A COMPARISON OF OXYGEN UTILIZATION DETERMINATION TECHNIQUES FOR THE ACTIVATED SLUDGE PROCESS

by

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in

Sanitary Engineering

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September 1976

Blacksburg, Virginia

ACKNOWLEDGEMENT

The accomplishment of even so humble an effort as this paper represents is not often made without the aid and support of a number of the friends, the advisors, and the family of the author. This aid and support is greatfully acknowledged. Although by no means representing all of the indiviuals who contributed to this effort the following are singled out for special thanks:

Dr. L. D. Benefield

Dr. C. W. Randall

Dr. J. H. Scherrard

Without their help and that of many others, this thesis and the accompanying degree would not have been possible.

Financial support for the pursuit of this degree was provided under a grant from the Enviromental Protection Agency.

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I INTRODUCTION

Associated with the discharge of untreated wastewaters to streams are a number of pollutants. The pollutants most commonly removed in treatment are unoxidized organic and nitrogen compounds in the discharge. These compounds act as a food source for aerobic microorganisms present in the stream water, requiring large amounts of oxygen for metabolism and often completely depleting the supply of oxygen dissovled in the water. Because of this lack of oxygen, other aqueous fauna, such as fish, crustaceans, etc. are unable to exist. Anaerobic conditions develop, accompanied by unpleasant odors, a black color, and septic conditions in the water.

Probably the most commonly used method for treatment of wastewaters for removal of oxygen demanding pollutants is the activated sludge treatment process. This is a biological process in which an attempt is made to duplicate and concentrate the conditions that esist in the stream. The waste is placed in a tank containing a very large concentration of aerobic microorganisms. Oxygen, usually in the form of air, is introduced into the mixed liquor by mechanical agitation or bubble aeration. The microorganisms remove the organic material from the wastewater by metabolism, with accompanying new microbial growth.

This metabolic process, whether occurring in a stream or an activated sludge treatment facility, may be described by the following simplified equation:

ORGANIC MATTER + 0₂ + NH₃ MICROBES NEW

2

MICROBIAL MASS + CO_2 + H_2O + NO_3

As can be seen in this equation, however, the consideration of oxygen is basic to the process. The fact that the process is termed aerobic implies that it will not proceed in the absence of available oxygen. The organic strength of wastewaters is most often measured in terms of the oxygen demand it can exert.

In addition to the oxygen required to stabilize the organics in a water, a surplus of reduced nitrogen in the waste can be expected to exert an oxygen demand of its own. Nitrogen is required in the synthesis of new cellular mass but the excess, under favorable conditions, will be oxidized to the nitrate form. This process is known as nitrification.

Design of treatment facilities for a wastewater is typically based upon certain kinetic coefficients evaluated for that particular waste. Evaluation of these constants by a batch reactor approach makes large use of oxygen uptake data. Continuous flow reactor experiments yield coefficients based on changes in organic strength and measured microbial mass production. There are a number of methods available for calculating oxygen uptake. The purpose of this paper is to examine and compare a number of these methods, and to test the applicability of the obtained data to evaluation of kinetic coefficients.

(1)

II. LITERATURE REVIEW

UNIFIED DESIGN APPROACHES

The activated sludge treatment process and its variations have been used for several years in treating wastewaters. Only in recent years, however, have mathematical models been developed that make design and operation of these facilities at least something of a science. Probably the two most commonly used of these models are the McKinney and Eckenfelder model (1) and the Lawrence and McCarty model (2) which apply to completely-mixed systems.

<u>McKinney and Eckenfelder Model</u>. McKinney and Eckenfelder developed independently what has been shown by Goodman and Englande (1) to be the same model. Its primary assumption is that the rate of organic removal in an activated sludge system is first order. Such an assumption yields a graph of organics remaining versus time similar to that shown in Figure 1. This approach was used to develop a model which relates organic removal to aeration tank mixed liquor volatile suspended solids (MLVSS) and aeration tank detention time. Performance of the system was found to be a function of organic loading and sludge age (3).

Lawrence and McCarty Model. In the early 1940's, Monod (4) published data indicating that substrate concentration and biological growth rate are related by the equation,

$$\frac{dS}{dt} = -\frac{\kappa SX}{K_S + S}$$
(2)

where:



Figure 1- Substrate Concentration as a Function of Time.

- k = maximum rate of substrate utilization per unit weight of microorganisms, time⁻¹;
- S = concentration of substrate surrounding the organism, mass
 per volume;
- K_s = substrate concentration when $\frac{dF}{dt} = \frac{1}{2}k$, mass per volume; X = microbial mass concentration, mass per volume.

A plot of this equation is shown in Figure 1. It can be seen that when $S << K_s$, the equation approaches first order. When $S >> K_s$, the equation approaches zero order. From this basic equation, Lawrence and McCarty (2) developed a unified design approach based upon solids retention time or sludge age.

COEFFICIENT DETERMINATION METHODS

Before either of these models may be applied to design of waste treatment facilities, certain kinetic coefficients must be evaluated. In the case of industrial wastes, for which the characteristics are often not as well known as for domestic sewage, this usually involves conducting lab or pilot plant experiments, the data collected being subsequently used to calculate the desired coefficients (1,3,5). These experiments often require operating continuous flow reactors, usually for long periods of time.

<u>Batch Reactor Method</u>. Weston and others have proposed that sufficient data for evaluation of these cofficients can be collected over a short period of time using batch, rather than continuous flow experiments (6,7,8). order plot, also shown in Figure 1. From mass balance and stoichiometric considerations, sludge production and substrate removal rate are related to chemical or biochemical oxygen demand and oxygen utilization data.

Oxygen utilization within this batch reactor system was an important parameter to these researchers. They theorized that removal of COD from solution may or may not occur at the actual rate of stabilization. Removal represents only a transfer of organic material into the cell, where it will continue to exert an oxygen demand as actual oxidation or stabilization occurs. They stated that this oxygen uptake time can never be less than removal time, since COD must be transferred before it can be oxidized. For this reason, the Weston group proposed that the time at which COD removal, or transfer, is complete not be used to calculate ths substrate utilization rate. Instead, they contended the actual time required for stabilization, represented by the time to complete oxygen uptake, should be used.

<u>Open Respirometer Methods</u>. Expanding upon the concepts proposed by Weston, Blok (9) has argued that much usable information may be obtained from oxygen utilization data, alone. He has classified batch experiments as being either short term or long term. Short term experiments were defined as having high MLVSS concentrations, extremely low initial loading factors, and very short completion times, usually from 30 to 60 minutes. Blok defined long term experiments as having higher initial loading factors and longer completion times. For the short term experiments there was no appreciable change in MLVSS concentration, while the long term experiments were characterized by large initial increases in MLVSS concentration, followed by virtually complete solids destruction. Blok attempted to confine his experiments to the short term variety, since these conditions allowed a number of simplifying assumptions.

Using an open resirometer technique, he investigated the effects of substrate and sludge concentration and characteristics on oxygen utilization, and evaluated surplus sludge formation using a series of batch experiments. Blok warned, however, that the longer the completion time for the experiments, the less applicable were his methods. He therefore proposed that open respirometer investigations be confirmed to short term experiments.

In evaluating surplus sludge formation, Blok proposed that a mass balance must exist within the reactor between the quanity of oxygen utilized, oxygen demanding material removed, and change in microbial mass. He therefore subtracted the quantity of oxygen utilized, less calculated nitrogenous oxygen demand, from the quantity of COD removed to obtain sludge production values. The experiments consisted of a series of short term batch reactor runs made by loading the same reactor with several separate slugs of substrate. The values for sludge production obtained agree very well with measured values.

Benefield, Randall, and King (10) have proposed that Blok's open respirometer technique can be applied to longer range batch experiments and combined with Weston's equations to yield a variety of design values. Since the rate of substrate metabolism is proportional to oxygen consumption, the rate and order of removal may be obtained from oxygen utilization data. Cell maintenance and yield coefficients may be obtained in the following manner:

$$\Delta X = \frac{(COD)_{removed} - (0_2)_{utilized}}{1.42}$$
(3)

where

$$\Delta X$$
 = change in biomass concentration

(COD) removed = chemical oxygen demand removed

 $(0_2)_{utilized} = oxygen utilized to metabolize the COD removed$ $It should be noted that <math>(0_2)_{utilized}$ must include the endogenous oxygen requirement whether microorganisms oxidize a portion of external substrate to satisfy maintenance energy requirements as proposed by Pirt (11), or oxidize cellular mass as proposed by Herbert (12).

$$K_{d} = \frac{R}{1.42X} \tag{4}$$

where:

$$K_{d} = \text{maintenance energy coefficient}$$

$$R = \text{endogenous respiration rate}$$

$$X = \text{biomass concentration}$$

$$Y_{t} = \frac{(\text{COD})_{\text{removed}} - (0_{2})_{\text{utilized}}}{1.42 \ (\text{COD})_{\text{removed}}}$$
(5)

where:

 Y_t = true yield coefficient Benefield, et al. (10) using the relationship,

$$\frac{\Delta O_2}{\Delta t} = a \frac{\Delta S}{\Delta t} + bX$$
(6)

where:

∆02 = total oxygen requirement of the biomass over some time interval ∆t X = biomass formed over some time interval ∆t a = oxygen required to form a unit of biomass b = oxygen required per unit of biomass for the maintenance of life per unit time ${}_{\Delta S}$ = quantity of COD removed over time interval ${}_{\Delta t}$ have proposed that

1.

$$b = \frac{R}{X}$$
(7)

and

2.
$$a = \frac{\Delta O_2 - \Delta t \ bX}{\Delta S}$$
(8)

OXYGEN TRANSFER

It is generally accepted that the transfer of oxygen from a gaseous to a liquid solution is best described by what is known as the "two-film theory", proposed in 1924 by Lewis and Whitman (13,14,15,16). According to this theory, boundary films form at the interface within both the liquid and the gas. The rate of diffusion through the films depends on the area of the interface and the concentration gradient within the films. In the case of gases of low solubility, such as oxygen, the differential equation for the rate of gas transfer into the liquid becomes:

$$\frac{dC}{dt} = K_1 a (C_s - C_t)$$
(9)

where

 $\frac{dC}{dt} = \text{the rate of transfer at time, t}$ $K_{1} = \text{a proportionality constant related to overall conductance}$ a = the interfacial area $C_{s} = \text{the saturation concentration}$

 C_{+} = the concentration at time, t

Neither K₁ nor a can be evaluated directly as a rule, so they are usually evaluated and expressed as a product, K₁a (14).

The foregoing discussion has been of oxygen transfer into a liquid

in which no microbial activity is occurring. If there is no purely chemical oxygen demand to be satisfied, the liquid being aerated will eventually reach saturation and the rate of oxygen transfer will drop to zero. However, if there are viable aerobic microorganisms present, respiration of these organisms will exert an oxygen demand and the resulting rate of oxygen transfer will be equal to the rate of oxygen usage by the microbial mass (9,10,14,17).

The rate of oxygen transfer for a mixed liquor being aerated may be expressed as

$$\frac{dC}{dt} = K_{la} \left(C_{s} - C_{t}\right) - R$$
(10)

where

R = rate of oxygen utilization for endogenous conditions. Under endogenous conditions, the rate of oxygen utilization and, consequently, the rate of oxygen transfer become essentially constant for finite time periods and the dissovled oxygen concentration becomes constant. Therefore,

$$\frac{dC}{dt} = 0 = K_{1}a (C_{s} - C_{e}) - R$$
(11)

or

 $R = K_1 a (C_s - C_e)$ (12)

where

C_e = the equilibrium dissolved oxygen concentration for endogenous conditions.

EVALUATION OF ${\rm K_1a}$ AND OXYGEN UTILIZATION

Several methods have been proposed for the determination of oxygen utilization within an activated sludge system (9,10,14,15,18). Except for those methods which are not dependent upon direct measurement of oxygen utilized, such as the Warburg device, all involve the use of oxygen uptake or transfer rate, the two being equivalent (14,17). All but one of these methods require evaluation of $K_{1}a$. The one exception relies upon direct measurement of uptake rate (18).

As has been stated previously, the oxygen transfer rate, in the absence of an immediate chemical oxygen demand, must be equal to the rate of biological oxygen utilization and proportional to the rate of substrate utilization (17). When this rate is plotted as a function of time, the area under the resulting curve is equal to the quantity of oxygen utilized.

The constant $K_{l}a$ is known to be a function of several system variables. Among these are temperature, the degree of mixing, liquid depth, and waste characteristics (15,17). Because there are so many variables involved, $K_{l}a$ is virtually impossible to calculate and must be evaluated experimentally.

 α <u>- β METHOD</u>. The selection of aeration equipment for activated sludge systems is most commonly based upon evaluation of oxygen transfer rate by what may be called the α - β method (15,18). The constant, α , is defined as the ratio of the K₁a for the waste to the K₁a for water. If the oxygen transfer equation

$$\frac{dC}{dt} = K_{la} (C_{s} - C_{t})$$
⁽⁹⁾

is solved for C as a function of t, it becomes

$$\frac{dC}{C_s - C_+} = K_{la} dt$$
(13)

$$(C_{s} - C_{t}) = -K_{l}at.$$
 (14)

 $K_{1}a$ for water is determined by removing oxygen from a sample of water by chemical addition or nitrogen stripping. The water is then reaerated while DO concentration is monitored as a function of time (15,18). The natural logarithm of the oxygen deficit, $C_{s} - C_{t}$, is then plotted versus time. The slope of the resulting line is equal to $-K_{1}a$.

 K_{l} a for the wastewater is determined in exactly the same way using a mixed liquor sample of the same concentration of MLVSS as will be used in the system. Calculation of K_{l} a is as described for pure water. β represents the ratio of the DO saturation value for the waste to that of water.

When these values have been evaluated in the lab, a K_1^a for the actual reactor vessel, whether a lab scale batch reactor or an aeration basin, is obtained using pure water. This determination is made by the methods described above, carried out in the reactor vessel. The following equation is then used to determine the uptake or transfer rate:

$$\frac{dC}{dt} = \alpha K_{l} a (\beta C_{s} - C_{t})$$

where:

 $K_{1}a$ is that for pure water in the reactor vessel (18).

This method has, however, been reported by Busch (17) and Ford and Eckenfelder (19) to give unsatisfactory results. In addition, for lab scale experiments, it seems particularily inappropriate, since a K_1 a for the waste must be evaluated anyway and the determination may be made in the reactor vessel using a waste and microbe sample without considering the K_1 a for water at all.

<u>NON-STEADY STATE METHOD</u>. Eckenfelder (15) has proposed that K₁ be evaluated using waste and microbial mass under actual operating conditions

in the reactor vessel. Dissolved oxygen is removed by addition of sodium sulfite with a catalyst of cobalt chloride. The reactor is then mixed and reaerated while DO concentration is monitored. Since

$$\frac{dC}{dt} = K_1 a \left(C_s - C_t \right) - R, \qquad (10)$$

$$\frac{dC}{dt} = (K_{la} C_{s} - R) - K_{la}C_{t}.$$
(16)

If the change in concentration with time is plotted versus the concentration of DO, the slope of the resultant line is equal to $-K_{l}a$ and the intercept equal to $(K_{l}a C_{s} - R)$.

Benefield (10) and Blok (9) have proposed that this method may be used for a reactor whose contents are endogenous, and the natural logarithm of the DO deficits obtained may be plotted versus time to yield a line whose slope is equal to $-K_1a$.

<u>STEADY STATE METHOD</u>. Eckenfelder (15) has also proposed that K_la for a reactor whose contents are endogenous may be determined by the following equation,

$$K_1 a = \frac{R}{(C_s - C_e)}$$
(17)

if the endogenous respiration rate, R, is known.

<u>DIRECT MEASUREMENT METHOD</u>. It has been proposed that determination of K_{1} a is unnecessary to the calculation of oxygen utilization (18). The oxygen uptake rate may be determined directly by placing a 300 ml. aerated sample of the mixed liquor in question in a BOD bottle. As the DO concentration begins to fall in the bottle, the concentration is recorded at various time intervals. DO concentration is then plotted versus time to yield a straight line whole slope is equal to the oxygen uptake rate (18).

III. MATERIALS AND METHODS

Experiments were conducted with three different wastewaters to test the agreement and applicability of oxygen uptake rate determination methods. The wastewaters used were a pulp and paper waste, a textile manufacturing waste, and a municipal waste. For data collection, each of these wastes was added to a batch reactor containing microorganisms that had been acclimated to that particular waste. Chemical oxygen demand (COD) and dissolved oxygen (D.O.) concentrations, pH, and oxygen uptake rates were then monitored either periodically or continuously until the oxygen uptake rate returned to what it had been before the waste was added. Each waste was run in this manner at three different loading conditions.

WASTEWATERS TESTED

<u>Pulp and Paper Waste</u>. The first waste tested was that from a pulp and paper mill utilizing the sulfite pulping process. The wastewater was collected from the treatment plant influent, immediately following screens where large cellulose fibers were removed. It was characterized by a total solids concentration of 6000 mg/l and a suspended solids concentration of 3000 mg/l. Despite this high colloidal content, however, the biochemical oxygen demand (BOD) of the filtered waste was very close to that of the unfiltered waste, indicating that this colloidal matter was, for the most part, non-biodegradable. COD for the waste was approximately 5000 mg/l. pH was found to be 7.0.

After collection, the waste was stored at 4°C until used. Activated sludge obtained from the Roanoke, Virginia, waste treatment facility was acclimated to this waste for ten days at 20°C in a continuous flow reactor The refrigerated waste was allowed to warm to 20°C and nitrogen and

Parameter Concentration Unfiltered COD 4430 mg/1 Filtered COD 3059 mg/1 31% % Colloidal COD Unfiltered BOD₅ 1860 mg/1 Filtered BOD₅ 1833 mg/1 Total Solids 6000 mg/1 Total Volatile Solids 3350 mg/1 Suspended Solids 3000 mg/1 2700 mg/1 Volatile Suspended Solids

Table 1- Characterization of Pulp and Paper Wastewater

phosphorus were added before it was fed to the microbial reactor.

Upon completion of the ten day acclimation period, flow to the reactor was halted and the mixed liquor allowed to enter endogenous respiration. A batch reactor with a liquid capacity of 3-1/2 liters was set up at this point. Figure 2 is a diagram of the unit. A DO probe, Y.S.I. model 54, was introduced through the side of the unit at approximately 1/4 of the reactor height above the base. A sampling port was located at the base of the reactor. For each wastewater, the reactor was loaded with three different ratios of waste to mixed liquor volatile suspended solids (MLVSS) concentration during separate experiments.

THE MLVSS concentration in the acclimation reactor was determined and sufficient mixed liquor was transferred to the batch reactor to provide the desired mass of volatile suspended solids for each run. Supernatant from the acclimation reactor was added to provide 3-1/2 liters of mixed liquor. The contents of the batch reactor were then aerated to an equilibrium dissolved oxygen concentration. Three hundred milliliters of mixed liquor were then withdrawn from the reactor and placed in a BOD bottle. A dissolved oxygen probe was inserted into the bottle and the DO decline recorded. The concentration was plotted versus time to obtain an oxygen uptake rate. The rate was assumed to be the endogenous oxygen uptake rate.

After the oxygen uptake rate was measured, the three hundred milliliter sample was returned to the batch reactor and the DO concentration allowed to drop to a very low value by turning off the compressed air. The reactor was then reaerated, and the DO rise monitored by the DO probe inserted in the reactor. This probe was connected to a YSI model 54 dissolved oxygen meter and the data recorded on a Sargent-Welch model SRG



Figure 2- Experimental Apparatus.

recorder. After the DO in the batch reactor had returned to its equilibrium value, the reactor contents were allowed to settle.

Three different experiments were performed with the pulp and paper waste. For what was called the "standard" run, a MLVSS concentration of approximately 3000 mg/l was used. The 3.5 liters of sludge and supernatant were settled toone liter, the supernatant withdrawn, and 2.5 liters of waste added. For the "1/2 standard" run, MLVSS concentration of 3000 milligrams per liter was again used. Reactor contents were settled to 2.25 liters and 1.25 liters of waste added. In the case of the "1-1/2 standard" run, the MLVSS concentration was dropped to 2000 milligrams per liter and the same procedure as for the "standard" run followed.

Before the waste was added to the reactor, a complete solids characterization was made. In addition, COD and BOD samples were collected and analyzed. COD and BOD samples of the reactor supernatant were also withdrawn. The waste was then aerated to the same DO concentration as was equilibrium during endogenous operation.

Immediately after the wastewater was added to the batch reactor, a 400 ml sample was withdrawn, aerated, and pH monitored in this reactor. AAFisher model 230 pH meter was used connected to a Bausch and Lomb model VDM-7 recorder. (pH monitoring in a separate sample was found to be necessary because of electrical interference between the pH meter and the DO probe.)

At the same time that the 400 ml sample was withdrawn, an additional sample was taken from the reactor and a suspended solids determination made of the reactor's contents. At the following times after loading of the

reactor, additional samples were withdrawn: 1, 5, 10, 15, 20, 25, 30, 40, 50, 60, 75, 90, 105, 120 minutes, and at 30 minute intervals after that until the oxygen uptake rate returned to its endogenous value where the run was considered to be complete.

At each sampling time, a 300 ml sample was withdrawn and placed in a BOD bottle, and the drop in the DO in that bottle monitored as described previously to obtain an oxygen uptake rate. The sample was then returned to the reactor. In addition to the 300 milliliter sample, a smaller sample was removed at the same time. This smaller sample was filtered through a Kimwipe tissue followed by a No. 4 Whatman filter to approximate settling. A COD and a BOD sample were prepared from the filtrate and the remainder passed through a 0.45μ Millipore filter. Again, a COD sample was prepared from this filtrate. This was referred to as the "filtered COD". That sample which had gone through only the No. 4 Whatman filter and the Kimwipe was called the "settled COD".

Throughout each run, the dissolved oxygen concentration in the reactor was continuously monitored. The DO probe was a YS1 model 54. The DO data were recored on a Sargent-Welch model SRG recorder. At the end of each run, a new suspended solids determination was made.

<u>Textile Waste</u>. A Cellulose manufacturing wastewater was chosen as an example of a simple organic substrate low in suspended matter. This particular wastewater was found to have a total solids concentration of 6000 mg/l of which only 30 mg/l was suspended solids. The COD was 1800 mg/l and the BOD was approximately 1700 mg/l illustrating that it was readily biodegradable. The initial pH of this waste was 4.5.

The treatment facility at the manufacturing plant where the

Concentration
1560 mg/1
1460 mg/1
6.5%
1175 mg/l
1040 mg/1
6200 mg/l
2600 mg/1
35 mg/l
neg.

Table 2- Characterization of Textile Wastewater

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wastewater was obtained consisted of a flow equalization basin followed by an aerated lagoon. The wastewater sample tested was removed from the equalization basin, neutralized, and nutrients were added before it was fed to acclimated microorganisms. Until feeding, the waste was stored at 4°C, as in the case of the pulp and paper waste. Sludge was removed from the lagoon and, because of poor settling characteristics exhibited by it, acclimated to a nutrient enriched waste feed until its settling properties were satisfactory, a period of approximately five days.

Batch experiments were performed using the textile waste following the same procedure as that outlined for the pulp and paper waste, except for minor changes. The removal of samples from the batch reactor was found to cause variations in the DO concentration in the reactor. This was particularily noticable when the 300 ml. sample for oxygen uptake rate determination was removed from and returned to the reactor. For this reason, a small side reactor was set up and DO monitored in it.

The DO probe was removed from the batch reactor and the hole plugged. The reactor was then filled with endogenous sludge and supernatant, as described for the pulp and paper waste. A five hundred ml. sample was withdrawn and placed in a small reactor. Deoxygenation and reaeration of the small reactor contents were performed as described for the pulp and paper waste. Also as in the case of the pulp and paper waste, a 300 ml. sample was withdrawn from the large reactor in a BOD bottle and the oxygen uptake rate was determined. Both samples were then returned to the large reactor.

The reactor contents were allowed to settle and the required volume of supernatant withdrawn. Loadings used for the textile waste were obtained

in the manner described for the pulp and paper waste. Upon removal of the supernatant, the remaining reactor contents were stirred and one seventh of the volume placed in the small DO monitor reactor. One seventh of the aerated waste volume was added to this reactor and six sevenths to the large reactor simultaneously. The experiment then progressed just as for the previously described pulp and paper waste runs. In the case of the textile waste, however, COD samples were not filtered through a Kimwipe tissue and no BOD samples were taken.

<u>Domestic Waste</u>. For the experiments using domestic wastewater, primary influent, after grit removal and grease removal, was collected from the Blacksburg, Virginia, trickling filter plant. Sludge from a rest stop on Interstate 81 was acclimated to this waste for ten days in a continuous flow reactor. The waste was obtained fresh each day. Characteristics of the waste used in the experiments are shown in Table III. The procedure followed during the run was identical to the procedure described for the pulp and paper waste except that samples were not filtered through tissues prior to the Whatman No. 4 filter, and nutrients were not added. ANALYTICAL PROCEDURE

A number of tests were used in conducting these experiments. All solids determinations, including total solids, dissolved solids, both volatile and fixed, and suspended solids, volatile and fixed, were made in accordance with the "Residue" section of <u>Standard Methods for the Analysis of Waste and</u> <u>Wastewaters</u>, 14th Edition, (18) utilizing gooch crucibles and glass filters. Chemical Oxygen Demand and Biochemical Oxygen Demand determinations were also done in accordance with <u>Standard Methods</u>. All other tests were made as described above.

Parameter	Conc. for Standard Run	Conc. for 1/2 and 1 1/2 Standard Run
Unfiltered COD	253 mg/1	217 mg/1
Filtered COD	152 mg/l	86 mg/l
% Colloidal COD	40%	60%
Unfiltered BOD ₅	132 mg/1	147 mg/l
Filtered BOD ₅	106 mg/1	119 mg/1
Total Solids	498 mg/l	530 mg/1
Total Volatile Solids	200 mg/1	220 mg/1
Suspended Solids	90 mg/1	97 mg/l
Volatile Suspended Solids	60 mg/1	62 mg/1

Table 3- Characterization of Domestic Wastewater

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IV RESULTS

The data collected during the series of experiments of this investigation included: COD data for both settled and dissolved samples, BOD data for settled samples for certain of the experiments, reactor dissolved oxygen concentration, pH, and oxygen uptake rates. Problems encountered during the collection of settled samples, e.g. loss of vacuum and resultant release of filter suction accompanied by contamination of the sample with microbial material, led to the decision to omit settled COD and BOD results. During each of the experiments, pH varied so little that nothing could be gained by its inclusion, either. The results of interest for these experiments are shown in Figures 3 through 21 and in Tables 4, 5, 6, and 7. Loading factors were calculated as total COD removed divided by initial microbial solids concentration as measured by MLVSS.

FILTERED COD DATA

The COD data presented are from those samples which were filtered through a 0.45 filter. Since this is generally accepted as the dividing point between molecular and colloidal particle size, the COD information represents only dissolved COD. The data is shown plotted as COD removed versus time. For the pulp and paper waste, results are shown in Figure 4 for the 0.32 loading, in Figure 6 for the 0.44 loading, and in Figure 8 for the 1.79 loading. For the textile waste, COD data for the 0.25 loading are shown in Figure 10, for the 0.49 loading in Figure 12, and for the 0.61 loading in Figure 14. Data for the domestic waste are shown for the 0.014 loading in Figure 16, in Figure 18 for the 0.029 loading, and for the 0.047 loading in Figure 20.

OXYGEN UPTAKE RATE DATA

DIRECT MEASUREMENT METHOD. During the course of each of the experiments, a sample of mixed liquor was drawn from the reactor periodically. Its dissolved oxygen concentration was determined as a function of time and the obtained values were plotted versus time. Slope of the straight line which best connected at least three of the points was taken as the oxygen uptake rate.

<u>BLOK-BENEFIELD STEADY STATE METHOD</u>. A K_1 a value for the waste and reactor was obtained using the method outlined by Blok (9) and Benefield (10). Aeration of the reactor containing an endogenous mixed liquor was halted and the DO concentration allowed to drop to an arbitrary low value. Aeration was resumed and the DO concentration was monitored as a function of time. The slope of the line obtained by plotting the natural logarithm of the DO deficit, $C_s - C_t$, versus time was taken to be K_1 a for the reactor. This K_1 a value was multipled by the DO deficit at any time, t, in the course of the run to yield the oxygen uptake rate at that time.

AVERAGED METHOD. If the oxygen uptake rate equation,

$$\frac{dC}{dt} = K_{l}a (C_{s} - C_{t})$$
(9)

is used in conjunction with known values of oxygen uptake rate, K_{1} a may be calculated by the following equation

$$K_{la} = \frac{\text{oxygen uptake rate}}{C_{s} - C_{t}}$$
(18)

Values of oxygen uptake rate at various times in the course of each run were known from the data of the direct measurement method described above. Since DO concentration in the reactor vessel was monitored continuously,

DO deficit information was available for each of these times. Between 5 and 10 times during each run were arbitarily chosen for which direct measurement uptake rates were known and K_{l} a values calculated for each time. These K_{l} a values were then averaged and the resulting K_{l} a used to obtain the graphs marked as "Averaged O₂ Uptake Rate".

MASS BALANCE METHOD. The Law of Conservation of Mass must hold for the experimental system. Therefore, the total oxygen utilized must equal the chemical oxygen demand removed less that portion of COD that goes to sludge production plus the oxygen utilized in satisfying nitrogeneous oxygen demand, and the quanity of oxygen which goes to satisfy cellular maintenance requirements. The cellular maintenance requirement term does not play a part in calculation, however. Whether the cell maintenance energy requirements are satisfied by metabolism of substrate or by metabolism of cellular mass is of no consequence to this balance. If the requirements are satisfied by metabolism of substrate, the oxygen requirements are reflected in the COD metabolized term (COD removed minus COD incorporated in new microbial mass). If satisfied by metabolism of cellular mass, the mass balance equation may be written as:

$$(0_2)_{\text{utilized}} = (COD)_{\text{removed}} - \frac{(CHANGE IN MICROBIAL MASS)}{1.42}$$
 (19)

+ (NOD) + CELL MAINTENANCE OXYGEN.

The change in microbial mass is, however, an apparent change. The quanity of mass oxidized to satisfy maintenance energy requirements must be replaced before any net increase is noted. Therefore,

CHANGE IN MICROBIAL MASS = APPARENT CHANGE IN MICROBIAL MASS

+ (1.42 x CELL MAINTENANCE OXYGEN) (20)

1.42 is simply a conversion factor for expressing cellular mass in terms of oxygen demand (5). Substituting this expression into the mass balance equation yields:

$$(0_2)_{utilized} = (COD)_{removed}$$

- (APPARENT CHANGE IN MICROBIAL MASS)+(1.42 x CELL MAINTENANCE OXYGEN)
1.42
+ (NOD) + CELL MAINTENANCE OXYGEN (21)
This reduces to
 $(0_2)_{utilized} = (COD)_{removed} - \frac{(APPARENT CHANGE IN MICROBIAL MASS)}{1.42}$
+ (NOD) (22)

It should be noted that the change in solids concentration need not always be an increase for this balance to hold true.

Based upon this argument, a K_la for the system was determined in the following way:

- 1. Assume $K_{la} = 1.0$. Calculate oxygen uptake rate as described for the Blok-Benefield method.
- 2. Obtain the quanity of oxygen utilized by taking the area under the curve of oxygen uptake rate versus time.
- 3. Calculate the quanity of oxygen theoretically utilized from:

 $(0_{2})_{\text{THEORETICALLY UTILIZED}} = (COD)_{\text{REMOVED}} - \frac{\text{APPARENT MLVSS}}{1.42}$ + NOD $4. \text{ K}_{1}a = \frac{(0_{2})_{\text{THEORETICALLY UTILIZED}}}{(0_{2})_{\text{UTILIZED FROM (2) ABOVE}}}$ (23)

Oxygen uptake rate was calculated from this K_{la} as described previously.

The oxygen uptake rates as a function of time are shown for the 0.32 loading of pulp and paper waste in Figure 3, for the 0.44 loading in Figure 5, and for the 1.79 loading in Figure 7. For the textile waste, oxygen uptake rate data are shown for the 0.25 loading in Figure 9, for the 0.49 loading in Figure 11, and in Figure 13 for the 0.61 loading. Domestic waste oxygen uptake rates obtained are shown in Figure 15 for the 0.014 loading, in Figure 17 for the 0.029 loading, and for the 0.047 loading in Figure 19.

OXYGEN UTILIZATION DATA

The quanity of oxygen utilized as a function of time was calculated for each oxygen uptake rate determination by taking the area under the oxygen uptake rate vs. time curve. The resultant data is shown in Figures 4, 6, and 8 for the pulp and paper waste, in Figures 10, 12, and 14 for the textile waste, and in Figures 16, 18, and 20 for the domestic waste. These curves do not include that portion of oxygen which goes to satisfy cellular maintenance energy requirements, often referred to as "endogenous oxygen".

OTHER DATA

Shown in Table 4 are the loading factors, COD removal and sludge production data for each of the experiments. The times for essentially complete COD removal and complete oxygen utilization are shown in Table 5. Also shown in this table are the percentage of soluable COD uptake in the first one minute after the reactor was loaded for each of the experiments and rate of COD removal assuming zero order. Table 6 contains data

showing the percentage of theoretical (mass balance) oxygen utilization obtained for each determination method. In Table 7 are shown kinetic coefficients calculated from the data collected.














































Variation in COD Removed and Oxygen Utilized with Time for 0.61 Initial Loading for Textile Waste. Figure 14-























Variation in COD Removed and Oxygen Utilized with Time for 0.047 Initial Loading for Domestic Waste. 20-Figure

Initial Loading Factor	Initial MLVSS Concentration (mg./l.)	Final MLVSS Concentration (mg./l.)	Initial COD Concentration (mg./1.)	Final COD Concentration (mg./l.)
Pulp and Paper Waste 0.32 0.44 1.79	1860* 2546* 946*	1930* 2541* 1634*	1506 2369 2370	912 1140 645
Textile Waste 0.25 0.49 0.61	2570 2000 1533	2350 1900 1600	787 1077 1077	137 97 139
Domestic Waste 0.014 0.029 0.047	3590 2760 2530	3590 2300 2620	91 125 139	42 45 21

*Does not include waste VSS concentration

Table 4- Initial and Final MLVSS and COD Concentrations

abilization Time (Time for Removal Time Complete Stabilization Time 02 Utilization) 22 (min.)	120 270 44 480 0.63 0.63	195 0.54 485 0.62 330 1.00	50 0.50 120 0.33 210 0.86
Zero Order Sta COD Removal (mg./lhr. mg./l. MLVSS*) (0.24 0.24 0.21	0.16 0.10 0.11	0.03 0.05 0.02
Removal Time (Time for Complete COD Removal) (min.)	175 120 300	105 300 330	25 40 180
% COD Uptaken Initially	aste 13.9 16.9 21.7	12.3 17.2 30.5	12.1 31.2 55.4
Initial Loading Factor	Pulp and Paper W 0.32 0.44 1.79	Textile Waste 0.25 0.49 0.61	Domestic Waste 0.014 0.029 0.047

Table 5- COD Removal and Stabilization Data

Table 6- 1 1	Percentage of Determination	Theoretical Oxygen Utilization	ı for Each Method of	^c Oxygen Utilization
	Initial Loading Factor	Blok-Benefield Determination Method	Averaged Determination Method	Direct Measurement Determination Method
Pulp and I	Paper Waste 0.32 0.44 1.79	10.0% 25.2% 10.5%	30.8% 31.5% 61.4%	40.5% 33.2% 51.7%
Textile Wa	aste 0.25 0.44 0.61	58.1% 61.8% 52.1%	62.9% 67.4% 47.8%	134.2% 40.4% 35.6%
Domestic \	Waste 0.014 0.029 0.047	100.0% 6.4% 134.5%	109.7% 35.5% 57.1%	196.0% 17.1% 129.3%

•r •

•

Initial Loading Factor	rð	(day ⁻ 1)	K _d (day ⁻¹)	۲ t
Pulp and Paper Waste 0.32 0.44 1.79	0.469 0.430 0.338	1.29 0.92 0.60	0.91 0.65 0.42	0.08 0.00 0.39
Textile Waste 0.25 0.49 0.61	0.585 0.726 0.663	1.12 0.61 0.55	0.79 0.43 0.39	-0.34 -0.10 0.04
Domestic Waste 0.014 0.029 0.047	0.295 4.630 0.287	0.16 0.14 0.28	0.11 0.10 0.20	0.00 -2.84 -0.39

Table 7 - Kinetic Coefficients Calculated from Mass Balance Data for Each Experiment.



Figure 21- $ln(C_{+}C_{+})$ versus Time for 0.44 Initial Loading for Pulp and Paper Waste, for Endogenous Uptake Rate and Blok-Benefield $K_{1}a$ Calculation.

V DISCUSSION OF RESULTS

The data obtained in the course of these experiments may be viewed in a number of different contexts. The various methods used to calculate the quanity of oxygen utilized obviously do not agree. The variation in the ratio of rate of organic transfer to rate of organic stabilization, measured as rate of oxygen transfer, seems to indicate a proportionality to initial loading rate. The importance of loading factor to a number of parameters certainly merits inspection. Finally, the question of the applicability of oxygen utilization data to proposed design approaches must be addressed.

OXYGEN UTILIZATION DETERMINATION

Stoichiometric considerations dictate that the quanity of potential oxygen demand satisfied in an aerobic treatment system must be equivalent to the quanity of oxygen utilized plus the quanity of organic carbon incorporated into new sludge. In these experiments, oxygen demand was measured as COD, a parameter which does not take into account the oxygen that potentially goes into oxidation of nitrogen compounds. However, because the pulp and paper and textile wastes were found to be nitrogen limited, the nitrogenous oxygen demand was ignored. This assumption apparently had no significant effect on the oxygen utilization determination techniques used since none of these techniques yielded a utilization greater than that predicted from mass balance considerations for the pulp and paper and textile wastes. If a sizeable nitrogenous oxygen demand had exsisted in any of the wastes, measured oxygen utilization should have exceeded the predicted quanity. In the case of the domestic waste, which was not nitrogen limited, the data is a bit more complicated.

Nitrification did apparently occur during these experiments. This was reflected by certain of the oxygen utilization analyses methods but not by others.

<u>DIRECT MEASUREMENT METHOD</u>. Certainly one of the most easily run and least subject to error test commonly employed by the sanitary engineer is the direct measurement of oxygen uptake rate. The data collected by this method in these experiments, however, yielded oxygen utilization values which varied from 196 percent of that predicted by mass balance consider ations for 0.014 initial loading of domestic waste to 17 percent for 0.029 initial loading of domestic waste. Generally, the values obtained for the pulp and paper waste were lower than predicted theoretically. The textile waste data was lower in the case of two of the experiments and higher for the third. Oxygen usage for the domestic waste calculated by this method apparantly reflected a nitrification demand, the values being higher than predicted for two of the runs. In the case of the 0.029 initial loading of domestic waste, however, the values obtained were lower.

<u>AVERAGED METHOD</u>. The idea of using these directly measured uptake rates to calculate a K_{1} a that could be used to, in turn, calculate oxygen utilization, yielded, as would be expected, no better results. The ratio between the values calculated by this method and the values calculated by the direct measurement method was a function of which direct measurement method values for uptake rate were selected. Because selection was random, this ratio varied widely from 2.07:1 for the 0.029 loading of domestic waste to 0.44:1 for the 0.014 loading of domestic waste. Generally an increase in loading factor tended to show a corresponding

increase in this ratio. No simple proportion, however, was found to exist. One interesting aspect of these two methods was the difference in endogenous uptake rate calculated from each. The direct measurement method yielded values that were generally lower, although the total quanity of oxygen utilized was usually higher for this method.

<u>BLOK-BENEFIELD STEADY STATE METHOD</u>. Oxygen utilization calculated useing the Blok-Benefield method for evaluating K_1^{a} generally were the lowest of the four methods used. Evaluation of K_1^{a} in the case of the pulp and paper waste was quite difficult since the reaeration of the mixed liquor did not yield a linear plot of the ln ($C_s - C_t$) versus time, as is shown in Figure 21. A possible, if somewhat unsatisfying, explaination is that the high concentration of colloidal matter in this waste caused some interference with the DO probe.

Although Blok reported very good results using his method and comparing the oxygen utilization values with those values predicted by a mass balance analysis of his system, these experiments yielded values which were much too low. Blok did, however, warn against the application of his theories to such long run experiments. In the case of the single experiment which was of the length Blok characterized as "short term" the oxygen utilization curve obtained coincided with the theoretical curve.

For each of these methods, the shape of the oxygen utilized versus time curve was consistent with the other methods. Comparison of more than two of these methods in this regard was somewhat repititious, since each of the indirect methods was an amplification of the same curve. Only the direct measurement method was unique. Whatever variations in shape may occur between the oxygen uptake rate curves obtained by the

direct measurements method and those curves obtained by the other methods, the shapes of the oxygen utilization curves were remarkably similar. The times required to complete non-endogenous transfer of oxygen were virtually the same for each run. This is, perhaps, an indication that the problem in evaluating oxygen utilization in a batch reactor is associated with evaluating K_1a . If this is the case, then use of the time to end of oxygen uptake as the time to end of stabilization as proposed by the Weston group is valid.

CONSIDERATION OF LOADING FACTOR

The difference between the ratio of time of COD transfer to time of COD stabilization, measured as non-endogenous oxygen uptake time, was found to vary as the initial loading factor. One possible explaination for this is that the initial uptake of COD by the organisms was a greater percentage of the COD stabilized at the lower loading factor. This idea might be used to explain the contact-stabilization variation of the activated sludge process. In the case of these wastes and loading factors, however, such was not found to be the case. The percentage of soluble COD removed in the first one minute of these experiments generally increased with increasing initial loading factor, as is shown in Table 5. If this were the case, the percentage of COD uptaken initially would be higher at lower loading factors. The difference in transfer and stabilization times was more likely a result of stabilization of microbial mass, loss of mass occurring at the lower loadings and after stabilization of biodegradable COD.

The rate of removal of COD, assumed to be zero order as proposed by Weston, was found to be generally unrelated to the initial loading factor,

shown in Table 5. While, substrate removal for most of the experiments appeared to follow a higher order of removal, this order was not easily discovered. In the case of the textile waste, the simplest of these wastes tested, removal was zero order, following an initial uptake. Despite this apparent removed behavior, however, oxygen utilization, and therefore substrate stabilization was closer to first order for all three wastes.

APPLICATION OF OXYGEN UTILIZATION DATA TO DESIGN

As has been previously discussed, the non-endogenous oxygen uptake time can probably be taken as equal to stabilization time, as long as solids destruction did not occur. The results of these experments cast grave doubt upon use of oxygen uptake data for other design purposes, however, The problem of mass balance of oxygen demand and oxygen utilized in the system has already been discussed. The idea that sludge production can be defined as

$$X = \frac{\text{COD}_{\text{removed}} - 0_{2}_{\text{utilized}}}{1.42}$$

is, nonetheless, directly based upon mass balance and an assumed microbial chemical formulation. The argument of Blok and Benefield that

$$K_{d} = \frac{R}{1.42 \text{ X}}$$

would imply that a change in solids concentration, X, must be accompanied by a corresponding change in R, the endogenous oxygen uptake rate. Although solids concentration decreased in the course of a number of the experiments, the endogenous uptake rate always remained constant or increased, and usually the latter. It is possible that the original

MLVSS concentration represented a very high proportion of non-viable but biodegradable matter. Growth of new microbical mass in the course of the experiment may have been insufficient to offset the loss of non-viable solids. This could account for this phenomona.

Evaluation of design parameters for these wastes by the method proposed by Benefield is highly dependent upon these solids data. Without some idea of what the endogenous utilization rate actually is, the oxygen requirement coefficients, a and b, and yield coefficient, Y, are apparently not obtainable for these wastes. The values shown in Table 7 assumes that final MLVSS represents all viable organisms and the endogenous respiration rate is calculated on this basis. It is apparent that these coefficients are not at all reasonable. The method of obtaining kinetic coefficients proposed by Benefield is, then, not applicable to these experiments.

VI CONCLUSIONS

Evaluation of the data from the series of batch experiments has led to the following conclusions:

- 1. Currently used methods of quantifying oxygen uptake rate, especially for batch reactors, yield values of oxygen utilization considerably lower than those predicted by mass balance considerations for these three wastes. In the face of Blok's published data indicating much better results with a short run reactor, it must be assumed that the length of run selected was at least partially responsible.
- 2. While quantitatively unsatisfactory, the methods for determining oxygen uptake used in these experiments seem to be of some use as monitors of biological systems. Changes in slope of the oxygen utilization curve were found to be more apparent at lower loadings.
- 3. For the pulp and paper waste, oxygen transfer appeared to be other than first order. This may have been due to interference with the DO prove by the colloidal material present in the waste.
- Apparent variations in the ratio of transfer time to stabilization time were probably due to biomass destruction.

- Percentage of soluble COD initially removed was found to vary with initial loading factor.
- 6. The method proposed by Benefield for quantifying the kinetic coefficients, Y, K_d , a, and b was not applicable to these wastes.

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APPENDIX

DATA FO	R 0.32 INITI	AL LOADING (OF PULP AND F	APER WASTE								·
	FILTER	D COD	DISSOLVED	OXYGEN	BLOK-BENEFIE K _l a=(ELD METHOD 0.157	AVERAGET K ₁ a=() METHOD).487	MASS BALAN ^K l ^{a=}	ICE METHOD	DIRECT MEA METH	SUREMENT
TIME min.	REMAINING mg./l.	REMOVED mg./1.	CONC. C mg ^t /1.	DEFICIT (CC_) mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTIL1ZED mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./l.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./1.
End.	1506	0	7.45	1.10	0.17	0.0	0.54	0.0	1.74	0.0	0.15	0.0
1	1296	210	6.20	2.35	0.37	0.1	1.14	0.3	3.71	1.0	1.40	0.6
6.5	1296	210	6.05	2.50	0.39	1.3	1.22	4.0	3.95	12.5	1,45	7.6
11	1200	306	5.80	2.75	0.43	2.3	1.34	7.1	4.35	23.3	1.60	13.7
15	1168	338	3.60	4.95	0.78	4.1	2.41	12.7	7.82	40.7	1.70	19.6
20			2.50	6.05	0.95	7.6	2.95	23.6	9.56	75.4	2.33	28.8
25	1024	482	2.25	6.30	0.99	11.6	3.07	36.0	9.95	115.5		
30	736	770	2.18	6.37	1.00	15.7	3.10	48.7	10.06	156.8	1.47	45.7
40	928	578	6.75	1.80	0.28	20.4	0.88	63.3	2.84	203.9	1.40	57.8
50	960	546	6.80	1.75	0.27	21.4	0.85	66.4	2.77	214.6	1.12	67.9
60	880	626	6.87	1.68	0.26	22.4	0.82	69.5	2.65	224.3	1.23	76.9
75	912	594	6.80	1.75	0.27	23.8	0.85	73.8	2.77	238.8	1.00	89.2
90	960	546	6.80	1.75	0.27	25.3	0.85	78.5	2.77	254.3	0.93	97.1
120	944	562	7.45	1.10	0.17	26.8	0.54	83.1	1.74	269.7	0.60	106.0
150	912	594	7.45	1.10	0.17	26.8	0.54	83.1	1.74	269.7	94.9	100.1

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DATA FOR 0.44 INITIAL LOADING OF PULP AND PAPER WASTE

	FILTERE	D COD	DISSOLVE	O XYGEN	BLOK-BENEFII Kja=0	LD METHOD 0.530	AVERAGE(K ₁ a=(D METHOD D.663	MASS BALAN Kja=	ICE METHOD	DIRECT ME/ METH	ISUREMENT IOD
TIME min.	REMAINING	REMOVED	CONC.	DEFICIT (C -C.)	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UT 11 17ED
	ing./1.	ilig., 1.	°t mg./l.	mg./1.	mg./lmin.	mg./1.	mg./1min.	mg./1.	mg./lmin.	mg./1.	mg./lmin.	mg.,1.
	2369	0	7.80	0.75	0.40	0.0	0.50	0.0	1.60	0.0	0.34	0.0
1	1308	1061	7.30	1.25	0.66	0.1	0.83	0.1	2.66	0.5	1.65	0.7
5	1707	662	6.14	2.41	1.28	4.8	1.60	5.9	5.14	7.4	1.65	4.6
10	1893	476	5.88	2.67	1.42	10.4	1.77	13.1	5.69	30.3	1.40	11,7
15	1838	531	5,87	2.68	1.42	15.6	1.78	19.5	5.71	50.8	1.64	17.6
20	1734	635	5,80	2.75	1.46	20.8	1.82	26.0	5.86	71.7	1.50	23.7
20	1289	1080	5.57	2.98	1.58	26.4	1.98	33.0	6.35	94.3	1.80	30,1
20	1481	888	5.72	2.83	1.50	32.0	1.88	40.1	6.03	117.2	1.33	36.2
30	1910	550	5.68	2.87	1.52	43.2	1.90	54.0	6.12	162.0	1.32	45.8
40	1810	943	4 75	3,80	2.01	56.8	2.52	71.0	8.10	217.1	2.10	59.2
50	1426	345	6.65	1 90	1.01	67.9	1.26	84.9	4.05	261.8	1.53	73.6
60	1584	750	6.72	1.83	0.97	76.8	1.21	96.0	3.90	297.4	1.20	895.2
/5	1019	1245	6.60	1.95	1.03	85.8	1.29	107.3	4.16	333.7	1.10	99.5
90	0.05	1245	6.72	1.83	0.97	94.8	1.21	118.5	3.90	370.0	1.02	109.2
105	905	1100	6.83	1.72	0.91	102.8	1.14	128.7	3.67	402.6	1.20	119.6
120	21.05	174	7.07	1.48	0.78	115.5	0.98	144.4	3.15	456.5	1.18	142.0
150	2195	1220	7 34	1 21	0.64	124.0	0.80	155.1	2.58	493.8	1.09	162.3
180	1139	1230	7.50	1.05	0.56	130.0	0.70	162.6	2.24	517.4	0.65	174.0
610	1200	1142	7 72	0.83	0.44	133.0	0.55	166.4	1.77	528.6	0.50	176.3
240	1227	1036	7 70	0.77	0.41	133.7	0.51	167.3	1.64	530.7	0.50	176.3
27.0	1333	1169	7 78	0.77	0,41	133.7	0.51	167.3	1.64	530.7	0.50	176.3

	FILTER	D COD	DISSOLVE	D OXYGEN	BLOK-BENEFII	ELD METHOD D.105	AVERAGEI Kja=0	0 METHOD 0.614	MASS BALAN Kja=1	ICE METHOD .03	DIRECT ME/ METH	ASUREMENT 100
nin.	REMAINING mg./l.	REMOVED mg./l.	CONC. ^C t	DEFICIT (C _s -C _t)	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED
				mg./1.	mg./1min.	mg./l.	mg./1min.	mg./1.	mg./l.~min.	mg./l.	mg./lmin.	mg./l.
End.	2370	0	7.95	0.60	0.06	0.0	0.37	0.0	0.62	0.0	0.19	0.0
1	1855	515	7.20	1.35	0.14	0.0	0.83	0.2	1.39	0.4	0.94	0.4
5	1960	410	7.10	1.45	0.15	0.4	0.89	2.2	1.49	3.7	1.45	4,4
10	1774	596	7.10	1.45	0.15	0.8	0.89	4.8	1.49	8.0	1.10	9.8
15		=-	7.20	1.35	0.14	1.2	0.83	7.3	1.219	12.1	1.10	14,3
20	1102	1268	7.30	1.25	0.13	1.6	0.77	9.4	1.29	15,7	0.95	18.3
25	1586	784	7.25	1.30	0.14	2.0	0.80	11.4	1.34	19.2	1.30	22.9
30	1492	. 878	7.20	1.35	0.14	2.3	n.83	13.6	1.39	22.9	1.07	27.8
40	1465	905	6.80	1.75	0.18	3.3	1.07	19.5	1.80	32.7	1.10	a11° C
50	1479	891	6.80	1.75	0.18	4.5	1.07	26.6	1.80	44.5	0.95	44.5
60	1465	905	6.80	1.75	0.18	5.8	1.07	33.6	1,80	56.3	0.93	51.6
75	1344	1026	6.60	1.95	0.20	7.7	1.20	45.1	2.01	75.5	1.20	63.9
90	1183	1187	6.45	2.10	0.22	10.0	1.29	58.2	2.16	97.5	1.25	78.4
105	1183	1187	5.95	2.60	0.27	12.7	1.60	74.3	2.68	124.5	1.30	93.5
120	1102	1268	6.20	2.35	0.25	15,7	1.44	91.6	2.42	153.3	1.10	107.2
150	1187	1183	6.10	2.45	0.26	21.3	1.50	124.7	2.52	208.5	1.20	132.7
180	1102	1268	6.60	1.95	0.21	26.4	1.20	154.2	2.01	257.6	0.87	154.0
210	927	1443	7.10	1.45	0.15	29.8	0.89	174.5	1.49	290.9	0.68	166.8
240	828	1542	7.45	1.10	0.12	32.0	0.66	186.8	1.13	311.0	0.75	177.4
300	645	1725	7.10	1.45	0.15	36.4	0.89	213.1	1.49	350.6	0,98	205,8
360	699	1671	7.00	1.55	0.16	42.1	0.95	246.2	1.60	404.3	0.72	20110
420	645	1725	7.40	1.15	0.12	46.8	0.71	273.0	1.18	448.1	0.60	237.6
480	607	1763	7.90	0.65	0.07	48.7	0.40	284.7	0.67	463.4	0.59	239.4

DATA FOR 1.79 INITIAL LOADING OF PULP AND PAPER WASTE

DATA FOR 0.25 INITIAL LOADING OF TEXTILE WASTE

TIME	FILTERE	D COD	DISSOLVE	D OXYGEN	BLOK-BENEF ^K l ^{a=0}	IELD METHOD	AVERAGE K ₁ a=	D METHOD D.920	MASS BALA ^K l ^{a=}	NCE METHOD	DIRECT MEA METH	ASUREMENT HOD
min.	REMAINING mg./l.	REMOVED mg./1.	CONC. ^C t mg./1.	DEFICIT (C _s -C _t) mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./l.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./l.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./l.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./l.
End.	787	0	7.30	1.25	1.06	0.0	1.15	0.0	1.84	0.0	0.25	0.0
1	690	97									2.49	1.1
5	675	112	4.90	3.65	3.10	5.1	3.36	5.5	5.36	8.8	5.10	15.1
10	646	141	3.90	4.65	3.95	17.4	4.28	18.8	6.83	30.1	9.00	43.8
15	646	141	3.75	4.80	4.08	32.2	4.41	34.8	7.05	55.6	9.60	94.0
20	623	164	3.65	4.90	4.17	47.5	4.51	51.4	7.20	82.0	9.40	140.2
25	574	213	3.54	5.01	4.26	63.3	4.61	68.5	7.36	109.2	9.20	185.4
30	597	190	3.50	5.05	4.29	79.4	4.64	85.9	7.42	137.0	9.00	229.6
40	556	231	3.47	5.08	4.32	111.8	4.67	121.0	7.46	193.0	7.60	310.0
50	504	283	3.50	5.05	4.29	144.3	4.64	156.1	7.42	249.0	5.70	373.7
60	302	485	3.70	4.85	4.12	175.7	4.46	190.1	7.12	303.3	4.80	423.4
75	258	529	6.12	2.43	2.06	206.2	2.23	223.1	3.57	355.8	4.30	487.2
90	183	604	6.45	2.10	1.79	219.5	1.93	237.5	3.08	378.1	1.50	526.1
105	138	649	6.73	1,82	1.55	228.3	1.67	247.0	2.67	393.6	0.80	538.7
120	123	664	7.07	1.48	1.26	233.5	1.36	252.6	2.17	402.3	0.45	543.4
135	116	671	7.15	1.40	1.19	236.0	1.29	255.3	2,06	406.5	0.50	545. h
165	131	656	7.27	1.28	1.09	238.4	1.18	257.9	1.88	410.4	0.45	549.6
105	123	664	7.30	1.25	1.06	238.8	1.15	258.4	1.84	411.0	0.38	551.3
240	138	649	7.30	1.25	1.06	238.8	1.15	258.4	1.84	411.0	0.37	551.5
270			7.30	1.25	1.06	238.8	1.15	258.4	1.84	411.0	0.39	551.5
300	101	686	7.30	1.25	1.06	238.8	1.15	258.4	1.84	411.0	0.37	551.5
500												

TIME	FILTER	ED COD	DISSOLVE	D OXYGEN	BLOK-BENEF K ₁ a=	IELD METHOD 0.330	AVERAGE Kja=	D METHOD 0.360	MASS BALA ^K 1 ^{a=1}	NCE METHOD D.520	DIRECT MEA METH	ASUREMENT 10D
min.	REMAINING mg./l.	REMOVED mg./l.	CONC. ^C t mg./1.	DEFICIT (C _s -C _t) mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./l.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./l.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./1.	UPTAKE RATE mg./lmin.	OXYSEN UTILIZED mg./1.
End.	1077	0	7.00	1.55	0.51	0.0	0.56	0.0	0.81	0.0	0.20	0.0
1	392	185	6.90	1.65	0.54	0.0	0.59	0.0	0.86	0.0	1.65	0.7
5	922	155	6.07	2.48	0.82	0.7	0.90	0.8	1.29	1.1	1.80	6.8
10	937	140	5.65	2.90	0.96	2.6	1.05	2.8	1.51	4.0	2.06	15.5
15	328	249	2.28	6.27	2.07	7.6	2.26	8.3	3.27	11.9	2.00	24.6
20	814	263	0.10	8.45	2.79	17.2	3.05	18.8	4.40	27.1	1.92	33.4
25	776	301	0.00	8.55	2.82	28.7	3.08	31.3	4.46	45.2	1.80	41.6
30	761	316	0.00								1.65	49.2
40	716	361	0.00								1.65	63.6
50	634	443	0.00								1.60	77.1
60	582	495	0.00								1.60	91.5
75			0.00								1.95	114.7
90	500	577	0.00								1.92	140.3
105	463	614	0.00								1.93	165.7
120	340	737	0.00								1.68	169.1
150	231	846	0.00								1.60	231.0
155	¹	'	n.00	8.55	2.82	317.4	3.08	346.6	4.46	519.7		
180	157	920	3.30	5.25	1.73	361.6	1.89	394.8	2.74	589.4	0.65	257.1
240	149	928	5.28	3.27	1.08	415.3	1.18	453.5	1.70	674.0	0.40	272.4
288			5.40	3.15	1.04	441.7	1.14	482.3	1.64	715.3		
289			6.45	2.10	0.69	442.0	0.75	482.6	1.09	715.8		
300	97	980	6.57	1.98	0.65	443.8	0.71	484.6	1.03	718.6	0.41	279.0
360	104	973	6.90	1.65	0.54	448.9	0.59	490.1	0.86	726.7	0.47	286.2
485	93	984	7.00	1.55	0.51	450.8	0.56	492.2	0.81	729.8	0.37	244.9
											1	

DATA FOR 0.61 INITIAL LOADING OF TEXTILE WASTE

TIME	FILTER	D COD	DISSOLVE	D OXYGEN	BLOK-BENEF K1 ^{a=0}	IELD METHOD 7.530	AVERAGE Kja=	D METHOD 0.486	MASS BALAN ^K l ^{a=1}	NCE METHOD	DIRECT ME/ METH	ASUREMENT 10D
min.	REMAINING mg./l.	REMOVED mg./1.	CONC. C _t mg./1.	DEFICIT (C _s -C _t) mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./l.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./1.	UPTAKE RATE mg./lmin.	OXYSEN UTILIZED mg./l.
End.	1077	0	8.15	0.40	0.21	0.0	0.20	0.0	0.41	0.0	0,25	0.0
1	748	329	7.10	1.45	0.70	0.3	0.70	0.2	1.47	0.5	0.93	0.3
5	701	376	6.45	2.10	1.11	3.2	1.02	2.9	2.14	6.1	1.25	3.7
10	712	365	5.77	2.78	1.47	8.6	1.35	7.9	2.83	16.5	1.27	8.8
15	672	405	5.38	3.17	1.68	15.4	1.54	14.1	3.22	29.5	1.27	13.8
20	672	405	5.10	3.45	1.83	23.0	1.68	21.1	3.51	44.2	1.53	19.6
25	661	416	4.88	3.67	1.95	31.4	1.78	28.8	3.73	60.2	1.60	26.1
30	555	522	4.75	3.80	2.01	40.1	1.84	36.8	3.86	77.0	1.53	32.6
10	577	500	4.50	4.05	2.15	58.7	1.97	53.8	4.12	112.6	1.40	44.7
50	569	508	4.37	4.18	2.22	78.2	2.03	71.7	4.25	150.1	1.47	5€.4
60	547	530	4.23	4.32	2.29	98.4	2.10	90.2	4.39	188.9	1.40	68.1
75	489	588	4.05	4.50	2.38	129.9	2.19	119.1	4.58	249.3	1.27	84.1
90	467	610	3.92	4.63	2.45	162.7	2.25	149.1	4.71	312.1	1.27	99.0
105	420	657	3.87	4.68	2.48	196.0	2.27	179.7	4.76	376.1	1.27	113.9
1.10	380	697	3,88	4.67	2.48	229.5	2.27	210.3	4.75	440.3	1.40	129.7
150	285	792	5.37	3.18	1.69	284.2	1.54	260.5	3.23	545.3	1.60	166.2
1:0	168	909	7.31	1.24	0.66	311.4	0.60	285.4	1.26	597.4	1,00	196.3
210	201	876	7.44	1.11	0.59	321.7	0.54	294.9	1.13	617.3	0.47	209.7
240	161	916	7.58	0.97	0.51	329.7	0.47	302.2	0.99	632.6	0.49	214.2
270			7.82	7.73	0.39	334.4	0.35	306.5	0.74	641.6	0.50	219.3
3.30	139	938	7.95	0.60	0.32	337.1	0.29	308.9	0.61	646.7	0.43	226.3
3:90	139	938	7.95	0.60	0.32	337.1	0.29	308.9	0.61	646.7	0.38	229.8
450	139	938	7.95	0.60	0.32	337.1	0.29	308.9	0.61	646.7	0.38	230.4

T 1 MF	FILTERE	D COD	DISSOLVE	D OXYGEN	BLOK-BENEF Kja=	TELD METHOD 0.320	AVERAGE ^K l ^{a=1}	D METHOD D.348	MASS BALAN Kja=1	NCE METHOD 0.317	DIRECT ME	ASCREMENT HOD
min.	REMAINING mg./l.	REMOVED mg./1.	CONC. ^C t mg./1.	DEFICIT (C _s -C) mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZED mg./1.	UPTAKE RATE mg./lmin.	OXYGEN UTILIZE mg./1.
End.	91	0	7.40	1.15	0.37	0.0	0.40	0.0	0.36	0.0	0,24	0.0
1	80	11	6.60	1.95	0.62	0.1	0.68	0.1	0.62	0.1	0.95	0.4
5	82	9	6.00	2.55	0.82	1.5	0.89	1.6	0.81	1.6	0.80	2.9
10	61	30	6.05	2.50	0.80	3.7	0.87	4.0	0.79	3.7	0.92	6.0
15	77	14	6.10	2.45	0.78 、	5.8	0.85	6.3	0.78	5.8	1.00	9.6
20	77	14	6.17	2.38	0.76	7.8	0.83	8.5	0.75	7.8	1.00	14.4
25	42	49	6.23	2.32	0.74	9.7	0.81	10.5	0.74	9.6	1.00	17.2
30	97		6.29	2.26	0.72	11.4	0.79	12.4	0,72	11.4	0.93	20.8
40	58	33	6.64	1.91	0.61	14.2	0.66	15.4	0.61	14.2	0.73	26.7
50	76	15	7.28	1.27	0.41	15.4	0.44	16.7	0.40	15.3	0.29	29.4
60		••	7.30	1.25	0.40	15.5	0.43	16.9	0.40	15.4	0,28	29.9
75	57	34	7.30	1.25	0.40	15.5	0.43	16.9	0.40	15.4	0,24	30.2
90			7.30	1.25	0.40	15.5	0.43	16.9	0.40	15.4	0.24	30.2

DATA FOR 0.029 INITIAL LOADING OF DOMESTIC WASTE

T IME	FILTER	D COD	DISSOLVE	D OXYGEN	BLOK-BENEF K _l a≖	IELD METHOD 0.147	AVERAGE K1ª=	D METHOD 0,816	MASS BALA ^K l ^{a=1}	NCE METHOD 2.28	DIRECT ME Meti	eub VilioEMENT
min.	REMAINING mg./1.	REMOVED mg./1.	CONC. Ct	DEFICIT (C _s -C _t)	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	orvgen of DE1210
			mg./1.	mg./1.	mg./lmin.	mg./1.	mg./lmin.	mq./1.	mg./lmin.	mg./1.	mg./l.~min.	mq./1.
End,	125	0	8.45	0.10	0.01	0.0	0.08	0.0	0.23	0.0	0.19	0.0
1	86	39	7.10	1.45	0.21	0.1	1.18	0.6	3.31	1.5	1.04	0.4
5	103	22	5.92	2.63	0.39	0.8	2.15	4.6	6.01	12.6	1.03	2.5
10	93	32	5.31	3.24	0,48	2.6	2.64	14.4	7.40	54.7	1.00	7.9
15	78	47	5.72	2.83	0.42	5.8	2.31	32.1	6.46	88.2		
20	65	60	5.96	2.59	0.38	7.7	2.11	43.0	5.91	118.0	0,90	15.5
25	61	64	6.20	2.35	0.35	9.5	1.92	52.8	5.37	145.0	0.87	19.0
30	64	61	6.65	1.90	0.28	11.0	1.55	61.3	4.34	168.2	1.07	22.9
40	46	79	6.95	1.60	0.24	13.5	1.31	74.9	3.65	205.8	0.80	÷0,3
50	44	81	7.04	1.51	0.22	15.7	1.23	87.1	3.45	239.0	0,80	36.4
60	40	85	7.15	1.40	0.21	17.7	1.14	98.3	3.20	270.0	0,80	42.5
75	52	73	7.31	1.24	0,18	20.1	1.01	111.6	2.83	311.7	0,80	51.7
90	46	79	7.48	1.07	0.16	23.0	0.87	127.5	2.44	347.8	0.68	59,9
105	42	83	8.14	0.41	0.06	23.8	0.33	132.3	0.94	369.7	0.23	63,9
120	45	80	8.45	0.10	0.01	24.0	0.08	133.0	0.21	375.0	0.20	+4.2

TIME min.	FILTERED COD		DISSOLVED OXYGEN		BLOK-BENEFIELD METHOD Kja=0.452		AVERAGED METHOD K ₁ a=0.192		MASS BALANCE METHOD Kja=0.336		DIRECT MEAKING MENT METHOD	
	REMAINING	REMOVED	CONC. Ct	DEFICIT (C _s -C _t)	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED	UPTAKE RATE	OXYGEN UTILIZED	UPTA+E PATE	074663 1211,1210
			mg./1.	mg./1.	mg./lmin.	mg./1.	mg./1min.	mg./1.	mg./lmin.	mg./1.	mg./lmin.	ng./1.
End.	139	0	7.33	1.22	0.55	0.0	0.23	0.0	0.41	0.0	0.10	0.0
1	62	77	6.48	2.07	0.94	0.2	0.40	0.1	0.70	0.1	0.40	0.1
5	49	90	6.70	1.85	0.84	1.6	0.35	0.7	0.62	1.2	0.40	1.4
10	94	45	6.70	1.85	0.84	3,0	0.35	1.3	0.62	2.2	0.50	3,1
15	66	73	6.67	1.88	0.85	4.5	0.36	1.9	0.63	3.3	0,60	5.4
20	53	86	6.62	1.93	0.87	6.0	0.37	2.5	0.65	4.5	0.48	7.5
25	78	61	6.59	1.96	0.89	7.6	0.38	3.2	0.66	5.6	0.45	9.3
30	127	12	6.55	2.00	0.90	9.2	0.38	3.9	0.67	6.8	0.48	11.1
40	156		6.48	2.07	0.94	12.8	0.40	5.4	0.70	9.5	0.40	14.4
50	49	90	6.41	2.14	0.97	16.6	0.41	7.0	0.72	12.3	0.46	17.6
60	57	82	6.38	2.17	0.98	20.6	0.42	8.7	0.73	15.3	0.37	20.6
75	69	70	6.54	2.01	0.91	26.0	0.39	11.0	0.68	19.3	0.35	24.2
90	57	82	6.60	1.95	0.88	30.6	0.37	13.0	0.66	22.7	0.35	27,6
105	41	98	6.64	1.91	0.86	34.7	0.37	14.7	0.64	25.8	0.33	30.8
120	62	77	6.70	1.85	0.84	38.4	0.35	16.3	0,62	28.5	0.31	33.6
150			6.75	1.80	0.81	44.7	0.35	19.0	0.60	33.2	0.30	38.7
180	29	110	6.70	1.85	0.84	50.2	0.35	21.3	0.62	37.3	0.35	44.1
210	37	102	6.97	1.58	0.71	53.8	0.30	22.8	0.53	40.0	0.28	48.9
300	21	118	7.00	1.55	0.70	56.5	0.30	24.0	0.52	42.0	0.18	54.3

DATA FOR 0.047 INITIAL LOADING OF DOMESTIC WASTE
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A COMPARISON OF OXYGEN UTILIZATION DETERMINATION TECHNIQUES FOR THE ACTIVATED SLUDGE PROCESS

by

Warren Michael Stallard

(Abstract)

Batch reactor experiments were conducted on three different wastewaters and the data obtained used to evaluate and compare oxygen utilization determination techniques. Also evaluated was a method for use of oxygen utilization data to determine certain kinetic coefficients required for design of activated sludge treatment systems.

Little agreement between the various oxygen utilization determination techniques was found, casting doubt upon all of the techniques. Consideration of the mass balance of the reactor contents yielded no agreement, either. The coefficient evaluation technique was not found to be applicable.

A description of the investigation and the various factors considered is included.