THE IMPACT OF SUBSTRATE MASS LOADING RATE (F/M RATIO) ON THE EFFLUENT QUALITY IN AN ACTIVATED SLUDGE PROCESS

By

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Dedicated to my parents, who always stimulated my initiative and never failed to make me proud.

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A very special acknowledgment is due to my parents and family for their sacrifices and encouragement during my stay in the United States.

I am also thankful to Mrs. Lou Ann Mitchel, for typing the rough draft of this thesis.

According to Helen Keller, "The best educated human being is one who understands most about the life in which he is placed" the author believes that life assumes validity and significance when one commits his life to a higher being. The author hopes that he may grow in love and help to construct a better world.

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LIST OF SYMBOLS AND UNITS USED IN THE STUDY

BOD_5	Biochemical oxygen demand, (mg/l).
COD	Chemical oxygen demand, (mg/l).
F	Flow rate, (l/day).
F/M	Food to microorganism ratio $\frac{FSi}{XV}$, (mg/mg:day)
Fw	Waste sludge flow rate, (l/day).
K	Lawerence and McCarty maximum substrate utilization rate, (1/day).
K_B	Kincannon and Stover saturation constant, (1/day).
Kd	Maintenance energy or decay coefficient, (1/day).
Ke	Eckenfelder's first order substrate removal rate constant, (1/mg/L-day).
Ks	Saturation constant, (mg/l).
MLSS	Mixed liquor suspended solids, (mg/l).
MLVSS	Mixed liquor volatile suspended solids, (mg/l).
S.D.	Standard deviation.
Se	Effluent substrate concentration. (mg/l).
Si	Influent substrate concentration, (mg/l).
SRT	Sludge retention time, Θc, (days).
t	Hydraulic detention time, (days).
U	$\frac{Si-Se}{Xt}$, specific substrate utilization rate. (1/ day).

Umax	Maximum substrate utilization rate, (1 day).
V	Reactor volume, (liters).
X	Biological solids, (mg/l).
EA	Egg Albumen.
Ke	Eckenfelder's second order substrate removal rate constant, (1/day).
Xe	Effluent suspended solids, (mg/L).
XR	Underflow solids concentration, (mg/L).
Yt	True cell yield.
μn	Observed growth rate, (1/day).
μmax	Maximum growth rate, (1/day).

CHAPTER I

INTRODUCTION

Since the discovery by man that water could be used to dilute and transport unwanted materials, the aquatic environment has been the unfortunate recipient of much of his waste products. The activated sludge process, where heterogeneous microbial populations are predominantly responsible for degradation of polluted matter, is widely used in treatment of municipal and industrial wastewaters. Considerable variations in both wastewater flow and the concentration and nature of its organic constituents occur as a function of time. Corresponding variations that occur in industrial wastewaters are even more extreme.

Due to these variations, it is becoming more and more difficult to maintain and achieve a high quality effluent. Several studies have been conducted to elucidate a model suitable for the prediction of future performance and the improvement and control of existing operations. In addition, if possible, the model should be suitable for scale-up of laboratory or pilot-plant data and the design and sizing of new equipment. Of particular interest is the formulation of the kinetic part of the model because the design or operation

of the aeration basin may be quite sensitive to changes in the kinetic coefficients.

The kinetics of biological reactions involved in wastewater treatment have been studied in laboratories and in operating plants for a long period of time. Many models have been used in attempts to describe biological treatment processes in terms of various easily-measured variables, but none of the models have been able to represent accurately all of the laboratory and field data. This is expected in view of the heterogeneous nature of the microbial populations and the difficulty of measuring the properties of the substrate.

Several investigators have proposed mathematical models describing the substrate removal mechanism. Monod was one of the first to propose a reasonable mathematical model defining the interaction between nutrient utilization and bacterial growth and the dependency of the growth rate constant on the concentration of the growth controlling nutrient.

Some investigators (15) (16) have made modifications in the original Monod equations in order to develop models that would accurately describe observed experimental data. Lawrence and McCarty, Eckenfelder, and Gaudy's models all state that the concentration of substrate in the effluent is independent of the influent substrate concentration.

Unfortunately, little work has been done on the effects of influent substrate concentration on the growth of microorganisms in continuous cultures. Harlow (13) and Grady et al., (12) found that in contrast to the pure culture

results, the effluent concentration was influenced by the concentration of the influent. Grady and Williams (14), using heterogeneous microbial population proposed an empirical model in which the proportionality constant was a function of the influent concentration.

In the face of variable hydraulic and organic loads, varying waste characteristics, and increasingly more stringent standards, the need for better predictive equations (models) for describing effluent quality exists.

In this study a biological reactor was subjected to synthetic wastewater composed of egg albumen. Two concentrations of the feed were utilized with several solids retention times (SRT) employed for each concentration. For the two substrate concentrations, separate treatability studies were conducted using internal recycle activated sludge treatment units to study the impact of the influent feed rate on the effluent quality and to determine the biokinetic constants for several models and evaluate which was better for predicting the effluent quality.

CHAPTER II

LITERATURE REVIEW

Performance of the activated sludge process is controlled by many different factors. In the past, activated sludge aeration tanks were often designed on the basis of a nominal wastewater retention time. Now, with the development of predictive models based on microbial kinetics, more rational specification of aeration tanks has been possible. The kinetic relationship between growth rate and limiting substrate concentration proposed by Monod (1) was used with success as the basis of the kinetic studies.

The need for a reliable basis for performance prediction in the activated-sludge system lead several investigators to propose mathematical models describing the substrate removal mechanism. The most common are those of Gaudy, Lawrence & McCarty, Eckenfelder, modified Eckenfelder, and Kincannon and Stover. When Lawrence & McCarty, Eckenfelder, and Gaudy's (1) (2) (3) models are used to describe the behavior of a completely mixed continuous flow microbial reactor, whether with or without recycle, the result is an equation which states that the concentration of substrate in the effluent from that reactor depends only upon the solids retention time (SRT) of the organisms within the reactor. In other

words, theoretically the effluent substrate concentration is independent of the influent substrate concentration. This lack of dependence between influent and effluent substrate concentrations implies that a constant effluent quality can be maintained during operation of wastewater treatment plant so long as (SRT) is fixed. Garrett, 1958 (4); Jenkins & Garrison, 1968 (5) have developed hydraulic strategies to control the solids retention time (SRT) and consequently control the activated-sludge process. This lack of dependence, also implies that bench and pilot scale studies are not necessary to be performed on wastes of concentration expected in the final facility. In other words, once the kinetics of a certain waste have been determined, they can be used for a waste with any concentration.

Unfortunately, little work has been done on the effects of influent substrate concentration on the growth of the microorganisms in continuous cultures. Contois (5) proposed that the saturation constant of the Monod equations (Ks) was a function of the growth-limiting nutrient concentration in the influent. Fujimoto (7) proposed equations similar to Contois (6), but reported no laboratory verification. Other researchers (8) (9) (10), however, have proposed that missing in the reactor effects the basic dependence of specific growth rate upon the concentration of growth-limiting nutrient. Riesing (11) tested two different cultures grown on glucose in a continuous stirred tank reactor and found

that the concentration of the nutrient (glucose) was indeed independent of the influent glucose concentration, as theory had stated (12).

Due to the complexity of the systems that are facing the bioenvironmental engineers, researchers started looking at mixed microbial cultures growing on glucose. Harlow (13) and Grady et al., (12) found that in contrast to the pure culture results, the glucose concentration of the effluent was influenced by that of the influent. Moreover, they found that the concentration of soluble organics measured as COD were significantly affected by the influent concentration in pure and mixed culture experiments. This tells us when dealing with wastewater, unknown composition, and using COD, non-specific measure of the composition is independent of the concentration of the incoming waste can no longer be of value. Grady and Williams (14), using heterogeneous microorganisms and a multicomponent substrate as the influent and employing the Monod model, with first-order approximation ($S<Ks$), proposed an emperical model in which the proportionality constant is a function of the influent concentration expressed as biodegradable COD.

Considerable progress has been made in the development of design methods for the sizing of activated-sludge wastewater treatment processes (15) (16). Mean cell residence time has been the major factor resulting from these developments. Most design models state that the concentration of biodegradable organic matter decreases as

the solids retention time increases. However, data collected by researchers (17) (18) from both laboratory experiments and full-scale treatment systems shows that design models do not always accurately predict effluent quality. Five of these models are shown in Table 1 extracted from Stover and Gomathinayagam (19) which shows the expression for substrate utilization rate of each model in terms of biokinetic constants or coefficients required for use in each of the design models.

Material balances for biomass and substrate may be drawn around the aeration basin as in Gaudy's and Weston models while the others draw their mass balances around both the aeration basin and the final clarifier. Assuming steady state conditions, the mass balance equations can be solved for effluent substrate concentration, mix liquor suspended solids volume of aeration basin and excess sludge production by substituting the appropriate utilization rate term into the material balance equations. An example is shown below:

$$\left(\frac{ds}{dt}\right)_R V = FSi - FSe - \left(\frac{ds}{dt}\right)_g V \quad (1)$$

change of mass in reactor = mass entering the reactor - mass leaving the reactor - mass consumed biologically

For steady state $\left(\frac{ds}{dt}\right)_R = 0$, and $\left(\frac{ds}{dt}\right)_g V = FSi - FSe$ (2)

A major difficulty with the use of current activated-sludge design models faced the investigators in Oklahoma State University laboratories when trying to apply the data collected from bench scale activated-sludge

TABLE I

KINETIC EXPRESSIONS FOR SUBSTRATE REMOVAL DUE TO GROWTH EMPLOYED FOR VARIOUS MODELS

Eckenfelder	$(ds/dt)g = Ke\ X\ Se$
Eckenfelder Modified	$(ds/dt)g = (Ke\ Se\ X/Si)$ $(ds/dt)g = (Ke\ Se\ X/Si)$
Kincannon and Stover	$(ds/dt)g = \frac{FSI/XV}{K_B + FSi/XV} \frac{Umax\ X\ (FSi/XV)}{K_B + (FSi/XV}$
Lawrence and McCarty	$(ds/dt)g = (K\ X\ Se)\ /\ (Ks + Se)$
Gaudy	$(ds/dt)g = (umax\ X\ Se)\ /\ [Yt\ (Ks + Se]$

treatability studies upon thirty-three synthetic wastewaters to determine the biokinetic coefficients for each of Eckenfelder (second order) and Lawrence and McCarty, and Gaudy's models (19). The data were so badly scattered so that little, if any, meaningful values for the so-called biokinetic constants could be determined, which made the accurate predictions of effluent organic matter not possible and called for reevaluation of the assumptions on which those models were based.

The inability of the design models to accurately predict effluent quality had led to the introduction of the Kincannon and Stover model (19) (20) (21) (22) in which the scatter of the data present by using the rest of the models was reduced considerably when plotting the substrate utilization rate Si-Se/Xt as a function of the total organic loading F/M ration (FSi/XV). From this plot, the relationship obtained also fits a Monod-type relationship.

The above model was developed by writing the following mass balance for substrate around the aerator-clarifier envelope and assuming steadystate operation the following equations may be developed:

$$\left(\frac{ds}{dt}\right)_g V = FSi - Fse \quad (1)$$

When the substrate removal term (due to growth) is expressed as:

$$\left(\frac{ds}{dt}\right)_g = Umax \times \frac{FSi/XV}{K_B + FSi/XV} \quad (2)$$

by substituting equation (2) in equation (1):

$$\frac{Umax \times FSi/XV \quad V}{K_B + FSi/XV} = FSi - FSe \quad (3)$$

From equation (3) the following equations may be developed:

$$Se = Si - \frac{Umax}{K_B + FSi/XV} \qquad (4)$$

$$XV = \frac{FSi}{[\ (Umax\ Si)\ /\ (Si-Se)\ ] - K_B} \qquad (5)$$

A reciprocal plot of substrate utilization rate (Si-Se)Xt versus F/M ratio (FSi/V) should yield a straight line with an intercept corresponding to the reciprocal of the maximum specific substrate utilization rate and slope equivalent to K_B/Umax (K_B = Kincannon and Stover saturation constant).

Kincannon and Stover model (22) is the only model that expresses substrate utilization rate as a function of mass loading, and so it has been successful in eliminating the scatter in the biokinetic constants determination. Therefore, the Kincannon and Stover model seems to provide a better tool for the design based on accurate and consistent predictions of effluent organic matter when the specific loading (F/M) ratio is maintained. This study was completed before the development of this model. The researcher will use the data from this study to evaluate the ability of this model and other models to predict the effluent quality.

CHAPTER III

MATERIALS AND METHODS

To study the impact of the feed rate (F/M ratio) on the concentration of soluble carbon source in the reactor effluent, pilot plant activated-sludge units were operated under continuous feed conditions. Description of the laboratory apparatus, feed solution, initial set up, and parameters monitored in their investigation follow.

Laboratory Apparatus

A schematic diagram of the laboratory set up used in this investigation is shown in Figure 1. The biological activated-sludge reactor employed was a rectangular plexiglass unit divided by an adjustable baffle into an aeration chamber and clarifier. A soluble Egg Albumen feed was supplied at a rate of 8.3 ml/minute to provide a hydraulic detention time of six hours in the 3 liter aeration chamber. This was done by variable speed Cole-Parmer master flex pump.

Air was supplied to the aeration chamber through diffuser stones to provide oxygen to the microbial population as well as to mix the reactor contents. Every time the feed solutions were made up, the feed tube line, feed bottles and

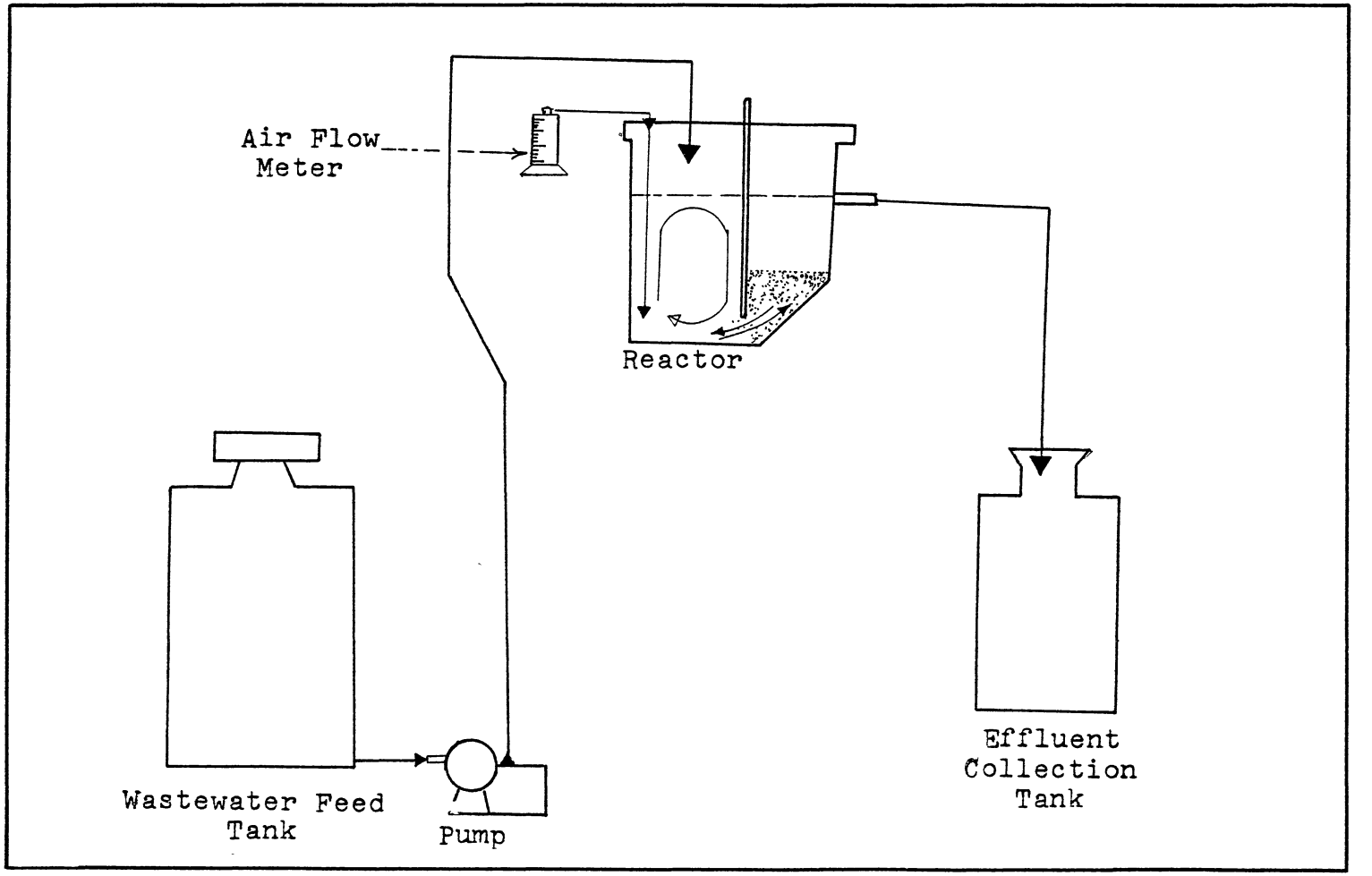


Figure 1. Schematic Diagram of Experimental System

the effluent bottles were cleaned with chlorox and rinsed several times with tap water to prevent bacterial growth in these parts of the system.

Egg Albumen was used as the carbon source. Two feed concentrations 150 and 300 ppm Egg Albumen were fed simultaneously to two reactors like the one shown in Figure 1. Tap water was used to provide the trace elements required for microbial growth. Egg Albumen was blended to homogenize the stock solution. A strong phosphate buffer (.01 M) was provided in the synthetic wastewater to supply phosphorus and, also, to maintain a neutral pH in the biological reactors.

Initial Setup

The original microorganism needed for the activated-sludge units came from the Tulsa, Oklahoma Municipal Wastewater Treatment Facility (southside plant) which utilizes activated-sludge treatment. Once an acclimated population was developed, this sludge was employed during the entire period where each of the synthetic wastewater concentrations were treated. After the steadystate conditions were achieved, the data necessary for the treatability study was collected.

The biological units were operated at different constant solids retention time. Four mean cell residence times were investigated for each concentration. Suspended solids were performed on the mixed liquor and effluent samples daily.

Solids wastage, based upon that day's suspended solids analysis, was done by wasting the appropriate volume from the aeration basin.

Analytical Techniques

Methods for the determination of experimental parameters are shown below:

Chemical Oxygen Demand (COD) Test. The COD technique was used to measure the strength of the organic compound in the feed, and effluent. The procedure followed was that outlined in Water and Wastewater Analysis Manual. Hach Chemical Company (25).

Egg Albumen. Colorometric; Coomassiedye binding technique on effluent samples concentrated by Lyophilization. The procedure followed was provided by Biorad Biochemical Company (24).

Biological Oxygen Demand (BOD) Test. The procedure followed was that outlined in standard methods with modified seed correction; Orion Research D.O. probe utilized (23) (26).

Suspended Solids. Samples were filtered through a dried, preweighed glass fiber filter (Reeve Angel 93A-AH) and dried in 103 degrees C oven. The filter was then combusted to 550 degrees C for twenty minutes then reweighed to determine volatile suspended solids.

pH. The Orion pH Meter (Model 701) was used to check the pH in the reactor.

CHAPTER IV

RESULTS

Figures 2-7 show the average performance for the two reactors, which were subjected to influent concentration of 150 and 300 mg/1 egg albumen, respectively. Hydraulic retention time was maintained at fairly constant value of 0.25 days. Four solids retention times, 1, 2, 6, and 10 days, were investigated for each concentration. The data collected from the activated sludge systems throughout the study were analyzed in terms of three substrate parameters (egg albumen, COD, and BOD). The test results of each parameter at the solids retention time investigated follow:

Egg Albumen

Figures 2 and 3 show the test results for each concentration of egg albumen. It presents values for influent, effluent, and feed rate (F/M ratio) at each solids retention time investigated.

The operational parameters of organic loading (F/M) and effluent substrate concentration for each activated sludge reactor were compared. Figure 2 clearly shows, that, at a solids retention time of one day (1.0), an increase in the organic loading (as measured by egg albumen) had a definite

Figure 2. Operational characteristics of an activated sludge process at different solids retention times when subjected to (Si) of 150.0 mg/L egg albumen

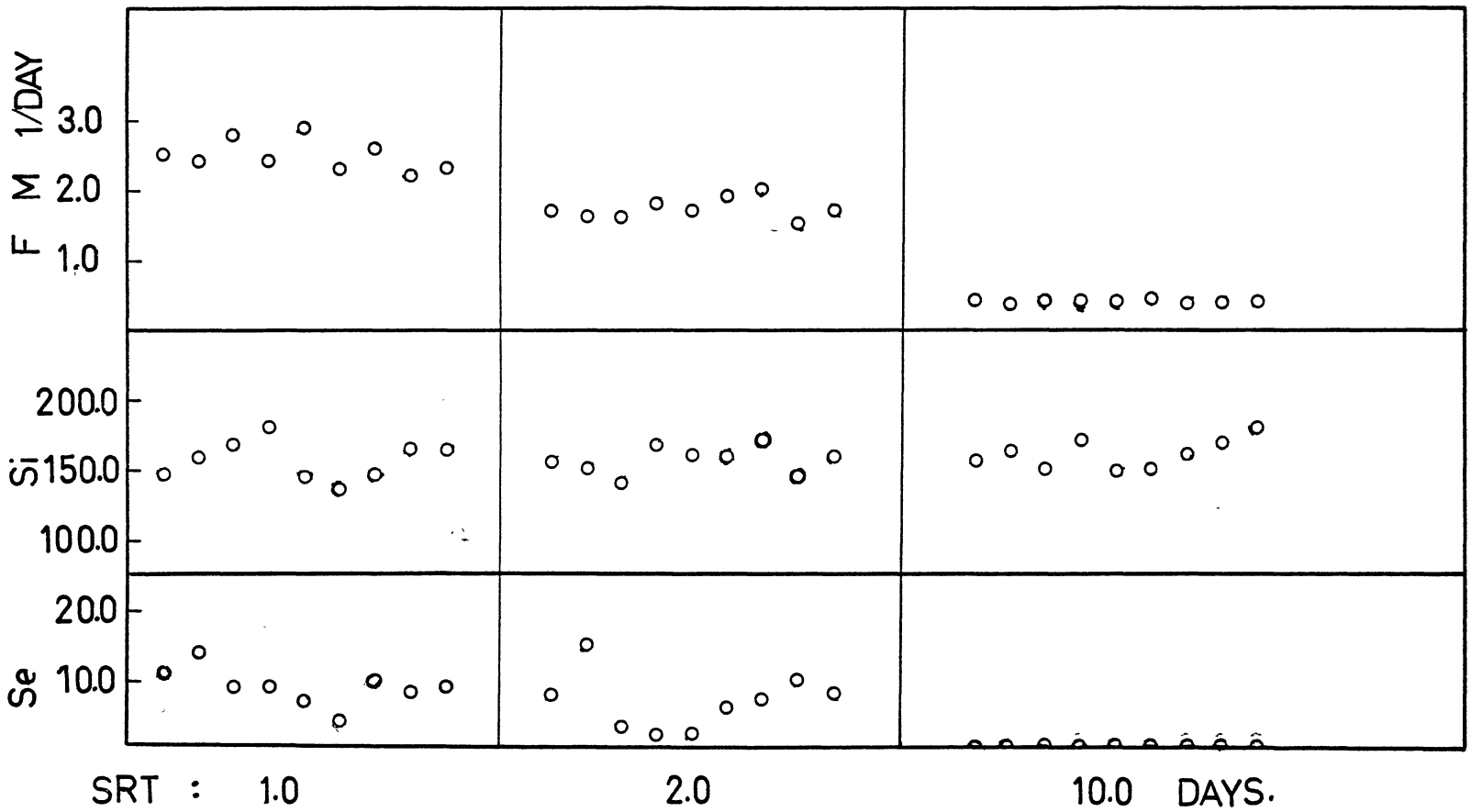
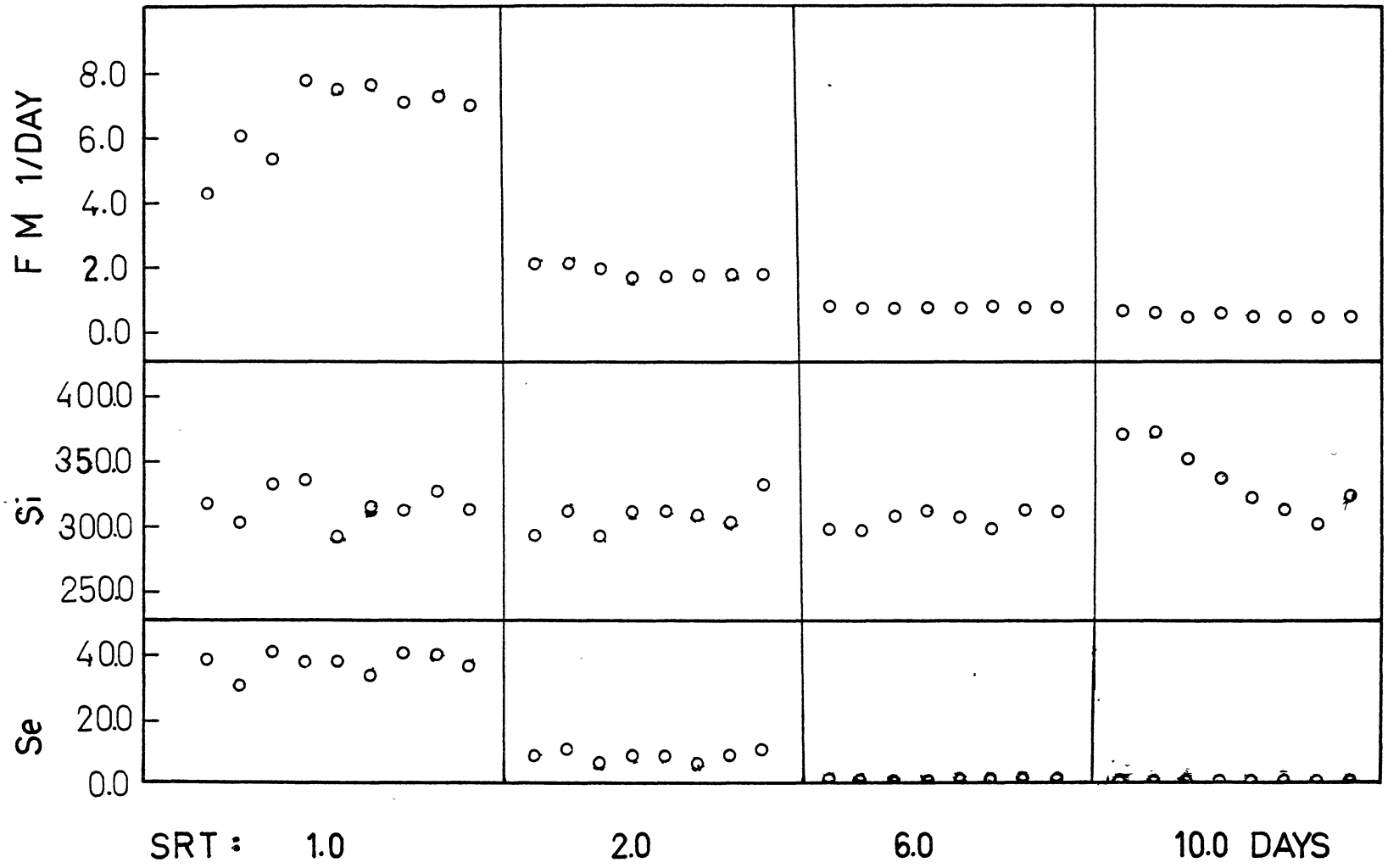

F M 1/DAY
3.0
2.0
1.0
Si
200.0
150.0
100.0
Se
20.0
10.0
SRT : 1.0
2.0
10.0 DAYS.

Figure 3. Operational characteristics of an activated sludge process at different solids retention times when subjected to 300 mg/L egg albumen. Si and Se in mg/l (F:M) in mg/mg. day (In Terms of Egg Albumen)


F M 1/DAY
8.0
6.0
4.0
2.0
0.0
Si
400.0
350.0
300.0
250.0
Se
40.0
20.0
0.0
SRT : 1.0
2.0
6.0
10.0 DAYS

impact on effluent quality. Under these conditions, the mean effluent soluble egg albumen concentration was 36.80 mg/1 for the system subjected to the higher loading and only 9.0 mg/1 for the system subjected to the lower loading rate at the same SRT (as shown in Figure 2).

When the reactors were operated at a solids retention time of 2.0 days smaller difference was observed in the effluent concentrations. Effluent from the reactor operated at F/M ratio of 1.70 averaged 6.8 mg/1, whereas the effluent from the reactor operated at F/M ratio of 1.8 averaged 7.8 mg/1.

When the reactors were operated at solids retention times of 6.0 and 10.0 days the effluent soluble egg albumen concentrations from both reactors were undetectable. The total organic loading (F/M) on both systems were less than 1.0.

Chemical Oxygen Demand

Figures 4 and 5 show the operational data measurements in terms of (COD). At a solids retention time of one day the effluent from the reactor operated at mean F/M ratio of 6.0 averaged 147.0 mg/1; whereas, the effluent from the reactor operated at mean F/M ratio of 2.6 averaged 37.0 mg/1.

When the reactors were operated at a solids retention time of 2.0 days smaller difference was observed in the effluent concentrations. Effluent from the reactor subjected to organic loading (F/M of 1.8 averaged 36.50 mg/1 soluble

Figure 4. Operational characteristic of an activated sludge process at different solids retention times when subjected to 150 mg/L egg albumen Si and Se in mg/l, (F:M) in mg/mg day. (In Terms of COD)

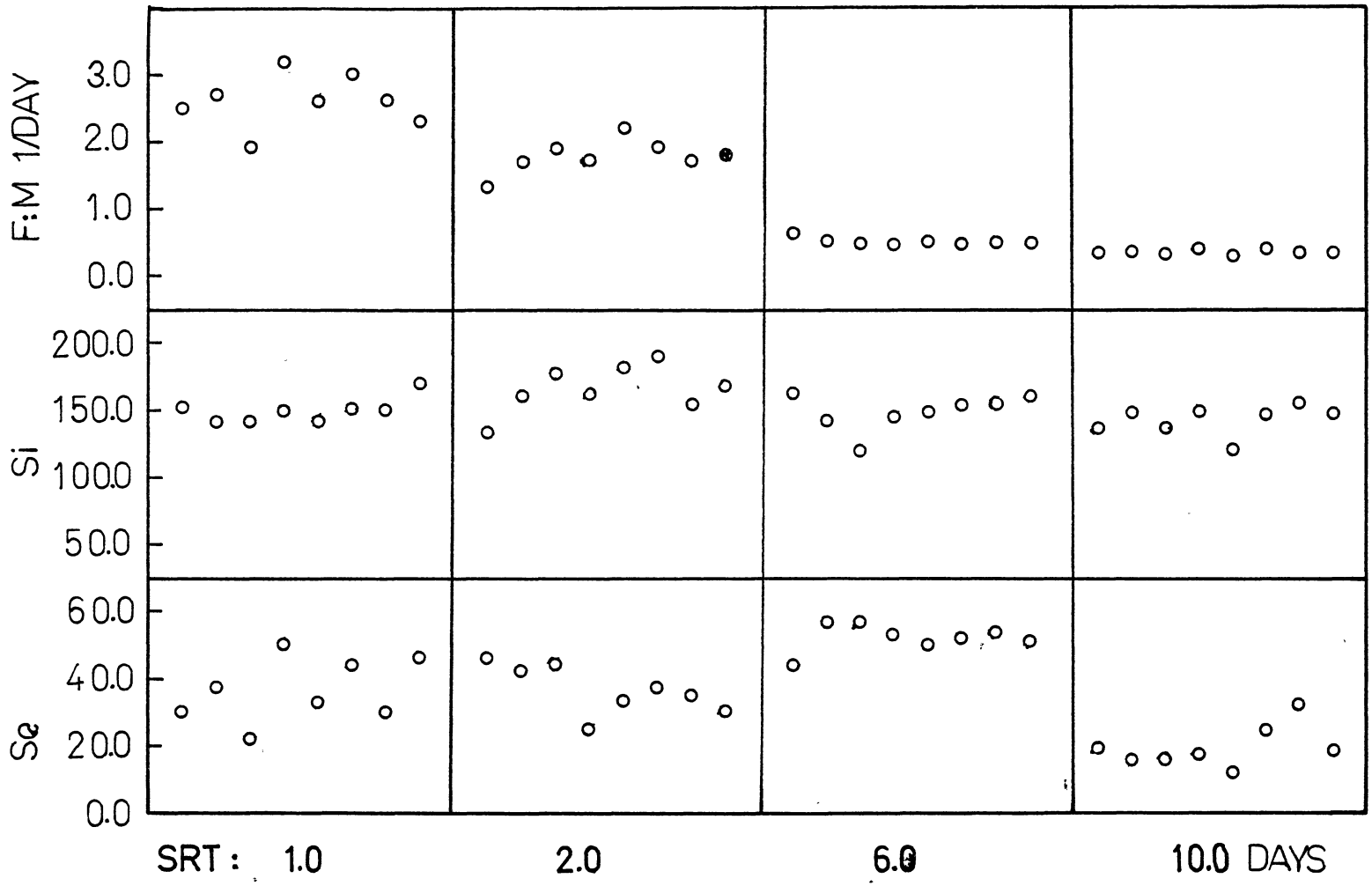
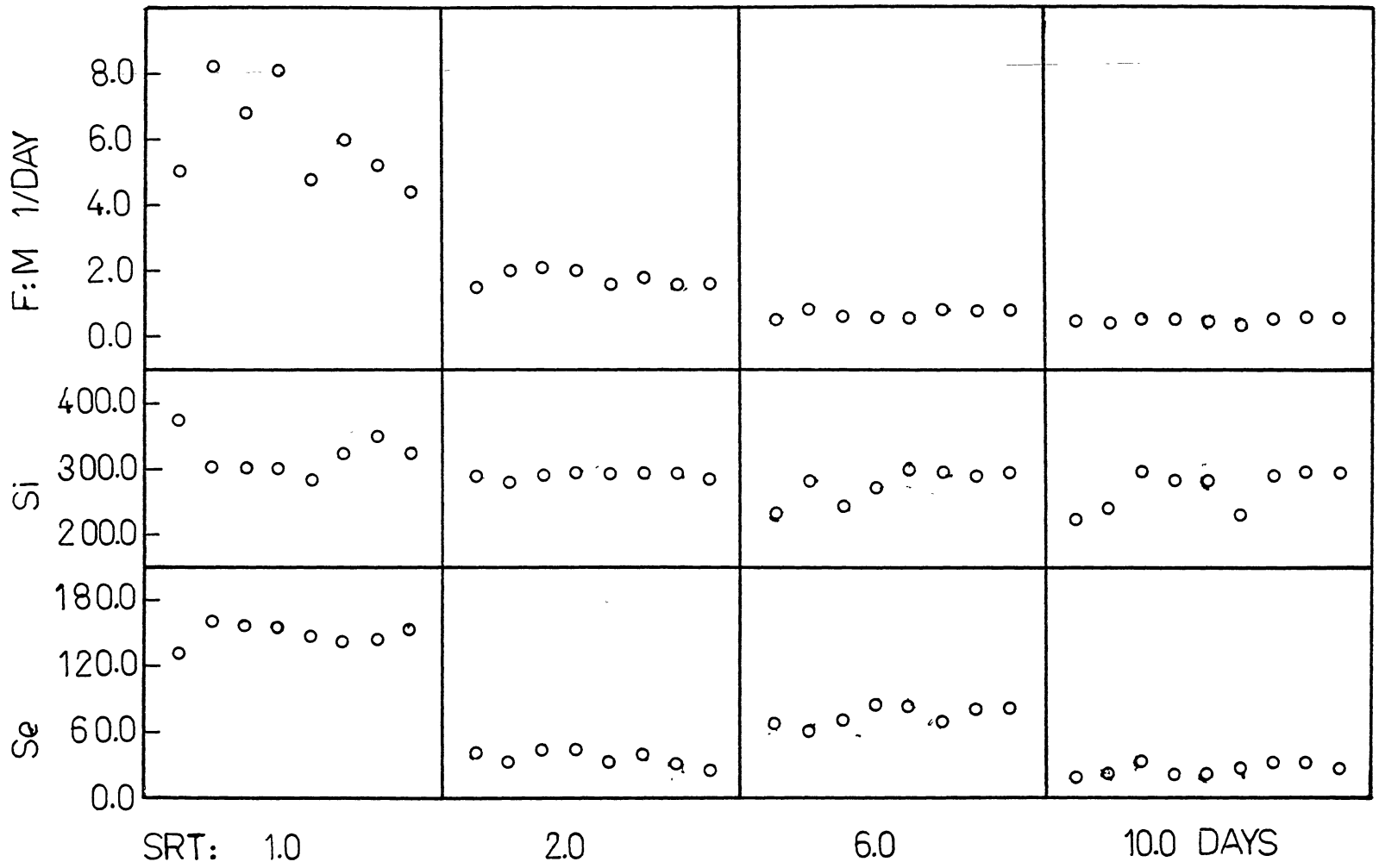

F:M 1/DAY
3.0
2.0
1.0
0.0
Si
200.0
150.0
100.0
50.0
Se
60.0
40.0
20.0
0.0
SRT : 1.0
2.0
6.0
10.0 DAYS

Figure 5. Operational characteristics of an activated sludge process at different solids retention times when subjected to 300 mg/L egg albumen Si and Se in mg/l, (F:M) in mg/mg day. (In Terms of COD)


F:M 1/DAY
8.0
6.0
4.0
2.0
0.0
Si
400.0
300.0
200.0
Se
180.0
120.0
60.0
0.0
SRT: 1.0
2.0
6.0
10.0 DAYS

COD, whereas the system subjected to F/M ratio of 1.7 averaged a soluble COD value of 35.75 mg/1).

Next the reactors were operated at a solids retention time of 6.0 days. Under this operational condition the system that was subjected to an F/M ratio of 0.70 showed an average soluble COD in the effluent of 75.0 mg/1, whereas the system subjected to an F/M ratio of 0.50 average an effluent COD of 52.0 mg/1.

Next the solids retention time was increased to 10.0 days, at this operational condition the loading on both reactors was less than 1.0 and the effluent soluble COD concentrations from the reactor subjected to F/M ratio of 0.44 averaged 24.0 mg/1, wereas the effluent from the reactor subjected to F/M ratio of 0.35 averaged 10.3 mg/1.

Biochemical Oxygen Demand (BOD)

Figures 6 and 7 show the operational data measurement in terms of (BOD). Starting at a solids retention time of one day the effluent from the reactor operated at mean F/M ratio of 3.4 averaged 52.80 mg/1; whereas, the effluent from the reactor operated at F/M ratio of 1.7 averaged 9.70 mg/1.

When the reactors were operated at solids retention time of 2.0 days a smaller difference was observed in the effluent concentration. Effluent from the reactor operated at F/M ratio of 0.86 averaged 5.50 mg/1, wereas the effluent from the reactor operated at F/M of 0.89 averaged only 4.30 mg/1 soluble BOD.

Figure 6. Operational characteristics of an activated sludge process at different solids retention times when subjected to (Si) of 150.0 mg/L egg albumen Si and Se in mg/l, (F:M) in mg/mg day. (In Terms of BOD)

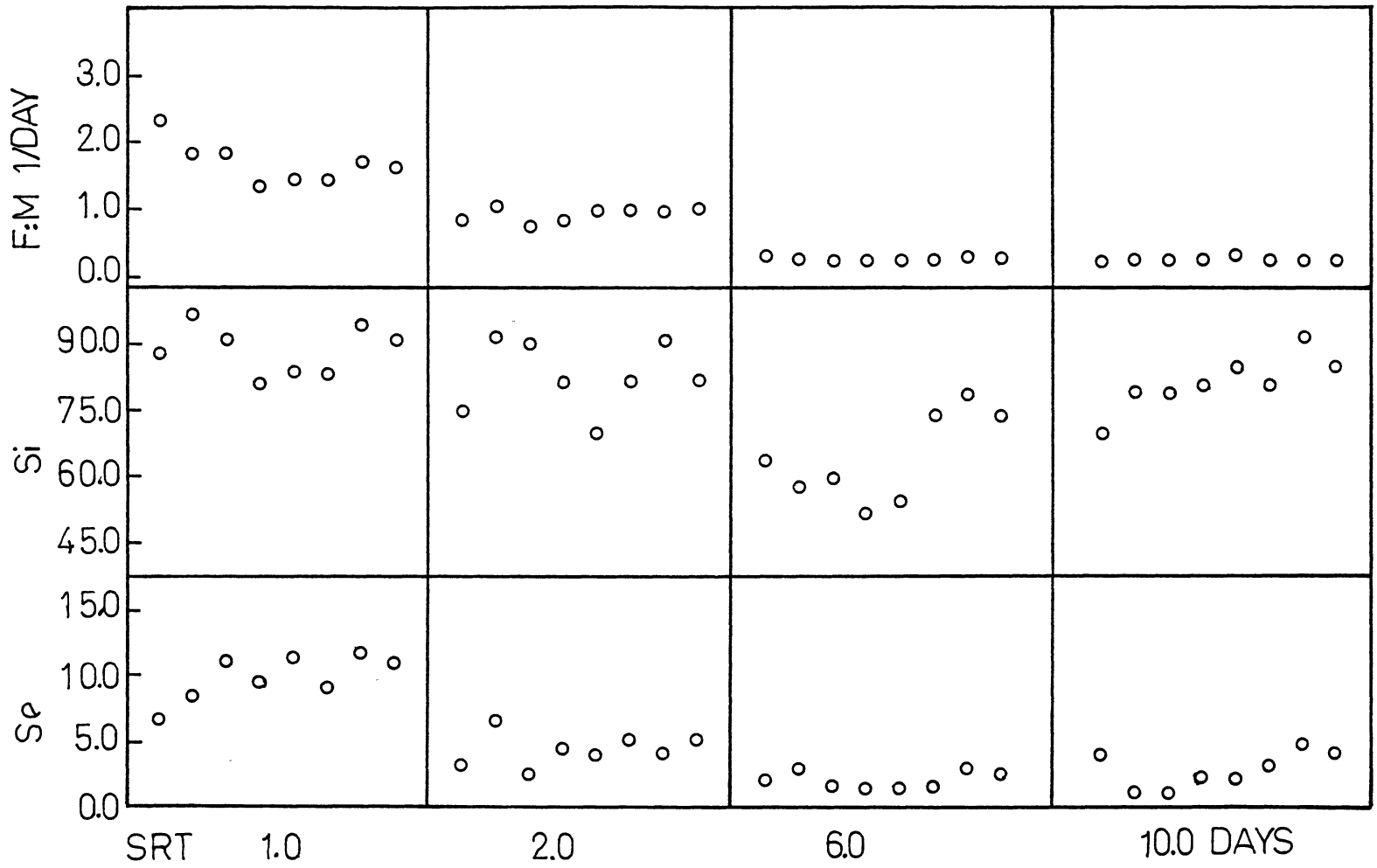
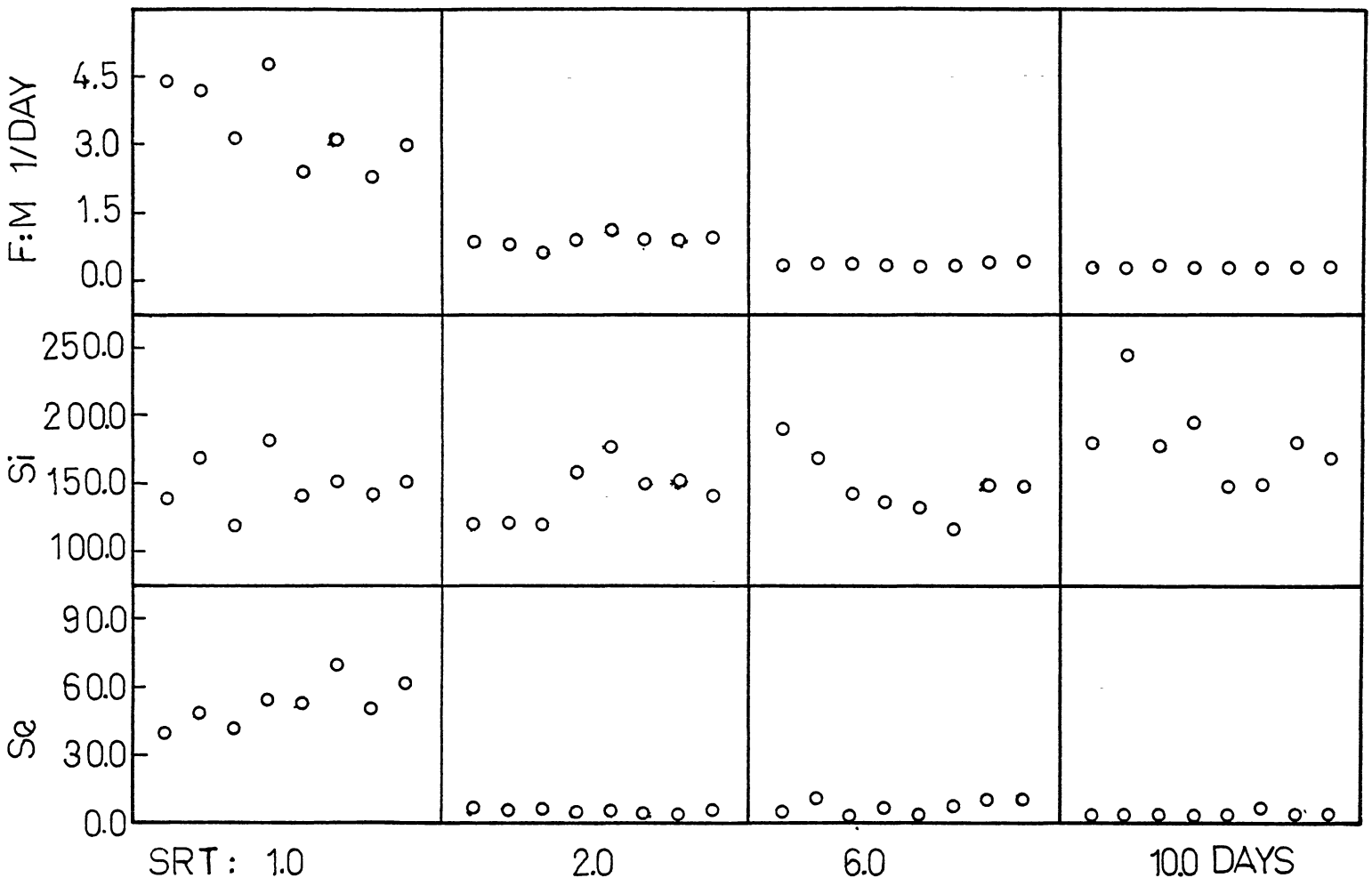

F:M 1/DAY
3.0
2.0
1.0
0.0
Si
90.0
75.0
60.0
45.0
Se
15.0
10.0
5.0
0.0
SRT
1.0
2.0
6.0
10.0 DAYS

Figure 7. Operational characteristics of an activated sludge process at different solids retention times when subjected to (Si) of 300.0 mg/L egg albumen, Si Se in mg/l, (F:M) in mg/mg day. (In Terms of BOD)


F:M 1/DAY
4.5
3.0
1.5
0.0
Si
250.0
200.0
150.0
100.0
Se
90.0
60.0
30.0
0.0
SRT: 1.0
2.0
6.0
10.0 DAYS

Next the solids retention time for both systems were increased to 6.0 and 10.0 days respectively. Under these operational conditions the reactors were subjected to BOD loading less that 0.50. The average effluent soluble BOD observed in both reactors ranged from 1.9 to 6.5 mg/1.

Kinetic Constant Determination

The data for each individual egg albumen concentration were utilized to determine combined biokinetic constants for Eckenfelder, Eckenfelder modified, Lawrence and McCarty, Gaudy, and Kincannon and Stover models. All the plots utilized to determine the biological constants were performed upon all three parameters (Egg Albumen, COD, and BOD).

In Figures, 8, 9, and 10 the net specific growth rate (μn) is plotted as a function of the specific substrate utilization rate (U) for determination of the true yield (Yt) and the endogenous decay or maintenance energy coefficient (Kd), as used in all kinetic design models. The Yt is the slope of the line and Kd is the Y-axis intercept. Yt values for egg albumen, COD and BOD were 0.37, 0.3, and 0.46 respectively. Kd values that correspond to those were 0.09, 0.06, and 0.067.

In Figure 11, 12, and 13, U is plotted as a function of the effluent substrate concentration (Se) for determination of Eckenfelder's first order substrate removal rate constant (Ke). The Ke values, slope of the line, for egg albumen, COD, and BOD were 0.15, 0.14, and 0.047. The Ke values for

egg albumen and COD were very close, however, Ke for BOD was rather low. In Figures 13, 15, and 16, (Si U) is plotted as a function of the effluent substrate concentration (Se) for determination of Eckenfelder`s modified model (second order) substrate removal rate constant. The Ke, slope of the line, for egg albumen, COD, and BOD were 44, 5.1, and 6.9. Ke value for COD and BOD were rather close but Ke of egg albumen was a lot higher.

In Figures 17, 18, and 19, the reciprocal of the specific growth rate, U, is plotted as a function of the reciprocal of Se for determination of the maximum specific growth rate, μmax, and the saturation constant, Ks, as used in the Gaudy design model. The Y-axis intercept is the reciprocal of umax, and the slope is equal to Ks/umax. The umax values for egg albumen, COD and BOD were 1.23, o.53 and 2.6 and the Ks values were 0.65, 45, and 28.2 respectively. As can be seen, the umax in terms of BOD were the highest followed by egg albumen then COD. Saturation constant, Ks, for COD was higher than the BOD and egg albumen saturation constants.

In Figures 20, 21, and 22, the reciprocal of U is plotted as a function of the reciprocal of Se for determination of the maximum substrate utilization rate (K) and the saturation constant, Ks, as used in Lawrence and McCarty design model. The Y-axis intercept is the reciprocal of K, and the slope is equal to Ks/K. The K value for egg albumen, COD, and BOD were 2.43, 1.15, and 2.35,

Figure 8. Graphical Determination of Y_t and K_d in terms of Egg Albumen.

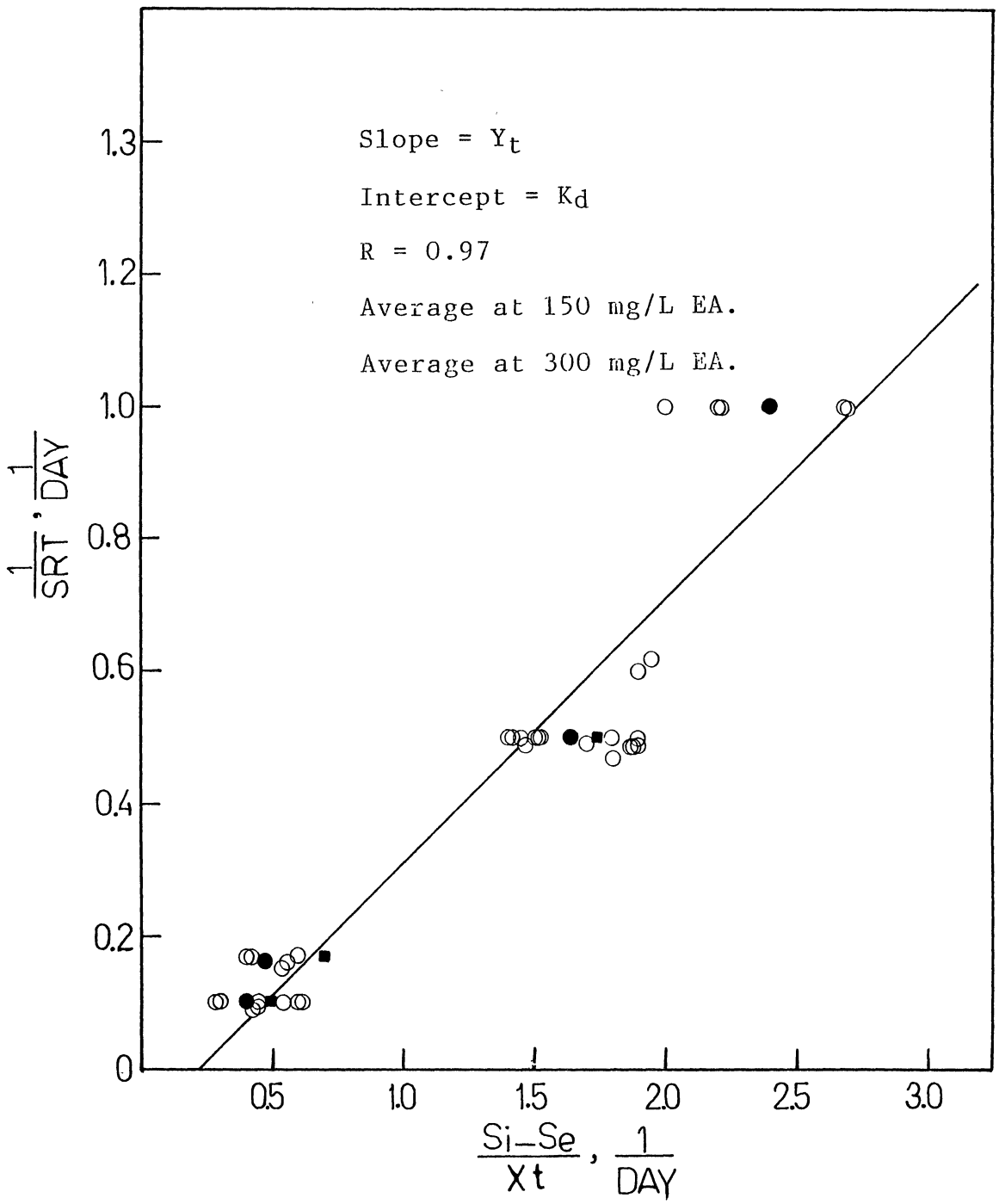

Slope = Y_t
Intercept = K_d
R = 0.97
Average at 150 mg/L EA.
Average at 300 mg/L EA.
1.3
1.2
1.0
0.8
0.6
0.4
0.2
0
$\frac{1}{SRT}, \frac{1}{DAY}$
0.5
1.0
1.5
2.0
2.5
3.0
$\frac{Si-Se}{Xt}, \frac{1}{DAY}$

Figure 9. Determination of Y_t and K_d in terms of COD.

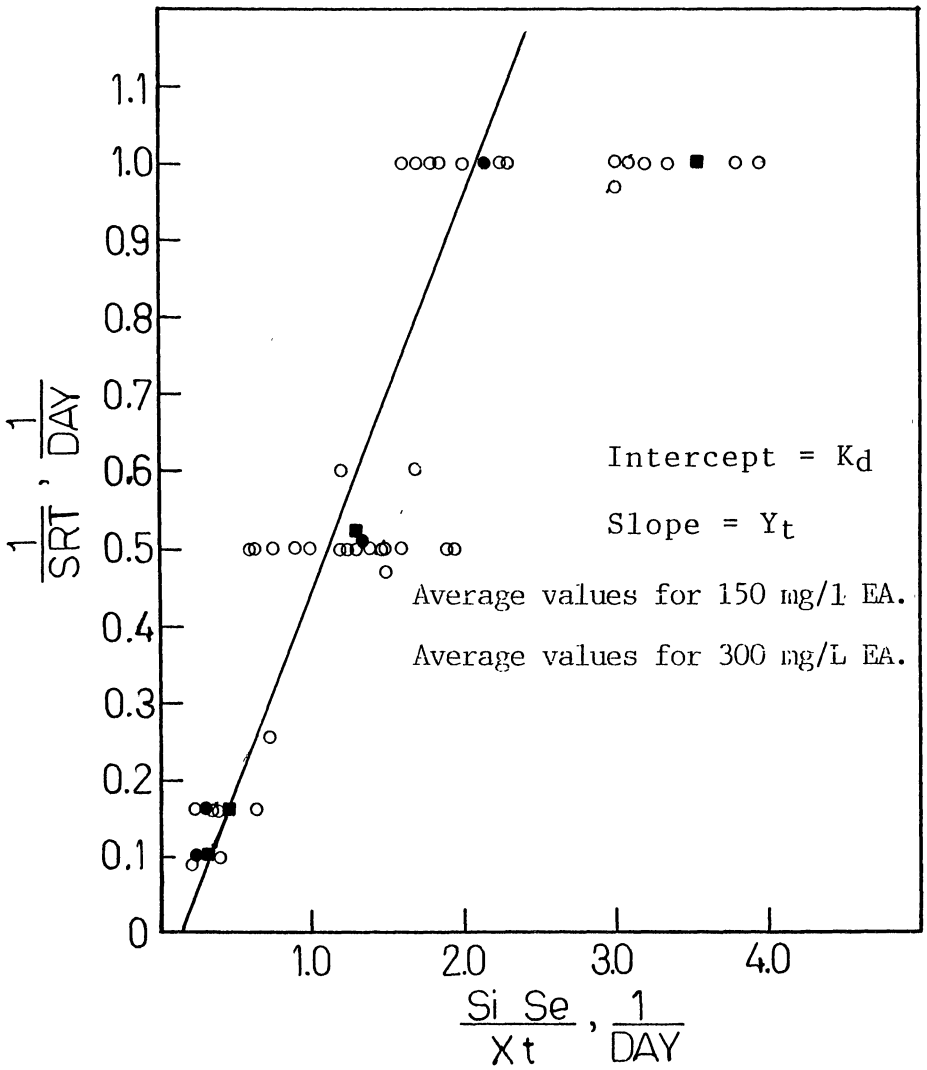

1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.0
2.0
3.0
4.0
1/SRT , 1/DAY
Si Se / Xt , 1/DAY
Intercept = Kd
Slope = Yt
Average values for 150 mg/l EA.
Average values for 300 mg/L EA.

Figure 10. Determination of Y_t and K_d in terms of BOD.

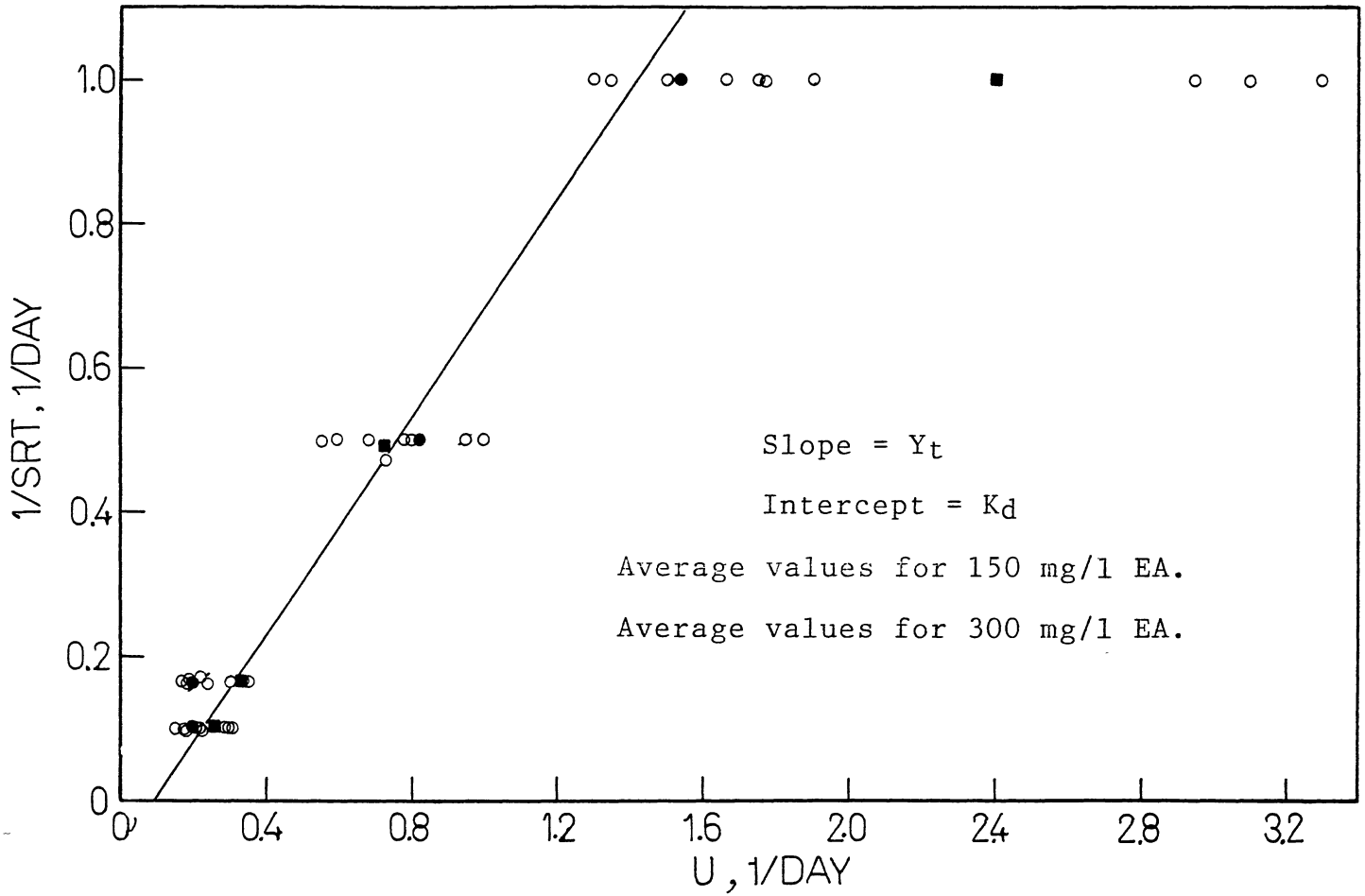

1/SRT, 1/DAY
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
U, 1/DAY
Slope = Y_t
Intercept = K_d
Average values for 150 mg/l EA.
Average values for 300 mg/l EA.

Figure 11. Determination of K_e in terms of Egg Albumen.

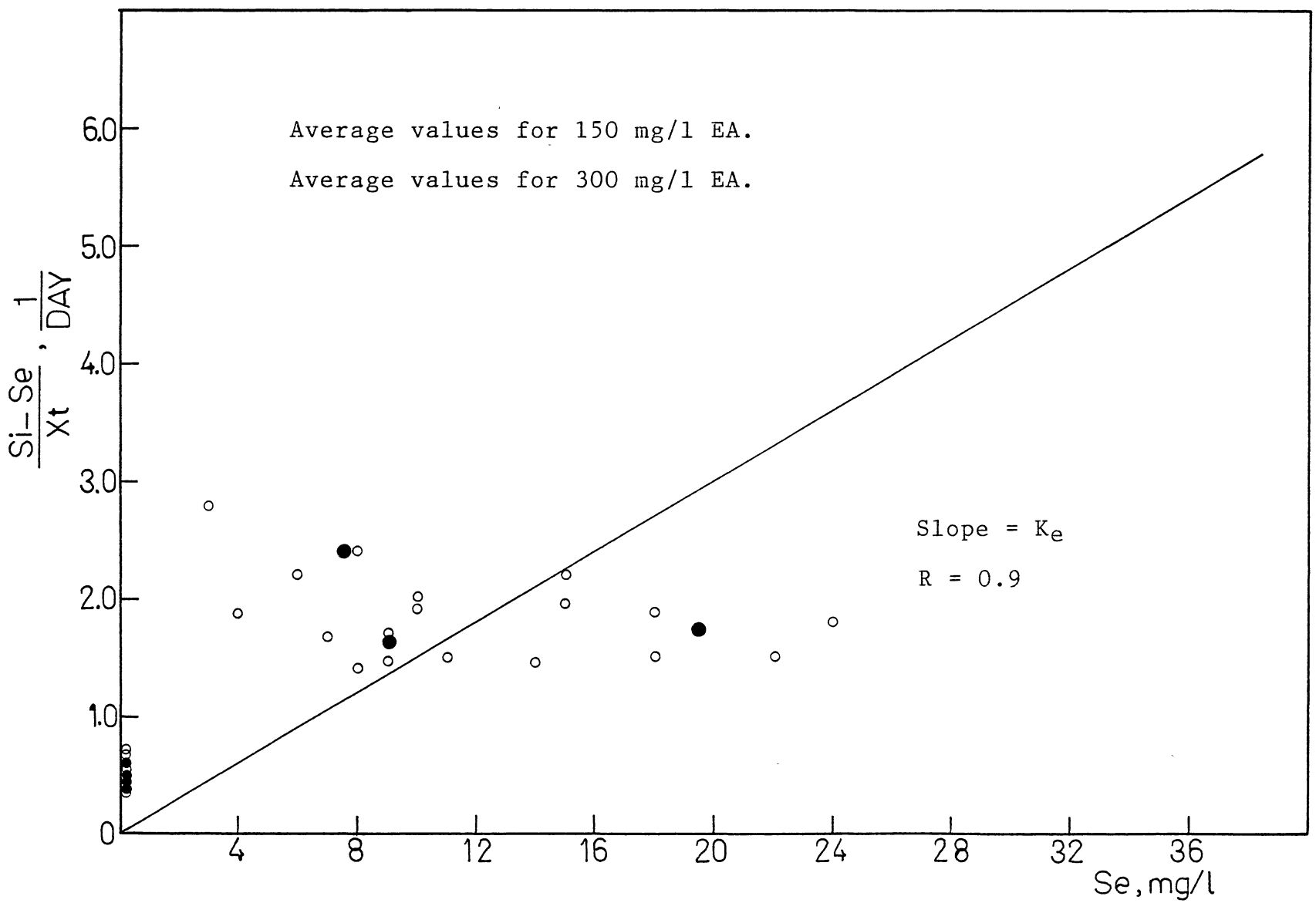

Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
Slope = K_e
R = 0.9
$\frac{Si - Se}{Xt}$, $\frac{1}{DAY}$
6.0
5.0
4.0
3.0
2.0
1.0
0
4
8
12
16
20
24
28
32
36
Se, mg/l

Figure 12. Determination of K_e in terms of COD.

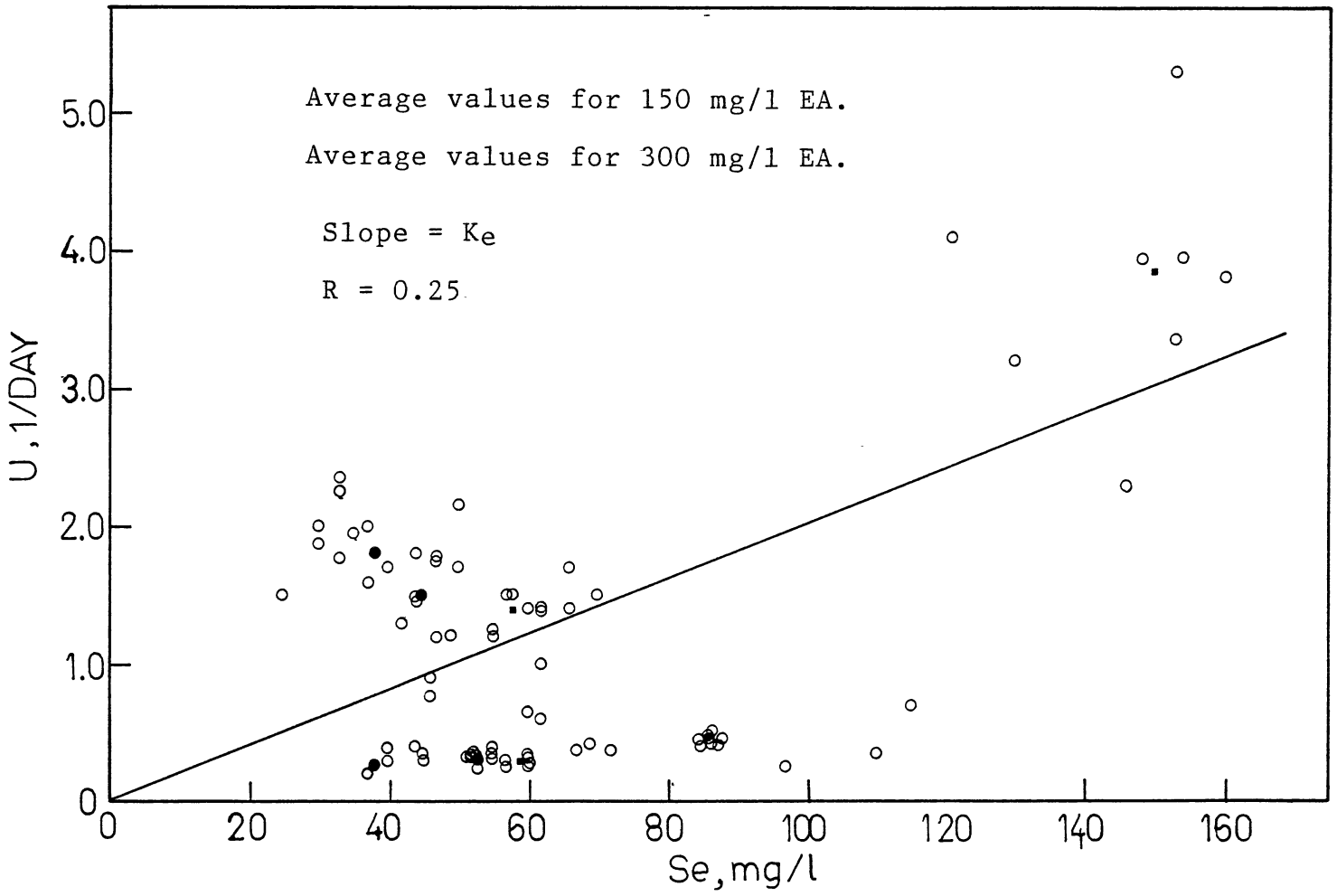

Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
Slope = Ke
R = 0.25
U, 1/DAY
5.0
4.0
3.0
2.0
1.0
0
0
20
40
60
80
100
120
140
160
Se, mg/l

Figure 13. Determination of K_e in terms of BOD.

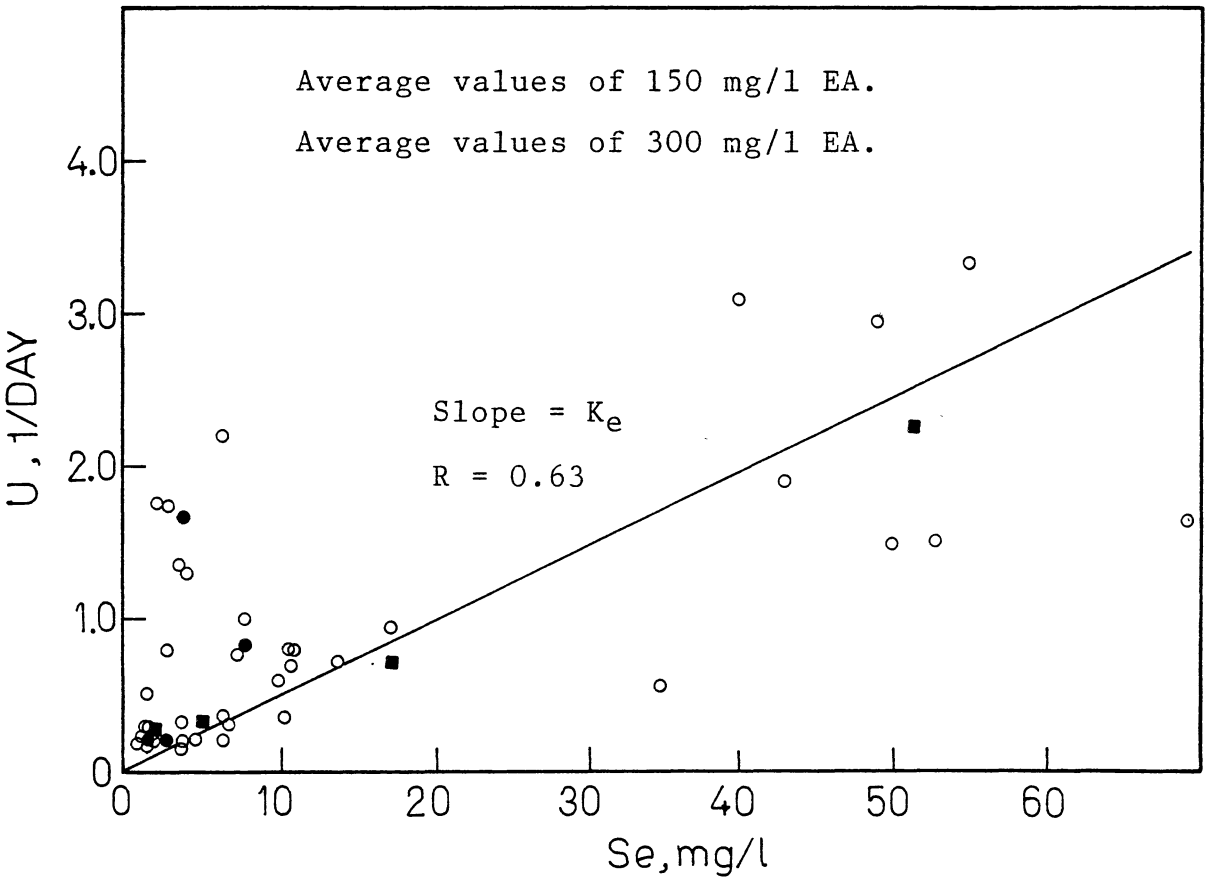

Average values of 150 mg/l EA.
Average values of 300 mg/l EA.
Slope = K_e
R = 0.63
U, 1/DAY
4.0
3.0
2.0
1.0
0
0
10
20
30
40
50
60
Se, mg/l

Figure 14. Determination of K_e' in terms of Egg Albumen.

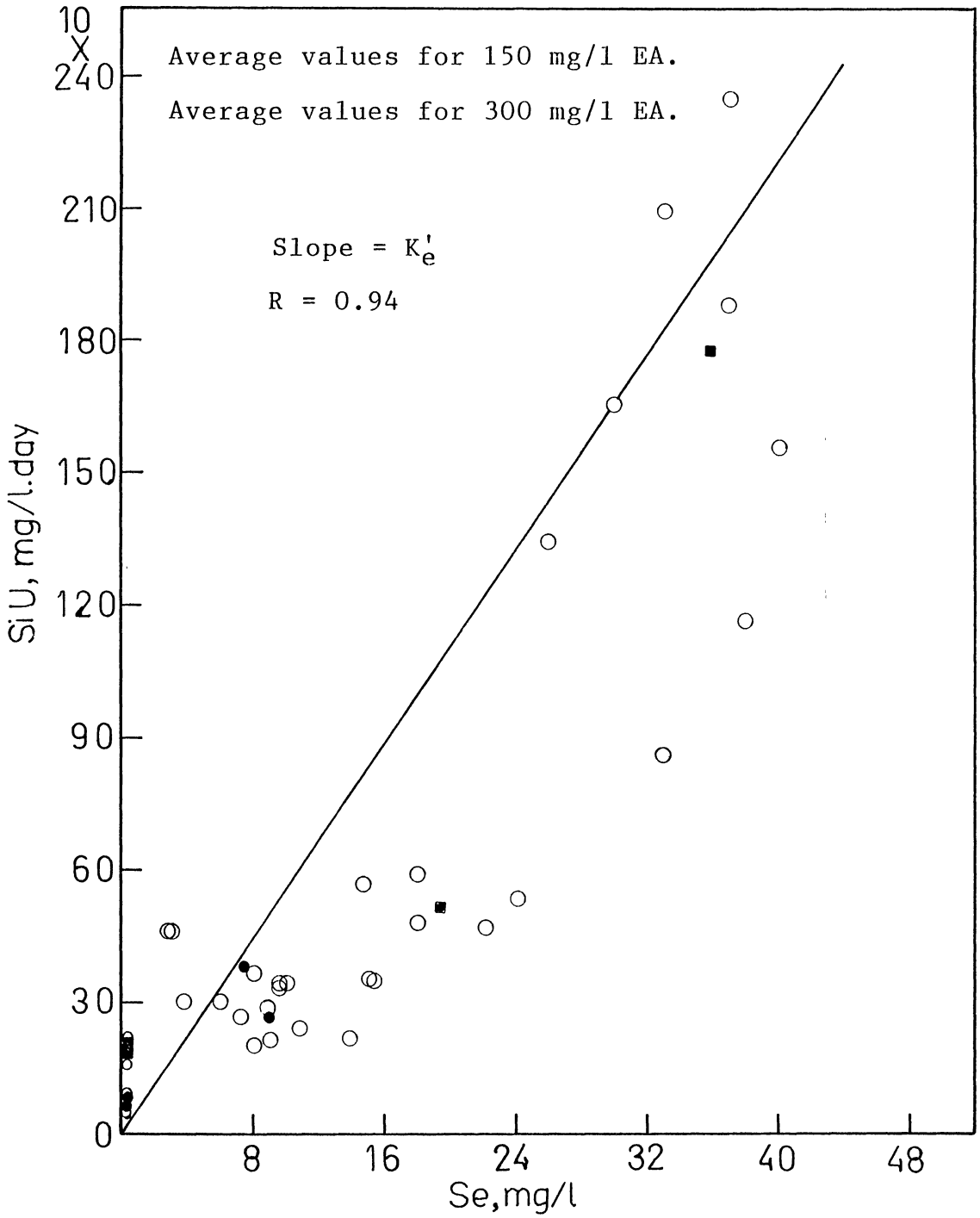

10
X
240
210
180
150
120
90
60
30
0
SiU, mg/l.day
Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
Slope = K_e'
R = 0.94
8
16
24
32
40
48
Se,mg/l

Figure 15. Determination of K_e' in terms of COD.

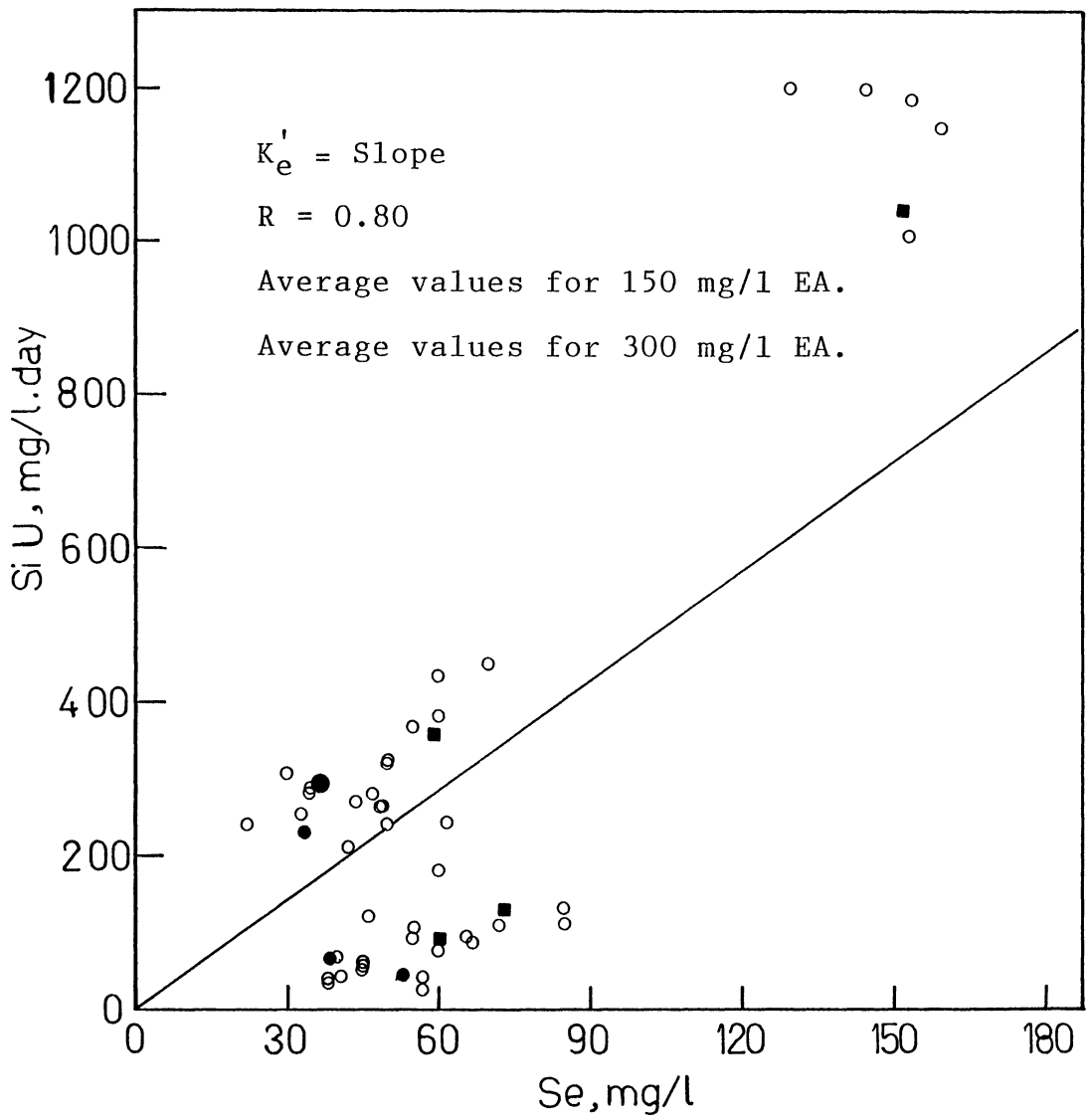

K_e' = Slope
R = 0.80
Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
Si U, mg/l.day
Se, mg/l
0
200
400
600
800
1000
1200
0
30
60
90
120
150
180

Figure 16. Determination of K_e' in Terms of BOD.

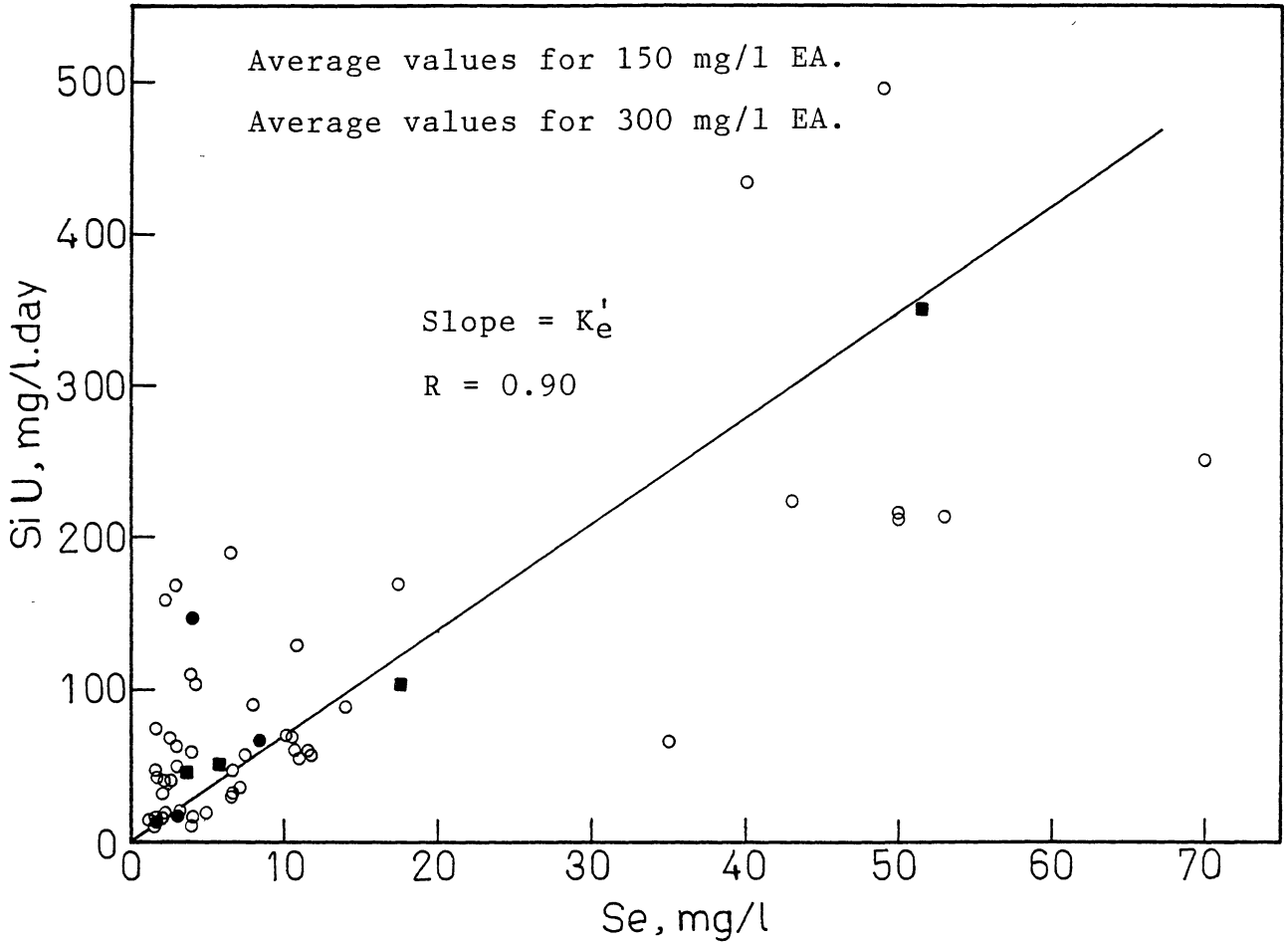

Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
Slope = K_e'
R = 0.90
Si U, mg/l.day
Se, mg/l
0
100
200
300
400
500
0
10
20
30
40
50
60
70

Figure 17. Determination of u_{max} and K_s in terms of Egg Albumen.

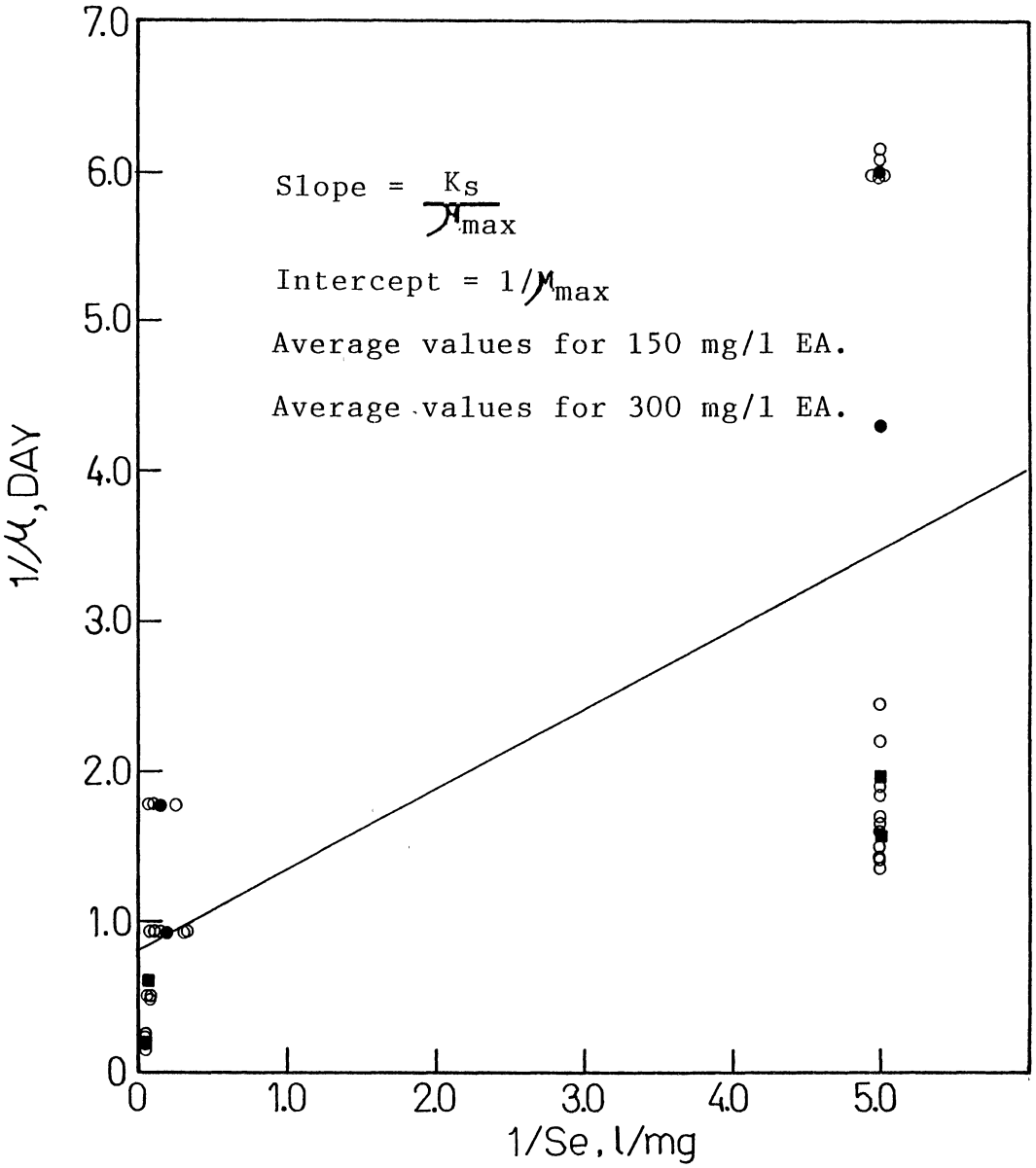

Slope = $\frac{K_s}{\mu_{max}}$
Intercept = $1/\mu_{max}$
Average values for 150 mg/1 EA.
Average values for 300 mg/1 EA.
1/μ, DAY
1/Se, l/mg
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0

Figure 18. Determination of u_{max} and K_s in terms of COD.

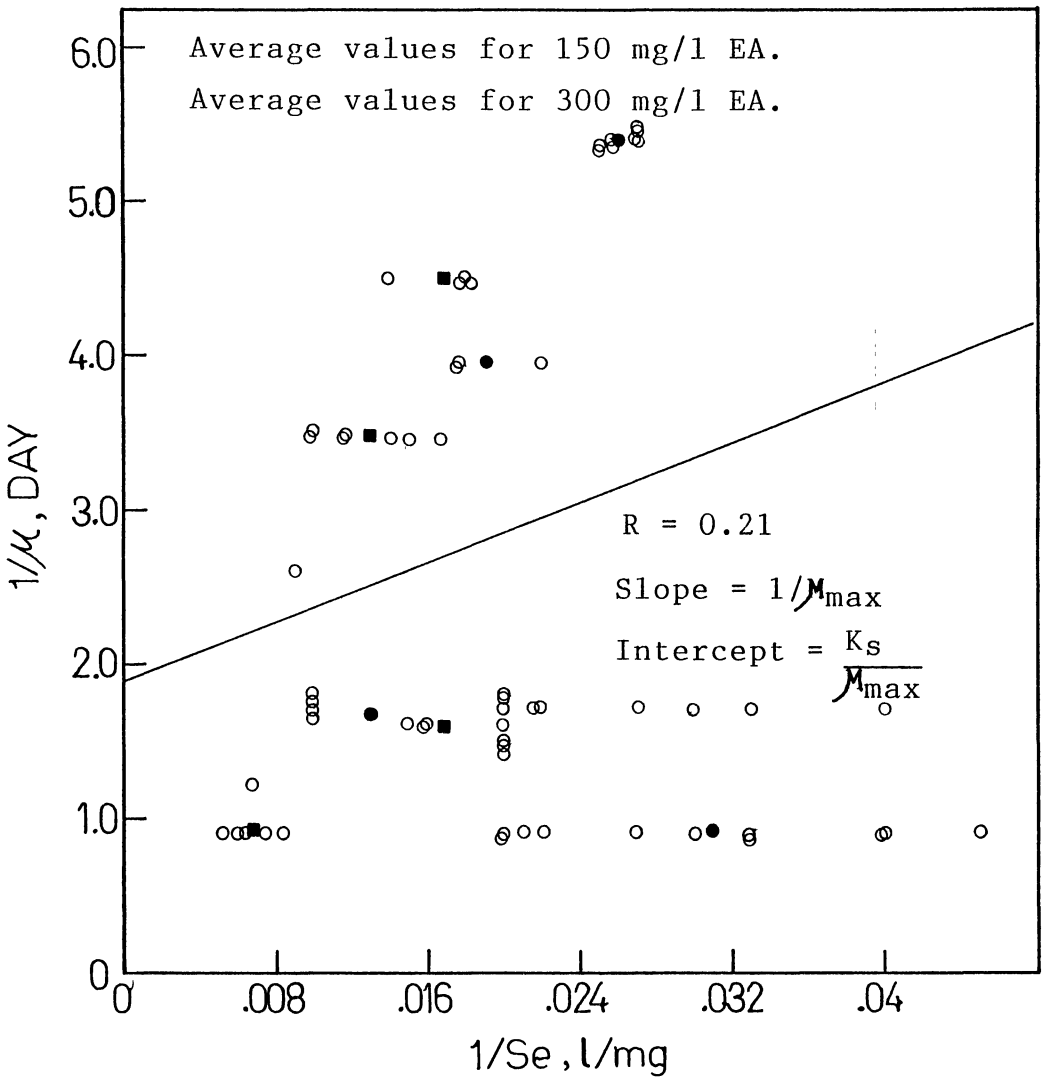
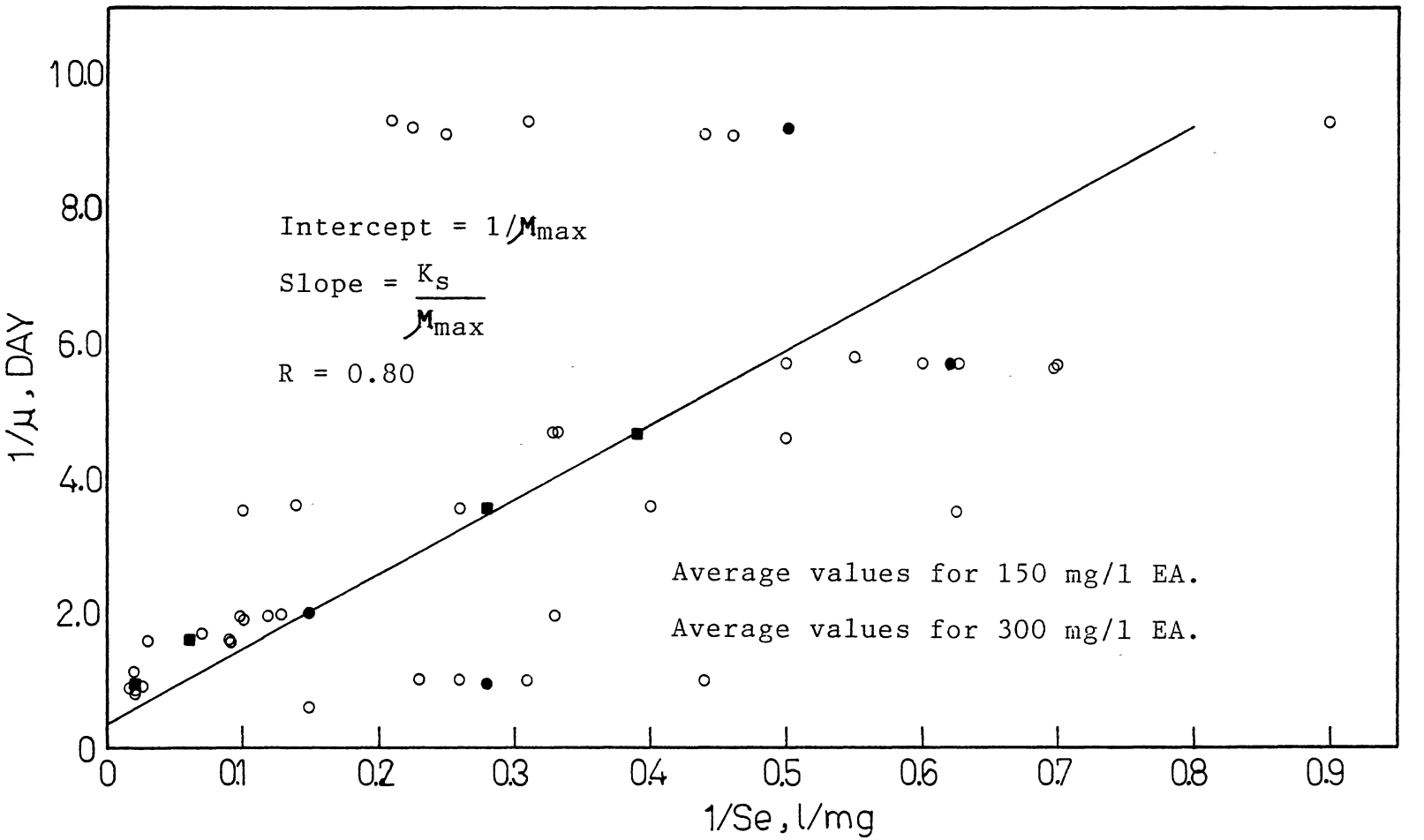

Average values for 150 mg/1 EA.
Average values for 300 mg/1 EA.
R = 0.21
Slope = 1/μmax
Intercept = Ks/μmax
1/μ, DAY
1/Se, l/mg
6.0
5.0
4.0
3.0
2.0
1.0
0
0
.008
.016
.024
.032
.04

Figure 19. Determination of u_{max} and K_s in terms of BOD.


10.0
8.0
6.0
4.0
2.0
0
1/μ, DAY
Intercept = 1/μmax
Slope = Ks / μmax
R = 0.80
Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1/Se, l/mg

respectively, and the Ks values were 0.78, 214.7, and 16.7.

In Figures 23, 24, and 25, the reciprocal of U is plotted as a function of the reciprocal of the specific loading rate, F/M, for determination of the maximum substrate utilization rate, Umax, and the substrate loading at which U is one-half of Umax, $K_B$after Kincannon and Stover. The Y-axis intercept is the reciprocal of Umax, and the slope is equal to K_B/Umax. The Umax value for egg albumen, COD, and BOD were 33.3, 28.6, and 10, respectively. The Umax value of 10 for BOD was relatively similar to other values obtained by other researchers. Figures 26, 27, and 28 show the relationship of the specific substrate utilization to the specific loading rate, F/M.

It should be noted here that the plots that do not include correlation coefficients was drown on a judgemental bases and past experience; this again one of the inherent problems associated with the scatter of the data.

All the biokinetic constants determined for each parameter can be found in Table II.

Figure 20. Determination of K and K_s in terms of Egg Albumen.

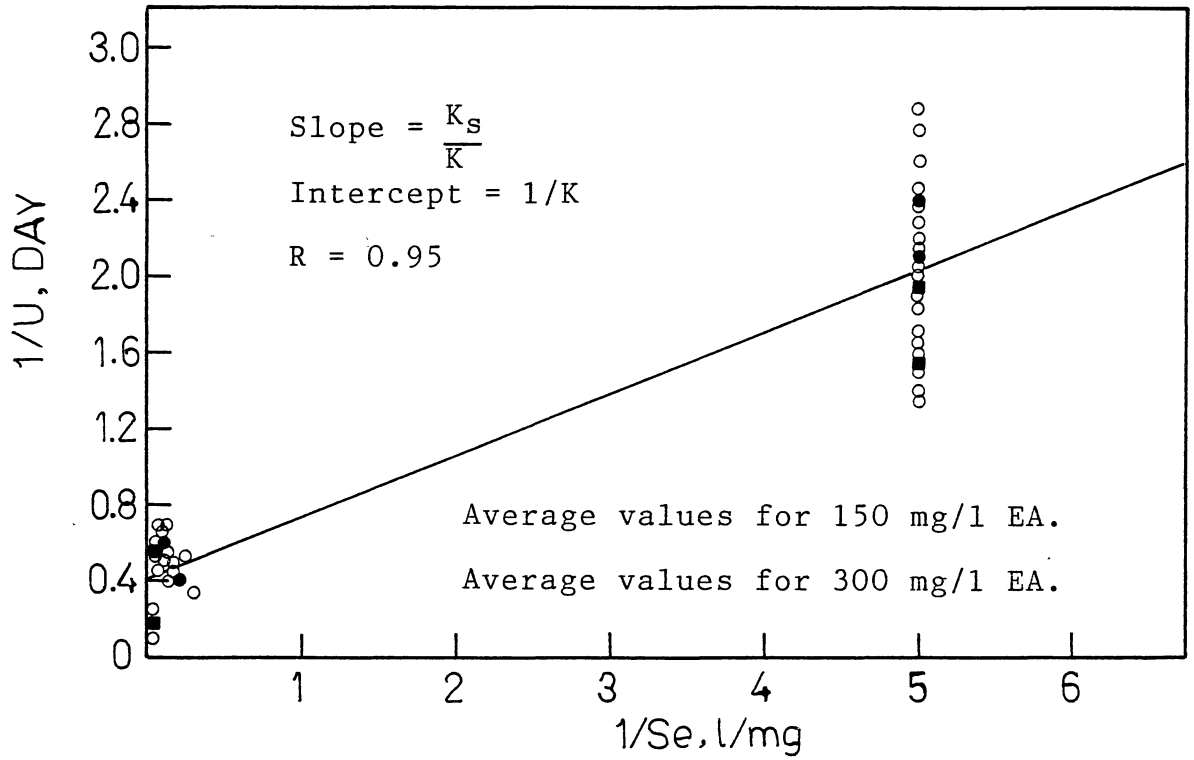

Slope = $\frac{K_s}{K}$
Intercept = 1/K
R = 0.95
Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
1/U, DAY
1/Se, l/mg
3.0
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0
1
2
3
4
5
6

Figure 21. Determination of K and K_s in terms of COD.

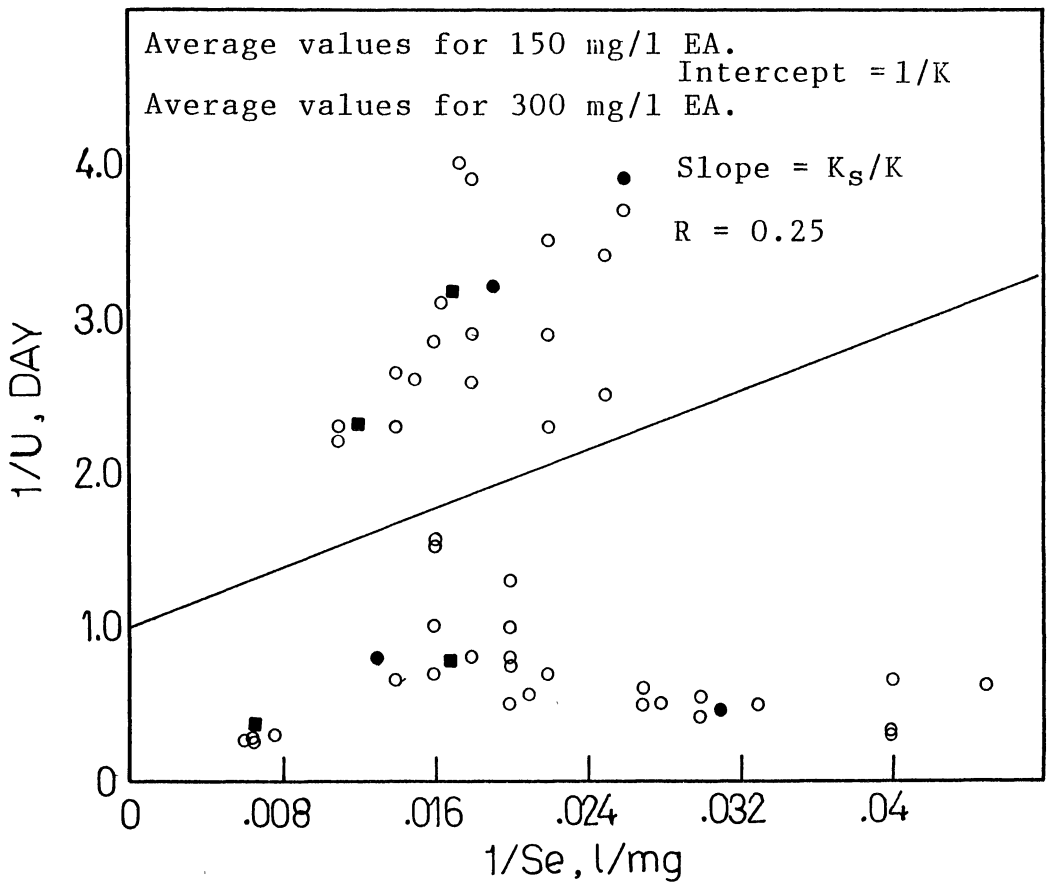

Average values for 150 mg/l EA.
Intercept = 1/K
Average values for 300 mg/l EA.
Slope = K_s/K
R = 0.25
4.0
3.0
2.0
1.0
0
1/U, DAY
0
.008
.016
.024
.032
.04
1/Se, l/mg

Figure 22. Determination of K and K_s in terms of BOD.

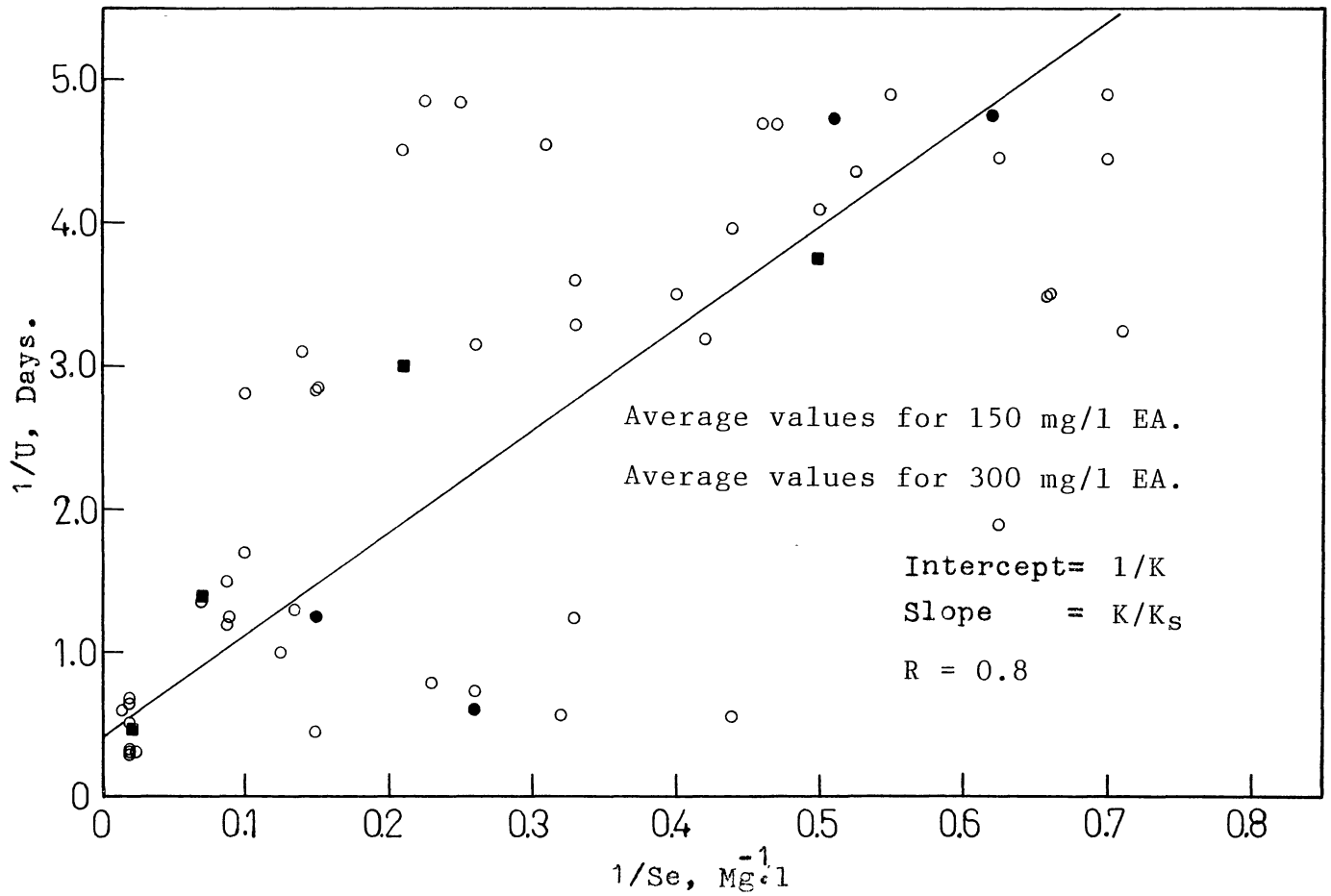

5.0
4.0
3.0
2.0
1.0
0
1/U, Days.
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1/Se, Mg⁻¹·l
Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
Intercept= 1/K
Slope = K/Ks
R = 0.8

Figure 23. Determination of U_{max} and K_B in terms of Egg Albumen.

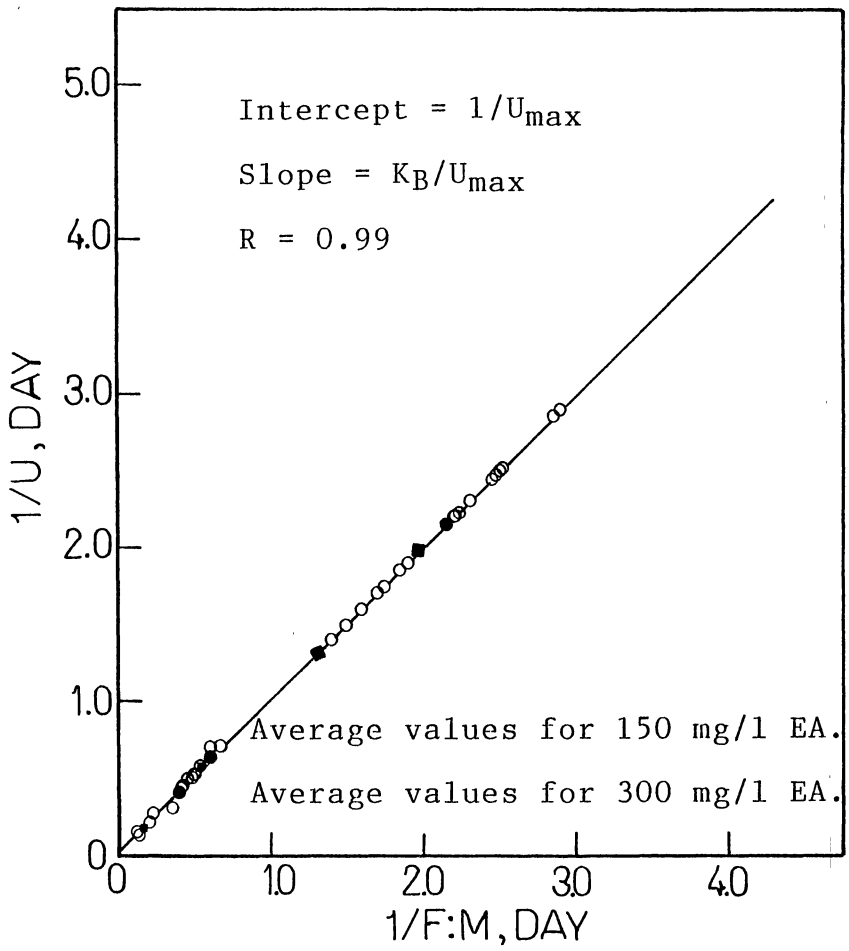

Intercept = 1/Umax
Slope = KB/Umax
R = 0.99
Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
1/U, DAY
1/F:M, DAY
0
1.0
2.0
3.0
4.0
5.0

Figure 24. Determination of U_{max} and K_B in terms of COD.

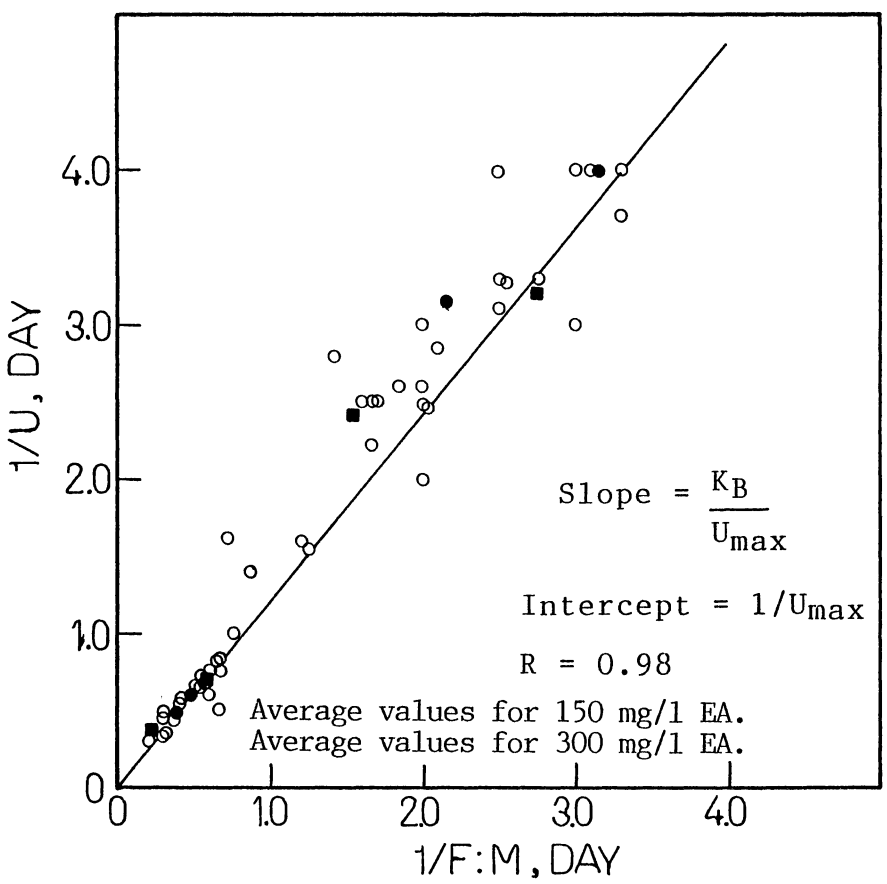

4.0
3.0
2.0
1.0
0
1/U, DAY
0
1.0
2.0
3.0
4.0
1/F:M, DAY
Slope = $\frac{K_B}{U_{max}}$
Intercept = $1/U_{max}$
R = 0.98
Average values for 150 mg/l EA.
Average values for 300 mg/l EA.

Figure 25. Determination of U_{max} and K_B in terms of BOD.

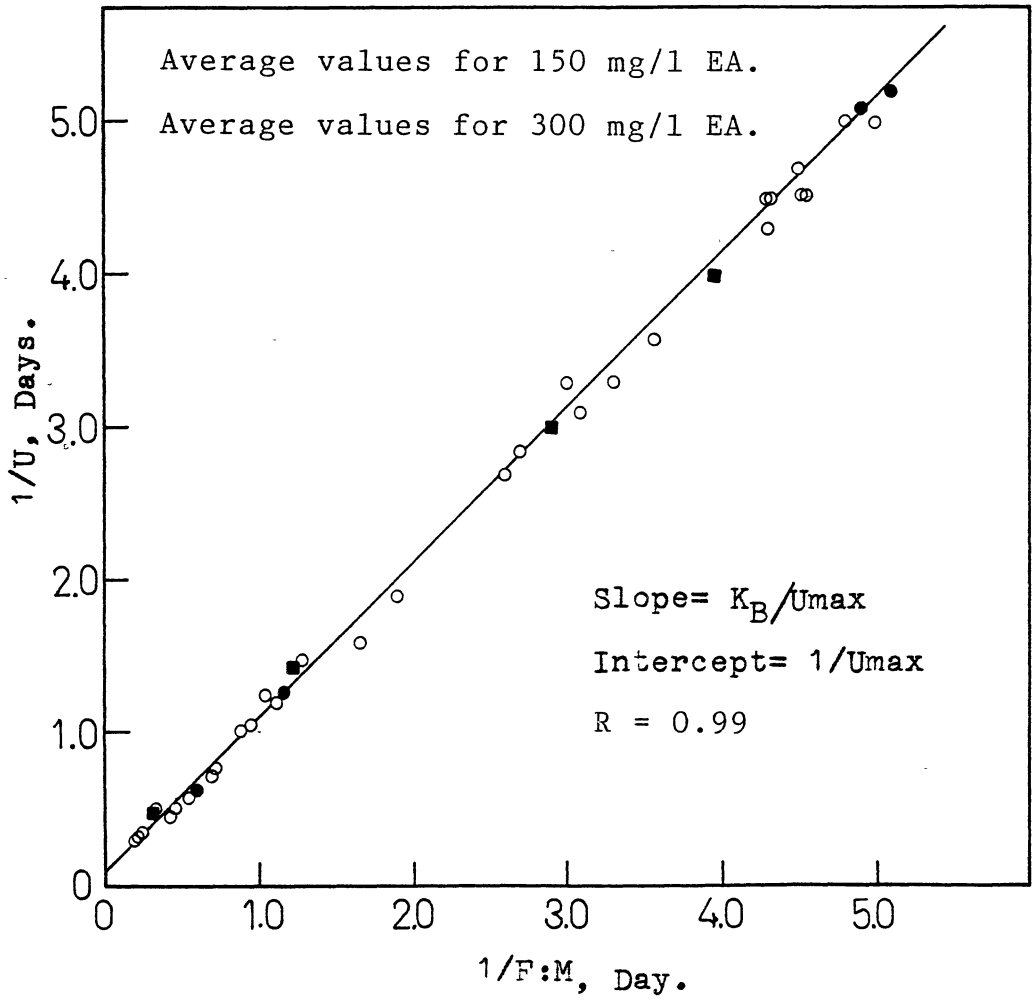

Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
Slope= K_B/Umax
Intercept= 1/Umax
R = 0.99
1/U, Days.
1/F:M, Day.
0
1.0
2.0
3.0
4.0
5.0

Figure 26. Specific substrate Utilization Rate vs. F:M Ratio in terms of Egg Albumen.

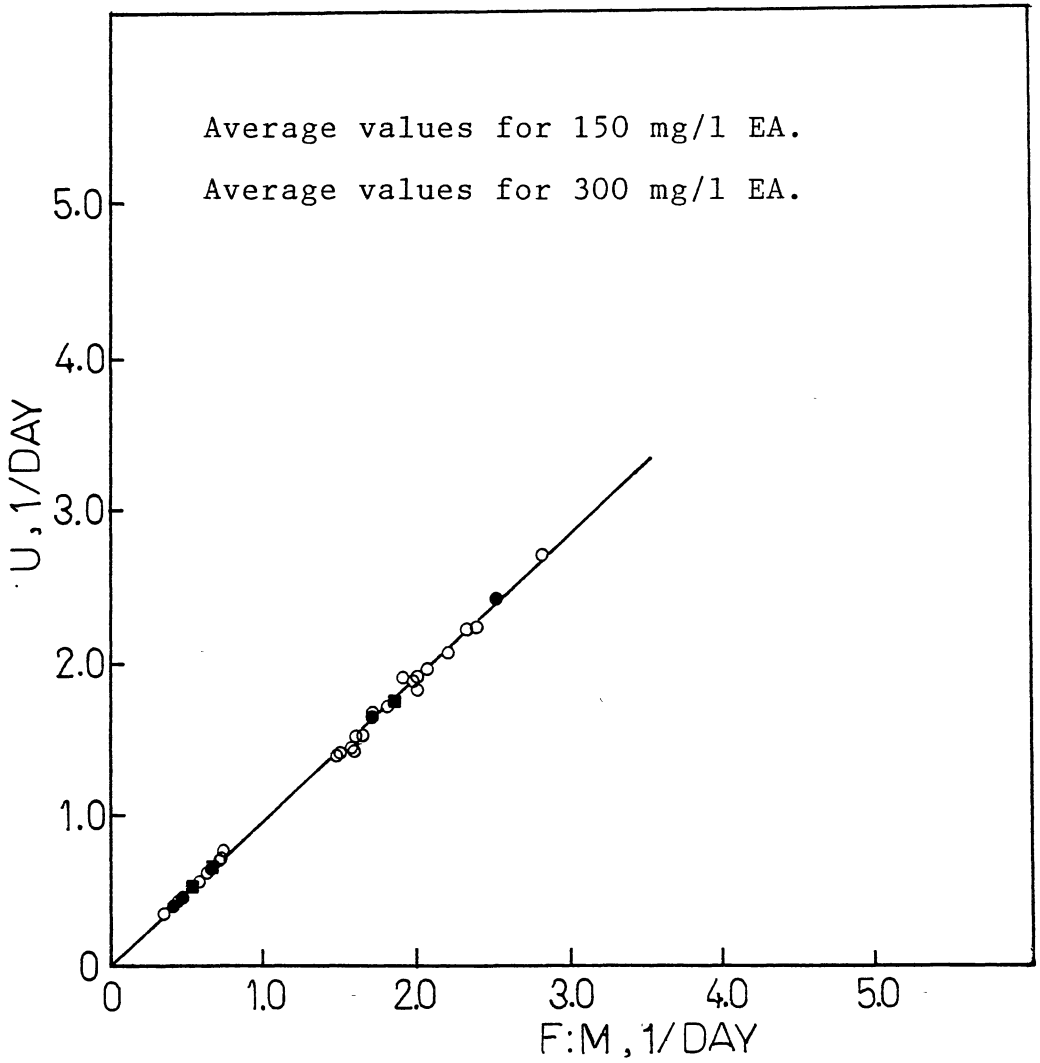

Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
U, 1/DAY
F:M, 1/DAY
0
1.0
2.0
3.0
4.0
5.0

Figure 27. Specific substrate Utilization Rate vs. F:M Ration in terms of COD.

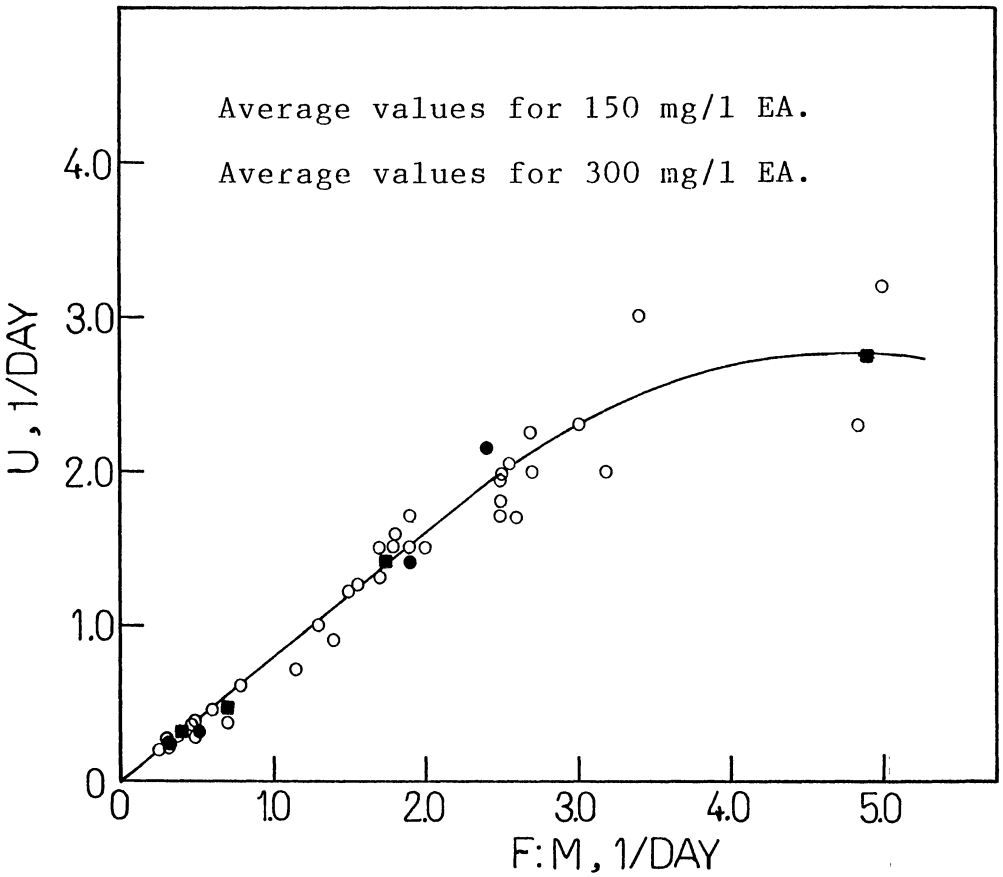

Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
U, 1/DAY
4.0
3.0
2.0
1.0
0
0
1.0
2.0
3.0
4.0
5.0
F:M, 1/DAY

Figure 28. Specific substrate Utilization Rate vs. F:M Ratio.

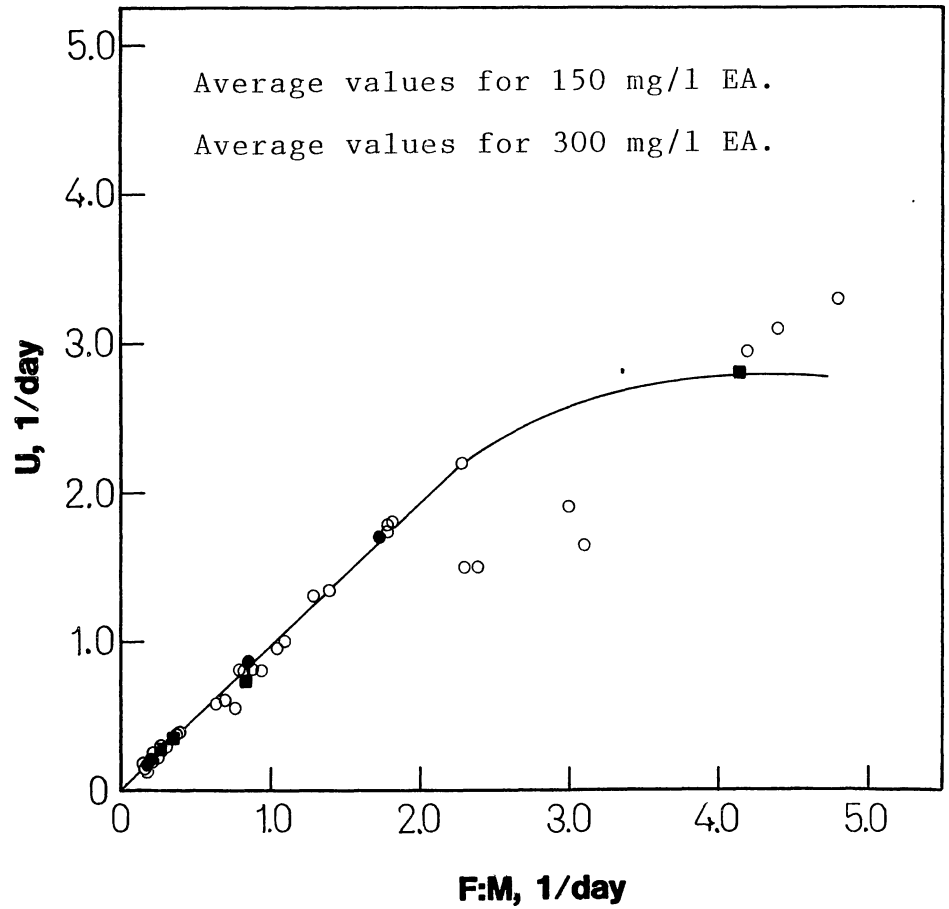

Average values for 150 mg/l EA.
Average values for 300 mg/l EA.
U, 1/day
F:M, 1/day
0
1.0
2.0
3.0
4.0
5.0

TABLE II

BIOKINETIC CONSTANTS DETERMINED
FOR THE COMBINED EGG ALBUMEN CONCENTRATIONS

			Eck.	Eck.Mod.	Law & McCarty		Gaudy		K & S	
	Yt	Kd	Ke	Ke	K	Ks	umax	Ks	Umax	K
		1/day	1/(mg/l-d)	1/day	1/day	mg/l	1/day	mg/l	1/day	1/day
In Terms of Egg Albumen	0.37	0.09	0.15	44.0	2.43	0.78	1.23	0.65	33.3	32.8
In Terms of COD	0.30	0.06	0.14	5.1	0.97	45.6	0.53	45	28.6	34.4
In Terms of BOD	0.46	0.06	0.04	6.9	2.35	16.7	2.6	28.2	10	9.9

CHAPTER V

DISCUSSION

The objective of this research was to show that in the steady state the effluent mass loading Se, is dependent on the substrate mass loading rate (F/M ratio). Both Si and Se were measured in terms of egg albumen, COD, and BOD (Figures 2 to 7). Biological activated sludge reactors were operated at steady state conditions, and four (4) solids retention times 1, 2, 6 and 10 days were investigated. In addition, values for biokinetic constants of Eckenfelder, Eckenfelder modified, Lawrence and McCarty, Gaudy, and Kincannon and Stover were determined. The numerical values for Yt and Kd were also obtained (Figures 8-10). All these values were summarized in Table II. Using the numerical values for these biokinetic constants and choosing several values for X as well as Si, the values of Se were then predicted using the equations for each of the models mentioned. The observed and the predicted values of Se, in terms of egg albumen, COD, and BOD were summarized in Tables III, IV, and V, respectively.

TABLE III

COMPARISON OF PREDICTED AND OBSERVED Se IN TERMS OF EGG ALBUMEN

Si mg/1	MLVSS mg/1	Se Obs. mg/1	Predicted Se, mg/1				
			ECK.	ECK. Mod.	L&M	GAUDY	K&S
75	200	-	9	2	1	<1	2
	650	-	3	<1	<1	<1	0
	1150	-	2	<1	<1	<1	0
	1600	-	1	<1	<1	<1	0
	2700	-	<1	<1	<1	<1	0
150	200	9	17	<1	0	5	10
	650	7	6	3	<1	<1	2
	1150	ND	3	2	<1	<1	<1
	1600	ND	2	1	<1	<1	0
	2700	-	1	<1	<1	<1	0
300	200	37	35	36	0	13	21
	650	8	12	12	3	<1	12
	1150	-	7	7	<1	<1	5
	1600	ND	5	5	<1	<1	2
	2700	ND	3	3	<1	<1	0
500	200	-	59	92	0	334	111
	650	-	20	32	0	7	36
	1150	-	11	19	2	<1	18
	1600	-	8	14	<1	<1	11
	2700	-	5	8	<1	<1	4
1000	200	-	117	312	0	834	369
	650	-	39	123	0	461	145
	1150	-	23	73	0	55	82
	1600	-	16	54	11	2	56
	2700	-	10	33	1	<1	29

TABLE IV

COMPARISON OF PREDICTED AND OBSERVED Se IN TERMS OF COD

Si mg/1	MLVSS mg/1	Se Obs. mg/1	Predicted Se, mg/1				
			ECK.	ECK. MOD.	L&M	GAUDY	K+S
75	200	-	9	17	50	36	15
	650	-	3	6	23	12	13
	1150	-	2	4	13	7	13
	1600	-	1	3	9	5	13
	2700	-	<1	2	5	3	12
150	200	37	19	56	115	91	35
	650	36	6	23	60	32	28
	1150	52	4	14	33	16	27
	1600	19	3	10	22	11	26
	2700		2	6	12	6	25
300	200	147	37	162	259	226	87
	650	36	13	79	175	101	63
	1150	75	7	50	105	45	57
	1600	24	5	38	68	28	55
	2700	-	3	24	32	14	53
500	200	-	63	331	456	420	177
	650	-	21	186	360	256	117
	1150	-	12	125	262	126	103
	1600	-	9	100	188	70	977
	2700	-	5	62	81	29	92
1000	200	-	125	797	954	916	473
	650	-	42	542	850	730	293
	1150	-	24	401	737	532	243
	1600	-	18	325	638	370	223
	2700	-	11	222	411	124	201

TABLE V

COMPARISON OF PREDICTED AND OBSERVED Se IN TERMS OF BOD

Si mg/1	MLVSS mg/1	Se Obs. mg/1	Predicted Se, mg/1				
			ECK.	ECK. MOD.	L&M	GAUDY	K&S
35	200	-	10	3	6	4	2
	650	-	4	1	2	1	<1
	1150	-	2	<1	<1	<1	<1
	1600	-	2	<1	<1	<1	0
	2700	-	1	<1	<1	<1	0
80	200	10	24	15	18	9	10
	650	4	9	5	4	3	3
	1150	2	5	3	2	1	1
	1600	3	4	2	2	<1	<1
	2700	-	2	1	<1	<1	<1
150	200	53	45	45	59	23	34
	650	6	17	18	10	5	11
	1150	-	10	10	5	3	6
	1600	6	8	8	3	2	4
	2700	3	5	5	2	1	2
250	200	-	75	105	145	59	82
	650	-	29	46	24	10	31
	1150	-	17	28	9	5	18
	1600	-	13	21	6	4	13
	2700	-	8	13	3	2	7
500	200	-	149	296	387	246	249
	650	-	58	154	155	30	115
	1150	-	34	100	36	12	70
	1600	-	25	77	18	8	52
	2700	-	15	49	8	4	30

IMPACT OF INFLUENT SUBSTRATE MASS LOADING RATE (F/M RATIO) ON EFFLUENT QUALITY

The impact of substrate mass loading (F/M ratio) on effluent mass loading expressed in effluent substrate concentration (Se) in mg/l (because the flow rate into the reactor was kept constant throughout the study) is clearly shown in Figures 2-7. They show the impact in terms of egg albumen, COD, and BOD. At solids retention time of one day, the leakage of egg albumen from the reactor subject to higher loading was much higher than that from the reactor subjected to lower loading. This observation for the one day solids retention time system was also valid when COD and BOD were considered. The soluble COD in the effluent were largely due to metabolic intermediates (clear from the difference between COD and egg albumen concentrations in the effluent from both reactors). The accumulation of metabolic intermediates due to rapid growth on certain compounds has been noted many times by several researchers (27). This observation is rather important because it emphasizes the need for a better tool in analyzing the substrate (as opposed to the composite carbon source (BOD or COD) in order to account for the effect of these intermediates on the observed kinetics of purification. It was also observed that the flocculant characteristics of the biomass in the reactor subjected to higher substrate mass loading rate (F/M) were severely deteriorated.

When the F/M ratio decreased or the solids retention time increased to two days (hence, lower growth rate) the leakage of egg albumen in the effluent egg albumen, the metabolic intermediates constitute the major part of the effluent COD. The biological solids concentration (MLVSS) in mg/1 were increased in both reactors which resulted in decrease in the specific organic loading rate (F/M). The effluent soluble BOD also decreased in both reactors. The increase in influent substrate mass loading (F/M) resulted in a concurrent increase in the effluent mass loading. Since, the flow rate to both reactors was constant, this translates into an increase in the concentration of effluent soluble substrate (Se, in mg/l).

As the specific growth rate decreased, i.e. solids retention time of six days, which resulted in higher biological solids concentration or lower specific organic loading, the effluent egg albumen in both reactors were undetectable. In terms of COD and BOD the impact of F/M on effluent quality was observed. It should be noted here that at solids retention time of 6 days the effluent COD mass loading was higher than that observed at solids retention time of 2 days. This unexpected response was observed by other researchers and could be due to the type of micro-organisms that predominate at this condition. Effluent soluble BOD in the reactor subjected to higher F/M ratio were higher than the effluent BOD in the reactor subjected to lower loading; however, the gap was not as severe as in

previous solids retention times, one and two days. At solids retention time of ten days (lower specific growth rate) the soluble BOD and COD in the effluent in both reactors were lower; however, the impact of increased F/M on effluent quality was still observed.

Observed Se values at solids retention time of six and ten days in terms of COD and BOD as compared to the undetectable concentrations in terms of egg albumen again emphasized the fact that metabolic intermediates, different from the feed, were produced.

It is essential, from both the design and operation standpoint, to determine if the mean observed Se values (in terms of egg albumen, COD and BOD) could be predicted using the design models of Eckenfelder, Eckenfelder modified, Lawrence and McCarty, Gaudy, and Kincannon and Stover and the appropriate values for the biokinetic constants for each model. Expressions for effluent substrate concentration of each model are presented in Table VI. Five biological solids concentrations, 200, 650, 1150, and 2700 mg/1 were used to predict Se values at feed concentrations of 75, 150, 500 and 10000 mg/1 egg albumen. These predicted results are given in Tables III, IV and V. Table III, egg albumen results, shows that Eckenfelder, Eckenfelder modified, and Kincannon and Stover models successfully predicted the impact on Se and F/M increased for each of the biological solids concentration chosen. However, Lawrence and McCarty, and Gaudy models didn't show the impact as good as the other models. This is

expected since these two models assume that changes in influent substrate concentration has no effect upon the prediction of effluent substrate concentration. Comparison of predicted and observed Se values clearly indicate, once again, the success of Eckenfelder, Eckenfelder modified, and Kincannon and Stover models in predicting the Se values at Si concentration of 150 and 300 mg/1 employed in the experiment.

In Table V, COD data, it is clear that all models used did show the impact on Se values as Si (F/M) increased at the same biological solids concentration. Comparison of predicted and observed Se values in terms of COD showed that Eckenfelder modified and Kincannon and Stover models were, generally, successful in predicting Se Values.

Table VI represents the BOD data, shows that all the models did predict the impact of (F/M) on Se. However, when the observed effluent BOD values at the two feed concentrations employed were compared to the corresponding predicted values all models showed rather conservative predictions.

CHAPTER VI

CONCLUSION

The analysis of the experimental results lead to the following conclusions:

1. The F/M ratio has a definite effect upon the effluent substrate mass loading. Since, the flow rate was constant, this translates into an increase in the concentration of effluent soluble substrate (Se, in mg/l).
2. A higher solids retention time, that is, lower net specific growth rate, will result in better response to increased organic loadings.
3 A deterioration in sludge settling properties and turbid effluent occurred for increased F/M at lower solids retention time.
4 In terms of all the parameters investigated, the determination of the biokinetic constants for all models, except Kincannon and Stover, were subject to much data scatter which made the calculations of these constants rather difficult.
5. All models were successful in predicting the impact of F/M on effluent quality in terms of COD and BOD, however, in terms of egg albumen Lawrence and

McCarty and Gaudy models failed in predicting the impact of F/M on effluent quality.

6. Eckenfelder modified, and Kincannon and Stover models were, generally, successful in predicting the Se values in both reactors in terms of egg albumen and COD. However, all models showed rather conservative prediction when BOD data was used.

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Appendix - Operational data in terms of egg albumen, COD, and BOD.

TABLE VI

DESIGN FORMULAS FOR STEADY STATE IN Se

Design Approach	Effluent Se
Eckenfelder	$Se = \frac{Si}{K_e\ Xt + 1}$
Eckendelder Modified	$Se = \frac{Si}{\frac{Ke'\ XV}{SiF} + 1}$
Kincannon and Stover	$Se = \frac{Umax\ Si}{K_B + FSi/Xv}$
Lawrence and McCarty	$Se = \frac{Ks\ [\frac{1}{SRT} + Kd]}{YtK - [\frac{1}{SRT} + d]}$
Gaudy	$\frac{Ks\ (un + Kd)}{umax - (un + Kd)}$

TABLE VII

OPERATIONAL DATA IN
TERMS OF COD

	Si, mg/L		F:M, mg/mg.d		Se, mg/L	
	mean	S.D.	mean	S.D.	mean	S.D.
1.0	149.0	9.70	2.60	0.40	37.0	10.18
	317.0	28.90	6.0	1.50	146.9	9.62
2.0	165.20	18.30	1.80	0.25	36.5	7.20
	288.80	5.10	1.78	0.23	35.75	6.60
6.0	148.0	13.65	0.50	0.04	52.20	4.20
	273.0	25.10	0.70	0.12	75.0	9.50
10.0	142.2	11.10	0.35	0.036	19.30	6.45
	267.0	31.20	0.44	0.065	24.15	5.84

- Aeration tank volume = 3.0 liters.
- Hydraulic detention time = 6.0 hours.

TABLE VIII

OPERATIONAL DATA IN
TERMS OF BOD

	Si, mg/L		F:M, mg/mg.d		Se, mg/L	
	mean	S.D.	mean	S.D.	mean	S.D.
1.0	88.0	5.6	1.70	0.32	9.70	1.75
	149.5	20.1	3.4	0.94	52.8	9.70
2.0	82.0	7.85	0.89	0.10	4.30	7.30
	142.6	20.86	0.86	0.14	5.50	1.04
6.0	63.5	10.0	0.21	0.028	1.90	0.57
	148.0	22.6	0.35	0.03	6.50	3.52
10.0	80.6	6.28	0.19	0.028	2.80	1.38
	179.8	30.9	0.26	0.03	2.80	1.60

- Volume of aeration tank = 3.0 liters.
- Hydraulic detention time = 6.0 hours.

TABLE IX

OPERATIONAL DATA IN TERMS OF EGG ALBUMEN

SRT	Si, mg/L		F:M, mg/mg.d		Se, mg/L	
	mean	S.D.	mean	S.D.	mean	S.D.
1.0	157.0	14.2	2.5	0.24	9.0	2.70
	314.0	14.3	6.6	1.20	36.8	3.50
2.0	156.70	10.0	1.70	0.16	6.80	4.20
	307.0	13.5	1.80	0.17	7.80	1.70
6.0	303.0	7.74	0.73	0.03	ND	-
10.0	160.50	11.20	0.40	0.035	ND	-
	334.60	26.50	0.45	0.073	ND	-

- Volume of aeration tank = 3.0 liters.
- Hydraulic retention time = 6.0 hours.

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