STUDIES ON THE KINETICS OF BOD EXERTION IN AN OPEN JAR REACTOR USING EFFLUENTS FROM A HYDROLYTICALLY ASSISTED EXTENDED AERATION PILOT PLANT

By

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CHAPTER I

INTRODUCTION

Many scientific investigations have been carried out on the removal of organic contaminants in wastewater and on oxygen utilization in receiving streams. As the presence of small amounts of sewage in wastewater can be injurious to the water resource, it is necessary to treat the wastewater for removal of organic matter. Furthermore, it is important to make an engineering prediction of the effects on the dissolved oxygen resources in the receiving stream resulting from introducing both treated and untreated waste into streams. The basic reason for removal of organic material from wastewater is prevention of decrease in the DO in the stream. A mathematical equation for predicting the dissolved oxygen concentration at any point in the stream was devised by Streeter and Phelps. Various researchers have objected to the "sag equation," largely because of the inadequacy of the first order model for exertion of BOD. Work on BOD exertion and O_2 prediction of the DO profile in receiving streams have been among long-term investigational interest of Gaudy and his co-workers in the bioenvironmental engineering laboratories of Oklahoma State University. Some of this work has led to the development of an open jar technique for developing the BOD curve and the numerical integration of this curve with the reaeration data for the stream.

The present laboratory investigation employing the open reactor

technique was carried out to study the effect of waste characteristics on the mode of oxygen uptake kinetics, and to determine the characteristic oxygen uptake when various amounts of biological solids are present in effluents from an extended aeration process using hydrolytically assisted operation.

CHAPTER II

LITERATURE REVIEW

Ever since Frankland (1) observed that sewage in a river was the cause of depletion of the dissolved oxygen, the effect of various organic substances on the aqueous environment has become a subject of active research in the field. Various researchers in Great Britain and the United States have tried to analyze the causes and effects of this detrimental phenomenon in nature. In 1925, Streeter and Phelps (2) proposed their famous oxygen sag equation to predict the dissolved oxygen deficit in the stream, which states

$$D = \frac{K_1 L_a}{K_2 - K_1} \left(e^{-K_1 t} - e^{-K_2 t} \right) + D_a e^{-K_2 t}$$

where

D = deficit from saturation at time, t

K_1 = deoxygenation coefficient, time^{-1}

K_2 = reoxygenation coefficient, time^{-1}

D_a = initial DO deficit from saturation, mg/l

L_a = initial oxygen demand of the organic matter of the water, mg/l

Streeter and Phelps (2) assumed that the rate of oxygen utilization by bacteria was proportional to the amount of unoxidized substrate remaining, thus assuming first order decreasing rate kinetics.

The deoxygenation coefficient, K, in the above equation, was assumed to be obtained using the BOD dilution bottle technique which was run under quiescent conditions. Various investigators questioned the validity of such a procedure for describing events in the complex environment in the stream. Thus, Ruchhoft, Placak, Kachmas, and Calbert (3), while studying the effect of sewage dilution on the BOD velocity constants, observed that the deoxygenation constant was higher at higher concentrations of sewage. Also, Jennelle and Gaudy (4), studying the mechanism and kinetic course of BOD exertion not only observed similar results, i.e., the rate of oxygen uptake increased with an increase in concentration of carbon source, but the kinetic mode of O_2 uptake changed from decreasing to increasing first order. Various investigators found that mixing or agitation affected exertion of BOD. Lordi and Heukelekian (5), Ali and Bewtra (6) investigated the invluence of stirrong on BOD rates, and found that the oxygen uptake was increased with stirring. Thus, the general consensus of research opinion has been against the direct use of the usual dilution technique for predicting the rate of deoxygenation in receiving streams. Jennelle and Gaudy recommended using an open stirred reactor rather than the standard BOD bottle technique.

Open jug techniques are not new. In 1900, Dibdin and Thudichum (7) used an open incubation test to make allowance for the replenishment of the oxygen supply by atmospheric reaction. But in the early stages of development of modern day BOD technique, Theriault (8) objected to the use of reaeration techniques on the theory that tests in open vessels are inadequate for the prediction of the course of oxygen utilization in a receiving stream. He concluded that:

> At first sight it might appear that the procedure of incubating a sample in an open vessel is preferable to the usual procedure of conducting the test in a completely filled and tightly stoppered bottle. It is probably necessary to conclude, however, that tests in open vessels are utterly inadequate for the purpose of supplying information concerning the balance which, under natural conditions, obtains between the rate of reaeration and the rate of deoxygenation of a polluted water. The separate consideration of these two distinct phases of the same problem simplifies the interpretation of the results and makes it possible to derive accurate information at least concerning the amount of organic matter present in a sample (page 56).

and he recommended the use of the quiescent incubation procedure. Later, however, during the last decade, Gates, et al. (9), comparing the sag curve produced from the Streeter and Phelps sag equation and those developed in open stirred reactors, found no agreement between them. Similarly, Isaacs and Gaudy (10) compared BOD exertion in the standard BOD bottle to that in a simulated channel. A sag curve was computed using the Streeter and Phelps equation and the K_1 value from the BOD bottle and then compared with the actual curve in the channel, and no similarity was found. One of the primary differences between the two oxygen uptake curves was observed to be the presence of a more pronounced lag in the BOD bottle than in the turbulent system.

These observations by various researchers in the field proved the inadequacy of using the K_1 determined from the BOD bottle technique. There are other arguments in favor of using more direct means for assessing the oxygen demanding characteristics of organic waste materials. Heukelekian (11) in discussing his observation that the BOD sometimes varies with the dilution employed, stated that the BOD test result has little meaning unless the dilution used is specified. He pointed out that there is no assurance that toxic materials may not be present. When high dilutions are employed as a result of high organic content,

toxic effects may be overcome (i.e., diluted out). Thus, at lower dilutions, the O_2 uptake may be lower than at higher concentrations of waste. In summing, he attributes this sliding scale, i.e., higher BOD values at high dilutions, to possible toxic components, and felt the more direct methodologies not involving dilution technique would give more realistic assessment to the effects of waste matter in the receiving streams.

Methods not requiring dilution techniques usually require some form of reaeration of the incubation mixture. Open jar techniques seem ideal, but they involve consideration of factors about both the waste and the jar (water) itself which may affect the reaeration rate.

Gates, Mancy, Shafie, and Pohland (9) reported the results of studies using open stirred reactors. They first investigated the sag equation at various reaeration rates and with various combinations of substrates and seeds, including pure cultures. They found no agreement in the sag curves with the Streeter-Phelps sag equation. They also concluded that the influence of the bacteria continues approximately four hours beyond the low point in the sag, due to either oxidation of stored material or oxidation of released metabolic intermediates. Their substrate had been removed by the time the minimum point of the sag occurred; however, with some multiple substrate systems--for example, glucose and lactose--the DO recovered after the glucose was removed. Then the lactose caused a second sag in DO. This verifies the results on sequential removal of substrate which had been reported by Gaudy and his co-workers (12)(13). Isaacs and Gaudy also investigated the ability of the Streeter-Phelps sag equation, using the BOD dilution bottle technique, to predict the DO profile, and they

concluded that the dilution technique was inadequate (10). Although most of the research on BOD exertion in receiving streams has centered on biological deoxygenation, the other factor in the Streeter-Phelps equation, i.e., reaeration, has not gone uninvestigated.

Isaacs and Gaudy (14) reviewed the work of many investigators who have studied river reaeration and proposed methods to calculate reaeration rate coefficient for any stream. Most of the formulas are given as a function of surface renewal rate and turbulence, although other physical and chemical factors affect the reaeration rate.

Kehr (15) compared K_2 values in tap water with those in sewage, and found that 0.5-10 percent of sewage, or equivalent in industrial wastes, decreased K_2, and the effect was especially evident in streams flowing at high velocities, i.e., at higher K_2 values. Kothandaraman (16) found that contaminants in receiving waters can cause the K_2 to be as much as 15 percent higher or 15 percent lower than the K_2 for distilled water at like conditions of temperature and pressure. Poon and Campbell (17) observed that organic substances such as glucine, glucose, and peptone reduce the oxygen transfer rate, whereas suspended particles at lower concentrations enhance it. Eckenfelder (18) compared the reaeration rate for tap water with that of a chemical waste and pulp and paper waste, and it was shown that there is a considerable effect of the organic substances on the reaeration rate. He concluded that:

> In the treatment of domestic sewage, four hours of aeration with activated sludge increased the α value from 0.68-0.76 to 0.73-1.00 Treatment of a Kraft mill waste increased the α value from 0.45 to 0.79 after three hours of aeration with activated sludge. In the biooxidation of a chemical waste, the α value decreased from 2.34 to 1.34 with a 90 percent reduction in BOD (page 1363).

Also, Ziemunski (19) studied the effect of substances such as acetic acid, butyl alcohol, and butyric acid on the liquid film coefficient, and observed that the values increased first with concentration and then dropped well below that for distilled water.

The above discussion indicates that for the success of the open stirred reactor technique, considerable attention should be paid to determination of the reaeration characteristics of the system, i.e., the reaction vessel and the chemical and physical makeup of the reaction liquor. There are many ways to estimate or determine the reaeration rate constant and the DO saturation values. Isaacs and Gaudy (20) have proposed the "α method" which was originally employed by Davis (21) as a general means of fitting data to a first order decreasing rate kinetic. This method was employed in the current research undertaking and is discussed in more detail in the next chapter.

Peil and Gaudy (22) compared the DO profile calculated in a simulated stream, using a BOD curve generated with open stirred reactor technique to the actual profile observed in the stream apparatus, and concluded that the method yielded an acceptable estimate of the DO profile. They recommended that the K_2 in the open jug be within $\pm$ 50 percent of the K_2 in the stream, since turbulence (as indicated by the K_2 value) seemed to affect the rate and amount of O_2 uptake, particularly after the substrate removal phase was completed. They suggested that one possible reason for the spread in O_2 uptake curves with increased K_2 was that in the later stages, the oxygen uptake was due largely to the metabolism of predators, e.g., protozoa, feeding on the bacterial cells which had been produced in the first phase of the oxygen

uptake. Since the discrete particulate "food" was rather low in concentration, rapid mixing could help bring the substrate and the feeding population together.

The above review was provided to gain background information on the use of the open jar method. The present laboratory investigation was undertaken to delineate the effect of the waste characteristics on the mode of oxygen uptake kinetics and to determine the characteristic O_2 uptake of biological solids in effluent from an extended aeration process using "hydrolytically-assisted" operation.

CHAPTER III

MATERIALS AND METHODS

An open stirred reactor was employed to evaluate the O_2 uptake kinetics of various types of effluent. In these studies, one of the major sources of effluent was that from an extended aeration pilot plant operated with the "hydrolytic assist."

Laboratory Apparatus

Open Stirred Reactor

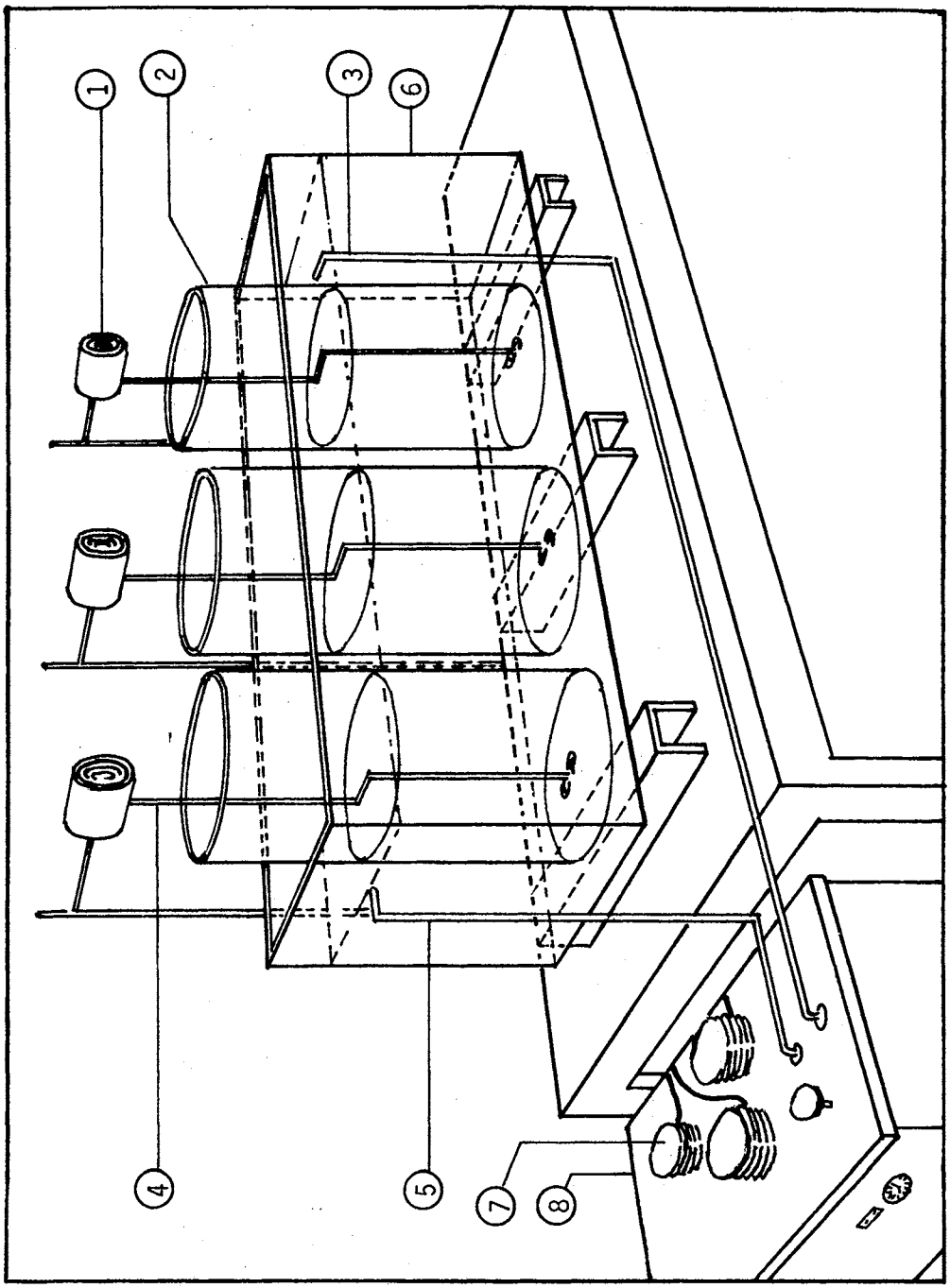
The reactor consisted of a flat-bottomed cylindrical Pyrex vessel with a diameter of 8.125 inches and a depth of 18 inches. Stirring was provided by a 2-inch propeller fixed at the bottom of a vertical shaft driven by a 1/50 HP Bodine motor, the speed of which was adjusted by a rheostat to permit attainment of the desired reaeration constant. A Precision Scientific Lo-Temptrol recirculating water bath was employed to control temperatures. The Pyrex vessels were placed into a rectangular plexiglass tank through which water of constant temperature was circulated. A drawing of the apparatus showing three open jar reactors is presented in Figure 1.

Extended Aeration Pilot Plant

An extended aeration pilot plant employing the "hydrolytic assist"

Figure 1. Perspective View of Experimental Open Jar Reactors.

Shown in the figure are:
1) 1/50 HP Bodine motor
2) flat-bottomed cylinderical Pyrex vessel
3) inlet line for recirculating water bath
4) vertical shaft with 2-inch propeller
5) outlet line for recirculating water bath
6) Plexiglass water bath tank
7) rheostats for control of propeller speed
8) water bath temperature controller


1
2
3
6
4
5
7
8

was operated as a source of treated effluent. Figure 2 is a flow diagram for such a plant. The aerator-settling chamber employed was identical to that employed by Murthy (23); a brief description follows:

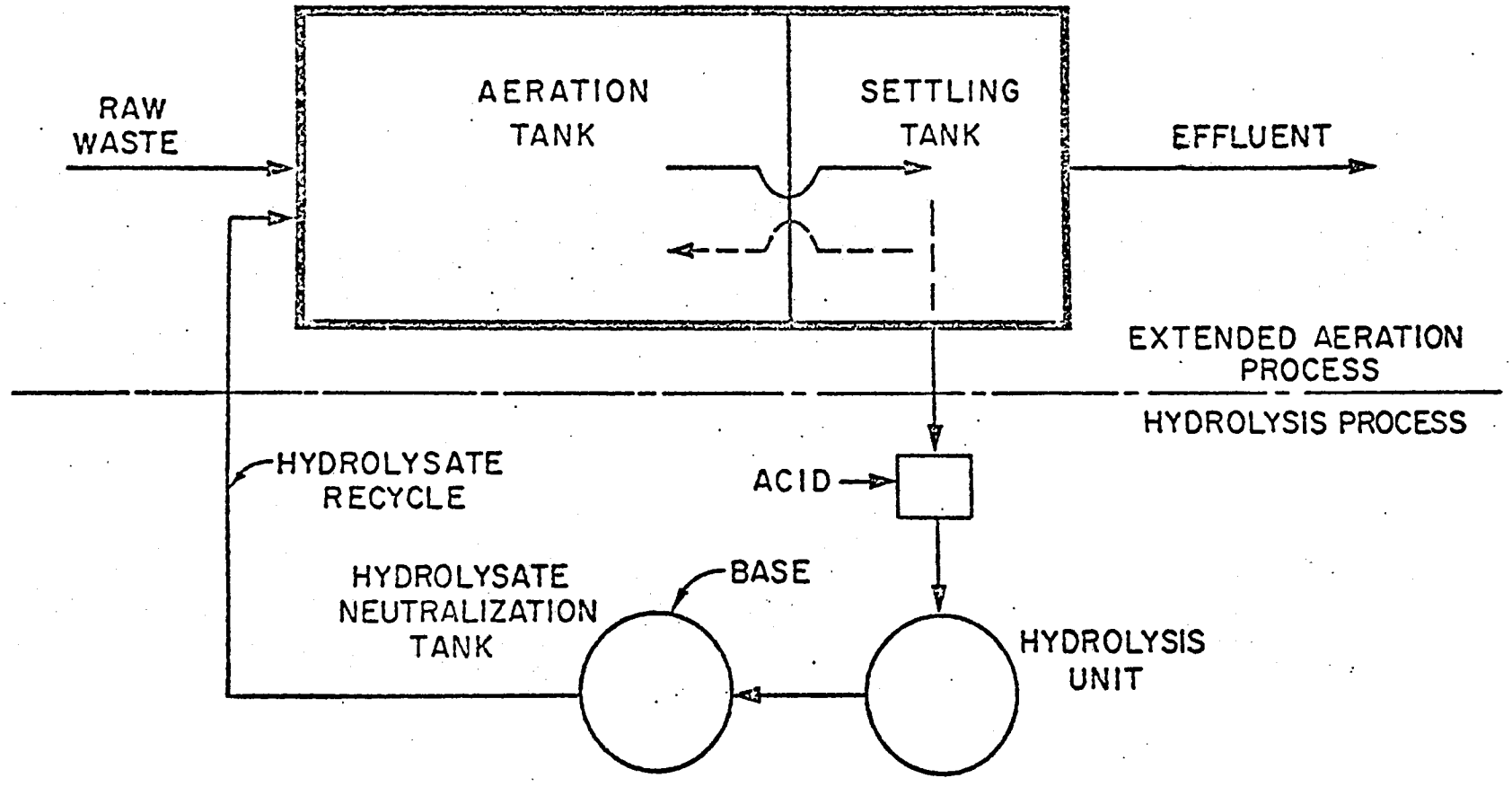
A 12-liter plexiglass reactor with internal recycle of bacterial cells served as the aeration tank; an adjustable baffle was used to separate the aeration and settling chambers. The aeration chamber volume was eight liters, and that of the settling chamber was four liters. The hydraulic detention time of 24 hours--16 hours in the aeration chamber and eight hours in the settling chamber--was provided at the feed rate of 12 liters per day. Air was supplied, through four porous diffuser stones, at a rate of approximately 2000 cc/min/l. A Milton Roy dual positive displacement pump (Mini pump Model MM2-B-96R) provided continuous feed to the aeration tank.

Experimental Procedures

Open Stirred Reactor

At the beginning of each experiment, reactors were thoroughly cleaned first by an acid rinse, then they were washed with "Alconox," then thoroughly rinsed several times with tap water to ensure that there was no extraneous organic matter in the system. A sample volume of 10 liters was transferred to the reactor (either from the extended aeration pilot plant or effluent from the Stillwater wastewater treatment plant). The DO was brought to approximately the saturation level by a brief period of aeration. Samples were taken periodically for determining the chemical oxygen demand (COD), biological solids concentration, NO_3-N, and NH_3-N. The dissolved oxygen was monitored at close

Figure 2. Extended Aeration Activated Sludge Process Incorporating Chemical Hydrolysis for Control of Sludge Concentration


RAW
WASTE
AERATION
TANK
SETTLING
TANK
EFFLUENT
EXTENDED AERATION
PROCESS
HYDROLYSIS PROCESS
HYDROLYSATE
RECYCLE
ACID
HYDROLYSATE
NEUTRALIZATION
TANK
BASE
HYDROLYSIS
UNIT

intervals for a period of five days (120 hours). Samples were also taken to determine COD, biological solids, NO_3-N, and NH_3-N at the end of the run. After taking samples, 20 ml of Clorox was added to kill the microorganisms, and a 12-hour contact period was allowed to accomplish complete kill. The absence of O_2 uptake was checked periodically in a Warburg apparatus. Stoichiometric amounts of sodium sulfite with cobalt chloride catalyst were added to remove the dissolved oxygen from the system. The dissolved oxygen was monitored at very close intervals until the DO in the system approached saturation. Then the reactors were thoroughly cleaned and an equal volume of tap water instead of the effluent was used, and the reaeration experiment was re-run.

Extended Aeration Pilot Plant

The chemical composition of the synthetic waste fed to the pilot plant in these studies is given in Table I. The substrate concentration of the influent was 500 mg/l glucose plus varying concentrations of hydrolysate COD. Every week, 900 ml of settled sludge was taken from the settling compartment, and hydrolysate was prepared. The pH of the removed sludge was lowered to pH 1 with sulfuric acid (N 36), and then the sample was placed in an autoclave for five hours at 15 psi and 121^{o}C; sodium hydroxide was used for neutralizing the sludge to pH 7. Hydrolysate thus prepared was divided into seven equal volumes (one week's supply), and was fed to the system every day along with the glucose feed. The feed reservoir was changed every day. Daily samples were taken to determine the solids concentration in the total system (aerator and settling tank), and the solids that were escaping in the effluent. Also, the COD of the effluent and filtered effluent were

TABLE I

CONSTITUENTS IN THE FEED DURING OPERATION WITH SUBSTRATE LOADING CONSISTING OF 500 mg/l GLUCOSE AND VARIABLE AMOUNTS OF SLUDGE HYDROLYSATE

Constituents	Concentration
Glucose	500 mg/l
Hydrolysate COD	30-90 mg/l
$(NH_4)_2\ SO_4$	250 mg/l
$MgSO_4 \cdot 7H_2O$	50 mg/l
$FeCl_3 \cdot 6H_2O$	0.25 mg/l
$CaCl_2$	3.75 mg/l
$MnSO_4 \cdot H_2O$	5 mg/l
Phosphate buffer 1.0 M, pH 7.6	
$(KH_2PO_4 + K_2HPO_4)$	5-15 ml/l
Tap water	50 ml/l
Distilled water	to volume

monitored in addition to NH_3-N and NO_3-N. Occasionally, dissolved oxygen in the aeration tank and settling tank were measured and pH was checked frequently to make sure that an acid condition did not develop.

Effluents Studied

Effluents for oxygen uptake characteristics were:

1) effluent obtained from the primary and secondary settling tanks of the Stillwater wastewater treatment plant; thus, the secondary effluent employed was that from a trickling filter;

2) effluent from an extended aeration pilot plant fed with packinghouse waste obtained from a local meat packing operation;

3) effluent from the hydrolytically assisted extended aeration plant previously described.

The effluent was supplemented with additional biological solids from the aeration chamber in some studies.

Analytical Procedures

The methods adopted to measure the dissolved oxygen, chemical oxygen demand (COD), biological solids concentration, NH_3-N, NO_3-N, pH, and temperature during this investigation are given below.

Dissolved Oxygen

The dissolved oxygen concentration was monitored electrically by the use of a Weston-Stack oxygen analyzer; the analyzer was standardized on alternate days using the Winkler method for dissoved oxygen, as given in Standard Methods (24). In early phases of the work, the instrument was standardized daily, but it was found that it did not

require such frequent standardization.

Chemical Oxygen Demand

Chemical oxygen demand was measured using the procedure given in Standard Methods (24).

Biological Solids

The suspended solids concentration was determined by filtering a 25-ml sample through a membrane filter (0.45 μ pore size, Millipore Filter Corp., Bedford, Mass.). The filters were weighed on a Mettler Instrument Corporation balance (No. 1-910). After filtration, the pans were replaced in the drying oven for two hours at 103°C, cooled in a desiccator containing calcium carbonate, and weighed to determine the biological concentration.

Nitrogen

Nitrate-nitrogen (NO_3-N) was determined by the Brucine method, as discussed in Standard Methods (24). NH_3-N was also measured, using a method developed by Ecker and Lockhart (25).

pH and Temperature

The pH was determined using a Beckman Expandometric 55-2 pH meter, and the temperature was measured with a Sargent Welch thermometer.

Methods of Data Analysis

The reaeration rate constant, K_2, and saturation constant, C_s, were determined from the experimental data using the α method, as

described by Isaacs and Gaudy (20), assuming that under all conditions the reaeration rate follows first order decreasing rate kinetics. The α method provides a procedure for obtaining a straight line fit on a semi-logarithmic graph paper. The dissolved oxygen deficit is plotted on the Y-axis and time elapsed on the X-axis. The deficit is calculated from trial estimates of the saturation value for DO. The value is adjusted after each trial plot until a straight line fit is obtained.

Oxygen uptake was computed using the experimentally determined dissolved oxygen profile, and the reaeration constant and DO of saturation values obtained by the α method. The procedure has been described in detail by Isaacs and Gaudy (20). Samples of O_2 uptake are given in Appendix A and Appendix B.

CHAPTER IV

RESULTS AND DISCUSSION

The results and discussion of this investigation will be presented in two major sections. The first phase deals with the "effect of the wastewater characteristics on the mode of kinetics" for primary and secondary effluent from the Stillwater, Oklahoma, treatment plant, and blood waste (the latter effluent was that from an extended aeration bench scale pilot plant operated by Mr. Sujarittanonta). The second phase of this chapter deals with the "oxygen uptake characteristics of biological solids in effluent taken from an "hydrolytically-assisted" extended aeration plant.

Phase I

Some Effects of Wastewater Characteristics on the Mode of O_2 Uptake

Primary Effluent. A sample from the primary effluent of the Stillwater, Oklahoma, wastewater treatment plant was withdrawn and placed in three open stirred reactors. The reaeration rate for each experiment was adjusted to give a range from a lower value of 0.088 hr^{-1} to a high value of 0.217 hr^{-1}. The initial dissolved oxygen concentration was raised to a value near saturation. This was done to help assure that DO in the experimental reactor did not go to zero at

the minimum sag point during the course of these studies. Results for the experiment run at the low K_2 value are shown in Figure 3. The reactor contained initially 47 mg/l of soluble organic material, 56 mg/l of suspended solids; total organic content of 102 mg/l measured as COD. The DO profile did approach zero. The minimum DO was attained within ten hours and stayed low for about twenty hours with a very slow recovery. After 35 hours, the recovery proceeded more rapidly, and then later in the experiment the DO showed the beginnings of a secondary sag which did not recover in 120 hours, when the experiment was terminated. After five days (120 hours), the oxygen uptake was 76 mg/l, while the total COD decreased by 43 mg/l (i.e., 102 - 59 mg/l); biological solids decreased from an initial 56 mg/l to a final 12 mg/l. There was a very small amount of nitrification.

Shown in Figure 4 are the results of an experiment with the same sample of primary effluent as in Figure 3, but with the higher reaeration rate of 0.117 hr^{-1}. The soluble substrate concentration remained at almost the same level, from an initial value of 43 mg/l to a final value of 47 mg/l, whereas the total COD decreased by about 47 mg/l with a corresponding decrease in biological solids concentration from 56 mg/l to 20 mg/l. In this experiment, a longer time was required to reach the lowest point of the sag, but the recovery phase started immediately and reached a DO concentration of 5.3 mg/l and then a secondary sag started. The oxygen uptake curve showed a decreasing rate up to 60 hours and then proceeded with an increasing rate to the terminal BOD value of 86 mg/l. In this experiment, also, the amount of nitrification was very low at the time of terminating the experiment. The total oxygen uptake exerted was 86 mg/l; in comparison, the

Figure 3. DO Profile and O_2 Uptake Curves for a Primary Effluent From the Stillwater Wastewater Treatment Plant With the Open Jar Reactor Operating at K_2 = 0.088 hr^{-1}

Effluent Characteristics:		Initial	Final
Filtrate COD		47 mg/l	24 mg/l
Total COD		102 mg/l	59 mg/l
Biological Solids		56 mg/l	12 mg/l
NO_3-N		6 mg/l	9 mg/l
C_s	8.8		
Temperature	25°C		
O_2 Uptake	76 mg/l		

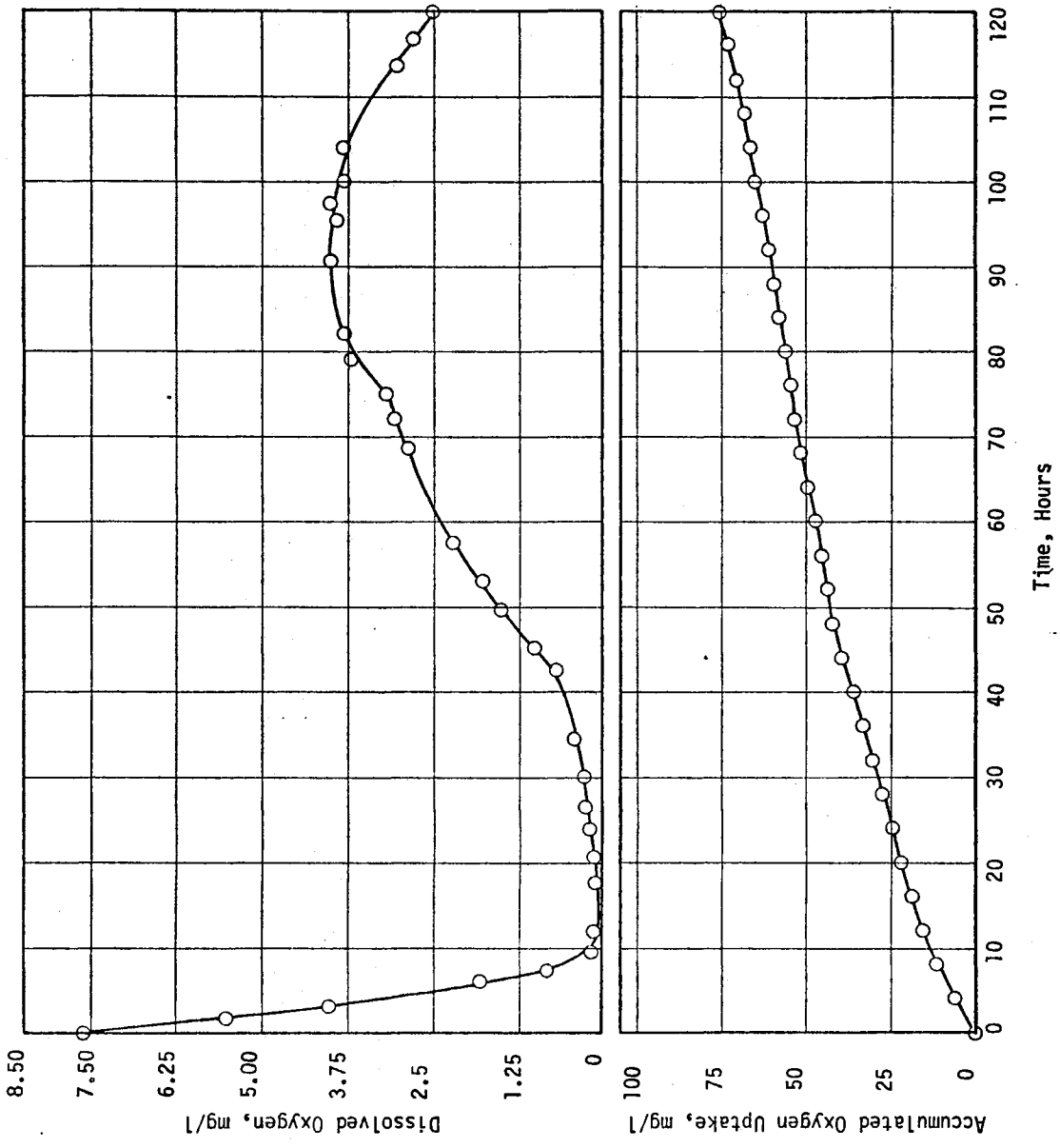
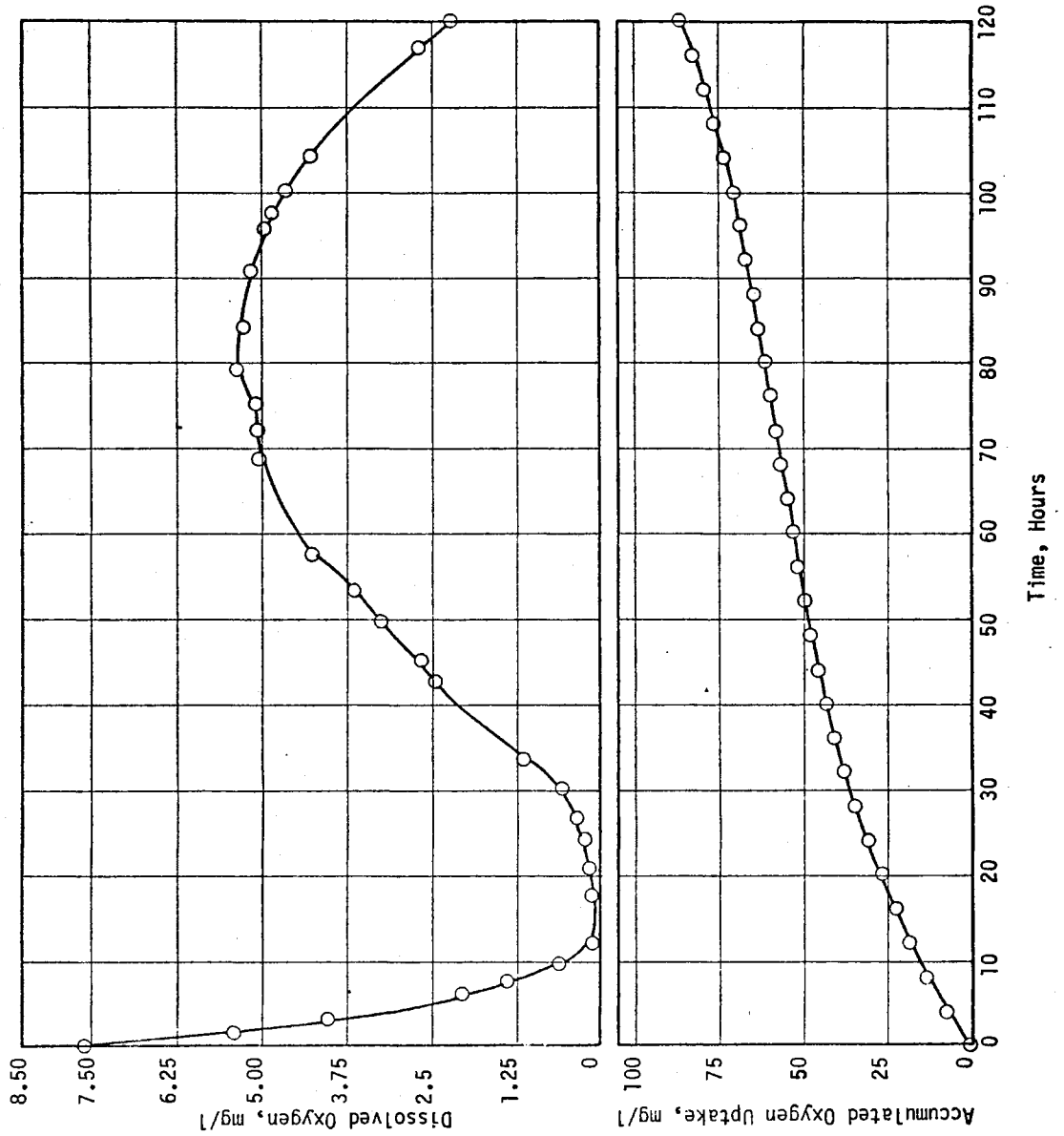

Dissolved Oxygen, mg/l
8.50
7.50
6.25
5.00
3.75
2.5
1.25
0
Accumulated Oxygen Uptake, mg/l
100
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

Figure 4. DO Profile and O_2 Uptake Curves for a Primary Effluent From the Stillwater Wastewater Treatment Plant With the Open Jar Reactor Operating at K_2 = 0.117 hr^{-1}

Effluent Characteristics:		Initial	Final
Filtrate COD		43 mg/l	47 mg/l
Total COD		114 mg/l	67 mg/l
Biological Solids		56 mg/l	20 mg/l
NO_3-N		0.000 mg/l	2 mg/l
C_s	8.8		
Temperature	25°C		
O_2 Uptake	85 mg/l		


Dissolved Oxygen, mg/l
8.50
7.50
6.25
5.00
3.75
2.5
1.25
0
Accumulated Oxygen Uptake, mg/l
100
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

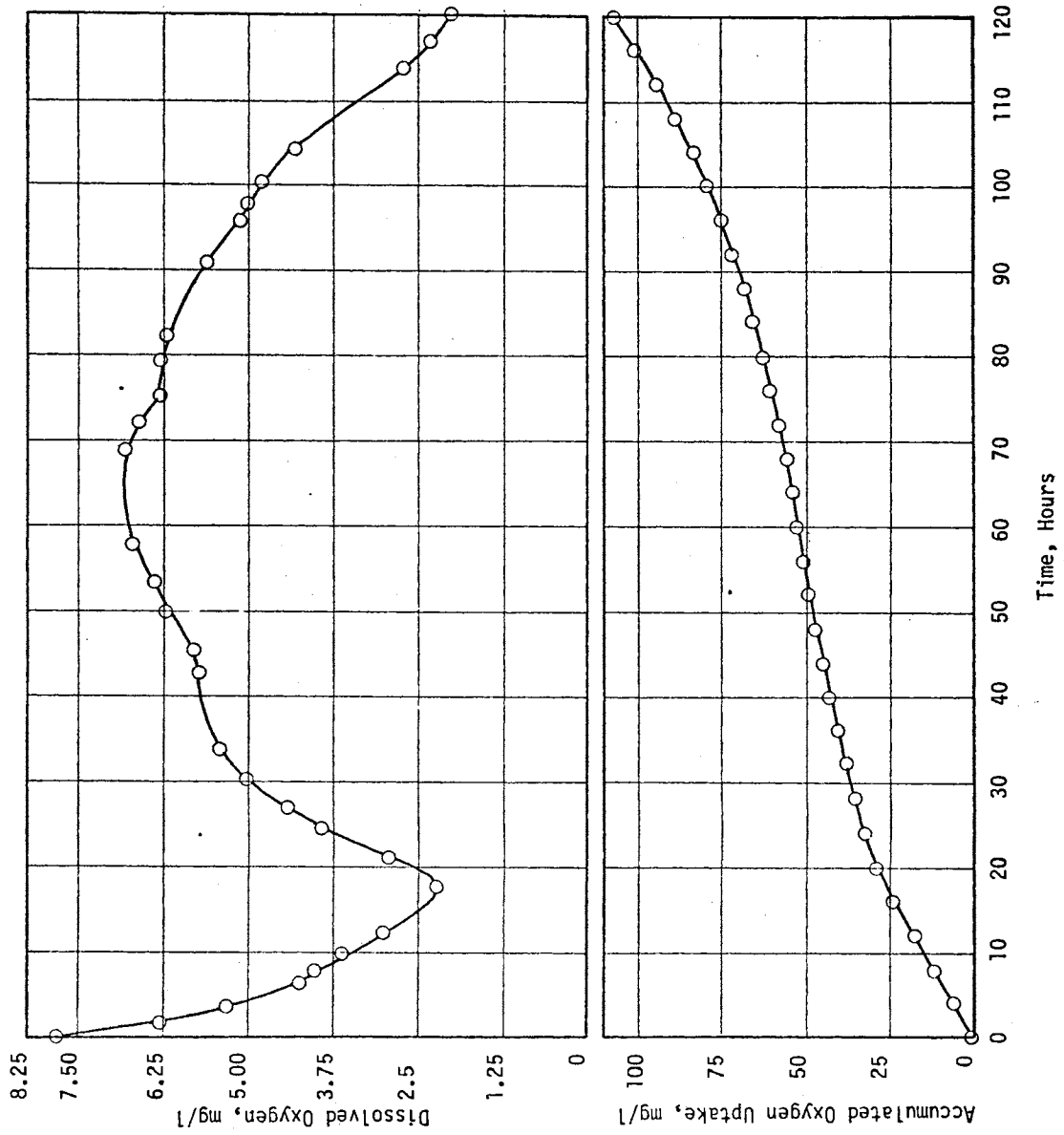
O_2 uptake in Figure 3 was less than for this experiment with a higher reaeration rate.

Figure 5 shows the results of the experiment conducted with a K_2 of 0.217 hr^{-1}. The sample of primary effluent was the same as that employed for the experiments shown in Figures 3 and 4. As with the previous two experiments, it is seen that the higher the K_2, the longer it takes to attain the minimum DO. Also, the recovery phase is faster, in this case reaching a higher intermediate DO concentration before the start of the secondary sag. The soluble organic substrate was initially 47 mg/l measured as COD, and was reduced to a value of 35 mg/l, whereas suspended solids decreased from 56 mg/l to 12 mg/l. An oxygen uptake of 106 mg/l was attained. There was an increase in NO_3-N concentration of 5 mg/l.

Figures 3, 4, and 5 show that higher values of reaeration rates gave higher O_2 uptake values. This confirms the results obtained by Peil and Gaudy (22). As would be expected, as the K_2 increased, it took a longer time to reach the minimum point of the sag, but the recovery was rather fast with increased reaeration rate. The reason for the secondary uptake cannot be discerned from these studies. It could be due partially to nitrification and partially to secondary organotrophic uptake. It is interesting to compare the accumulated O_2 uptake at the time of recovery from the first phase of uptake. For example, in Figure 3, the DO recovered at approximately 90 hours (see the DO profile) at the time O_2 uptake was 60 mg/l. Similarly, in Figures 4 and 5, recovery at 80 hours yielded an O_2 uptake of 61 mg/l (Figure 4), and at 70 hours, approximately 57 mg/l O_2 (Figure 5). Thus, the first phase of uptake was approximately the same regardless of the K_2.

Figure 5. DO Profile and O_2 Uptake Curves for a Primary Effluent From the Stillwater Wastewater Treatment Plant With the Open Jar Reactor Operating at K_2 = 0.217 hr^{-1}

Effluent Characteristics:		Initial	Final
Filtrate COD		47 mg/l	35 mg/l
Total COD		122 mg/l	71 mg/l
Biological Solids		56 mg/l	12 mg/l
NO_3-N		5 mg/l	10 mg/l
C_s	8.8		
Temperature	25°C		
O_2 Uptake	106 mg/l		


Dissolved Oxygen, mg/l
8.25
7.50
6.25
5.00
3.75
2.5
1.25
0
Accumulated Oxygen Uptake, mg/l
100
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

However, the rate at which these values were approached was slightly higher as K_2 was increased, since less time was required to attain recovery. In no case was there any approach to first-order increasing rate kinetics in the first phase of O_2 uptake.

Secondary Clarifier Effluent. Effluent from the secondary clarifier of the Stillwater wastewater treatment plant (trickling filter) was also employed. Shown in Figure 6 are the DO sag and O_2 uptake on a system which initially contained 52 mg/l of soluble organic material, 16 mg/l of suspended solids, total organic content of 68 mg/l measured as COD. The reaeration rate was 0.086 hr^{-1}. The oxygen uptake exerted in five days (120 hours) was 30 mg/l. DO profile showed an initial sag and then slowly started to recover. Before it recovered fully, a secondary sag started from which the DO did not recover in five days. After 120 hours, the soluble COD decreased to 48 mg/l and the biological solids decreased by 8 mg/l. The total COD decreased by 16 mg/l. Unfortunately, nitrification data were not obtained in this experiment.

Shown in Figure 7 is the oxygen uptake and DO profile of a sample of secondary effluent which was the same as that in Figure 6; however, a higher reaeration rate (0.090 hr^{-1}) was employed. The sample had initial suspended solids concentration of 20 mg/l, soluble organic material of 44 mg/l, with total organic content of 72 mg/l measured as COD. The DO profile after an initial decrease did not show any increasing trend as in Figure 6, but it stayed almost constant for about 12 hours before the start of a secondary phase of uptake. After the secondary phase of uptake, the DO was well on the way to recovery at the termination of the experiment. After five days, there was a decrease

Figure 6. DO Profile and O_2 Uptake Curves for a Secondary Clarifier Effluent From the Stillwater Wastewater Treatment Plant With the Open Jar Reactor Operating at K = 0.086 hr^{-1}

Effluent Characteristics:		Initial	Final
Filtrate COD		52 mg/l	48 mg/l
Total COD		68 mg/l	52 mg/l
Biological Solids		16 mg/l	8 mg/l
C_s	8.6		
Temperature	25°C		
O_2 Uptake	30 mg/l		

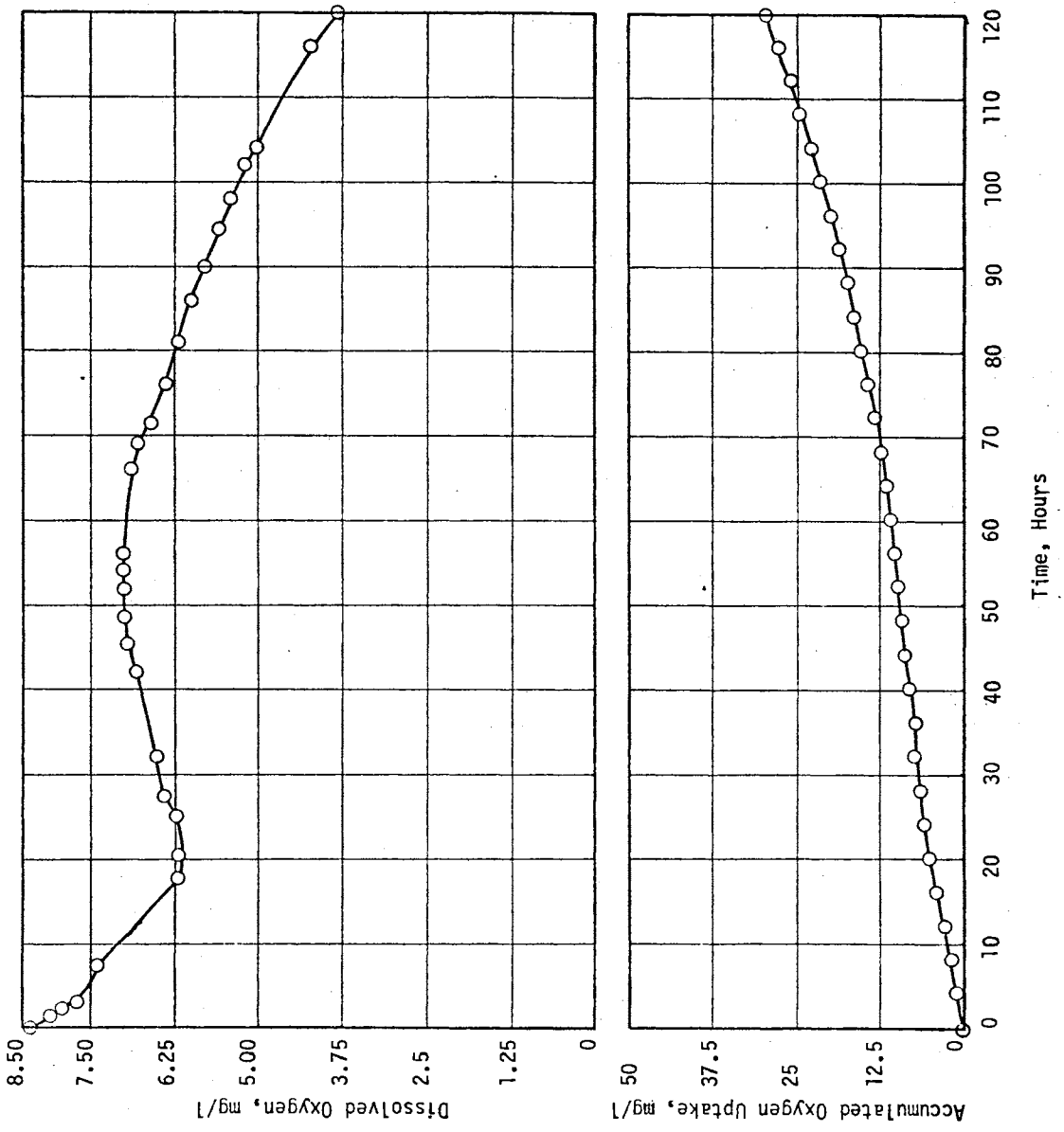
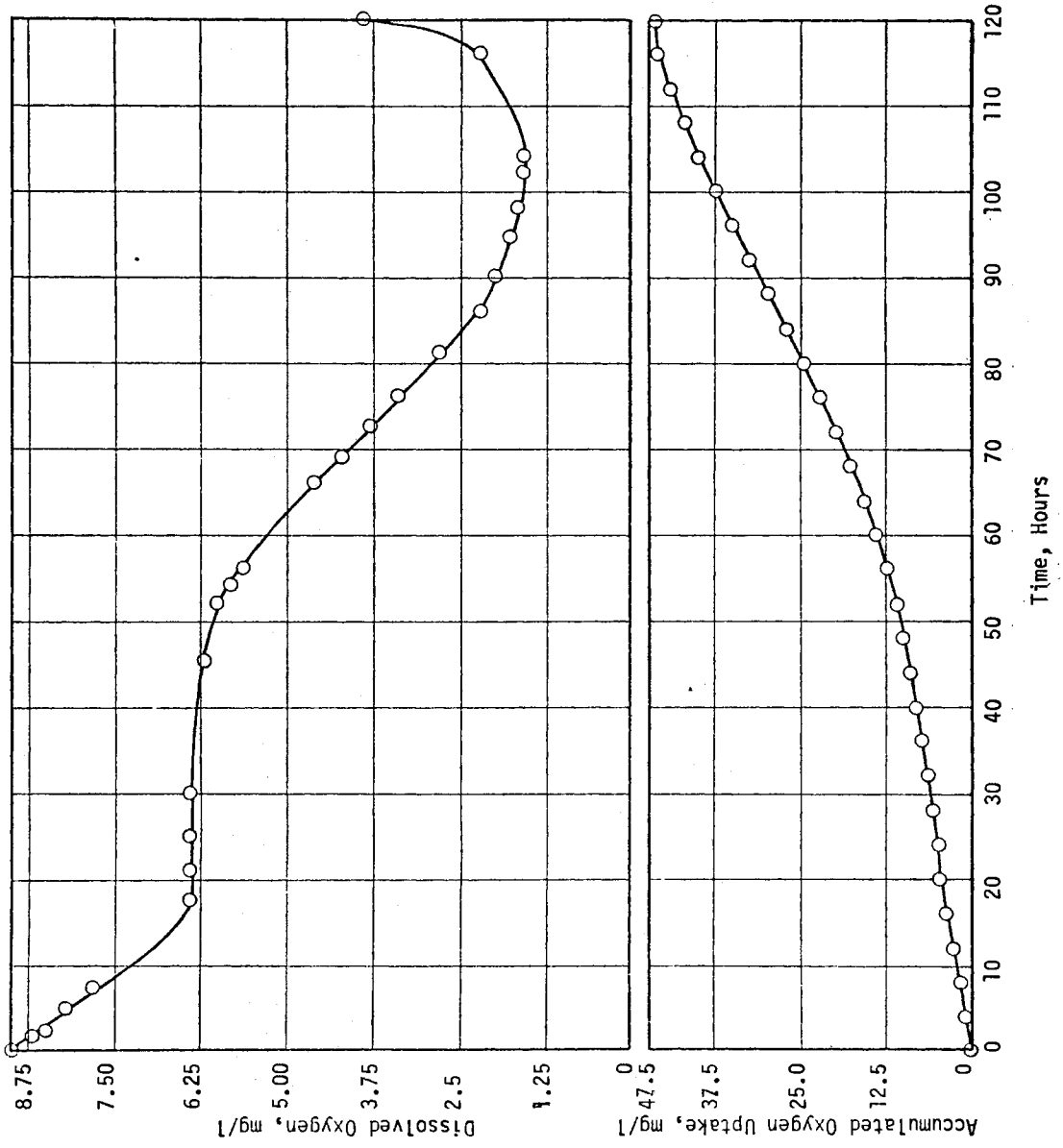

Dissolved Oxygen, mg/l
8.50
7.50
6.25
5.00
3.75
2.5
1.25
0
Accumulated Oxygen Uptake, mg/l
50
37.5
25
12.5
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

Figure 7. DO Profile and O_2 Uptake Curves for a Secondary Clarifier Effluent From the Stillwater Wastewater Treatment Plant With the Open Jar Reactor Operating at K = 0.09 hr^{-1}

Effluent Characteristics		Initial	Final
Filtrate COD		44 mg/l	41 mg/l
Total COD		72 mg/l	60 mg/l
Biological Solids		20 mg/l	8 mg/l
C_s	8.4		
Temperature	25°C		
O_2 Uptake	46 mg/l		


Dissolved Oxygen, mg/l
8.75
7.50
6.25
5.00
3.75
2.5
1.25
0
Accumulated Oxygen Uptake, mg/l
47.5
37.5
25.0
12.5
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

in suspended solids by 12 mg/l, and in total COD by 12 mg/l. The oxygen uptake exerted was 46 mg/l. As for the previous experiment, it is unfortunate that NO_3-N was not run, but it seems likely that a significant uptake was due to nitrification.

Treated Slaughterhouse Waste Effluent. The blood waste effluent was taken from the extended aeration pilot plant of Mr. Sujarittanonta, which was operating with feed concentration of 1583 mg/l as COD on June 27, 1974. The filtrate COD of the effluent was 29 mg/l. The biological solids concentration in the effluent sample was raised from an original value of 22 mg/l to a value of 124 mg/l. In this experiment, the K_2 was 0.113 hr^{-1}; the results are shown in Figure 8. The DO profile showed a fast recovery. The oxygen uptake was essentially completed within 100 hours. The total COD decreased by 33 mg/l (from 169 mg/l to 136 mg/l); the biological solids decreased by 100 mg/l, and soluble organic material decreased from 29 mg/l to 20 mg/l. Total value of O_2 uptake exerted was 59 mg/l. Another sample was taken with the feed concentration of 1543 mg/l as COD on July 10 from the same unit, shown in Figure 9. The biological solids in the effluent on that day was 26 mg/l, with soluble organic material in the effluent of 28 mg/l measured as COD. The biological solids concentration in the effluent sample was raised to 168 mg/l in the open stirred reactor by adding the aeration tank solids from the extended aeration pilot plant to 168 mg/l. There was a rather sharp decrease in DO, but recovery of the DO profile was very slow. The total COD in the system decreased by 37 mg/l from an initial value of 224 mg/l to a final value of 187 mg/l, and the biological solids concentration decreased by only 8 mg/l. The

Figure 8. DO Profile and O_2 Uptake Curves for Treated Slaughterhouse Waste Effluent With the Open Jar Reactor Operating at K_2 = 0.113 hr^{-1}

Effluent Characteristics:		Initial	Final
Filtrate COD		29 mg/l	20 mg/l
Total COD		169 mg/l	136 mg/l
Biological Solids		124 mg/l	24 mg/l
C_s	8.8		
Temperature	25°C		
O_2 Uptake	59 mg/l		

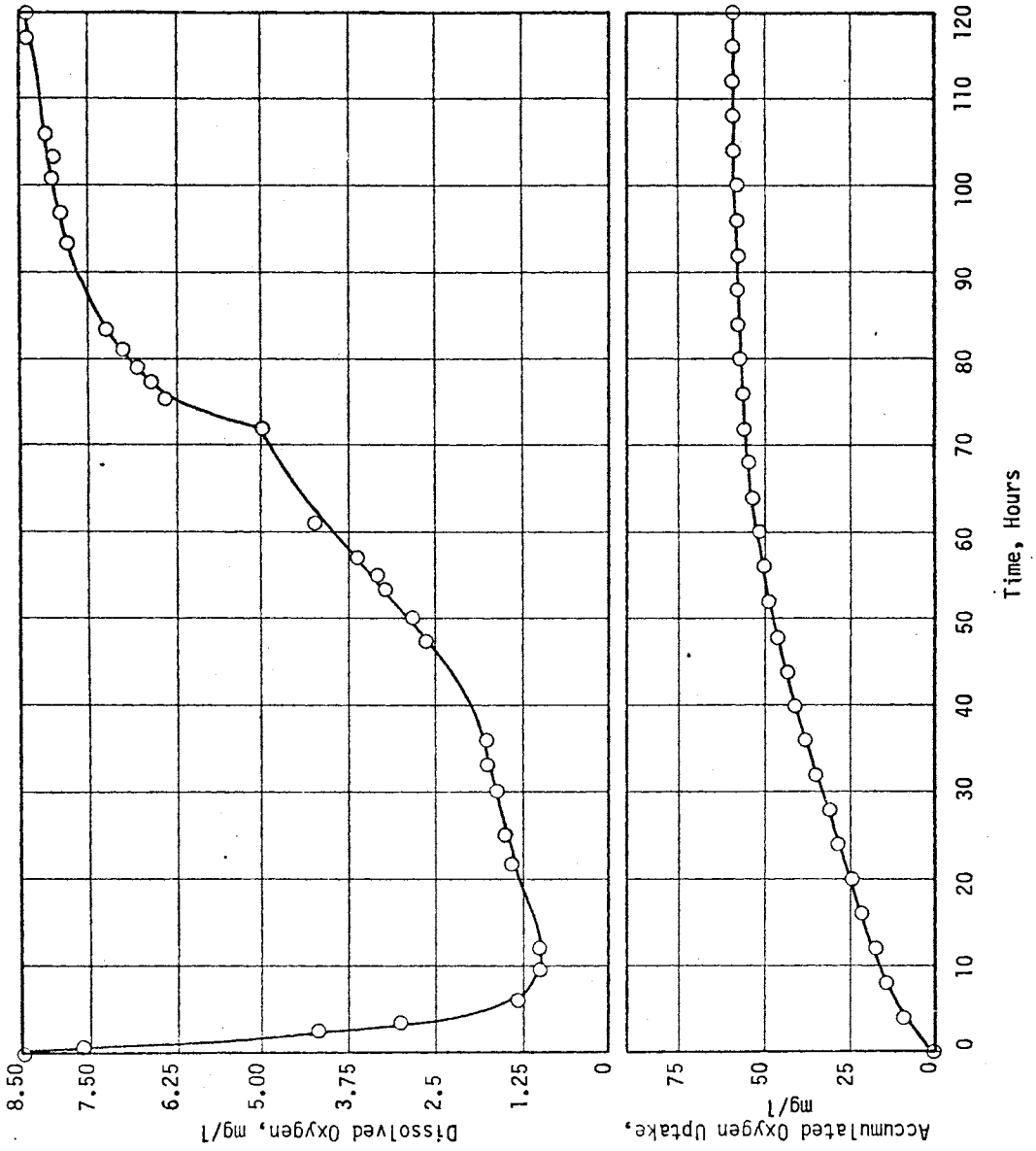
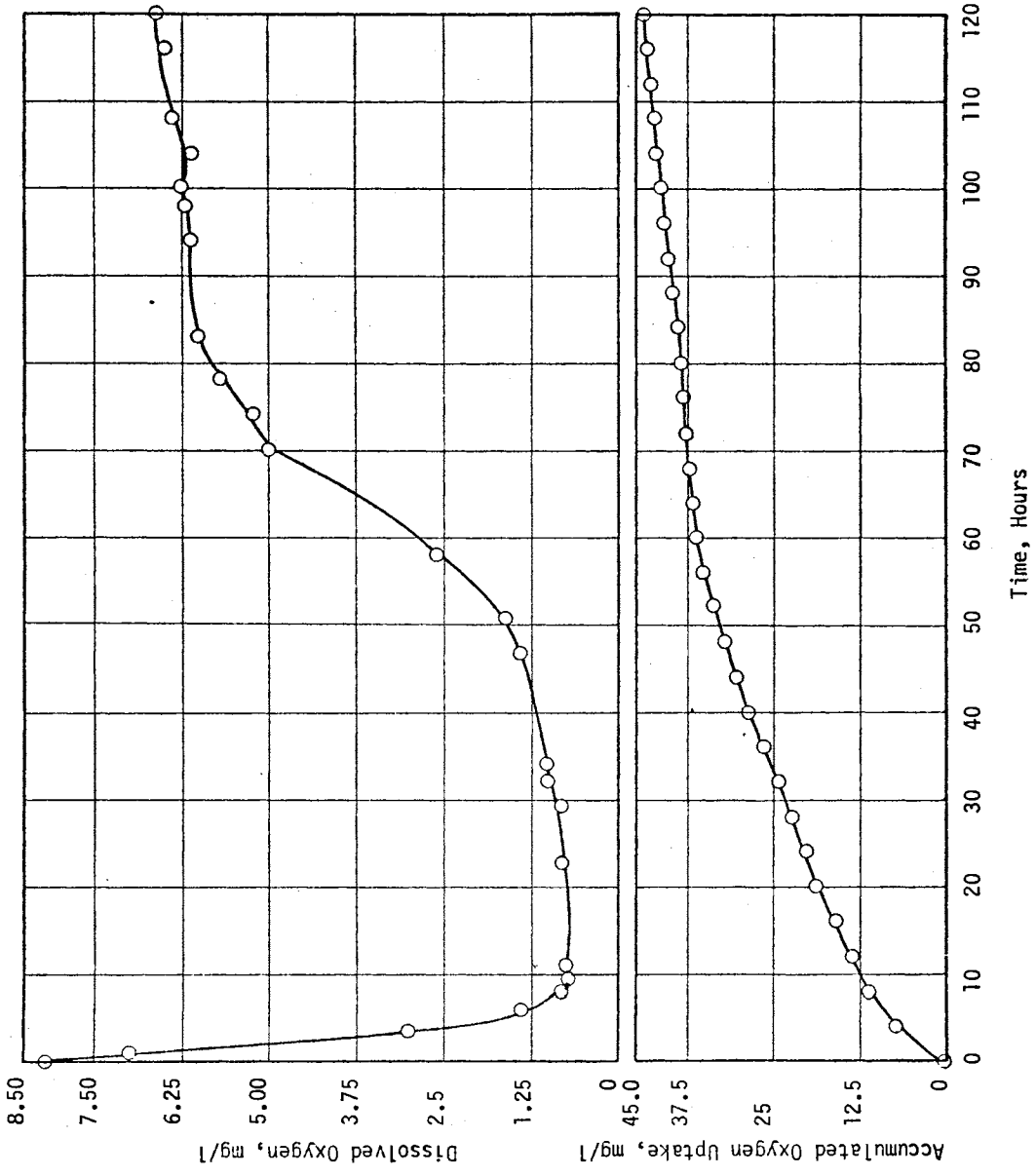

Dissolved Oxygen, mg/l
8.50
7.50
6.25
5.00
3.75
2.5
1.25
0
Accumulated Oxygen Uptake, mg/l
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

Figure 9. DO Profile and O_2 Uptake Curves for Treated Slaughterhouse Waste Effluent in the Open Jar, the Reactor Operating at $K_2 = 0.072\ hr^{-1}$

Effluent Characteristics:		Initial	Final
Filtrate COD		28 mg/l	28 mg/l
Total COD		224 mg/l	187 mg/l
Biological Solids		168 mg/l	160 mg/l
NO_3-N		33 mg/l	38 mg/l
C_s	8.4		
Temperature	25°C		
O_2 Uptake	44 mg/l		


Dissolved Oxygen, mg/l
8.50
7.50
6.25
5.00
3.75
2.5
1.25
0
Accumulated Oxygen Uptake, mg/l
45.0
37.5
25
12.5
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

system was operated at a K_2 value of 0.072 hr^{-1} and an oxygen uptake exerted was 44 mg/l in five days. Slow recovery might have been due to nitrification (NO_3-N increased from 33 mg/l to 38 mg/l). The level of soluble COD was unchanged.

Phase II

Open jar studies were conducted on the effluent of the extended aeration pilot plant. The pilot plant operation was started by Murthy (23) to investigate the possibility of nitrification in the hydrolytically assisted extended aeration process at high organic loadings. He operated the unit for 174 days (i.e., from September 7, 1973, to February 27, 1974). Thereafter it was operated jointly by the author and Murthy, and finally by the author alone. A feed of 2000 mg/l + hydrolysate was gradually reduced to 500 mg/l of glucose + hydrolysate from day 174 to day 189.

Figures 10 through 14 are a detailed presentation of 364 days performance of the pilot plant while undergoing weekly hydrolysis and refeeding. As shown in Figure 10, the biological solids decreased in a few weeks from 10,000 mg/l to 6000 mg/l. There was no appreciable leakage of suspended solids. The purification efficiency based on filtered COD was often as high as 90 percent; however, the unit was not producing a highly nitrified effluent during this period. Murthy had reported that at the 2000 mg/l glucose level, nitrification was not obtained. Now at the reduced loading, it appeared that time would be required before the return to nitrification. On day 204, there was significant leakage of substrate and also biological solids in the effluent. The biological solids concentration, X, in the system

Figure 10. Operational Characteristics of the Hydrolytically-Assisted Extended Aeration Pilot Plant From Day 175 to Day 214 (February 28, 1974, to April 8, 1974)

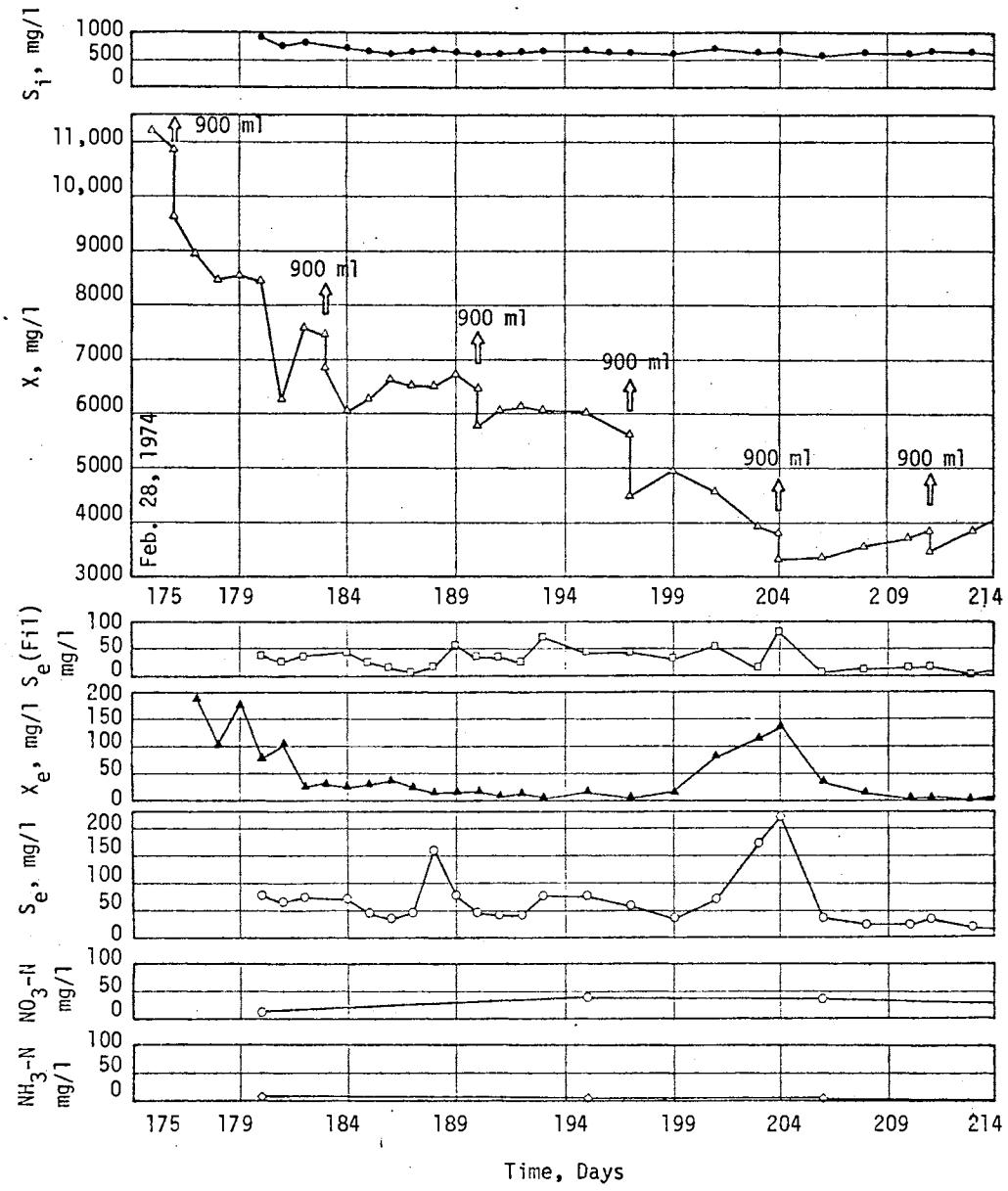

S_i, mg/l
1000
500
0
X, mg/l
11,000
10,000
9000
8000
7000
6000
5000
4000
3000
900 ml
900 ml
900 ml
900 ml
900 ml
900 ml
Feb. 28, 1974
S_e(Fil) mg/l
100
50
0
X_e, mg/l
200
150
100
50
0
S_e, mg/l
200
150
100
50
0
NO_3-N mg/l
100
50
0
NH_3-N mg/l
100
50
0
175
179
184
189
194
199
204
209
214
Time, Days

Figure 11. Operational Characteristics of the Hydrolytically-assisted Extended Aeration Pilot Plant From Day 214 to Day 254 (April 8, 1974, to May 18, 1974)

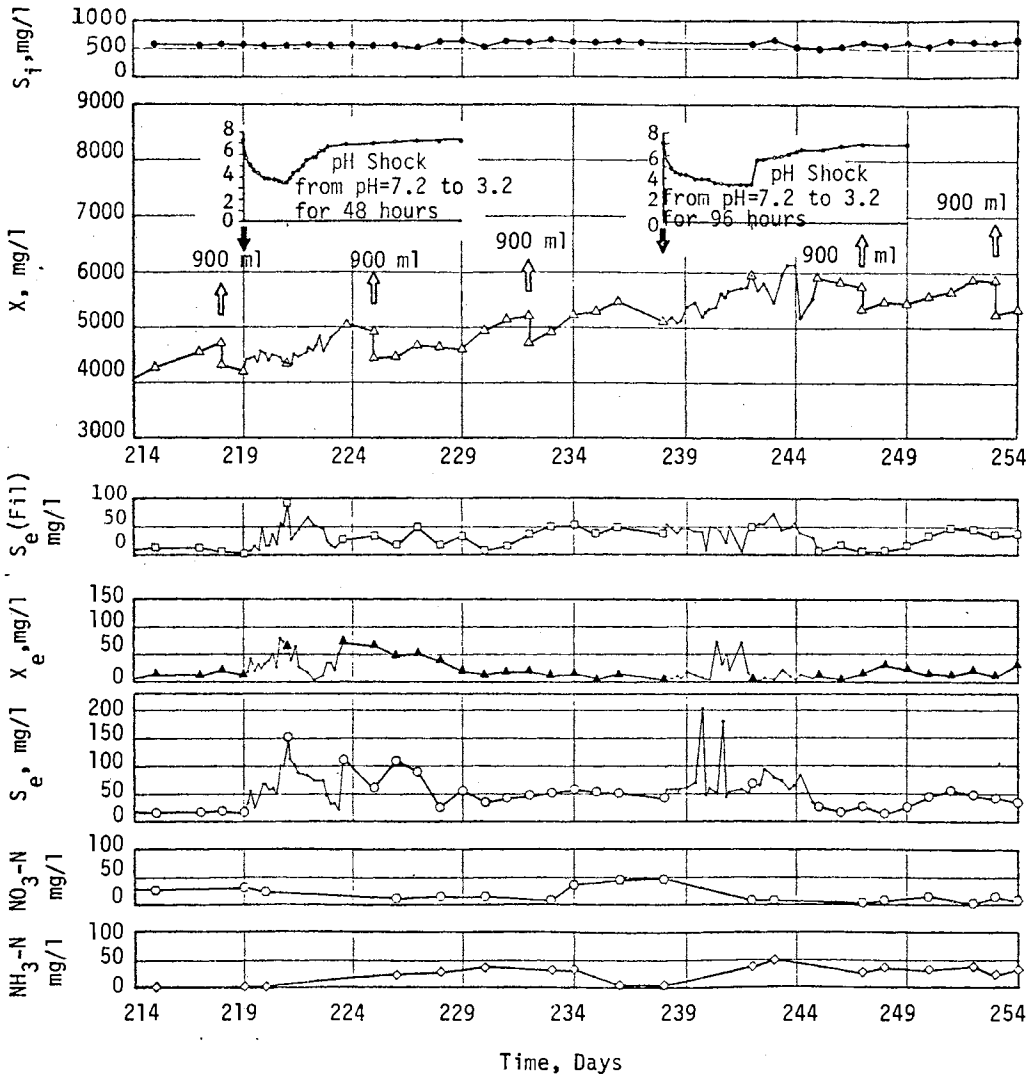

S_i, mg/l
1000
500
0
X, mg/l
9000
8000
7000
6000
5000
4000
3000
pH Shock
from pH=7.2 to 3.2
for 48 hours
pH Shock
from pH=7.2 to 3.2
for 96 hours
900 ml
900 ml
900 ml
900 ml
900 ml
S_e(Fil) mg/l
100
50
0
X_e, mg/l
150
100
50
0
S_e, mg/l
200
150
100
50
0
NO_3-N mg/l
100
50
0
NH_3-N mg/l
100
50
0
214
219
224
229
234
239
244
249
254
Time, Days

Figure 12. Operational Characteristics of the Hydrolytically-Assisted Extended Aeration Pilot Plant From Day 254 to Day 294 (May 18, 1974, to June 27, 1974)

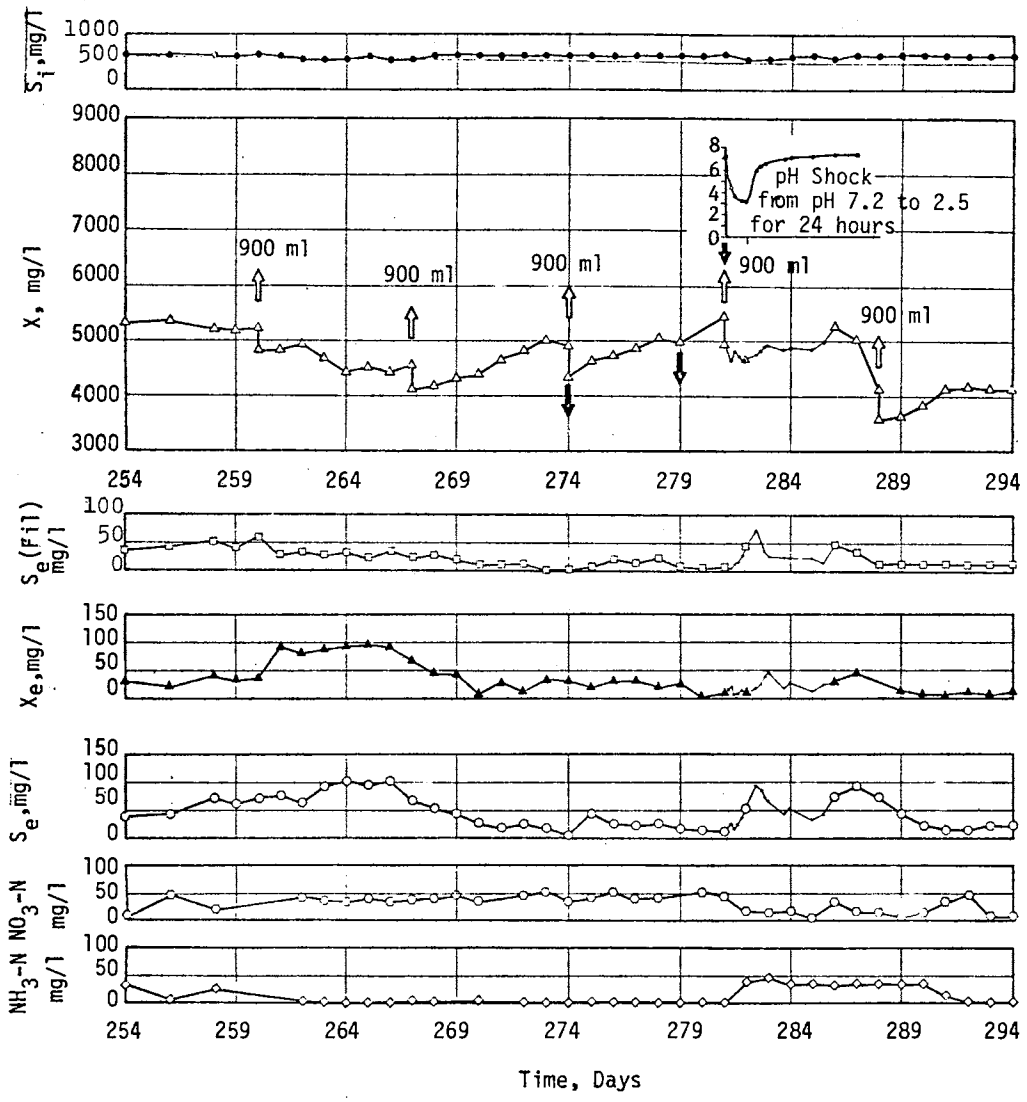

S_i, mg/l
1000
500
0
X, mg/l
9000
8000
7000
6000
5000
4000
3000
900 ml
900 ml
900 ml
900 ml
900 ml
pH Shock
from pH 7.2 to 2.5
for 24 hours
8
6
4
2
0
254
259
264
269
274
279
284
289
294
S_e(Fil) mg/l
100
50
0
X_e, mg/l
150
100
50
0
S_e, mg/l
150
100
50
0
NO_3-N mg/l
100
50
0
NH_3-N mg/l
100
50
0
Time, Days

Figure 13. Operational Characteristics of the Hydrolytically-Assisted Extended Aeration Pilot Plant From Day 294 to Day 334 (June 27, 1974, to August 6, 1974)

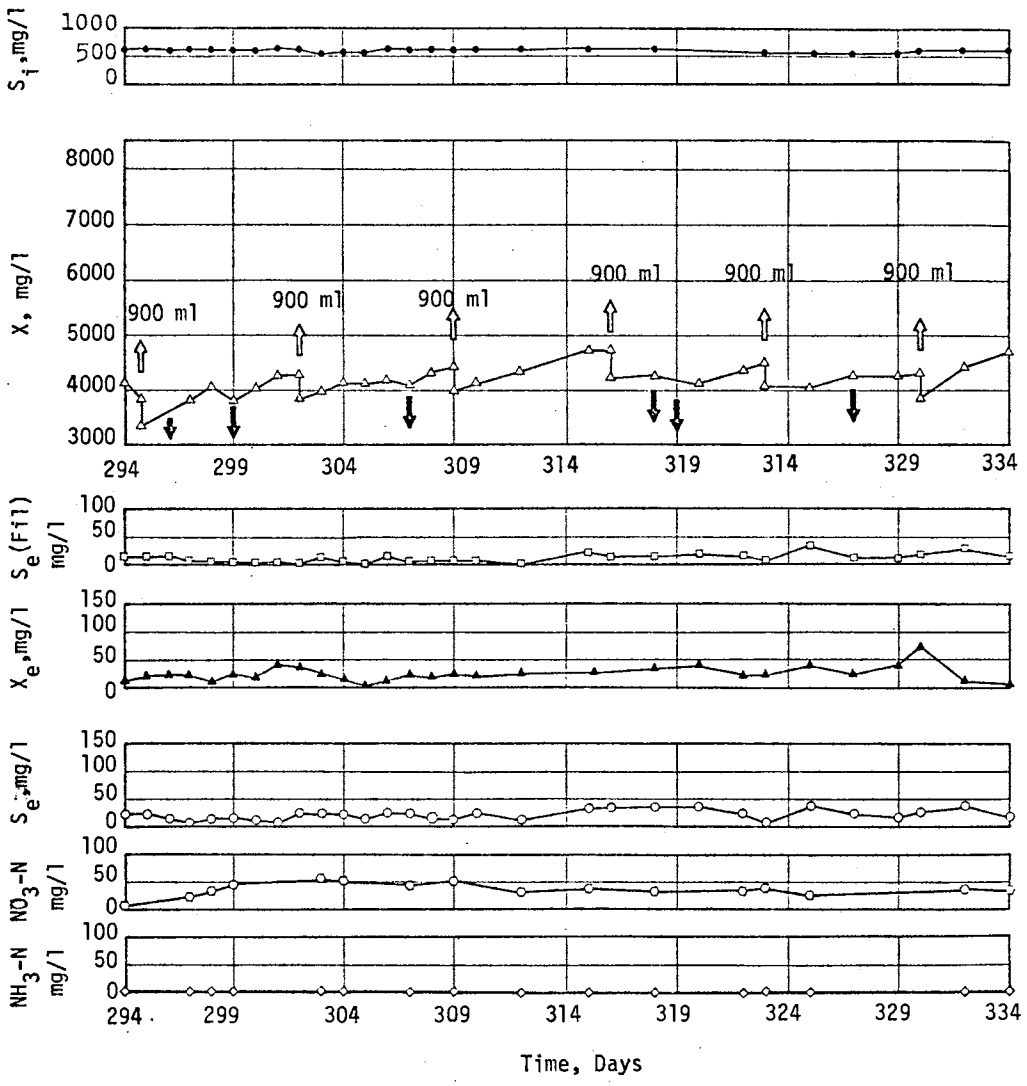
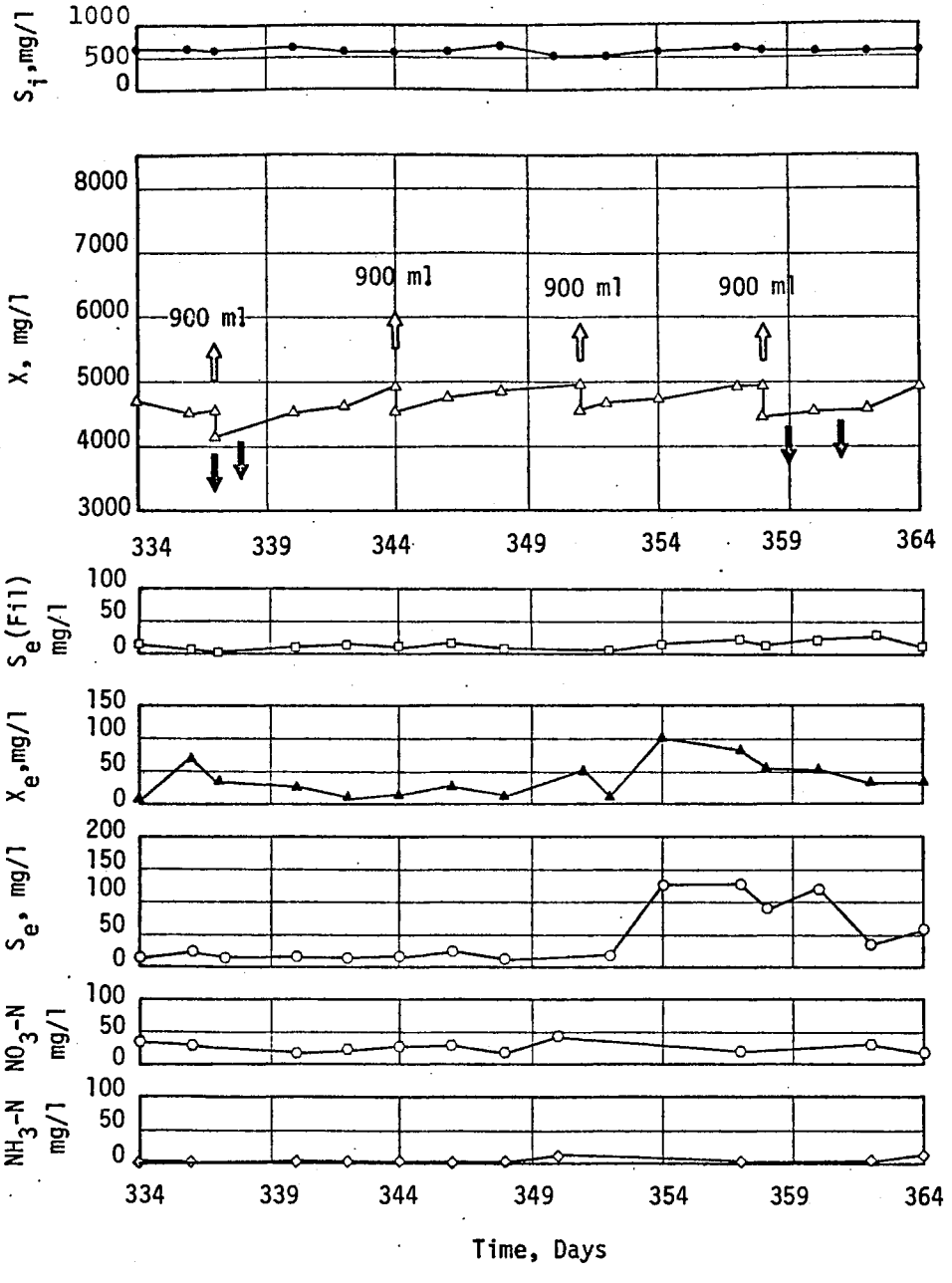

S_i, mg/l
1000
500
0
X, mg/l
8000
7000
6000
5000
4000
3000
900 ml
900 ml
900 ml
900 ml
900 ml
900 ml
S_e(Fil) mg/l
100
50
0
X_e, mg/l
150
100
50
0
S_e, mg/l
150
100
50
0
NO_3-N mg/l
100
50
0
NH_3-N mg/l
100
50
0
294
299
304
309
314
319
324
329
334
Time, Days

Figure 14. Operational Characteristics of the Hydrolytically-Assisted Extended Aeration Pilot Plant From Day 334 to Day 364 (August 6, 1974, to September 5, 1974)


S_i, mg/l
1000
500
0
X, mg/l
8000
7000
6000
5000
4000
3000
900 ml
900 ml
900 ml
900 ml
S_e(Fil) mg/l
100
50
0
X_e, mg/l
150
100
50
0
S_e, mg/l
200
150
100
50
0
NO_3-N mg/l
100
50
0
NH_3-N mg/l
100
50
0
334
339
344
349
354
359
364
Time, Days

decreased to 3500 mg/l. However, between day 204 and day 219, the solids concentration increased to 4600 mg/l. During this increase in solids concentration, the efficiency was above 95 percent, based on the glucose feed and effluent filtrate COD. Also, by this time the NO_3-N in the effluent was running approximately 30 mg/l, whereas the influent NH_3-N concentration in the feed was 53 mg/l.

On day 219, the first pH shock was given to the pilot plant. The shock was held on the system for 48 hours, reducing the pH from 7.2 to 3.2. Because of this shock load, there was a slight leakage of solids in the effluent and the substrate removal efficiency decreased to 90 percent on day 53. Between days 223 to 237, the solids in the system levelled off somewhat at approximately 4800 mg/l, and the nitrification in the unit recovered and attained a value of 43 mg/l; the overall efficiency after the first pH shock and just before the second was observed to be as high as 93 percent. On day 238, the unit was subjected to a prolonged pH shock load for 96 hours, reducing pH from 7.2 to 3.2. There was no appreciable leakage of either solids or substrate in the effluent between days 244 and 250, i.e., just after the shock load efficiency was above 90 percent. It was noticed that about two weeks after putting on the second shock load, the supernatant became turbid; during days 261 to 269, there was leakage of solids, and effluent COD was 80-100 mg/l. One of the methods for control of non-settling sludge previously found to be useful in other studies in our laboratories (26)(27) is the addition of chemical flocculants. Therefore, on day 266, the system received slug doses of ferric chloride. This caused no effect on the purification efficiency as measured by filtrate COD, and on day 272, good settling and clear supernatant were observed

in the settling chamber.

From day 269 to day 281, efficiency of the unit was well above 92 percent. On day 281, the third severe pH shock was given, reducing the pH from 7.2 to 2.5 for 24 hours. There was no appreciable leakage of solids in the effluent, and biological solids levelled off at approximately 4500 mg/l. Again, the shock caused a decrease in nitrification, but the system did again recover and produce a highly nitrified effluent.

Between days 289 to 364, the unit operated rather steadily with respect to effluent quality. During this period, the biochemical efficiency in the system remained above 90 percent based on the filtrate COD, and the effluent concentration and unfiltered COD was very low. In general, the operational performance of the unit was excellent with very good settling characteristics of the sludge in the clarifier. The large arrows (pointed upward) mark the times of removal of 900 ml of sludge for hydrolysis and refeeding to the aeration chamber.

Oxygen Uptake Characteristics of Effluent Taken From an Extended Aeration Pilot Plant Using "Hydrolytically-Assisted" Operation

Twelve tests were made taking effluent from the extended aeration bench scale pilot plant; these times are indicated with inverted arrows on Figures 11 through 14, and the results are shown in Figures 15 through 26. In all of these experiments, initial biological solids concentrations were increased by adding the MLSS (mixed liquor suspended solids) from the aeration chamber of the pilot plant. In general, the pilot plant was producing such a good effluent that the O_2 uptake was almost too low to study and the addition of MLSS was decided upon

in order to simulate a condition wherein biological solids were escaping in the effluent. The results are presented in chronological order.

Shown in Figure 15 is one effluent taken during the 274th day of operation of the pilot plant, and biological solids from the aeration chamber were added so that the initial concentration was increased to 208 mg/l and the filtrate COD was 12 mg/l. The reactor was operated at a reaeration rate of 0.125 hr^{-1}, and a corresponding saturation value of 84 mg/l. At this K_2, the system yielded an O_2 uptake (5-day BOD) of 26 mg/l, for which the reduction in the total COD was 9 mg/l--i.e., from 190-181 mg/l--and the biological solids in the system increased by 40 mg/l from 208 to 248 mg/l. The dissolved oxygen profile showed an initial decrease in DO within eight hours, but failed to recover during the period of the experiment, giving an almost straight line kinetic for O_2 uptake. Similarly, in Figure 16, the initial biological solids were increased to 280 mg/l for the effluent taken on the 279th day of operation. In this experiment, the biological solids decreased to 248 mg/l and the reduction of total COD was 20 mg/l (298-278 mg/l). The O_2 uptake exerted was 82 mg/l at a reaeration rate constant of 0.163 hr^{-1}, and saturation value of 8.4 mg/l. The DO sag was well rounded, unlike that shown in Figure 15; however, the system did not recover all of the DO.

The above two figures show that the O_2 uptake was not fully comparable to the reduction in the total COD during the experiment, and other substances like nitrogen resources of the stream might be exerting the O_2 uptake. So in the following experiments, the nitrification characteristics were determined.

Figure 17 gives the O_2 uptake characteristics of a sample of

Figure 15. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at K_2 = 0.125 hr^{-1}

Effluent Characteristics:

Extended Aeration Effluent
Day of Operation, 274 (June 7, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	12 mg/l	36 mg/l
Total COD, S_e =	190 mg/l	181 mg/l
Biological Solids, X_e =	208 mg/l	248 mg/l
NO_3-N =	-	-

Temperature, 25°C
Total O_2 Uptake, 26 mg/l

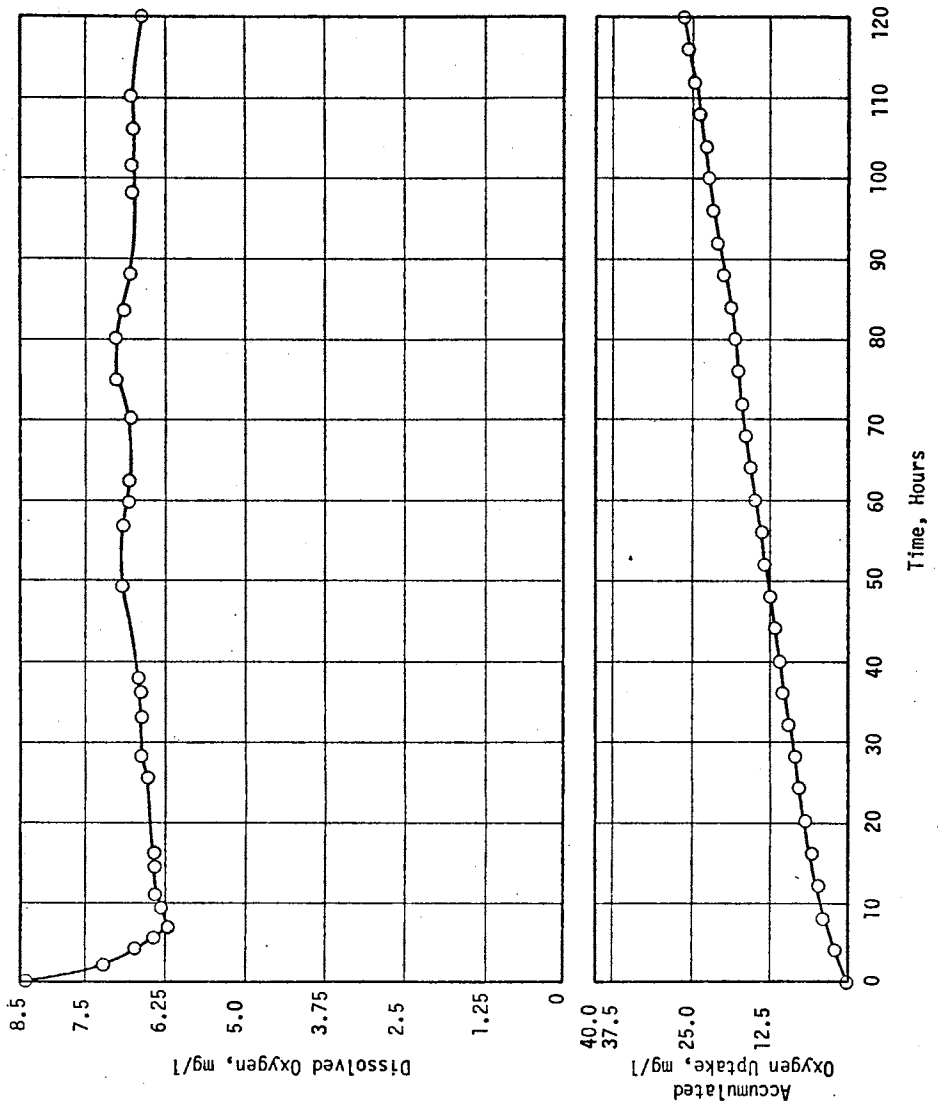

Dissolved Oxygen, mg/l
8.5
7.5
6.25
5.0
3.75
2.5
1.25
0
Accumulated
Oxygen Uptake, mg/l
40.0
37.5
25.0
12.5
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

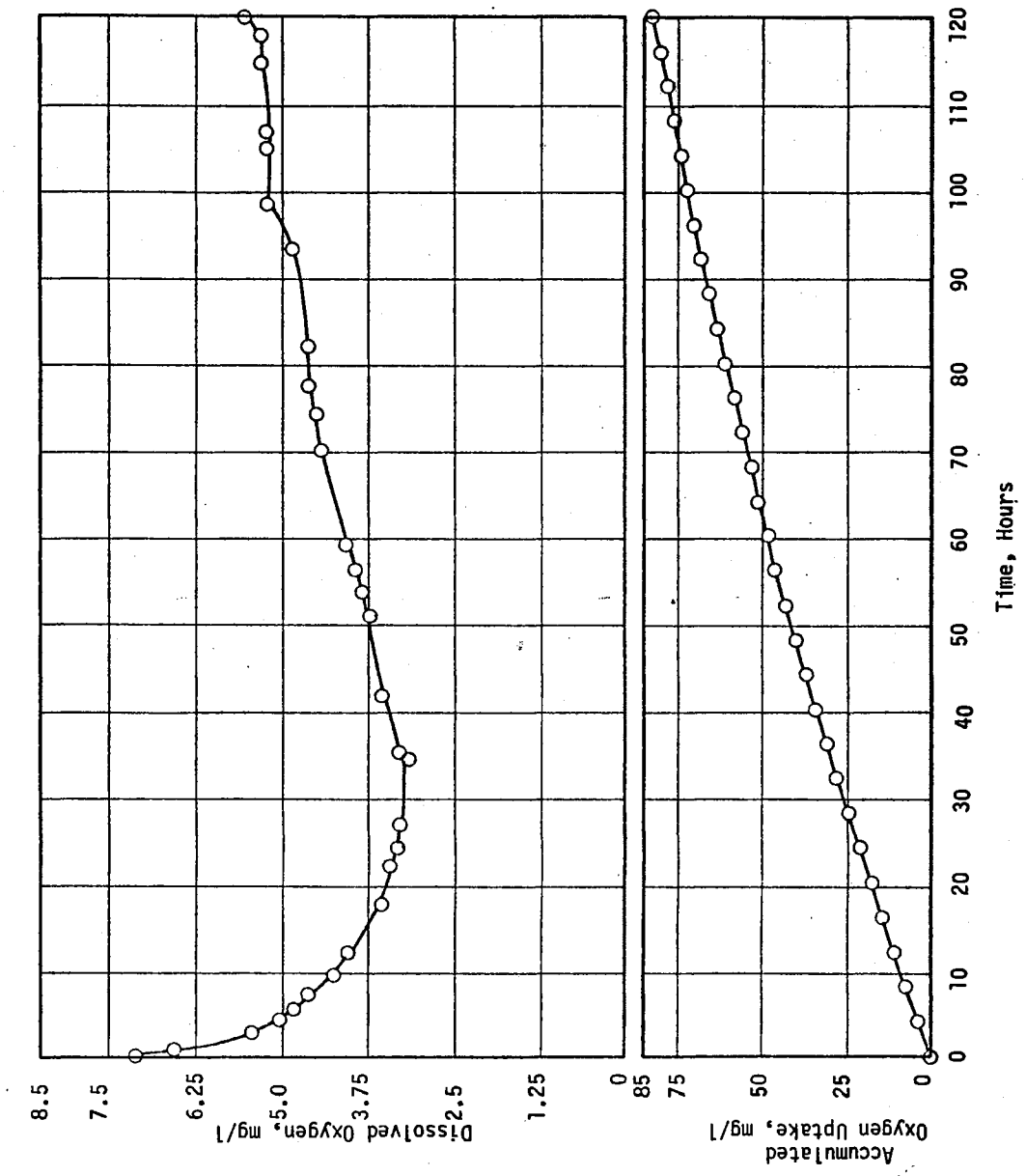
Figure 16. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at K_2 = 0.163 hr^{-1}

Effluent Characteristics:

Extended Aeration Effluent
Day of Operation, 279 (June 12, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	28 mg/l	24 mg/l
Total COD, S_e =	298 mg/l	278 mg/l
Biological Solids, =	280 mg/l	248 mg/l

Temperature, 25°C
Total O_2 Uptake, 82 mg/l


Dissolved Oxygen, mg/l
8.5
7.5
6.25
5.0
3.75
2.5
1.25
0
Accumulated
Oxygen Uptake, mg/l
85
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

effluent taken during the 296th day of operation; in this case, biological solids in the system were raised to 114 mg/l by addition of MLSS. After five days, the concentration of biological solids was 128 mg/l, and the total COD increased from 151 mg/l to 167 mg/l. NO_3-N concentration was increased from an initial 23 mg/l to a final value of 47 mg/l. The total oxygen uptake (5-day BOD) was 32 mg/l with a K_2 of 0.11 hr^{-1} at a C_s of 84 mg/l. On day 299, another sample was taken for open jar O_2 uptake assessment, and the biological solids were increased to 176 mg/l; the results are shown in Figure 18. After five days, the biological solids remained at the same level (172 mg/l) but the total COD decreased from 200 mg/l to 163 mg/l. In this experiment, NO_3-N concentration decreased from 46 mg/l to 38 mg/l, and NH_3-N concentration was nearly zero throughout the experiment. The BOD_5 was 79 mg/l; the reaeration rate was 0.151 hr^{-1}, and the dissolved oxygen saturation value was 8.4 mg/l. The filtrate COD remained at the same level (8 mg/l). The oxygen uptake curve was of the general shape of a first-order-like decreasing rate kinetic, and the DO profile was similar to that of the previous experiment.

Figure 19 is a plot of the dissolved oxygen profile and the accumulated oxygen uptake of a sample taken on day 307 of the pilot plant operation. The initial biological solids were 276 mg/l (after adding some MLSS). After five days, biological solids concentration was reduced to 232 mg/l, and the 5-day uptake was 95 mg/l with a reaeration rate, K_2, of 0.12 hr^{-1} and saturation value of 8.8 mg/l. There was practically no change in the initial and final concentrations of NH_3-N and NO_3-N. Also, the soluble organic material remained almost at the same level. With regard to the DO profile, the DO decreased within

Figure 17. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at K_2 = 0.11 hr^{-1}

Effluent Characteristics:

Extended Aeration Effluent
Day of Operation, 296 (June 29, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	4 mg/l	20 mg/l
Total COD, S_e =	151 mg/l	167 mg/l
Biological Solids, X_e =	114 mg/l	128 mg/l
NO_3-N =	23 mg/l	45 mg/l

Temperature, 25°C
Total O_2 Uptake, 32 mg/l

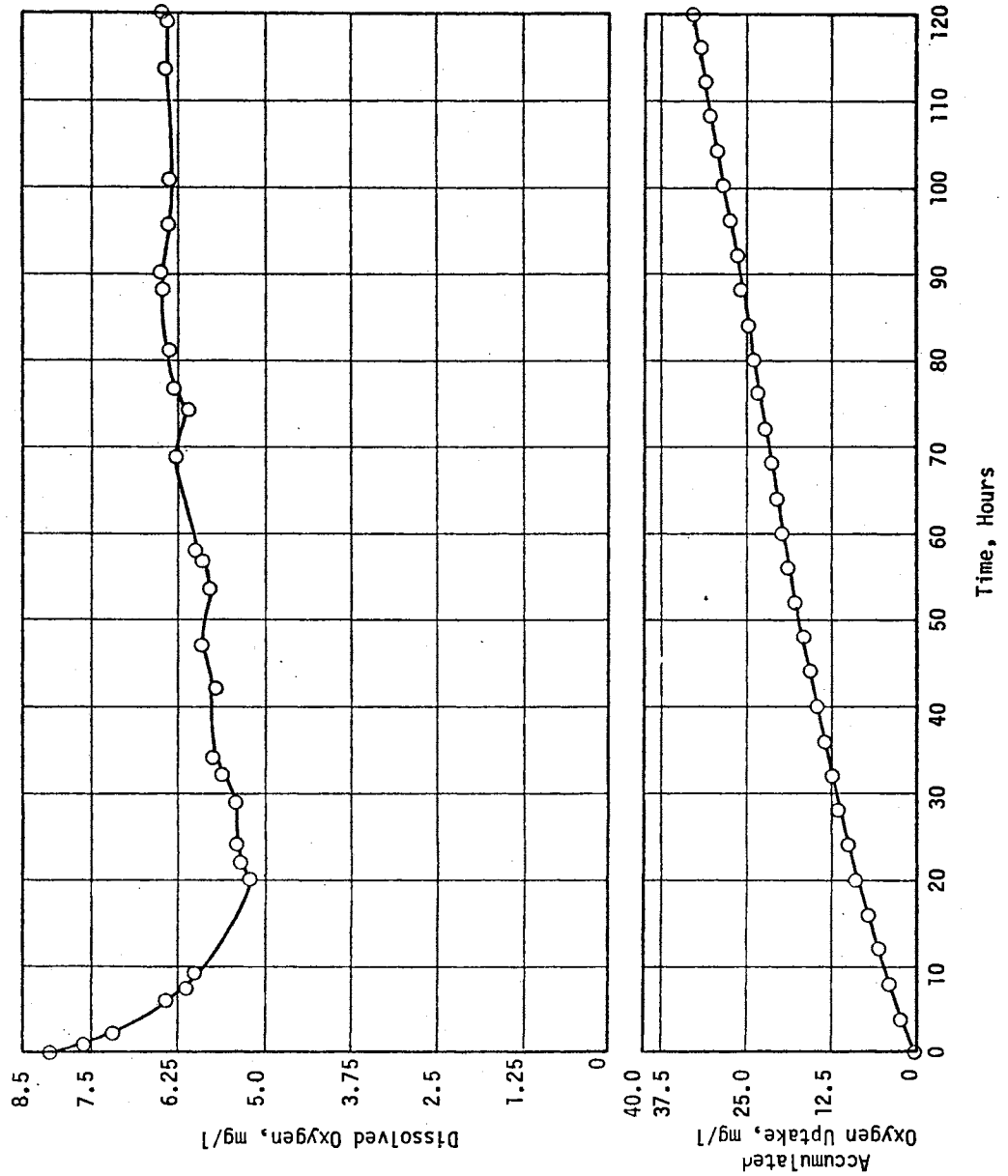

Dissolved Oxygen, mg/l
8.5
7.5
6.25
5.0
3.75
2.5
1.25
0
Accumulated
Oxygen Uptake, mg/l
40.0
37.5
25.0
12.5
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

Figure 18. DO Profile and O_2 Uptake Curves for an Effluent With Open Jar Reactor Operating at K_2 = 0.151 hr^{-1}

Effluent Characteristics:
Day of Operation, 299 (July 2, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	8 mg/l	8 mg/l
Total COD, S_e =	200 mg/l	163 mg/l
Biological Solids, X_e =	176 mg/l	172 mg/l
NO_3-N =	48 mg/l	38 mg/l

Temperature, 25°C
Total O_2 Uptake, 79 mg/l

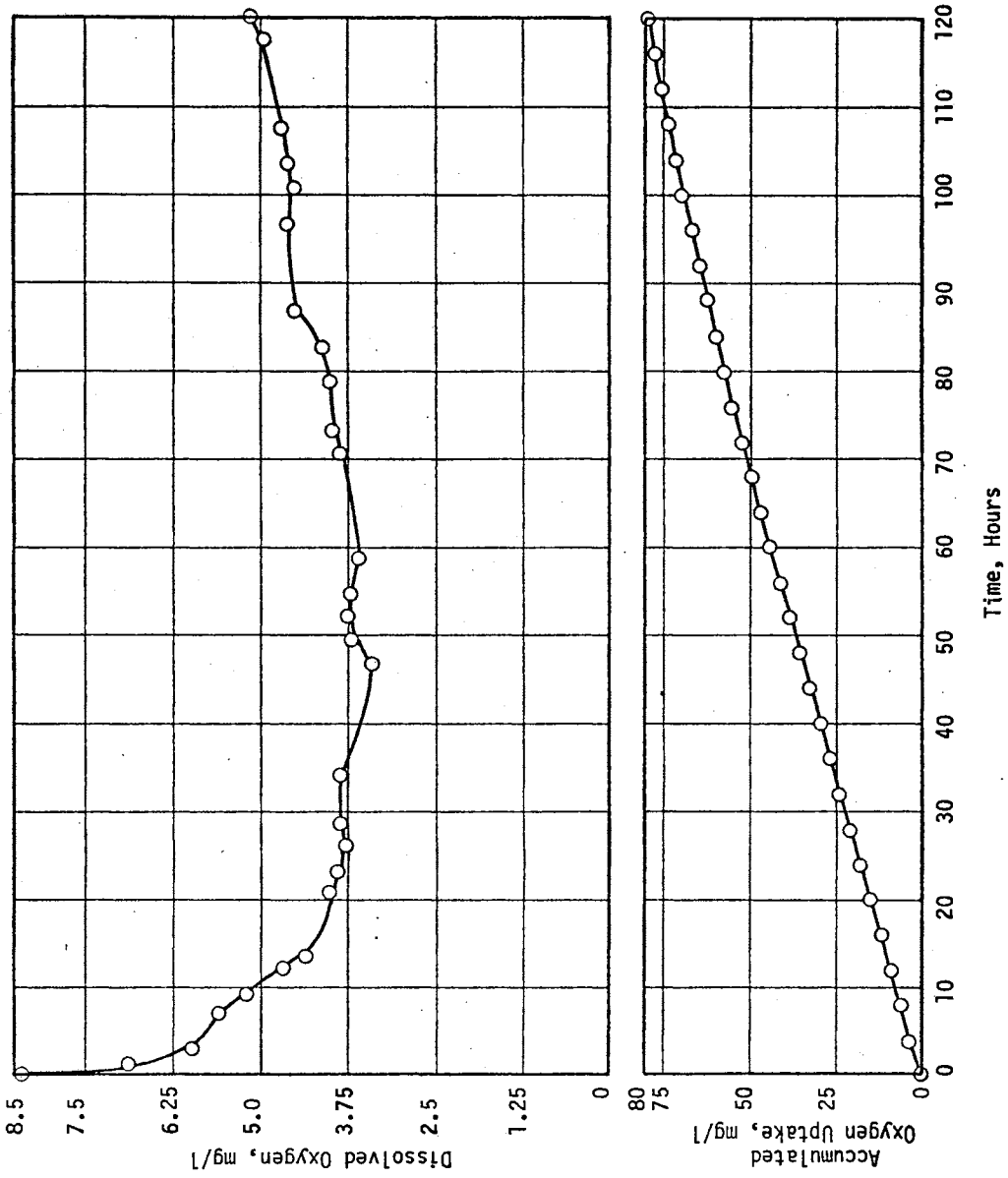
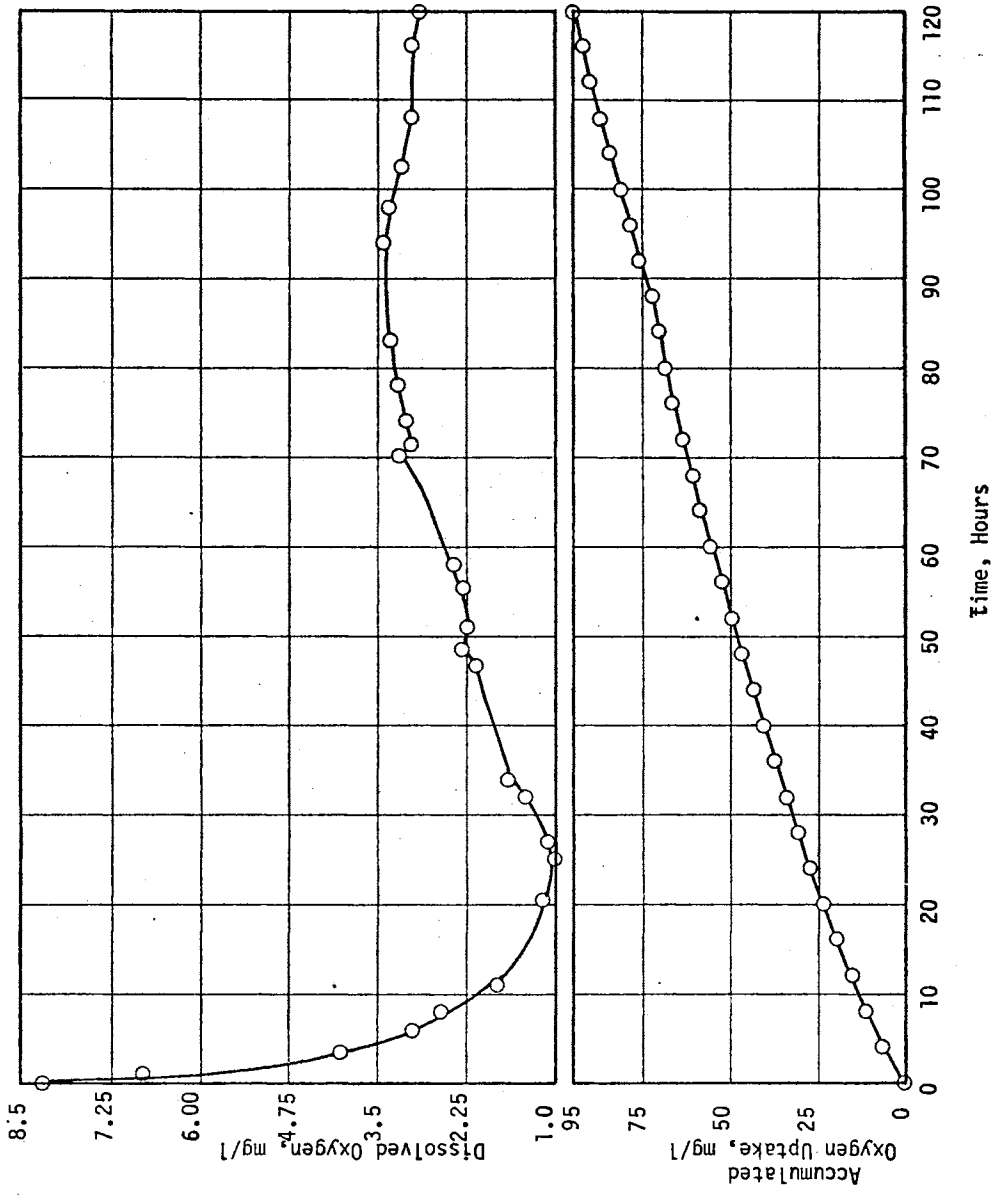

Dissolved Oxygen, mg/l
8.5
7.5
6.25
5.0
3.75
2.5
1.25
0
Accumulated
Oxygen Uptake, mg/l
80
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

Figure 19. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at K_2 = 0.12 hr^{-1}

Effluent Characteristics:
Extended Aeration Effluent
Day of Operation, 307 (July 10, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	16 mg/l	12 mg/l
Total COD, S_e =	314 mg/l	293 mg/l
Biological Solids, X_e =	276 mg/l	232 mg/l
NO_3-N =	46 mg/l	48 mg/l

Temperature, 25°C
Total O_2 Uptake, 95 mg/l


Dissolved Oxygen, mg/l
8.5
7.25
6.00
4.75
3.5
2.25
1.0
Accumulated
Oxygen Uptake, mg/l
95
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

20 hours to a very low level, i.e., one mg/l. The dissolved oxygen curve showed a slight plateau corresponding to the secondary sag in the DO profile which began after the 90th hour.

In Figure 20, the initial biological solids concentration was 212 mg/l, and the initial total COD was 267 mg/l. This sample was taken during day 310 of operation. After five days, biological solids concentration decreased to 192 mg/l, but the COD decreased by 51 mg/l to a value of 216 mg/l. There was practically no nitrification, and the O_2 uptake was 58 mg/l. The jar system was operated at a reaeration rate of 0.145 hr^{-1}, with a DO saturation value of 8.6 mg/l. In this experiment, the DO profile recovered at a faster rate than in the previous experiment. The O_2 uptake curve shows first-order-like decreasing rate kinetics.

Figure 21 shows the DO profile and O_2 uptake curve for a sample taken on day 319. The initial biological solids concentration was brought to 160 mg/l, and NO_3-N curve was 7 mg/l; however, the NH_3-N concentration was low during the experiment (0.9-1.2 mg/l). It is believed that the 7 mg/l NO_3-N value is in error, since the NO_3-N concentration in the pilot plant effluent on day 318 was 33 mg/l, and on day 322 it was 33 mg/l. The final NO_3-N concentration was 40 mg/l, an increase of 33 mg/l, and this does not seem possible in view of the O_2 uptake and the NH_3-N data. The total COD remained almost at the same level from an initial value of 208 mg/l, and the biological solids concentration was slightly increased to 176 mg/l. The DO profile showed a slow recovery after an initial sag, and the O_2 uptake gave the appearance of a first-order-like decreasing rate curve. The BOD_5 was 44 mg/l. On day 337, the sample produced the profile and O_2 curve

Figure 20. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at K_2 = 0.145 hr^{-1}

Effluent Characteristics:
Extended Aeration Effluent
Day of Operation, 318 (July 21, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	19 mg/l	11 mg/l
Total COD, S_e =	267 mg/l	216 mg/l
Biological Solids, X_e =	212 mg/l	192 mg/l
NO_3-N =	44 mg/l	44 mg/l

Temperature, 25°C
Total O_2 Uptake, 58 mg/l

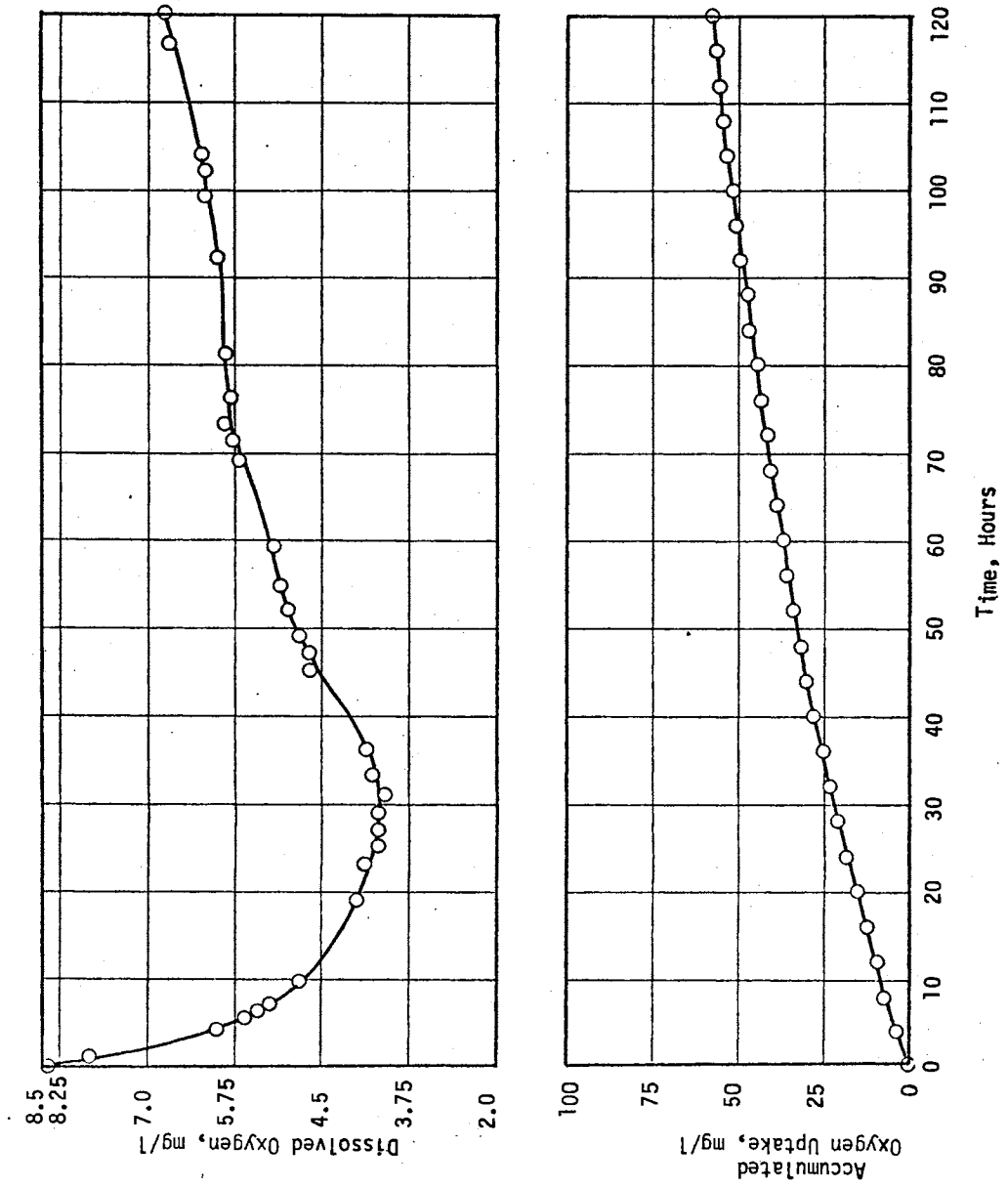
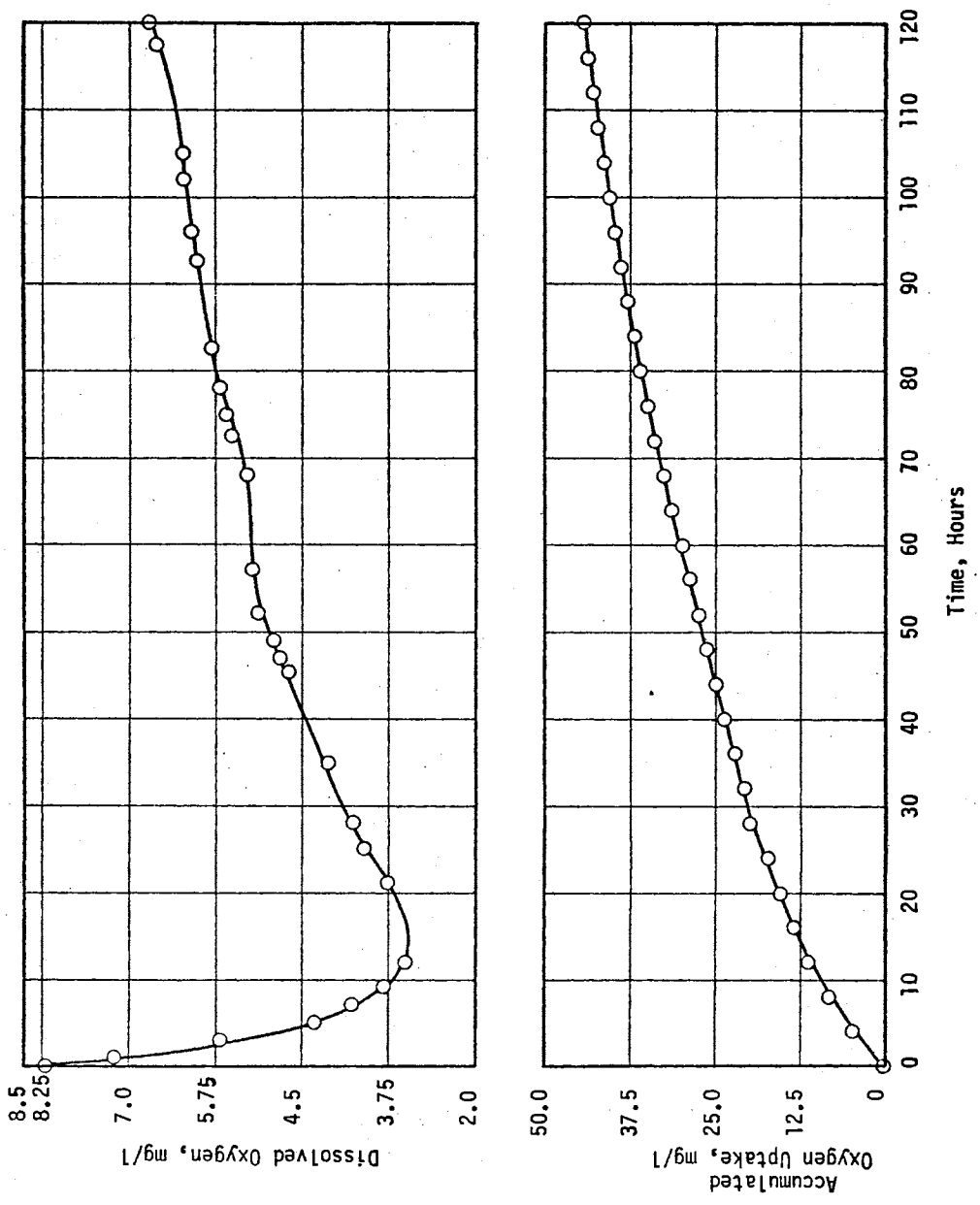

Dissolved Oxygen, mg/l
8.5
8.25
7.0
5.75
4.5
3.75
2.0
Accumulated
Oxygen Uptake, mg/l
100
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

Figure 21. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at $K_2 = 0.106\ hr^{-1}$

Effluent Characteristics:
Extended Aeration Effluent
Day of Operation, 319 (July 22, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	35 mg/l	47 mg/l
Total COD, S_e =	216 mg/l	208 mg/l
Biological Solids, X_e =	160 mg/l	176 mg/l
NO_3-N =	7 mg/l	40 mg/l

Temperature, 25°C
Total O_2 Uptake, 44 mg/l


Dissolved Oxygen, mg/l
8.5
8.25
7.0
5.75
4.5
3.75
2.0
Accumulated
Oxygen Uptake, mg/l
50.0
37.5
25.0
12.5
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

shown in Figure 22. The initial biological solids concentration was raised to 204 mg/l. The final biological concentration was 164 mg/l, a reduction of 40 mg/l, and the total COD decreased from an initial value of 204 mg/l to 148 mg/l. Also, there was a considerable reduction in the NO_3-N concentration from a value of 23 mg/l to 14 mg/l after five days. Also, in Figure 18 the NO_3-N value decreased from 48 mg/l to 38 mg/l, and the total COD decreased from 200 to 163 mg/l; whereas the biological solids remained at almost the same level. These results suggest that a significant portion of the O_2 uptake was due to exertion of carbonaceous BOD. The DO profile in Figure 22 shows a secondary sag which would not seem to have been due to nitrification.

Shown in Figure 23 is the O_2 uptake of effluent taken on day 338 of operation. Initial biological solids concentration was very low, i.e., 48 mg/l compared to the other experiments of this section. The system was operated at a reaeration rate of 0.074 hr^{-1} with a saturation value of 8.4 mg/l. A 5-day BOD of 15 mg/l was exerted, and the NO_3-N concentration increased from an initial 23 mg/l to a final 30 mg/l. The total organic material was reduced from 76 mg/l to 60 mg/l. The dissolved oxygen profile showed two distinct sags similar to Figure 22. The corresponding oxygen uptake showed a plateau.

Shown in Figure 24 is the profile and BOD of effluent comparable to the low biological solids concentration of the previous experiment. The sample was taken on day 359 of pilot plant operation. The total COD of the system remained constant at 105 mg/l during the experiment, as did the biological solids concentration at 88 mg/l. The NO_3-N concentration increased from an initial value of 28 mg/l to a final value of 41 mg/l, and NH_3-N curve was very low. At a K_2 of 0.071 hr^{-1} with

Figure 22. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at K_2 = 0.135 hr^{-1}

Effluent Characteristics:

Extended Aeration Effluent
Day of Operation, 337 (August 9, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	8 mg/l	8 mg/l
Total COD, S_e =	204 mg/l	140 mg/l
Biological Solids, X_e =	204 mg/l	164 mg/l
NO_3-N =	23 mg/l	14 mg/l

Temperature, 25°C
Total O_2 Uptake, 92 mg/l

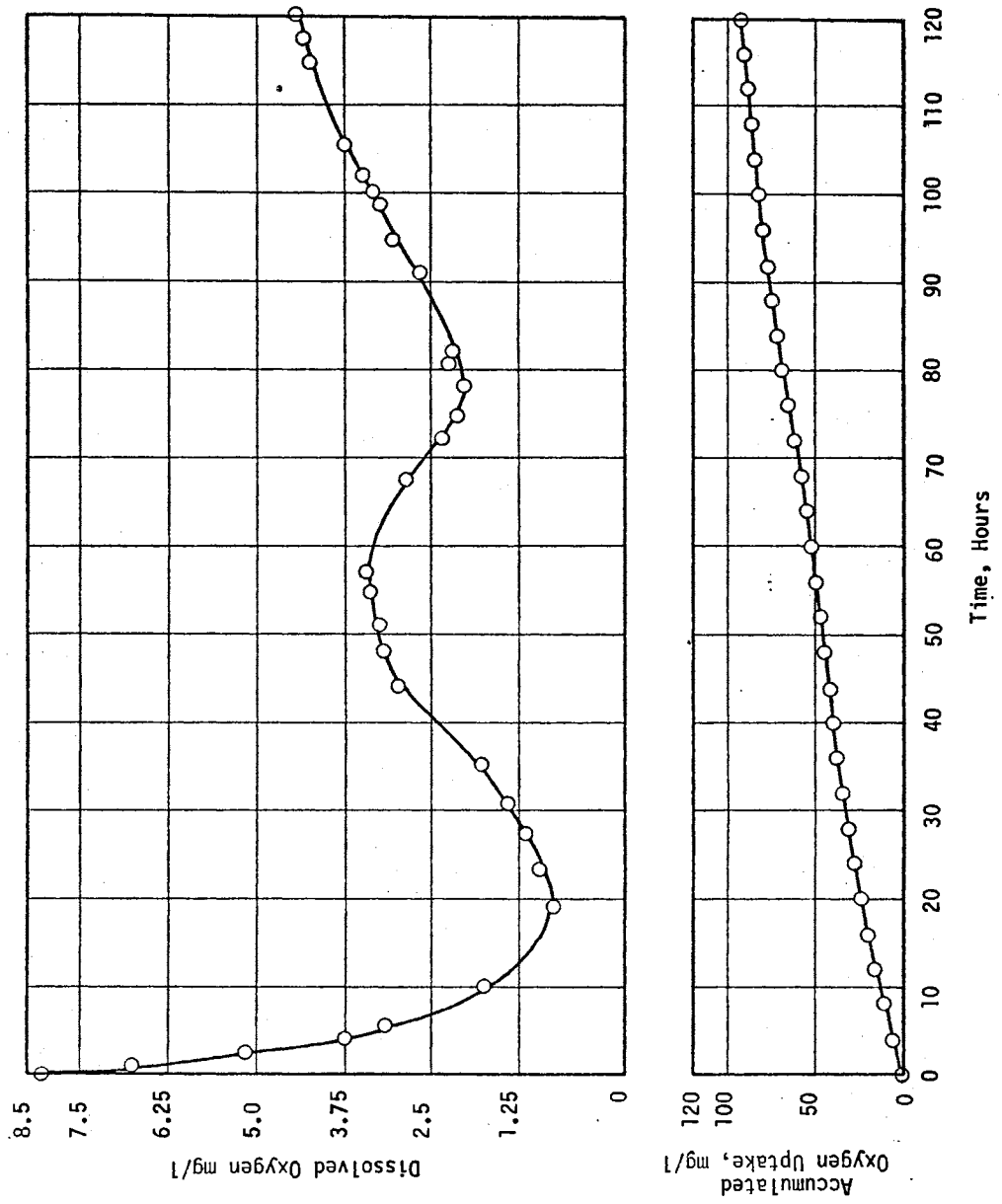

Dissolved Oxygen mg/l
8.5
7.5
6.25
5.0
3.75
2.5
1.25
0
Accumulated
Oxygen Uptake, mg/l
120
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

Figure 23. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at $K_2 = 0.066\ hr^{-1}$

Effluent Characteristics:

Extended Aeration Effluent
Day of Operation, 338 (August 10, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	8 mg/l	16 mg/l
Total COD, S_e =	76 mg/l	60 mg/l
Biological Solids, X_e =	48 mg/l	52 mg/l
NO_3-N =	23 mg/l	30 mg/l

Temperature, 25°C
Total O_2 Uptake, 15 mg/l

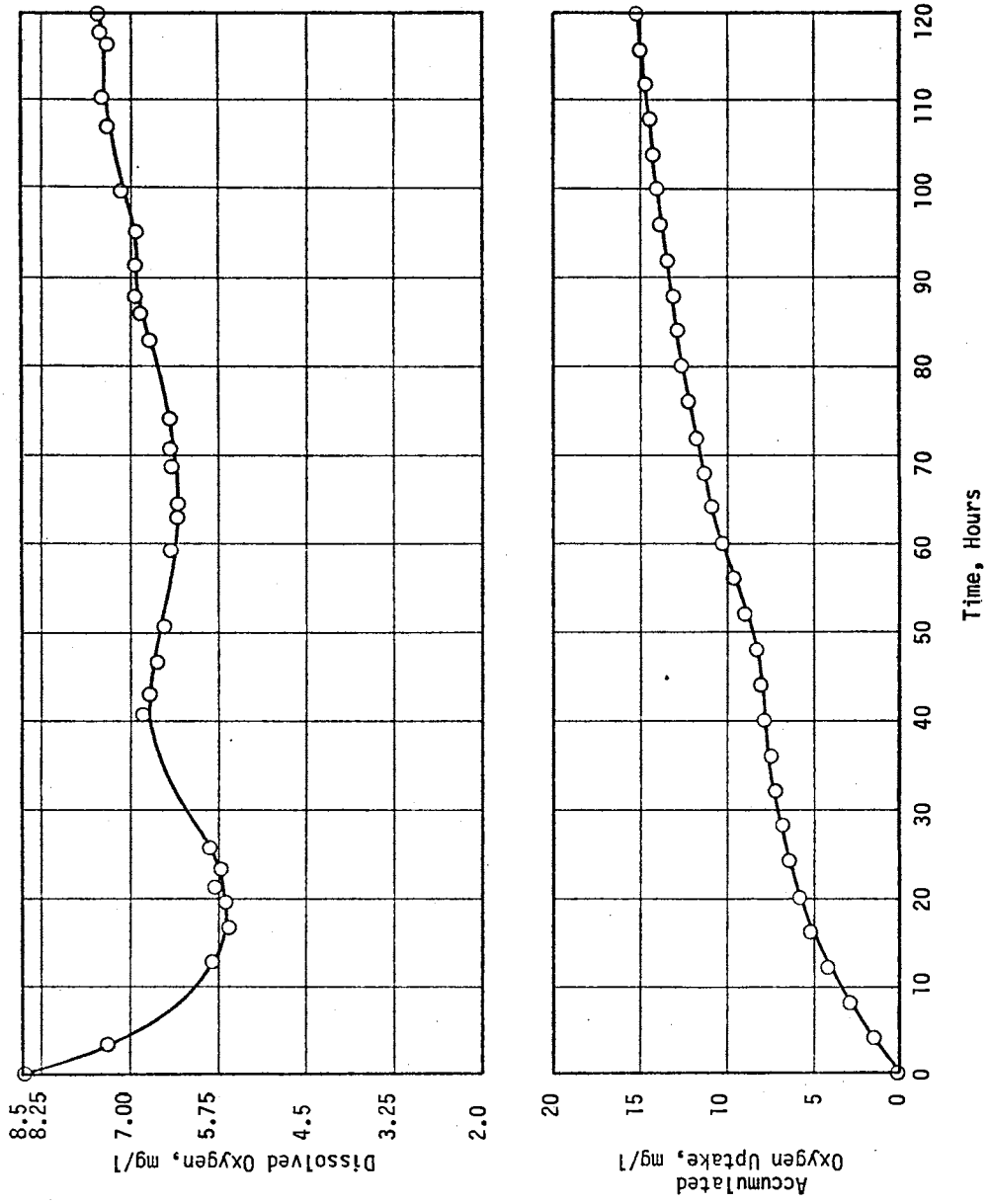

Dissolved Oxygen, mg/l
8.5
8.25
7.00
5.75
4.5
3.25
2.0
Accumulated
Oxygen Uptake, mg/l
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

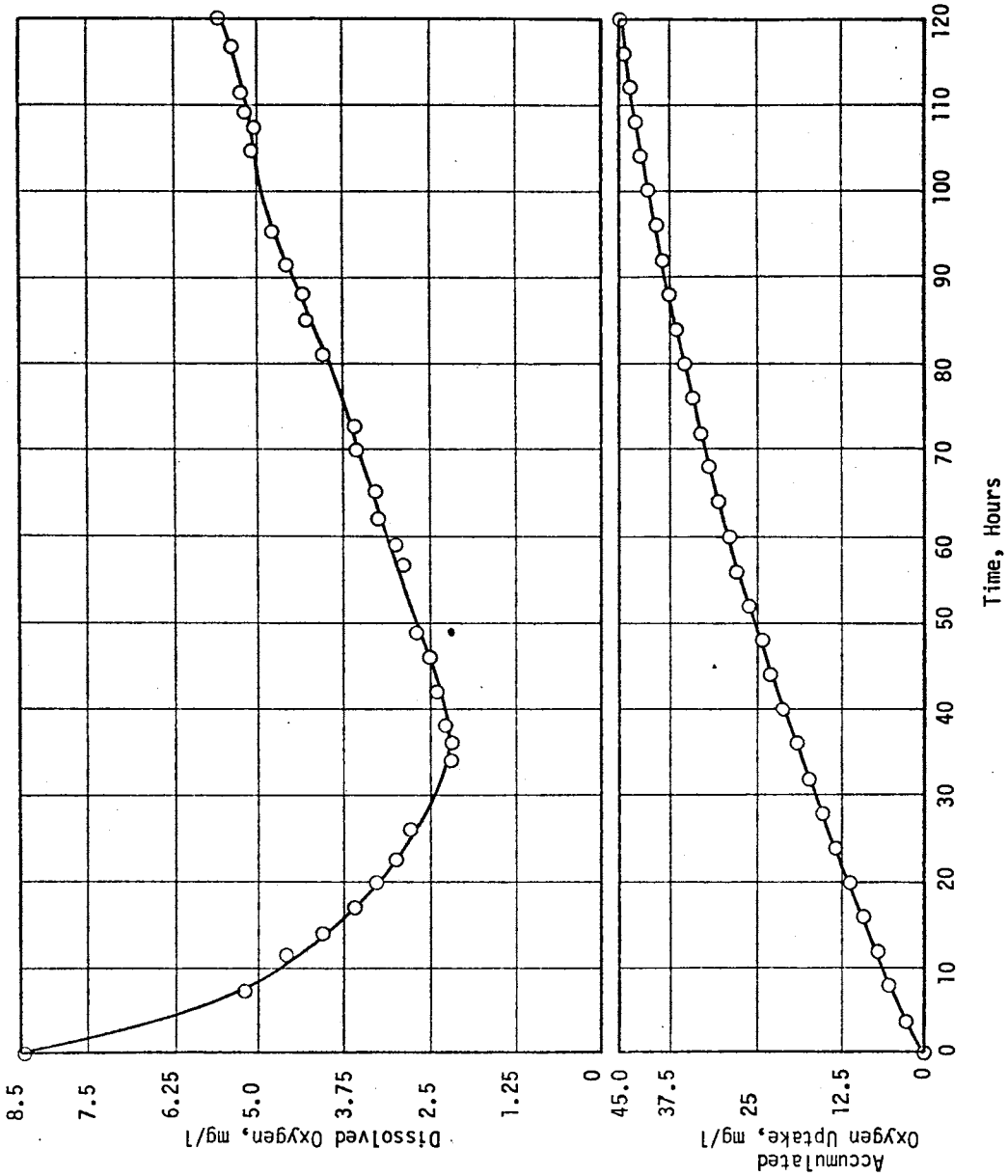
Figure 24. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at K_2 = 0.071 hr^{-1}

Effluent Characteristics:

Extended Aeration Effluent
Day of Operation, 359 (August 31, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	23 mg/l	15 mg/l
Total COD, S_e =	105 mg/l	105 mg/l
Biological Solids, X_e =	88 mg/l	84 mg/l
NO_3-N =	28 mg/l	41 mg/l

Temperature, 25°C
Total O_2 Uptake, 45 mg/l


Dissolved Oxygen, mg/l
8.5
7.5
6.25
5.0
3.75
2.5
1.25
0
Accumulated
Oxygen Uptake, mg/l
45.0
37.5
25
12.5
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

dissolved oxygen saturation of 8.8 mg/l, O_2 uptake was 45 mg/l. The DO profile showed a well rounded sag with a very slow recovery; the O_2 curve appeared to approximate first-order decreasing rate oxygen uptake kinetics.

Figure 25 was also taken on day 359, i.e., the effluent was pooled for 48 hours (day 357-day 359), and equal portions used for experiments shown in Figures 24 and 25. However, the initial solids concentration was increased to 120 mg/l; total COD was initially 168 mg/l. The final value of total COD was 149 mg/l, and the biological solids concentration decreased by 12 mg/l to 108 mg/l. The DO profile showed a well rounded sag, and the recovery phase was interrupted after 90 hours by a secondary sag. The curve shows a trend similar to that of Figure 24, but the secondary sag is not clearly seen in Figure 24. The NO_3-N concentration increased slightly from 14 mg/l to 17 mg/l. The O_2 uptake was 65 mg/l with a reaeration rate constant of 0.084 hr^{-1} and saturation value of 8.8 mg/l. The initial and final NH_3-N concentration was very low (0.2-2.2 mg/l).

Figure 26 is a plot of the DO profile and BOD for the effluent sample taken on day 361 of operation of the extended aeration pilot plant. The initial biological solids were raised to 228 mg/l. After five days, they were reduced to 216 mg/l, and the total COD decreased from an initial concentration of 333 mg/l to final concentration of 274 mg/l, i.e., a reduction of 59 mg/l as COD. The nitrification in the system was considerable; the NO_3-N concentration increased from an initial value of 18 mg/l to a final value of 37 mg/l. The filtrate COD remained almost the same (19 to 27 mg/l). The total 5-day O_2 uptake computed from the DO profile was 150 mg/l, with a K_2 of

Figure 25. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at $K_2 = 0.084\ hr^{-1}$

Effluent Characteristics:

Extended Aeration Effluent
Day of Operation, 359 (August 31, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	15 mg/l	23 mg/l
Total COD, S_e =	168 mg/l	149 mg/l
Biological Solids, X_e =	120 mg/l	108 mg/l
NO_3-N =	14 mg/l	17 mg/l

Temperature, 25°C
Total O_2 Uptake, 65 mg/l

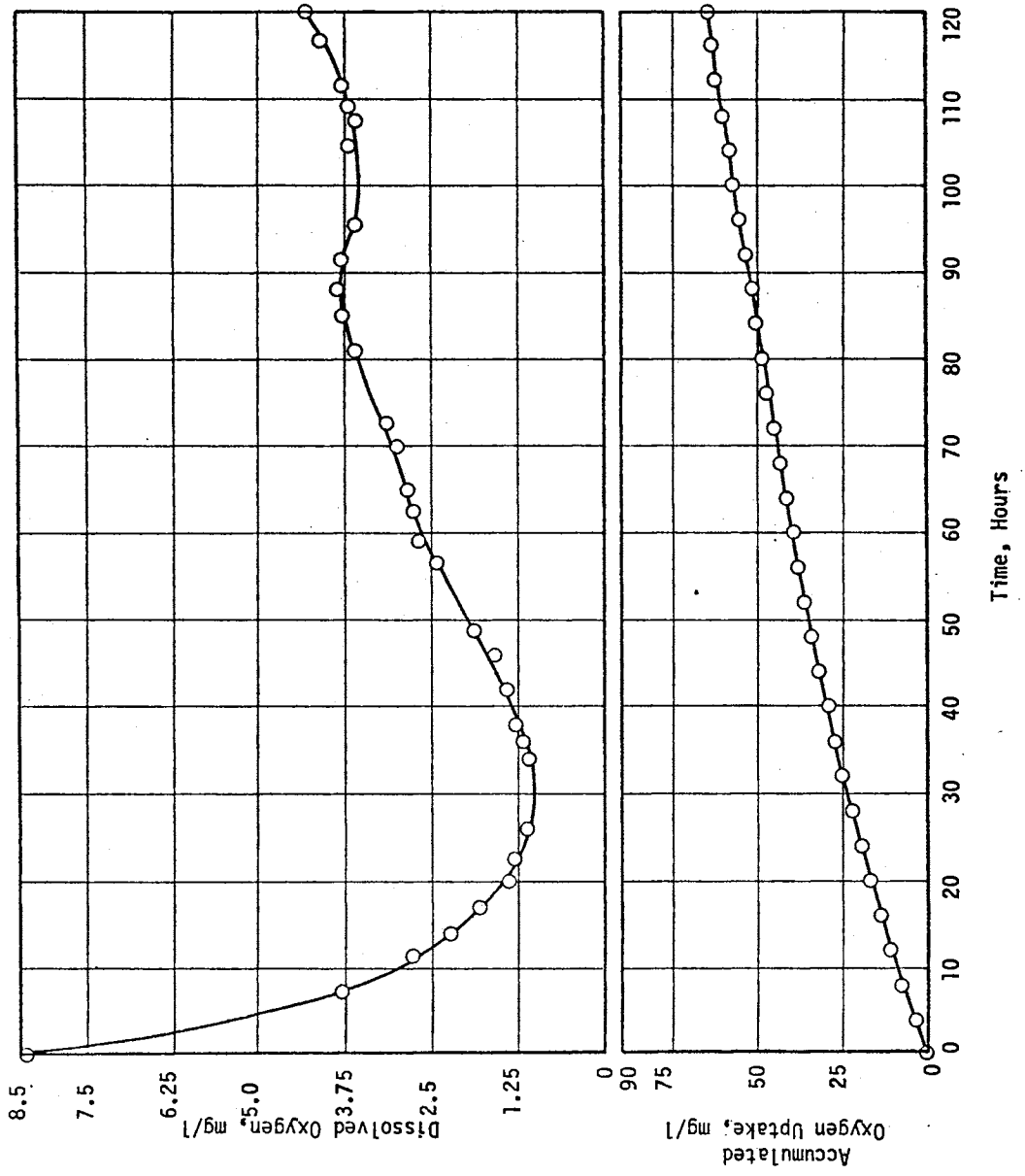

Dissolved Oxygen, mg/l
8.5
7.5
6.25
5.0
3.75
2.5
1.25
0
Accumulated
Oxygen Uptake, mg/l
90
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

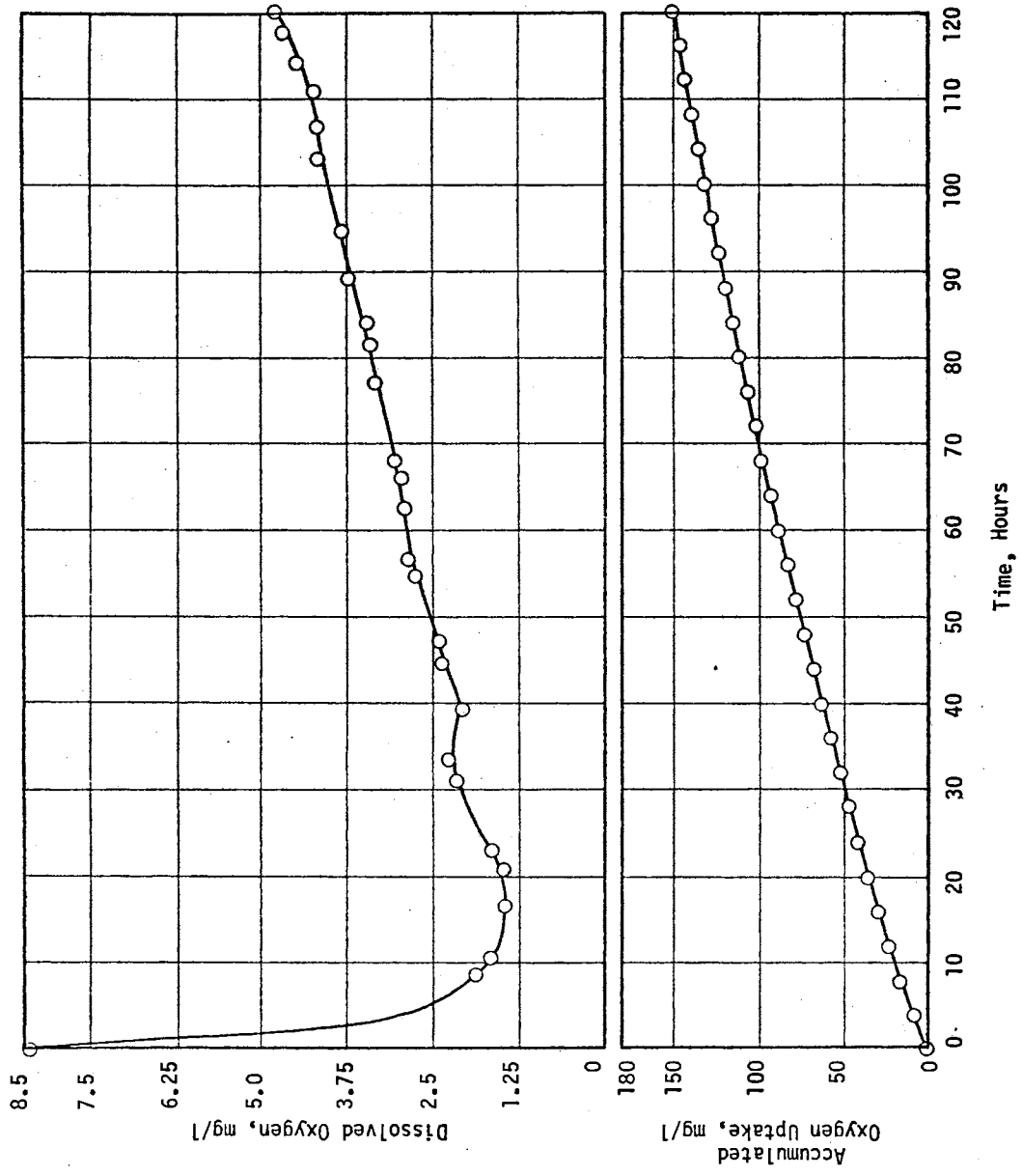
Figure 26. DO Profile and O_2 Uptake Curves for an Effluent With the Open Jar Reactor Operating at $K_2 = 0.213\ hr^{-1}$

Effluent Characteristics:

Extended Aeration Effluent
Day of Operation, 361 (September 2, 1974)

	Initial	Final
Filtrate COD (S_e Fil) =	19 mg/l	27 mg/l
Total COD, S_e =	333 mg/l	274 mg/l
Biological Solids, X_e =	228 mg/l	216 mg/l
NO_3-N =	18 mg/l	37 mg/l

Temperature, 25°C
Total O_2 Uptake, 150 mg/l


Dissolved Oxygen, mg/l
8.5
7.5
6.25
5.0
3.75
2.5
1.25
0
Accumulated
Oxygen Uptake, mg/l
180
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time, Hours

0.213 hr^{-1} and a saturation value of 8.8 mg/l. The DO decreased very rapidly to a low value of nearly 1.3 mg/l, and the recovery phase was very slow.

Table II gives the values of parameters determined in the experiments of Phases I and II. The table also gives the values of K_2 for tap water as well as the waste sample, both determined under identical conditions (mixer rpm, temperature, volume, etc.). It is seen that for both primary and secondary municipal effluent, the reaeration constant for water compares rather well, i.e., the α factor is approximately one. However, for the slaughterhouse waste, the K_2 if much depressed compared to that for tap water. The K_2 data, beginning with that of Figure 15 for the extended aeration pilot plant effluents, indicate that α varied from 0.441 to 1.383. It is difficult to determine any general trend in these α values with initial suspended solids, total COD, or with observed O_2 uptake. It can be seen, however, that for the system yielding the three highest O_2 uptakes, i.e., Figures 19, 22, and 26, the α values are high. It is also interesting to note in the experiments on the pilot plant effluent that the concentration of soluble COD did not vary considerably during any experiment. It might be said that it did not really influence the oxygen uptake characteristics. Thus, the oxygen uptake was due mainly to the influence of the added biological solids and the process of nitrification. The low initial soluble COD and the fact that it did not change much indicate the high degree of treatment provided by the "hydrolytically-assisted" extended aeration process. This is particularly evident in the experiment shown in Figure 23 for which the added MLSS was low and the O_2 uptake, 15 mg/l, could be ascribed almost entirely to the pilot plant effluent characteristics.

TABLE II

THE PARAMETERS DETERMINED IN EXPERIMENTS OF PHASES I AND II

Fig.	Solids (X_e) mg/l Initial	Final	Substrate (COD) mg/l N.Fil.	Fil.	N.Fil.	Fil.	Temp. °C	c_s mg/l	K_2 hr^{-1} Sample	Tap Water	α	F/M	O_2 Uptake mg/l	NH_3-N mg/l Initial	Final	NO_3-N mg/l Initial	Final	Remarks
3	56	12	102	47	59	24	25	8.8	0.088	0.088	1.000	0.839	76	-	-	6	9	Primary effluent, Stillwater Wastewater Treatment Plant
4	56	20	114	43	67	47	25	8.8	0.117	0.108	1.083	0.767	85	-	-	0	2	" " "
5	56	12	122	47	71	35	25	8.8	0.217	0.277	0.783	0.839	106	-	-	5	10	" " "
6	16	8	68	52	52	48	26	8.6	0.086	0.077	1.116	3.25	30	-	-	-	-	Secondary effluent, Stillwater Wastewater Treatment Plant
7	20	8	72	44	60	41	25	8.4	0.090	0.082	1.097	2.200	46	-	-	-	-	" " "
8	124	24	169	29	136	20	25	8.8	0.113	0.132	0.856	0.233	59	-	-	-	-	200 MLSS added from the pilot plant (slaughterhouse effluent)
9	168	160	224	28	187	28	25	8.4	0.072	0.163	0.441	0.166	44	-	-	33	38	225 MLSS added from the pilot plant (slaughterhouse effluent)
15	208	248	190	12	181	36	25	8.4	0.125	0.115	1.086	0.058	26	-	-	38	-	200 MLSS added from author's pilot plant
16	280	248	298	28	278	24	25	8.4	0.163	-	-	0.100	82	-	-	31	-	350 " " "
17	114	128	151	4	167	20	25	8.4	0.110	0.130	0.846	0.035	32	0	1.2	23	45	350 " " "
18	176	172	200	8	163	8	25	8.4	0.151	-	-	0.046	79	0	3.5	48	38	400 " " "
19	276	232	314	16	293	12	25	8.8	0.120	0.102	1.176	0.059	95	1.2	0.8	46	48	500 " " "
20	212	192	267	19	216	11	25	8.6	0.145	0.147	0.986	0.089	58	1.9	0.2	44	44	450 " " "
21	160	176	216	35	208	47	25	8.4	0.106	0.136	0.779	0.221	44	0.9	1.2	7	40	250 " " "
22	204	164	204	8	148	8	25	8.4	0.135	0.099	1.363	0.039	92	2.2	2.1	23	14	350 " " "
23	48	52	76	8	60	16	25	8.4	0.066	0.074	0.891	0.166	15	0.4	2.2	23	30	100 " " "
24	88	84	105	23	105	15	25	8.8	0.071	0.066	1.075	0.261	45	0.0	0.7	28	41	50 " " "
25	120	108	168	15	149	23	25	8.8	0.084	0.069	1.217	0.125	65	0.2	2.2	14	17	150 " " "
26	228	216	333	19	274	27	25	8.8	0.213	0.154	1.383	0.083	150	0.7	0.2	18	37	500 " " "

CHAPTER V

SUMMARY AND CONCLUSIONS

In general, the oxygen uptake curves in open stirred reactors did not follow any definable kinetic order; they varied in a definable manner for the primary effluents (untreated) to that of the secondary effluent (after treatment by a trickling filter). The primary effluent reached the low point of the DO sag rapidly, and the secondary phase of O_2 uptake started after a pause. However, for the secondary effluent, uptake was exerted almost immediately after the first uptake with negligible recovery of DO after the first phase of O_2 uptake, i.e., there was essentially no plateau in the BOD curve for secondary effluent. The soluble organic material (COD) in the effluents did not exert much of the oxygen uptake, and in general, a considerable part of the oxygen uptake observed could be attributed to nitrification. Even when high biological solids concentrations from the extended aeration pilot were purposely added to the effluent in the open jug reactors, the results indicated that this material would not be expected to cause serious depletion of the O_2 reserve. In this study, the oxygen uptake was observed to be higher when higher reaeration rate was employed, thus agreeing with conclusions of Peil and Gaudy (22). The extended aeration activated sludge process is quite capable of withstanding quantitative and pH shock loads. From the results it is very clear that even the nitrification was excellent except for a short duration after the pH shock.

CHAPTER VI

SUGGESTIONS FOR FUTURE WORK

1. Study should be made to evaluate more fully the effect of nitrification on the dissolved oxygen resources of the stream.

2. The effect of "contaminants" on the wastewater reaeration rate constants (K_2) and saturation constants (C_s) should be studied in detail to determine more accurately the reaeration parameters.

3. It would be ideal to run some open stirred reactor tests with continuous recording of DO. In this way, subtle changes in DO which may permit useful insight into kinetic factors could be uncovered.

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APPENDIX A

CALCULATION OF OXYGEN UPTAKE FROM OPEN JAR REACTORS

Oxygen uptake was computed using the experimentally determined dissolved oxygen profile. In these studies, the reaeration rate constant, K_2, and saturation constant, C_s, were determined from the experimental data using the α method discussed in Materials and Methods Chapter on page 20.

To calculate the oxygen utilized by the microorganisms while stabilizing organic waste, the DO values recorded during the experiment are given in column 2 of Table II. The deficit at each time may be found by subtracting the DO from the saturation value. Table III includes the complete data used to determine the O_2 uptake for Figure 23.

Column 3 shows the deficit at each time. The deficit is multiplied by the reaeration rate for the jar (0.066 hr^{-1}) and is recorded in column 4. The time interval, i.e., Δt between DO determinations is listed in column 5. The amount of DO put into the system during a specific time interval by reaeration is determined by multiplying $K_2 \cdot D \times \Delta t$ and is recorded in column 6; the change in DO during each interval is the difference in DO recorded in column 7. The oxygen utilization during the time interval is given in column 8, and is measured by subtracting column 7 from column 6. Column 9 is the summation of oxygen uptake during the experiment.

TABLE III

CALCULATION OF OXYGEN UPTAKE FROM OPEN JAR REACTORS

1	2	3	4	5	6	7	8	9
Hour	DO mg/l	D mg/l	K_2D mg/l-hr	Δt Hour	$K_2D\Delta$ mg/l	ΔDO mg/l	6-7 mg/l	O_2 Uptake mg/l
0	8.40	0.00	0.00	0.0	0.00	0.00	0.00	0.00
4	7.15	1.25	0.08	4.0	0.33	-1.25	1.58	1.58
8	6.40	2.00	0.13	4.0	0.52	-0.75	1.27	2.95
12	5.90	2.50	0.16	4.0	0.66	-0.50	1.16	4.01
16	5.60	2.80	0.18	4.0	0.73	-0.30	1.03	5.05
20	5.70	2.70	0.17	4.0	0.71	0.10	0.61	5.67
24	5.75	2.65	0.17	4.0	0.69	0.05	0.64	6.31
28	6.00	2.40	0.15	4.0	0.63	0.25	0.38	6.70
32	6.20	2.20	0.14	4.0	0.58	0.20	0.38	7.08
36	6.50	1.90	0.12	4.0	0.50	0.30	0.20	7.28
40	6.75	1.65	0.10	4.0	0.43	0.25	0.18	7.74
44	6.70	1.70	0.11	4.0	0.44	-0.05	0.39	7.87
48	6.55	1.85	0.12	4.0	0.48	-0.15	0.33	8.20
52	6.45	1.95	0.12	4.0	0.51	0.10	0.61	8.82
56	6.40	2.00	0.13	4.0	0.52	-0.15	0.67	9.50
60	6.35	2.05	0.13	4.0	0.54	-0.05	0.59	10.09
64	6.30	2.10	0.13	4.0	0.55	-0.05	0.60	10.69
68	6.33	2.05	0.13	4.0	0.54	0.05	0.49	11.18
72	6.40	2.00	0.13	4.0	0.52	0.05	0.47	11.66
76	6.50	1.90	0.12	4.0	0.50	0.10	0.40	12.06
80	6.60	1.80	0.11	4.0	0.47	0.10	0.37	12.44
84	6.75	1.65	0.10	4.0	0.43	0.15	0.28	12.72
88	6.90	1.50	0.09	4.0	0.39	0.15	0.24	12.97
92	6.90	1.50	0.09	4.0	0.39	0.00	0.39	13.37
96	6.95	1.45	0.09	4.0	0.38	0.05	0.33	13.70
100	7.10	1.30	0.08	4.0	0.34	0.15	0.19	13.89
104	7.20	1.20	0.07	4.0	0.31	0.10	0.21	14.11
108	7.30	1.10	0.07	4.0	0.29	0.10	0.19	14.30
112	7.35	1.05	0.06	4.0	0.27	0.05	0.22	14.53
116	7.30	1.10	0.07	4.0	0.29	-0.05	0.34	14.87
120	7.40	1.00	0.06	4.0	0.26	0.10	0.16	15.03

c_s = 8.40 mg/l K_2 = 0.066 hr^{-1}

APPENDIX B

LIST OF SYMBOLS

BOD - biochemical oxygen demand (mg/l)

BOD_5 - biochemical oxygen demand has been expressed in five days (mg/l)

COD - chemical oxygen demand (mg/l)

DO - dissolved oxygen (mg/l)

C_s - oxygen saturation constant (mg/l)

D - oxygen deficit from saturation at any specific time (mg/l)

K_2 - rate of reaeration constant (hr^{-1})

S_i - initial substrate (COD) of the feed (mg/l)

X - mixed liquor suspended solids (MLSS), (mg/l)

X_e - dry weight concentration of effluent biological solids (mg/l)

S_e - total supernatant COD (mg/l)

α - ratio between K_2 of waste (effluent) sample to K_2 of tap water

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