STUDIES ON BOD EXERTION IN OPEN STIRRED REACTORS

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STUDIES ON BOD EXERTION IN OPEN STIRRED REACTORS

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CHAPTER I

INTRODUCTION

The depletion of dissolved oxygen in receiving streams due to the discharge of raw wastewaters and treated effluents has been the subject of intensive research since the latter part of the last century. Considerable effort has been expended in devising ways to predict the effect of organic substrates on the dissolved oxygen resources in the receiving stream. Streeter and Phelps proposed the "sag" equation for predicting the dissolved oxygen concentration at any downstream point on the stream as a resultant due to the deoxygenation constant, K_1, determined in the closed BOD bottle, assuming the rate of accumulated oxygen uptake follows first order decreasing rate kinetics and the reaeration constant, K_2, which also followed kinetcs of a monomolecular reaction. Later work proved that the deoxygenation constant, K_1, does not exactly follow monomolecular reaction kinetics, and that the Streeter-Phelps sag equation was inadequate to predict the exact nature of changes in the DO profile in receiving streams.

Work has been underway for some time in the bioengineering laboratories of Oklahoma State University to overcome the shortcomings of the sag equation. An open stirred reactor technique has been proposed to simulate conditions in receiving streams; agitation and reaeration are provided by a mechanical stirrer, the speed of which can be varied as needed. Oxygen uptake determined from data obtained in the open stirred

reactors has been compared to that obtained in a "simulated stream" and found comparable. However, the determination of the reaeration rate, K_2, and the saturation constant, C_s, is very important in this method, since the substrate and cells concentrations vary and these variations can change the values of K_2 and C_s. If the K_2 and C_s employed are inaccurate for the particular conditions under which an open reactor test is run, the open jug technique may not yield unseable information. As part of a continuing research effort, part of this work was undertaken to assess factors which affect the kinetics of reaeration and to determine some substrate seed relationship which might affect kinetics of O_2 uptake using the open jar technique. Also an important part of this study involved use of the technique to assess the O_2 uptake characteristics of effluent from a laboratory operated extended aeration pilot plant.

CHAPTER II

LITERATURE REVIEW

As far back as 1870, Frankland (1) said of sewage let into rivers and ponds in which some fish had died: "Sewage contains no dissolved oxygen, and if any is absorbed from the air, it is quickly taken up by organic matter. The precipitated sewage also contains no oxygen" (p. 10). He believed the mechanism to be strictly chemical and that the oxidation of organic matter in water is effected chiefly, if not exclusively, by the atmospheric oxygen dissolved in the water.

In 1884, Dupre (2) stated that microphytes in water have the property of consuming oxygen from the air for their own process, deriving such oxygen from the air dissolved in the water. In 1908, Adeney (3) published results on the rate of deoxygenation in a closed bottle using the dilution technique.

Dibdin and Thudichum (4) in an attempt to make some allowance for the replenishment of oxygen supply by atmospheric reaeration, used an open incubation test. Theriault (5) did not like the idea of an open vessel, and said that they 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. He thought that the separate consideration of these two distinct phases of the same problem simplfies the interpretation of the results and makes it possible to derive accurate

information concerning the amount of organic matter.

While the above attempts at predicting the effect of pollution on dissolved oxygen were being developed, the importance of estimating the amount of transfer of oxygen from the atmosphere to the body of water was also being investigated by Adeney and Becker (6) in their studies on the rate of solubility of atmospheric oxygen in water.

Streeter and Phelps (7) in 1925, while studying the pollution effect on the Ohio River, combined both deoxygenation and reoxygenation effects and derived an equation for predicting the saturation deficit:

$$D = \frac{K_1 L_a}{K_2 - K_1} \left(e^{-K_1 t} - e^{-K_2 t} \right) + D_a e^{-K_2 t} \qquad (1)$$

where

D = saturation deficit at any time, t

D_a = initial DO deficit from saturation

L_a = initial oxygen demand of the organic matter

K_1 = rate of deoxygenation constant

K_2 = rate of reoxygenation constant

They felt that the reoxygenation rate follows kinetics of monomulecular reactions, and that it is dependent on temperature and, to a large extent, on the degree of turbulence, other things being equal. They further assumed that the deoxygenation reaction is an orderly and consistent one proceeding at a measurable rate according to the following definite law: "The rate of biochemical oxidation of organic matter is proportional to the remaining concentration of unoxidized substance, measured in terms of oxidizability." This law is one of a monomolecular

reaction, and it states that in equal periods of time, an equal proportion of the remaining demand will be satisfied and the rate of satisfaction of the demand is equivalent to the rate of oxygen depletion. During the course of time, many researchers doubted the ability of the Streeter-Phelps sag equation to predict the deficit accurately. For the development of any mathematical model, prediction is more important, as Gates, et al. (8) put it: "With any engineering problem, the emphasis is not on measuring the event but on being able to predict accurately" (p. 665).

In order to be able to predict the exact values of the oxygen sag curve requires that one also be able to determine correctly the rates of deoxygenation and reoxygenation under various conditions. Thus, Heukelekian (9), while studying the use of the dilution method for determining the BOD exertion of industrial wastes, concluded that the BOD determined applies only to the concentrations employed. If it were possible to use higher concentrations, a different value might be obtained. He believed this effect to be due to possible toxic components in the waste. Many organic substances are oxidizable at low concentrations and toxic at higher concentrations. While they have an oxygen demand at low concentrations, they may not only remain unoxidized at higher concentrations but may retard oxidation of an otherwise oxidizable substrate such as sewage. Heukelekian felt that only within a narrow range could these effects be studied by the dilution method, but by a direct method the oxygen utilization over any range of concentrations could be studied. To test the effect of various chemicals and organic wastes on oxygen depletion at various concentrations, Heukelekian used a reaeration method, i.e., he reaerated the incubation mixture

before complete DO depletion to extend the range of concentration in his work.

Ruchhoft, et al. (10) found the assumption that the course of biological oxidation is the same in each bottle no matter what the dilution is, may lead to serious errors because nitrification and biological oxidation rates are apparently affected by the concentration of organic material in BOD substrate.

To overcome this difficulty, Kittrel and Kochtitisky (11) incubated a large volume of each sample in an unstoppered bottle from which BOD bottles were filled for initial and final DO determinations. The final DO was determined after a limited period of incubation that would not cause total oxygen depletion. When the final DO was determined, another set of BOD bottles was filled from the large bottle which had been stored unstoppered in the incubator to permit continuing aerobic action. For the long term BOD, several BOD bottles were incubated each time it was necessary to refill from the large bottle to permit a final DO determination each day.

Orford, Rand, and Gellman (12) proposed a single dilution technique called the "jug dilution technique," using two one-gallon jugs with the diluted mixture to be studied. The first jug was completely full and stoppered. Samples for dissolved oxygen and any other desired analysis were siphoned from the first jug and replaced from the second jug after sampling, so that the first jug was completely full and reaeration was prevented. When the dissolved oxygen content of the jugs was near depletion, the contents were reaerated and the process continued, thus making it possible to use a single diluted sample. Elmore and Harold (13) also used a similar technique for the determination of BOD.

Orford and Ingram (14) in their work on deoxygenation of sewage, critically reviewed the monomolecular formula. They stated that there is no fundamental biological reason why oxidation should take place according to a monomolecular oxidation reaction, and further concluded that the monomolecular equation is a poor expression for analysis of biological oxidation because the two parameters of the equation K and L are constant.

Jennelle and Gaudy (15) studied the mechanism and kinetic course of BOD exertion in both open and closed systems, and observed that oxygen uptake rate constants increased with increasing concentrations of carbon source, thus militating against direct use of the usual dilution technique for predicting the rate of deoxygenation in receiving streams. They recommended using an open stirred reactor rather than the standard BOD bottle dilution technique. Also, they studied the effect of agitation and found that the degree of agitation employed in their studies did not affect oxygen uptake in their system. However, Lordi and Heukelekian (16), working on the effect of stirring on rate of deoxygenation, observed that the deoxygenation rate increased with stirring. Also Ali and Bewtra (17) investigated the influence of turbulence on various parameters of BOD progression. They used two sets of BOD bottles for each experiment, with one set sealed and quiescent and the other set sealed and stirred by a magnetic stirrer. The oxygen uptake rate was found to increase significantly with stirring when either sewage or glucose was used as substrate.

Thus far, aspects of deoxygenation and the inadequacy of taking the values of deoxygenation rate constants determined in dilute quiescent bottles has been discussed. However, it is also important to

review the reoxygenation aspects to clearly understand the sag equation.

In the past, various attempts have been made to define and predict the reaeration rate constant, K_2, as a function of turbulence and surface renewal rate, although there are other physical and chemical factors which can affect the rate of transfer of oxygen to the system.

Poon and Campbell (18) studied the effect of polluted water on diffused aeration and found that organic substances such as glycine, glucose, and peptone reduce the oxygen transfer rate. Kothandaraman (19) investigated the effects of contaminants as found in a natural river system on the reaeration rate coefficient, and concluded that the contaminants in river water alter the reaeration rate to the extent of $\pm$ 15 percent compared to the rate for distilled water.

Kehr (20) observed that concentrations of sewage or of industrial wastes in natural receiving streams may range from 0.5 to 10 percent or more. These impurities can cause an appreciable retardation of atmospheric reaeration and impose a burden on the stream's recovery capacity quite distinct from and in addition to that which is represented by the oxygen demand of these wastes. Eckenfelder (21), working on the effect of undiluted chemical and pulp and paper mill wastes on the dissolved oxygen saturation rates, found that the saturation values in pulp and paper mill wastes vary from 77 to 97 percent compared to water. A chemical waste containing organic acids, alcohols, aldehydes, and ketones exhibited a saturation value only 60 percent of that for water, and the oxygen transfer coefficient, α, was found to vary with the nature of the industrial wastes. It was observed that for chipboard and repulping wastes, α was 0.6, for kraft mill wastes, α was observed at 0.7, and for semi-chemical paper machine wastes, 1.4. Chemical wastes containing

organic acids, aldehydes, etc., exhibited an α value of 2.34.

Over the years, researchers have developed various mathematical expressions for K_2, the reaeration constant; most of the expressions are derived either as a function of velocity, depth, turbulence, and diffusitivity. The most extensive study on reactions of natural streams was that reported by Churchil, et al. (22). They took field measurements of the actual reaeration rates of river waters which were low in dissolved oxygen. The waters were released from the lower depths of impoundments; thus they were of low DO content. Using multiple regression techniques, they arrived at a relationship for the reaeration rate in terms of velocity and depth. This study indicated that inclusion of other hydraulic variables in a prediction equation did not offer a significant increase in the accuracy of the predicted reaeration rate.

Krenkel and Orlob (23), and Thackston and Krenkel (24), using a recirculating flume, gave expressions in terms of longitudinal mixing, relating the parameters to flow and channel characteristics, respectively. Isaacs and Gaudy (25) employed a "simulated" stream channel and from their experimental data proposed an empirical formula in terms of velocity and channel depths. These authors also introduced to reaeration calculations a method of determining the reaeration rate constant assuming the oxygen transfer rate follows monomolecular form (25). The method is that of Davis (26), i.e., the α method, and is essentially a curve fitting procedure.

Since it is not always possible to represent adequately all of the physical and chemical factors which affect the stream's assimilative capacity, it is natural that the Streeter and Phelps sag equation is inadequate to predict the exact nature of the sag equation. Thus Fair

(27) put it in plain terms when he concluded that

> ...Because of the intricacy of the microenvironment of receiving waters, their behavior can hardly be equated with any degree of true resemblance to the results of the BOD bottle test supplemented by coefficient of reaeration. Nevertheless, we admire the audacity of the Streeter and Phelps formulation of the oxygen sag. In its present form, it is a first, though greatly simplified mathematical model, of what actually takes place in nature. It was so conceived by its inventors, but not necessarily by its users (p. XVI).

He further states that

> ...Of greater concern, however, is the temptation to over-interpret BOD findings in terms of the constants of a first order reaction. Statistical 'goodness of fit' does not, in fact, identify the mechanism of purification. The procedure is purely pragmatic. Purification BOD (i.e., as it occurs in the receiving stream) and bottle BOD itself--may result from summing up of several zero-order reactions, including inhibition or catalysis, by reaction products, from one or more second-order reactions, or from combinations of different orders of reactions. Modern biological treatment is accomplished by relatively complex ecological systems. It is hardly conceivable, therefore, that a 250-ml BOD bottle is a more perfect instrument for wastewater treatment than the biomass in trickling filters or activated sludge tanks even if mathematical manipulation of observed data results in a well fitting curve (pp. XXII-XXIII).

Thus, attempts have been made to pin down, determine, and predict the various parameters that affect the ecological systems in a natural stream.

Thomas (28) proposed the introduction of a rate constant, K_3, as a means of accounting for the removal or addition of BOD by deposition and resuspension. O'Connor (29) introduced the effect of longitudinal dispersion and demonstrated its importance in slow moving, highly mixed streams such as estuaries. Gannon (30) studied the effect of BOD rate on the oxygen balance in the river and observed that the BOD rates in the river are higher than in the BOD rate from laboratory experiments.

They also observed that the period of rapid oxygen utilization was associated with active nitrification in the laboratory studies, but did not observe any considerable nitrification in the river, at least up to the low point of the oxygen sag. Velz and Gannon (31) thought that the high BOD removal from the stream is due to two processes. One is the normal biochemical respiration, and the other is biological extraction for synthesis of storage material.

Courchaine (32) studied the significance of nitrification on the oxygen balance in Grand River, Michigan, and observed that the demand due to nitrification is considerable and should be considered as a significant demand on the oxygen resources of the stream.

Dobbins (33) listed the various parameters affecting the oxygen balance in the stream in the evaluation of the effect on a stream's assimilative capacity as

1) the removal of BOD by sedimentation or adsorption;

2) the addition of BOD along the stretch by the scour of bottom deposits or by the diffusion of partly decomposed organic products from the benthal layer into the water above;

3) the addition of BOD along the stretch by the local runoff;

4) the removal of oxygen from the water by diffusion into the benthal layer to satisfy the oxygen demand in the aerobic zone of this layer;

5) the removal of oxygen from the water by purging action of gases rising from the benthal layer;

6) the addition of oxygen by the photosynthetic action of plankton and fixed plants;

7) the removal of oxygen by the respiration of plankton and fixed

plants, and

8) the continuous redistribution of both the BOD and oxygen by the effect of longitudinal dispersion.

He thought that longitudinal dispersion has negligible effect on the oxygen profile, but stressed the accurate estimate of the rate of surface reaeration.

Wuhrmann, Ruchti, and Eichenberger (34) conducted qualitative experiments on self-purification in a model river of 545 meters after pollution with diluted sugar beet molasses fortified with glutamic acid. They thought that the rates of pollutant elimination are strongly dependent on the proportion of heterotrophic and phototrophic organisms in the biomass and on the absolute concentrations of the polluting substrate. Self-purification may vary within short periods of time (constant flow and pollution conditions provided) because of external and internal factors acting on the biocenosis which are independent of the polluting matter.

Gates, Mancy, Shafie, and Pohland (8) have reported the results of studies using open stirred reactors. They investigated the sag equations at various reaeration rates and with various combinations of substrates and seeds. They found no agreement in their sag curves with those of Streeter and Phelps. With multiple substrate systems such as glucose-lactose, the DO recovered after glucose was removed, then the lactose exerted a second sag. Their work substantiated the previous results of Gaudy and his co-workers regarding phasic substrate removal, microbial growth, and accumulated O_2 uptake, i.e., BOD (35)(36)(37).

Isaacs and Gaudy (38) compared BOD exertion in the standard BOD bottle to that in a simulated stream. A sag curve was calculated, using

the Streeter-Phelps equation and the deoxygenation constant taken from the BOD bottle. There was little or no similarity between the observed profile and that calculated using the Streeter-Phelps equation.

Later, Jennelle and Gaudy (15) compared the sag curve in an open stirred reactor and the simulated stream apparatus cited above (38), and found them comparable. The rate of oxygen uptake was found to be dependent upon initial substrate concentrations. This finding was important because of the fact that the early rate of oxygen uptake controls the downward leg of the sag curve and thus determines the minimum DO in a receiving stream. They proposed a relationship between the rate of oxygen uptake and substrate concentration of the same form as the Monod relationship between microbial growth and substrate concentration. Gates, Marlar, and Westfield (39) made use of the Monod equation for relating specific growth rate, μ, and substrate concentration, S_o. They felt that this relationship applied well to the dilute system in receiving streams.

Peil and Gaudy (40) in their study compared O_2 uptake curves using the 10-liter open jar reactors with O_2 uptake curves obtained in a 670-liter simulated stream apparatus, and found the open jar technique to provide a fairly good prediction of the actual dissolved oxygen profile observed in the receiving stream. However, investigations on the effect of the reaeration constant, K_2, on the kinetics of oxygen uptake showed that increased agitation (higher K_2 value) caused some increase in the accumulated oxygen uptake (BOD) curve, with most of the increase coming after the "plateau" area in the O_2 uptake curve, i.e., after the low point along the DO sag curve. They suggested that the K_2 of the jar should probably be within $\pm$ 50 percent of that estimated for the near

downstream reaches, in the interest of providing engineering safety factors.

The foregoing review has been given as background information for the present work undertaken by the author in which the open jug technique was employed to assess the O_2 uptake characteristics and type of kinetic expresssion for various types of treated effluents.

CHAPTER III

MATERIALS AND METHODS

To study the influence of substrate-to-cell ratio (i.e., food-to-microorganism ratio) on kinetics of oxygen uptake, and to test the effluent obtained from a bench scale pilot plant, an open stirred reactor was operated under closely controlled conditions. The bench scale pilot plant which was operated was a total oxidation unit using hydrolyzed sludge as the feed.

Description of Equipment and Apparatus

Open Stirred Reactors

The open stirred reactor used in this study was a 8.125-inch diameter cylindrical pyrex vessel with a depth of 18 inches. The stirring was provided by a 2-inch propeller located one inch from the bottom of the vessel. The mixer was driven by a 1/50 hp Bodine motor. The speed of the propeller was regulated by a rheostat. The temperature in the reactor was maintained constant by a Precision Scientific Lo-Temptrol recirculating water bath. The reactors were placed in a rectangular plexiglass vessel serving as a water bath (Figure 1).

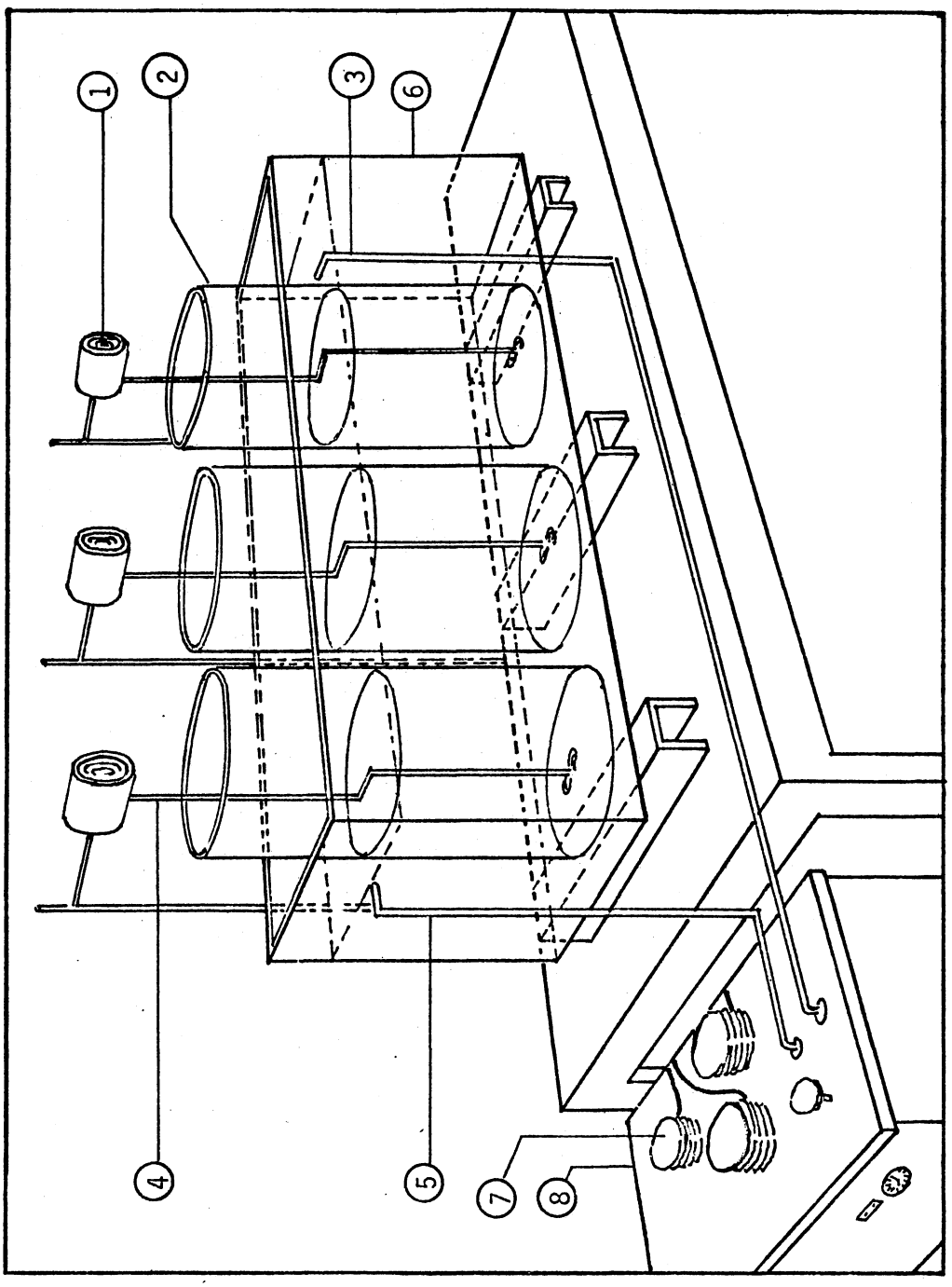
The Pilot Plant

The bench scale pilot plant was operated to study aerobic digestion

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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of sludge after hydrolysis. The pilot plant operation was begun by Saidi; after Mr. Saidi's departure, the author took over operation of the pilot plant.

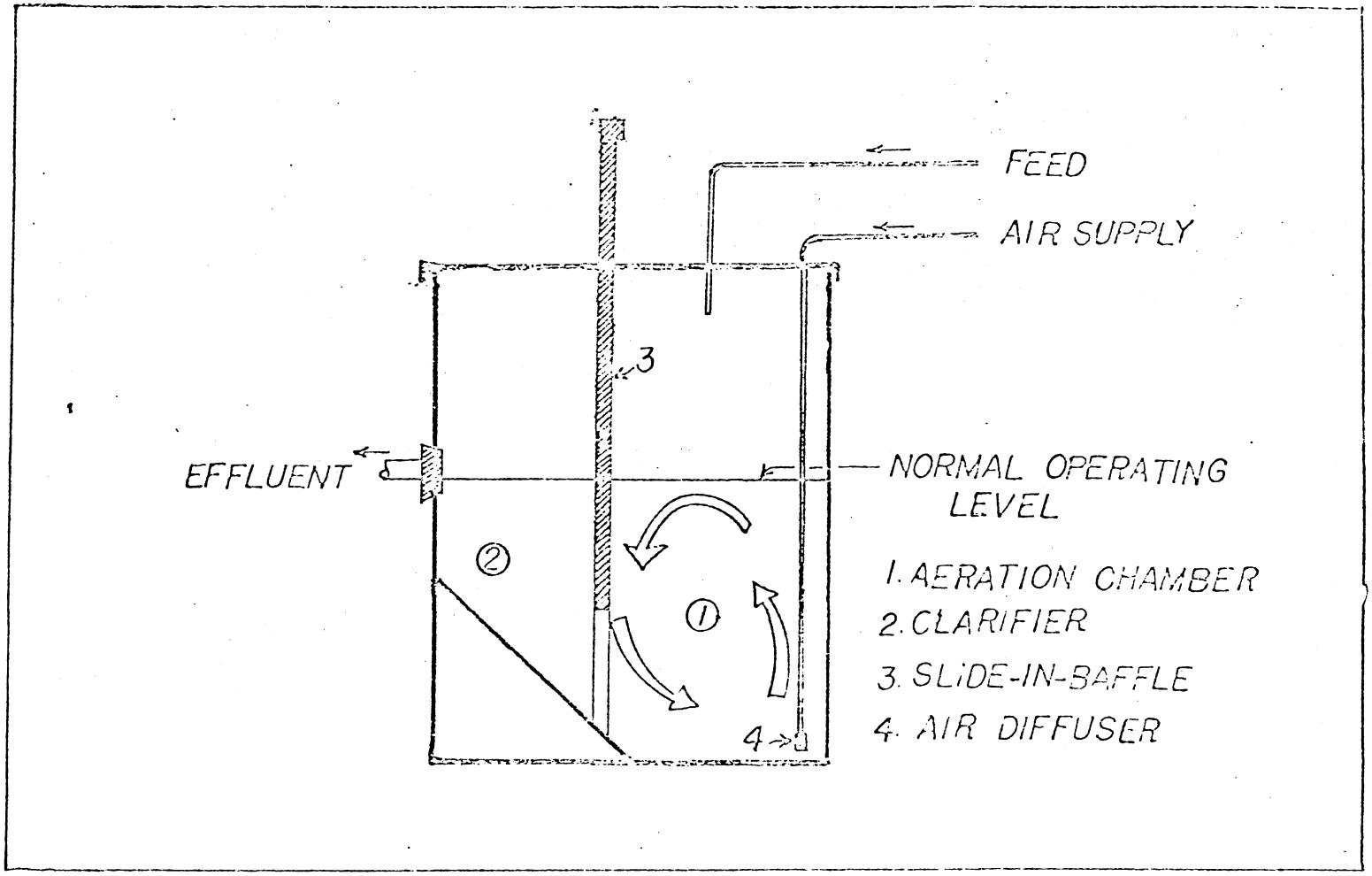
The pilot plant employed was a plexiglass unit with a 6.2-liter aeration basin and a 3.2-liter settling chamber with a net volume of 9.4 liters (Figure 2). The two chambers were separated by a movable baffle leaving a gap between it and the tank bottom so that the mixed liquor could pass to the settling tank. Aeration was provided by compressed air through sintered glass diffusers. The flow rate of 9.4 liters per day was provided by a mini-pump (Milton Roy Model MM2-B-96R) to allow a detention time of 16 hours in the aeration chamber and eight hours in the settling chamber, with a total detention time of 24 hours. Later, since problems developed with the Milton Roy pump due to suspended solids in the feed, a Sigmamotor Zero-max model was used to pump the feed. The experiments were run at room temperature, which varied from approximately 24-27^{o}C. The pH of the system was maintained at 7 ± 0.4 throughout the experiment. The feed solution came from the hydrolysate of trickling filter sludge obtained from the secondary clarifier of the Stillwater waste treatment plant, Stillwater, Oklahoma. Also fed was hydrolysate of the excess sludge from this laboratory pilot plant, i.e., the system was hydrolytically-assisted.

Substrates and Seeds

Stirred Reactors

To study the kinetics of oxygen uptake in the open stirred reactors with respect to food-to-microorganism ratio, synthetic waste was used

Figure 2. Longitudinal Section of Pilot Plant Aeration Basin and Settling Tank


FEED
AIR SUPPLY
3
EFFLUENT
NORMAL OPERATING LEVEL
2
1
4
1. AERATION CHAMBER
2. CLARIFIER
3. SLIDE-IN-BAFFLE
4. AIR DIFFUSER

with glucose as the carbon source. The composition of the growth medium is given elsewhere (41). The seed was taken from an extended aeration pilot plant and from a batch fed pilot plant. Both the substrate and seed were added to tap water in the reactor which had been previously brought to a constant temperature.

The treatment plant effluents used in this study were taken from the pilot plant operated on hydrolysate of a trickling filter sludge described above, and an additional three runs were made using effluent from an extended aeration pilot plant operated by Roach, a fellow graduate student engaged in research. The synthetic waste he employed contained glucose as the carbon source and mineral nutrients with a COD:N ratio of 10:1, along with the hydrolysate of the excess sludge from the same unit. The detention time was 24 hours; the feed concentration was 1000 mg/l COD. His investigation pertains to biological response to quantitative and hydraulic shock loads. However, the effluents used in this study were taken during steady state operating conditions.

The Pilot Plant

The feed for the hydrolytically-assisted extended aeration pilot plant operated by the author was obtained from the secondary clarifier (trickling filter sludge) of the Stillwater municipal wastewater treatment plant. This sludge was acidified to pH 1, and subjected to high temperature (121^{o}C) and high pressure (15 psi) for five hours in a laboratory autoclave. The hydrolysate was removed, cooled to room temperature and finally neutralized, and was added at known concentration (COD) to the feed reservoir. To this sludge hydrolysate the sludge

hydrolysate obtained from the excess sludge from the pilot plant, using the same procedure, was added to the feed reservoir and diluted to the desired feed concentration with tap water.

Experimental Procedures

The Open Stirred Reactor

The reactor was initially cleaned with acid and rinsed thoroughly to make sure that the contaminants did not distort the dissolved oxygen profile during the course of the experiment. The experimental procedures are given separately below for the experiments with glucose and for the experiments with effluents.

Experiments Using Synthetic Waste. The cleaned reactors were placed in the water bath and ten liters of tap water were added. After fixing the propellers in position, the motor was started. After making sure that the water in the reactor reached the equilibrium temperature ($22.5 \pm 0.5^{o}C$), a stoichiometric amount of sodium sulfite (0.7 gm) and cobalt chloride catalyst were added to remove the dissolved oxygen in the system, and DO in the system was monitored at close intervals. After recovery of DO in the system and after assurance that enough data were obtained to determine the reaeration rate and the saturation value, feed solutions in pre-determined volumes were added to the reactor from the stock solutions already prepared. A sample for COD determination was then taken. The seed was added; suspended solids concentration of the seed was determined on a concentrated sample and the concentration in the open jar was calculated from a knowledge of the seed dilution. The experiment was continued and DO was monitored at close intervals

daily for five days to determine the dissolved oxygen profile in the system. After five days, the filtrate COD and suspended solids were determined. The oxygen uptake was calculated from the dissolved oxygen profile obtained, using the reaeration rate constant, K_2, and the saturation value, C_s, determined graphically from the reaeration data.

Experiments Using Effluents. Effluent from bench scale pilot plants was added to the already cleaned reactors; the propeller was fixed in position, and the experiment started. In some experiments, the DO was brought to a value of 80-90 percent of saturation and other experiments were conducted with the effluent as it came from the pilot plant. Samples were taken both in the beginning and at the end of the experiments to determine total and filtrate COD, suspended solids, and NO_3-N. However, in some experiments, the DO profile was determined before measuring K_2. In some experiments, the K_2 value was attained before running the DO profile as per experiments using synthetic wastes. After a reasonably good DO profile was obtained, 20 ml of Clorox was added to kill the microorganisms, and twelve hours' time was allowed to complete the kill. It was essential to assure that the only mechanism changing the DO was reaeration. The absence of O_2 uptake was checked on a Warburg apparatus in preliminary studies. Reaeration experiments were performed similar to those described above using glucose as substrate. The reactor was then taken out of the water bath, cleaned thoroughly, and the reaeration experiment was again run with the tap water keeping the system constant (temperature, stirring rate) except that the sample was tap water instead of the effluent. This was done to determine the effect of effluents on the reaeration rate, K_2, and

saturation values compared to tap water.

A few runs were made in which additional solids from the pilot plant and hydrolysate from the sludges of the pilot plant were added to simulate conditions of release of substrate and solids from the pilot plant. These studies will be discussed in detail in the next chapter.

Regardless of the nature of the effluent, the sample volume was ten liters. In general, effluents were employed without any dilution. In a few cases, the effluent was diluted and these will be delineated as the results are presented in the next chapter.

Experiments on Factors Affecting K_2

It is well known that various constituents of the effluent as well as physical factors regarding the reactor can affect the values of K_2. It was therefore of interest to investigate these aspects. Special studies were conducted to determine the effect of propeller speed on K_2; studies to determine the effect of biological solids concentration on K_2 were also made. Also, since K_2 was determined in some studies after measuring the DO profile, it was essential to add a microbial killing agent. Experiments were conducted using Clorox and cyanide as killing agents and their effect on K_2 was determined.

Pilot Plant Operation

The pilot plant feed was prepared on alternate days each time providing enough feed for two days in the feed reservoir. The procedure followed in operating the unit was as follows: The feed line was removed from the unit and the suction end removed from the feed reservoir and placed in the Clorox solution. This was done to clean and

disinfect the feed line. Immediately after removing the feed line from the aeration tank of the pilot plant, the effluent port was stoppered, the clarification tank baffle was removed, and the total contents of the system momentarily mixed. At this time, a sample was taken to determine the biological solids concentration in the system, and the baffle was reset. Also during this time, samples were removed from the effluent collection reservoir after thoroughly mixing it for measurement of biological solids, filtrate COD, and total COD. Then the feed reservoir was cleaned with dichromate solution and thoroughly rinsed free of spent solution with distilled water. The hydrolysate of the trickling filter sludge was added to the feed reservoir and the liquor was brought to half the reservoir volume with tap water. A sample was taken for COD (total), then hydrolysate of the excess sludge from the pilot plant was added and the volume made up to the operating feed reservoir capacity; samples for total and filtrate COD and biological solids were taken. The total sampling period usually required approximately one hour, and during this time the feed lines were being cleaned with Clorox solution, rinsed with tap water, and flushed with new feed. The line was then re-engaged with fresh medium, and the pilot plant set into continuous flow operation until the following sampling period. Periodically, a portion of the settled sludge was withdrawn from the bottom of the clarifier and biological solids determinations were made prior to hydrolyzing it. After acidifying to pH 1, this portion of sludge was subjected to high temperature (121^{o}C) and high pressure (15 psi) for five hours in a laboratory autoclave. The hydrolysate was removed, cooled to room temperature, and finally neutralized. Equal portions were added each two days over a period of 7-10 days, at which

time a new sample of sludge was withdrawn and hydrolyzed for gradual refeeding to the reactor.

Analytical Procedures

Dissolved Oxygen

For the runs made with glucose, dissolved oxygen was monitored electrometrically using a Precision Scientific Company DO analyzer. The instrument was calibrated before each experiment and checked daily, using the Winkler Method, as explained in Standard Methods (42).

For the runs with effluents, the dissolved oxygen concentration was monitored electrometrically by using a Weston-Stack oxygen analyzer which was standarized periodically by using the Winkler Method.

Chemical Oxygen Demand

COD determinations were made according to Standard Methods (42).

Biological Solids Concentration

Solids concentrations were determined by filtering a 40-ml sample through tared membrane filters (0.45 μ pore size, Millipore Filter Corp., Bedford, Mass.). The filtered sample was dried in an oven at 103^{o}C for two hours, and cooled in a desiccator for two hours before the final weight was taken.

Nitrate-Nitrogen

Nitrate-nitrogen was determined (using the Brucine Method) according to Standard Methods (42) for the treatment of water and wastewater.

Methods of Analyses

The saturation value, C_s, and the reaeration rate, K_2, were determined by using the following procedures:

1) The method described by Isaacs and Gaudy (43), herein termed the "α Method," was employed.

2) The reaeration rate and saturation values were also determined using a different method, for which details are given below.

The equation was given by

$$dC/dt = K_2(C_s - C_t) \qquad (1)$$

where

dC/dt = rate of transfer of oxygen per unit time

K_2 = reaeration rate constant, hr^{-1}

C_s = saturation value of DO concentration under the test conditions, mg/l

C_t = DO concentration at any time, t

Equation (1) is a monomolecular equation; thus, it follows first order reaction kinetics.

Substituting $dC/dt = 0$ in equation (1):

$$\begin{aligned} 0 &= K_2(C_s - C_t) \\ &= C_s - C_t = 0 \\ C_s &= C_t \end{aligned} \qquad (2)$$

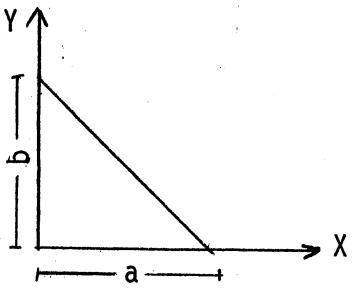
Thus, it can be seen that when the rate of transfer of DO approaches zero, the dissolved oxygen in the stream approaches the saturation value, C_s.

Rewriting equation (1)

$$dC/dt = K_2C_s \left(1 - \frac{C_t}{C_s}\right) \tag{3}$$

and expanding the equation (3), the reaeration equation can be arranged in a standard straight line form:

$$dC/dt = K_2C_s - \frac{K_2C_s}{C_s} C_t \tag{4}$$



This equation is similar to the standard form:

$$Y = b - b/ax \tag{5}$$

wherein the parameters X and Y are C_t and dC/dt, respectively. 'a' and 'b,' the intercepts, are 'C_s' and 'K_2C_s.' respectively. The slope of the straight line is given by

$$- b/a = \frac{K_2C_s}{C_s} = K_2,$$

the reaeration constant. The saturation value, C_s, is determined by measuring the intercept 'a' = C_s on the X-axis.

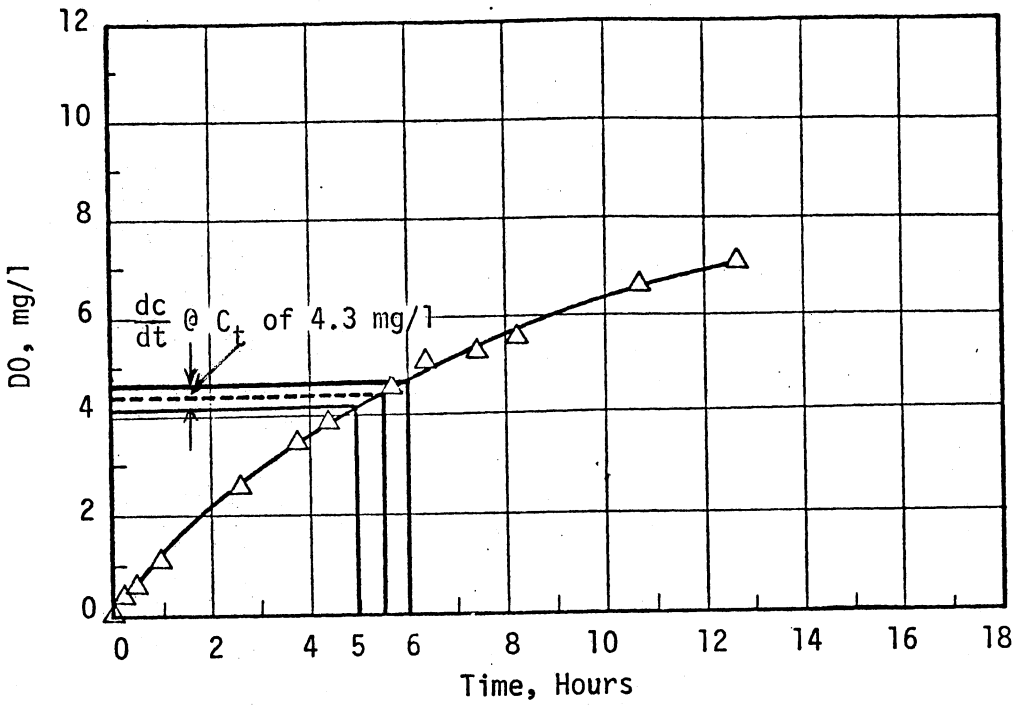
The intercept on the Y-axis, 'b' = K_2C_s is the maximum rate of transfer, where the DO concentration in the system is zero.

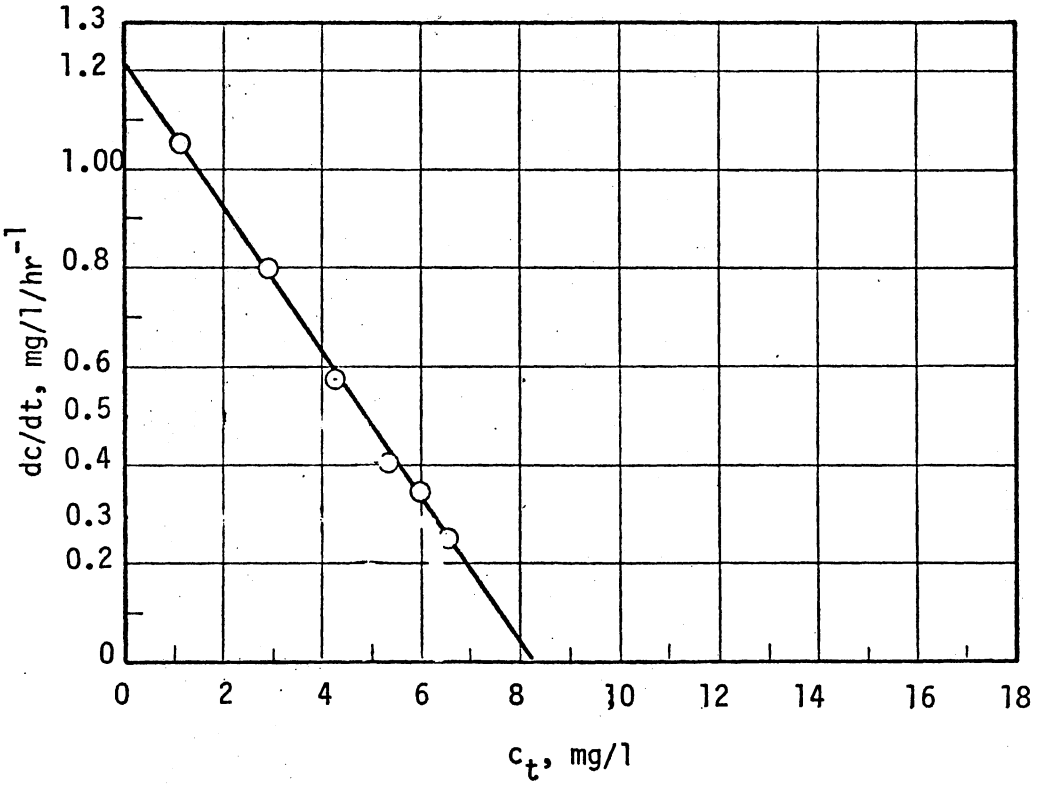
An example of reaeration data is shown in Figure 3. The plot shows the value of dC/dt at a t of 5.5, using a one-hour interval for computation. The value of dC/dt (0.58) is ΔDO between hours six and five. This dC/dt exists at a DO level (C_t) of 4.3 mg/l. Similarly, values of

Figure 3. Arithmetic Plot of the Reaeration Data, DO versus Time

Figure 4. Arithmetic Plot of the Reaeration Data, dC/dt versus C_t (Method 2)

$K_2 = 0.145\ hr^{-1}$ $C_s = 8.4\ mg/l$


DO, mg/l
dc/dt @ C_t of 4.3 mg/l
Time, Hours


dc/dt, mg/l/hr^{-1}
c_t, mg/l

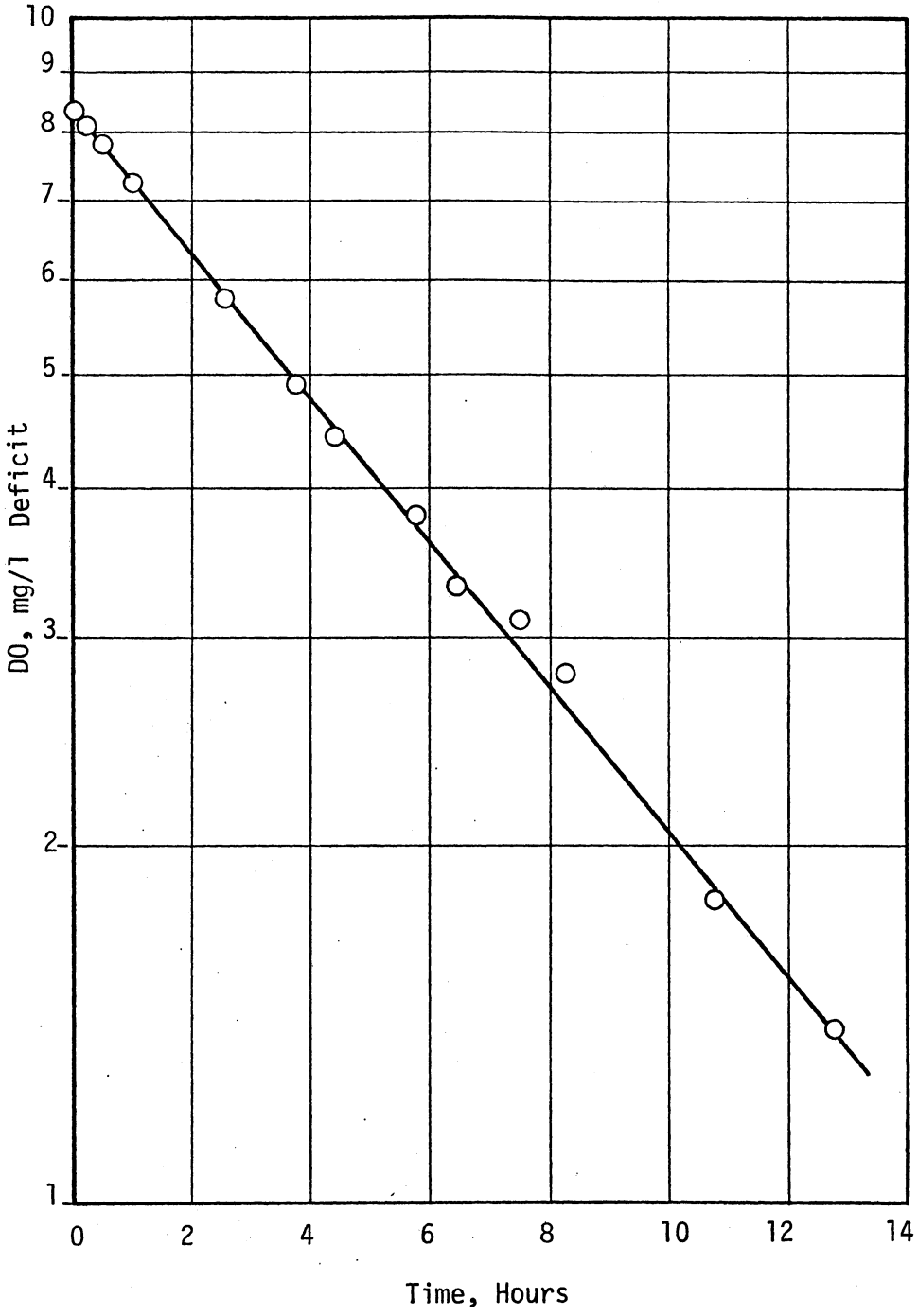
rate of transfer for each successive time interval during the length of the experiment (i.e., the DO level and the corresponding oxygen transfer rates) are computed and plotted in Figure 4, which is a plot of the straight line in accordance with equation (4). The intercept on the X-axis in Figure 4 is the saturation value, and the slope of the straight line is the reaeration rate constant, K_2. (Also, the reaeration rate can be computed by $\frac{\text{intercept on Y-axis}}{\text{intercept on X-axis}}$.

The values of DO saturation, C_s, and the reaeration rate, K_2, using the above method (Figure 4) are in good agreement with the values determined using the method suggested by Isaacs and Gaudy (see Figure 5).

The oxygen uptake was calculated from the dissolved oxygen profiles and corresponding reaeration rate, K_2, and the saturation values, C_s, determined using the dC/dt method (Method No. 2). An example of the calculation of accumulated oxygen uptake (i.e., BOD curve) is shown in Appendix A.

Figure 5. Logarithmic Plot of DO Deficit (Method No. 2) versus Time

$K_2 = 0.141\ hr^{-1}$ $C_s = 8.4\ mg/l$


10
9
8
7
6
5
4
3
2
1
DO, mg/l Deficit
0
2
4
6
8
10
12
14
Time, Hours

CHAPTER VI

RESULTS AND DISCUSSION

The results presented below are divided into two distinct categories: 1) tests on the kinetics of oxygen uptake, and 2) tests using effluents from the laboratory bench scale extended aeration pilot plants to evaluate the oxygen uptake characteristics in the receiving stream using an open stirred reactor. Also, some of the factors affecting the reaeration rate will be discussed in this chapter. Discussion of the data proceeds as the results are presented.

Studies on the Kinetics of Oxygen Uptake Using Open Stirred Reactors With Seed From a Batch Operated Activated Sludge Unit

The results are presented in decreasing order of F/M ratio. Shown in Figure 6 is the dissolved oxygen profile and the corresponding oxygen uptake for an initial F/M ratio of 18.7 with an initial concentration of 112 mg/l of soluble organic material (COD) and a biological solids concentration of 6 mg/l; the carbon source consisted of 90 mg/l glucose. The system was operated at a K_2 of 0.117 hr^{-1} and a DO saturation value of 7.4 mg/l; total oxygen uptake exerted in five days was 44 mg/l. The O_2 uptake curve shows a slight upward concavity during the downward leg of the DO sag curve, suggesting that first order decreasing rate O_2 uptake may have been attained.

Figure 6. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Young" Cell Seed at F/M Ratio of ≈ 18.7

S_{og}	Initial Substrate Concentration	90 mg/l
S_oCOD	Initial COD	112 mg/l
X_o	Initial Cell Concentration	6.00 mg/l
K_2	Reaeration Constant	0.117 hr^{-1}
c_s	Saturation DO	7.4 mg/l

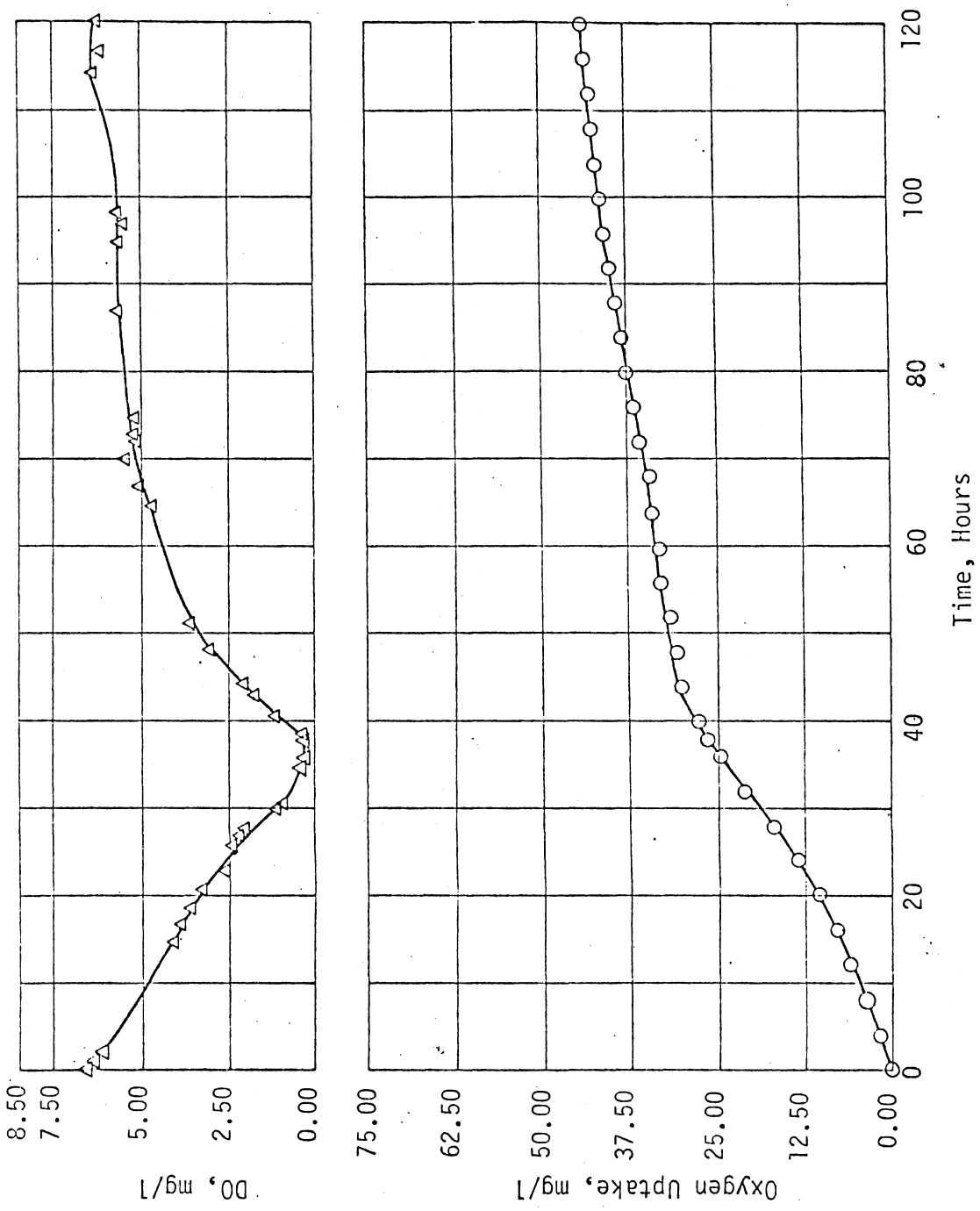

DO, mg/l
8.50
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
75.00
62.50
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

Figure 7 gives the dissolved oxygen profile and the corresponding oxygen uptake with an F/M ratio of 16.80. The added glucose concentration was 120 mg/l, and the measured initial COD was 134 mg/l. Biological solids (suspended solids) concentration at the start of the test was 8 mg/l. The experiment was performed at a K_2 of 0.128 hr^{-1} and C_s of 7.1 mg/l, as determined from the reaeration data. The oxygen uptake was 36 mg/l; the sag curve was well rounded when compared to the experiment in Figure 6. The low point was reached a little earlier in this experiment. The oxygen uptake curve showed a slight upward concavity until the low point of the sag was attained.

The initial glucose concentration for the experiment shown in Figure 8 was 100 mg/l and the observed initial COD was 120 mg/l. Initial biological solids concentration (X_o), was 8 mg/l, giving an F/M ratio of 15.00. When operated at a K_2 of 0.11 hr^{-1} and a saturation value of 7.7 mg/l, the system yielded an oxygen uptake of 44 mg/l. The sag of the dissolved oxygen profile was well rounded, and reached the low point earlier than in Figure 7.

The experiment in Figure 9 was conducted at a K_2 of 0.097 hr^{-1}, and the saturation value obtained from the reaeration data was 7.5 mg/l. The nominal glucose concentration was 50 mg/l, and the measured COD was 56 mg/l. The initial seed concentration was 6 mg/l, giving an F/M ratio of 9.3. The oxygen uptake at 120 hours was 31 mg/l. In this experiment, the low point of the sag was reached faster than those with higher F/M values, but the recovery of dissolved oxygen was somewhat slower, which may have been due to the fact that K_2 was lower in this experiment.

In Figure 10, it is seen that 31 mg/l of oxygen was used in metabolizing 60 mg/l glucose (initial COD = 65 mg/l). The seed concentration

Figure 7. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Young" Cell Seed at F/M Ratio of 16.80

S_{og}	Initial Substrate Concentration	120 mg/l
S_oCOD	Initial COD	134 mg/l
X_o	Initial Cell Concentration	8 mg/l
K_2	Reaeration Constant	0.128 hr^{-1}
c_s	Saturation DO	7.4 mg/l

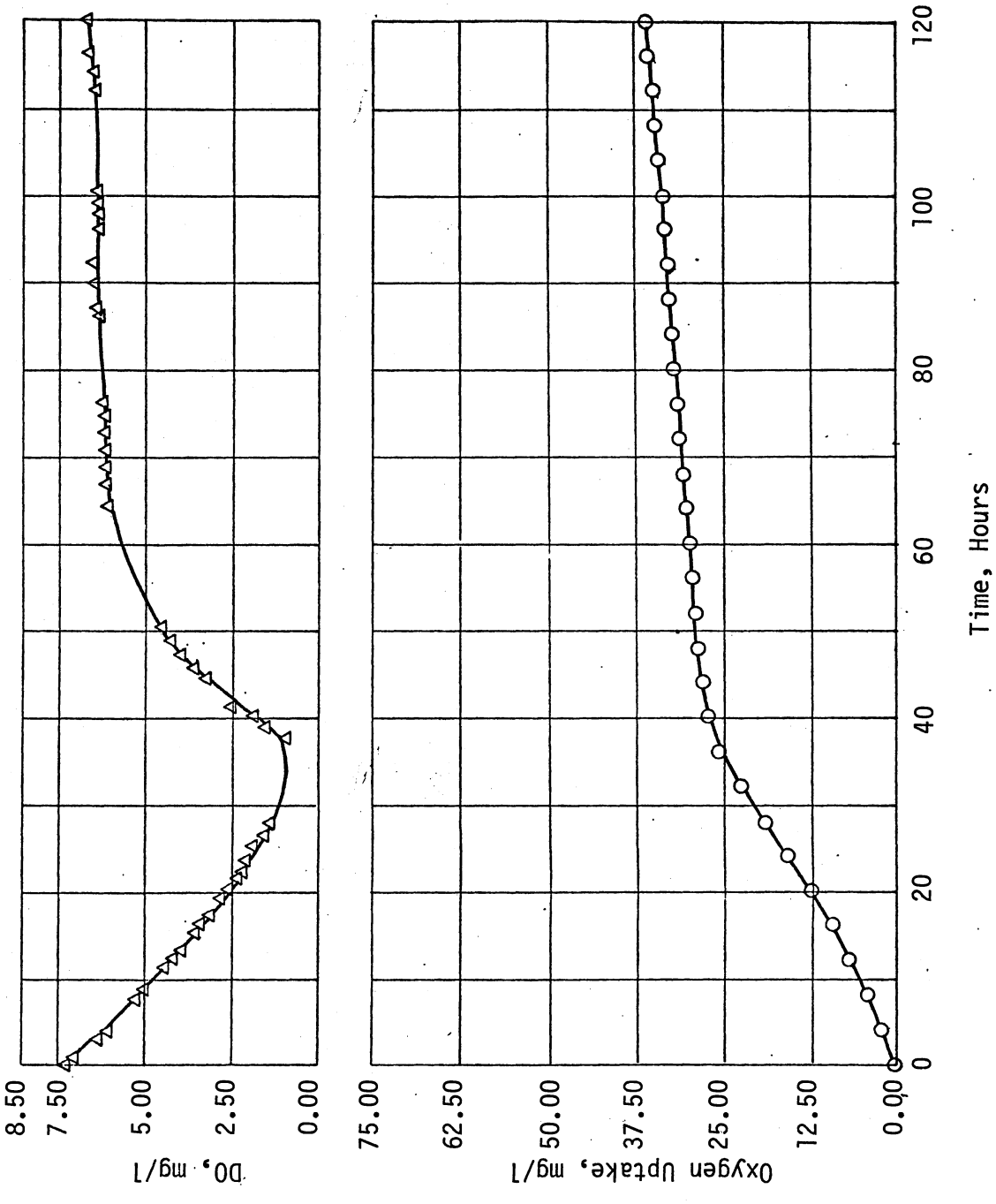

DO, mg/l
8.50
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
75.00
62.50
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

Figure 8. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Young" Cell Seed at F/M Ratio of ≃ 15

S_{og}	Initial Substrate Concentration	100 mg/l
S_o COD	Initial COD	120 mg/l
X_o	Initial Cell Concentration	8.00 mg/l
K_2	Reaeration Constant	0.11 hr^{-1}
c_s	Saturation DO	7.7 mg/l

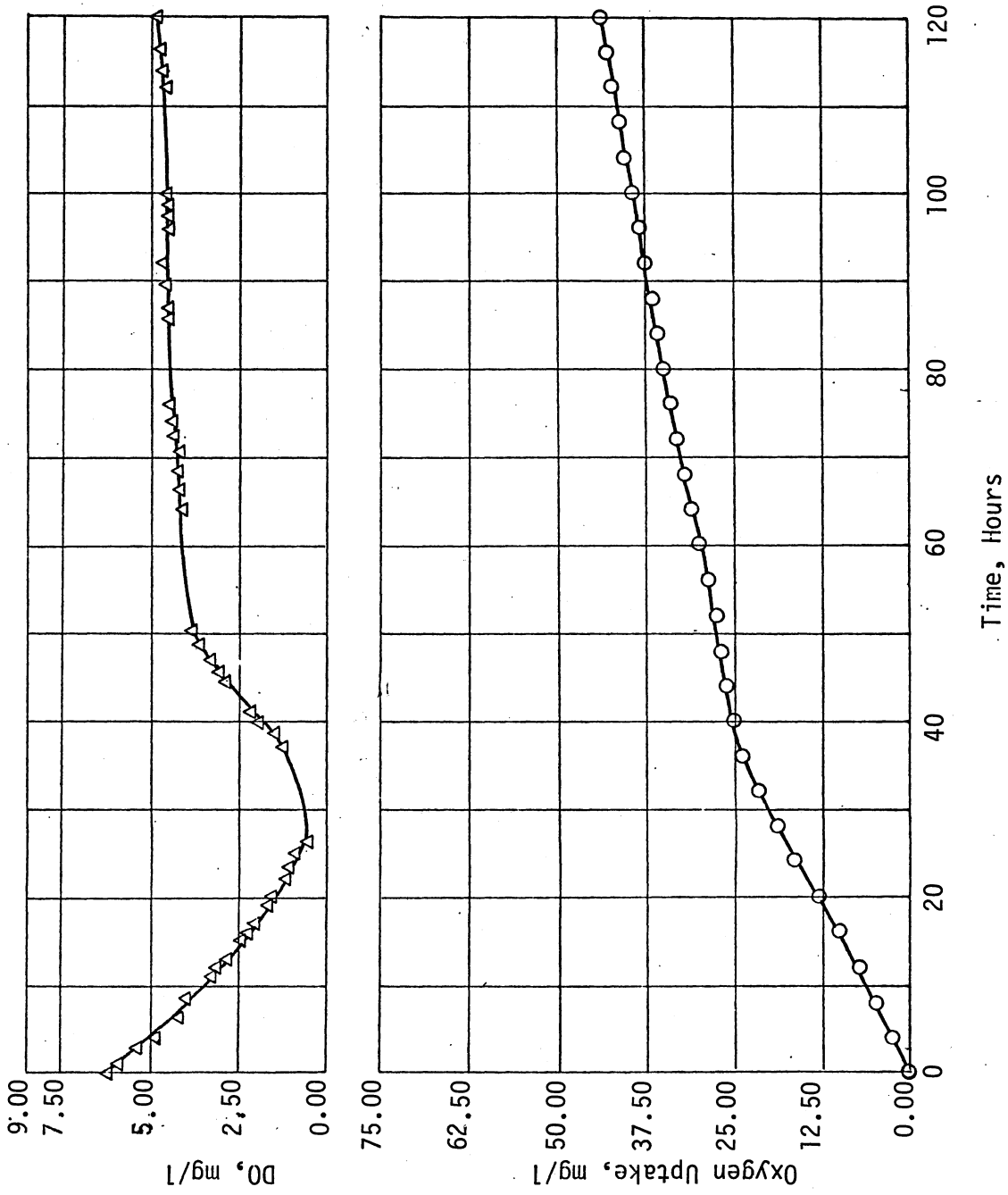

DO, mg/l
9.00
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
75.00
62.50
50.00
37.50
25.00
12.50
0.000
0
20
40
60
80
100
120
Time, Hours

Figure 9. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Young" Cell Seed at F/M Ratio of ≈ 9.3

S_{og}	Initial Substrate Concentration	50 mg/l
S_oCOD	Initial COD	56 mg/l
X_o	Initial Cell Concentration	6.00 mg/l
K_2	Reaeration Constant	0.097 hr^{-1}
c_s	Saturation DO	7.5 mg/l

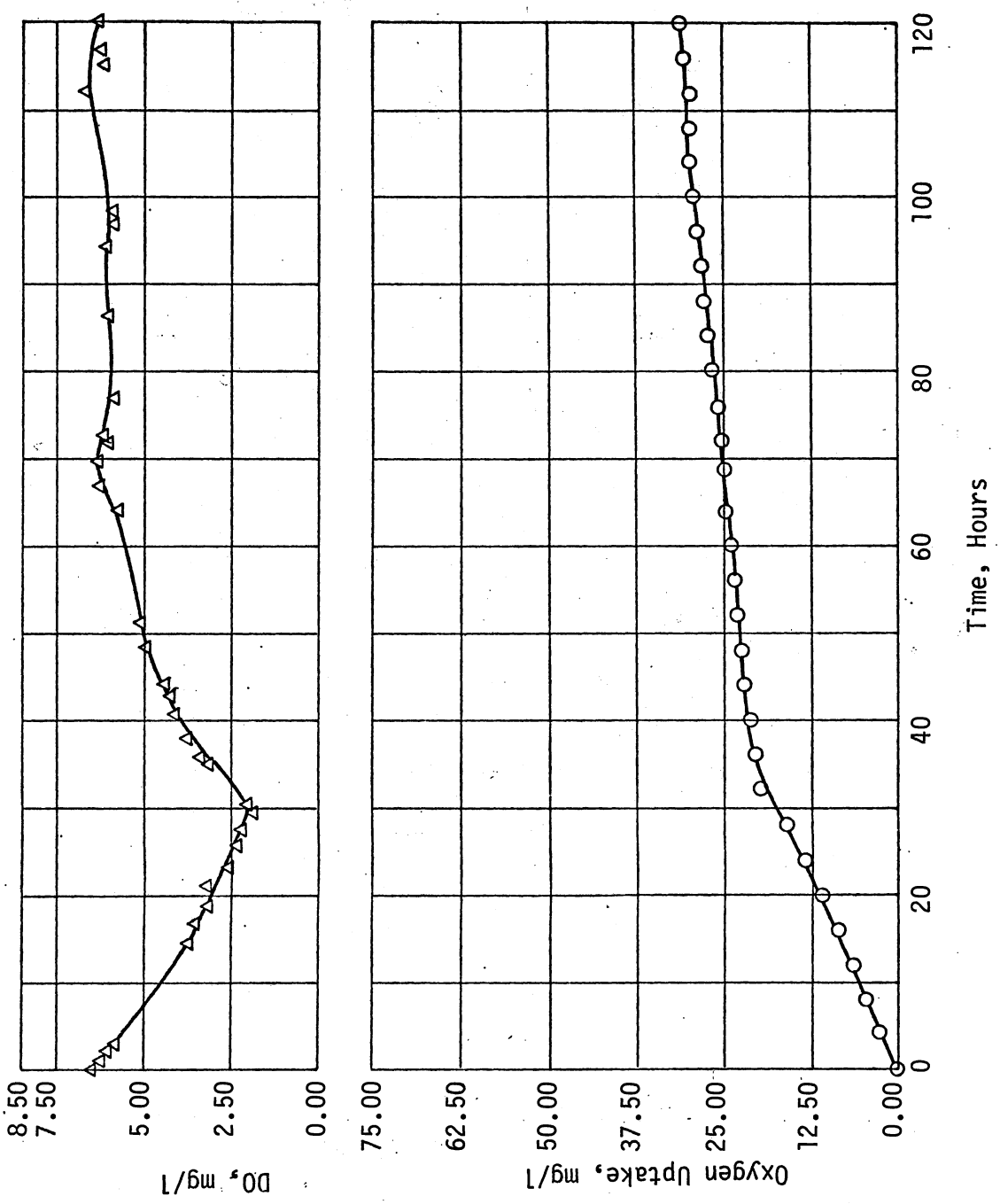
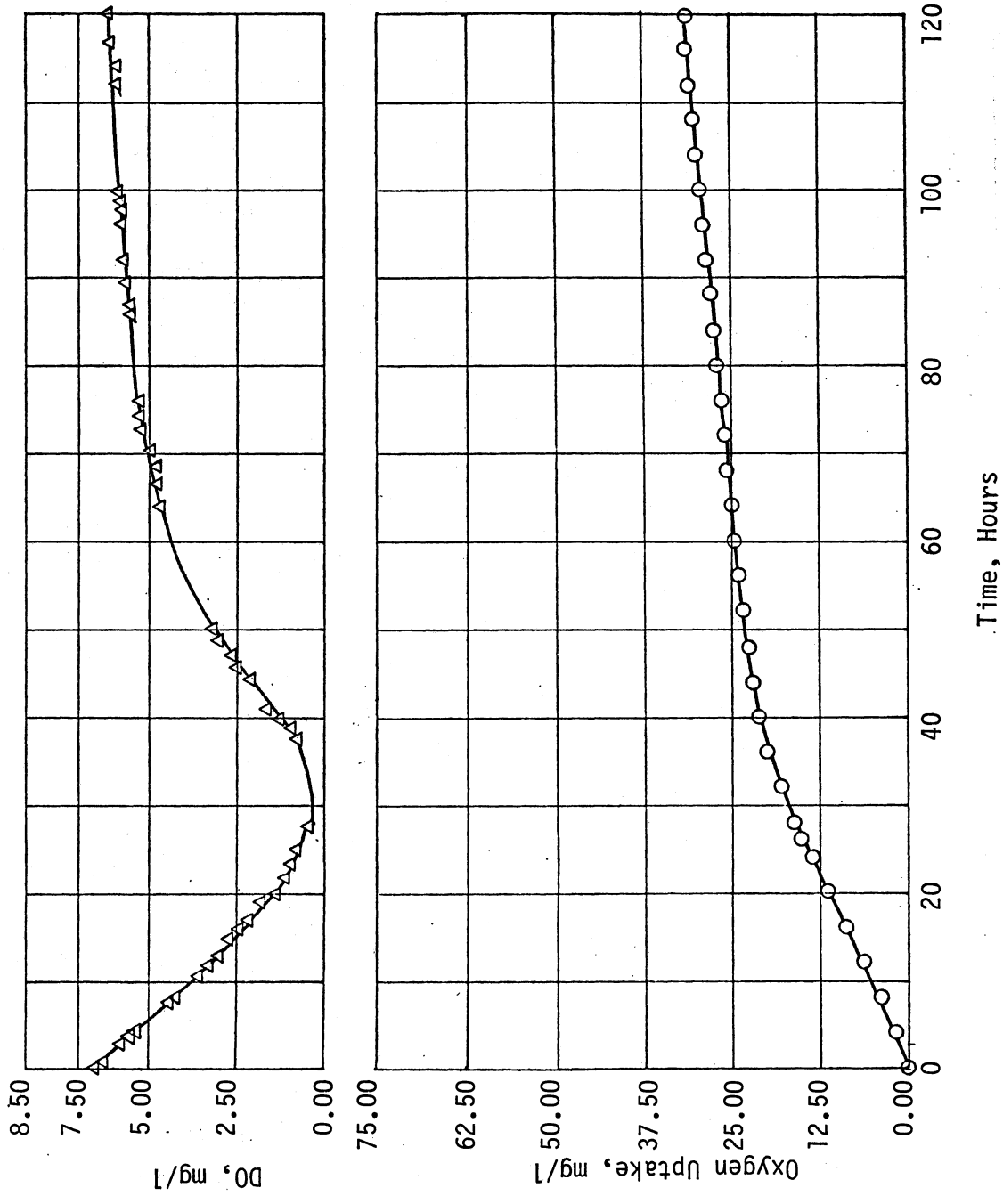

DO, mg/l
8.50
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
75.00
62.50
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

Figure 10. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Young" Cell Seed at F/M Ratio of ≈ 8.1

S_{og}	Initial Substrate Concentration	60 mg/l
S_oCOD	Initial COD	65 mg/l
X_o	Initial Cell Concentration	8.00 mg/l
K_2	Reaeration Constant	0.07 hr^{-1}
c_s	Saturation DO	7.7 mg/l


DO, mg/l
8.50
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
75.00
62.50
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

was 8.0 mg/l, and the F/M ratio was 8.1. The experiment was conducted at a K_2 of 0.07 hr^{-1} and a saturation value of 7.7 mg/l. When reviewed in relation to the previous figures, there appears to be a general trend in that as F/M decreases, the lower point of the sag is reached earlier.

The experiment in Figure 11 was conducted at an F/M ratio of 7.9, with an initial glucose concentration of 55 mg/l and an observed initial COD of 71 mg/l. The initial biological solids concentration was 9 mg/l, and the reaeration rate was 0.13 hr^{-1} at a saturation value of 8.00 mg/l. The oxygen uptake exerted was 39 mg/l. The trend of the dissolved oxygen profile remained similar to the previous ones in that the minimum dissolved oxygen level of the sag curve was reached more rapidly as F/M increased. In Figure 12, the glucose concentration was 40 mg/l, and the measured initial COD was 52 mg/l. The initial biological solids concentration was 9 mg/l providing an F/M ratio of 5.80. The oxygen uptake exerted was 27 mg/l. The experiment was conducted at a reaeration rate of 0.107 hr^{-1}, and a dissolved oxygen saturation value of 8.0 mg/l.

The fact that in all of these experiments the nature of the substrate was the same (glucose) and the seed was taken from the same batch unit, facilitates comparison of the kinetics. The K_2 values were not all the same, but the largest difference was from a high of 0.130 hr^{-1} (Figure 11) to a low of 0.07 hr^{-1} (Figure 10). Figures 6-12 show that as the F/M ratio decreases, the shape of the dissolved oxygen profile changes in a particular way, i.e., the low point of the sag is reached earlier with decreasing F/M ratios. This trend may be due in part to a slightly decreasing trend in K_2 as the F/ M ratio was decreased, but in the main it appears that it can be attributed to the fact that the time

Figure 11. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Young" Cell Seed at F/M Ratio of ≃ 7.9

S_{og}	Initial Substrate Concentration	55 mg/l
S_oCOD	Initial COD	71 mg/l
X_o	Initial Cell Concentration	9.00 mg/l
K_2	Reaeration Constant	0.13 hr^{-1}
c_s	Saturation DO	8.00 mg/l

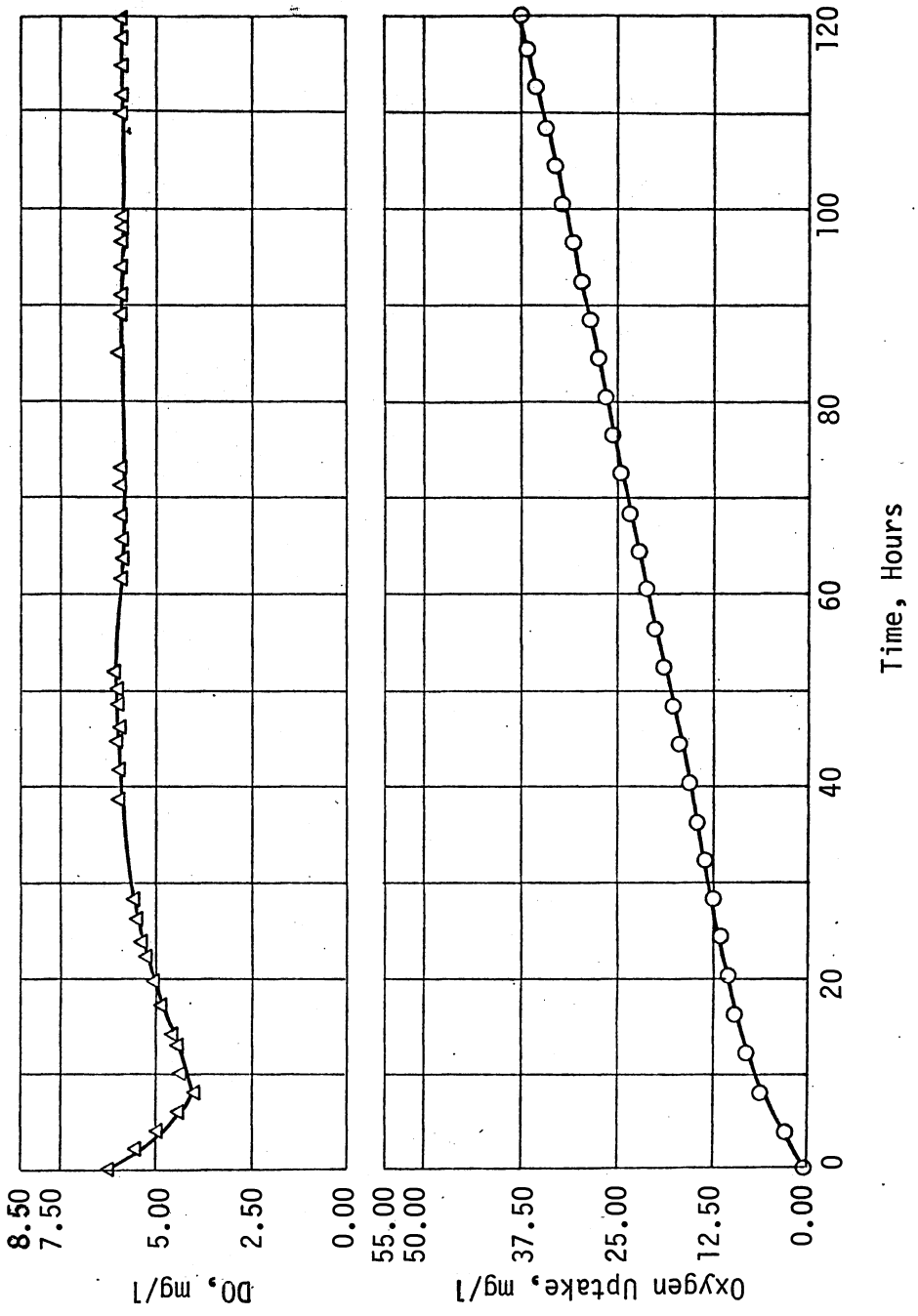
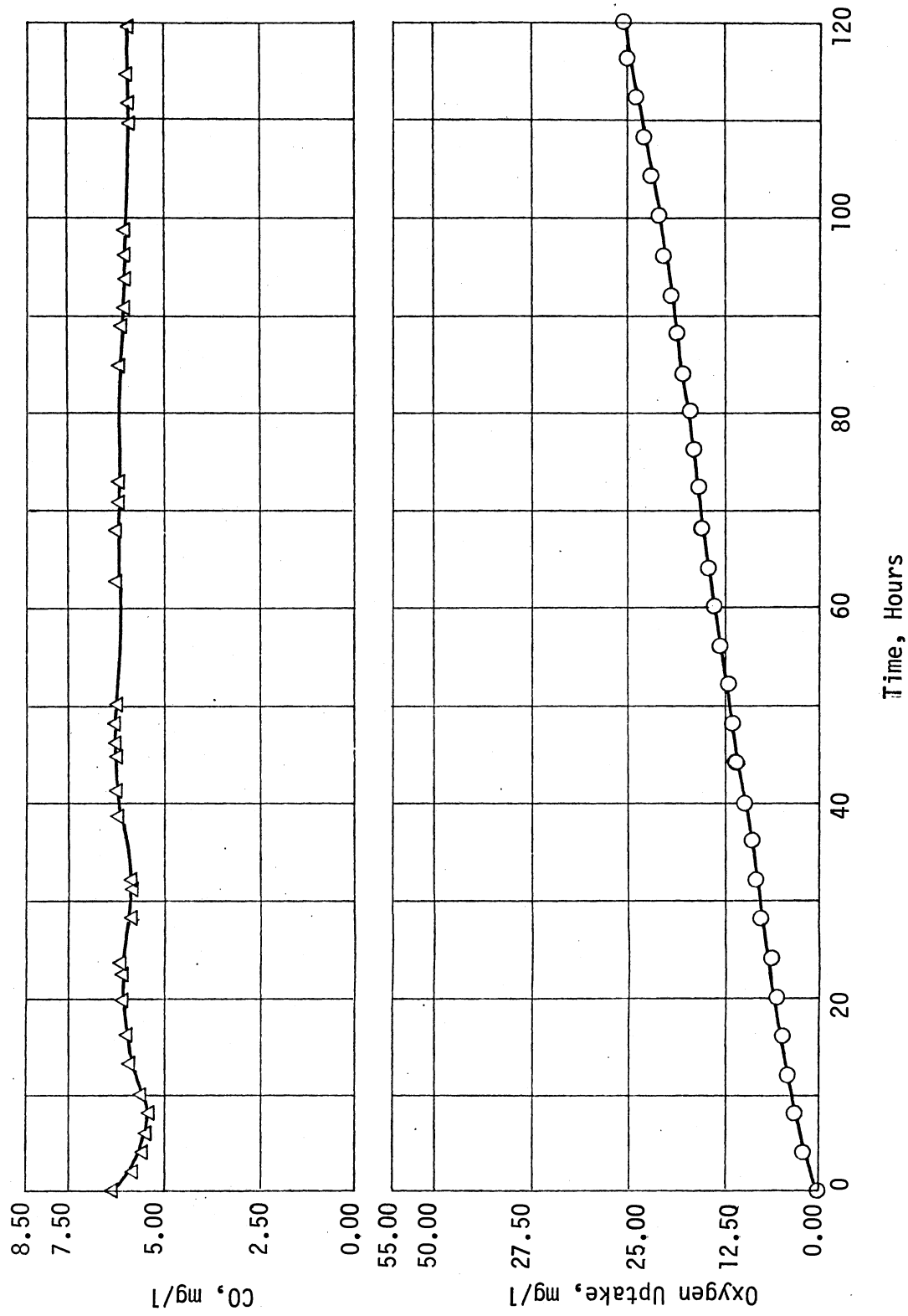

DO, mg/l
8.50
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
55.00
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

Figure 12. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Young" Cell Seed at F/M Ratio of 5.80

S_{og}	Initial Substrate Concentration	40 mg/l
$S_{o}COD$	Initial COD	52 mg/l
X_o	Initial Cell Concentration	9.00 mg/l
K_2	Reaeration Constant	0.107 hr^{-1}
c_s	Saturation DO	8.00 mg/l


8.50
7.50
5.00
2.50
0.00
CO, mg/l
55.00
50.00
27.50
25.00
12.50
0.00
Oxygen Uptake, mg/l
0
20
40
60
80
100
120
Time, Hours

to reach the low point in the sag depends upon the time to attain maximum total growth, and at higher F/M ratios more time is required because there is a proportionally greater amount of substrate to exhaust before attaining maximum population. The recovery phase of the DO profile can be expected to occur after exhaustion of exogenous substrate and attainment of maximum population. The speed of recovery of DO would be expected to depend upon the biomass concentration present for endogenous and/or autodigestive metabolism as well as the reaeration rate. For the studies shown in Figures 6-12, the initial solids concentrations were small and the size of the population after removal of substrate depended on "F" rather than on "M," thus for lower F/M ratio, the endogenous phase of O_2 uptake would be expected to be lower and the recovery of DO more rapid. Such a trend was not evidenced. In fact, there was a tendency toward somewhat slower recovery at the lower F/M ratios. In these experiments, this was probably due to the slightly lower K_2 values which were employed as F/M was decreased. Lower K_2 values were used since it was necessary to develop a "sag" in order to calculate the O_2 uptake.

It was seen that there was in some experiments an upward concavity in the O_2 uptake curve, which suggested the possibility of attainment of exponential uptake in the early portion of the BOD curves. Figure 13 is a plot of O_2 uptake versus time on semilog coordinates. The origin on the X-axis was shifted, for each experiment, to the right to facilitate plotting all seven curves in the same figure. The accumulated O_2 uptake curves are plotted in decreasing order of F/M ratio from left to right. Curves are numbered 6 through 12, corresponding to Figures 6 through 12. At the high F/M ratio, there is some evidence that an exponential phase of O_2 uptake developed between hours 10 and

Figure 13. Logarithmic Oxygen Uptake versus Time for Experiments With "Young" Cell Seed (Figures 6-12)

Figure	F/M	$K_2(hr^{-1})$
6	18.70	0.117
7	16.80	0.128
8	15.00	0.110
9	9.30	0.097
10	8.10	0.070
11	7.90	0.130
12	5.80	0.107

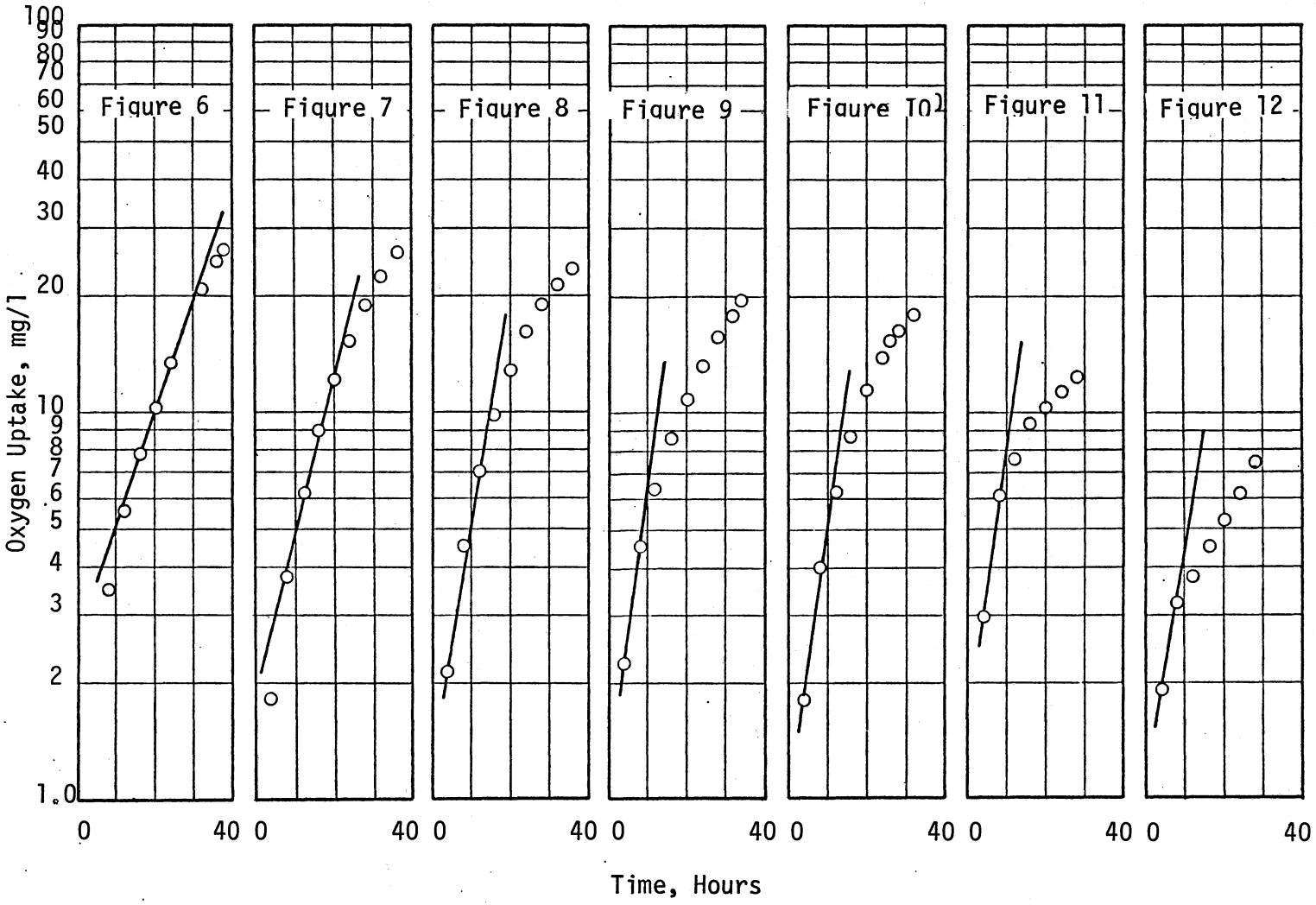


Figure 6
Figure 7
Figure 8
Figure 9
Figure 10
Figure 11
Figure 12
Oxygen Uptake, mg/l
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1.0
0
40
Time, Hours

30. Straight lines are fitted to early portions of the other curves as well, although evidence for development of an exponential phase is seen to diminish as the F/M ratio (i.e., initial substrate concentration) decreases.

Studies on the Kinetics of Oxygen Uptake Using Open Stirred Reactors With Seed From a Laboratory Extended Aeration Pilot Plant

It was of interest to study the effect of types of seed cells on oxygen uptake kinetics. The following runs were made using seed from an extended aeration pilot plant. These seed cells represented a much "older" or more mature population than those from the batch unit which were employed in the studies of the previous section.

The slow-growing character of the seed from an extended aeration plant is shown in Figure 14. The F/M ratio was 100, and 96 hours were required for attainment of the low point of the sag; the DO recovered rapidly. The seed concentration was less than one mg/l, and the nominal glucose concentration was 75 mg/l (measured COD = 86 mg/l). At a K_2 of 0.07 hr^{-1} and a corresponding saturation value of 8.6 mg/l, the oxygen uptake exerted was 32 mg/l.

The experiments in Figures 15-17 indicate that as F/M ratio is decreased, recovery of the sag curve proceeds somewhat more slowly, and the low point of the sag occurs in a shorter time period. For the experiment shown in Figure 15, the substrate was 50 mg/l glucose, and the measured initial COD was 76 mg/l. Initial biological solids concentration was less than one mg/l (0.86 mg/l calculated by dilution factor) and the F/M was 88. The 5-day oxygen uptake was 26 mg/l at a K_2 of

Figure 14. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Old" Cell Seed at F/M Ratio of 100

S_{og}	Initial Substrate Concentration	75 mg/l
S_oCOD	Initial COD	86 mg/l
X_o	Initial Cell Concentration	1.00 (0.86) mg/l
K_2	Reaeration Constant	0.07 hr^{-1}
c_s	Saturation DO	8.6 mg/l

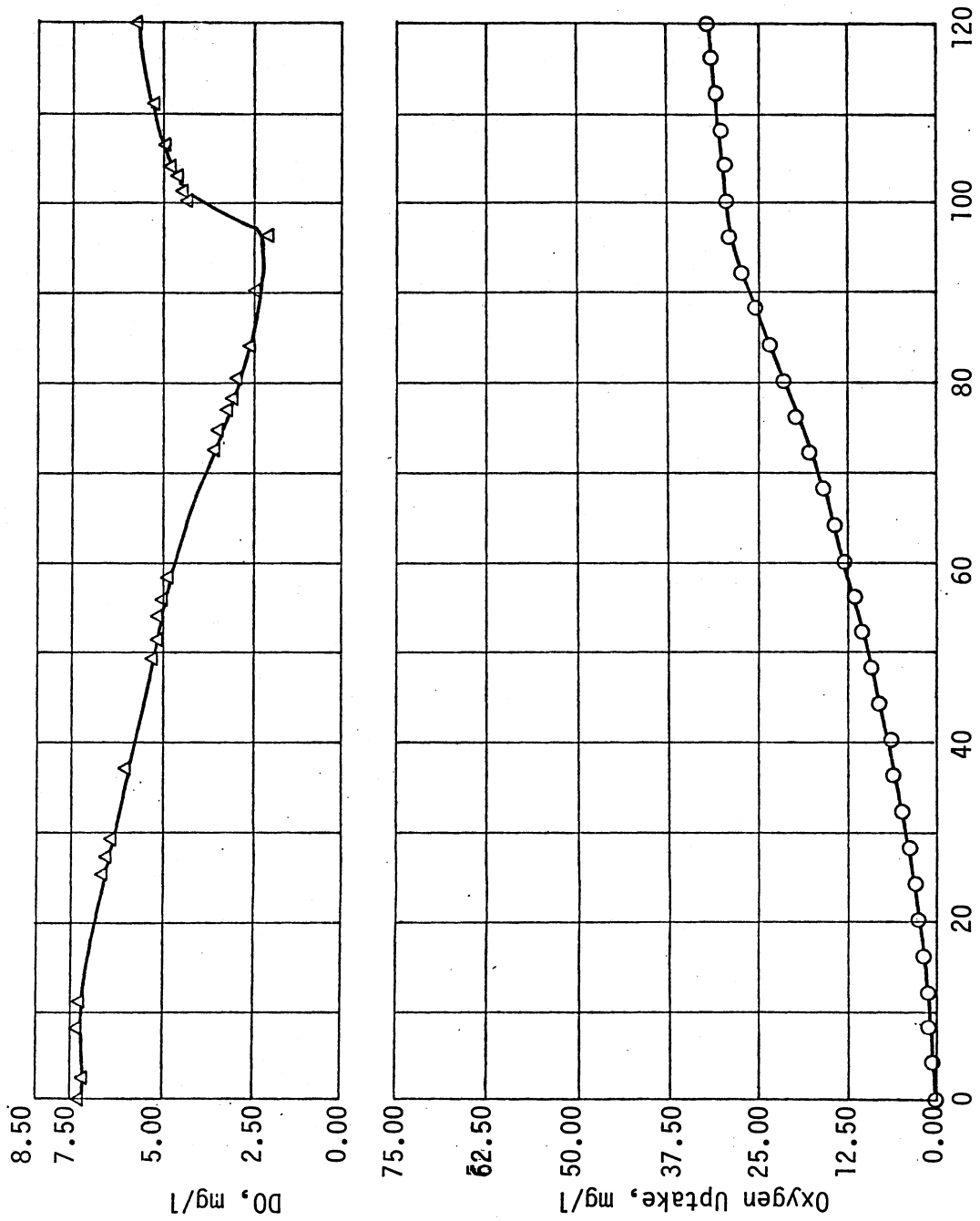
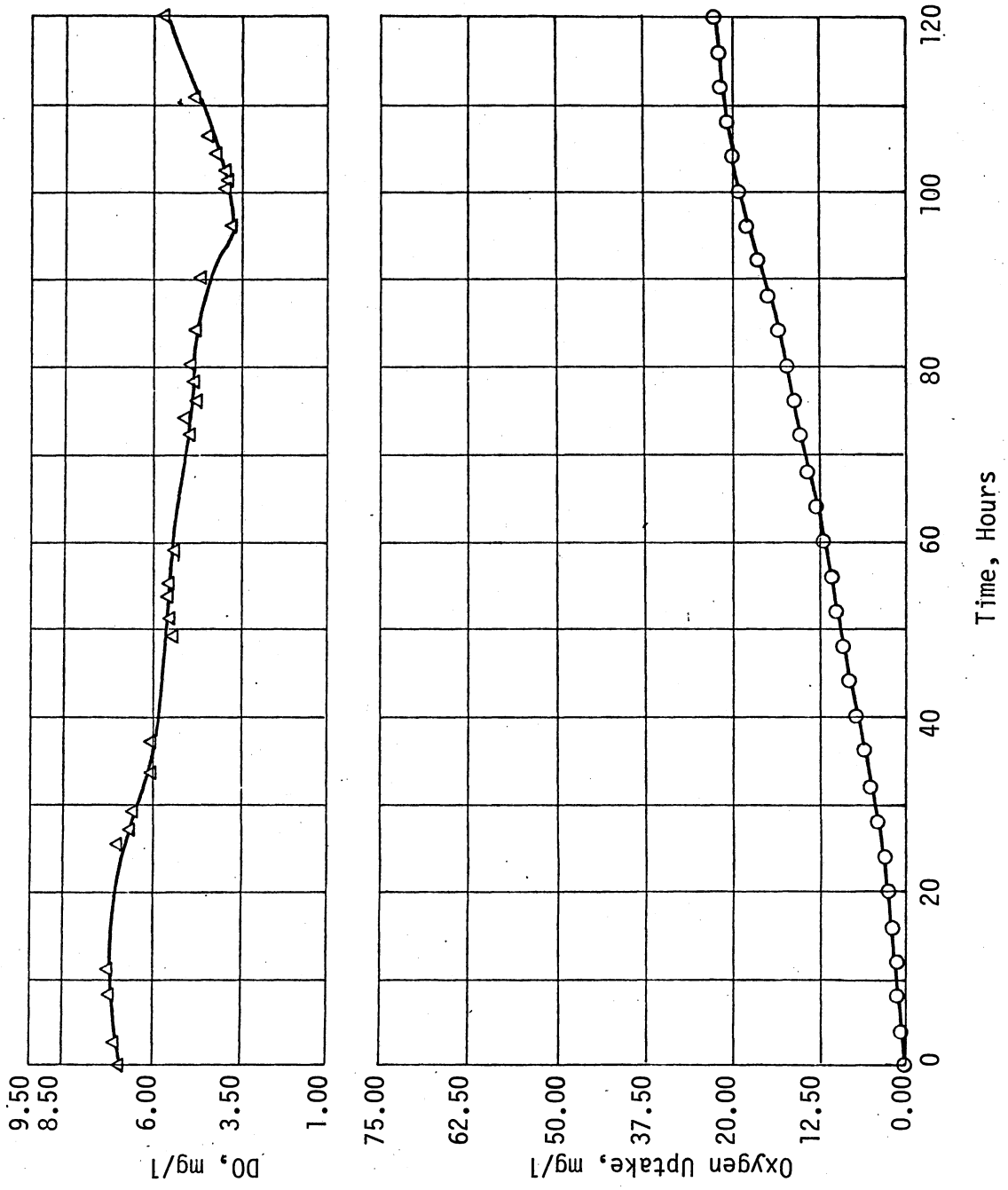

DO, mg/l
8.50
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
75.00
62.50
50.00
37.50
25.00
12.50
0.000
0
20
40
60
80
100
120
Time, Hours

Figure 15. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Old" Cell Seed at F/M Ratio of 88 ≃ 76

S_{og}	Initial Substrate Concentration	50 mg/l
S_oCOD	Initial COD	76 mg/l
X_o	Initial Cell Concentration	1.00 (0.86) mg/l
K_2	Reaeration Constant	0.068 hr^{-1}
c_s	Saturation DO	8.75 mg/l


DO, mg/l
9.50
8.50
6.00
3.50
1.00
Oxygen Uptake, mg/l
75.00
62.50
50.00
37.50
20.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

0.068 hr^{-1}; saturation value was 8.75 mg/l. The oxygen uptake was exerted very slowly. The lowest point of the sag was reached at the same time as in Figure 14, but the recovery of oxygen in the system was rather slow compared to Figure 14.

Figure 16 shows the results of an experiment with an F/M ratio of 47. Initial biological solids concentration was 2.3 mg/l (by calculation), the glucose concentration was 90 mg/l, and the measured initial COD was 107.0 mg/l. This experiment was run at a K_2 of 0.123 hr^{-1}, and the saturation value determined from the reaeration data corresponding to this K_2 was 8.00 mg/l. The minimum point of the sag was reached at 76 hours, compared to 96 hours for the experiments in Figures 14 and 15. The oxygen recovery also was a little slower. The 5-day BOD was 44 mg/l.

The experiment shown in Figure 17 was conducted with an initial substrate of 70 mg/l glucose and a measured COD of 91 mg/l. Biological solids concentration was 2.3 mg/l, with an F/M ratio of 40. The oxygen uptake exerted in five days was 33 mg/l at a K_2 of 0.097 hr^{-1} and a corresponding C_s of 8.1 mg/l. The lowest point of the sag was reached at 44 hours, compared to 76 hours in Figure 16.

Figure 18 is a plot of oxygen uptake versus time on semilog coordinates. At the highest F/M ratio, there is some suggestion of the development of an exponential phase.

The general trends of the curves of this section and the previous one are similar, and the major difference between them is attributable to the intrinsic growth behavior of the seeds. The "younger" cells of the previous section exerted a faster O_2 uptake rate than did the "older" cells taken from the extended aeration pilot plant. In both

Figure 16. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Old" Cell Seed at F/M Ratio of 47

S_{og}	Initial Substrate Concentration	90 mg/l
S_oCOD	Initial COD	107 mg/l
X_o	Initial Cell Concentration	2.3 mg/l
K_2	Reaeration Constant	0.123 hr^{-1}
c_s	Saturation Constant	8.00 mg/l

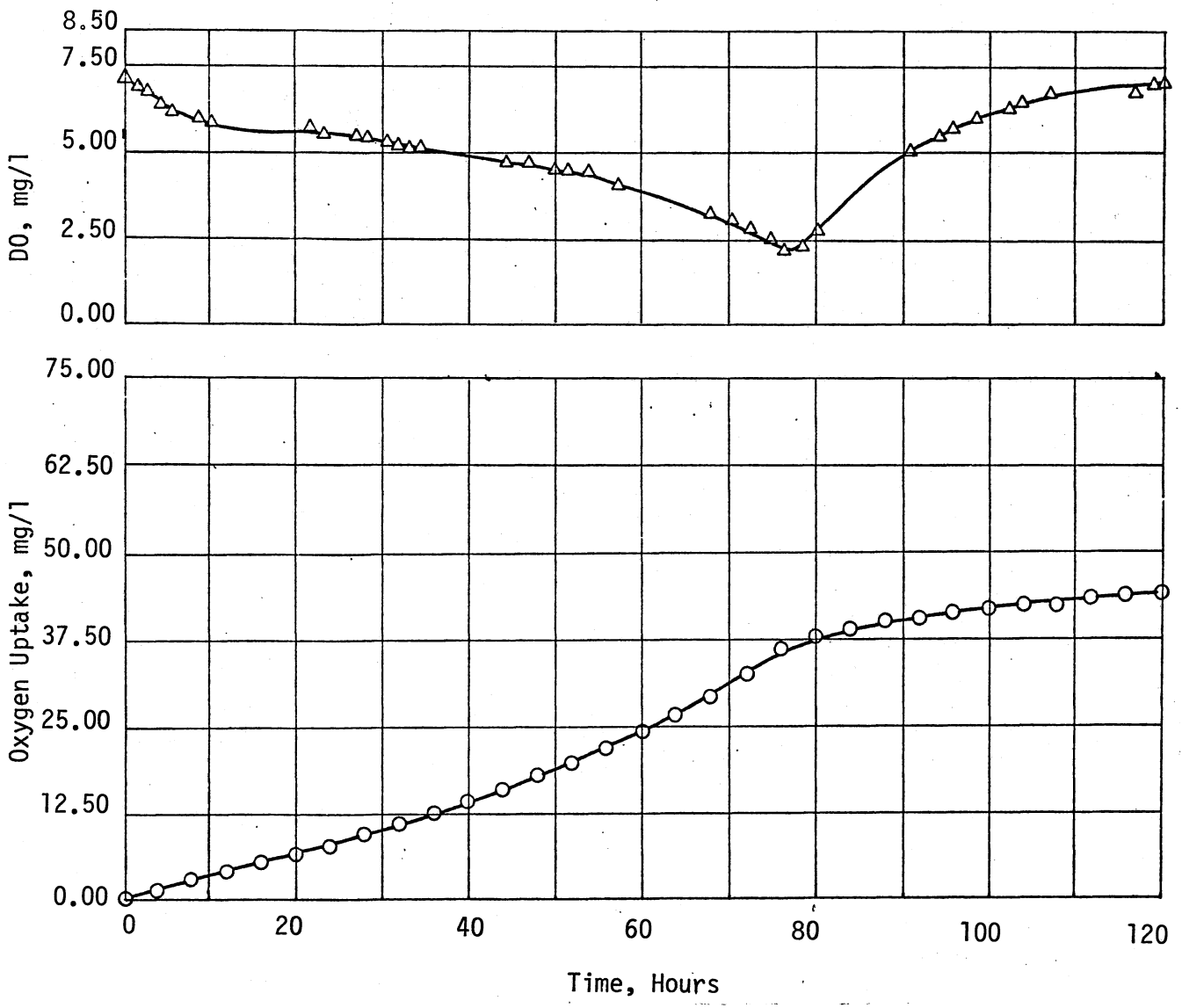

8.50
7.50
5.00
2.50
0.00
DO, mg/l
75.00
62.50
50.00
37.50
25.00
12.50
0.00
Oxygen Uptake, mg/l
0
20
40
60
80
100
120
Time, Hours

Figure 17. Dissolved Oxygen Profile and Accumulated Oxygen Uptake (BOD) Curve for "Old" Cell Seed at F/M Ratio of 40

S_{og}	Initial Substrate Concentration	70 mg/l
S_oCOD	Initial COD	91 mg/l
X_o	Initial Cell Concentration	2.3 mg/l
K_2	Reaeration Constant	0.097 hr^{-1}
c_s	Saturation DO	8.1 mg/l

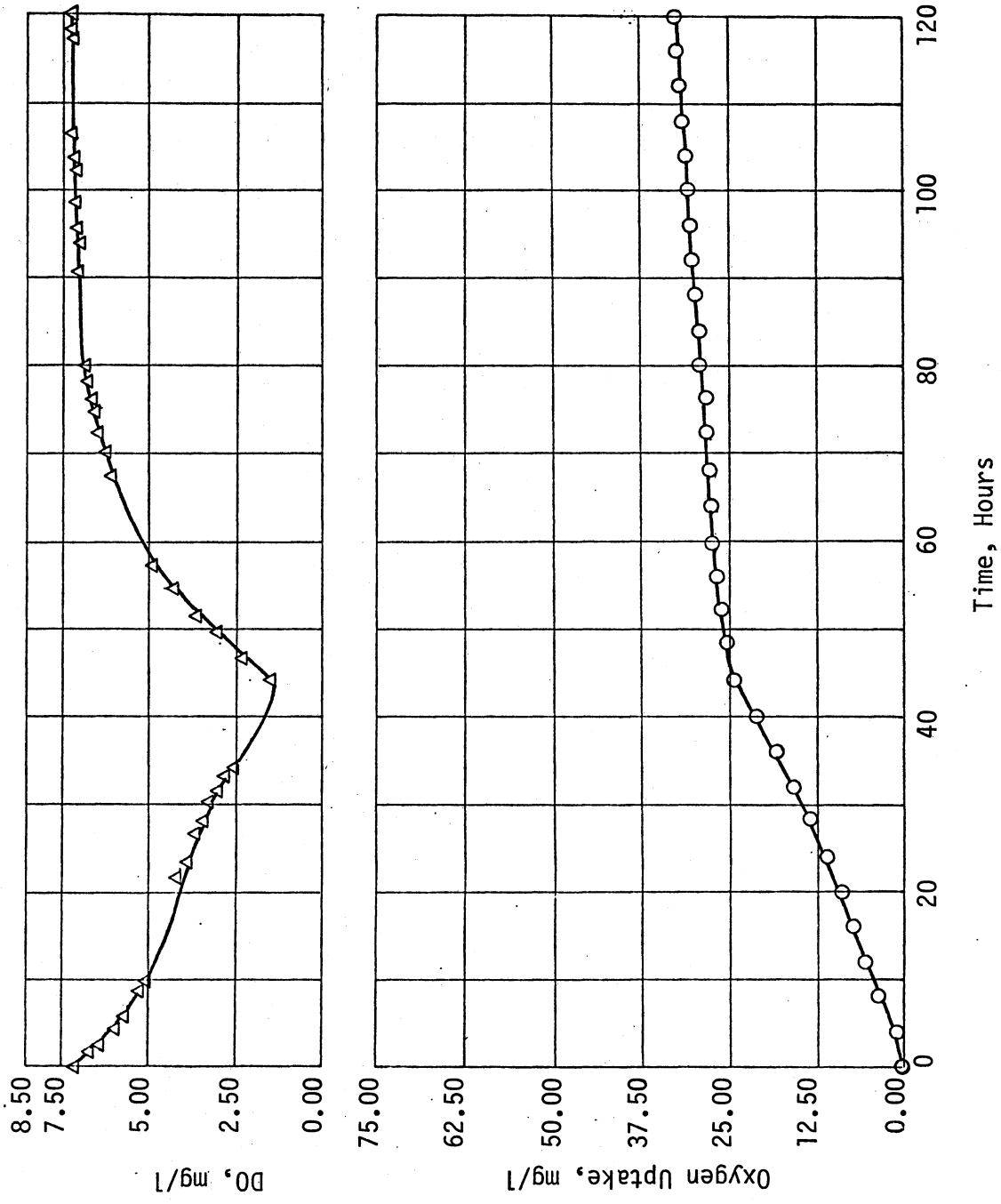

DO, mg/l
8.50
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
75.00
62.50
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

Figure 18. Logarithmic Oxygen Uptake versus Time for Experiments With "Old" Cell Seed (Figures 14-17)

Figure No.	F/M	$K_2(hr^{-1})$
14	100	0.070
15	88	0.068
16	47	0.123
17	40	0.097

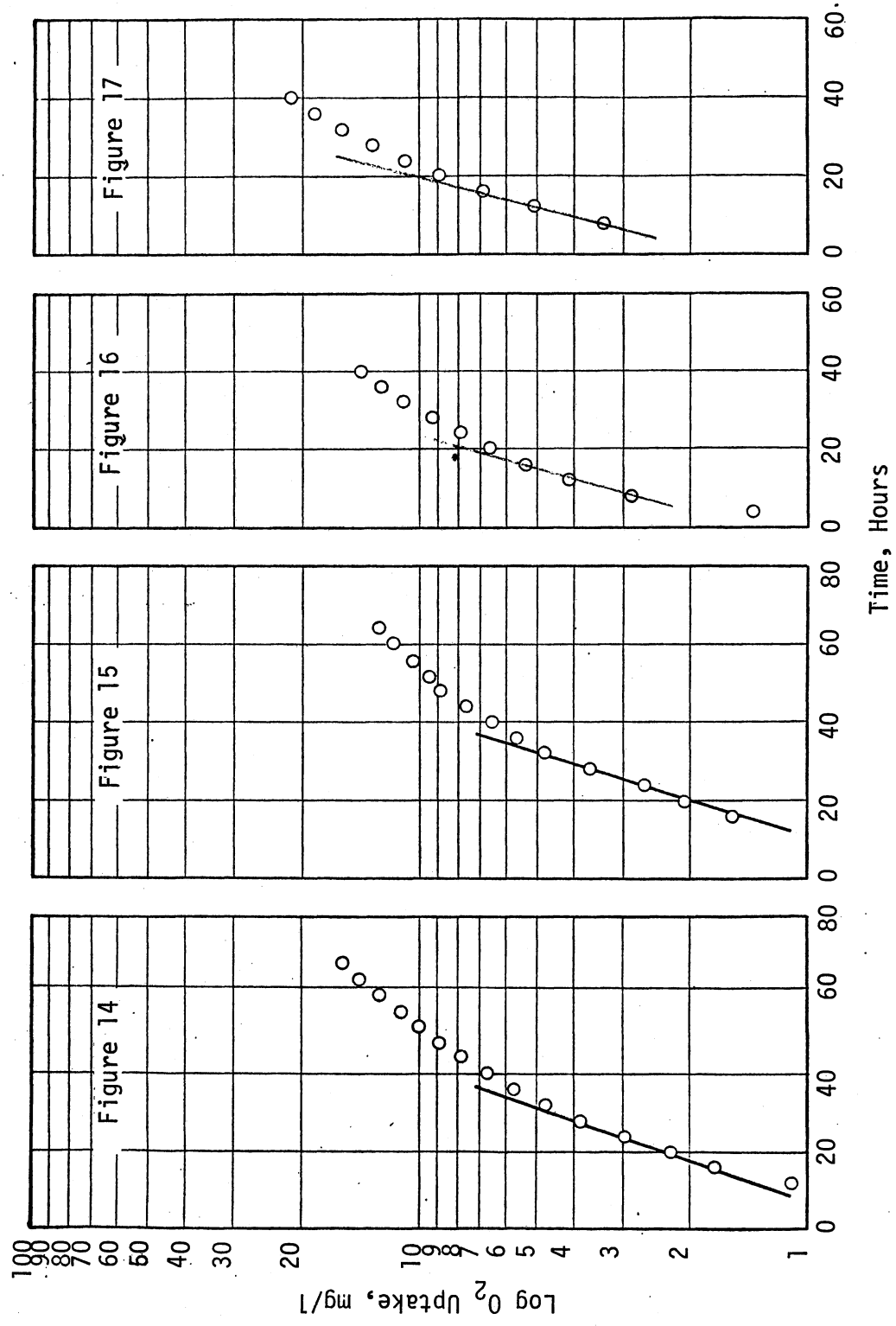


Figure 14
Figure 15
Figure 16
Figure 17
Log O_2 Uptake, mg/l
Time, Hours

cases, the data provide some suggestion that exponential O_2 uptake was attained at the higher F/M ratios employed.

Studies on the Kinetics of Oxygen Uptake of Effluents From Laboratory Bench Scale Extended Aeration Pilot Plants

Effluents were taken from two extended aeration pilot plants: 1) effluents from the extended aeration pilot plant operated by the author, and 2) effluents from the extended aeration pilot plant operated by Mr. Roach, a fellow graduate student researcher. The first unit was fed hydrolysate of secondary clarifier sludge from the Stillwater treatment plant. This pilot plant was operated in accordance with the concept of the "hydrolytic assist." The second unit was fed glucose; it was also "hydrolytically assisted." The operational details of the pilot plants have been given in the Materials and Methods chapter.

One of the primary purposes of this study was to determine the purification ability of the extended aeration treatment by testing the effluents with regard to oxygen uptake using the open reactor technique. So the author took over operation of an extended aeration pilot plant which had been previously operated as part of a past Master's research effort of a fellow graduate student, Mr. Saidi. The study was performed with the aim of determining whether the "hydrolytically assisted" extended aeration process could be successfully employed as a sludge disposal unit for secondary sludge. On April 21, 1974, the author took charge of the unit which had been operating for 161 days. The mixed liquor suspended solids concentration was approximately 14,000 mg/l. The aeration chamber suspended solids were later slowly reduced. The

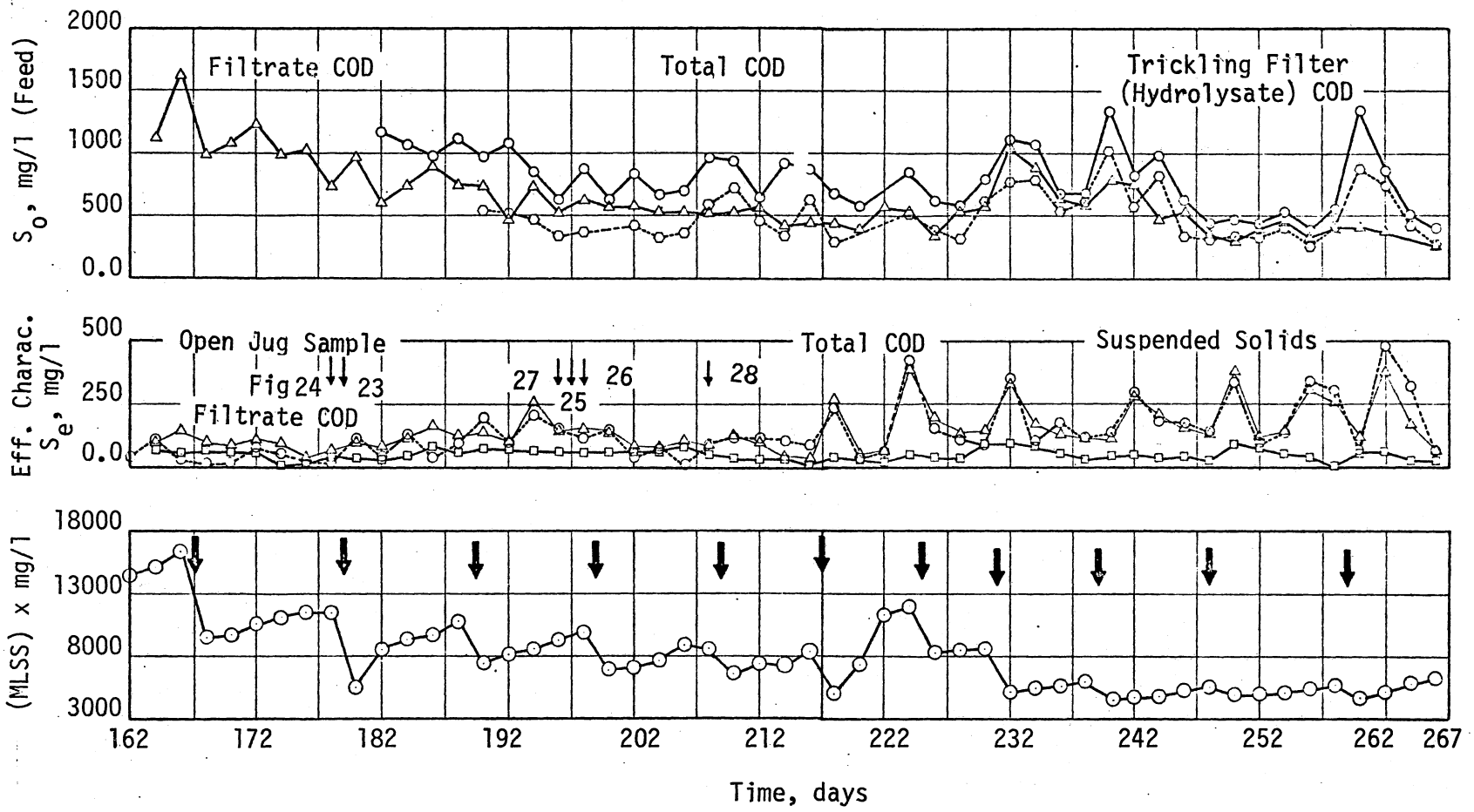
reduction in mixed liquor suspended solids was due to the fact that the feed COD concentration in subsequent weeks was lower compared to the previous concentrations which had been approximately 1200 mg/l, and to the fact that relatively large concentrations of biological solids were withdrawn for hydrolysis and refeeding (e.g., two liters at 30,000 mg/l compared to much lower values and concentrations prior to this time). All pilot plant operational data during the period of operation by the author are shown in Figure 19. The mixed liquor suspended solids concentration is plotted on the lower graph. The broad arrows mark the times of sludge withdrawal from the unit settling chamber for hydrolysis and refeeding. The sludge concentration and volume withdrawn are given in the figure legend. For example, on day 167, 2000 ml of sludge at a concentration of 30,000 mg/l were withdrawn, hydrolyzed, and refed in equal portions during the time elapsed between days 167 and 179, at which time another 2000 ml at 28,540 mg/l were withdrawn. The inflow concentration is shown in the top graph. The COD concentration of the inflowing hydrolysate of the municipal secondary sludge (trickling filter sludge) is designated by hexagons, the total COD, i.e., municipal sludge hydrolysate, plus internal mixed liquor suspended solids hydrolysate by circles, and the total filtrate COD by triangles. The effluent characteristics are shown in the center graph. The effluent was characterized by total COD (clarifier effluent), biological solids concentration in the effluent, and soluble COD, i.e., filtrate COD (small arrows).

From day 162 to day 216, the effluent characteristics remained at rather steady low levels. After day 217, the effluent supernatant CODs showed an increase due to the leakage in biological solids concentrations.

Figure 19. Performance of an Aerobic Digestion Pilot Plant Employing Pre-hydrolyzed Sludge as Feed Stock (from 162 days to 267 days of operation)

The thin arrows designate the times that pilot plant effluent samples were studied in open jar reactors for determination of O_2 uptake. The numbers for each arrow designate the number each experiment presented in the report. Sludge withdrawals from the pilot plant are represented by thick arrows, and the details are given below:

Day of Withdrawal	Volume of MLSS Withdrawn, ml	Conc. of MLSS Withdrawn, mg/l
167	2000	30,000
179	2000	28,540
190	1800	19,570
199	1800	15,120
209	1500	11,870
217	1500	13,240
225	1500	11,950
231	1500	8,580
239	1500	5,920
248	900	5,480
259	900	5,560


2000
1500
1000
500
0.0
S_o, mg/l (Feed)
Filtrate COD
Total COD
Trickling Filter
(Hydrolysate) COD
500
250
0.0
Eff. Charac.
S_e, mg/l
Open Jug Sample
Fig 24
23
27
26
25
28
Filtrate COD
Total COD
Suspended Solids
18000
13000
8000
3000
(MLSS) x mg/l
162
172
182
192
202
212
222
232
242
252
262
267
Time, days

However, substrate utilization was not affected, as shown by the effluent filtrate COD, which remained rather steady at low levels. After day 217, the leakage of solids might possibly be attributed to fluctuations in feed concentrations.

The last O_2 uptake study in an open jar was performed on day 208 (see narrow arrow marker). After day 208, the author's main purpose in running the unit was to keep this process operational until another investigator could assume operational responsibility. After nearly 2/3 of a year into the operation with the high ash feed, it was desirable that the unit remain functional. Thus, while the feed was allowed to vary and there was some relaxation of operational care, the unit operated continuously. It is interesting to note that the filtrate COD remained low throughout this period, i.e., the efficiency did not suffer due to the load fluctuations.

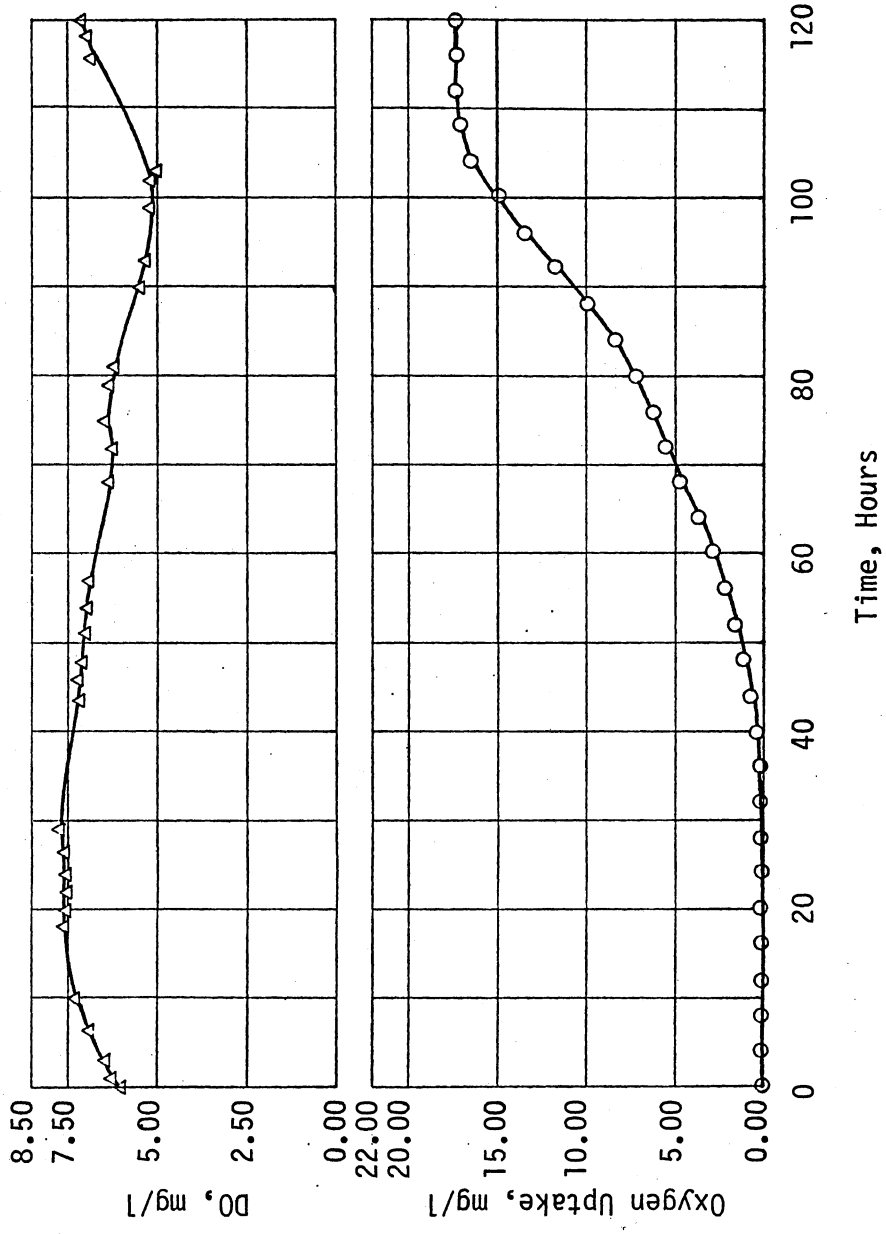
At various times during the operational life of the pilot plant, effluents were tested in open stirred reactors to determine O_2 uptake. The results are presented in chronological order.

Shown in Figure 20 is the dissolved oxygen profile and the oxygen uptake curves for effluent taken from the total oxidation pilot plant during the 112th day of operation (during this time Mr. Saidi, not the author, was operating the pilot plant). The feed concentration on that day was 1200 mg/l of trickling filter sludge hydrolysate, and the total inflow COD (i.e., including internal hydrolysate) was 1730 mg/l. The effluent was diluted with an equal amount of tap water. After dilution, the dissolved organic material had a COD of 49 mg/l, and suspended solids concentration was 12 mg/l. The system was operated at a reaeration rate of 0.162 hr^{-1}, with a corresponding saturation value, C_s, equal to

Figure 20. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant

	Initial	Final
Substrate Concentration		
Filtrate COD	49 mg/l	-
Suspended Solids Conc.	12 mg/l	16 mg/l

Reaeration Rate Constant, K_2, 0.162 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 7.55 mg/l
Oxygen Uptake, 17 mg/l
Dilution Rate, 1/1


8.50
7.50
5.00
2.50
0.00
DO, mg/l
22.00
20.00
15.00
10.00
5.00
0.00
Oxygen Uptake, mg/l
0
20
40
60
80
100
120
Time, Hours

7.55 mg/l. The O_2 uptake at the end of the experiment was 17 mg/l. The dissolved oxygen profile increased initially, followed by a slow sag before the DO recovered in the system. The initial increase in DO attests to the lag period which existed. This is also reflected in the rather long lag in O_2 uptake. After this lag period, the O_2 uptake curve was concave upward, suggesting autocatalytic growth of the microorganisms exerting the BOD.

The results shown in Figure 21 are the DO profile and O_2 uptake of a sample of effluent taken on the 119th day of operation. On this day, the feed to the unit consisted of 1240 mg/l COD of trickling filter hydrolysate. No internal sludge hydrolysate was fed on this day. The filtrate effluent COD was 76 mg/l. The effluent was tested directly, i.e., it was not diluted. The initial biological solids concentration was 12 mg/l, and the system exerted an oxygen demand of 28 mg/l. The final soluble organic material (COD) after five days was reduced to 59 mg/l, and biological solids to 8 mg/l. The reactor was operated at a K_2 of 0.095. Similar to Figure 20, this experiment also showed an initial DO increase and a gradual reduction in DO concentration. However, the DO changes in the system were not pronounced. The oxygen uptake curve showed essentially zero order kinetics, as the DO remained in the system at practically the same level throughout the experiment.

Figure 22 shows results for a similar experiment, but with low initial DO of 3.3 mg/l. The soluble substrate concentration was rather low--24 mg/l--but the biological solids concentration was a little higher than the previous experiment, 56 mg/l. There was a rather rapid increase in the dissolved oxygen concentration to about 5 mg/l, attesting, again, to the apparent lag in metabolism. The DO remained at

Figure 21. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant

	Initial	Final
Substrate Concentration		
Filtrate COD	50 mg/l	59 mg/l
Suspended Solids Conc.	12 mg/l	8 mg/l

Reaeration Rate Constant, K_2, 0.095 hr^{-1}
Dissoved Oxygen Saturation Constant, C_s, 7.80 mg/l
Oxygen Uptake, 28.00 mg/l

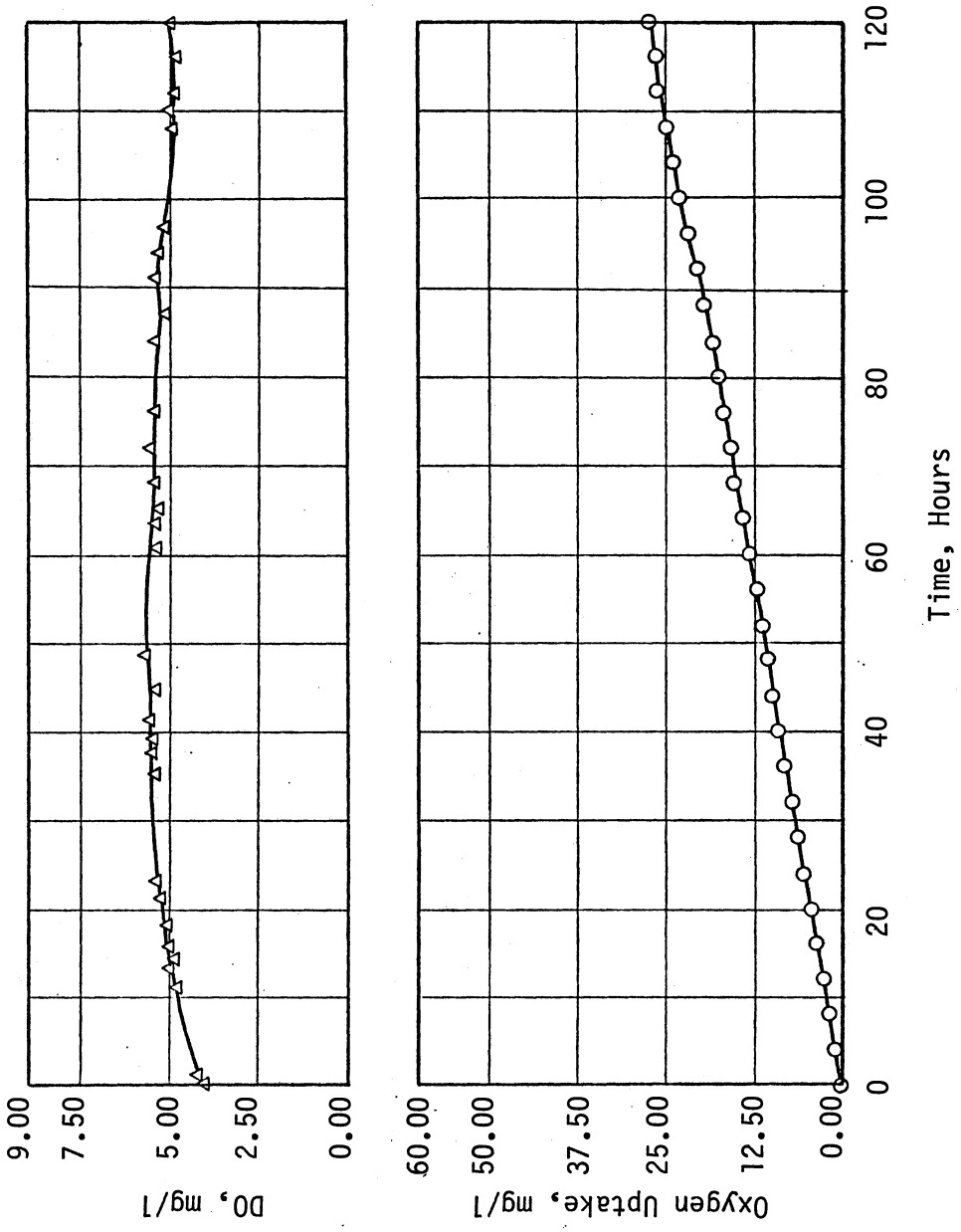
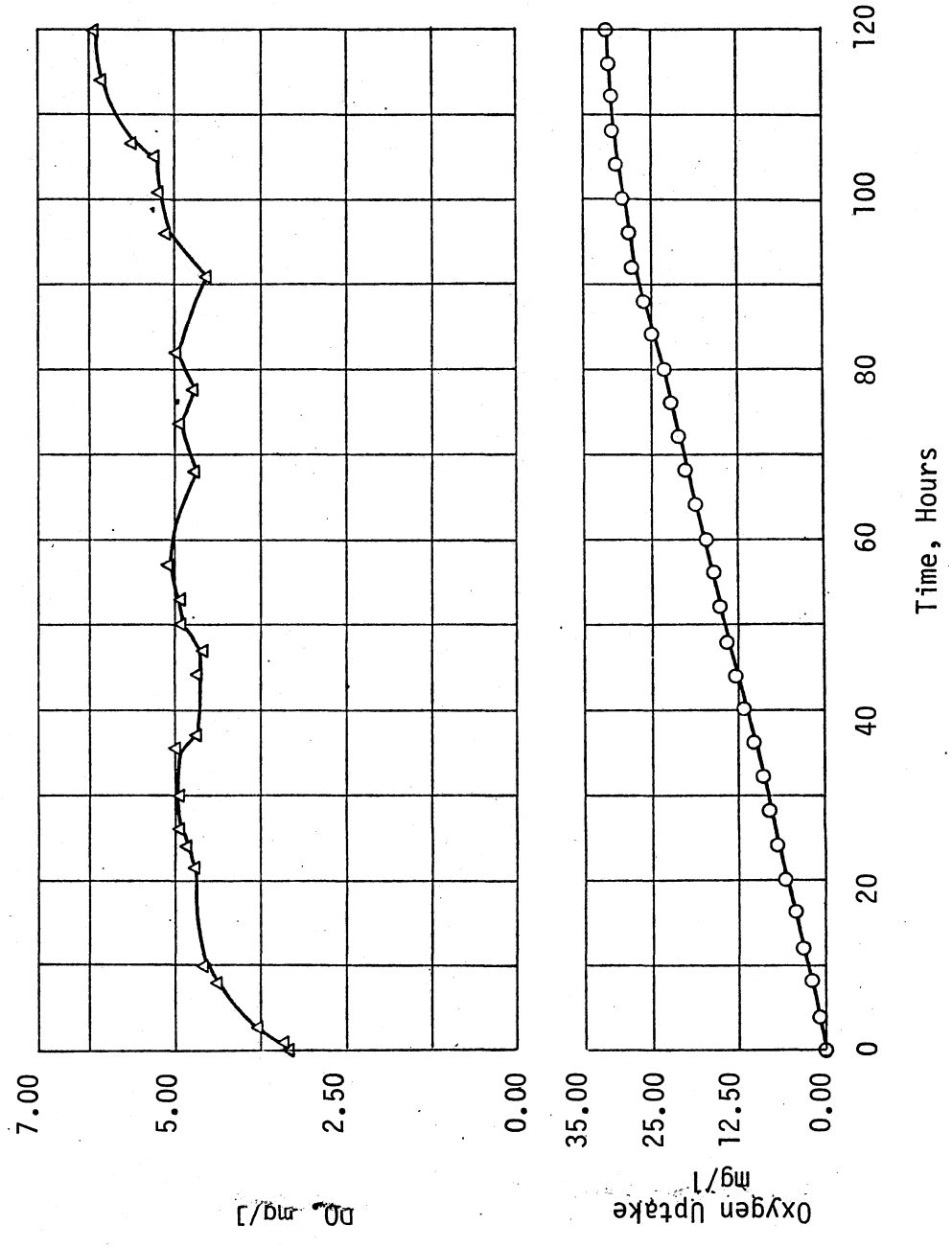

DO, mg/l
9.00
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
60.00
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

Figure 22. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant

	Initial	Final
Substrate Concentration		
Filtrate COD	24 mg/l	-
Suspended Solids Conc.	56 mg/l	

Reaeration Rate Constant, K_2, 0.13 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 7.20 mg/l
Oxygen Uptake, 32.00 mg/l


7.00
5.00
2.50
0.00
DO, mg/l
35.00
25.00
12.50
0.00
Oxygen Uptake
mg/l
0
20
40
60
80
100
120
Time, Hours

slightly below 5 mg/l until after the 90th hour, when recovery began. The reaeration rate was 0.13 hr^{-1}, and the saturation value was 7.2 mg/l. The oxygen uptake (BOD) exerted was 32 mg/l.

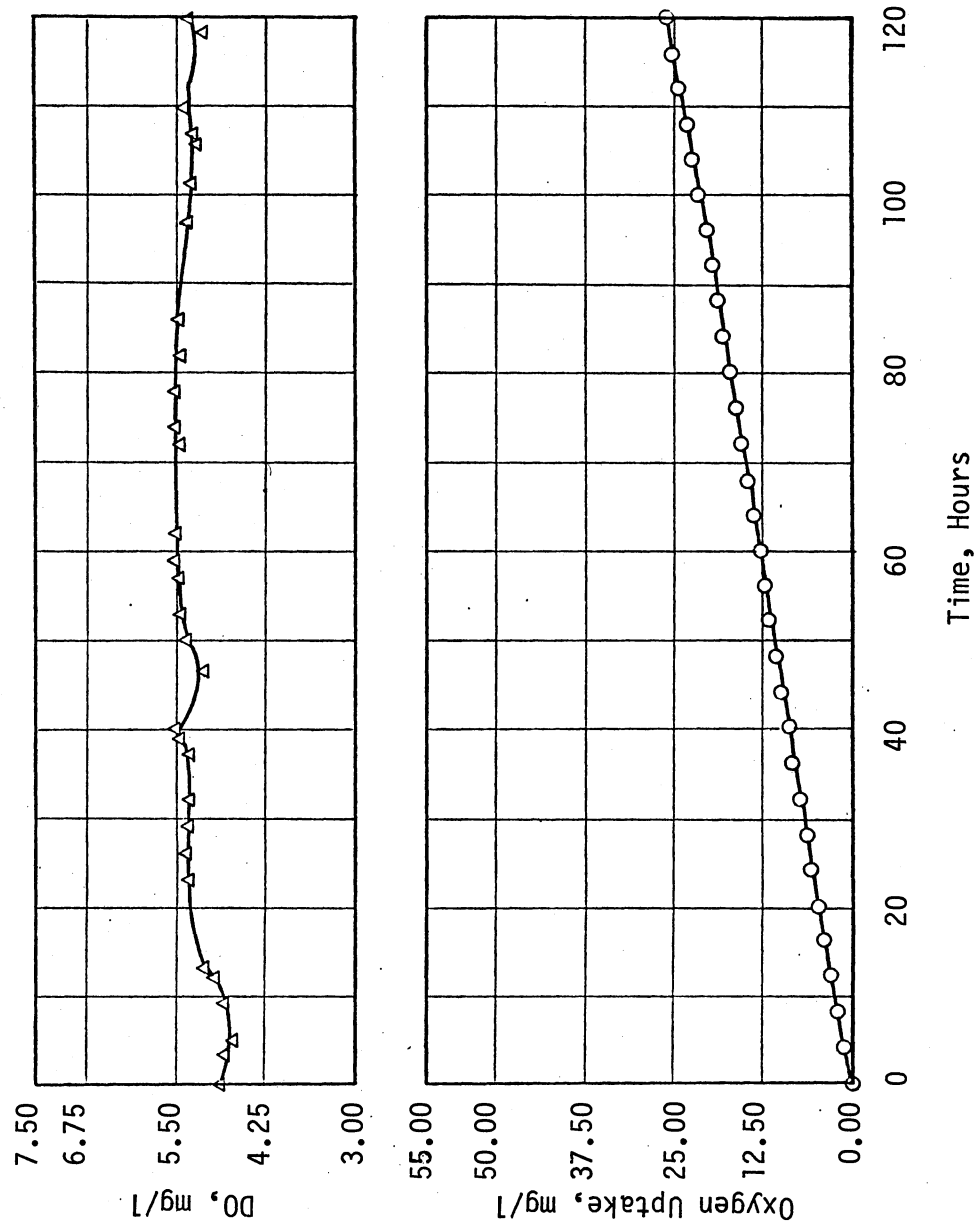
O_2 uptake of the pilot plant effluent on day 179 is shown in Figure 23. The initial soluble COD was 32 mg/l, and the biological solids concentration was 76 mg/l. After five days, the concentration of soluble organic material decreased to 28 mg/l, and the biological solids to 73 mg/l. With a reaeration rate of 0.09 hr^{-1} and a corresponding saturation value of 7.65 mg/l, the BOD of the effluent was 20 mg/l. Analyses for NO_3-N were made, and there was no nitrification during the course of the experiment.

The above Figures (20-23) show that in all cases there was an initial increase in DO concentration. The effluent was employed as it existed in the effluent holding tank, and the DO there was not saturated. Thus, the lower DO values together with the metabolic lag exhibited by the cells from this extended aeration unit brought about the initial increase in DO. In general, the results showed that if the effluents were let into a receiving stream with reasonably low K_2, they would not cause any stress to the oxygen resources of the stream. The experiment of Figure 20, for which the sample was diluted with 50 per cent tap water, was the only one which showed any recognizable sag. The other three experiments (Figures 21-23) did not show any sag at all, yielding almost straight line kinetics for oxygen uptake. In Figure 23, even though the suspended solids concentration, 76 mg/l, was the highest of any tested in this series, it produced the lowest BOD_5, attesting to the low biological activity of suspended solids from this treatment process.

Figure 23. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant

	Initial	Final
Substrate Concentration		
Filtrate COD	32 mg/l	28 mg/l
Suspended Solids Conc.	76 mg/l	73 mg/l
Nitrate Nitrogen	0.00 mg/l	0.00 mg/l

Reaeration Rate Constant, K_2, 0.09 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 765 mg/l
Oxygen Uptake, 26 mg/l


DO, mg/l
7.50
6.75
5.50
4.25
3.00
Oxygen Uptake, mg/l
55.00
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

From the results, it can be seen that the organic matter (COD) in the effluent from a hydrolytically assisted extended aeration unit treating hydrolyzed trickling filter sludge is slowly metabolized and there is an apparent metabolic lag. The results indicate that this waste is subject to a high degree of biological treatment, and the effluent does not cause serious stress to the stream. Only scant nitrification data were collected during this span of operation. For the experimental results shown in Figure 23, determination for NO_3-N was made, and none was found. However, it is known from the previous operation by Saidi that the effluent exhibited varying degrees of nitrification during the first 105 days of operation. Thus, some of the O_2 uptake shown in Figures 20, 21, and 22 could have been due to nitrification.

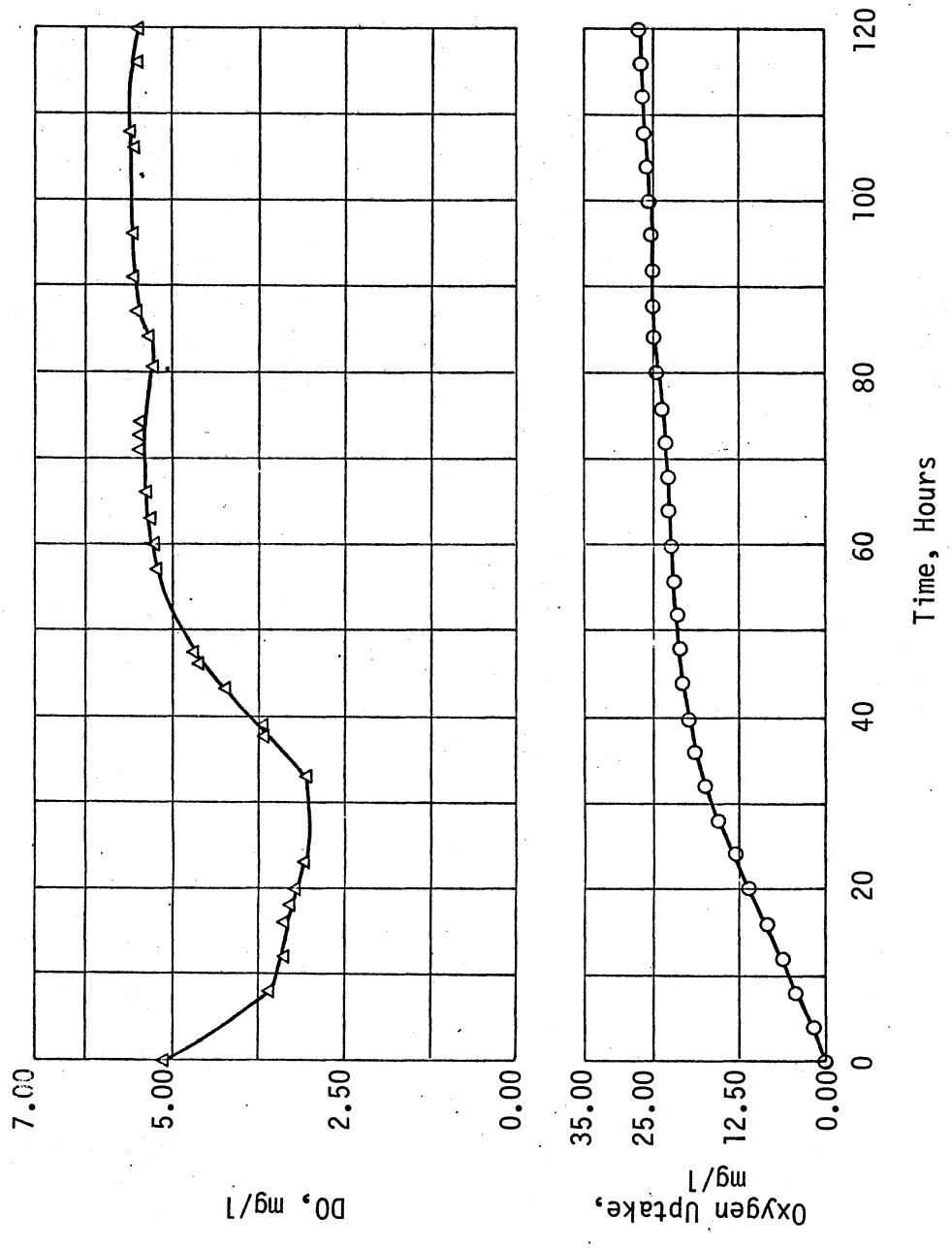
The next three experiments (Figures 24, 25, and 26) were undertaken to observe the type of kinetics in the receiving stream when a high concentration of biologicals was contained in the effluent. Therefore, additional mixed liquor solids were added to the effluent samples in the open stirred reactors before the start of the experiment.

Figure 24 shows results of an experiment using effluent and biological solids taken during the 16th day of operation. The biological solids concentration was increased from 16 mg/l to 178 mg/l by addition of mixed liquor solids from the aeration chamber. The soluble COD was 42 mg/l. At the end of five days, the biological solids concentration decreased slightly to 160 mg/l (i.e., by 18 mg/l), and there was little or no difference in the soluble organic material measured as COD (it changed from 42 mg/l to 40 mg/l). At a K_2 of 0.185 hr^{-1} with a C_s of 5.9 mg/l, the oxygen uptake exerted was 27 mg/l. No nitrification was

Figure 24. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant With the Addition of Mixed Liquor Suspended Solids

	Initial	Final
Substrate Concentration		
Filtrate COD	42 mg/l	40 mg/l
Suspended Solids Conc.	178 mg/l	160 mg/l
Nitrate Nitrogen Conc.	0.00 mg/l	0.00 mg/l

Reaeration Rate Constant, K_2, 0.185 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 5.90 mg/l
Oxygen Uptake, 27.00 mg/l


7.00
5.00
2.50
0.00
DO, mg/1
35.00
25.00
12.50
0.000
Oxygen Uptake, mg/1
0
20
40
60
80
100
120
Time, Hours

observed during the experiment. The DO profile exhibited a well rounded sag. Approximately 24 hours were required for both the falling leg and the rising leg of the oxygen sag curve. After apparent zero order kinetics in the early phase of uptake, a decreasing rate curve developed.

Figure 25 is an experiment with almost the same amount of initial biological solids as that used in the experiment shown in Figure 24, run on day 197 of the pilot plant operation. During the course of the experiment, the concentrations of total and soluble organic material measured as COD did not show any change. (Initial filtrate COD, 56 mg/l, final filtrate COD, 56 mg/l, initial total COD, 172 mg/l, final total COD, 172 mg/l). But there was a considerable amount of nitrification. The NO_3-N Concentration increased from zero mg/l to a final concentration of 23 mg/l. Biological solids concentration increased by 17 mg/l, i.e., from 165 to 182 mg/l. The total oxygen uptake computed using a K_2 of 0.093 hr^{-1} and a saturation value, C_s, of 8.95 mg/l, was 23 mg/l. The oxygen uptake curve did not flatten out as in Figure 24, because the DO in the system recovered rather slowly.

The results shown in Figure 26 are the O_2 uptake of a sample of effluent taken on the 198th day of operation of the pilot plant. The biological solids were increased to an initial value of 337 mg/l. Also, the initial DO was raised by aeration prior to making the test. During the period of the experiment, the filtrate COD did not change significantly; it showed a decrease of 4 mg/l from an initial value of 56 mg/l to a final value of 52 mg/l. The biological solids increased slightly from 337 mg/l to 345 mg/l. But the total organic material measured as COD decreased from 308 mg/l to 288 mg/l, i.e., a decrease

Figure 25. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant With the Addition of Mixed Liquor Suspended Solids

	Initial	Final
Substrate Concentration		
Non-filtrate COD	172 mg/l	172 mg/l
Filtrate COD	56 mg/l	56 mg/l
Suspended Solids Conc.	165 mg/l	182 mg/l
Nitrate Nitrogen Conc.	0.00 mg/l	23.00 mg/l

Reaeration Rate Constant, K_2, 0.093 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 8.95 mg/l
Oxygen Uptake, 23.00 mg/l

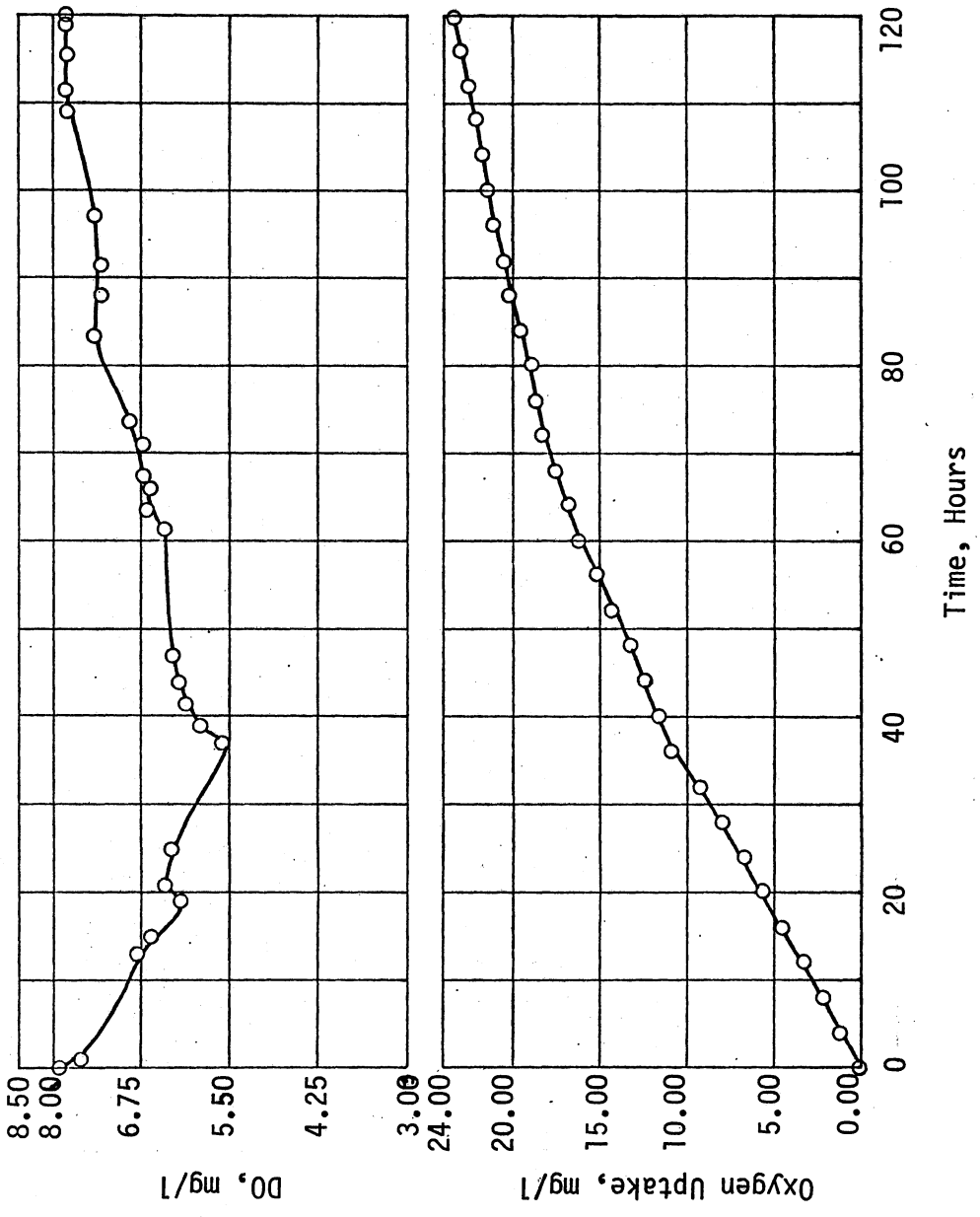
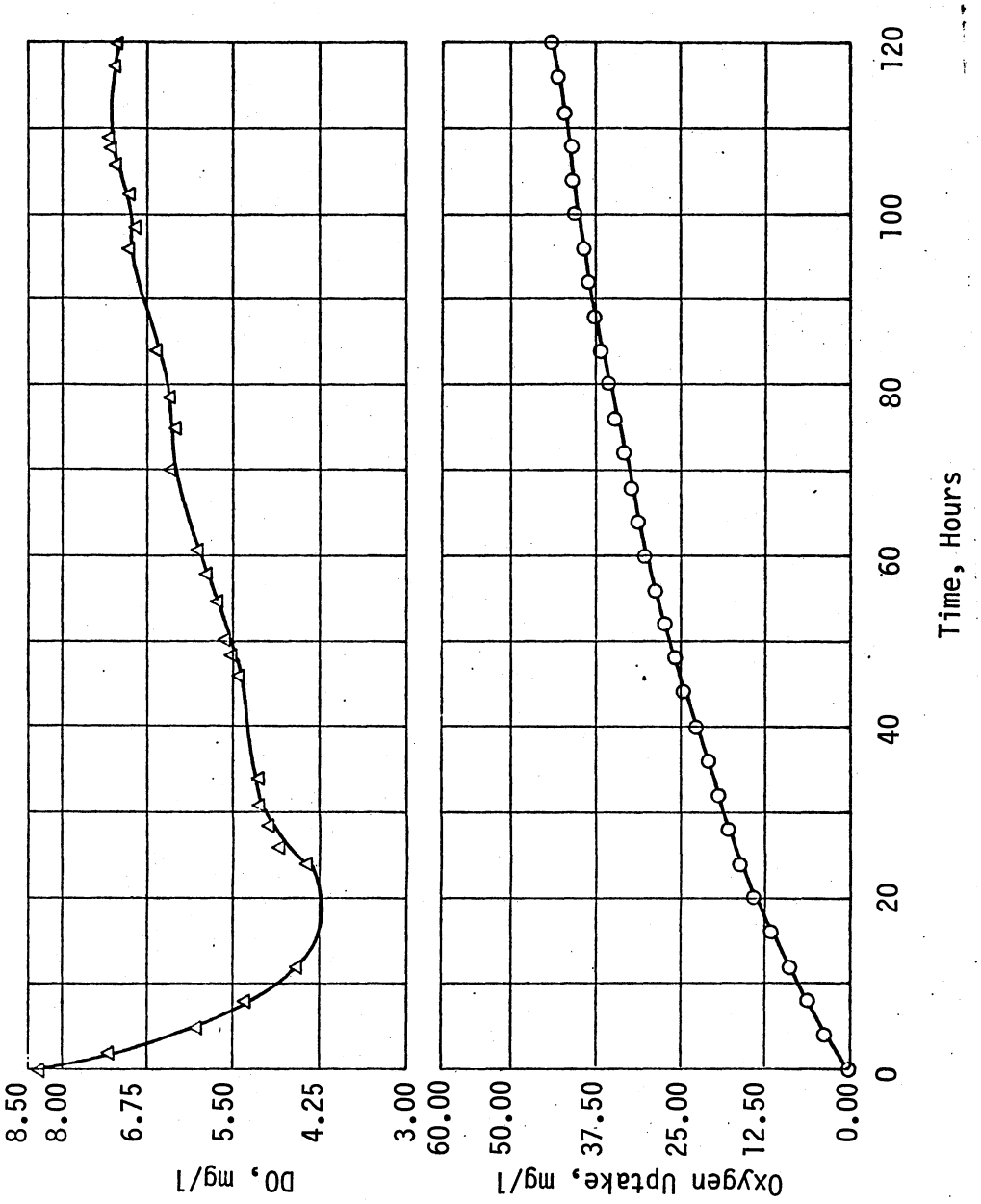

8.50
8.00
6.75
5.50
4.25
3.00
DO, mg/l
24.00
20.00
15.00
10.00
5.00
0.00
Oxygen Uptake, mg/l
0
20
40
60
80
100
120
Time, Hours

Figure 26. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant With the Addition of Mixed Liquor Suspended Solids

	Initial	Final
Substrate Concentration		
Non-filtrate COD	308 mg/l	288 mg/l
Filtrate COD	56 mg/l	52 mg/l
Suspended Solids Conc.	337 mg/l	345 mg/l

Reaeration Rate Constant, K_2, 0.125 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 8.80 mg/l
Oxygen Uptake, 44.00 mg/l


8.50
8.00
6.75
5.50
4.25
3.00
DO, mg/l
60.00
50.00
37.50
25.00
12.50
0.00
Oxygen Uptake, mg/l
0
20
40
60
80
100
120
Time, Hours

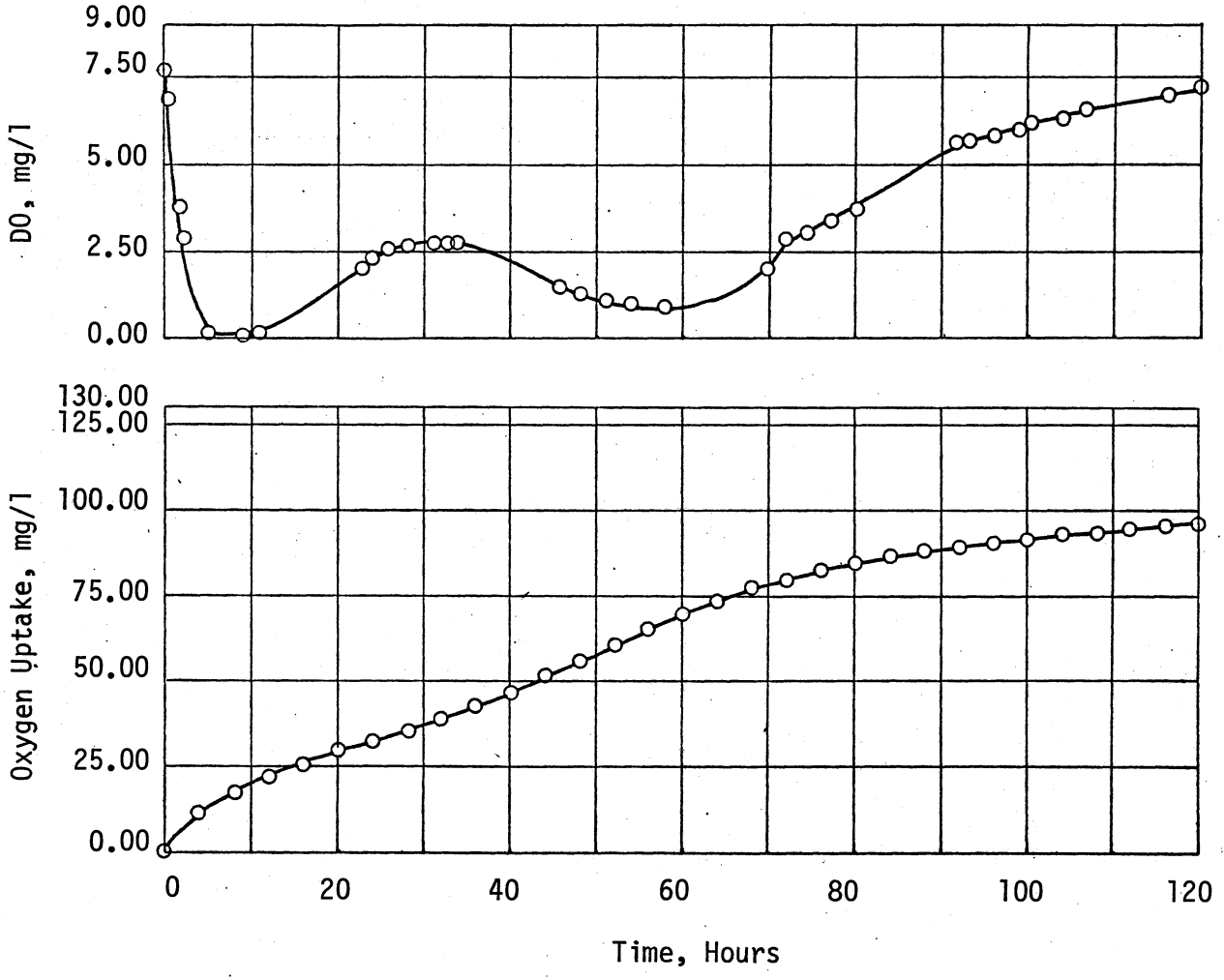
of 20 mg/l of total COD. The NO_3-N concentration decreased from 29.5 mg/l to a low value of 14.7 mg/l. There is no apparent explanation for this decrease, since the trickling filter hydrolysate was known to contain excess nitrogen in relation to carbon source. The DO in the system came down faster than in the previous two experiments. The system was operated at a reaeration rate of 0.125 hr^{-1} and a corresponding saturation value of 8.8 mg/l. The computed oxygen uptake was 44 mg/l.

Two experiments were performed to observe the O_2 uptake behavior when significant amounts of both substrate and biological solids were present in the effluent. In these experiments, the effluents were initially aerated to increase initial DO concentrations in the system. The substrate consisted of hydrolysate of the sludge withdrawn from the pilot plant. The results are shown in Figure 27. The actual effluent at the pilot plant had an initial soluble COD of 64 mg/l (196th day of operation), and a suspended solids concentration of 138 mg/l. After the addition of both the hydrolysate and the biological solids from the aeration chamber, concentrations were raised to 160 mg/l of COD and 305 mg/l, respectively. After five days, the total COD concentration decreased only 50 mg/l (312 mg/l to 264 mg/l), whereas the soluble organic material decreased by 100 mg/l (160 mg/l to 60 mg/l), but the biological solids concentration remained at almost a constant level (initial concentration 305 mg/l; final concentration 297 mg/l). The system showed nitrification (24 mg/l) from an initial 14 mg/l concentration to a final value of 38 mg/l of NO_3-N. The total oxygen uptake exerted was 96 mg/l at a K_2 of 0.145 hr^{-1} and a saturation value of 8.7 mg/l. The DO profile showed a distinct secondary sag which was expressed as a "plateau" in the oxygen uptake curve.

Figure 27. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant With the Addition of MLSS and the Recycle Sludge Hydrolysate

	Initial	Final
Substrate Concentration		
Non-filtrate COD	312 mg/l	264 mg/l
Filtrate COD	160 mg/l	60 mg/l
Suspended Solids Conc.	305 mg/l	297 mg/l
Nitrate Nitrogen Conc.	14 mg/l	38 mg/l

Reaeration Rate Constant, K_2, 0.145 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 8.7 mg/l
Oxygen Uptake, 96 mg/l


9.00
7.50
5.00
2.50
0.00
DO, mg/l
130.00
125.00
100.00
75.00
50.00
25.00
0.00
Oxygen Uptake, mg/l
0
20
40
60
80
100
120
Time, Hours

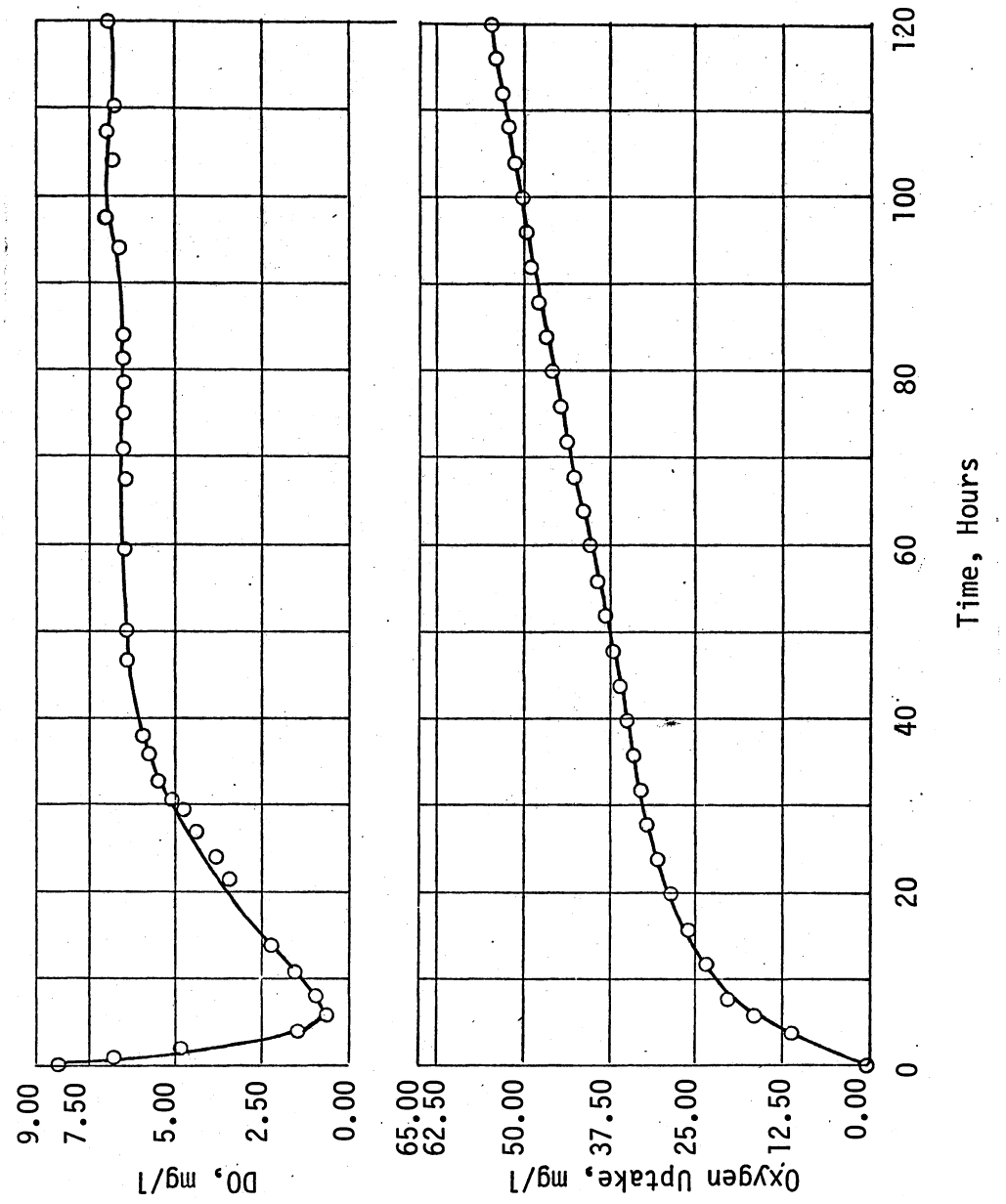
For the experiment shown in Figure 28, hydrolysate of the trickling filter sludge was added to the reactor along with the mixed liquor suspended solids from the aeration tank of the pilot plant (206th day of operation). The day the experiment was run, the effluent of the pilot plant contained 7.5 mg/l suspended solids and 90 mg/l of soluble COD. After the addition of the trickling filter hydrolysate and the solids, the concentration of the soluble substrate was 112 mg/l and that of suspended solids, 222 mg/l. Within five hours, the DO in the system reached the minimum point of the sag, but the DO quickly recovered and remained at a rather constant level. After five days, the soluble COD value decreased by 64 mg/l (112 mg/l to 48 mg/l), whereas the suspended solids increased by about 50 mg/l (222 mg/l to 272 mg/l). Total COD decreased by about 20 mg/l, from 214 to 174 mg/l, and there was a small amount of nitrification, 6 mg/l (from an initial value of 20 mg/l to a final value of 26 mg/l. The total oxygen uptake was 55 mg/l at a K_2 of 0.141 hr^{-1} and a dissolved oxygen saturation value of 8.4 mg/l.

Figures 20 to 28 give a fair idea of the efficiency of the pilot plant. Figures 20 to 23 show that the actual effluents from the pilot plant did not cause any appreciable reduction in the oxygen resources of the stream for medium values of reaeration constant; also the BOD values were rather low. Even when large amounts of "biological" solids were purposely added to the effluent, the recovery after an early sag was rather rapid (e.g., Figure 24) except when there were significant amounts of nitrification. The results shown in Figures 27 and 28 indicate that although the treated effluents plus addition of excessive solids did not cause appreciable oxygen uptake, the leakage of both suspended solids and either cell hydrolysate or raw trickling filter

Figure 28. DO Profile and O_2 Uptake Curves for the Effluent From the Pilot Plant With the Addition of MLSS and the Trickling Filter Sludge Hydrolysate

	Initial	Final
Substrate Concentration		
Non-filtrate COD	214 mg/l	194 mg/l
Filtrate COD	112 mg/l	48 mg/l
Suspended Solids Conc.	222 mg/l	272 mg/l
Nitrate Nitrogen Conc.	20 mg/l	26 mg/l

Reaeration Constant, K_2, 0.141 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 8.4 mg/l
Oxygen Uptake, 55 mg/l


DO, mg/l
9.00
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
65.00
62.50
50.00
37.50
25.00
12.50
0.00
0
20
40
60
80
100
120
Time, Hours

sludge hydrolysate may cause considerable strain on the oxygen resources of the stream.

An additional three runs were made using effluent from a hydrolytically assisted extended aeration pilot plant operated by Mr. Roach, a fellow graduate student engaged in research. The operational procedure for the pilot plant was given in detail in the Materials and Methods chapter.

On March 2, 1974, effluent was taken from Mr. Roach's unit, placed in the open jar reactor and diluted with 50 percent tap water (Figure 29). On the day the sample was taken, the feed COD for the unit was 1950 mg/l, filtrate COD of the effluent was 20 mg/l, with a suspended solids concentration of 10 mg/l. After dilution, the COD of the filtrate was 36 mg/l. It would appear that either the original effluent COD value or the one with dilution was in error, since the COD of the tap water has been found to be 10-11 mg/l. The dissolved oxygen in the system increased slightly before a slow sag occurred. This general behavior was similar to that shown in Figure 20 for the effluent which was taken from the author's pilot plant. The oxygen uptake showed an initial lag before showing an increase in the rate of BOD. The soluble organic material was reduced from 36 mg/l to 7 mg/l; the biological solids increased by a slight amount (4 mg/l). The reaeration rate was 0.23 hr^{-1} at a saturation value of 7.85 mg/l. The oxygen uptake exerted was 12 mg/l of BOD.

Figure 30 is an experiment similar to Figure 29 with 50 percent dilution with tap water. The initial soluble organic material was 30 mg/l, and the biological solids concentration was 12 mg/l. After five days, the filtrate COD was 15 mg/l and the final biological solids

Figure 29. DO Sag and O_2 Uptake Curves for the Effluent From Mr. Roach's Extended Aeration Pilot Plant

	Initial	Final
Substrate Concentration		
Filtrate COD	36 mg/l	7 mg/l
Suspended Solids Conc.	16 mg/l	12 mg/l

Reaeration Rate Constant, K_2, 0.23 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 7.85 mg/l
Oxygen Uptake, 12 mg/l
Dilution Ratio, 50/50

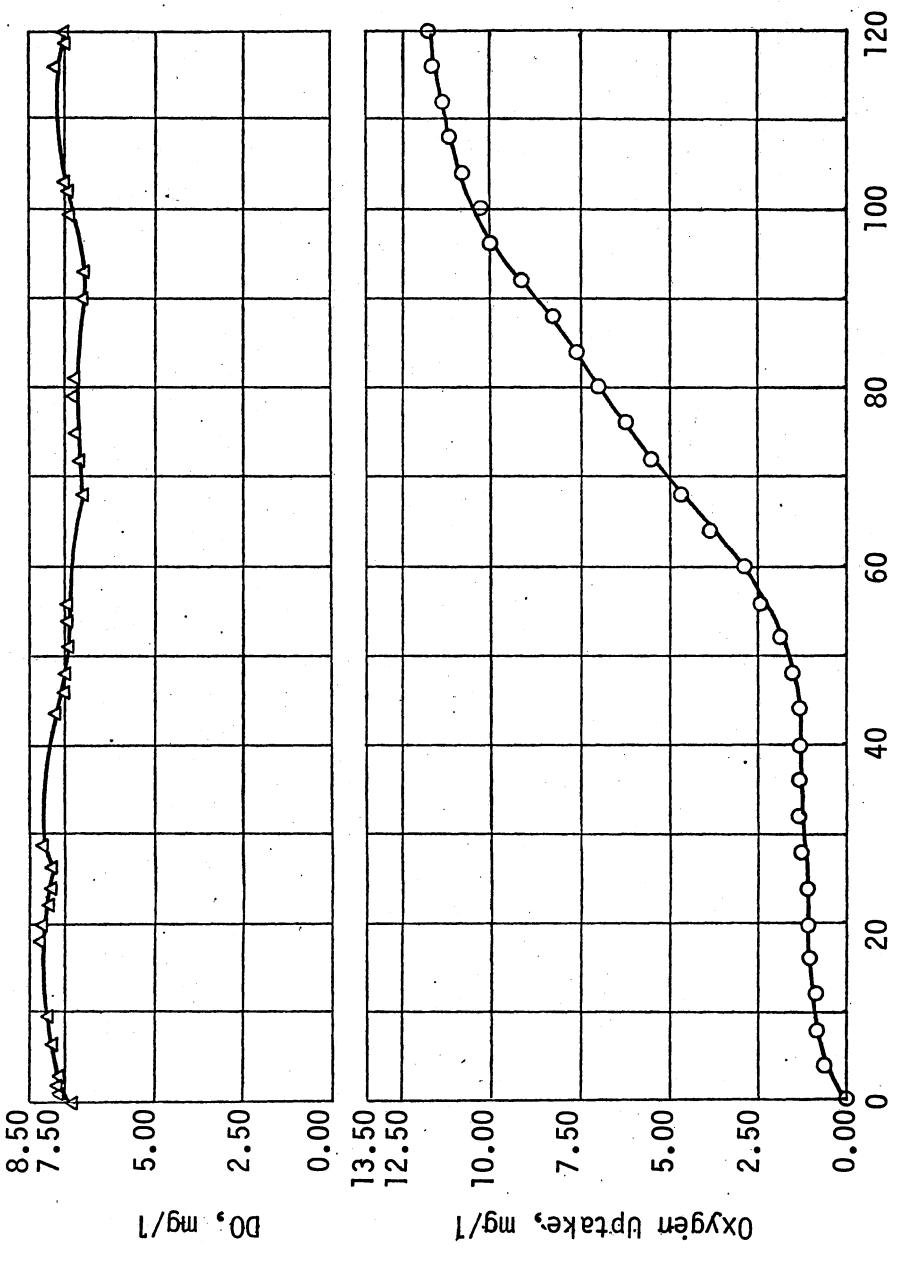
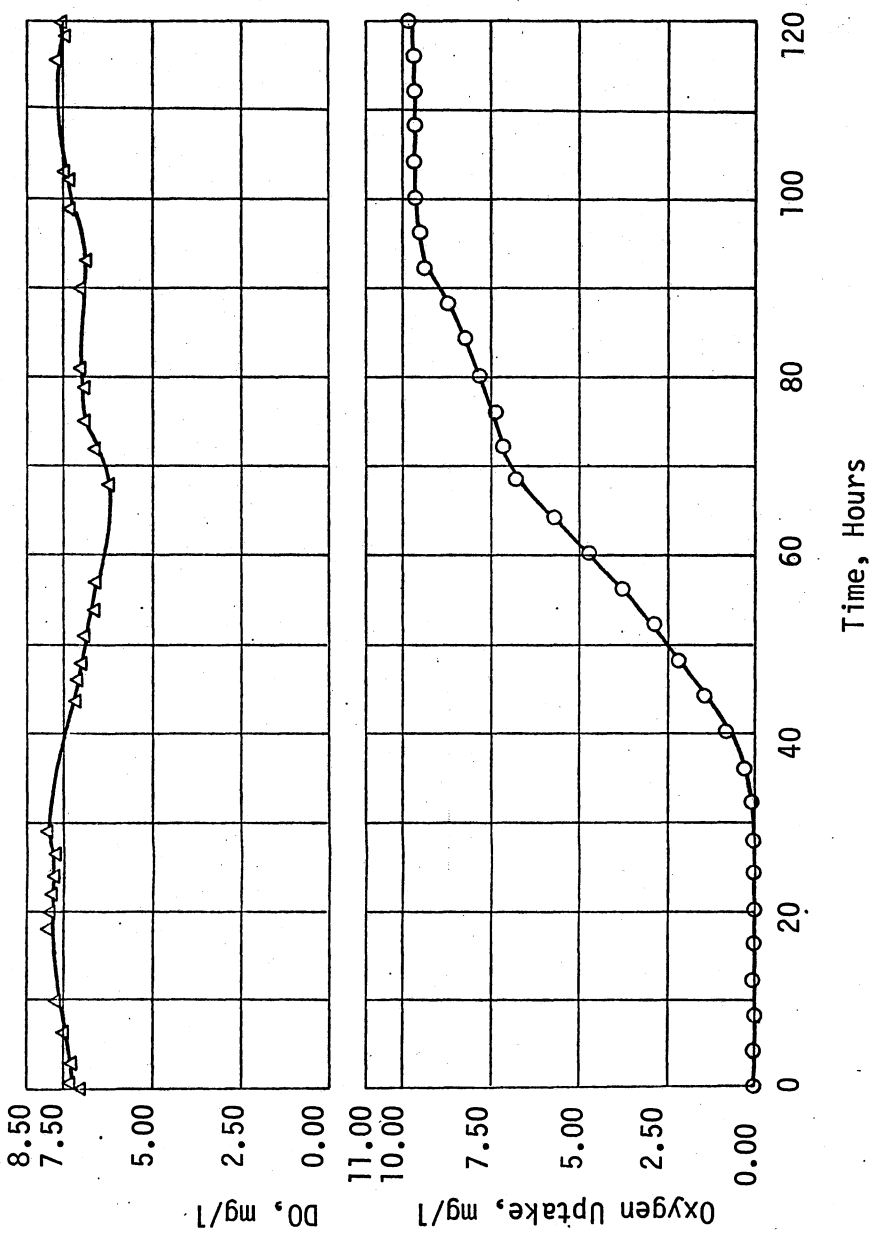

8.50
7.50
5.00
2.50
0.00
DO, mg/l
13.50
12.50
10.00
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
0
20
40
60
80
100
120
Time, Hours

Figure 30. DO Sag and O_2 Uptake Curves for the Effluent From Mr. Roach's Extended Aeration Pilot Plant

	Initial	Final
Substrate Concentration		
Filtrate COD	30 mg/l	15 mg/l
Suspended Solids Conc.	12 mg/l	8 mg/l

Reaeration Rate Constant, K_2, 0.163 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 7.6 mg/l
Oxygen Uptake, 10.00 mg/l
Dilution Ratio, 50/50


8.50
7.50
5.00
2.50
0.00
DO, mg/l
11.00
10.00
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
0
20
40
60
80
100
120
Time, Hours

concentration was 8 mg/l. The sag curve showed a trend similar to Figure 29 and Figure 20, i.e., an initial increase in DO followed by a slow sag and a slow recovery. The oxygen uptake curve showed an initial lag before the rate increased. The oxygen uptake exerted was 10 mg/l at a reaeration rate of 0.163 hr^{-1} and a saturation value of 7.6 mg/l. Mr. Roach took no effluent data on this day, but it is apparent from the results of the open jar test that the effluent was of a high quality.

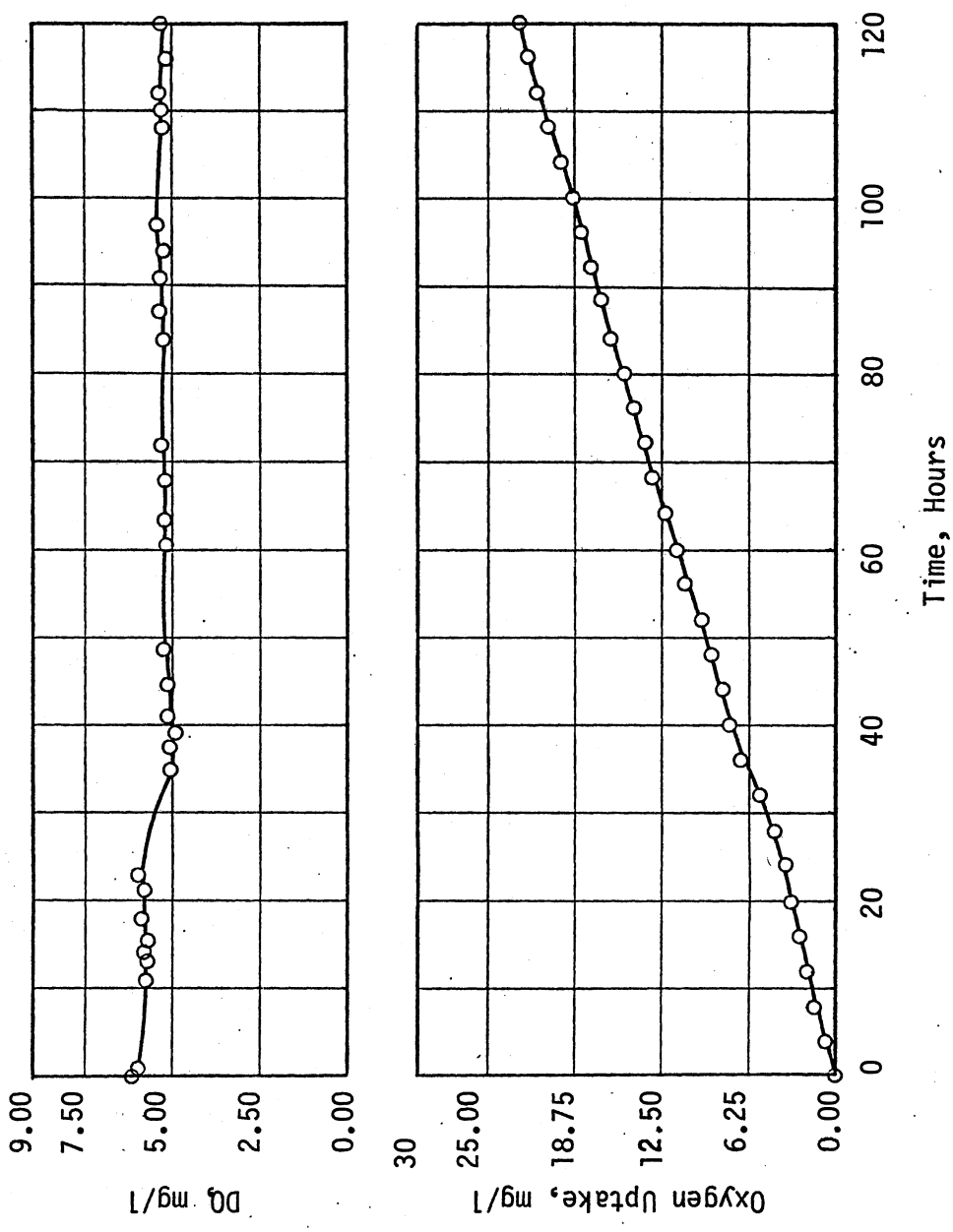
The plot in Figure 31 is the O_2 uptake for a sample taken on March 9, 1974, from Mr. Roach's pilot plant. In this experiment, no dilution water was added to the sample. The initial soluble substrate concentration was 45 mg/l, and the biological solids 12 mg/l. After five days, the soluble COD was 36 mg/l and the biological solids concentration was 16 mg/l. At a K_2 of 0.103 hr^{-1} and a saturation value of 7.1 mg/l, the sample exerted an oxygen uptake of 23 mg/l. This result is similar to that shown in Figure 23, wherein the sample was not diluted and oxygen uptake showed straight line kinetics, i.e., there was no sag in the DO profile.

The results of Figures 20, 29 and 30 show that when the sample was diluted with tap water they showed a lag period followed by a period of more rapid O_2 uptake. The lag might be due to a reduction in concentration of viable seed organisms. The later period of semi-rapid O_2 uptake (compared with steady straight line O_2 uptake of undiluted samples) might be due to the diluting out of possible inhibitory substances in the effluent. When the effluents were diluted with tap water, there was a significant reduction in soluble COD during the 5-day incubation period. But when the samples were taken without any

Figure 31. DO Sag and O_2 Uptake Curves for the Effluent From Mr. Roach's Extended Aeration Pilot Plant

	Initial	Final
Substrate Concentration		
Filtrate COD	45 mg/l	36 mg/l
Suspended Solids Conc.	12 mg/l	16 mg/l

Reaeration Constant, K_2, 0.103 hr^{-1}
Dissolved Oxygen Saturation Constant, C_s, 7.1 mg/l
Oxygen Uptake, 23 mg/l


DO, mg/l
9.00
7.50
5.00
2.50
0.00
Oxygen Uptake, mg/l
30
25.00
18.75
12.50
6.25
0.00
0
20
40
60
80
100
120
Time, Hours

dilution, less change in the soluble COD took place. Unfortunately, during this time nitrification data were not taken. While it must be admitted that the data leave much to be desired, the overall trend regarding O_2 uptake of the effluents without added seed, suspended solids, and/or substrates, is that the "residual" COD in the effluents from the pilot plant is indeed rather slowly metabolized biologically resistant organic matter, and it should not be expected that it can be removed by normal secondary treatment processes. Also, these results indicate that the condition of discharge with respect to stream flow, i.e., dilution of the effluent, may exert subtle effects upon the observed kinetics beyond the usually expected effect of substrate concentration on rate of O_2 uptake.

Table I gives values of important parameters determined during the early open jar experiment. Also shown are the values of K_2, the reaeration rate constant, and the dissolved oxygen saturation concentration, C_s, calculated using the two different methods described in detail in the Materials and Methods chapter. In this study, oxygen uptake was computed using the constants K_2 and C_s obtained from Method No. 2. However, the C_s values used in the first trial of the α Method (Method No. 1) were those obtained as a result of employing Method No. 2. Thus, in a real sense, both methods were employed and it would appear that Method No. 2 not only provides a more direct way of determining C_s from a limited amount of data, but also gives K_2 values which compare well with those obtained by the α method. Based upon the experience gained here, it appears ideal to employ both methods; i.e., use Method No. 2 to determine the saturation value, then employ Method No. 1 using the C_s from Method No. 2 to determine K_2; and finally check the K_2 using

TABLE I

VALUES OF THE PARAMETERS DETERMINED

Figure	Non-Filt. COD mg/l Initial	Non-Filt. COD mg/l Final	Filt. COD mg/l Initial	Filt. COD mg/l Final	Suspended Sol. mg/l Initial	Suspended Sol. mg/l Final	Reaeration Rate, K_2, hr^{-1} Method No. 2 dC/dt	Reaeration Rate, K_2, hr^{-1} Method No. 1 α	Saturation Const., Cs Method No. 2 dC/dt	Saturation Const., Cs Method No. 1 α	Nitrate Nitrogen Conc. mg/l Initial	Nitrate Nitrogen Conc. mg/l Final	F/M	Oxygen Uptake	Temp.°C	Remarks
6	-	-	112(90)	15	6	16	0.117	0.107	7.40	7.40	-	-	18.70	44	22.5	"Young" Cell Seed
7	-	-	134(120	9	8	45	0.128	0.128	7.10	7.10	-	-	16.80	36	22.5	" " "
8	-	-	120(100)	9	8	93	0.11	0.107	7.70	7.60	-	-	15.00	44	"	" " "
9	-	-	56(50)	9	6	20	0.097	0.085	7.50	7.40	-	-	9.30	31	"	" " "
10	-	-	54(60)	10	8	37.5	0.07	0.718	7.70	770	-	-	8.1	31	"	" " "
11	-	-	71(55)	9	9	15	0.13	0.114	8.00	8.00			7.9	39	"	" " "
12	-	-	52(40)	9	9	-	0.107	0.107	8.00	8.00	-	-	5.80	27	"	" " "
14			86(75)	19	1(0.86)	15	0.07	0.073	8.60	8.60	-	-	100	32	"	"Old" " "
15			76(50)	9	1(0.86)	13	0.068	0.064	8.75	8.80	-	-	88	26	"	" " "
16			107(90)	10	2.3	50	0.123	0.118	8.00	8.00	-	-	47	44	"	" " "
17			91(70)	7	2.3	30	0.097	0.098	8.10	8.10	-	-	40	33	"	" " "
20			49	-	12	16	0.162	0.147	7.55	7.4	-	-	4.05	17	25	Effluent from pilot plant (diluted 50/50)
21			60	59	12	8	0.095	0.092	7.8	7.8	-	-	5.00	28	"	Eff. from p.p. (not diluted)
22			24	-	56	-	0.130	0.126	7.2	7.65	-	-	0.428	32	"	
23			32	28	76	73	0.09	0.091	7.65	7.65	-	-		26	"	
24			42	40	178	160	0.185	0.204	5.9	5.9	0.00	0.00	0.236	27	"	Effluent suspended
25	172	172	56	56	165	182	0.093	0.106	8.95	8.95	0.00	23.00	0.039	23	"	Solids, no dilution
26	308	288	56	52	337	345	0.125	0.120	8.85	8.60	29.50	14.70	0.166	44	"	
27	312	264	160	60	305	297	0.145	0.167	8.7	8.7	14.00	38.00	0.525	96	"	Recycle sludge hydrolysate + MLSS added to the effluent
28	214	194	112	48	222	272	0.141	0.144	8.4	8.4	20	26	0.507	55	"	Trickling filter sludge hydrolysate + MLSS added to the effluent
29			36	7	16	12	0.23	0.22	7.85	7.85	-	-	2.289	12	"	Mr. Roach's effluent (50 + 50 dilution)
30			30	15	12	8	0.163	0.163	7.6	7.4	-	-	2.507	10	"	(50 + 50 dilution)
31			45	36	12	16	0.103	0.1026	7.1	7.1			3.750	23	"	No dilution

In experiments 24-28, the K_2 values employed in O_2 uptake calculations were obtained using actual experimental reactor mixed liquor after running the DO profile. The K_2 values were also run on tap water to determine α values for experiments 24-28. These were 1.49, 0.80, 1.16, 0.83, and 1.01, respectively.

Method No. 1.

A Study of the Factors Affecting the Reaeration Rate and Some Useful Aids to the Methodology

For the success of the open stirred reactor technique, the determination of the best estimate of the value of reaeration rate constant, K_2, and the dissolved oxygen saturation value, C_s, in the system, is important. Since the various parameters, like the solubility and type of organic material, concentration of biological solids, pressure, and agitation may affect the oxygen transfer rate and the saturation value, the determination of these values is a matter of considerable concern in the field. In addition to natural components of the liquor, one has to add sodium sulfite, or bubble nitrogen gas to remove the dissolved oxygen to conduct the reaeration rate test. It is also necessary to add an inhibitory agent to stop the oxygen uptake due to the microorganisms. It has been reported that even the addition of double the normal value of sodium sulfite might affect the reaeration rate (44).

While a comprehensive study of all of the parameters affecting the reaeration rate and the technique of obtaining K_2 may be somewhat beyond the scope of this work, a few of the aspects have been investigated and are reported in this chapter.

Relation Between Mixing Propeller Speed and the Reaeration Rate, K_2

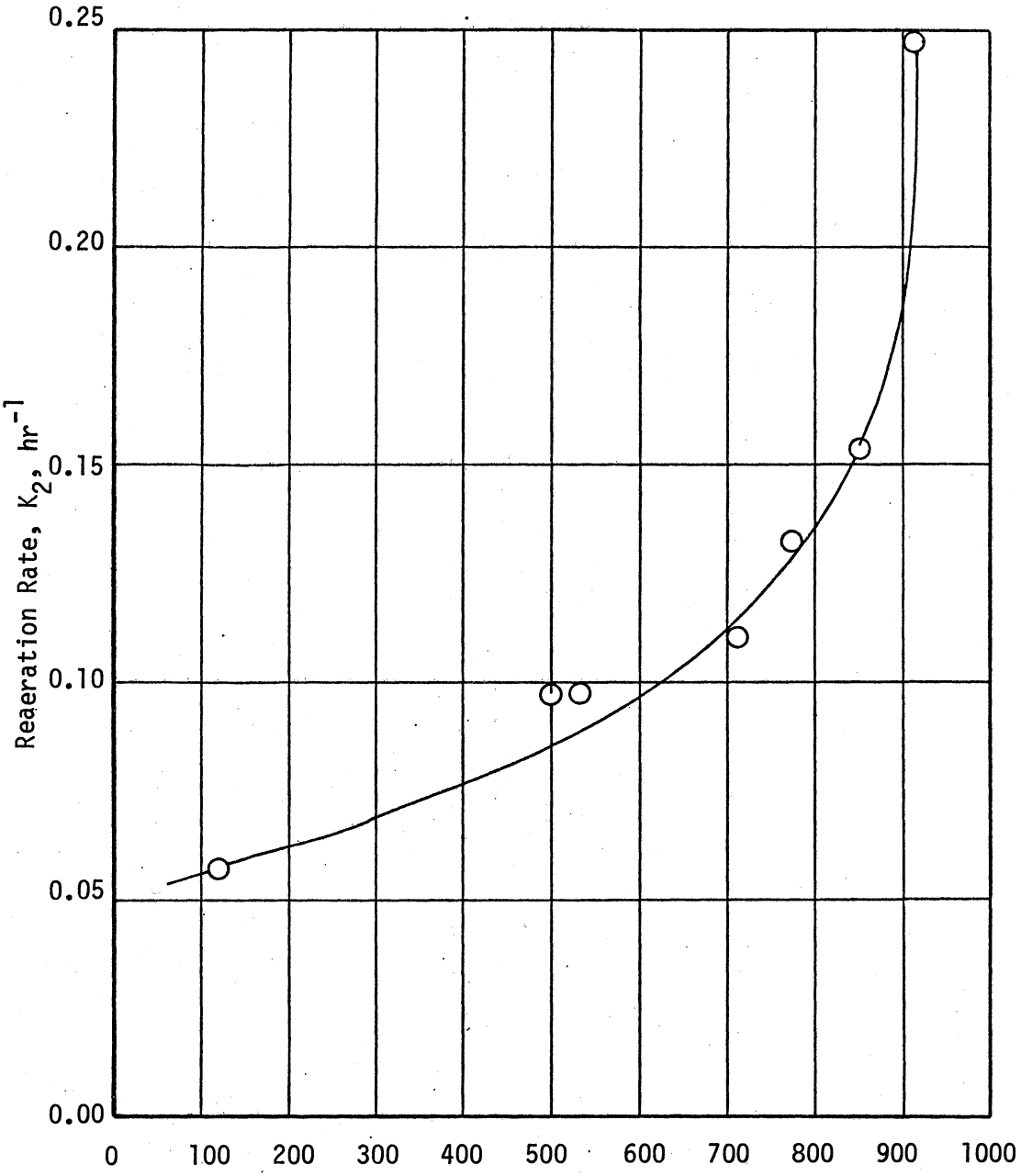
To simulate stream conditions in the open jug, the reaeration rate in the reactor should be adjusted to a value somewhere near the value

of that in the receiving stream. Figure 32 gives an arithmetic plot of the reaeration rate versus the speed of the propeller; the transfer medium was tap water. The speed of the propeller was measured with a Precision Stroboscope (Sargent-Welch Company, Skokie, Ill.). The reaeration rate increased slowly in a straight line up to 675 rpm. At speeds higher than 675, the reaeration rates increased enormously for a small increase in the speed of the propeller. Figure 33 is a semi-logarithmic plot of the data; the general trend is one of exponential increase in K_2 with increasing rpm over the range studied.

Relation Between Biological Solids Concentration and the Reaeration Rate Constant

The effect of biological solids on the reaeration rate should be studied more extensively than was done in this investigation. However, the experimental results which were obtained herein showed that the effect is two-fold: 1) biological solids do affect the reaeration rate, and 2) the effect is apparently different, depending upon the value of K_2 (assumedly dependent upon agitation and/or mixing velocity). In Tables II and III, the K_2 data are presented in increasing order of suspended solids. Table II covers low K_2 values, i.e., those up to $\pm$ 0.2 hr^{-1}. It is seen that except for the study at 42 mg/l suspended solids, the effect of the solids was to increase the value of K_2 over that at the corresponding rpm in tap water. Table III shows the results for higher K_2 values. At the lowest suspended solids concentration, the K_2 was increased because of the presence of solids, but as the solids concentration was increased, the K_2 was decreased because of the presence of suspended solids.

Figure 32. Arithmetic Plot of Propeller Speed versus Reaeration Rate, K_2, hr^{-1}


0.25
0.20
0.15
0.10
0.05
0.00
Reaeration Rate, K_2, hr^{-1}
0
100
200
300
400
500
600
700
800
900
1000

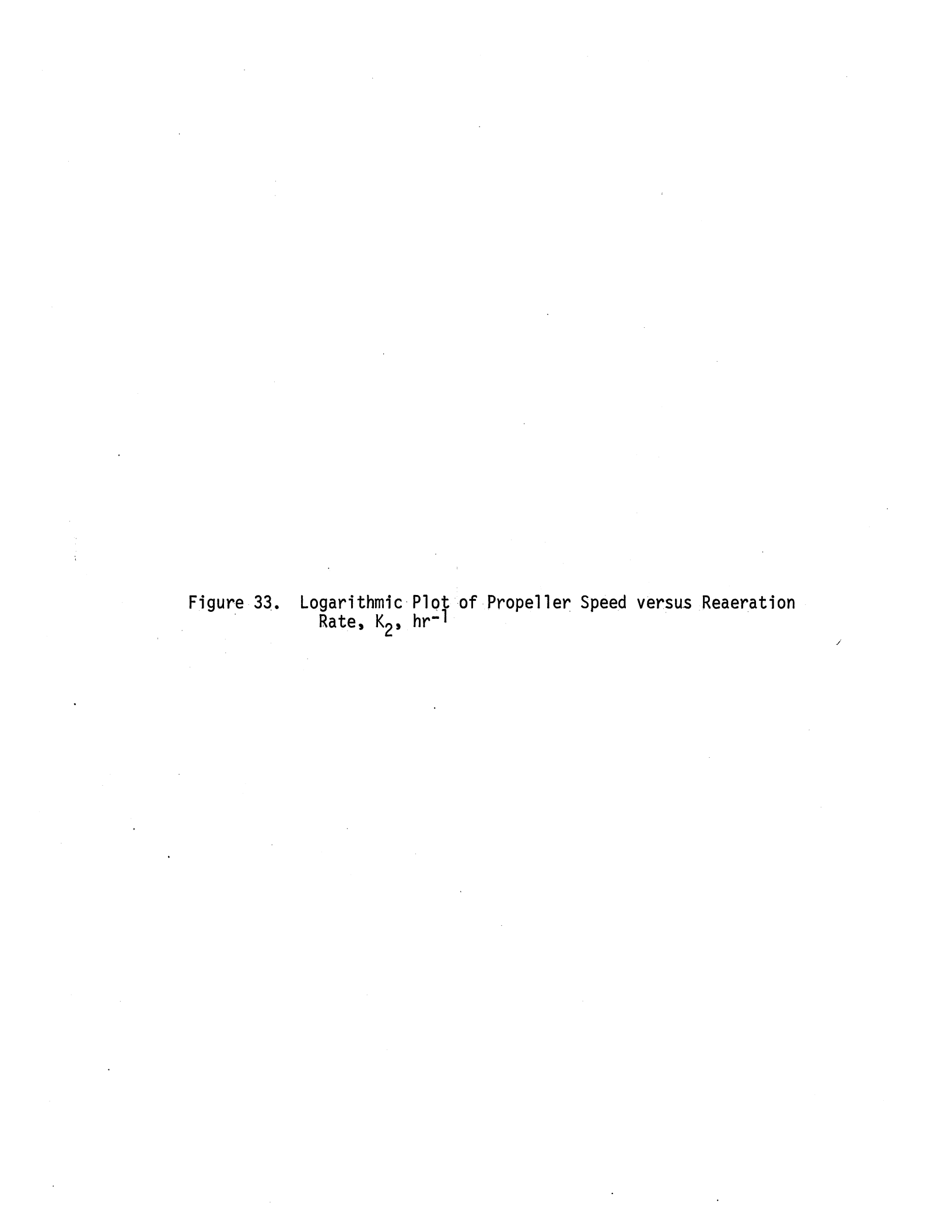


Figure 33. Logarithmic Plot of Propeller Speed versus Reaeration Rate, K_2, hr^{-1}

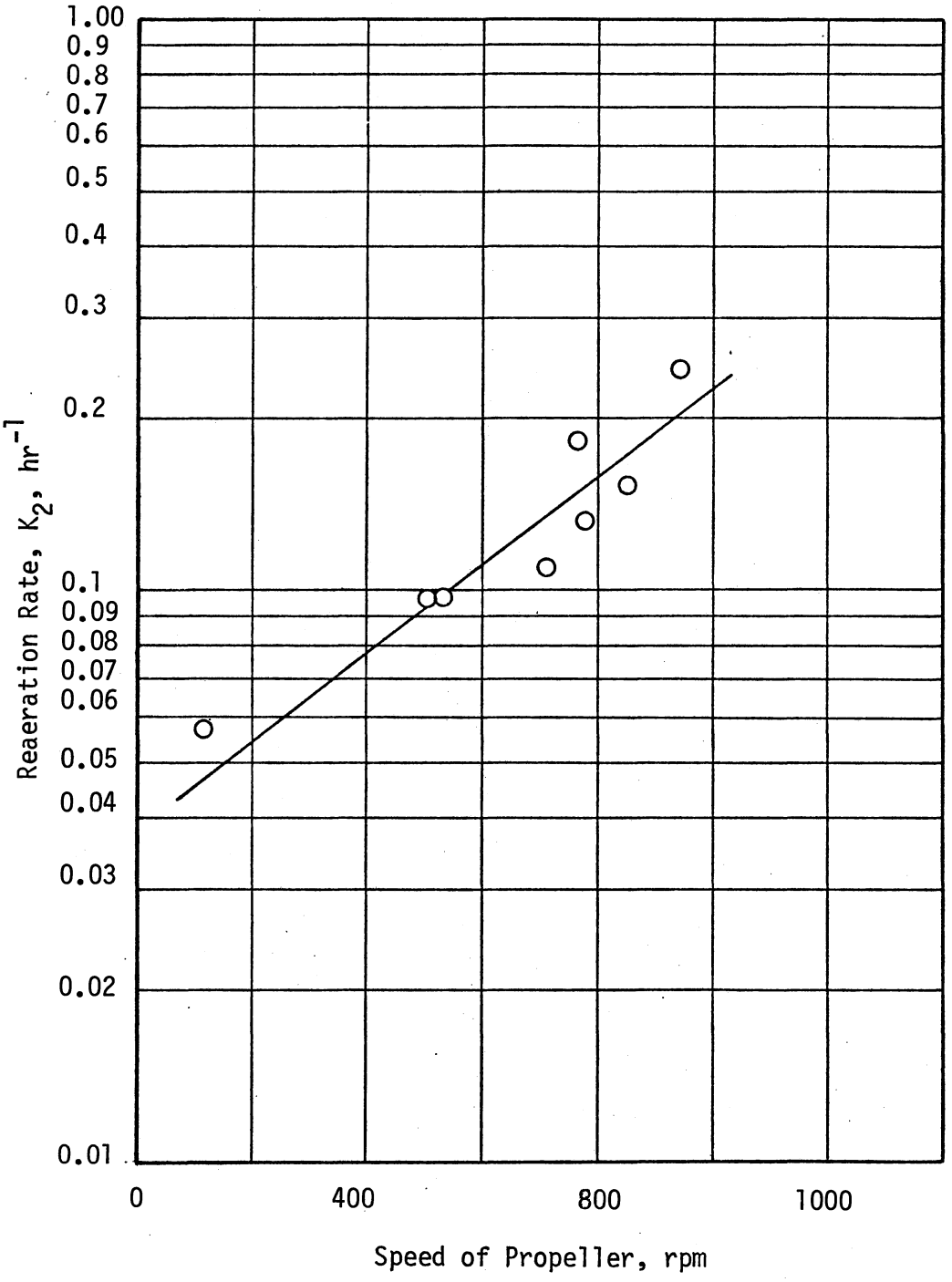

1.00
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
Reaeration Rate, K_2, hr^{-1}
0
400
800
1000
Speed of Propeller, rpm

TABLE II

EFFECT OF SUSPENDED SOLIDS ON LOW REAERATION RATES, $\pm$ 0.2 hr^{-1}

Suspended Solids	Reaeration Rate, K_2		K_2 With Solids
	Tap Water (no Solids)	Solids	K_2 With Tap Water
0.25	0.165	0.174	1.054
25	0.151	0.167	1.105
25	0.163	0.193	1.184
42	0.231	0.173	0.748
75	0.198	0.347	1.752
95	0.203	0.267	1.315
102	0.239	0.287	1.200

TABLE III

EFFECT OF SUSPENDED SOLIDS ON HIGH REAERATION RATES >0.25 hr^{-1}

Suspended Solids	Reaeration Rate, K_2		K_2 With Solids
	Tap Water - No Suspended Solids	Tap Water + Suspended Solids	K_2 With Tap Water
35	1.43	2.19	1.531
50	0.83	0.73	0.879
70	1.49	1.26	0.845
105	1.60	0.78	0.787

Note: 15 ml Clorox added to all reactors

The results agree with Poon and Campbell (18) in that at low reaeration rates and low suspended solids concentrations there is an increase in the amount of reaeration rate, K_2. With the results at hand, further conclusions are diffiuclt to make and would seem to require a considerable amount of research data.

Effect of Chlorine and Cyanide on Reaeration Rate, K_2

Chlorine has benerally been used by workers in the field to inhibit O_2 utilization by microorganisms. The brief investigation made in these studies provided some indication that microorganisms killed by chlorine released lysis products, as measured by an increase in the soluble organic material (COD), whereas for the same concentration of biological solids, there was no release of soluble products when cyanide was used instead of chlorine as the inhibitory agent. The results are summarized in Tables IV and V.

Experiments indicated that addition of Clorox to water did not affect the K_2 to any significant amount at levels of 1-3 ml/l (Table VI). A series of experiments was conducted to compare the K_2 values (at identical propeller speed) for tap water, tap + Clorox, and tap + cyanide, with various amounts of suspended (biological) solids added to the system containing Clorox and cyanide. The results are summarized in Table VII. It is seen that except for the experiment at 50 mg/l suspended solids, killing cells with cyanide yielded K_2 values closer to those observed for tap water at identical propeller speed. Further work on the advisability of employing cyanide rather than chlorine is being planned in the bioenvironmental engineering laboratories.

TABLE IV

CONCENTRATIONS OF SOLUBLE ORGANIC MATERIAL (COD) BEFORE AND AFTER INHIBITION WITH CLOROX AS THE INHIBITORY AGENT

Exp. No.	Clorox Conc. ml/l	Suspended Solids Conc., mg/l	Filtrate COD Before Killing mg/l	Filtrate COD After Killing mg/l
1	2.0	35	62.5	58.59
2	2.5	70	85.93	97.65
3	3.0	105	74.27	85.84

TABLE V

CONCENTRATIONS OF SOLUBLE ORGANIC MATERIAL (COD) BEFORE AND AFTER INHIBITION WITH CYANIDE AS THE INHIBITORY AGENT

Exp. No.	Cyanide Conc. mg/l	Suspended Solids Conc., mg/l	Filtrate COD Before Killing mg/l	Filtrate COD After Killing mg/l
1	100	35	46.87	46.87
2	150	70	58.59	58.59
3	200	105	62.5	46.87

TABLE VI

EFFECT OF CLOROX ON REAERATION RATE

Conc. of Clorox	Reaeration Rate		K_2 With Chlorine / K_2 With Tap Water
	Tap Water	Tap Water + Chlorine	
1 ml/l	0.336	0.378	1.125
2 ml/l	0.540	0.462	0.855
3 ml/l	0.540	0.5696	1.054

TABLE VII

COMPARISON OF REAERATION RATES BETWEEN CHLORINE AND CYANIDE AS INHIBITORY AGENTS

Suspended Solids Conc. mg/l	Tap Water Without Solids	Tap Water + Solids + Clorox	Tap Water + Solids + Cyanide	K_2 With Clorox / K_2 With Tap Water	K_2 With Cyanide / K_2 With Tap Water
25	0.163	0.495	0.1925	0.036	1.180
35	1.4337	2.1883	1.89	1.526	1.318
50	0.8316	0.7294	0.495	0.877	0.595
70	1.485	1.26	1.485	0.848	1.00
75	0.198	0.3465	0.308	1.75	1.55
105	1.5992	0.7845	0.9039	0.490	0.565

CHAPTER V

SUMMARY AND CONCLUSIONS

In this work, the open stirred reactor technique was used to study the kinetics of oxygen uptake with respect to initial "food" (COD) to cell concentration (suspended solids) ratio, and it was found that with "young" cell seed and glucose as substrate, the oxygen uptake curves followed logarithmic rate kinetics in the early phase of O_2 uptake; but the duration of the logarithmic phase decreased with decreasing F/M ratios. With "old" cell seed, the oxygen uptake curves did not show any definite logarithmic rate kinetics; at very high F/M ratios, logarithmic uptake was approached.

Effluents from the laboratory extended aeration pilot plants were tested in the open jars for their effect on the oxygen resources of a receiving stream. In these studies, the effluents were diluted by 1/1 ratio; undiluted samples were also tested in the open stirred reactors. It was found in these studies that in both of these cases the extended aeration effluents do not deplete the oxygen resources of the stream in any appreciable manner. Also, the experiments operated by adding the mixed liquor solids to the effluents would not cause any severe depletion of the oxygen resources of the receiving stream. But the experiments operated to test the effect of leakage of both the soluble substrate (in this case, sludge hydrolysate) and biological solids showed considerable oxygen uptake, thus they could cause severe strain on the

oxygen resources of streams without abnormally high reaeration constants.

This study also gave an idea of the efficiency of treatment in the pilot plants operated in the laboratory. It was observed that the treatment efficiency was rather high; most of the soluble COD fed to the pilot plants was removed in the pilot plant itself and the soluble COD which was released can be removed only very slowly. This removal cannot possibly be accomplished in the pilot plant operation at the usually low hydraulic detention times. Thus, this study shows that all of the possible organic material (soluble COD) was removed in the treatment plants, and further reduction is not possible within the relatively short hydraulic detention time in these systems.

A few experiments were performend on the effect of suspended solids on the reaeration rate, K_2, and it was found that low suspended solids concentration and relatively low K_2 values tended to increase the α factor. However, at higher K_2 values (i.e., greater mixing speed), α decreased with increased solids.

Preliminary studies on the use of cyanide as the inhibitory agent for microbial respiration instead of chlorine indicated that the use of cyanide should be investigated further, since the results were favorable. Chlorine gave reasonably good results, but its use did cause some release of soluble organic material (COD).

CHAPTER VI

SUGGESTIONS FOR FUTURE WORK

1. Additional studies should be made to determine the effect of the source of the seed on the oxygen uptake kinetics.

2. The O_2 uptake kinetics due to nitrification in the receiving stream should be studied in more detail.

3. In-depth studies should be conducted to determine the effect of contaminants on the reaeration rate constants and the dissolved oxygen saturation constants.

4. Studies should be made on a variety of possible microbial inhibitory agents to employ during reaeration studies in determination of K_2 and C_s when samples contain biological solids. Study of the use of cyanide should prove useful, based on the preliminary studies in this investigation.

5. The possibility of determining the amount of change, if any, of reaeration rates during the course of a jar study might be accomplished if one could measure O_2 uptake manometrically along with the DO sag measurement. This independent measure of the BOD curve along with the profile data would allow one to back calculate the K_2 values for various time intervals. Thus one might determine the degree of constancy of K_2 throughout the experiment. Also, the average K_2 thus calculated could be compared to the K_2 determined at the end of the open jar test.

SELECTED BIBLIOGRAPHY

1. Frankland, E., "First Report of the Rivers Pollution Commission of 1868," 18 (1870). Extracted from the Royal Commission, Fifth Report, App. VI, 10 (1908).

2. Dupre, A., "Report on the Changes in the Aeration of the Wastes, as Indicating the Nature of the Impurities Present in It." Fourteenth Annual Report of the Local Government Board (1883-1884). Supplement Containing the Report of the Medical Officer 1884, App. B, No. 11, 304-312.

3. Adeney, W. E., Reprint of Papers by Adeney (1895-1897). Fifth Report of the Royal Commission App. PPs, 49-105.

4. Dibdin, J., and Thudichum, G., "Aeration as a Test for Purity of Sewage Effluents." J. Soc. Chem. Indus., 19:497 (1900).

5. Theriault, E. J., "The Oxygen Demand of Polluted Waters. I. A Critical Review. II. The Rate of Deoxygenation." Public Health Service Bulletin No. 173 (1927).

6. Adeney, W. E., and Becker, H. G., "The Determination of the Rate of Solution of Atmospheric Nitrogen and Oxygen by Wastes." Philosophical Magazine, 38, 317-337 (1919).

7. Streeter, H. W., and Phelps, E. B., "A Study of the Pollution and Natural Purification of the Ohio River. Factors Concerned in the Phenomena of Oxidation and Reaeration." Public Health Service Bulletin No. 146, U. S. Public Health Service, Washington, D. C. (1925).

8. Gates, W. E., Mancy, K. H., Shafie, F. R., and Pohland, F. G., "A Physical Model for Studying Assimilative Capacity." Proceedings, 20th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 121, 665-687 (1966).

9. Heukelekian, H., "The Use of the Dilution Method for Determining the Effect of Industrial Wastes on Deoxygenation." Sewage Works Journal, 19, 612-620 (1947).

10. Ruchhoft, C. C., Placak, O. R., Kachmas, J. F., and Calbert, C. E., "Variations in Sewage Velocity Constants of Sewage Dilutions." Industrial and Engr. Chem., 40, 1290 (1948).

11. Kittrel, F. W., and Kochtitsky, O. W. Jr., "Natural Purification Characteristics of a Shallow Turbulent Stream." Sewage Works Journal, 19, 10-32 (1947).

12. Orford, H. E., Rand, M. C., and Gellman, I., "A Single Dilution Technique for BOD Studies." Sewage and Industrial Wastes, 30, 1335-1349 (1958).

13. Elmore, Harold L., "Deterimation of BOD by a Reaeration Technique." Sewage and Industrial Wastes, 27, 993 (1955).

14. Orford, Harold E., and Ingram, William T., "Deoxygenation of Sewage. I. Critical Review of the Monomolecular Formula." Sewage and Industrial Wastes, 25, 419-424 (1953).

15. Jennelle, E. M., and Gaudy, A. F. Jr., "Studies on Kinetics and Mechanisms of BOD Exertion in Dilute Systems." Biotechnology and Bioengineering, XII, 519-539 (1970).

16. Lordi, D., and Heukelekian, H., "Effect of Rate Mixing on Deoxygenation of Polluted Water." J. San. Engr. Div., ASCE, 109, 530-539 (1961).

17. Ali, Hi, and Beutra, J. K., "Influence of Turbulence on BOD Progression." J. Water Pollution Control Federation, 44, 1798-1807 (1972).

18. Poon, C. P. C., and Campbell, H., "Diffused Aeration in Polluted Water." Water and Sewage Works, 114, 461 (1967).

19. Kothandaraman, V., "Effect of Contaminants on Reaeration Rates in Riber Waters." J. Water Pollution Control Federation, 45, 806-817 (1971).

20. Kehr, R. W., "Measures of Normal Oxidation in Polluted Streams. VI. Effect of Sewage on Atmospheric Reaeration." Sewage Works Journal, 10, 228 (1938).

21. Eckenfelder, W. W., Raymond, L. W., and Laurion, Donald T., "Effects of Various Organic Substances on Oxygen Absorption Efficiency." Sewage and Industrial Wastes, 28, 1357-1364 (1956).

22. Churchil, P. V., Elmore, H. L., and Buchingham, R. A., "Prediction of Stream Reaeration Rates." J. San. Engr. Div., ASCE, 88, SA4, 1-46 (1962).

23. Krenkel, P. A., and Orlob, G. T., "Turbulent Diffusion and the Reaeration Coefficient." J. San. Engr. Div., ASCE, 88, SA5, 53-83 (1962).

24. Thackston, W. L., and Krenkel, P. A., "Longitudinal Mixing and Reaeration in Natural Streams." Technical Report No. 7, Sanitary and Water Resources Div. Engr., Vanderbilt University, Nashville, Tennessee (1966).

25. Isaacs, W. P., and Gaudy, A. F. Jr., "Atmospheric Oxygenation in a Simulated Stream." J. San. Engr. Div., ASCE, 94, SA2, 319-344 (1968).

26. Davis, D. S., Empirical Equations and Nomography, 2nd Ed., McGraw-Hill, New York (1962).

27. Fair, Gordon M., Introductory Address, "Water Pollution Research and the Revolution in Science and Technology." Advances in Water Pollution Research, 1, XI-XXV, September (1962).

28. Thomas, H. A. Jr., "Pollution Load Capacity of Streams." Water and Sewage Works, 95, 409 (1948).

29. O'Connor, D. J., "Oxygen Balance of an Estuary." J. San. Engr. Div., ASCE, 126, SA4, 126, 556 (1961).

30. Gannon, John J., "River and Laboratory BOD Rate Considerations." J. San. Engr. Div., ASCE, 92, SA5, 114-116 (1966).

31. Velz, C. J., and Gannon, J. F., "Biological Extraction and Accumulation in Stream Self-purification." Advances in Water Pollution Research, 1, 1-15 (1962).

32. Courchaine, Robert J., "The Significance of Nitrification in Stream Analysis. Effects on the Oxygen Balance." Proceedings, 17th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 115, 38-50 (1963).

33. Dobbins, W. E., "BOD Oxygenation Relationship in Streams." J. San. Engr. Div., ASCE, 91, SA1, 82-90 (1964).

34. Wuhrmann, K. F., Ruchti, F., and Eichenberger, E., "Quantitative Experiments on Self-purification With Pure Organic Compounds." Advances in Water Pollution Research, 1, 229-251 (1966).

35. Gaudy, A. F. Jr., Komolrit, K., and Gaudy, E. T., "Sequential Substrate Removal in Response to Qualitative Shock Loading of Activated Sludge Systems." Appl. Microbiol., 12, 286 (1964).

36. Bhatla, M. N., and Gaudy, A. F. Jr., "Sequential Substrate Removal in a Dilute System by Heterogeneous Microbial Populations." Appl. Microbiol., 13, 345-347 (1965).

37. Bhatla, M. N., and Gaudy, Anthony F. Jr., "Role of Protozoa in the Diphasic Exertion of BOD." J. San. Engr. Div., ASCE, 91, SA1, 63-87 (1965).

38. Isaacs, W. P., and Gaudy, A. F. Jr., "Comparison of BOD Exertion in a Simulated Stream and Standard BOD Bottles." Proceedings, 21st Industrial Waste Conference, Purdue University, Lafayette, Indiana, 165-182 (1967).

39. Gates, W. E., Marlar, F. T., and Westfield, F. D., "The Application of Bacterial Process Kinetics in Stream Simulation and Stream Analysis." Water Research, 3, 663-686 (1969).

40. Peil, K. M., and Gaudy, A. F. Jr., "A Rational Approach for Predicting the DO Profile in Receiving Waters." (Submitted for publication, Biotechnology and Bioengineering, 1974).

41. Peil, K. M., and Gaudy, A. F. Jr., "Kinetic Constants for Aerobic Growth of Microbial Populations Selected With Various Single Compounds and With Municipal Wastes as Substrates." Appl. Microbiol., 21, 253-25 6 (1971).

42. Standard Methods for the Examination of Water and Waste Water, 13th Ed., American Public Health Association, New York, N. Y. (1971).

43. Isaacs, W. P., and Gaudy, A. F. Jr., "A Method for Determining Constants of First-Order Reaerations From Experimental Data." Biotechnology and Bioengineering, X, 69-82 (1968).

44. Benedik, Andrew, "Problems With the Use of Sodium Sulfite in Aerator Evaluation." Proceedings, 26th Industrial Waste Conference, Purdue University, Lafayette, Indiana, Engineering Extension Series No. 140, 947-976 (1971).

APPENDIX A

CALCULATION OF O_2 UPTAKE USING THE OPEN STIRRED REACTOR PROCEDURE

In the successful use of the open stirred reactor technique, the accuracy of determining the reaeration rate constant, K_2, and the dissolved oxygen saturation constant, C_s, is vital to determination of oxygen uptake values in the receiving stream. In this study, reaeration rate, K_2, and the saturation constant, C_s, were calculated using a graphical method (Method No. 2--see Chapter III, Materials and Methods), and these values were checked with another method (Method No. 1--see Chapter III, Table I). After obtaining the best estimate of K_2 and C_s, and after measuring the DO profile during the given jar test, the oxygen uptake can be calculated using a numerical integration technique. The calculations are illustrated in Table XIII. Employing the DO profile (column 1) and calculating the deficit from saturation (column 2), this deficit is multiplied by the reaeration rate, K_2, and the selected interval of time, Δt, to yield the total oxygen transferred to the reactor (column 6). This value is summed with the change in DO concentration in the system during Δt (column 7), yielding the oxygen uptake exerted by the microorganisms in the stabilization of organic waste during the time interval (column 8). The accumulated oxygen uptake is given by the successive summation of these values over the length of the experiment (column 9). The data presented in this table were obtained during the study presented in Figure 10.

TABLE VIII

CALCULATION OF OXYGEN UPTAKE FROM OPEN STIRRED REACTORS

1 Time Hour	2 DO mg/l	3 D mg/l	4 K_2D mg/l-hr^{-1}	5 Δt Hour	6 $K_2D\Delta t$ mg/l	7 ΔDO mg/l	8 6-7 mg/l	9 O_2 Uptake mg/l
0	6.55	1.15	0.0805	0.00	0.00	0.00	0.00	0.00
4	5.40	2.30	0.1610	4.00	0.644	-1.15	1.794	1.79
8	4.25	3.45	0.2415	4.00	0.966	-1.15	2.116	3.91
12	3.25	4.45	0.3115	4.00	1.246	-1.00	2.246	6.15
16	2.35	5.35	0.3145	4.00	1.498	-0.90	2.398	8.55
20	1.40	6.30	0.4410	4.00	1.764	-0.95	2.714	11.26
24	0.90	6.80	0.476	4.00	1.904	-0.50	2.404	13.67
26	0.35	7.35	0.5145	2.00	1.029	-0.55	1.5790	15.25
28	0.48	7.22	0.5054	2.00	1.0908	+0.13	0.8808	16.13
32	0.60	7.10	0.4970	4.00	1.988	+0.12	1.868	17.99
38	0.70	7.00	0.4900	4.00	1.960	+0.10	1.860	19.85
40	1.30	6.40	0.4480	4.00	1.792	+0.60	1.192	21.05
44	2.10	5.60	0.392	4.00	1.568	+0.80	0.768	21.81
48	2.80	4.90	0.3430	4.00	1.372	+0.70	0.672	22.49
52	3.35	4.35	0.3045	4.00	1.218	+0.55	0.668	23.15
56	3.75	3.95	0.2765	4.00	1.106	+0.40	0.706	23.86
60	4.25	3.45	0.2415	4.00	0.966	+0.50	0.466	24.33
64	4.65	3.05	0.2135	4.00	0.854	+0.40	0.454	24.78
68	4.75	2.95	0.2065	4.00	0.826	+0.10	0.726	25.51
72	5.10	2.60	0.1820	4.00	0.728	+0.35	0.378	25.88
76	5.30	2.40	0.1680	4.00	0.672	+0.20	0.472	26.36
80	5.35	2.35	0.1645	4.00	0.658	+0.05	0.608	26.96
84	5.50	2.20	0.1540	4.00	0.616	+0.15	0.466	27.43
88	5.55	2.15	0.1505	4.00	0.6020	0.05	0.5520	27.98
92	5.70	2.00	0.1400	4.00	0.56	+0.15	0.41	28.39
96	5.80	1.90	0.1330	4.00	0.532	+0.10	0.432	28.82
100	5.80	1.90	0.1330	4.00	0.532	0.00	0.432	29.26
104	5.85	1.85	0.1295	4.00	0.518	+0.05	0.468	29.72
108	5.85	1.85	0.1295	4.00	0.518	+0.00	0.518	30.24
112	5.55	1.85	0.1295	4.00	0.518	0.00	0.518	30.76
110	6.00	1.70	0.1190	4.00	0.476	+0.15	0.326	31.09
120	610	1.60	0.1120	4.00	0.448	+0.10	0.348	31.43

c_s = 7.7 mg/l K_2 = 0.07 hr^{-1}

APPENDIX B

LIST OF SYMBOLS

BOD - biochemical oxygen demand, mg/l

COD - chemical oxygen demand, mg/l

C_s - dissolved oxygen saturation constant, mg/l

DO - dissolved oxygen deficit from saturation at any time, t, mg/l

C_t - dissolved oxygen at any time, t, mg/l

$\frac{dC}{dt}$ - rate of transfer of dissolved oxygen per unit time, mg/l/hr^{-1}

K_2 - reaeration rate constant, base e(hr^{-1})

$S_o gl$ - initial substrate concentration (mg/l) as glucose

$S_o COD$ - initial soluble COD, mg/l

X_o - initial biological solids concentration (suspended solids), mg/l

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

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