameters are BOD_5 and SS. Graphs showing influent and effluent values for each of the four sets of data are shown in Figure 11 to 14 for BOD_5 and Figures 15 to 18 for SS Mean BOD and SS values for each of the sets are shown in Table 7.

This data will be discussed in the next section.

Table 4

Testing Period - Physical Data

Date	Flow Rate Ld^{-1}	Loading Rate ($gBOD_5L^{-1}d^{-1}$)	Water Temperature, ^{o}C Effluent	pH Inf	pH Eff	Alkalinity, (mgL^{-1}) as $CaCO_3$ Influent	Alkalinity, (mgL^{-1}) as $CaCO_3$ Effluent
3/11	95.9	0.74	17.5	6.7	7.1	101	123
3/19	92.7	-	17.0	6.7	7.1	125	131
4/1	120.3	0.70	18.5	6.8	7.1	113	152
4/8	113.1	0.57	19.5	6.7	7.0	107	148
5/6	118.5	0.51	22.0	6.6	7.0	99	135
5/13	109.1	0.30	21.5	6.7	7.1	106	145
5/18	112.1	0.38	23.0	6.8	7.1	107	141
5/20	106.4	0.21	-	6.9	7.1	98	140
5/25	106.7	0.17	25.0	6.6	6.6	104	134
5/27	107.6	0.28	21.0	6.6	6.7	98	128
6/1	216.5	0.21	24.0	-	-	-	-
6/3	221.5	0.24	23.5	-	-	-	-
6/8	228.6	0.38	24.0	6.4	6.9	67	117
6/10	216.0	0.28	24.0	6.6	7.0	89	127
6/14	223.3	0.43	28.5	6.6	6.8	99	126
6/16	224.4	0.45	27.0	6.7	6.9	99	121
6/21	216.0	0.53	26.0	6.6	6.7	118	116
6/23	427.7	0.68	27.0	6.7	7.0	85	108
6/28	419.4	0.90	23.0	6.7	6.9	130	129
6/30	415.4	0.94	26.0	6.6	6.5	97	147
7/5	427.7	0.55	27.0	6.3	6.6	82	109
7/7	432.0	0.73	25.0	-	-	-	-

Table 4, Continued

Date	Flow Rate	Loading Rate	Water Temperature, °C	pH		Alkalinity, (mgL^{-1}) as $CaCO_3$	
	Ld^{-1}	($gBOD_5L^{-1}d^{-1}$)	Effluent	Inf	Eff	Influent	Effluent
7/12	382.3	0.92	26.5	6.4	6.8	110	138
7/14	340.1	0.75	27.0	-	-	-	-
7/19	144.7	0.38	27.5	6.7	7.0	122	152
7/21	143.8	0.32	28.0	6.5	6.7	102	148
7/26	134.2	0.34	25.0	6.7	7.0	117	147
7/28	153.2	0.32	27.0	7.3	6.8	131	145
8/2	143.5	0.34	27.0	6.4	6.8	99	124
8/4	134.2	0.28	25.0	6.8	6.9	103	133
8/9	137.8	0.30	28.0	6.4	6.9	117	139
8/11	138.5	0.36	23.5	6.5	6.8	102	140
8/12	146.4	0.38	22.0	6.8	6.9	133	147

Table 5

Testing Period - Operational Data

Date	$BOD_5(mgL^{-1})$		TCOD(mg/L)		$SCOD(mgL^{-1})$		$SS(mgL^{-1})$		Cum. Gas
	in	eff	in	eff	in	eff	in	eff	Prod/L
3/3									0
3/11	199	60	>1000	175	270	100	-	-	2.28
3/19	-	-	1106	225	328	100	-	-	10.35
4/1	170	81	227	178	135	97	-	-	17.60
4/8	148	67	167	124	124	81	-	-	25.84
5/6	129	68	173	201	140	178	-	-	59.61
5/13	81	47	170	128	115	101	-	-	69.04
5/18	101	74	143	92	102	74	37	13	78.23
5/20	56	57	104	113	64	81	25	19	82.34
5/25	47	30	159	74	98	60	135	144	95.13
5/27	77	52	156	109	134	61	116	24	99.13
6/1	28	13	117	63	62	77	-	-	105.14
6/3	32	24	46	43	24	11	29	20	107.41
6/8	50	42	152	71	108	65	8	7	113.59
6/10	38	36	148	55	77	48	16	17	116.56
6/14	58	32	187	79	106	69	35	26	126.23
6/16	59	48	95	77	83	54	19	26	132.56
6/21	71	38	143	76	93	68	30	13	148.68
6/23	47	50	70	63	55	50	10	7	152.70
6/28	63	66	129	108	114	85	17	55	170.45
6/30	67	62	116	90	83	70	7	55	178.30
7/5	38	38	119	114	45	16	7	63	202.71
7/7	50	30	130	104	88	79	16	33	210.55

Table 5, Continued

Date	BOD_5 (mgL^{-1})		TCOD (mg/L)		SCOD (mgL^{-1})		SS (mgL^{-1})		Cum. Gas
	in	eff	in	eff	in	eff	in	eff	Prod/L
7/12	71	48	164	110	120	101	47	43	235.22
7/14	65	39	150	113	127	93	10	17	250.98
7/19	78	34	156	70	111	65	22	8	281.50
7/21	67	35	171	101	60	60	31	11	293.18
7/26	73	27	130	92	181	-	-	-	313.22
7/28	60	53	117	94	83	84	27	38	316.84
8/2	71	52	152	96	110	77	52	26	326.04
8/4	63	57	138	82	107	79	48	22	327.20
8/9	66	47	127	78	98	61	53	25	334.55
8/11	76	56	157	84	117	69	55	21	336.61
8/12	75	46	167	74	93	71	-	-	337.75

Table 6

Gas Composition Data

Date	% CH_4	%CO_2	%N_2
5/20	53.8	3.5	42.7
5/27	58.8	0	41.2
6/17	47.8	1.7	50.5
7/11	54.2	2.6	43.2
8/2	60.0	3.5	36.5

Table 7

Mean Data Values for Sets 1, 2, 3, and 4

Data Set Number	n[1]	Mean HRT (hours)	Mean Influent $BOD_5 (mgL^{-1})$	Mean OVLR $gBOD_5 mgL^{-1} d^{-1}$	Mean Effluent $BOD_5 (mgL^{-1})$	Mean %BOD Removal	Mean Influent Suspended Solids, (mgL^{-1})	Mean Suspended Solids, (mgL^{-1})
1	9	6.67	112.0	0.22	59.5	40.1	78.3	50.0
2	7	3.34	48.0	0.19	33.3	29.9	22.8	18.2
3	7	1.67	57.2	0.41	47.5	17.1	16.3	39.0
4	9	5.00	69.8	0.18	45.2	37.8	41.4	21.6

1. For BOD data only.

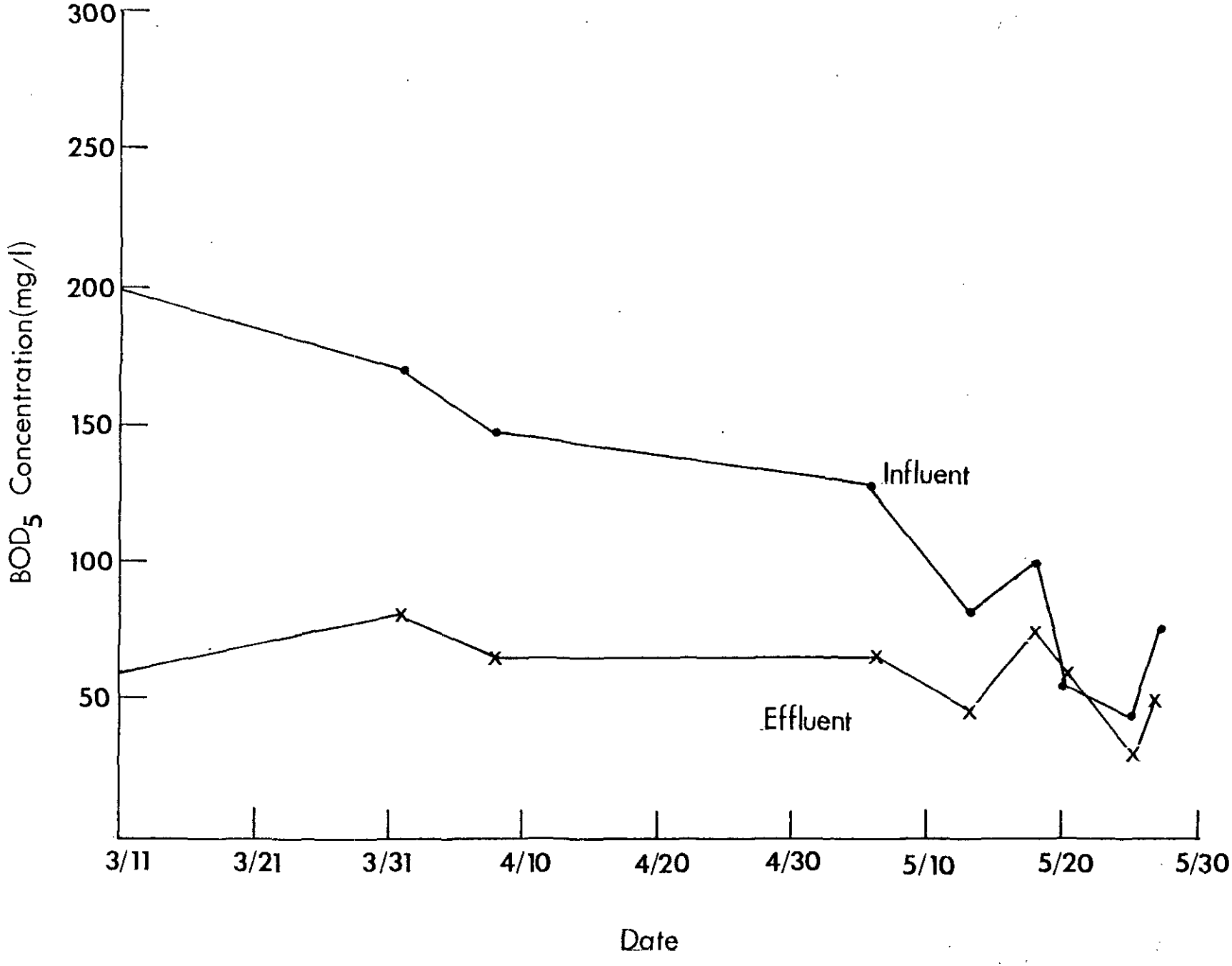


Figure 11. Set #1 - BOD_5 Data

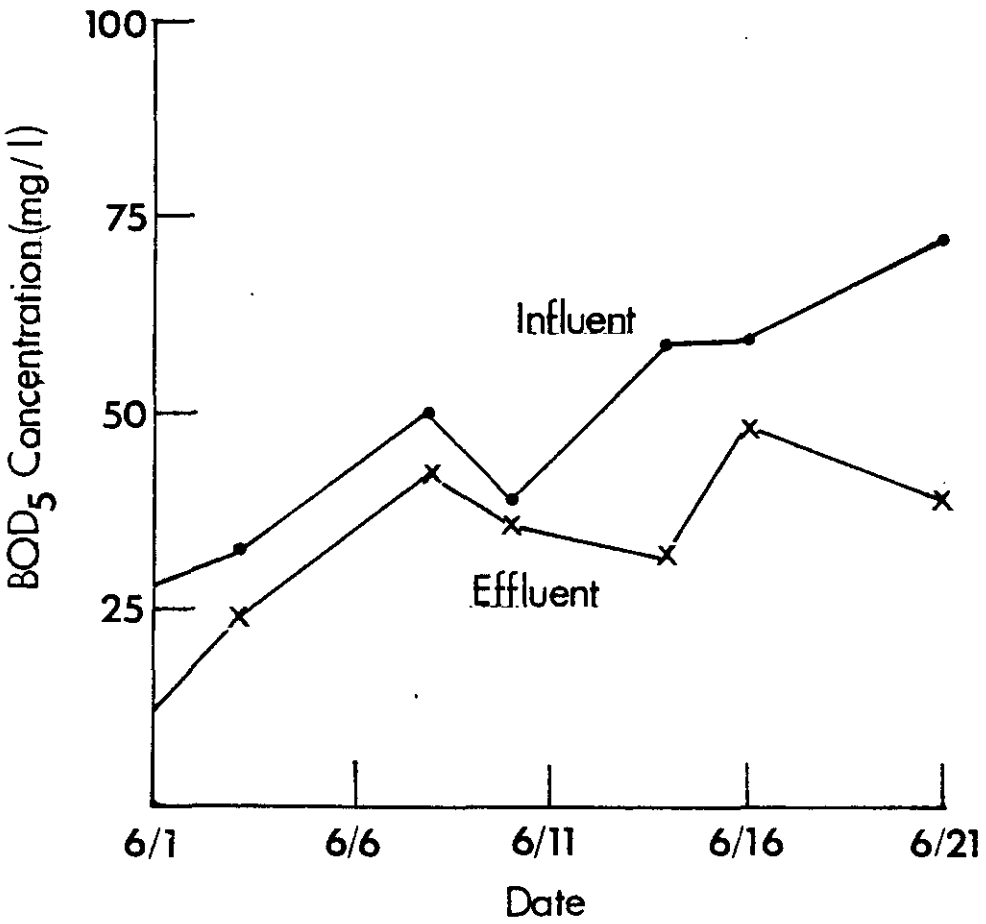


Figure 2. Set #2 - BOD_5 Data.

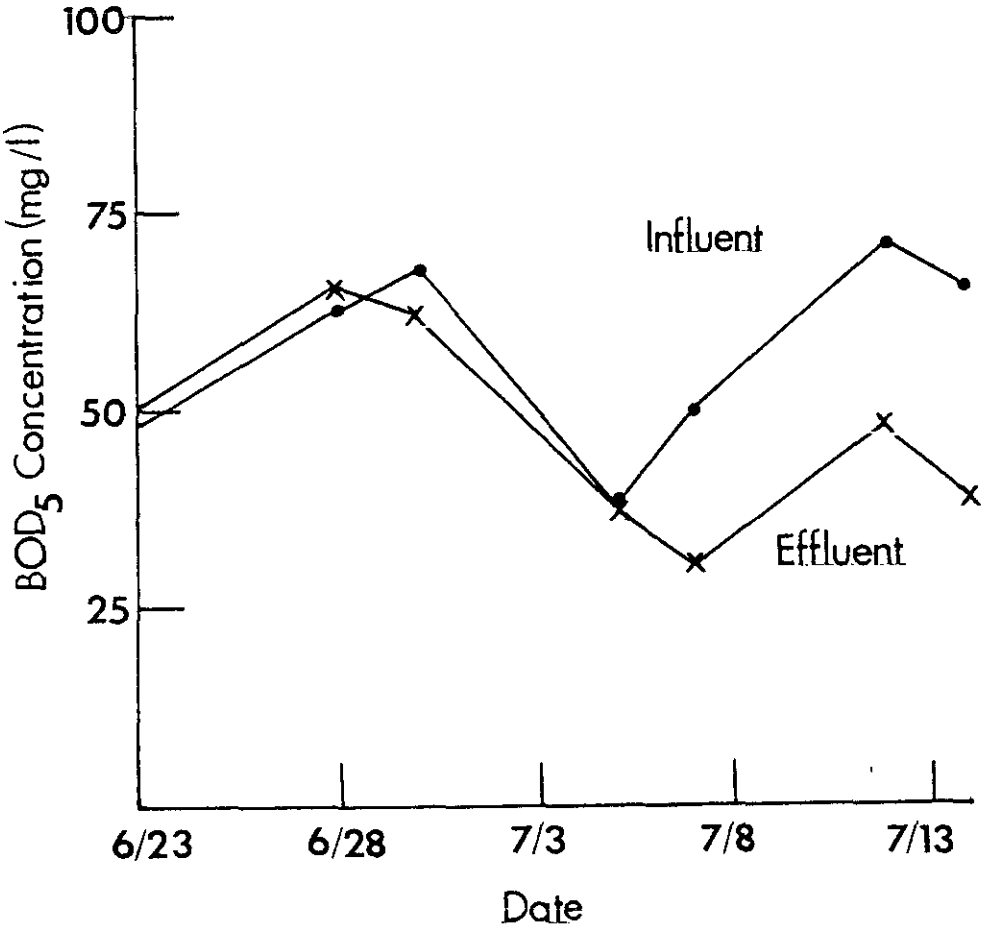


Figure 13. Set #3 - BOD_5 Data.

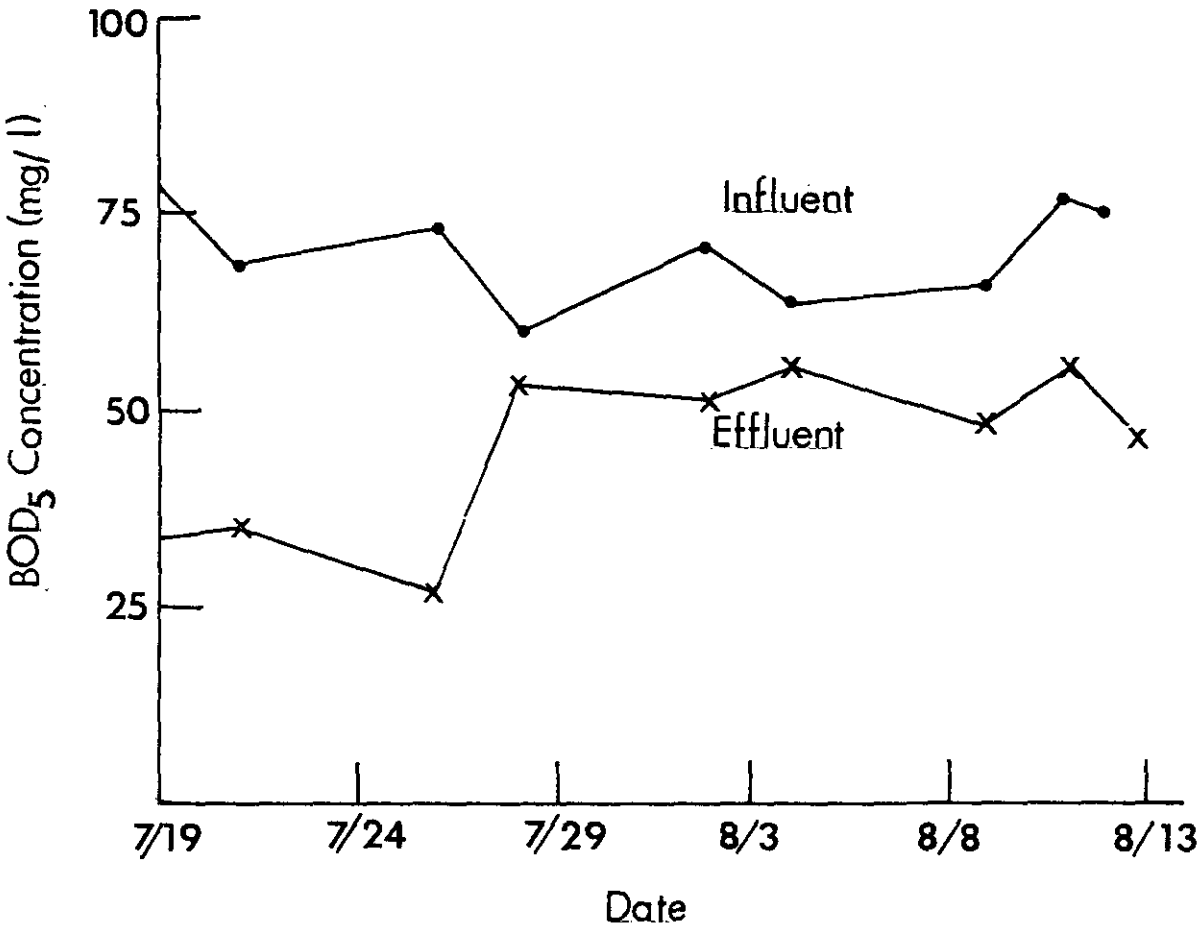


Figure 14. Set #4 - BOD_5 Data.

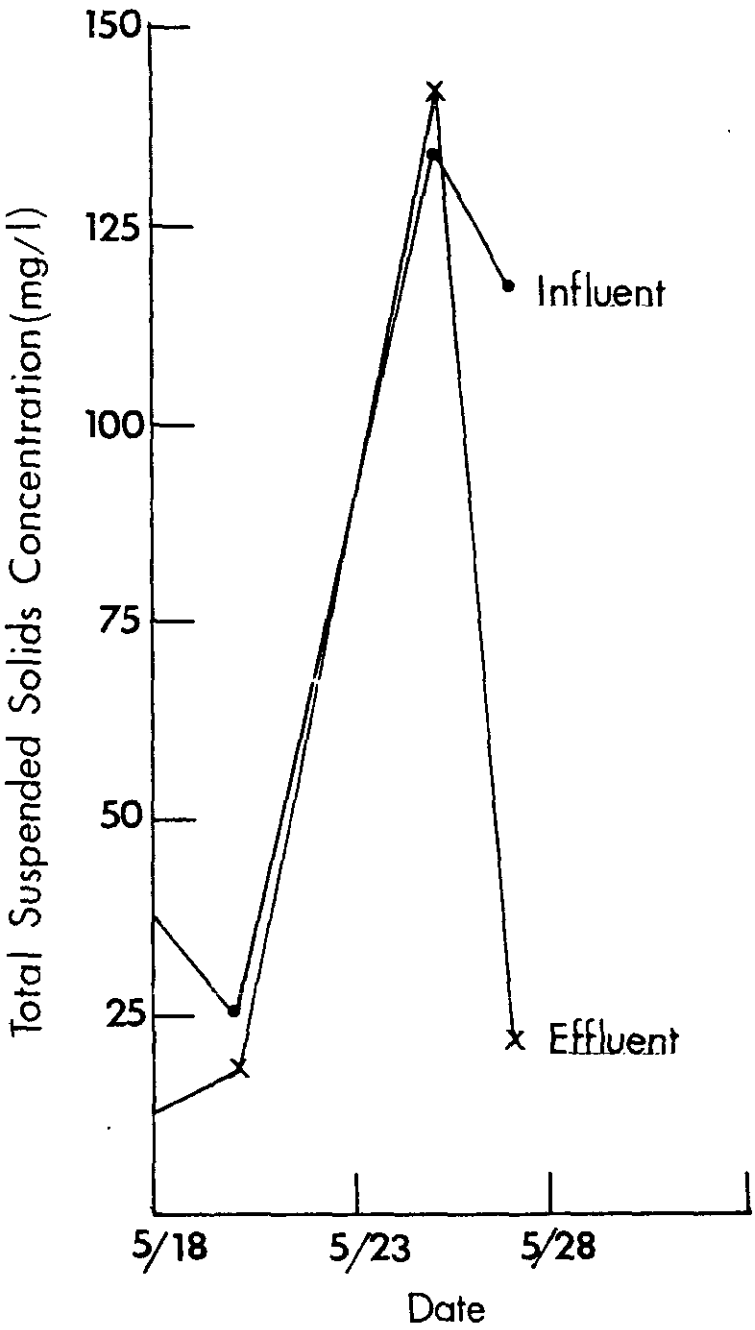


Figure 15. Set #1 - SS Data.

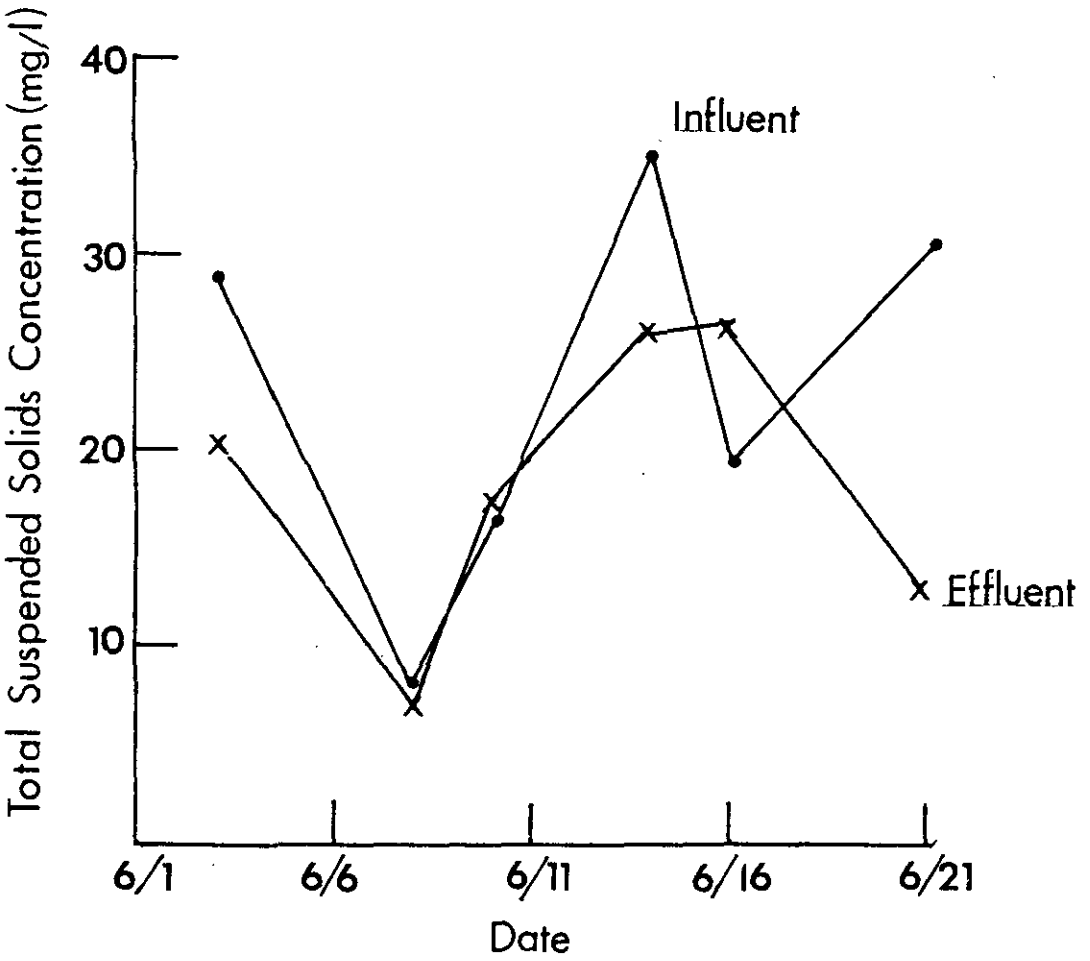


Figure 16. Set #2 - SS Data.

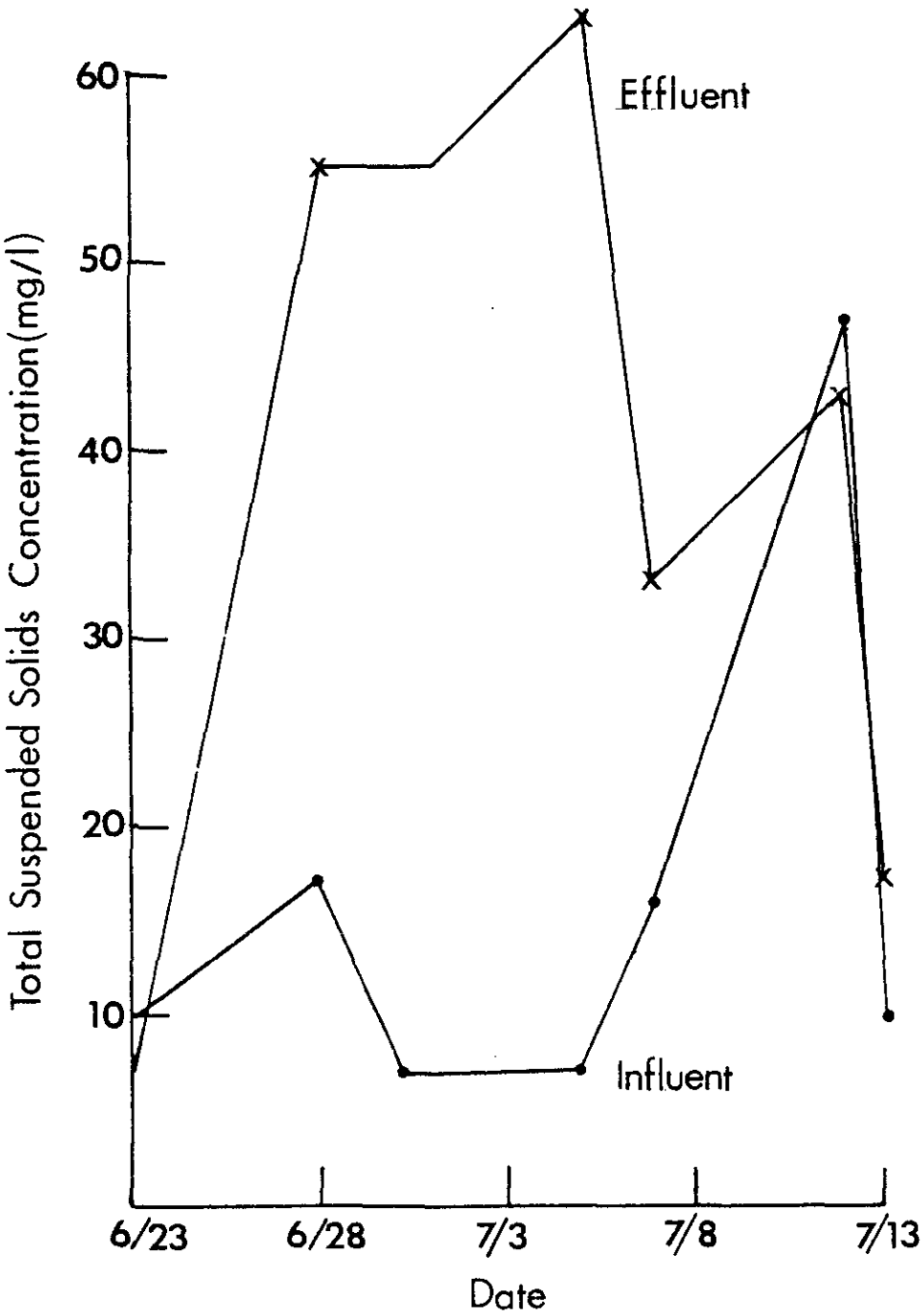


Figure 17. Set #3 - SS Data.

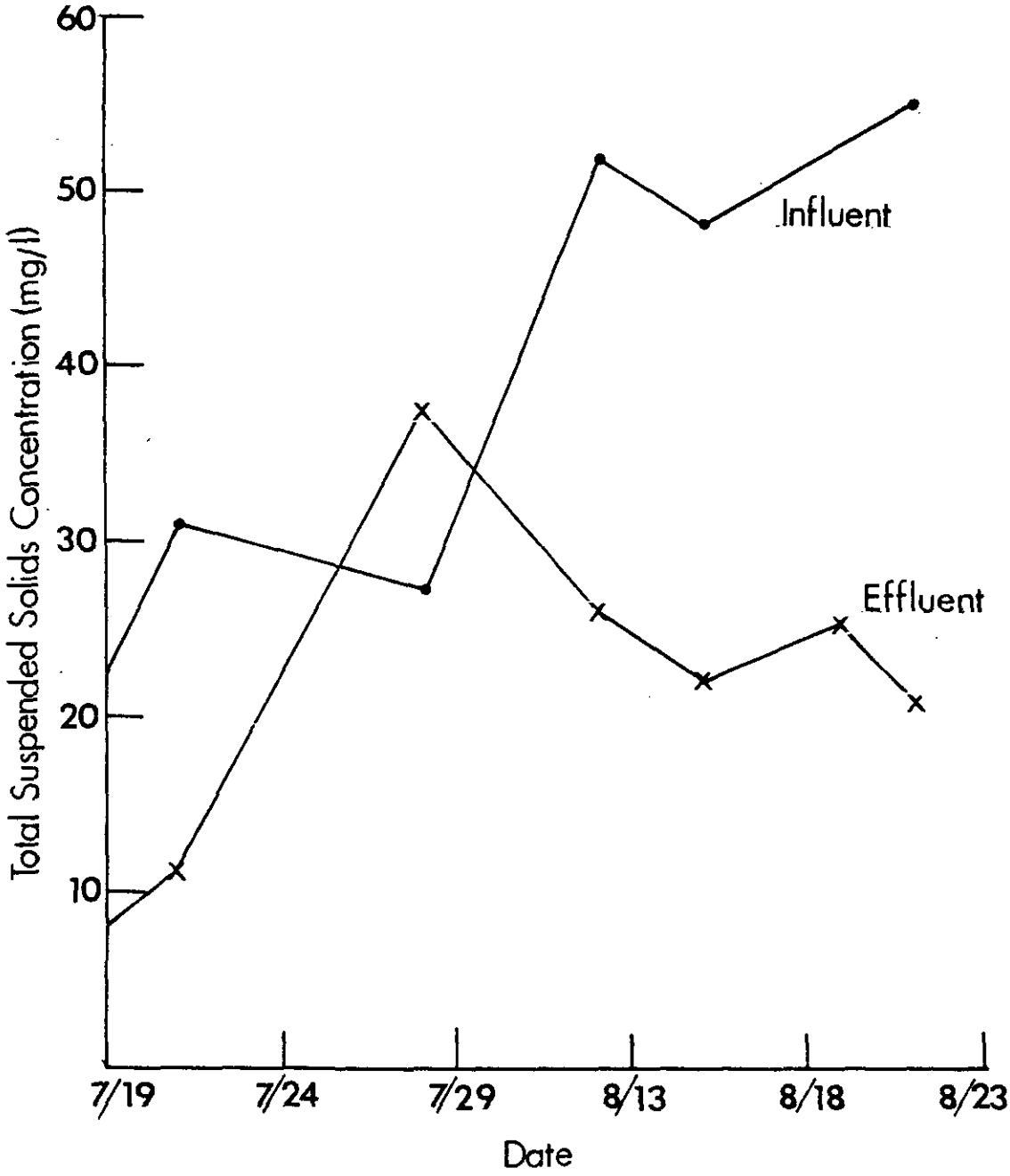


Figure 18. Set #4 - SS Data.

DISCUSSION

1. Analysis of Variance

The experimental design for the anaerobic fluidized bed testing centered around the influence of retention time on reactor performance in terms of removal of organic matter, solids, and gas production. Sets 1, 2, 3 and 4 cover a range of retention times of 1.67 to 6.67 hours. Examination of the percent of removals and effluent concentration of each of the sets of data can be made to discern the influence of retention time on reactor performance.

However, there are other independent variables which overlap this range of HRTs. The organic strength of the primary effluent used is this study was not constant over the time period of testing. For anaerobic treatment of wastewater, the influent substrate concentration is an important parameter (2).

In order to better analyze these data, and separate variables, the data can be arranged in various categories, and then an analysis of variance can be performed to detect a difference in a set of more than two population means. For the pilot data, the influence of HRT, influent substrate concentration (S_o), and organic volumetric loading rate (OVLR) on effluent BOD_5 concentration (S_e), and $\%BOD_5$ removal are examined by analysis of variance. A summary of these analyses are shown in Table 8.

Table 8 shows F values for the comparisons. In all, 32 data points were used in these comparisons, and the data were split into four different groups for each of the comparisons. For HRT effects, the data were kept in their original groups and this corresponds to four different HRTs. For S_o effects, the 32 data points were put into four ranges of influent substrate concentration (0-50 mgL^{-1}, 51-100 mgL^{-1}, 101-150 mgL^{-1}, and 151-200 mgL^{-1}), while for OVLR effects, the data were put into four ranges of loading rates (0-0.20, 0.21-0.30, 0.31-0.40 and 0.41-0.50 g BOD/liter/day). The groupings and calculations for each group are shown in Appendix I of this report. A description of analysis of variance testing can be found in Mendehall (55).

In examining Table 8 several interesting observations are noted. There exist a significant difference among the mean S_e values for each of the four sets of HRTs examined, ($F = 5.53 > F_{.05} = 2.95$), yet there is a greater, that is more significant difference among the influent BOD_5 concentrations at the 95 percent level of testing. Clearly S_o is not a function of HRT. What this implies, is that there existed a wide range of S_o concentrations throughout the testing period. In Amherst, this was due to the absence/presence of students, and weather conditions (i.e. heavy spring rainfall). In fact, S_o effects had the most significant influence on S_e. Note that there was no significant

Table 8

Statistical Summary - Analysis of Variance of BOD Data

Comparison	F*
BOD_5 effluent f (HRT)	5.53
BOD_5 influent f (HRT)	7.43
BOD_5 effluent f (OVLR)	1.08
BOD_5 effluent f (BOD_5 influent)	12.41
%BOD_5 removal f (HRT)	2.42
%BOD_5 removal f (OVLR)	1.30
%BOD_5 removal f (BOD_5 influent)	2.89

*Critical F value

$F_{.05}$ (28,3) = 2.95

difference among the S_e values as a function of OVLR ($F = 1.08 < F_{.05} = 2.95$) at the 95 percent level of testing.

Similar testing was performed for suspended solids (SS) effluent data. A summary is shown in Table 9. Again, a wider variation in influent data (than effluent values) was found among the data indicating the varying seasonal nature of the wastewater characteristics. There were no significant differences among the effluent suspended solids concentration as functions of HRT and OVLR, and only slight significant differences as functions of influent SS concentrations.

In summary, the most significant parameter influencing BOD_5 effluent concentrations, and $\%BOD_5$ removals, was the influent BOD_5 concentration. The most significant parameter influencing effluent suspended solids concentrations was influent suspended solids concentration. All testing was done at the 95 percent level.

2. Regression Analysis

The BOD_5 and SS data can be further analyzed by regression analysis. The coefficient of correlation, r, is an indicator of the strength of the linear relationship between two variables, which will be independent of their respective scales of measurement. This measure of linear correlation is also called the Pearson product moment coefficient of correlation, and is commonly used in statistics.

Mean values for the various groupings used for the Analysis of Variance testing are shown in Tables 10 and 11 for BOD_5 and SS data respectively. Also shown for each of the groupings, are r values.

It can be seen S_e concentration shows a high correlation coefficient value with S_o, and OVLR but not HRT. The linear relationship between S_e and OVLR is particularly good ($r = 0.99$). The $\%BOD_5$ removal showed a very strong linear relationship with S_o ($r = 0.99$), and HRT (0.95), but not OVLR. However, if the last point is omitted, $\%BOD_5$ removal and OVLR correlate well ($r = 0.98$), indicating linearity until overloading occurs.

Effluent suspended solids concentrations only correlated well with influent suspended solids concentration.

3. Low Strength Sewage

Based on the statistical analyses previously presented it appears that both BOD_5 effluent concentrations and $\%BOD_5$ removals are strongly related to influent BOD_5 concentration. The average organic influent (primary effluent) concentrations for all samples are shown in Table 12. Also, in Table 4 the data are split into mean values for data set #1 and sets #2, 3 and 4 (sets based on average HRT).

Table 9

Statistical Summary - Analysis of Variance of Suspended Solids Data

Comparison	F*
SS effluent f (HRT)	1.51
SS influent f (HRT)	6.12
SS effluent f (OVLR)	0.68
SS effluent f (SS influent)	3.38

*Critical F Value

$F_{.05}(20,3) = 3.10$

Table 10

Regression Analysis of BOD Data

X	Y	Coefficient of Correlation, r
HRT	S_e	0.49
HRT	$\%BOD_5 rem$	0.95
OVLR	S_e	0.99
OVLR	$\%BOD_5 rem$	-0.58
S_o	S_e	0.93
S_o	$\%BOD_5 rem$	0.99

Table 11

Regression Analysis of SS Data

X	Y	Coefficient of Correlation, r
HRT	SS eff	0.31
OVLR	SS eff	0.56
SS	SS eff	0.92

Table 12

Primary Effluent Composition

Parameter	Average (mgL^{-1})	Range(mgL^{-1})	Std. Dev.	Average Set 1 (mgL^{-1})	Average Sets 2,3,4 (mgL^{-1})
BOD_5	74.2	28-199	38.1	112.0	59.4
TCOD	171.4	70-1106	173.9	267.2	133.9
SCOD	130.4	55-225	128.3	151.0	113.4
TSS	35.5	7-116	31.7	78.2	15.6

These data are indicative of relatively weak domestic wastewater. Note that Set #1 covers the period of 3/11-5/27 while Sets 2, 3 and 4 cover the period 6/1-8/12. In other words Set #1 covers the period when the University is in spring session, while the other data covers the summer period, when the population of Amherst is considerably lower. The mean BOD_5 value for the summer period is only 59.4 mgL^{-1}, which is quite weak wastewater. This helps to explain the low percentages of BOD_5 removal observed in this study. Higher removal percentages have been observed in the past with anaerobic fluidized bed treatment of more concentrated wastes (27).

It should be noted that the standard deviations for the influent parameters are quite large. This indicates a wide range of influent concentration (i.e. sewage strength) over the five month testing period.

4. Protein Data

During the collection of data Set #4, it was decided to measure protein, both total and soluble in the influent and effluent stream. This data is shown in Table 13 and Figure 19.

Note that the soluble protein removal was extremely low. Some recent research has shown that an anaerobic heterotrophic population will remove carbohydrates in preference to proteins in mixed substrates (56). Also, at the relatively low contact times in this study, it is possible that the deamination of the proteins is incomplete. This is one possible explanation as to why S_e increases with S_o ($r = 0.93$); that is with increasing protein concentration of the influent, there is a fraction of the BOD_5 which is not going to be removed.

There are other possible explanations. Grady and Williams (57) have developed a simple model for the effects of influent substrate concentration on biological reactor performance, and Switzenbaum and Jewell (2) found a similar relationship for anaerobic treatment of a carbohydrate waste (i.e. without any protein). Thus another mechanism was responsible.

This area of research (dual substrate reactions) would seem to warrant further study.

5. Comparison to Lab Scale Data and Pilot Scale Testing

The average effluent concentrations for the study are shown in Table 14. Most significant are the BOD_5 and SS data. The effluent from the anaerobic fluidized bed had an average BOD_5 concentration of 47.2 mgL^{-1} and suspended solids concentration of 30.5 mgL^{-1} over the five month test period. The standard deviation of both parameters is much smaller than the influent data.

Table 13

Protein Data

Date	Total Protein (mgL^{-1}) Influent	Effluent	Soluble Protein (mgL^{-1}) Influent	Effluent
7/14	37	36	0.5	24
7/19	48	39	-	34
7/21	30	24	26	16
7/26	40	>100	26	-
7/28	45	46	28	16
8/2	41	28	28	11
8/4	38	36	23	28
8/9	31	40	29	34
8/11	39	25	25	29
8/12	39	27	27	31
Mean	38.8	29.5	23.6	18.9

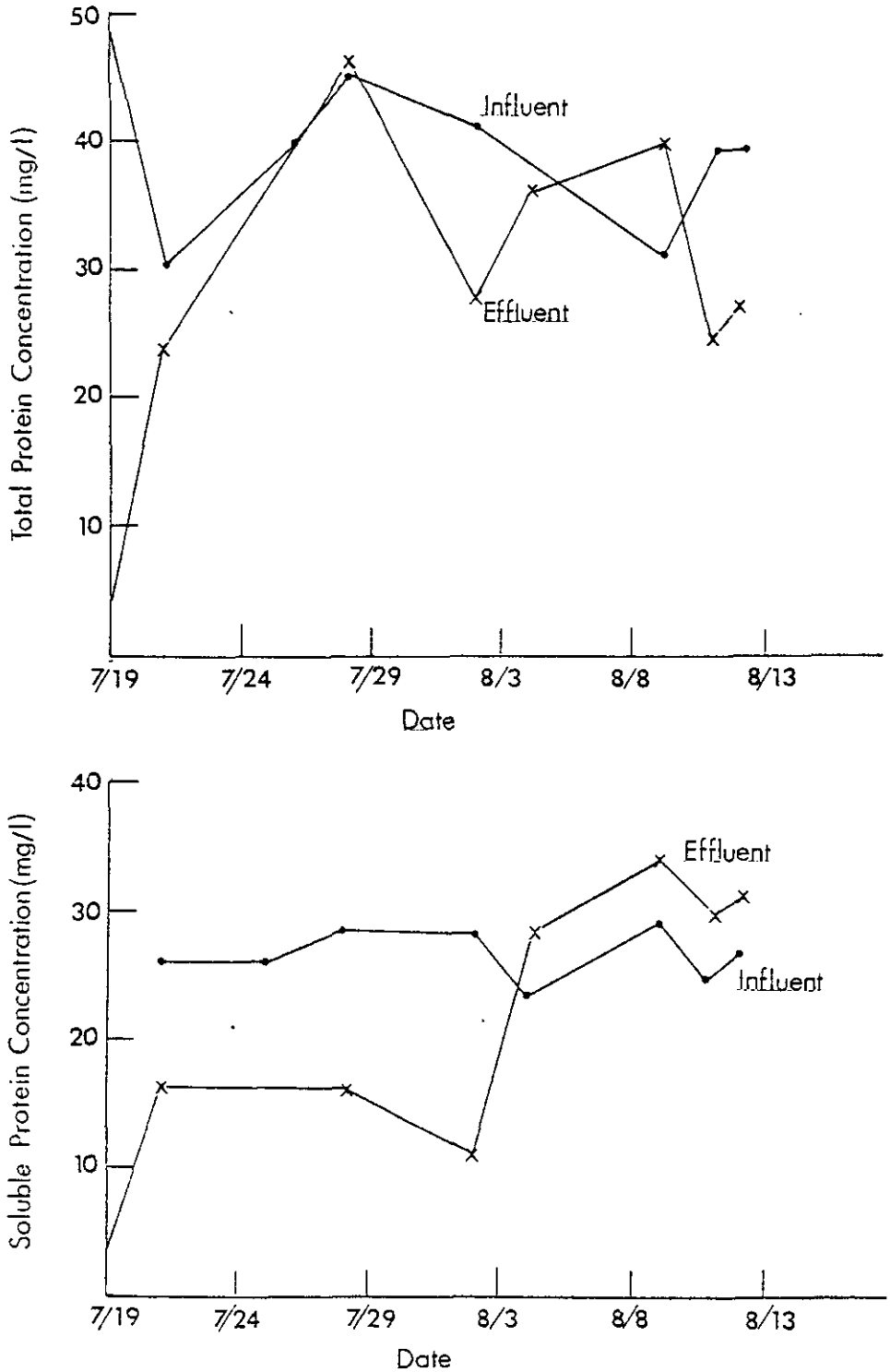


Figure 19. Total and soluble protein data.

Table 14

Anaerobic Fluidized Bed Effluent Data

Parameter	Average (mgL^{-1})	Range (mgL^{-1})	Std.Dev.	Average Set #1	Average Set #2,3,4
BOD_5	47.2	13-74	15.5	59.5	42.3
TCOD	101.7	43-225	40.9	141.9	84.2
SCOD	76.7	11-178	26.3	93.3	69.1
SS	30.5	7-144	16.6	50.0	26.7

The only lab scale data available on the anaerobic fluidized bed treating domestic wastewater is the expanded bed data of Jewell et al (3). This is shown in Table 15. It would seem that the lab scale reactor performed at a significantly better level.

There are several major differences between the lab and pilot scale studies which should be noted. First of all, the lab study was performed at a constant temperature of 20°C, with a constant wastewater composition over the course of the day. The sewage tank was filled as needed. In the pilot study temperature was not controlled, and the sewage was pumped directly from the wastewater plant as is; therefore the concentration varied throughout the day. Previous research has shown that unsteady-state conditions lowered the performance of an expanded bed treating sewage (58).

The lab scale unit was equipped with an elaborate tube settler/clarifier. Effluent samples were taken after clarification. The pilot unit had no such clarifier. Finally, the lab scale unit was seeded with rumen fluid, while the pilot unit was seeded with dairy manure. Anaerobic protozoa were observed in the lab unit, but not in the pilot unit. The significance of this last observation is not known.

Finally, the lab data was collected with a reactor which had a different support material and support size (spendion exchange resin and PVC particles, 1 mm apparent diameter).

It is also of interest to compare the result of this study with other pilot testing. Genung et al (51) reported on a pilot study with a 200 ft^3 ANFLOW bioreactor (anaerobic filter) treating raw municipal wastewaters at ambient temperatures. A summary of the 18 month period reported data is shown in Table 16. Slightly higher BOD_5 and SS effluent solids concentrations are noted, over a generally higher mean HRT (9.43 to 64 hours). This process is currently being evaluated at a prototype level.

Lettinga et al (46) recently presented pilot scale data for the upflow anaerobic sludge blank (UASB) reactor treating raw domestic wastewater. These data are shown in Tables 17 and 18. Table 17 data were generated with sludge floc's developed from raw domestic sewage, while Table 18 data were developed with the granular type of sludge developed from sugar beet wastewater processing. The authors believe that this is a higher grade quality sludge which should result in better process performance.

The results are somewhat similar to those in this study. At hydraulic retention times as low as 12 hours, 65-85 percent COD reduction can occur, but with heavy rainfall (i.e. low influent COD's), COD reduction drops to 50-70 percent, and at very low COD's, less than 50 percent. Over the course of the experiments in Table 18, the average total COD concentration is 163.2 mgL^{-1}.

Table 15
Comparison of Lab and Pilot Scale Units

Parameter	Influent (mgL^{-1}) Mean	Range	Effluent (mgL^{-1}) Mean	Range
Pilot Scale				
TCOD	171.4	(70-1106)	101.7	(43-225)
SS	35.5	(7-116)	30.5	(7-144)
Lab Scale[1]				
TCOD	186	(88-306)	49.2	(22-126)
SS	86	(40-186)	16.5	(3-90)

1. Data of Jewell et al (5).

Table 16
ANFLOW Summary Data

Parameter	Influent (mgL^{-1})	Effluent (mgL^{-1})	% Removal
SS	140.6	42.8	69.4
BOD_5	135.7	62.6	52.9

1. Average of 18 monthly average values for 19 m^3d^{-1} pilot test at Oak Ridge, TN (Mean HRT - 9.43-62.4 hours), Genung et al (51).

Table 17

Experimental Results Obtained with Raw Domestic Waste Using 30-120 L UASB Reactors (Ref. (46))

Experiment Number	UASB Reactor Volume	UASB Reactor Height	Hydraulic Load ($m^3m^{-3}day^{-1}$)	Surface Load (mh^{-1})	Temp. Range (^oC)	Exptl. period (days)	Tot.COD ($mgl.^{-1}$)	Dissolved COD (%)	COD reduction Total[a] (%)	COD reduction Dissolved[b] (%)	SS red. (%)
II	30	1	3.8	0.16	30	6	480-660	67-76	62-75	51-57	-
II	30	1	2.7-2.8	0.11-0.16	23	21	330-520	48-67	54-68	20-52	30-75
IIIA	30	1	1.2	0.05	21	26	700-860	56-68	50-78	50-55	70-80[c]
IIIB	30	1	1.2	0.05	21	26	700-860	56-68	52-77	50-55	-[c]
IIIA	30	1	2.6	0.11	26	71	550-760	66-73	58-72	54-57	50-80[c]
IIIB	30	1	2.6	0.11	26	63	550-760	66-73	54-73	55-60	50-80[c]
IIIB	30	1	3.6	0.15	26	6	530-570	75-80	55-69	ca.50	50-70
IIIB	30	1	3.6	0.15	21	12	420-620	77-85	59-70	55-60	20-60
IIIB	30	1	2.6	0.11	21	24	520-590	73-75	57-79	50-60	30-70
IV	120	1.75	1.2	0.08	16-18	40	450-910	47-71	55-75	20-60	55-80
IV	120	1.75	2.0	0.145	18-21	65	700-1200	40-60	72-78	25-60	70
V	120	1.75	1.6	0.12	13-17	28	450-730	62-85	50-68	21-51	90[d]
V	120	1.75	1.0	0.07	14-17	17	470-750	69-85	49-63	27-55	90[d]
V	120	1.75	0.06-0.75	0.04-0.05	12-18	110	420-920	55-95	48-70	30-45	90[d]

a. Based on raw influent and filtered effluent samples
b. Based on filtered influent and effluent samples.
c. Parallel experiments in two identical UASB reactors.
d. In these experiments, the effluent weir contained a sponge in order to reduce washout of sludge.

Table 18

Experimental Data Obtained Over Various Periods of the Experiment in the 120L UASB Reactor (Ref. (46))

Period	No. of Samples	Influent COD* Raw Range	Influent COD* Raw Ave.	Influent COD* Filtered Range	Influent COD* Filtered Ave.	Effluent COD* Raw Range	Effluent COD* Raw Ave.	Effluent COD* Filtered Range	Effluent COD* Filtered Ave.	E_{tot} (%)n	E_{diss} (%)	Gas production Lkg^{-1} COD_{inf}	Temperature (^{o}C)
(1979)													
17/5-31/5	6	588-754	666	361-386	374	127-304	177	95-253	127	81	66	110	13-15
1/6-15/6	9	363-1253	948	262-371	309	79-294	154	40-181	102	89	67	108	14-15
18/6-29/6	10	204-608	467	182-439	341	99-157	129	60-128	97	79.5	71.5	320	12-16
4/7-30/7	12	307-703	504	227-513	366	100-227	157	81-163	131	74	64.5	171	16-19
7/8-29/8	13	222-709	523	202-486	415	139-215	181	107-172	143	73	65.5	204	17-18
4/9-27/9	9	451-761	585	302-537	429	150-265	196	115-227	168	71.5	61	195	17.5-16.5
2/10-31/10	10	459-824	625	387-522	459	153-250	194	125-186	161	74	65	182	17.5-13
1/11-29/11	11	156-720	491	145-454	349	98-202	166	97-182	147	70	58	124	13-11.5
(1980)													
3/12-18/12	5	200-820	513	144-436	257	100-189	132	75-144	108	79	58	113	12-9
2/1-30/1	15	153-629	434	147-452	337	100-203	153	93-190	125	71	63	94	9.5-6.5
1/2-29/2	11	144-1100	546	86-572	322	35-235	154	10-157	112	79.5	65	85	6.5-10
4/3-31/3	9	146-662	426	97-450	318	119-245	190	110-184	148	65	54	132	8.5-10.5
2/4-9/5	8	195-866	581	135-450	330	113-231	190	101-187	141	76	57	123	10-14
4/6-30/6	10	295-768	472	156-388	291	121-253	175	105-184	130	72.5	56	176	15-18
2/7-31/7	12	117-539	322	69-359	235	72-155	105	63-126	90	68	62	150	16-17
1/8-30/8	12	254-882	542	162-666	383	101-299	176	100-203	148	72.5	61	187	16-18
1/9-8/9	6	248-581	433	163-376	323	104-175	146	93-150	122	72	62	192	18-19.5

*values in $mgl.^{-1}$

6. Design Implications

The pilot scale testing of the anaerobic fluidized bed can be interpreted as a successful application of anaerobic fermentation as a pretreatment process. Due to the relative insensitivity of the process performance to hydraulic retention time, the system should be designed at a low HRT (on the order of several hours). The actual design HRT will depend on sewage organic strength.

Following anaerobic treatment, post treatment will be necessary if a 30 mgL^{-1} BOD_5 effluent concentration is required. This can certainly be met by an aerobic process, which would have a greatly lower oxygen demand due to the anaerobic pretreatment. It may be possible to meet this 30 mgL^{-1} level with a physical operation such as gravity filtration or microscreening. This should be further investigated.

One interesting observation during this study, was the excessive quantity of nitrogen gas making up the gas composition of gas produced. This will cause problems in gas utilization.

A highly significant aspect, is the low sludge production from the anaerobic fluidized bed. Solids were never wasted from the reactor over the entire course of testing. It should be noted that the sewage treated was relatively weak in composition. However, this is still a very positive consideration.

CONCLUSIONS AND FUTURE WORK

The anaerobic fluidized bed reactor was studied over a five month intensive testing period for the treatment of primary municipal wastewater effluent. Based on the results of this study, the following conclusions can be made:

1) Over a range of hydraulic loading rates, a mean effluent BOD_5 concentration of 47.2 mgL^{-1} was achieved, and a mean suspended solids concentration of 30.5 mgL^{-1} was achieved.

2) The system required no solids wasting.

3) The system compared favorably with other pilot scale anaerobic processes.

4) Statistical analysis of the data indicated that influent substrate concentration and organic volumetric loading rate had the most influence on effluent BOD_5 concentration and $\%BOD_5$ removal.

5) Excellent correlations existed between effluent BOD_5 concentration and influent BOD_5 concentration, and effluent BOD_5 concentrations and organic loading rate. The $\%BOD_5$ removal correlated very well with the same independent variables.

6) An anaerobic fluidized bed would be a good pretreatment process for domestic wastewater treatment, followed by some post-treatment process.

Based on the results obtained, the following are recommended as future areas of research:

1) Post treatment options such as aerobic processes, gravity filtration or microscreening should be examined for the anaerobic fluidized bed effluent.

2) The influence of low temperature should be examined on the fluidized bed equipment and process.

3) A careful mass balance should be made to better define sludge production.

4) The interaction between protein and other electron donors in sewage in an anaerobic process should be studied.

5) The role of protozoa in anaerobic fermentation should be studied.

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APPENDIX

Analysis of Variance - Comparison of More Than Two Means

$$CM = \frac{\left(\sum_{i=1}^{p}\sum_{j=1}^{n} Y_{ij}\right)^2}{n}$$ = correction for the mean

$$\text{Total SS} = \sum_{i=1}^{p}\sum_{j=1}^{n} Y_{ij}^2 - CM$$ = total sum of squares

$$SST = \sum_{i=1}^{n} \frac{T_i^2}{n_i} - CM$$ = sum of squares for treatment

SSE = Total SS - SST = sum of squares for error

$$MST = \frac{SST}{P-1}$$ = Mean squares for treatment

$$MSE = \frac{SSE}{n-P}$$ = Mean squares for error

$$F = \frac{MST}{MSE}$$ = F test ratio

$V_1 = P-1$ = degrees of freedom

$V_2 = n_i - P$ = degrees of freedom

1. BOD_5 Effluent Data f (HRT)

Set 1 (HRT = 6.67 hrs)

60,81,67,68,47,74,57,30,52 $T_i = 536$

$\bar{T} = 59.6$

Set 2 (HRT = 3.34 hrs)

13,24,42,36,32,48,38 $T_i = 233$

$\bar{T} = 33.3$

Set 3 (HRT = 1.67 hrs)

50,66,62,38,30,48,39 $T_i = 333$

$\bar{T} = 47.6$

Set 4 (HRT = 5.00 hrs)

34,35,27,53,52,57,47,56,46 $T_i = 407$

$\bar{T} = 45.2$

CM = 71158.8
Total SS = 7432.2
SST = 2765.3
SSE = 4666.9
MST = 921.8
MSE = 167.7
F = 5.53
V_1 = 3
V_2 = 28
$F_{.05}$ = 2.95

2. BOD_5 Influent Data f (HRT)

Set 1 (HRT = 6.67 hrs)

199,170,148,129,81,101,56,47,77 $T_i = 1008$

$\bar{T} = 112$

Set 2 (HRT = 3.34 hrs)

28,32,50,38,58,59,71 $T_i = 336$

$\bar{T} = 48$

Set 3 (HRT = 1.67 hrs)

47,63,67,38,50,71,65 $T_i = 401$

$\bar{T} = 57.2$

Set 4 (HRT = 5.00 hrs)

78,67,73,60,71,63,66,76,75 $T_i = 629$

$\bar{T} = 69.8$

CM = 176121.1
Total SS = 44744.9
SST = 19834.6
SSE = 24910.3
MST = 6611.5
MSE = 889.7
F = 7.43

V_1 = 3

V_2 = 28

$F_{.05}$ = 2.95

3. BOD_5 f (S_o)

0-50 ($\overline{41.3}$)

30,13,24,42,36,50,38,30 $T_i = 263$

$\bar{T} = 32.9$

51-100 ($\overline{68.3}$)

47,57,52,32,48,38,66,62,48,56 $T_i = 896$

39,34,35,27,53,52,57,47,46 $\bar{T} = 47.1$

101-150 ($\overline{129}$)

67,68,74 $T_i = 209$

$\bar{T} = 69.7$

151-200($\overline{184.5}$)

60,81 $T_i = 141$

$\bar{T} = 70.5$

CM	=	71158.8
Total SS	=	7432.2
SST	=	4241.7
SSE	=	3190.6
MST	=	1413.9
MSE	=	113.9
F	=	12.41
V_1	=	3
V_2	=	28
$F_{.05}$	=	2.95

4. %BOD_5 Removal f (HRT)

Set 1 (HRT = 6.67 hrs)

69.8, 52.3, 54.7, 47.2, 41.9,26.7,0,36.1, T_i = 361.2

32.5 $\bar{T}$ = 40.1

Set 2 (HRT = 3.34 hrs)

53.5,25,16,5.3,44.8,18.6,46.5 T_i = 209.7

$\bar{T}$ = 29.9

Set 3 (HRT = 1.67 hrs)

0,0,7.5,0,40,32.4,40.0 T_i = 119.9

$\bar{T}$ = 17.1

Set 4 (HRT = 5.00 hrs)

56.4,47.8,63.0,10.6,26.8,41.2,28.3,26.3, T_i = 340.5

38.6 $\bar{T}$ = 37.8

CM = 33236.8
Total SS = 12007.1
SST = 2477.3
SSE = 9529.8
MST = 825.8
MSE = 340.4
F = 2.42
V_1 = 3
V_2 = 28
$F_{.05}$ = 2.95

5. %BOD_5 Removal f (S_o)

0-50 ($\overline{41.3}$)

36.1,53.5,25,16,5.3,0,0,40 $T_i = 175.9$

$\bar{T} = 22$

51-100 ($\overline{68.3}$)

32.5,0,41.9,44.8,18.6,46.5,0,7.5,32.4,40 $T_i = 604.7$

56.4,47.8,63,11.6,26.8,41.2,28.8,26.3,38.6 $\bar{T} = 33.6$

101-150 ($\overline{126}$)

26.7,47.2,54.7 $T_i = 128.6$

$\bar{T} = 42.9$

151-200($\overline{184.5}$)

69.8,52.3 $T_i = 122.1$

$\bar{T} = 61$

CM = 33236.8
Total SS = 12007.1
SST = 2843.0
SSE = 9164.1
MST = 947.7
MSE = 327.3
F = 2.89

V_1 = 3

V_2 = 28

$F_{.05}$ = 2.95

6. BOD_5 f (OVLR)

0.0-0.2 ($\overline{0.16}$)

47,74,57,52,13,24,42,36,34

35,27,53,52,57,47,56,46,30

$T_i = 782$

$\bar{T} = 43.4$

0.21-0.30 ($\overline{0.27}$)

67,68,32,48,38,38

$T_i = 291$

$\bar{T} = 48.5$

0.31-0.40 ($\overline{0.37}$)

60,81,50,30,39

$T_i = 260$

$\bar{T} = 52$

0.41-0.50 ($\overline{0.49}$)

66,62,48

$T_i = 176$

$\bar{T} = 58.7$

CM	=	71158.8
Total SS	=	7432.2
SST	=	773.6
SSE	=	6658.6
MST	=	257.8
MSE	=	237.8
F	=	1.08
V_1	=	3
V_2	=	28
$F_{.05}$	=	2.95

7. %BOD_5 Removal f (OVLR)

0.0-0.20 ($\overline{0.16}$)

41.9,26.7,0,32.5,53.5,25,16,5.3,56.4,36.1 $T_i = 577.5$

47.8,63.0,11.6,26.8,41.2,28.8,26.3,38.6 $\bar{T} = 32.1$

0.21-0.30 ($\overline{0.27}$)

54.7,47.2,44.8,18.6,46.5,0 $T_i = 211.8$

$\bar{T} = 35.3$

0.31-0.40 ($\overline{0.37}$)

69.8,52,3,0,40,40 $T_i = 202.1$

$\bar{T} = 40.4$

0.41-0.50 ($\overline{0.49}$)

0,7.5,32.4 $T_i = 39.9$

$\bar{T} = 13.3$

CM	=	33236.9
Total SS	=	12007.1
SST	=	1467.4
SSE	=	10539.7
MST	=	489.1
MSE	=	376.4
F	=	1.30
V_1	=	3
V_2	=	28
$F_{.05}$	=	2.95

8. SS f (HRT)

Set 1 (HRT = 6.67 hrs)

13,19,144,24

$T_i = 200$

$\bar{T} = 50$

Set 2 (HRT = 3.34 hrs)

20,7,17,26,26,13

$T_i = 109$

$\bar{T} = 18.2$

Set 3 (HRT = 1.67 hrs)

7,55,55,63,33,43,17

$T_i = 273$

$\bar{T} = 39$

Set 4 (HRT = 5.00 hrs)

8,11,38,26,22,25,21

$T_i = 151$

$\bar{T} = 21.6$

CM = 22387
Total SS = 18864
SST = 3497.4
SSE = 15366.6
MST = 1165.8
MSE = 768.3
F = 1.51
V_1 = 3
V_2 = 20
$F_{.05}$ = 3.10

9. SS f (OVLR)

0.0-0.20 ($\overline{0.16}$)

13,19,144,24,20,7,17,
8,11,38,26,22,25,21

$T_i = 395$

$\bar{T} = 28.2$

0.21-0.30 ($\overline{0.27}$)

26,26,13,63

$T_i = 128$

$\bar{T} = 32$

0.31-0.40 ($\overline{0.37}$)

7,33,17

$T_i = 57$

$\bar{T} = 19$

0.41-0.50 ($\overline{0.49}$)

55,55,43

$T_i = 153$

$\bar{T} = 51$

CM = 22387
Total SS = 18864
SST = 1739.6
SSE = 17124.4
MST = 579.8
MSE = 856.2
F = 0.68

V_1 = 3

V_2 = 20

$F_{.05}$ = 3.10

10. SS f ($SS_{influent}$)

0-25 ($\overline{14.3}$)

19,7,17,26,7,55

55,63,33,17,8

$T_i = 307$

$\bar{T} = 27.9$

26-50 ($\overline{35.5}$)

13,20,26,13

43,11,38,22

$T_i = 186$

$\bar{T} = 23.2$

51-75 ($\overline{53.3}$)

26,25,21

$T_i = 72$

$\bar{T} = 24$

76-150 ($\overline{125.5}$)

144,24

$T_i = 168$

$\bar{T} = 84$

CM = 22387
Total SS = 18864
SST = 6345.6
SSE = 12518.4
MST = 2115.2
MSE = 625.9
F = 3.38

V_1 = 3

V_2 = 20

$F_{.05}$ = 3.10

11. TSS f (HRT)

Set 1 (HRT = 6.67 hrs)

37,25,135,116

$T_i = 313$

$\bar{T} = 78.3$

Set 2 (HRT = 3.34 hrs)

29,8,16,35,19,30

$T_i = 137$

$\bar{T} = 22.8$

Set 3 (HRT = 1.67 hrs)

10,17,7,7,16,47,10

$T_i = 114$

$\bar{T} = 16.3$

Set 4 (HRT = 5.00 hrs)

22,31,27,52,48,53,55

$T_i = 288$

$\bar{T} = 41.1$

CM = 30246
Total SS = 23144
SST = 11080
SSE = 12064
MST = 3693.3
MSE = 603.2
F = 6.12
V_1 = 3
V_2 = 20
$F_{.05}$ = 3.10