THE EFFECTS OF DISSOLVED OXYGEN CONCENTRATION ON THE KINETICS AND SETTLEABILITY OF ACTIVATED SLUDGE

by

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To My Parents: Their many sacrifices in making my college education possible shall never be forgotten.

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CHAPTER I

INTRODUCTION

Pure oxygen has recently become an economically attractive alternative to air in the activated sludge treatment process. The major advantage of substituting oxygen for air derives from the higher biological solids concentrations which can be aerobically maintained with oxygen. This allows a reduction in reactor volume without reducing treatment efficiency. It has also been claimed that the higher dissolved oxygen concentrations easily obtained with oxygen will result in improved treatment efficiency, lower sludge yield, and greater sludge settleability. These claims are less obvious and have been a very controversial subject since the introduction of the process modification.

The relationship between dissolved oxygen concentration (DO) and microorganism activity has always been a topic of great interest to microbiologists. The results of numerous pure culture studies have revealed that each species of bacteria examined had its own unique critical dissolved oxygen concentration below which aerobic respiration was drastically reduced. Further investigation found that the activity of some species actually increases with increasing oxygen concentration (1).

Such fragmentary evidence was of little value to sanitary engineers when dealing with the vast variety or organisms found in activated sludge. Furthermore, early studies with sewage organisms at high DO levels were inconclusive and often contradictory (2, 3, 4, 5). As a result, for many years it was widely accepted that DO was of little significance in the activated sludge process as long as it was maintained above 1 mg/l (6).

In the past twenty years a mathematical model of the complete mix activated sludge process has been proposed and verified. This model was derived from biological principles to provide the engineer with a scientific approach for the design of wastewater treatment facilities. Solids production, oxygen requirements, and detention time can be approximated from the model once the appropriate kinetic coefficients are determined from a laboratory treatability study. The effects of DO levels higher than 1 mg/l were not considered in the development of the model. In fact, most laboratory studies are conducted at much higher DO levels than the full scale prototypes operate at (7).

Several investigators studied the effects of various DO levels on the kinetic coefficients and settling properties of activated sludge. The conflicting results reported indicated additional research was necessary.

The objective of this research was to analyze any variations in the kinetic coefficients or sludge settleability resulting from running bench scale activated sludge reactors at 4 different DO levels. The operating conditions selected were similar to those found in conventional activated sludge treatment plants and in laboratory treatability studies. The practical intent of the study was to determine whether or not it is necessary to carefully maintain the DO in a laboratory model equal to the DO in the full scale prototype. Furthermore, it was hoped the results of this investigation would contribute to the understanding of how the DO affects biological waste treatment.

CHAPTER II

LITERATURE REVIEW

The past studies dealing with the effects of dissolved oxygen concentration (DO) on activated sludge performance produced inconsistent results. However, many of the observed discrepancies have been accounted for by analyzing the test conditions involved in each study. The subsequent literature review briefly outlines what is known about the relationship between DO and microorganism activity.

Before examining the studies pertaining directly to the subject matter, a summary of the activated sludge treatment process and biological kinetic theory is provided. Then the suggested mechanisms through which high DO levels could produce superior treatment are discussed. Finally, the important studies related to the effects of high DO levels on kinetics and settleability are described and compared in light of the biological principles and terminology already presented.

Principles of the Complete Mix Activated Sludge Treatment Process

The activated sludge treatment process was first developed in England during the early 1900's. In this process, a waste is stabilized biologically in a reactor under aerobic conditions. Organic waste introduced into the reactor comes in contact with a biological floc. The organic matter is utilized by microorganisms in the production of cellular material. Treated effluent is separated from sludge in a clarifier. The settled sludge is then returned to the reactor in order to maintain the desired mixed liquor volatile suspended solids concentration (MLVSS). Excess sludge produced in the reactor must be wasted.

The pollutional strength of influent waste or treated effluent is most often evaluated in terms of its biochemical oxygen demand (BOD). BOD is defined as the amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions (8). Several reactions are involved in the removal of BOD in the activated sludge reactor. Suspended organic particles are enmeshed in the biological floc and eventually broken down into a soluble form. Soluble organics are absorbed into the cells and stored as a reserve food source. The organic material stored within the cell is converted into cellular material according to the following equation:

$$C_xH_yO_z + NH_3 + O_2 \xrightarrow{\text{enzyme}} \text{cells} + CO_2 + H_2O + \text{heat}$$

The oxygen which is incorporated as cell material is obtained from water or carbon dioxide and not from dissolved oxygen. Cell synthesis requires energy which is obtained from the oxidation of organic matter as follows:

$$C_xH_yO_z + O_2 \xrightarrow{\text{enzyme}} CO_2 + H_2O + \text{heat}$$

McKinney (9) has stated that one-third of the organic material is completely oxidized to carbon dioxide and water while two-thirds of the organic material is used for synthesis. Cellular material is continually oxidized by its own mass to obtain energy for cell maintenance. Auto-oxidation, also known as endogenous respiration, is represented by the following formula:

$$\text{Cells} + O_2 \xrightarrow{\text{enzyme}} CO_2 + H_2O + NH_3 + \text{heat}$$

A complete mix activated sludge process is one in which the untreated wastes are instantaneously mixed throughout the entire aeration tank. This process has become very popular because it serves as an equalization basin to smooth out shock loads and because it produces a uniform oxygen demand throughout the basin.

Two apparently different mathematical models for the completely mixed activated sludge process have been presented by Eckenfelder (10, 11, 12) and McKinney (9). Although the models use different terminology, Goodman and Englande (13) have shown that both models are actually identical in describing the process. Nomenclature from the Eckenfelder model was used throughout this research paper.

The major activated sludge process design parameters are the substrate removal rate, sludge yield, and oxygen uptake rate. Eckenfelder's model can be used to approximate these parameters for a full scale plant if the appropriate kinetic coefficients are known. The determination of these coefficients involves a laboratory study in which bench scale activated sludge reactors are run at several different food to microorganism rations (F/M). At each F/M, influent BOD, effluent BOD, MLVSS, and oxygen uptake are recorded. From this data the kinetic coefficients are obtained.

The substrate removal rate is defined as the amount of BOD which can be removed per unit MLVSS per unit time. A reactor materials balance under steady state conditions results in the relationship:

$$QS_o - QS_e = dS/dt \cdot V \tag{1}$$

where:

Q = flow

V = reactor volume

S_o = influent substrate BOD

S_e = soluble effluent BOD

t = reactor detention time

dS/dt = rate of substrate utilization

Activated sludge systems are designed to operate in the declining growth phase in which growth is limited by a substrate deficiency. In this phase the rate of substrate utilization is controlled by the substrate concentration remaining according to first order kinetics (11):

$$dS/dt = kX_aS_e$$

where:

X_a = the average MLVSS over the time period t

k = the substrate removal rate coefficient

Substituting for dS/dt and rearranging equation (1) gives:

$$(S_o - S_e)/(X_at) = KS_e$$

A plot of substrate removal rate versus effluent BOD can be made from lab data. The slope of the line drawn through the data points is the substrate removal rate coefficient. Given S_o, S_e, and X_a for a full scale plant, k can be used to approximate, t, the required reactor detention time.

The substrate removal rate coefficient is often interpreted as a measure of the efficiency of the bio-oxidation process. The higher k is, the easier the waste is to degrade and the smaller the required detention time.

The amount of sludge production can be estimated from the following empirical relationship:

$$(dX/dt)/X_a = a(S_o - S_e)/(X_a t) - b$$

where:

dX/dt = excess sludge production per unit time

a = the fraction of BOD removed which is synthesized into cellular material

b = the auto-oxidation rate constant

The constants a and b are determined from lab data and can be used to predict the amount of excess sludge produced in the prototype. This information is used to design sludge handling and sludge disposal facilities.

It is important to distinguish between the true yield and the observed yield. The constant, a, is often referred to as the true yield because it doesn't account for the solids lost through auto-oxidation. The observed yield includes auto-oxidation and is defined as the actual amount of sludge produced per unit of substrate removed.

The oxygen uptake rate is defined as the weight of oxygen consumed per unit weight of MLVSS per unit time. Oxygen uptake is related to the amount of oxygen consumed to supply energy for synthesis and endogenous respiration. This relationship is expressed in the following equation:

$$R_r = a'(S_o - S_e)/(X_a t) - b'$$

where:

R_r = oxygen uptake rate

a' = the fraction of BOD removed which is used to provide energy for growth

b' = the endogenous respiration rate

The constants a' and b' are determined from a plot of oxygen uptake rate versus substrate removal rate. The amount of oxygen required to support biological oxidation in a full scale treatment plant can be calculated from these coefficients.

A high value of a' indicates a large amount of oxygen is required to stabilize the waste. It also suggests that an increased amount of substrate is being used for energy instead of synthesis. Therefore, sludge disposal costs must be compared with aeration equipment costs before judging whether a high value for a' is good or bad.

The mathematical model assumes every type of waste has its own unique kinetic coefficients. These coefficients are related to the series of enzymatic reactions involved in the bio-oxidation process. Any variations in the coefficients for a given waste must be attributed to either an inactive biological floc or an alteration in cell metabolic activity towards the substrate.

Although sludge settling properties were not included in the mathematical model, an empirical relationship between settleability and sludge age can be obtained from laboratory data. Sludge age is defined as the mean cell residence time and is equal to the total active microbial mass in the reactor divided by total quantity of active mass withdrawn daily. It has been shown that optimum biological flocculation occurs when organisms are in the endogenous growth phase (14). During this phase, a sticky polysaccharide slime layer is formed around the cell surface which encourages the formation of large floc particles. Therefore sludge can be expected to settle more rapidly at higher sludge ages if the ages are not extremely large.

The settleability of sludge has always been a difficult parameter to measure. In the past the most widely used measure has been the sludge volume index (SVI). SVI is defined as the volume in milliliters occupied by one gram of mixed liquor suspended solids (MLSS), dry weight, after settling for 30 minutes in a 1,000 ml graduated cylinder (15). Another measure of settleability is the initial settling velocity (ISV). The ISV may be defined as the rate of subsidence of the sludge liquid interface before the settling velocity decreases due to the increase in solids concentration in a layer from accumulation of particles from slower moving lower layers (16).

Oxygen as a Limiting Factor in Biological Waste Treatment

Cell metabolism is defined as the process of energy production and energy utilization necessary for cell preservation. Included under energy utilization are the construction of physical parts of the cell, synthesis of chemical components such as enzymes and nucleic acids, cell maintenance, and cell multiplication. A large amount of energy is required for these functions. For example, some bacteria have been found capable of metabolizing an amount of nutrient equivalent to their own weight every few seconds in order to produce energy (17). Energy is usually obtained from a series of chemical reactions in which high energy transfer compounds such as adenosine triphosphate (ATP) are used to store and release cell energy.

In the aerobic respiration system, energy is produced through a sequence of oxidation reactions known as the electron transport system, illustrated in Figure 1. Electrons are transferred from an oxidized substrate through a series of oxidative enzymes to oxygen resulting in the formation of water. At several steps along the transport system the voltage difference is large enough to synthesize ATP.

If the DO surrounding a cell in a liquid medium is continually diminished, eventually the amount of oxygen transferred is exceeded by the amount of oxygen consumed. At this point the electron transport system is seriously disrupted because electrons can no longer be disposed of. Unless the transport system can be altered quickly and a suitable electron acceptor found, cell metabolism will stop. The DO at which oxygen becomes a limiting factor in respiration has been termed the critical DO.

Critical DO levels have been reported for many pure cultures under dispersed growth conditions. The critical DO was usually defined in these studies as the DO at which oxygen uptake begins to sharply decrease. Critical DO varied from organism to organism and different values were often observed for the same species (1). Harrison (1) stated that the critical DO is only an approximation because a species will respond differently to low DO conditions depending upon past environmental history. The results of the pure culture

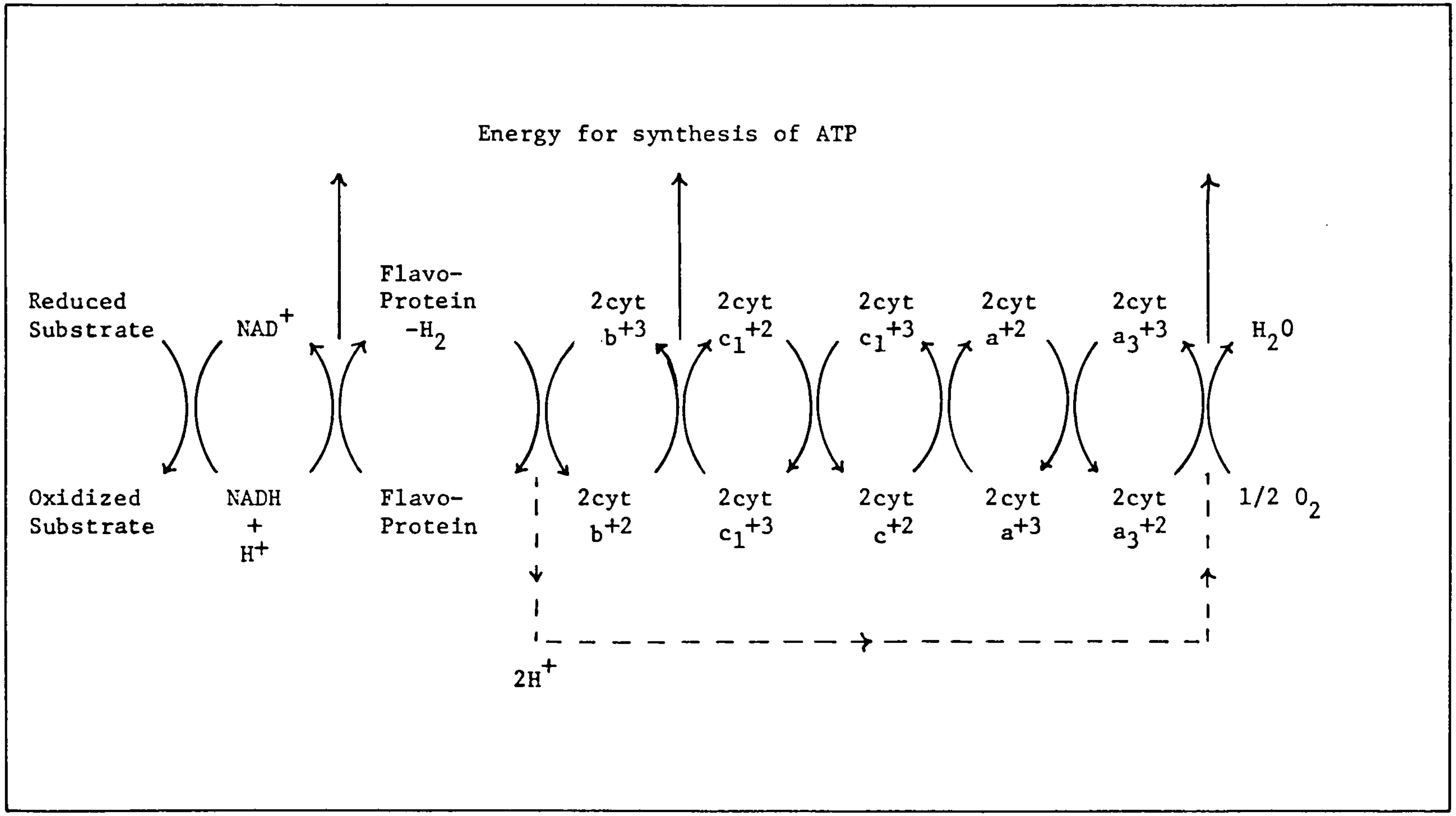

Figure 1. Electron Transport System (17)

studies indicated that the average DO required for aerobic metabolism in dispersed cells is 0.1 mg/l (18). However, activated sludge is composed of clumps of cells referred to as floc particles. Oxygen transfer to cells within the floc particle is hindered by the surrounding cellular material. Consequently, the critical DO for activated sludge is greater than 0.1 mg/l. In 1942, a DO of 2 mg/l was recommended by the American Public Health Association Committee on Sewage Disposal on the basis of operating experience (6). This DO level is still a popular design criteria today. Higher DO levels are very expensive to maintain with conventional air aeration equipment. Furthermore, the increased turbulence resulting from increased aeration is detrimental to sludge settling properties. However, several reports have suggested a DO of 2 mg/l may not guarantee a completely aerobic floc (20, 21, 24). These reports advocated the use of higher DO levels to make sure DO is never a limiting factor in the treatment process.

Although higher DO levels might produce a more aerobic floc, this would probably not increase the substrate removal rate. Bailloid and Boyle (19) monitored glucose and oxygen uptake rates for the floc forming bacterium Zoogloea ramigera. They found the glucose uptake rate was limited by the glucose concentration and not by the oxygen concentration at any floc size. The floc particle diffusion coefficient for oxygen has been reported to be five times greater than the coefficient for glucose (20). At conventional loading levels the concentrations of the individual substrate components are usually less than the DO. Therefore, it is doubtful that substrate would be able to penetrate through the floc particle if oxygen was unable to do so. Increasing the DO to supply oxygen to interior cells would be wasteful in terms of substrate removal, because there would not be any substrate to remove.

It has been suggested that increasing the DO might result in a lower observed yield because of increased endogenous respiration (21). Assuming the cells in the interior of the floc particle were oxygen starved they would not be able to auto-oxidize their own cellular material aerobically. Higher DO levels would increase the amount of oxygen transferred to the floc particle interior, and thus provide the oxygen needed for auto-oxidation. The true yield would probably not decrease but the auto-oxidation rate constant would increase. Although the same amount of substrate would be removed, the solids production in the reactor would decrease. Therefore, the observed yield would decrease.

On the other hand, convincing evidence has been presented indicating a DO of 2 mg/l will maintain aerobic conditions throughout the floc. Wuhrmann (18) and Mueller _et_ _al_. (22) supplied most of the information supporting this claim. Wuhrmann proposed a mathematical model describing the extent of oxygen diffusion through a biological floc particle. The following equation was derived for a spherical particle:

$$d = (C_a - C_i)\ 24D/Z$$

where:

D = diffusion coefficient of oxygen in cell material, usually estimated at about 5 X 10 cm^2/sec at 15°C

d = diameter or thickness of the aggregate (cm)

z = specific consumption of oxygen per unit floc volume and per unit time, ranges generally between a minimum of 10^{-4} mg $O_2/cm^3/sec$ to a maximum of 5 X 10^{-3} mg $O_2/cm^3/sec$ at 15°C

C_a = concentration of dissolved oxygen at the surface of the aggregate (g/cm^3), assumed to be identical with the concentration in the surrounding medium

C_i = dissolved oxygen concentration surrounding the innermost cell of the aggregate (g/cm^3) considered as the oxygen concentration which must be maintained within a floc for aerobic metabolism of all cells and taken as 0.1 mg O_2/l.

Wuhrmann's model states that the required oxygen gradient (C_a - C_i) for aerobic metabolism is directly proportional to the floc particle diameter. Given activated sludge floc particle diameters as large as 400 to 500 microns, the model specified a required oxygen concentration of only 1.5 to 2.5 mg/l.

Mueller _et_ _al_. (22) studied the relationship between critical DO and floc particle size with the bacterium _Zoogloeal_ _ramigera_. The floc size was controlled by the amount of agitation. They found the critical DO increased from 0.6 to 2.5 mg/l with increasing floc particle diameter. A linear relationship between diffusion coefficient and floc size was reported. Mueller _et_ _al_. also measured the average floc particle diameters for a variety of sludge samples from different treatment plants. The average floc particle diameter in 75% of the samples was less than 43 microns. Using Wuhrmann's model with a diffusion coefficient corresponding to a diameter of 43 microns, the required DO level was calculated to be only 0.6 mg/l.

Kalinsky (20) suggested the critical DO might also vary with MLVSS. At high MLVSS localized areas of oxygen depletion are more likely to occur, because oxygen is consumed by surrounding organisms before it can reach cells located in the floc particle interior. Thus a DO of 2 mg/l may exceed the critical DO for a MLVSS of 2000 mg/l but not for a MLVSS of 4000 mg/l.

In the conventional activated sludge process, microorganisms must survive without oxygen during the settling period. Okun and Lynn (23) speculated the repeated periods during which the aerobic organisms are deprived of oxygen reduces the overall activity of these organisms. They decided to examine the effects of the settling period with three batch reactors each with a different initial DO. Twice daily the mixed liquor was allowed to settle for 1 hour. The results indicated treatment efficiency increased with increasing initial DO. When the settling period was reduced to 30 minutes, the reactors run at higher DO levels still exhibited superior treatment efficiency but the differences were smaller. Okun and Lynn concluded the higher DO increased the oxygen resources within the floc particle and perhaps even within the cell cytoplasm. This reduced the period of zero DO and resulted in better treatment. In contrast, Wuhrmann (18) found no significant changes in endogenous respiration or substrate respiration after a 4 hour period of anaerobiosis. He concluded the purification capacity of sludge is unaffected by limited periods of zero DO.

Microorganism activity as measured by oxygen uptake has been observed to increase with increasing DO for several different species (1). This phenomenon has been attributed to increased enzyme activity induced by the higher DO levels. It has also been suggested that higher DO levels may produce a population change within the reactor (18). Species which exhibit increased activity in the presence of high DO might dominate resulting in a greater substrate removal rate and a lower yield. Wuhrmann (12) surmised an increase in DO increases the ratio of aerobic organisms to less efficient facultative organisms.

Because high DO levels are usually achieved with pure oxygen, there is a possibility that the direct contact with oxygen affects microorganism activity. Unfortunately, little information is available on this subject.

Several investigators have reported an improvement in sludge settleability at higher DO levels (23, 24, 25, 26). This phenomenon has been attributed to an increase in the zoogloeal masses and a decrease in the filamentous organisms at high DO levels (18). At low DO levels the zoogloeal organisms have difficulty obtaining oxygen, whereas the filamentous organisms are still able to obtain oxygen because of their large surface area per unit weight. When sufficient oxygen is provided for the entire population, filamentous organisms such as Sphaerotilus suffer in the competition for substrate.

Comparative Studies with High DO and Low DO Activated Sludge Systems

The effects of DO variations in an actual biological treatment process were first observed by Okun in 1948 (24). He experimented with a modified activated sludge system called the bio-precipitation process. In this process influent waste and recycled effluent were mixed and aerated in an absorber before entering the reactor. The oxygen saturated waste was then pumped upwards through a sludge blanket which had no other source of oxygen. Treated effluent was separated from the sludge in a clarifier section directly above the sludge blanket. Okun compared a bio-precipitation lab model using oxygen in the absorber with a model using air. In the oxygen model the influent waste usually had a DO of 30 mg/l after passing through the absorber while the treated effluent had a DO of 7 mg/l. In the air unit the influent DO was usually 8 mg/l while the effluent was about 1 mg/l. Okun observed no difference in treatment efficiency, but the oxygen sludge always had a lower SVI.

Ball and Humenick (27) analyzed Okun's data. Although the yield and oxygen uptake coefficients couldn't be calculated, enough data were available to determine the substrate removal rate coefficients. This coefficient was found to be identical for both the air system and the oxygen system. Ball and Humenick also stated the settling data were not convincing because over three times as much effluent had to be recycled in the air unit to maintain aerobic conditions. Therefore, the mixing intensity was probably greater in the air unit than in the oxygen unit.

In 1969, a full scale comparison between a conventional activated sludge system and a pure oxygen system was undertaken by the Union Carbide Corporation in Batavia, New York (27). The air system consisted of a single plug flow aeration tank while the oxygen system was composed of several complete mix reactors in series. The average DO in the oxygen system was 8 mg/l while the average DO in the air system was only 0.8 mg/l. The results of the study indicated the oxygen system produced less sludge than the air system. The true yield and auto-oxidation coefficients were reported as 1.05 and 0.27 for the oxygen system and 1.38 and 0.17 for the air system. In addition, the oxygen sludge exhibited a lower SVI throughout the study. Although no scientific explanation for the settling phenomenon was proposed, Union Carbide claimed improved settleability was an inherent characteristic of the oxygen system.

Ball and Humenick (27) suggested the difference in yield and settleability reported in the Batavia study was partly related to the difference in sludge age. The oxygen system was always operated at a higher sludge age than the air system. As explained earlier, settleability can be expected to improve with increasing sludge age. The Batavia plant did not have primary clarification facilities. This resulted in weekly average influent volatile suspended solids concentrations as high as 557 mg/l. Some of these solids probably escaped oxidation in both systems and were included in the yield calculations as synthesized cellular material. The solids were exposed to the biological floc for a longer time in the oxygen system because of the higher sludge age. Therefore, the volatile suspended solids were more likely to escape treatment in the air system resulting in a higher true yield. In addition, Sherrard and Schroeder (28) examined the Batavia data and found a uniform decrease in observed yield with increasing sludge age as illustrated in Figure 2. They concluded it was impossible

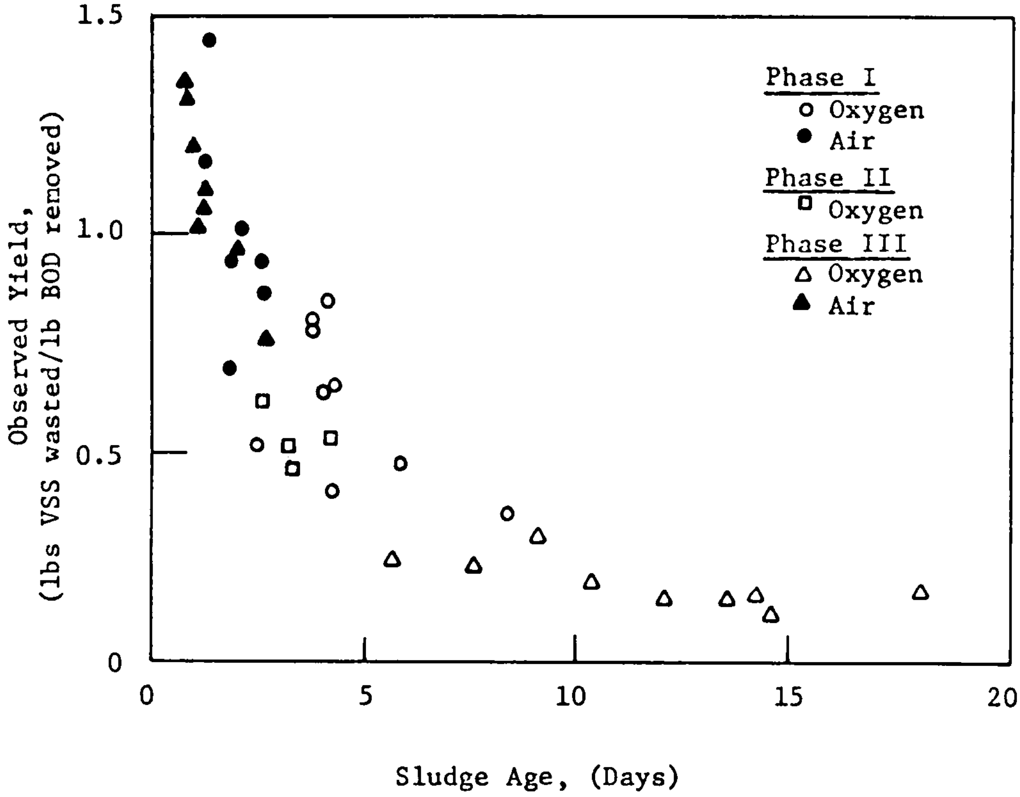

Figure 2. Effect of sludge age on observed yield in Batavia air and oxygen systems (28).

to determine whether or not the oxygen system produced a smaller yield because the systems were operated at different ranges of sludge age. If both systems had been operated at sludge ages from 1 to 20 days, any fundamental difference in yield would have been indicated by two different curves. However, from the data which were obtained it appears as if one smooth curve will fit the points plotted in Figure 2. This suggested there probably wasn't any difference in the yield coefficients for both systems.

Following the release of the Batavia data several independent laboratory studies were launched in an effort to resolve the controversy over the effects of DO on sludge performance. In most of the studies bench scale reactors were continuously fed with a synthetic substrate at different loading levels. The DO was varied while the other environmental conditions were held constant. The significant findings of these studies are summarized and discussed in the following paragraphs.

Rickard and Gaudy (29) ran a continuous flow reactor at DO levels of 1.4, 3.6, and 7.1 mg/l and found no significant variations in observed yield or oxygen uptake rate. This study was conducted at an average MLVSS of 400 mg/l and a mixing intensity of 1000 sec^{-}. At this high level of agitation and low solids concentration, it seems likely most of the cells were dispersed. Therefore the possibility of oxygen limitation because of diffusional resistance was not a factor in this investigation. The study did indicate the higher DO levels didn't exert any noticeable effect upon cell metabolism.

Eckenfelder and Englande (7) studied the effects of increased DO levels and increased mixing intensity (G) on sludge yield with three reactors. One reactor operated at a DO greater than 6 mg/l and a G of 200 sec^{-}, another at a DO of 1 mg/l and a G of 47 sec^{-}, and the third at a DO greater than 6 mg/l and a G of 911 sec^{-}. Conventional loadings of 0.12, 0.20, and 0.40 on a BOD basis were applied to each reactor. The true yield coefficient and auto-oxidation constant obtained for each reactor are presented below:

	a	b
High Turbulence and High DO	.63	0.030
Intermediate Turbulence and High DO	.64	0.016
Low Turbulence and Low DO	.74	0.034

Although the coefficients varied, no general trend in relationship to DO or mixing intensity was discovered. The average floc particle diameter was approximately 150 microns in the low turbulence low DO reactor. If the cells within the floc particles in this reactor were oxygen starved, the amount of endogenous activity would be less than in the high DO reactors. However, the data indicated the auto-oxidation rate constant was greatest in the low DO reactor. Hence, Eckenfelder and Englande concluded neither DO nor mixing intensity had any significant effect upon the sludge production coefficients at conventional loading levels.

Humenick _et_ _al_. (16, 30) evaluated the yield coefficients, substrate removal coefficients, and sludge settling properties for an air system and an oxygen system maintained at identical sludge ages. The sludge ages investigated were 1.0, 2.5, and 5 days. The mixing intensity ranged from 40 to 160 sec^{-} and the loadings ranged from 0.5 to to 3.0 on a COD basis. The average DO in the air system was 4 mg/l while the average DO in the oxygen system was 8 mg/l. No significant differences in the kinetic coefficients were observed. Although the ISV was observed to vary with mixing intensity, sludge age, and solids concentration, there was no difference in ISV between the aerated sludge and the oxygenated sludge when compared under the same operating conditions.

In contrast, Jewell and Mackenzie (31) observed significant differences in the true yield coefficients at two different DO levels. At a DO of 5 mg/l the true yield was 0.60 while at a DO of 17 mg/l the true yield was 0.47. The difference in observed yields appeared to increase with increasing F/M. Furthermore a plot of observed yield versus sludge age revealed the observed yield in the oxygen unit was less than the observed yield in the air unit at any sludge age. Jewell and Mackenzie attributed the lower observed yield to increased endogenous activity in the high DO unit. However, the auto-oxidation constants of 0.10 for the air unit and 0.059 for the oxygen unit did not coincide with their theory.

Using a batch feed reactor, Poon and Wang (32) also reported a decrease in observed yield at higher DO levels. A plain aeration reactor with an average DO of 5 mg/l was compared with a reactor supplied with enough oxygen to maintain a DO greater than 15 mg/l. The difference in observed yield only became apparent when the F/M exceeded 2.5 on a COD basis and the MLVSS was greater than 10,000 mg/l. The substrate removal rate was higher in the oxygen system at F/M levels ranging from 1.0 to 3.0. At F/M levels greater than 3.0 the substrate removal rate was constant for both systems because the maximum substrate removal rate had been reached. Poon and Wang believed a much greater oxygen transfer rate was required in their study because of the high solids concentration. In the low DO reactor, oxygen was depleted in the immediate vicinity of the floc particles because oxygen was consumed faster than it could be replaced by diffusion, whereas oxygen was replaced as fast as it could be consumed in the high DO reactor. Differences were observed only at very high F/M values because the substrate penetrated throughout the floc particles at these loadings. In the low DO reactor not enough oxygen was available in the floc particle interior to oxidize the substrate and thus the substrate removal rate was lower than in the high DO reactor.

In all of the comparative studies mentioned so far, the sludge was never subjected to a period of zero DO in a settling tank. Benefield (33) recently completed a laboratory study with a model employing a separate settling tank and sludge recycle. He found no difference in the observed yield in an air system and an oxygen system when both units were run at similar solids concentration in the range of 1,500 to 3,000 mg/l and identical sludge ages. However, a significant decrease in yield was observed when an oxygen unit was run at a high solids concentration in the range of 3,000 to 6,000 mg/l.

With the exception of the report by Jewell and Mackenzie (32), the results of the comparative studies seem to suggest high DO levels are only advantageous at high solids concentrations and high loadings. The reason for differences appears to be due to an increased oxygen transfer rate and not because of a change in cell metabolic activity. Unfortunately, not enough data were provided in the reports by Humenick et al., Eckenfelder and Englande, and Jewell and Mackenzie to calculate the exact solids concentrations used in these studies. Furthermore, constant DO levels were not maintained in most of the studies. Therefore, additional research was required with emphasis upon solids concentration, loading levels, and the lowest DO level above 2 mg/l at which variations are significant. Of particular interest are the conventional solids concentrations and loading levels. Laboratory treatability studies usually employ conventional operating parameters. However, the DO is often greater than 2 mg/l because increased aeration is required to maintain the solids in suspension and because it is very difficult to maintain a constant DO level. If higher DO levels influence the kinetic coefficients obtained from these studies, these coefficients may be non-conservative when used to design full scale treatment plants. Therefore, a solids concentration of 2,000 mg/l was maintained throughout the subsequent study. Conventional loadings of 0.25, 0.50 and 0.75 were applied to reactors run at DO levels of 2, 4, 8, and 10 mg/l. The kinetic coefficients and settling properties were evaluated at each DO level.

CHAPTER III

MATERIALS AND METHODS

Description of Experimental Apparatus

Two identical bench scale activated sludge treatment units were used throughout this investigation. One of the units is illustrated in Figure 3. Each reactor was constructed out of 3/8 inch plexiglass and had a volumetric capacity of 9.3 liters. A 3/8 inch baffle divided each reactor into an aeration basin and a settling basin. The height of the baffle was adjusted to obtain the clearest effluent possible without creating a stagnant sludge layer at the bottom of the settling basin.

The aeration basin had a capacity of 6.9 liters. Air obtained from a compressed air supply was supplied through a bar diffuser at the head end of the tank. Oxygen was required to maintain the DO levels of 8 and 10 mg/l. The oxygen was purchased from Airco, Inc. in steel cylinders containing 260 cubic feet of oxygen and was diffused into the aeration tank through a single stone diffuser. Air was still supplied at the high DO levels to provide the required mixing intensity and to aid in maintaining constant DO levels. The air stripped the oxygen bubbles out of solution uniformly and this had a dampening effect on the DO fluctuations.

The air flow rate and oxygen flow rate were measured and regulated with flow gauges. Constant DO levels were maintained by adjusting the

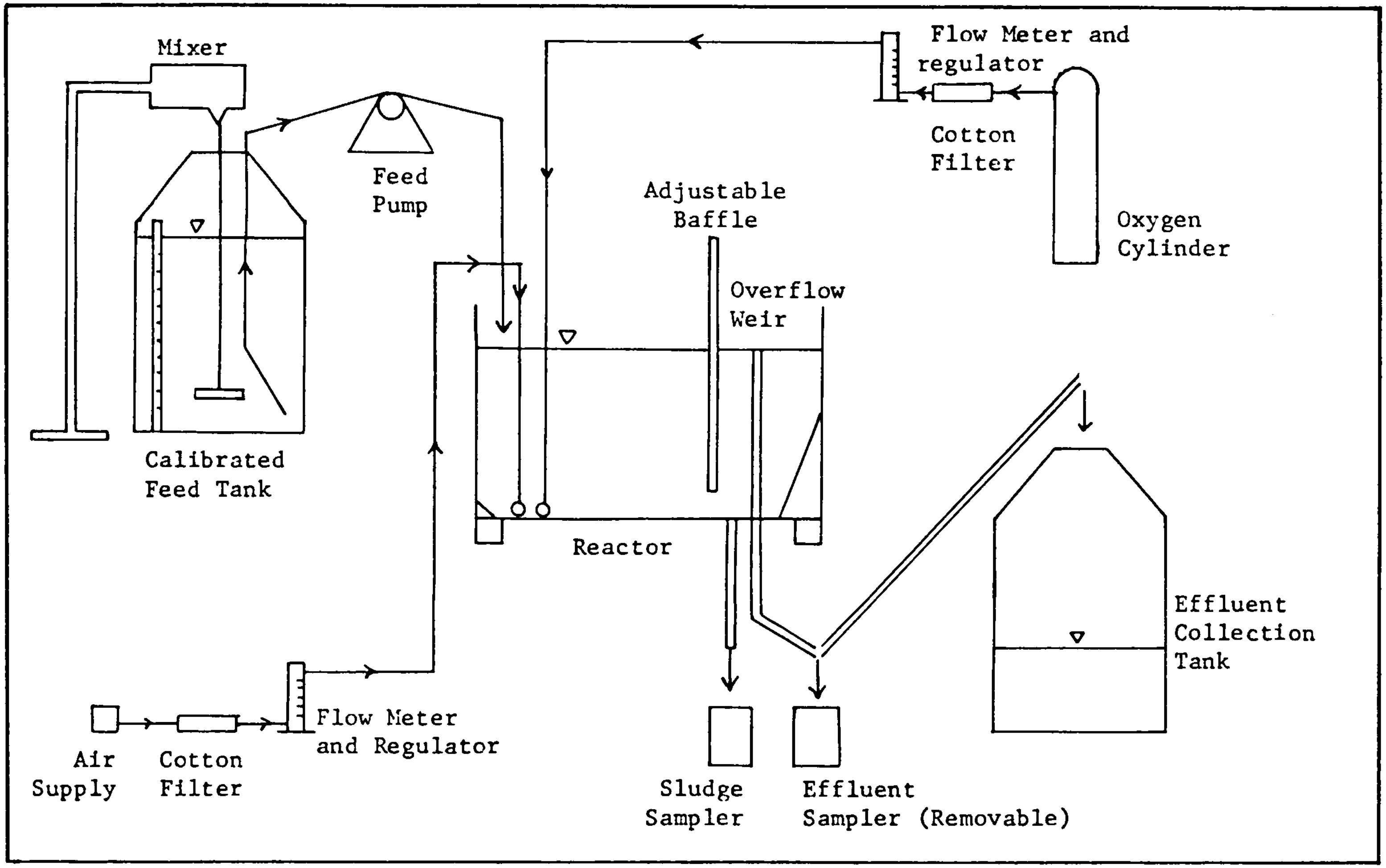

Figure 3. Schematic of Experimental System

flow rates whenever fluctuations occurred. The air flow rate required to maintain a constant DO of 2 mg/l did not always create enough turbulence to keep the biological solids in suspension. Therefore a variable speed mixer was used to provide additional mixing intensity whenever it was required.

The settling basin had a capacity of 2.4 liters. Two holes in the bottom of the settling basin contained rubber hoses. A glass tube was inserted through one hose and acted as an overflow weir. Effluent flowed through the tube and hose into a 5 gallon polyethylene carboy. The other hose was used to sample the mixed liquor and to waste excess sludge.

A glass container holding 18 liters served as a feed tank. Continuous mixing was required because some of the synthetic substrate ingredients were insoluble. This was accomplished with a Waco Supreme mixer using a 1/2 x 2 inch flat blade. Pumps were used to convey the substrate from the feed bottle into the reactor. A Sigmamotor Model TM-35 peristaltic pump was used for one treatment unit while a Sigmamotor Model T-8 peristaltic pump was used for the other treatment unit. The desired flow rate was initially set and periodically checked by collecting substrate in a 25 ml graduated cylinder for 1 minute.

Methods of Sampling and Analysis

The following tests were used throughout the investigation:

1. Dissolved Oxygen Concentration (DO)
2. Total Suspended Solids (TSS)
3. Total Volatile Suspended Solids (TVSS)
4. Oxygen Uptake

5. Biochemical Oxygen Demand (BOD)
6. Sludge Volume Index (SVI)
7. Initial Settling Velocity (ISV)

Oxygen Uptake, TSS, TVSS, SVI, and ISV tests were performed on mixed liquor samples. Solids in the settling basin were included in these samples because they played an active role in the bio-oxidation process. Therefore the baffle was removed and the reactor contents were completely mixed before samples were taken from the reactor.

The DO in each reactor was usually checked at least 4 times each day with a Yellow Springs Instrument Company Model 51 Oxygen Probe. A submersible probe was placed in the mixed liquor to obtain the DO readings. At the DO levels of 2 and 4 mg/l the reactor contents were completely mixed before the DO was measured. At the higher DO levels of 8 and 10 mg/l the difference between the DO in the aeration basin and the DO in the settling basin was negligible. Therefore it was much more convenient to just measure the aeration tank DO at the higher DO levels.

All solids determinations were made according to <u>Standard Methods</u> (15). A special wide mouth pipet was used to withdraw 10 ml samples from the mixed liquor. Effluent samples ranging from 20 to 100 ml were taken from full effluent collection tanks after thoroughly mixing the effluent inside the containers. Duplicate samples were filtered through Gooch Crucibles holding Size 2.1 cm, Grades 934AH glass fiber filters manufactured by Reeve Angel.

Oxygen uptake was measured by aerating a mixed liquor sample in a beaker until the DO was at least 5.0 mg/l. The sample was then poured into a standard BOD bottle and an oxygen probe with an attached mixer was placed inside the bottle. The DO in the bottle was recorded every 30 seconds until a DO of 1.5 mg/l was reached. The oxygen uptake rate was obtained by determining the average decrease in DO per day and dividing by the MLVSS. Oxygen uptake tests were run just prior to the solids determinations so that the MLVSS was the same in both tests.

Five day BOD tests were run on influent and effluent samples according to Standard Methods (15). Influent substrate samples were seeded with 1 ml of effluent per liter of dilution water. Effluent samples were filtered through 2.1 cm, Grade 934AH glass fiber filters to remove any biological solids in the effluent. Dilutions ranging from 0.5 to 1.5% for influent samples and 15 to 30% for effluent samples were made in a 1 liter graduated cylinder. At least 2 BOD bottles were used for each sample. A Y.S.I. Co. oxygen probe was used to measure the DO in the bottles. The five day BOD was obtained by subtracting the blank drawdown from the drawdown in the sample bottle and dividing by the per cent dilution in the sample bottle.

SVI tests were performed as outlined in Standard Methods (15). In addition, the height of the sludge liquid interface in the 1 liter graduated cylinder was recorded every minute for the first 10 minutes and every 3 minutes for the next 20 minutes. A plot of interface height versus time was used to determine the ISV as illustrated in Figure 4.

Additional tests were run periodically to make sure environmental conditions were almost the same throughout the research. The pH of mixed liquor samples was checked with a Fischer Model 120 pH meter.

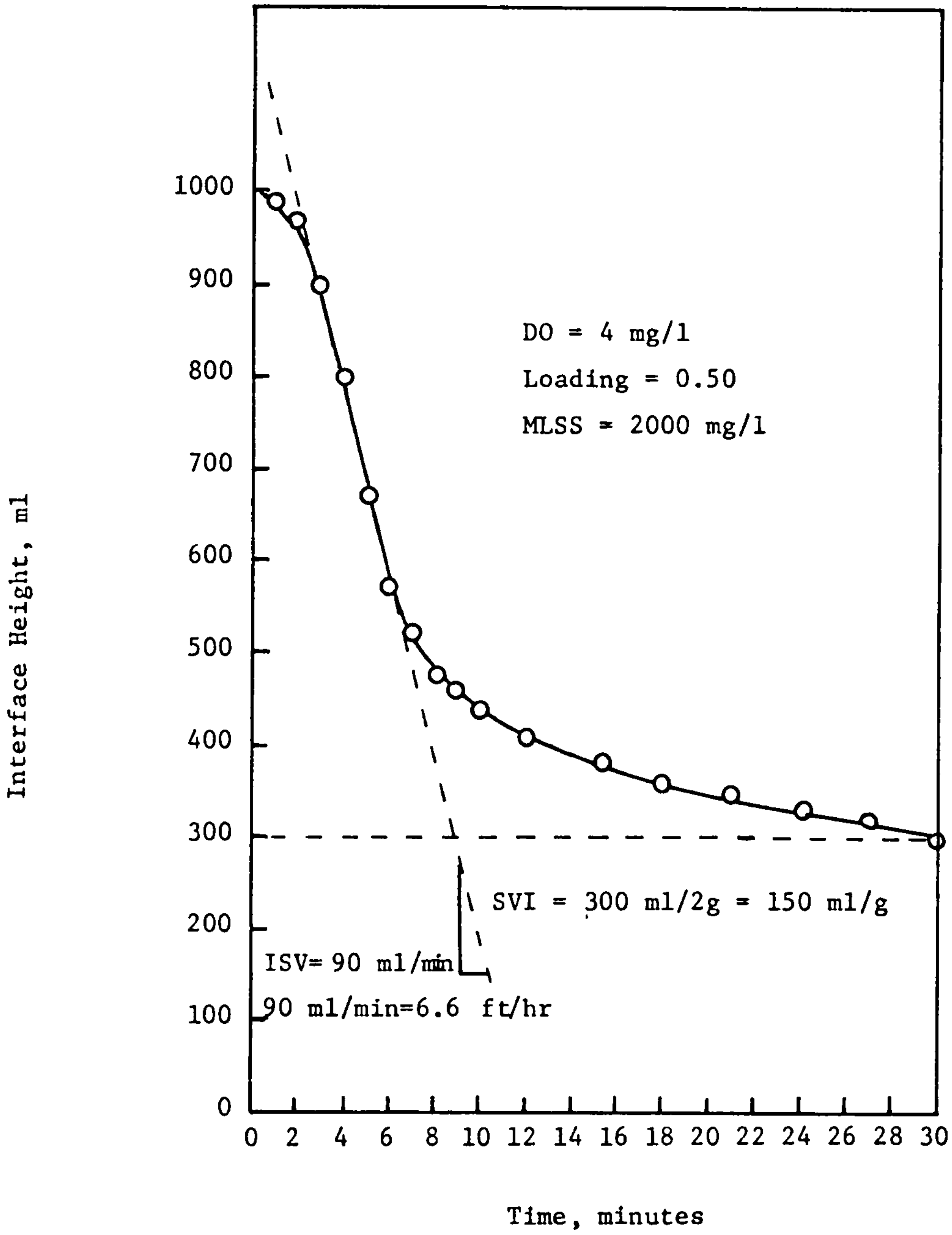

Figure 4. Typical Setting Curve.

The desired pH range was from 7.0 to 7.5. It was also necessary to monitor temperature variations. During the study the temperature was observed to vary from a low of 19°C to a high of 27°C. The desired mixing intensity range was from 100 to 250 sec^{-1}, which is a normal operating range for conventional activated sludge reactors. The mixing intensity was controlled by checking the air and oxygen flow rates and the rpm of the variable speed mixer. The following equations were used to calculate the mixing intensity in each reactor.

Mechanical Mixing:

$$G = (P/C\mu)^{1/2}$$

where:

G = mixing intensity, sec^{-1}

P = useful power imput, ft-lbs/sec

C = fluid volume, ft^3

μ = viscosity lb-sec/ft^2

Once the dimensions and rpm of the paddle blade are known, the useful power imput can be calculated from a series of equations presented by Fair *et al*. (34).

Bubble Mixing:

$$G = (Q'hg/K)$$

where:

Q' = gas flow per unit volume of fluid, $ft^3/sec\text{-}ft^3$

h = diffuser depth

g = 32.2 ft/sec^2

K = kinematic viscosity, ft^2/sec

Experimental Plan

Both units were seeded with activated sludge obtained from the Roanoke Water Pollution Control Plant. Substrate was continually fed to the sludge for more than one month before full scale testing was begun. During this period the sludge became acclimated to the synthetic substrate. The research was conducted in two different phases. During the first phase DO levels of 2 and 4 mg/l were investigated at three different loading levels. During the second phase the DO levels were changed to 8 mg/l and 10 mg/l and the loading sequence was repeated.

Three different loading levels were applied by varying either the flow rate or the substrate composition. The composition of the synthetic substrate is given in Table I. The average five day BOD was determined from the results of several tests on different substrate samples. Although the BOD values obtained varied considerably, these variations were attributed to errors in the tests and not to differences in BOD. Therefore the average BOD values given in Table I were used in determining the loadings and substrate removal rates. The loading levels used in the study and the corresponding flow rates are listed in Table II.

Total volatile suspended solids tests and oxygen uptake tests were run on mixed liquor samples every day. The amount of sludge which had to be wasted each day to maintain a MLVSS of 2000 mg/l was determined from the TVSS test. Steady state conditions were assumed whenever the oxygen uptake rates began to even out. However, the reactors were run at each loading for at least three days before steady state testing was begun. The oxygen uptake test and TVSS were run at the

TABLE I

COMPOSITION OF SUBSTRATE

Component	Concentration mg/l
Nutrient Broth	400
Urea	60
Potato Starch	200
KCl	7
$CaCl_2$	7
$MgSO_4 \cdot 7H_2O$	5
$Al_2SO_4 \cdot 18H_2O$	25
$FeSO_4 \cdot 7H_2O$	10
$MnSO_4 \cdot H_2O$	10
NaCl	30
Na_2HCO_3	168
KH_2PO_4	58

Note--To achieve a loading of 0.75 the substrate was concentrated. The formula for the concentrated substrate is the same but all the component concentrations are multiplied by a factor of 1.5.

BOD_5 = 240 mg/l concentrated substrate BOD_5 = 360 mg/l

COD = 400 mg/l concentrated substrate COD = 600 mg/l

TABLE II

LOADINGS

Loading	Flow Rate	Flow Rate	Substrate	Detention Time
0.25	12.5 ml/min	18 l/day	normal	12.4 hours
0.50	25.0 ml/min	36 l/day	normal	6.2 hours
0.75	25.0 ml/min	36 l/day	concentrated	6.2 hours

same time each day. Sludge wasting also occurred at the same time each day.

Once a steady state was achieved additional tests were conducted including effluent BOD, effluent TVSS, SVI, ISV, and mixed liquor TSS. The steady state testing period lasted from 2 to 5 days. Usually tests were run daily but at the higher DO levels tests were run every 12 hours to conserve pure oxygen. In addition, sludge samples were examined under an Olympus Phase Contrast microscope at each loading.

Difficulties Encountered

Floating sludge was a problem which plagued both phases of the research. Gas bubbles appeared when the floating sludge clumps were broken up suggesting denitrification was the cause. Denitrification is the biological process through which nitrates are anaerobically converted to nitrogen gas. The nitrogen gas lifted the sludge clumps to the water surface. The anaerobic conditions required for denitrification were created whenever a sludge layer formed at the bottom of the settling basin. This explains why floating sludge was observed at all of the DO levels investigated.

Throughout most of the research the DO was maintained within 1 mg/l of the desired DO level. The only major DO fluctuations occurred when pure oxygen was used at the DO levels of 8 and 10 mg/l. The oxygen flow rate varied and this caused DO fluctuations when the reactors were left unattended. However, the DO levels were always well above 4 mg/l during the steady state testing period when oxygen was used.

Mechanical difficulties were often encountered, particularly during the early stages of the research. On several occasions the feed pump broke down overnight. Data were not recorded whenever this happened.

At the 0.50 and 0.75 loadings the mixed liquor pH dropped below 7. Additional phosphate buffer had to be added to the substrate to keep the pH above 7 at these loadings.

CHAPTER IV

EXPERIMENTAL RESULTS

The results of this investigation are presented in this chapter. Average steady state values of oxygen uptake rate, effluent BOD, substrate removal rate, and excess sludge production were calculated from the data listed in Appendix A. These values were used to graphically determine the kinetic coefficients through a least mean squares analysis. The kinetic coefficients obtained are tabulated in Table III and the graphs from which they were determined are shown in Figures 5 through 16. Settleability data and microscopic observations are also included in this chapter. The results are grouped in the following order: substrate removal rate coefficients, yield coefficients, oxygen uptake coefficients, settleability data, and microscopic observations.

Substrate Removal Rate Coefficients

Substrate removal rate coefficients were determined for each DO level from the graphs shown in Figures 5 through 8. Although the data points were scattered, there was a remarkable similarity in the k values obtained for each DO. No relationship between the substrate removal rate coefficients and the operating DO levels was observed. The DO of 10 mg/l had the highest k but the DO of 8 mg/l had the lowest k.

TABLE III

KINETIC COEFFICIENTS

DO Level (mg/l)	Substrate Removal Rate (day^{-1})	True Yield	Auto-oxidation (day^{-1})	Energy Oxygen	Endogenous Oxygen (day^{-1})
2	0.053	0.87	0.10	1.16	0.39
4	0.051	1.21	0.20	1.35	0.15
8	0.050	0.83	0.02	1.04	0.36
10	0.058	1.07	0.14	1.68	0.07

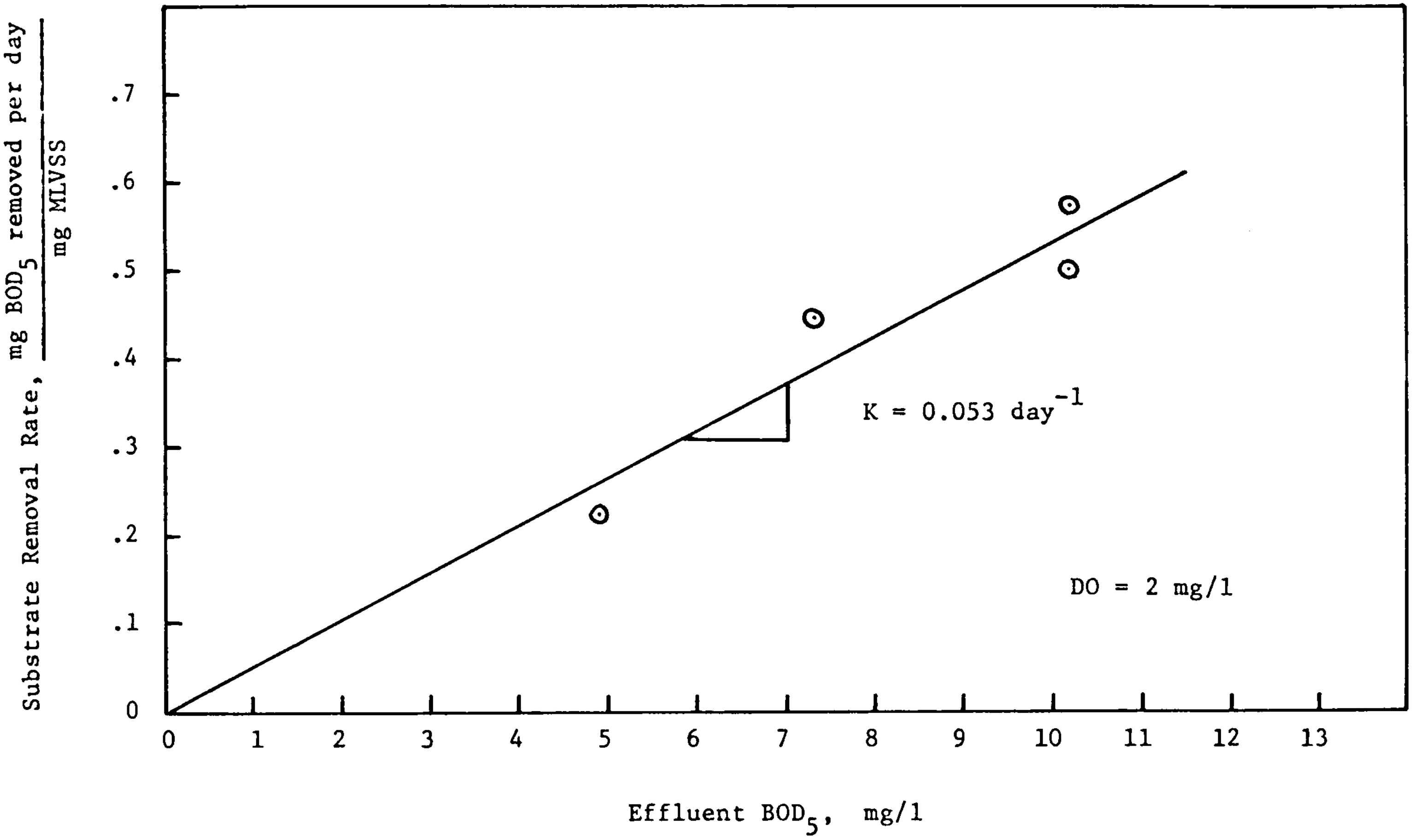

Figure 5. Substrate Removal Rate Coefficient: DO = 2 mg/l

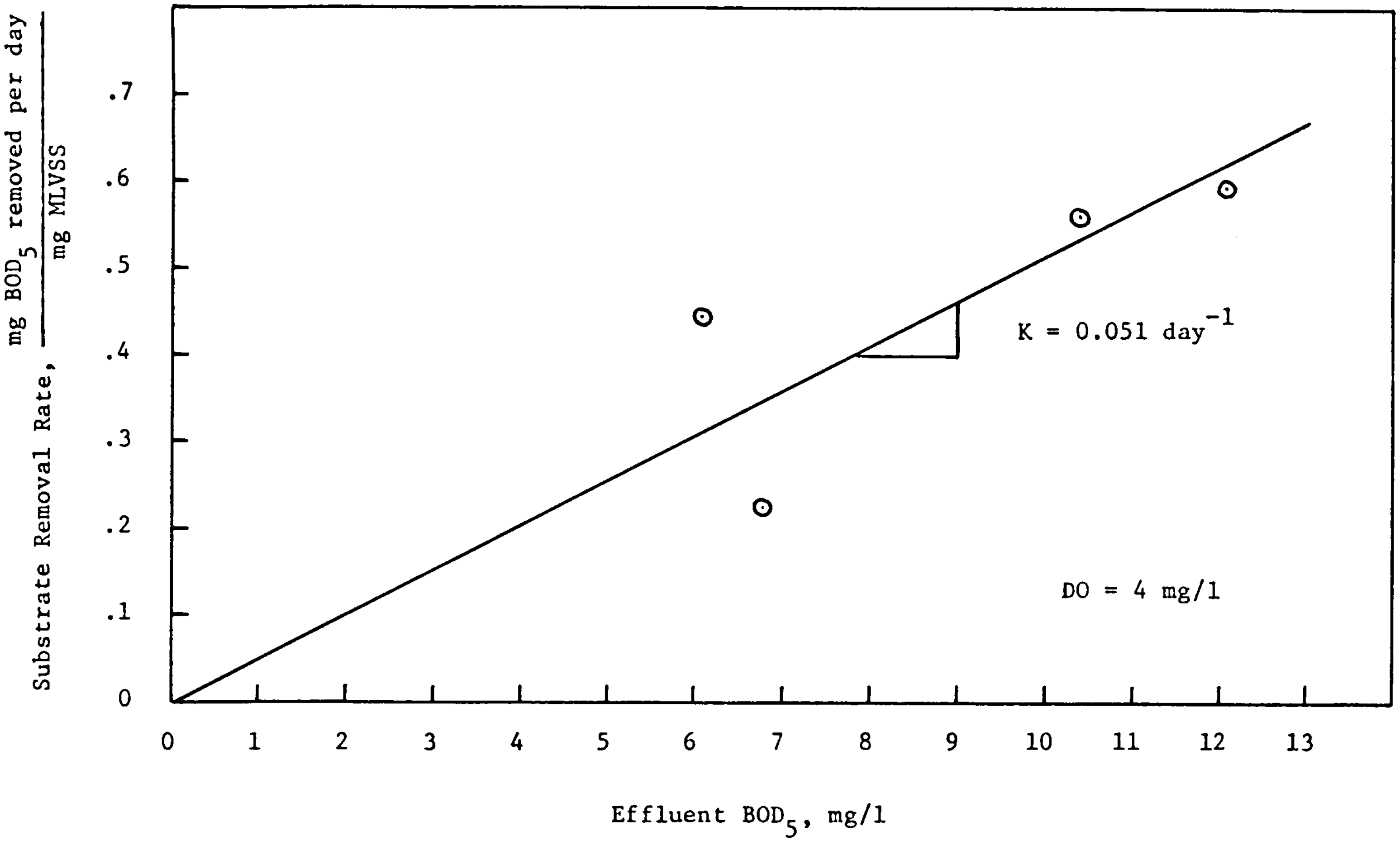

Figure 6. Substrate Removal Rate Coefficient: DO = 4 mg/l

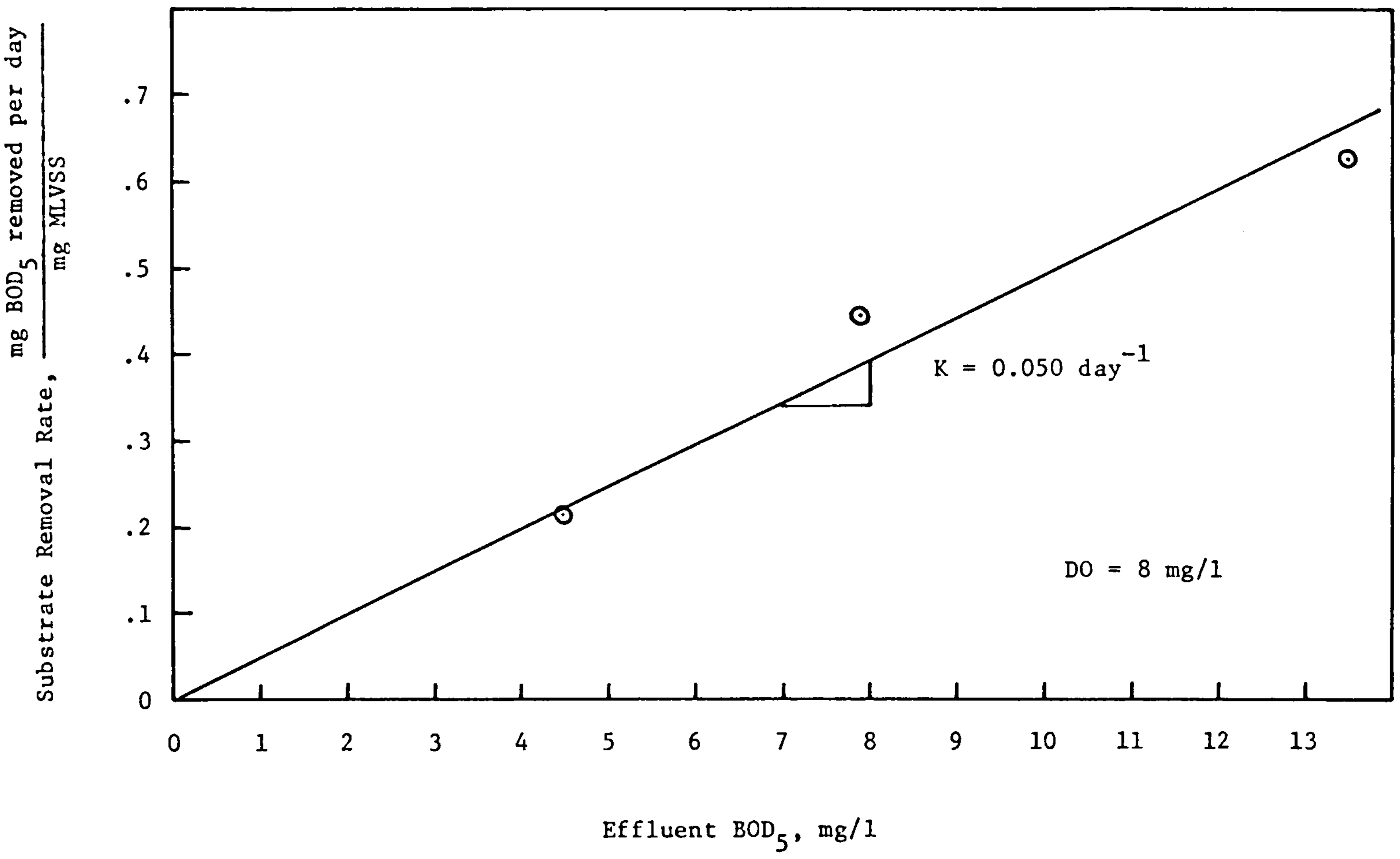

Figure 7. Substrate Removal Rate Coefficient: DO = 8 mg/1

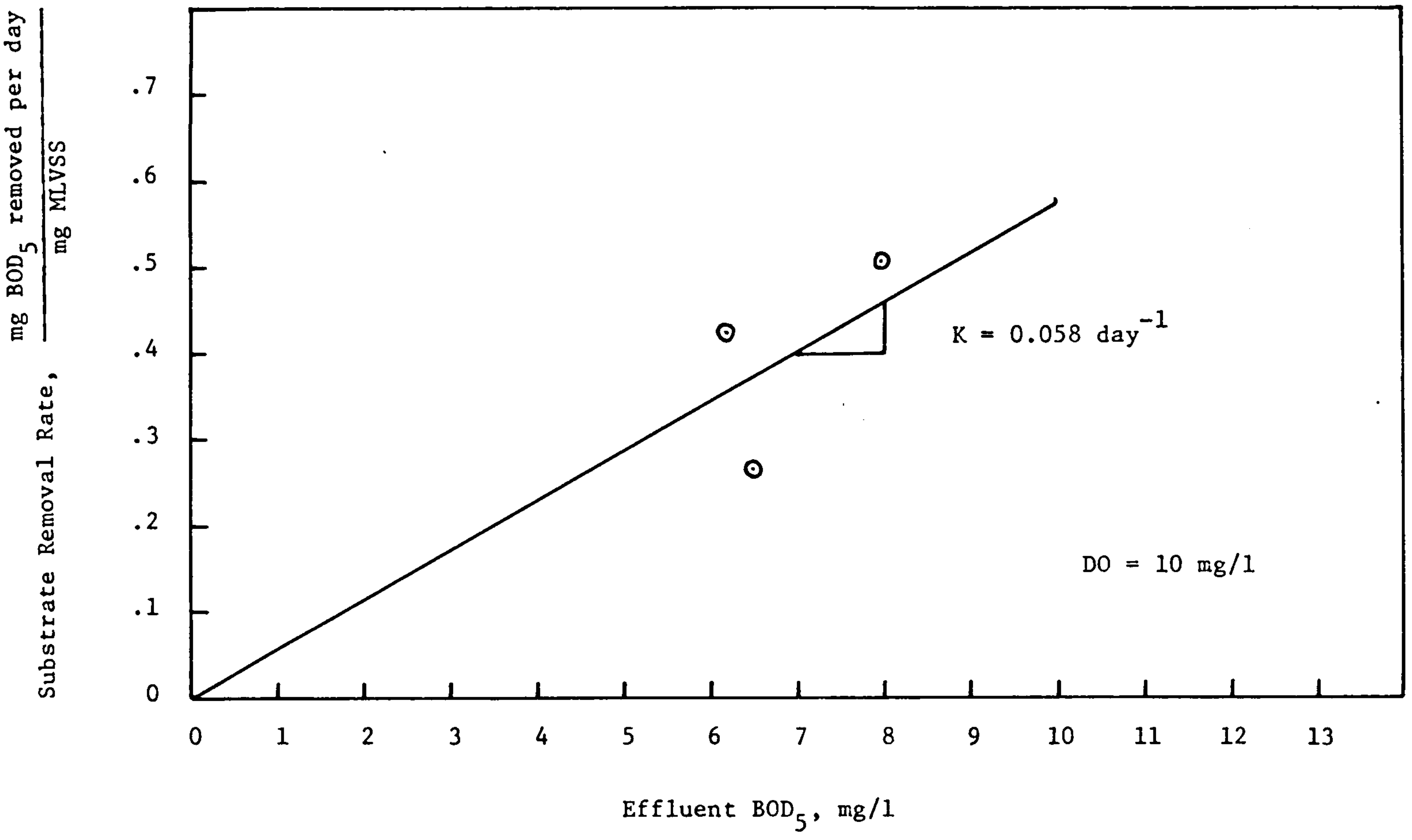

Figure 8. Substrate Removal Rate Coefficient: DO = 10 mg/1

An additional loading was investigated at the DO levels of 2 and 4 mg/l because filamentous organisms were dominant in the 4 mg/l reactor at the 0.75 loading. Several investigators have claimed filamentous organisms exhibit superior treatment characteristics compared to zoogloeal organisms because of their greater surface area per unit volume (35). However, they are undesirable in conventional activated sludge systems because of their poor settling properties. Therefore, after steady state data were collected for the 0.75 loading the reactors were aerated without substrate until the filamentous organisms were destroyed. Then the 0.75 loading was repeated. However, no major differences were observed between the two sets of data for the same loading. Therefore, both sets of data were plotted on all of the kinetic coefficient graphs for the DO levels of 2 and 4 mg/l.

Throughout the investigation high blank drawdowns plagued the BOD tests. Whenever these excessive drawdowns appeared to interfere with the test results the results were not used in any calculations. Fortunately, at least one BOD test was successful at every loading.

Yield Coefficients

The true yield coefficients and auto-oxidation coefficients obtained from Figures 9 through 12 varied considerably, but none of these variations could be attributed to differences in DO. There was no indication that endogenous activity was increased at the higher DO levels. The DO of 8 mg/l had a very small auto-oxidation constant equal to 0.02 whereas the DO of 4 mg/l had an auto-oxidation constant equal to 0.20.

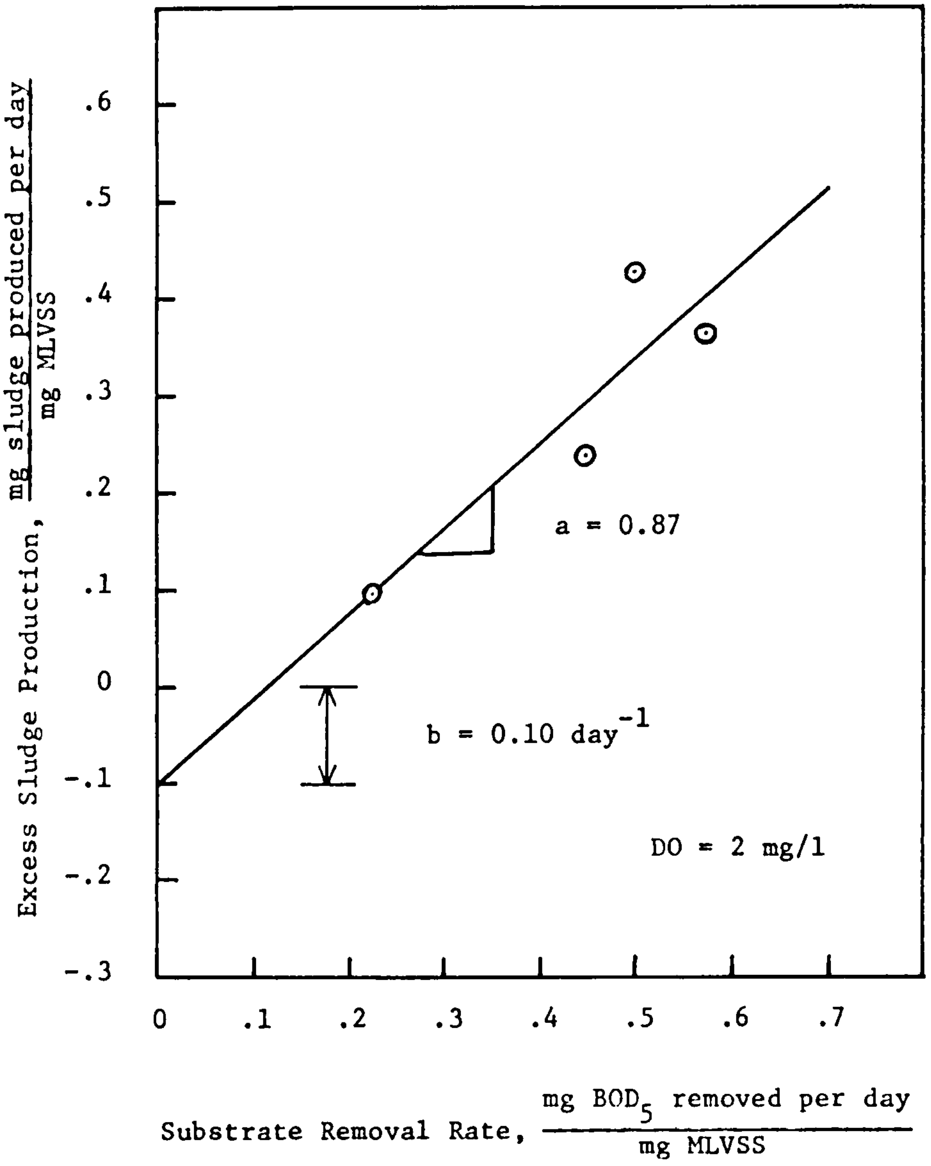

Figure 9. Yield Coefficients: DO = 2 mg/l

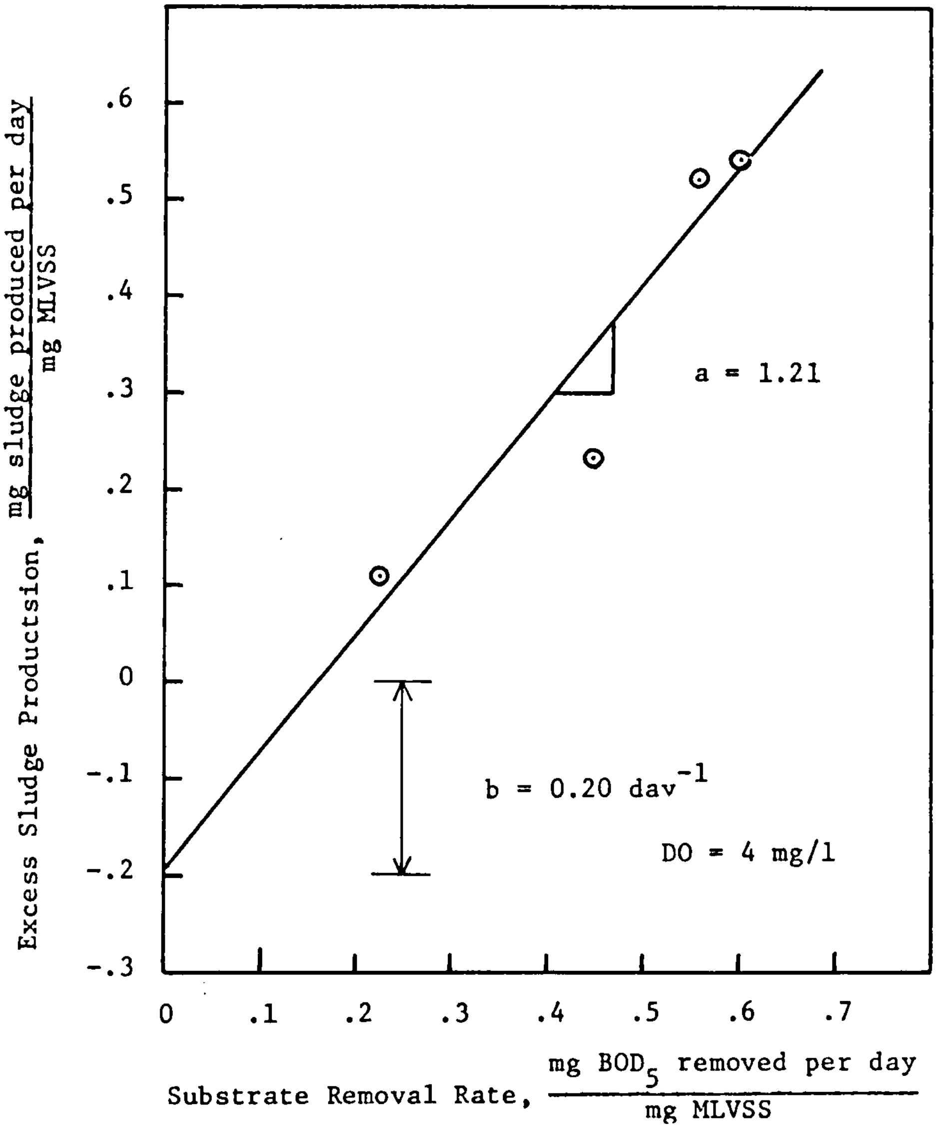

Figure 10. Yield Coefficients: DO = 4 mg/l

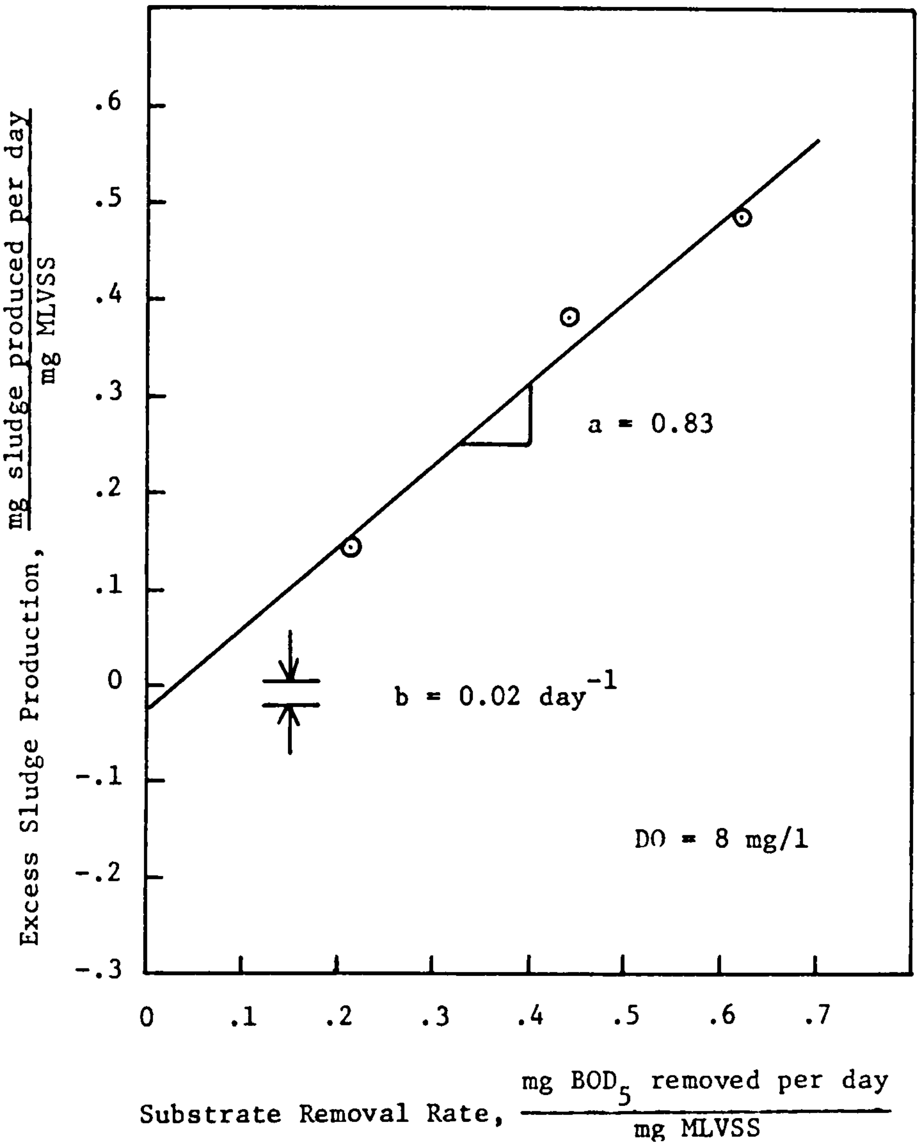

Figure 11. Yield Coefficients: DO = 8 mg/l

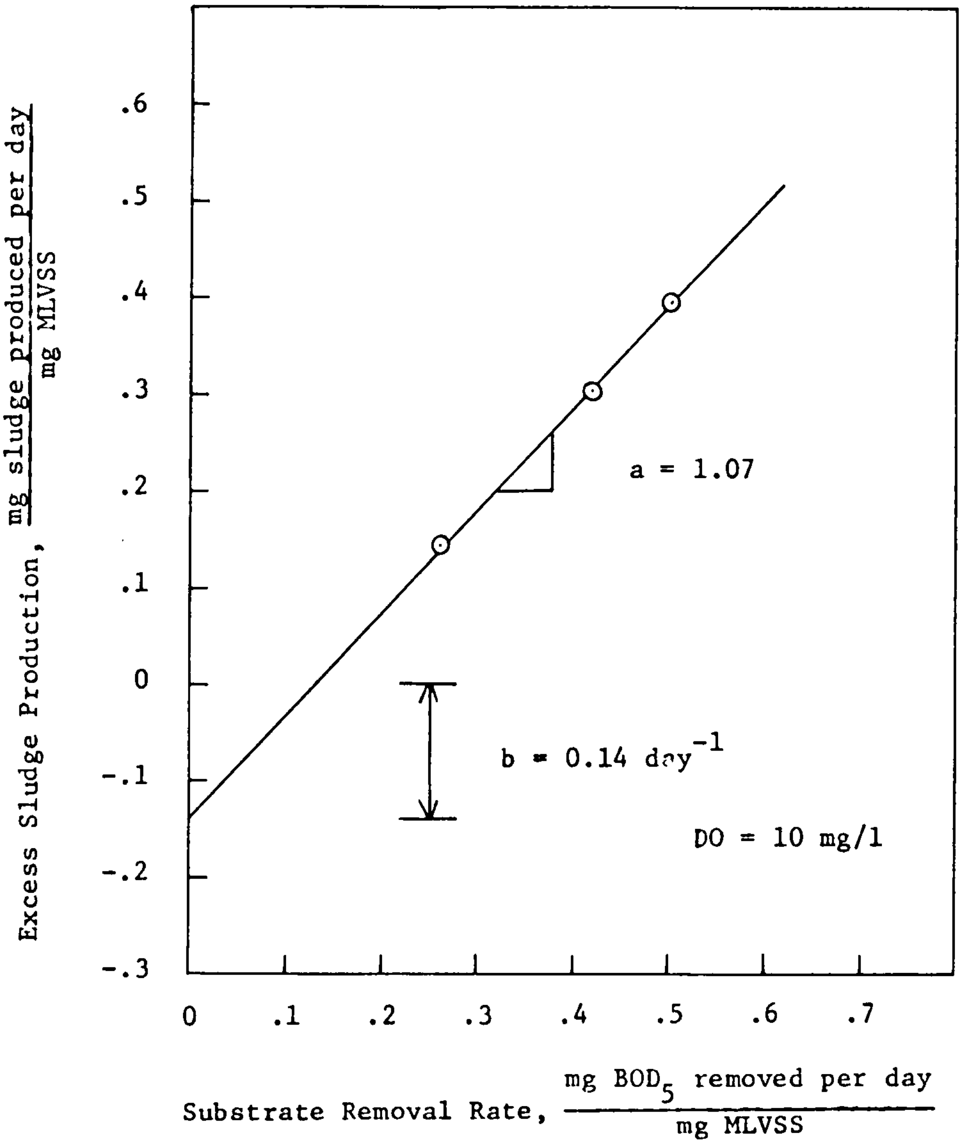

Figure 12. Yield Coefficients: DO = 10 mg/l

Large variations in the day to day sludge production were observed as can be seen from the data listed in Appendix A. By strict definition, steady state conditions imply that a constant solids production rate exists (36). However, the oxygen uptake rate was used to determine whether or not steady state conditions existed because the solids production rate was never constant for any of the loadings. It is possible, but not likely, that steady state conditions were never achieved during the one to two week time period in which loadings were applied. The variations might also have resulted from temperature fluctuations or inaccuracies in the solids determinations. It has been reported that observed yields tend to increase with decreasing temperature (11). Mixed liquor temperatures fluctuated as much as 6°C during the steady state testing period. The TVSS test doesn't differentiate between active and inactive cells. If the ratio of active cells to inactive cells varied from day to day the amount of sludge production measured by the TVSS test would also vary. Furthermore, the duplicate mixed liquor samples often exhibited different solids concentrations. The concentration used in the calculations had to be averaged from the two values obtained and this introduced another possible error in the sludge production analysis.

The true yield values obtained are very high compared to values often reported in the literature. This was probably because the substrate removal rates were measured in terms of BOD_5 instead of COD or ultimate BOD. The substrate BOD_5 was equal to 0.60 the COD. Therefore, if the substrate removal rate had been calculated in terms of COD the true yield values probably would have been smaller.

Oxygen Uptake Coefficients

The energy oxygen coefficients and the endogenous oxygen coefficients were evaluated from the graphs shown in Figures 13 through 16. No relationship between the DO and variations in the coefficients was discovered. More than three data points were plotted in the graphs for a DO of 2 mg/l and a DO of 4 mg/l. The extra points were added because the 0.75 loading was repeated and because a dramatic change in the oxygen uptake rate occurred at the 0.75 loading. The first time this loading was applied to both reactors, the oxygen uptake rate was initially greater than 1.00. However, after 3 days the oxygen uptake rate dropped sharply in each reactor, and remained at a level similar to the oxygen uptake rate observed with the 0.50 loading. When the 0.75 loading was repeated the same phenomenon occurred in the reactor with a DO of 2 mg/l but not in the reactor with a DO of 4 mg/l. The higher values of oxygen uptake were used in determining the oxygen uptake coefficients. The lower values were included in the graphs to illustrate the magnitude of the difference. This phenomenon was not observed at the higher DO levels of 8 and 10 mg/l.

Settleability

The results of the settling tests were plotted against the substrate removal rate in Figures 17 and 18 and against the sludge age in Figures 19 and 20. The substrate removal rate was approximately equal to the food to microorganism ratio because the effluent BOD's were usually very small. As expected, the settling properties deteriorated as the substrate removal rate increased or as the sludge age decreased. However, there wasn't any apparent relationship between sludge settle-

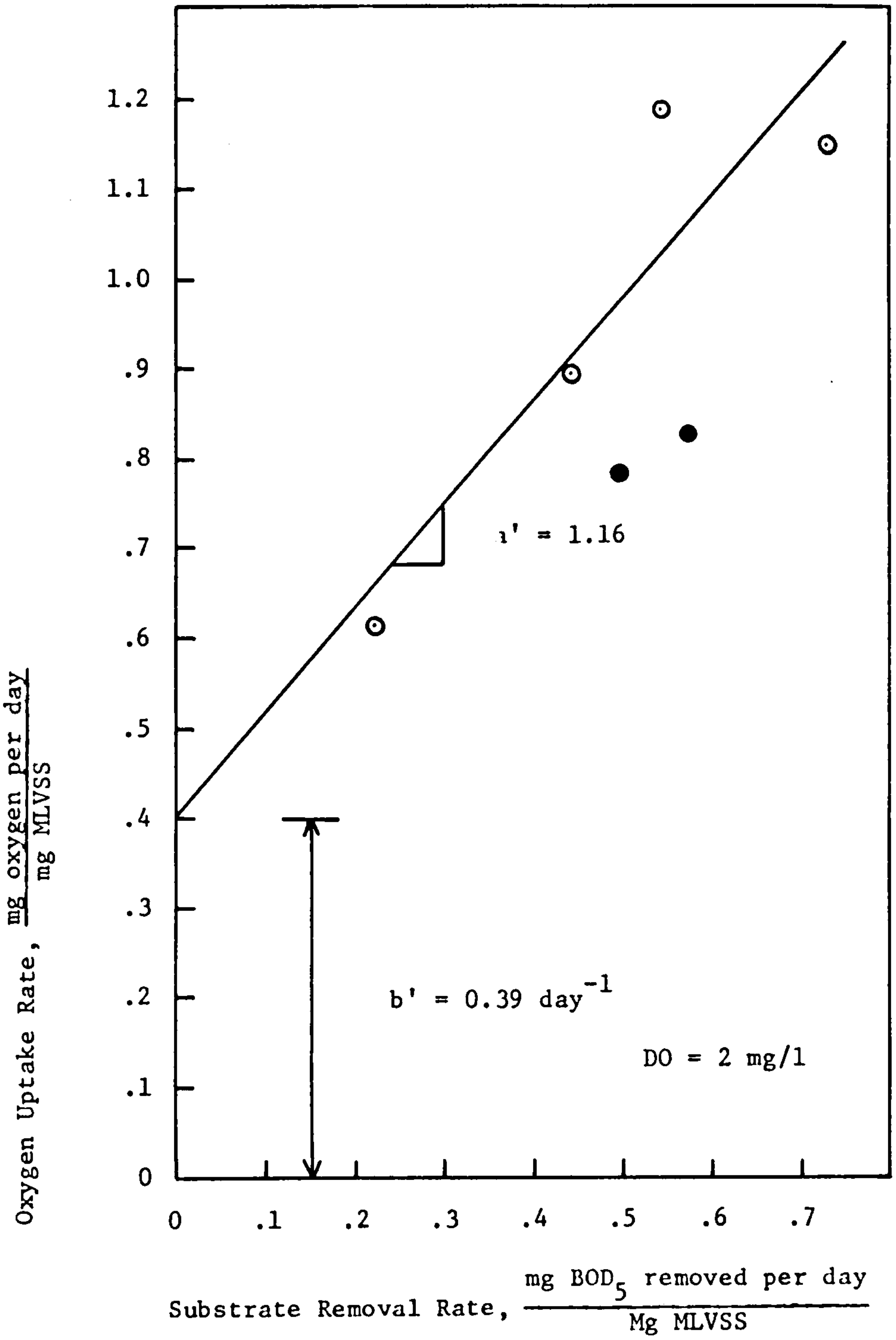

Figure 13. Oxygen Uptake Coefficients: DO = 2 mg/l

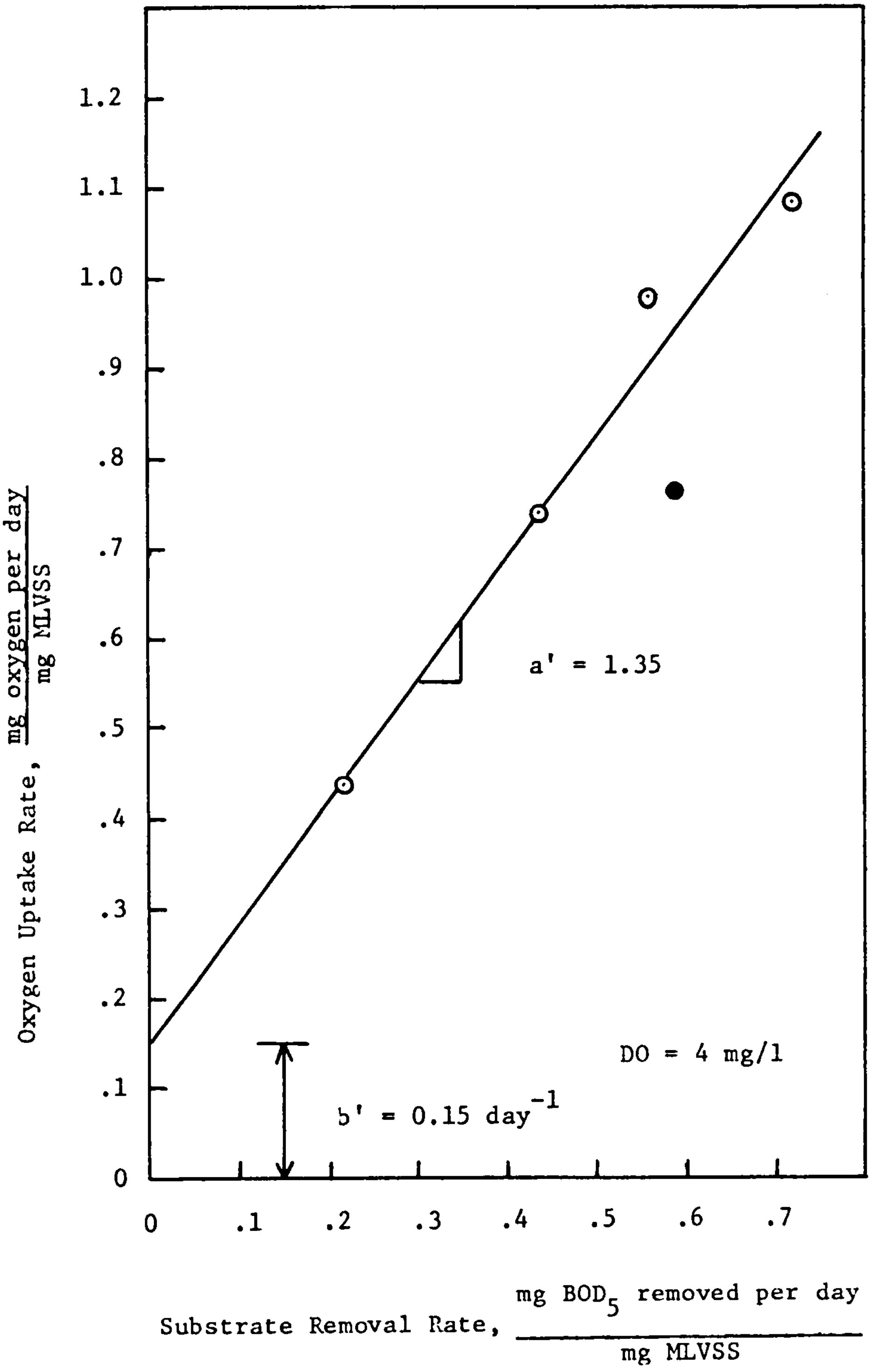

Figure 14. Oxygen Uptake Coefficients: DO = 4 mg/l

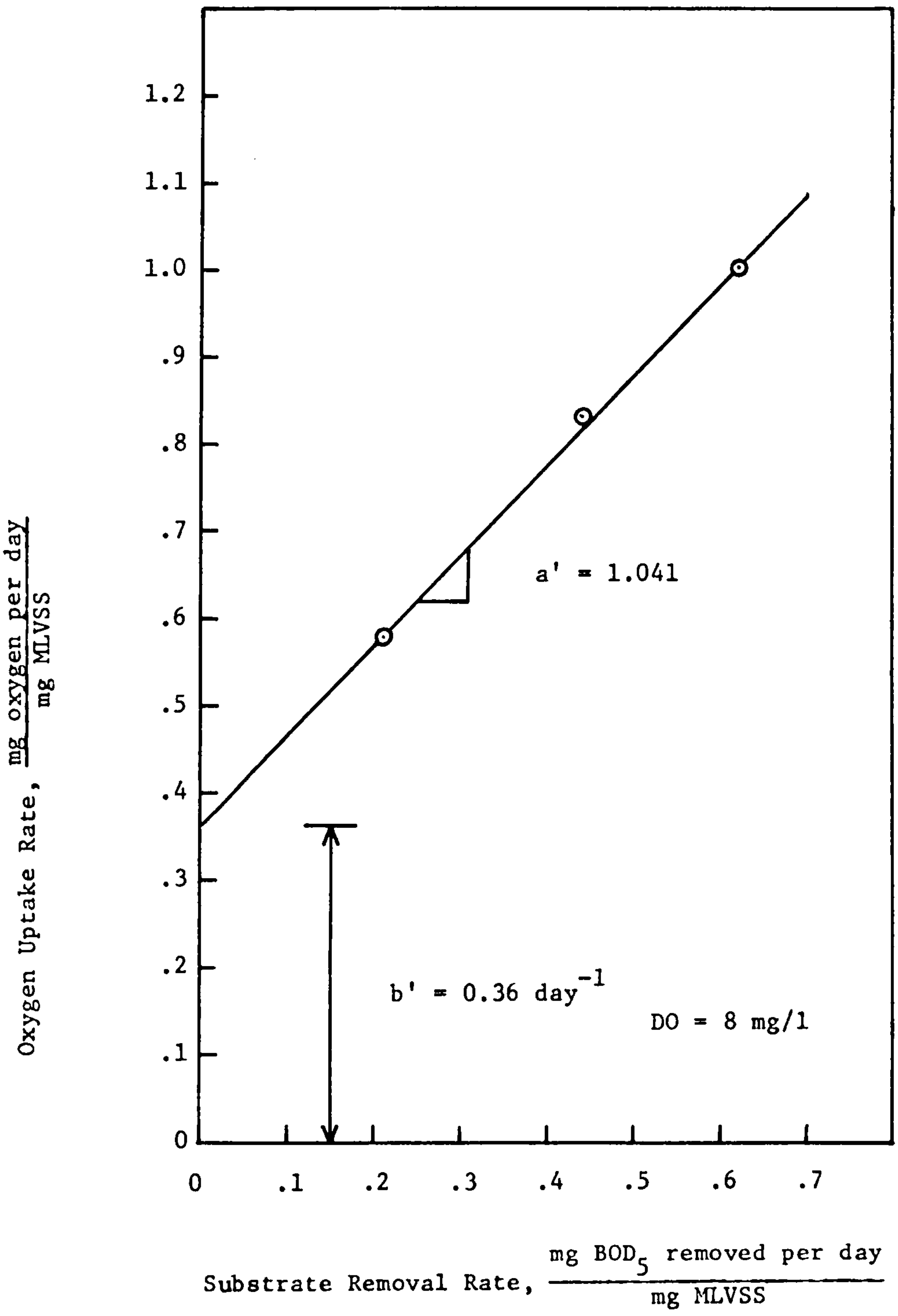

Figure 15. Oxygen Uptake Coefficients: DO = 8 mg/l

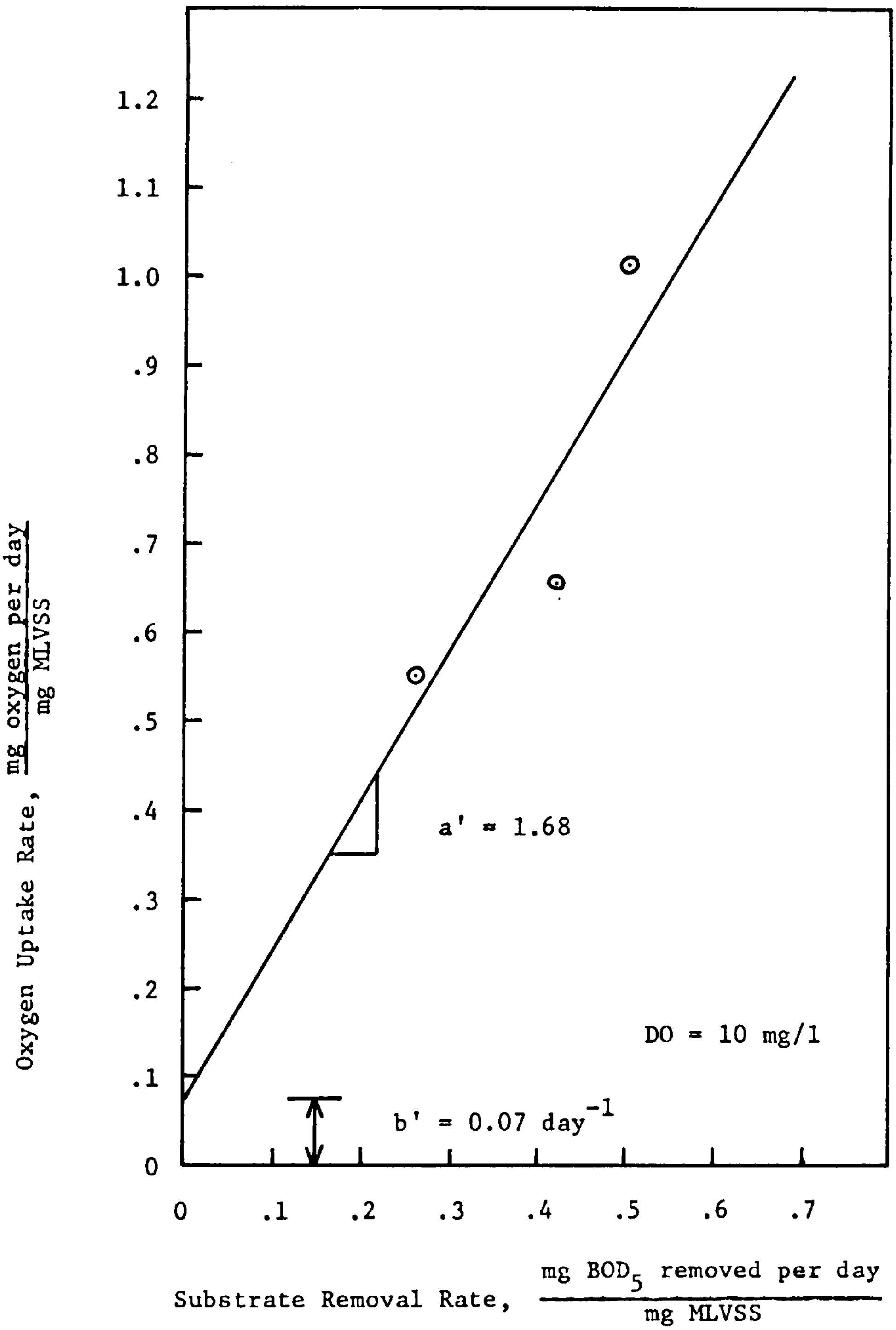

Figure 16. Oxygen Uptake Coefficients, DO = 10 mg/l

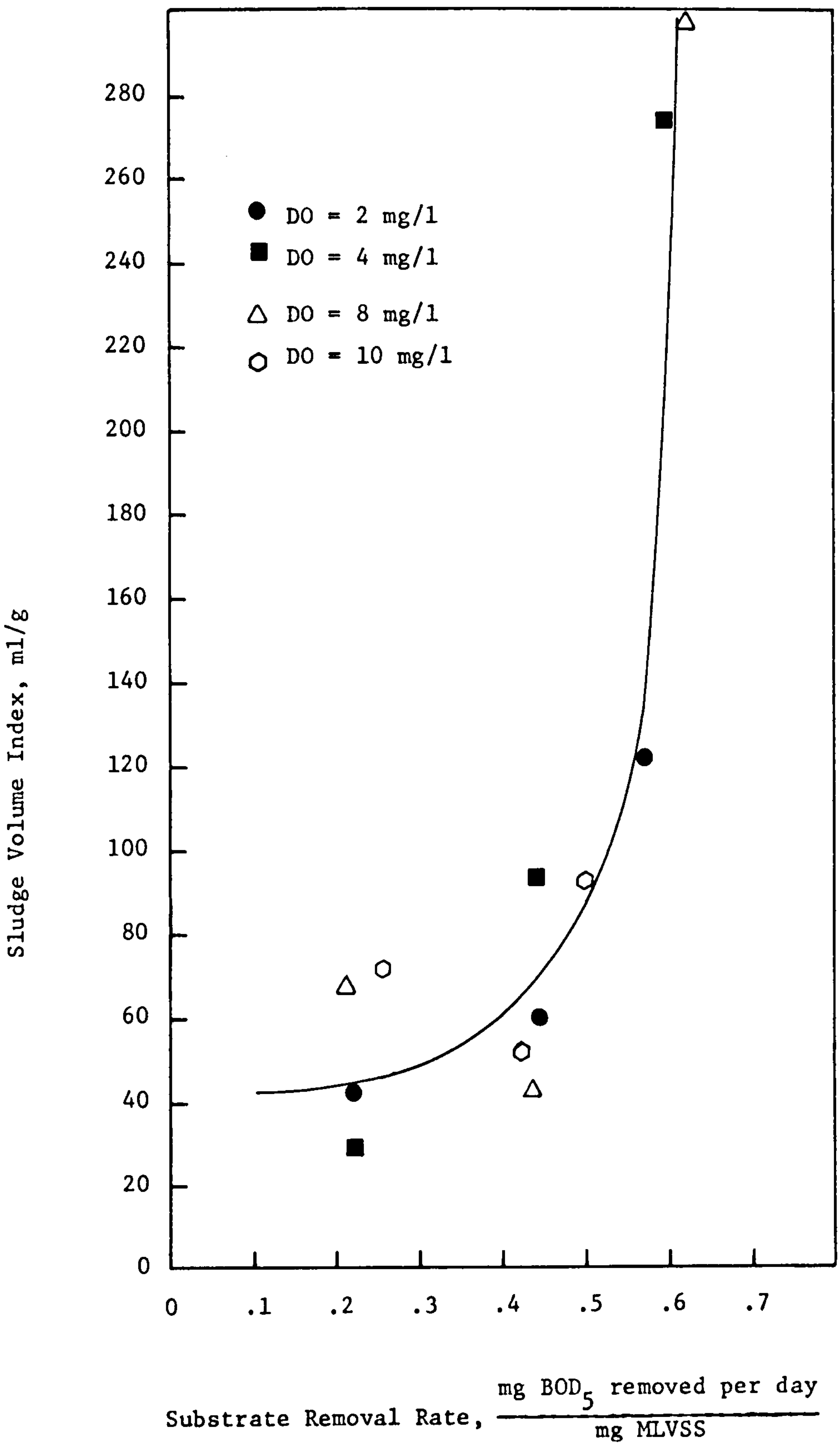

Figure 17. SVI versus Substrate Removal Rate

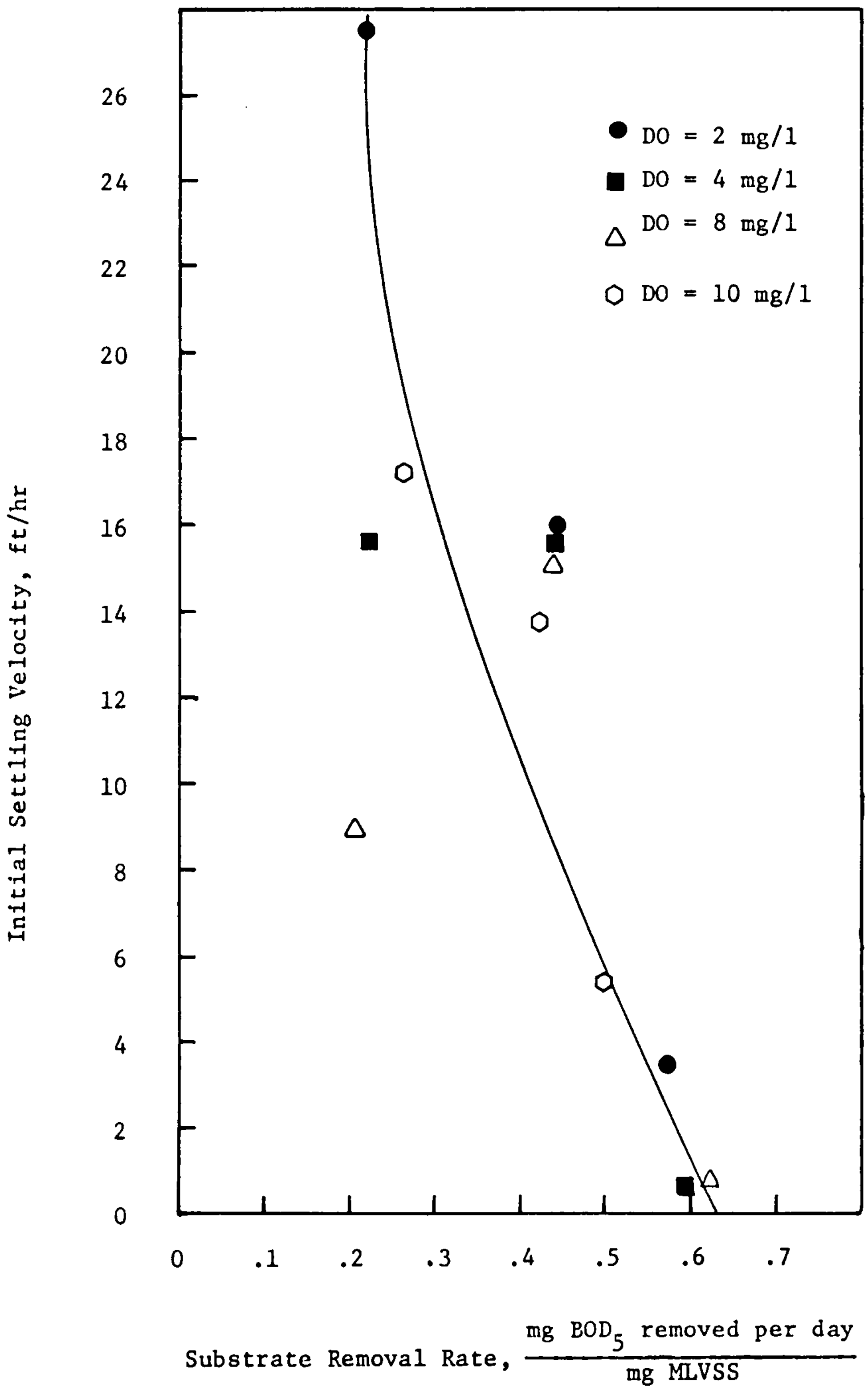

Figure 18. ISV versus Substrate Removal Rate

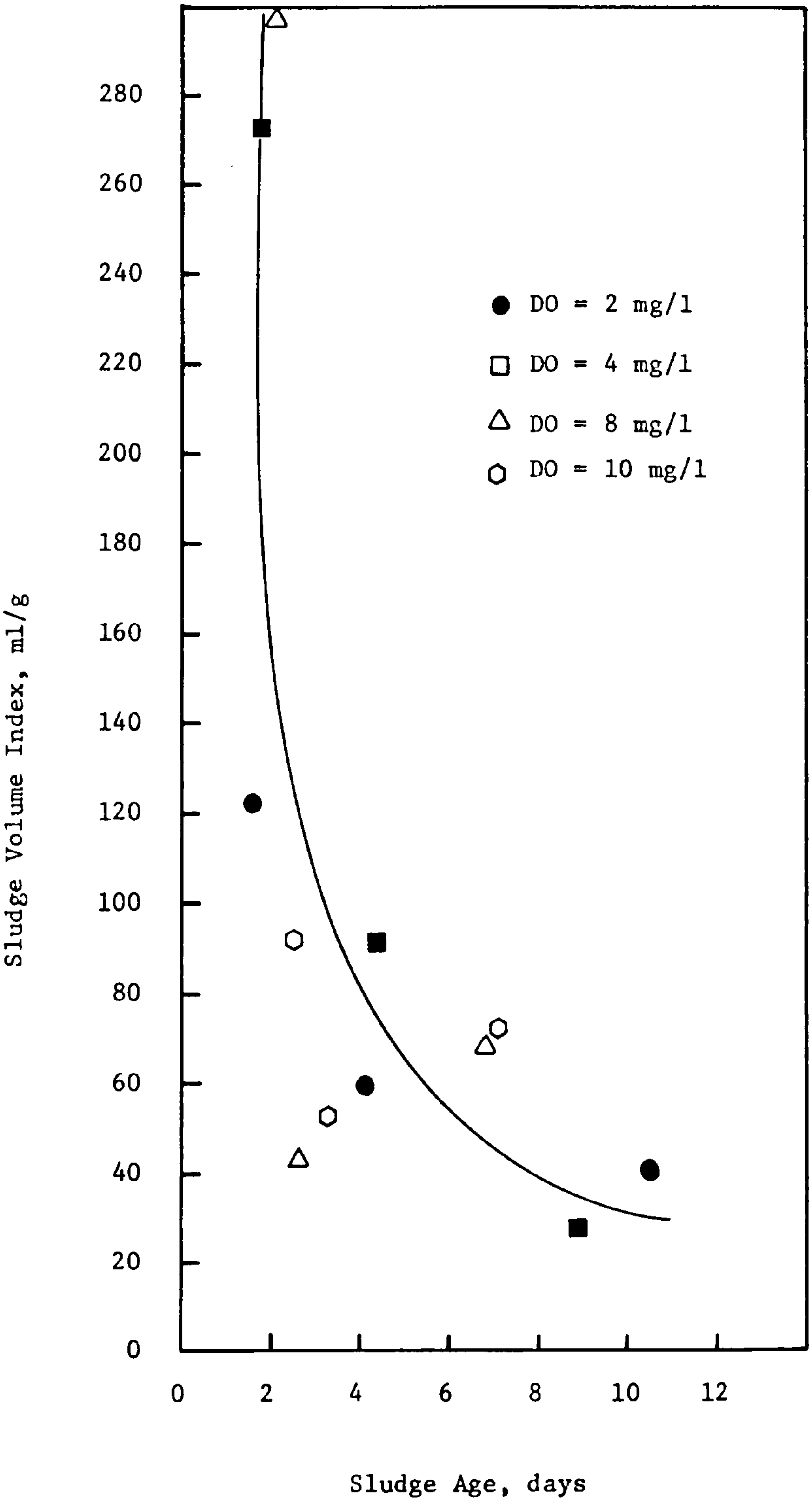

Figure 19. SVI versus Sludge Age

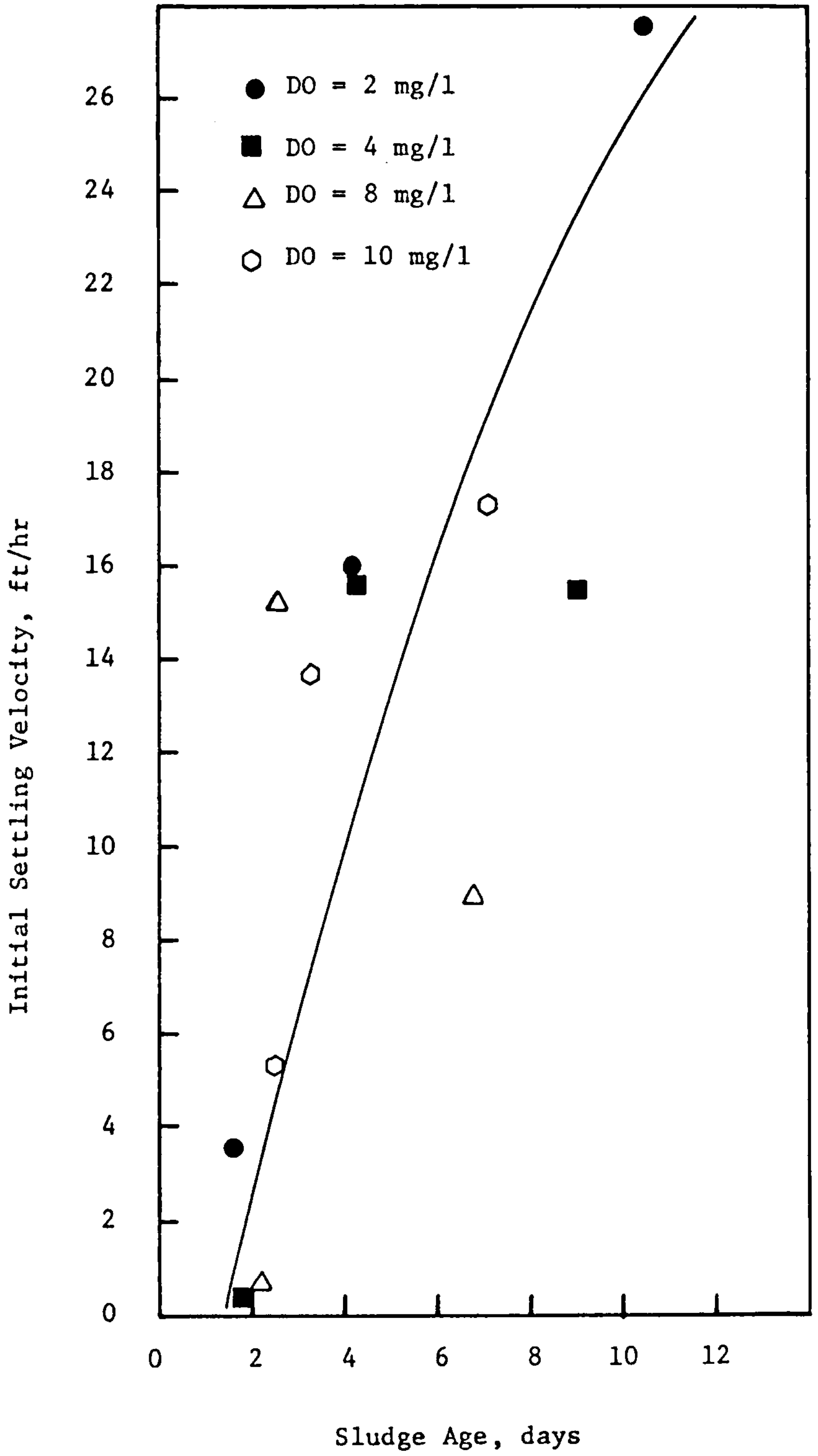

Figure 20. ISV versus Sludge Age

ability and DO.

Microscopic Investigations

Rotifers and ciliates were observed in sludge samples throughout the study. Filamentous organisms were never observed at the 0.25 loading. They were observed at the 0.50 loading in samples from the reactors run at DO levels of 2 and 4 mg/l. Filamentous organisms appeared in all of the sludge samples at the 0.75 loading and they dominated the populations in the 4 mg/l and 8 mg/l reactors at this loading. This explained the poor settling properties exhibited in these reactors at the 0.75 loading. In general, the DO level had no significant effect upon the microbial populations.

CHAPTER V

DISCUSSION OF RESULTS

There were no obvious indications that the variations in the kinetic coefficients and sludge settleability presented in the last chapter were caused by differences in DO. The purpose of this chapter is to further elaborate on these variations and their significance in relation to the biological principles presented in the literature review. The major topics discussed are whether or not the observed variations really existed, and if so could they be related to differences in DO.

Substrate Removal Rate Coefficients

Table III shows the substrate removal rate coefficients determined for the four DO levels investigated were almost identical. The data points obtained for each DO were plotted on one graph and a linear regression line was drawn for the combined data as shown in Figure 21. From this graph it can be seen that the data points intermingle. In other words, points representing each DO appear on either side of the linear regression line in a random manner. The maximum per cent difference between the k value obtained from a linear regression analysis of the combined data and the k values obtained for the individual DO levels was only 8.6%. For all practical purposes differences less than 10% are negligible. A close look at the data listed in Appendix A

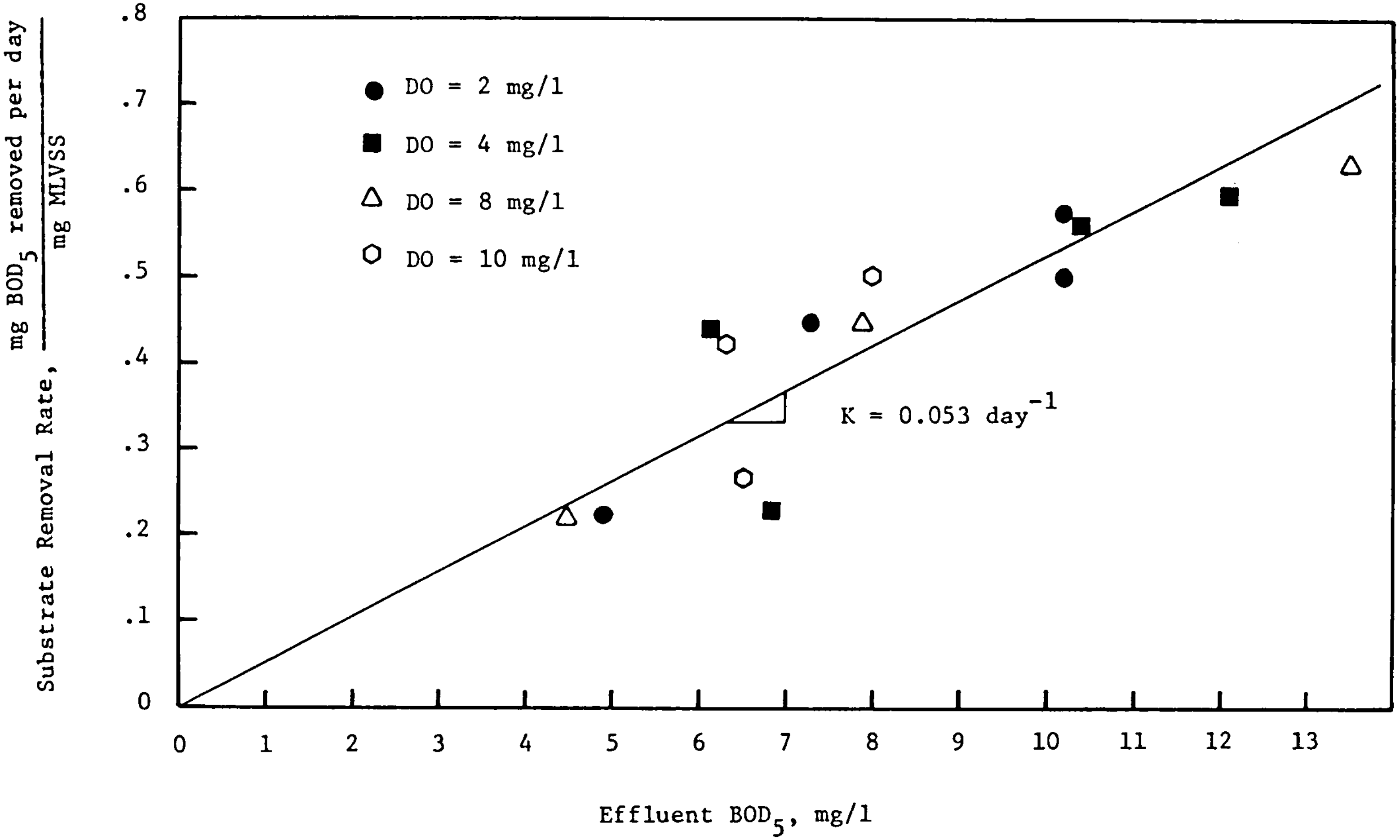

Figure 21. Substrate Removal Rate v Effluent BOD_5.

shows that large variations in the effluent BOD occurred at some of the loadings. The small differences in the substrate removal rate coefficients were probably due to errors in the BOD test.

Therefore, it is reasonably safe to assume DO had no effect upon the substrate removal rate coefficient in this study. High DO levels and the direct contact with oxygen gas may have increased the metabolic activity towards the substrate in some of the organisms, but the net effect upon the entire population was negligible. However, the time period during which the organisms were subjected to the higher DO levels of 8 and 10 mg/l might not have been long enough to bring about a major population change. Oxygen did not appear to be a limiting factor in the substrate removal process at the conventional loadings and solids concentrations used in this experiment. If the DO levels were not great enough to supply the cells in the floc particles with sufficient oxygen, although substrate was able to reach these cells, the k value would decrease with decreasing DO. This was not observed in this study because the substrate concentration was never great enough to allow the substrate penetration rate to exceed the oxygen penetration rate. Ball and Humenick (30) also reported that DO had no effect upon the substrate removal rate coefficient. Poon (32) observed differences, but they only occurred at loadings and solids concentrations well above the ones used in this investigation.

Yield Coefficients

Although large differences in the yield coefficients were observed a graph including sludge production data from each DO level revealed a highly linear relationship as shown in Figure 22. The intermingling of

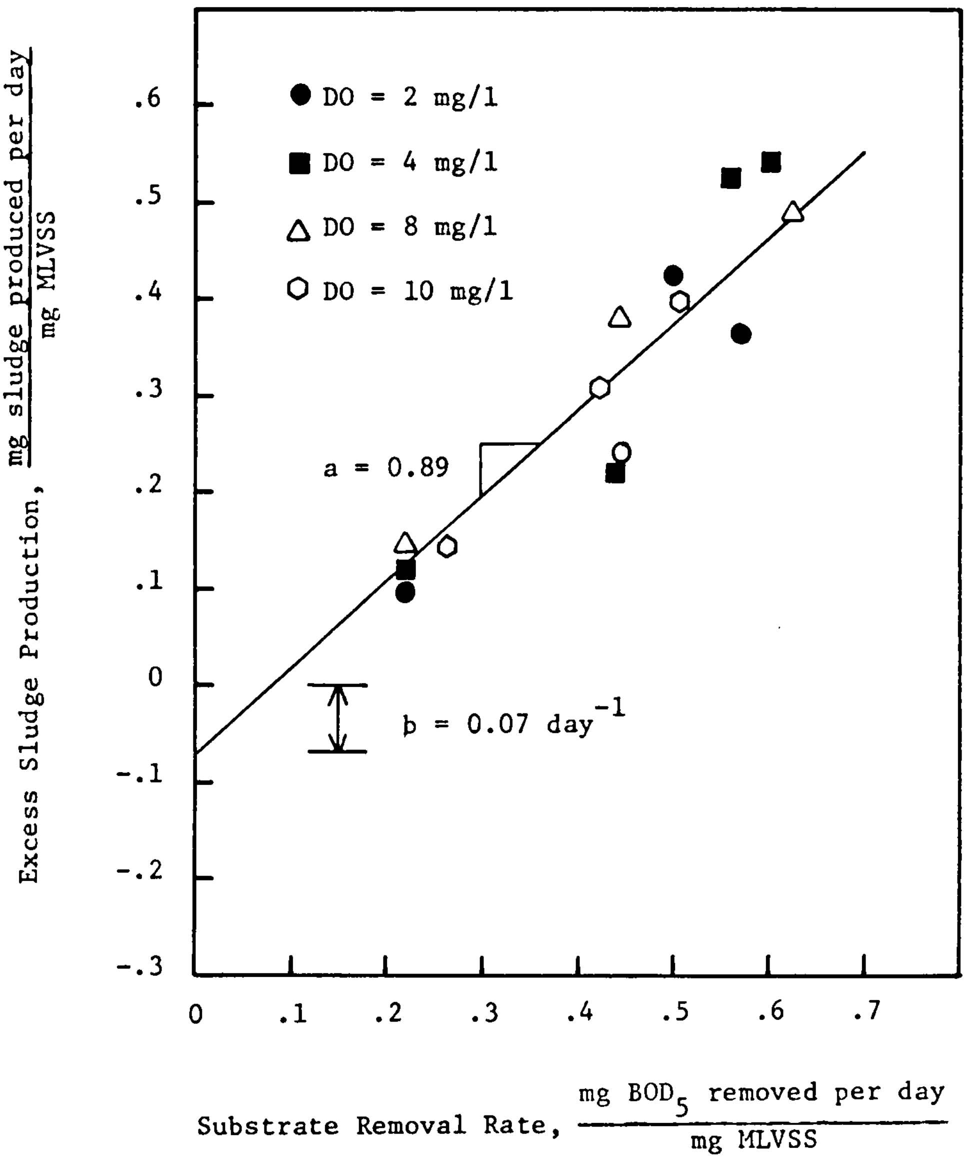

Figure 22. Excess Sludge Production v Substrate Removal Rate.

the data points suggests there might not have been any differences in the true yield and auto-oxidation coefficients. The maximum per cent difference between the values of a and b obtained for the individual DO levels and the coefficients obtained from the combined linear regression analysis were 34.8% and 185% respectively. These differences were probably due to the large day to day variations in sludge production more than anything else.

Although there apparently wasn't any connection between the variations in the yield coefficients and the DO levels, a definite relationship between the true yield coefficient and the auto-oxidation coefficient was discovered. The increases in true yield coincided with increases in the auto-oxidation coefficient as shown below:

DO	a	b
DO = 8 mg/l	$a = 0.83$	$b = 0.02$
DO = 2 mg/l	$a = 0.87$	$b = 0.10$
DO = 10 mg/l	$a = 1.07$	$b = 0.14$
DO = 4 mg/l	$a = 1.21$	$b = 0.20$

As a result, the actual differences in the observed yields were not as great as the differences in the true yield coefficients. For example, the DO of 4 mg/l had a greater true yield than any other DO level but it also exhibited the greatest rate of sludge destruction through auto-oxidation. A mathematical relationship between the observed yield and the yield coefficients can be derived as follows:

substituting:

$$U = \text{substrate removal rate} = (S_o - S_e)/(X_a t)$$

$$\Theta_c = \text{sludge age} = X_a/(dx/dt)$$

gives

$$1/\Theta_c = aU - b$$

by definition

$$Y_{obs} = \text{observed yield} = 1/(U\Theta_c)$$

or $$U = 1/(Y_{obs}\Theta_c)$$

substituting for U gives

$$1/\Theta_c = a/(Y_{obs}\Theta_c) - b$$

or $$Y_{obs} = a/(1 + \Theta_c b)$$

According to the above equation, the net effect of an increase in a and the corresponding increase in b depends largely upon the magnitude of the sludge age.

The yield coefficients determined for each DO level were used to calculate the theoretical observed yield versus sludge age curves illustrated in Figure 23. Although the reactor with a DO of 8 mg/l had the lowest true yield, the curve in Figure 23 indicates it had the highest observed yield at sludge ages greater than 3 days. Surprisingly, the reactor with a DO of 2 mg/l exhibited a lower observed yield than the reactors run at DO levels of 8 and 10 mg/l for sludge ages ranging from 0.5 to 12 days. The reactor with a DO of 4 mg/l also exhibited a lower observed yield than the higher DO reactors for sludge ages greater than 2.5 days. Both of the reactors run at DO levels of 2 and 4 mg/l displayed lower observed yields than the reactor with a DO of 10 mg/l and sludge age from 0 to 12 days according to the curves in Figure 23. These findings conflicted with the results of the study by Jewell and Mackenzie (31). They reported a reactor with a high DO had

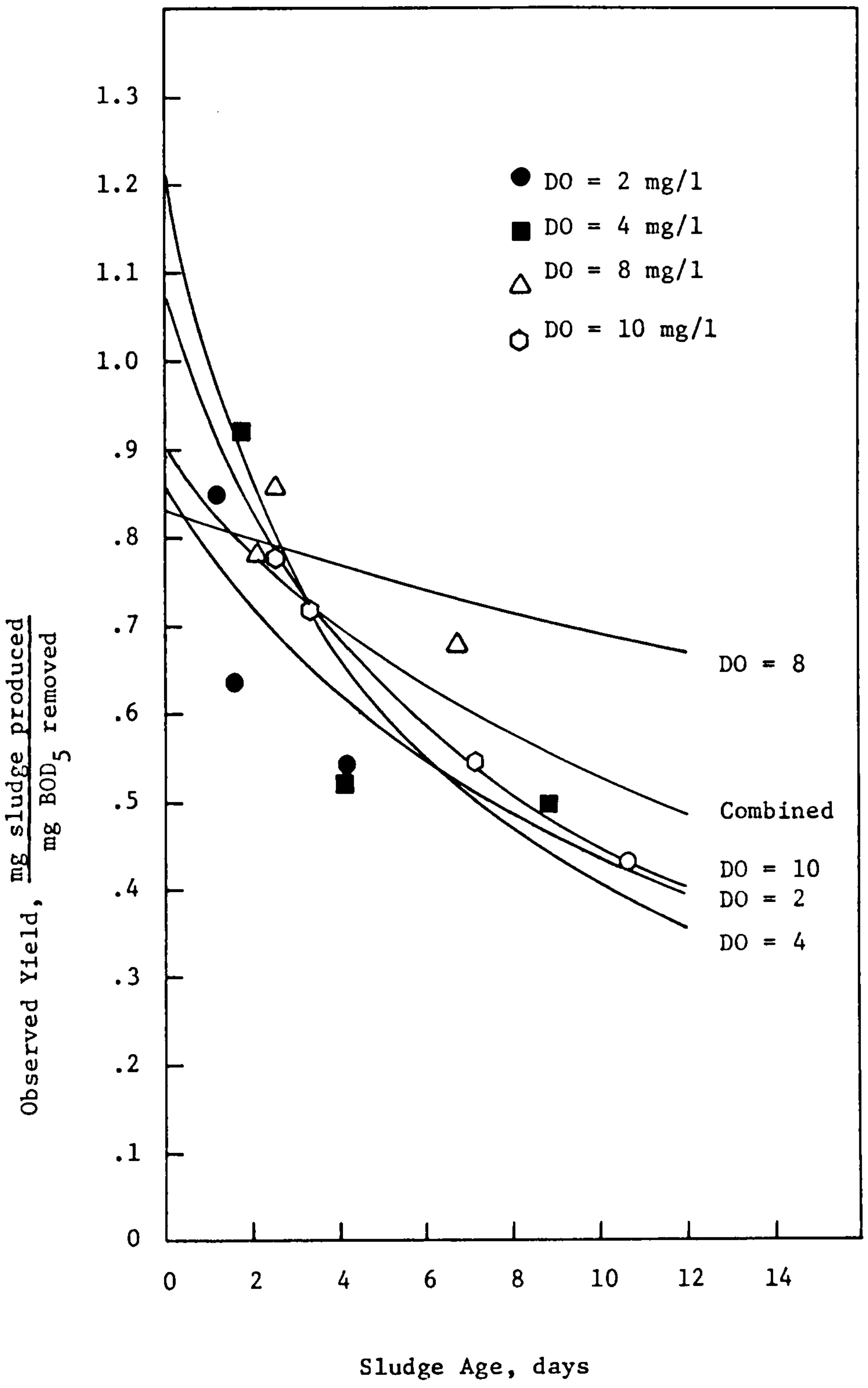

Figure 23. Observed Yield versus Sludge Age

a lower observed yield than a reactor with a low DO for sludge ages ranging from 1 to 120 days. Sherrard's (28) analysis of the Batavia data suggested there might not be any difference between the observed yields of an air system and an oxygen system when compared at the same sludge age.

However, it is important to remember that the theroetical curves shown in Figure 23 were calculated from the yield coefficients obtained for the different DO levels. The validity of these coefficients is certainly questionable. Included in Figure 23 are the points obtained from actual laboratory data. With the exception of the data points obtained for the reactor with a DO of 10 mg/l, most of the data points do not fit the shape of the curves very well. Therefore, the theoretical curves shouldn't be taken at face value because there may not have been any differences in the yield coefficients. The theoretical curve derived from the yield coefficients for the combined data is also shown in Figure 23, but it doesn't represent the data points very well either. The important point is that the graph in Figure 23 reveals that the observed yield for the reactors with conventional DO levels was almost always equal to or less than the observed yield for the reactors run at higher DO levels.

Oxygen Uptake Rate Coefficients

Oxygen uptake data from each DO level was plotted on one graph as shown in Figure 24. Once again the intermingling of points indicates the differences in the oxygen uptake rate coefficients were probably due to the scatter of the data points. The maximum per cent difference between the values of a' and b' obtained for the individual

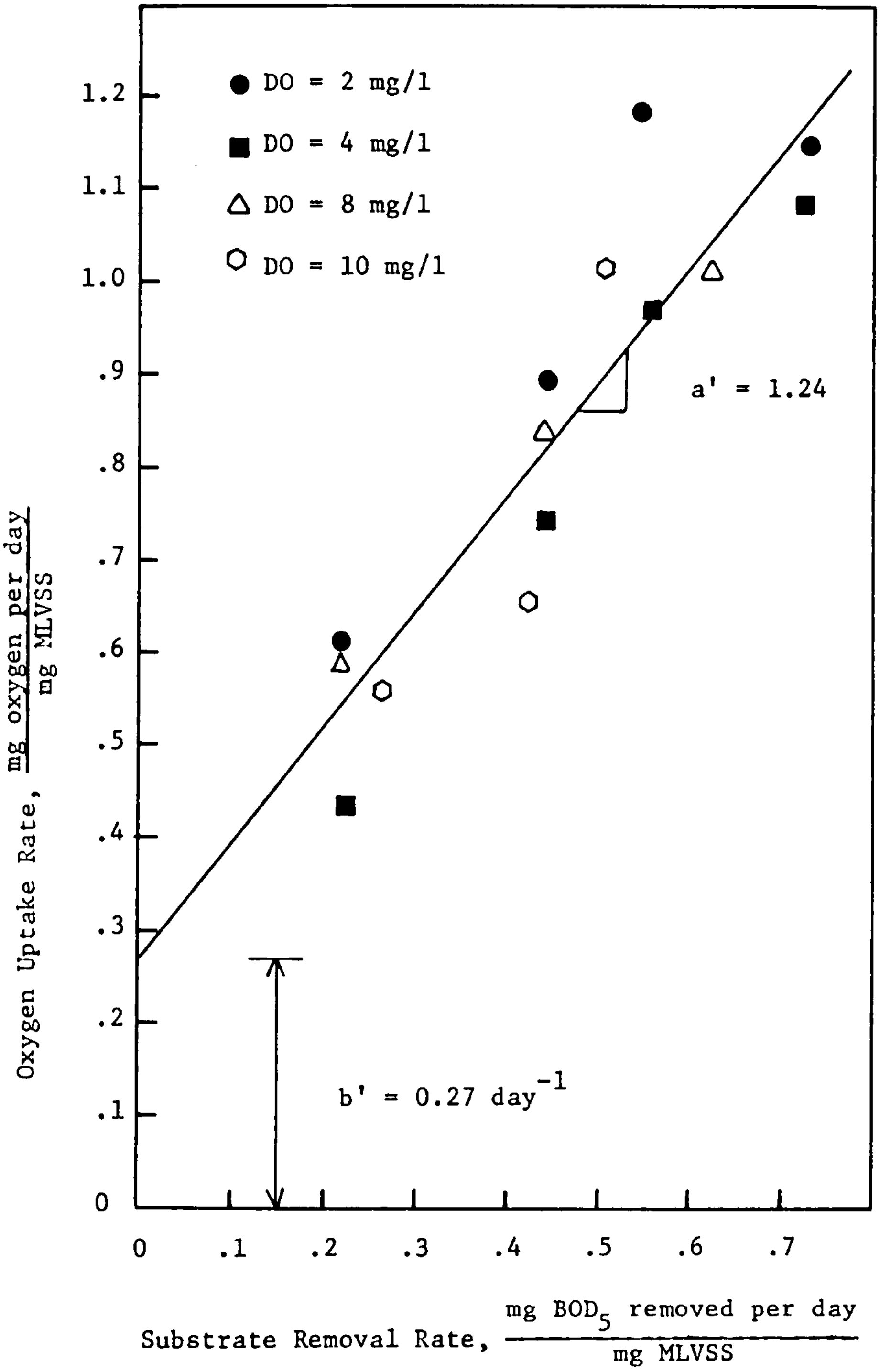

Figure 24. Oxygen Uptake Rate v Substrate Removal Rate

DO levels and the values of a' and b' obtained from the combined data linear regression analysis were 35.5% and 74% respectively.

Although no connection between the oxygen uptake rate coefficients and DO was apparent, a relationship between the energy oxygen coefficient and the endogenous oxygen coefficients was discovered. Decreases in the energy oxygen coefficient usually coincided with increases in the endogenous coefficient as shown below:

DO = 10 mg/l	a' = 1.68	b' = 0.07
DO = 4 mg/l	a' = 1.35	b' = 0.15
DO = 2 mg/l	a' = 1.16	b' = 0.39
DO = 8 mg/l	a' = 1.04	b' = 0.36

The oxygen uptake rate is related to the oxygen uptake coefficients by the following equation:

$$R_r = a'(S_o - S_e)/X_a t) + b'$$

Therefore the inverse relationship between the coefficients indicates the per cent difference in the oxygen uptake rates obtained at each loading for each DO were probably not as great as the per cent difference in the oxygen uptake coefficients.

The true yield coefficient has been defined as the fraction of organic matter converted to cellular material while the energy oxygen coefficient has been defined as the fraction of organic matter consumed to supply energy for synthesis. The sum of the two coefficients should equal unity, but a list of various coefficients compiled by Eckenfelder (11) shows this seldom is the case. However, the magnitude of the differences between the sums and unity reported by Eckenfelder are much smaller than the differences observed in this study. The most likely explanation for this phenomenon is that the five day BOD of the synthetic waste was actually much greater than the average value obtained from numerous tests. In any case, the true yield coefficient and the energy oxygen coefficient are complementary. If the true yield decreases because of an alteration in metabolic pathways, the energy oxygen coefficient must increase. The true yield coefficients are listed below in decreasing order along with the corresponding energy oxygen coefficients and the sums of the coefficients.

DO = 8 mg/l $a = 0.83$ $a' = 1.04$ sum = 1.87
DO = 2 mg/l $a = 0.87$ $a' = 1.16$ sum = 2.03
DO = 10 mg/l $a = 1.07$ $a' = 1.68$ sum = 2.75
DO = 4 mg/l $a = 1.21$ $a' = 1.35$ sum = 2.56

In most cases the energy oxygen coefficient increased with increasing true yield. This observation defies logical explanation unless it is attributed to erroneous coefficients. If high DO levels optimized cell metabolism, the true yield coefficient would decrease and the energy oxygen coefficient would increase with increasing DO. However, the results indicate there was no correlation between DO and the two coefficients.

A definite relationship between the auto-oxidation coefficient and the endogenous oxidation coefficient should be evident if these coefficients are valid. The auto-oxidation coefficient is a measure of the rate in which cellular material is being oxidized. The endogenous oxygen coefficient is a measure of the amount of oxygen consumed in the auto-oxidation process. Therefore, the coefficients should be proportional to each other. The auto-oxidation constants are listed below in increasing order along with the corresponding energy oxygen coefficients:

DO = 8 mg/l $b = 0.02$ $b' = 0.36$
DO = 2 mg/l $b = 0.10$ $b' = 0.39$
DO = 10 mg/l $b = 0.14$ $b' = 0.07$
DO = 4 mg/l $b = 0.20$ $b' = 0.15$

The coefficients listed above did not always display a proportional relationship. In some cases increases in the auto-oxidation coefficient were accompanied by decreases in the endogenous oxygen coefficient. If DO was a limiting factor in the interior of floc particles, increasing the DO would increase the amount of oxygen transferred to the cells in the floc particle interior resulting in an increased auto-oxidation rate. However, the coefficients listed above appear to be independent of DO.

Settleability

Little useful information was obtained from the settling tests. The purpose of the tests was to analyze any differences in settling properties between sludges developed at different DO levels but subjected to the same loading levels. Improved settleability could result from an increase in the production of slime material due to an alteration in metabolism, because of an increase in the ratio of zoogloeal organism to filamentous organisms or because of increases in the predator population. The scatter of data points in Figures 16 through 19 suggested settleability was independent of DO. However, the settleability tests were hindered by filamentous growth at high loading levels. The filamentous growth dominated the reactors with DO levels of 4 and 8 mg/l and was observed in the other reactors at the 0.75 loading. The ratio of filamentous organisms to zoogloeal organisms appeared to be a function of loading instead of DO.

In summary, differences in the settleability and kinetics coefficients were observed but there was no evidence linking these differences to the variations in DO. Furthermore the differences in the kinetic coefficients appear to be distributed randomly instead of in a logical manner. This suggests the differences were probably due to erroneous testing methods. Therefore, the actual kinetic coefficients are best represented by the coefficients obtained by combining all of the data.

CHAPTER VI

CONCLUSIONS

Based on the results obtained from bench scale activated sludge reactors operated at food to microorganism levels of approximately 0.25, 0.50, and 0.75 and a mixed liquor volatile suspended solids concentration of approximately 2000 mg/l, the following conclusions were made:

1. The substrate removal rate coefficient was the same at every DO level investigated.

2. Variations in the energy oxygen uptake coefficients and the endogenous oxygen uptake coefficients could not be correlated with variations in DO.

3. Variations in the true yield coefficients and the auto-oxidation coefficients could not be correlated with variations in DO.

4. The observed yield in the reactors run at DO levels of 2 and 4 mg/l was almost always equal to if not less than the observed yield in the reactors run at DO levels of 8 and 10 mg/l.

5. Sludge settling properties as measured by the SVI and the ISV appeared to be independent of DO. The settling properties deteriorated at the higher loadings because of an increase in the number of filamentous organisms.

6. The differences in the kinetic coefficients determined at each DO level can be attributed to fluctuating environmental conditions, inaccurate testing methods, and possibly non-steady state conditions.

7. The kinetic coefficients for the synthetic waste used throughout the investigation are probably most accurately represented by the coefficients determined from the combined data.

8. It is not necessary to carefully monitor the DO in a bench scale reactor when determining the kinetic coefficients to be used in the design of a full scale plant if both are to be operated at loadings and biological solids concentrations similar to the ones used in this study.

9. The magnitude of the differences in the yield and oxygen uptake coefficients determined at each DO level suggested that more than three loadings are required in laboratory treatability studies.

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APPENDIX A

Kinetics Data at DO = 2 mg/l

Date	Oxygen Uptake (mg/mg-day)	Effluent BOD$_5$ (mg/l)	Substrate Removal Rate (mg/mg-day)	Excess Sludge Production (mg/mg-day)
5/21	.633			
5/22	.860			
5/24	.576	16.0*	.177*	.132
5/25	.612			.052
5/26	.677	5.5	.214	.040
5/27	.648			.148
5/28	.549	4.3	.228	-.031*
5/29	.461*			
6/5				
6/6		8.5*		
6/7	.720*	5.2*		
6/8	.997*			
6/9	.913	10.5	.499	.306
6/10	.910	7.8	.460	.587
6/11	.912	3.8	.431	.019
6/12	.897	21.6*	.416	.218
6/13	.840	7.2	.436	.065
6/15	1.090		.764	
6/16	1.250	9.5	.823	
6/17	1.100	4.1*	.607	.495
6/18	.829	10.0	.479	.403
6/19	.870	9.5	.538	.393
6/20	.745	6.7	.684	.400
6/21	.864	15.0	.594	.254

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*Value wasn't used in calculating the average value because of non-steady state conditions or experimental errors.

Kinetics Data at DO = 2 mg/l - Cont.

Date	Oxygen Uptake (mg/mg-day)	Effluent BOD$_5$ (mg/l)	Substrate Removal Rate (mg/mg-day)	Excess Sludge Production (mg/mg-day)
7/7	1.474		.600	
7/8	1.025		.479	
7/19	1.069	9.8	.565	.310
7/9	.838	1.0*	.520	.536
7/10	.671	10.5	.437	.923
7/10	.701	30.0*	.395	.167
7/11	.850	40.0*	.645	.170
7/11	.845			.444

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*Value wasn't used in calculating the average value because of non-steady state conditions or experimental errors.

Kinetics Data at DO = 4 mg/l

Date	Oxygen Uptake (mg/mg-day)	Effluent BOD_5 (mg/l)	Substrate Removal Rate (mg/mg-day)	Excess Sludge Production (mg/mg-day)
5/21	.352*	5.0*		
5/22	.449*	11.3*		
5/24	.525*	9.1*	.246*	-.005*
5/25	.396	6.9	.225	.138
5/26	.461	5.6	.227	.156
5/27	.454	6.5	.216	.025
5/28	.406	8.4	.224	.127
5/29	.446			
6/5		6.1*		
6/6	.888*	8.5*		
6/7	.720	5.2	.465	
6/8	.761	7.2	.421	.384
6/9	.970*	7.4	.498	.138
6/10	.761	6.2	.421	-.326
6/11	.708	4.7	.384	.606
6/12	.864	1.0	.462	.363
6/15	.841		.744	
6/16	1.160	19.5	.792	
6/17	1.240	7.3	.630	.734*
6/18	.847	12.4	.505	.630
6/19	.694	12.7	.533	.476
6/20	.730	17.0	.728	.652
6/21	.779	11.2	.624	.434

*Value wasn't used in calculating the average value because of non-steady state conditions or experimental errors.

Kinetics Data at DO = 4 mg/l - Cont.

Date	Oxygen Uptake (mg/mg-day)	Effluent BOD_5 (mg/l)	Substrate Removal Rate (mg/mg-day)	Excess Sludge Production (mg/mg-day)
7/7	1.330		.539	
7/8	.966		.573	
7/9	1.155	12.0	.641	.412
7/9	.838	13.0	.529	.602
7/10	.758	10.5	.615	.628
7/10	.746	6.0	.521	.408
7/11	1.131		.573	.517
7/11	.847		.481	.578

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*Value wasn't used in calculating the average value because of non-steady state conditions or experimental errors.

Kinetics Data at DO = 8 mg/l

Date	Oxygen Uptake (mg/mg-day)	Effluent BOD$_5$ (mg/l)	Substrate Removal Rate (mg/l)	Excess Sludge Production (mg/mg-day)
6/26	.560	4.8	.228	.123
6/27	.522	4.3	.228	.073
6/28	.702	3.7	.229	.060
6/29	.650	6.3*	.227	.245
6/30	.460	7.0*	.203	
6/30	.602	5.1	.188	.234
7/1	.733*			
7/2	.668*			
7/3	.780*			.509*
7/4	.923	8.4	.448	.413
7/4	.766	7.8	.368	.605
7/5				.139
7/5		5.6	.542	.547
7/6	.850	2.8	.459	.677
7/6	.918	14.0	.398	.128
7/7	.718	8.8	.447	.148
7/12	.810	46.0*	.611	.211
7/12		5.0*	.610*	
7/13	.778	13.5	.670	.580
7/13	1.031	21.0*	.643	.586
7/14	.960		.641	.368
7/14	.971		.614	.426
7/15	1.485		.567	.751

*Value wasn't used in calculating the average value because of non-steady state conditions or experimental errors.

Kinetics Data at DO = 10 mg/l

Date	Oxygen Uptake (mg/mg-day)	Effluent BOD$_5$ (mg/l)	Substrate Removal Rate (mg/l)	Excess Sludge Production (mg/mg-day)
6/26	.469	9.6	.262	.136
6/27	.504	2.7	.250	.062
6/28	.864	31.0*	.258*	-.020
6/29	.701	7.3	.296	.222
6/30	.443	12.5*	.253*	
6/30	.351	6.3	.245	.304
7/1	.589*			
7/2	.421*			
7/3	.353*			.487*
7/4	.534	5.6	.437	.435
7/4	.880	10.4	.362	.588
7/5				
7/5	.728	2.2	.456	.221
7/6	.659	2.8	.442	.348
7/6	.505	7.2	.409	.417
7/7	.613	8.8	.447	.238
7/12	1.066	9.5	.587	.275
7/12	.706	5.0*	.580*	.196
7/13	.883	9.0	.501	.494
7/13	1.324	9.5	.401	.473
7/14	.939	9.0	.506	.381
7/14	1.413	7.5	.484	.387
7/15	.768	3.7	.537	.543

*Value wasn't used in calculating the average value because of non-steady state conditions or experimental errors.

APPENDIX B

Observed Yield Data

DO (mg/l)	Average Substrate Removal Rate (mg/mg-day)	Average Excess Sludge Production (mg/mg-day)	Average Observed Yield (mg/mg)	Average Sludge Age (day)
2	.221	.095	.431	10.5
	.448	.239	.533	4.2
	.573	.362	.632	1.6
	.500	.425	.850	1.2
4	.223	.112	.502	8.9
	.442	.233	.527	4.3
	.597	.548	.918	1.8
	.559	.524	.937	1.9
8	.217	.147	.677	6.8
	.444	.380	.857	2.6
	.624	.487	.780	2.1
10	.263	.141	.540	7.1
	.426	.305	.716	3.3
	.503	.393	.775	2.5

APPENDIX C

Settleability Data

DO (mg/l)	Average Substrate Removal Rate (mg/mg-day)	Average Sludge Age (day)	Average SVI (ml/g)	Average ISV (ft/hr)
2	.221	10.5	42	27.5
	.448	4.2	59	16.0
	.573	1.6	122	3.4
4	.223	8.9	28	15.5
	.442	4.3	92	15.6
	.597	1.8	273	0.2
8	.217	6.8	68	8.9
	.444	2.6	42	15.3
	.624	2.1	298	.5
10	.263	7.1	71	17.2
	.426	3.3	52	13.7
	.503	2.5	92	5.3

THE EFFECTS OF DISSOLVED OXYGEN CONCENTRATION ON THE KINETICS AND SETTLEABILITY OF ACTIVATED SLUDGE

by

Jeffrey Brian Chapin

(ABSTRACT)

The objective of this research was to determine whether or not variations in dissolved oxygen concentration above the critical dissolved oxygen concentration affect the kinetic coefficient and settleability of activated sludge. Synthetic substrate loadings of 0.25, 0.50, 0.75 were applied to bench scale activated sludge reactors with average mixed liquor volatile suspended solids concentrations of 2000 mg/l. The substrate removal rate coefficient, oxygen uptake coefficients, yield coefficients, and sludge settling properties were evaluated at dissolved oxygen concentrations of 2, 4, 8, and 10 mg/l.

The kinetic coefficients were different at each dissolved oxygen concentration investigated but the differences could not be correlated with dissolved oxygen concentration variations. Instead, the variations in the coefficients appeared to be distributed in a random manner due to inaccurate test methods and fluctuating environmental conditions. Sludge settling properties as measured by the sludge volume index and the initial settling velocity were independent of dissolved oxygen concentration.

The results of the study indicated dissolved oxygen concentration

has no noticeable effect upon the kinetic coefficients and sludge settleability in activated sludge systems operated at loading levels and solids concentrations similar to the ones employed in this study.