EFFECTS OF THE AERATION RATE, DISSOLVED OXYGEN CONCENTRATION AND CHOICE OF AERATION GAS ON AEROBIC DIGESTION PERFORMANCE

By

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K_s - A biological constant used in the hyperbolic expression relating specific growth rate to substrate concentration. It is known as the saturation constant. It is numerically equal to the substrate concentration at which specific growth rate is equal to half the maximum specific growth rate for the system, mg/l.

S - Substrate concentration, measured as COD, mg/l.

μ - Specific growth rate for a system in exponential growth, hr^{-1}.

μ_{max} - Maximum specific growth rate for a system in exponential growth, hr^{-1}.

CHAPTER I

INTRODUCTION

In an era of soaring construction and labor costs, many small communities and even larger ones are experiencing difficulties in meeting the obligations outlined in the new laws aimed at eliminating point sources of water pollution. They are finding that they can no longer justify primary treatment and are now having to utilize secondary treatment and occasionally even tertiary treatment.

The kind of secondary treatment most commonly used consists of biological treatment in the form of biological trickling filters/towers or activated sludge processes. A by-product of these types of treatment is biological sludge, part of which is recycled and part is wasted.

There are currently two types of disposal methods available to municipalities for the disposal of primary and excess secondary sludge. In one, sludge is dewatered and dried and disposed of in sanitary landfills. In the other method, the dewatered sludge is incinerated. Since incineration requires relatively sophisticated equipment and takes skilled personnel to operate it properly, it is impractical for many communities. They, therefore, utilize the first option.

Before the raw sludge can be dried and ultimately disposed of, it is usually digested to render it less noxious. This can be done through aerobic or anaerobic digestion. Because the anaerobic process is efficient only under controlled conditions and pH, knowledgeable and experienced personnel must be provided to maintain the process.

On the other hand, aerobic digestion is a simpler process for which a sludge holding tank and an adequate supply of air are needed. This reduces the initial capital cost and supervision requirements, therefore, making the process better suited to smaller communities.

As with all other waste treatment processes, the need to continually investigate and optimize the efficiency of the aerobic digestion process is required. Three major operational parameters with respect to aeration that may be controlled are air flow, dissolved oxygen concentration, and the type of aeration such as pure oxygen and/or air. It is the purpose of this work to investigate the effects of varying the air flow rate and the D.O. concentration on the efficiency of the process and to study the effects of using pure oxygen versus using air.

CHAPTER II

LITERATURE REVIEW

Aerobic Digestion

As with most of the present day processes for the purification of wastewater, aerobic digestion has been in use for only a relatively short time. Some of the first studies were begun by Coackley (1) in 1950. In experiments designed to study the dewatering characteristics of sludge, Coackley subjected sludge that had previously been anaerobically digested to aerobic digestion. The results obtained showed that with digestion at 18°C, there was a reduction of 34% in volatile solids after 48 days of digestion compared to 64% reduction in volatile solids at 37°C. There was also a slight decrease in the total nitrogen content which was not found in the anaerobically digested sludge. Drygen (2) in 1953 obtained a volatile solids reduction of 55% to 60% after 4 to 6 days of aeration in batch studies of pharmaceutical wastes.

In 1956, Eckenfelder (3) completed a study on aerobic digestion using waste activated sludge from activated sludge plants treating domestic wastes, pulp and paper wastes, and pharmaceutical wastes. Eckenfelder found that the oxidation rate approximated monomolecular kinetics during the early phases of the oxidation process but with increasing times of aeration, the rate progressively decreased and approached a limit of about 40% to 60% volatile solids reduction. He stated that the remaining constituents provided a residual for disposal in that they were resistant to further oxidation. In respect to the study on domestic waste, he obtained a reduction of volatile solids from 78% to 64% after 7 days aeration. Akers (4) also studied the auto-oxidation rate of biological sludges. He found higher auto-oxidation rates for sludges of lesser age.

In order to improve the efficiency of the aerobic digestion process, Singh and Patterson (5) studied the effects of hydrolysis. In laboratory batch fed units, they found that at a detention time of three days and substrate loading of 0.15 to 0.20 lb COD/lb MLVSS, a total solids reduction of 60% was achieved. A control digester operating at a 4 day detention time and receiving untreated waste activated sludge provided solids reduction of 15% to 20%. Reductions in COD of 85% were observed in the digester receiving hydrolyzed sludge and effluent COD values of 100 to 200 mg/l were observed in the control units.

In 1961, Jaworski et al. (6) reported on a comprehensive study done at the University of Wisconsin with a follow-up study done by Lawton and Norman (7) in 1963. In the three year aerobic digestion study, the effects of detention time, temperature, pH, aeration rate, and loading on the reduction of volatile solids and the characteristics of the digested sludge were investigated. The initial sludge sample used for the experiments consisted of a primary sludge and secondary sludge mixture in the ratio of 1.75:1.00. Researchers found that although temperature affects the rate of digestion, it has little effect on digestion at long detention times, such as 60 days, since digestion is essentially completed at all temperatures. They also found that the COD values of supernatant liquors ranged from 360 mg/l to 670 mg/l for the various time and temperature conditions studied. pH readings tended to increase in the first 10 to 12 days but then decreased to values as low as 5 after 60 days. These low values did not appear to significantly affect the digestion efficiency. Other conclusions drawn from the study were that increasing the air flow rates produced no significant improvements in volatile solids reduction, and that supernatant liquors from aerobic digestion showed relatively low BOD values when compared to anaerobic digester liquors.

Up until now most of the research done on aerobic digestion had been done with laboratory scale models. In 1971, Cook and Graves et al. (8) published a report on a pilot plant study of aerobic digestion of primary sludge. The study was conducted at the Stillwater, Oklahoma Municipal Sewage Treatment Plant. The digesters consisted of 180 gallon plastic tanks, each placed inside a 250 gallon tank. A constant temperature bath maintained the reactor liquor at 25°C. The sludge was retained for a detention period of either 2, 4, 8, or 12 days depending on the reactor it supplied. The parameters examined were pH, nitrates, phosphates, ammonia, COD and volatile solids. Nitrate, phosphate, ammonia and COD analyses were run on the mixed liquor suspended solids (MLSS) and the filtrate. The concluded after reviewing the data that the 4 day detention time out-performed the other detention times used during the research project.

To verify all the previous laboratory and pilot plant studies done, Ahlberg and Boyko (9) undertook a field study consisting of seven full scale aerobic digestion units in the Province of Ontario. Some of the areas investigated included biological oxygen requirements, the practical operating range for suspended solids, the effects of recycled supernatant on the activated sludge unit, and volatile solids destruction. In studying volatile solids reduction, they observed that normally, the volatile solids reduction in the first stage or single stage units ranged from 10% to 25% and may reach a maximum of 45% to 50% reduction in the two-stage digesters. However, they noted that in some cases the volatile solids fraction increased rather than decreased. They attributed this to the periodic fluctuations in the volatile fraction of the waste sludge. To show a constant volatile solids reduction, Ahlberg and Boyko suggested a complete mass balance of the system would have to be done and therefore, concluded that the performance of an aerobic digester cannot be judged only on the basis of volatile solids reduction.

To determine the effects of recycling the digester supernatant to the activated sludge system, Ahlberg and Boyko had to find the true supernatant loading. This was done by determining the soluble BOD of the supernatant. A range of 4 to 183 mg/l BOD was observed with an overall average of 51 mg/l. This verified Jaworski's findings of relatively low BOD concentrations for the digesters supernatant. They also found the range for the total solids in the digester to be 13,600-39,400 mg/l with an overall average of 27,600 mg/l.

To compare oxygen uptake rates in the various reactors, Ahlberg and Boyko first had to establish a common basis for comparison. They decided that the absolute basis for comparison would be the specific uptake rates in mg O_2/g VSS/hour. They found that for first and single-stage aerobic digesters, the uptake rate ranged from 0.5 to 6.3 mg O_2/g VSS/hour with most of the data falling in the range of

2-4 mg O_2/g VSS/hour. For the second-stage digesters, the range was 0.5-2.4 mg O_2/g VSS/hour. Because of the continual loading and the oxygen uptake rates of waste sludges from conventional activated sludge plants, the authors concluded that a two-stage digester system is necessary to produce a stabilized sludge.

Pure Oxygen Versus Air

The types of systems studied by Ahlberg and Boyko used air to meet the oxygen requirements of the digesting sludge. In 1972, the Union Carbide Company extended their patent for the use of pure oxygen as the aeration gas in the activated sludge process to include aerobic digestion as well. Pure oxygen systems are called UNOX wastewater treatment systems. Some of the advantages of pure oxygen systems claimed by UNOX are as follows: (10)

1. Elevated DO causes a basic change in the metabolic activity and the characteristics of the organisms constituting an activated sludge floc or agglomerate.

2. The flocculant suspension will settle at a higher velocity for any given concentration of such flocculant biomass.

3. The metabolic characteristics of the organisms in a floc will be so changed by an elevated DO that the growth of microbial cells or the synthesis will be reduced for the removal of a given amount of organic substrate or BOD.

4. The different character of the organisms in a floc mass resulting from an elevated DO will permit a higher rate of bio-oxidation and thus higher BOD loadings for comparable removals of BOD.

Although there has been only a few published studies done using oxygen as the aeration gas for aerobic digestion, there are numerous articles on using it in the activated sludge process. One of the first persons to recommend the use of oxygen was Malcolm Pirnie (11) in 1946. He suggested a process which consisted of aerating a mixture of settled sewage and recirculating the final effluent in an oxygenated column. This process of bio-precipitation using pure oxygen was further studied by Okun (12)(13)(14) and by Budd and Lambeth (15). In separate studies these researchers concluded that with the use of pure oxygen, a faster settling sludge was produced which would result in smaller settling basin requirements and that more oxygen was able to penetrate the floc particles. This phenomena did not, however, increase the biological activity but did reduce or eliminate periods of zero DO which would damage aerobic sludge. Okun suggested that if oxygen is no longer limiting, a higher solids content could be maintained, thus increasing the efficiency of the process or decreasing the plant size.

The idea that with the use of oxygen enriched air or pure oxygen a high F:M ratio could be maintained in the aeration basin and that a faster settling sludge was produced started an international controversy in the field of wastewater treatment that is still going on (16)(17)(18)(19)(20)(21)(22)(23)(24)(25)(26). This controversy was even heightened with the advent of the UNOX system by Union Carbide.

In November of 1976, three articles were published in the WPCF Journal which summarized all arguments to date. The first article was written by A. A. Kalinske (10). He undertook to verify or disprove each specific claim made by the proponents of pure oxygen systems using existing data. In rebuttal of Kalinske's interpretation of existing data, Chapman et al. (27) wrote a paper in defense of pure oxygen systems. In their paper, they used side-by-side comparisons of air versus pure oxygen systems whenever possible to support their conclusions. In the third article, Parker and Merrill (28) tried to resolve the conflicting arguments of the first two papers.

Major areas discussed in all three papers included the effects of DO on the metabolic activity of the activated sludge floc, waste sludge production, and the level of MLSS that can be effectively maintained in the activated sludge unit. In the following paragraphs, each of these three items and the conclusions drawn by Kalinske, Chapman et al. and Parker and Merrill will be presented. Additional topics covered by these authors in their papers but not included in this review are nitrification, shock loads and toxicity effects, sludge bulking, thickening and dewatering, power consumption, and capital costs.

In his investigation of the effects of DO on the metabolic activity of activated sludge floc, Kalinske showed through numerous references to past work covering a period of several decades that there was no benefit from a metabolic standpoint in maintaining DO levels in activated sludge units above 2 mg/l. In fact work was cited in which it was found that the removal rate was independent of DO concentration above 0.5 mg/l. All of the work that Kalinske cited had been done in small laboratory units or pilot plants.

In opposition to Kalinske's conclusions, Chapman et al., using deductive reasoning more than facts and figures concluded that the floc in a full scale activated sludge plant is larger than the floc in laboratory units. Because of this size difference, Chapman et al. concluded that laboratory studies with respect to the effects of DO levels on the metabolic activity of activated sludge flocs do not apply to full scale units. The authors went on to explain that because of the higher substrate levels and the size of the floc, higher bulk DO levels must be maintained in order to have proper oxygen penetration of the floc.

In reviewing the arguments put forth by Kalinske and Chapman et al. Parker and Merrill noted that Chapman et al. used a model that they had developed in dismissing much of the laboratory and pilot plant studies cited by Kalinske. Unfortunately, the studies used in formulating Chapman's model have not been published nor was any of the data obtained in these studies included in the article. As for Kalinske, Parker and Merrill claimed that some of the investigations cited by him were atypical and not representative of either the oxygen or air activated sludge systems. They, therefore, concluded that more study is required to establish more exact and definitive relationships.

The next item that Kalinske looked at was waste sludge production. Through biokinetic relationships, controlled laboratory studies, pilot plant tests and data that he gained from large scale demonstration plants, he showed that there was no noticeable difference in sludge production for the air and oxygen activated sludge processes as long as the DO level in the air systems was maintained at a minimum of 2 mg/l. Chapman et al. again used their unsupported model of DO floc penetration in dismissing Kalinske's references. In support of their claim of less sludge production by oxygen aerated systems, they cited several side-by-side studies done by them. In reviewing Chapman's data, Parker and Merrill noted that for two of the seven plants described, no DO data was given. Of the five remaining plants, four of them were operated at DO levels which dropped below 2 mg/l. Parker and Merrill concurred with Kalinske's conclusions that air and oxygen activated sludge systems, when operated at the same organic loading rates and when there is no oxygen deficiency, will produce equal amounts of waste sludge.

Another benefit of pure oxygen claimed by its proponents is the higher level of MLSS that can be maintained in the activated sludge unit while still meeting present day effluent standards. These claims report a maximum of 6000 mg/l MLSS in pure oxygen systems compared with a normal operating range of 2500-3500 mg/l MLSS for air operated systems treating municipal sewage. Kalinske showed through several references that the reason for the lower MLSS concentration in the air systems is not because of any biokinetic deficiency but because of past engineering design and safety factors. Kalinske maintained that air systems are fully capable of operating at higher MLSS concentrations while still maintaining high effluent standards as long as the aeration system is efficient enough to supply the required oxygen at the necessary rate. Chapman et al. unsuspectingly confirmed Kalinske's conclusions in their attempt to show superiority of oxygen systems over air systems in maintaining high removal rates with high MLSS levels. In their side-by-side comparisons of nine plants, they showed the breakdown of the air systems with respect to effluent quality at high F:M ratios while the oxygen systems maintained a fairly high effluent quality. They state that most of these breakdowns were due to settling limitations and not from kinetic limitations. Parker and Merrill also concurred in interpreting the breakdown of the air systems at high F:M ratios to be related to floc breakup rather than metabolic failure. They cite a study done by Scherb (29) on wastewater from a treatment plant in Munich, Germany. Two large parallel pilot plants were established that differed only in the method of oxygenation. One pilot plant used fine bubbled air activated sludge and the other used fine bubbled oxygen activated sludge. Two tests were run at equal aeration periods (2.7 hours and 2 hours) and were run at nearly the same F:M ratios (0.7 day^{-1} and 0.8-0.9 day^{-1}). The effluent quality was found to be the same in both systems for both tests.

As for using pure oxygen in aerobic digestion, most of the arguments on how pure oxygen affects metabolic activity of sludge floc would apply. One study that has been done by Union Carbide (30) showed the effects of covering and insulation the aerobic digestion unit while using pure oxygen as the aeration gas. One of the advantages in covering the system and using oxygen according to Union Carbide Company, is that the vaporization loss and thus the energy loss is kept at a minimum. This will take advantage of the exothermal nature of the endogenous metabolism and maintain the temperature in the unit above ambient. An important by-process of an increased operating temperature is an increase in the rate of digestion which will allow a decrease in the retention time required to achieve a stable sludge. Union Carbide maintains that at temperatures in excess of 45°C, a high degree of digestion can be attained at residence times of 5 days or less. Other advantages of the system are 1. a sludge essentially free of pathogenic organisms which will dewater as well as an anaerobically digested sludge is produced, 2. the process is very stable and can recover from extreme equipment malfunctions and operation errors within a few hours after the problem has been corrected, and 3. the system is self regulating with respect to the rate of digestion and temperature. As the temperature of the system surpasses 60°C-65°C, the thermophilic microbial population is decreased causing a decrease in the rate of digestion which consequently causes a decrease in the amount of exothermal heat generated.

CHAPTER III

MATERIALS AND METHODS

Experimental Apparatus

Two studies were made on the effects of maintaining constant dissolved oxygen levels in the digesters and one study was made to determine the effects of constant air flow rates. The digesters used for the first study on maintaining a constant DO were two 24 inch high cylindrical jars with an 18 inch diameter. The digesters used for the second study on constant DO and the digesters used for the study of the effects of a constant air flow rate were made from 5 gallon distilled water bottles. The necks of the bottles were removed.

In studying the effects of maintaining a constant dissolved oxygen level, two levels were chosen; a high DO level in which 7 mg/l dissolved oxygen was maintained in the digester and a low DO level in which the dissolved oxygen level was approximately 0.5 mg/l which was just enough to keep the systems aerobic. Air was supplied to the 7 mg/l digester with the use of diffusers which also kept the systems well mixed. Since the air flow rate could not be maintained low enough and still have proper mixing for the low DO systems, a Lightning Mixer, Model Number V7 was used. The mixer operating at a low speed was able to create enough turbulence to keep the system mixed and to allow sufficient oxygen transfer to keep the system aerobic. The DO in both studies was monitored periodically with a Weston and Stack Dissolved Oxygen Analyzer, Model 330.

Two air flow rates were investigated in the study on the effects of a constant air flow. These rates were 1000 cc/min for a low flow and 5000 cc/min for a high flow. The rates were measured using air flow meters which were mounted on the sides of the tanks.

The experiments for the determination of the effects of using air versus pure oxygen as the aeration gas were conducted using a New Brunswick Table Top Fermenter, Model No. MF 214. The New Brunswick Fermenter was selected because of its ability to be sealed at the top. The oxygen used was 99% pure. The air and oxygen flow rates were maintained at 1000 cc/min by two manometers built into the fermenters. The gas flow was maintained at a pressure of 10 psi for both systems. The pressure on the air system was measured by a built in gage while the oxygen was measured by a regulator mounted on the oxygen cylinder. To insure complete mixing in the reactors, the agitation system of the New Brunswick Fermenters was used and operated at 200 RPM.

All sludge used for the experiments was from Ponca City Waste Treatment Plant, Ponca City, Oklahoma. The amount of sludge used per digester was 5 liters with a ratio of secondary return sludge to aerobic digested sludge of 4:1. Daily evaporation losses in the digestors were made up with distilled water.

Sampling and Experimental Procedures

Daily samples were withdrawn from all eight digesters for the determination of total COD and soluble COD. Weekly samples were also taken for the determination of total suspended solids and total volatile solids. All four experimental tests were run in accordance with the procedures in the 14th edition of Standard Methods for the Examination of Water and Wastewater (31). pH readings were taken periodically using an Orion Research Model 601 Al Digital Ionalyzer.

Growth studies were run on cells from the constant DO concentration experiments and on the oxygen versus air experiments to determine μ_{max} and K_s. The growth studies were run in 250 ml Erlenmeyer flasks with glucose concentrations ranging from 100 to 1000 mg/l. The growth media was designed so that glucose was the limiting nutrient. Other components of the media with the concentrations used per 1000 mg/l glucose are listed in Table I. The initial seed concentration was the same in all flasks with an initial optical density of approximately 0.0362 (percent transmission-92%). Optical density measurements were made at a wavelength of 540 nm. The total volume in each flask was 40 ml. The flasks were placed on a Eberbach Corporation oscillating shaker which was adjusted to 100 oscillations per minute. The growth curves were obtained by measuring the optical density at regular intervals. μ_{max} and K_s were then calculated using data obtained from the growth study experiments.

Tests run during the air versus oxygen experiment only, included streak plates made from the mixed liquor of both digesters and a shock loading study made after 50 days of digestion. Agar for the streak plates was Tryptic Soy Agar (Difco). The shock loading of the two systems was accomplished by adding 1500 mg/l glucose to each. Twenty-five milliliter samples were then withdrawn periodically from each unit during the shock loading study to determine filtrate COD, the solids concentration, soluble carbohydrate and glucose, and the percent

TABLE I

COMPOSITION OF SYNTHETIC SUBSTRATE

Glucose	1000 mg/l
$(NH_4)_2SO_4$	500 mg/l
$MgSO_4$	50 mg/l
$FeCl_3$	0.25 mg/l
$MnSO_4$	5 mg/l
$CaCl_2$	3.75 mg/l
KH_2PO_4	387.5 mg/l
K_2HPO_4	1245 mg/l

carbohydrate and protein in the sludge. To measure the carbohydrate content of the filtrate and the biological sludge, the Anthrone test was used and the protein analyses were made using the Biuret Test. The concentration of glucose in the filtrate was determined using an enzymatic determination of glucose. The four bioassay tests were run in accordance with Manual M-2, "Selected Analytical Methods for Research in Water Pollution Control" which was published at Oklahoma State University, Stillwater, Oklahoma (32).

CHAPTER IV

RESULTS

Constant Dissolved Oxygen Levels

In Figure 1, data are presented showing the comparison of total and soluble COD for the first study on constant DO levels using a high DO of 7 mg/l and a low DO of 0.5 mg/l. By the end of the reporting period, the 7 mg/l digester had been operating for 222 days. The digester operated at 0.5 mg/l DO was accidentally discarded at the end of 174 days. Solids data for the study are shown in Figure 2. In this figure, total solids and total volatile solids are plotted for the study condition indicated.

Figure 3 shows the data for a duplicate study using the same DO levels. Both units were operated for 52 days. The odor produced by the sludge in the second experiment was more noticeable than the odor produced by the sludge in the first minimum DO study.

To examine the effects of digestion on the biological constants μ_{max} and K_s, growth studies were run at the beginning and at the end of the first constant DO level studies. Figure 4 shows data obtained from growth experiments using fresh sludge as a seed. Using this data $1/\mu$ vs. $1/s$ were plotted in Figure 4B and the constants μ_{max} and K_s were determined. These constants were then substituted into Monod's relationship as shown in Equation 1 to get a comparison of the

Figure 1. Total and Soluble COD vs. Time for the 7 mg/l DO System and the Minimum DO System-Study 1

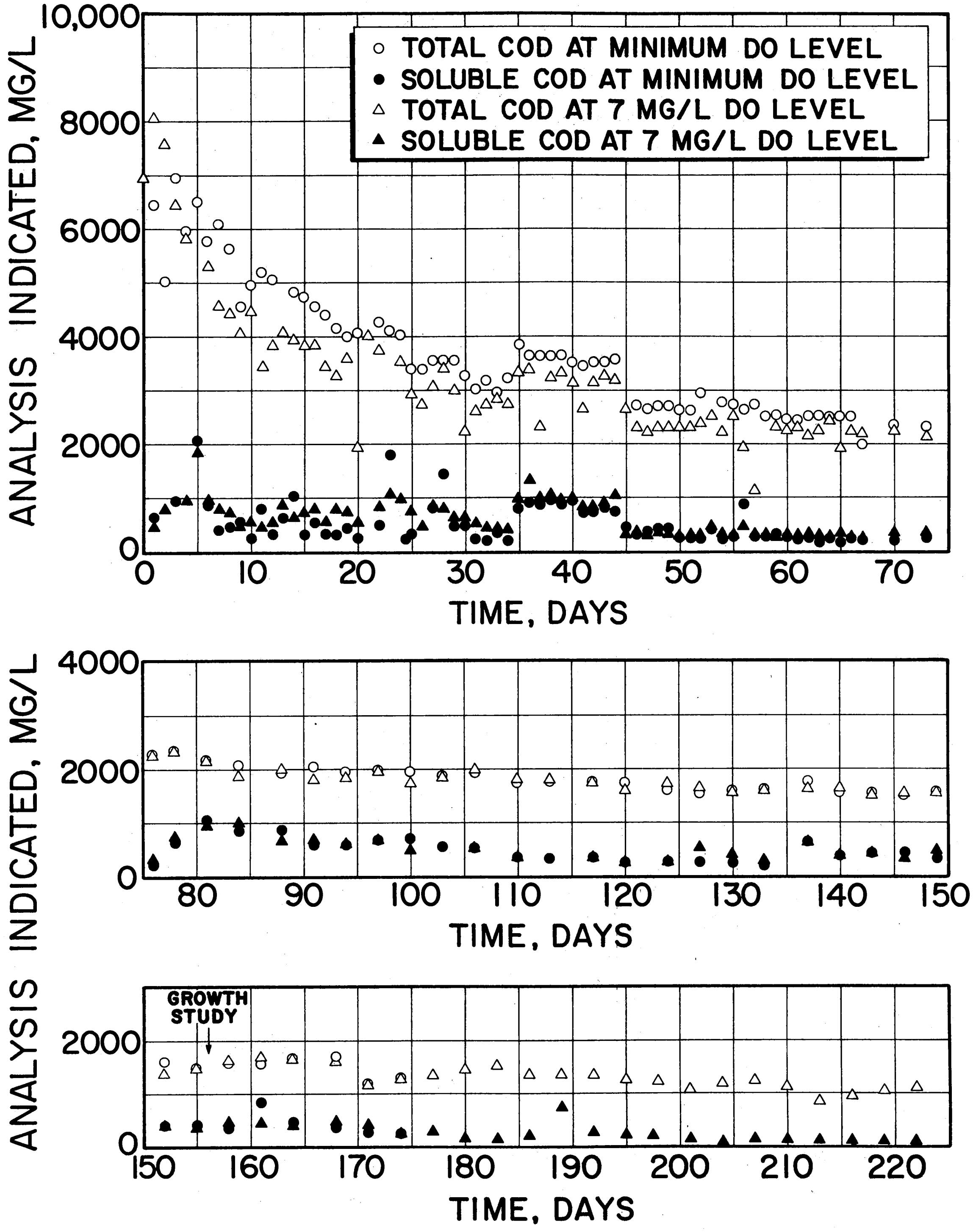

○ TOTAL COD AT MINIMUM DO LEVEL
● SOLUBLE COD AT MINIMUM DO LEVEL
△ TOTAL COD AT 7 MG/L DO LEVEL
▲ SOLUBLE COD AT 7 MG/L DO LEVEL
ANALYSIS INDICATED, MG/L
10,000
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
TIME, DAYS
ANALYSIS INDICATED, MG/L
4000
2000
0
80
90
100
110
120
130
140
150
TIME, DAYS
GROWTH STUDY
2000
0
150
160
170
180
190
200
210
220
TIME, DAYS

Figure 2. Total and Total Volatile Solids vs. Time for the 7 mg/l DO System and the Minimum DO System-Study 1

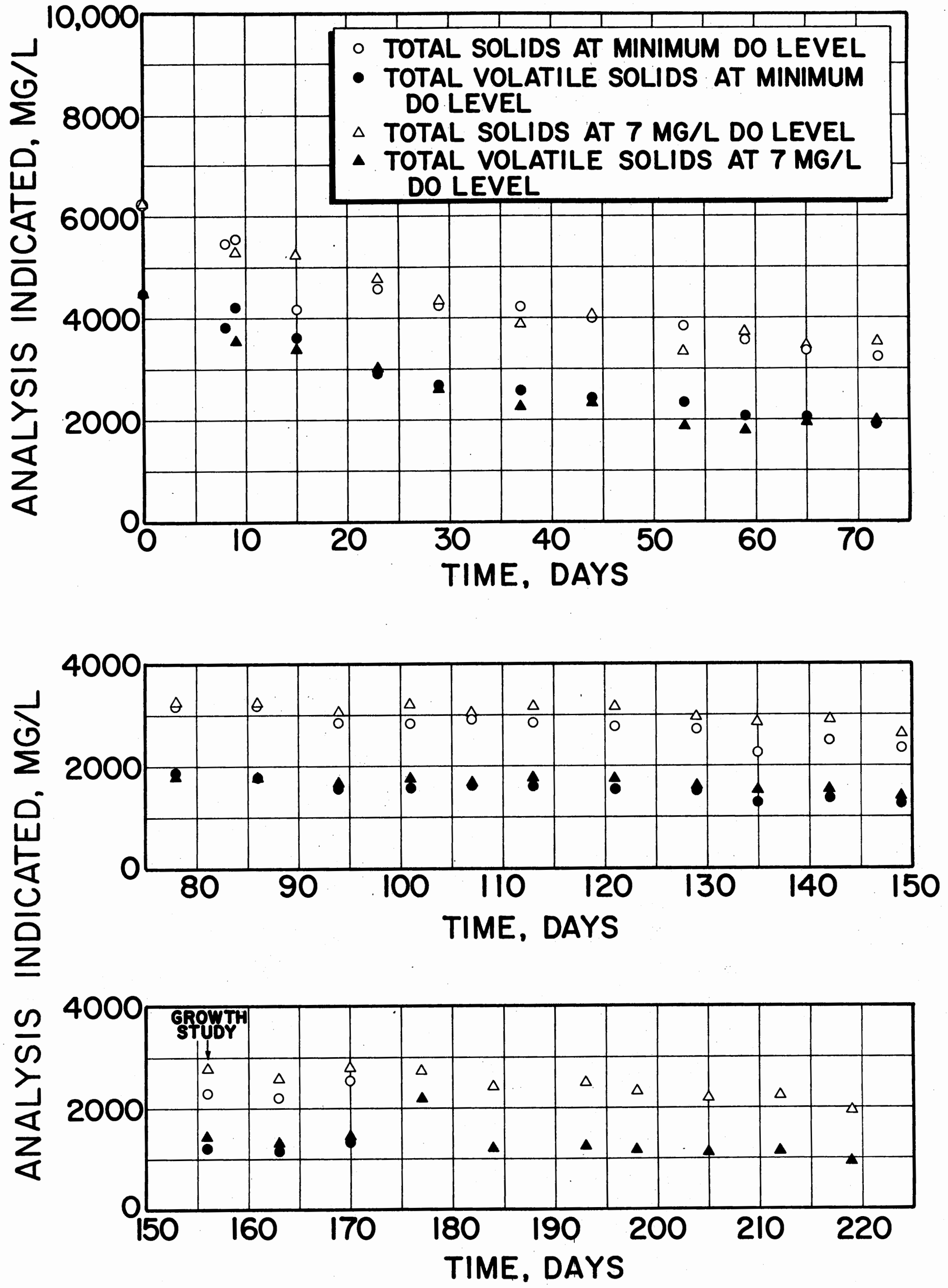
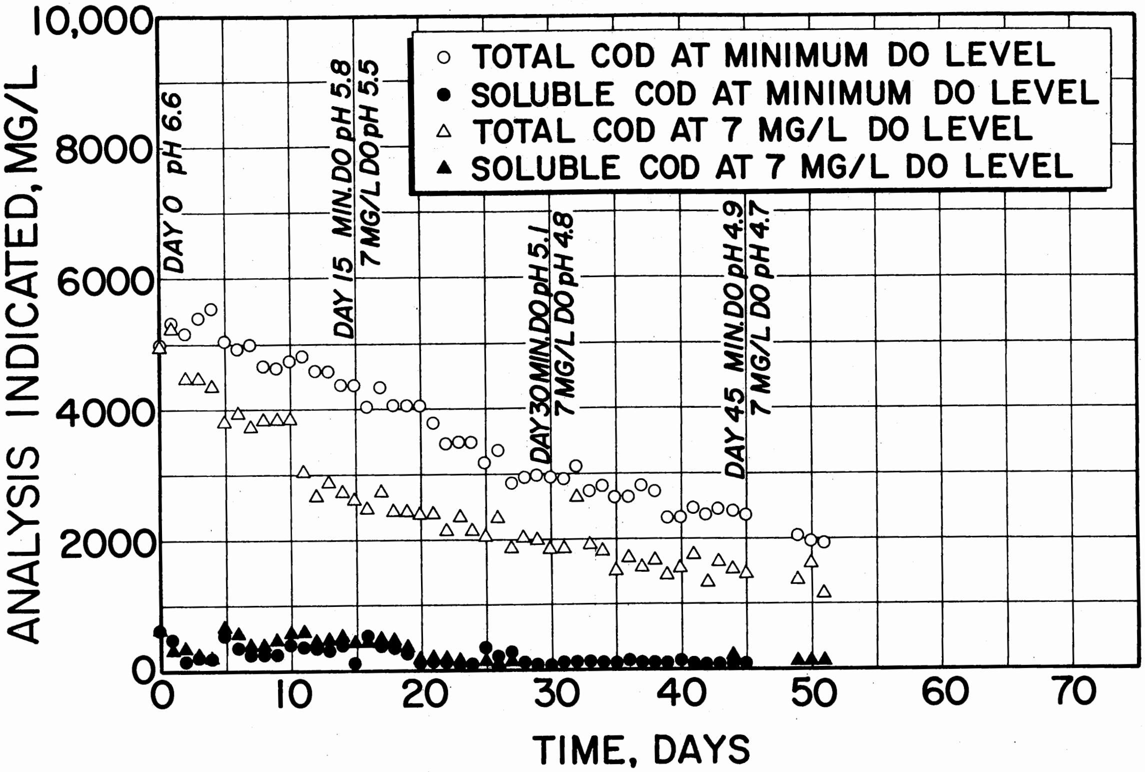

○ TOTAL SOLIDS AT MINIMUM DO LEVEL
● TOTAL VOLATILE SOLIDS AT MINIMUM DO LEVEL
△ TOTAL SOLIDS AT 7 MG/L DO LEVEL
▲ TOTAL VOLATILE SOLIDS AT 7 MG/L DO LEVEL
ANALYSIS INDICATED, MG/L
10,000
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
TIME, DAYS
4000
2000
0
80
90
100
110
120
130
140
150
TIME, DAYS
ANALYSIS INDICATED, MG/L
GROWTH STUDY
4000
2000
0
150
160
170
180
190
200
210
220
TIME, DAYS

Figure 3. A. Total and Soluble COD vs. Time for the 7 mg/l DO System and the Minimum DO System-Study 2

B. Total and Total Volatile Solids vs. Time for the 7 mg/l DO System and the Minimum DO System-Study 2


10,000
8000
6000
4000
2000
0
ANALYSIS INDICATED, MG/L
0
10
20
30
40
50
60
70
TIME, DAYS
○ TOTAL COD AT MINIMUM DO LEVEL
● SOLUBLE COD AT MINIMUM DO LEVEL
△ TOTAL COD AT 7 MG/L DO LEVEL
▲ SOLUBLE COD AT 7 MG/L DO LEVEL
DAY 0 pH 6.6
DAY 15 MIN. DO pH 5.8
7 MG/L DO pH 5.5
DAY 30 MIN. DO pH 5.1
7 MG/L DO pH 4.8
DAY 45 MIN. DO pH 4.9
7 MG/L DO pH 4.7

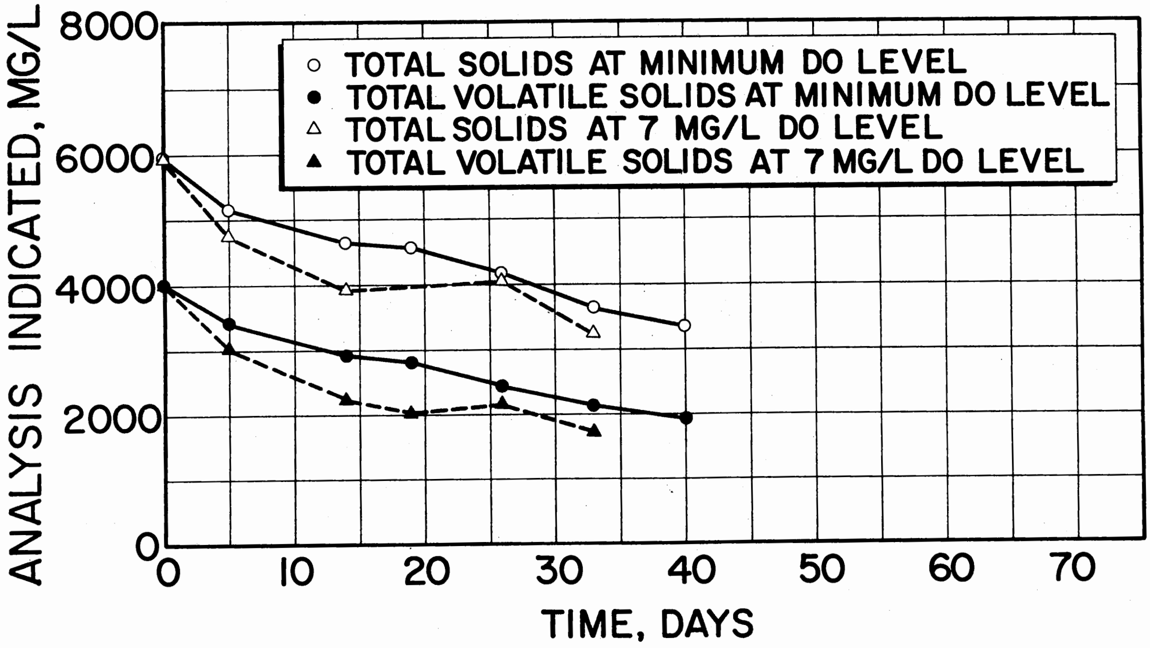
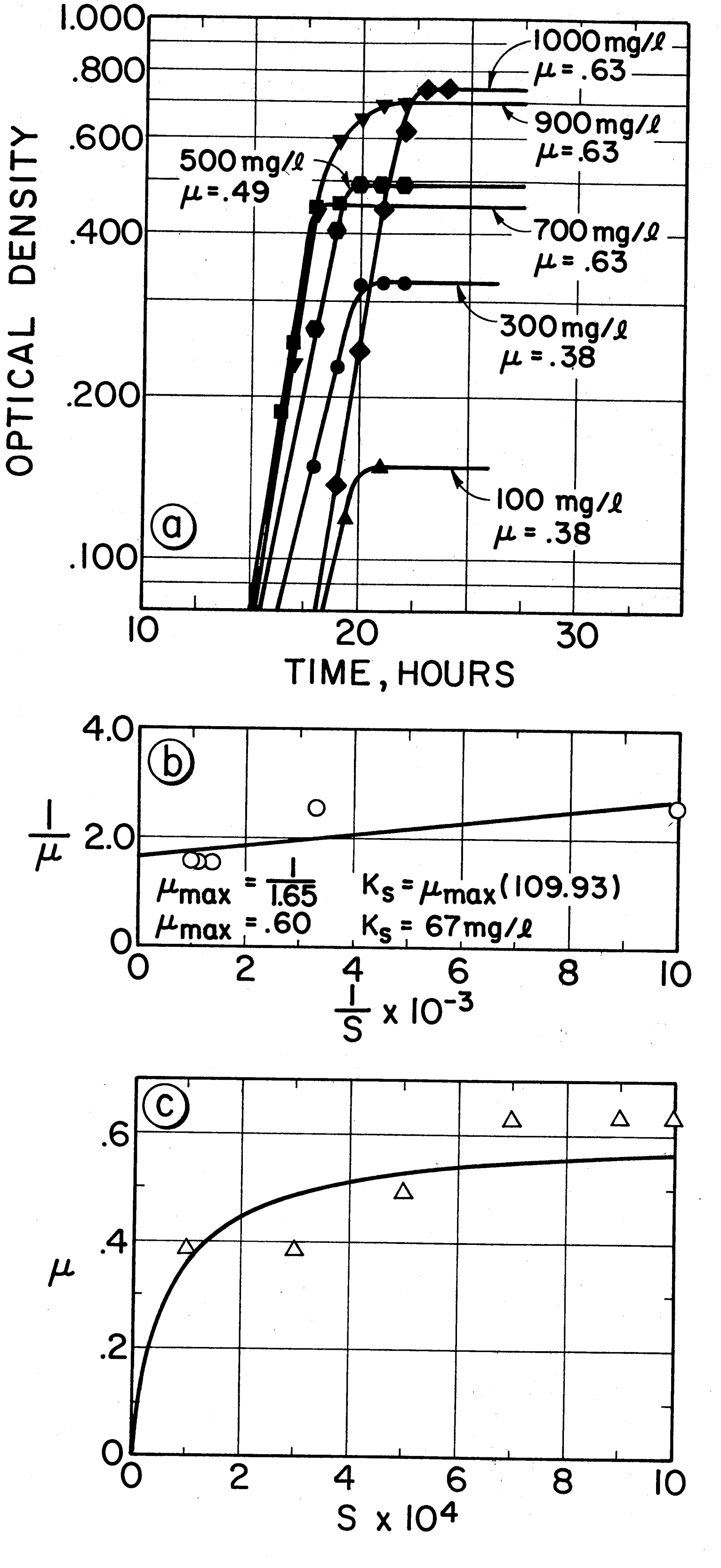

8000
6000
4000
2000
0
ANALYSIS INDICATED, MG/L
0
10
20
30
40
50
60
70
TIME, DAYS
○ TOTAL SOLIDS AT MINIMUM DO LEVEL
● TOTAL VOLATILE SOLIDS AT MINIMUM DO LEVEL
△ TOTAL SOLIDS AT 7 MG/L DO LEVEL
▲ TOTAL VOLATILE SOLIDS AT 7 MG/L DO LEVEL

Figure 4. A. Growth Study (Optical Density vs. Time)-Fresh Sludge Sample from Return Sludge Line, September 21-22, 1977

B. Determination of the Biological Constants, μ_{max} and K_s

C. Plot of the Theoretical Curve and the Actual Experimental Data Points


1.000
.800
.600
.400
.200
.100
OPTICAL DENSITY
10
20
30
TIME, HOURS
ⓐ
1000 mg/ℓ
μ = .63
900 mg/ℓ
μ = .63
500 mg/ℓ
μ = .49
700 mg/ℓ
μ = .63
300 mg/ℓ
μ = .38
100 mg/ℓ
μ = .38
ⓑ
4.0
2.0
0
$\frac{1}{\mu}$
$\mu_{max} = \frac{1}{1.65}$
μ_{max} = .60
$K_s = \mu_{max}(109.93)$
K_s = 67 mg/ℓ
0
2
4
6
8
10
$\frac{1}{S} \times 10^{-3}$
ⓒ
.6
.4
.2
0
μ
0
2
4
6
8
10
$S \times 10^4$

theoretical curve to the experimental data as shown in Figure 4C.

$$\mu = \mu_{max} \frac{S}{K_s + S} \qquad (1)$$

It must be noted that although the values determined for K_s in these experiments are low, the experimental data fits fairly well with the theoretical curve. Figures 5 and 6 show data obtained from growth studies conducted on the high and low DO systems towards the end of the first study.

Constant Air Flow Rates

A comparison of both total and soluble COD concentrations of the mixed liquor of the two digesters maintaining constant air flow rates of 1000 cc/min and 5000 cc/min are shown in Figure 7A. Figure 7B shows data on comparison of the reduction of total solids and total volatile solids for each digester. Dissolved oxygen readings taken occasionally showed the DO of both digesters to be 6.0 mg/l and 8.0 mg/l for the low and high flow rates respectively. pH readings taken periodically on the mixed liquor of both digesters during the test period are shown on Figure 7A.

Air Aeration vs. Oxygen Aeration

Figure 8 presents data showing the comparison of total COD and soluble COD with respect to time for the digester oxygenated with pure oxygen and for the digester oxygenated with air. Values of pH taken periodically during the experiment are noted on the figure. Part B of Figure 8 shows total solids and total volatile solids for

Figure 5. A. Growth Study (Optical Density vs. Time)- 7 mg/l DO System, Study 1, June 26-27, 1977

B. Determination of the Biological Constants μ_{max} and K_s

C. Plot of the Theoretical Curve and the Actual Experimental Data Points

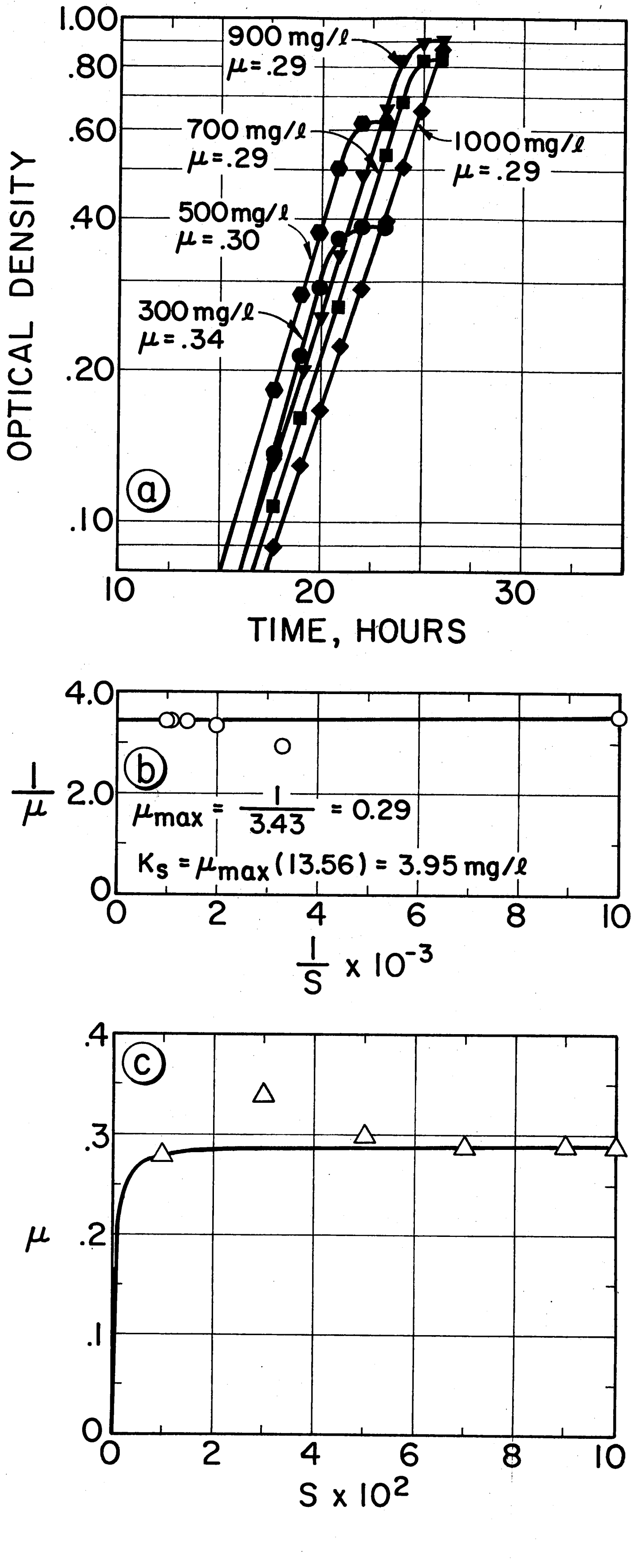

1.00
.80
.60
.40
.20
.10
OPTICAL DENSITY
900 mg/ℓ
μ = .29
700 mg/ℓ
μ = .29
1000 mg/ℓ
μ = .29
500 mg/ℓ
μ = .30
300 mg/ℓ
μ = .34
ⓐ
10
20
30
TIME, HOURS
4.0
2.0
0
1/μ
ⓑ
μmax = 1/3.43 = 0.29
Ks = μmax (13.56) = 3.95 mg/ℓ
0
2
4
6
8
10
1/S x 10^-3
.4
.3
.2
.1
0
μ
ⓒ
0
2
4
6
8
10
S x 10^2

Figure 6. A. Growth Study (Optical Density vs. Time)- Minimum DO System, Study 1, June 26-27, 1977

B. Determination of the Biological Constants μ_{max} and K_s

C. Plot of the Theoretical Curve and the Actual Experimental Data Points

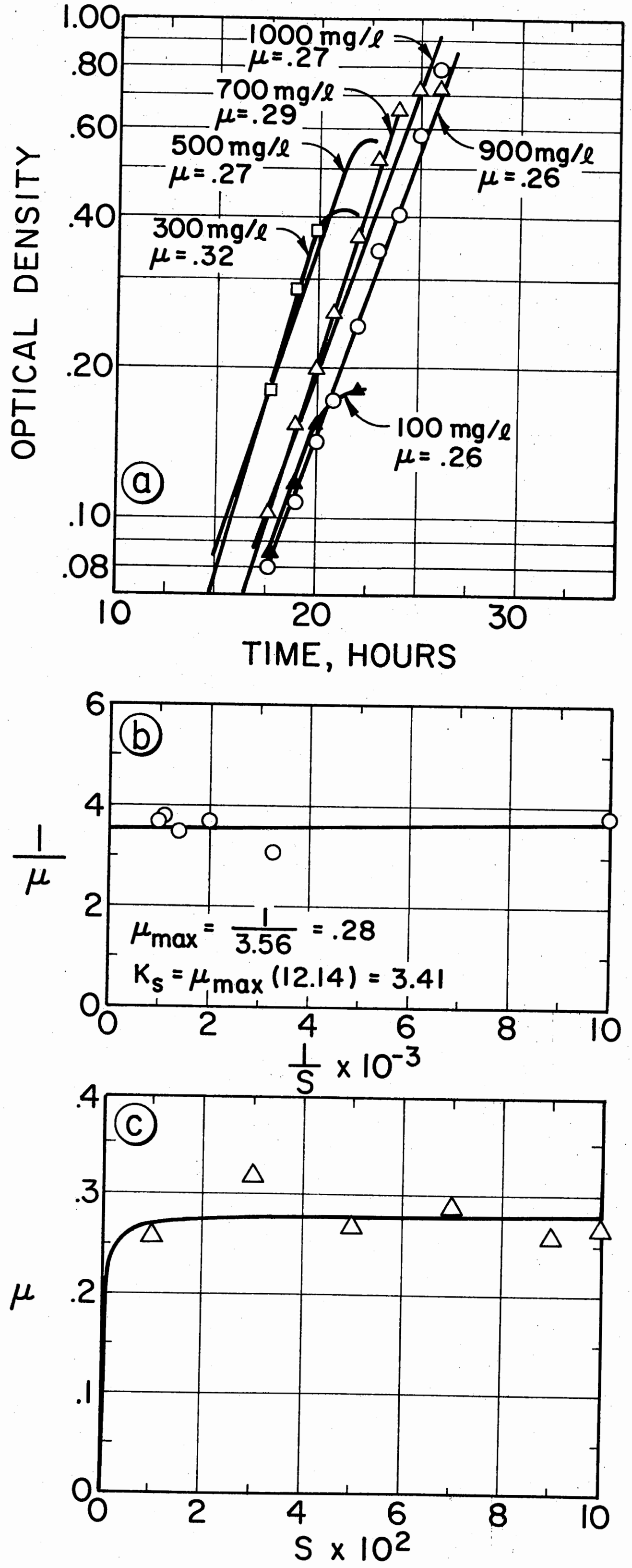
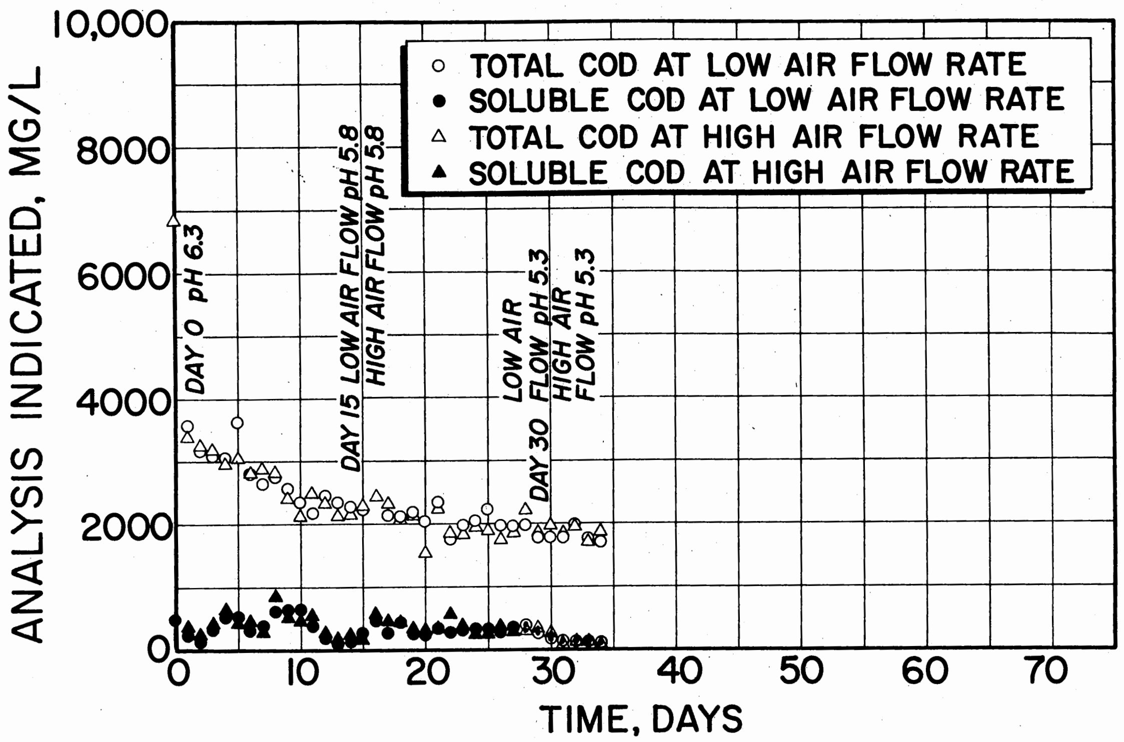

ⓐ
OPTICAL DENSITY
1.00
.80
.60
.40
.20
.10
.08
10
20
30
TIME, HOURS
1000 mg/ℓ
μ=.27
700 mg/ℓ
μ=.29
500 mg/ℓ
μ=.27
300 mg/ℓ
μ=.32
900 mg/ℓ
μ=.26
100 mg/ℓ
μ= .26
ⓑ
$\frac{1}{\mu}$
6
4
2
0
0
2
4
6
8
10
$\frac{1}{S}$ x 10^{-3}
$\mu_{max} = \frac{1}{3.56} = .28$
$K_s = \mu_{max} (12.14) = 3.41$
ⓒ
μ
.4
.3
.2
.1
0
0
2
4
6
8
10
S x 10^2

Figure 7. A. Total and Soluble COD vs. Time for the Low (1000 cc/min) and the High (5000 cc/min) Air Flow Rate Systems

B. Total and Total Volatile Solids vs. Time for the Low (1000 cc/min) and the High (5000 cc/min) Air Flow Rate Systems


○ TOTAL COD AT LOW AIR FLOW RATE
● SOLUBLE COD AT LOW AIR FLOW RATE
△ TOTAL COD AT HIGH AIR FLOW RATE
▲ SOLUBLE COD AT HIGH AIR FLOW RATE
DAY 0 pH 6.3
DAY 15 LOW AIR FLOW pH 5.8
HIGH AIR FLOW pH 5.8
DAY 30 LOW AIR FLOW pH 5.3
HIGH AIR FLOW pH 5.3
ANALYSIS INDICATED, MG/L
10,000
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
TIME, DAYS

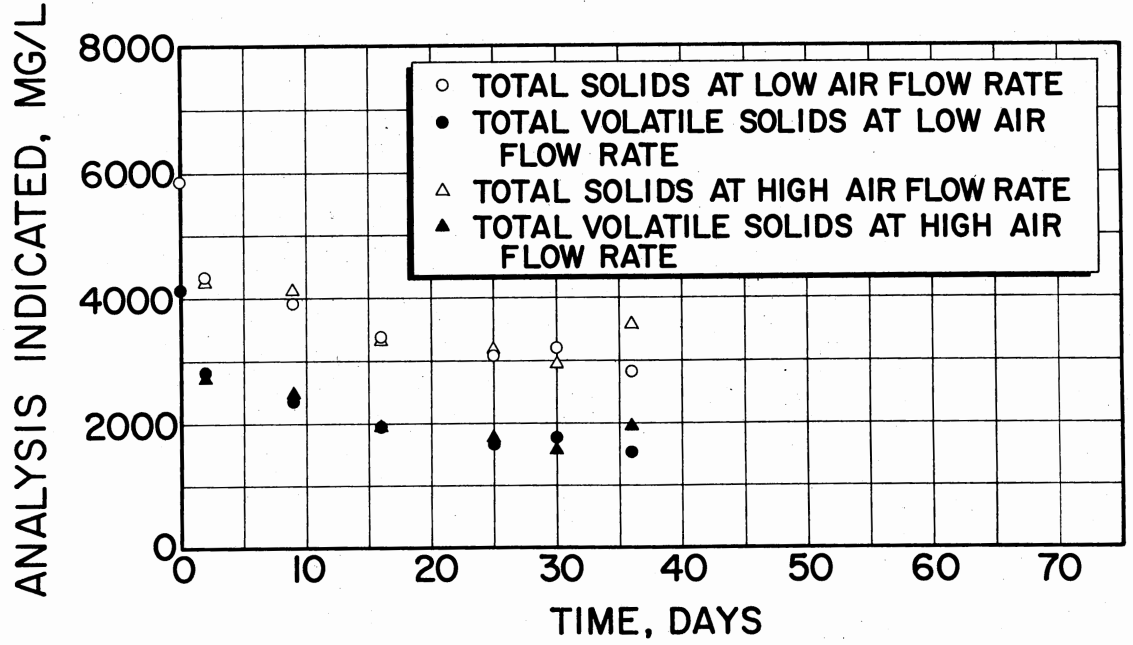
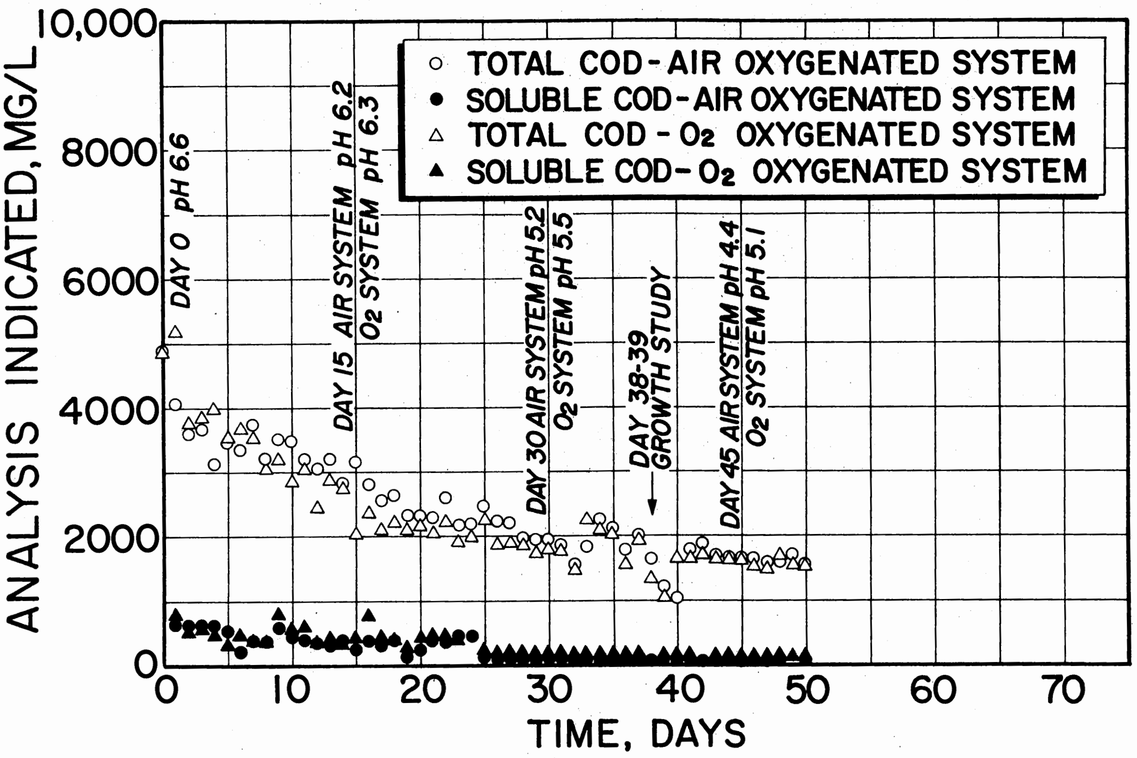
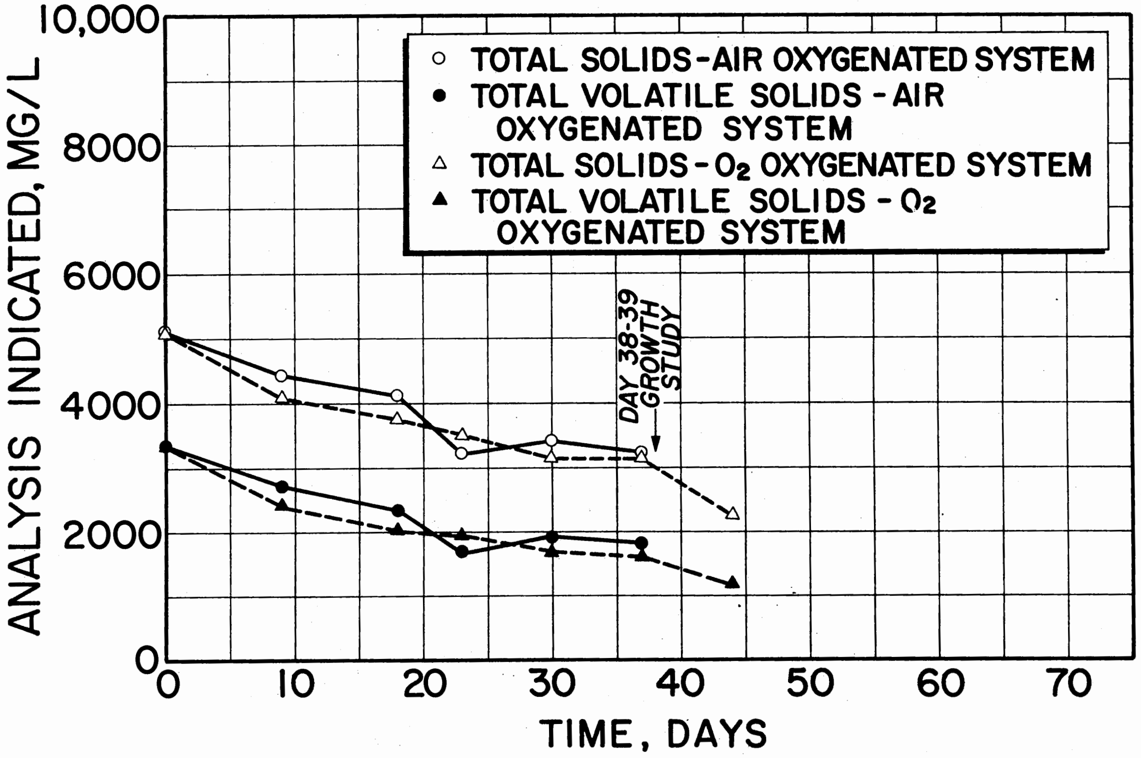

○ TOTAL SOLIDS AT LOW AIR FLOW RATE
● TOTAL VOLATILE SOLIDS AT LOW AIR FLOW RATE
△ TOTAL SOLIDS AT HIGH AIR FLOW RATE
▲ TOTAL VOLATILE SOLIDS AT HIGH AIR FLOW RATE
ANALYSIS INDICATED, MG/L
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
TIME, DAYS

Figure 8. A. Total and Soluble COD vs. Time for the Air and Oxygen Oxygenated Systems

B. Total and Volatile Solids vs. Time for the Air and Oxygen Oxygenated Systems


10,000
8000
6000
4000
2000
0
ANALYSIS INDICATED, MG/L
0
10
20
30
40
50
60
70
TIME, DAYS
○ TOTAL COD-AIR OXYGENATED SYSTEM
● SOLUBLE COD-AIR OXYGENATED SYSTEM
△ TOTAL COD-O2 OXYGENATED SYSTEM
▲ SOLUBLE COD-O2 OXYGENATED SYSTEM
DAY 0 pH 6.6
DAY 15 AIR SYSTEM pH 6.2
O2 SYSTEM pH 6.3
DAY 30 AIR SYSTEM pH 5.2
O2 SYSTEM pH 5.5
DAY 38-39 GROWTH STUDY
DAY 45 AIR SYSTEM pH 4.4
O2 SYSTEM pH 5.1


10,000
8000
6000
4000
2000
0
ANALYSIS INDICATED, MG/L
0
10
20
30
40
50
60
70
TIME, DAYS
○ TOTAL SOLIDS-AIR OXYGENATED SYSTEM
● TOTAL VOLATILE SOLIDS-AIR OXYGENATED SYSTEM
△ TOTAL SOLIDS-O2 OXYGENATED SYSTEM
▲ TOTAL VOLATILE SOLIDS-O2 OXYGENATED SYSTEM
DAY 38-39 GROWTH STUDY

the two digesters plotted with respect to time.

DO readings could not be taken during the study because the probe was too large to fit through the sampling port. It was reasoned though that if the DO level of the 1000 cc/min constant air flow rate study was 6.0 mg/l, then the DO in the digesters of this study would be more than adequate.

After 12 days of digestion, a slight color change was noted in the oxygen aerated system. Af the end of the fifteenth day of digestion, the oxygen aerated system had turned from a dark brown to a cream color. Other than this color change, no other physical differences between the oxygen aerated sludge and the air aerated sludge were noticed.

Growth studies done on the mixed liquors of both systems after 39 days of digestion are shown in Figures 9 and 10.

To compare the ability of each sludge to remove substrate after a long period of digestion, a shock load of 1500 mg/l of glucose was applied to both systems. The solids growth curve and the subsequent COD removal curve generated by the shock load studies can be seen in Figures 11 and 12 for the air system and the oxygen system respectively. The carbohydrate and glucose concentrations of the filtrate with respect to time are also shown. The protein and carbohydrate content of the sludge during this experiment are shown in Figure 13. The decrease in biological solids concentration which occurred in both systems 20-25 hours after initiating the experiment is attributed to cell lysis. During this period, there was a considerable amount of foaming in the reactors.

Figure 9. A. Growth Study (Optical Density vs. Time)- Air Oxygenated System, August 22-23, 1977

B. Determination of the biological Constants μ_{max} and K_s

C. Plot of the Theoretical Curve and the Actual Experimental Data Points

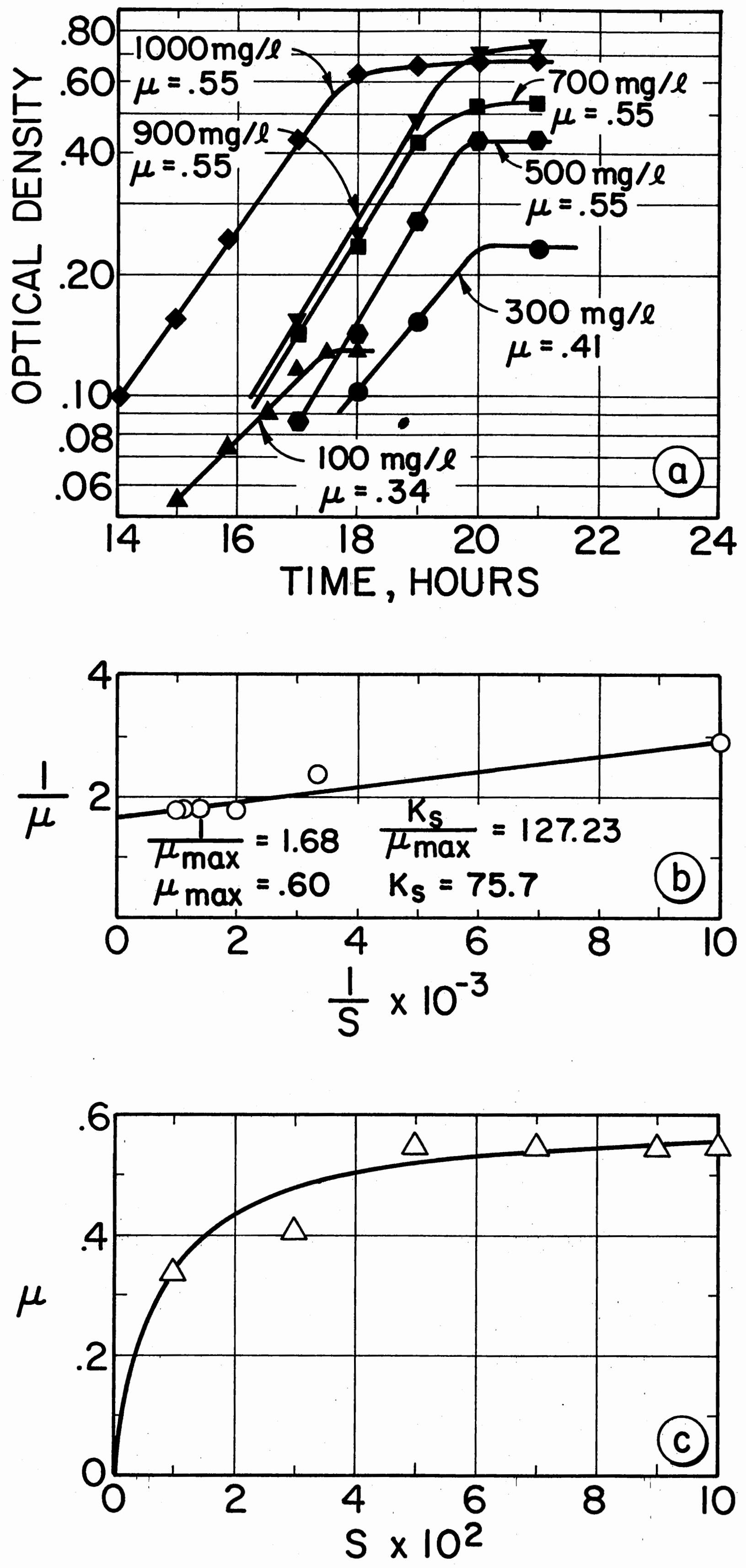
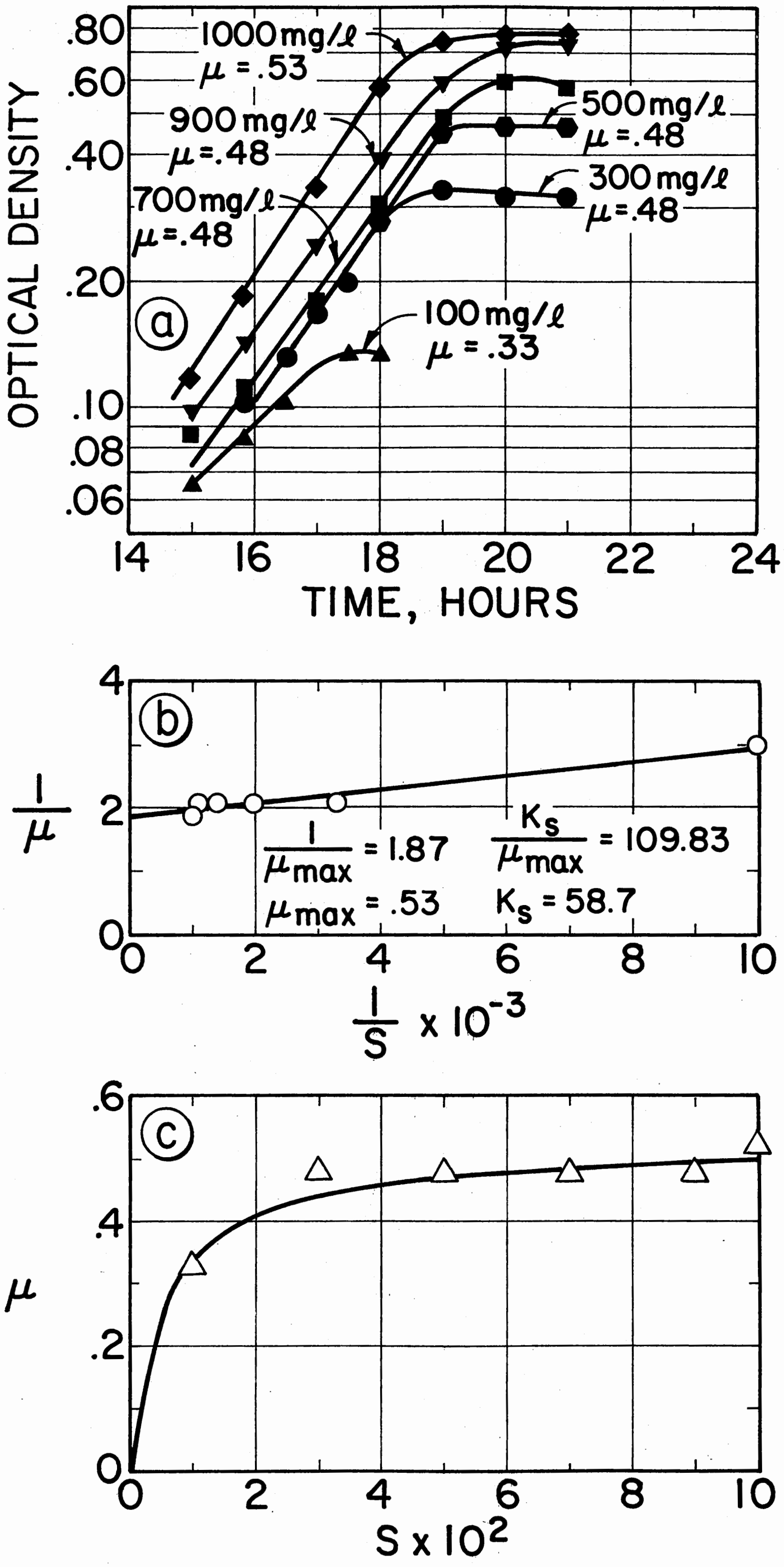

.80
.60
.40
.20
.10
.08
.06
OPTICAL DENSITY
1000 mg/ℓ
μ = .55
900 mg/ℓ
μ = .55
700 mg/ℓ
μ = .55
500 mg/ℓ
μ = .55
300 mg/ℓ
μ = .41
100 mg/ℓ
μ = .34
a
14
16
18
20
22
24
TIME, HOURS
4
2
$\frac{1}{\mu}$
$\frac{1}{\mu_{max}}$ = 1.68
$\frac{K_s}{\mu_{max}}$ = 127.23
μ_{max} = .60
K_s = 75.7
b
0
2
4
6
8
10
$\frac{1}{S} \times 10^{-3}$
.6
.4
.2
0
μ
c
0
2
4
6
8
10
$S \times 10^2$

Figure 10. A. Growth Study (Optical Density vs. Time)-Oxygen Oxygenated System, August 22-23, 1977

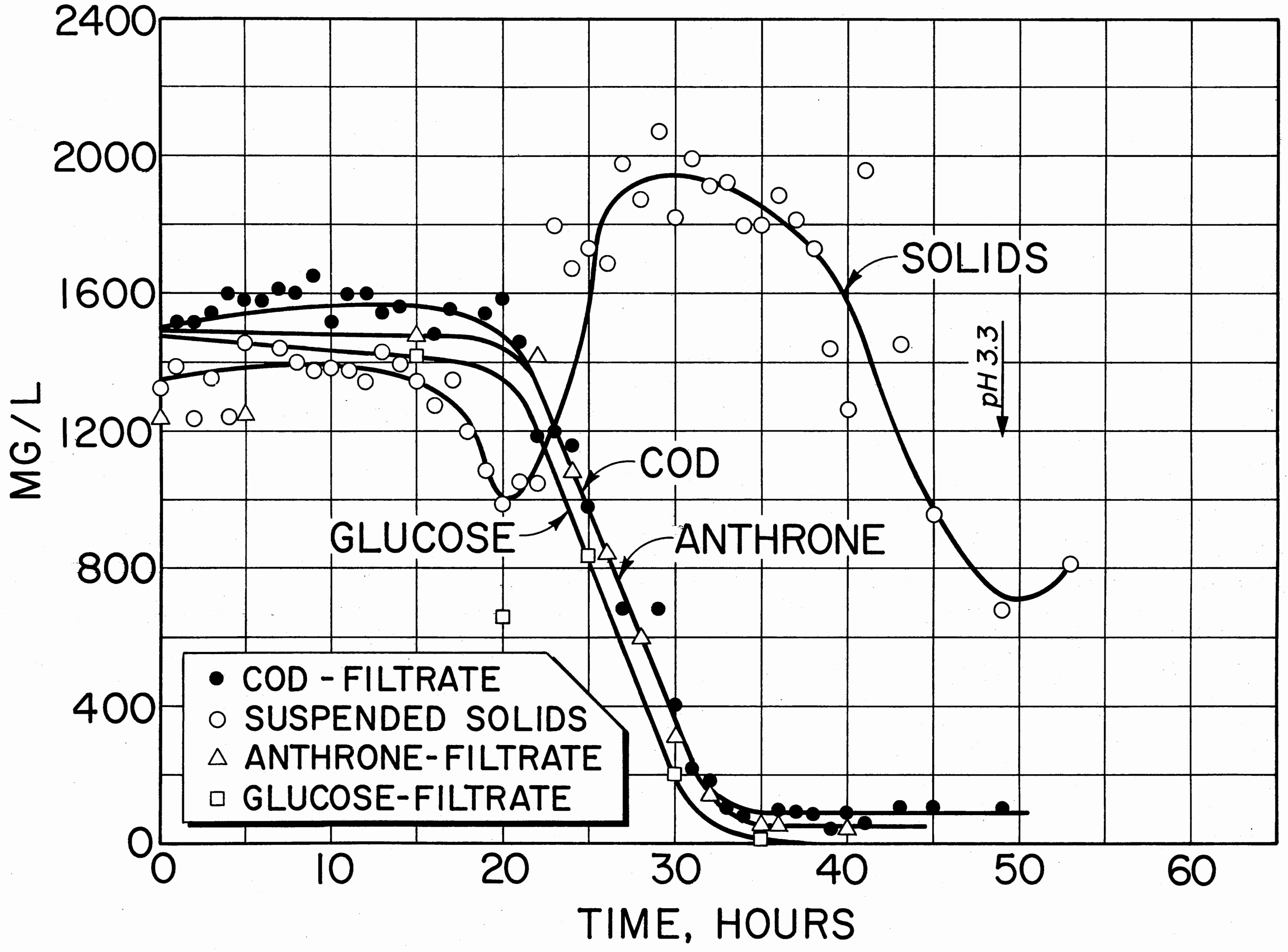
B. Determination of the biological Constants μ_{max} and K_s

C. Plot of the Theoretical Curve and the Actual Data Points



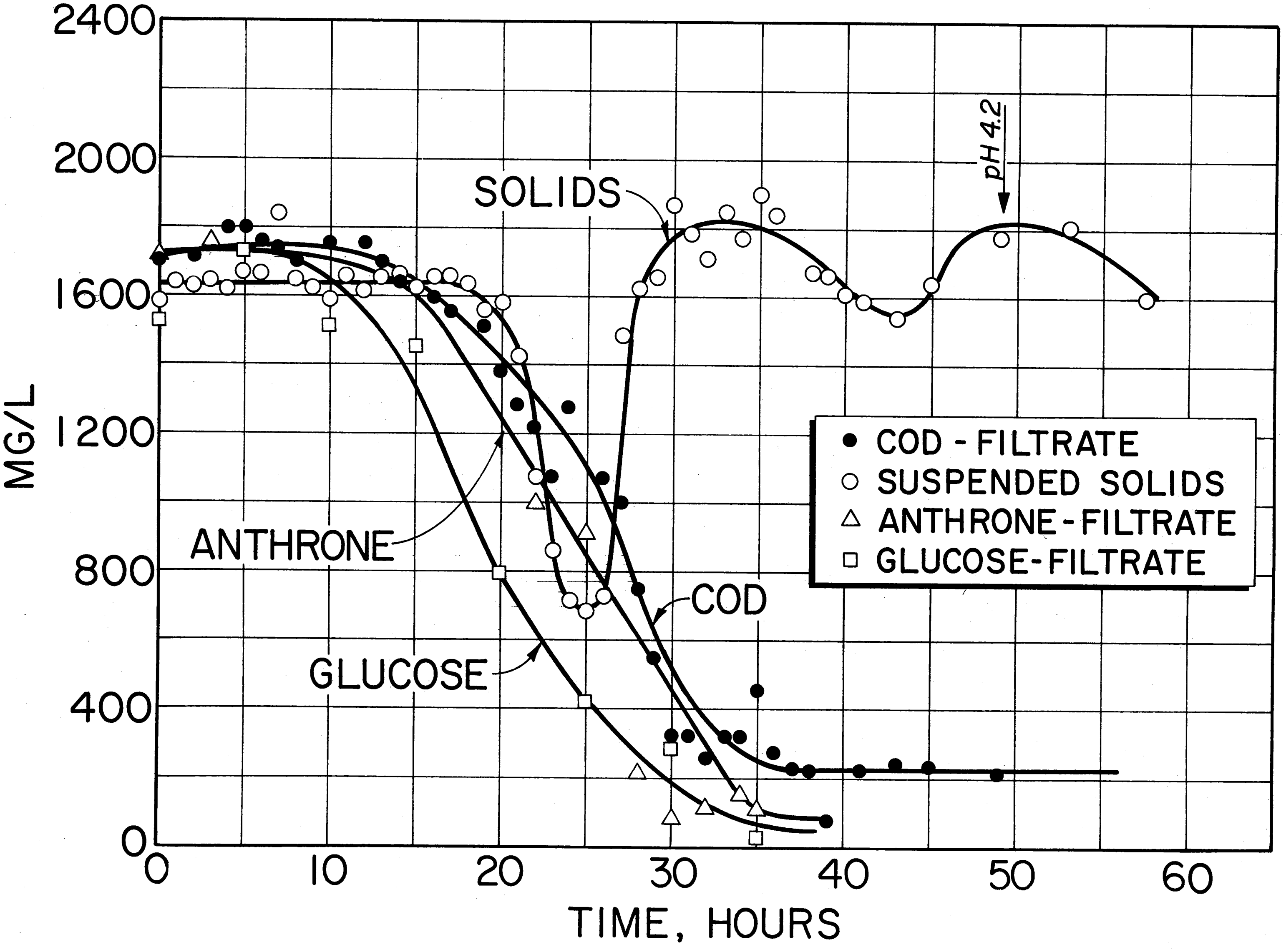
a
OPTICAL DENSITY
.80
.60
.40
.20
.10
.08
.06
14
16
18
20
22
24
TIME, HOURS
1000 mg/ℓ
μ = .53
900 mg/ℓ
μ = .48
700 mg/ℓ
μ = .48
500 mg/ℓ
μ = .48
300 mg/ℓ
μ = .48
100 mg/ℓ
μ = .33
b
$\frac{1}{\mu}$
4
2
0
0
2
4
6
8
10
$\frac{1}{S}$ x 10^{-3}
$\frac{1}{\mu_{max}}$ = 1.87
μ_{max} = .53
$\frac{K_s}{\mu_{max}}$ = 109.83
K_s = 58.7
c
μ
.6
.4
.2
0
0
2
4
6
8
10
S x 10^2

Figure 11. Total COD, Total Solids, Anthrone and Glucose vs. Time-Results from Shock Loading the Air Oxygenated System with 1500 mg/l Glucose.



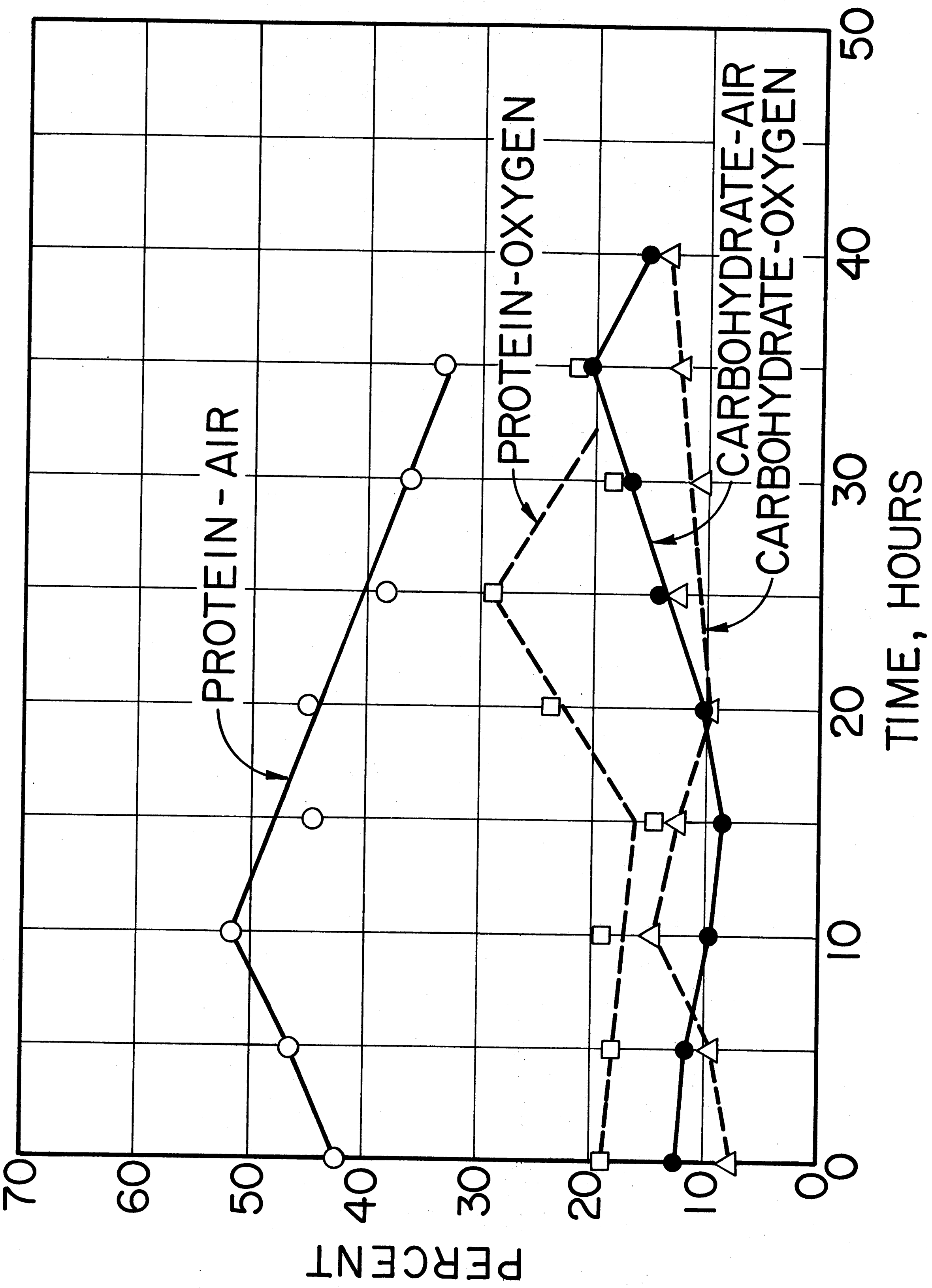
2400
2000
1600
1200
800
400
0
MG / L
0
10
20
30
40
50
60
TIME, HOURS
SOLIDS
pH 3.3
COD
GLUCOSE
ANTHRONE
● COD - FILTRATE
○ SUSPENDED SOLIDS
△ ANTHRONE-FILTRATE
□ GLUCOSE-FILTRATE

Figure 12. Total COD, Total Solids, Anthrone and Glucose vs. Time-Results of Shock Loading the Oyxgen Oxygenated System with 1500 mg/l Glucose



2400
2000
1600
1200
800
400
0
MG/L
0
10
20
30
40
50
60
TIME, HOURS
SOLIDS
pH 4.2
ANTHRONE
GLUCOSE
COD
● COD - FILTRATE
○ SUSPENDED SOLIDS
△ ANTHRONE - FILTRATE
□ GLUCOSE - FILTRATE

Figure 13. Plot of the % Protein and Carbohydrate Content in the Biological Sludges of the Air and Oxygen Oxygenated Systems During the Shock Loading Study


PERCENT
0
10
20
30
40
50
60
70
TIME, HOURS
0
10
20
30
40
50
PROTEIN - AIR
PROTEIN-OXYGEN
CARBOHYDRATE-AIR
CARBOHYDRATE-OXYGEN

CHAPTER V

DISCUSSION

Constant Dissolved Oxygen Levels

In both studies at constant DO levels, total COD concentrations for the 7 mg/l digesters were less than for the minimum DO digesters as shown in Figures 1 and 3. However, this difference was minimal for study one. When comparing the solids data in Figure 2 with respect to total solids and total volatile solids reduction, it can be seen that there is no advantage in maintaining a high DO system over a low DO system. Growth studies from both systems shown in Figures 5 and 6 indicated that there was little difference between the two systems. Because the results from the high and low DO level in study one were so close, it would be difficult to conclude that one system was better than the other.

In the second study with constant DO levels, the differences between the total COD concentrations for both systems were more significant as shown in Figure 3. A difference in the two DO levels is also apparent in the solids data as shown in Figure 3. It can be seen that the total solids concentration and the total volatile solids concentration for the 7 mg/l DO system were lower than those for the minimum DO system. These differences could possibly be due to the more odorous sludge which existed in the low DO digester of the second study. As brought out in Kalinske's arguments earlier, the critical DO level for activated sludge floc is approximately 0.5 mg/l. Therefore, it is possible that the sludge from the minimum DO digester of the second study was slightly oxygen starved and therefore, the digester was incapable of performing as well as the high DO digester.

Constant Air Flow Rates

As can be seen in Figure 7, there was virtually no difference in varying the air flow rates of the two digesters. Since the DO level in the digesters was well above the recommended minimum of 2 mg/l, this was to be expected.

Air Aeration vs. Oxygen Aeration

On examination of the data collected on the pure oxygen system and the air system, it would seem that the type of aeration did not affect the rate of digestion. In Figure 8, the COD data points and the solids data points for the mixed liquor of the two systems are almost identical. The total solids and the total volatile solids concentrations in the oxygen aerated system seem to be somewhat lower than those concentrations for the air aerated systems, but here again the difference is minimal and it would be rather hard to conclude the superiority of one system over the other from the data collected in this experimental work. The biological constants μ_{max} and K_s found from the growth studies conducted on the sludge from both systems as shown in Figures 9 and 10 were also found to be similar.

With respect to the ability of each digester to recover from a shock load, the air system performed better when looking at the experimental results (Figures 11 and 12) from the standpoint of the degree of cell lysing and the speed of recovery. However, the difference in recovery time was only about five hours.

Examination of the sludge protein and carbohydrate content as shown in Figure 13 shows the same amount of carbohydrate in both sludges but a large difference in protein content. Since the sludge consisted of approximately 50% ash at the start of the shock loading studies, the 40% protein content in the air oxygenated sludge would seem too high when based on total solids. Since all other data were comparable the larger value obtained for the protein content of the air oxygenated system may be attributable to experimental error rather than to a difference in the two systems.

CHAPTER VI

CONCLUSIONS

From the previously discussed experimental data and observations, the following conclusions may be drawn:

1. The dissolved oxygen concentration does not affect the rate of digestion as long as the DO level maintained is above a critical level. In these experiments, it would seem that the critical level was around 0.5 mg/l, but this will vary depending on the size of the sludge floc.

2. The air flow rate maintained in aerobic digestion does not affect the rate of digestion as long as the DO is kept above a minimum level.

3. Pure oxygen offers no advantages over air with respect to digestion rate at atmospheric pressure and ambient temperature.

CHAPTER VII

RECOMMENDATIONS FOR FUTURE STUDY

From the review of the literature and based on the findings of this study, the following suggestions are made for future investigations concerning aerobic digestion:

1. Side-by-side comparisons made of laboratory scale bench units with full scale aerobic digestion plants to determine any differences in the floc size and the critical DO concentration.
2. Side-by-side comparisons made of air oxygenated and oxygen oxygenated enclosed, insulated autothermal aerobic digesters.

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VITA 2

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