STUDY OF A REFINERY UNIT WASTEWATER WITH AN ASBF: KINETICS AND TOXICITY

By

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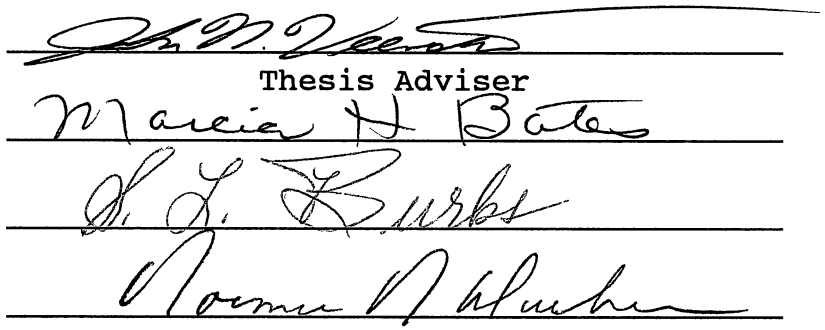

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Abstract-The kinetic constants for an Aerated Submerged Biological Filter (ASBF) used to reduce the toxicity of a petroleum refinery process wastewater were determined. The system was run at three different organic loadings and data were collected at steady state conditions for each loading. These data along with data obtained for three other loading conditions done in a previous study (Carroll, 1990) were used to determine the biokinetic constants which are required for the design of a full scale system. To measure the acute toxicity reduction, a 48-hour static bioassay was done on the ASBF unit influent and effluent. An attempt was also made to identify the fraction causing toxicity by running the samples through a Clinoptolite column and then running a bioassay on the treated samples.

Key Words-aerated submerged biological filter, sour water, LC_{50}, bioassay, Ceriodaphnia dubia, fathead minnow, organic loading, clinoptiltolite, kinetics.

INTRODUCTION

Recent amendments made to the Clean Water Act (1981, 1985, 1987) and the acquisition of increasing amounts of data on the toxicity of effluents point to the need for an expanded effort to control the discharge of toxic pollutants. As a result, increased regulatory attention has been focused on the control of possible toxic pollutants released by industries to surface water in order to protect water quality using the National Pollutant Discharge Elimination System (NPDES) permit program. If a wastewater exhibits significant toxic effects on biological life in the receiving stream, the United States Environmental Protection Agency (USEPA) and the states impose permit limits on the effluent toxicity and may require an NPDES permittee to conduct a Toxicity Reduction Evaluation (TRE).

The oil refining industry has anticipated some difficulty in meeting new toxicity standards. As a result, a joint project of the Oil Refiners Waste Control Council, Oklahoma State University Water Quality Research Lab, and School of Civil Engineering was undertaken to evaluate the ability of several treatment alternatives to reduce toxicity of various refinery wastewater streams (Burks and Wagner et al., 1989). The wastewater from a particular process viz. Sour Water Stripper, was identified as a toxic stream. Untreated stripped sour water is a complex mixture of organic compounds of which some fractions have been shown to be acutely toxic (Burks and Wagner, 1984).

Extensive research was done to evaluate the ability of an Aerated Submerged Biological Filter (ASBF) to reduce acute toxicity of process wastewater from the sour water stripper unit (Carroll, 1990). The choice of an ASBF as the biological system was made because it incorporates the best features of both fixed film and completely-mixed suspended growth units allowing instantaneous dilution of concentrated influents and maintenance of a high bacterial concentration (Hamoda and Abd-El-Bary, 1987; Gonzalez, 1984; Rusten, 1984; Huang 1982). The ASBF is a compact unit with no moving parts and is comparatively easy to operate. It requires no effluent recirculation or sludge recycling for efficient operations (Hamoda and Al Haddad, 1987; Hamoda, Al-Haddad and Abd- El-Bary, 1987; Bartoldi et al., 1987). In addition, the ASBF can handle refinery effluents as well as shock loads of solvents and high strength phenolic wastes that commonly occur in oil refineries (Hamoda and Al-Haddad, 1987; Hamoda, Al-Haddad and Abd-El-Bary, 1987; Bartoldi et al., 1987).

In Carroll's (1990) work the ASBF, was operated at three organic loading rates to evaluate its performance for treating refinery wastewater. It was shown that the ASBF considerably reduces acute toxicity (Carroll, 1990). This finding pointed out the need for developing the kinetics for this treatment so that a full-scale system can be designed. In order to arrive at the biokinetic constants, the ASBF was operated at three additional organic loading rates. The data collected for all the six loading rates were used to develop the kinetics. Knowledge of the biokinetic constants can be used to calculate the area

required for a given design flow at different influent and effluent concentrations or predicting the effluent quality given a set of flow, area, and influent substrate concentration.

A number of models can be used to describe the kinetics of a biological reactor. An empirical model that utilizes the total organic loading concept (Kincannon and Stover, 1982) has been used for describing fixed film biological reactors treating many types of waste. This model has been used to obtain the kinetic constants for the biological treatment of municipal wastewater (Karunanidhi, 1986). It has also been used in the study of alcohol stillage (Gomathinayagam, 1984) and in the study of alcohol waste using an ASBF (Gonzalez, 1984). This model has also been used to predict the kinetic constants for a biological unit used to remove organic priority pollutants and was reported to reduce the variability in the kinetic plots that occurred when using other design methods (Kincannon and Stover, et al, 1982). An empirical model assuming that substrate diffusion controls the overall reaction rate and a simple first-order rate model have been used for rotating biological reactor (RBC), (Friedman et al, 1976). The model using multiple zero order organic removal concept has also been presented, (Eckenfelder et al, 1969). A model has been proposed based on biological growth using Monod kinetics which neglects mass transfer resistance, (Kornegay and Andrews, 1968). A model based on Monod growth kinetics has been used to describe an ASBF type biological reactor, (Hamoda, 1989). The substrate utilization relationships used for fixed film reactors in these models are given in

Table 1. Some of these models have been used in this paper to develop the kinetic constants for the ASBF reactor.

EXPERIMENTAL APPROACH

Experimental Unit

The ASBF used in this project had a total empty bed reactor volume of 0.0127 m^3. The plastic media which had a specific surface area of 137 m^2/m^3 was contained in 0.0096 m^3 yielding a total media surface area in the unit of 1.32 m^2. The total empty bed reactor volume occupied by the media was 0.0003 m^3 leaving a void volume of 0.0124 m^3 and a porosity of 97.6% in the unit (Carroll, 1990).

The system used is shown in Figure 1. It was an upflow unit fed by an influent line from a 26.5 liter reservoir bottle. The media was supported on a highly perforated plastic false bottom. A uniform air flow system was provided by four inch long air diffusers which were concentrically arranged beneath the plastic support. These diffusers served to keep the system completely mixed, by supplying 0.28 m^3/hr to 0.4 m^3/hr of air depending on the organic loading, and also maintaining aerobic conditions in the unit. In such a system, the concentration of influent substrate is uniform throughout the reactor (Grady and Lim, 1980). Completely mixed conditions were verified by performing a dilute-in-tracer study (Carroll, 1990).

The effluent samples used were taken from a teflon spigot at the point where the effluent was allowed to drain from the unit by gravity into a plastic container. The influent samples were taken directly from the feed bottles. Since soft plastic tubing has been suspected of leaching

TABLE 1.

SUBSTRATE UTILIZATION RELATIONSHIPS, $(ds/dt)_A$, FOR FIXED FILM BIOLOGICAL REACTORS

MODEL	VALUE OF* $(ds/dt)_A$
Friedman	$K_1S^2/(Ks+S)$
Kincannon and Stover	(UmaxFSi/A)/(Kd+(FSi/A)
Eckenfelder	KSe
Korengay and Andrews	PSe/(Ks+Se)
Hamoda	K_1XSi/(Ks+Si)

* The terms given here are defined in the table of nomenclature in the appendix.

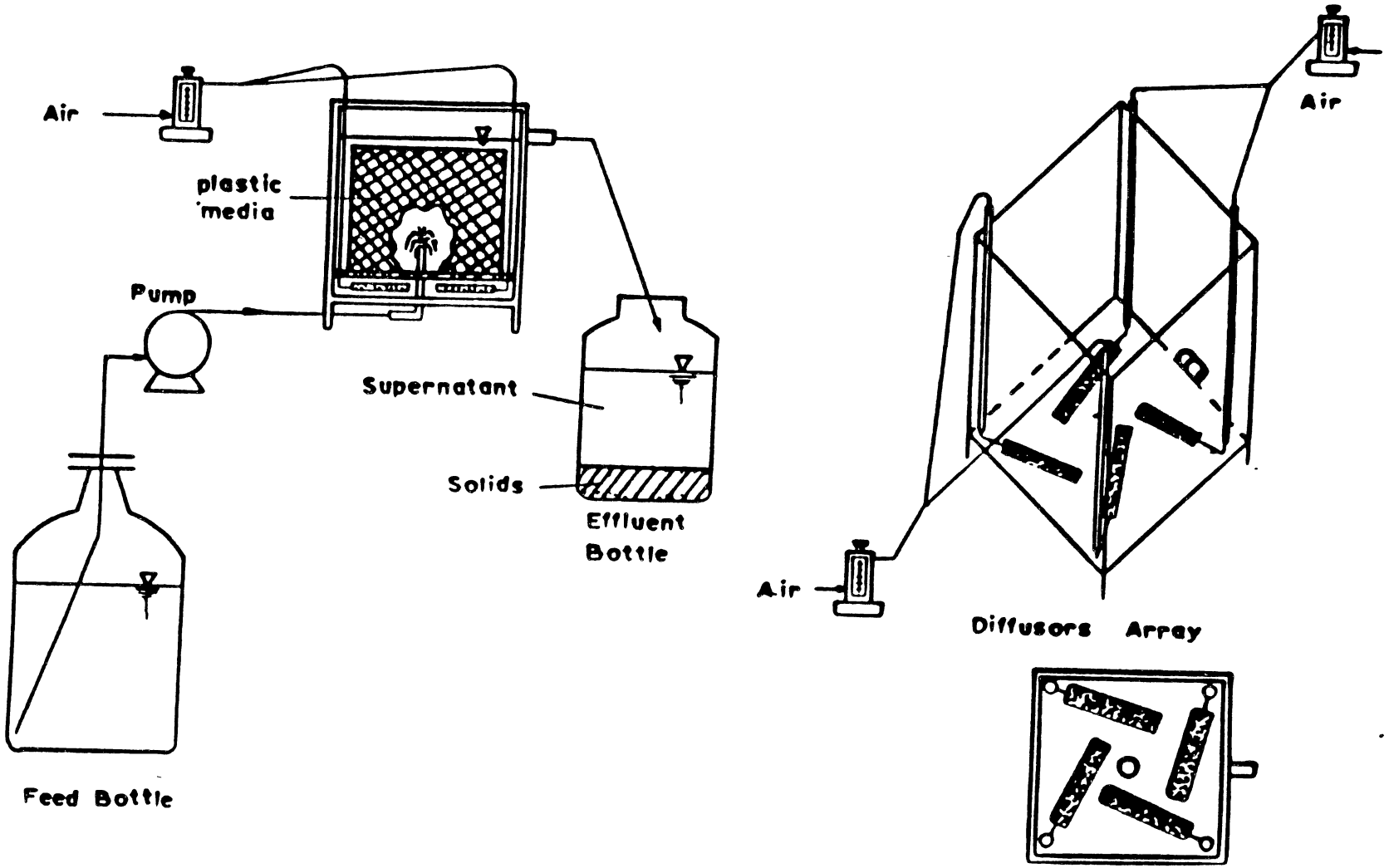

Figure 1. Schematic of the ASBF System

plasticizers which cause problems in bioassay tests, it was avoided.

Wastewater Characteristics

The wastewater from the sour water stripper unit of the participating refinery was shipped to Oklahoma State University in 55 gallon Teflon lined barrels once a month. K_2HPO_4 and KNO_3 were added to the feed to meet microbial phosphorous and nitrogen requirements respectively. The characteristics of the wastewater are shown in Table 2.

Experimental Design

The microorganisms used to seed the unit were taken from an aerated lagoon at the same oil refinery which provided the stripped sour water. Since the lagoon has been in operation for over twenty years, and has been fed with the wastewater from the sour water stripper, no acclimation of the microorganisms was needed. The nutrients added to the influent to obtain a $SBOD_5$: N: P ratio of 100: 5: 1 helped in enhancing growth conditions (Sawyer, 1956).

The ASBF was operated at three different loading conditions (14.0, 20.8, 24.0 g COD/m^2/day). The loading rates were changed by varying the flow rate and keeping the substrate concentration as constant as possible. The substrate concentrations varied from time to time, depending on the refinery operating conditions, as shown in Figure 2 and hence the loading rates could be kept only within a particular range rather than an exact desired value. For each loading, 6 to 10 data points were collected. These data were collected on an every other day

TABLE 2.

SOUR WATER STRIPPER WASTEWATER CHARACTERISTICS

PARAMETER	MEAN	MINIMUM	MAXIMUM
pH, SU	--	6.8	8.0
COD, mg/l	1927	1240	2800
$SBOD_5$, mg/l	1153	840	1560
NH_3 - N, mg/l	46.6	23.8	66.9
ORG. - N, mg/l	3.5	0.8	5.8

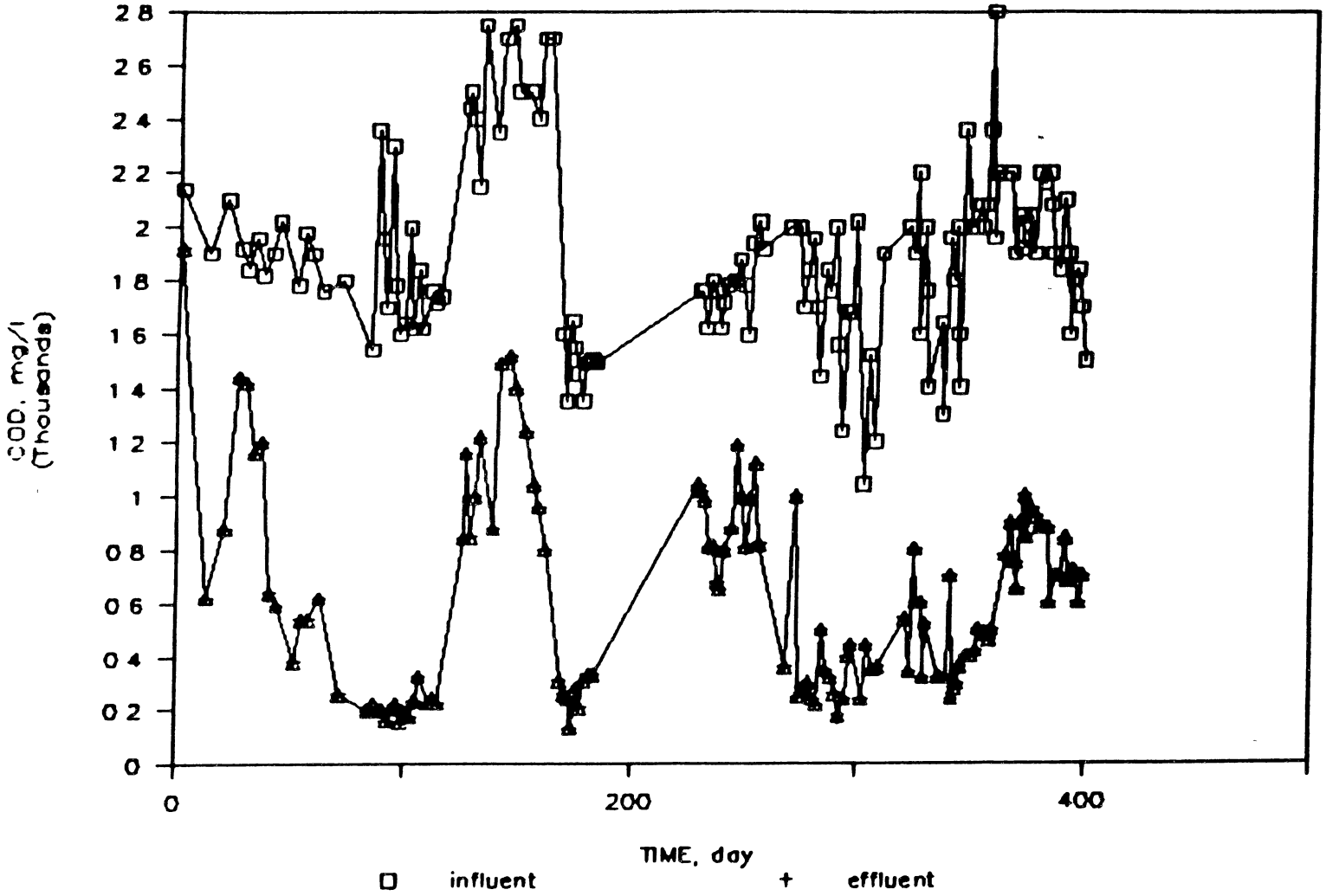

Figure 2. COD vs Time

basis. A period of three to four weeks was allowed for the unit to stabilize during each change of loading conditions. When the unit reached steady state condition, all the data for that run were collected over a two to three week period of time. The parameters monitored were Chemical Oxygen Demand (COD), pH, temperature (influent and effluent), total and volatile suspended solids (influent, effluent, solids wasted from the bottom and suspended solids), flow rate and dissolved oxygen. These physical/chemical parameters are listed in Table A1. In order to prevent solids accumulation and anaerobic conditions at the bottom of the reactor, a constant amount of sludge (200 mls) was wasted every other day. Previous investigators have used the same operational strategy (Gonzalez, 1984). The hydraulic retention times ranged from 12 to 31 hours during the period of study.

The nutrients required for the microbial population were determined every time a new feed was brought from the refinery. This was done by running a soluble biochemical oxygen demand ($SBOD_5$) analyses and calculating the nitrogen and phosphorous requirements. The nutrients already present in the refinery wastewater were determined by analyzing for nitrogen and phosphorous. For each loading, the $SBOD_5$ of the influent and effluent were found to estimate the biodegradable matter content.

Total suspended solids (TSS), fixed solids (FS), volatile suspended solids (VSS), $SBOD_5$, ammonia, Total Kjeldhal Nitrogen (TKN), and phosphorous were determined using the procedures outlined in Standard Methods for the Examination of Water and Wastewater (1976). COD was

measured using techniques described in the Hach Water Analysis Handbook (1982).

In order to determine the toxicity of the influent and effluent to aquatic life, a static 48-hour bioassay was performed twice for each loading condition. The bioassays were performed with Ceriodaphnia dubia and fathead minnows. They were set up using seven cups for Ceriodaphnia and seven bowls for fathead minnows. Each container represented a different dilution factor. The dilutions used were 1, 3, 10, 30, 50 and 100 percent by volume. Dilution water used in bioassays was classified as very hard (USEPA, 1985). Very hard water used for dilution because the test organisms were cultured in very hard water and so the dilution water itself was not toxic to the test organisms. Further more it was determined that the hardness of the dilution water as well as the samples were comparable. Water used for dilutions was passed through a Photronix RGW-5 (Reagent Grade Water) system, which is equivalent to the MILLIPORE MILLI-Q system, then rehardened with $CaSO_4$ (240 mg/l), $MgSO_4$ (240 mg/l), $NaHCO_3$ (384 mg/l), and KCl (16 mg/l) (USEPA, 1985). A blank set using only dilution water was also run to insure no mortality resulted from exposure to dilution water itself.

For the bioassays, each cup contained five or six Ceriodaphnia and each bowl five or six fathead minnows. Mortality rate was monitored by counting surviving organisms at set time intervals over a 48-hour period and recording the results as shown in Table A2. A series of dilutions was used to provide finer resolution of toxicity reduction occurring during tests. These data were used to

calculate the LC_{50} values. A graphical method was used for estimating the LC_{50} as per the procedure indicated by the USEPA, (1985). In order to quantify potential toxic components, an analysis of nitrogen content (organic nitrogen and ammonia) was done for the same samples used to determine toxicity. The samples for the toxicity testing taken from the unit for the lowest and highest loading conditions were also run through a Clinoptiltolite column to reduce ammonia and a static 48-hour bioassay was run on the treated samples. Clinoptiltolite is an ion exchange resin used to exchange cations.

At each loading condition, a settling test was done in order to determine the settling characteristics of the sludge. This was done by transferring one liter of mixed liquor from the reactor to a 1000 ml graduated cylinder and reading the sludge blanket height at time (t) intervals for one hour. This was done using the procedures outlined in Standard Methods for the Examination of Water and Wastewater (1976). Then the mixed liquor was transferred back to the reactor. The settling test curves are shown in Figure 3. The zone settling velocity (ZSV) and sludge volume index (SVI) were determined and are shown in Table 3. It was found that the settling characteristics were good for the higher loading rates since the SVI was below 150 mg/l which is an indication of good settling as given by Metcalf and Eddy, (1972).

At the end of the study, the mass of solids attached to the media was determined. This was done by examining two representative pieces of media taken from the middle of the unit. The average weight of the solids attached to the

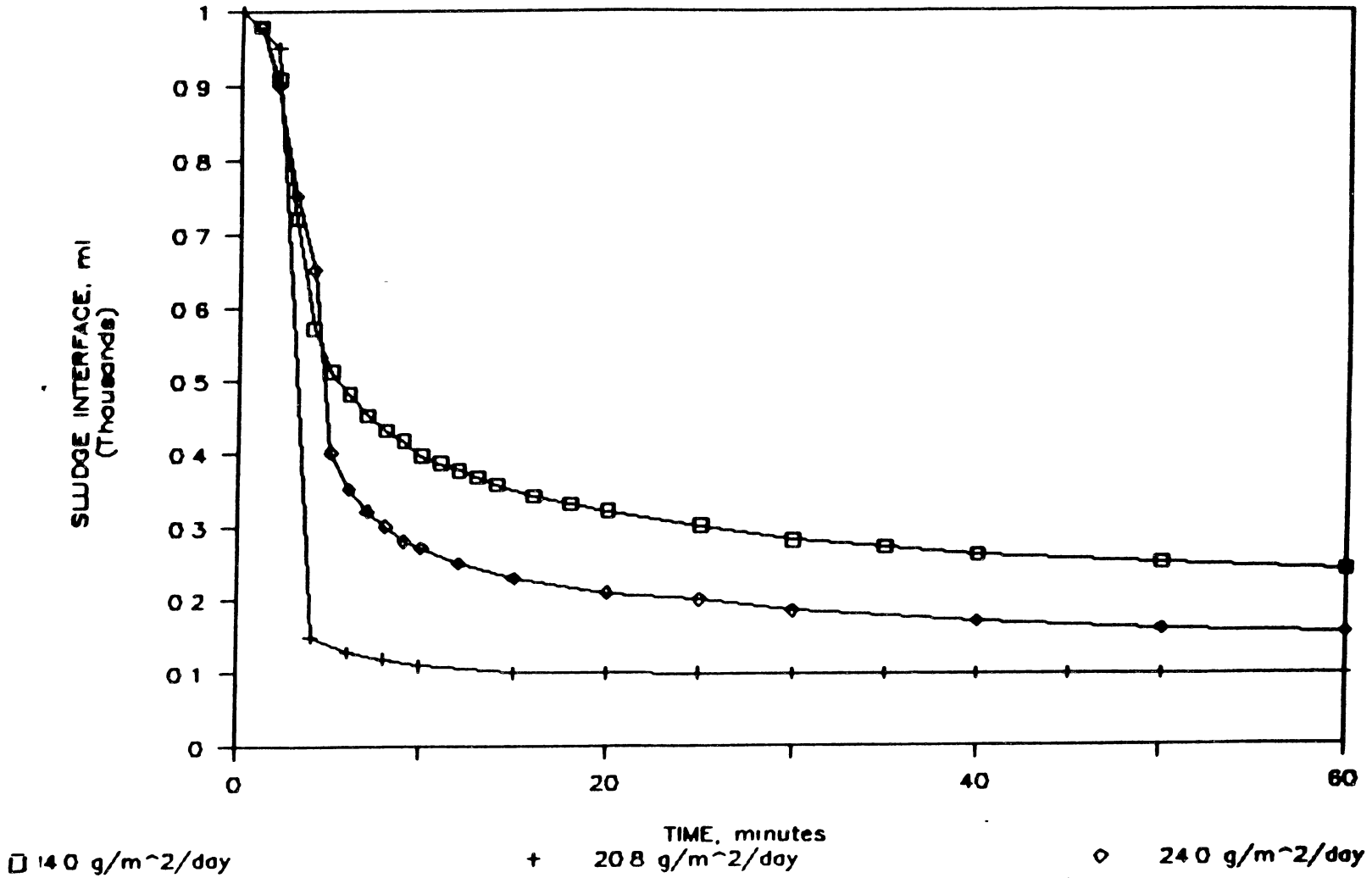

Figure 3. Settling Test Curves

TABLE 3

RESULTS OF SETTLING TESTS

LOADING RATE ($g\ COD/m^2/day$)	ZSV (m/sec)	SVI (ml/g)
14.0	0.012	301
20.8	0.018	450
24.0	0.012	135

media was 1.2 g/m^2.

In order to show that aeration alone did not reduce toxicity, the microorganisms from the reactor were completely removed and the unit was aerated as before. The unit was then fed with the same wastewater and a 48-hour static bioassay was run on this sample and the LC_{50} was determined.

Treatment Performance

The performance of the ASBF was judged by its ability to reduce the organic load to the unit using gross measurements like COD. The toxicity data showing increased LC_{50} values for the effluent also determined the treatment ability. Due to the complex nature of the waste stream, it was virtually impossible to trace reduction of any single compound through the ASBF. The variability in the waste stream coming directly from the process unit made it very difficult to maintain the loading rate at a desired value. Even though the COD of the feedstream was measured as often as possible, the variability was such that it was difficult to alter the flow rates into the reactor accordingly to maintain a constant loading condition.

Normally steady state conditions were reached within two to three weeks after changing the flow rate which was used to effect a change in organic loading. This was the time required for the microorganisms to get acclimated to the new loading condition. The steady state was operationally defined as having the COD removal efficiency vary 10% or less for a week prior to the start of data collection. The ASBF performed well and remained at steady

state as long as there was no major variation in the waste or the flow rate.

The dissolved oxygen level at the bottom of the reactor dropped due to the accumulation of biological solids in the bottom of the reactor. But this was taken care of by wasting solids from the bottom on an every other day basis. The aerators located inside the reactor performed well in keeping the unit aerobic and helping to maintain completely mixed conditions. All the monitored parameters except ammonia were reduced by this treatment. In general, higher removal efficiency was obtained at lower loading rates as shown in Figure 4.

RESULTS

Toxicity

The percent removal of COD for the different loading conditions at which the ASBF was operated are shown in Figure 4. It was seen that at lower loading conditions (14.0 g COD/m^2/day), the ASBF gave maximum reduction of monitored parameters except ammonia. At the higher loading conditions (20.8 g COD/m^2/day and 24.0 g COD/m^2/day), the reductions were smaller because the unit seemed to be approaching its maximum organic loading capacity. It was noted that at a high loading rate such as 32.0 g COD/m^2/day, difficulties were encountered in maintaining steady state conditions indicating that the unit was approaching its maximum organic loading capacity (Carroll, 1990).

Bioassays showed the LC_{50} increased after ASBF treatment, indicating toxicity reduction as shown in

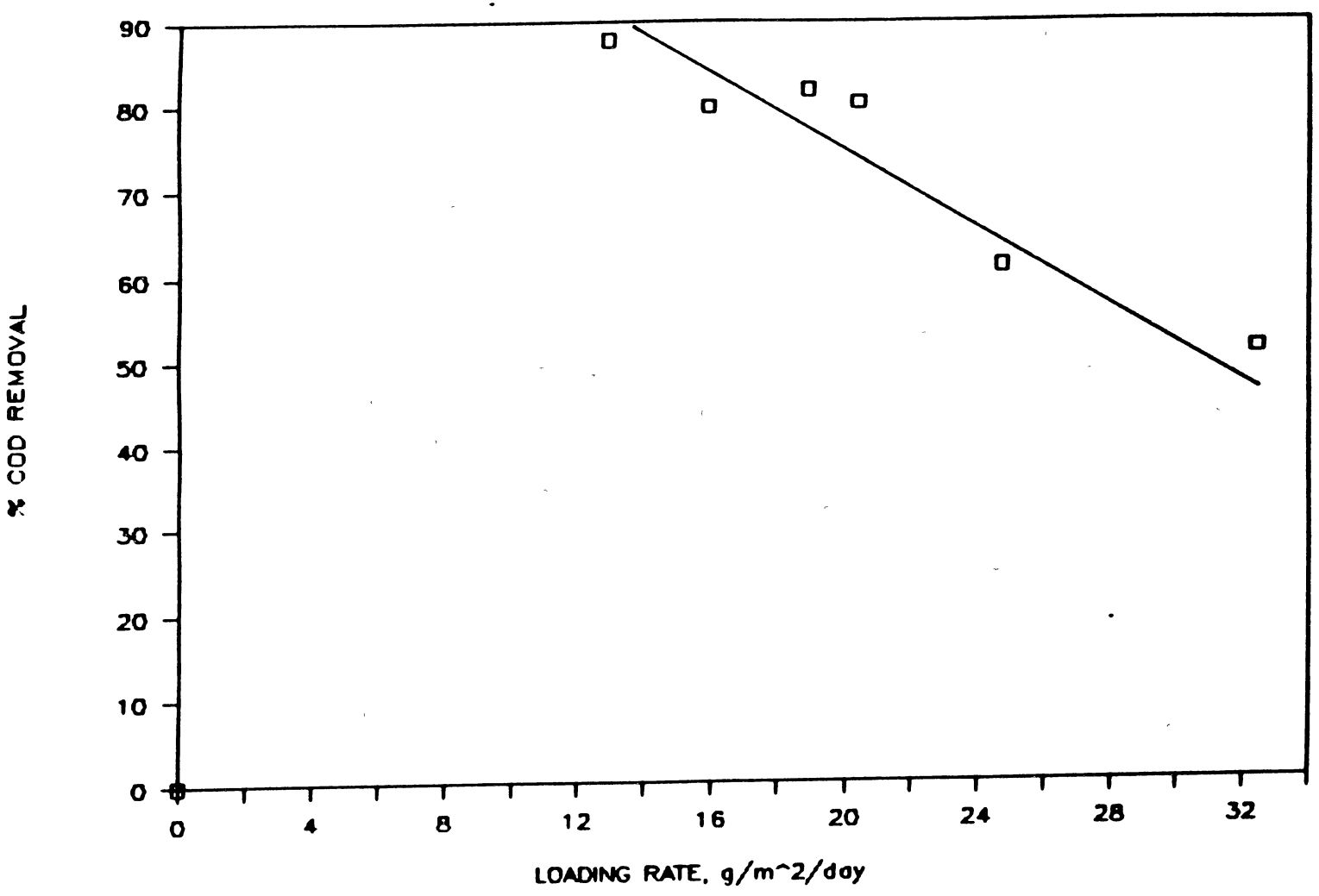

Figure 4. Organic Loading Vs Percent Removal

Figures 5, 6, and 7. During each run two bioassays were performed each week during the two week sampling period and these are shown as bioassays 1 and 2 in the figures. These results are also shown in Table 4. In the figures the results obtained for the fathead minnow are shown as minnow and that for Ceriodaphnia dubia as dubia. The acute toxic units were calculated by dividing 100 by the LC_{50} (USEPA, 1987). Since all the components except ammonia were reduced by passing through the ASBF reactor, ammonia was suspected to contribute significantly to the toxicity in the effluent. The samples for the lowest (14.0 g COD/m^2/day) and highest (24.0 g COD/m^2/day) loading conditions were treated with Clinoptiltolite to reduce ammonia. The reduction in ammonia content is shown in Table 5.

Clinoptiltolite is an ion-exchange resin used to exchange ammonium ion. Once all of the ionized ammonia is exchanged by the resin, the equilibrium between the unionized and ionized ammonia shifts towards the formation of more ionized ammonia and hence more of the ammonia is exchanged. Thus the ammonia was reduced by the resin which is shown in Table 5. The bioassays of the samples treated with Clinoptiltolite showed a further increase in the LC_{50} for the ASBF unit effluent indicating that ammonia is contributing to the toxicity of the ASBF unit effluent. This is shown in Figures 6 and 7.

Ammonia exists in the ionized and unionized form depending on the pH and temperature. However the unionized ammonia has been demonstrated to be the principal toxic form of ammonia (USEPA, 1985). The unionized fraction of ammonia in the analyzed samples is given in parenthesis in

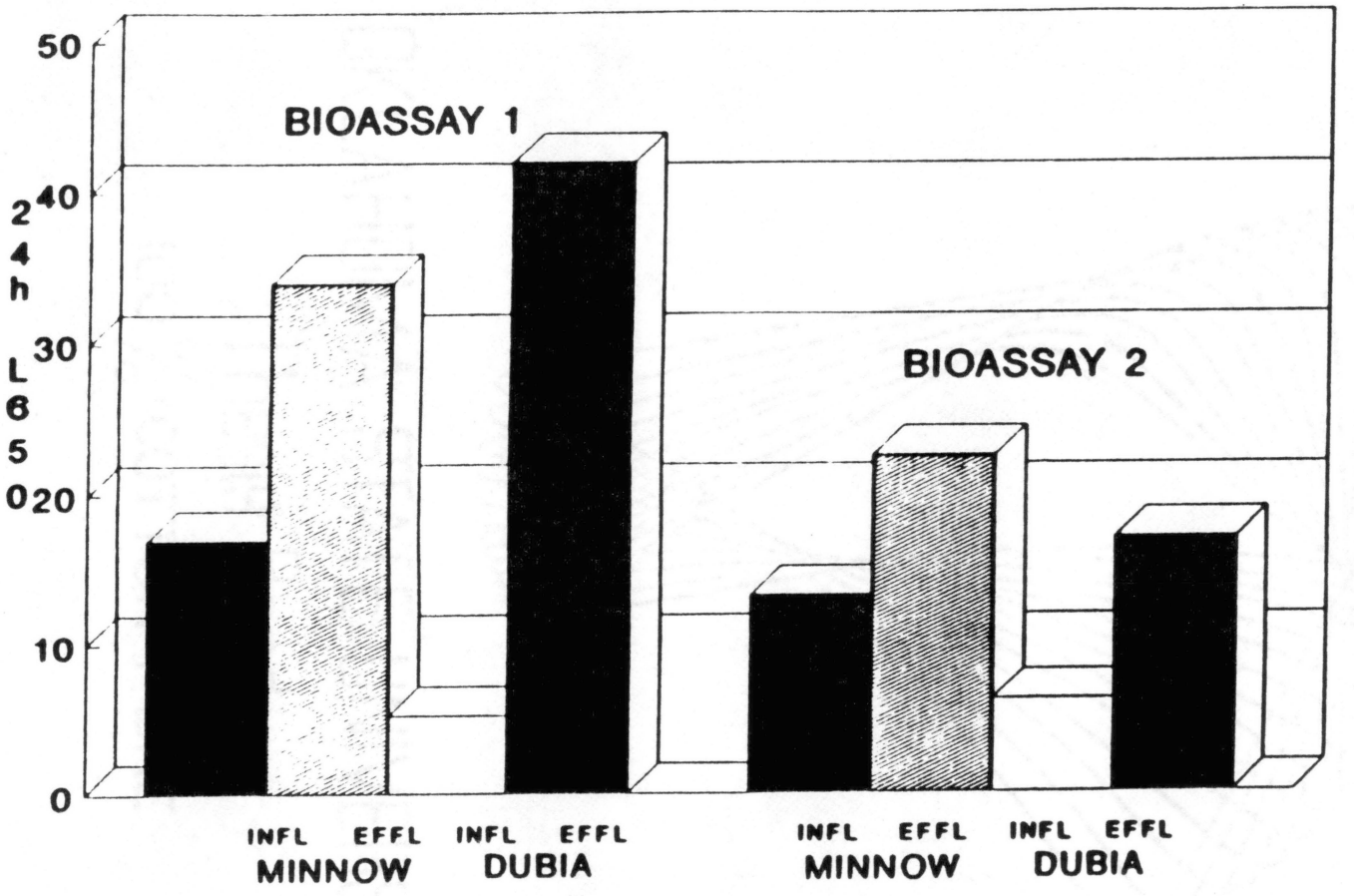

Figure 5. Results of Bioassays for Loading of 21.0 g COD/m^2/Day

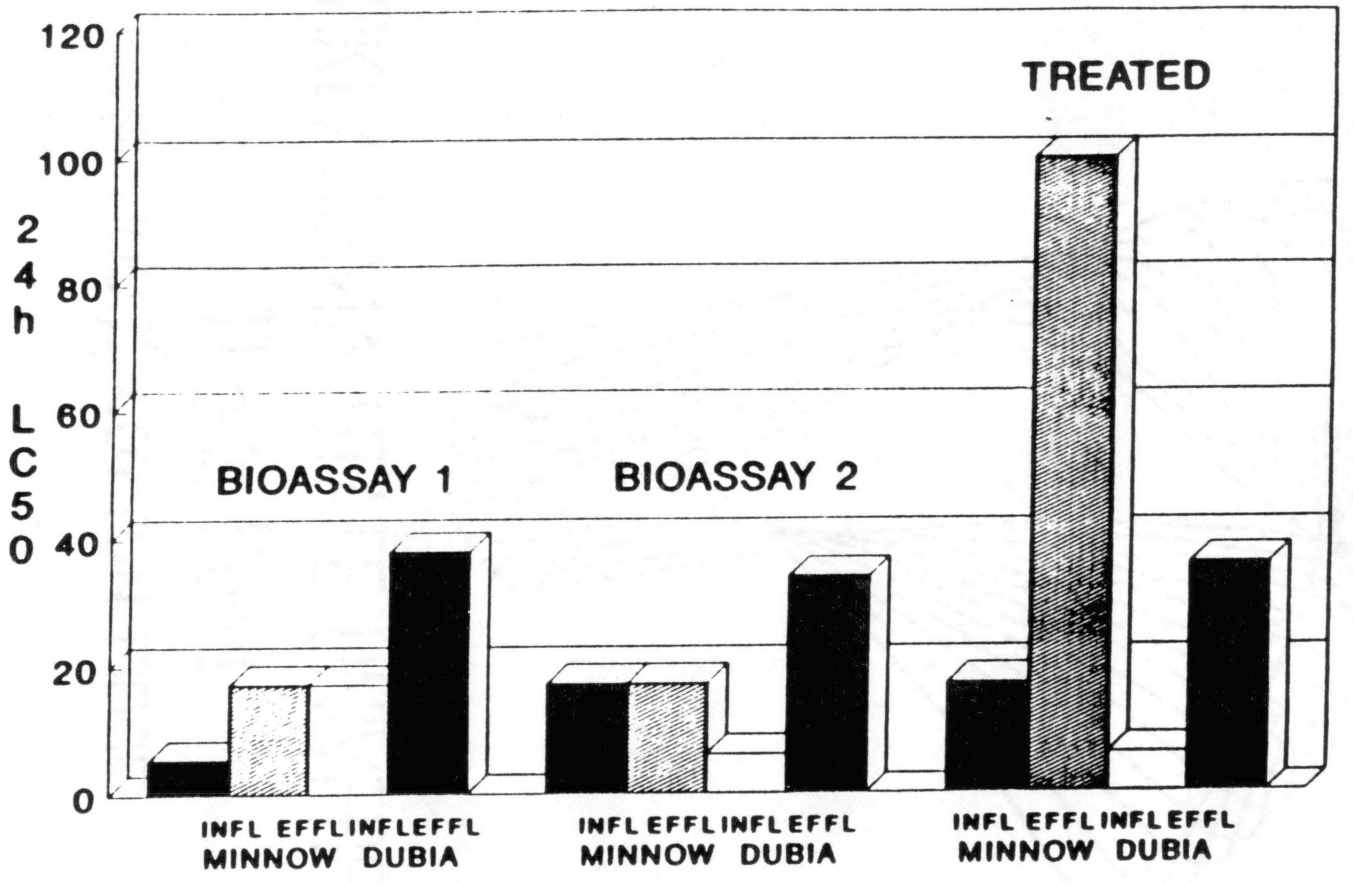

Figure 6. Results of Bioassays for Loading of 14.0 g COD/m^2/Day

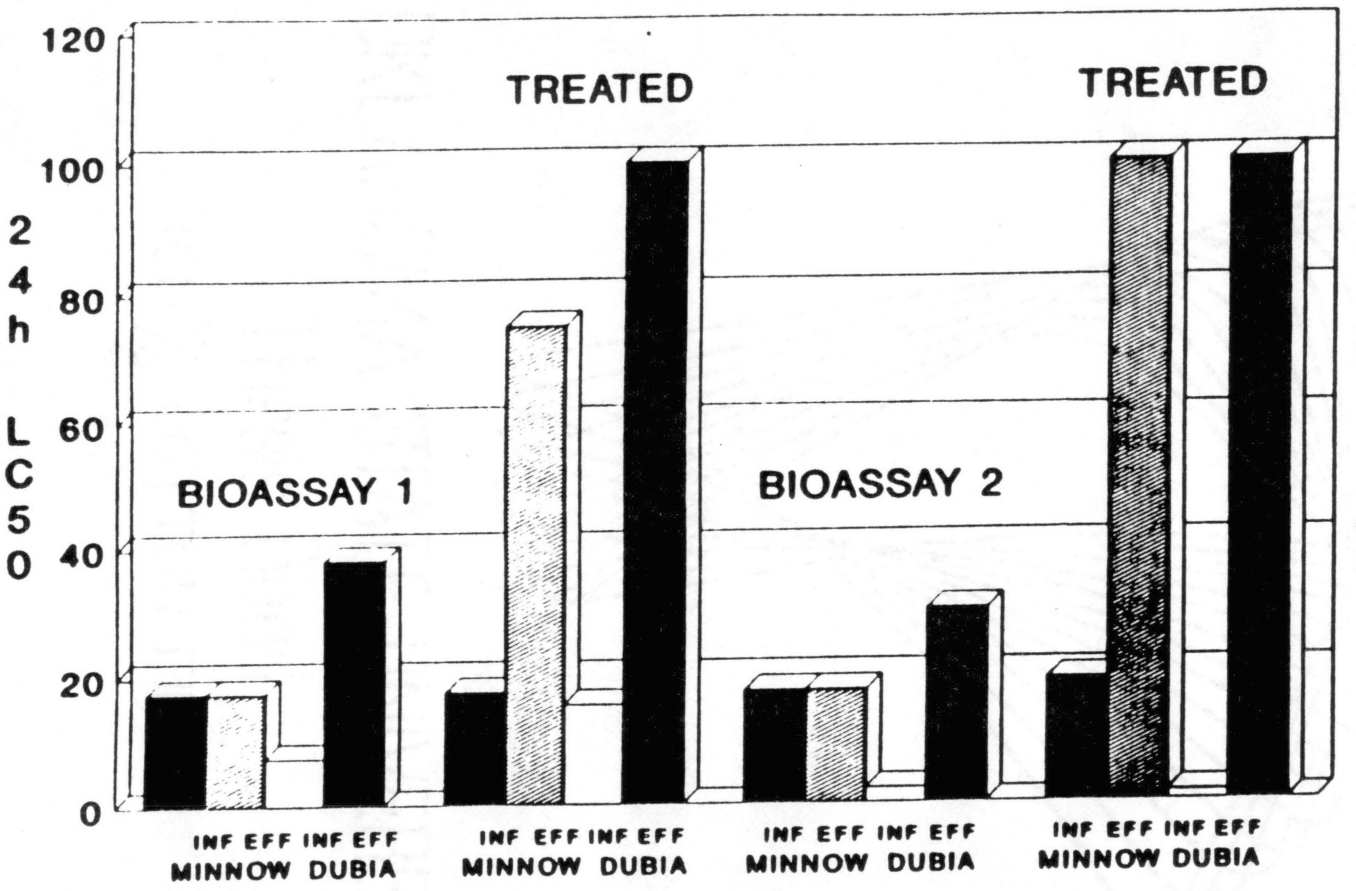

Figure 7. Results of Bioassays for Loading of 24.0 g COD/m^2/Day

TABLE 4

BIOASSAY RESULTS - LC_{50} AND TOXIC UNITS (TU)

LOADING RATE g/m2/day	FATHEAD MINNOW influent LC_{50}	TU	effluent LC_{50}	TU	CERIODAPHNIA DUBIA influent LC_{50}	TU	effluent LC_{50}	TU
14.0	5.4	18.5	17.2	5.8	17.2	5.8	38	2.6
	17.3	5.8	17.3	5.8	6.1	16.4	34	3
	*17.3	5.8	100	1	6.1	16.4	36	2.8
20.8	17	5.9	34	3	5.2	19.2	42	2.4
	13.2	7.6	22.5	4.4	6.2	16.1	17	5.9
24.0	17.5	5.7	17.5	5.7	7.4	13.5	38	2.6
	*17.5	5.7	75	1.3	15.5	6.5	100	1
	17.5	5.7	17.5	5.7	2.3	44.4	30	3.3
	*19	5.3	100	1	1.4	71.4	100	1

* These are the values for the samples treated with Clinoptiltolite.

TABLE 5

AMMONIA CONTENT OF THE TREATED AND UNTREATED SAMPLES*

LOADING RATE g COD/m^2/day		UNTREATED SAMPLE NH_3-N, mg/l	TREATED SAMPLE NH_3-N, mg/l
14.0	INFL	50.3 (0.28)	0.0
	EFFL	69.4 (9.9)	0.0
24.0	INFL	66.9 (0.5)	1.0
	EFFL	64.4 (6.4)	1.5
24.0	INFL	69.5 (0.2)	0.0
	EFFL	66.9 (9.4)	0.8

* The value in parenthesis gives the unionized fraction of ammonia in mg/l.

Table 5. This was calculated using a table which gave the percent unionized ammonia for several pH and temperature intervals (USEPA, 1985).

It is possible that the sour water has more than one fraction that causes toxicity. One of them may be a mixture of organics which are very complex and causes toxicity problems (Burks and Wagner, 1984). The LC50's determined by the bioassay showed that the effluent is less toxic than the influent. This is seen in Table 4. The reduction in toxicity may be due to the removal of organics by the ASBF treatment as measured by a reduction of COD. It is seen from the raw physical/chemical data given in the appendix that the pH of the effluent is much higher than the influent and also in most samples tested the ammonia content is also higher in the effluent. More ammonia exists in the unionized form at higher pH's. Since it is known that the unionized form of ammonia is more toxic to aquatic organisms (USEPA, 1985), ammonia may now be the dominant fraction that causes toxicity in the effluent.

The relationship for the pH dependence of acute ammonia toxicity is that the acute ammonia toxicity is equal to the LC50 value at pH 8. This relationship is used for pH's 8.0 and above. The pH of the ASBF unit effluent was always greater than or equal to 8.0. For pH above 8.0 the theoretical toxic LC50 concentration of unionized ammonia for Ceriodaphnia has been determined to be 3.0 mg/l (USEPA, 1985). For those samples in which the ammonia was reduced using the Clinoptiltolite treatment and toxicity evaluation performed, the concentration of unionized ammonia for the LC50 dilution was determined. These are

shown in Table 6. It is seen that the concentration of unionized ammonia before the treatment is close to the theoretical toxic concentration. A sample of the same effluent treated with Clinoptiltolite had its LC50's increased to 100% as shown in Table 4. Therefore, the toxicity could be due to cations that are removed by the resin which is a cation exchange resin. If the unionized ammonia concentration is above the theoretical limit, it may be that the toxicity of the unionized ammonia is dampened by other constituents of the matrix while if it is below the theoretical limit it may be that there are also some additional toxicants, in this case cations, that contribute to the overall toxicity. However, since the unionized concentration of ammonia is close to the theoretical toxic concentration, the unionized ammonia may be the predominant toxic component in the ASBF unit effluent.

The following determinations show how the unionized ammonia concentrations can be correlated to the theoretical toxic unit for unionized ammonia concentration. It is assumed that 3.0 mg/l of unionized ammonia is equal to one toxic unit for the unionized ammonia toxicity alone. This is the theoretical toxic 24-hour LC50 concentration of unionized ammonia. Using this, the toxic unit for the ASBF unit effluent can be determined by dividing the concentration of unionized ammonia that has been corrected for the LC50 dilution by the 24-hour LC50 concentration toxic unit for unionized ammonia (3.0 mg/l). The values of the effluent toxic unit obtained for the samples shown in Table 6. are 1.1, 0.8 and 0.93 for the loading rates 14.0 g

TABLE 6

CONTRIBUTION OF AMMONIA TOXICITY

LOADING RATE g COD/m^2/day	UNIONIZED AMMONIA mg/l *	LC50 %	UNIONIZED AMMONIA FOR THE LC50 DILUTION mg/l	THEORETICAL TOXIC CONC. OF UNIONIZED AMMONIA mg/l
14.0	9.9 (8.5)	34	3.4	3.0
24.0	6.4 (8.2)	38	2.4	3.0
24.0	9.4 (8.4)	30	2.8	3.0

* The number given in the parenthesis is the pH of the samples.

COD/m^2/day and 24.0 g COD/m^2/day. Since all of the above values are close to the one toxic unit it is shown that the unionized ammonia may be the dominant toxic fraction in the ASBF unit effluent.

Since the ASBF is an aerated system it was decided to test the effect of aeration on toxicity reduction. When the unit was run without the biofilm, it was seen that aeration alone did not reduce the toxicity of the wastewater. The bioassay results gave an LC50 value of 15% for both the influent and effluent samples showing that the toxicity was not reduced by aeration alone.

Kinetics

A plot of the specific substrate removal rate as a function of the substrate loading rate is shown in Figure 8. The specific loadings and the specific substrate removal rates were calculated using the influent substrate concentration, Si, as the influent COD to the reactor and effluent substrate concentration, Se, as the effluent COD from the reactor. The area, A, is the total surface area of the media and the flow into and out of the system is given as F. This plot indicates that the specific substrate removal rate is a hyperbolic function of substrate loading rate and hence the two may be mathematically related by an expression similar to the Monod growth kinetics of bacteria, (Monod, 1949).

The relationship obtained in Figure 8 was used to develop the kinetic constants for the ASBF treating the refinery wastewater. Some assumptions were made in order to arrive at the constants. The amount of biomass contributed by suspended growth is very small compared to the amount

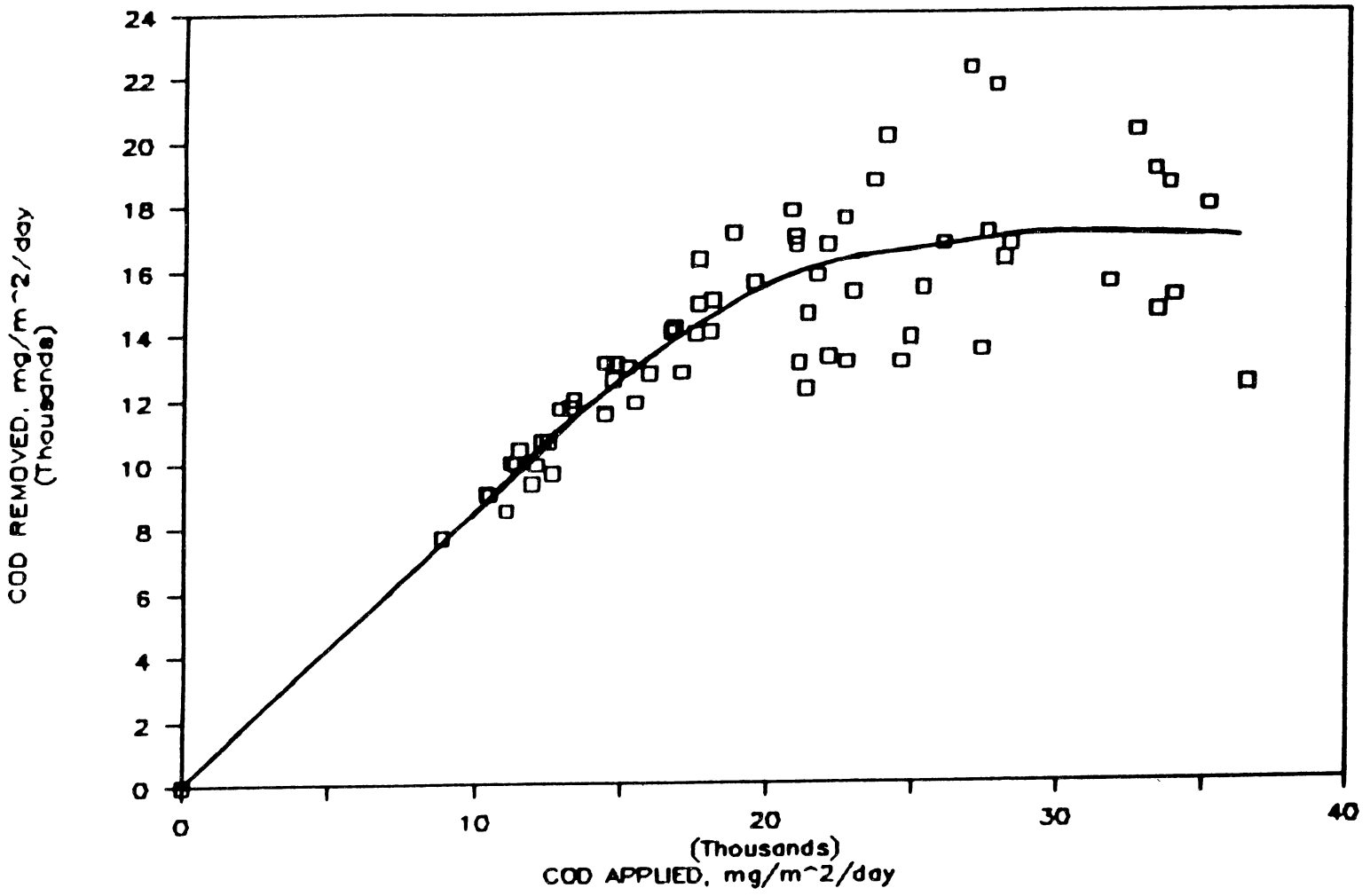

Figure 8. Plot of COD Applied Vs COD Removed

contributed by the attached growth so that any contribution to substrate removal from suspended growth can be neglected (Hamoda, 1989). Hence the ASBF reactor is essentially considered to be an attached film reactor in deriving the kinetic constants.

Two semi-empirical models were analyzed to obtain the kinetic constants. The basis for the model proposed by Eckenfelder (Eckenfelder et al, 1980) is that the organic removal rate is proportional to the organic concentration. The interpretation of this model is done by plotting the removal rate per unit area, F(Si-Se)/A, versus Se. This gives a linear plot as shown in Figure 9 with a slope equal to a proportionality constant, K. The value for K is 4.58 $l/m^2/day$. The plots show a lot of scatter which is seen with any biological reactor. A few outliers were eliminated to obtain the most linear fit. Due to the scatter in the data the correlation coefficient was low. For this model the correlation coefficient was equal to 0.46.

The model proposed by Korengay and Andrews, 1968, is also based on the Monod kinetics. A reciprocal plot of 1/Se versus 1/F(Si-Se) was made as shown in Figure 10. This was done according to the following equation;

$$F(Si-Se) = P\ (Se/(Ks+Se))$$

In this equation, P, is the area capacity constant and Ks is the saturation constant. The slope gives the value of Ks/P and the intercept gives the value of 1/P. It was determined that P was equal to 22.8 $g/m^2/day$ and Ks was equal to 88.8 mg/l. The correlation coefficient for this plot was equal to 0.56. The constant P incorporates the surface area, concentration of organisms in the biological

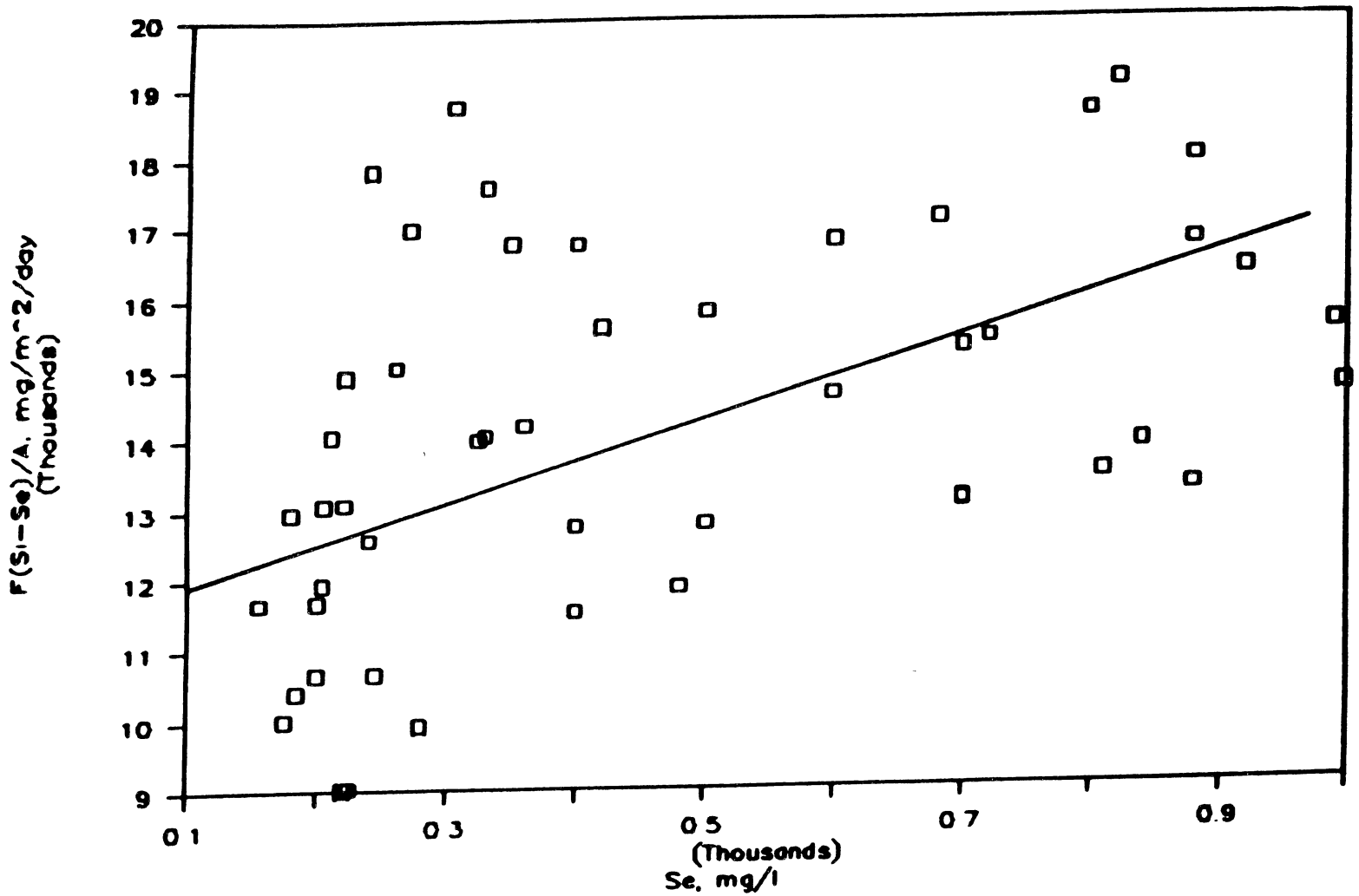

Figure 9. Plot for Eckenfelder Model

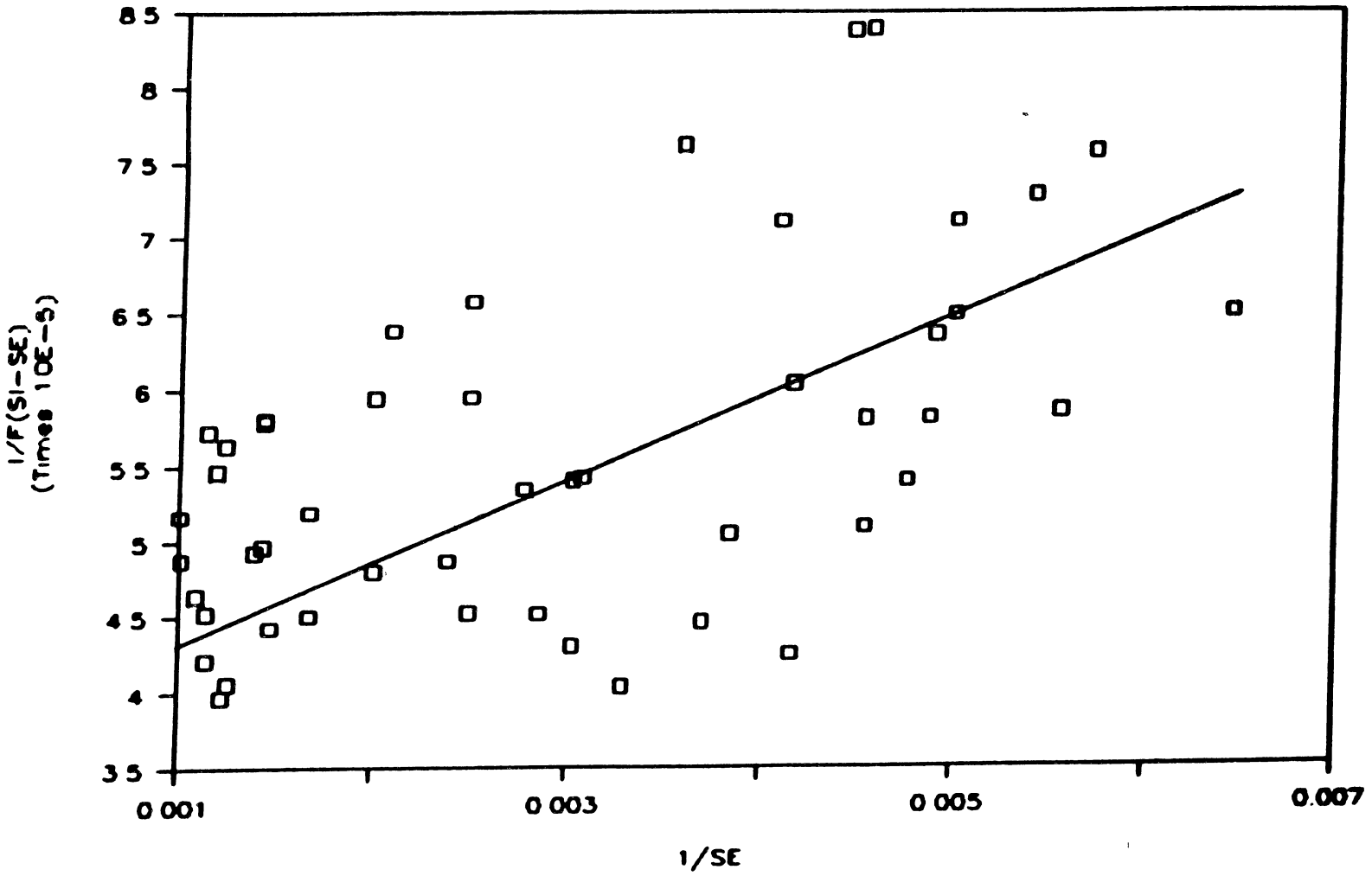

Figure 10. Plot for Korengay and Andrews Model

film, depth of active organisms, specific growth rate and the yield factor.

A model proposed by Kincannon and Stover (1982) was also used to determine the kinetic constants. This is an empirical model based on the total organic loading. This model was also based on the hyperbolic relationship shown by Monod equation. The biological kinetic constants, maximum specific substrate removal rate, Umax, and a proportionality constant, K_B, were determined using this model. This was done by plotting reciprocals of the specific substrate utilization, F(Si-Se)/A and the organic loading applied to the system, FSi/A, as shown in Figure 11. The correlation coefficient for this fit was equal to 0.89. This plot gave an intercept equal to 1/Umax and slope equal to K_B/Umax. The value of Umax was equal to 33.33 $g/m^2/day$ and that for K_B was equal to 23.7 $g/m^2/day$. K_B is equal to the substrate concentration when the substrate removal rate is half the maximum.

For the purpose of design, the constants obtained from the model proposed by Kincannon and Stover can be used to determine the area required by using the following equation;

$$A = (FSi)/((UmaxSi/(Si-Se))-K_B)$$

For a flow of 0.4 MGD, which was the wastewater flow from the sour water stripping unit in the refinery that provided the wastewater the area required to reduce the wastewater from an influent substrate concentration of 1900 mg/l to a concentration of 300 mg/l would equal 52103 m^2. If a media with specific surface area of 137 m^2/m^3 is used, a volume equal to 380 m^3 would be required for this

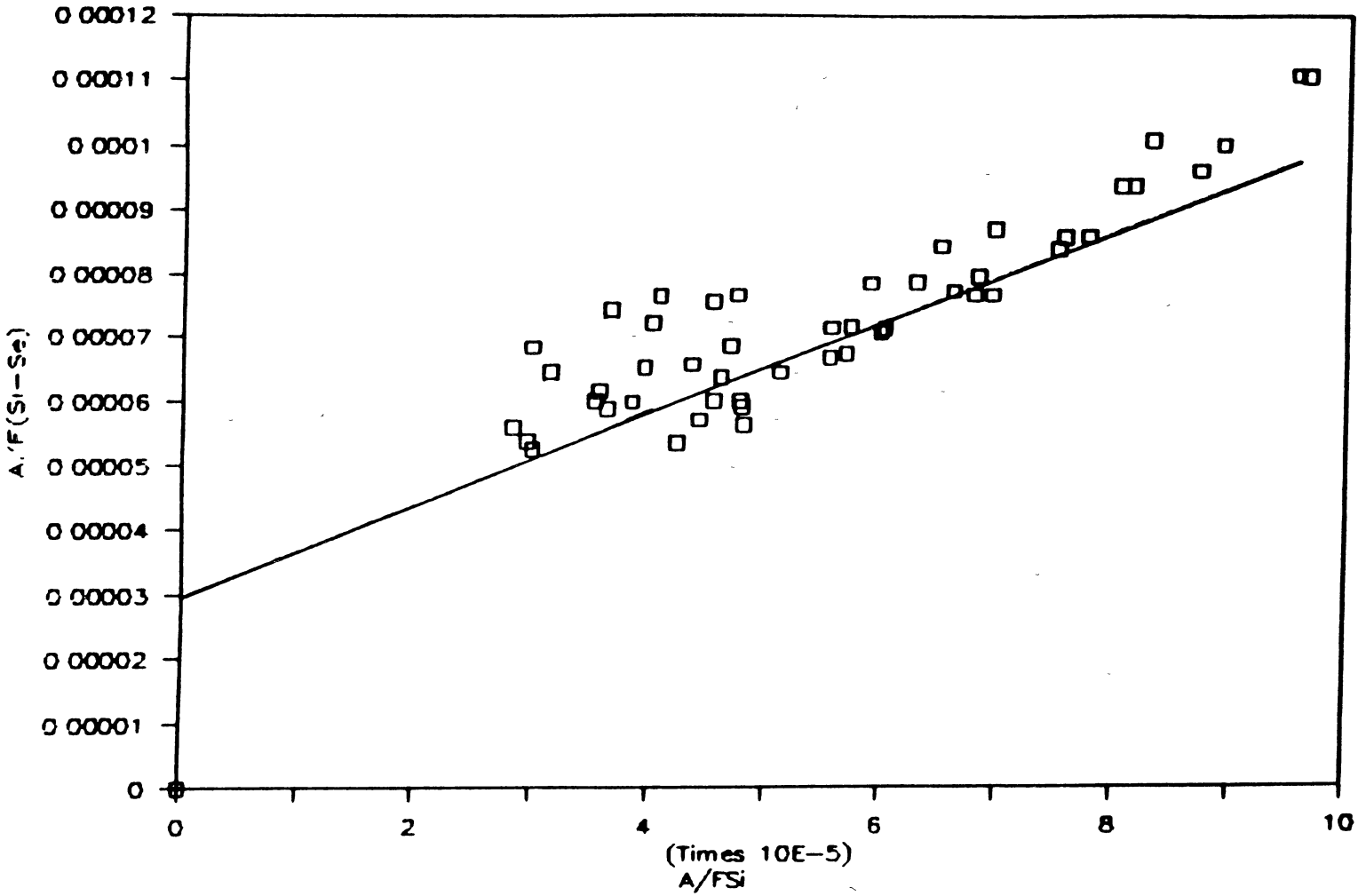

Figure 11. Plot for Kincannon and Stover Model

treatment.

This model can also be used to predict the sludge production from a fixed film reactor. This was done by making a plot of solids produced per day per square meter, F(Xi-XE)/A, as a function of the specific substrate utilization, F(Si-SE)/A as shown in Figure 12. The Y-axis intercept corresponds to the decay coefficient, Kd, and the slope of the line gives the true yield, Yt. The value of Kd was determined to be equal to 16.65 g solids produced/day/m^2 and that of Yt was 0.00163 g solids produced/g COD removed.

CONCLUSIONS

Based on the results obtained from this study, a number of conclusions can be drawn about the performance of the ASBF used to treat refinery wastewater. At lower loading rate (14.0 g/m^2/day) higher removal efficiency is obtained than at higher loading rate (20.8 g/m^2/day and 24.0 g/m^2/day). The toxicity of the ASBF effluent is less than the influent as shown by the increase in LC_{50}. Since the pH of the effluent is higher more of the ammonia exists in an unionized form and may be the dominant fraction that causes toxicity in the effluent. This was shown by the increase in the LC50 values for the samples treated with Clinoptiltolite to reduce toxicity. It was also shown that the concentration of the unionized ammonia in the effluent was close to the theoretical toxic concentration. It was shown that the aeration alone did not remove the toxicity of the wastewater. The settling characteristics of the sludge from the ASBF were good for the higher loading

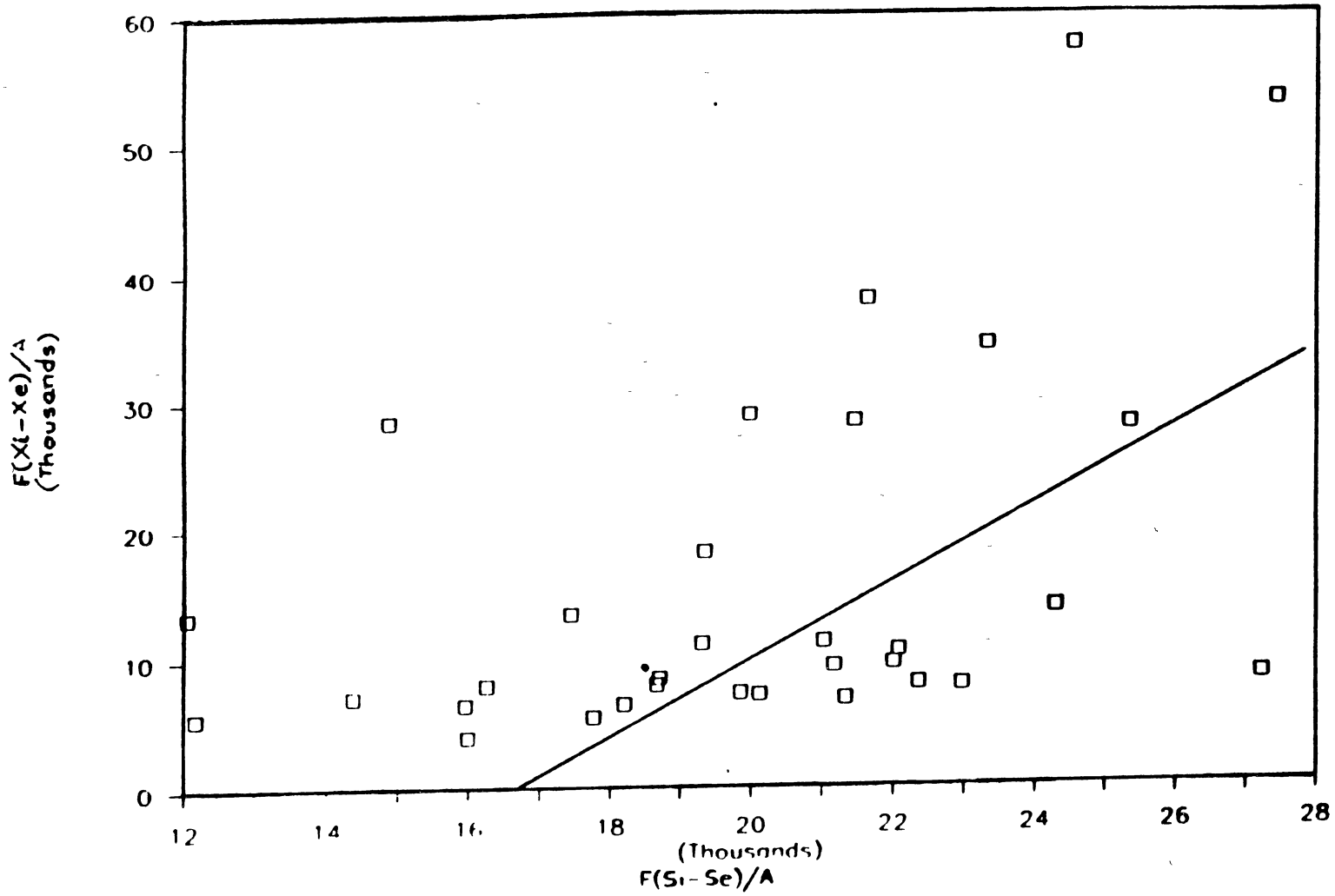

Figure 12. Solids Relationships

rates.

Since the specific substrate removal rate is a hyperbolic function of the substrate loading rate, the two can be mathematically related similar to a Monod Growth Model. The model proposed by Eckenfelder gave a proportionality constant, K, as 4.58 $l/m^2/day$. Using the model proposed by Korengay and Andrews the area capacity constant, P, was determined to be equal to 22.8 $g/m^2/day$ and the saturation constant was equal to 88.8 mg/l. The model proposed by Kincannon and Stover gave a proportionality constant, K_B, equal to 23.7 $g/m^2/day$ and the value of Umax was determined to be 33.33 $g/m^2/day$. This model also gave the values of Kd to be equal to 16.65 g solids produced/day/m^2 and that of Yt was equal to 0.00163 g solids/day/m2.

Wastewater coming directly off a process unit was treated in this experiment and the COD's and BOD's were at least two to three times greater than those of municipal wastewater. Hence the absence of huge decrease in toxicity should not necessarily be taken as a sign of poor reactor performance. The ASBF has potential in terms of treatment ability due to its ease of operation relative to other biological systems, its ability to withstand a certain amount of influent substrate variation and demonstrated ability to remove waste stream toxicity.

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APPENDIX

Table A1. Raw physical-chemical data collected at the three loading rates.

DATE	FLOW RATE (ml/min)	INFL pH (SU)	INFL TEMP. (C)	INFL COD (mg/l)	EFFL pH (SU)	EFFL TEMP. (C)	EFFL COD (mg/l)
09-17-90	5.20	6.80	24.00	2000.0	7.80	23.00	240.0
09-18-90	6.90	7.00	24.50	1600.0	7.90	23.00	280.0
09-19-90	7.80	7.00	24.00	1400.0	8.20	22.00	300.0
09-20-90	6.50	6.80	24.00	2360.0	8.50	24.50	360.0
09-23-90	6.60	6.80	23.00	2000.0	8.50	22.00	400.0
09-25-90	7.30	7.20	23.00	2000.0	8.00	23.00	400.0
09-27-90	8.60	7.50	24.00	2080.0	7.90	23.50	420.0
09-28-90	7.80	7.20	24.50	2000.0	8.00	22.50	500.0
09-30-90	6.80	7.30	24.00	2080.0	8.10	22.00	480.0
10-01-90	5.60	7.30	24.00	2360.0	8.00	22.50	480.0
10-02-90	8.80	7.70	24.50	2800.0	8.20	24.00	480.0
10-03-90	5.90	7.20	25.00	1960.0	8.00	23.00	460.0
10-04-90	4.60	7.50	23.00	2200.0	8.30	22.00	500.0
07-17-90	11.20	7.90	23.00	1700.0	8.00	20.30	240.0
07-19-90	11.20	7.70	24.00	1440.0	7.90	23.00	220.0
07-21-90	10.80	7.30	25.00	1840.0	7.80	25.00	500.0
07-23-90	10.90	7.50	24.50	1760.0	7.80	24.00	350.0
07-25-90	11.00	7.40	24.00	2000.0	8.00	24.00	320.0
07-27-90	10.60	7.00	25.00	1560.0	8.00	23.50	260.0
07-29-90	11.20	7.00	24.50	1240.0	7.80	23.00	180.0
07-31-90	8.00	7.30	24.00	1680.0	8.30	23.00	240.0
08-02-90	12.00	7.00	23.00	1680.0	7.80	22.00	400.0
08-03-90	12.60	8.00	24.00	2020.0	8.00	23.00	440.0
10-23-90	11.70	7.50	24.00	2200.0	8.00	23.00	920.0
10-25-90	12.00	7.40	23.00	2160.0	8.00	22.00	880.0
10-27-90	9.20	7.00	24.00	2200.0	8.00	23.00	880.0
10-28-90	10.00	7.50	24.00	2080.0	8.20	23.00	880.0
10-29-90	10.30	7.20	24.00	1900.0	7.90	23.00	600.0
11-01-90	10.50	6.90	24.00	1840.0	7.90	22.50	700.0
11-03-90	10.00	7.20	24.00	2100.0	8.10	22.50	700.0
11-05-90	12.00	7.20	24.00	1900.0	8.00	22.00	840.0
11-06-90	12.20	7.80	22.00	1600.0	8.00	21.00	680.0
11-07-90	14.00	7.75	23.00	1800.0	8.10	21.50	680.0
11-09-90	12.60	7.10	23.00	1840.0	7.90	22.00	720.0
11-11-90	14.00	7.30	22.50	1700.0	7.80	23.50	600.0
11-13-90	15.00	7.80	23.50	1500.0	8.00	22.50	700.0

Table A1 (continued)*

DATE	BOT. DO	INF TSS	EFF TSS	SUS TSS	BOT. TSS	INF VSS	EFF VSS	SUS VSS	BOT. VSS
09-17-90	6.8	32	448	970	1290	20	402	890	1140
09-18-90	5.6	40	368	730	1280	40	334	690	1170
09-19-90	7.2	60	126	1640	1020	26	120	600	870
09-20-90	6.0	18	598	1310	1830	12	548	1310	1660
09-23-90	5.0	10	110	1740	1200	8	96	1590	1140
09-25-90	5.2	8	154	480	780	8	148	460	780
09-27-90	4.8	6	150	1060	3850	6	140	970	3760
09-28-90	5.0	22	290	1510	1250	20	276	1460	1150
09-30-90	1.8	20	152	950	610	14	142	880	590
10-01-90	2.6	24	204	630	800	18	186	530	720
10-02-90	2.6	24	358	540	700	24	332	500	660
10-03-90	5.5	26	284	1030	650	24	280	980	600
10-04-90	4.0	18	250	930	580	2	226	870	490
07-17-90	2.8	172	186			70	172		
07-19-90	5.4	48	256			46	248		
07-21-90	3.6	162	198			10	196		
07-23-90	4.0	44	132		620	20	128		582
07-25-90	4.6	27	96		322	12	81		298
07-27-90	5.7	258	602		350	18	26		324
07-29-90	3.6	36	118		264	20	112		264
07-31-90	6.3	8	112	314	270	2	106	196	248
08-02-90	4.6	8	182	186	274	6	158	164	252
08-03-90	2.8	26	146	220	294	20	130	200	258
10-23-90	2.6	16	62	1100	480	16	56	1060	350
10-25-90	6.6	2	100	500	2440	2	92	400	2390
10-27-90	5.0	8	152	1960	540	2	146	1870	480
10-28-90	5.0	6	152	1240	1700	6	146	120	1640
10-29-90	4.0	14	104	860	670	2	92	770	600
11-01-90	5.0	50	98	2850	4100	36	98	2700	340
11-03-90	3.8	6	64	1080	730	6	64	1040	730
11-05-90	5.0	6	84	3730	1460	2	82	3450	1450
11-06-90	5.0	6	66	2050	1660	4	52	1920	1590
11-07-90	5.0	0	96	2560	1670	0	96	2380	1550
11-09-90	4.0	22	132	2120	1510	8	102	1990	1380
11-11-90	1.8	10	172	1690	1890	0	158	1560	1770
11-13-90	3.0	38	282	1370	1440	24	252	1350	1300

* All units are in mg/l.

Table A1 (continued)*

DATE	INFL NH3	EFFL NH3	INFL ORG.N2	EFFL ORG.N2	INFL BOD5	EFFL BOD5
09-17-90						
09-18-90						
09-19-90						
09-20-90	50.00	60.00	3.75	4.75	1380	225
09-23-90						
09-25-90						
09-27-90	63.75	60.00	4.25	3.75	840	195
09-28-90						
09-30-90						
10-01-90						
10-02-90						
10-03-90						
10-04-90						
07-17-90						
07-19-90						
07-21-90	23.75	47.00	0.75	1.50	990	90
07-23-90						
07-25-90	37.25	36.25	2.25	3.50	1050	68
07-27-90						
07-29-90						
07-31-90						
08-02-90						
08-03-90						
10-23-90						
10-25-90	66.92	64.38			1170	263
10-27-90						
10-28-90	40.00	45.00	1.88	4.13		
10-29-90						
11-01-90	57.50	22.50	5.75	6.25	1560	495
11-03-90						
11-05-90						
11-06-90	33.50	41.00	5.75	6.13	1080	210
11-07-90						
11-09-90						
11-11-90						
11-13-90						

* All units are in mg/l

Table A2.a Raw data for first bioassay performed with fathead minnows at loading rate of 20.8 g COD/m^2/day. Test start date = 7/19/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. fathead minnows alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
10%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
30%	INFL	6	6	6	2	0	-	-	-
	EFFL	6	6	6	6	4	5	4	3
50%	INFL	6	6	6	0	-	-	-	-
	EFFL	6	6	6	3	0	-	-	-
100%	INFL	6	6	0	-	-	-	-	-
	EFFL	6	2	2	0	-	-	-	-

Table A2.b Raw data for first bioassay performed with ceriodaphnia dubia at loading rate of 20.8 g COD/m^2/day. Test Start Day = 7/19/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. ceriodaphnia dubia alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	4	4	4	4	4	4	4	4
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	4	4	4	4	4	4	4	4
3%	INFL	6	6	6	6	6	6	6	6
	EFFL	5	5	5	5	5	5	5	5
10%	INFL	6	6	6	6	6	6	6	-
	EFFL	5	5	5	5	5	5	5	5
30%	INFL	6	6	6	6	6	6	0	-
	EFFL	4	4	4	4	4	4	4	4
50%	INFL	6	6	6	0	-	-	-	-
	EFFL	4	4	4	4	4	4	1	1
100%	INFL	6	6	0	-	-	-	-	-
	EFFL	4	4	4	4	4	4	0	-

Table A2.c Raw data for first bioassay performed with fathead minnows at loading rate of 20.8 g COD/m^2/ day. Test start date = 7/25/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. fathead minnows alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
10%	INFL	6	6	6	6	6	5	4	4
	EFFL	6	6	6	6	6	6	6	6
30%	INFL	6	6	6	6	0	-	-	-
	EFFL	6	6	6	6	6	5	2	0
50%	INFL	6	6	6	0	-	-	-	-
	EFFL	6	6	6	6	2	0	-	-
100%	INFL	6	6	3	0	-	-	-	-
	EFFL	6	6	6	0	-	-	-	-

Table A2.d Raw data for first bioassay performed with ceriodaphnia dubia at loading rate of 20.8 g COD/m^2 day. Test start date = 7/25/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. ceriodaphnia dubia alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	3	6	2
	EFFL	6	6	6	6	6	6	6	6
10%	INFL	6	6	6	6	6	3	1	1
	EFFL	6	6	6	6	6	6	6	0
30%	INFL	6	5	5	5	4	2	0	-
	EFFL	6	6	6	6	6	2	0	-
50%	INFL	6	1	0	-	-	-	-	-
	EFFL	6	6	6	6	6	2	0	-
100%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	6	6	4	0	-	-	-

Table A2.e Raw data for first bioassay performed with fathead minnows at loading rate of 14.0 g COD/m^2 day. Test start date = 9/20/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. fathead minnows alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
10%	INFL	6	6	6	6	6	6	0	-
	EFFL	6	6	6	6	6	6	6	6
30%	INFL	6	6	6	6	0	-	-	
	EFFL	6	6	6	6	3	1	0	-
50%	INFL	6	6	6	0	-	-	-	-
	EFFL	6	6	5	2	0	-	-	-
100%	INFL	6	6	0	-	-	-	-	-
	EFFL	6	1	0	-	-	-	-	-

Table A2.f Raw data for first bioassay performed with ceriodaphnia dubia at loading rate of 14.0 g COD/m^2 day. Test start date - 9/20/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. ceriodaphnia dubia alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	5
	EFFL	6	6	6	6	6	6	6	6
10%	INFL	6	6	6	6	6	6	6	0
	EFFL	6	6	6	6	6	6	6	6
30%	INFL	6	6	0	-	-	-	-	-
	EFFL	6	6	6	6	6	6	6	5
50%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	6	6	6	6	5	0	-
100%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	1	0	-	-	-	-	-

Table A2.g Raw data for first bioassay performed with fathead minnows at loading rate of 14.0 g COD/m^2 day. Test start date = 9/27/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. fathead minnows alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
10%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
30%	INFL	6	6	6	0	-	-	-	-
	EFFL	6	6	6	6	6	0	-	-
50%	INFL	6	6	6	0	-	-	-	-
	EFFL	6	6	6	0	-	-	-	-
100%	INFL	6	6	0	-	-	-	-	-
	EFFL	6	0	-	-	-	-	-	-

Table A2.h Raw data for first bioassay performed with ceriodaphnia dubia at loading rate of 14.0 g COD/m^2 day. Test start date = 9/27/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. ceriodaphnia dubia alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	0
	EFFL	6	6	6	6	6	6	6	6
10%	INFL	6	6	6	6	6	6	1	0
	EFFL	6	6	6	6	6	6	6	6
30%	INFL	6	6	2	1	1	1	0	-
	EFFL	6	6	6	6	6	6	4	1
50%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	6	6	6	6	6	0	-
100%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	0	-	-	-	-	-	-

Table A2.i Raw data for first bioassay performed with fathead minnows at loading rate of 24.0 g COD/m^2 day. Test start date = 10/25/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. fathead minnows alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	2
10%	INFL	6	6	6	6	6	6	6	4
	EFFL	6	6	6	6	6	6	2	0
30%	INFL	6	6	6	6	6	6	6	1
	EFFL	6	6	6	6	0	-	-	-
50%	INFL	6	6	6	5	5	5	0	-
	EFFL	6	6	4	1	0	-	-	-
100%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	6	4	0	-	-	-	-

Table A2.j Raw data for first bioassay performed with ceriodaphnia dubia at loading rate of 24.0 g COD/m^2day. Test start date = 10/25/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. ceriodaphnia dubia alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	2
10%	INFL	6	6	6	6	6	6	6	4
	EFFL	6	6	6	6	6	6	2	0
30%	INFL	6	6	6	6	0	-	-	-
	EFFL	6	6	6	4	0	-	-	-
50%	INFL	6	6	6	4	0	-	-	-
	EFFL	6	1	0	-	-	-	-	-
100%	INFL	6	4	1	0	-	-	-	-
	EFFL	6	0	-	-	-	-	-	-

Table A2.k Raw data for first bioassay performed with fathead minnows at loading rate of 24.0 g COD/m^2 day. Test start date - 11/1/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. fathead minnows alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	-
	EFFL	6	6	6	6	6	6	2	0
10%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	0	-
30%	INFL	6	6	0	-	-	-	-	-
	EFFL	6	6	5	3	0	-	-	-
50%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	0	-	-	-	-	-	-
100%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	0	-	-	-	-	-	-

Table A2.1 Raw data for first bioassay performed with ceriodaphnia dubia at loading rate of 24.0 g COD/m^2 day. Test start date = 11/1/90.

Conc. of Waste (% by vol.)		No. of Test Animals	No. ceriodaphnia dubia alive at						
			1 hrs	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs
Controls (0%)	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
1%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
3%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
10%	INFL	6	6	6	6	6	6	6	6
	EFFL	6	6	6	6	6	6	6	6
30%	INFL	6	6	5	5	2	1	3	0
	EFFL	6	6	6	6	0	-	-	-
50%	INFL	6	6	6	6	5	0	-	-
	EFFL	6	6	4	1	0	-	-	-
100%	INFL	6	0	-	-	-	-	-	-
	EFFL	6	0	-	-	-	-	-	-

The following symbols are used in this paper:

A = Total surface area of the media

F = Flow into and out of the reactor

K = Proportionality constant for Eckenfelder model

K_1 = Removal rate constant

K_B = Propotionality constant for Kincannon and Stover model

Kd = Decay coefficient

Ks = Saturation constant

P = Area capacity constant

t = Time interval

Se = Substrate concentration in the effluent

Si = Substrate concentration in the influent

SVI = Sludge Volume Index

Umax = Maximum specific substrate removal rate

Yt = True yield

ZSV = Zone Settling Velocity

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