THE INVESTIGATION OF OXYGEN CONSUMPTION RATE IN THE CHARACTERIZATION OF BIOLOGICAL SOLIDS IN THE ACTIVATED SLUDGE SYSTEM

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LIST OF SYMBOLS

Cdd - Concentration after dd days. Used in discussing the exponential decay function.

Co - Initial concentration at the start of Exponential decay.

dd - Decay days when discussing the exponential decay function.

F - The flow rate of feed into the continuous reactor in liters per day.

K - The viable solids decay rate per day.

Kb - The saturation constant in terms of milligram of feed substrate to milligram of volatile suspended solids per day of a limiting exponential curve. Used in the Kincannon/Stover model which uses feed mass to solids mass ratio as the controlling factor.

Kc - The substrate utilization rate per day used in the McKinney substrate limiting model.

Kd - The endogenous factor of the decay of solids per day in the continuous reactor system.

Kdv - The solids decay rate per day of viable solids similar to the endogenous factor except only viable solids are considered.

Km - The metabolism rate per day of substrate used in growth of viable solids. This rate produces the observed yield and is the exponential rate that substrate is used for energy in growth of new viable solids.

Kmaint- The substrate equivalent of the endogenous factor used when referring to the substrate being used to maintain vital functions in the bioligical solids when insufficient substrate is available.

Ks - The saturation constant of a limiting exponential curve. It has units of milligrams per liter and is numerically equal to the substrate concentration at which the substrate utilization rate is half of the maximum substrate utilization rate. This is also the point where the utilization of substrate is the most efficient.

Kv - The substrate utilization rate specific to viable solids in units of milligram of substrate per milligram of viable solids using the substrate per day.

n - The number of times 50 ml of mixed-liquor solids is with drawn in conducting the Modified Oxygen Consumption rate test.

R - Correlation coefficient use in regression analysis to identify relationship between value of two different factors.

R^2 - The correlation index. Is equivalent to the correlation coefficient squared and is used as a rough indicator of the fraction of correlation of two different variable in regression.

Resp - The concentration of BOD in milligrams per liter which is used in growth as an energy source when new biological solids are produced.

Se - The substrate concentration in BOD milligrams per liter of effluent leaving the reactor through the clarifier.

Sg - The substrate concentration in BOD milligrams per liter used in the growth of new solids.

Si - The substrate concentration in BOD milligrams per liter of the feed entering the continuous reactor.

SRT - The sludge retension time of a continuous reactor and the inverted net growth rate of solids.

T - The temperature in Celsius used in analysing factors affecting decay of biological solids.

U - The specific substrate utilization rate per day which has the maximum of Umax.

Umax - The maximum specific substrate utilization in terms of milligrams of substrate used per milligrams of solids using it per day. Used in the models which use effluent substrate as the controlling factor in substrate utilization.

Um - The maximum specific substrate utilization rate per day used in the Kincannon/Stover model.

Un - The net specific growth rate of solids per day in a reactor specific to volatile suspended solids.

Uv - The growth rate of solids in the reactor specific to only viable solids in units of per day.

V - The volume of the continuous reactor in liters.

VSS - The volatile suspended solids.

Vw - The volume of mixed-liquor solids wasted each day.

Xe - The concentration of volatile suspended solids leaving the reactor through the clarifier in milligram per liter.

Xv - The viable solids in milligrams per liter calculated from the volatile suspended solids using the decay and substrate metabolism rate.

Xt - The volatile suspended solids concentration in the continuous reactor in milligrams per liter.

Y - The true yield of solids produced to the substrate used in the utilization of substrate. This is the yield term determined from regression of net specific growth rate versus the specific substrate utilization rate.

Yo - The observed mean yield of solids produced to the substrate used in the utilization of substrate at a specific growth rate.

CHAPTER I

INTRODUCTION

In the realm of waste water treatment high quality effluent and efficient operation become prime goals. Activated sludge systems at one time were viewed as the best overall system because of the additional flexibility allowed in changing the solids concentration by recycling clarified solids back into the reaction chamber. These systems, however, have not been exempt from the difficulties of meeting effluent requirements characteristic of the industry. Feliciano (1) reported that a General Accounting Office investigation in 1980 indicated that 50 to 75% of the treatment plants investigated were in violation of their discharge permits and that deficiencies of design, equipment, overload, operation and maintenance were the chief causes. It is not uncommon for an activated sludge treatment plant to have to make modification in operation such as turning off half of the aeration capacity of the plant to meet effluent requirements because the plant was overdesigned or underdesigned.

In order to properly design an activated sludge treatment process bench scale tests must be conducted for several months and the data collected and analyzed to determine the appropriate characteristics of the biological organisms. These tests increase the design costs of a treatment plant due to the extensive care required to operate the bench scale units. The data from these tests generally is analyzed by one of the standard biokinetic models for determination of the size of the reaction chamber. Judgement errors such as using average values or an inappropriate percentile of the data can occur due to the characteristic variability of the bench scale test data when analyzed using various accepted models. Because of the cost and difficulty in understanding these concepts, many consultants bypass these important bench scale tests and take the risk of improperly designing the treatment plant.

Reinvestigation into the biological activity of this type of process appears warranted to develop a better understanding of the process and to identify potentials for less expensive methods of obtaining design data. An original modification by the author of the oxygen consumption rate test was used in this thesis to investigate the biological activity of a bench scale system in order to determine additional insight to the biological process and to investigate the potential for obtaining design data from oxygen consumption test analysis.

CHAPTER II

LITERATURE REVIEW

In order to follow the determination in this investigation an understanding of the basic Activated Sludge models as well as microbial viability and microbial mortality determination is important. All of the various models arise out of assumptions made from the mass balance of the microbial solids or the mass balance of the substrate. The mass balance for microbial solids in a system is that the rate of change of solids is equal to the solids leaving the system through wasting or effluent flow and the accumulation of solids due to growth

$$dXt/dt*V = - Vw*Xt - (F-Vw)Xe + \text{net growth rate} \quad (2\text{-}1)$$

where Xt equals volatile suspended solids concentration, V is the volume of the aeration chamber or reactor, Vw is the volume of mix-liquor wasted each day from the reactor, F is the flow of feed into the reactor and Xe is the effluent volatile suspended solids concentration leaving the system. At steady state the net change of solids is zero and the Solids Retension Time (SRT) can be determined as the inverse of the net growth rate.

$$SRT = \frac{Xt*V}{(F-Vw)Xe + Vw*Xt} \quad (2\text{-}2)$$

The SRT can be altered simply by changing the daily volume wasted (Vw) from the reactor. The net growth rate or inverse SRT can be converted to substrate utilization rate, discussed next, by dividing by the yield ratio of biological mass produce to substrate mass utilized (Y).

The activated sludge models are most often discussed from a substrate mass balance concept. At steady state the substrate entering the system (Si) must match the substrate utilized by the microorganisms plus the substrate leaving the system (Se).

$$F*Si = \text{Microbial Utilization} + F*Se \qquad (2\text{-}3)$$

The microbial utilization of substrate can be expressed as a substrate utilization specific to microbial mass dSg/(Xt*dt) or as simply substrate utilization dSg/dt. In the first case the substrate into the system equation would be:

$$F*Si = \frac{dSg}{Xt*dt}*Xt*V + F*Se \qquad (2\text{-}4)$$

The second choice would be:

$$F*Si = \frac{dSg}{dt}*V + F*Se \qquad (2\text{-}5)$$

The various models differ only in how they express this substrat utilization term. One of the models expresses the substrate utilization term as proportional to effluent substrate; other models express it as a Monod function of the effluent substrate. Another model expresses the specific substrate utilization as a Monod function of the ratio of substrate mass into the system to the mass of microbial solids in the system.

A. Kinetic Models

The various models used in water treatment design fall into three major groups depending upon how the substrate utilization is expressed.

The first group is the Kincannon/Stover (2) model. It is unique in that it uses the ratio of substrate mass into the system to mass of microbial solids (F*Si/(Xt*V)) as the key control factor acting on specific substrate utilization through a Monod relationship where the maximum substrate utilization is Um and the substrate concentration of the mid utilization point is Kb.

$$\frac{dSq}{Xt*dt} = \frac{Um(F*Si/(Xt*V))}{Kb + (F*Si/(Xt*V))} = \frac{1}{\frac{Kb}{Um}\frac{(Xt*V)}{(F*Si)} + \frac{1}{Um}} \quad (2\text{-}6)$$

In the determination of the Um and Kb constants, the equation is converted to its linear form by inverting the specific substrate utilized and the feed to mass ratio. This linear plot gives high correlation where R^2 is usually above 90%. The apprehensions with this model is that a) the solids concentration term is on both sides of the equation possibly inflating the R^2 term and b) it yet remains as an unexplained empirical model. The model has been used with success in solving operational problems. Such a case is that of Daigger and group using it to increase the capacity of their plant (3).

An interesting similarity to this model, arises in the alternate theory proposed by Sykes (4). Sykes discussed the failings of the standard kinetic theory in basing the substrate utilization rate on the effluent substrate (Se) when in fact the effluent substrate is actually microbial by-product. He modified the theory such that all the substrate entering the reactor was used by the cell to produce the solids, plus respiration and the effluent substrate as a cell growth byproduct

$$F*Si = Vw*Xt + F*Se + Resp \qquad (2-7)$$

He explained further that all the terms on the right side of the equation were functions of growth or SRT with the respiration term bringing in the cell maintenance term. The cell maintenance term is just the specific solids decay rate Kd converted to its substrate equivalent with the yield factor (Kmaint = Kd/Y). Since the cell maintenance was included on the substrate balance it would not be included in the determination of the yield term equation. The determination of yield is determined from regressing the inverse SRT versus the feed to mass ratio or F*Si/(V*Xt). Note that the substrate term does not include the effluent substrate (Se) because all of the feed is converted for cell usage.

$$\frac{dSq}{Xt*dt} = \frac{F*Si}{V*Xt} = \frac{Constant}{SRT} + \frac{Kd}{Y} \qquad (2-8)$$

At steady state this equation is simply the feed to mass ratio times SRT times the yield factor which is equal to one.

$$Y\frac{(F*Si)}{(V*Xt)}SRT = 1 \qquad (2-9)$$

The effluent concentration (Se) was identified as a function of the feed concentration (Si) and the yield (Y) factor

$$Se = constant*Si*Y \qquad (2-10)$$

To compare this model with the Kincannon/Stover model it is necessary to get the terms in a similar form. If the effluent is moved to the left side of the substrate balance equation (2-7) then it gives the following:

$$F(Si-Se) = Vw*Xt + Resp \qquad (2-11)$$

Dividing through by the mass of solids V*Xt gives:

$$\frac{F(Si-Se)}{V*Xt} = \frac{Vw*Xt}{V*Xt} + \frac{Resp}{V*Xt} \qquad (2-12)$$

The right side of the equation can be written as a function of SRT as follows:

$$\frac{F(Si-Se)}{V*Xt} = constant\left(\frac{1}{RST}\right) + \frac{Kd}{Y} \qquad (2-13)$$

In Sykes model, the SRT can be exchanged for the feed to mass ratio with a yield term included which gives:

$$\frac{F(Si-Se)}{V*Xt} = (Constant)(Y)\frac{(F*Si)}{(V*Xt)} + \frac{Kd}{Y} \qquad (2-14)$$

This form of the model is quite similar to the Kincannon/Stover model with the Monod function simplified to a constant, as such it would be the linear portion of the Kincannon/Stover model in a specific substrate utilization versus feed to mass ratio plot. Sykes further explained how this model gives better modeling of data for high SRT systems but gives poorer prediction than the standard model for low SRT systems. The advantages in the Syke model would also be advantages in the Kincannon/Stover model because of the similar form.

The second group of models includes the McKinney (5) model which uses two possible rates conditional upon active mass as the limiting factor or the substrate as the limiting factor. In the first rate where mass is the limiting factor, the substrate utilization is simply a constant times the mass concentration in the reactor.

$$\frac{dSg}{dt} = constant * Xt \qquad (2-15)$$

or

$$dSg/(Xt*dt) = constant \qquad (2-16)$$

McKinney indicated that most domestic activated sludge units with recycle systems would be operating on substrate limiting conditions, so McKinney's model would be identified by the following form, dependent upon effluent substrate concentration (Se).

$$dSg/dt=Kc*Se \qquad (2\text{-}17)$$

The key point to notice with this model is that solids are not a factor of the utilization rate. McKinney explains that when the solids are recycled, the solids will be in excess competing for the limiting substrate. Eventually at steady state, the rate of synthesis will balance with the rate of mortality producing a constant level of active bio-mass. McKinney identified that the preferred operational range of SRT was between 3 - 7 days.

The last group of models uses specific substrate utilization relative to biological solids which is dependent upon effluent substrate concentration through a Monod function. The Lawrence/McCarty (6) model and the Gaudy (7) model fall into this group. Both use effluent substrate as the chief controlling factor. Even though Gaudy's model is not expressed as a substrate utilization rate it can be converted to such with the biological mass to substrate mass yield factor (Y). The model in substrate utilization form is expressed as follows where Umax is the maximum substrate utilization and Ks is the subtrate concentration of the mid utilization point.

$$\frac{dSg}{dt} = \frac{(Umax*Se)}{(Ks + Se)}(Xt) \qquad (2\text{-}18)$$

When determining the constants, Umax and Ks, in this model the substrate utilization is converted to specific substrate utilization and then linearized by plotting the inverse of specific substrate utilization and the inverse of effulent substrate. In order to reduce the inherent variability in plotting this model, averages of data for each SRT is plotted. If this is not done the correlation index of all the data points may be as low or lower than 30%. A special case of this model is the Eckenfielder (8) model where the specific substrate utilization is directly proportional to the substrate effluent concentration without the Monod relationship.

$$dSg/(Xt*dt) = constant*Se \qquad (2-19)$$

Generally when this model is used the bench scale test data is run at the same SRT as the treatment plant is expected to be operated at, so the constant would be approximately correct for the plant operation.

This last group of models plus McKinney's model, which use the effluent substrate concentration have recently fallen under criticism because analysis of the effluent substrate from activated sludge systems reveals that the effluent is not the same material as the influent substrate to the reactor but cell by-products of the bacteria in the system (9)(10)(11). As such it becomes questionable that the effluent concentration controls substrate utilization.

These three groups of models have an analogy in hydraulics that would clarify their differences. In McKinney's first model of limiting solids controlling, can be compared to small water pipes being connected to a reservoir. Since the pipes are small they would have a high friction loss delivering a small amount of water independent of the head in the reservoir. The pipes would be compared to the biological solids in the model. McKinney's second model of limiting substrate indicates that a larger size pipe would be connected to the reservoir such that the level of water in the reservoir determines the rate of flow. The head of water in the reservoir would be similar to the substrate concentration in biological growth.

The last group of models (Lawrence/McCarty and Gaudy) using specific substrate utilization and the Monod function of substrate, includes both of the analogies above plus a transition state. This can be compared to a series of pipes with friction loss similar to a critical orifice connected to a reservoir of varying water head. The rate of flow depends both on how many pipes are connected and also the head of water in the reservoir. As the head of water increases, the rate of flow increases while the head of water is below the critical head of the orifice. As the head of water increases in the reservoir to the critical pressure of the critical orifice the flow begins to approach a limiting flow rate through the pipe. Once the water head has passed the critical water head the flow rate will not change. The only way to increase the flow rate once the critical head is reached is to increase the number of pipes connected to the resevoir. If the number of pipes connected is doubled then the flow rate will double. This last group of models, thus become equivalent to McKinney's limiting solids model at high concentrations of substrate. However, at subcritical concentrations the models are quite different from McKinney's limiting substrate model since the solids term is still included. The Lawrence/McCarty and Gaudy models thus maintain the concept of solids concentration limiting growth whether the substrate concentration is critical or subcritical.

Another hydraulic analogy which compares well with the Sykes model and has some connection to the Kincannon/Stover model, is where an excessive number of large diameter pipes are connected to the resevoir. The pipes are never filled completely because they have a greater capacity than the reservoir. Thus the rate of flow in the pipes out of the reservoir are independent of resistance or head but only dependent upon how fast water is delivered to the reservoir. The capacity of the pipes thus relate to the mass of the biological solids, and the flow rate into the reservoir relates to the mass feed rate. Since the mass of solids is in excess the only factor that determines the substrate utilization is how fast the substrate mass flows into the system. This concept fits well if the feed is highly biodegradable and quickly absorbed. This concept will be discussed further in the results chapter where the

Kincannon/Stover model form will be derived using the information from this study as a guide.

B. Solids Viability

Another criticism of the specific substrate utilization models is the practice of using the volatile suspended solids (VSS) concentration for the concentration of biological solids. Weddle and Jenkins (12) used cell ATP as an indicator of viability to identify that the viability in activated sludge was not equivalent to the VSS concentration. However, they indicated at the typical operating range of activated sludge system this difference was small. Nelson and Lawrence (13) using ATP as a viability indicator, recommended that the VSS be divided up into three fractions including 1) viable microbial solids; 2) inert solids, and 3) nonviable biodegradable microbial solids. Benefield and Lawrence (14) using oxygen utilization rates to determine viable solids investigated the effect of sludge viability on the determination of bio-kinetic coefficients and concluded that the microbial decay coefficient (Kd) and the substrate utilization rate were significantly different when viability was included but that the yield coefficient was not affected. The viability determination was made by measuring the oxygen uptake in an open respirometer where a sample of mix-liquor was diluted into an environment containing excess substrate. It was allowed to come to its' maximum growth rate from which a sample was taken and again placed into an excess substrate environment. This process was continued until the growth rate of the mass stabilized at a maximum growth rate. The oxygen utilization rate for a new sample from the reactor was then measured in substrate rich environment and compared with the oxygen utilization of the maximum growth rate mass. The ratio of the two oxygen utilization rates was identified as the viability ratio of viable micro-organisms in the reactor.

Grady and Roper (15) approached the solids viability by developing a model which included a viability decay constant (K), along with the endogenous constant (Kdv) in a mass balance of viable solids at steady state.

$$0 = Vw*Xv + (F-Vw)Xe - U*Xv*V + Kdv*Xv*V + K*Xv*V \quad (2\text{-}20)$$

Solving for utilization rate (U) gives:

$$U = \frac{Vw*Xv + (F-Vw)Xe}{Xv*V} + K + Kdv \quad (2\text{-}21)$$

The sludge retention time (SRT) was substituted into the equation to give:

$$U = \frac{1}{SRT} + K + Kdv \quad (2\text{-}22)$$

A mass balance was also conducted on the substrate concentration in the reactor to give:

$$F*Si = Vw*Se + (F - Vw)Se + U*Xv*V/Y \quad (2\text{-}23)$$

Solving for viable solids (Xv) gives:

$$Xv = \frac{Y*F(Si - Se)}{V(1/SRT + K + Kdv)} \qquad (2\text{-}24)$$

The nonviable solids were determined from a mass balance equation including a new decay term for nonviable solids (Kd).

$$Xn = \frac{K*Xv}{((1/SRT) + Kd)} \qquad (2\text{-}25)$$

The total solids was determined as the sum of the viable and nonviable solids.

$$Xt = \frac{Y*F(Si-Se)\ (1/SRT + Kd + K)}{V(1/SRT + Kd)\ (1/SRT + Kdv + K)} \qquad (2\text{-}26)$$

The viability was the ratio of viable to total solids.

$$\text{viability} = \frac{1/SRT + Kd}{1/SRT + Kd + K} \qquad (2\text{-}27)$$

If the substrate balance equation is solved for specific substrate utilization, it gives the following equation as a function of SRT.

$$\frac{F(Si-Se)}{V*Xt} = (1/SRT + K + Kd)(1/Y)(Xv/Xt) \qquad (2\text{-}28)$$

Substituting viability for the Xv/Xt term gives;

$$\frac{F(Si-Se)}{V*Xt} = \frac{(1/SRT + Kdv + K)}{(1/SRT + Kd + K)} \frac{(1/SRT + Kd)}{Y} \qquad (2\text{-}29)$$

If Kd and Kdv can be assumed to be almost equal then two bracketed terms would cancel out giving:

$$\frac{F(Si-Se)}{V*Xt} = (1/Y)(1/SRT + Kd) \tag{2-30}$$

Rearranging this equation gives the familiar equation which provides the yield (Y) and endogeneous term (Kd). In this equation the endogeneous term is identified as only a nonviable solids decay term.

$$\frac{1}{SRT} = \frac{Y*F(Si-Se)}{V*Xt} - Kd \tag{2-31}$$

Since the decay rate of the viable solid (Kdv) is not in this final equation nor in the viability equation, it may be possible to omit it from the mass balance equation. As Grady and Roper solved for the viability term they invoked Lawrence/McCarty's SRT definition several times. As such, Grady and Roper's model is the Lawrence and McCarty's model with an additional complication of solids viability.

Grady and Roper concluded that viability was dependent only upon sludge retension time (SRT) and the death rate of viable cells (K) and the decay rate of nonviable cells (Kd). The viable solids had no effect on viability (only its death rate, K) at the steady state conditions and the effluent substrate was controlled by the sludge retension time.

Blok (16) used two different respirometers, the Sapormat and the open respirometer to determine the overall viability of the bacteria from the point of view of respiration. He concluded that at high SRT's the effluent is polluted with cell decay products which would have a slower uptake rate than the feed substrate. As such the effluent would not agree with the standard model prediction for the effluent. He also concluded that cell viability relative to oxygen uptake was not the same as cell viability from ATP method and that some solids do take up substrate but are not viable relative to cell proliferation.

Walker and Davies (17) compared respiration rate and viability of solids to cell plating. They concluded that the respiration rate was much higher than the cell viability would predict. As such respiration was occurring in nonviable cells not shown by cell plating techniques. They indicated that maximum respiration rate was reached at one day SRT and at this point only viable cells would be in the mixed-liquor solids.

Apparently the determination of viability of the solids in activated sludge should be conducted using respiration as the determining factor rather than ATP or cell plating techniques.

Huang, Cheng and Mueller (18) further substantiated the use of oxygen uptake rates as an indicator of viability by conducting oxygen uptake tests in a respirometer which was started with a substrate concentration of 800 mg/L chemical oxygen demand and allowed to run for 30 hours from which the maximum specific oxygen uptake rate was determined from a Lineweaver-Burk double-reciprocal plot. They next assumed that zero day SRT would be 100% viable and projected the maximum specific oxygen uptake rate for SRT to a maximum specific oxygen uptake rate to correspond to 100% viability at zero day SRT. The viability was then determined as the ratio of the maximum specific oxygen uptake rate for each SRT divided by the maximum value at zero day SRT. A two day SRT had a 54% viability, four day had a 45% viability, eight day had a 39% viability and SRT's greater than eight days were approximately equal to 39% viability. A plot of net specific growth rate versus specific oxygen uptake rate was used while discussing the viability and has been included as Figure 1. In this figure the oxygen uptake curve curves down more than expected such that less solids are produced for small specific oxygen uptake rates.

C. Microbial Mortality Rates

Another factor that should be reviewed for recycle systems is the mortality rate of microbial solids. Marais (18) discussed die-off kinetics in stabilization ponds as following Chick's law, where the rate of reduction in viable concentration of microorganisms (Xv) is first order decreasing rate relative to the microorganisms concentration.

$$dXv/dt = -K*Xv \qquad (2\text{-}32)$$

This is also known as a decreasing exponential rate. He postulated that the decay constant was a factor of temperature as is typically used in waste treatment systems

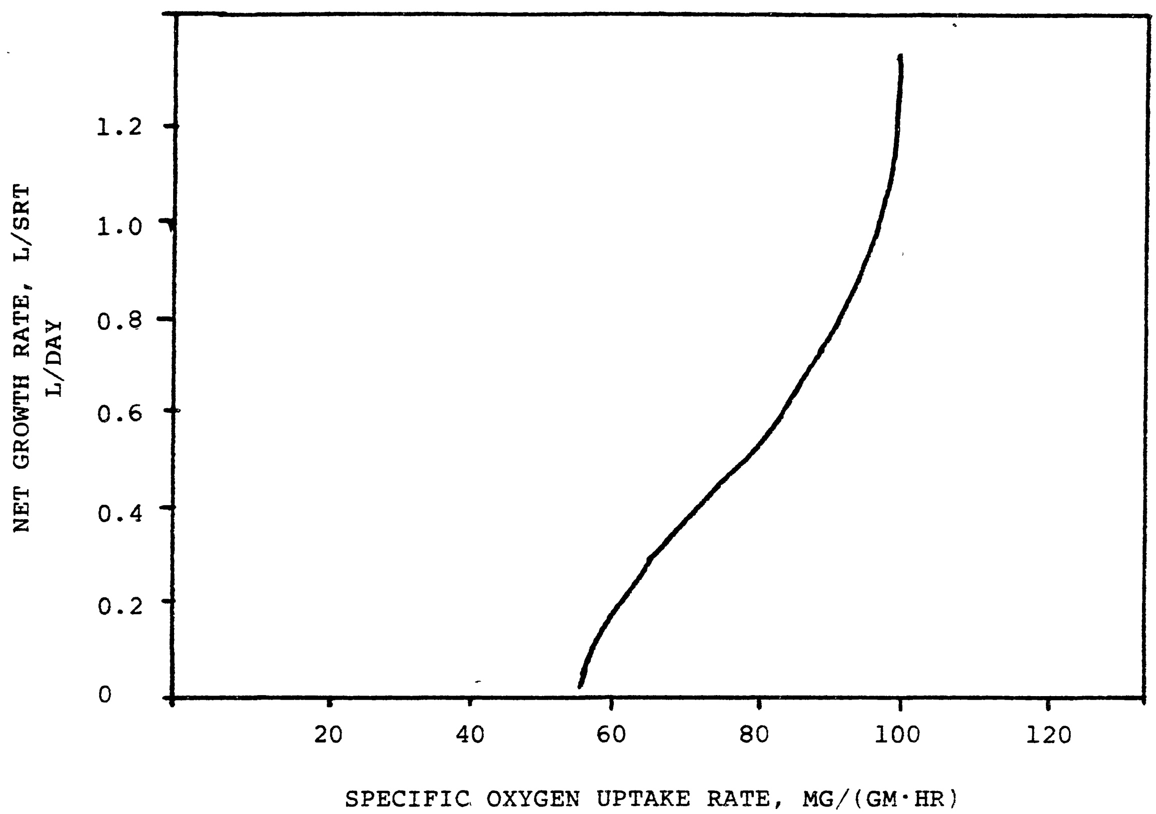


Figure 1. Net specific growth rate versus specific oxygen uptake rate (18)

or

$$K = (\text{decay constant at } 20\ C)(1.19)^{(T-20)} \qquad (2\text{-}33)$$

where T is temperature in celsius. He continues in relating how this rate is applied to single and series ponds for determining the microbial death rate for a particular pond system.

Mancini (20) discussed log concentration versus time plots for determining the mortality rate constant from populations of coliform with a number of mortality patterns. Emphasis was placed on identifying the appropriate linear segment of the log plot of the data.

Polprasert and group (21) looked at mortality as an exponential where the mortality rate was affected not only by temperature but also by Ph, dissolved oxygen, and nutrient content in the pond.

In all of these papers the mortality rate was viewed as a decreasing exponential rates and that the temperature and dissolved oxygen in the mix-liquor would be important to control.

CHAPTER III

GENERAL THEORY OF RESEARCH

The basic concept of this experiment centers in the Monod (22) model of substrate uptake. Monod identified that substrate uptake by bacteria increases as the concentration of the substrate increases up to a limiting point. This means that uptake is first order or exponential up to a point where a decreasing exponential rate begins to take over and limit the uptake rate stabilizing it at a maximum rate. The maximum rate of uptake and the exponential rate of uptake are both specific characteristics of the bacteria being tested. In aerobic bacteria, oxygen consumption parallels this substrate uptake because oxygen is required as a terminal electron acceptor in the metabolism of the substrate. The most efficient point on the Monod type uptake curve would be the point where the exponential uptake ends and the decreasing exponential begins. This is generally recognized as where the uptake rate is one half of the maximum uptake. Activated sludge units operating at optimum conditions would have a steady state with oxygen uptake near this point. Measuring oxygen uptake presents a problem because the exponential portion of the uptake curve is more sensitive to change due to small changes in substrate concentration. Thus the mixing which occurs in extracting the mixed-liquor from the reactor for running the oxygen consumption test could effect massive changes in results of traditional oxygen consumption tests in determining oxygen uptake rates. If the uptake test could be forced to occur in the decreasing exponential or the maximum uptake ranges then more reliable data, less influenced by the test itself, could be obtained for characterizing the biological activity of the unit.

Blok (16) and Walker/Davies (17) used oxygen uptake of the biological solids in determining viability of the solids. The samples were placed in a substrate rich solution and the oxygen uptake measured in a respirometer. Their attempts were directed to determine if the oxygen viability was the same as ATP or plate count division viability in their samples. They found that oxygen viability was higher than either ATP or plate count viability measurements.

This study uses the dissolved oxygen probe typically used in running Biological Oxygen Demand tests, to determine viability. The dissolved oxygen probe is more common than a respirometer in waste treatment systems and also easier to operate. A test using this probe and standard BOD bottles generally used for running effluent quality tests would be within the capability of most operating plants.

Grady and Roper (15) suggested that after viability was determined then the viability decay constant could be solved for by graphing the viability of the biological solids and solving the mass balance equations applicable. However, if the decay constant is a unique characteristic of the sludge it would tend to be independent of the sludge retention time and thus could be determined directly by measuring the maximum oxygen uptake as it died out. The viability of the solids could then be determined from the mass balance equations. The mass balance rate equation of viable solids indicates that the viable rate of growth will equal the decay rate plus the wasting rate of viable solids.

$$Uv = K + Vw/V \qquad (3\text{-}1)$$

The mass of this viable growth must also equal the mass of the net growth of the reactor.

$$Uv*Xv = Un*Xt \qquad (3\text{-}2)$$

The endogenous term (Kd) has been omitted for simplicity purposes since including it would give the same viability equation as Grady and Roper derived. The net specific growth rate (Un) is equal to the wasting rate from the reactor (Vw/V) at steady state. Therefore, the equation for viable solids concentration is obtained by solving for viable solids (Xv) after substituing equation (3-1) into (3-2).

$$Xv = \left(\frac{Vw/V}{k + Vw/V} \right) Xt = \left(\frac{1}{K*(V/Vw) + 1} \right) Xt \qquad (3\text{-}3)$$

The SRT could be substitued for V/Vw in this equation to give:

$$Xv = \left(\frac{1}{K*SRT + 1} \right) Xt \qquad (3\text{-}4)$$

The volatile suspended solids (Xt) and the SRT are generally available from plant operation data or from bench scale unit reactors. Bench scale reactors because of their small size produce limited mixed-liquor solids which adds an additional restraint on a test to determine the decay rate of oxygen viability of solids. The direction of this work was to develop an oxygen consumption test using equipment readily available to most plant operations that could be used in determining the oxygen viability decay constant of the biological solids.

Initial tests were conducted adding concentrated reactor feed to the oxygen consumption test in an attempt to reach the maximum uptake. The maximum uptake was never reached because the magnesium sulfate salt in the feed at high concentrations started to exhibit inhibitive characteristics. Glucose was also used but slight inhibition was also evident at high concentrations. Because of the limited mixed-liquor available from the bench scale units it was determined that a series of oxygen consumption tests would have to be conducted by removing geometrically increasing volumes of the mixed-liquor from the oxygen consumption bottle after running each test, replacing it with concentrated glucose solution and running the oxygen consumption test again. The oxygen consumption tests exhibited an exponential decrease in consumption rate, appearing much like that due to inhibition, beginning midway in the exponential decreasing rate range. However, the decrease was not due to inhibition but the withdrawal of the mixed-liquor solids. The maximum point of consumption obtained, thus, was the intersection of the oxygen consumption rate and the mixed-liquor withdrawal curve. This relative maximum oxygen consumption rate would not be the actual maximum consumption rate but would be simply a set fraction of it which may give a better characterization of the biological activity of the activated sludge unit since it would not be affected by either the test itself or the inhibition characteristics of the feed.

The oxygen consumption rate could also be conducted on mixed-liquor isolated from the bench scale unit and the maximum rate used to identify the loss in viability of oxygen consumption as the bacteria die out. If the test is conducted over a several day period then the cell death rate could be determined from the decrease in the oxygen consumption rate over time.

Results from this modified oxygen consumption test could be used to determine which kinetic model is appropriate. The traditional models of Gaudy and Lawrence/McCarthy assume that the mixed-liquor solids are homogeneous in biological makeup and have a unique maximum substrate utilization rate or growth rate. This maximum substrate utilization rate is determined by plotting the linearized version of the Monod equation and identifying the maximum substrate utilization rate as the inverse of the intercept on the vertical axis. In such a model, the effluent concentration of substrate would be reduced simply by increasing the mixed-liquor concentration of biological solids. If these models were true the modified oxygen consumption test on a high SRT system would yield a greater maximum than on a low SRT system due simply to the greater concentration of bacteria in the reactor. The oxygen consumption test however would yield the same` maximum rate independent of SRT if McKinney's effluent substrate model were appropriate.

CHAPTER IV

MATERIALS AND METHODS

A. Continuous Flow Reactor Unit

The configuration of the bench scale units used in this investigation is shown in Figure 2. These units were internal recycle with an adjustable baffle to separate the reactor from the clarifier. The baffle was used to adjust the recycle of the mixed-liquor between the reactor and the clarifier each day by first mixing the unit then inserting the baffle and closing it completely so the solids in the clarifier side could settle. After several minutes of settling the height of the settled mass was noted and the baffle gradually opened to allow recycle and some mixing of the clarifier solids. The baffle was adjusted so the mass height in the clarifier showed neither an increasing nor decreasing trend from the settled state.

The reactor chamber was mixed by aeration from two fritted diffusers located in each reactor at approximately one half inch up from the bottom and approximately one inch diagonally from the outside corners of the reactor chamber. In order to maintain proper mixing the air flow was set between 2.5 - 3 liters per minute. The volumes of the continuous reactor units are as follows:

	Total Volume	Reactor Chamber	Clarifier
Reactor 1	4.56 liters	2.92 liters	1.64 liters
Reactor 2	4.67	2.86	1.81
Reactor 3	4.7	2.85	1.85

The reactor was controlled at a selected SRT by wasting the required volume of mixed-liquor from the reactor as calculated in the following SRT equation solved for the volume wasted. Vw is the volume wasted in liters per day, V is the volume of the reactor in liters, Xt is the concentration of volatile suspended solids in the reactor, F is the feed flow rate in liters per day, Xe is the volatile suspended solids in the effluent and SRT is the sludge retension time in days.

$$Vw = \frac{\frac{V*Xt}{SRT} - F*Xe}{Xt - Xe} \qquad (4-1)$$

All concentrations and the flow were measured prior to wasting of the mixed-liquor.

For this study, reactor 1 was operated at SRTs of 0.9, 1, 1.5, 2 and 20 days. Reactor 2 was operated at 3, 7 and 9 day SRTs and reactor 3 was operated at 5 and 15 day SRTs.

The synthetic feed fed to the reactors has the composition of carbon and salts as shown in Table I. The salts and carbon solutions were mixed double strength and fed from separate bottles not being mixed until right before entering the reactor. The two feed bottles for a reactor were pneumatically driven by a rotating hose pump set to

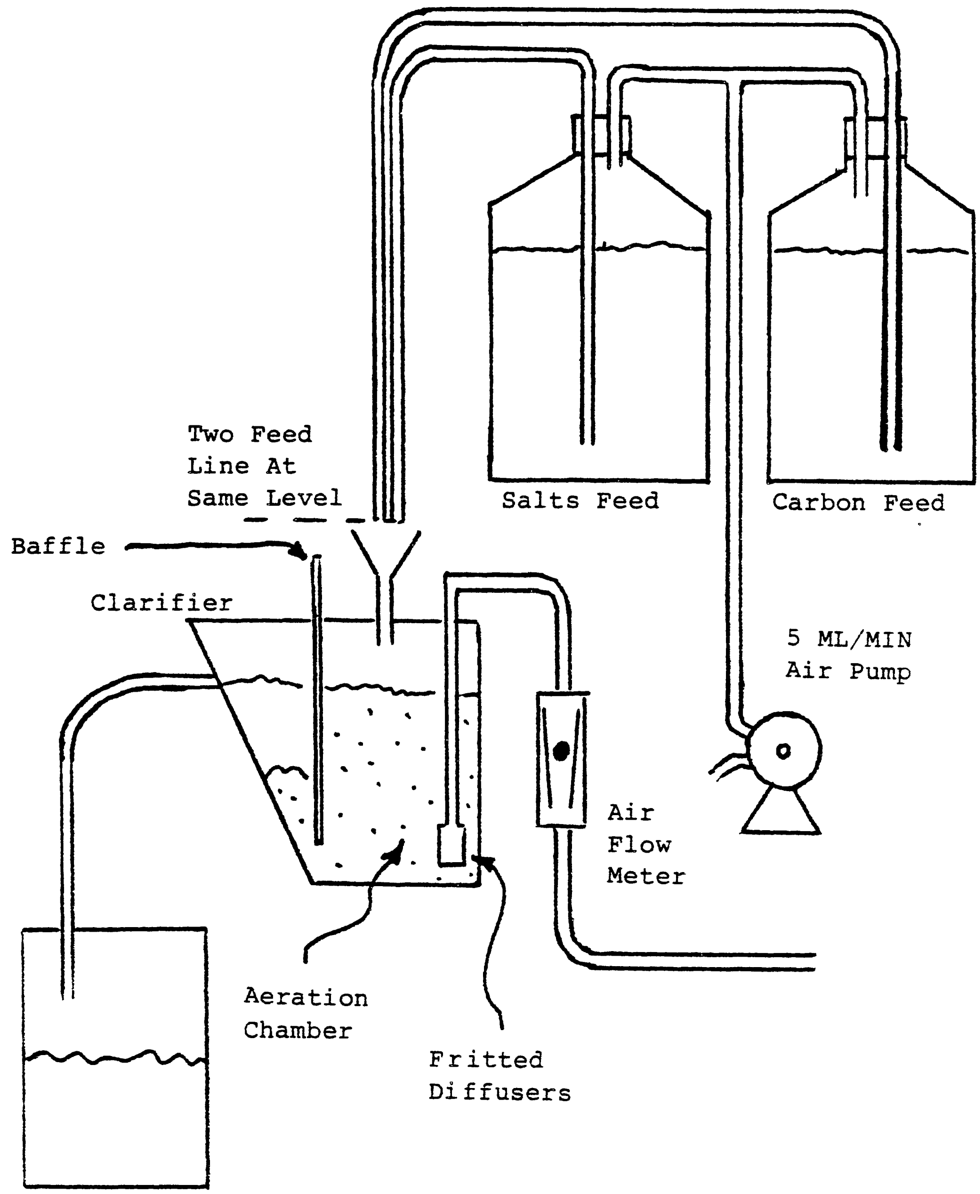


Figure 2. Continuous Flow Reactor Unit

TABLE I

SYNTHETIC FEED COMPOSITION

Carbon Mix	Concentration	
Acetic Acid	0.113	ml/l
Ethyl Alcohol	0.113	ml/l
Ethylene Glycol	0.113	ml/l
Phenol	0.0048	ml/l
Glucose	0.113	mg/l
Glutamic Acid (plus 8.3 mg/l KOH)	0.113	mg/l

Salt Mix	Concentration	
Ammonium Chloride	162	mg/l
Phosphoric Acid	0.019	ml/l
Magnesium Sulfate, MgSO4.7H2O	80	mg/l
Manganese Sulfate, MnSO4.H2O	8	mg/l
Calcium Chloride, CaCl3	8	mg/l
Ferric Chloride, FeCl3.6H2O	0.4	mg/l

deliver five milliliters per minute to each unit.

B. Analytical Procedures

Modified Oxygen Consumption Test

The technique of determining the oxygen consumption rate was the same as in Standard Methods (23), where a direct reading oxygen probe is used. The concentration of dissolved oxygen was recorded every half minute and the oxygen consumption rate determined from the slope of the dissolved oxygen versus time plot. A strip chart recorder was connected to the oxygen probe for these tests and the slope was easily extracted from the strip chart recording.

The series of tests conducted on one sample withdrawn from the reactor were as follows. A 300 ml sample was withdraw from the reactor after mixing. After aerating the sample, it was placed in a 300 ml BOD bottle and the oxygen consumption recording taken. Next 10 ml of mixed-liquor was removed from the BOD bottle for volatile solids determination and the volume replaced with 10 ml of glucose solution of 36.16 grams per liter. This was again aerated and the oxygen consumption test again recorded. 10 ml of mixed-liquor was again removed from the BOD bottle, replaced by the glucose solution, and the test conducted. This procedure was repeated two more times. The next volume withdrawn out of the BOD bottle was 30 ml, replaced by the glucose solution. The oxygen consumption test conducted and volatile solids conducted on the 30 ml aliquot. The next two volumes withdrawn were 60 ml and 120 ml after which oxygen consumption texts were conducted. Volatile solids were also completed on the 120 ml aliquot. The maximum of the oxygen consumption test was determined as the largest oxygen consumption rate recorded for each sample run.

Determination of Decay by Oxygen Consumption

The decay of oxygen consumption was measured by removing a sample of mixed-liquor solids from the continuous reactor, placing it in a batch reactor and allowing it to aerate for the selected days of decay. After which the Modified Consumption test was conducted. No feed was added to the batch reactors during the decay period.

The reactors operating at five, six and seven day SRT's did not produce enough mixed-liquor solids in one day to allow all decay tests to be conducted on the same sample. Therefore samples were removed from the reactor on consecutive days until sufficient samples were obtained for the desired number of tests. The Modified Oxygen Consumption Test was then conducted after each selected period of decay days had elasped from the time the sample was taken. The reactors of 15 and 20 day SRT's did not produce sufficient mixed-liquor solids to allow even one Modified Oxygen Consumption test without disturbing the steady state of the reactor. Therefore all mixed-liquor solids were sacrificed to allow sufficient volume of mixed-liquor solids to run the oxygen decay tests. The reactors operating at three and less day SRT's produced sufficient mixed-liquor solids so the sample could be split to allow the various selected oxygen decay tests to be run on the mixed-liquor solids of one sampling period. In this case the mixed-liquor sample was taken, split into several separate batch reactors and then the Modified Oxygen Consumption test conducted on each after the desired days of decay had passed. A zero decay day corresponds to the Modified Oxygen Consumption test being conducted right after the sample was taken from the continuous reactor where no decay time was allowed. A three day decay time corresponds to the sample being removed from the continuous reactor, placed in a batch reactor for three day duration and then the Modified Oxygen Consumption test being conducted. Sampling from the reactor for all these test was not conducted until the reactor was perceived to be operating at steady-state or very near steady-state conditions.

Volatile Suspended Solids

The technique for determining the volatile suspended solids is in Standard Methods (23) where a 103 C drying oven is used and a muffle furnace. The filter paper was glass fiber of 4.5 um pore size. The various mixed-liquor solutions were filtered using a vacuum pump, dried in the 103 C drying oven, weighed and then incinerated in the muffle furnace. After cooling it was weighed and the volatile suspended solids determined as the difference of the two weights.

Biological Oxygen Demand For Five Days (BOD5)

The test used to identify the substrate concentration in oxygen demand equivalents was the Biological Oxygen Demand for five days test method as in Standard Methods (23). A 300 ml standard BOD bottle was used with an Orion direct reading oxygen probe to measure the dissolved oxygen concentration. The substrate concentration oxygen equivalent was determined as the difference between the oxygen concentration of the sample in the bottle at the start of the five days of incubation and at the end of the five days.

CHAPTER V

RESULTS

A. Reactor Data

Figure 3 though 12, shows the reactor substrate feed rate (F), solids concentration (Xt) and effluent concentration (Xe) plotted over time as an indication of the steady state of the reactors. The 0.9 day SRT reactor was the only reactor which decreased rapidly in solids concentration. In Figure 3, the solids concentration in the reactor decreased rapidly causing the system to fail within three days. Steady state was not achieved because the wasting rate was greater than the growth rate of the solids. Figure 4 containing the one day SRT had an irratic solids concentration which was difficult to control. The solids concentration in the reactor seemed to have a cyclic characteristic of high and low concentrations on alternating days. The effluent solids increased to 13 mg/l with the larger increases being one day delayed from the increases in the reactor solids. Effluent solids can reach 30 mg/l in practice so 13 mg/l is still within expected concentrations. The effluent solids concentration is proportionally more variable than reactor solids concentration as shown for all

SRTs in Figures 3 through 12. Even though the effluent solids concentrations varied, this variability was well below the 30 mg/l concentration except for the seven day SRT system. On the sixteenth day of the seven day SRT system the effluent pipe to the reactor was clogged and then released causing a very high effluent concentration. The effluent concentration was considered in the wasting rate so the effect was compensated by the wasting volume.

Figures 5, 6, 7, 8, 9 and 12 demonstrate the horizontal characteristic of reactor solids at steady state conditions. Figures 7 and 12 of 3 day and 20 day SRT have the greatest variablility of reactor solids of this group of conditions with a few concentrations above the rest. The variability of the solids in these two situations can best be attributed to the difficulty of sampling these solids which had larger flock particle than the other systems.

The flow rate of these systems shown in Figure 3 through 12, indicates variability that is more a characteristic of the short sampling period of less than two minutes. Since the feed was driven by the pumping of air into closed feed bottles, variations should be expected due to small changes in barometric pressure over a short period of time or a small change in temperature. Since the pumps were pumping in a set volume of air into the closed bottles a daily feed rate was much closer to 7.2 liters than the figures indicate.

Figures 8 and 11, five and fifteen day SRTs were

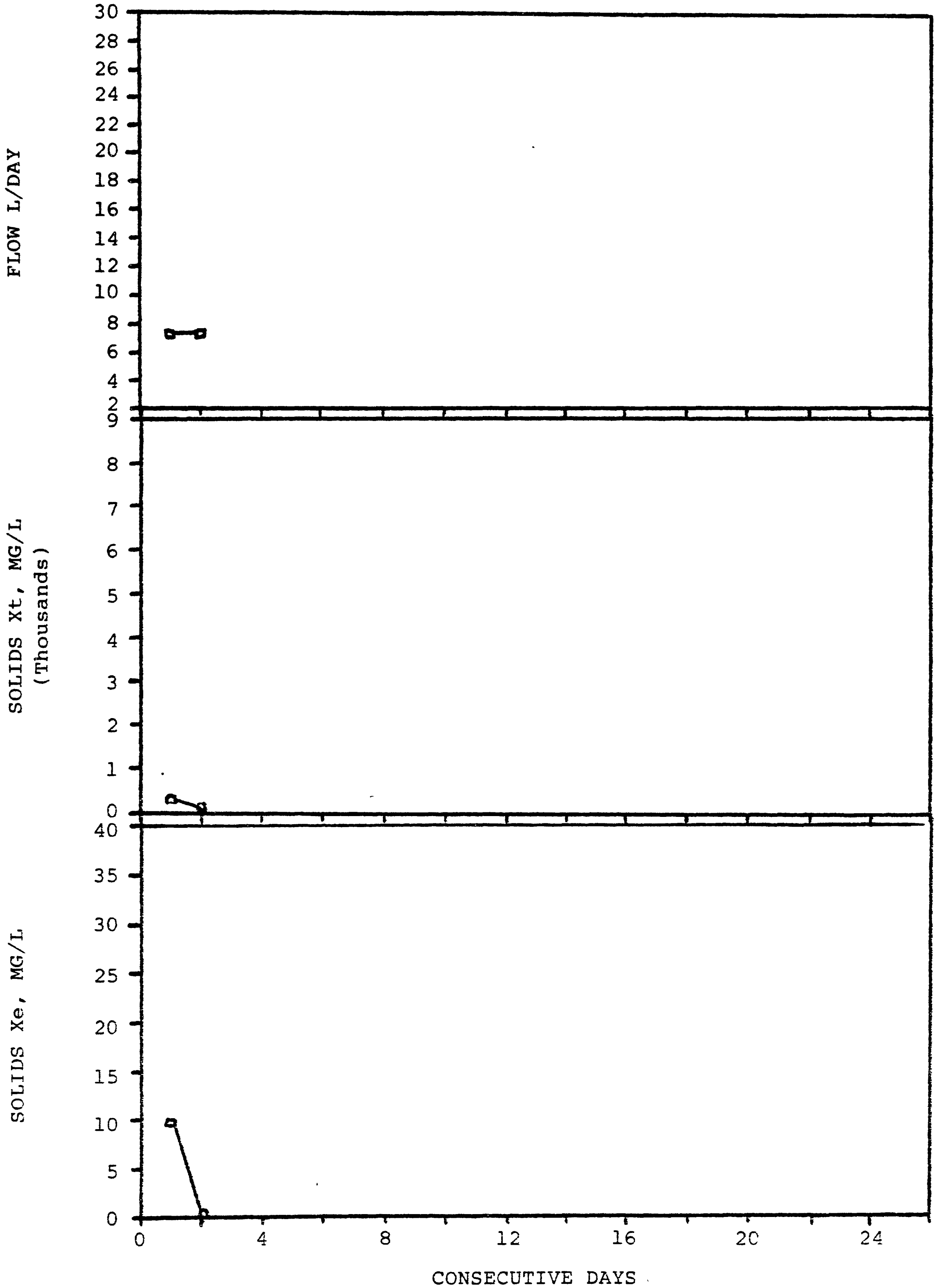


Figure 3. 0.9 Day SRT Consecutive Day Steady State Plot Beginning at 2/21/85

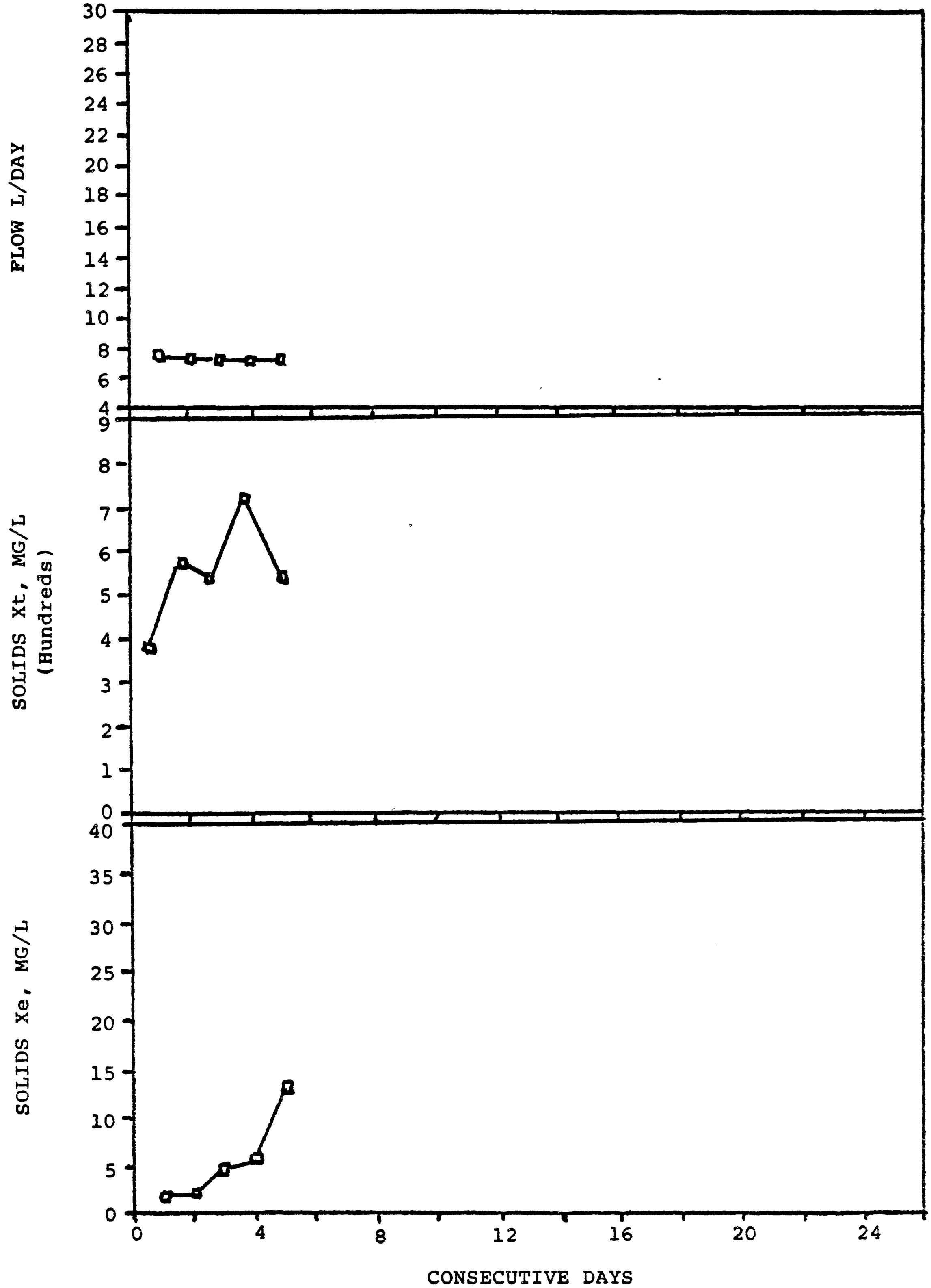


Figure 4. One Day SRT Consecutive Day Steady State Plot Beginning at 2/16/85

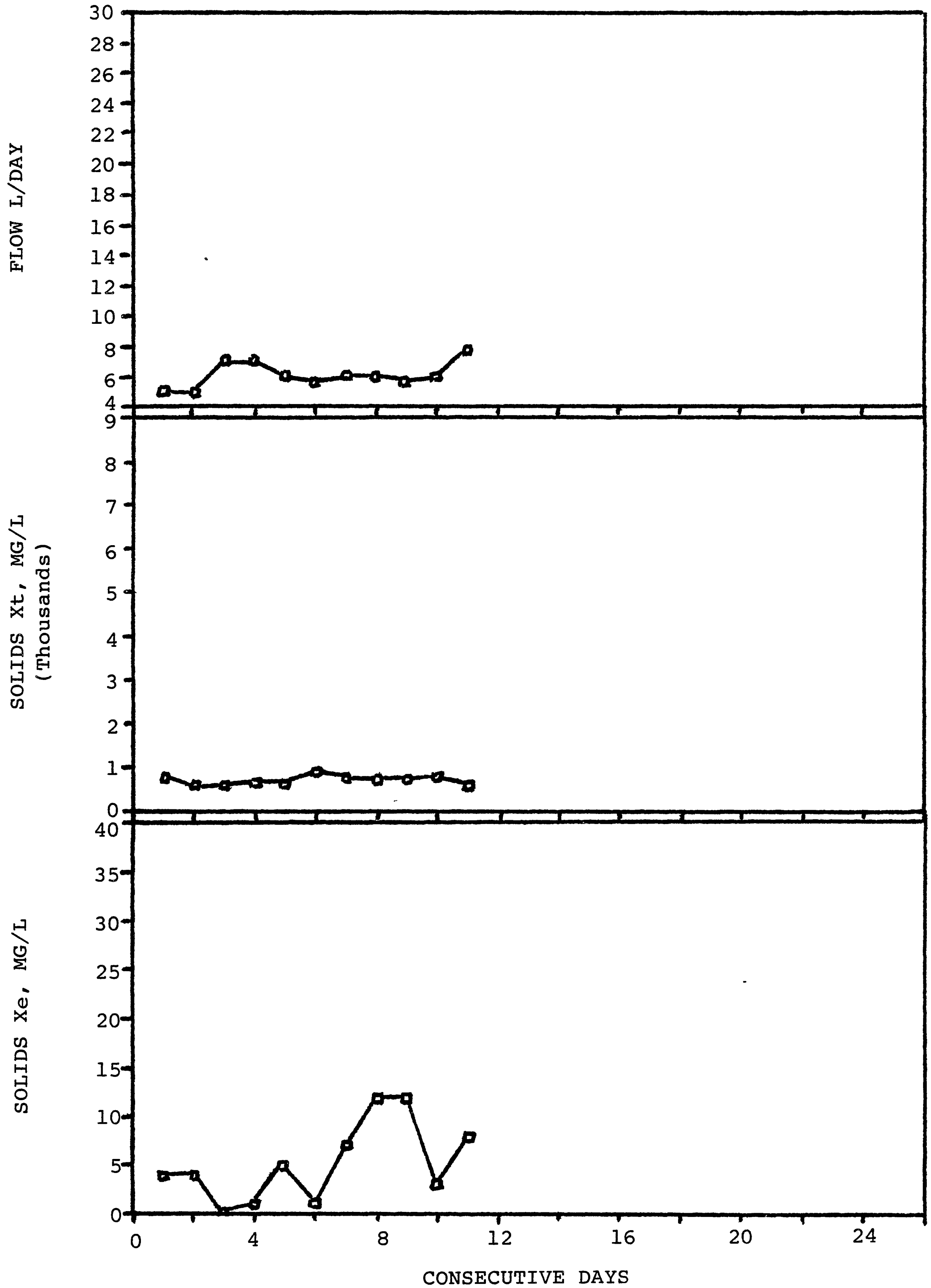


Figure 5. 1.5 Day SRT Consecutive Day Steady State Flow Beginning at 2/5/85

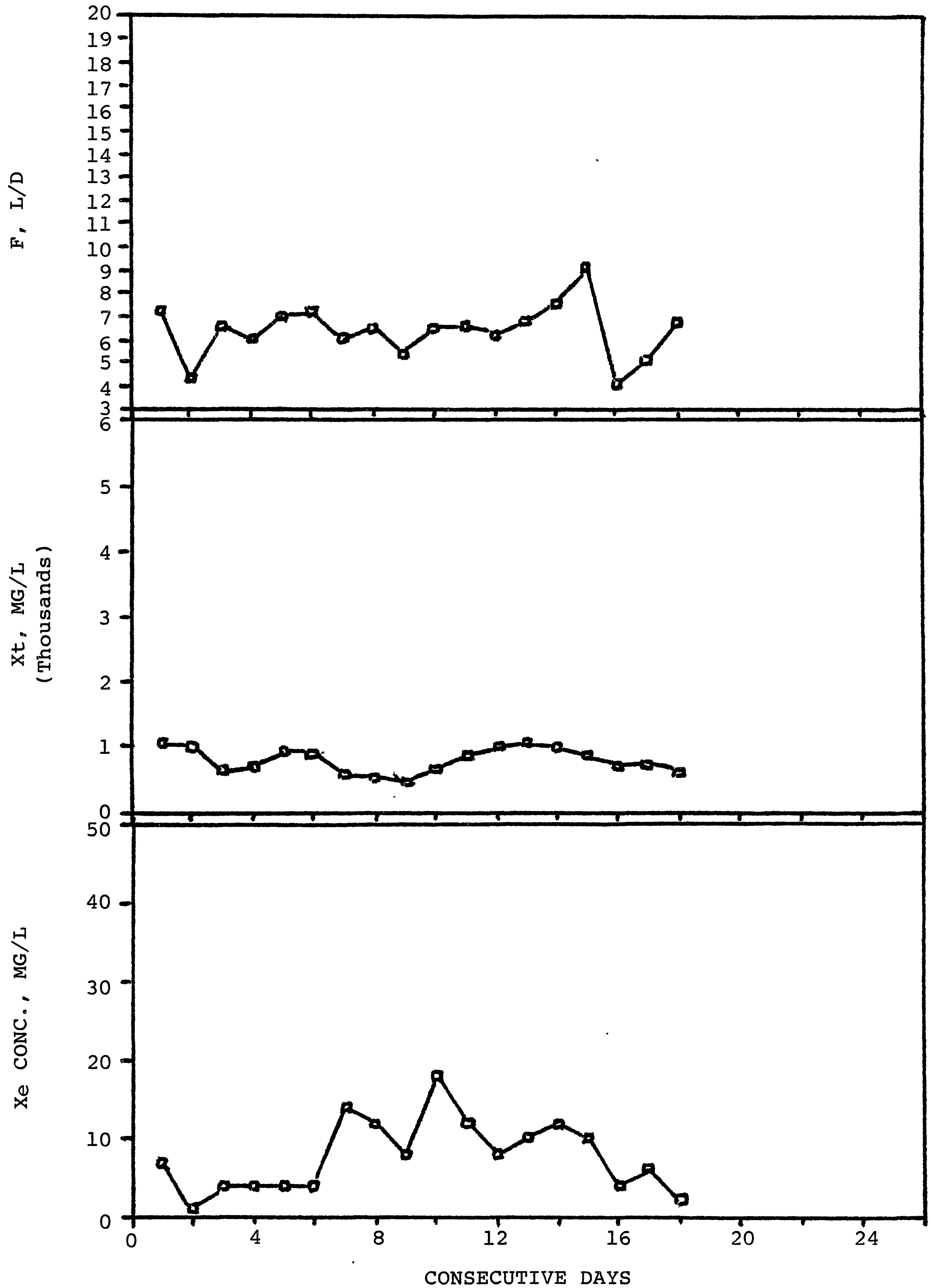


Figure 6. Two Day SRT Consecutive Day Steady State Plot Beginning at 1/18/85

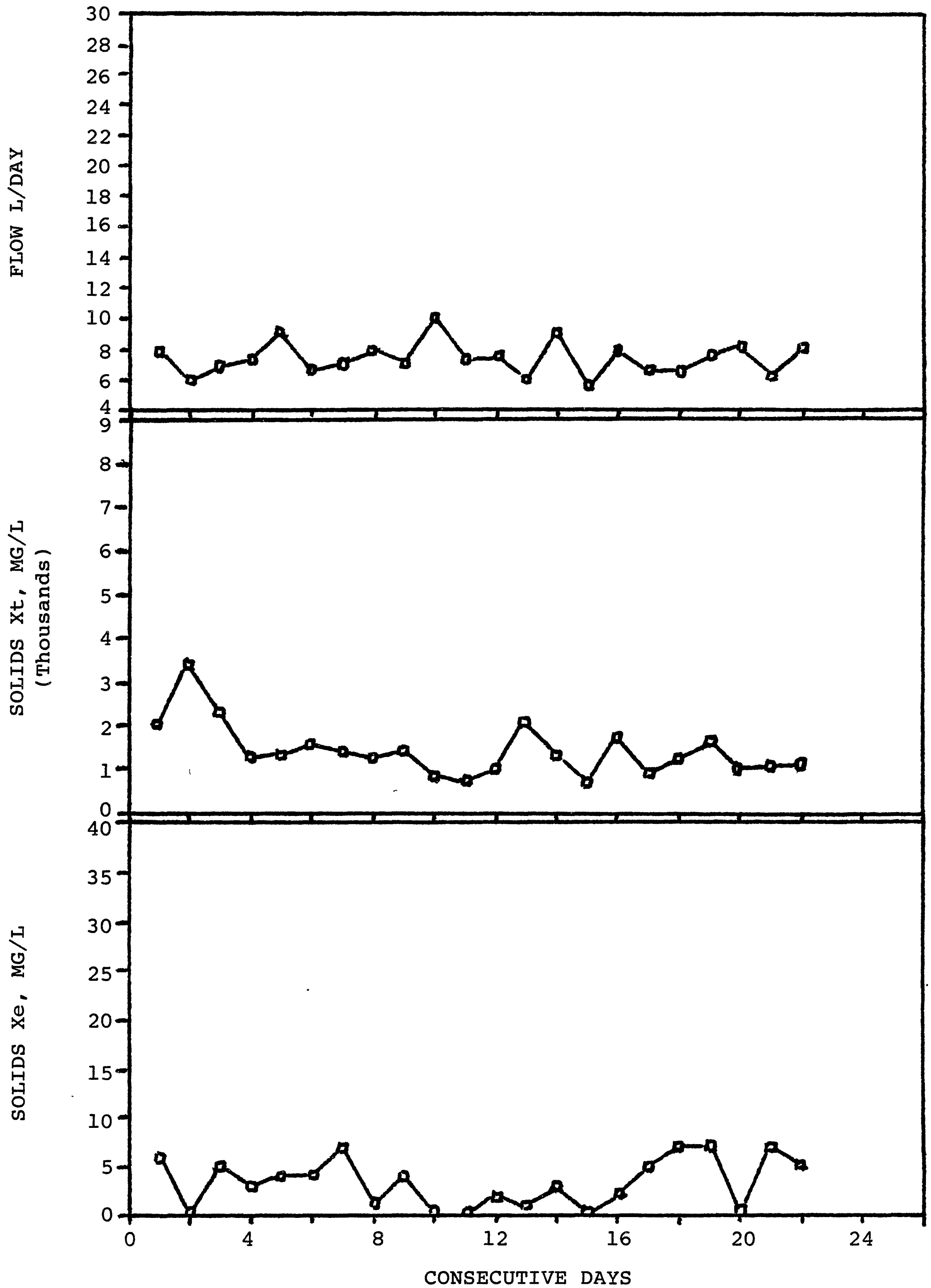


Figure 7. Three Day SRT Consecutive Day Steady State Plot Beginning at 12/27/84

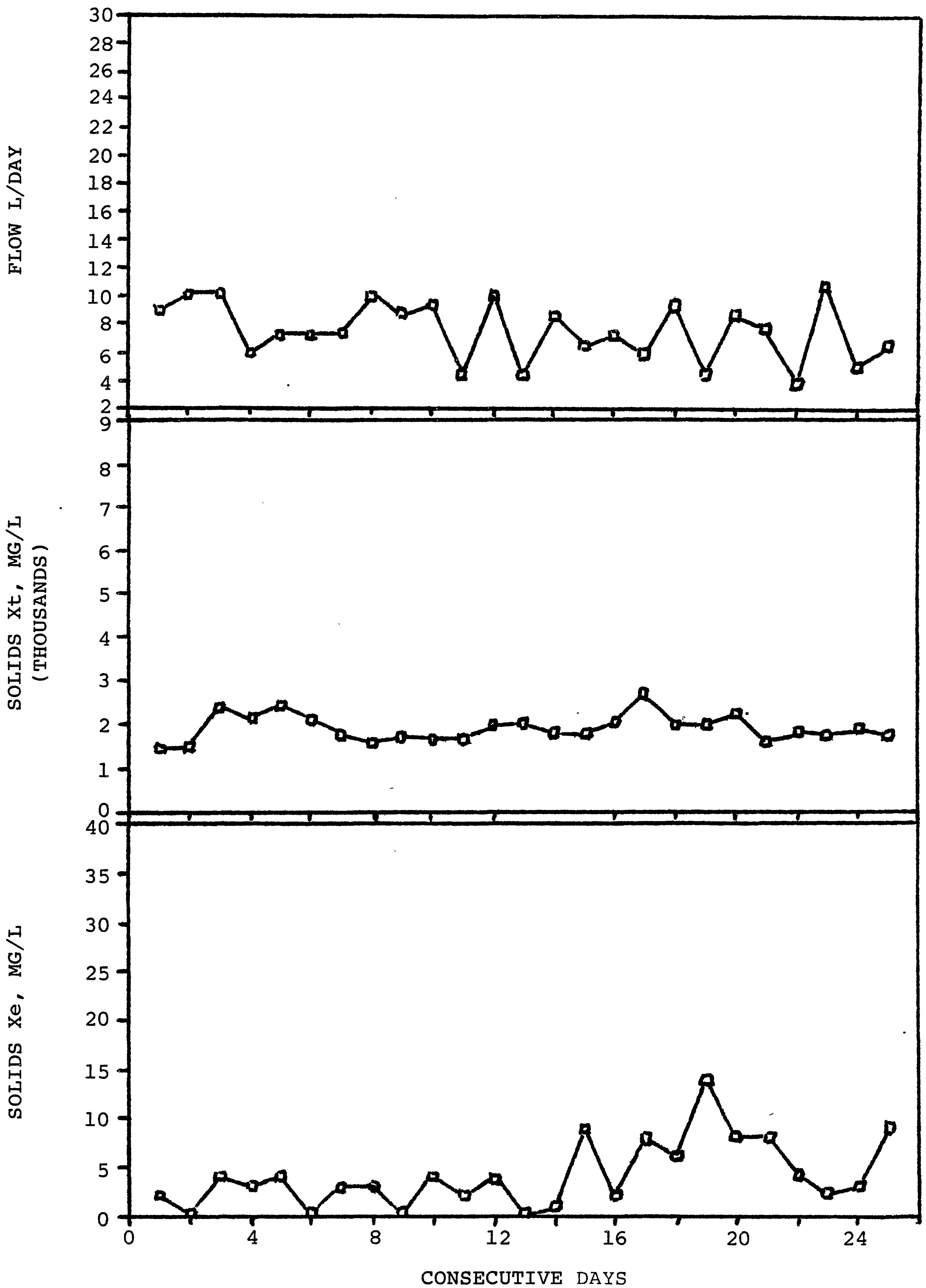


Figure 8. Five Day SRT Consecutive Day Steady State Plot Beginning at 12/29/84

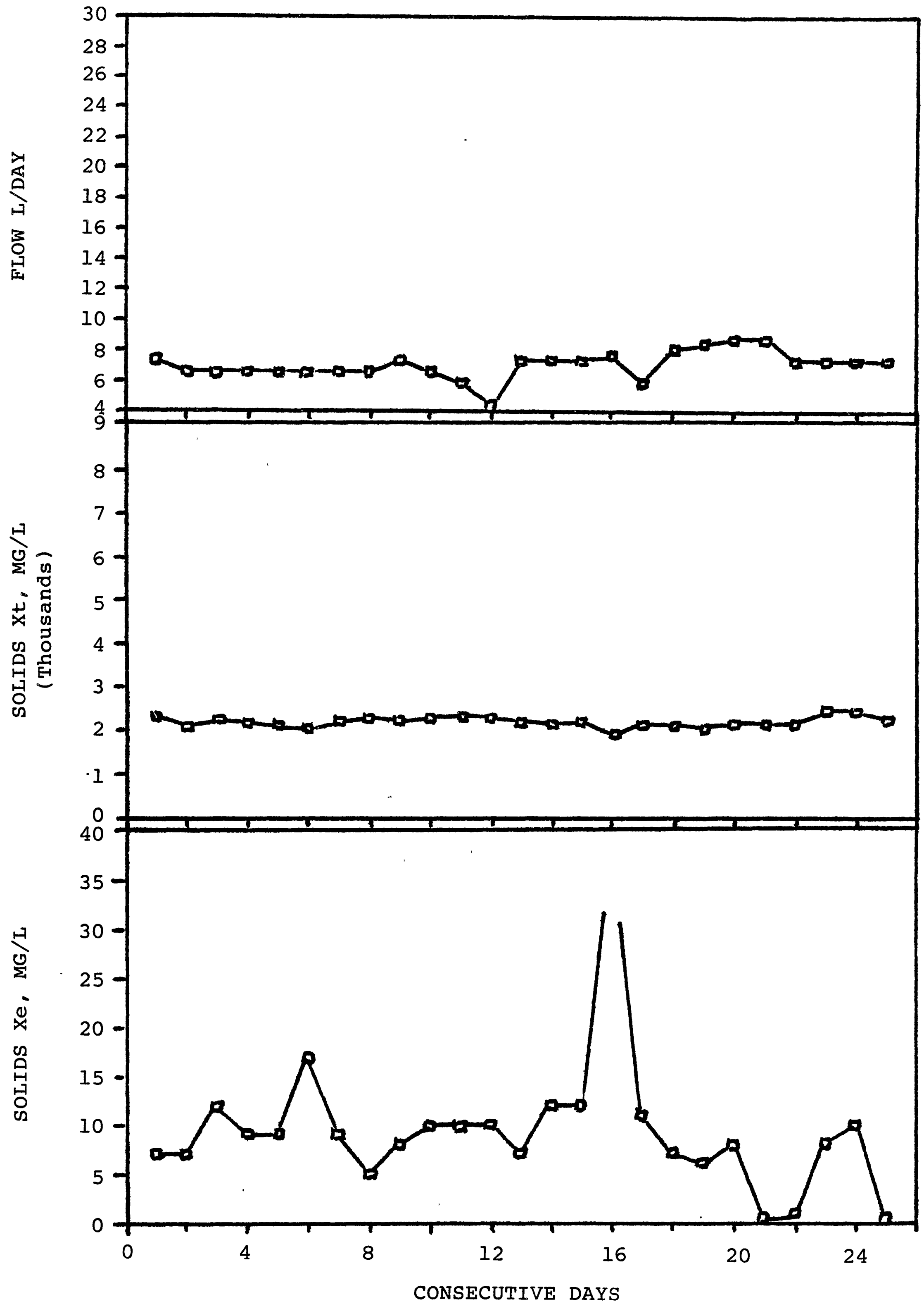


Figure 9. Seven Day SRT Consecutive Day Steady State Plot Beginning at 12/1/84

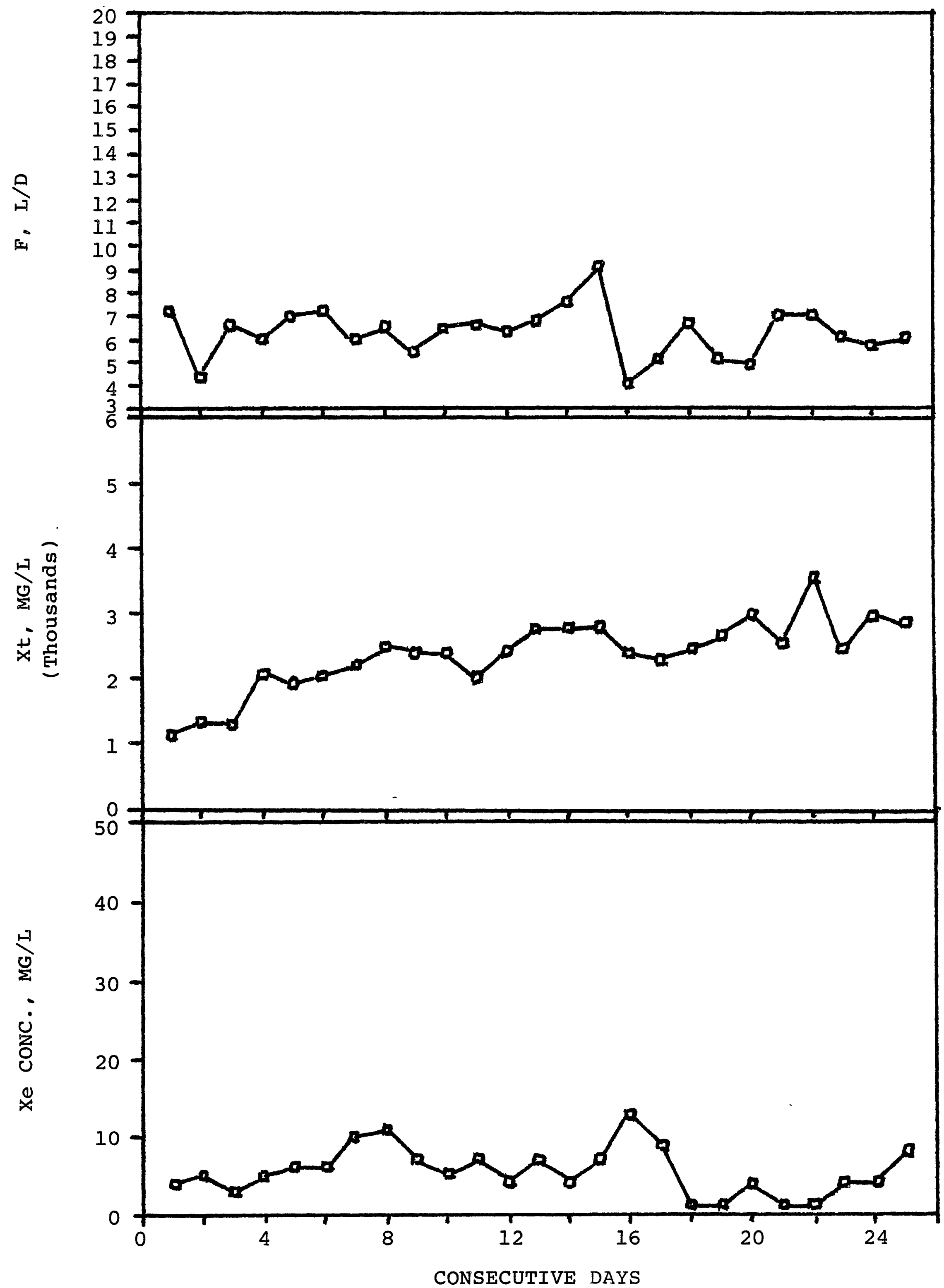


Figure 10. Nine Day SRT Consecutive Day Steady State Plot Beginning at 1/18/85

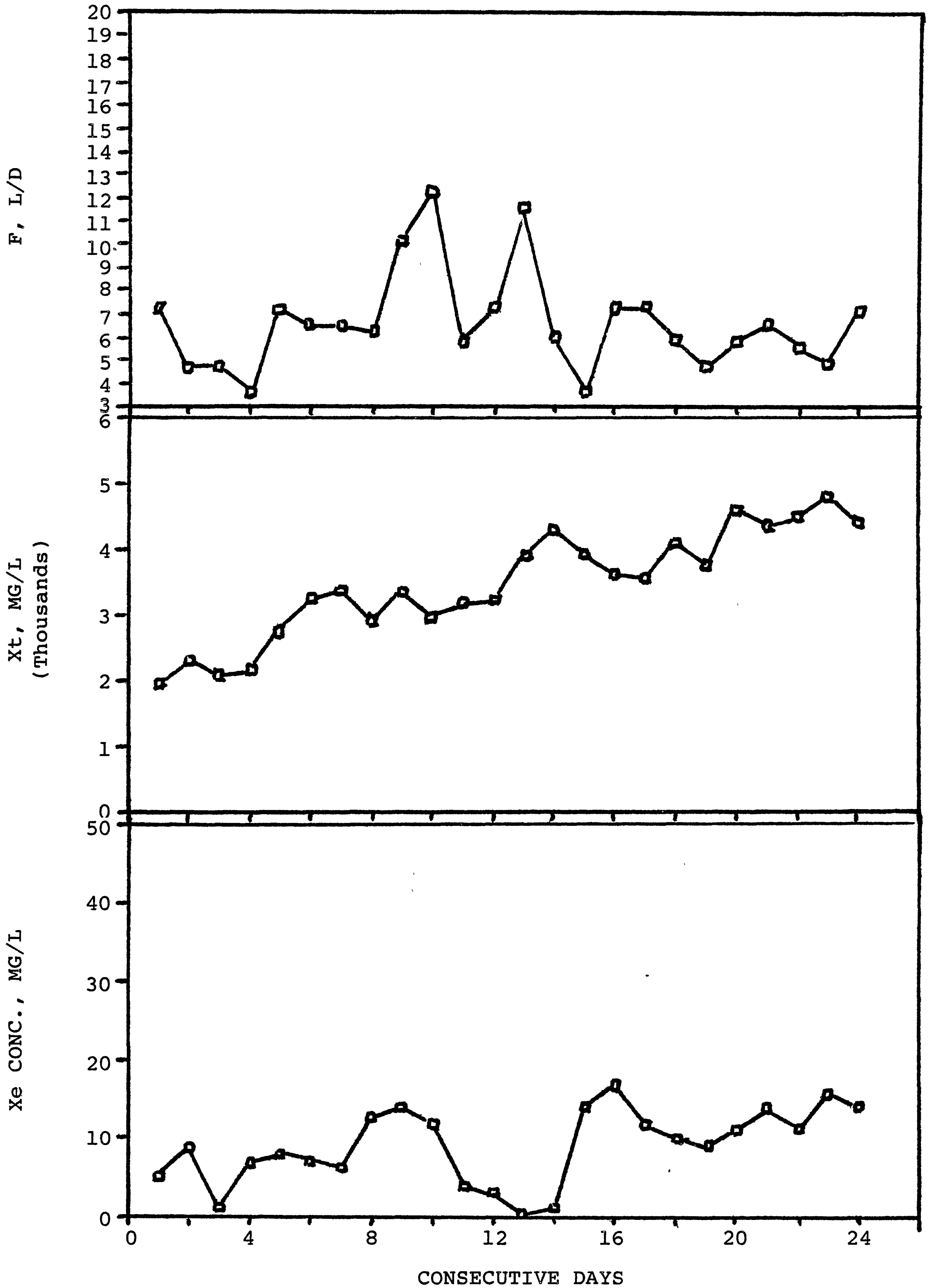


Figure 11. Fifteen Day SRT Consecutive Day Steady State Plot Beginning at 1/23/85

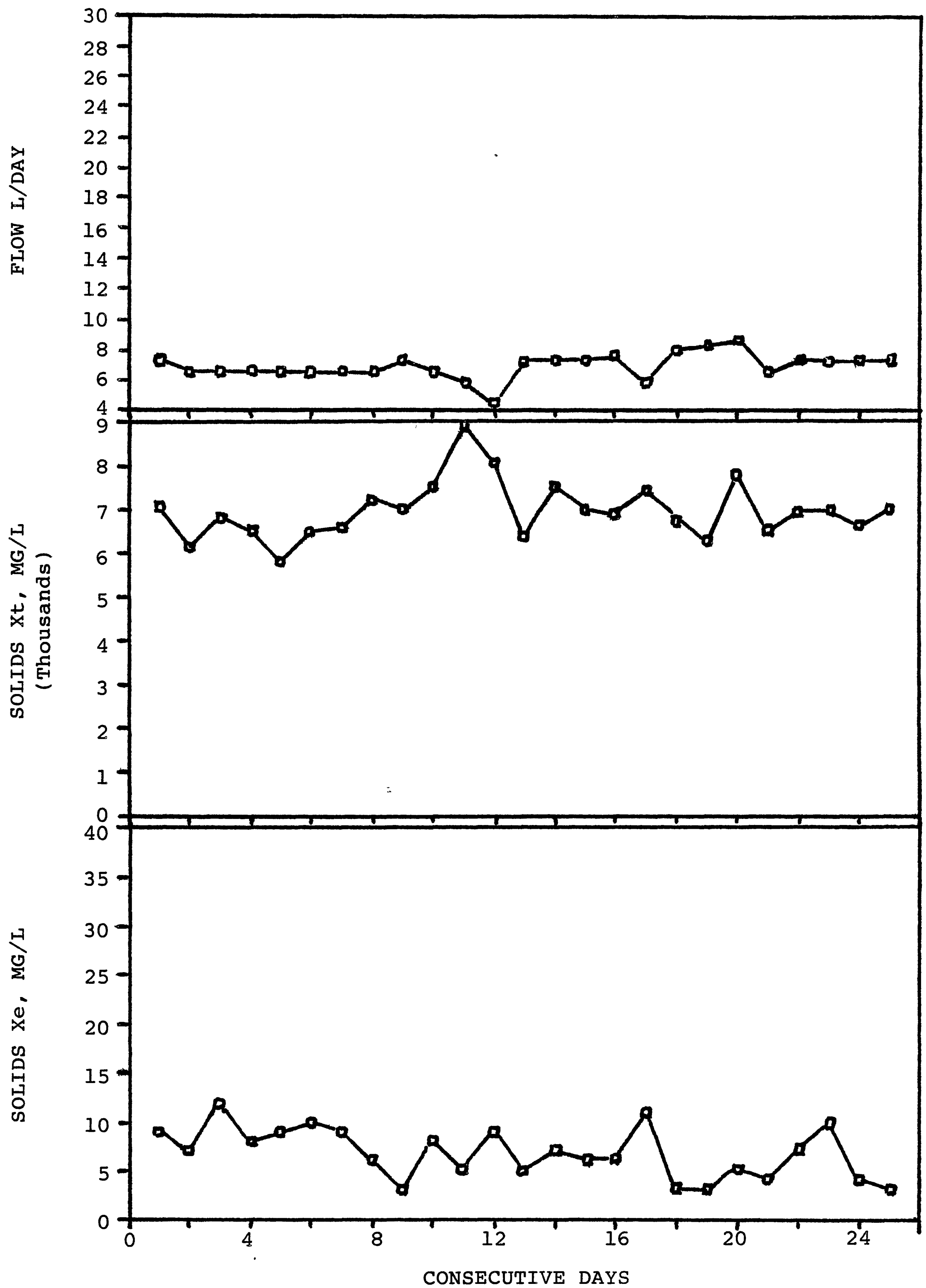


Figure 12. Twenty Day SRT Consecutive Day Steady State Plot Beginning at 12/1/84

completed in the 2.85 liter reactor. The feed system for this reactor was much more difficult to control with the feed variability increasing as shown from Figure 8 and then 11 to the point that the system had to be shut down. The other two reactors were run by one pump that had a more consistent feed flow rate.

The data used in the various model regressions are shown in Table II and include the substrate influent and effluent concentrations, the wasted volume per day, the feed flow rate per day, the volume of the reactor and the sludge retention time for each operational setting. The volatile suspended solids (Xt) increase as the SRT increases while the wasting per day (Vw) decreases. The complete data for the continuous reactors is included in Appendix A.

In order to summarize the operational data into a manageable fashion simple linear regression was used to identify how the operation data fits the various kinetic models. The slopes, intercepts, correlation index and calculated constants for each kinetic model is shown in Table III. The Kincannon/Stover model was the only model which had a high correlation index near one. The Lawrence/McCarty model has a low slope which produces a Ks factor of 213. Since the effluent substrate concentration was below this concentration in the operational data the bacteria should be operating at a low substrate utilization over the range of the operational data. In Table III, the Kincannon/Stover

TABLE II

OPERATIONAL DATA USED IN KINETIC MODELS

DATE MO/DA/YR	Si MG/L	Se MG/L	Xt MG/L	Xe MG/L	Vw L/DAY	F L/DAY	V L	SRT DAYS
2/6/85	317	1.7	580	4	1.93	4.8	2.92	1.5
2/11	457	4	800	7	1.91	6.0		
1/18/85	237	11	1060	7	1.42	7.2	2.92	2
1/21	351	1.4	680	4	1.43	6.0		
1/23	348	2.6	900	4	1.43	7.2		
1/28	425	6.8	848	12	1.39	6.6		
1/30	353	4.2	1060	10	1.41	6.72		
2/1	301	3.2	860	10	1.37	9.07		
2/4	374	1.7	600	2	1.44	6.72		
12/30/84	357	1.4	1280	3	.939	7.2	2.86	3
1/1/85	319	3	1580	4	.939	6.48		
1/3	307	2.8	1260	1	.948	7.92		
1/7	332	1.6	1000	2	.940	7.56		
1/9	328	1.3	1340	3	.935	9.24		
1/11	229	1.6	1760	2	.945	7.92		
1/14	327	2.6	1640	7	.925	7.56		
1/16	321	4.1	1080	7	.920	2.86		
12/22/84	244	2.2	1620	6	.523	7.92	2.85	5
12/30	375	1.3	1500	0	.570	10.08		
1/1/85	213	1	2140	3	.572	5.76		
1/3	222	2.7	2140	0	.57	7.2		
1/7	353	1.8	1660	4	.549	9.36		
1/9	356	1.9	1980	4	.551	10.03		
1/11	238	1.9	1780	1	.565	8.64		
1/14	443	3.3	2720	8	.555	5.76		
1/16	344	7.4	1980	14	.543	4.32		
1/18	264	4.0	1560	8	.534	7.56		
1/21	341	1.7	1880	3	.563	4.8		
11/3/84	264	1.1	2380	8	.382	8.28	2.86	7
11/6	257	2.2	2420	12	.368	8.64		
11/8	223	2.5	2380	8	.382	8.28		
12/1	306	5.8	2320	7	.388	7.2		
12/4	290	2.7	2180	9	.383	6.48		
12/6	329	3.4	2020	17	.357	6.48		
12/18	342	1.6	2100	7	.383	7.92		
12/20	239	2.9	2160	8	.378	8.64		
12/22	238	1.9	2160	1	.405	7.2		

TABLE II (Continued)

DATE MO/DA/YR	Si MG/L	Se MG/L	Xt MG/L	Xe MG/L	Vw L/DAY	F L/DAY	V L	SRT DAYS
1/18/85	304	2.1	1140	4	.294	7.2	2.86	9
1/21	386	1.8	2080	5	.304	6.0		
1/23	346	2.7	2060	6	.298	7.2		
1/28	379	3.5	2020	7	.296	6.6		
1/30	329	2.5	2780	7	.302	6.72		
2/1	296	2.8	2820	7	.296	9.07		
2/4	315	1.7	2480	1	.315	6.72		
2/6	313	1.0	3000	4	.312	4.80		
1/23/85	386	2.8	1940	5	.172	7.2	2.85	15
1/28	450	2.5	3240	7	.176	6.48		
1/30	364	7.7	2920	13	.163	6.12		
2/1	362	6.1	2960	12	.141	12.24		
2/4	351	2.7	3900	0	.190	11.52		
2/6	305	7	3920	14	.178	3.6		
2/11	444	3.8	4620	11	.177	5.76		
11/3/85	264	1	5760	5	.139	8.28	2.92	20
12/18	319	3.9	6760	3	.143	7.92		
12/20	276	2.8	7800	5	.141	8.64		
12/30	386	1.3	5860	1	.145	7.2		
1/1/85	311	4	6280	7	.139	6.48		

TABLE III

REGRESSION RESULTS OF KINETIC MODELS AND YIELD AND ENDOGENOUS FACTORS

MODELS	SLOPE	INTERCEPT	CORRELATION INDEX R^2	STANDARD ERROR
Kincannon/Stover	1.013	-0.0083	0.9999	0.0256
Um = infinite		Kb/Um = 1.013		
Lawrence/McCarty	0.0655	3.0687	0.00004	2.2492
Umax = 0.33	Ks = 213.4			
McKinney, Se model	-12.18	847.54	0.0115	222.32
Km = -12.18				
McKinney, Xt model	0.0059	796.93	0.0017	223.42
constant = 0.0059				

Yield and Endogenous Factor

Y = 0.442 Kd = 0.0072
Correlation Index (R^2) = 0.6704
Standard Error = 0.0952

model had the highest correlation index near one with a slope of 1.013 and an intercept of -0.0083. This produces a Um which should be infinite and a Kb/Um which would be a constant near one. The other models all had very low correlation indexes indicating little correlation. The regression for Yield (Y) and Endogenous (Kd) factors are also listed with a correlation index of 67%. The Yield factor equaling 0.44 and the Kd factor equal to 0.01.

B. Oxygen Consumption

The complete oxygen consumption test data with the test dates is included in Table IV. This table contains the oxygen consumption rate used to determine the maximum oxygen consumption rate and also data used to determine the oxygen decay rate. Under each SRT condition tested the row of oxygen consumption rates is preceded by the decay days. A zero decay day corresponds to the oxygen consumption test being conducted on mixed-liquor solid just sampled from the continuous reactor unit. A one day decay indicates the solids were sampled from the continuous reactor and placed in a batch reactor for one day and then the oxygen consumption test being conducted. The columns indicate the glucose concentration in the test bottle for each oxygen consumption determination. A Se concentration of glucose means that no glucose was added to the test bottle and the oxygen consumption test conducted on undiluted mixed-liquor solid

TABLE IV

COMPLETE OXYGEN CONSUMPTION DATA

	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC.						
DECAY DAYS	Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
SRT 7 DAY, 12/12/84							
0	.52	.55	.57	.57	.54	.47	.29
X MG/L	2500				2100		1660
1	.26	.41	.43	.45	.43	.39	.25
X MG/L	2240				2020		1560
8	.15	.17	.17	.19	.19	.17	.11
X MG/L	1700				1620		1280
17	.10	.11	.11	.11	.12	.11	.07
X MG/L	1700				1620		1440
SRT 7 DAY, 12/1/84							
0	.54	.56	.59	.61	[illegible]	.51	.33
X MG/L	2420				2140		1460
1	.23	.38	.40	.45	.45	.40	.26
X MG/L	2140				2020		1520
4	.25	.27	.30	.31	.31	.27	.19
X MG/L	2040				1760		1360
7	.17	.19	.21	.22	.21	.18	.13
X MG/L	1880				1800		1440
SRT 7 DAY, 11/23/84							
0	.33	.43	.47	.54	.55	.46	.28
X MG/L	2460				2040		1600
1	.32	.27	.31	.39	.41	.35	.22
X MG/L	2320				2060		1600
2	.27	.31	.29	.34	.36	.33	.20
X MG/L	2100				1840		1600
3	.26	.31	.32	.32	.33	.30	.19
X MG/L	2000				1820		1440
SRT 3 DAY, 1/15/85							
0	.60	.58	.57	.59	.57	.46	.21
X MG/L	1200				1260		1300
1	.24	.29	.31	.32	.33	.28	.13
X MG/L	1080				1080		1240
7	.10	.13	.10	.15	.15	.13	.07
X MG/L	920				880		900
10	.05	.09	.10	.09	.10	.08	.04
X MG/L	960				920		1180
SRT 3 DAY, 1/14/85							
0	.54	.53	.53	.51	.48	.40	.17
X MG/L	1180				1020		1120
1	.29	.33	.34	.35	.33	.27	.12
X MG/L	1000				1120		1140
3	.19	.23	.23	.25	.25	.21	.11
X MG/L	920				1180		1200
11	.05	.09	.11	.11	.11	.09	.06
X MG/L	1340				1360		1280

TABLE IV (Continued)

DECAY DAYS		OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC. Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
SRT 3 DAY, 1/7/85								
	0	.64	.59	.59	.59	.57	.47	.23
X MG/L		1400				1400		1300
	1	.17	.35	.39	.41	.39	.36	.19
X MG/L		1360				1260		1620
	3	.18	.23	.25	.27	.25	.22	.13
X MG/L		1060				1000		1480
	6	.17	.20	.22	.24	.23	.21	.13
X MG/L		1200				1380		1080
SRT 9 DAY, 2/16/85								
	0	.58	.65	.68	.71	.69	.58	.38
X MG/L		3220				2800		2780
	1	.18	.41	.44	.48	.48	.43	.27
X MG/L		2980				2820		2400
	4	.23	.35	.38	.41	.39	.35	.25
X MG/L		3140				3060		2620
	6	.15	.21	.23	.25	.25	.23	.15
X MG/L		2500				2980		1620
SRT 9 DAY, 2/16/85								
	0	.57	.65	.69	.72	.69	.59	.37
X MG/L		3260				2860		2700
	1	.36	.45	.48	.52	.51	.45	.29
X MG/L		2820				2560		2300
	4	.19	.26	.27	.28	.27	.22	.16
X MG/L		2160				2240		1580
	11	.09	.12	.14	.14	.13	.12	.07
X MG/L		1640				1720		1240
SRT 9 DAY, 2/11/85								
	0	.59	.71	.73	.72	.69	.57	.33
X MG/L		2540				2540		2340
	1	.54	.65	.67		.68	.58	.35
X MG/L		2800				2680		1760
	4	.20	.29	.29	.30	.27	.23	.15
X MG/L		2060				1960		1500
	11	.07	.11	.11	.12	.12	.11	.07
X MG/L		1580				1700		1400
SRT 9 DAY, 2/4/85								
	0	.59	.67	.67	.67	.63	.53	.29
X MG/L		2520				2360		1961
	1	.41	.51	.53	.55	.52	.44	.22
X MG/L		2380				2180		1880
	2	.28	.37	.40	.41	.39	.35	.21
X MG/L		2360				2020		1940
	6	.14	.21	.21	.23	.21	.19	.11
X MG/L		1860				1740		1340

TABLE IV (Continued)

DECAY DAYS	Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC.						
SRT 20 DAY, 1/2/85							
0	.53	.51	.48	.47	.43	.36	.23
X MG/L	6440				6080		4420
SRT 20 DAY, 12/25/84							
0	.55	.51	.53	.53	.51	.49	.42
X MG/L	6820				6600		3680
SRT 2 DAY, 2/4/85							
0	.39	.47	.47	.48	.45	.36	.11
X MG/L	760				720		700
2	.13	.39	.39	.41	.37	.28	.09
X MG/L	670				590		500
4	.19	.15	.16	.16	.16	.13	.06
X MG/L	460				410		510
SRT 2 DAY, 1/31/85							
0	.43	.49	.49	.49	.45	.37	.12
X MG/L	820				840		1000
1	.12	.41	.41	.41	.38	.30	.09
X MG/L	840				920		1020
3	.15	.25	.27	.26	.24	.21	.13
X MG/L	760				820		840
4	.10	.12	.13	.13	.13	.11	.05
X MG/L	440				500		540
8	.05	.07	.08	.07	.08	.07	.03
X MG/L	520				560		500
SRT 2 DAY, 1/28/85							
0	.57	.56	.55	.53	.50	.41	.26
X MG/L	960				820		800
1	.29	.38	.37	.37	.35	.30	.17
X MG/L	640				760		860
4	.15	.20	.19	.20	.19	.17	.09
X MG/L	460				580		680
6	.05	.12	.13	.13	.13	.12	.07
X MG/L	640				620		560

TABLE IV (Continued)

DECAY DAYS	Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC.						
SRT 1.5 DAY, 2/15/85							
0	.20	.31	.30	.31	.29	.24	.09
X MG/L	630				550		630
1	.11	.25	.27	.28	.26	.22	.09
X MG/L	520				520		360
3	.07	.16	.17	.17	.17	.14	.07
X MG/L	450				430		660
5	.04	.10	.11	.11	.11	.09	.05
X MG/L	530						420
SRT 1.5 DAY, 2/11/85							
0	.60	.62	.62	.61	.57	.47	.23
X MG/L	950				790		670
1	.31	.44	.45	.45	.42	.35	.13
X MG/L	740				680		650
SRT 1 DAY, 2/18/85							
0	.49	.51	.50	.51	.46	.39	.22
X MG/L	610				520		570
7	.09	.13	.14	.13	.13	.11	.07
X MG/L	320				324		295
9	.06	.09	.09	.10	.10	.09	.05
X MG/L	260				240		250
SRT 0.9 DAY, 2/22/85							
0	.26	.20	.19	.17	.16	.13	.07
X MG/L	200				200		167
1	.03	.10	.11	.12	.12	.08	.06
X MG/L	140				150		143
3	.03	.09	.09	.10	.09	.08	.06
X MG/L	120				160		150
5	.03	.06	.07	.07	.07	.06	.04
X MG/L	120				127		136
SRT 5 DAY, 1/21/85							
0	.65	.69	.69	.71	.65	.54	.23
X MG/L	2040				1840		1600
1	.35	.43	.46	.46	.43	.38	.12
X MG/L	2120				1940		1700
4	.28	.35	.37	.38	.35	.29	.17
X MG/L	1880				1660		1760
14	.05	.11	.13	.13	.13	.11	.07
X MG/L	1440				1280		1580
SRT 5 DAY, 1/11/85							
0	.47	.55	.57	.58	.55	.48	.21
X MG/L	1800				1720		1400
2	.32	.41	.42	.43	.41	.35	.18
X MG/L	2120				1880		1720
4	.13	.34	.35	.36	.33	.29	.17
X MG/L	1880				1780		1500

TABLE IV (Continued)

DECAY DAYS	Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC.						
SRT 5 DAY, 1/3/85							
0	.39	.43	.44	.46	.43	.36	.17
X MG/L	2280				1920		1400
1	.27	.33	.35	.36	.36	.31	.17
X MG/L	2040				1800		1700
2	.21	.27	.28	.31	.25	.25	.15
X MG/L	1980				1560		1580
8	.09	.15	.14	.15	.14	.12	.07
X MG/L	1560				1500		1280
SRT 15 DAY, 2/15/85							
0	.61	.67	.68	.71	.67	.61	.39
X MG/L	3860				3580		2460
1	.37	.53	.57	.64	.62	.53	.35
X MG/L	4360				6080		4800
3	.32	.43	.48	.49	.49	.47	.33
X M/L	5300				5780		4100
5	.23	.25	.25	.27	.26	.27	.19
X MG/L	4600				4280		3320
SRT 15 DAY, 2/15/85							
0	.44	.58	.60	.65	.65	.57	.38
X MG/L	4120				3800		2540
1	.38	.48	.57	.61	.60	.54	.36
X MG/L	4500				4500		4260
3	.37	.45	.47	.49	.52	.49	.33
X MG/L	4900				4800		5100
5	.21	.22	.23	.25	.25	.23	.19
X MG/L	4660				4300		4660
SRT 1 DAY, 2/18/85							
AFTER WASTING	.44	.32	.28	.26	.23	.18	.08
X MG/L	240				300		260
SRT 10 DAY VEGETOA TYPE SOLIDS, 1/16/85							
0	.96	1.07	1.08	1.09	1.05	.85	.51
X MG/L	3420				3160		1880
1	.48	.57	.61	.62	.62	.53	.34
X MG/L	3320				3200		2000
2	.35	.48	.59	.59	.58	.46	.28
X MG/L	3180				2940		2200
SRT 20 DAY, 12/25/84, FEED MIXTURE USED INSTEAD OF GLUCOSE							
0	.53	.24	.13	.09	.08	.05	.03
X MG/L	6940				5860		3300
SRT 7 DAY, 12/16/84, FEED MIXTURE USED INSTEAD OF GLUCOSE							
1	.19	.79	.30	.15	.11	.05	.02
X MG/L	2180				1880		980
3	.63	.59	.27	.15	.08	.03	.03
X MG/L	2000				1700		1020
6	.41	.38	.26	.14	.07	.04	.03
X MG/L	2280				1960		940

TABLE IV (Continued)

DECAY DAYS	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC. Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
SRT 20 DAY, 1/1/85, SOLIDS DILUTED ABOUT ONE HALF							
0	.17	.17	.18	.20	.20	.15	.11
X MG/L	2660				2560		1860
1	.08	.09	.11	.11	.11	.11	.07
X MG/L	2660				2560		1920
4	.03	.04	.03	.05	.03	.03	.01
X MG/L	3000				2680		2080
5	.05	.06	.08	.09	.07	.06	.04
X MG/L	2680				2820		2080

either directly from the continuous reactor as in the case of zero decay days or on the undiluted mixed-liquor solid from the batch reactors after decay days have been allowed to pass. Generally all oxygen consumption rates decreased as the decay days increased. The oxygen consumption rate would tend to increase with the glucose concentration increase up to a point then decrease as the glucose concentration further increased. This decrease was expected since the mixed-liquor solids had to be removed as the glucose solution was added. The solids concentration for the decay rate test was less then the sample initial solids concentration and decreased as the decay days increase within each SRT set of data. Such should be expected as endogenous respiration would break down the solids in the batch reactor. The endogeneous factor since it is an exponential decay factor can be checked quickly by dividing the solid concentration for a large decay day test by the solids concentration of the initial sample, then taking the natural log of the dividend and dividing by the number of decay days. For example, the seven day SRT data with a solids concentration of 1700mg/L after 17 days of decay and 2500mg/L at the initial sample time would give:

$$\ln(1700/2500) = -.386 \qquad (5\text{-}1)$$

$$-.386/17 = -.0227/\text{day} \qquad (5\text{-}2)$$

This doesn't agrees with the endogeneous factor (Kd) of 0.0072 obtained in Table III, however, this test was not designed to test for the endogenous factor and wouldn't have the accuracy of the endogenous factor regression. Since the calculated endogenous value is within an order of magnitude of the regressed endogenous constant that is probably the best agreement that can be expected.

Several sets of data at the end of this table were not used in this analysis because of different techniques used in conducting the tests. The last 20 day SRT set was not used because the mixed-liquor solids sampled from the continuous reactor was diluted to about half concentration sampled. The next 7 day and 20 day SRT sets of data were not used because the reactor feed mixture was used instead of glucose and it was discovered that the magnesium sulfate solids in the feed at the high test concentration caused an inhibition of oxygen consumption. The 10 day SRT beggiatoa type solids data was not used because the biological solids were not of the same appearance and characteristics as the rest of the data and the initial oxygen consumption tests indicated that the oxygen consumed was much higher than was needed for utilization of the feed to the reactors. The SRT of one day after wasting data set was not used in the analysis because it was conducted on mixed-liquor solids taken from the reactor about one hour after wasting when the solids concentration in the continuous reactor would be at its lowest concentration. All the other zero decay day tests were conducted on mixed-liquor solids taken from the continuous reactor prior to wasting of the solids when the solids concentration would be at its highest concentration.

The oxygen consumption rate of the one day SRT for zero decay days increase after a few additions of glucose and then decrease. The oxygen consumption rate for the one day SRT after wasting decreased with each addition of glucose solution. This would indicate that the solids in the reactor after wasting altered their oxygen consumption rate to the maximum rate due to the smaller concentration of solids in the reactor while using the same amount of feed into the reactor. The solid accumulated during a day of growth so there is an excess of solids when the oxygen consumption test is conducted prior to wasting.

The data in Table IV has been rearranged for discussion in Tables V through X. Table V lists the oxygen consumption test data for the tests run on the day the sample was extracted from the reactor. The table lists the SRT the reactor was operated at, the solids concentration of the sample when it was extracted from the reactor and the various oxygen consumption rates from zero glucose added (just extracted from the reactor) to a glucose concentration of 22,000 mg/l in the test bottle.

The oxygen consumption data from Table V was corrected for the solids withdrawn from the test bottle during the test as shown in Table VI. The correction factor used to obtain the corrected oxygen consumption rate is listed at the top of the table above the oxygen consumption data. The correction factor was determined from calculating the serial removal of the mixed-liquor solids from the test bottle. For example,

TABLE V

OXYGEN CONSUMPTION BY SRT AND BY GLUCOSE CONCENTRATION

SRT DAYS	SOLIDS MG/L	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC. Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
.9	200	.26	.20	.19	.17	.16	.13	.07
1	610	.49	.51	.50	.51	.46	.39	.22
1.5	630	.20	.31	.30	.31	.29	.24	.09
1.5	950	.60	.62	.62	.61	.57	.47	.23
2	760	.39	.47	.47	.48	.45	.36	.11
2	820	.43	.49	.49	.49	.45	.37	.12
2	820	.43	.49	.49	.49	.45	.37	.12
2	960	.57	.56	.55	.53	.50	.41	.26
3	1200	.60	.58	.57	.59	.57	.46	.21
3	1180	.54	.53	.53	.51	.48	.40	.17
3	1400	.64	.59	.59	.59	.57	.47	.23
5	2040	.65	.69	.69	.71	.65	.54	.23
5	1800	.47	.55	.57	.58	.55	.48	.21
5	2280	.39	.43	.44	.46	.43	.36	.17
7	2500	.52	.55	.57	.57	.54	.47	.29
7	2420	.54	.56	.59	.61	.61	.51	.33
7	2460	.33	.43	.47	.54	.55	.46	.28
9	3220	.58	.65	.68	.71	.69	.58	.38
9	3260	.57	.65	.69	.72	.69	.59	.37
9	2540	.59	.71	.73	.72	.69	.57	.33
9	2520	.59	.67	.67	.67	.63	.53	.29
15	3860	.61	.67	.68	.71	.67	.61	.39
15	4120	.44	.58	.60	.65	.65	.57	.38
20	6440	.53	.51	.48	.47	.43	.36	.23
20	6820	.55	.51	.53	.53	.51	.49	.42

TABLE VI

CORRECTED OXYGEN CONSUMPTION FOR SOLIDS BY SRT AND GLUCOSE CONCENTRATION

		OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC.						
SRT DAYS	SOLIDS MG/L	Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
Correction factor		1.00	1.03	1.07	1.11	1.23	1.54	2.56
.9	200	.26	.21	.20	.19	.20	.20	.18
1	610	.49	.53	.54	.56	.57	.60	.56
1.5	630	.20	.32	.32	.34	.36	.37	.23
1.5	950	.60	.64	.66	.68	.70	.72	.59
2	760	.39	.49	.50	.53	.55	.55	.28
2	820	.43	.51	.52	.54	.55	.57	.31
2	820	.43	.51	.52	.54	.55	.57	.31
2	960	.57	.58	.59	.59	.62	.63	.67
3	1200	.60	.60	.61	.65	.70	.71	.54
3	1180	.54	.55	.57	.56	.59	.62	.44
3	1400	.64	.61	.63	.65	.70	.72	.59
5	2040	.65	.71	.74	.79	.80	.83	.59
5	1800	.47	.57	.61	.64	.68	.74	.54
5	2280	.39	.44	.47	.51	.53	.55	.44
7	2500	.52	.57	.61	.63	.66	.72	.74
7	2420	.54	.58	.63	.68	.75	.78	.85
7	2460	.33	.44	.50	.60	.68	.71	.72
9	3220	.58	.67	.73	.79	.85	.89	.97
9	3260	.57	.67	.74	.80	.85	.91	.95
9	2540	.59	.73	.78	.80	.85	.88	.85
9	2520	.59	.69	.72	.74	.77	.82	.74
15	3860	.61	.69	.73	.79	.82	.94	1.00
15	4120	.44	.60	.64	.72	.80	.88	.97
20	6440	.53	.53	.51	.52	.53	.55	.59
20	6820	.55	.53	.57	.59	.63	.75	1.08

the 0.19 mg/l/min. oxygen consumption rate for 0.9 day SRT would be corrected by a factor of 1.07 because 10 ml out of 300 ml of solids solution was removed for the 1200 mg/l glucose concentration test and another 10 ml of the 300 ml of solids solution was removed for the 2400 mg/l glucose concentration test. This equals

$$\frac{(300 - 10)}{300} * \frac{(300 - 10)}{300} = 0.934 \qquad (5\text{-}3)$$

or 93% of the solids concentration remaining in the test bottle. Inverting this number produces 1.07 which will bring the oxygen consumption rate up to the level as if no solids had been removed.

Figures 13 and 14 are characteristic plots of the oxygen consumption rate data. Figure 12 is a plot of the oxygen consumption rate data for the first nine day SRT set and Figure 14 is the same data corrected for solids removed. Figure 14 plot has the resemblance of the Monod type of curve characteristic of this data. The maximum oxygen consumption rate in the uncorrected Figure 13 occurs around the 3500 mg/l glucose concentration while the maximum in the corrected for solids, Figure 14, occurs at the highest glucose concentration of 22000 mg/l. This characteristic of the uncorrected maximum occurring near 3500mg/l and the corrected maximum occurring near the highest glucose concentration is consistent in all the SRT data except for the smallest SRT of 0.9 days. The 0.9 day SRT oxygen consumption rate data had a different type of consumption

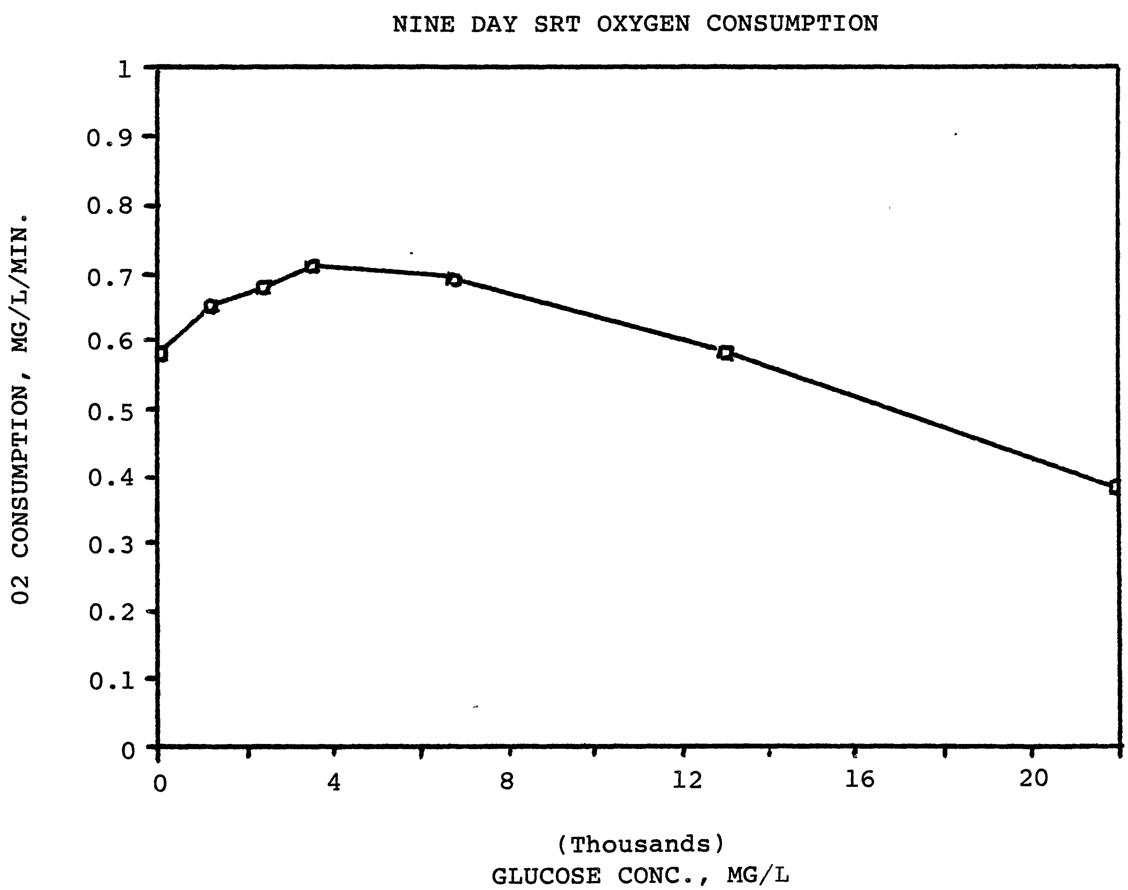


Figure 13. Nine Day SRT Oxygen Consumption Rate

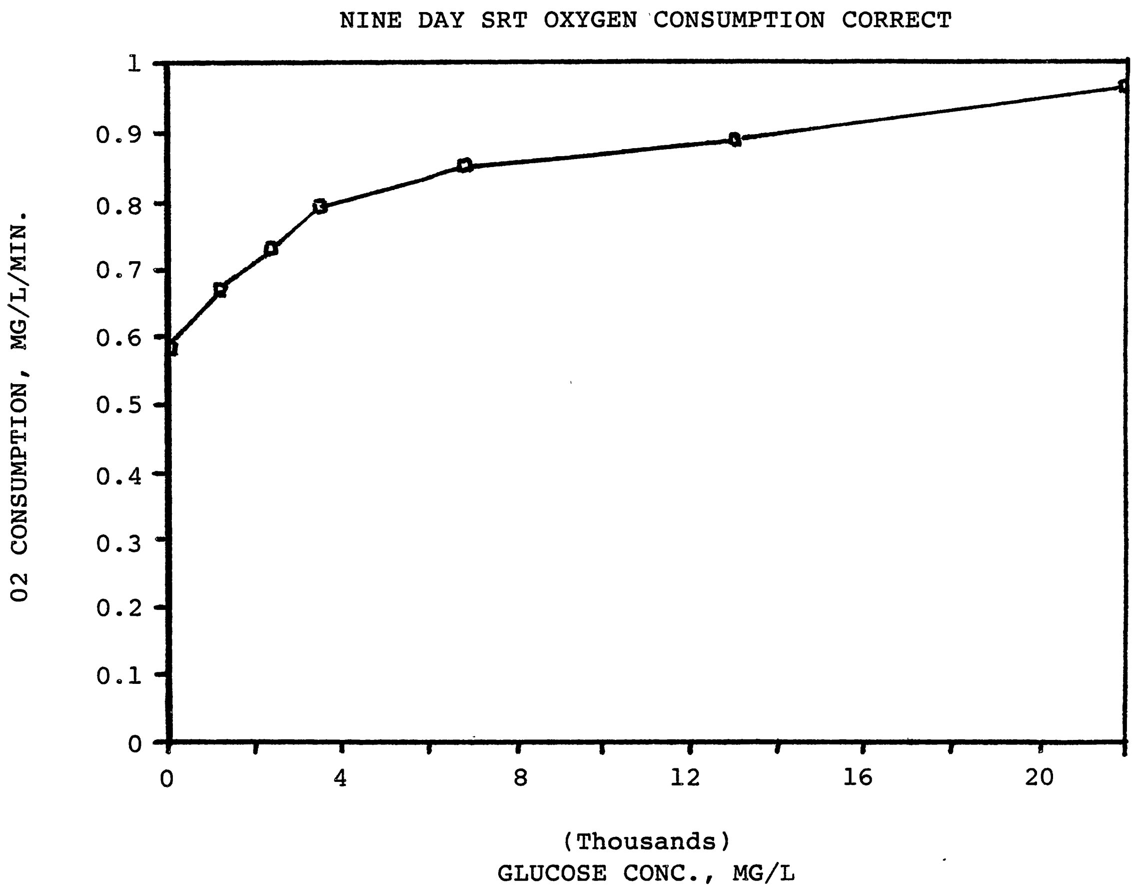


Figure 14. Nine Day SRT Oxygen Consumption Rate Corrected

curve. Figure 15 shows the uncorrected and Figure 16 shows the corrected consumption rates. The 0.9 day SRT reactor was operating at its maximum consumption rate when extracted from the reactor and showed no increase as glucose was added.

The maximum oxygen consumption rates and the initial consumption rates for each SRT are given in Table VII. Table VII also contains the ratio of the initial oxygen consumption rate to the maximum and also to the corrected maximum oxygen consumption rates from the tests. It appears from these ratios that the initial oxygen consumption rate is generally above half the maximum oxygen consumption rate, and the over all average of the initial to corrected maximum is 0.71 and the initial to maximum is 0.88. The ratio did not decrease rapidly as the SRT and solids (Xt) increased as most Monod type kinetic models would predict.

Table VIII contains the initial day test as well as results of oxygen consumption rate for the various days of decay for each SRT condition. Table IX contains the same data corrected for solids withdrawn in the oxygen consumption test. As the glucose concentration increases the oxygen consumption increases and then decreases again at the high glucose concentrations. The oxygen consumption rates decrease as the decay days increase as would be expected. The larger decay day oxygen consumption rate rows of data show the least amount of change as the glucose concentration increases indicating few viable solids remaining. The maximum oxygen consumption rate for each row of Table VIII

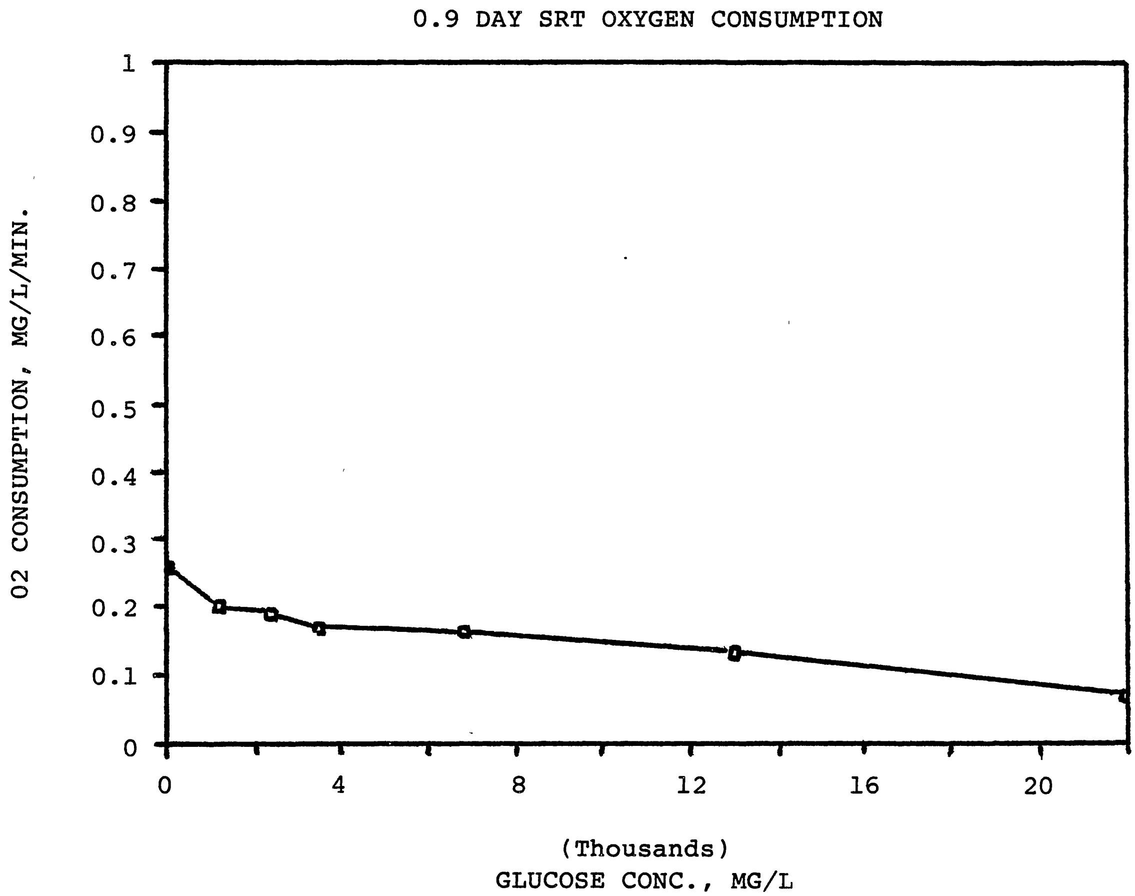


Figure 15. 0.9 Day SRT Oxygen Consumption Rate

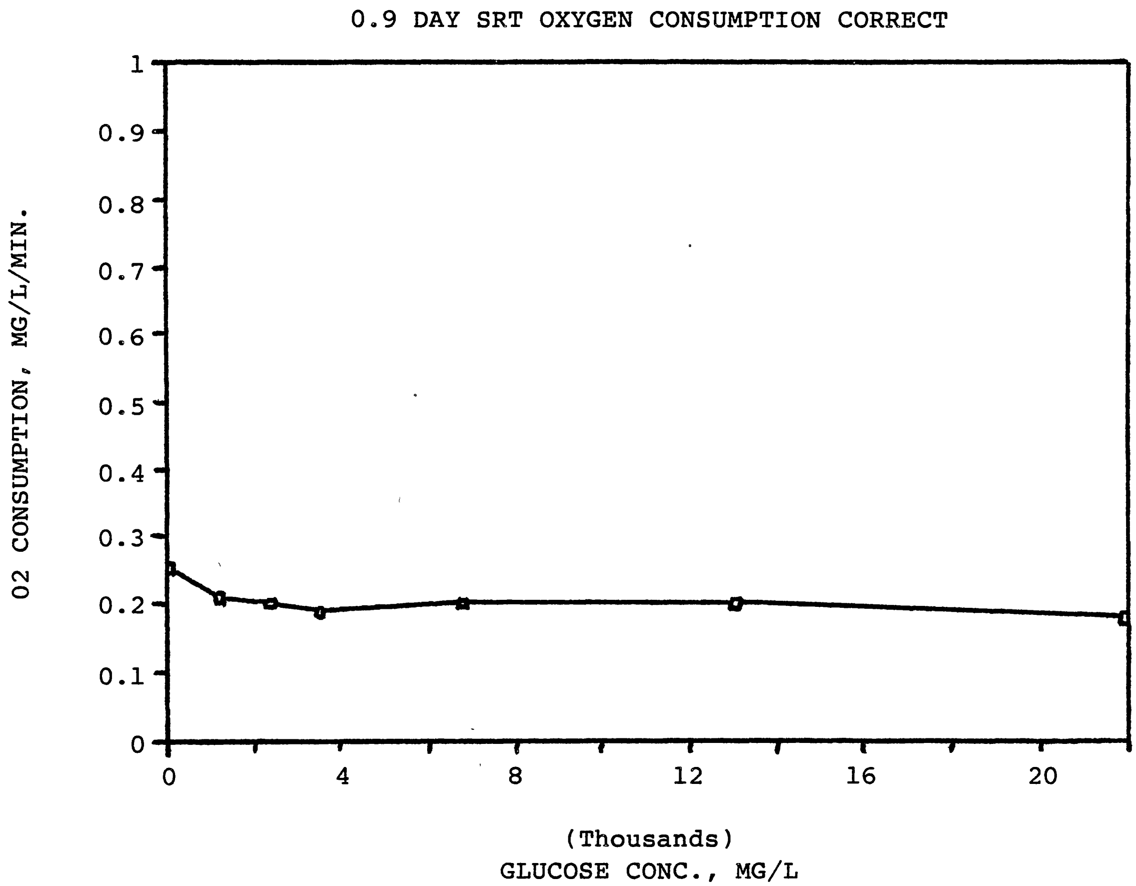


Figure 16. 0.9 Day SRT Oxygen Consumption Rate Corrected

TABLE VII

MAXIMUMS AND INITIAL OXYGEN CONSUMPTION BY SRT

SRT DAYS	CORRECTED MAX. CONS. MG/L/MIN	MAXIMUM CONS. MG/L/MIN	INITIAL CONS. MG/L/MIN	INITIAL DIV. BY CORR MAX	INITIAL DIV. BY MAX
.9	.26	.26	.26	1.00	1.00
1	.60	.51	.49	.82	.96
1.5	.37	.31	.20	.54	.65
1.5	.72	.62	.60	.83	.97
2	.55	.48	.39	.71	.81
2	.57	.49	.43	.75	.88
2	.57	.49	.43	.75	.88
2	.67	.57	.57	.85	1.00
3	.71	.59	.60	.85	1.00
3	.62	.54	.54	.87	1.00
3	.72	.64	.64	.89	1.00
5	.83	.71	.65	.78	.92
5	.74	.58	.47	.64	.81
5	.55	.46	.39	.71	.85
7	.74	.57	.52	.70	.91
7	.85	.61	.54	.64	.89
7	.72	.55	.33	.46	.60
9	.97	.71	.58	.60	.82
9	.95	.72	.57	.60	.79
9	.88	.73	.59	.67	.81
9	.82	.67	.59	.72	.88
15	1.00	.71	.61	.61	.86
15	.97	.65	.44	.45	.68
20	.59	.53	.53	.90	1.00
20	1.08	.55	.55	.51	1.00
			TOTAL	17.85	21.97
			AVERAGE	.71	.88

TABLE VIII

OXYGEN CONSUMPTION DECAY
WITHIN SRT

SRT DAYS	DECAY DAYS	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC. Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
.9	0	.26	.20	.19	.17	.16	.13	.07
	1	.03	.10	.11	.12	.12	.08	.06
	3	.03	.09	.09	.10	.09	.08	.06
	5	.03	.06	.07	.07	.07	.06	.04
1	0	.49	.51	.50	.51	.46	.39	.22
	7	.09	.13	.14	.13	.13	.11	.07
	9	.06	.09	.09	.10	.10	.09	.05
1.5	0	.20	.31	.30	.31	.29	.24	.09
	1	.11	.25	.27	.28	.26	.22	.09
	3	.07	.16	.17	.17	.17	.14	.07
	5	.04	.10	.11	.11	.11	.09	.05
1.5	0	.60	.62	.62	.61	.57	.47	.23
	1	.31	.44	.45	.45	.42	.35	.13
2	0	.39	.47	.47	.48	.45	.36	.11
	2	.13	.39	.39	.41	.37	.28	.09
	4	.19	.15	.16	.16	.16	.13	.06
2	0	.43	.49	.49	.49	.45	.37	.12
	1	.12	.41	.41	.41	.38	.30	.09
	3	.15	.25	.27	.26	.24	.21	.13
	4	.21	.31	.37	.39	.37	.30	.11
2	0	.43	.49	.49	.49	.45	.37	.12
	1	.29	.38	.39	.40	.35	.29	.12
	4	.10	.12	.13	.13	.13	.11	.05
	8	.05	.07	.08	.07	.08	.07	.03
2	0	.57	.56	.55	.53	.50	.41	.26
	1	.29	.38	.37	.37	.35	.30	.17
	4	.15	.20	.19	.20	.19	.17	.09
	6	.05	.12	.13	.13	.13	.12	.07
3	0	.60	.58	.57	.59	.57	.46	.21
	1	.24	.29	.31	.32	.33	.28	.13
	7	.10	.13	.10	.15	.15	.13	.07
	10	.05	.09	.10	.09	.10	.08	.04

TABLE VIII (Continued)

SRT DAYS	DECAY DAYS	Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
		OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC.						
3	0	.54	.53	.53	.51	.48	.40	.17
	1	.29	.33	.34	.35	.33	.27	.12
	3	.19	.23	.23	.25	.25	.21	.11
	11	.05	.09	.11	.11	.11	.09	.06
3	0	.64	.59	.59	.59	.57	.47	.23
	1	.17	.35	.39	.41	.39	.36	.19
	3	.18	.23	.25	.27	.25	.22	.13
	6	.17	.20	.22	.24	.23	.21	.13
5	0	.65	.69	.69	.71	.65	.54	.23
	1	.35	.43	.46	.46	.43	.38	.12
	4	.28	.35	.37	.38	.35	.29	.17
	14	.05	.11	.13	.13	.13	.11	.07
5	0	.47	.55	.57	.58	.55	.48	.21
	2	.32	.41	.42	.43	.41	.35	.18
	4	.13	.34	.35	.36	.33	.29	.17
5	0	.39	.43	.44	.46	.43	.36	.17
	1	.27	.33	.35	.36	.36	.31	.17
	2	.21	.27	.28	.31	.25	.25	.15
	8	.09	.15	.14	.15	.14	.12	.07
7	0	.52	.55	.57	.57	.54	.47	.29
	1	.26	.41	.43	.45	.43	.39	.25
	8	.15	.17	.17	.19	.19	.17	.11
	17	.10	.11	.11	.11	.12	.11	.07
7	0	.54	.56	.59	.61	.61	.51	.33
	1	.23	.38	.40	.45	.45	.40	.26
	4	.25	.27	.30	.31	.31	.27	.19
	7	.17	.19	.21	.22	.21	.18	.13
7	0	.33	.43	.47	.54	.55	.46	.28
	1	.32	.27	.31	.39	.41	.35	.22
	2	.27	.31	.29	.34	.36	.33	.20
	3	.26	.31	.32	.32	.33	.30	.19
9	0	.58	.65	.68	.71	.69	.58	.38
	1	.18	.41	.44	.48	.48	.43	.27
	4	.23	.35	.38	.41	.39	.35	.25
	6	.15	.21	.23	.25	.25	.23	.15

TABLE VIII (Continued)

SRT DAYS	DECAY DAYS	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC. Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
9	0	.57	.65	.69	.72	.69	.59	.37
	1	.36	.45	.48	.52	.51	.45	.29
	4	.19	.26	.27	.28	.27	.22	.16
	11	.09	.12	.14	.14	.13	.12	.07
9	0	.59	.71	.73	.72	.69	.57	.33
	1	.54	.65	.67		.68	.58	.35
	4	.20	.29	.29	.30	.27	.23	.15
	11	.07	.11	.11	.12	.12	.11	.07
9	0	.59	.67	.67	.67	.63	.53	.29
	1	.41	.51	.53	.55	.52	.44	.22
	2	.28	.37	.40	.41	.39	.35	.21
	6	.14	.21	.21	.23	.21	.19	.11
15	0	.61	.67	.68	.71	.67	.61	.39
	1	.37	.53	.57	.64	.62	.53	.35
	3	.32	.43	.48	.49	.49	.47	.33
	5	.23	.25	.25	.27	.26	.27	.19
15	0	.44	.58	.60	.65	.65	.57	.38
	1	.38	.48	.57	.61	.60	.54	.36
	3	.37	.45	.47	.49	.52	.49	.33
	5	.21	.22	.23	.25	.25	.23	.19
20	0	.53	.51	.48	.47	.43	.36	.23
20	0	.55	.51	.53	.53	.51	.49	.42

TABLE IX

CORRECTED OXYGEN CONSUMPTION DECAY WITHIN SRT

SRT DAYS	DECAY DAYS	OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC. Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
Correction factor		1.00	1.03	1.07	1.11	1.23	1.54	2.56
.9	0	.26	.21	.20	.19	.20	.20	.18
	1	.03	.10	.12	.13	.15	.12	.15
	3	.03	.09	.10	.11	.11	.12	.15
	5	.03	.06	.07	.08	.09	.09	.01
1	0	.49	.53	.54	.56	.57	.60	.56
	7	.09	.13	.15	.14	.16	.17	.18
	9	.06	.09	.10	.11	.12	.14	.13
1.5	0	.20	.32	.32	.34	.36	.37	.23
	1	.11	.26	.29	.31	.32	.34	.23
	3	.07	.17	.18	.19	.21	.22	.18
	5	.04	.10	.12	.12	.14	.14	.13
1.5	0	.60	.64	.66	.68	.70	.72	.59
	1	.31	.46	.48	.50	.52	.54	.33
2	0	.39	.49	.50	.53	.55	.55	.28
	2	.13	.40	.42	.45	.46	.43	.23
	4	.19	.16	.17	.18	.20	.20	.15
2	0	.43	.51	.52	.54	.55	.57	.31
	1	.12	.42	.44	.45	.47	.46	.23
	3	.15	.26	.29	.29	.30	.32	.33
	4	.21	.32	.40	.43	.46	.46	.28
2	0	.43	.51	.52	.54	.55	.57	.31
	1	.29	.39	.40	.41	.43	.46	.44
	4	.15	.21	.20	.22	.23	.26	.23
	6	.05	.12	.14	.14	.16	[illegible]	.18
2	0	.57	.58	.59	.59	.62	.63	.67
	1	.29	.39	.40	.41	.43	.46	.44
	4	.15	.21	.20	.22	.23	.26	.23
	6	.05	.12	.14	.14	.16	.18	.18
3	0	.60	.60	.61	.65	.70	.71	.54
	1	.24	.30	.33	.35	.41	.43	.33
	7	.10	.13	.11	.17	.18	.20	.18
	10	.05	.09	.11	.10	.12	.12	.10

TABLE IX (Continued)

		OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC.						
SRT DAYS	DECAY DAYS	Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
3	0	.54	.55	.57	.56	.59	.62	.44
	1	.29	.34	.36	.39	.41	.42	.31
	3	.19	.24	.25	.28	.31	.32	.28
	11	.05	.09	.12	.12	.14	.14	.15
3	0	.64	.61	.63	.65	.70	.72	.59
	1	.17	.36	.42	.45	.48	.55	.49
	3	.18	.24	.27	.30	.31	.34	.33
	6	.17	.21	.24	.27	.28	.32	.33
5	0	.65	.71	.74	.79	.80	.83	.59
	1	.35	.44	.49	.51	.53	.58	.31
	4	.28	.36	.40	.42	.43	.45	.44
	14	.05	.11	.14	.14	.16	.17	.18
5	0	.47	.57	.61	.64	.68	.74	.54
	2	.32	.42	.45	.48	.50	.54	.46
	4	.13	.35	.37	.40	.41	.45	.44
5	0	.39	.44	.47	.51	.53	.55	.44
	1	.27	.34	.37	.40	.44	.48	.44
	2	.21	.28	.30	.34	.37	.38	.38
	8	.09	.16	.15	.17	.17	.18	.18
7	0	.52	.57	.61	.63	.66	.72	.74
	1	.26	.42	.46	.50	.53	.60	.64
	8	.15	.18	.18	.21	.23	.26	.28
	17	.10	.11	.12	.12	.15	.17	.18
7	0	.54	.58	.63	.68	.75	.78	.85
	1	.23	.39	.43	.50	.55	.62	.67
	4	.25	.28	.32	.34	.38	.42	.49
	7	.17	.20	.22	.24	.26	.28	.33
7	0	.33	.44	.50	.60	.68	.71	.72
	1	.32	.28	.33	.43	.50	.54	.56
	2	.27	.32	.31	.38	.44	.51	.51
	3	.26	.32	.34	.35	.41	.46	.49
9	0	.58	.67	.73	.79	.85	.89	.97
	1	.18	.42	.47	.53	.59	.66	.69
	4	.23	.36	.41	.45	.48	.54	.64
	6	.15	.22	.25	.28	.31	.35	.38

TABLE IX (Continued)

SRT DAYS	DECAY DAYS	Se MG/L	1200 MG/L	2400 MG/L	3500 MG/L	6800 MG/L	13000 MG/L	22000 MG/L
		OXYGEN CONSUMPTION MG/L/MIN. FOR GLUCOSE CONC.						
9	0	.57	.67	.74	.80	.85	.91	.95
	1	.36	.47	.51	.58	.63	.69	.74
	4	.19	.27	.29	.31	.33	.34	.41
	11	.09	.12	.15	.15	.16	.18	.18
9	0	.59	.73	.78	.80	.85	.88	.85
	1	.54	.67	.72		.84	.89	.90
	4	.20	.30	.31	.33	.33	.35	.38
	11	.07	.11	.12	.13	.15	.17	.18
9	0	.59	.69	.72	.74	.77	.82	.74
	1	.41	.53	.57	.61	.64	.68	.56
	2	.28	.38	.43	.45	.48	.54	.54
	6	.14	.22	.22	.25	.26	.29	.28
15	0	.61	.69	.73	.79	.82	.94	1.00
	1	.37	.55	.61	.71	.76	.82	.90
	3	.32	.44	.51	.54	.60	.72	.85
	5	.23	.26	.27	.30	.32	.42	.49
15	0	.44	.60	.64	.72	.80	.88	.97
	1	.38	.50	.61	.68	.74	.83	.92
	3	.37	.47	.50	.54	.64	.75	.85
	5	.21	.23	.25	.28	.31	.35	.49
20	0	.53	.53	.51	.52	.53	.55	.59
20	0	.55	.53	.57	.59	.63	.75	1.08

and Table IX were identified and placed in Table X under the headings "MAX. OXYGEN CONSUMPTION" and "COR. MAX. OXYGEN CONS." It is from these maximums that the uncorrected and corrected oxygen decay constants were determined as discussed next.

C. Development of Decay Constants

Since the oxygen consumption decay is a decreasing exponential, the decay constant can be found by linearizing the negative exponential decay equation as follows, where Co is the oxygen consumption rate for day zero, Cdd is the oxygen consumption rate for a selected day dd and the decay constant K.

$$Cdd = Co*Exp(-K*dd) \tag{5-4}$$

$$\ln(Cdd/Co) = -K*dd \tag{5-5}$$

The decay constant K is the magnitude of the slope of the regression line of the natural log of the ratio of the oxygen consumption rate to the initial consumption rate versus the decay days.

In Table X, the maximum oxygen consumption rate for each decay day was divided by the zero day maximum. This result is listed under the column labelled "STANDARDIXED BY INITIAL" and "CORRECTED STANDARDIZED BY INITIAL." The zero data ratio was omitted since it would always be equal to unity and in statistical analysis should be removed so as not to bias regression results. A simple statistical parallel in the

TABLE X

STANDARDIZED MAXIMUM OXYGEN CONSUMPTION BY INITIAL OXYGEN CONSUMPTION

SRT DAY	DECAY DAY	MAX. OXYGEN CONSUMPTION MG/L/MIN.	STAND. BY INITIAL	COR. MAX. OXYGEN CONS. MG/L/MIN.	STAND. BY INITIAL
0.9	0	.26		.26	
	1	.12	.46	.15	.58
	3	.10	.38	.15	.58
	5	.07	.27	.09	.35
1	0	.51		.60	
	7	.14	.27	.18	.30
	9	.10	.20	.14	.23
1.5	0	.31		.37	
	1	.28	.90	.34	.92
	3	.17	.55	.22	.59
	5	.11	.35	.14	.38
1.5	0	.62		.72	
	1	.45	.73	.54	.75
2	0	.48		.55	
	2	.41	.85	.46	.84
	4	.16	.33	.20	.36
2	0	.49		.57	
	1	.41	.84	.47	.82
	3	.27	.55	.33	.58
	4	.39	.80	.46	.81
2	0	.49		.57	
	1	.40	.82	.46	.81
	4	.13	.27	.26	.46
	6	.08	.16	.18	.32
2	0	.57		.67	
	1	.38	.67	.46	.69
	4	.20	.35	.26	.39
	6	.13	.23	.18	.27
3	0	.60		.71	
	1	.33	.55	.43	.61
	7	.15	.25	.20	.28
	10	.10	.17	.12	.17

TABLE X (CONTINUED)

SRT DAY	DECAY DAY	MAX. OXYGEN CONSUMPTION MG/L/MIN.	STAND. BY INITIAL	MAX. OXYGEN CONSUMPTION MG/L/MIN.	STAND. BY INITIAL
3	0	.54		.62	
	1	.35	.65	.42	.68
	3	.25	.46	.32	.52
	11	.11	.20	.15	.24
3	0	.64		.72	
	1	.41	.64	.55	.76
	3	.27	.42	.34	.47
	6	.24	.38	.33	.46
5	0	.71		.83	
	1	.46	.65	.58	.70
	4	.38	.54	.45	.54
	14	.13	.18	.18	.22
5	0	.58		.74	
	2	.43	.74	.54	.73
	4	.36	.62	.45	.61
5	0	.46		.55	
	1	.36	.78	.48	.87
	2	.31	.67	.38	.69
	8	.15	.33	.18	.33
7	0	.57		.74	
	1	.45	.79	.64	.86
	8	.19	.33	.28	.38
	17	.12	.21	.18	.24
7	0	.61		.85	
	1	.45	.74	.67	.79
	4	.31	.51	.49	.79
	7	.22	.36	.33	.39
7	0	.55		.72	
	1	.41	.75	.56	.78
	2	.36	.65	.51	.71
	3	.33	.60	.49	.68
9	0	.71		.97	
	1	.48	.68	.69	.71
	4	.41	.58	.64	.66
	6	.25	.35	.38	.39

TABLE X (CONTINUED)

SRT DAY	DECAY DAY	MAX. OXYGEN CONSUMPTION MG/L/MIN.	STAND. BY INITIAL	MAX. OXYGEN CONSUMPTION MG/L/MIN.	STAND. BY INITIAL
9	0	.72		.95	
	1	.52	.72	.74	.78
	4	.28	.39	.41	.43
	11	.14	.19	.18	.19
9	0	.73		.88	
	1	.68	.93	.90	1.02
	4	.30	.41	.38	.43
	11	.12	.16	.18	.20
9	0	.67		.82	
	1	.55	.82	.68	.83
	2	.41	.61	.54	.66
	6	.23	.34	.29	.35
15	0	.71		1.00	
	1	.64	.90	.90	.90
	3	.49	.69	.85	.85
	5	.27	.38	.49	.49
15	0	.65		.97	
	1	.61	.94	.92	.95
	3	.52	.80	.85	.88
	5	.25	.38	.49	.51
20	0	.48		.48	
20	0	.53		1.08	

average and standard deviation calculation can help to explain why these unity data points should be excluded. When the average of 10 data points is taken the average value essentially contains one tenth of each data point of information which totals to what is called one degree of freedom of the 10 degrees of freedom of the 10 data points. When a standard deviation is calculated this average is subtracted from each data point prior to squaring and summing. This subtracts one tenth of its own information from each data point prior to squaring which leaves only nine degrees of freedom of information in the standard deviation calculation. Therefore the sum of the squares is divided by one less than the number of data points used in the calculation. In the decay constant regression if the maximum oxygen consumption for each zero day is included in the regression there would be a variability around the intercept (zero day) and around the slope (decay constant). Since this study is interested mainly in the decay constant then dividing each maximum oxygen consumption by its zero day maximum forces each slope to begin at the same intercept of one, removing the variability of the intercept term. By dividing by the zero day maximum the information in that zero day value is divided into the rest of the data points. In logarithms division becomes substraction and the log of the initial maximum being substracted from all the rest of the logs. If all the unity values are left in the regression, the regression intercept would be erroneously forced to be one by all the unity values which contain no information. By removing the unity values the regression will be only analyzing the slope variability and the degrees of freedom of information remaining after excluding the unity terms will be appropriate for the slope variability determination.

The plot of the natural log of the oxygen maximum divided by the initial maximum on the vertical axis and the decay days on the horizontal axis is shown in Figure 17. The line from this plot has an intercept less than the ln(1) = 0, but has the expected negative slope for decay. Table XI contain results from regression of the natural log of this standardized ratio versus the day of decay. The correlation index (R^2) was 73% indicating good correlation of the data. The slope of -0.12572 has units of 1/days and as such corresponds to an average time of decay of 7.95 days. The regression of the natural log of the corrected standardized rates shown in Figure 18 has a slope of -0.1175 with a correlation index of 77%. This slope corresponds to 8.51 day average time of decay. These two averages differ by 7% with the corrected data producing the larger average time of decay. When data of eleven days and older is deleted from the set the correlation index for the natural log of the standardized oxygen consumption remains the same while the correlation index of the corrected set of data decreases to 57% as shown in Table XI. The intercept term of the uncorrected set changes from -0.24 to -0.13 while the

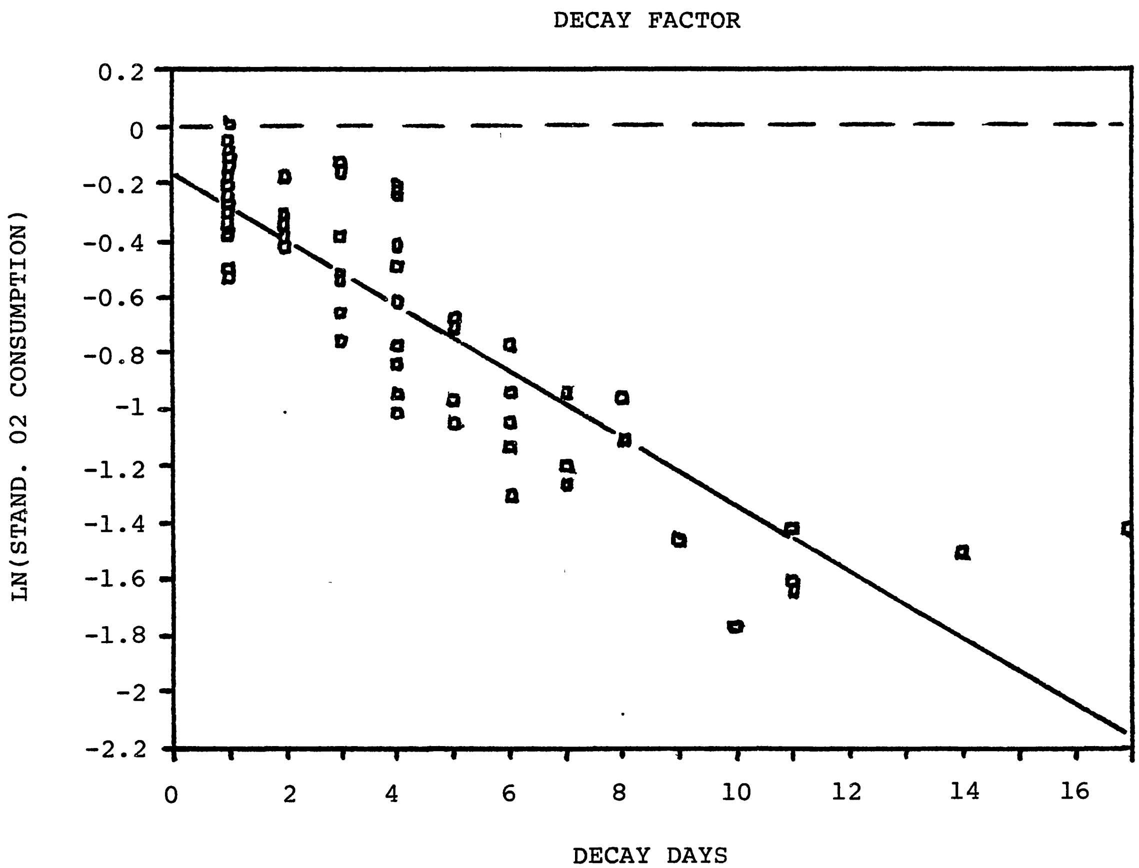


Figure 17. Decay Constant Regression All Data

TABLE XI

REGRESSION OF DECAY CONSTANT

DATA SET	SLOPE	INTERCEPT	CORRELATION INDEX, R^2	STANDARD ERROR
NATURAL LOG OF STANDARDIZED OXYGEN CONSUMPTION	-0.1257	-.2444	0.7280	0.2703
NATURAL LOG OF STANDARDIZED CORRECTED OXYGEN CONSUMPTION	-0.1175	-0.1655	0.7702	0.2257
DATA SETS WITH DATA CORRESPONDING TO ELEVEN DAYS AND OLDER DELETED FROM REGRESSION				
NATURAL LOG OF STANDARDIZED OXYGEN CONSUMPTION	-0.1638	-0.1304	0.7325	0.2382
NATURAL LOG OF STANDARDIZED CORRECTED OXYGEN CONSUMPTION	-0.1334	-0.1509	0.5746	0.2762

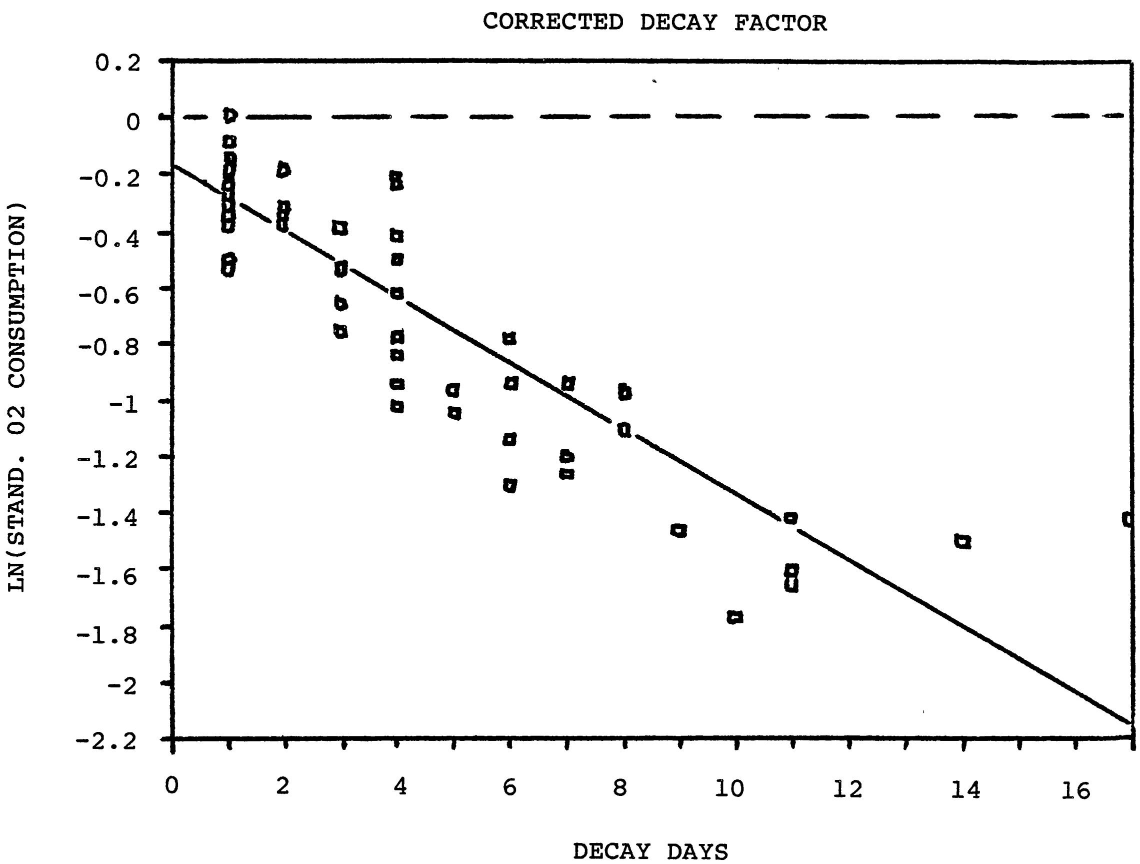


Figure 18. Decay Constant Regression All Data Corrected

corrected set of data changes from -0.17 to -0.15. These two plots can be seen in Figure 19 and 20. Ideally the log of the zero day standardized data of one would be zero. The regression intercept, however, was less than zero indicating the zero day oxygen maximum consumption was greater than what the decay data predicts. The zero day solids test was conducted on solids withdrawn from the continuous reactor. A fraction of these solids would still be in the growth stage utilizing the feed that was entering the reactor prior to sampling. If the decay days from the inverted slope were 7.7 day then one day out of this 7.7 days of solids would still be in biological growth. (The decay days would be like a sludge retension time of only viable solids.) Biological growth or cell division is very demanding on energy and oxygen consumption because one cell becomes two in cell division. The zero day decay oxygen consumption would essentially have one extra day oxygen consumption not predicted from the rest of the test results. If this one day equivalent of oxygen consumption were subtracted from the zero day oxygen consumption then the best regression equation could be found as the intercept best matching this new zero day oxygen consumption which excludes the growth. The slope of each regression is the inverted decay days which is the same as one decay day divided by the decay days (K = 1/decay days). Subtracting the slope from one would give the fraction of oxygen consumption excluding a one day fraction

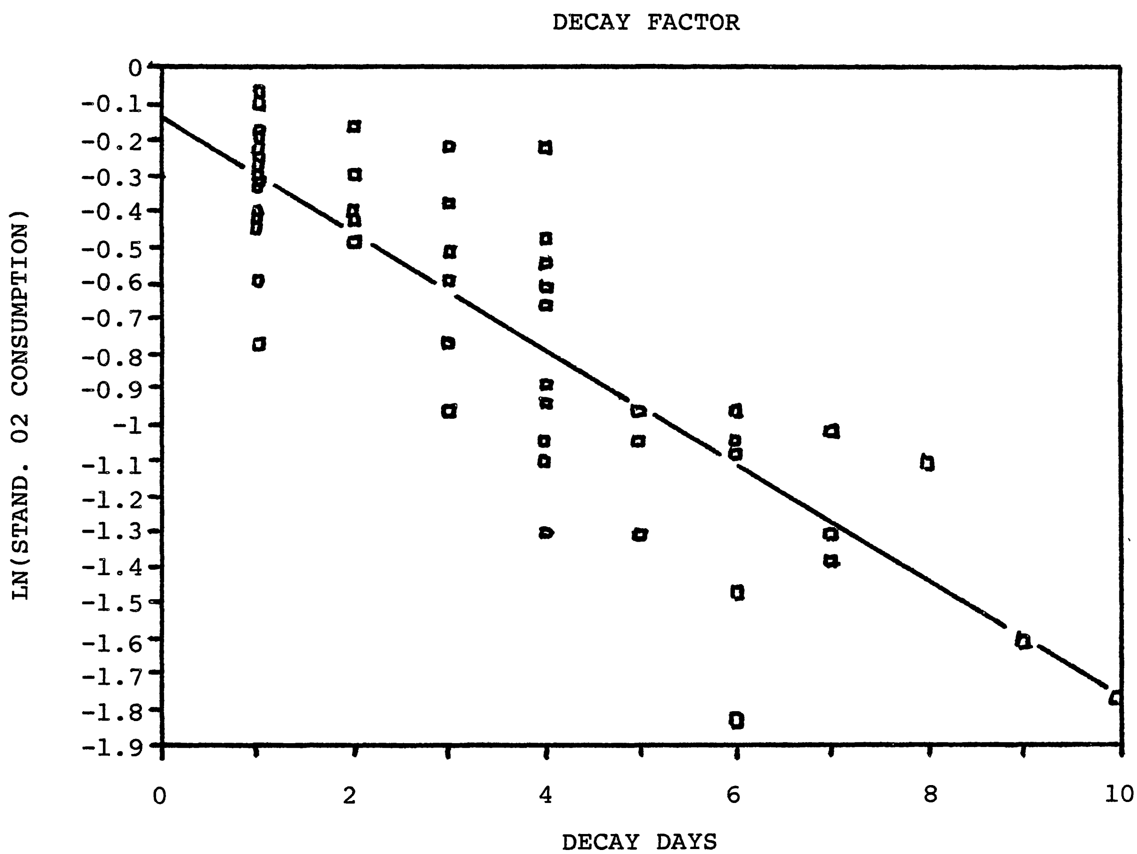


Figure 19. Decay Constant Regression Less Than Eleven Day Data

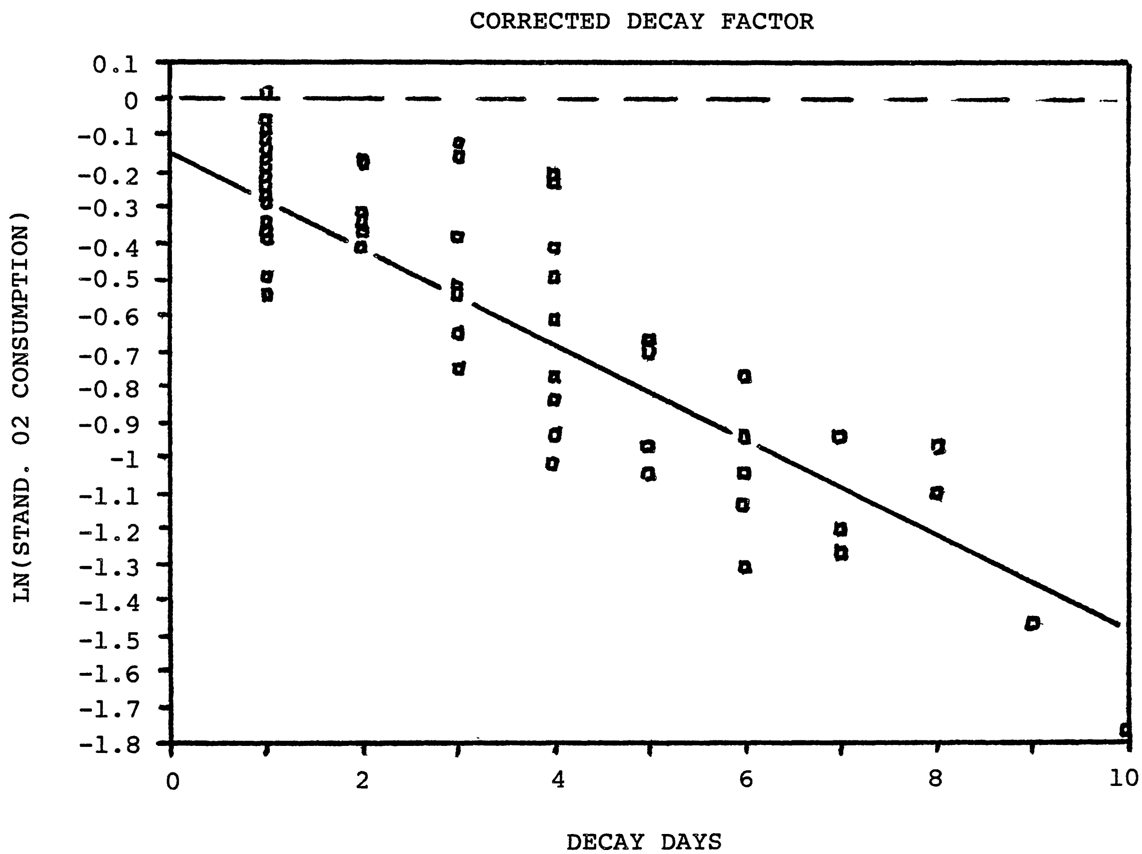


Figure 20. Decay Constant Regression Less Than Eleven Day Data Corrected

of oxygen consumption. Taking the natural log of this term should give a number equal to the intercept of the regression. Table XII lists these calculations for each of the decay constant regression. In Table XI the calculation from the slope which best predicts the intercept is the decay constant -0.1334 for the corrected data set excluding data greater than or equal to eleven decay day because it has the smallest percent difference from the calculated intercept from the slope.

A comment on the effect of the substrate in the continuous reactor on the decay rate is appropriate here, to point out some differences between the decay of viability in the batch reactors and the action occurring in a continuous reactor. The decay factor, K = .13/day, found in the batch reactors for greater than one day decay would correspond to a predominance of solids viability decay. The decay recognized in the first day of decay was much higher due to the fact that a continuous reactor has substrate being introduced into it all the time which caused the initial oxygen consumption to be inordinately too high. If the substrate effect, identified here as Km, is recognized to be at least as large as the decay effect, K, then when analyzing the continuous reactor data the expected decay constant should be the summation of both factors, Km + K, instead of only the decay factor. Because of this complication the equation (3-4) for viable solids will need to be corrected for continuous

TABLE XII

Zero Day Intercept Calculations

Slope Magnitude	Fraction Calc. for Zero Day	ln(Fraction)	Actual Intercept	% Different from Calc.
All data points included				
Not corrected				
0.1257	0.8743	-0.1343	-0.2444	82%
Corrected				
0.1175	0.8825	-0.1250	-0.01655	32
Eleven day and older decay data excluded				
Not corrected				
0.1638	0.8362	-0.1789	-0.1304	27
Corrected				
0.1334	0.8666	-0.1432	-0.1509	5

reactors as follows:

$$Xv = \left(\frac{1}{((Km + K)*SRT + 1)} \right) Xt \qquad (5\text{-}6)$$

Because the batch reactor for the first day of decay is a discontinuation from the continuous reactor, the appropriate value for the Km factor is hard to ascertain from batch data but appears to be as large as the decay constant.

A statistical factorial design, Table XIII, was constructed to test if the corrected and noncorrected decay constants were equivalent and to test if the decay constant was independent of the SRT of the reactors. An analysis of variance (ANOVA), Table XIV, summarizes these results. The hypothesis that the corrected and noncorrected decay rates were equal was rejected at the 95% confidence level indicating that the data should be corrected for solids removal. The hypothesis that the decay rate was independent of SRT was rejected when all the data was compared together with an F ratio of 9.43. When the SRTs were separated into group A of 3, 7, and 9 day SRTs and group B of less than 2, 2, and 15 day SRTs, the hypothesis of independence could not be rejected within the groups. The among groups test contrasts the two groups with the rejected hypothesis indicating that the two group were different from each other. This indicates that the 3, 7, and 9 day SRT decay constants are essentially the same and the less than 2, 2, and 15 day SRT decay constants are essentially the same. As indicated in Table XIII, the 3, 7, and 9 day SRT data came from the

TABLE XIII

STATISTICAL FACTORIAL DESIGN

SRT	DECAY CONSTANT, K NOT CORRECTED	CORRECTED	TOTALS
Group A			
from 2.86 liter reactor			
3 day	0.1306	0.1402	
	0.0987	0.0931	0.4625
7 day	0.1201	0.1176	
	0.1116	0.0686	0.4179
9 day	0.0929	0.0103	
	0.1675	0.1687	0.4394
Group B			
from 2.92 liter reactor			
less than 2 days			
.9 day	0.1332	0.1263	
1.5 day	0.2361	0.2211	0.7166
2 day	0.3302	0.1860	
	0.2140	0.1879	0.9181
from 2.85 liter reactor			
15 day	0.2156	0.1520	
	0.2264	0.1555	0.7495
Totals	2.0768	1.6271	3.7039
Average	0.1731	0.6271	0.1543

TABLE XIV

ANOVA TABLE OF STATISTICAL FACTORIAL DESIGN

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F RATIO	F 95% TEST
Mean	1	0.5716	0.5716		
SRTs all	5	0.0533	0.0107	9.43	5.19
				rejected	
Group A SRT 3, 7, &9	2	0.00025	0.00012	0.11	5.79
				okay	
Group B SRT (2, 2, &15	2	0.0058	0.0029	2.58	5.79
				okay	
Among Groups	1	0.0472	0.0472	41.77	6.61
				rejected	
Corrected vs not corrected	1	0.0085	0.0085	7.52	6.61
				rejected	
Experimental Error	5	0.0057	0.0011		
Sampling Error	12	0.03478	0.0029		

2.86 liter reactor while the 2 day and less SRT data came from the 2.92 liter reactor. The 15 day SRT reactor was started with seed from the 2.92 liter reactor. Apparently these two groups developed biological solids of different predominance of bacteria with different decay rates.

The decay constant selected as best from these analyses was the slope of the natural log of the standardized oxygen consumption rate corrected where the eleven day or older data has been deleted has a slope of -0.13 which corresponds to a 7.7 day average time of death for the biological organisms relative to oxygen consumption. The corrected rate was selected because statistically the rates are not equal and intuitively the corrected rate would be more characteristic of the maximum oxygen consumption. This was born out by the calculation of what the intercept should be if the growth continuing from the reactor feed were removed and then compared to the intercept as in Table XII. The corrected rate has less correlation apparently because the accumulated error from the serial removal of solids during the oxygen consumption rate test which would be much greater for the higher glucose tests.

Using this decay constant of K = 0.13/day, and assigning zero to the Km term, the viable solids can be calculated using equation (5-6). This equation needs to be corrected because the solids in the reactors near one day SRT are operating in the continuous reactor at their maximum rate. This corresponds to all solids being viable as Walker and

Davies found and also agrees with the 0.9 day SRT oxygen consumption data. Since the decay days for a reactor are one day less than the SRT, the viable solids equation should be corrected by substracting one day from the SRT, as follows with Km assigned equal to zero.

$$Xv = \left(\frac{1}{(Km+K)*(SPT-1) + 1} \right)*Xt \qquad (5\text{-}7)$$

The mixed-liquor solids viabilities calculated for various SRT conditions using this equation are shown in Table XV. When the solids concentration corresponding to each SRT taken from Table V is multiplied by the viability in Table XV, the viable solids concentrations increase to the 1400 mg/l concentration when it reaches five day SRT and then remains in that range of concentration for the higher SRTs as shown in Table XV.

When the initial oxygen consumption is divided by the viable solids as shown in Table XV, this specific oxygen uptake rate decreases quickly for small SRTs but the decrease for SRTs above five days is small as compared with the large increases in the volatile suspended solids (Xt). When considering variability of biological data the specific oxygen uptake could even be considered as a constant above five day SRT due to the small change as SRT increases. A plot of this specific oxygen uptake relative to viable solids as shown in Figure 21, demonstates that the decrease in specific oxygen uptake for SRTs less than five days is of a

TABLE XV

VIABILITY AND UPTAKE OF MIXED-LIQUOR SOLIDS FOR SELECTED SRT

SRT	Xt	VIABLE SOLIDS $\frac{Xt}{.13(SRT-1)+1}$	INITIAL OXYGEN CONSUMP.	INITIAL OXYGEN UPTAKE	MAX. OXYGEN CONSUMP.	MAX. OXYGEN UPTAKE
0.9	200	200	.26	0.0013	.26	0.00130
1	610	610	.49	0.00080	.60	0.00098
2	760	673	.39	0.00058	.55	0.00082
3	1200	952	.60	0.00063	.71	0.00075
5	2040	1342	.65	0.00048	.83	0.00062
7	2500	1404	.52	0.00037	.74	0.00050
9	3220	1578	.58	0.00037	.97	0.00061
15	3860	1369	.61	0.00045	1.00	0.00073
20	6440	1856	.53	0.00029	.59	0.00032

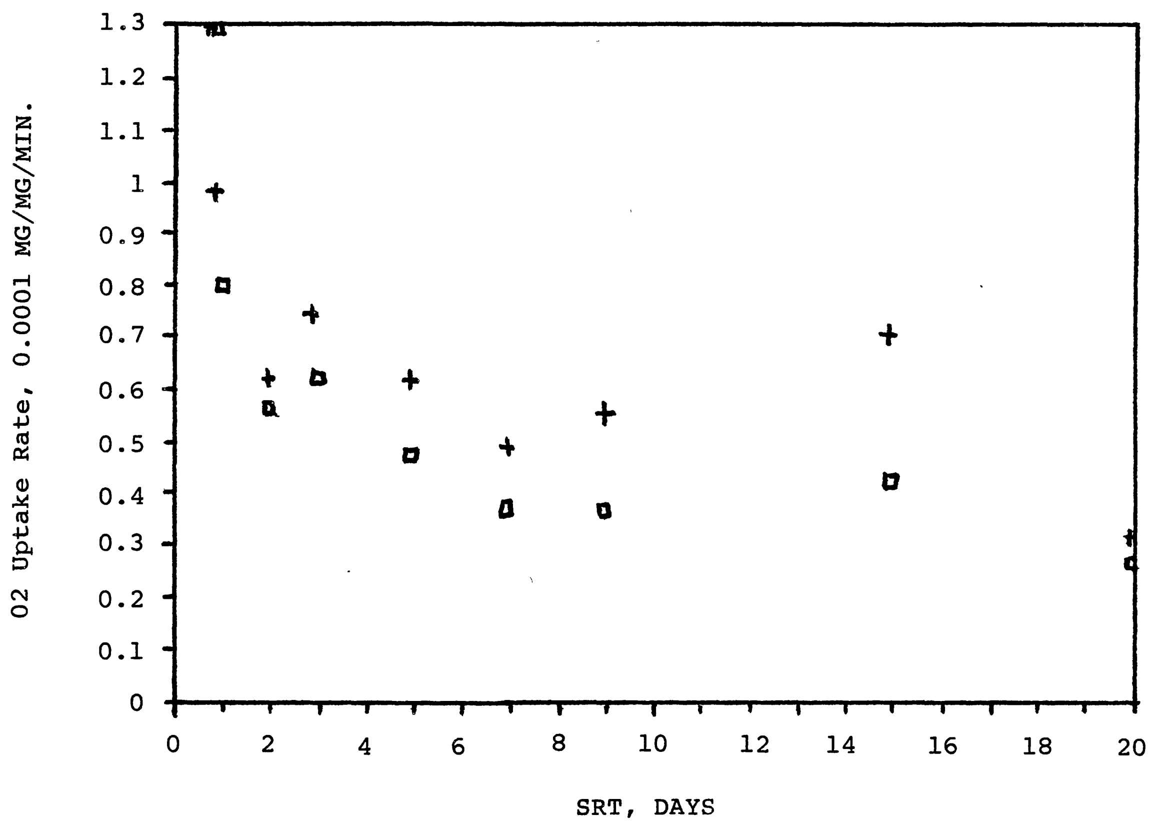


Figure 21. Oxygen uptake and maximum oxygen uptake using decay constant K = 0.13 to determine viable solids

decreasing exponential character but the specific oxygen uptake for SRTs greater than five days seems to deviate from this trend and become constant. Also in Figure 21, the maximum specific oxygen uptake has been plotted. The maximum specific oxygen uptake curve and the specific oxygen uptake curve at one day SRT are the same but as the SRT increases the two curves separate with the specific oxygen uptake curve values at about half the value of the maximum curve. The maximum curve decreases exponentially as the SRT increases from one day. One would expect the maximum curve to remain fairly constant and not decrease as the SRT increased. The decay constant was determined from the decaying solids while the initial and maximum oxygen consumption were from samples removed from the continuous reactor. As such, other factors relative to the continuous reactor characteristics could be confusing the results in the oxygen uptake determinations. This maximum oxygen uptake using the decay constant and the maximum oxygen uptake using volatile suspended solids has been plotted in Figure 22 to show that the volatile suspended solids produces a maximum uptake curve which decreases faster than the curve corrected for viability indicating that the use of volatile suspended solids with out correction for viability is less characteristic of the viable fraction of biological solids in the reactor than the concentration of solids corrected using the decay constant.

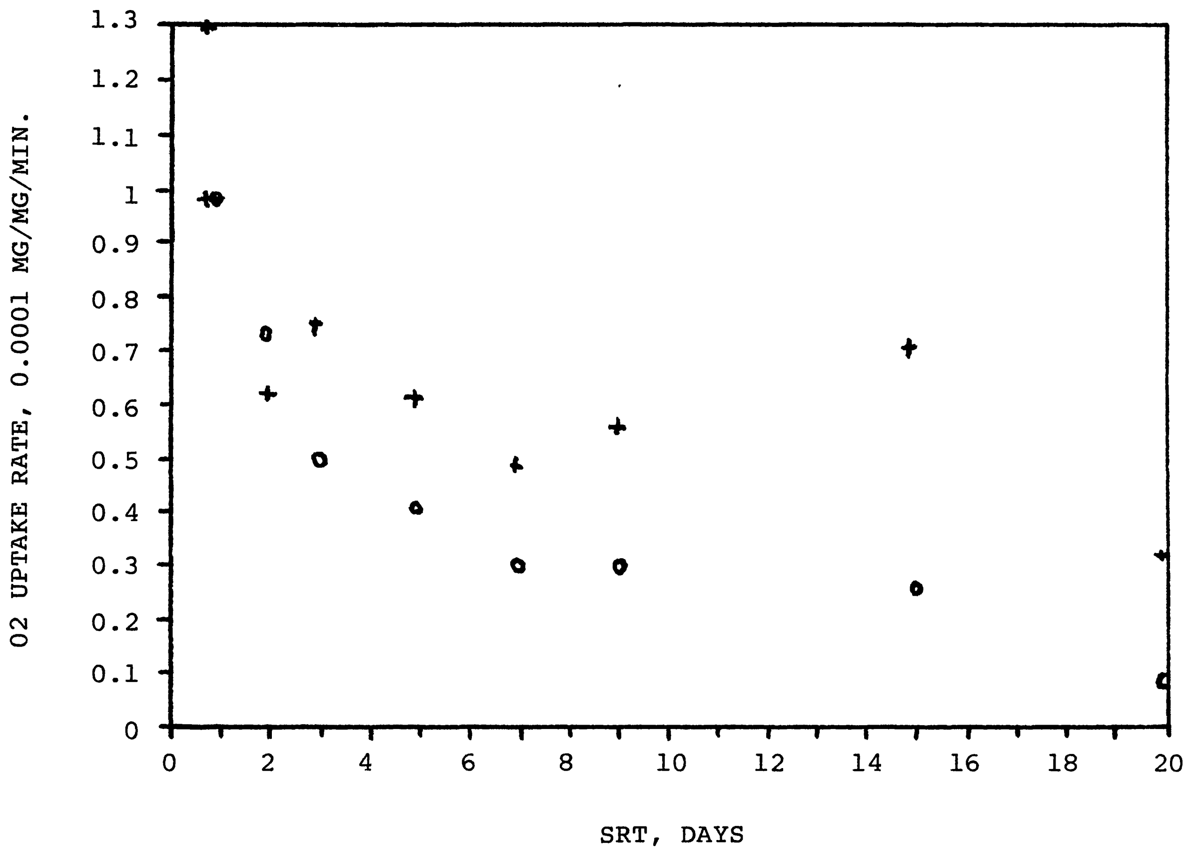


Figure 22. Maximum oxygen uptakes relative to viable solids and volatile suspended solids

D. Viability of Mixed-liquor Volatile Suspended Solids

In the results section concerning oxygen consumption tests, a decay rate of K = 0.13/day and an equation equating viable solids to volatile suspended solids was developed from solids decaying in batch reactors where Km equal zero and (SRT-1) equals the decay days.

$$Xv = Xt/(Km+K)*(SRT-1) + 1) \qquad (5-7)$$

The rate of decay of the zero to one day decay was larger than the rest of the decay curve. This high rate was attributed to the first day of decay starting out with the same mix that was in the continuous reactor which included feed which would be used for growth. The rest of the decay days would not have this feed available due to it being used up in the first day of the batch reactor. Since the value of this substrate factor, Km, would be difficult to verify in a batch reactor the value of zero was assigned to Km in calculating the specific oxygen uptake using viable solids.

From the oxygen consumption rates for the 0.9 SRT it was apparent that the solids were operating at their maximum oxygen consumption so the viable equation was corrected by subtracting one day from the SRT. This decay of viable solids can be expressed in a rate equation relative to viable solids.

$$\frac{dX}{Xv*dt} = Kv \qquad (5-8)$$

Substituting equation (5-7) for viable solids gives a rate equation relative to volatile suspended solids.

$$\frac{dX}{Xt*dt} = \frac{Kv}{.13(SRT-1)+1} \qquad (5\text{-}9)$$

Using the solids viability equation (5-7) viable solids were calculated and the specific oxygen uptake relative to viable solids was determined for the initial oxygen consumption and the maximum oxygen consumption. Both the maximum specific oxygen uptake and the initial oxygen uptake decreased as the SRT increased with the initial oxygen data points being located just above half of the maximum rate for the high SRT conditions and then becoming equal to the maximum rate as the SRT approached one. This indicated that using only the decay constant of 0.13 in the viable solids equation, the maximum oxygen uptake rate decreased with an increase of SRT instead of being constant. As such it becomes necessary to determine the substrate term, Km from the continuous reactor data.

Since the initial oxygen consumption rate in Table VII was about 70% of the maximum oxygen consumption rate and the viable solids concentration in Table XV appears to be fairly constant for SRTs of five and greater, a constant specific substrate utilization relative to viable solids can be assumed for these large SRTs, as follows where Kv is the specific substrate utilization rate relative to viable solids.

$$\frac{dS}{Xv*dt} = Kv \qquad (5\text{-}10)$$

Moving the viable solids term to the right side of the equation and substituting equation (5-6) for the viable solids then moving the Xt term back to the left side of the equation gives the following:

$$\frac{dS}{dt} = Kv\frac{Xt}{((Km+K)*(SRT-1)+1)} \qquad (5\text{-}11)$$

$$\frac{dS}{Xt*dt} = Kv\frac{1}{((Km+K)*(SRT-1)+1)} \qquad (5\text{-}12)$$

Inverting this equation gives a linearized form relative to SRT-1. Regressing the SRT-1 term is somewhat ackward so the minus one from the SRT was placed into the intercept term as follows:

$$\frac{Xt*dt}{dS} = \frac{(Km+K)}{Kv}*(SRT-1) + \frac{1}{Kv} \qquad (5\text{-}13)$$

$$\frac{Xt*dt}{dS} = \frac{(Km+K)}{Kv}*SRT + \frac{1}{Kv} - \frac{(Km+K)}{Kv} \qquad (5\text{-}14)$$

$$Xt*dt = slope*SRT + Intercept \qquad (5\text{-}15)$$

where the slope equals (Km+K)/Kv and the intercept equals 1/K2 - slope. This equation was regressed using continuous reactor data producing a slope of 0.31 and an intercept of 0.72 with a correlationg index of 60% as shown in Table XVI. Solving for Kv gives 0.97 and Km equals 0.17 where K equal 0.13.

$$Kv = 1/(\text{Intercept} + \text{slope}) = 1/(.72+.31) = .97 \qquad (5\text{-}16)$$

$$Km = Kv*\text{slope} - K = .97*.31 - .13 = .17 \qquad (5\text{-}17)$$

In equation (5-10) the Kv term indicates the ratio of viable solids mass to substrate mass necessary to utilize the substrate. Since Kv is equal to 0.97, then it takes about one milligram of viable solids to utilized one milligram of substrate. Expressed in equation form, the mass of substrate plus the mass of viable solids produces the new viable solids, (1+Y)*Xv, where the difference in mass is used as energy of growth.

$$1mg\ S + 1mg\ Xv = (1+Y)mg\ Xv + \text{Energy of Growth} \qquad (5\text{-}18)$$

If 7.2 liters/day of feed at 325 mg/l is fed to a three liter reactor, then there only needs to be 780 mg/l of viable solids in the reactor to utilize all of the substrate. The wasting rate would have to be very high to waste out enough viable solids to cause a solids limiting condition.

The values of the constants can now be substituted into equation (5-13), Kv can be divided into the various constants and the Km and K term separated as follows:

$$\frac{Xt*dt}{dS} = \frac{(.17+.13)}{.97}*(SRT-1) + \frac{1}{.97} \qquad (5\text{-}19)$$

$$\frac{Xt*dt}{dS} = .18(SRT-1) + .13(SRT-1) + 1.03 \qquad (5\text{-}20)$$

$$\frac{dS}{Xt*dt} = \frac{1}{.31(SRT-1)+ 1.03} \qquad (5\text{-}21)$$

$$\frac{dS}{Xt*dt} \text{ approx. equal to } \frac{1}{.31(SRT-1)+1} \qquad (5\text{-}22)$$

The first term Taylor series expansion of the exponential function is Exp(z) = 1 + z. The same exponential inverted or in decreasing exponential form is:

$$Exp(-z) = 1/(1+z) \qquad (5\text{-}23)$$

Both equations (5-22) and (5-9) can be expressed as an exponential as follows.

$$\frac{dS}{Xt*dt} = Exp(-.31(SRT-1)) \qquad (5\text{-}24)$$

$$\frac{dX}{Xt*dt} = Kv*Exp(-.13(SRT-1)) \qquad (5\text{-}25)$$

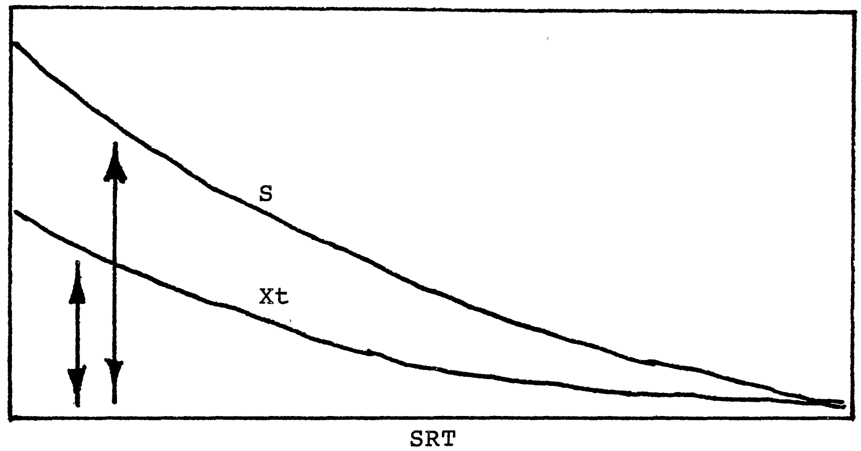
These two equations should be related by an observed yield term (Yo) as follows.

$$\frac{dX}{Xt*dt} = \frac{Yo*dS}{Xt*dt} \qquad (5\text{-}26)$$

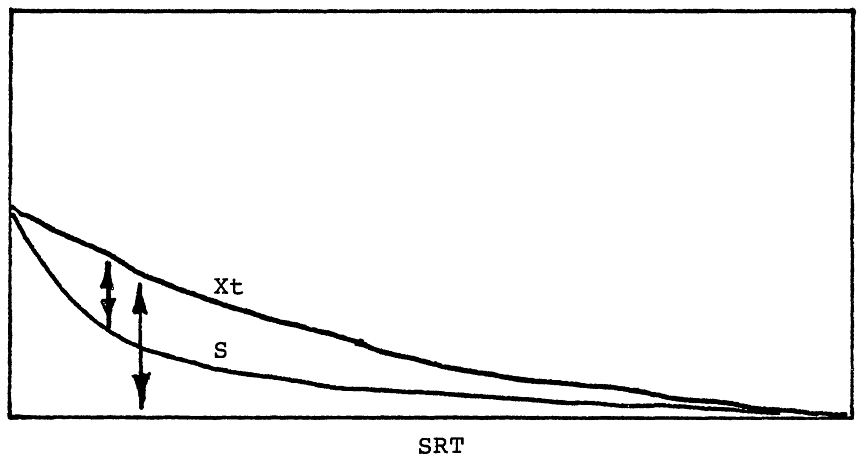
Solving for the observed yield term gives:

$$Yo = \frac{dX/(Xt*dt)}{dS/(Xt*dt)} = \frac{dX}{dS} \qquad (5\text{-}27)$$

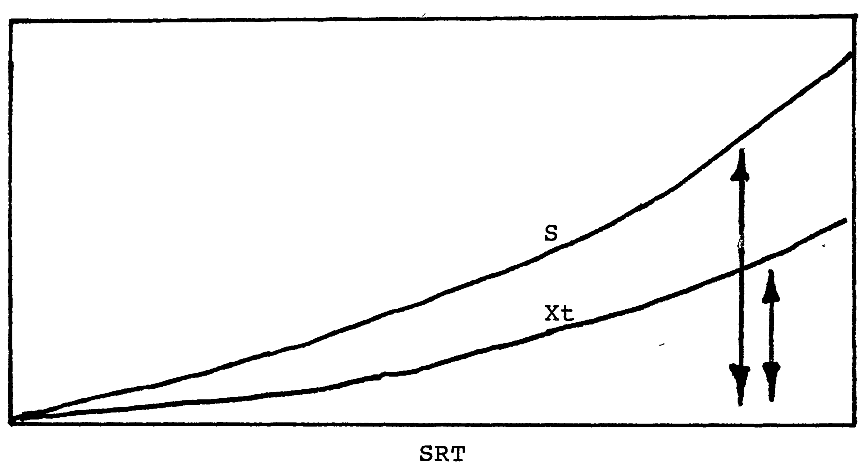
One would think that by just dividing equation (5-25) by (5-24) would give the yield term, this is incorrect since for values greater than one the observed yield is above one or produces more mass of solids than the mass used in substrate utilized. Figure 23 can be used to illustrate the problem inherent in negative exponentials. Diagram (a) of Figure 23 shows the two typical curves that correspond to the two decreasing exponential functions in this study, where the initial substrate level would be greater than the solids initial level. Diagram (b) illustrates the problem when the negative exponentials are divided by each other. The result is the relationship of the sloped of each exponential, not the whole function. This shows the substrate curve below the solids curve with a decreasing rate much faster than the solids curve. The value of dividing these two negative exponential produces a value greater than two which is way out of line for a yield factor. The yield factor is the relationship of the curves to each other not just the slopes. If the exponentials are changed from negative to positive exponentials then dividing one exponential by the other is similar to comparing one curve to the other as shown in diagram (c) of Figure 23, where the common point on the diagram is the point where their initial starting points are zero. Recognizing this difficulty in working with negative exponentials the observed yield term can be determined by changing the signs on the exponentials and then dividing the substrate function into the solids funciton. (The Kv term was assigned equal to one to make the explaination easier at this point. Why it is equal to one will be discussed after the observed yield equation is developed.)



A. TWO DECREASING EXPONENTIALS



B. NEGATIVE EXPONENTIALS DIVIDED



C. DIVIDING POSITIVE EXPONENTIALS

Figure 23. Exponential Diagrams

$$\frac{dX}{dS} = \frac{dX/(Xt*dt)}{dS/(Xt*dt)} = \frac{Exp(.13(SRT-1))}{Exp(.31(SRT-1))} = Exp(-.18(SRT-1)) \quad (5-28)$$

$$Yo = dX/dS = Exp(-.18(SRT-1)) \quad (5-29)$$

This solution can be related back to using the Taylor series equations (5-9) and (5-22) in determing the observed yield term. Since the Taylor series expansion has the same problem in division as the negative exponential, the terms should not be inverted in determining the observed yield but the regular Taylor series expansion should be used as follows.

$$Yo = \frac{dX/(Xt*dt)}{dS/(Xt*dt)} = \frac{.13(SRT-1) + 1}{.31(SRT-1) + 1} \quad (5-30)$$

In equation (5-30) the positive exponential expansion was used instead of the negative expansion for each term similar to using the positive exponential in equation (5-28). The observed yield has been tabulated in Table XVI using both the exponential equation (5-29) and the Taylor series expansion equation (5-30) for various SRTs. The Taylor series equation decreases from one at SRT equal to one to a limiting observed yield of 0.42, which is characteristic of actual data. If the exponential is considered to be the appropriate function the relationship of viable solids and volatile suspended solids and their effect on the exponential rate must be recognized. The exponential equation decreases from one at one day SRT to the 0.44 value at a SRT of 5.5 days. For larger SRTs the value continues to decrease. As shown in Table XV the viable solids become fairly constant for SRT values above 5.5 days. If the viable solids are constant then the concentration of volatile suspended solids becomes independent of the viable solids. The viable solids are in excess so the wasting rate has no effect on the viable solids concentration. The major factor controlling the viable solids concentration is the decay rate which was found by batch studies to be equal to 0.13/day. Since the system is at steady state then the growth rate of new viable solids would be equal to the death rate of viable solids. Since the feed rate into the reactor is controlled at a constant rate then the whole system attains constant rates and concentrations in viable solids. The rate equation for solids (5-9) with Kv equal to one

$$\frac{dX}{Xt*dt} = \frac{1}{.13(SRT-1) + 1} \qquad (5\text{-}31)$$

becomes for viable solids:

$$\frac{dX}{Xt*dt} = 0.13/day \qquad (5\text{-}32)$$

The rate equation for substrate

$$\frac{dS}{Xt*dt} = \frac{1}{.31(SRT-1)+1} \qquad (5\text{-}33)$$

becomes for viable solids:

$$\frac{dS}{Xt*dt} = .31/day \qquad (5\text{-}34)$$

TABLE XVI

THE OBSERVED YIELD TABULATION USING THE TAYLOR SERIES AND EXPONENTIAL EQUATIONS

SRT days	EXPONENTIAL		TAYLOR SERIES
1	1.00		1.00
2	.84		.86
3	.70		.78
4	.58		.72
5	.48		.68
5.5	.44	(.42) *	.66
6	.41	(.42)	.65
7	.34	(.42)	.62
8	.28	(.42)	.60
9	.24	(.42)	.59
10	.20	(.42)	.57
100	0.00	(.42)	.44
INFINITY	0.00	(.42)	.42

* Viable solids become independent

The observed yield for these two equations is:

$$Yo = \frac{dX}{dS} = \frac{dX/(Xv*dt)}{dS/(Xv*dt)} = \frac{.13}{.31} = .42 \qquad (5\text{-}35)$$

$$Yo = K/(Km+K) \qquad (5\text{-}36)$$

Thus the observed yield for all SRTs over 5.5 days would be equal to equation (5-36).

The Kv term can now be discussed, by inserting it on the top of the right side of the equation (5-30).

$$Yo = \frac{Kv(.13(SRT-1) + 1)}{(.31(SRT-1) + 1)} \qquad (5\text{-}37)$$

The value of Kv can be checked by looking at the extreme values of SRT of one and then a very large value for SRT. If the SRT equals one then the observed yield equals Kv value. If the SRT is very large then the observed yield equals Kv times 0.42. Since the true yield was 0.44 from the operational data regression then it appears that Kv for this equation is approximately equal to one. Therefore at a SRT of one the Uv approximately equals one (equation 5-17), the Kv is approximately equal to one, and the observed yield is approximately equal to one.

$$Uv*Yo = 1*1 = Kv = 1 \qquad (5\text{-}38)$$

Since most of the data for this analysis was for SRTs above one the SRT equal to one becomes an extrapolated term which ties all the equations together. The major concepts involved for SRTs below 5.5 days and above one day is that only the viable solids concentration limits growth. As a reactor is operated at SRTs of one or below other factors could become the predominant mechanism controlling rather than solids limiting. However, for this study the derived equations appear sufficient to analyse the data obtained.

By looking at equation (5-21) the various components of the substrate utilization can be identified.

$$\frac{Xt*dt}{dS} = .18(SRT-1) + .13(SRT-1) + 1.03 \qquad (5-21)$$

The .18 and .13 total as the substrate utilization rate, the .13 is the solids rate of production, and the .18 is the rate of energy used in metabolism which produces the yield factor. The 1.03 term is the maximum term which produces the effect of solids limiting for small SRTs and thus is closely related to the wasting rate.

The significance of equation (5-36) is that knowing the yield and the slope for equation (5-13) the viable solids decay rate, K, can be calculated without running all the batch tests if the continuous reactors are run at a wide variety of SRTs including those above 7.7 days. Conversely, if the decay rate, K, is known, continuous reactor data for only a few SRTs need to be run to predict over a wide range of SRTs. Substituting 0.13 divided by the yield .44 for the slope in equation (5-13) gives the following equation.

$$\frac{Xt*dt}{dS} = \frac{K}{Y}(SRT-1) + \frac{1}{Kv} \qquad (5-39)$$

Using the 0.31 decay constant, viable solids for various SRTs were calculated in Table XVII. The viable solids concentration for the larger SRT was at a concentration of 900mg/L, several hundred mg/L below the viable concentration calculated in Table XV. The concentration of viable solids concentrations for the one, two and three day SRT's were also much closer. The maximum specific oxygen uptake and the initial specific oxygen uptakes are plotted in Figure 24 along with the maximum specific oxygen uptakes relative to the volatile suspended solids concentration. The maximum rates for the volatile suspended solids decreased quickly in Figure 22, as the SRT increases but the maximum rate for the viable solids calculated with the 0.31 decay constant maintain a high horizontal profile in Figure 24. The initial oxygen uptake again approaches the half maximum rate for high SRT's and becomes equal to the maximum uptake rate as it approaches an SRT of one day. The oxygen uptake calculated using the 0.31 decay constant is more in agreement to what should be expected in specific uptake rates, where the maximum specific oxygen uptake should remain constant. The viable solids concentration in Table XVII for an SRT of one day and above are all quite close together in value. This indicates that looking at specific oxygen uptake from the substrate point of view (using the rate value of .31/day) the utilization is essentially uninhibited for SRTs above 3.2 days.

E. Evaluation of Kinetic Models

If a linear regression is attempted substituting the viable solids calculated with 0.31/day constant for the volatile suspended solids in McKinney's limiting solids model very little correlation would be attained because all the data points are essentially the same with little variation in viable solids. Without at least three distinct data points regression is useless. Substitution into the Lawrence/McCarty Model would also cause a decrease in correlation because the dS/(Xt*dt) would become more constant. This indicates that viable solids are not limiting substrate utilization.

The 0.13/day decay rate inverted to 7.7 days provides additional information about controlling continuous reactors. Where the SRT is controlled above 7.7 days, the viable solids decay rate will determine the substrate utilization adding more stability, also indicating that viable solids are not limiting substrate utilization.

If the reactor is operating at the 7.7 day SRT additional variability will be introduced to the system because it will be swithing back and forth between two different controlling factors, wasting and decay. Below 7.7 days and above 3.2 days the substrate will not be inhibited in uptake but the wasting rate is large enough to cause a wasting of the viable solids before they complete their

TABLE XVII

VIABLE SOLIDS AND UPTAKE USING K = 0.31
FOR SELECTED SRT

SRT	XT	VIABLE SOLIDS $\frac{Xt}{.31(SRT-1)+1}$	INITIAL OXYGEN CONSUMP.	INITIAL OXYGEN UPTAKE	MAX. OXYGEN CONSUMP.	MAX. OXYGEN UPTAKE
0.9	200	200	.26	0.0013	.26	0.00130
1	610	610	.49	0.00080	.60	0.00098
2	760	580	.39	0.00067	.55	0.00095
3	1200	741	.60	0.00081	.71	0.00096
5	2040	911	.65	0.00071	.83	0.00091
7	2500	874	.52	0.00059	.74	0.00085
9	3220	925	.58	0.00063	.97	0.00105
15	3860	723	.61	0.00084	1.00	0.00138
20	6440	935	.53	0.00057	.59	0.00063

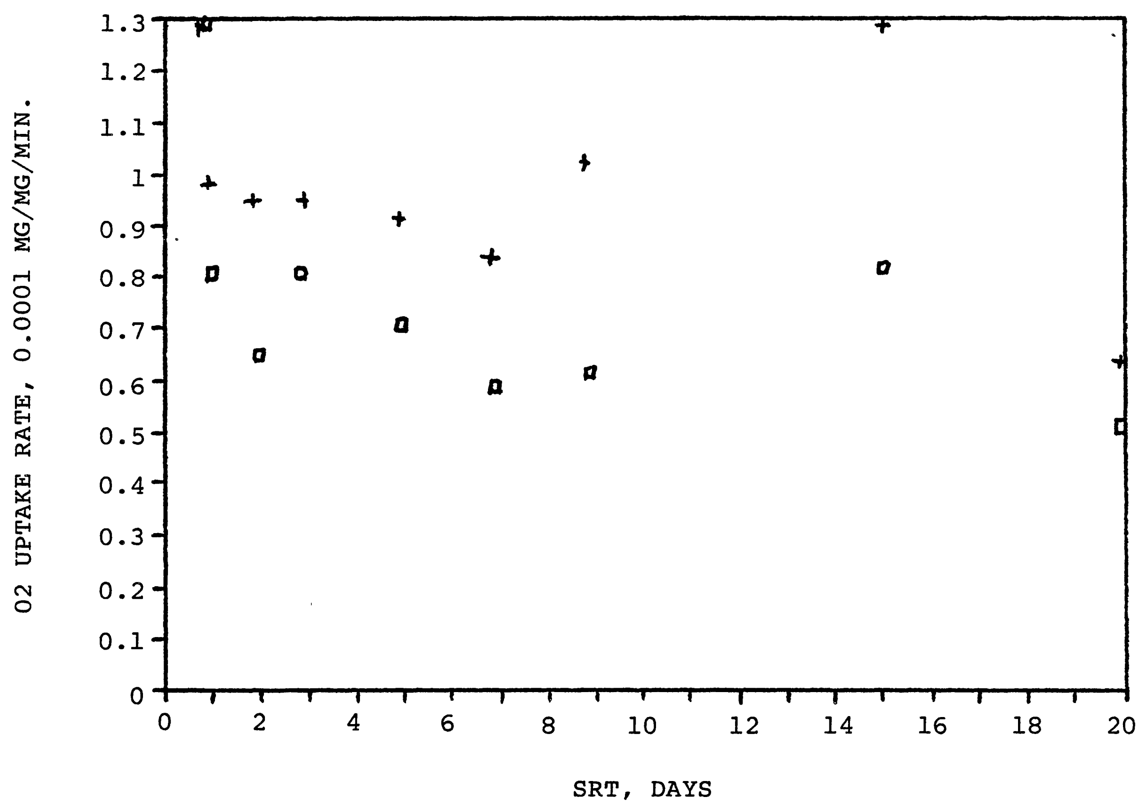


Figure 24. Oxygen uptake and maximum oxygen uptake using decay constant k = 0.31 to determine viable solids.

growth cycles, thus, limiting solids production but not substrate utilization.

If 7.2 Liter per day of feed at a concentration of 325 mg/l is fed to a 3 liter reactor then the same concentration of viable solids, 780 mg/l, is recognized as necessary to metabolized all the feed each day. In Table XVII, the viable solids concentration is 741 mg/l at the three day SRT, so 760 mg/l should be attained just above three days. The net effect of the 0.31 slope in calculating the viable solids indicates that only a fraction of the viable solids just coming out of cell division would be necessary in the next round of growth. The viable solids for the seven day SRT condition in Table XVI is 874 mg/l. The viable solids in Table XV for viability using only a decay factor is 1404 mg/l. Therefore only 62% of the total viable capacity (874/1404 = .62) is being used. Such explains why the initial oxygen uptake is just above half of the maximum oxygen uptake rate and that the viable solids are not limiting substrate utilization.

In operation of reactors additional variability would be introduced into the system if the SRT is below 3.2 days because the viable solids concentration will be wasted out at such a high rate that the remaining solids will be insufficient to handle all the substrate feed and will continually attempt to attain a concentration sufficient to handle all the substrate entering the reactor. This suggests that the lowest officient operation SRT would be 3.2 days or

1/(Km + K) days.

The equation (5-39) can be further analyzed relative to the Kincannon/Stover model and the Sykes model by substituting for SRT the equivalent SRT from Sykes (2-9) equation.

$$SRT = Xt*V/(Y*F*Si) \qquad (5\text{-}40)$$

$$\frac{Xt*dt}{dS} = \frac{(\ K\ )(Xt*V)}{(Y*Y)(F*Si)} + \frac{1}{Kv} - \frac{K}{Y} \qquad (5\text{-}41)$$

This substitution is appropriate since the effluent substrate has been identified as cell by-product and not the feed substrate. The equation (5-41) is essentially the same as the Kincannon/Stover equation where the slope term K/(Y*Y) would be equal to Kb/Um and the intercept term (1/Kv - K/Y) would be equal to 1/Um. When the SRT equals one, the feed to mass ratio in equation (5-41) would be equal to 2.27.

$$\frac{F*Si}{Xt*V} = \frac{1}{SRT(Y)} = \frac{1}{1(.44)} = 2.27 \qquad (5\text{-}42)$$

At this 2.27 feed to mass ratio all of the solids in the reactor would be viable, thus the decay constant would be equal to zero, eliminating the mass to feed term leaving only the intercept of 1/Kv. At this point a horizontal constant substrate utilization line would appear on the Kincannon/Stover linear plot which would intersect the vertical axis at the 1/Kv value. A special case of the Kincannon/Stover model is where the intercept term is zero (indicating no maximum uptake limit). This is the same as

Syke's model where the substrate utilized is equal to the substrate available.

$$dS*V/dt = F*Si \qquad (5\text{-}43)$$

When this equation is put in the specific substrate utilization form and inverted to match the Kincannon/Stover model form, a slope of unity and zero intercept is produced.

$$\frac{Xt*dt}{dS} = 1*\frac{(Xt*V)}{(F*Si)} \qquad (5\text{-}44)$$

The unity slope can be expressed using the various constants of growth and death such that the death and wasting rates equal the growth rates.

$$1 = \frac{Km+K+Vw/V}{Kv*Y} \qquad (5\text{-}45)$$

Substituting these constants for the unity slope term produces an equation that can be compared to the Kincannon/Stover model to identify what causes the intercept term to become zero.

$$\frac{Xt*dt}{dS} = \frac{(Km+K+Vw/V)(Xt*V)}{(\quad Kv*Y \quad)(F*Si)} \qquad (5\text{-}46)$$

$$\frac{Xt*dt}{dS} = \frac{(Km+K)(Xt*V)}{Kv*Y(F*Si)} + \frac{(Vw/V)(Xt*V)}{(Kv*Y)(F*Si)} \qquad (5\text{-}47)$$

The wasting rate has been separated in the equation to leave the same slope constants on the first term on the right side of the equation as the Kincannon/Stover model would have. The right most term is the term corresponding to the intercept term in the Kincannon/Stover model. In this equation the intercept term is a function of the feed to mass ratio. As such if a regression is conducted of inverse substrate utilization versus the inverted feed to mass ratio the intercept term cannot be identified because it changes with the feed to mass ratio. Such would occur when the viable solids are in excess of that which is needed to utilize the feed substrate and if the reactor can increase its viable solids concentration when the feed rate is increased. In essence, the solids concentration in the reactor changes until at steady state the volume wasted will remove the mass of solids produced. If the wasting rate is less than the decay rate then viable solids decay controls the concentration of viable solids in the reactor. If the wasting rate is greater than the decay rate then the viable solids are controlled by the wasting rate. In either case the viable solids will begin to be in excess just above the one day SRT. The point where the wasting rate equals the decay rate is where the SRT is 7.7 days and the feed to mass ratio is 0.30.

The regression of the continuous reactor operational data using the inverse specific substrate versus mass to feed ratio as shown in Table III produced a slope of 1.01 and an intercept of -0.0083 with a correlation index of almost 100%. Since the slope is near one and the intercept is near zero. The continous reactor would be using all the substrate available feeding into it. This certainly is not in contradiction to the fact that the constituents of the feed in Table I are highly biodegradable.

The information supplied by the Kincannon/Stover model linearized regression slope and intercept can be summarized as shown in Table XVIII. If the slope is one and the intercept is zero then the continuous reactor is operating on a substrate available mechanism. If the intercept is greater than zero and the slope is horizontal or zero then the continuous reactor is operating at its maximum substrate utilization rate. If the intercept is greater than zero and the slope is less than one then the continuous reactor is operating with a limiting viable solids concentration controlling.

F. Formatted Procedure for Determining the Viable Solids Decay Factor

In previous sections of this chapter, it was determined that the corrected oxygen consumption data produced the better viability decay constant. This indicates that the oxygen consumption rates in the Modified Oxygen Consumption test should be corrected for the solids withdrawn during the test. Also, the smaller glucose concentrations for the Modified Oxygen Consumption test are therefore unnecessary and introduce additional systemic error of technique into the resultant determination of the decay rate. In this section the Modified Oxygen Consumption test is presented with a constant 50 ml volume of solids to be withdrawn after each

TABLE XVIII

INTERPRETATION OF THE KINCANNON/STOVER MODEL

KINCANNON/STOVER MODEL		MECHANISM CONTROLLING
SLOPE	INTERCEPT	
$\frac{Kb}{Um} = 1.0$	$\frac{1}{Um} = 0.0$	Excess viable solids, substrate availability controlling substrate utilization.
$\frac{Kb}{Um} < 1.0$	$\frac{1}{Um} > 0.0$	Viable solids limiting substrate utilization.
$\frac{Kb}{Um} = 0.0$	$\frac{1}{Um} > 0.0$	Viable solids so small that the biological solids are operating at their maximum substrate utilization rate.

oxygen rate reading and replaced with glucose solution prior to the subsequent oxygen rate determination.

In order to obtain sufficient data for analysis at least three additional oxygen rate determinations plus the initial oxygen rate reading should be made after allowing the solids to decay prior to each rate determination. The decay days selected for this procedure were 0, 1, 2, 4 and, if desired, 8 decay days, as shown in Table XIX.

It is suggested that at least three different SRT conditions be used so differences in decay rate caused by the change in predominance of the biological solids can be identified if necessary. The SRTs suggested in this procedure are 3, 5, and 9 days.

The solids correction factor is determined from the fractional volume remaining after the 50 ml of mixed-liquor are removed from the BOD test bottle divided into 300 ml total volume. Each additional 50 ml removal of mixed-liquor volume will also need to be corrected by this correction factor. As such the correction factor for each test can be obtained by raising the 300 ml divided by 250 ml quantity to the power corresponding to the number of consecutive 50 ml withdrawn.

$$\text{Solids correction} = (300/250)^n \qquad (5\text{-}23)$$

where n = number of times 50 ml has been withdrawn

The correction factor for each test is listed in Table XIX ranging from 1.00 for no correction to 2.07 for the highest

TABLE XIX

DECAY RATE DETERMINATION

		C = GLUCOSE CONC. OF STOCK SOL. (40,000 MG/L)					
		0.000C	0.167C	0.305C	0.421C	0.518C	
	DECAY	Solids Correction Factor					
SRT	DAYS	1.000	1.200	1.440	1.728	2.07	COR. MAX
		OXYGEN CONSUMPTION RATE					
3	0						
	1						
	2						
	4						
	8						
5	0						
	1						
	2						
	4						
	8						
9	0						
	1						
	2						
	4						
	8						

SRT	DECAY DAYS	COR. MAX	STANDARDIZED DIVIDE BY ZERO MAX	NATURAL LOG OF STAND. MAX.
3	0		---------------	------------
	1			
	2			
	4			
	8			
5	0		---------------	------------
	1			
	2			
	4			
	8			
9	0		---------------	------------
	1			
	2			
	4			
	8			

$0.167C = 50C/300$ $\qquad$ $1.2 = 300/250$

$$0.305C = \frac{(50C)(250)}{(300)(300)} + \frac{50C}{300} \qquad 1.44 = \frac{(300)(300)}{(250)(250)}$$

correction.

Each new glucose concentration is determined by first correcting the glucose concentration in the test bottle for the 50 ml of volume withdrawn and then adding 50 ml of glucose stock solution to the 300 ml test bottle to obtain the resultant concentration of glucose after the first 50 ml of 40,000 mg/l glucose stock has been added will be:

$$(50/300)40{,}000 \text{ mg/l} = 6670 \text{ mg/l} \qquad (5\text{-}24)$$

The glucose concentration after adding the second 50 ml of 40,000 mg/l glucose stock solution will be a (250/300) multiple of glucose in the test bottle plus (50/300)40,000 mg/l added from stock totaling:

$$(250/300)6670 + (50/300)40{,}000 = 12{,}225 \text{ mg/l} \qquad (5\text{-}25)$$

Each consecutive glucose concentration will need to be corrected for the 50 ml withdrawn and for 50 ml of glucose stock solution added. The procedure form in Table XIX expresses each concentration as a fraction of the glucose stock concentration where C represents the glucose stock concentration. Four glucose stock additions are indicated in the form on Table XIX corresponding to 0.167C to 0.518C where 0.518*40,000 mg/l equals 21000 mg/l of glucose. If it is found that the glucose concentration will not encompass the maximum oxygen consumption rate range, the glucose stock concentration can be increases and the same fractions can be used without recalculation. However, if the 50 ml volume is changed then the constants on the form will need to be recalculated.

The procedure for filling out the form is as follows:

1. A sample volume of 1200 mg/L is taken from the three day SRT reactor and 300ml is placed into each of three batch reactor.

2. The remaining 300 ml is immediately aerated by placing it in a 300 ml BOD bottle with a stirring rod and the oxygen probe placed in it. The mixture is mixed by the magnetic stirring rod over a magnetic stirrer. The oxygen consumption test is conducted recording the oxygen concentration every half minute. The consumption rate should stabilize after one and a half minutes. Oxygen concentration readings can be taken for three or four more minutes, noting both concentration and time. The oxygen consumption rate is determined as the change in oxygen concentration divided by the time between the concentration change.

3. The oxygen consumption rate is corrected for solids by multiplying by the appropriate solids correction factor. The first undiluted reading is multiplied by 1.00 and recorded on the form under the column with the 1.00 solids correction factor and in the row of zero decay days.

4. 50 ml of mixed-liquor is removed from the test bottle and 50ml of glucose stock solution is added. The contents are aerated and the oxygen consumption test completed again as

instep 2 and 3. The second rate will be corrected by multiplying by 1.20 and the results placed under the column of 1.20 solids correction and in the zero decay row. The rest of the row up to and including the 2.07 correction factor by removing 50 ml, adding 50 ml of glucose stock solution, determining the oxygen consumption rate and then correcting this rate by the solids correction factor above each column. .

5. The one decay day determination is determined one day after placing the samples in the batch reactor. The test procedure in steps 2 through 4 would be completed on one of the 300 ml volumes in a batch reactor.

6. The test for the two decay day and four decay day would be completed after wasting two days from the initial sampling and four days for each and then conducting the tests in steps 2 through 4 on each 300 ml.

7. For each SRT condition the test conducted would include steps 1 through 6 using the samples of mixed-liquor from the appropriate SRT condition.

8. After determining all corrected oxygen rates, the maximum corrected oxygen rate for each row is placed in the column "COR. MAX" by selecting the maximum rate in that row.

9. After all maximum corrected rates are determined the rates can be standardized by dividing each rate within a SRT condition by the corrected oxygen consumption rate at zero

decay days. This result is placed under the column "STANDARDIZED DIVIDE BY ZERO MAX" for decay day one through four days.

10. The natural log of each of these standardized rates is taken and placed in column labeled "NATURAL LOG OF STAND. MAX."

11. Simple linear regression would next be conducted by regressing the natural log of the standardized rate (Y axis) versus the decay days (X axis) for each. The decay constant is the absolute value of the slope produced in the regression.

CHAPTER VI

DISCUSSION

In this study a 0.13/day oxygen decay rate was determined from batch decay tests and a 0.31/day substrate utilization rate was determined from continuous reactor data. The difference of these two rates, 0.18/day, was shown to be a metabolism rate which can be converted to the observed yield. Thus the 0.13/day and the yield terms are unique characteristics of the biological solids which can be related to the 0.31/day substrate utilization rate. The 0.13/day rate can be used at steady state to identify the viable solids in the reactor while the 0.31/day rate can be used to identify the viable solids being used in each day of growth which is generally a fraction of the viable solids available. Since viable solids are in excess of that required, viable solids would not be limiting the growth of viable solids. This information on viability of solids can be used to develop effective strategies in treatment plant operations. For example, most kinetic models which ignore viability suggest that the increase of solids concentration in a reactor can be used to fine tune and maintain effluent quality when the influent substrate mass flow rate increases. The viability information, however, suggests that since only a fraction of the viable solids are being used in substrate utilization, that most influent excursions can be handled by the reactor without massive changes in concentration of solids in the reactor. If the variability of influent is extensive then consideration in design of the reactor system should be dictated by the variability of the influent feed mass. The viability capacity of the biological solids should be a determining factor in the choice of number and size of reactors designed to meet the influent variability. Thus viability information tends to discourage short term changes in solids concentration in the reactor but suggests the viability should be considered for proper design of system.

The (Km + K) factor can be used to predict volatile suspended solids concentration required in high SRT's system for a new SRT if the volatile suspended solids are known for an initial SRT condition of the reactor. For example if 1200mg/L are in a three day reactor, the concentration of volatile suspended solids in a 15 day SRT reactor would be:

$$1200\text{mg/L}\ \frac{(.31(15-1)+1)}{(.31(\ 3-1)+1)} = 3956\ \text{mg/L} \qquad (6\text{-}1)$$

This prediction works best for SRT's above 1/(Km+K) days. SRT's smaller than this, are affected by the wasting in the reactor and as a result have a smaller viable solid and volatile suspended solids concentration. If the concentration of solids for the reactor are not known they can be predicted from the mass feed rate into the reactor.

The viable solids used in substrate utilization must be equal to the mass of substrate feed to the reactor. Since volatile suspended solids is related to the viable solids used in the reactor through the (Km + K) constant, the volatile suspended solids can be determined by the following equation using a constant of 0.31/day and a three day SRT.

$$Xt = F*Si*((Km+K)*(SRT - 1) + 1)/V \qquad (6\text{-}2)$$

For a feed concentration of 325mg/L and a feed rate of 7.2 L/day and a reactor volume of 3L, the concentration in the reactor for a three day SRT would be 1264 mg/L. This calculation will work best for SRT's greater than 1/(Km + K) days where the effects of wasting on the solids concentration can be ignored. This information suggests that solids concentration in a reactor is determined by the viable solids used in the reactor rather than just the wasting rate.

In systems where viable solids are in excess, there is a possibility that only the viable solids most recently coming out of growth will have the greater vitality and ability to wrestle substrate from the older viable solids. The overall effect of this is a weaker system which would be more susceptible to competition by bulking microorganisms. A possible technique to maintain a greater viability of all viable solids in the reactor, would be to mix the solids recycled from the clarifier with the influent substrate just before returning the solids to the reactor. This would allow the older viable solids in the recycle to begin substrate utilization in a fairly noncompetitive environment prior to entrance to the reactor. The overall effect would be less disparity between the viability of the viable solids and an overall stronger reactor less influenced by competitive microorganisms.

The oxygen decay constant, K, of 0.13/day, indicates that for high SRT systems the fraction of nonviable solids would become large. It is also recognized that high SRT biological solids settle faster than low SRT solids. Most sludge settling equations ignore the viability and nonviable fractions, only using physical and chemical equations to predict settling rates. Where the viability fraction of the biological solids can be readily determined, the effect of the nonviable or viable fraction could be quantified in settling thus improving the prediction rate of settling equations.

Another factor that was not considered part of this study that might be correlated with the decay rate, K, is the source of effluent substrate, Se. Since the effluent of high SRT systems is recognized not to be the same as the feed, there is the possibility that the effluent substrate is produced as the viable organism decay and lose their viability, or a waste product of growth. In a continuous reactor at steady state the decay rate and the growth rate are equivalent, as such, determining if the effluent substrate is either a cell production by-product or a decay product is very difficult. Gaudy and Backly (24) in studying the biodegradability of the residual COD, collected effluent COD data from a reactor which was fed continuously but closed to effluent flow so the system accumulated what was fed and what grew. The mixed-liquor substrate concentration in the reactor, which in continuous reactors is considered equivalent to the effluent substrate, increased at a fast rate until about fifty days had past and then remained fairly constant or increased at a very slow rate much below what was predicted. Gaudy used these results as an indication that the effluent substrate was much more biodegradable than has generally been assumed of effluent substrate. This drastic change in substate accumulation may also be used to indicate whether the effluent is a byproduct of growth or viability decay. If the effluent substrate is a cell byproduct of growth then it should continue to accumulate at a constant rate. If it is a result of cell decay then it would accumulate at a geometric rate as the viable solid accumulated until the viable mass was large enough so that the viable decay rate equaled the growth rate. At this point the decay would be constant, not increasing with increasing solids and would become a much slower rate drastically lower than the initial increase. Gaudy's data seems to indicate the effluent substrate is possibly related more to viability decay rather than a byproduct of growth.

Another factor not encompassed in this study, which might be affected by non-viability and viability, is the solids decay factor, Kd. Generally when this factor is applied the solids are assumed to be homogeneous and the Kd factor is explained to be the result of the microorganisms using more substrate than expected for growth at substrate limiting conditions. Thus fewer solids are produced because more substrate is burned to produce a maintenance level of energy. Since the solids are not homogeneous, the Kd factor can also be explained as an actual mass decay of old nonviable solids. As such the decay of solids would increase with the increase of non-viable solids at high SRT's and not with the volatile suspended solids or total solids concentration. In a plot of net growth rate (1/SRT) versus the specific substrate utilization (F(Si-Se)/(Xt*V)), the Kd factor is determined as the magnitude of the negative value where the best fit line intersects the vertical axis. If the Kd is actually a factor of non-viable solids then the best fit line should not be straight but curve down as the specific substrate utilization approaches zero. This type of down curve was apparent in the net growth rate versus specific oxygen uptake rate plot that Huang, Cheng and Mueller (18) found when using oxygen uptake to determine viability of solids, suggesting that the Kd factor may be a nonviable solids decay rate, as shown in Figure 1.

In this study the feed substrate was highly biologically degradable. If the feed is more complex, then the Km metabolism rate would need to be larger to aid the breakdown of the complex feed, causing the yield to decrease. There is a possibility that for very complex feeds that the Km factor could become so large producing a very small yield such that the biological microorganisms produced could not maintain a viable fraction. The solids in such a system would decrease until it failed. If a toxic feed were used the decay factor, K, would increase shortening the length of time to decay such that the viable fraction would die out before it could be replaced. Both factors cause failure of the system and would be hard to differentiate by standard techniques even though they affect different factors in the system. Using the viability information by determining the yield and the (Km + K) constant from equation (5-14) and finally the Km rate from equation (5-36) toxicity and complex feed can be analyzed individually. The toxicity could also be quantified as the change in rate of the decay rate. The complexity of the feed could also be quantified relative to the Km rate change or the change in yield. Relative to complex waste, if these rates are understood, it would be possible to determine how much of a simpler feed waste would need to be added to a complex feed so that the mixture would be able to produce sufficient viable solids so it would not fail.

Toxic feeds which kill out the organisms at a high rate could also be designed for by using a two stage reactor, where the first stage would use a simple feed source to produce the viable solids at a sufficient rate so that when fed into the second reactor the toxic material could not kill out all the viable organisms before it was assimilated. There is a possibility that many materials generally considered nonbiodegradable could be biodegraded if the reactor is designed to compensate for either a high decay rate or a low yield.

CHAPTER VII

CONCLUSION

The results of this investigation support the following conclusions:

1. The oxygen decay rate, K, determined using the Modified Oxygen Consumption test on biological solids from continuous reactors isolated in batch reactors, is a unique characteristic of the biological solids in the continuous reactors independent of SRT. The oxygen decay rate, however, would be expected to change if a change of predominance occurs in the reactor.

2. The Oxygen Decay rate can be used to calculate the concentration of viable solids in the reactor that have not had sufficient time to lose their viabilty, using the following equation:

$$Xv = Xt/((Km+K)*(SRT-1)+1) \qquad (5\text{-}7)$$

where the Km is equal to zero and K is the oxygen decay rate. These calculations are most accurate for SRTs greater than 1/K days where the wasting rate has a small effect on the concentration of viable solids.

3. The Observed Yield was found to correspond to an energy metabolism rate, Km, related to the substrate utilized

as energy for growth of new biological solids. The equation for this relationship was as follows:

$$Yo = \frac{K(SRT-1) + 1}{(Km+K)(SRT-1) + 1} \qquad (7\text{-}1)$$

with the K substituted for the .13/day and (Km+K) substituted for the .31/day values in equation (5-30).

4. The decay rate, K, and the energy metabolism rate, Km, summed was equal to the rate at which the substrate was taken up by the viable solids referred to as a rate of substrate utilzation in terms of SRT.

5. The rate of substrate utilization, (Km+K), was used to calculate the fraction of viable solids involved in substrate utilization, using equation (5-7), indicating that the viable solids were not a limiting factor of substrate utilization.

6. The specific substrate utilization rate derived in a form containing the SRT was converted to the same form as the Kincannon/Stover model which allowed interpretation of the model depending upon the value of the constant in the model.

7. When conducting the Modified Oxygen Consumption test the oxygen consumption rate should be corrected for the solids withdrawn during the test before selecting the maximum oxygen consumption rate.

CHAPTER VIII

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are recommended for futher investigation to better clarify the characteristics of the biological action occurring in activated sludge systems.

1. Evaluation of toxic and complex feeds to quantify there effects on the decay rate, K, and the energy metabolism rate, Km, should be most useful in classifying toxic and complex substrates.

2. Tests to clarify if the endogenous rate, Kd, is actually a nonviable solids decay rate would make it possible to more accurately evaluate the kinetics occurring in activated sludge systems.

3. Tests specifically designed to identify if the effluent substrate arises from the viable decay of viable solids or as a byproduct of growth metabolism would futher clarify the mechanisms occurring in the growth of biological solids.

A SELECTED BIBLIOGRAPHY

1. Feliciano, D. V., "Project Performance: A Question of Accountability." J. Water Pollution Control Federation, 55, 217-220 (1983).

2. Stover, E. L., Gomathinayagam, G., "Biological Treatment of Synthetic Fuel (Alcohol Production) Waste." Presented at the Water Pollution Control in Synfuel Production Session, 55th Annual Water Pollution Control Federation Conference, October 3-8, 1983, St. Louis, Missouri.

3. Daigger, G. T., Richter, G. A., Collins, J. R., and Smith, J. W., "Team Effort Solves Operational Problems." J. Water Pollution Control Federation, 55, 17-22 (1983).

4. Sykes, R.M., "Limiting Nutrient Concept in Activated Sludge Models." J. Water Pollution Control Federation, 53, 1213-1218 (1981).

5. McKinney, R. E., "Design and Operational Model for Complete Mixing Activated Sludge System." Biotechnology and Bioengineering, 16, 703-722 (1974).

6. Lawrence, A. W., and McCarty, P. L., "A Unified Basis for Biological Treatment Design and Operation." J. Sanitation Engineering Division of ASCE, 96, (1970).

7. Gaudy, A. F. Jr., and Gaudy, E. T., "Quantitative Description of Growth." In Microbiology for Environmental Scientists and Engineers, McGraw-Hill, New York (1980).

8. Eckenfelder, W. W. Jr., "Theory and Prediction of Activated Sludge Process Modifications." Water and Sewage Works, 108, 145 (1961).

9. Chudoba, J., "Quantitative Estimation in COD Units of Refractory Organic Compounds Produced by Activated Sludge Microorganisms." Water Research, 19, 37-43 (1985).

10. Novak, J. T., Mines, R. O., and Sherrard, J. H., "Activated Sludge Processes and Effluent Standards." J. Water Pollution Control Federation, 55, 332-335 (1983).

11. Sykes, R. M., "Hydraulic Regime and Activated Sludge Performance." J. Environmental Engineering Division of ASCE, 108, 286-296 (1982)

12. Weddle, C. L., and Jenkins, D., "The Viability of Activated Sludge." Water Research, 5, 621-640 (1971).

13. Nelson, P. O., and Lawrence A. W., "Microbial Viability Measurements and Activated Sludge Kinetics." Water Research, 14, 217-225 (1980).

14. Benefield, L., Lawrence, D., and Randall, C., "The Effect of Sludge Viability on Biokinetic Coefficients Evaluation." J. Water Pollution Control Federation, 51, 187-194 (1979).

15. Grady, C. P. L. Jr., and Roper, R. E. Jr., "A Model for the Bio-oxidation Process which Incorporates the Viability Concept." Water Research, 8, 471-483 (1974).

16. Blok, J., "Measurements of the Viable Biomass Concentration in Activated Sludge by Respirometric Techniques." Water Research, 10, 919-925 (1976).

17. Walker, I., and Davies, M., "The Relationship between Viability and Respiration Rate in the Activated Sludge Process." Water Research, 11, 575-578 (1977).

18. Huang, Y. C., Cheng, M., and Mueller, J. T., "Oxygen Uptake for Determining Microbial Activity and Application."Water Research, 19, No. 3, 373-381 (1985)

19. Marais, C. V. R., "Faecal Bacteria Kinetics in Stabilization Ponds." J. Environmental Engineering Division of ASCE, 100, 119-139 (1974).

20. Mancini, J. L., "Numerical Estimates of Coliform Mortality Rates Under Various Conditions." J. Water Pollution Control Federation, 50, 2477 (1978).

21. Polprasert, C., Dissanayake, M. G., and Thanh, N. C., "Bacterial Die-off Kinetics in Waste Stabilization Ponds." J. Water Pollution Control Federation, 55, 285-296 (1983).

22. Monod, J., "The Growth of Bacterial Cultures." _Annual Review of Microbiology_, _3_, 371-394 (1949).

23. _Standard Methods for the Examination of Water and Wastewater_. American Public Health Association, 18th Edition, New York (19).

24. Gaudy, A. F., and Blachly, T. R., "A Study of the Biodegradability of Residual COD." _J. Water Pollution Control Federation_, _57_, No. 4, 332-338 (1985).

APPENDIX A

CONTINUOUS UNIT OPERATIONAL DATA

TABLE XX

CONTINUOUS UNIT OPERATIONAL DATA

DATE MO/DA/YR	F L/DAY	Xt MG/L	Xe MG/L	Vw L/DAY	Si MG/L	Se MG/L
SEVEN DAY SRT REACTOR, VOLUME OF 2.86 LITERS						
11/15/84	6.48	2180	9	.383		
11/16	6.84	2260	13	.371		
11/17	6.84	2400	14	.371		
11/18	6.0	2260	6	.394		
11/19	6.48	2240	5	.395		
11/20	6.48	2180	19	.355		
11/21	7.92	2240	8	.382		
11/22	8.64	2220	7	.383		
11/23	6.48	2480	6	.394		
11/24	6.48	2240	19	.357		
11/25	7.2	2120	9	.380		
11/26	7.2	2300	38	.294		
11/27	6.84	2220	4	.397		
11/28	8.28	2280	9	.377		
11/28	7.92	2480	13	.369		
11/30	6.84	2140	7	.389		
12/1	7.2	2320	7	.388	306	5.8
12/2	6.48	2100	7	.388		
12/3	6.48	2240	12	.376		
12/4	6.48	2180	9	.383	290	2.7
12/5	6.48	2120	9	.383		
12/6	6.48	2020	17	.357	329	3.4
12/7	6.48	2240	9	.384		
12/8	6.48	2280	5	.395		
12/9	7.2	2220	8	.384		
12/10	6.48	2280	10	.382		
12/11	5.76	2360	10	.386		4.2
12/12	4.32	2300	10	.391		
12/13	7.2	2200	7	.387		1.1
12/14	7.2	2160	12	.371		
12/15	7.2	2180	12	.371		2.5
12/16	7.56	1880	225.30			
12/17	5.76	2140	11	.381		
12/18	7.92	2100	7	.383	342	1.6
12/19	8.28	2060	6	.386		
12/20	8.64	2160	8	.378	239	2.9
12/21	8.64	2160	0	.409		
12/22	7.2	2160	1	.405	238	1.9
12/23	7.2	2460	8	.385		
12/24	7.2	2420	10	.380		
12/25	7.2	2220	0	.409		1.2
12/26	6.48	2320	0	.409		

TABLE XX (Continued)

DATE MO/DA/YR	F L/DAY	Xt MG/L	Xe MG/L	Vw L/DAY	Si MG/L	Se MG/L
THREE DAY SRT REACTOR, VOLUME OF 2.86 LITERS						
12/27/85	7.92	2020	6	.933		1.3
12/28	6.0	3460	0	.953		
12/29	6.84	2320	5	.941		
12/30	7.2	1280	3	.939	357	1.4
12/31	9.12	1340	4	.929		
1/1/85	6.48	1580	4	.939	319	4
1/2	6.91	1400	7	.923		
1/3	7.92	1260	1	.948	307	2.8
1/4	6.91	1420	4	.937		
1/5	10.08	860	0	.953		
1/6	7.2	740	0	.953		
1/7	7.56	1000	2	.940	332	1.6
1/8	6.0	2100	1	.951		
1/9	9.24	1340	3	.935	328	1.3
1/10	5.51	700	0	.953		
1/11	7.92	1760	2	.945	229	1.6
1/12	6.48	880	5	.922		
1/13	6.48	1220	7	.921		
1/14	7.56	1640	7	.925	327	2.6
1/15	8.06	1020	0	.953		
1/16	6.12	1080	7	.920	321	4.1
1/17	8.04	1140	5	.922		
NINE DAY SRT REACTOR, VOLUME OF 2.86 LITERS						
1/18	7.2	1140	4	.294	304	2.1
1/19	4.32	1340	5	.303		
1/20	6.6	1280	3	.303		
1/21	6.0	2080	5	.304	389	1.8
1/22	6.96	1920	6	.297		
1/23	7.2	2060	6	.298	346	2.7
1/24	6.0	2200	10	.292		
1/25	6.48	2520	11	.291		
1/26	5.4	2400	7	.303		
1/27	6.48	2420	5	.305		
1/28	6.6	2020	7	.296	376	3.5
1/29	6.24	2440	4	.308		
1/30	6.72	2780	7	.302	329	2.5
1/31	7.56	2780	4	.307		
2/1	9.07	2820	7	.296	296	2.8
2/2	4.08	2420	13	.297		
2/3	5.04	2300	9	.299		
2/4	6.72	2480	1	.315	315	1.7
2/5	5.04	2660	1	.316		
2/6	4.8	3000	4	.312	313	1
2/7	6.96	2560	1	.315		

TABLE XX (Continued)

DATE MO/DA/YR	F L/DAY	Xt MG/L	Xe MG/L	Vw L/DAY	Si MG/L	Se MG/L
NINE DAY SRT (CONT)						
2/8	6.96	3600	1	.316		
2/9	6.0	2460	4	.309		
2/10	5.64	3000	4	.311		
2/11	6.0	2880	8	.302	349	3.1
2/12	6.0	2660	5	.307		
2/13	5.75	2880	4	.310		
2/14	6.0	2840	22	.273		
2/15	7.76	2980	8	.298		1.6
2/16	7.56	2880	4	.308		
2/17	7.2	3520	5	.308		
2/18	7.2	2600	4	.307		1.8
2/19	7.2	2460	3	.309		
2/20	7.2	2420	4	.306		2.3
2/21	7.2	2740	10	.293		
2/22	7.2	3140	17	.280		
TWENTY DAY SRT REACTOR, VOLUME OF 2.92						
11/3/84	8.28	5760	5	.139	264	.9
11/4	6.7	5400	2	.144		
11/5	7.63	6700	4	.142		
11/6	8.64	5200	5	.138	285	1.3
11/7	6.91	6000	4	.141		
11/8	8.28	5100	6	.136	299	1.4
11/9	6.48	6100	5	.141		
11/10	6.48	5320	5	.140		
11/11	6.48	5020	14	.128		
11/12	7.2	5840	9	.135		
11/13	7.56	5560	8	.135		
11/14	8.64	5860	5	.139		
11/15	6.48	5380	6	.139		
11/16	6.84	5640	14	.129		
11/17	6.84	5660	16	.127		
11/18	6.0	5860	10	.136		
11/19	6.48	5960	10	.135		
11/20	6.48	5640	10	.135		
11/21	7.92	5820	7	.137		
11/22	8.64	6100	10	.132		
11/23	6.48	6840	9	.138		
11/24	6.48	6680	11	.136		
11/25	7.2	6460	10	.135		
11/26	7.2	6860	10	.136		
11/27	6.84	7560	5	.142		
11/28	8.28	6320	6	.138		
11/29	7.92	6460	16	.127		
11/30	6.48	7000	10	.137		

TABLE XX (Continued)

DATE MO/DA/YR	F L/DAY	Xt MG/L	Xe MG/L	Vw L/DAY	Si MG/L	Se MG/L
TWENTY DAY SRT (CONT)						
12/1	7.2	7060	9	.137	367	4.7
12/2	6.48	6140	7	.139		
12/3	6.48	6820	12	.135		
12/4	6.48	6520	8	.138	339	6.6
12/5	6.48	5780	9	.136		
12/6	6.48	6460	10	.136	281	6.8
12/7	6.48	6580	9	.137		
12/8	6.48	7240	6	.141		
12/9	7.2	6980	3	.143		
12/10	6.48	7520	8	.139		
12/11	5.76	8900	5	.143		6
12/12	4.32	8060	9	.141		
12/13	7.2	6360	5	.140		3.2
12/14	7.2	7520	7	.139		
12/15	7.2	6920	6	.140		4.2
12/16	7.56	6880	6	.140		
12/17	5.76	7440	11	.138		
12/18	7.92	6760	3	.143	319	3.9
12/19	8.28	6260	3	.142		
12/20	8.64	7800	5	.141	276	2.8
12/21	6.48	6500	4	.142		
12/22	7.2	6940	7	.139	345	3.2
12/23	7.2	6960	10	.136		
12/24	7.2	6620	4	.142		
12/25	7.2	7040	3	.143		3.7
12/26	6.48	6140	3	.143		
12/27	7.92	6120	1	.145		.9
12/28	6.0	6000	3	.143		
12/29	6.84	5900	4	.141		
12/30	7.2	5860	1	.145	386	1.3
12/31	9.12	6840	5	.139		
1/1/85	6.48	6280	7	.139	311	4
1/2	6.91	6500	11	.135		
1/3	7.92	5880	11	.278	277	6
TWO DAY SRT REACTOR, VOLUME OF 2.92 LITERS						
1/18/85	7.2	1060	7	1.42	237	11
1/19	4.32	980	1	1.46		
1/20	6.6	640	4	1.43		
1/21	6.0	680	4	1.43	351	1.4
1/22	6.96	920	4	1.44		
1/23	7.2	900	4	1.43	348	2.6
1/24	6.0	580	14	1.35		
1/25	6.48	520	12	1.34		
1/26	5.4	460	8	1.39		

TABLE XX (Continued)

DATE MO/DA/YR	F L/DAY	Xt MG/L	Xe MG/L	Vw L/DAY	Si MG/L	Se MG/L
TWO DAY SRT (CONT)						
1/27	6.48	660	18	1.32		
1/28	6.6	848	12	1.39	425	6.8
1/29	6.24	980	8	1.42		
1/30	6.72	1060	10	1.41	353	4.2
1/31	7.56	980	12	1.38		
2/1	9.07	860	10	1.37	301	3.2
2/2	4.08	700	4	1.45		
2/3	5.04	740	6	1.43		
2/4	6.72	600	2	1.44	374	1.7
ONE AND A HALF DAY SRT REACTOR, VOLUME OF 2.92 LITERS						
2/5/85	5.04	800	4	1.93		
2/6	4.8	580	4	1.93	317	1.7
2/7	6.96	600	0	1.95		
2/8	6.96	660	1	1.94		
2/9	6.0	660	5	1.92		
2/10	5.64	920	1	1.94		
2/11	6.0	800	7	1.91	457	4
2/12	6.0	760	12	1.88		
2/13	5.75	760	12	1.89		
2/14	6.0	820	3	1.93		
2/15	7.76	580	8	1.87		3.2
ONE DAY SRT REACTOR, VOLUME OF 2.92 LITERS						
2/16/85	7.56	380	2	2.90		
2/17	7.2	560	2	2.91		
2/18	7.2	510	5	2.88		9.2
2/19	7.2	720	6	2.88		
2/20	7.2	520	13	2.81		7.2
0.9 DAY SRT REACTOR, VOLUME 2.92 LITERS						
2/21	7.2	320	10	3.1		
2/22	7.2	130	0			
FIVE DAY SRT REACTOR, VOLUME OF 2.85 LITERS						
12/22/84	7.92	1620	6	.523	244	2.2
12/23	8.64	1820	11	.501		
12/24	7.2	3720	0	.570		
12/25	7.92	2600	4	.559		1.2
12/26	7.92	1520	0	.565		
12/27	7.92	3300	0	.570		.9
12/28	4.0	3140	0	.570		

TABLE XX (Continued)

DATE MO/DA/YR	F L/DAY	Xt MG/L	Xe MG/L	Vw L/DAY	Si MG/L	Se MG/L
FIVE DAY SRT (CONT)						
12/29	9.0	1440	2	.558		
12/30	10.08	1500	0	.570	375	1.3
12/31	10.08	2420	4	.554		
1/1/85	5.76	2140	3	.572	213	1
1/2	7.2	2460	4	.559		
1/3	7.2	2140	0	.570	222	2.7
1/4	7.2	1760	3	.559		
1/5	10.03	1580	3	.551		
1/6	8.64	1740	0	.570		
1/7	9.36	1660	4	.549	353	1.8
1/8	4.32	1660	2	.565		
1/9	10.03	1980	4	.551	356	1.9
1/10	4.32	2020	0	.570		
1/11	8.64	1780	1	.565	238	1.9
1/12	6.48	1760	9	.540		
1/13	7.2	2040	2	.563		
1/14	5.76	2720	8	.555	443	3.3
1/15	9.36	1980	6	.543		
1/16	4.32	1980	14	.543	344	7.4
1/17	8.64	2220	8	.541		
1/18	7.56	1560	8	.534	264	4
1/19	3.6	1820	4	.563		
1/20	10.8	1740	2	.558		
1/21	4.8	1880	3	.563	341	1.7
1/22	6.48	1740	9	.539		
FIFTEEN DAY SRT REACTOR, VOLUME OF 2.85 LITERS						
1/23/85	7.2	1940	5	.172	386	2.8
1/24	4.7	2300	9	.172		
1/25	4.7	2080	1	.188		
1/26	3.6	2160	7	.179		
1/27	7.2	2760	8	.170		
1/28	6.48	3240	7	.176	450	2.5
1/29	6.48	3360	6	.179		
1/30	6.12	2920	13	.163	364	7.7
1/31	10.08	3360	14	.149		
2/1	12.24	2960	12	.141	362	6.1
2/2	5.76	3180	4	.183		
2/3	7.2	3220	3	.183		
2/4	11.52	3900	0	.190	351	2.7
2/5	6.0	4320	1	.189		
2/6	3.6	3920	14	.178	305	7
2/7	7.2	3620	17	.157		
2/8	7.2	3540	12	.166		
2/9	5.76	4100	10	.176		

TABLE XX (Continued)

DATE MO/DA/YR	F L/DAY	Xt MG/L	Xe MG/L	Vw L/DAY	Si MG/L	Se MG/L
FIFTEEN DAY SRT (CONT)						
2/10	4.68	3720	9	.179		
2/11	5.76	4620	11	.177	444	3.8
2/12	6.5	4360	14	.170		
2/13	5.45	4500	11	.177		
2/14	4.8	4820	16	.175		
2/15	7.06	4420	14	.168		4.6

APPENDIX B

REGRESSION DATA

TABLE XXI

SIMPLE LINEAR REGRESSION OF THE LINEARIZED KINCANNON/STOVER MODEL

NO.	X VALUE Xt*V/F/Si	Y VALUE Xt*V/F/(Si-Se)	NO.	X VALUE	Y VALUE
1	0.852	0.859	46	5.149	5.193
2	1.113	1.119	47	10.175	10.414
3	0.697	0.700	48	2.749	2.770
4	0.920	0.930	49	1.904	1.937
5	1.305	1.321	50	3.736	3.816
6	0.883	0.897	51	3.167	3.184
7	1.049	1.057	52	1.989	2.004
8	0.943	0.947	53	9.099	9.218
9	1.814	1.902	54	6.157	6.178
10	1.572	1.592	55	9.551	9.649
11	1.897	1.913	56	7.813	7.910
12	2.775	2.795	57	7.694	7.724
13	1.265	1.270			
14	1.139	1.145			
15	1.482	1.496			
16	2.186	2.207			
17	1.424	1.430			
18	3.273	3.290			
19	2.228	2.262			
20	3.797	3.881			
21	3.038	3.061			
22	2.467	2.487			
23	1.580	1.589			
24	1.432	1.439			
25	3.816	3.863			
26	4.971	4.995			
27	1.131	1.135			
28	2.389	2.411			
29	3.605	3.634			
30	2.992	3.028			
31	2.217	2.228			
32	2.710	2.738			
33	3.318	3.349			
34	3.012	3.070			
35	3.686	3.728			
36	3.117	3.144			
37	3.114	3.127			
38	5.711	5.729			
39	3.351	3.369			
40	3.004	3.033			
41	3.596	3.624			
42	2.310	2.331			
43	2.365	2.384			
44	2.569	2.581			
45	1.490	1.500			

57 = N
174.8 = SUM OF X
176.6 = SUM OF Y
807.1 = SUM OF X^2
825.3 = SUM OF Y^2
816.1 = SUM OF X*Y
3.066 = X MEAN
3.098 = Y MEAN
1.013 = SLOPE
-0.0083 = INTERCEPT
0.99994 = R
0.99987 = R^2
0.02561 = SD
0.00066 = STAND VAR

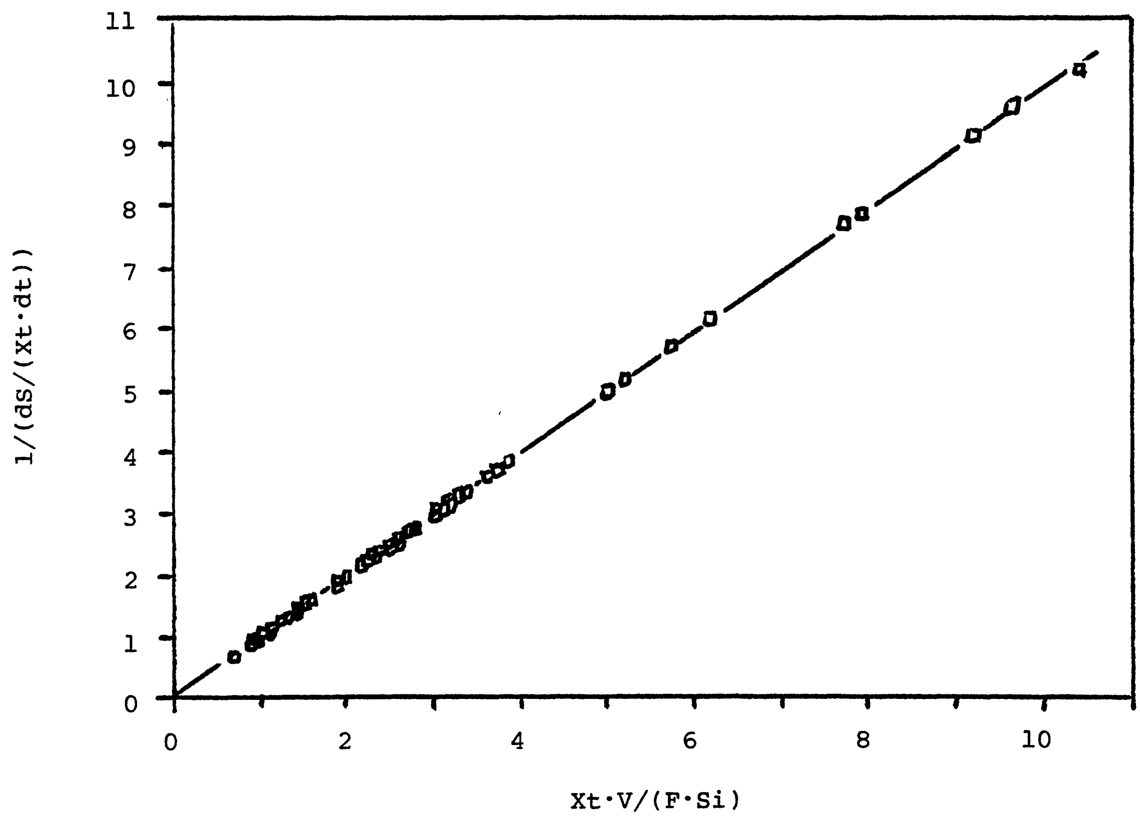


Figure 25. Regression Plot of the Linearized Kincannon/
Stover Model

TABLE XXII

SIMPLE LINEAR REGRESSION OF THE LINEARIZED LAWRENCE/MCCCARTY MODEL

NO.	X VALUE 1/Se	Y VALUE Xt*V/F/(Si-Se)	NO.	X VALUE	Y VALUE
1	0.250	0.859	46	0.263	5.193
2	0.588	1.119	47	0.143	10.414
3	0.588	0.700	48	0.370	2.770
4	0.313	0.930	49	0.164	1.937
5	0.238	1.301	50	0.130	3.816
6	0.147	0.897	51	0.400	3.184
7	0.385	1.057	52	0.357	2.004
8	0.714	0.947	53	0.250	9.218
9	0.091	1.902	54	0.769	6.178
10	0.244	1.593	55	0.357	9.649
11	0.385	1.913	56	0.256	7.910
12	0.625	2.795	57	1.000	7.724
13	0.769	1.270			
14	0.625	1.145		57 = N	
15	0.357	1.496		25.44 = SUM OF X	
16	0.333	2.207		176.6 = SUM OF Y	
17	0.714	1.430		14.27 = SUM OF X^2	
18	0.588	3.290		825.3 = SUM OF Y^2	
19	0.250	2.262		78.99 = SUM OF X*Y	
20	0.135	3.881		0.446 = X MEAN	
21	0.303	3.061		3.098 = Y MEAN	
22	0.526	2.487		0.0655 = SLOPE	
23	0.526	1.589		3.0687 = INTERCEPT	
24	0.556	1.439		0.00671 = R	
25	0.370	3.862		0.000044 = R^2	
26	1.000	4.995		2.24923 = SD	
27	0.769	1.135		5.05905 = STAND VAR	
28	0.455	2.410			
29	0.526	3.634			
30	0.345	3.028			
31	0.625	2.228			
32	0.294	2.738			
33	0.370	3.349			
34	0.172	3.070			
35	0.400	3.728			
36	0.455	3.144			
37	0.909	3.127			
38	1.000	5.729			
39	0.588	3.369			
40	0.357	3.033			
41	0.400	3.624			
42	0.286	2.331			
43	0.370	2.384			
44	0.556	2.581			
45	0.476	1.500			

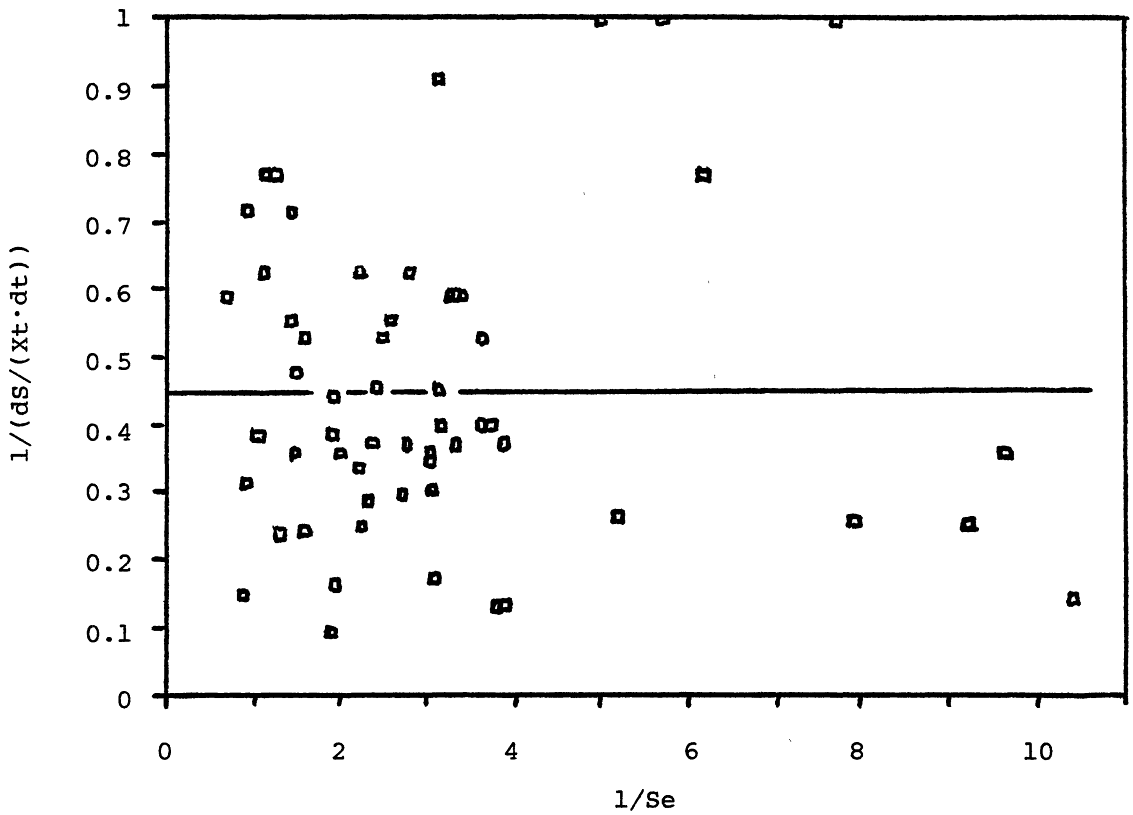


Figure 26. Regression of the Linearized Lawrence/McCarty Model

TABLE XXIII

SIMPLE LINEAR REGRESSION OF THE MCKINNEY EFFLUENT SUBSTRATE MODEL

NO.	X VALUE Se	Y VALUE F(Si-Se)/V	NO.	X VALUE	Y VALUE
1	4	930.8	46	3.8	889.7
2	1.7	518.3	47	7	376.4
3	1.7	856.8	48	2.7	1407.9
4	3.2	925.1	49	6.1	1528.5
5	4.2	802.7	50	7.7	765.1
6	6.8	945.2	51	2.5	1017.5
7	2.6	851.7	52	2.8	968.1
8	1.4	718.4	53	4	681.3
9	11	557.3	54	1.3	948.6
10	4.1	678.1	55	2.8	808.4
11	2.6	857.5	56	3.9	854.7
12	1.6	629.7	57	1	745.8
13	1.3	1055.5			
14	1.6	873.4			
15	2.8	842.4			
16	3	716.0			
17	1.4	895.2			
18	1.7	571.5			
19	4	689.7			
20	7.4	510.2			
21	3.3	888.7			
22	1.9	715.8			
23	1.9	1246.2			
24	1.8	1153.4			
25	2.7	554.0			
26	1	428.5			
27	1.3	1321.7			
28	2.2	671.9			
29	1.9	594.4			
30	2.9	713.3			
31	1.6	942.6			
32	3.4	737.7			
33	2.7	650.9			
34	5.8	755.7			
35	2.5	638.4			
36	2.2	769.7			
37	1.1	761.1			
38	1	523.6			
39	1.7	736.1			
40	2.8	929.8			
41	2.5	767.2			
42	3.5	866.5			
43	2.7	864.3			
44	1.8	806.0			
45	2.1	760.0			

57	= N
172	= SUM OF X
46214.8	= SUM OF Y
732.22	= SUM OF X^2
40220513	= SUM OF Y^2
136858.4	= SUM OF X*Y
3.017	= X MEAN
810.8	= Y MEAN
-12.180	= SLOPE
847.54	= INTERCEPT
-0.10724	= R
0.01150	= R^2
222.324	= SD
49428.2	= STAND VAR

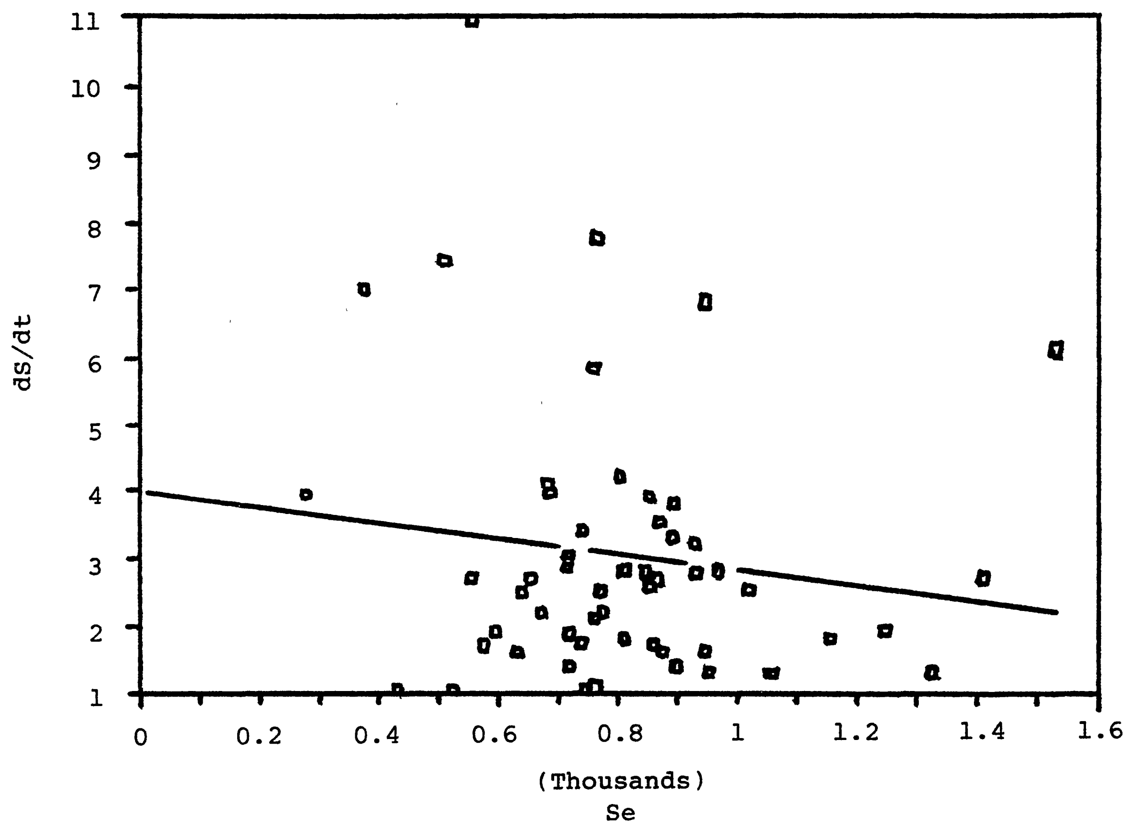


Figure 27. Regression of the McKinney Effluent Substrate Model

TABLE XXIV

SIMPLE LINEAR REGRESSION OF THE MCKINNEY LIMITING SOLIDS MODEL

NO.	X VALUE Xt	Y VALUE F/(Si-Se)/V	NO.	X VALUE	Y VALUE
1	800	930.8	46	4620	889.7
2	580	518.3	47	3920	376.4
3	600	856.8	48	3900	1407.9
4	860	925.0	49	2960	1528.5
5	1060	802.7	50	2920	765.1
6	848	945.2	51	3240	1017.5
7	900	851.7	52	1940	968.1
8	680	718.4	53	6280	681.3
9	1060	557.3	54	5860	948.6
10	1080	678.1	55	7800	808.4
11	1640	857.5	56	6760	854.7
12	1760	629.7	57	5760	745.8
13	1340	1055.5			
14	1000	873.4		57 = N	
15	1260	842.4		133748 = SUM OF X	
16	1580	716.0		46214.8 = SUM OF Y	
17	1280	895.2		4.5E+08 = SUM OF X^2	
18	1880	571.5		40220513 = SUM OF Y^2	
19	1560	689.7		1.1E+08 = SUM OF X*Y	
20	1980	510.2		2346.5 = X MEAN	
21	2720	888.7		810.8 = Y MEAN	
22	1780	715.8		0.0059 = SLOPE	
23	1980	1246.2		796.93 = INTERCEPT	
24	1660	1153.4		0.04153 = R	
25	2140	554.0		0.00172 = R^2	
26	2140	428.5		223.421 = SD	
27	1500	1321.7		49917.0 = STAND VAR	
28	1620	671.9			
29	2160	594.4			
30	2160	713.3			
31	2100	942.6			
32	2020	737.7			
33	2180	650.9			
34	2320	755.7			
35	2380	638.4			
36	2420	769.7			
37	2380	761.1			
38	3000	523.6			
39	2480	736.1			
40	2820	929.8			
41	2780	767.2			
42	2020	866.5			
43	2060	864.3			
44	2080	806.0			
45	1140	760.0			

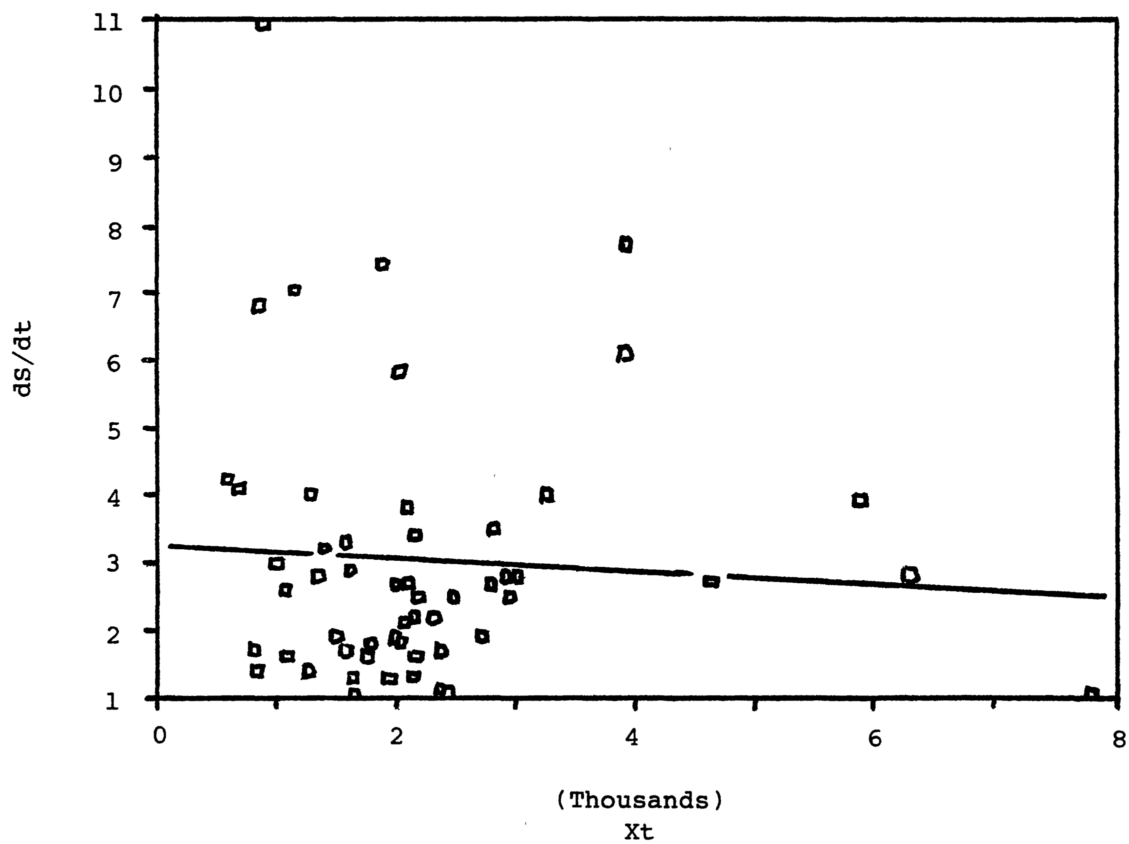


Figure 28. Regression Plot of the McKinney Limiting Volatile Solids Model

TABLE XXV

SIMPLE LINEAR REGRESSION OF THE YIELD AND ENDOGENOUS TERMS

NO.	X VALUE F*(Si-Se)/XT/V	Y VALUE 1/SRT	NO.	X VALUE	Y VALUE
1	1.164	0.667	46	0.193	0.067
2	0.894	0.667	47	0.096	0.067
3	1.428	0.5	48	0.361	0.067
4	1.076	0.5	49	0.516	0.067
5	0.757	0.5	50	0.262	0.067
6	1.115	0.5	51	0.314	0.067
7	0.946	0.5	52	0.499	0.067
8	1.056	0.5	53	0.108	0.05
9	0.526	0.5	54	0.162	0.05
10	0.628	0.333	55	0.104	0.05
11	0.523	0.333	56	0.126	0.05
12	0.358	0.333	57	0.129	0.05
13	0.788	0.333			
14	0.873	0.333		57 = N	
15	0.669	0.333		27.56 = SUM OF X	
16	0.453	0.333		12.59 = SUM OF Y	
17	0.699	0.333		18.52 = SUM OF X^2	
18	0.304	0.200		4.294 = SUM OF Y^2	
19	0.442	0.200		8.383 = SUM OF X*Y	
20	0.258	0.200		0.484 = X MEAN	
21	0.327	0.200		0.220 = Y MEAN	
22	0.402	0.200		0.4420 = SLOPE	
23	0.629	0.200		0.0072 = INTERCEPT	
24	0.695	0.200		0.81876 = R	
25	0.259	0.200		0.670368 = R^2	
26	0.200	0.200		0.09521 = SD	
27	0.881	0.200		0.00906 = STAND VAR	
28	0.415	0.200			
29	0.275	0.143			
30	0.330	0.143			
31	0.449	0.143			
32	0.365	0.143			
33	0.299	0.143			
34	0.326	0.143			
35	0.268	0.143			
36	0.318	0.143			
37	0.320	0.143			
38	0.175	0.111			
39	0.297	0.111			
40	0.330	0.111			
41	0.276	0.111			
42	0.429	0.111			
43	0.420	0.111			
44	0.388	0.111			
45	0.667	0.111			

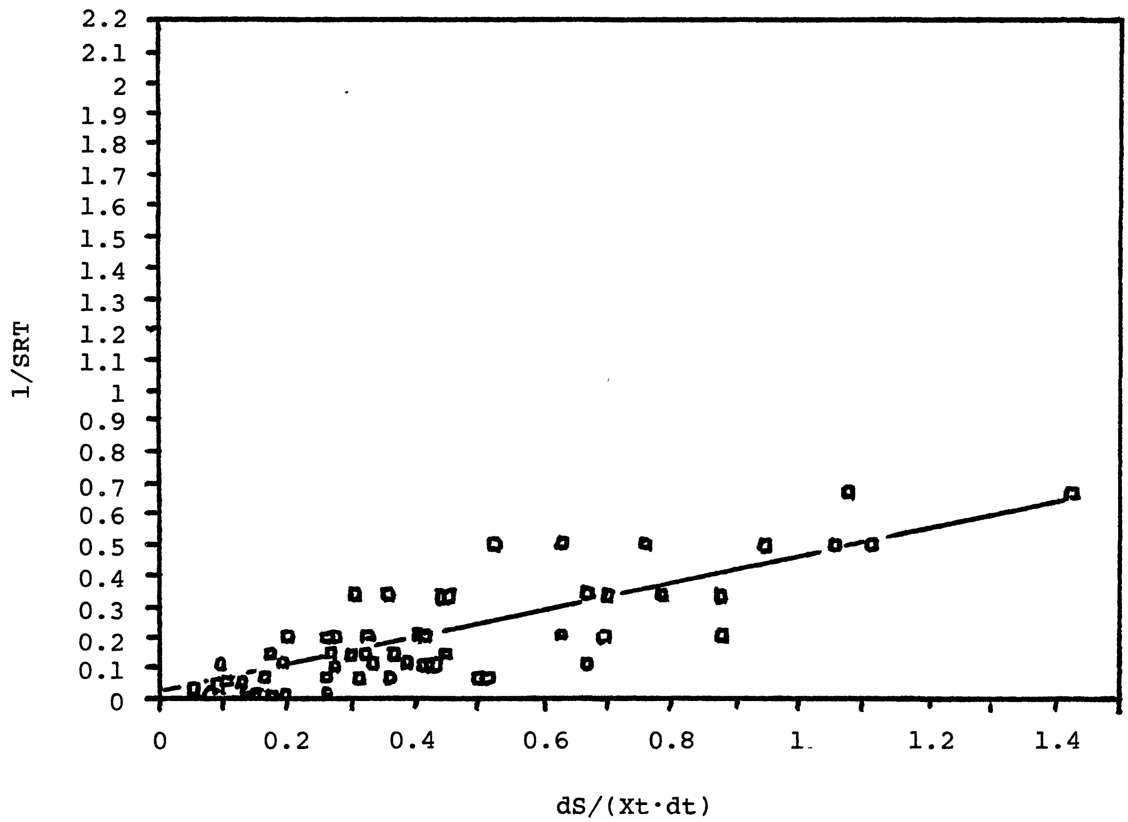


Figure 29. Regression Plot to Determine the Yield and Endogenous Factor

VITA 2

Laurence Gene Lee

Candidate for the Degree of

Doctor of Philosophy

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