STUDIES ON THE EFFECTS OF EFFLUENT FROM AN EXTENDED AERATION PLANT ON ASSIMILATIVE CAPACITY OF RECEIVING STREAMS

By

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CHAPTER I

INTRODUCTION

For nearly one hundred years the removal of organic contaminants present in waste waters and the prediction of O_2 utilization in streams receiving those contaminants has been the subject of many scientific investigations. In general, if the rate of oxygen replenishment is greater than (or at least equal to) the rate of oxygen depletion by the microorganisms in the stream, the dissolved oxygen (DO) will remain at a level sufficient to maintain a healthy natural aquatic biosphere. In 1925, Streeter and Phelps developed an equation to predict the effects of these two opposing forces, i.e., reaeration and deoxygenation, upon the DO reserves in receiving streams. However, since this mathematical model requires that the deoxygenation reaction always fit first order decreasing rate kinetics, which may or may not be the case, new procedures have been devised in an attempt to predict more accurately the assimilative capacity of receiving streams.

The procedure under study, i.e., the utilization of open-stirred reactors, has been developed to simulate as closely as possible in the laboratory the conditions which occur in a natural hydrosphere polluted by an organic waste water. Since the kinetics of BOD exertion by microorganisms is a metabolic function and may not necessarily follow the laws of a monomolecular reaction, the procedure developed in the bioenvironmental laboratories at Oklahoma State University has an

advantage in that it describes O_2 utilization accurately regardless of the kinetics involved in the reactions. By monitoring the DO in both deoxygenation and recovery periods of the DO profile and combining this data with the rate of reaeration in the stream (reactors), the O_2 uptake which can be expected in the receiving stream can be predicted.

In one phase of this study, effluent from an extended aeration activated sludge pilot plant was utilized in open-stirred reactors to predict the effects of a treated waste water upon the assimilative capacity of a receiving stream. The rate of reaeration and the dilution volumes used could be varied to simulate conditions found in many small natural streams. In another phase of the study, bacterial hydrolysate, i.e., an untreated complex waste, was utilized in the open vessels to determine the BOD exertion of a raw waste. To conclude this study and to relate O_2 uptake curves produced from both BOD bottles and the open-stirred reactors, a study was made using both treated effluents and bacterial hydrolysate in simultaneous tests using the BOD test and the open-stirred vessels.

CHAPTER II

LITERATURE REVIEW

In the aqueous environment, organic and some inorganic substances serve as substrate for the heterogeneous microbial population in a stream. During the metabolic utilization of this external food source, bacteria in the stream require varing degrees of dissolved oxygen. The substrate in a waste water is stabilized by the bacteria with byproducts being carbon dioxide and water. Some of the food source is also used for the synthesis of new bacterial cells. The former requires large amounts of dissolved oxygen and releases energy, while the latter utilizes the energy released in microbial respiration, but requires no oxygen. To determine the effect of biologically treated effluents upon the oxygen resource of the hydrosphere, adequate methods must be developed to ascertain the assimilative capacity of the receiving stream.

In a stream, a delicate balance exists between the processes of deoxygenation and reaeration. Should excess pollutants be released into the water, the balance tips in favor of the deoxygenation process thus reducing the dissolved oxygen content of the stream, possibly to an ecologically dangerous level. As discussed by Gates (1), in evaluating the oxygen requirements of a waste discharge, the emphasis should not be in measuring any single event but on being able to predict its effect accurately. If the dissolved oxygen profile resulting from oxygen depletion in a natural stream can be accurately evaluated, the degree of

purification required to make optimum use of the oxygen resource of the stream can be evaluated.

Until recently, the only method available for evaluating a waste discharge was the classical Biochemical Oxygen Demand test. The conceptual principle for the test was suggested nearly 100 years ago. In 1870, Frankland (2) theorized that

> "the amount of oxygen resource required to oxidize an organic material was solely dependent upon the time of storage, and ...the gradual diminution in the amount of dissolved oxygen in a closed environment indicates exactly the process involved in the oxidation of an organic material."

In 1925, Streeter and Phelps (3) incorporated the principle of the BOD test into a mathematical model which was designed to predict the course of oxygen utilization in a naturally flowing receiving stream by observing the oxygen profile resulting from adding a waste water to the stream. This mathematical equation now known as the Oxygen Sag Equation took the form of

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

where D_a = initial DO deficit from saturation, D = deficit from saturation at time t, L_a = initial BOD of the organic matter, K_1 = deoxygenation coefficient, and K_2 = reoxygenation coefficient. Streeter and Phelps assumed that the rate of oxygen utilization by bacteria was proportional to the amount of unoxidized substrate remaining. Thus, both the deoxygenation due to organic constituents and reaeration from the atmosphere were thought to follow first order decreasing rate kinetics. Since first order decreasing rate kinetics were assumed to be obtained during the BOD test, it was concluded that their theory and equation were sufficient to predict the DO in the stream at any point below a

waste discharge. However, the applicability of such a mathematical model, developed using data from such a quiescent system as a BOD bottle to describe the reactions occurring in the dynamic environs of a naturally flowing stream, has been questioned by many workers in the area of stream pollution control engineering.

A specific limitation of the sag equation was noted by Streeter and Phelps at the beginning of their experimentation. They agreed that factors other than deoxygenation by organic substances in a waste and atmospheric reaeration contributed to the dissolved oxygen concentration of the stream. However, it was assumed that these were the major phenomena controlling the amount of molecular oxygen in the stream, and that other factors need not be considered.

In 1965, Dobbins (4) outlined the four principal factors which affect a stream's oxygen supply: 1) organic deoxygenation resulting from the microbial injestion of a waste product with concurrent oxygen utilization; 2) atmospheric reaeration which depends upon the degree of oxygen deficiency in the water; 3) oxygen depletion due to suspended benthic materials and respiration of photosynthetic plants; and 4) stream reoxygenation due to the replenishment of the dissolved oxygen in the water by phototropic plants. The interplay among these four factors determines the oxygen supply of a receiving stream and the significance of each varies from stream to stream. Since Streeter and Phelps disregarded the presence of the last two factors, their model has been the source for much controversy and investigation.

Since K_2, the reaeration coefficient, is an important parameter of any sag model, it must be estimated as accurately as possible for the receiving stream. However, the value of K_2 has, for most practical

purposes, been considered proportional to the velocity of the stream. Rivers were classified as being slow, intermediate, or fast, and the K_2 values were so proportioned. A slow-moving stream had a lower K_2 coefficient, gradually increasing as the velocity of the stream increased. Thus, it was recognized that K_2 changes from stream to stream and even between different reaches of the same stream. Turbulence also affects the rate of reaeration of a stream and assumedly the higher the velocity, the greater the turbulence. It is the physical characteristics of a stream which determine the degree of agitation or turbulence. The presence of significant amounts of organic pollutants can hamper the transfer of oxygen from the air into the aquasphere, thus decreasing the available molecular oxygen for use by the biosphere. The assimilative capacity of the stream is closely related to the rate at which the stream can renew its oxygen resource. This requires measurement of K_2 values specific for the reach of stream in question, rather than assumed values generalized from a broad category based solely upon the velocity of the stream.

A theory common to almost all mathematical descriptions of atmospheric reaeration is that it varies in proportion to the degree of agitation of the water, and inversely to the volume (or depth) of the water. It has also been determined that the rate can vary significantly with increasing concentration of pollutants. In 1938, Kehr (5) observed that domestic sewage, even in small concentrations, greatly reduced the transfer of oxygen into surface waters. Rand, et al. (6) in 1959 also came to the same conclusion with these refinements: 1) domestic sewage will depress the K_2 of water depending upon its strength and volume; 2) the K_2 of undiluted sewage is about 60 percent that of unpolluted

water; and 3) polluted streams are unlikely to contain enough domestic waste to depress the rate to less than 95 percent that of the clean water value for K_2. It was also noted that domestic waste did not appreciably affect the solubility of oxygen in the water. Compared with distilled water, the saturation constant, (C_s), varied a maximum of four percent at 30^o in a sample containing 100 percent domestic sewage. Recently, Kothandaraman (7) noted the cause for a reduction in reaeration rate due to the addition of contaminants. According to him, as pollutants enter a stream, they interfere with the even distribution of molecular oxygen throughout the oxygen-deficient liquid phase.

Factors which might affect the distribution of oxygen in many rivers were discussed by Owens, Knowles, and Clark (8). Major contributing factors cited were due to photosynthetic plants, light intensity, temperature, and the initial deficit from saturation. Their proposed equation was an attempt to explain the complex interrelationships between physical, chemical, and biological processes which affect the distribution of oxygen in streams.

The preceding review has been a short summary relative to one major component of every mathematical model used to predict the assimilative capacity of a receiving stream. However, consideration must be given to the second major component of these equations, the determination of the organic load entering the stream. The BOD test has until recently been the only procedure for measuring the "strength" of a wastewater. The use of this test has been the basis for much criticism of these models. A further review of the deoxygenation process, as measured by the BOD test, is warranted to help understand why an improved procedure is necessary to predict the oxygen requirments of a

receiving stream more accurately.

Orford (9) has outlined the most apparent difficulties involved in the BOD test. Large numbers of incubation bottles are required for each test, with several different dilutions also necessary. It is assumed that the course of biological oxidation is identical in each bottle, regardless of the dilution. However, as pointed out by Gaudy (10), biological oxidation is significantly affected by the substrate concentration; therefore, the rate and course of substrate removal will be affected by the dilutions used in the incubation bottles. Continuing along this line of reasoning, if the rates vary among the dilutions, then the rate would also vary between the BOD bottles and the stream.

It is generally understood, but sometimes ignored, that the BOD test actually measures the quantity of oxygen consumed, i.e., respiration, by the biological species of an aquatic hydrosphere rather than the amount of organic substrate contained in the sample. But all growth and substrate removal have been observed to follow, in general, autocatalytic curves; therefore, it is no surprise that O_2 uptake (exertion of BOD) also follows the same kinetic mode. Furthermore, in 1959, Busch (11) reported that O_2 uptake occurred in two phases separated by a "plateau."

Various theories have been postulated to account for the existence of the plateau (12)(13)(14)(15)(16). A general review of these theories will not be presented here, as they are adequately discussed in the literature. To summarize, however, the plateau is thought to be caused by an acclimation or "lag" period in which the predominant microbial species, be they bacteria or higher predatory organisms, switch from the utilization of the initial exogenous substrate to that of a secondary

food source. The secondary food source could be the less easily utilized substrates in the initial waste water, intermediates produced during the metabolic degradation of the initial substrate, or the endogenous respiration or predatory injestion of the biomass synthesized during the previous utilization of the available substrates, whether soluble or insoluble.

The prime purpose of the previous discussion was to emphasize that mathematical models of assimilative capacity based on first order decreasing rate kinetics--in particular, the first order utilization of the available organic material--are inadequate for the accurate prediction of the course of oxygen uptake which was, in the main, caused by the "non-first order" removal of substrates in the waste water. Thus, it is critical that a more relevant procedure be developed--one that is not kinetically rigid, but one which can be accommodated to each situation independently.

In 1961, Lordi and Heukelekian (17) experimented to determine the validity of Theriault's (18) theory that tests in open vessels are inadequate for the prediction of the course of oxygen utilization in a receiving stream. They found that by comparing results from closed reactors, quiescent open reactors, and open-stirred reactors that, while no difference occurred between the closed and open quiescent bottles, the increased stirring increased oxygen consumption.

Comparing sag curves produced from the Streeter-Phelps sag equation and those developed in open stirred reactors, Gates, et al. (1) found no agreement. Similarly, Isaacs and Gaudy (19), comparing oxygen uptake curves generated from a BOD test and using an open-stirred simulated river, found no agreement. However, if the wastes were diluted

equally and the relative concentration of initial seeding organisms were identical, the two curves more generally resembled each other.

More recently, Jennelle and Gaudy (20) compared BOD exertions from closed bottles, closed stirred BOD bottles, open-stirred reactors, and an open channel. No increase in the rate of oxygen uptake between the standard BOD bottle and the one modified by stirring was noted. At similar initial solids concentrations, the rate of oxygen utilization varied proportionally as the initial substrate concentration. Their results demonstrated that larger logarithmic rates of oxygen utilization occur in the presence of higher substrate concentrations. Since the deoxygenation portion of the sag curve and thus the measurement of the critical DO in the receiving stream are governed by the exponential rates of oxygen uptake, the direct use of the rate constant, in any sag equation which was obtained by the standard BOD dilution technique, would not result in the accurate prediction of the minimum DO in the receiving stream, caused by the addition of an organic pollutant, unless the dilution factor for the bottles was the same as that for the stream. In general, the critical DO computed using the rate from the BOD bottle would be higher than actual, because the substrate concentration in the BOD bottle was lower than the substrate concentration entering the stream.

Since the previous experiments were performed using only synthetic food sources, and more exhaustive studies were required to relate reaeration rates to BOD exertion, Peil (21) experimented using industrial wastes to substantiate previous theories on the utilization of open-stirred reactors for the prediction of oxygen utilization in a receiving stream. He also investigated the effects of reaeration rate on

oxygen uptake. By adjusting laboratory reaeration rates from high rates to low rates within the range of those expected in the various streams, he found that the laboratory procedure using open-stirred reactors resulted in the prediction of minimum DO and oxygen utilization more closely resembling the actual occurrences in a receiving stream than could be done employing the "sag" equation. It was also noted that significant increases in reaeration rate could cause concurrent increases in the amount of oxygen utilized. This latter result was in accord with the findings of Lordi and Heukelekian (17).

If one concludes that this new method of assessing the effect of a wastewater on the oxygen resource of a receiving stream may be sufficiently accurate and is potentially useful, and additional avenue of study seems advisable to prove its validity. Since all previous experimentation involved use of a "raw waste," a study of the effect of biologically treated effluents on receiving waters using the open-stirred reactors is a justifiable avenue of approach. Since extensive study had been performed at the Oklahoma State University bioenvironmental laboratories on the extended aeration modification of the activated sludge process, and since such a pilot plant is currently in operation, effluent from the pilot plant operation was the major "substrate" chosen for study in the current research.

The extended aeration process involves the total recycling of all biological material produced during the aerobic stabilization of organic matter in the waste water. The major criticism of this modification of the activated sludge process was that, over a period of time, inert biological material would increase in the process, causing a gradual increase in the biological mass in the system until some

critical concentration was reached wherein large amounts of bacteria would be swept over the weir in the effluent, causing a deleterious reduction of the oxygen reserves in the receiving stream. Even if all of the biomass could be retained, it was supposed that the system would eventually undergo biochemical failure because of the constant buildup of biologically inert sludge.

To catalyze and enhance the autodigestion of biological solids, Gaudy, Yang, and Obayashi (22) proposed the employment of a "hydrolytic assist." The new modification to the extended aeration process required that at a certain point, sludge would be withdrawn from the settling chamber, acidified, autoclaved to solubilize the insoluble biomass, thereby breaking down the macromolecules chemically. After neutralizing the solution with a base, the solubilized sludge could then be recycled as substrate to the aeration tank.

Recently, Yang and Gaudy (23) have presented results of pilot plant operation employing this new mode of operation for the control of biological solids, showing the conceptual feasibility of the process. At present, David Scott (24) is studying the hydrolytically-assisted extended aeration process using soluble organic wastes to develop the necessary engineering controls for the efficient operation of this process. The author has worked with Scott in some of the operational phases of his pilot plant studies, and it is the effluent from this pilot plant which comprises the major substrate employed in the present study.

Thus, the study herein reported represents a practical application of the approach proposed by Jennelle and Gaudy, and evaluated by Peil, to test the quality of effluent of a hydrolytically-assisted extended

aeration system. The general aim of the study was to assess the quality of effluent from the pilot plant and to gain further insight into the application of the open jar procedure for making such assessments of the effect of effluent on receiving streams.

CHAPTER III

MATERIALS AND METHODS

A. Laboratory Apparatus

The biological reactor used was a flat-bottomed cylindrical Pyrex vessel having a diameter of 8.125 inches and a depth of 18 inches. Oxygen diffusion into the reactor from the atmosphere was facilitated through the use of a mechanical stirrer. A two-inch propeller was mounted at the bottom of a vertical shaft driven by a 1/50 hp Bodine motor. The propeller was positioned about one inch from the bottom of the jar. The speed of the propeller was adjusted by a rheostat to vary the rate of reaeration. Since the solubility of oxygen in water varies with slight temperature changes, control of temperature is imperative. To maintain an essentially constant temperature, a Precision Scientific Lo-Temptrol recirculating water bath was used. The Pyrex vessels were placed into a rectangular plexiglass trough through which water of constant temperature was circulated. Figure 1 is a picture of the labaratory apparatus.

The concentration of dissolved oxygen in the reactor jars was measured by a Weston-Stack Oxygen Analyzer. To measure the dissolved oxygen, the lead-platinum probe was slowly immersed into the water, the amount of DO was recorded, and the probe removed slowly. To ensure consistent results, each measurement was taken at the same depth.

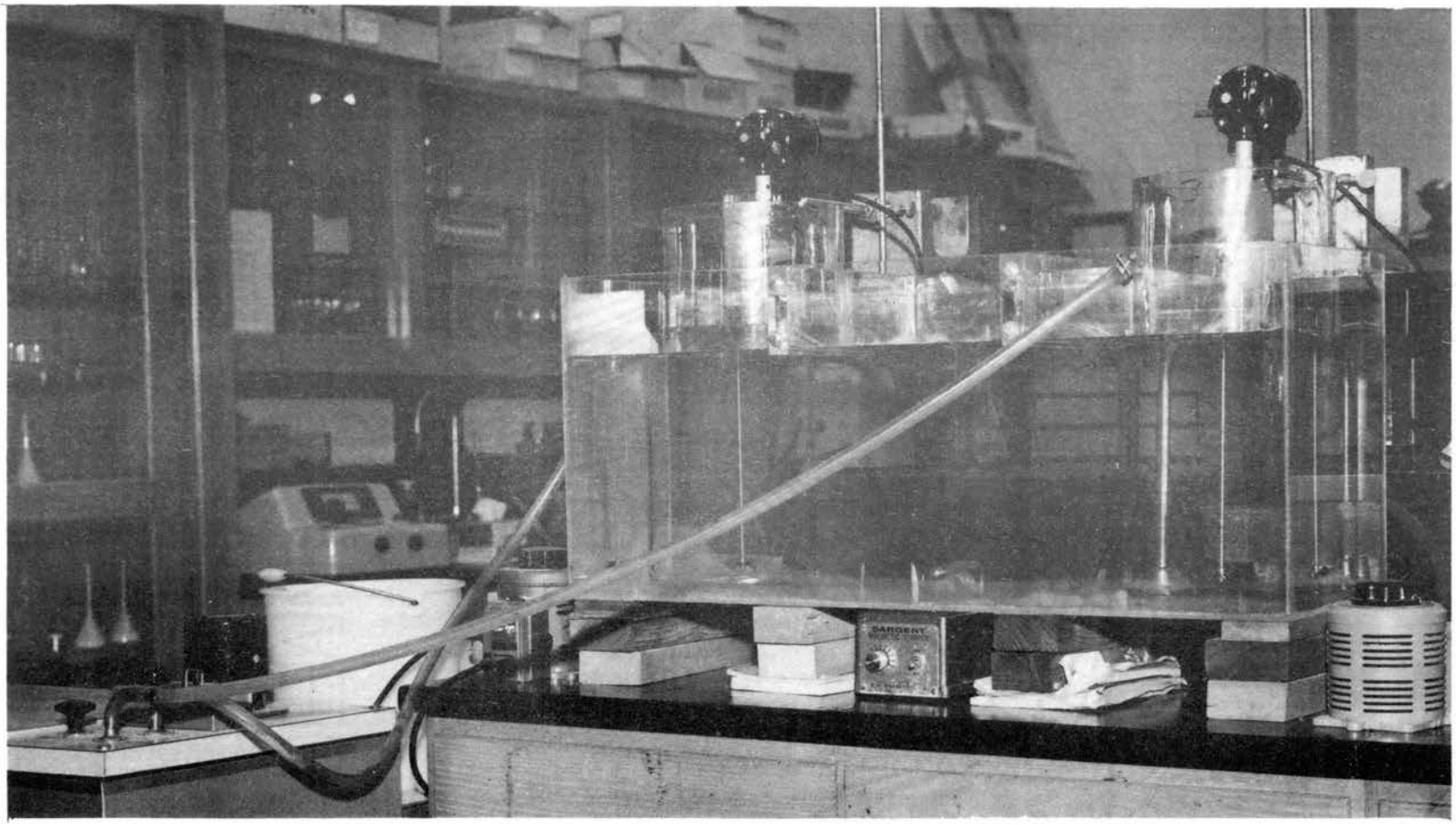


Figure 1. Photograph of Experimental Apparatus

According to manufacturer specifications, the probe will provide accurate readings for two months. Nevertheless, before each test, the probe was restandardized.

B. Experimental Procedures

Prior to each study, the Pyrex reactor vessels were cleansed thoroughly and rinsed with distilled water to remove any organic contaminants to prevent distortion of the dissolved oxygen profile in the reactor. For each test, two reactors were placed into the plexiglass trough and 10 liters of tap water were added to the Pyrex jars. Water at a specified temperature (usually $22^{o}C \pm 0.5^{o}$) was circulated through the trough from the water bath. Mechanical stirrers were placed into the reactors and the water was agitated slowly overnight to allow the water temperature to equilibrate at $22^{o}C$ and to bring the dissolved oxygen in the system to its saturation point.

To check the sensitivity of the DO probe, a 2-liter beaker was filled with water from one of the reactors and stirred slowly by means of a magnetic stirrer to maintain saturation. The probe was then immersed into the water and the DO reading was recorded. Concurrently, a 300-ml BOD bottle was also immersed slowly into the beaker and allowed to fill with water. The remaining water was returned to the reactor and its volume readjusted to 10 liters. Manganous sulfate and alkali-iodide-azide reagents were added to the BOD bottle and the actual DO was measured using the Alsterburg azide modification of the Winkler method (26). A comparison was made between the actual DO and the DO recorded from the oxygen analyzer. If a significant variation existed, the probe was immersed into the reactor and adjusted to the actual DO

through use of an adjustment screw on the analyzer. Usually, the sensitivity of the analyzer would remain stable for approximately six weeks, after which the probe was "renewed" according to the manufacturer's instructions.

Since the rate of reaeration, K_2, is an important parameter in assessing the effect of an organic waste on the receiving stream, its accurate determination is essential. The dissolved oxygen in the reactors was removed chemically by addition of sufficient amounts of sodium sulfite (0.7 grams) to remove 8.0 mg/l of oxygen with 0.02 mg/l of cobalt chloride added as the catalyst. The concentration of DO in the reactor was monitored at 15-minute intervals until no further decrease in DO was observed. For future calculations, this point was assumed as zero time for the prediction of aeration rate. Sufficient DO readings were taken over the next 24 hours to describe adequately the course of reaeration. This procedure was followed prior to each study. Since reaeration rates vary significantly from stream to stream, it is essential that effects of effluent on the assimilative capacity be studied at various reoxygenation rates, both high and low. An inherent advantage of this experimental technique is its ability to alter K_2 values by changing the stirring speeds of the impeller. Thus, K_2, in natural logarithms, has units of $hour^{-1}$.

Physical reaeration of a body of water follows first order decreasing rate kinetics. Thus the profile of DO accumulation by an oxygen-deficient stream, measured as the deficit from saturation versus time, will plot as a straight line on semi-logarithmic graph paper. The rate of reaeration is the slope of such a plot.

Upon completion of the reaeration phase of an experiment, the

stirring was suspended until the waste was added. A specific volume of water was removed from the reactor, and an equal volume of pollutant, plus buffer if necessary, was added. The mechanical stirrers were restarted and a zero time DO was taken. For each experiment, the time lapse of discontinued stirring was less than one minute. The organic content of the waste was measured as COD prior to each test. When studies were made on the extended aeration supernatant, approximately six liters of the waste were placed into the reactors. It was felt that this dilution would simulate one of the most serious situations which could exist in the receiving stream, i.e., the majority of the volume consists of the waste water. No microbial seed additions were necessary, since adequate numbers of bacteria were carried over in the effluent. Buffer also was unnecessary as the pH of the supernatant would sustain microbial growth, and the pilot plant from which the effluent was taken contained ample phosphate buffer.

When studies were made on other biologically-produced material, i.e., sludge hydrolysate, aliquots from the stock solution of sample were added to the reactor to obtain the desired concentration of organic material, measured as COD. The seeding material consisted of 0.5 percent acclimated cells (50 ml) from the effluent of the extended aeration pilot plant. Buffer was added in sufficient quantities to maintain a pH near 7.0. No mineral nutrients were necessary, because the hydrolysate contained sufficient amounts of nitrogen, phosphorus and inorganic salts to sustain bacterial growth.

Zero time for the deoxygenation portion of each experiment was established after all of the previously mentioned materials were added to the reactor and the stirring restarted. A zero time DO measurement

was recorded as in the previous experiments using effluent as substrate. The DO was monitored throughout the deoxygenation and recovery periods. The accumulated oxygen uptake curve was calculated using the reaeration rate established in the reactor and the dissolved oxygen profile resulting from the deoxygenation and recovery of oxygen after adding the waste. The procedure for calculating O_2 uptake has been discussed elsewhere (20)(21). Sample calculations are presented in the appendix of this report.

The last two experiments in this study include joint use of the BOD test and the open-stirred reactors to assess O_2 uptake of the waste. The procedure previously outlined for the open reactors was employed, and BOD-O_2 uptake curves were also calculated using the standard dilution BOD bottle technique. The substrate was prepared in a similar manner to that used in the reactors; however, they were appropriately diluted within the range of the BOD test. The BOD seed, required for hydrolysate only, consisted of 0.5 percent acclimated cells (1.5 ml) from the extended aeration plant. Prior to adding the above constituents to the BOD bottles, the tap water was aerated with compressed air to saturation. Also to the BOD bottles were added buffer compounds in the same concentration as those added to the reactor jars, if the additions were necessary. It is important to note that the concentration of organic material added to the reaction vessels and the degree of agitation were the only differences between the open-stirred reactors and the BOD bottles.

After adding the substrate, seed and buffer (if necessary) to the BOD bottles, the dilution water was siphoned slowly into the bottles and then tightly stoppered. The BOD bottles were incubated at 22^{o}C,

the same temperature at which the open reactors were operated. Periodically, the bottles were removed and analyzed for dissolved oxygen, and the subsequent BOD by the standard bottle technique.

C. Biological Materials

1. Effluent. The effluent under consideration consisted of unfiltered supernatant from a laboratory bench scale model of an extended aeration activated sludge treatment facility.

2. Hydrolysate. The hydrolysate was prepared from an extended aeration "sludge." At various times, 900 ml of settled solids were removed from the pilot plant, acidified to pH 1 by addition of concentrated H_2SO_4, autoclaved for five hours at 15 psig, and then neutralized to pH 7 by addition of saturated NaOH.

D. Analytical Procedures

1. Dissolved Oxygen. The dissolved oxygen concentration was monitored electrically by use of a Weston-Stack Oxygen Analyzer, and standardized periodically by using the Winkler Method discussed in Standard Methods (26).

2. Chemical Oxygen Demand. The COD test procedure is discussed in Standard Methods (26) for 20 ml volume samples.

CHAPTER IV

RESULTS

The results are not necessarily presented in chronological order. They are, however, divided into four distinct categories; tests on effluent using a high reaeration rate, tests on effluent using a lower reaeration rate, tests using hydrolysate produced from the settled solids in the pilot plant, and tests comparing the BOD exertion in BOD bottles and open-stirred reactors.

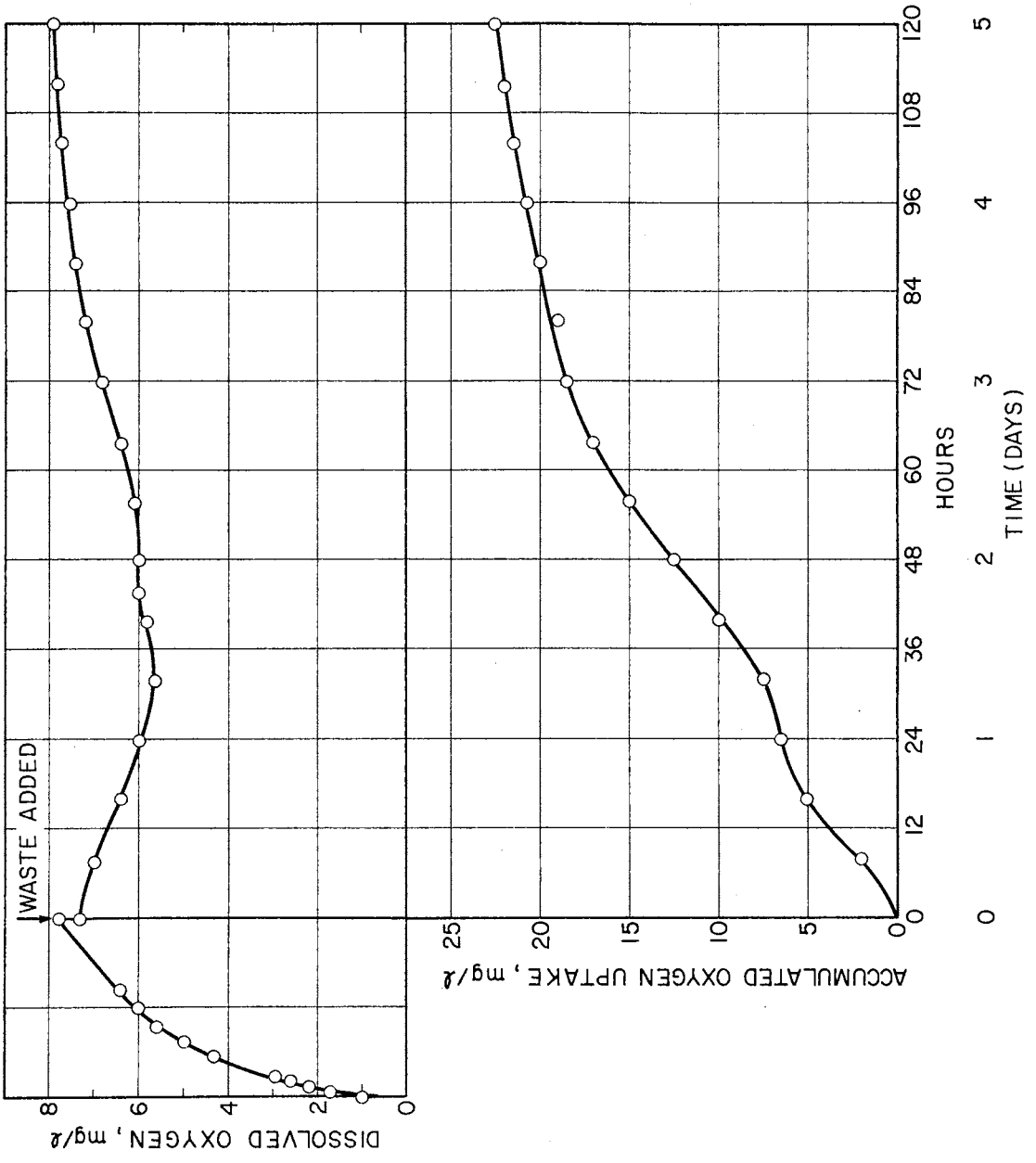
Shown in Figure 2 is one complete test using the open-stirred jar technique. During the first 24 hours, the dissolved oxygen previously removed chemically by addition of sodium sulfite and cobalt chloride, monitored to determine the rate of atmospheric reaeration, K_2. This DO profile of reoxygenation corresponded to a K_2 of 0.099 hr^{-1}. After the preparatory phase, substrate was added in a 50/50 ratio with tap water, and the DO was measured during both the deoxygenation and recovery phases. In this experiment, effluent from days 239-240 of pilot plant operation contained 43 mg/l of soluble organic material, 54 mg/l of biological solids, and a total organic content of 130 mg/l measured as COD. After dilution in the open reactors, soluble COD was 22 mg/l. COD and the suspended solids content was 27 mg/l. The initial depression of oxygen from 7.6 to 7.3 was due to the large dilution factor involved and the fact that the effluent remained in a collection basin for approximately 24 hours prior to addition to the reactors while the volume

Figure 2. Representative DO Profile and O_2 Uptake Curve for Open-stirred Reactors Including Initial Reaeration Phase Prior to Addition of Waste Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 239-240 (May 18-19, 1972)
Total Supernatant COD (Se) = 130 mg/l
Biological Solids (Xe) = 58 mg/l
Filtrate COD (S_f) 43 mg/l

Dilution Ratio = 50/50

$K_2 = 0.099\ hr^{-1}$ Temp. = 22^oC


DISSOLVED OXYGEN, mg/ℓ
WASTE ADDED
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
HOURS
TIME (DAYS)

necessary to run the test accumulated from the extended aeration pilot plant. This curve shows a slow decrease in DO with an accompanying slow recovery period. The bottom of the sag curve was rounded, as was the case in the majority of the runs using effluent containing sufficient organic matter to produce a discernible sag. The corresponding O_2 uptake curve indicates that a total of 22.5 mg/l of oxygen was required by the microorganisms after five days. In this figure there is evidence for the "plateau" in the BOD exertion curve corresponding closely to the low point in the DO profile curve. For the remaining experiments, the reaeration period prior to introducing the pollutant will not be shown.

A. Studies on the Effects of Effluent on Receiving Streams with a High Rate of Reaeration

The following four experiments were performed to provide a better understanding of the effects of varying substrate concentrations and varying concentration of bacterial seed escaping an extended aeration treatment facility on receiving streams with relatively high reaeration rates.

The DO profile and accumulated O_2 uptake from an effluent collected on days 250-251 of pilot plant operation is shown in Figure 3. The open-stirred reactors were polluted with 60 percent effluent and 40 percent pure (tap) water. This 60/40 dilution ratio was used in the reactors for each of the following experiments using effluent. The effluent contained 81 mg/l total COD with 45 mg/l soluble COD and 12 mg/l suspended solids. After dilution, the substrate COD was 27 mg/l and the solids concentration was 7 mg/l. Jar 1, stirred to produce a

a K_2 of 0.120 hr^{-1}, showed an oxygen increase for 28 hours before a slight sag occurred. Jar 2, with a K_2 value of 0.091 hr^{-1}, produced a similar increase for 36 hours before deoxygenation was noticed. The O_2 utilization in Jar 2 was relatively constant for the 5-day test. After 120 hours of operation the accumulated O_2 uptake for Jar 1 was 14.5 mg/l, and for Jar 2, 11.75 mg/l.

The results of an experiment using effluent from days 262-263 are shown in Figure 4. The effluent from the pilot plant had 40 mg/l of total COD containing 6 mg/l of bacterial solids and 25 mg/l soluble COD. Using a 60/40 dilution ratio, effluent to tap water, the soluble COD in the reactors was 15 mg/l, and the solids concentration was 10 mg/l. In reactor 1 with a K_2 of 0.120 hr^{-1} there was no sag for 120 hours. Jar 2, with a K_2 of 0.094 hr^{-1}, began a slow deoxygenation phase after 24 hours, followed by a slow but continuous recovery of oxygen until termination of the experiment. The O_2 uptake curves for each reactor followed first order-like kinetics with a slowly decreasing rate over the test period. The final O_2 uptake in Jar 1 was 17.0 mg/l, while in Jar 2, 15.0 mg/l of oxygen was utilized.

The substrate used in Figure 5 was pilot plant effluent from days 282-283. The two reactors were aerated to produce K_2's of 0.108 hr-1 and 0.086 hr^{-1} in jars containing 55 mg/l of total COD with 38 mg/l of suspended solids and 30 mg/l of soluble COD. After a 60/40 dilution, the reactors contained 18 mg/l of soluble organic material and 24 mg/l biological solids. After 50 hours of operation, a secondary sag occurred in each reactor, while yielding a slight increase in the rate of oxygen utilization during the deoxygenation portion of the sag. After five days, Jar 1 with the higher rate of reaeration had an O_2 uptake of

Figure 3. DO Profile and O_2 Uptake Curves for an Effluent with High S_e, Low X_e, and High K_2

Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 250-251 (May 29-30, 1972)
Total Supernatant COD (Se) = 81 mg/l
Biological Solids (Xe) = 12 mg/l
Filtrate COD (S_f) = 45 mg/l

Dilution Ratio = 60/40

○ = Jar 1, K_2 = 0.120 hr^{-1}

□ = Jar 2, K_2 = 0.091 hr^{-1} Temp. = 22°C

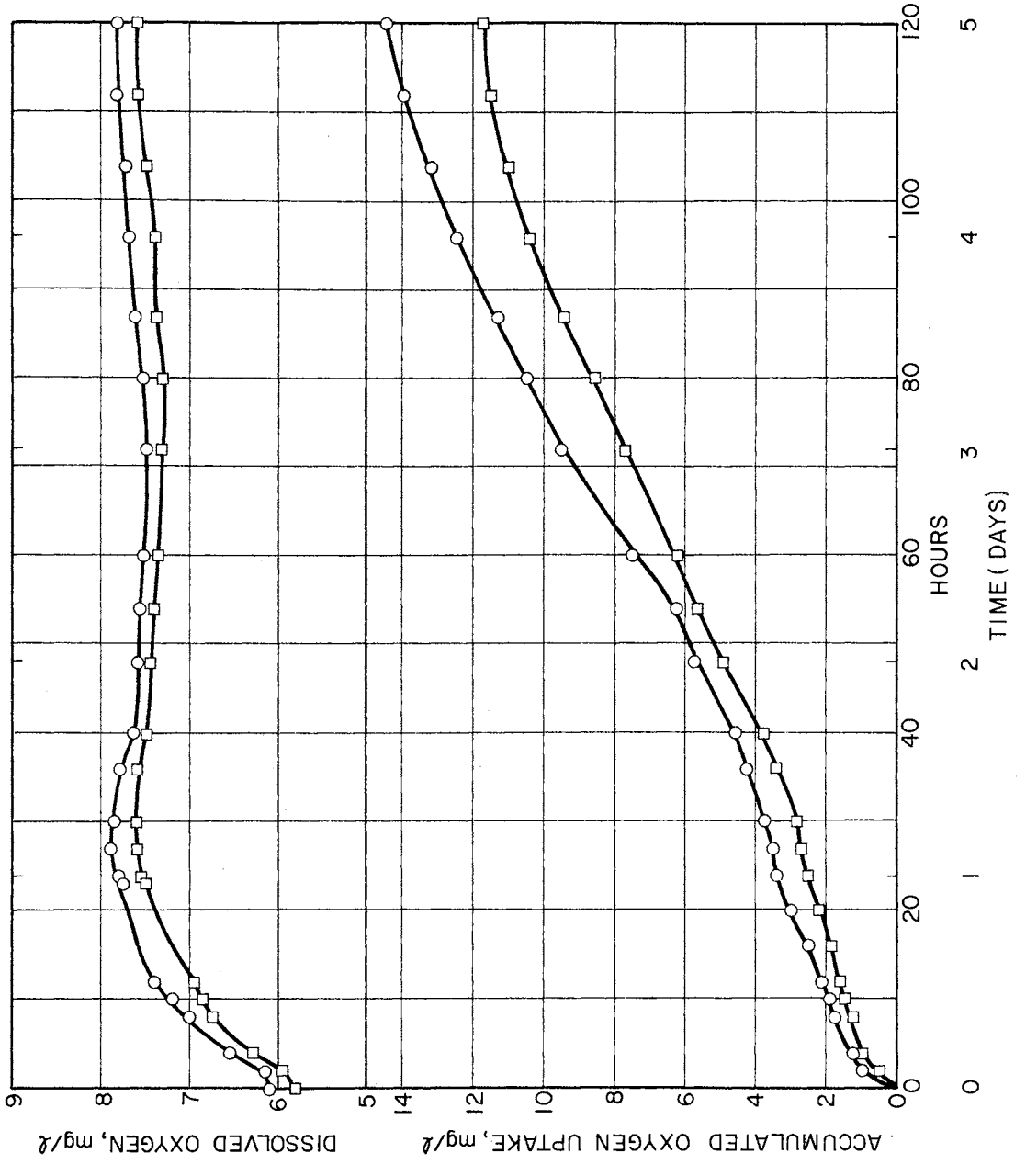

DISSOLVED OXYGEN, mg/ℓ
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
HOURS
TIME (DAYS)

Figure 4. DO Profile and O_2 Uptake Curves for an Effluent with Medium S_e, Low X_e, and High K_2

Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 262-263 (June 10-11, 1972)
Total Supernatant COD (Se) = 40 mg/l
Biological Solids (Xe) = 15 mg/l
Filtrate COD (S_f) = 25 mg/l

Dilution Ratio - 60/40

○ = Jar 1, K_2 = 0.120 hr^{-1}

□ = Jar 2, K_2 = 0.094 hr^{-1} Temp. = 22°C

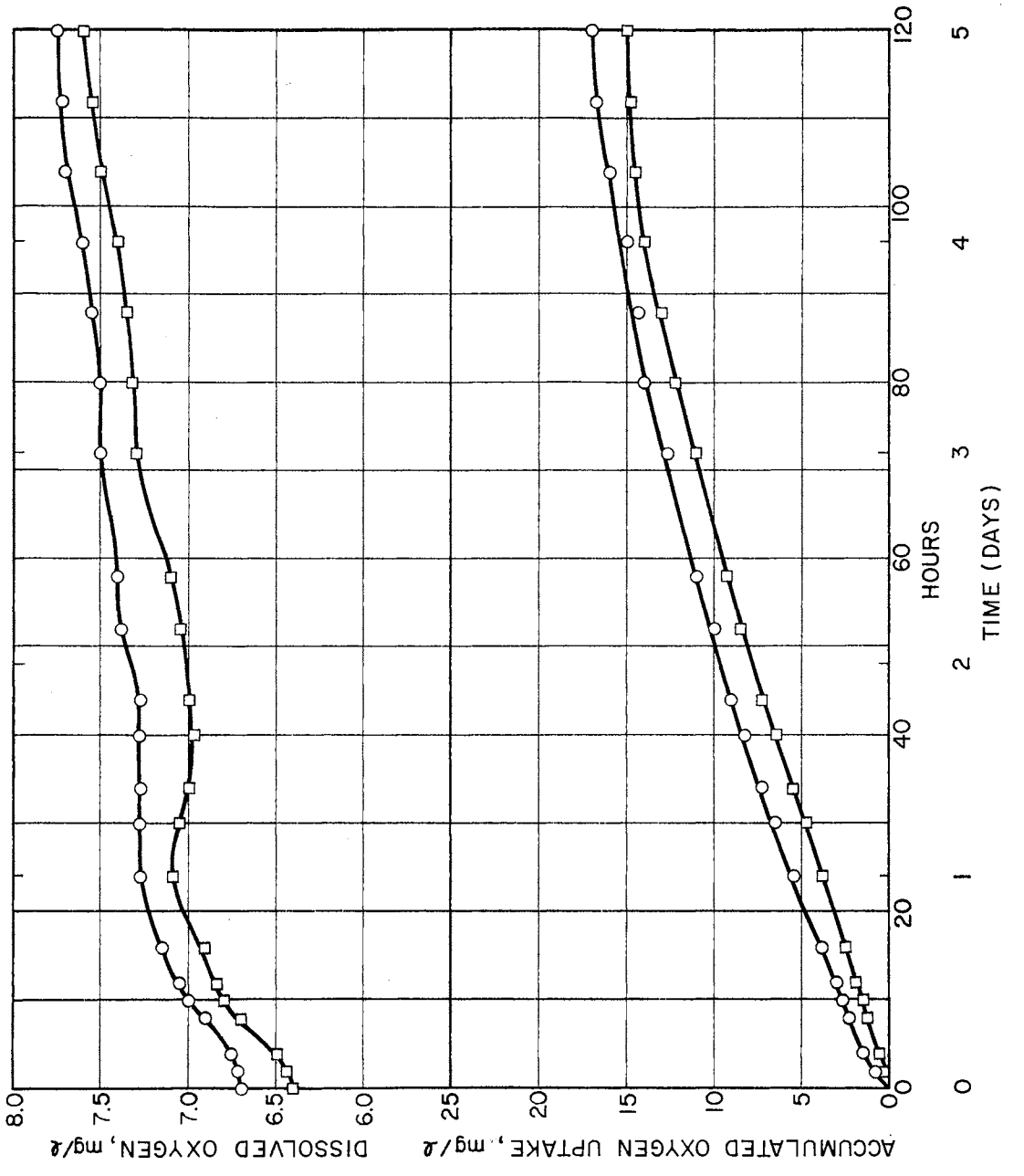

DISSOLVED OXYGEN, mg/ℓ
8.0
7.5
7.0
6.5
6.0
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
25
20
15
10
5
0
0
20
40
60
80
100
120
HOURS
0
1
2
3
4
5
TIME (DAYS)

Figure 5. DO Profile and O_2 Uptake Curves for an Effluent with Medium S_e, Medium X_e, and High K_2

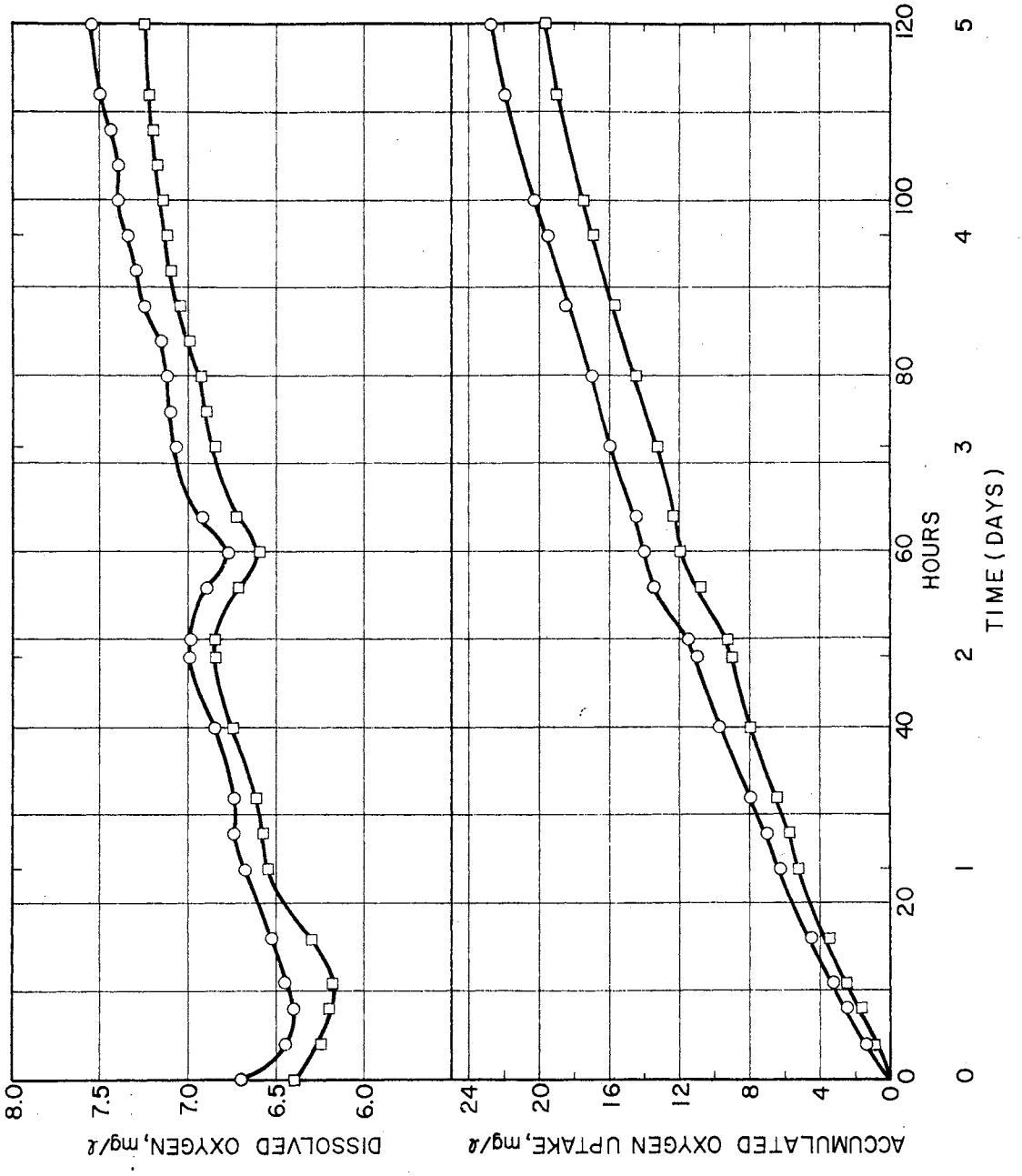
Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 282-283 (June 29-30, 1972)
Total Supernatant COD (Se) = 55 mg/l
Biological Solids (Xe) = 38 mg/l
Filtrate COD (S_f) = 30 mg/l

Dilution Ratio = 60/40

O = Jar 1, K_2 = 0.108 hr^{-1}

□ = Jar 2, K_2 = 0.086 hr^{-1}


DISSOLVED OXYGEN, mg/ℓ
8.0
7.5
7.0
6.5
6.0
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
24
20
16
12
8
4
0
0
20
40
60
80
100
120
HOURS
0
1
2
3
4
5
TIME (DAYS)

22.4 mg/l, while in Jar 2, 19.8 mg/l of oxygen were utilized.

In Figure 6, an effluent substrate concentration of 20 mg/l with solids concentration of 8 mg/l and a total COD of 35 mg/l was added to the reactors. The substrate concentration and solids content of the reactors after 60/40 dilution were 12 mg/l and 5 mg/l, respectively. The effluent was obtained from the pilot plant on days 340-341 of operation. Jar 1 with the higher rate of reaeration, 0.120 hr^{-1}, produced a small sag from hours 32 to 48, followed by a steady increase of O_2 in the system. Jar 2, with a K_2 of 0.092 hr^{-1}, showed no signs of oxygen reduction; however, the DO profile did remain essentially constant over a 32-hour period, indicating an increased utilization of oxygen by the microbial population in the reactor. Consistent with the oxygen profile, the O_2 uptake in Jar 1 exhibited a slightly increased rate between the 40th and 48th hour of operation. Similarly, the BOD exertion in Jar 2 showed a slight increase in rate between hours 52 and 60. However, the increased rates of oxygen utilization were not sufficient to alter significantly the final accumulated O_2 uptake in either reactor. For Jar 1, the O_2 uptake was 15.2 mg/l, while that for Jar 2 was 13.5 mg/l.

B. Studies on the Effects of Effluent on Receiving Streams with Lower Reaeration Rates

As in the previous experiments, the next four studies demonstrate the possible effect of varying qualities of effluent upon a receiving stream. However, the rate of reaeration was reduced to simulate a stream with a low degree of turbulence, thus generating a low K_2.

In Figure 7 it is seen that the DO profiles in each reactor were

Figure 6. DO Profile and O_2 Uptake Curves for an Effluent with Low S_e, Low X_e, and High K_2

Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 340-341 (Aug. 27-28, 1972)
Total Supernatant COD (Se) = 35 mg/l
Biological Solids (Xe) = 8 mg/l
Filtrate COD (S_f) = 20 mg/l

Dilution Ratio = 60/40

○ = Jar 1, K_2 = 0.120 hr^{-1}

□ = Jar 2, K_2 = 0.092 hr^{-1} Temp. 22°C

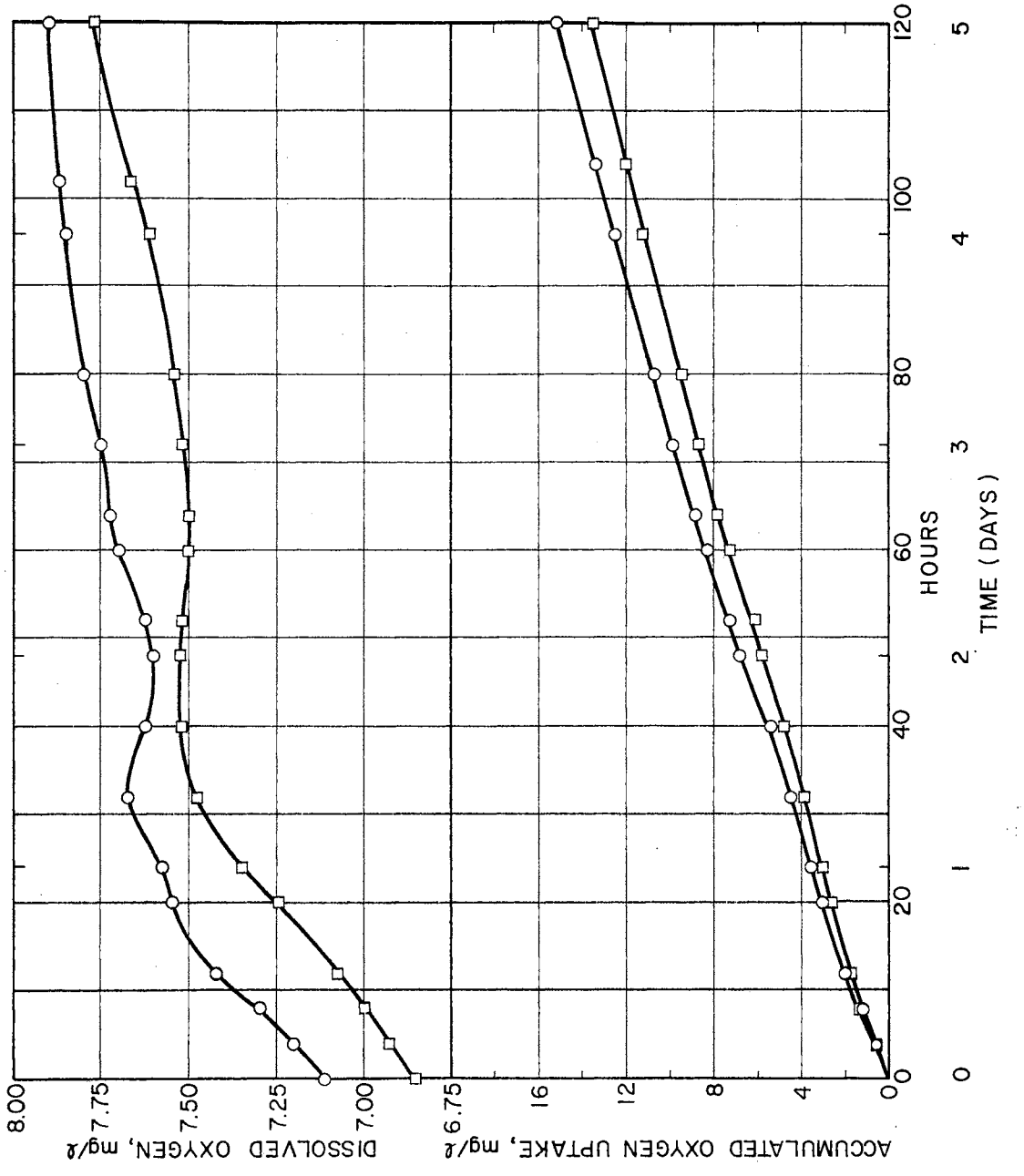

DISSOLVED OXYGEN, mg/ℓ
8.00
7.75
7.50
7.25
7.00
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
6.75
16
12
8
4
0
0
20
40
60
80
100
120
HOURS
0
1
2
3
4
5
TIME (DAYS)

Figure 7. DO Profile and O_2 Uptake Curves for an Effluent with Low S_e, Low X_e, and Low K_2

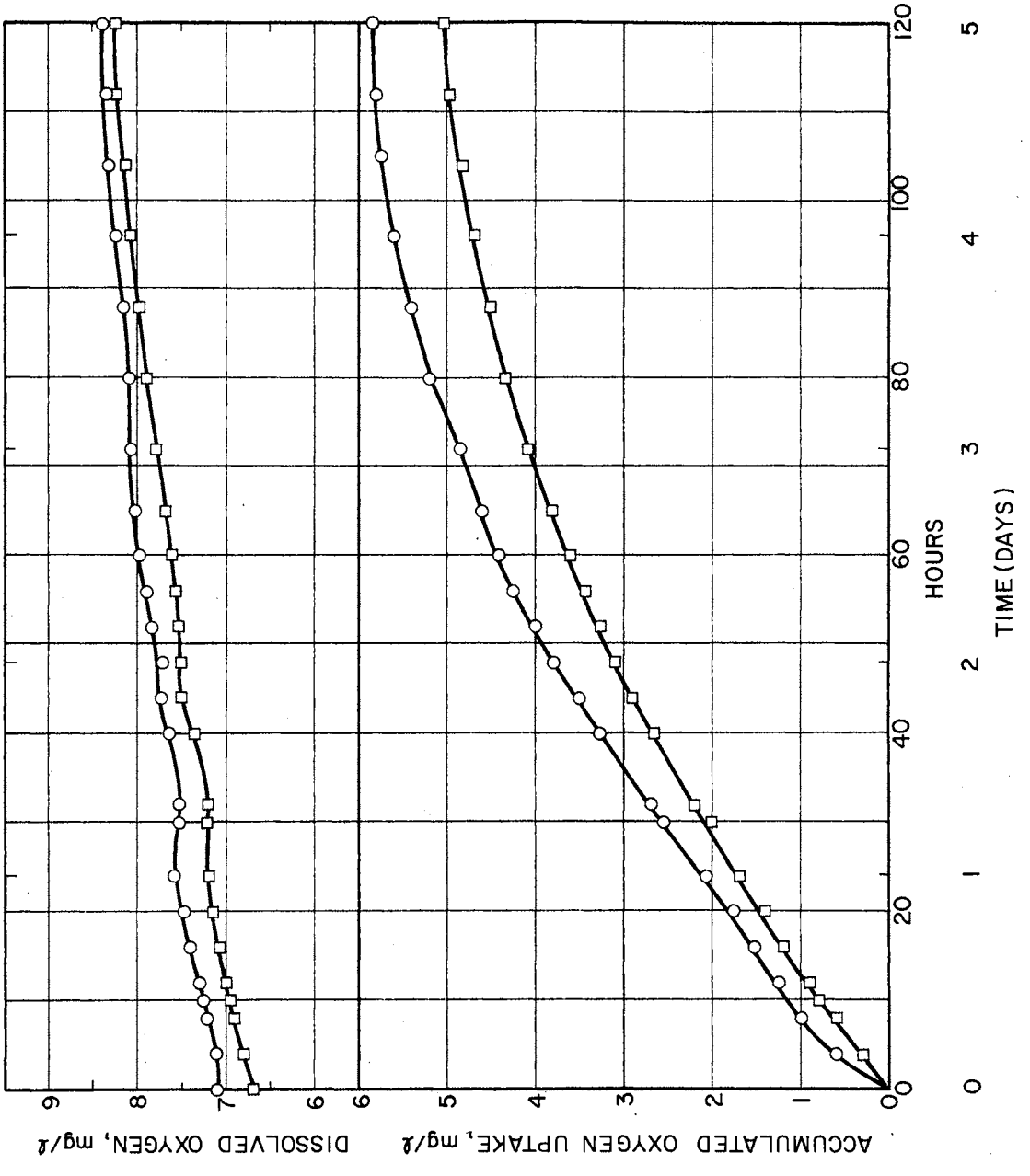
Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 372-373 (Sept. 28-29, 1972)
Total Supernatant COD (Se) = 26 mg/l
Biological Solids (Xe) = 16 mg/l
Filtrate COD (S_f) = 10 mg/l

Dilution Ratio = 60/40

O = Jar 1, K_2 = 0.070 hr^{-1}

□ = Jar 2, K_2 = 0.050 hr^{-1}


ACCUMULATED OXYGEN UPTAKE, mg/ℓ
DISSOLVED OXYGEN, mg/ℓ
HOURS
TIME (DAYS)
0
20
40
60
80
100
120
1
2
3
4
5

essentially the same. The rate of reaeration in Jar 1 was 0.070 hr^{-1}, compared to a K_2 in Jar 2 of 0.050 hr^{-1}. After 60 hours of operation, the microorganisms in the reactors began to settle to the bottom. This may account for the low total amount of O_2 utilized by the microorganisms in this experiment, and the progressively lower rate of O_2 uptake. At the end of the experiment, the majority of the microbes in the reactor were protozoa. After 120 hours, the microorganisms had utilized 5.9 mg/l of oxygen in Jar 1, and 5.1 mg/l in Jar 2. The effluent from days 372-373 of pilot plant operation contained 26 mg/l of total COD with 10 mg/l of soluble substrate and 16 mg/l biological solids. Using a 60/40 dilution ratio, each reactor contained a soluble COD concentration of 6 mg/l with 11 mg/l of suspended solids.

The dissolved oxygen curves in Figure 8 were dissimilar throughout most of the experiment. The effluent from days 357-358 containing a total organic content of 55 mg/l COD with soluble substrate of 20 mg/l COD and 30 mg/l of suspended solids. After 60/40 dilution ratio, effluent to tap water, the vessels contained 12 mg/l of soluble COD and 18 mg/l of suspended matter. The K_2s were 0.070 hr^{-1} and 0.055 hr^{-1} in Jar 1 and Jar 2, respectively. The DO profile produced in Jar 1 showed a rapid oxygen increase, and later, during the second and third days, a deoxygenation phase of 30 hours' duration, followed by a slow recovery period until termination of the experiment. The corresponding O_2 uptake curve showed an increased rate during the deoxygenation portion of the DO profile. The final O_2 uptake was 14.0 mg/l. By contrast, the effluent in Jar 2 with the lower rate of reoxygenation produced two distinct depressions in the DO profile curve, each of approximately 12 hours duration. The resultant O_2 uptake curve produced two separate

Figure 8. DO Profile and O_2 Uptake Curves for an Effluent with Medium S_e, Low X_e, and Low K_2

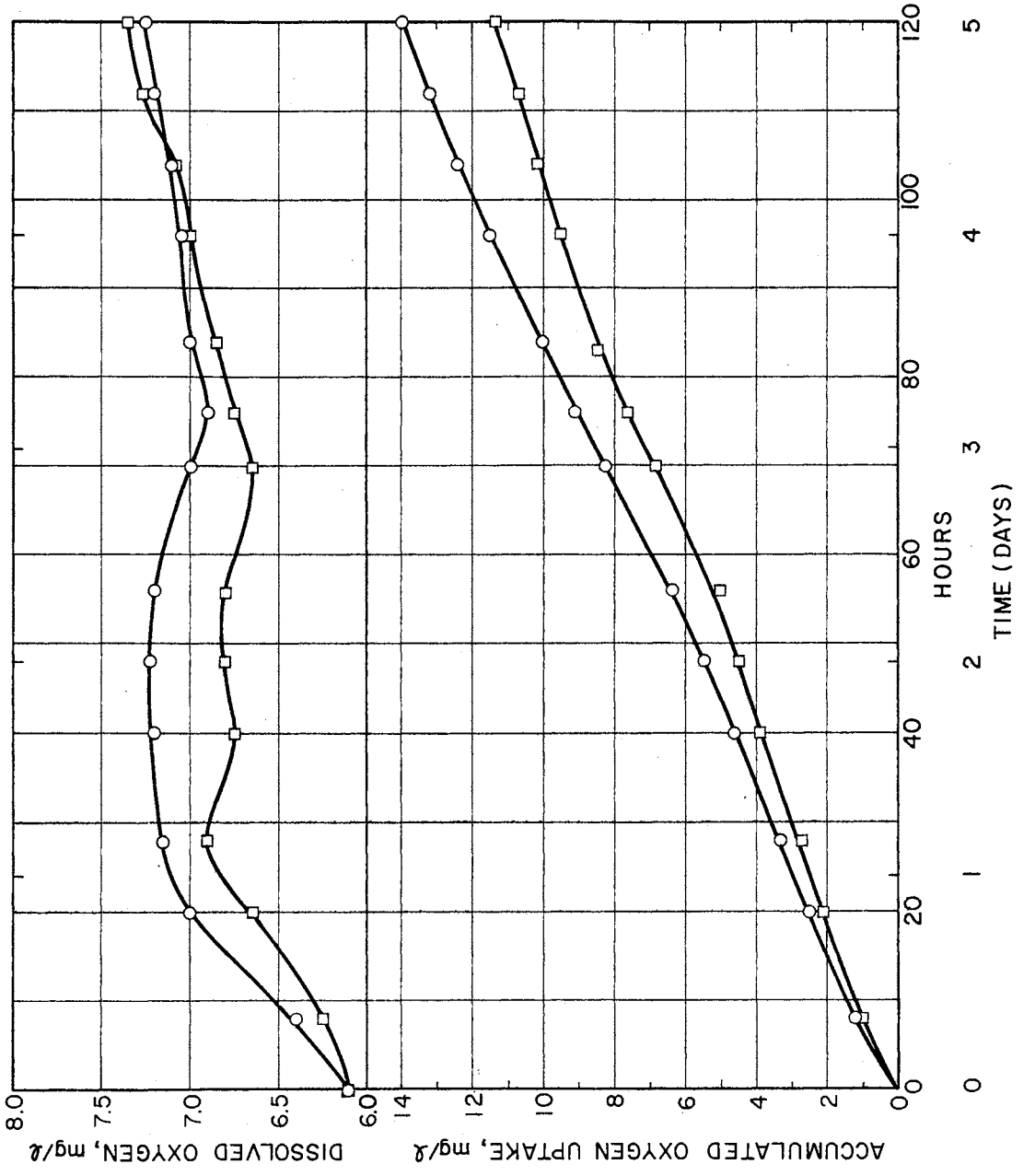
Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 357-358 (Sept. 13-14, 1972)
Supernatant COD (Se) = 55 mg/l
Biological Solids (Xe) = 30 mg/l
Filtrate COD (S_f) = 20 mg/l

Dilution Ratio = 60/40

O = Jar 1, K_2 = 0.070 hr^{-1}

□ = Jar 2, K_2 = 0.055 hr^{-1} Temp. = 22°C


DISSOLVED OXYGEN, mg/ℓ
8.0
7.5
7.0
6.5
6.0
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
HOURS
0
1
2
3
4
5
TIME (DAYS)

phases with an accelerated rate of O_2 utilization corresponding to the deoxygenation phases of the DO profile. The O_2 uptake after five days was 11.3 mg/l.

The DO profiles in Figure 9 were also dissimilar. Jar 1 was stirred to produce a K_2 of 0.075 hr^{-1}, while the K_2 in Jar 2 was 0.050 hr^{-1}. Effluent from the pilot plant on days 398-399 was used in this experiment. The COD of the supernatant was 80 mg/l containing 35 mg/l soluble COD and 26 mg/l of suspended cells. Using a dilution ratio of 60/40, the reactors contained 21 mg/l COD of filtrate and 16 mg/l solids. The reactor with the greater rate of reaeration produced one sag phase of eight hours' duration, followed by a steady increase in the DO content. The O_2 uptake curve followed essentially first order-like decreasing rate kinetics for the entire experiment with a final utilization of O_2 of 14.2 mg/l. The DO profile in the reactor using a lower K_2 was sinusoidal in nature. It was thought that the oscillating nature of the curve could have been due to "failure" of the probe; however, a check proved that the probe had lost none of its original sensitivity. The O_2 uptake curve also exhibited first order-like decreasing rate with an ultimate oxygen utilization of 10.75 mg/l.

Effluent from days 332-333 used in the study shown in Figure 10 contained a total amount of organic material of 95 mg/l COD with 25 mg/l of soluble COD and 65 mg/l of biological solids. Using a 60/40 dilution ratio, the reactors contained 15 mg/l soluble COD and 39 mg/l of suspended solids. Jar 1 with a K_2 of 0.080 hr^{-1} showed a higher rate of oxygen recovery than Jar 2 with a K_2 of 0.053 hr^{-1}. Evidence of the more or less "classical" type of deoxygenation and reaeration sag curve (i.e., according to the Streeter-Phelps equation) was found in Jar 1.

Figure 9. DO Profile and O_2 Uptake Curves for an Effluent with Medium S_e, Low X_e, and Low K_2

Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 398-399 (Oct. 24-25, 1972)
Total Supernatant COD (Se) = 80 mg/l
Biological Solids (Xe) = 26 mg/l
Filtrate COD (S_f) = 35 mg/l

Dilution Ratio = 60/40

O = Jar 1, K_2 = 0.075 hr^{-1}

□ = Jar 2, K_2 = 0.050 hr^{-1} Temp. = 22°C

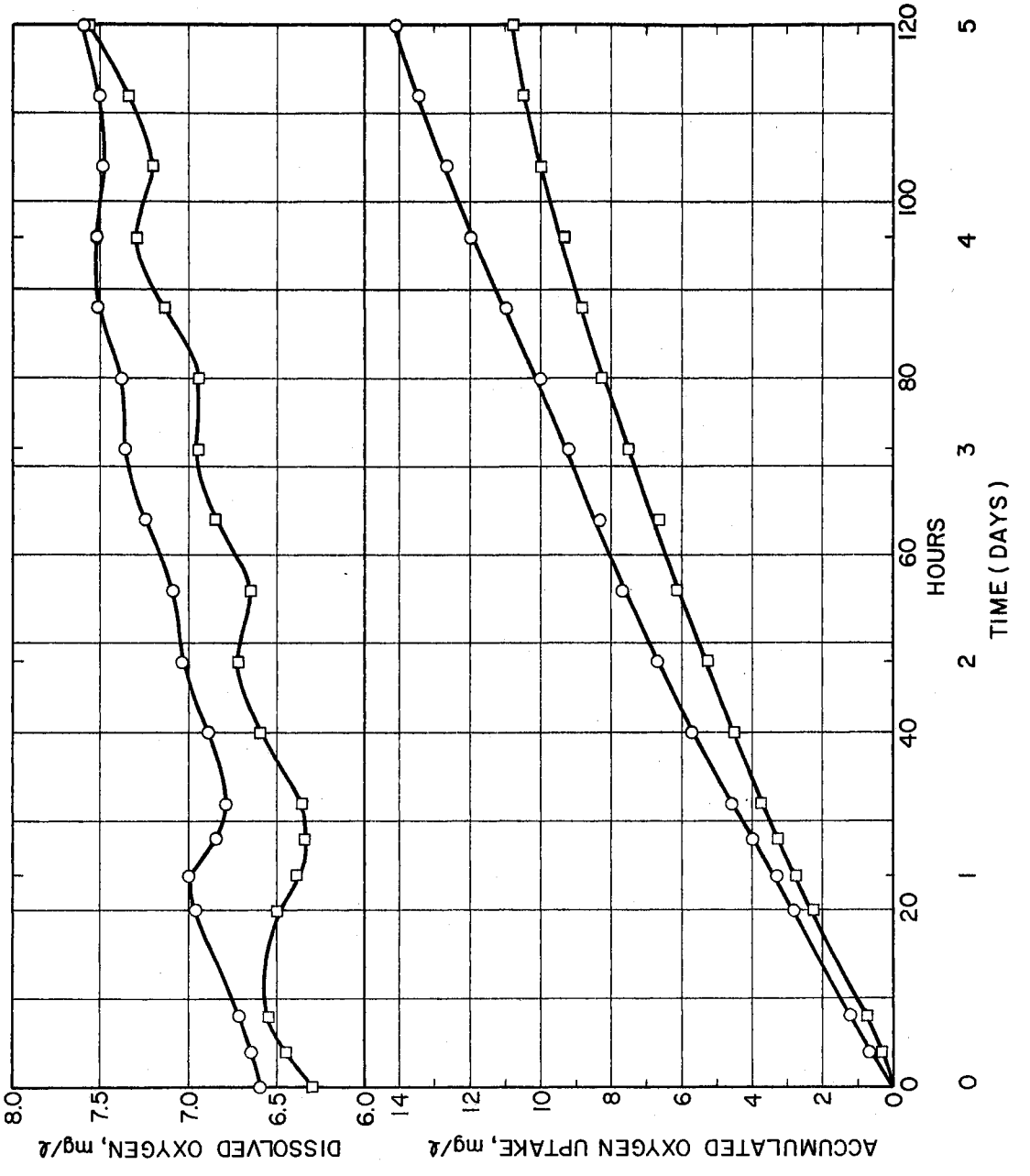

DISSOLVED OXYGEN, mg/ℓ
8.0
7.5
7.0
6.5
6.0
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
HOURS
0
1
2
3
4
5
TIME (DAYS)

Figure 10. DO Profile and O_2 Uptake Curves for an Effluent with High S_e, Low X_e^2, and Low K_2

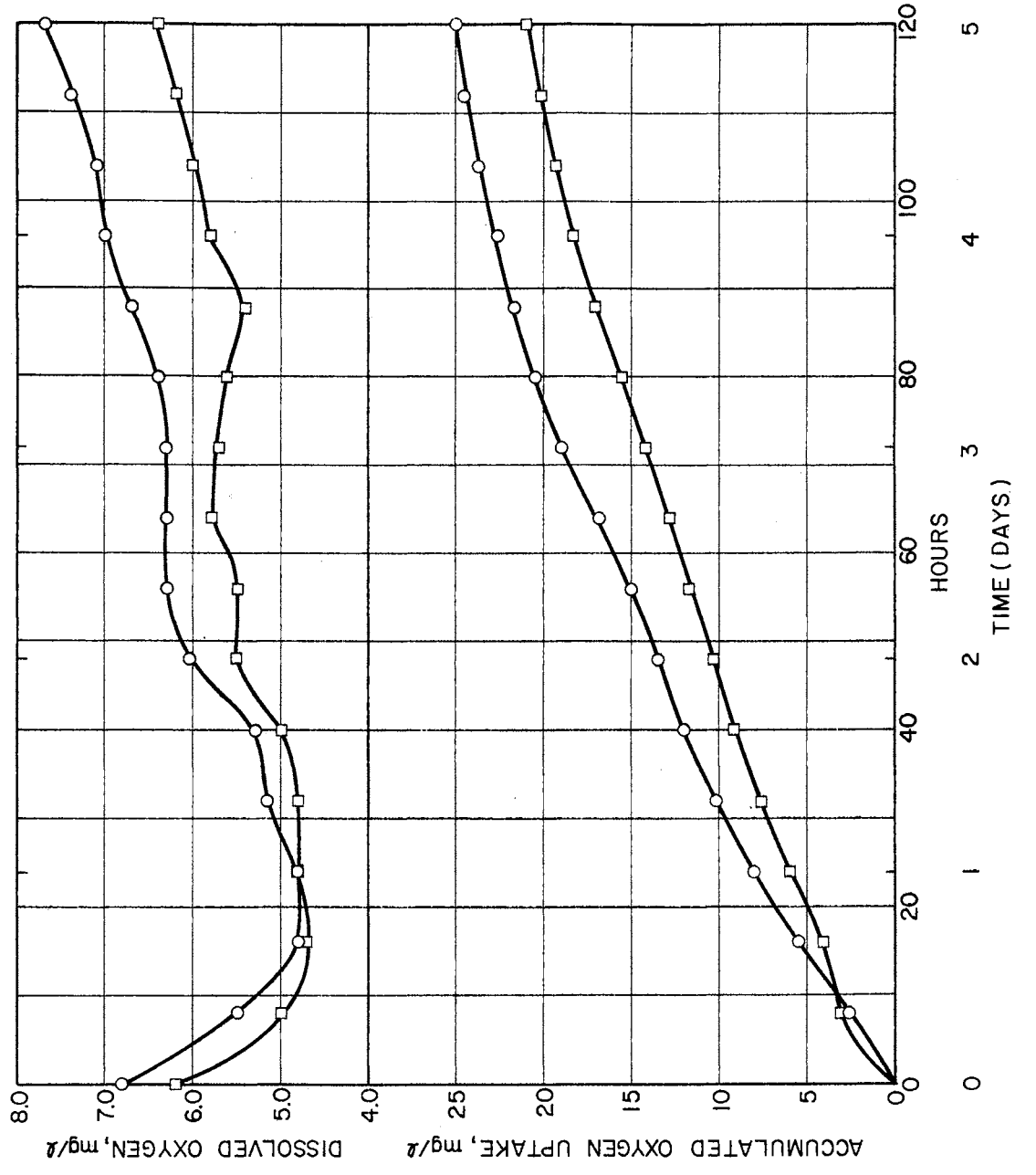
Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 332-333 (Aug. 19-20, 1972)
Total Supernatant COD (Se) = 95 mg/l
Biological Solids (Xe) = 25 mg/l
Filtrate COD (S_f) = 65 mg/l

Dilution Ratio = 60/40

O = Jar 1, K_2 = 0.080 hr^{-1}

□ = Jar 2, K_2 = 0.053 hr^{-1} Temp. = 22°C


DISSOLVED OXYGEN, mg/ℓ
8.0
7.0
6.0
5.0
4.0
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
25
20
15
10
5
0
0
20
40
60
80
100
120
HOURS
0
1
2
3
4
5
TIME (DAYS)

Jar 2, however, produced a DO profile with varying periods of oxygenation and deoxygenation. The rate of O_2 utilization in Jar 2 with a low K_2 was higher than in Jar 1 with a higher K_2 for the first 10 hours of the experiment. However, the rate in Jar 1 increased over Jar 2 for the remainder of the test. Both followed first order-like decreasing rate kinetics. The final O_2 uptake in Jar 1 was 25.2 mg/l compared with that for Jar 2 of 21.0 mg/l.

C. Studies to Determine the Mode of Bacterial O_2 Uptake Using Hydrolysate from an Extended Aeration Pilot Plant as Substrate

Two experiments were run using the hydrolysate obtained from cells taken from the pilot plant on day 369 of operation. In each experiment an acclimated seed was taken from the settling tank of the pilot plant, and adequate phosphate buffer was added to maintain the pH near 7.0. The hydrolysate had an undiluted COD of 6400 mg/l, and was appropriately diluted for each experiment.

Results from an open-stirred reactor study on hydrolysate containing initially 75 mg/l of organic material (COD) with 0.5 percent by volume of acclimated cells are shown in Figure 11. Using reaeration rates of 0.120 hr^{-1} and 0.088 hr^{-1} in Jar 1 and Jar 2, respectively, each DO profile curve showed two separate sag phases. In Jar 1, the minimum DO of the first sag was 2.4 mg/l, while the second sag was much less severe, producing a low point of 5.4 mg/l. The resultant O_2 uptake curve was of the "autocatalytic" type with distinct phases of increasing rate corresponding to the deoxygenation portions of the DO profile. The final O_2 uptake was 36.5 mg/l. In Jar 2, the first sag produced a minimum DO of 0.2 mg/l, while the second had a low point of 3.45 mg/l.

Figure 11. DO Profile and O_2 Uptake Curves for Open Reactors with 75 mg/l of Hydrolysate

Substrate Characteristics:

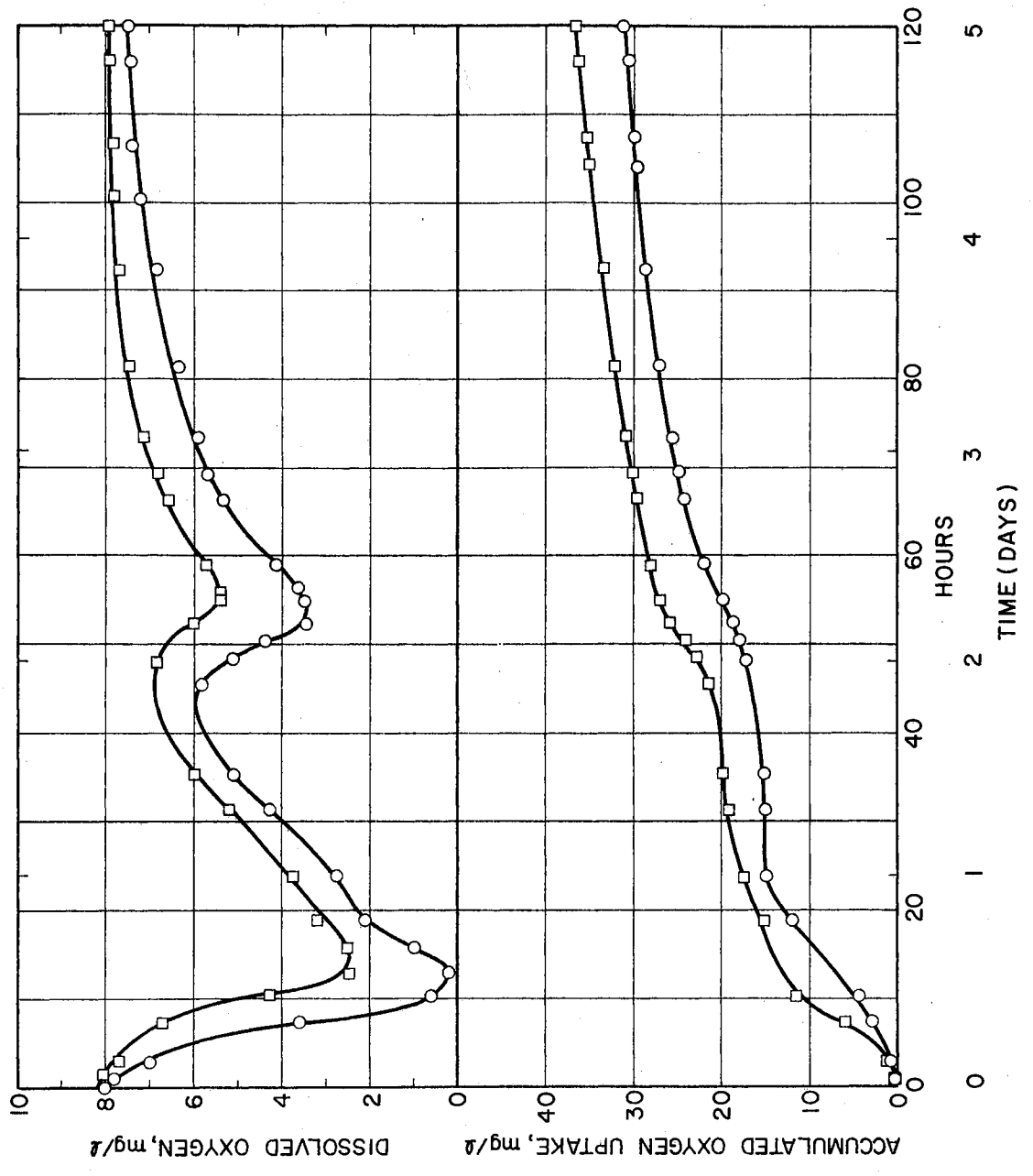
Hydrolysate from Extended Aeration Unit
Day of Operation, 369 (Sept. 25, 1972)
Total COD = 6400 mg/l
Seed = Extended Aeration Effluent

Conditions in Open Reactors:

Total COD = 75 mg/l
Seeding Volume = 50 mg/l

○ = Jar 1, $K_2 = 0.120\ hr^{-1}$

□ = Jar 2, $K_2 = 0.088\ hr^{-1}$ Temp. = $22^{o}C$


DISSOLVED OXYGEN, mg/ℓ
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
HOURS
TIME (DAYS)

Both reaeration rates produced smooth, V-shaped, diphasic DO profile curves. As in Jar 1, the O_2 uptake curve showed "autocatalytic"-like effects. The final O_2 uptake was 31.3 mg/l.

The concentration of hydrolysate added to the reactors for the experiment shown in Figure 12 was reduced to 50 mg/l. The seed concentration added remained at 0.5 percent by volume of acclimated cells from the pilot plant. The deoxygenation produced at this level of substrate addition was less than that observed in the previous experiment. The rates of reaeration were unchanged from the previous experiment. As in the previous experiment, the DO profiles in each reactor showed two separate phases of deoxygenation and oxygen recovery. Closely related to the DO profile, the O_2 uptake produced S-shaped (autocatalytic) curves. The accumulated O_2 uptakes after five days in the reactors were 26.2 mg/l and 21.4 mg/l in Jar 1 and Jar 2, respectively.

D. Comparison of BOD Exertion in BOD Bottles and Open-stirred Reactors

For the experiment shown in Figure 13, data from the BOD test and open-stirred reactors using hydrolysate from day 407 of pilot plant operation are compared. The hydrolysate had an organic content of 10,067 mg/l COD. In the open vessel, the initial concentration of hydrolysate was 50 mg/l COD. At 0.5 percent seed by volume from the settling tank of the pilot plant was added. The hydrolysate was appropriately diluted within the range of the BOD test (6.0 mg/l COD) and added to the bottles with a similar seed concentration (0.5 percent by volume, i.e., 1.5 ml of effluent solids). Phosphate buffer was also added to each reactor as in the previous tests using hydrolysate. The BOD bottles were incubated at 22°C, the operation temperature of the

Figure 12. DO Profile and O_2 Uptake Curves for Open Reactors with 50 mg/l of Hydrolysate

Substrate Characteristics:

Hydrolysate from Extended Aeration Unit
Day of Operation, 369 (Sept. 25, 1972)
Total COD = 6400 mg/l
Seed = Extended Aeration Effluent

Conditions in Open Reactors:

Total COD = 50 mg/l
Seeding Volume = 50 mg/l

○ = Jar 1, $K_2 = 0.120\ hr^{-1}$

□ = Jar 2, $K_2 = 0.088\ hr^{-1}$ Temp. = $22^{o}C$

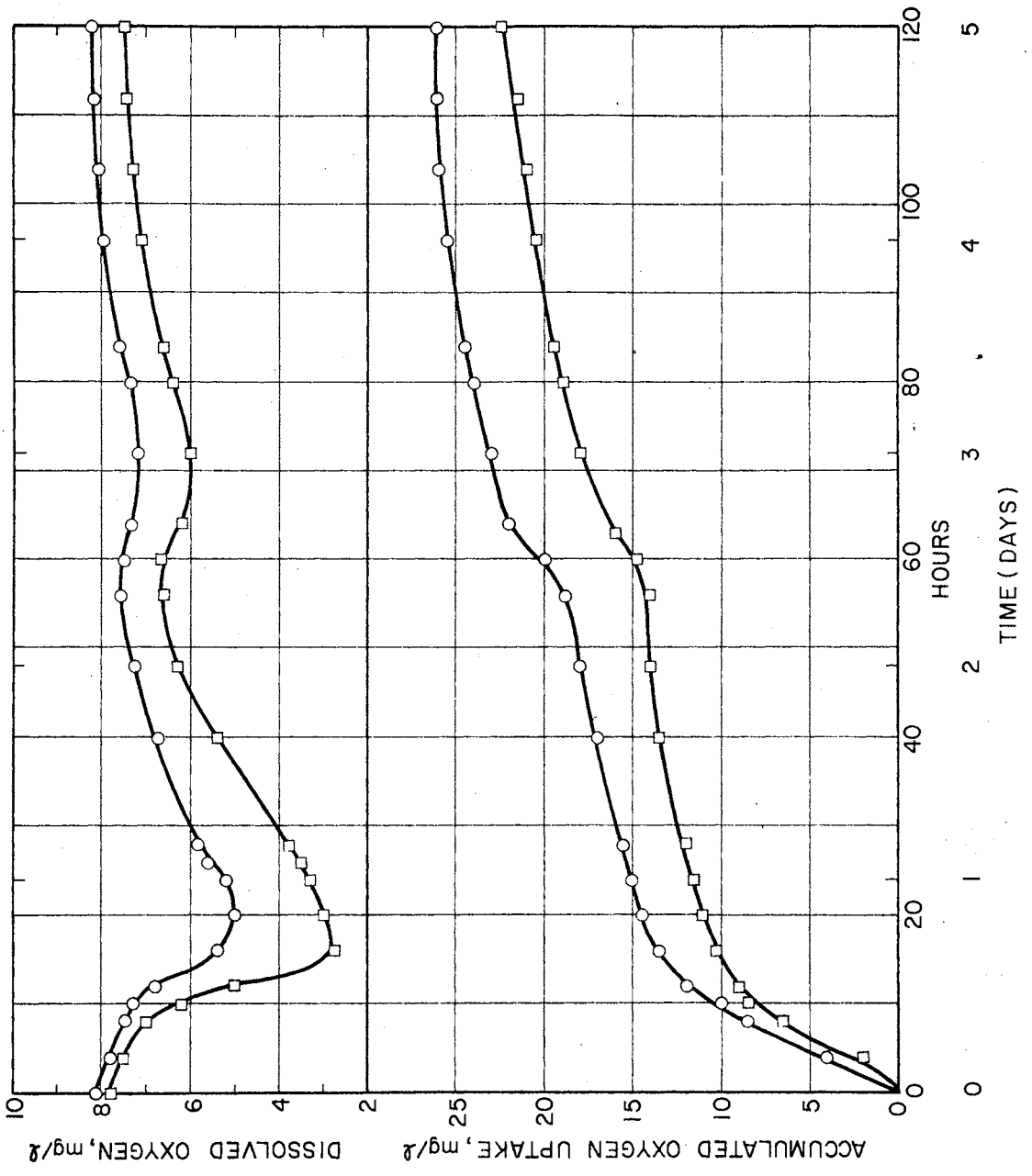

DISSOLVED OXYGEN, mg/ℓ
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
HOURS
TIME (DAYS)

Figure 13. Reactor DO Profile, Reactor O_2 Uptake Curve, and BOD Bottle O_2 Uptake Curves for Hydrolysate

Substrate Characteristics:

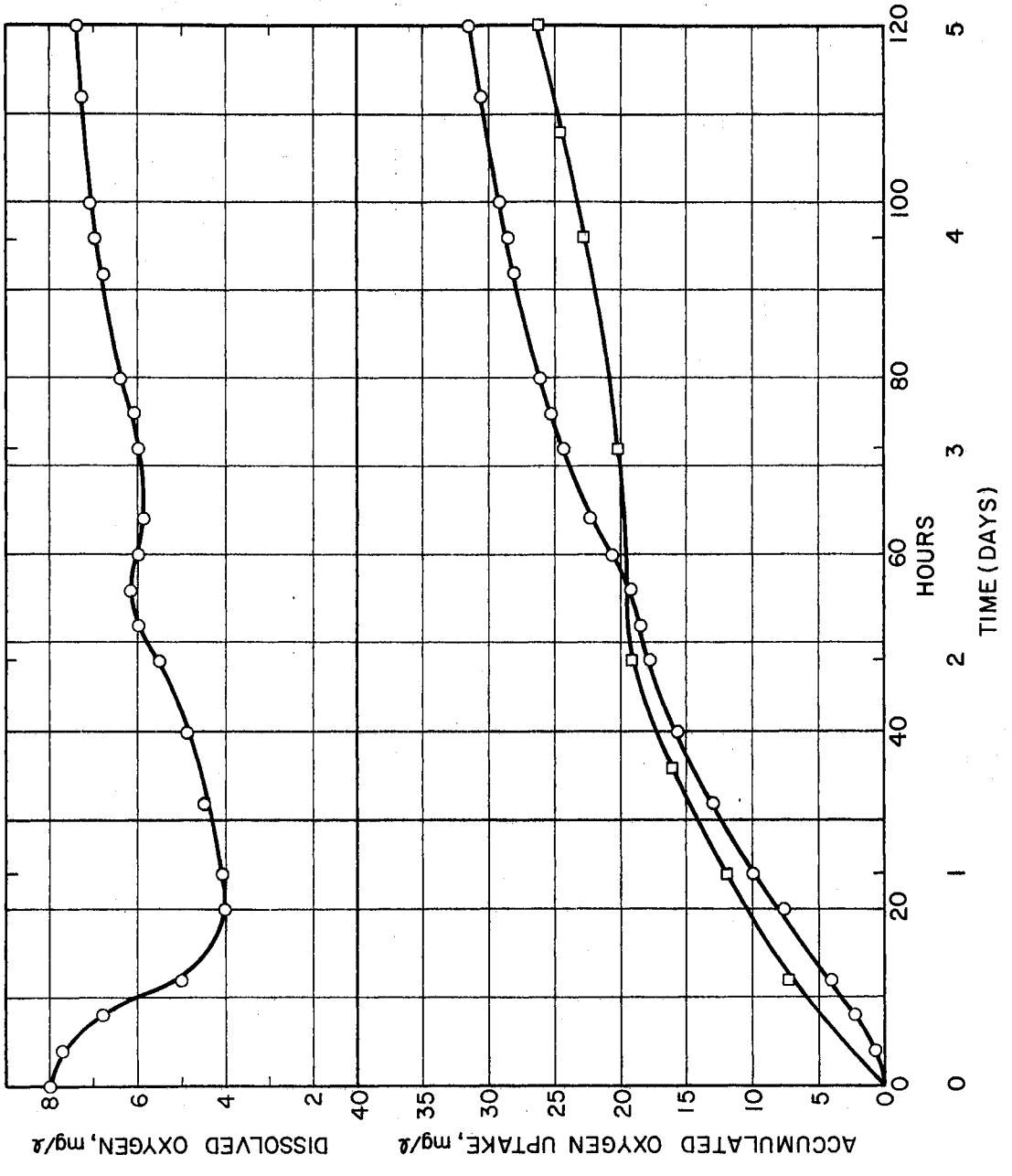
Hydrolysate from Extended Aeration Unit
Day of Operation, 407 (Nov. 2, 1972)
Total COD = 10,067 mg/l
Seed = Extended Aeration Effluent

Conditions in Open Reactor - O

Total COD = 50 mg/l
Seeding Volume = 50 ml
K_2 = 0.094 hr^{-1}
Temp. = 22°C

Conditions in BOD Bottles - □

Total COD = 6.0 mg/l
Seeding Volume = 1.5 ml
Temp. = 22°C


ACCUMULATED OXYGEN UPTAKE, mg/ℓ
DISSOLVED OXYGEN, mg/ℓ
0
5
10
15
20
25
30
35
40
2
4
6
8
0
20
40
60
80
100
120
HOURS
1
2
3
4
5
TIME (DAYS)

open reactor. The open jar was stirred to produce a rate of reaeration of 0.094 hr^{-1}. The DO profile in the jar was similar to previous experiments using hydrolysate, i.e., diphasic. The BOD exertion from the BOD bottles proceeded at a somewhat higher rate for 56 hours of the experiment. However, during the last 64 hours of the study, a higher O_2 uptake was observed in the open vessels. The O_2 uptake after five days was 26.3 mg/l in the BOD bottles compared to 31.4 mg/l in the stirred reactors.

In Figure 14, effluent from days 410-411 was used to compare results from BOD bottles and the open-stirred reactor. Effluent from those days contained 100 mg/l total supernatant COD of which 30 mg/l was soluble COD and the suspended solids concentration was 54 mg/l. The oxygen profile exhibited an almost continuous increase throughout this experiment in which the K_2 was 0.097 hr^{-1}. The resultant O_2 uptake curve exhibited first order-like decreasing rate kinetics in the reactor diluted with 60 percent effluent and 40 percent tap water containing 60 mg/l of total organic matter, 18 mg/l soluble organic matter (COD), and 33 mg/l of biological solids. The final O_2 uptake was 18.0 mg/l. Effluent was placed into the BOD bottles at a 1/6 ratio, effluent to dilution water. After dilution, the bottle contained 5.0 mg/l of soluble organic material (COD) and 9.0 mg/l of biological solids. The O_2 uptake was slightly higher in the bottle test than in the open-stirred reactors for the first 22 hours of the experiment. During the remaining four days of study, however, the rate of uptake in the stirred jar was significantly higher than the O_2 uptake rate in the BOD bottles. The five-day uptake of oxygen from the BOD bottles was 11.4 mg/l.

Figure 14. Reactor DO Profile, Reactor O_2 Uptake Curve, and BOD Bottle O_2 Uptake Curves for Effluent

Substrate Characteristics:

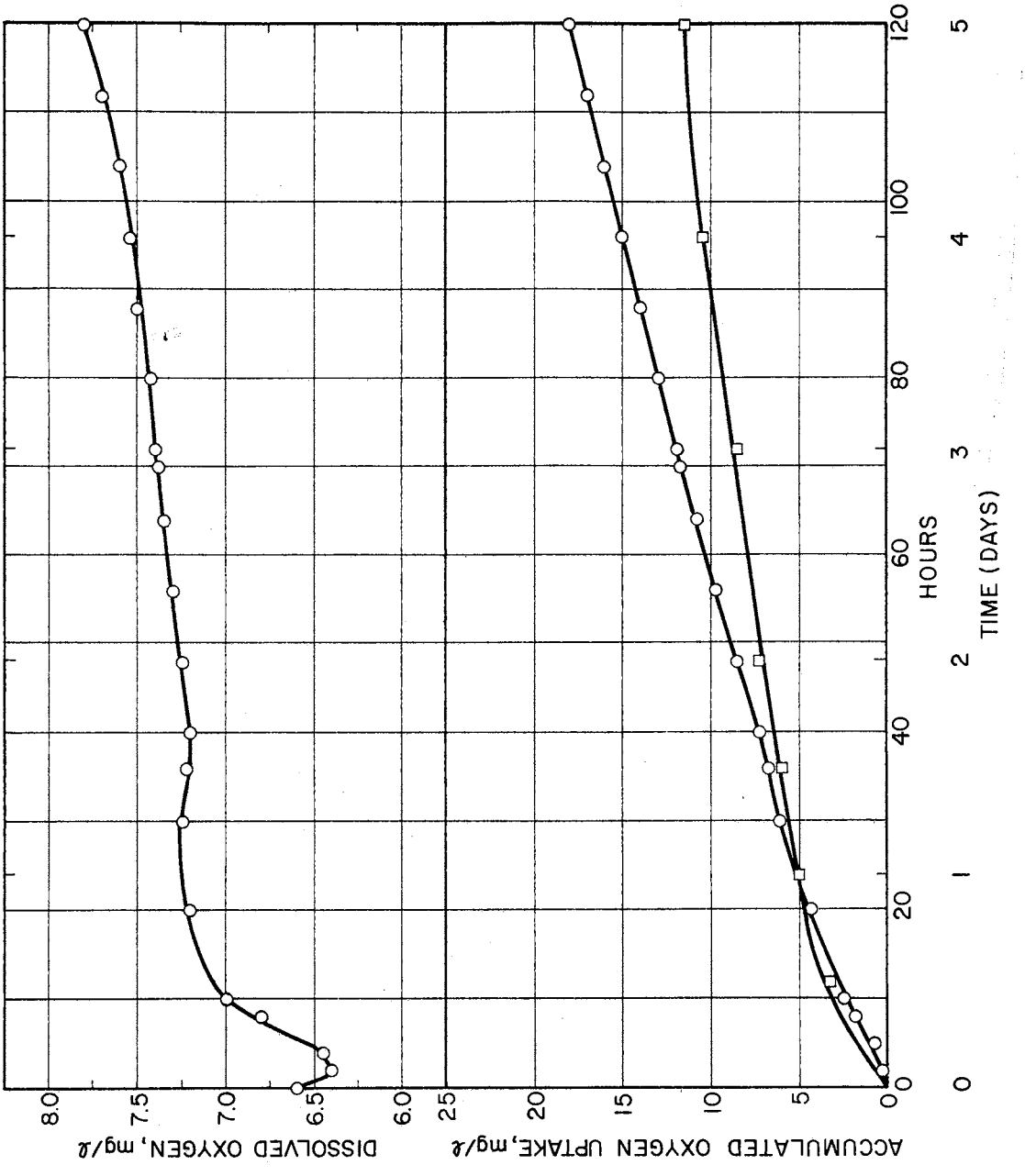
Extended Aeration Effluent
Days of Operation, 410-411 (Nov. 5-6, 1972)
Total Supernatant COD (Se) = 100 mg/l
Biological Solids (Xe) = 54 mg/l
Filtrate COD (S_f) = 30 mg/l

Conditions in Open Reactors - ○

Dilution Ratio = 50/40
K_2 = 0.097 hr^{-1}
Temp. = 22°C

Conditions in BOD Bottles - □

Dilution Ratio = 1/6
Temp. = 22°C


DISSOLVED OXYGEN, mg/ℓ
8.0
7.5
7.0
6.5
6.0
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
25
20
15
10
5
0
0
20
40
60
80
100
120
HOURS
1
2
3
4
5
TIME (DAYS)

CHAPTER V

DISCUSSION

A. Effect of Extended Aeration Effluent upon Receiving Streams at Varying Reaeration Rates

As previously outlined, a major aim of this study was to gain further insight into the operation of open-stirred reactors, with particular emphasis on the effect of biologically-treated effluent from an extended aeration activated sludge plant on receiving streams. To accomplish this goal, effluents of varying quality were analyzed in the jar reactors at dilutions that would ensure that the majority of the flow in this simulated stream consisted of treated effluent. One of the values of the procedure is that the course of O_2 uptake can be determined for the dilution factor which will occur in the field; such is usually not the case in using the BOD test. Reaeration rates were also varied in the reactors to bracket adequately those values which might reasonably be expected to exist in receiving streams. As with the dilution factor, the rate of reaeration chosen should be as close as possible to that which exists in the stream.

It is apparent (Figures 2-9; Table I) that the reactor stirred to produce a higher reaeration rate resulted in a consistently higher amount of oxygen utilization than in the vessel with the lower reaeration rate. In general, the rate of BOD exertion in the jar with the

TABLE I

SUMMARY OF EXPERIMENTAL DATA

Figure No.	Waste	Effluent Characteristics Se (mg/l)	Xe (mg/l)	S_f (mg/l)	Dilution Ratio	K_2 (hr^{-1}) Jar 1	K_2 (hr^{-1}) Jar 2	O_2 Uptake (mg/l) Jar 1	O_2 Uptake (mg/l) Jar 2
1	Effluent	130	58	43	50/50	0.099	-	22.5	-
3	Effluent	81	12	45	60/40	0.120	0.120	14.5	11.75
4	Effluent	40	15	25	60/40	0.120	0.094	17.0	15.0
5	Effluent	55	38	30	60/40	0.108	0.086	22.4	19.8
6	Effluent	35	8	20	60/40	0.120	0.092	15.2	13.5
7	Effluent	26	16	10	60/40	0.070	0.050	5.9	5.1
8	Effluent	55	30	20	60/40	0.070	0.055	14.0	11.3
9	Effluent	80	26	35	60/40	0.075	0.050	14.2	10.75
10	Effluent	95	25	65	60/40	0.080	0.053	25.2	21.0
14	Effluent	100	30	54	Jars 60/40	0.097	-	18.0	-
					BODs 1/6	-	-	11.4	-

Figure No.	Waste	Hydrolysate Characteristics (mg/l COD)		Substrate Concentration in Reactors (mg/l)	Seed Volume in Reactors ml (%)	K_2 (hr^{-1}) Jar 1	K_2 (hr^{-1}) Jar 2	O_2 Uptake (mg/l) Jar 1	O_2 Uptake (mg/l) Jar 2
11	Hydrolysate	6400		75	50 (0.5%)	0.120	0.088	36.5	31.3
12	Hydrolysate	6400		50	50 (0.5%)	0.120	0.088	26.2	21.4
13	Hydrolysate	10067	Jars	50	50 (0.5%)	0.097	-	31.4	-
			BODs	6.0	1.5 (0.5%)	-	-	26.3	-

greater reaeration potential was slightly higher than the jar with a lower K_2, causing gradual separation of the O_2 uptake curves as the experiment continued. However, this effect may not always be manifested, as recently seen in an open-reactor test on effluent from a paper-pulp waste performed by D. Scott (24). After seven days, no appreciable difference was noted between the accumulated O_2 uptake curves for reactors stirred at different K_2 values. As noted by Peil (21), further study on a variety of effluents is needed to determine the effect of K_2 upon oxygen utilization.

During a short period of time in which the treatment unit (extended aeration pilot plant) was experiencing settleability problems, both biological solids and substrate concentration in the effluent were considerably above average. For example, the experiment shown in Figure 2 was conducted using pilot plant effluent during such a period. The pilot plant at the time was being fed 1000 mg/l glucose and 180 mg/l of bacterial hydrolysate COD for a total of 1296 mg/l COD. Even at such a high organic loading, the pilot plant effluent caused no serious reduction of the DO supply in the reactors. While operating at 90 percent efficienty (plant average was 97.5 percent based on removal of initial exogenous substrate), the effluent in a 50/50 ratio with tap water produced an oxygen deficit of less than 2.0 mg/l in the open reactors (K_2 = 0.099 hr^{-1}). The presence of a sufficient O_2 reserve to maintain natural aquatic life in the receiving stream was apparent in each of the tests. At no time was the reduction of oxygen of such magnitude as to cause concern about the potential harm of polluting the stream with effluent. Thus, regardless of the nature of the DO profiles or the BOD exertion curves produced by the effluent, one important fact is

apparent; the degree (efficiency) of treatment of a soluble organic substance in an extended aeration plant is sufficiently high to produce an effluent quality which will not deleteriously affect the aqueous environment of receiving streams with more or less average reaeration characteristics.

For the experimental results shown in Figure 7, an interesting phenomenon occurred. Toward the end of the third day of operation, the microbial population began to settle to the bottom of the reactors. Both reactors were being aerated at a rate consistent with a reach of stream of low K_2 value; however, the microbes settled more rapidly in the reactor stirred at the lower K_2 value. After five days, microscopic observation revealed that the majority of solids in the reactor were protozoa. Due to the low amount of agitation in the reactors, the protozoa were unable to remain in suspension. Should this occur in a stream, the biological material would settle to the river bed becoming a part of the benthic deposits, which could eventually create an O_2 demand in the river.

Comparing BOD exertion curves in the reactors caused by the effluent, only results shown in Figure 2 demonstrated the presence of a distinct "plateau." The remaining curves showed either first order-like decreasing rate kinetics, straight-line kinetics or, in some cases where the effluent COD was slightly high, a straight line portion is followed by one of slightly higher slope. Regardless of the type of curve, the fact that they do not always fit the "monomolecular" configuration assumed by the classical sag equation militates against the use of such an equation for the prediction of assimilative capacity of receiving streams.

The presence of the "plateau" in Figure 2 may be accurately explained by two possible theories. The second stage of metabolism could be due to the injestion of bacteria by protozoa in the system (11); however, microscopic analysis of several samples failed to substantiate this theory in that no increase in protozoan population was noticed. A second reason for development of a plateau is sequential exogenous substrate removal. Since the pilot plant was not operating at its typically high rate of efficiency, this cause seems like a more reasonable possibility. Various portions of cell hydrolysate along with other soluble byproducts from the unit could have been sequentially metabolized and this sequential removal of substrate could have produced a phasic O_2 uptake curve.

B. Mode of Bacterial O_2 Uptake Using Hydrolysate from an Extended Aeration Activated Sludge Plant as Substrate

Hydrolyzed activated sludge is a highly complex substrate material. It contains both DNA and RNA material, sections of the cell wall, membrane, and the extracellular polysaccharide layer (if present), etc. It, in essence, constitutes a raw complex waste distinguishable from a treated waste in much the same manner as raw sewage is distinguished from treated municipal effluent.

As would be expected from a raw substrate, the BOD exertion curves in Figures 11 and 12 exhibit diphasic O_2 requirements, i.e., two autocatalytic-like curves connected by an extended "plateau." The hydrolysate produced two distinct phases of DO depression (sag) in the reactors with the initial depression being the most severe in its oxygen requirements. This type of O_2 uptake curve has been observed in many instances

where a raw or synthetic waste is being metabolized by an acclimated population (11)(13)(14). In general, the periods of deoxygenation in the reactor produced logarithmic-like (first order increasing rate) oxygen utilization followed by a period of first order-like decreasing rate kinetics during the recovery phase.

It is interesting to compare the BOD exertion curves obtained from the open-stirred reactor data for both treated effluents and bacterial hydrolysate (raw waste). It would seem that the inherent differences between raw and treated wastes are reflected in the kinetics one might reasonably expect from each. It has generally been shown that the assumption of first order kinetics for the exertion of the BOD of a raw waste is incorrect, and that there often exists a "plateau" separating two distinct phases of O_2 utilization. Thus the general kinetic mode of exertion of the BOD test is discredited because of its reliance upon the existence of a monomolecular-like--i.e., first order decreasing rate--expression. A more reasonable statement would be that raw or untreated substrates will, in general, produce autocatalytic effects. However, highly purified wastes (effluent) in a necessarily dilute system (receiving stream) might be expected to produce either zero or first order-like consumption of oxygen.

Based on the results of this study, it can be concluded that the treated effluent did approach first order utilization of O_2 while hydrolysate produced the typical diphasic BOD exertion. Similar results have been noted by Gaudy, Obayashi, and Kelly (25) using cell sonicate as a raw waste and biologically treated cell sonicate as an "effluent" or purified waste. This should not be taken as cause to endorse the use of the classical sag equation based upon the BOD test for treated

effluent, since it is felt that the open-stirred reactor method more closely simulates actual stream conditions in any event.

C. Comparison of BOD Exertion in BOD Bottles and Open-stirred Reactors

These experiments (Figures 13 and 14) were conducted using bacterial hydrolysate and biologically-treated effluent in order to compare the oxygen sag model proposed, i.e., open-stirred reactors, and the Streeter-Phelps sag equation. Since the Streeter-Phelps model requires direct use of the BOD test, the substrates were appropriately diluted within the range of the test. As nearly as possible, the only difference in the conditions of the two tests, which were run simultaneously on the same type of substrate, was the concentration of substrated added to either the BOD bottles or the open reactors. The concentration of substrate that could be added to the open reactors was higher than that which could be added to the closed quiescent BOD bottles. For both experiments, the final accumulated O_2 uptake was higher in the open jars than in the BOD bottles. It is believed that this was due to either the increased stirring in the open reactors or the higher initial concentration of substrate in the jars. However, the weight of evidence of previous investigations indicates that substrate concentration causes a greater difference than agitation within the range of K_2 values observed for most receiving streams (20)(21). It is evident, however, that the systems are not comparable, and the condition of the experiment, i.e., incubation conditions, affects the course of O_2 uptake.

In summary, the open-stirred reactor technique does have certain advantages over the classical sag equation in that it is modeled to fit the natural situation occurring in the stream, i.e., the O_2 uptake

curves are actually generated, not fit into some standard mathematical relationship, as is done using the BOD dilution technique with its assumed first order decreasing rate of oxygen utilization. Thus, if one has available a fairly good estimate of K_2, it is possible to depict the course of O_2 uptake, hence the DO profile and estimate of assimilative capacity, with more accuracy by the open jar method than by the Streeter-Phelps sag equation using the BOD dilution technique.

CHAPTER VI

CONCLUSIONS

Based on the results of this study, the following general conclusions can be made:

1) The effluent from an extended aeration activated sludge treatment plant will, in general, cause no ecologically dangerous reduction in DO content in receiving streams, even if the majority of the flow in the stream is effluent. At both high and low reaeration rates, the stream can be expected to assimilate the organic material in the effluent.

2) Although the O_2 uptake curves produced in open-stirred reactors need not fit any definable kinetic order to employ the procedure herein studied, a definite difference existed between the kinetics of O_2 utilization of a highly purified effluent and a raw (untreated) waste, i.e., hydrolysate in this study. The treated effluent produced either zero order-like or first order-like decreasing rate kinetics. In one situation in which the effluent was not highly purified, i.e., it still contained some highly complex substances, autocatalytic effects were exhibited. The hydrolysate, however, always exhibited autocatalytic-like kinetics.

3) In this study, the rate of reaeration in the reactors had an effect upon the O_2 utilization by the microorganisms. In each case, the reactor with the higher K_2 resulted in a somewhat higher O_2 uptake.

4) The kinetics of BOD exertion and the total O_2 uptake in the BOD bottles vary from those in the open reactors. The degree of difference is due to both the higher concentration of substrate which is added to the reactors and, very possibly, to the increased rate of oxygen replenishment in the open vessels. From these results it cannot be stated whether the somewhat higher O_2 uptake values in the jar with higher K_2 values is due to agitation (mixing) or higher oxygen concentration. However, the results are consistent with those of Peil and Gaudy (21), and it would appear since the DO values were rather high that the effect is not due to DO concentration.

Since the open-stirred jar technique obviates the need for a dilution factor greater than that extant in the receiving stream and, since mixing in the jar can be adjusted to yield K_2 values in the range of those expected in the receiving stream, the technique would appear to provide a much more realistic appraisal of the course of O_2 uptake in a natural receiving stream.

CHAPTER VII

SUGGESTIONS FOR FUTURE WORK

1) Additional study should be conducted to determine the effect of reaeration upon the BOD exertion of wastes other than those used in this study. Although all experiments in this study did exhibit a higher O_2 uptake in the reactors with higher K_2 values, subsequent tests (not herein reported) using a paper-pulp effluent did not produce such results.

2) Since the DO depletion in most of the experiments was less than 2.0 mg/l (the minimum deficit studied in previous experiments), further studies should be made to determine if such a slight oxygen deficit affects O_2 uptake calculations.

3) Studies should be conducted to determine which factors cause the higher O_2 uptake in open reactors over that in the BOD bottles. It is known that increased substrate concentration caused an increase in the rate of O_2 uptake in closed bottles, but further studies are needed to determine the relative contribution of increased substrate concentration and increased agitation (mixing) on the rate and amount of O_2 uptake in the open reactors.

4) Additional studies (similar to those performed by Jennelle and Gaudy) should be made to determine the effect of increased agitation in closed BOD bottles on the rate of oxygen utilization. Separate BOD dilution bottles can be used, one stirred and one unstirred, and the DO depression measured constantly by use of a DO probe.

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APPENDIX

APPENDIX

A. Calculation of O_2 Uptake Using the Open-stirred Reactor Procedure (Table II)

An important factor to remember in calculating O_2 uptake using an open stirred reactor is that accuracy depends upon being able to measure accurately the reaeration rate for the receiving stream below the waste discharge outfall. In these studies, K_2 was accurately measured using a graphical modification of the α method discussed in the Materials and Methods section (page 14).

To calculate the O_2 utilized by the microorganisms while stabilizing an organic waste, the DO must be measured during both deoxygenation and recovery phases (column 2). The deficits from saturation (column 3) are then calculated for the operating temperature (22^oC in this study, $C_s = 8.8$). The deficit produced in the jars is then multiplied by the reaeration rate existing in the vessels (column 4).

The amount of oxygen introduced into the system by atmospheric reaeration during an interval of time, Δt (column 5) is determined by multiplying K_2, deficit, and Δt (column 6). The differences in DO between two periods of time gives a measure of the effect of both reaeration and deoxygenation occurring in the system for an interval of time (column 7). The integral O_2 uptake caused by O_2 utilization by the microbes for a specific time period can be measured by subtracting column 7 from column 6 (column 8). Column 9 is the summation of O_2

uptake for the experiment. This table corresponds to the study presented in Figure 5.

B. List of Symbols

BOD - biochemical oxygen demand (mg/l)

COD - chemical oxygen demand (mg/l)

C_s - oxygen saturation constant (mg/l)

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

DO - dissolved oxygen (mg/l)

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

Se - total supernatant COD (mg/l)

S_f - soluble supernatant COD (mg/l)

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

TABLE II

CALCULATION OF OXYGEN UPTAKE FROM OPEN-STIRRED JARS

1	2	3	4	5	6	7	8	9
Hour	DO mg/l	D mg/l	K_2D mg/l-hr	Δt hr	$K_2D' t$ mg/l	ΔDO mg/l	6-7 mg/l	O_2 Uptake mg/l
0	6.59	2.21	0.24					0
				0.5	0.12	.06	0.06	
0.5	6.65	2.15	0.23					0.06
				0.5	0.12	-.16	0.28	
1.0	6.49	2.31	0.25					0.34
				0.5	0.14	-.21	0.34	
1.5	6.28	2.52	0.27					0.68
				4.0	1.06	.11	0.95	
5.5	6.39	2.41	0.26					0.64
				2.5	0.65	.05	0.59	
8.0	6.44	2.36	0.26					2.23
				3.0	0.77	-.05	0.82	
11.0	6.39	2.41	0.26					3.05
				10.0	2.52	.15	2.37	
21.0	6.54	2.26	0.24					5.42
				4.0	0.94	.13	0.82	
25.0	6.67	2.13	0.23					6.23
				2.5	0.57	.05	0.51	
27.5	6.72	2.08	0.23					6.75
				4.5	1.03	-.05	1.07	
32.0	6.67	2.13	0.23					7.82
				4.0	0.92	0	0.92	
36.0	6.67	2.13	0.23					8.75
				12.0	2.57	.31	2.26	
48.0	6.98	1.82	0.19					11.01
				3.0	0.59	0	0.59	
51.0	6.98	1.82	0.19					11.60
				4.0	0.79	-.05	0.85	
55.0	6.93	1.87	0.20					12.45
				4.0	0.84	-.16	1.00	
59.0	6.77	2.03	0.22					13.45
				10.5	2.13	.31	1.82	
69.5	7.08	1.72	0.19					15.27
				4.0	0.74	0	0.74	
73.5	7.08	1.72	0.19					16.01
				4.5	0.82	.05	0.77	
78.5	7.13	1.67	0.18					16.79
				5.0	0.90	0	0.900	
83.0	7.13	1.67	0.18					17.69
				10.5	1.79	.19	1.59	
93.5	7.32	1.48	0.16					19.28
				4.0	0.62	.05	0.57	
97.5	7.37	1.43	0.15					19.86
				5.0	0.77	0	0.77	
102.5	7.37	1.43	0.15					20.63
				2.5	0.38	.05	0.33	
105.0	7.42	1.38	0.15					20.96
				3.0	0.44	.05	3.93	
108.0	7.47	1.33	0.14					21.35
				12.0	1.24	.11	1.13	
120.0	7.58	1.22	0.13					22.50

C_s = 8.80 mg/l

K_2 = 0.108 hr^{-1}

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