THE EFFECT OF FOOD:MICROORGANISM RATIO AND SLUDGE RESIDENCE TIME IN OPERATING AND CONTROLLING AN ACTIVATED SLUDGE PROCESS

By

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LIST OF SYMBOLS

SRT	sludge residence time θ_c
F:M	food:microorganism ratio $= \frac{(\text{Lbs}\cdot\text{BOD})}{(\text{Lbs.MLVSS})\ \text{day}}$
S_i	influent soluble substrate concentration (mg/ℓ)
S_e	effluent soluble substrate concentration (mg/ℓ)
X	mixed liquor volatile suspended solids concentration just before wasting mg/ℓ
X_o	mixed liquor volatile suspended solids concentration just after wasting mg/ℓ
X_{av}	average mixed liquor volatile suspended solids concentration mg/ℓ
X_e	effluent volatile suspended solids concentration mg/ℓ
U	Specific substrate utilization rate
Y_t	true yield
K_d	decay coefficient
K_e	Eckenfelder's original model coefficient
K_e'	Eckenfelder's modified model coefficient
R_r	oxygen utilization per unit time
a'	fraction of substrate used for oxidation
b'	fraction per unit time of suspended solids oxidized
V	volume of aeration tank
F	design flow rate ℓ/d
F_w	solids wastage flow rate
K	maximum rate of waste utilization
K_s	waste concentration at which the rate of waste utilization is one-half the maximum rate

K_m	McKinny's substrate removal rate
K_s	saturation constant
U_{max}	Maximum cell growth rate
K_B	Substrate loading at which the rate of substrate utilization is one-half the maximum rate
$\frac{FS_i}{xv}$	organic loading or F:M ratio.

CHAPTER I

INTRODUCTION

Activated sludge is a well-known and flexible process employed in municipal and industrial wastewater treatment for removal of organic matter.

Studies by Angus Smith in 1882 have caused the activated sludge process to become the most widely used process for biological treatment of wastewaters. Studies carried out showed activated sludge to be a promising and more economical treatment alternative to physiochemical treatment processes. It has been known to even remove priority pollutants and other normally toxic materials from wastewaters. Probably due to these and the stringent control on pollution of natural resources, the activated sludge system has come a long way.

Modern approaches to design of activated sludge processes employ mathematical process models depicting the relationships among factors affecting the kinetics of wastewater purification. Each model contains biokinetic constants that are usually determined from biological treatability studies. It has generally been assumed that the biokinetic constants are true constants. Most models are developed by writing material balances describing the mass rate of change in substrate and in biomass. Describing mathematically these two functions is where the various design models differ.

A great deal of scatter of the data has been found with several of the models. However, a model developed by Kincannon and Stover (17) has very little data scatter. This model is based upon the concept that substrate utilization is a function of the Food:Microorganism ratio (F:M).

The purpose of this research was to determine whether or not an activated sludge process operated by controlling the F:M would operate under a more pure steady state than when operated by controlling the SRT.

CHAPTER II

LITERATURE REVIEW

Activated sludge is the name used to describe an aerobic biochemical operation which uses a flocculent microbial slurry to remove soluble and colloidal organic matter. Before a fundamental theory of activated sludge kinetics was developed, design was generally based upon empirical guide lines adopted as standard (1). Since the activated sludge process was incepted by Arden and Lockett (2) in 1914, the activated sludge process has grown in popularity until today it is the biochemical operation most widely used in wastewater treatment. During that time it has undergone much experimentation and modification so that today a number of variations are in use.

With the exception of extended aeration activated sludge, the primary objective of the activated process is the removal of soluble organic matter.

The majority of work on model verification has been performed on the simple soluble substrate model. Herbert and his colleagues (3, 7, 8) were instrumental in the verification of the theory for pure microbial cultures so that today the studies performed using the theory are too numerous to mention.

Several studies are of particular importance, however, because they represent refinements of the basic models as originally presented. Within the field of wastewater treatment, the validity of the trends predicted by the model has been established through the efforts of many researchers. Those efforts were organized and summarized by Lawrence and McCarty (9) into a unified concept which put biochemical operation design on a rational basis. Lawrence and McCarty's model also assumes that the specific substrate utilization rate is a function of the effluent substrate concentration.

Eckenfelder's (6) original model assumes that the specific substrate utilization rate (u) is a function of the effluent substrate concentration. McKinney's model (33) is identical to Eckenfelder's original model. The work of Chiu, Fan, Kao, and Erickson (10) demonstrated good coorelation between predicted and observed results with a model of this general form even through significant shifts in microbial predominance (11).

Further, the work of Jorden, Pohland, and Kornegay (12), Chiu, Fan, Kao, and Erickson (13), and Kormanik (14) have demonstrated the applicability of the general equations to actual wastewaters. Gaudy and Gaudy (15) have made a valuable point concerning the verification of kinetic equations. Gaudy's model (15) relates substrate removal directly to specific growth rate by use of the Monod relationship. Chapter 7 of the design manual published by the Bioenvironmental Engineering Department of Oklahoma State University (17) provides an excellent in-depth comparison of the various kinetic models, and is highly recommended for the interested reader.

For a number of years, the food:microorganism ratio (F:M) has been used. McKinney (18) developed the concept of F:M ratio as a control parameter. McKinney verified the use of the F:M ratio and a first order kinetic model for growth and organic removal in studies on an activated sludge process treating municipal wastewaters and on data from 17 pure oxygen pilot plant studies. Sherrard and Kincannon (21) and Sherrard et al. (22) discussed the implications of currently used process models on the operation of activated sludge systems.

Comparison of solid retention time (SRT) and food:microorganisms (F:M) ratio as design parameters was investigated by Stensel and Shell (19). Both approaches gave similar results, although (SRT) allowed the prediction of stoichiometric quantities such as oxygen uptake. In addition, (SRT) was directly transferrable to nitrification and denitrification processes, while the F:M ratio was not.

Theoretical stoichiometric and rate constants were developed by Hultman (23) and Sykes (24). Christensen and McCarty (25) used a similar approach in developing a design model for a wide range of biological processes. The purpose of this model is to show the design engineer to compare processes. Gagnon, Grandall, and Zanoni (26) utilized daily operation data from a large-scale activated sludge plant to evaluate the relationship between process efficiency and several selected loading parameters. However, efficiency of BOD removal increased as F:M values increased from 0.1 to 0.7.

Sherrard (27) related θ_c or (SRT) to various empirical parameters and formulations used in design of activated sludge systems. Relationships between (SRT), food:microorganism (F:M) ratio and volumetric organic loading were shown through the use of an example problem. The concept of hydraulic control of θ_c values for activated sludge suspensions was expanded by Koper and Grady (28) to include consideration of wastage of suspended matter in a secondary clarifier effluent. Stall and Sherrard (20) evaluated the use of numerous control parameters including F:M ratio and total system sludge age.

Benedict, Merrill, and Mauseth (30) offered a new methodology for predicting sludge production from the activated sludge process. The technique illustrated the interaction between waste composition solids retention time (SRT) and applied loading rates. Siber and Eckenfelder (31) performed a laboratory study on a multicomponent substrate and showed that the overall total organic carbon (TOC) removal rate was the sum of individual specific removal rates. Effluent quality measured as (TOC) was related to the food:microorganism (F:M) ratio and a sludge age (SRT).

Kincannon and Stover (32) assume that the specific substrate utilization rate is a function of the mass loading per mass of microorganisms (F:M) rather than the substrate concentration alone with the other models. A lot of rationalization is required to determine the respective biokinetic coefficient due to the large scatter of data points when plotted for each model. When the specific substrate utilization rate is plotted as a function of the total organic loading or (F:M) ratio, a relationship is established with very little scatter (34). Kincannon and Stover (34, 35) have recently introduced a kinetic model that eliminates the variability of the biological response to the wastewater being treated which exists with the other models.

A relationship between the specific substrate removal rate and the specific organic loading provides very little scatter of the data. In fact, this scatter suggests that the substrate removal rate may not be the best parameter for relating substrate removal (34).

CHAPTER III

MATERIALS AND METHODS

General Research Approach

To study the effects of food:microorganism loading ratio and mean cell residence time on the activated sludge system two bench-scale activated sludge reactors were operated.

These two bench-scale units were completely mixed continuous flow bioreactors operated in parallel under steady-state conditions. The activated sludge systems were operated at mean cell residence time (SRT) of 3,6 and 10 days, and food:microorganism loading ratio (F:M) of 0.3, 0.5, and 0.75.

Activated sludge for initial seeding was obtained from a local municipal activated sludge wastewater treatment plant. For (SRT) and (F:M) loading ratio, two individual systems were acclimated to the synthetic wastewater.

A diagram of the bench-scale activated sludge pilot plant used is presented in Figure 1.

Description of Pilot Plants

The reactors were constructed of clear plexiglass, each contained both an aeration section and internal clarifier. The aeration and settling compartments were separated by an adjustable plexiglass baffle.

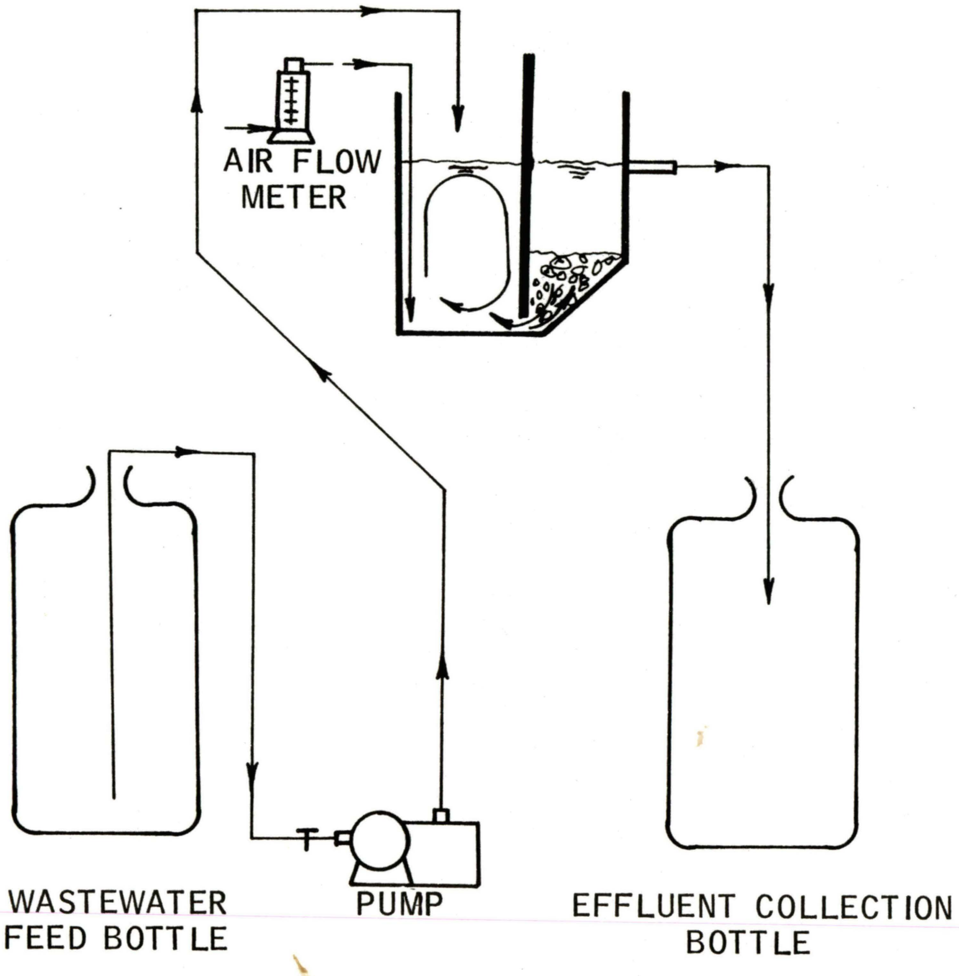

Figure 1. Experimental Activated Sludge Reactor

The volume of each aeration basin was 2.85 filters.

Air was supplied to the aeration chamber through two fine bubble diffusers. The air flow was regulated with a Gelman air flow meter to provide an adequate dissolved oxygen level in the aeration chamber.

Positive displacement pumps were used to provide a continuous feed flow to the system. Plastic tubing was used for both the suction and delivery side of the feed pump. To prevent bacterial growth, the feed lines, feed bottles, and the effluent bottles were cleaned with chlorox and rinsed out several times with tap water every time the feed was made up. The effluent flowed by gravity from the settling chamber from each reactor to two collection bottles.

Synthetic Wastewater

Stock solutions were made and mixed in a 25 liter capacity bottle and the mixture diluted to 20 liters with tap water. The constituents of the complex wastewater included "sego," NH_4 SO_4 and H_3 PO_4.

The ingredients listed on the "sego" label included concentrated skimmed milk, sugar, vegetable oils, edible cellulose, magnesium sulfate, artificial flavor, salt, cellulose gum, magnesium oxide, sodium ascorbate (Vitamin C), ferric orthophosphate, carrageenan, atocopherylacetate (Vitamin E), niacinamide, zincoxide, copper gluconate, calcium pantothenate, Vitamin A plamitate, pyridexine hydrochloride (Vitamin B_6), riboflavin phosphate (Vitamin B_2), thiamin hydrochloride (Vitamin B_1), folic acid, biotin, potassium iodide, Vitamin D_3, and Vitamin B_{12}.

According to the nutritional information given by the manufacturer, a ten-ounce (295.7 mℓ) can of "sego" contains eleven grams of protein, 34 grams of carbohydrate, and five grams of fat.

A volume of 1.5 mℓ of "sego" was dissolved in one liter of tap water to form the complex wastewater which produced 100-135 mg/ℓ BOD. In addition to 1.5 mℓ/ℓ of sego as carbon source, 0.047 g of nitrogen as $NH_4\ SO_4$, 0.0025 mℓ of phosphorous as $H_3\ PO_4$ were added to one liter of tap water.

The feed was prepared once every day. The pH of the fresh feed and mixed liquor were checked and adjusted if required. The pH of the systems was maintained at a range of 6.8 to 7.5. A pump was used to deliver the synthetic feed from the feed bottle into the aeration chambers. The pump was regulated to deliver a flow at a continuous rate of 6 mℓ/minute for each reactor. The flow rate was measured regularly to ensure a constant flow rate. By controlling the flow rate, the hydraulic detention time in the aeration chambers was maintained at eight hours throughout the study.

Operation of Pilot Plant

The sludge age (SRT) and food:microorganism ratio (F:M) within each reactor were controlled by controlling the rate of wastage. Sludge wasting was made once a day directly from the aeration chambers. At about the same time everyday the MLVSS were measured just before and immediately after wasting. A volume of the effluent was used to replace the sludge volume wasted from the aeration chambers so that the level of mixed liquor in the aeration chambers was maintained.

The mean cell residence time is defined as the total activated microbial mass in the treatment sludge (XT) divided by the total active microbial mass wasted daily $\left(\frac{\Delta x}{\Delta\ r}\right)_t$. The equation for calculation of (SRT) for activated sludge is

$$SRT = \frac{VX}{F_w X_r + (F - F_w) X_e} \qquad \text{Equation (1)}$$

The sludge waste flow rate was calculated by rearranging Equation (1) as follows:

$$F_w = \frac{\frac{VX}{SRT} - FX_e}{X_r - X_e} \qquad \text{Equation (2)}$$

where

SRT = sludge age (days)

V = the reactor volume (liters)

X = mixed liquor suspended solids (mg/ℓ)

F_w = wastage rate (ℓ/day)

F = influent flow rate wastewater (ℓ/d)

X_e = solid concentration in the effluent (mg/ℓ)

X_r = solid concentration for the return sludge = (x) mixed liquor solid concentration (mg/ℓ)

The sludge food:microorganism ratio is defined as follows:

$$F{:}M = \frac{FS_i}{VX} \qquad \text{Equation (3)}$$

The daily sludge wastage was calculated using:

$$F_w = \frac{V (X_{24} - X_o)}{X_{24}} \qquad \text{Equation (4)}$$

The target X_o was calculated using the expression

$$X_o = 2 X_a - X_{24} \qquad \text{Equation (5)}$$

where

F_w = wastage rate (ℓ/day)

V = the reactor volume (ℓ)

X_{24} = mixed liquor suspended solids before wasting (mg/ℓ)

X_o = mixed liquor suspended solids after wasting (mg/ℓ)

X_a = mixed liquor average suspended solids that is required in the aeration chamber to maintain the required F:M ratio (mg/ℓ).

The system was allowed to acclimate for four weeks before collecting any data. During the study, at times the MLVSS in the reactor dropped below the desired level, sludge wasting was stopped, and the solids were allowed to build up to the desired level again.

Analytical Technique

The analyses employed for determining the experimental data consisted of biochemical oxygen demands (BOD_5), suspended solids (SS), Volatile Solids (VSS), pH, oxygen uptake, and temperature. Table 1 shows the analytical techniques used in these investigations.

TABLE I

ANALYTICAL TECHNIQUES USED IN THESE INVESTIGATIONS

Type of Test	Frequency	Method	Source
Suspended solids (SS)			
a - before wasting	daily	glass fiber 934-AH	Standard Methods (62)
b - after wasting	daily	glass fiber 934-AH	
Volatile suspended solids (VSS)			
a - before wasting	daily	glass fiber 934-AH	Standard Methods (62)
b - after wasting	daily	glass fiber 934-AH	
BOD	daily		Standard Methods
Oxygen uptake rate	daily	Orion Research Model Probe, reduction of Oxygen concentration monitored with time	
pH			
a - feed	daily	pH Probe	
b - mixed liquor	daily		
Temperature	daily	Temperature Probe	

CHAPTER IV

RESULTS

General

Two activated sludge reactors were operated, one based on food: microorganism ratio and the other on the sludge residence time. The reactors were started with the same activated sludge under the same conditions, and with the same feed.

This study was based on three phases

Phase (1) SRT = 10 days and F:M = 0.3 $\frac{(\text{Lbs}\cdot\text{BOD})}{(\text{Lbs.MLVSS})\text{ days}}$

Phase (2) SRT = 6 days and F:M = 0.5 $\frac{(\text{Lbs.Bod})}{(\text{Lbs.MLVSS})\text{ days}}$

Phase (3) SRT = 3 days and F:M = 0.75 $\frac{(\text{LBS.BOD})}{(\text{LBS.MLVSS})\text{ days}}$

By controlling the amount of solid wasted from each reactor in each phase, the phases were controlled. The flow rates through both reactors were 6 mℓ/min and this maintained the detention time at 8 hours.

$$\text{for SRT} = \frac{XV}{F_w + (F - F_w)X_e} = \text{days} \qquad \text{Equation (1)}$$

the solids wastage flow rate (ℓ/d)

$$F_w = \frac{\frac{VX}{SRT} - F_{Xe}}{X - X_e} \qquad \text{Equation (2)}$$

$$\text{for F:M} = \frac{S_i F}{XV} = \frac{(\text{Lbs}\cdot\text{BOD})}{(\text{Lbs}\cdot\text{MLVSS})\text{ day}} \qquad \text{Equation (3)}$$

$$\text{for } F{:}M = \frac{S_i F}{XV} = \frac{(\text{Lbs}\cdot\text{BOD})}{(\text{Lbs.MLVSS})\ \text{day}} \qquad \text{Equation (3)}$$

the solids wastage flow rate ℓ/d

$$F_w = \frac{V\ (X_{24} - X_o)}{X_{24}} \qquad \text{Equation (4)}$$

Phase (1) SRT = 10 days; F:M = 0.3

Both reactors were started with solids concentration equal to 1200 mg/ℓ, so they were under the same conditions. The reactors had only one feed bottle (Figure 1) with average influent BOD_5 concentration of 125 mg/ℓ (Figures 2, 3, 4, 5, 6). No pH adjustment was required after the feed was made up; it was in the range between 7.0 and 7.3 (Figure 3-c).

The sludge flocculated quite well and settling in the clarifier was very good, producing a quite clear effluent with average suspended solids concentration of 30 mg/ℓ (Figure 4, 5, 6 and Figure 7-a). For only one day the solids did not flocculate well and therefore did not settle well in the clarifier. The result was an increase in the suspended solids concentration in the effluent to about 60 mg/ℓ. Overall, the golden-brown colored sludge compacted well in the clarifier and recycled well. The baffles openings were about 3/4 inch and this enabled a good recycle sludge.

The substrate removal efficiency was about 99% (Figure 2-c and 5-c) with average effluent BOD_5 concentration of 1.5 mg/ℓ (Figures 2-a and 5-a).

For food:microorganism ratio (F:M), the mixed liquor average suspended solids concentration was 1080 mg/ℓ (Figures 4, 5, 6) so the F:M ratio was about 0.3 to 0.34 (Figure 4-a).

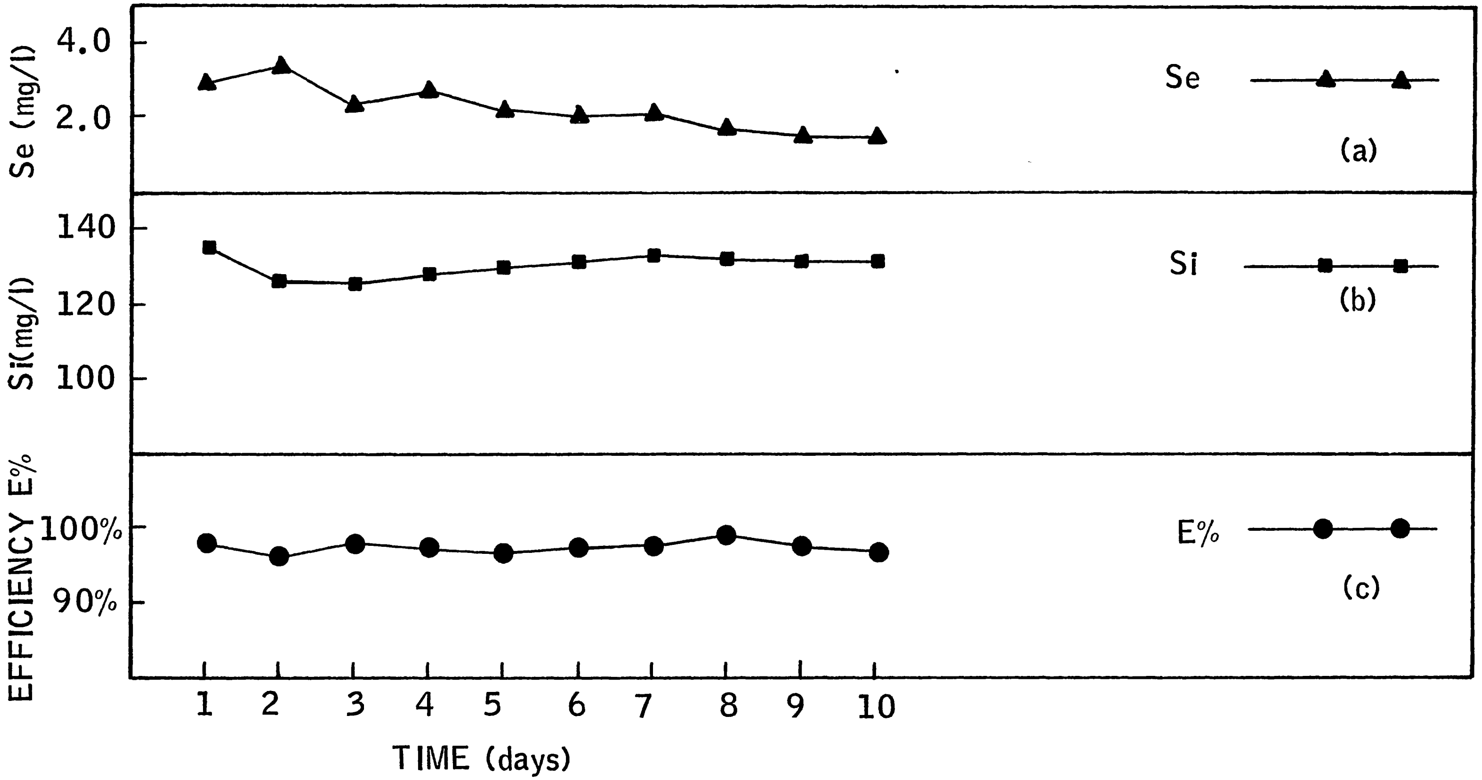

Figure 2. Some Parameters Monitored with Time at F:M Loading Ratio of 0.3
E% S_i S_e

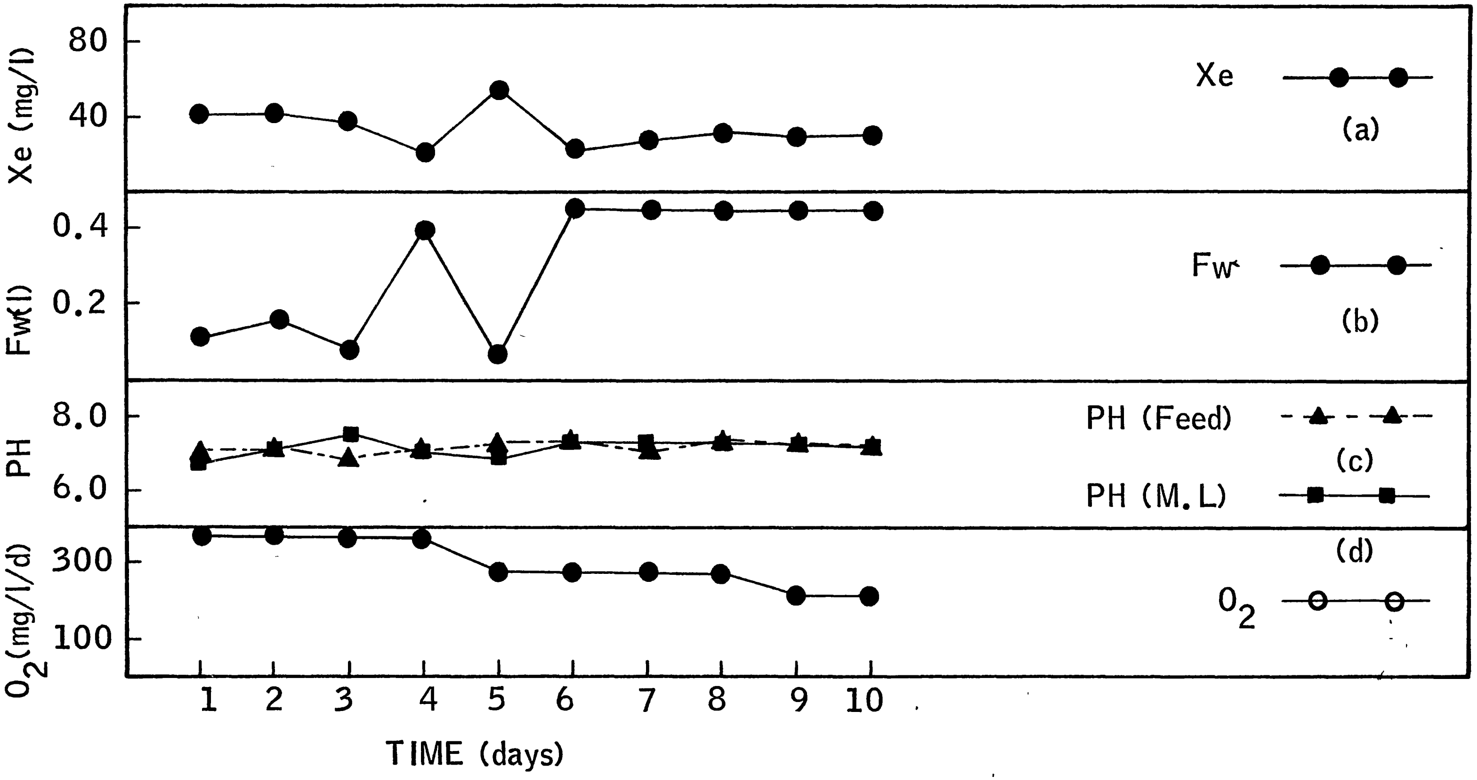

Figure 3. Some Parameters Monitored with Time at F:M Loading Ratio of 0.3
O_2, pH, F_w, X_e

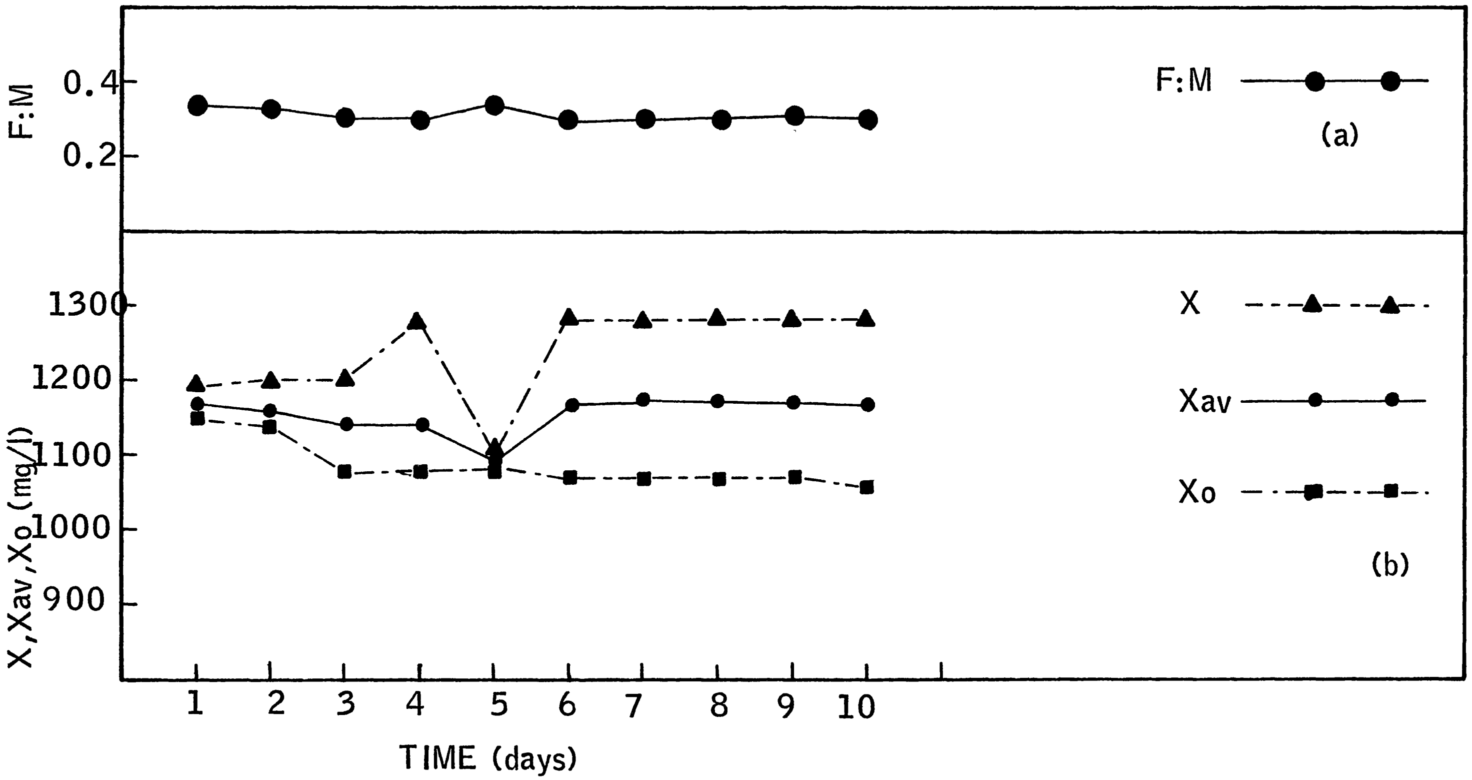

Figure 4. Some Parameters Monitored with Time at F:M Loading Ratio of 0.3
X, X_{av}, X_o

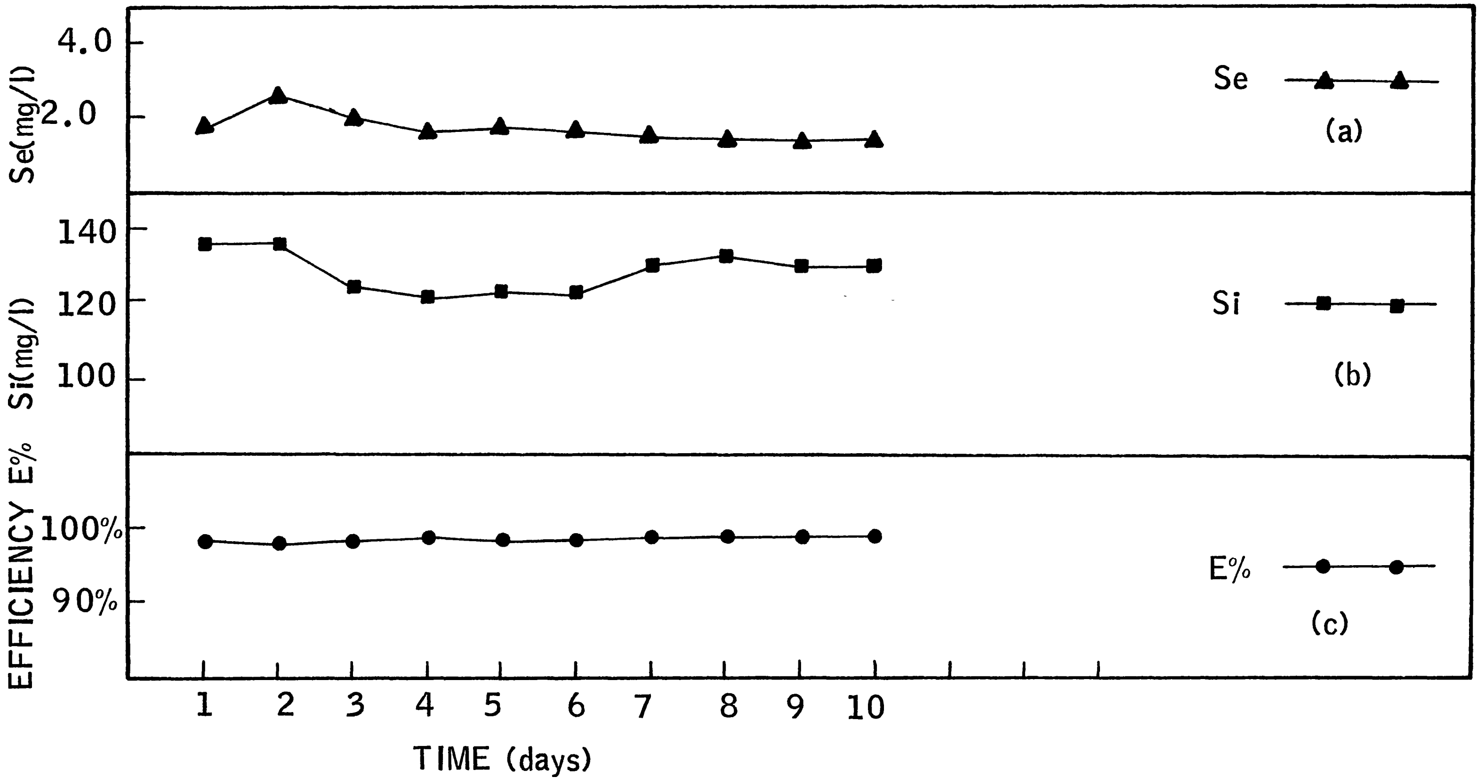

Figure 5. Some Parameters Monitored with Time at SRT = 10 days E% S_i S_e

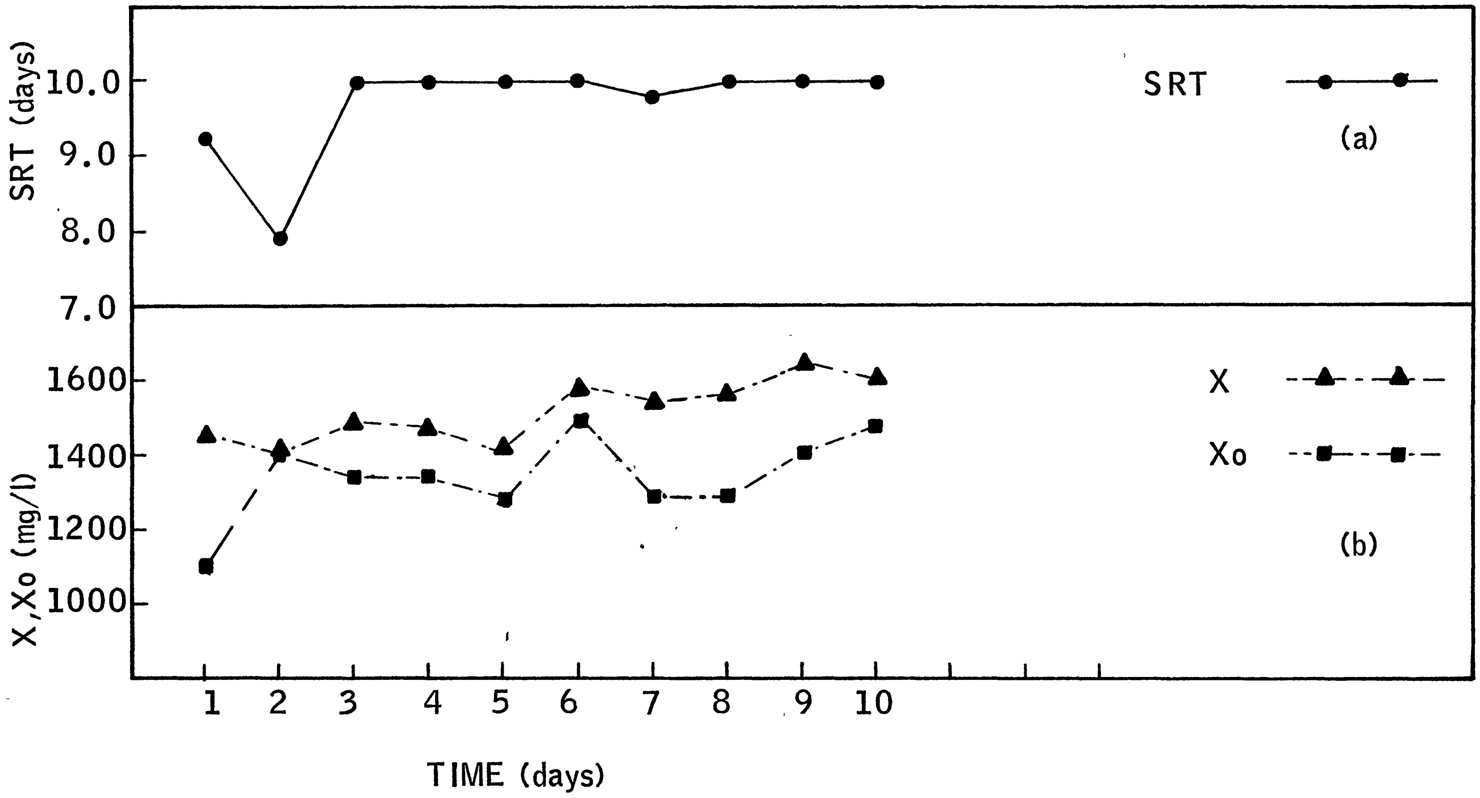

Figure 6. Some Parameters Monitored with Time at SRT = 10 days X, X_o

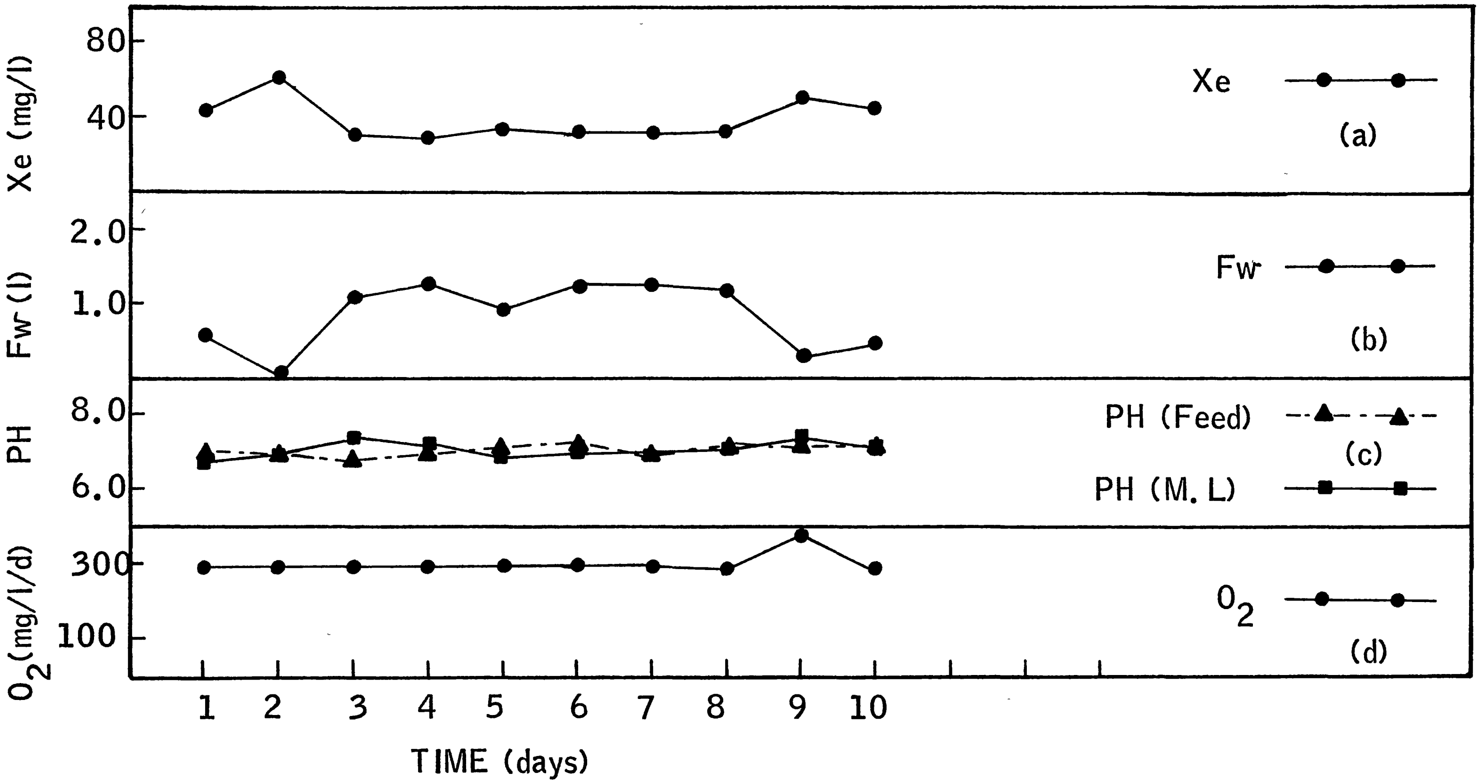

Figure 7. Some Parameters Monitored with Time at SRT = 10 days O_2, pH, F_w, X_e

To control (F:M) ratio the average amount of solids that were wasted from the reactor daily was 0.45 ℓ, dropped sometimes to 0.1ℓ when the system was losing solids (Figures 3, 4, 5, 6). The pH throughout the reactor was usually equal to 7.3 (Figure 3-c).

For sludge residence time (SRT), the mixed liquor suspended solids concentration increased to 1600 mg/ℓ (Figure 6-b). The system was controlled by wasting from the reactor based on Equation (2). The average daily amount of solids wasted was 0.125ℓ (Figure 7-b). The pH inside the reactor was 7.2.

To be sure that the detention time remained constant and equal to eight hours, the flow rate for both the reactors was measured three times per day.

Phase (2) SRT = 6 days; F:M = 0.5

When the amount of wasted sludge was increased to attain the new phase, the mixed liquor solids started to wash-out from the systems. The mixed liquor had changed in color to a white milky color. The clarifiers could not handle the dispersed and non-flocculated solids, and the effluent suspended solids increased.

When this happened, sludge wasting was stopped. The systems were totally upset. The dose of Nitrogen source in the feed was doubled, but the solids continued to wash-out and nothing could be done to correct it.

The reactors, the feed bottles, the effluent bottles, and every thing were cleaned very well with chlorox and rinsed several times with tap water. Fresh sludge was used from the same municipal treatment plant to re-seed the systems.

After running the reactors for three weeks and when the systems were stable, both systems were started with average solid concentration of 800 mg/ℓ. The reactors were started under the same conditions and the data was collected. The average feed BOD_5 concentration was 120 mg/ℓ (Figure 8-b). The feed pH was 7.6 and no pH adjustment was needed (Figure 10-c). It was noticed that the reactor which was controlled by food:microorganism ratio had darker brown color than the one controlled by sludge residence time.

To maintain an F:M ratio of 0.5, the sludge was wasted based on Equation (4). The amount of daily wasted sludge varied from day to day, but the average F:M ratio was 0.48 (Figure 9-a). The reactor's pH was 7.3 (Figure 10-c). The baffle opening was kept at the same height all the time (3/4 inches). The average mixed liqur suspended solids was 800 mg/ℓ (Figure 9-b), and the average effluent suspended solids concentration was 40 mg/ℓ (Figure 10-a).

It was a problem to control the six days sludge retention time. After collecting very good data for one week, the system started to wash-out. When this happened, sludge wasting was stopped and the solids were allowed to build up to the required level again. During the build up period, the SRT dropped to 3 days. To help the system to recover, the baffle opening was lowered to 1/4 inch, and the air flow rate was lowered.

After the system recovered, the settling characteristics improved tremendously and the effluent suspended solid concentration was reduced from 126 mg/ℓ to 20 mg/ℓ and the mixed liquor suspended solids increased to 1500 mg/ℓ. The pH in the reactor was 7.2. The treatment efficiency was 98% (Figure 8-c, 11-c), and the average effluent BOD_5

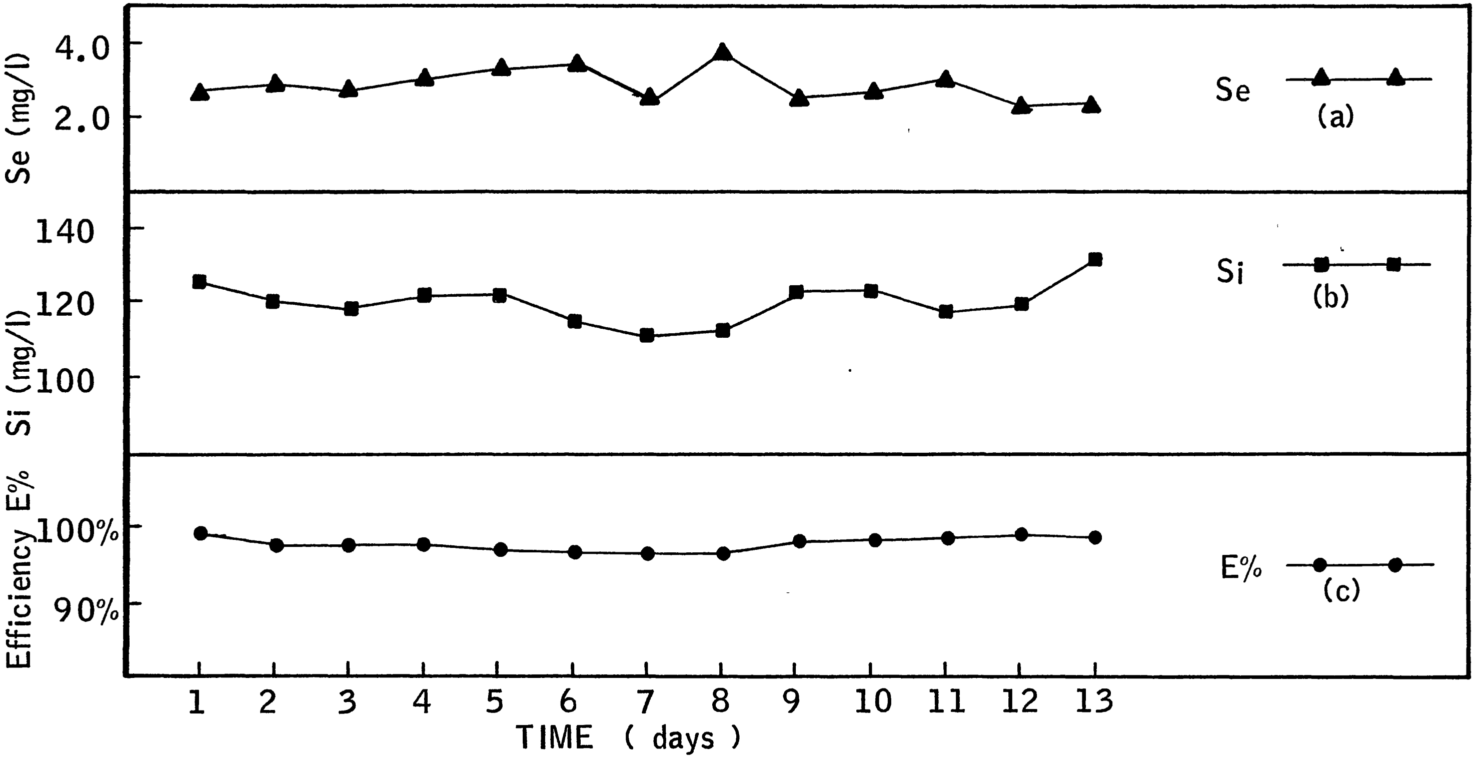

Figure 8. Some Parameters Monitored with Time at F:M Loading Ratio of 0.5

E% S_i S_e

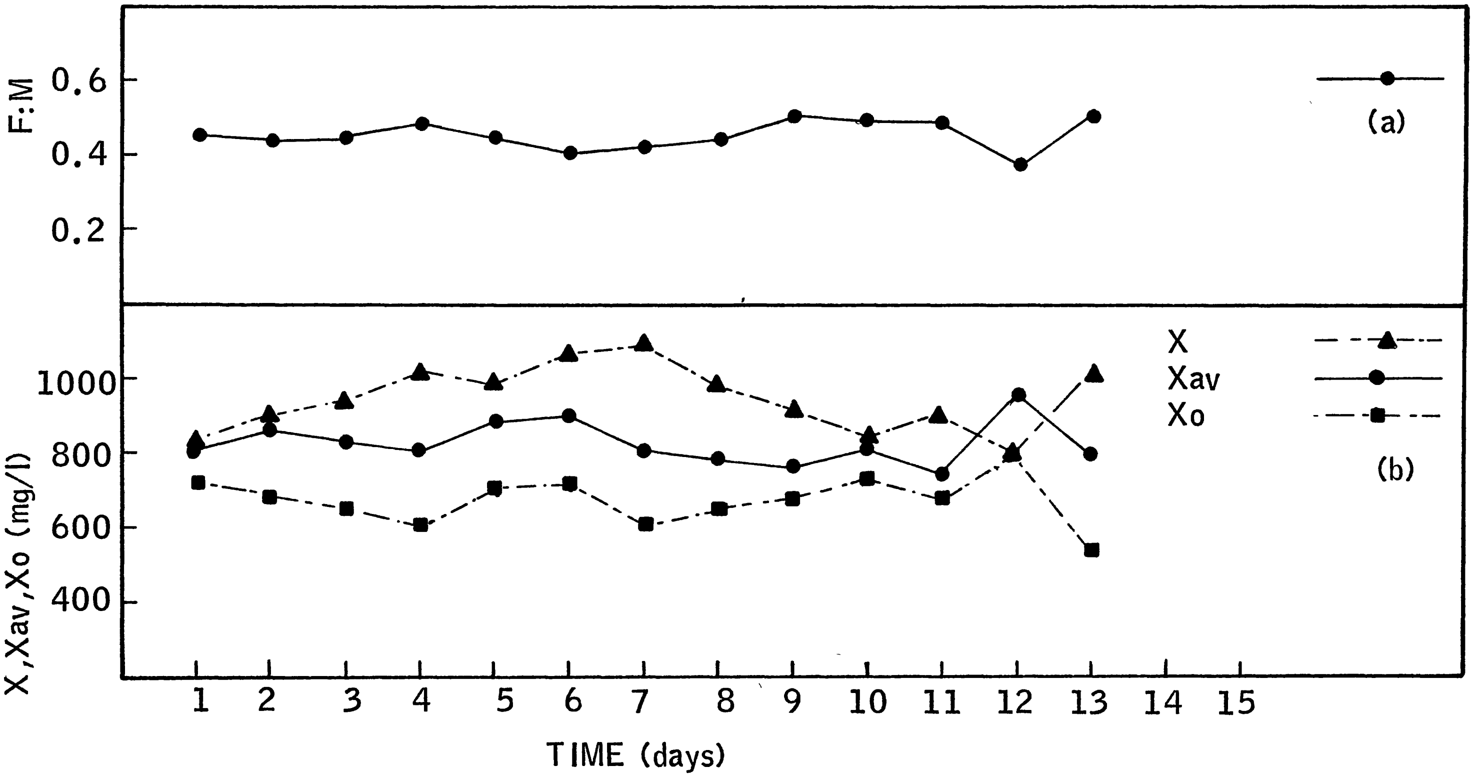

Figure 9. Some Parameters Monitored with Time at F:M Loading Ratio of 0.5

X, X_{av}, X_o

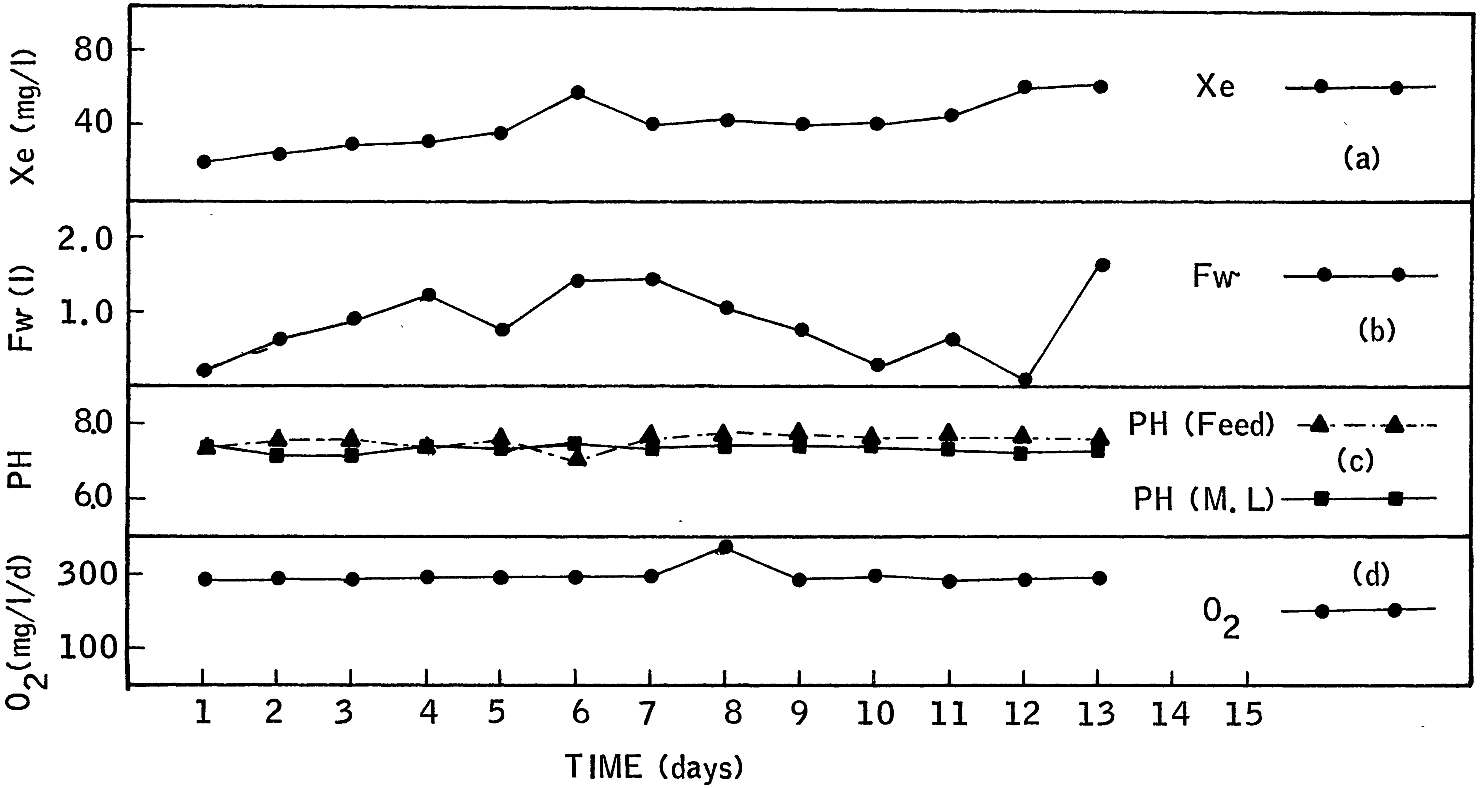

Figure 10. Some Parameters Monitored with Time at F:M Loading Ratio of 0.5
O_2 pH, F_w, X_e

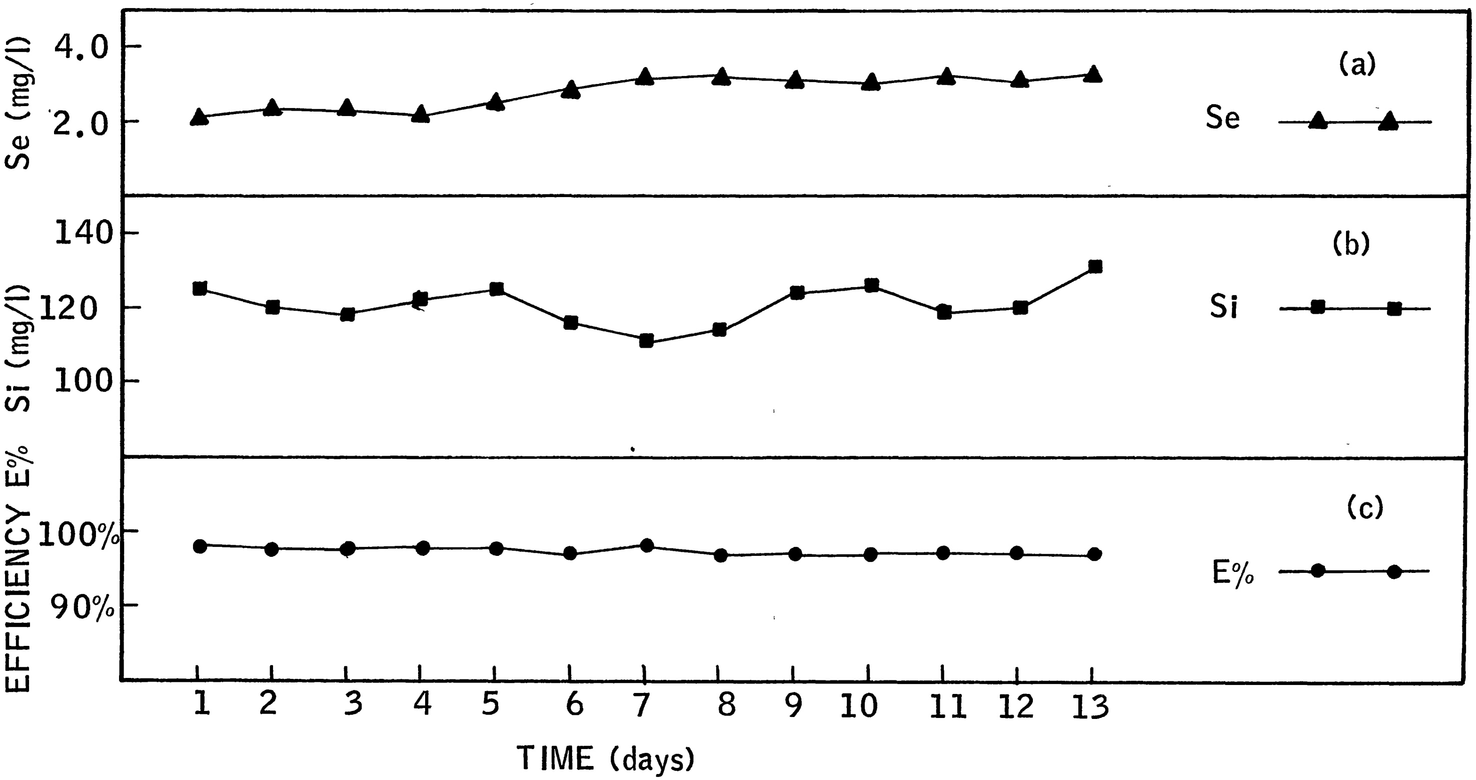

Figure 11. Some Parameters Monitored with Time at SRT = 6.0 days E% S_i S_e

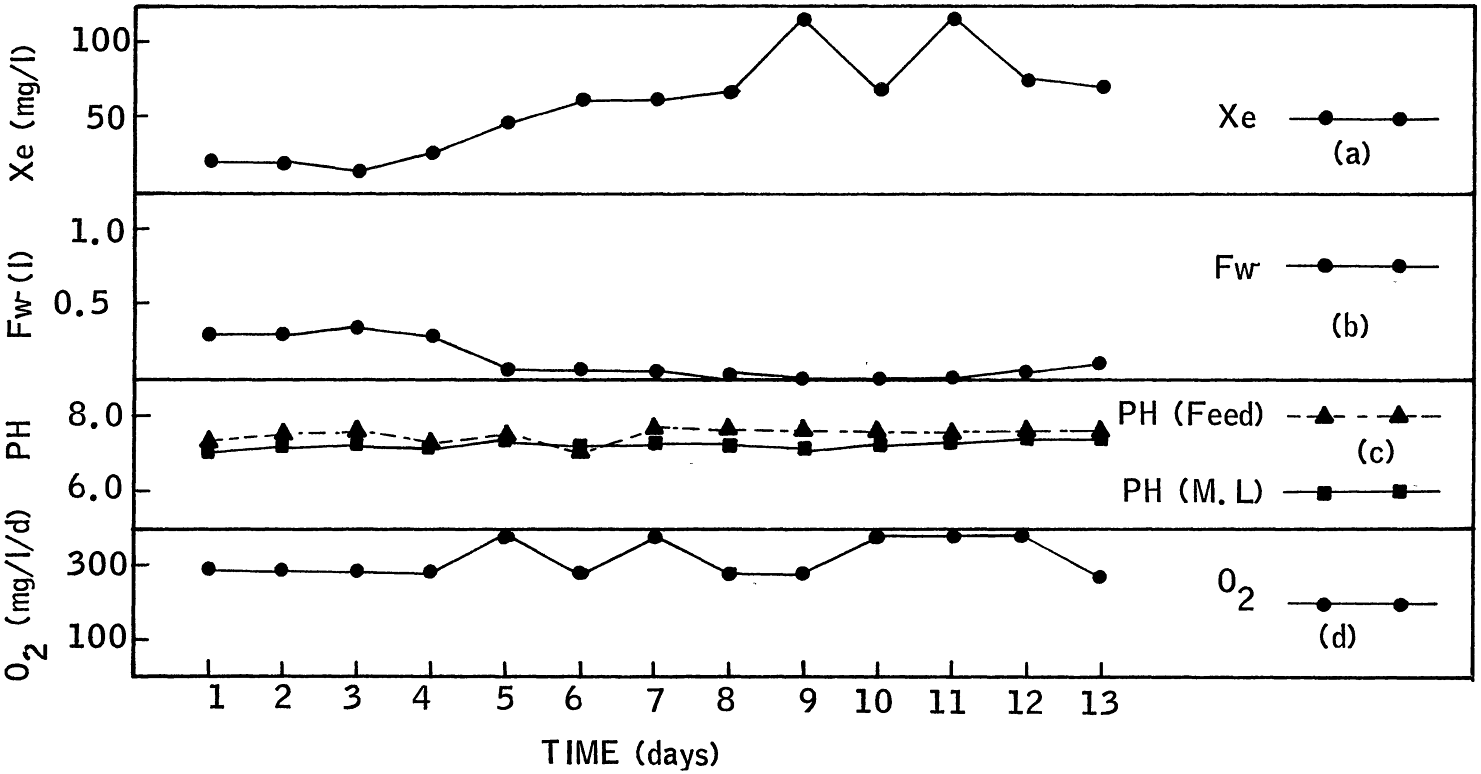

Figure 12. Some Parameters Monitored with Time at SRT = 6.0 days O_2, pH, F_w, X_e

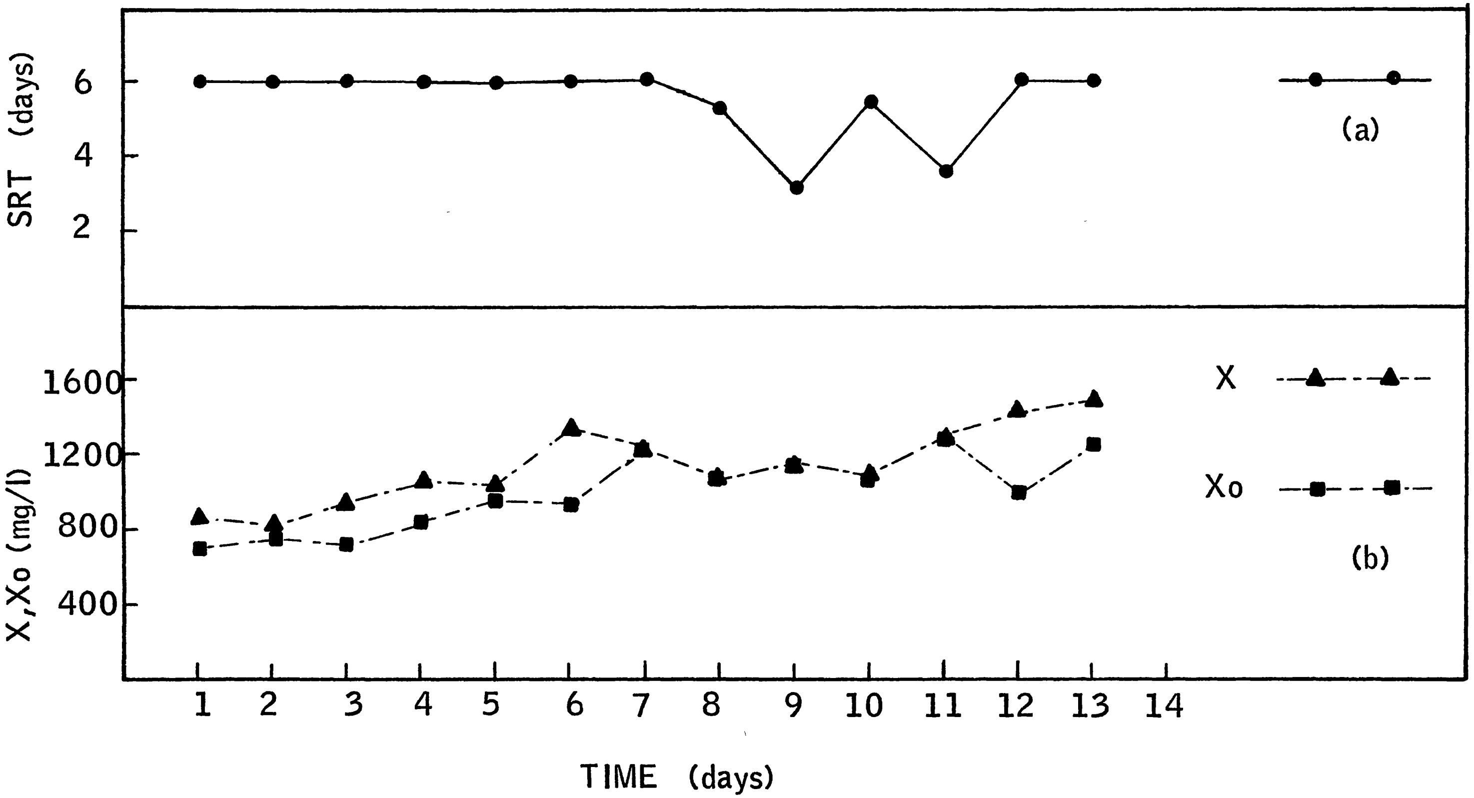

Figure 13. Some Parameters Monitored with Time at SRT = 6.0 days X, X_o

concentration was 2.5 mg/ℓ.

Phase (3) SRT = 3 days; F:M = 0.75

During the transition from phase (2) to phase (3) the system seemed to be trying to prevent a higher loading than it was used to. A tremendous amount of care was needed for this phase. The very fast growth caused dispersed solids which did not flocculate well and therefore did not settle in the clarifiers. The result was an increase in the suspended solids in the effluent to about 250 mg/ℓ. This in turn caused a reduction in the mixed liquor suspended solids, and the system was upset. The mixed liquor had changed in color to a light yellow. A predominance change seemed to have occurred in the reactors during the night when the units were not monitored. Sludge wastage was stopped and the solids were allowed to build up to the required level again.

The systems were allowed to acclimate for four weeks. After the systems were stable, data were collected.

Starting both reactors with mixed liquor suspended solids concentration equal 500 mg/ℓ, the reactors were under the same conditions. The baffles openings were 1/2 inch high all the time. The feed pH was in the range of 7.0 to 7.5, and the average BOD_5 concentration was 125 mg/ℓ.

The treatment efficiency was 97% with average effluent BOD_5 concentration 4.0 mg/ℓ. The effluent suspended solids concentration was about 25 mg/ℓ. After one week the (X_e) increased from 25 mg/ℓ to 175 mg/ℓ and the systems were losing solids. The systems recovered after two weeks and the data were collected.

The average food-microorganism ratio was 0.75 with average mixed

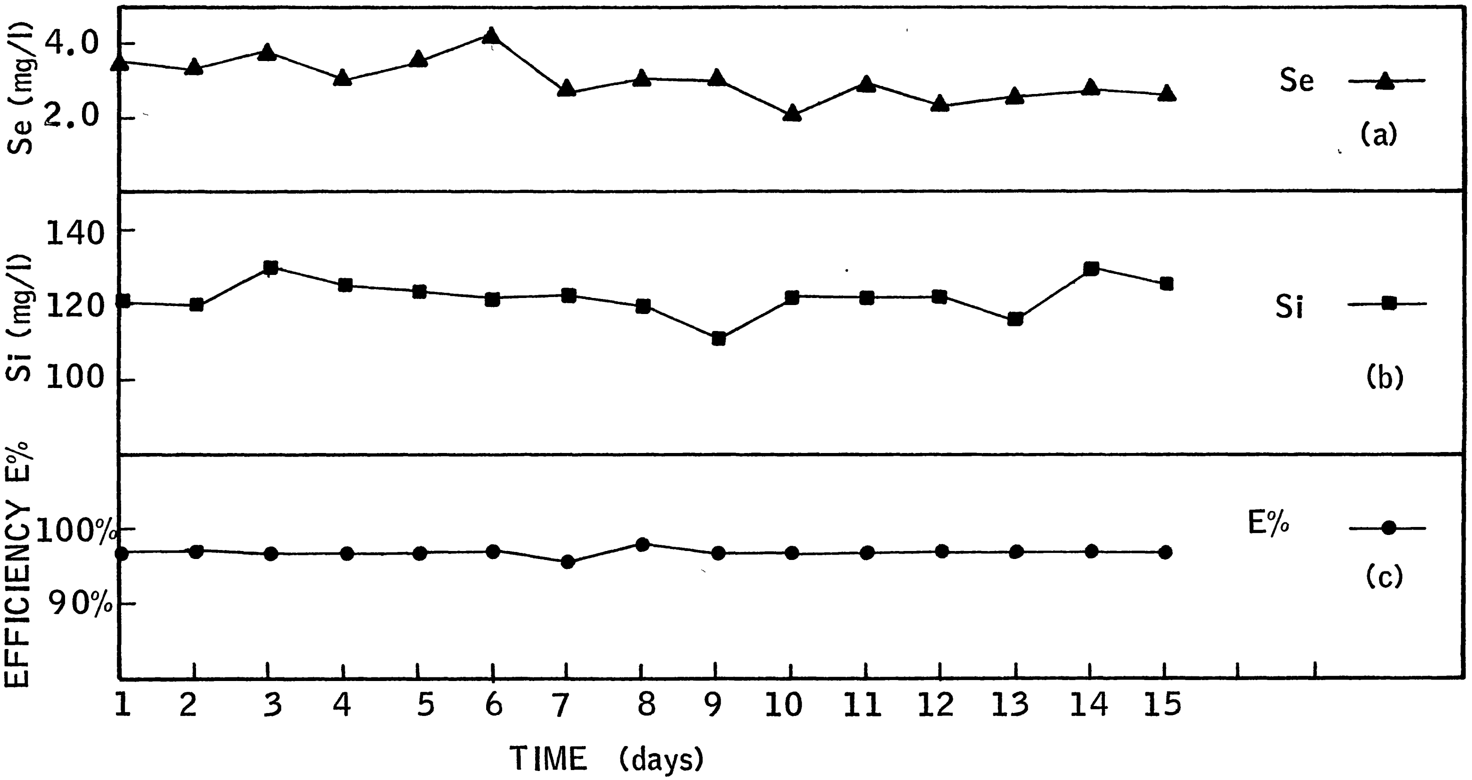

Figure 14. Some Parameters Monitored with Time at F:M Loading Ratio of 0.75
E% S_i S_e

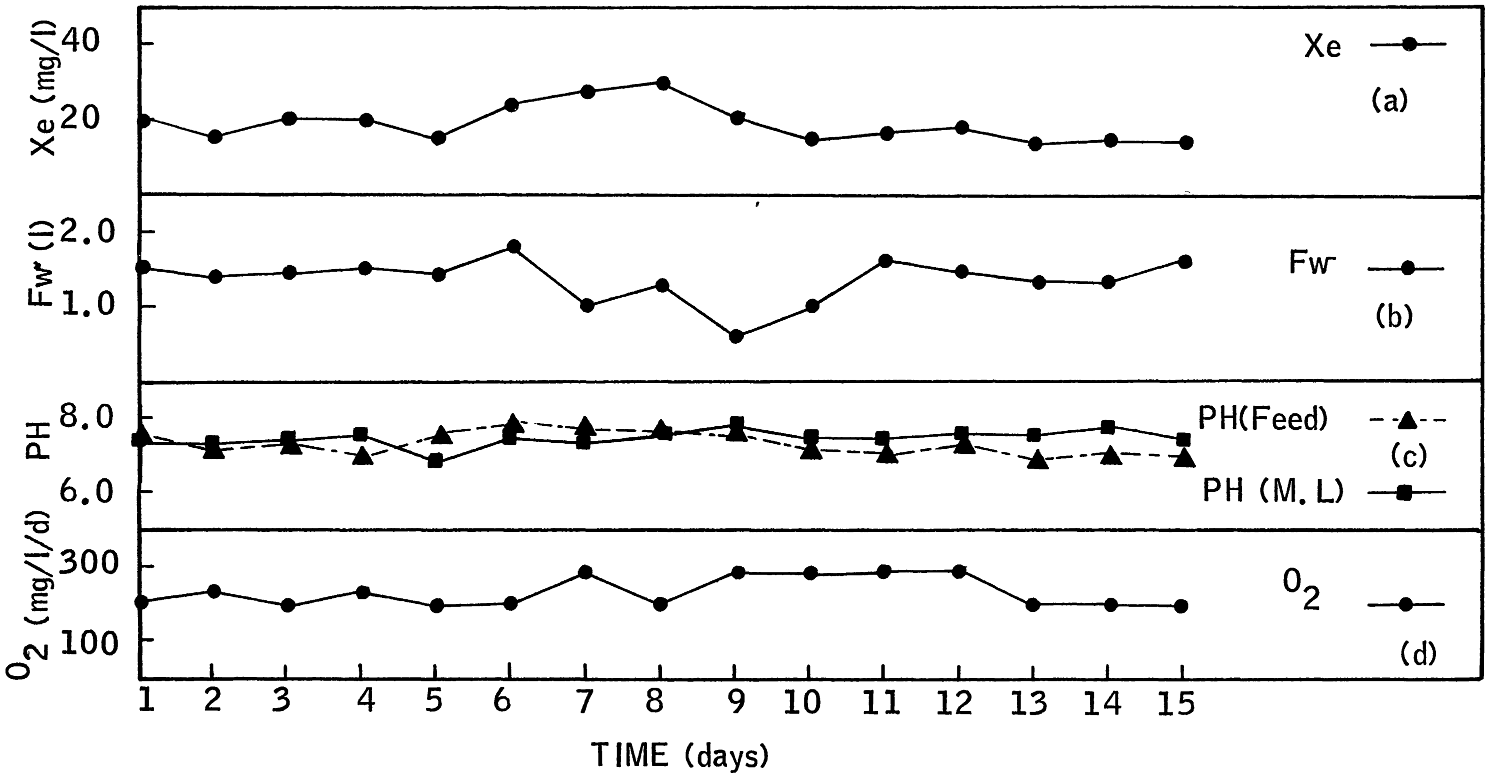

Figure 15. Some Parameters Monitored with Time at F:M Loading Ratio of 0.75 O_2, pH, F_w, X_e

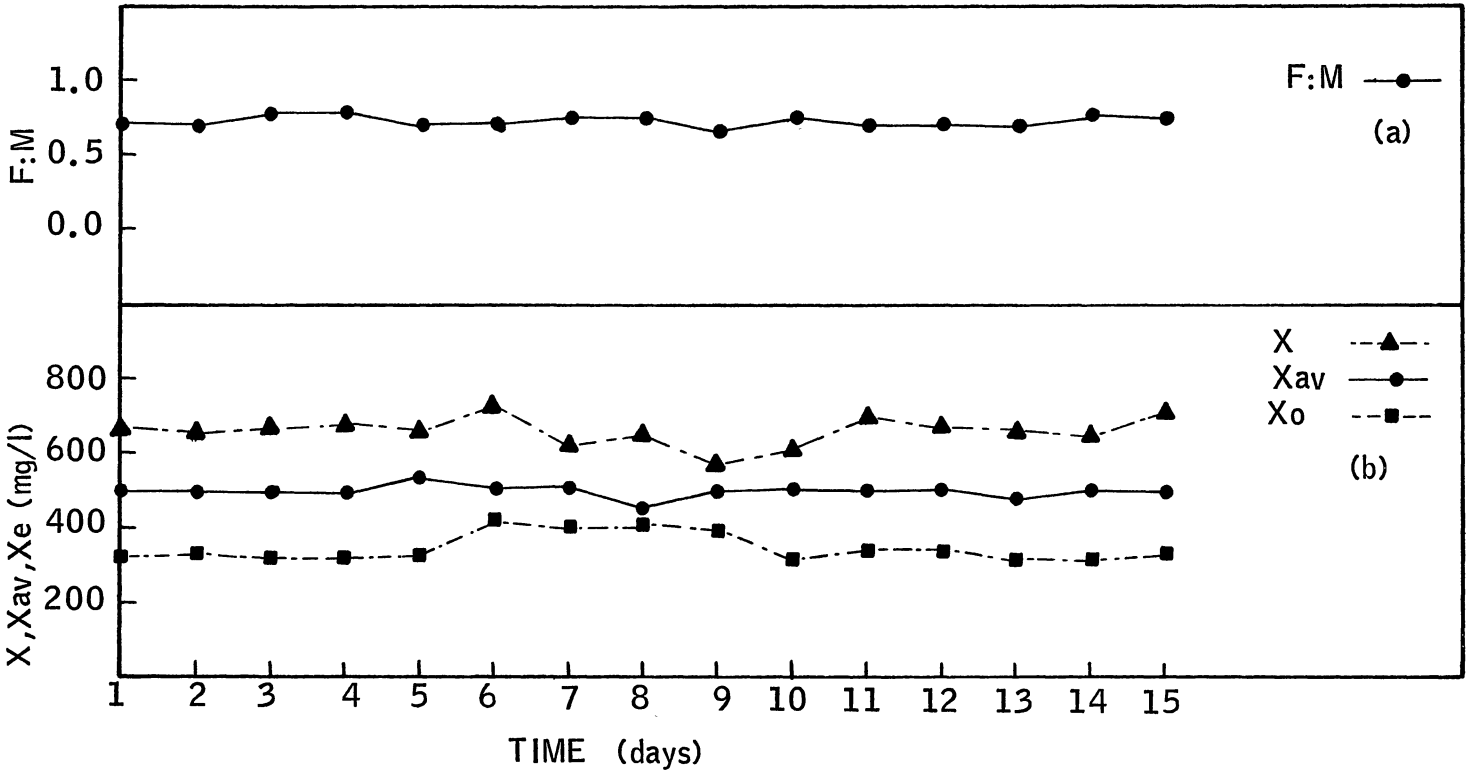

Figure 16. Some Parameters Monitored with Time at F:M Loading Ratio of 0.75 X, X_{av}, X_e

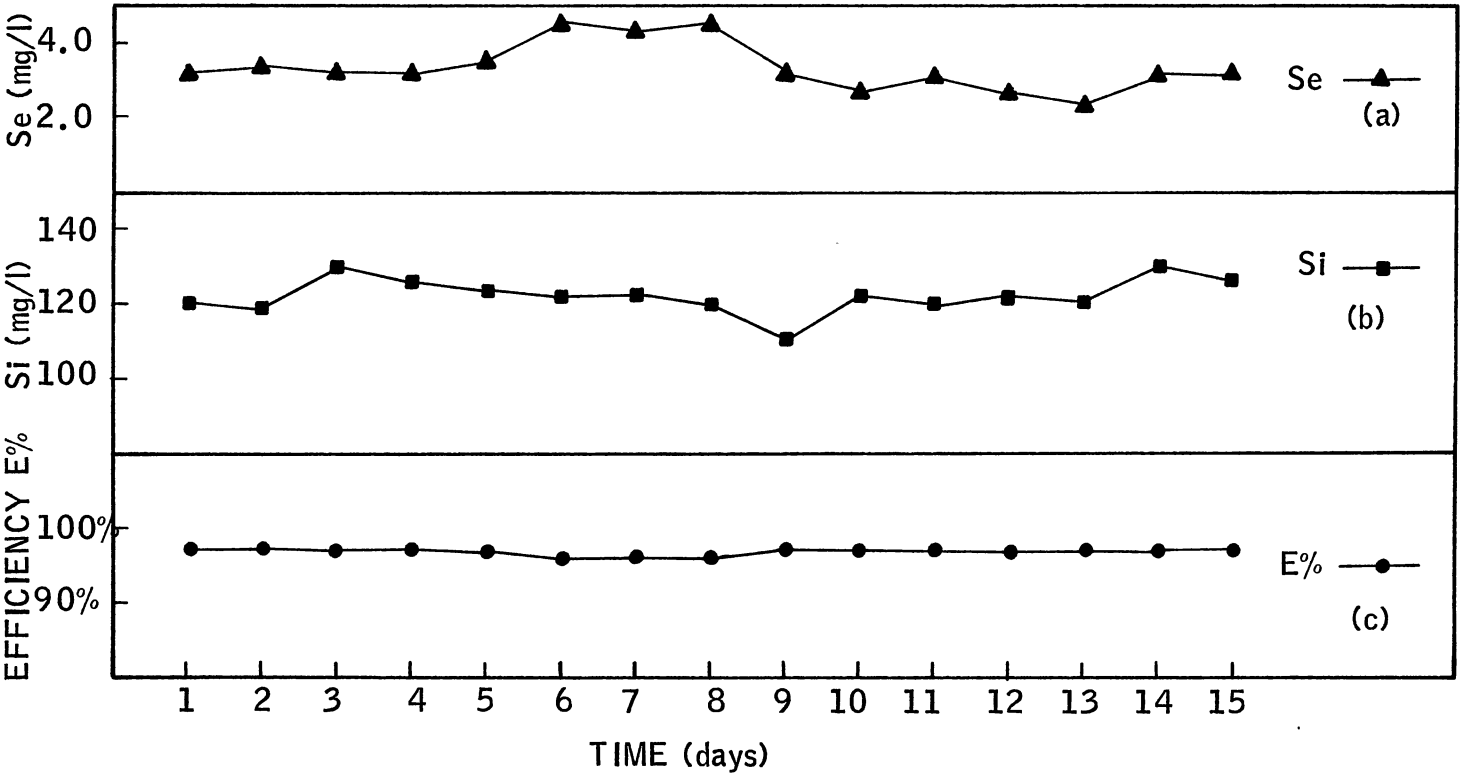

Figure 17. Some Parameters Monitored with Time at SRT = 3 days E% S_i S_e

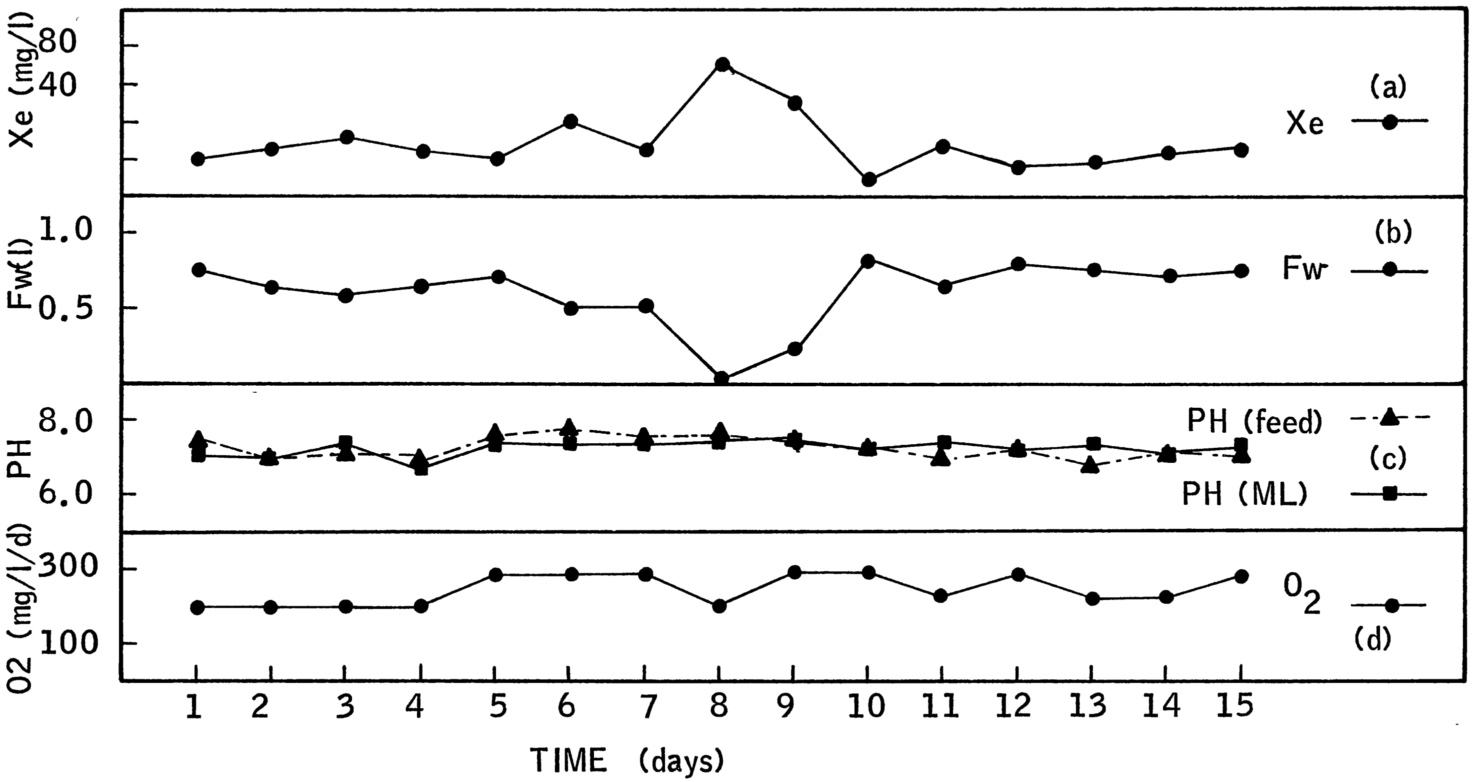

Figure 18. Some Parameters Monitored with Time at SRT = 3 days O_2, pH, F_w, X_e

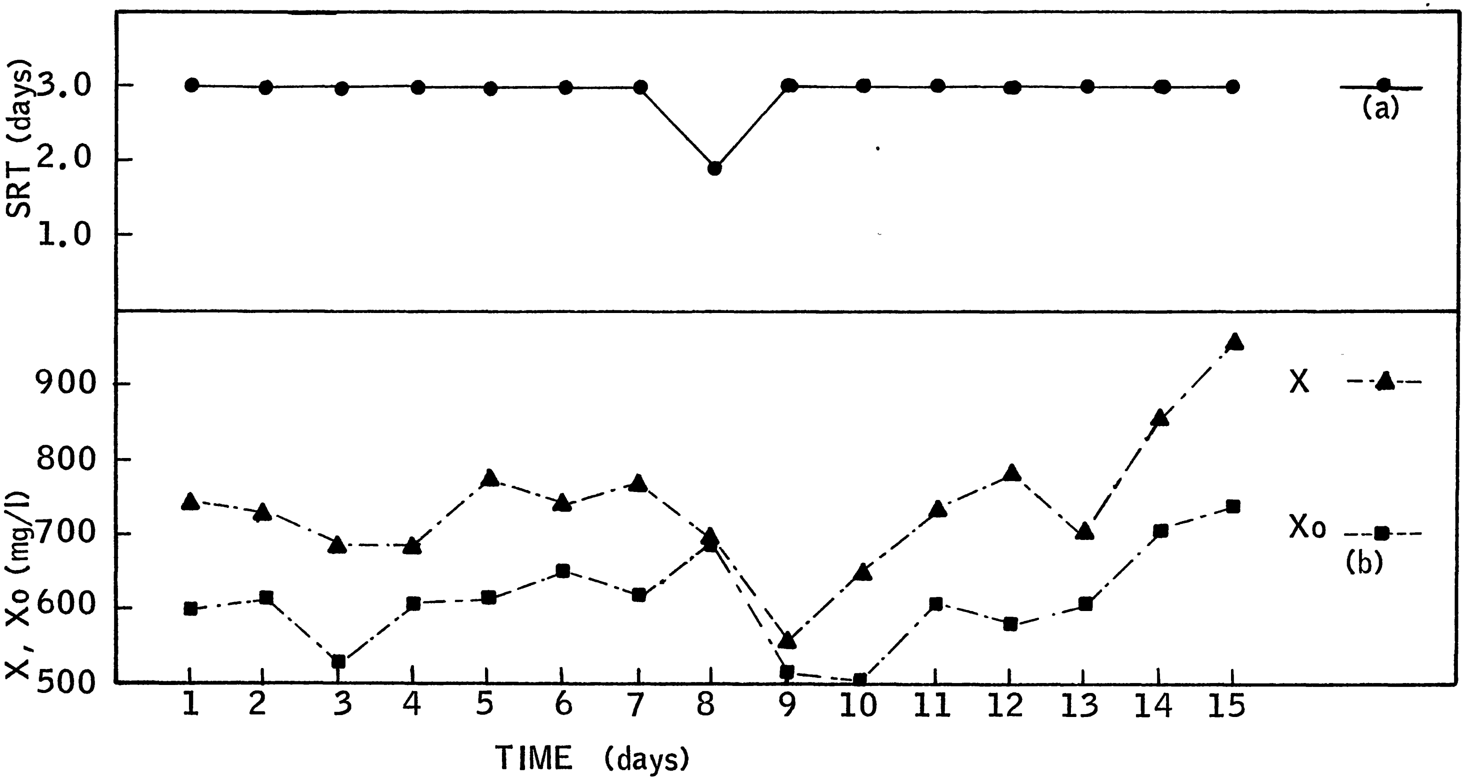

Figure 19. Some Parameters Monitored with Time at SRT = 3 days X, X_o

liquor suspended solids concentration 500 mg/ℓ. The sludge retention time was three days and dropped, when the system washed-out, to one day. Data for this phase can be seen in figures 14 through 19.

CHAPTER V

EVALUATION OF THE KINETIC MODELS

If a mass balance for substrate is written around the entire process (Figure 20):

Rate of change of substrate in reactor	=	Rate of substrate inflow to reactor	-	Rate of substrate outflow from reactor	-	Rate of substrate utilization

$$\left(\frac{ds}{dt}\right)_R V = FS_i - FS_e - \left(\frac{ds}{dt}\right)_G V$$

For steady-state conditions $\left(\frac{ds}{dt}\right) R = 0$

therefore $\left(\frac{ds}{dt}\right)_G V = FS_i - FS_e$

The various models differ by the assumption for $\left(\frac{ds}{dt}\right)_G$:

1. Eckenfelder (First Order) Model

$$\left(\frac{ds}{dt}\right)_G = K_e . x . S_e \qquad \text{Equation (5)}$$

2. Eckenfelder Modified Model

$$\left(\frac{ds}{dt}\right)_G = \frac{K. x . S_e}{S_i} \qquad \text{Equation (6)}$$

3. Lawrence and McCarty Model

$$\left(\frac{ds}{dt}\right)_G = \frac{K. x . S_e}{K_s + S_e} \qquad \text{Equation (7)}$$

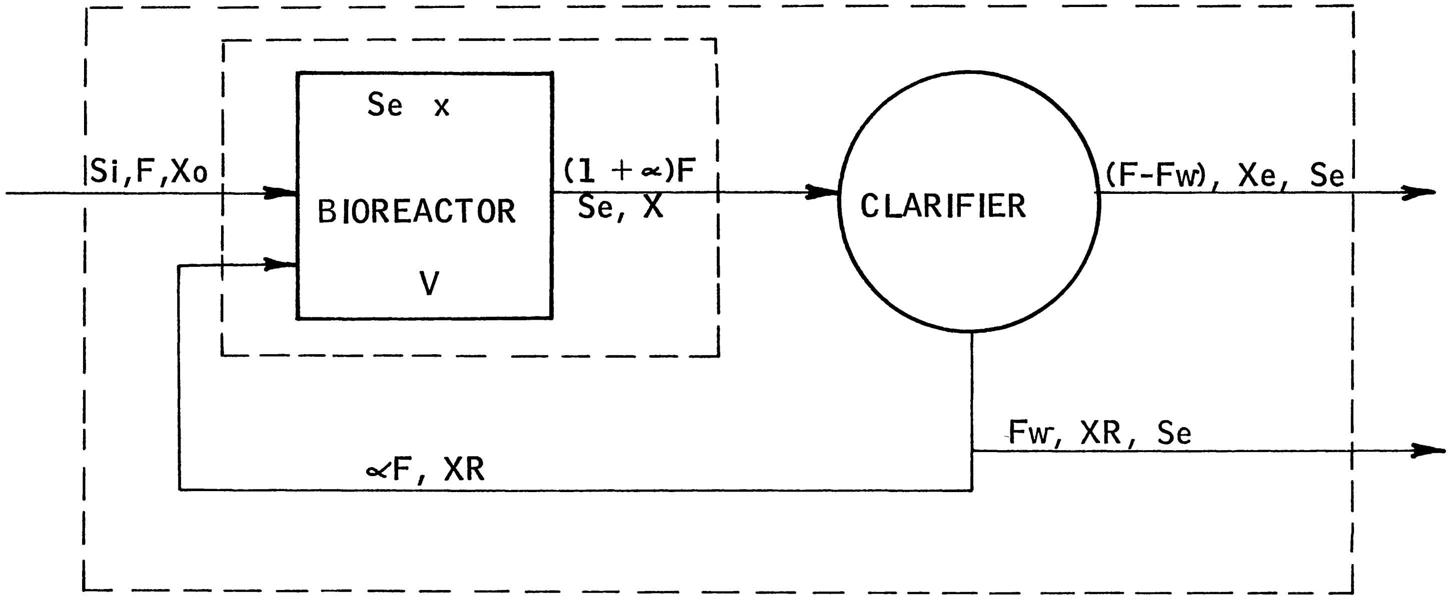

Figure 20. Flow Diagram, Activated Sludge Process

4. Kincannon and Stover Model

$$\left(\frac{ds}{dt}\right)_G = \frac{U_{max} \cdot x \cdot \frac{FS_i}{XV}}{K_B + \frac{FS_i}{XV}} \qquad \text{Equation (8)}$$

where:

F = flow rate ℓ/d

F_w = waste sludge flow rate ℓ/d

K_e = Eckenfelder's first order substrate removal rate

K_e' = Eckenfelder's second order substrate removal rate

X = Mixed liquor suspended solids concentration (mg/ℓ)

S_e = effluent substrate concentration (mg/ℓ)

S_i = influent substrate concentration (mg/ℓ)

V = reactor volume (ℓ)

U_{max} = maximum substrate utilization rate

K_B = substrate loading at which the rate of substrate utilization is one-half the maximum rate

$\frac{FS_i}{XV}$ = F:M

By plotting the data obtained from the three phases based on SRT once and on F:M another time, the kinetic constants can be obtained.

The coefficient K_e can be determined by plotting the effluent substrate concentration as a function of the specific substrate utilzation rate. The coefficient K_e is the slope of the resultant straight line (Figure 21-a, 21-b).

To determine Eckenfelder's modified coefficient K_e', the effluent substrate concentration was plotted as a function of the specific substrate utilization rate and the influent substrate concentration. The

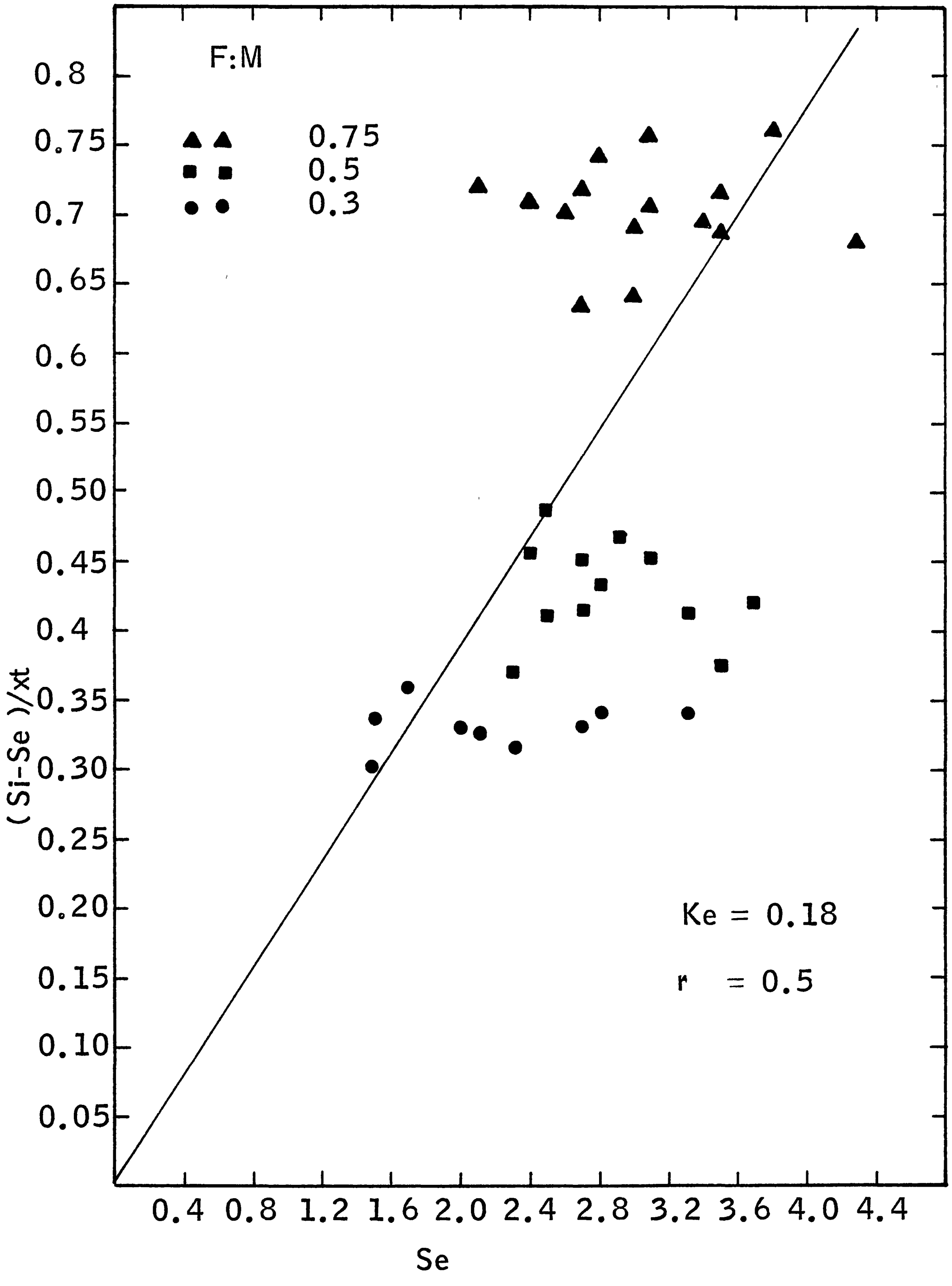

Figure 21-A. Graphical Determination of K_e, S_i, S_e

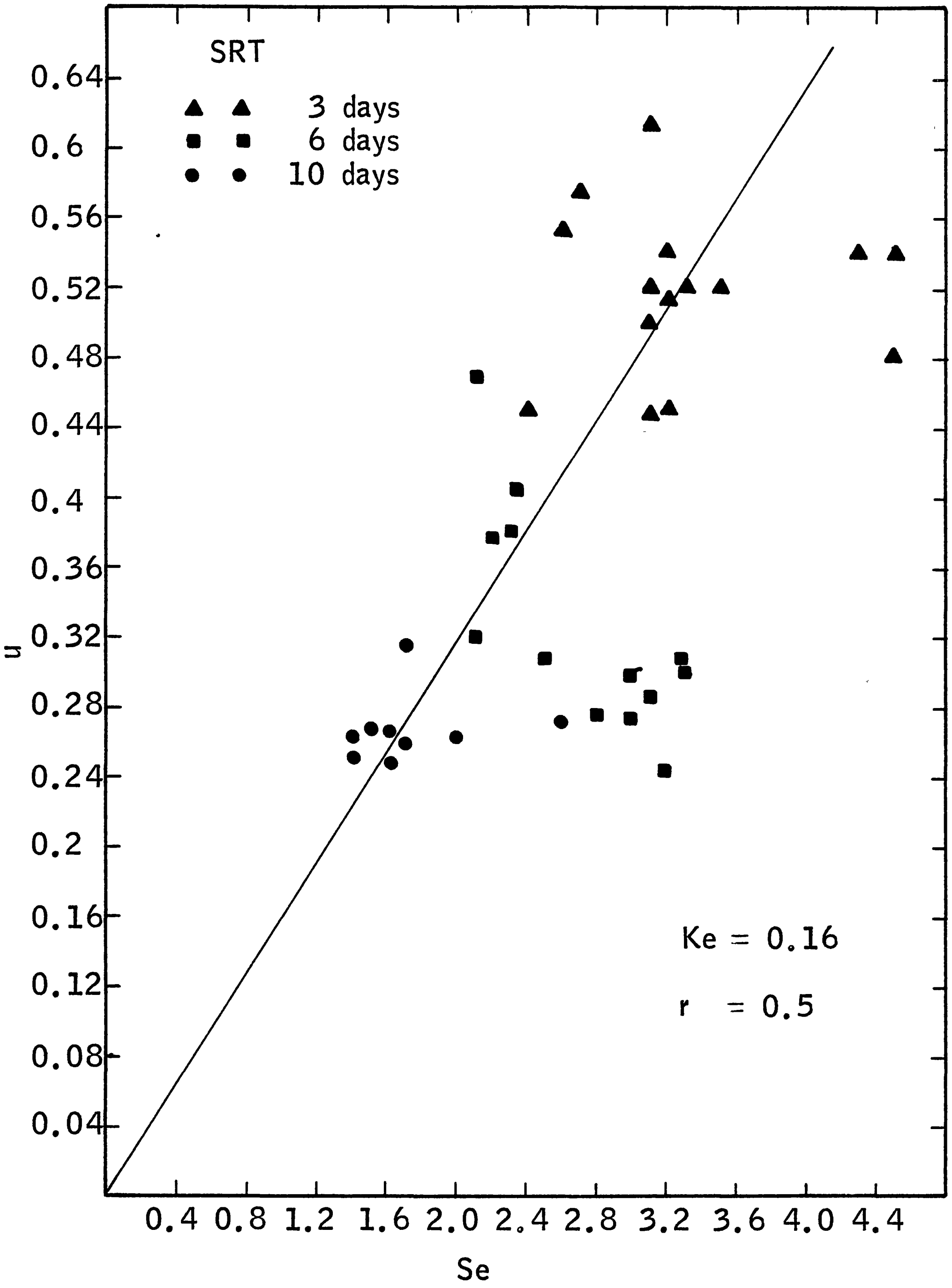

Figure 21-B. Graphical Determination of K_e u

The coefficient K_e' is the slope of the resultant line (Figure 22-a, 22-b).

In Lawrence and McCarty's design model, the biokinetic constant (K_s) can be determined from

$$\frac{1}{\frac{ds/dt}{X}} = \frac{K_s}{K}\,\frac{1}{S_e} + \frac{1}{K} \qquad \text{Equation (9)}$$

K and K_s can be determined from Figure 23-a and 23-b, from the intercept $(\frac{1}{K})$ and the slope $(\frac{K_s}{K})$.

For Kincannon and Stover's model, where

$$\left.\frac{ds}{dt}\right._G = \frac{U_{max} \cdot x.. \frac{FS_i}{VX}}{K_B + \frac{FS_i}{VX}}$$

the biokinetic coefficient K_B and U_{max} were obtained by linearizing the above equation

$$\frac{1}{\frac{ds/dt}{X}} = \frac{K_B}{U_{max}}\,\frac{1}{\frac{FS_i}{XV}} + \frac{1}{U_{max}}$$

by plotting $\frac{1}{\frac{ds/dt}{X}}$ vs. $\frac{1}{\frac{FS_i}{XV}}$, the Y-axis intercept is equal to $\frac{1}{U_{max}}$ value and the slope of the line is equal to K_B/U_{max}. Computer linear regression was used to determine the slope and intercept of the lines (Figure 24-a, 24-b).

The reciprocal of the sludge residence time was plotted vs. the substrate utilization rate for both F:M and SRT, and an attempt was made to determine the true yields (Y_t) and the decay coefficient from

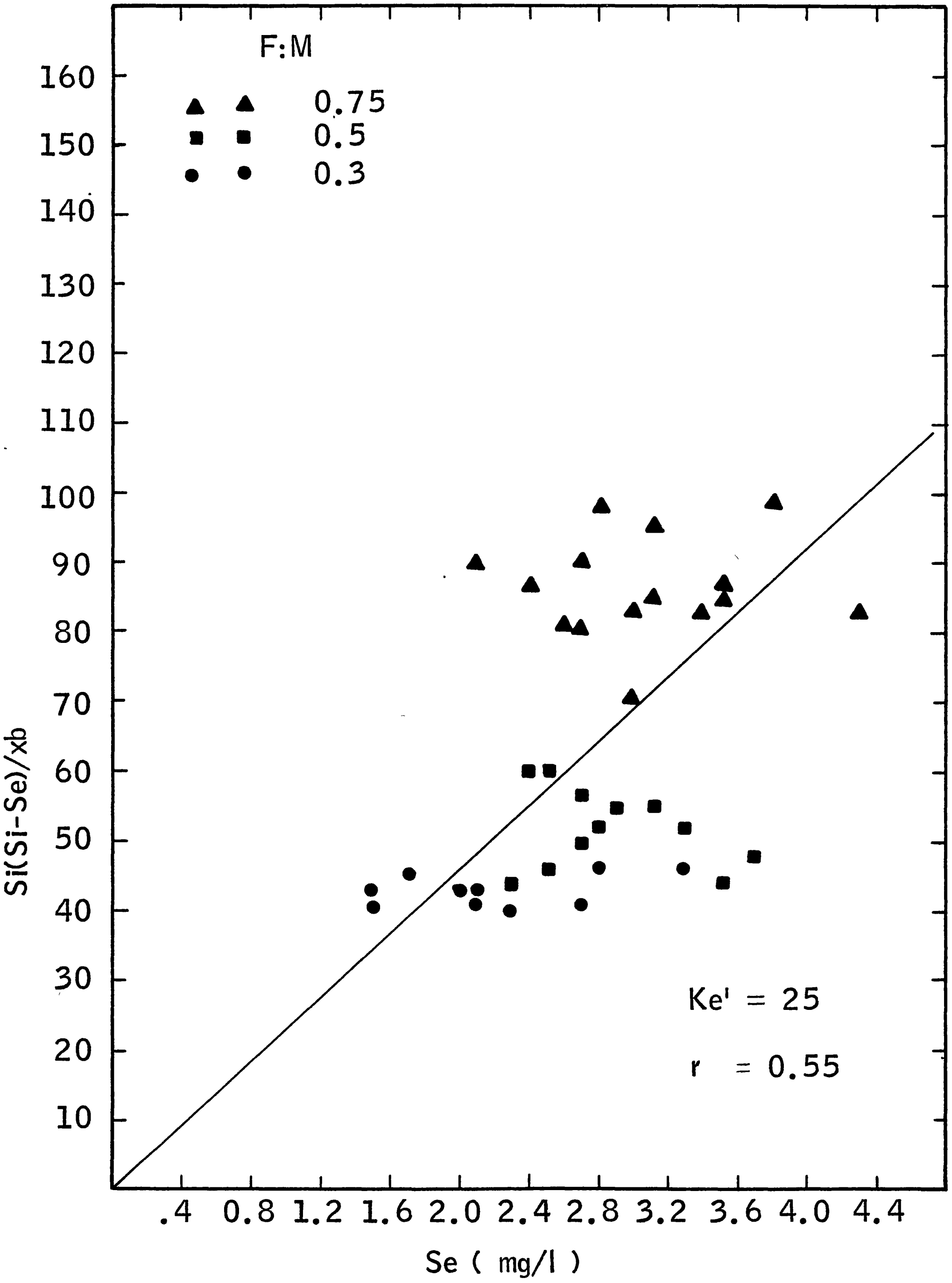

Figure 22-A. Graphical Determination of K_e' S_i S_e

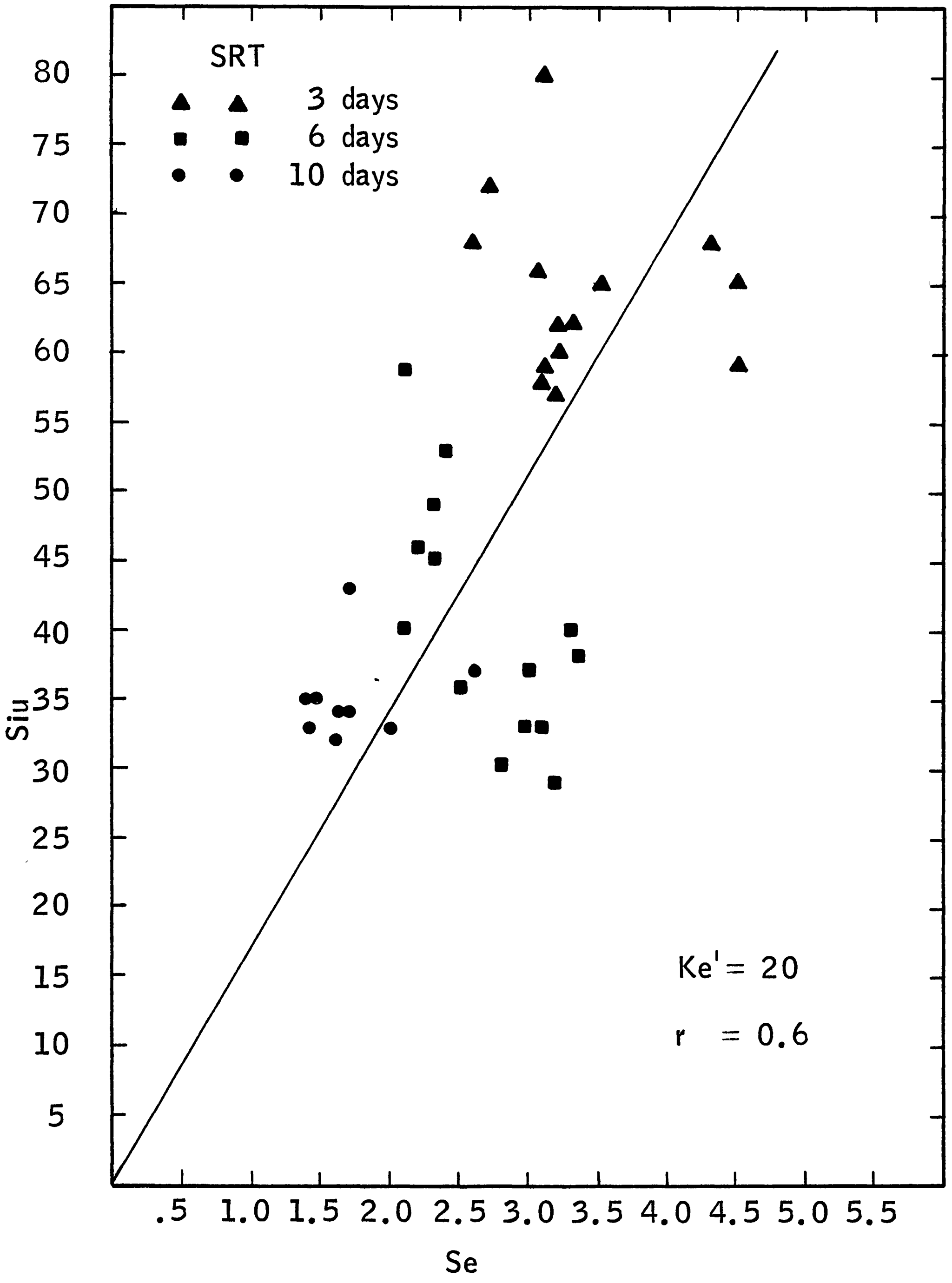

Figure 22-B. Graphical Determination of K_e' S_{iu}

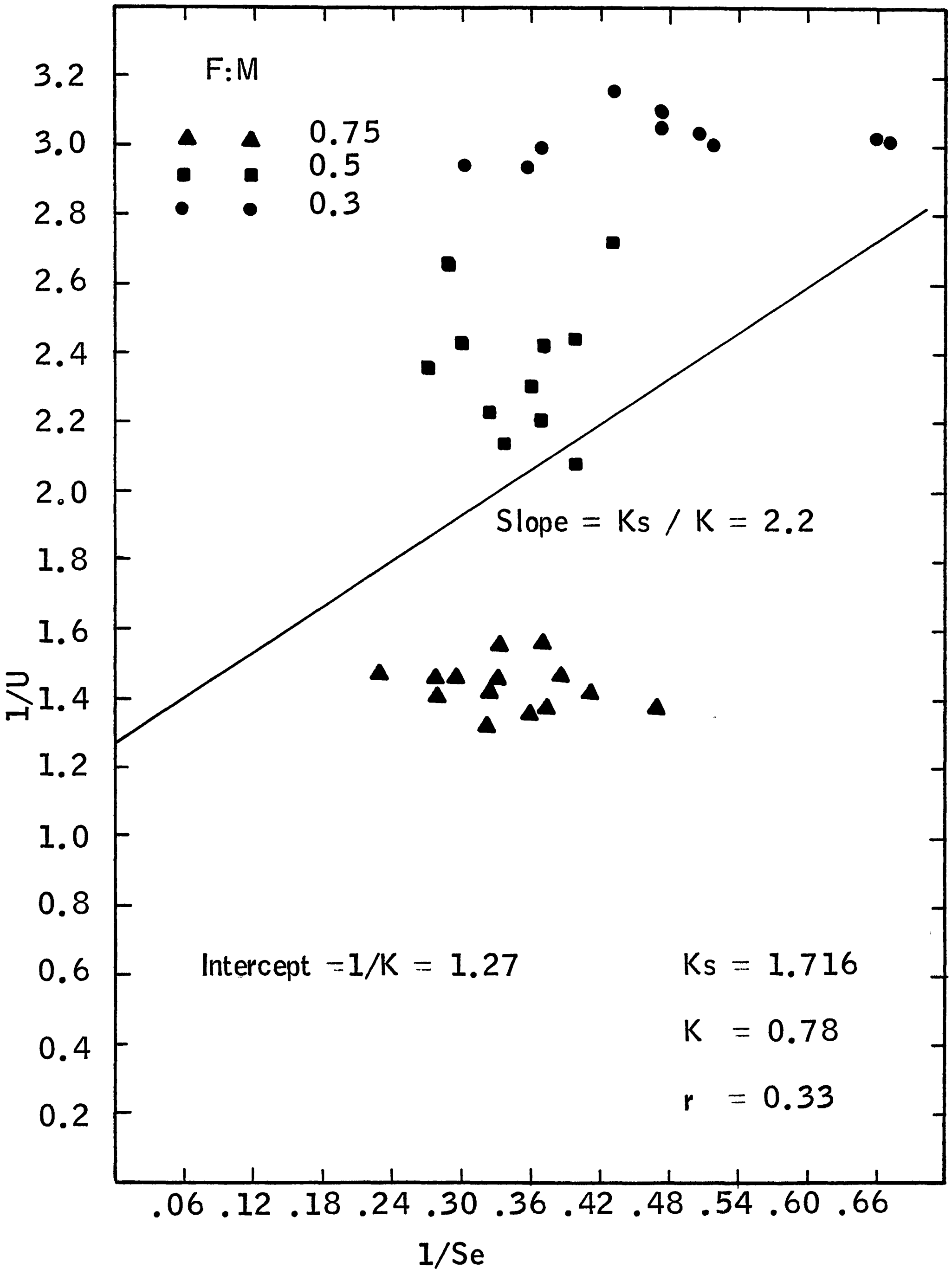

Figure 23-A. Graphical Determination of K and K_s 1/U

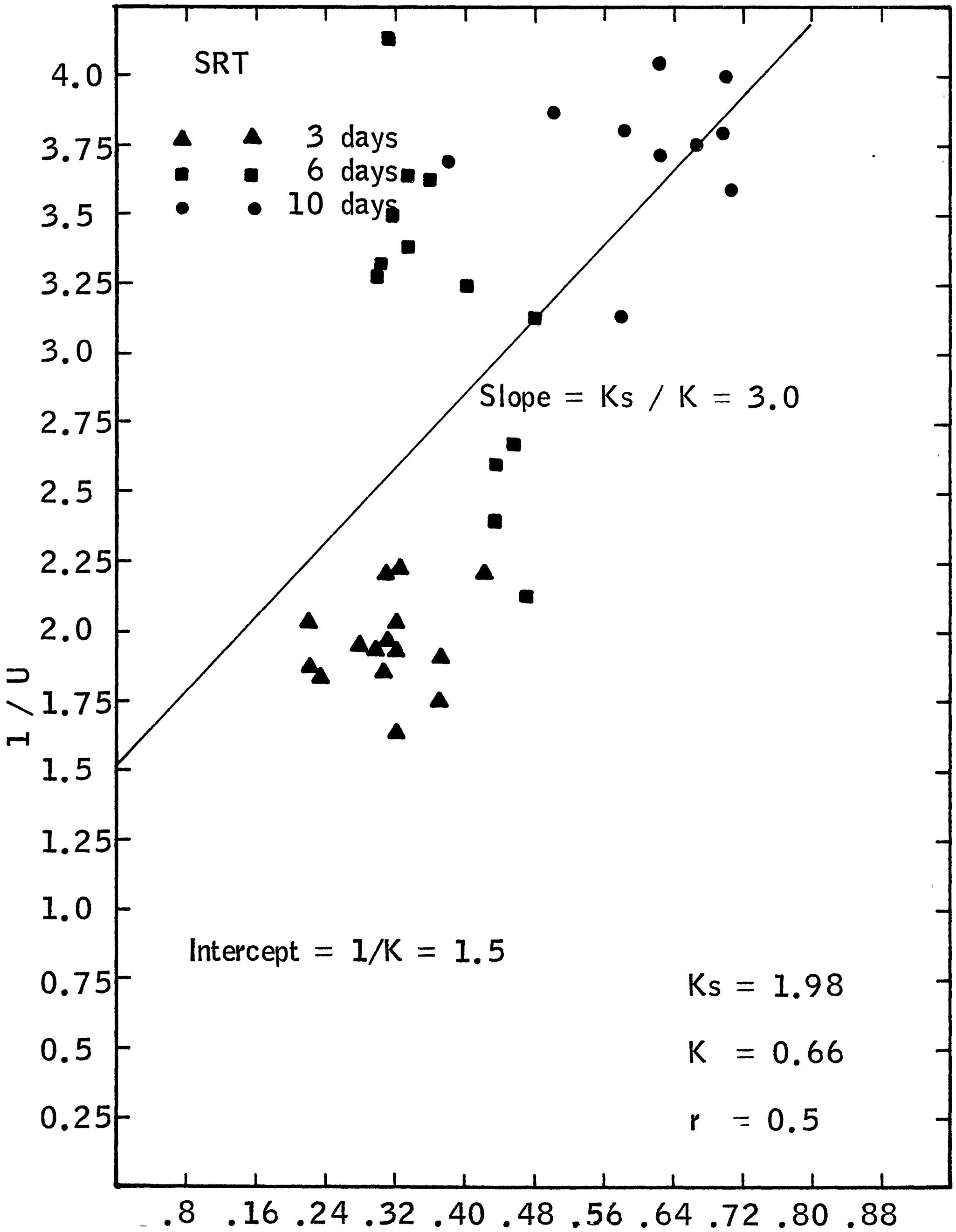

Figure 23-B. Graphical Determination of K and K_s 1/U

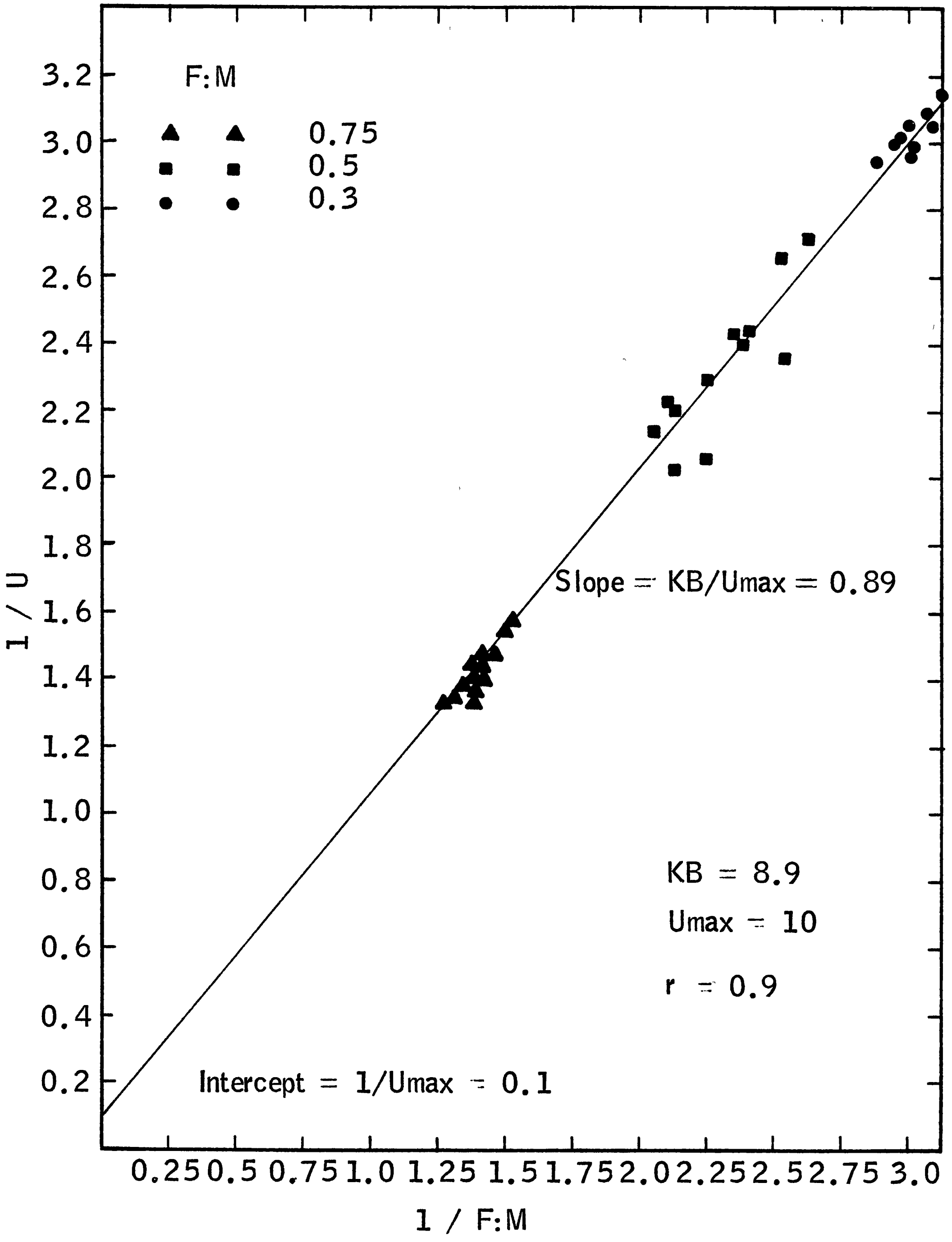

Figure 24-A. Graphical Determination of U_{max} and K_B

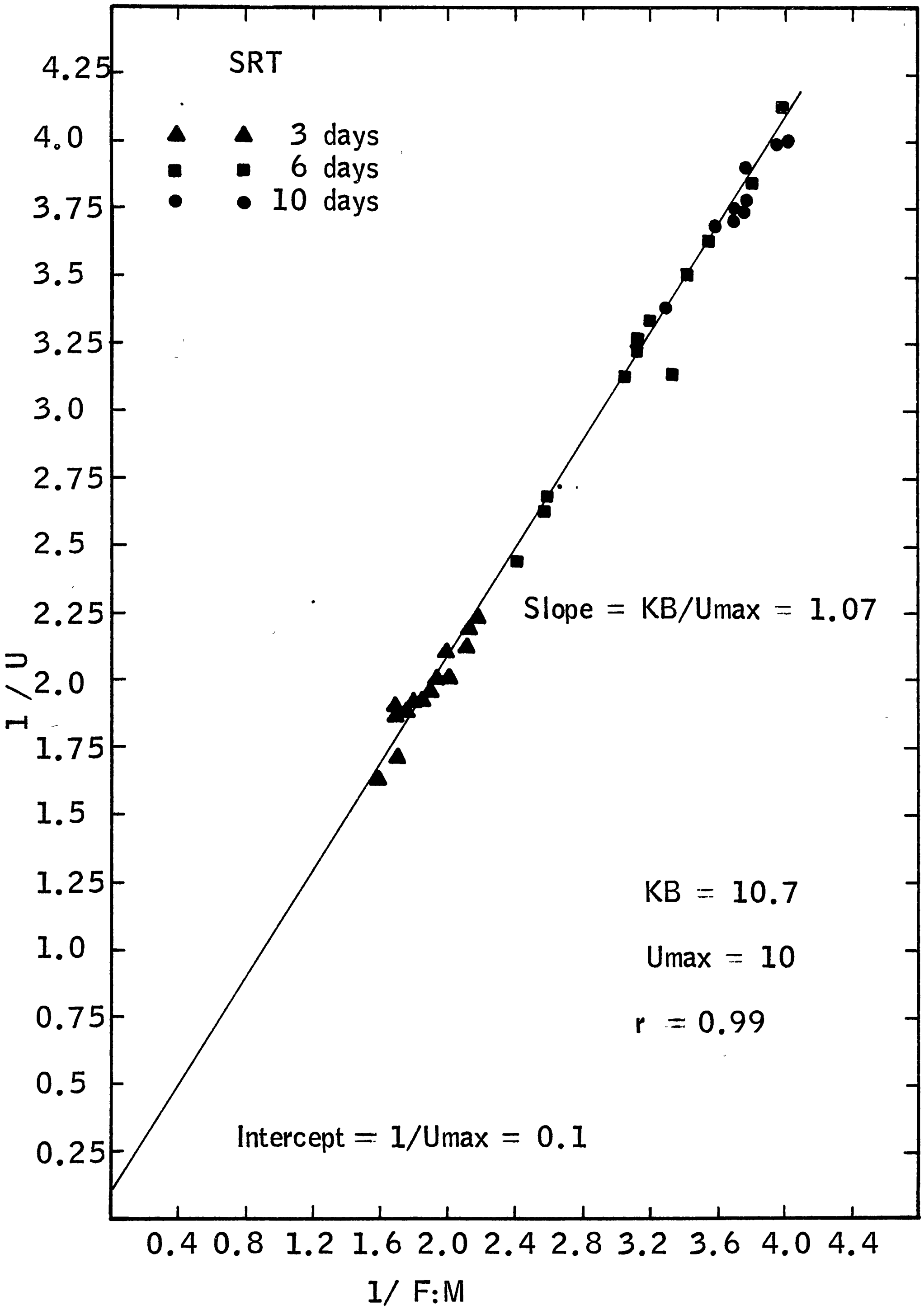

Figure 24-B. Graphical Determination of U_{max} and K_B

the slope of the lines and the intercept on the Y-axis is respectively Figures 25-a and 25-b.

The total oxygen requirements in a biological system include that required to supply energy for synthesis and the oxygen consumed for endogenous respiration. This can be expressed as

$$\frac{R_r}{X} = a' \frac{(S_i - S_e)}{Xt}$$

where:

R_r = oxygen utilization per unit time

a' = fraction of substrate used for oxidation

b' = fraction per unit time of suspended solids oxidized

The results are shown in Figures 26-a and 26-b. Linear regression was used to determine the slope and intercept of the lines.

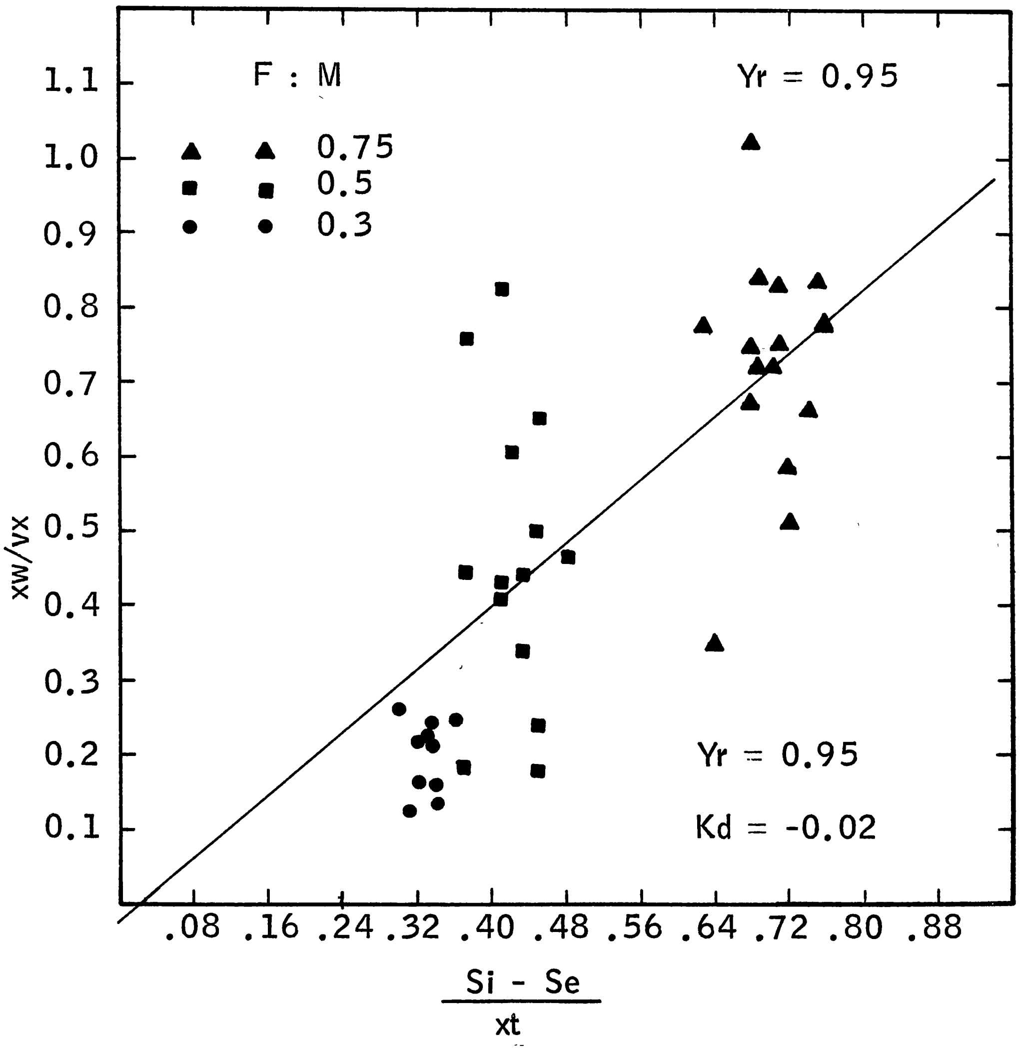

Figure 25-A. Reciprocal Sludge Retention time (θ_c) vs. Specific Substrate Utilization Rate x_w/v_x

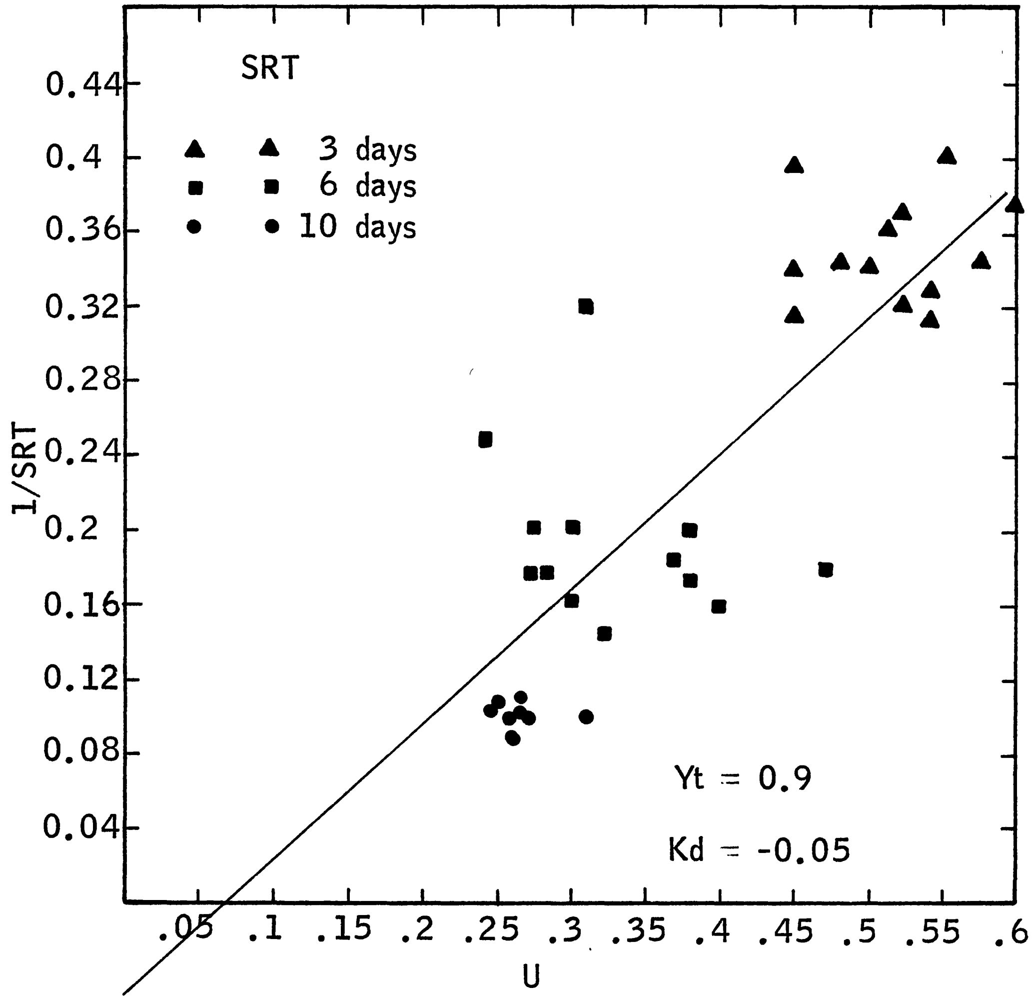

Figure 25-B. Reciprocal Sludge Retention Time (θ_c) vs. Specific Substrate Utilization Rate U

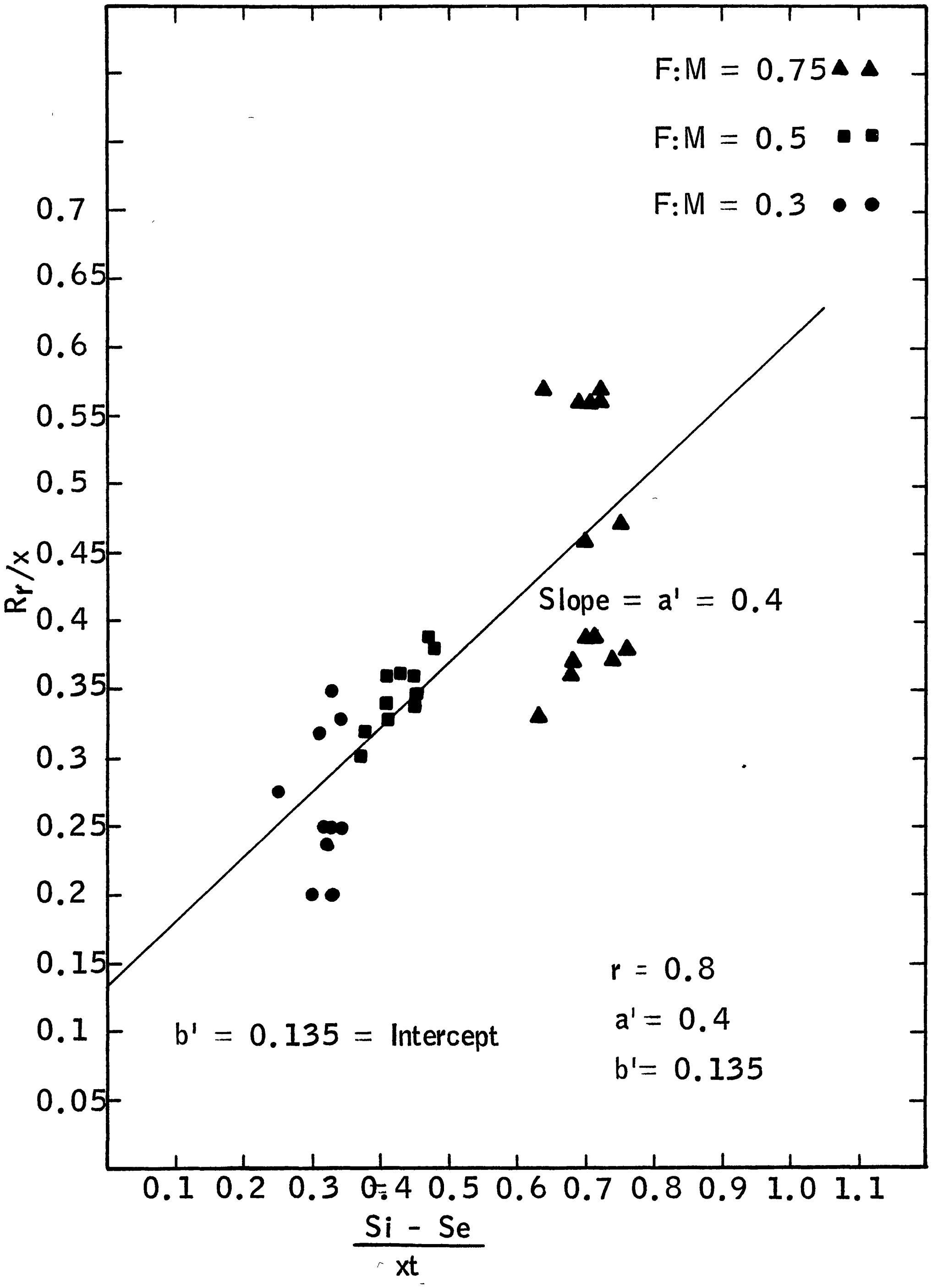

Figure 26-A. Determination of a'b'

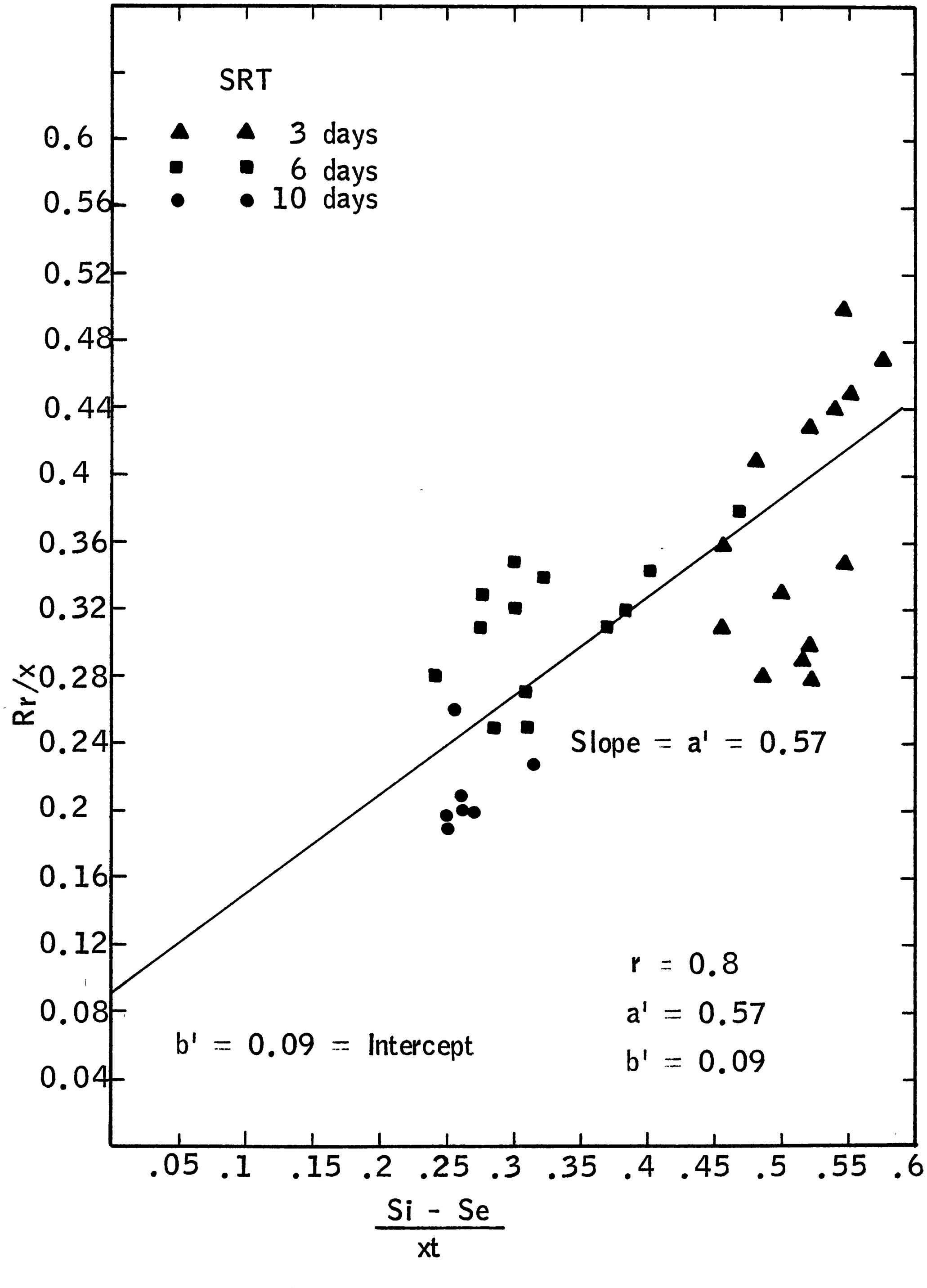

Figure 26-B. Determination of a'b'

CHAPTER VI

DISCUSSION

The results of this study have shown that biological reactors can be operated at steady-state conditions in regards to the SRT or the F/M ratio. That is, if the system is operated by controlling the SRT, the SRT can be maintained at a steady-state level. Likewise, if the system is operated by controlling the F/M, the F/M can be maintained at a steady-state level. This study has also shown that the system operated by controlling the F/M ratio produced a much better steady-state level for the mixed liquor suspended solids. There was less variation in MLSS in the F/M controlled system than in the SRT controlled system.

This study has also shown that the same biokinetic constants are produced no matter which way the systems are controlled. There was no difference in the scatter of the data between the two systems. Therefore, it must be assumed that the lack of data scatter in the Kincannon/Stover Model is due to the concepts of the model and is not based upon the way the systems are controlled. Thus, the specific substrate utilization rate is a function of the organic loading and not a function of the effluent substrate concentration.

It is of interest to note the influence that one control mechanism has on the other. Figures 27 a, 27-b, and 27-c show both the SRT and the F/M for the systems which were controlled based upon the SRT. It is seen that the F/M ratio was fairly steady as well as the SRT.

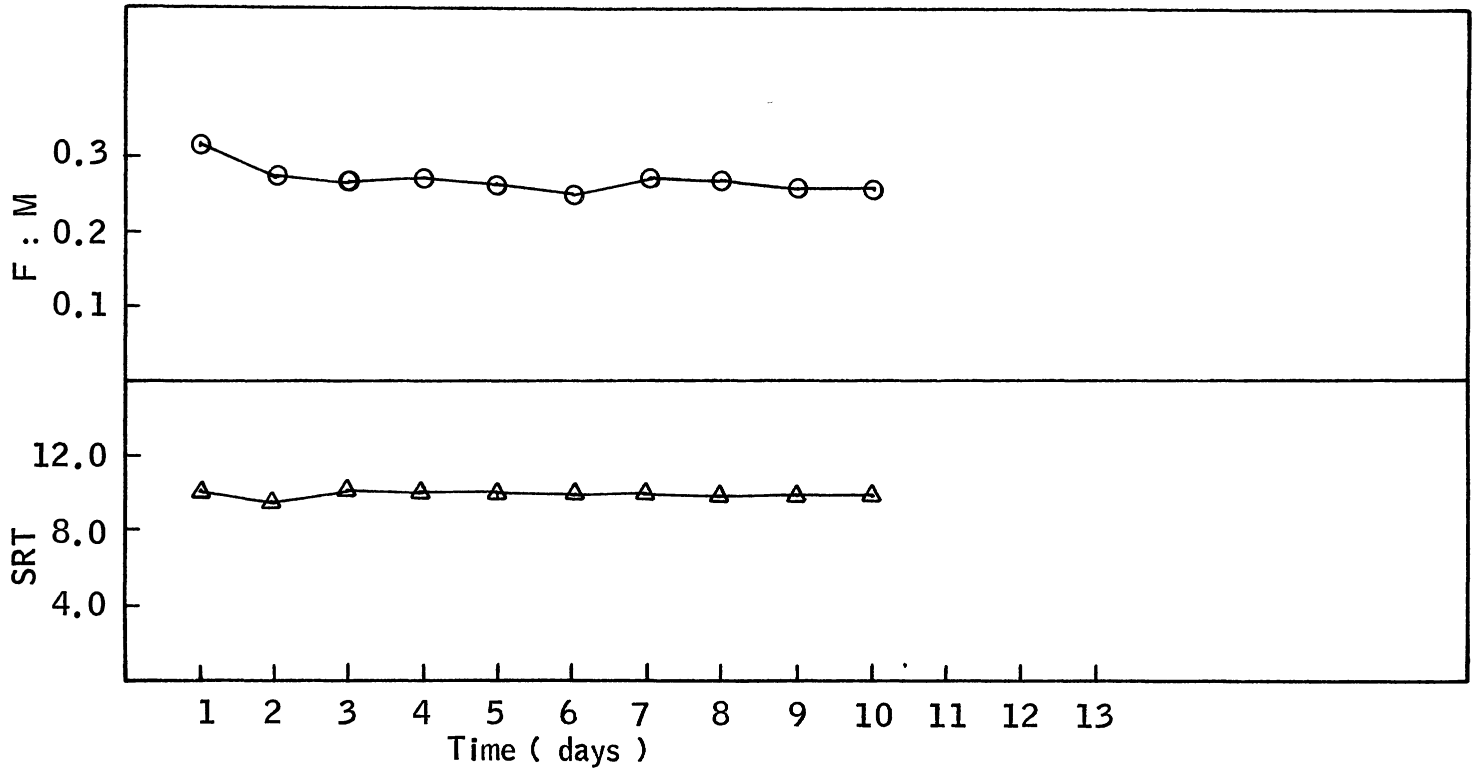

Figure 27-A. The Effect of SRT on F:M at SRT = 10 days

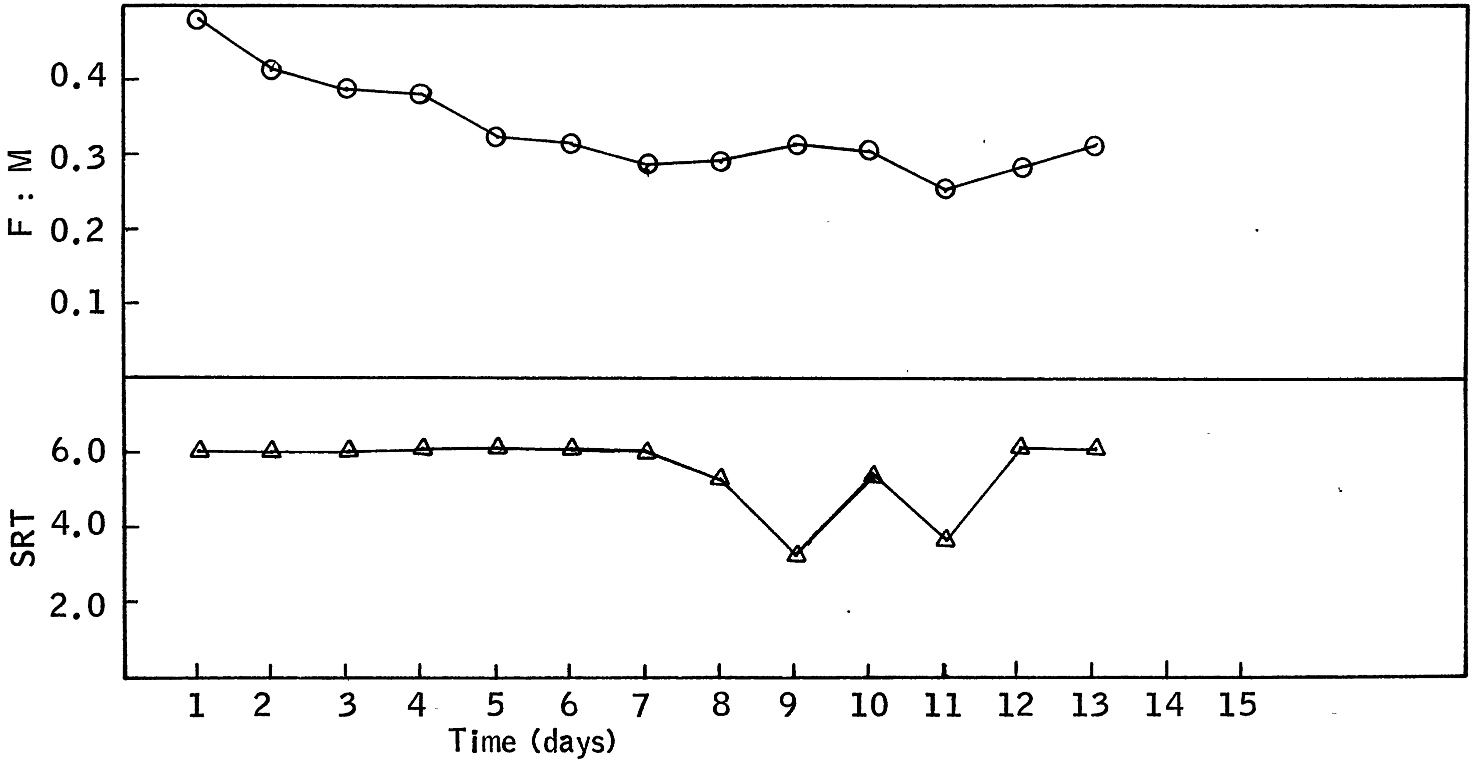

Figure 27-B. The Effect of SRT on F:M at SRT = 6 days

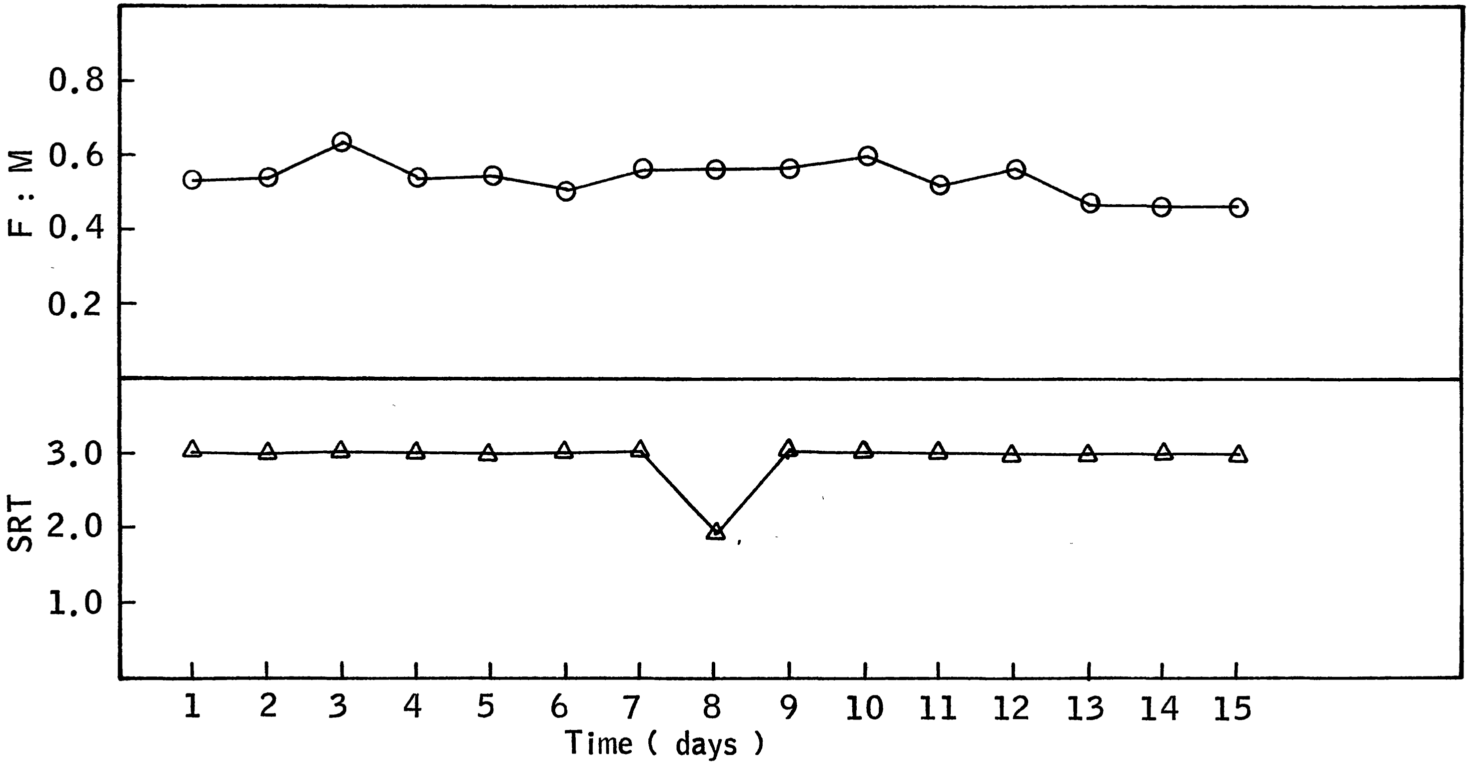

Figure 27-C. The Effect of SRT on F:M at SRT = 3 days

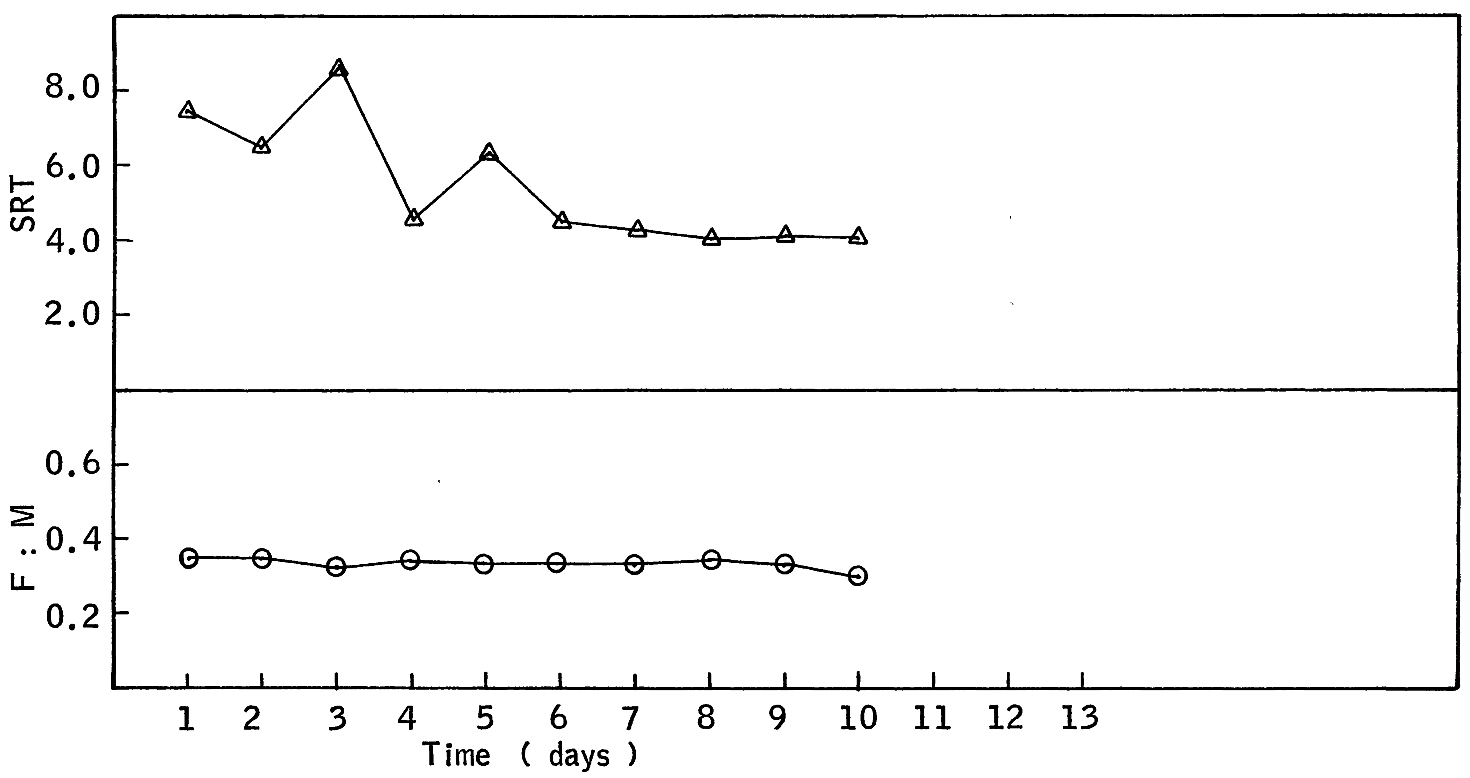

Figure 28-A. The Effect of F:M on SRT at F:M = 0.3

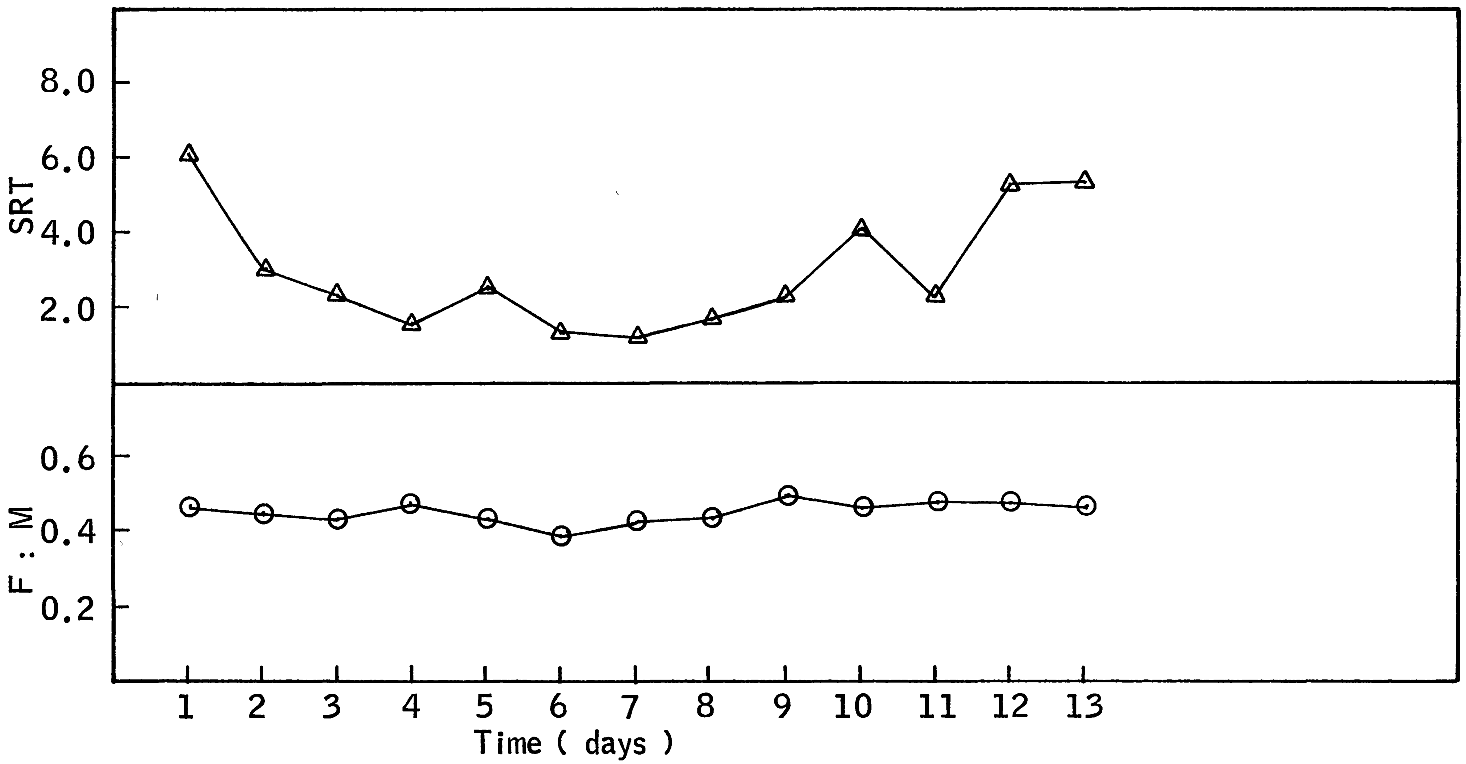

Figure 28-B. The Effect of F:M on SRT at F:M = 0.5

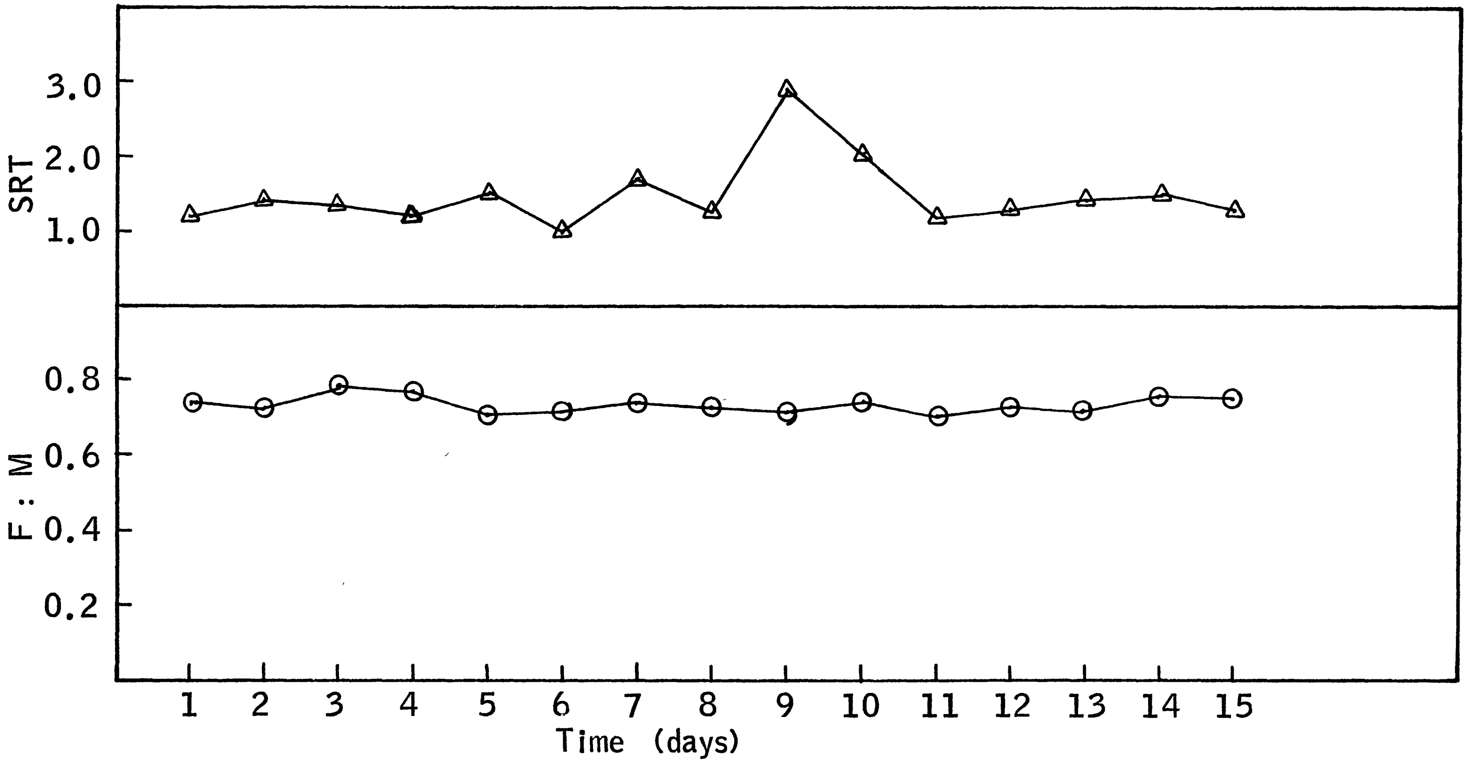

Figure 28-C. The Effect of F:M on SRT at F:M = 0.75

Figures 28 a, 28-b, and 28-c show both the F/M ratio and the SRT for the systems which were controlled based upon the F/M ratio. It is seen that, even though the F/M ratio was maintained fairly constant, the SRT's had considerable variation. This would indicate that the systems could be controlled by the SRT and still provide a constant F/M ratio. Some difficulties could be encountered in field conditions in which the flow rate is variable and the influent BOD is variable. If the F/M ratio could be controlled by controlling the SRT, then the control of the F/M in field conditions would be much easier.

CHAPTER VII

CONCLUSIONS

From the experimental data and observation obtained through this study, the following may be drawn.

1. By controlling SRT, it seems to control F:M
2. F:M ratio has no effect on SRT
3. Both SRT and F:M systems tend to have almost the same kinetic constant and the same correlation coefficient. That means that, under steady conditions, no matter how the systems are operated, the kinetic constant is equal.
4. All the models show data scatter except the Kincannon and Stover model which tends to give relatively high correlation coefficient.
5. The fact that all relationships show scatter except Kincannon and Stover's model suggests that the substrate removal rate is a function of the organic loading instead of the effluent substrate concentration.
6. High F:M loading ratio on an activated sludge system tends to produce poorly settling sludge.

TABLE II

RAW DATA FOR SLUDGE RETENTION TIME OF 10 DAYS

S_i mg/ℓ	S_e mg/ℓ	X mg/ℓ	X_o mg/ℓ	X_{av} mg/ℓ	X_e mg/ℓ	F_w (ℓd)	u	1/u	F:M	1/F:M	θ_c	$1/\theta_c$	S_iu	$1/S_e$	td (d)
136	1.7	1460	1100	1250	44	0.054	0.315	3.176	0.319	3.136	10.0	0.1	43	0.588	0.33
136	2.6	1400	1400	1440	16	0.00	0.271	3.684	0.277	3.613	19.5	0.1	37	0.385	0.33
126	2.0	1480	1340	1400	30	0.114	0.26	3.853	0.264	3.792	10.0	0.1	33	0.5	0.33
126	1.6	1460	1340	1370	28	0.123	0.266	3.758	0.27	3.710	10.0	0.1	34	0.625	0.33
129	1.7	1400	1280	1430	32	0.092	0.261	3.833	0.264	3.783	10.0	0.1	34	0.588	0.33
130	1.6	1580	1500	1520	30	0.125	0.248	4.040	0.25	3.99	10.0	0.1	32	0.625	0.33
131	1.5	1540	1270	1415	30	0.125	0.268	3.729	0.27	3.686	10.0	0.1	35	0.667	0.33
133	1.4	1560	1270	1455	30	0.120	0.265	3.773	0.268	3.733	10.0	0.1	35	0.714	0.33
131	1.4	1640	1400	1500	48	0.037	0.253	3.949	0.256	3.907	10.0	0.1	33	0.714	0.33
132	1.4	1600	1480	1500	45	0.047	0.253	3.949	0.256	3.907	10.0	0.1	35	0.714	0.33

TABLE III

RAW DATA FOR SLUDGE RETENTION TIME OF 6 DAYS

S_i mg/ℓ	S_e mg/	X mg/ℓ	X_o mg/ℓ	$X_{av.}$ mg/ℓ	X_e mg/ℓ	F_w (ℓ)	u	1/u	F:M	1/F:M	θ_c	1/θ	S_iu	1/S_e	td (d)
125	2.1	855	710	765	20	0.279	0.471	2.124	0.479	2.088	6.0	0.166	59	0.476	0.33
120	2.3	820	750	848	20	0.27	0.407	2.457	0.415	2.410	6.0	0.166	49	0.435	0.33
118	2.3	945	735	893	16	0.33	0.380	2.634	0.384	2.582	6.0	0.166	45	0.435	0.33
122	2.2	1051	815	938	25	0.276	0.374	2.670	0.381	2.622	6.0	0.166	46	0.455	0.33
125	2.1	1060	940	1125	48	0.062	0.320	3.124	0.326	3.071	6.0	0.166	40	0.476	0.33
116	2.5	1310	930	1080	62	0.069	0.308	3.247	0.315	3.177	6.0	0.166	36	0.400	0.33
111	2.8	1230	1230 230	1155	68	0.007	0.275	3.643	0.282	3.551	6.0	0.166	30	0.357	0.33
114	3.1	1080	1080	1135	68	0.00	0.286	3.492	0.294	3.397	5.3	0.188	33	0.323	0.33
124	3.3	1190	1190	1145	126	0.00	0.309	3.237	0.317	3.151	3.17	0.315	38	0.303	0.33
125	3.0	1100	1100	1205	68	0.00	0.297	3.370	0.304	3.290	5.4	0.188	37	0.333	0.33
118	3.2	1310	1310	1390	120	0.00	0.242	4.132	0.249	4.020	3.6	0.277	29	0.313	0.33
120	3.0	1470	1000	1245	76	0.049	0.275	3.631	0.282	3.540	6.0	0.166	33	0.333	0.33
132	3.3	1490	1260	1245	68	0.090	0.303	3.301	0.311	3.218	6.0	0.166	40	0.303	0.33

TABLE IV

RAW DATA FOR SLUDGE RETENTION TIME OF 3 DAYS

S_i mg/ℓ	S_e mg/ℓ	X mg/ℓ	X_o mg/ℓ	X_{av} mg/ℓ	X_e mg/ℓ	F_w ℓ/d	u	1/u	F:M	1/F:M	θ_c	$1/\theta_c$	$S_i u$	$1/S_e$	td (d)
120	3.2	740	600	665	20	0.730	0.515	1.943	0.529	1.891	3.0	0.33	62	0.313	0.33
119	3.3	730	610	650	26	0.662	0.522	1.917	0.537	1.864	3.0	0.33	62	0.303	0.33
130	3.1	690	525	605	30	0.599	0.615	1.627	0.63	1.588	3.0	0.33	80	0.323	0.33
126	3.1	685	610	690	26	0.644	0.522	1.916	0.535	1.869	3.0	0.33	66	0.323	0.33
124	3.5	770	610	675	20	0.738	0.523	1.911	0.538	1.858	3.0	0.33	65	0.286	0.33
122	4.5	740	650	710	39	0.524	0.485	2.062	0.504	1.982	3.0	0.33	59	0.222	0.33
125	4.3	770	620	655	25	0.500	0.540	1.852	0.559	1.788	3.0	0.33	68	0.233	0.33
120	4.5	690	690	623	70	0.000	0.544	1.839	0.565	1.770	1.9	0.526	65	0.222	0.33
111	3.2	555	510	580	50	0.207	0.545	1.836	0.561	1.783	3.0	0.33	60	0.313	0.33
124	2.7	650	500	615	10	0.821	0.578	1.730	0.591	1.692	3.0	0.33	72	0.370	0.33
120	3.1	730	605	693	28	0.641	0.495	2.021	0.508	1.969	3.0	0.33	59	0.323	0.33
123	2.6	780	580	640	15	0.791	0.551	1.814	0.563	1.776	3.0	0.33	68	0.385	0.33
116	2.4	700	610	733	18	0.741	0.454	2.200	0.464	2.155	3.0	0.33	53	0.417	0.33
130	3.1	855	700	830	23	0.736	0.448	2.232	0.459	2.179	3.0	0.33	58	0.323	0.33
126	3.2	960	735	795	23	0.754	0.453	2.209	0.464	2.153	3.0	0.33	57	0.313	0.33

TABLE V

RAW DATA FOR F:M LOADING RATIO OF 0.3 $\frac{(\text{Lbs}\cdot\text{BOD})}{(\text{Lbs.MLVSS})\ \text{day}}$

S_i mg/ℓ	S_e mg/ℓ	X mg/ℓ	X_o mg/ℓ	X_{av} mg/ℓ	X_e mg/ℓ	F_w ℓ/d	u	1/u	F:M	1/F:M	θ_c day	$1/\theta_c$	$S_i u$	$1/S_e$	td day
136	2.8	1190	1150	1175	40	0.095	0.341	2.934	0.348	2.874	7.4	0.135	46	0.357	0.33
136	3.3	1200	1190	1176	42	0.142	0.341	2.933	0.349	2.862	6.4	0.157	46	0.303	0.33
126	2.3	1200	1080	1180	36	0.071	0.315	3.173	0.321	3.115	8.6	0.116	40	0.435	0.33
124	2.7	1280	1080	1090	20	0.410	0.335	2.989	0.342	2.924	4.5	0.221	41	0.370	0.33
129	2.1	1100	1080	1180	56	0.051	0.323	3.093	0.329	3.043	6.3	0.159	42	0.476	0.33
130	2.1	1280	1070	1175	20	0.450	0.327	3.056	0.333	3.006	4.5	0.220	43	0.476	0.33
131	2.0	1280	1070	1175	26	0.450	0.330	3.030	0.335	2.984	4.3	0.235	43	0.500	0.33
133	1.7	1280	1070	1175	32	0.445	0.336	2.977	0.340	2.939	4.0	0.248	45	0.588	0.33
131	1.5	1280	1070	1175	30	0.445	0.331	3.018	0.335	2.984	4.1	0.243	43	0.667	0.33
132	1.5	1280	1060	1175	30	0.450	0.3	3.018	0.3	2.984	4.1	0.26	43	0.667	0.33

TABLE VI

RAW DATA FOR F:M LOADING RATIO OF 0.5 $\frac{(\text{Lbs}\cdot\text{BOD})}{(\text{Lbs}\cdot\text{MLVSS})\text{ day}}$

S_i mg/ℓ	S_e mg/ℓ	X mg/ℓ	X_o mg/ℓ	X_{av} mg/ℓ	X_e mg/ℓ	F_w ℓ/d	u	1/u	F:M	1/F:M	θ_c day	$1/\theta_c$	S_{iu}	$1/S_e$	td day
125	2.7	840	725	813	20	0.270	0.453	2.210	0.463	2.162	5.9	0.170	57	0.370	0.33
120	2.8	900	680	810	26	0.633	0.435	2.299	0.445	2.245	3.0	0.336	52	0.357	0.33
118	2.7	940	650	835	30	0.849	0.415	2.409	0.425	2.354	2.3	0.433	49	0.370	0.33
122	3.1	1020	610	795	32	1.22	0.450	2.224	0.461	2.168	1.5	0.653	55	0.323	0.33
125	3.3	980	700	885	38	0.756	0.413	2.419	0.425	2.355	2.4	0.411	52	0.303	0.33
116	3.5	1070	720	900	58	1.430	0.376	2.661	0.387	2.581	1.3	0.758	44	0.286	0.33
111	2.5	1080	610	795	40	1.470	0.410	2.437	0.42	2.382	1.2	0.826	46	0.400	0.33
114	3.7	980	650	785	44	1.040	0.422	2.367	0.437	2.290	1.7	0.604	48	0.270	0.33
124	2.5	920	680	760	40	0.743	0.481	2.081	0.491	2.039	2.2	0.460	60	0.400	0.33
125	2.7	840	725	813	40	0.270	0.453	2.210	0.463	2.162	4.1	0.241	57	0.370	0.33
118	2.9	900	680	740	45	0.633	0.468	2.139	0.479	2.086	2.3	0.439	55	0.345	0.33
120	2.3	800	800	960	60	0.000	0.369	2.713	0.476	2.661	5.3	0.188	94	0.435	0.33
132	2.4	1120	570	855	60	1.600	0.456	2.194	0.464	2.155	5.3	0.19	60	0.417	0.33

TABLE VII

RAW DATA FOR F:M LOADING RATIO OF 0.75 $\frac{(\text{Lbs}\cdot\text{BOD})}{(\text{Lbs}\cdot\text{MLVSS})}$ day

S_i mg/ℓ	S_e mg/ℓ	X mg/ℓ	X_o mg/ℓ	X_{av} mg/ℓ	X_e mg/ℓ	F_w ℓ/d	u	1/u	F:M	1/F:M	θ_c day	$1/\theta_c$	$S_i u$	$1/S_e$	td day
120	3.5	675	320	490	20	1.500	0.715	1.399	0.74	1.358	1.2	0.826	86	0.286	0.33
119	3.4	660	330	500	15	1.381	0.695	1.439	0.72	1.398	1.4	0.715	83	0.294	0.33
130	3.8	670	320	500	20	1.446	0.759	1.318	0.78	1.279	1.3	0.78	99	0.263	0.33
126	3.1	680	320	490	20	1.500	0.754	1.326	0.77	1.294	1.2	0.832	94	0.323	0.33
124	3.5	660	330	530	15	1.381	0.684	1.463	0.71	1.422	1.5	0.675	85	0.286	0.33
122	4.3	730	416	518	24	1.848	0.683	1.464	0.71	1.412	1.0	1.023	83	0.233	0.33
125	2.7	620	370	510	28	1.028	0.721	1.387	0.74	1.357	1.7	0.584	90	0.370	0.33
120	3.1	650	410	498	30	1.315	0.706	1.416	0.73	1.379	1.3	0.756	85	0.323	0.33
111	3.0	585	400	505	19	0.600	0.643	1.555	0.7	1.513	2.9	0.349	71	0.333	0.33
124	2.1	610	320	508	15	1.027	0.722	1.385	0.74	1.361	2.0	0.511	90	0.476	0.33
120	3.0	695	350	510	17	1.577	0.690	1.450	0.71	1.414	1.2	0.836	83	0.333	0.33
123	2.4	670	350	510	18	1.446	0.711	0.407	0.73	1.379	1.3	0.755	86	0.417	0.33
116	2.6	670	320	488	14	1.346	0.699	1.430	0.72	1.398	1.4	0.722	71	0.385	0.33
130	2.8	655	320	515	13	1.348	0.743	1.347	0.76	1.318	1.5	0.666	97	0.357	0.33
126	2.7	710	330	585	14	1.685	0.634	1.578	0.76	1.544	1.3	0.775	80	0.370	0.33

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