EVALUATION OF AN AERATED SUBMERGED BIOLOGICAL FILTER IN THE TREATMENT OF ALCOHOL WASTEWATER

By

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CHAPTER I

INTRODUCTION

Fixed-film systems have been used for the treatment of wastewaters since the late 1860's. Throughout their evolution, there have been many changes in the configuration of the systems, type of media used, and purpose of their use. One of these modifications is the aerated submerged biological filter (ASBF) which was developed in a search for a compact treatment system that could be loaded at the same influent concentrations as the conventional filters yet give better effluent quality.

The ASBF system borrows its design from both the biological filters and the activated sludge systems. Its physical configuration is similar to a conventional filter in that packed media is used as a support for microbial growth. However, unlike the conventional filters, the ASBF is a totally submerged, upflow system which requires diffused aerators, similar to those employed in activated sludge systems, to maintain aerobic conditions. In this way, organic removal is accomplished by the attached microbial film as well as the microorganisms suspended in the mixed liquor. Since the amount of biological solids present in an ASBF is higher than in a biological tower the loading to these systems can also be higher.

A high strength alcohol wastewater was treated using an ASBF in order to take advantage of the high loadings applicable to it. The wastewater was supplied by the Oklahoma State University Agricultural Engineer's

200,000 gallon per year fuel alcohol facility. This research was part of an extensive fuel alcohol wastewater treatability study performed by the Bioenvironmental Engineering group at OSU. Systems used in the treatability tests included RBC's, activated sludge units, and anaerobic suspended-growth and fixed-film reactors.

The biokinetics for fuel alcohol wastewater treatment by the ASBF were developed for the design of full-scale systems. Based on these biokinetics, the ASBF was evaluated by comparing it to two down-flow biological towers (BT), using similar wastewaters (brewery waste and carbohydrate waste).

CHAPTER II

LITERATURE REVIEW

A. History of the ASBF Process

Fixed-Film wastewater treatment systems have been used since late 1860's. Mueller, from Berlin, demonstrated, in 1865, the treatability of sewage by living organisms in a filtration column packed with media ranging from coarse gravel to peaty soil (1). In 1868, Sir Edward Frankland performed a four-month successful study of filtration on raw London sewage in laboratory packed columns (1). Although the filter's treatment capability was considered to be a physical-chemical process, resting or aeration periods between sewage applications were required. Following the work done by Mueller, several researchers successfully proved the microbial aspect of sewage purification. Schloesing and Müntz first demonstrated soil nitrification in 1877. Winogradsky succeeded in identifying Nitrosomonas bacteria in 1890 (1). In 1887, the Lawrence Experimental Station group, directed by Allen Hanzen, began a series of filtration experiments in Massachusetts which were similar to the previous Frankland tests on intermittent dosing (1). Due to the success of the Lawrence experiments, biological treatment systems rapidly expanded.

In the search for better systems, different modifications and types of media, such as coke breeze, gravel, burnt clay, and coarse chalk, were used. In 1893, two men independently developed modifications of the serial filter scheme in order to better distribute the influent sewage across the

bed. Corbett used an additional wooden trough whereas Stoddart used coarse filter media to achieve improved distribution. In either case, the trickling filter was conceived.

Another modification was the contact bed, first used in Europe by Crimp and Dibdin in 1891. They experimented with a dosing pattern which flooded a coarse media filtration bed for 8 hours followed by 16 hours in a drained state (1). Although a few large scale units were built in the United States, contact beds did not receive much interest outside Europe. Due to the involved flooding routine, anaerobic conditions deteriorated the effluent quality. In addition to this problem, the frequent clogging of the media decreased the use of contact beds.

In 1904, Dibdin experimented with forced bed aeration and the coarse media was replaced with slate slabs packed in horizontal layers to facilitate flushing solid matter from the bed. The operation still followed the fill-and-draw routine (1). This may be considered to be the first contact aerator, or aerated submerged biofilter. Buswell and Pearson suggested a "Nidus (Nest) Tank" (2). The arrangement was a two-stage contact surface separated by intermediate sedimentation. The contact surface consisted of mats, woven from veneer or basket strips, placed vertically in the aeration tank. Compressed air was introduced through perforated pipes placed underneath the Nidus racks.

In 1930, Hays developed a contact aeration process and patented it as the "Hays Process" (2). It employed large asbestos-concrete sheets vertically stacked with 1" to 2" spacing along with a diffused aeration system. The first municipal contact aeration plant in the United States was constructed at Elgin, Texas, in 1939 and used rock as the contact media (2). Over seventy Hays Process installations were in operation by

1943. These plants could obtain 80 to 95 percent BOD_5 removal at favorable loading conditions.

In 1967, a new process called the "Fixed Activated Sludge Process" was studied. This system was a contact aeration system which used plastic net panels as the contact surface (2). In 1971, McCarty used an upflow submerged filter to study nitrification (2). Today there are only a few aerated submerged biological filters in operation in the United States in spite of the ease of operation (no sludge recycle as in activated sludge process and no effluent recirculation as in trickling filters).

B. The Biofilm

In fixed-film reactors, the microorganisms are attached to a solid medium where they grow as a film and remove the organic matter present in the liquid phase. This organic matter must be transported into the biofilm before being used by the microorganisms. In the movement of the organics from the liquid phase to the biofilm, it is necessary to consider the mass transfer resistance due to the liquid-solid interface and the mass transfer resistance within the fixed-film. These mass transfer resistances cause the substrate concentration around the microorganisms to be less than the concentration in the liquid phase.

Grady and Lim (3) idealized a substrate concentration profile by hypothesizing a stagnant liquid film, between the biofilm and the bulk liquid phase which causes a change in substrate concentration (see Figure 1). According to them, the rate of mass transfer of substrate across the stagnant liquid film, called the flux, is proportional to the change in substrate concentration across the stagnant layer. The proportionality

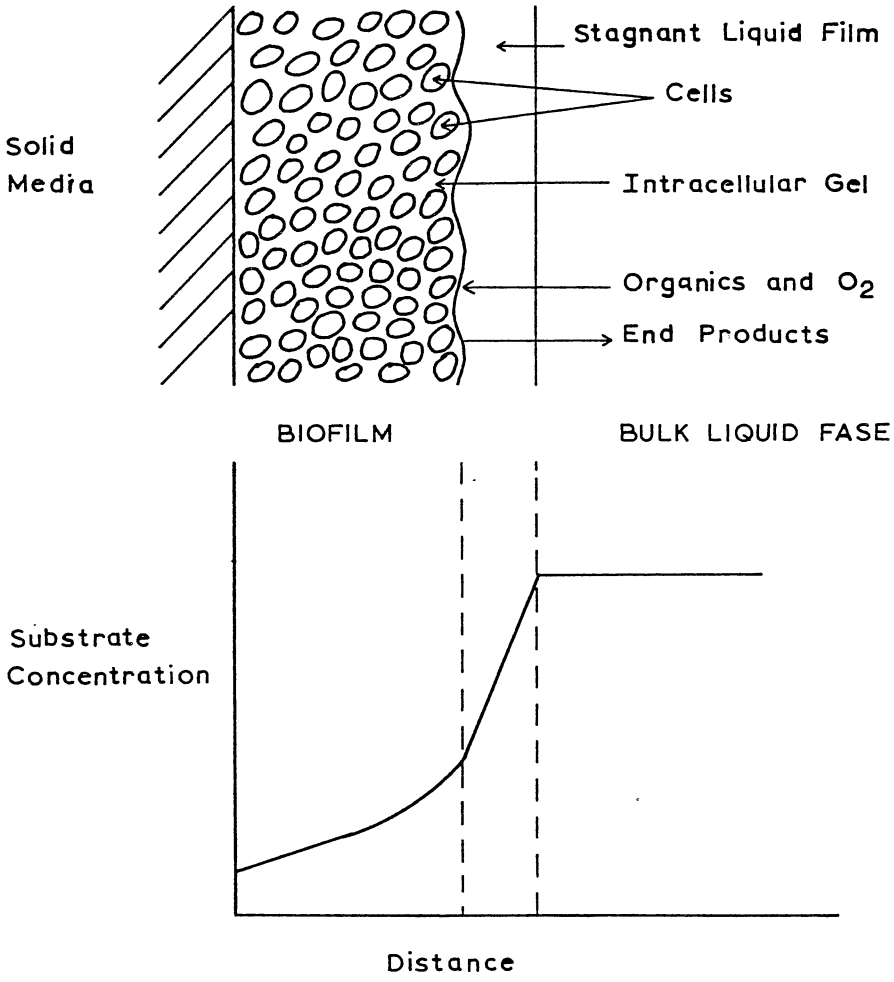

Figure 1. Profile of Substrate Concentration and Interactions Occurring at the Biofilm

constant, called the mass transfer coefficient (3), includes the effects of diffusive and convective mass transfer processes and its value depends on the properties of the fluid.

Clear evidence for external mass transport comes from the microprobe measurements of the dissolved oxygen profile up to and through a biofilm done by Bungay and coworkers (4). They demonstrated that the oxygen concentration at the liquid-solid interface can be less than that in the bulk liquid phase.

For the mass transfer within the biofilm, the substrate reaches the microorganisms by the diffusion process which is characterized by Fick's law (3). This law was developed for free diffusion in aqueous solutions and states that the rate of diffusion is proportional to the concentration gradient. The proportionality constant is referred to as the free diffusion coefficient. Since the biofilm is a gelatinous and complex geometric arrangement, the situation is rather similar to diffusion through catalysts which is Fick's law, but with the free diffusion coefficient replaced by the effective diffusion coefficient.

Two important characteristics of the biofilm are thickness and density. When considering the thickness of the biofilm, it is necessary to distinguish the total film thickness from the active film thickness. The total film thickness has been found to be between 0.07 and 4.00 milimeters while the active film thickness varies between 70 and 100 microns (4). Some investigators have reported values between 50 and 150 microns. Evidence of the active film's presence is based upon the relation between substrate removal rate and biofilm thickness. The rate of substrate consumption increase as the depths of the biofilm increases up to a limiting depth (the active film thickness) at which the removal is

maximum. Once the active film thickness is reached, the removal is independent of depth (see Figure 2). According to Grady, "It is now generally accepted that the active biofilm thickness is a result of transport limitations within the biofilm" (4). The depth of the biofilm may increase continuously until sloughing from the media occurs or it may reach a natural steady state where the growth is controlled by decay and attrition losses.

The detachment rate is a function of thickness and density. The density of the biofilm was generally assumed to be constant until Hoehn and Ray (4) discovered that the density depends on the thickness of the biofilm. Evidence of this is shown in Figure 3, where it can be seen that the maximum density corresponds to the active film depth. Beyond this depth the density decreases due to the lysis of cells under anaerobic conditions.

C. Kinetic Considerations

When steady state conditions exist at the surface and within the biofilm, the rate of substrate supplied by mass transfer must equal the rate of substrate utilization. In order to calculate the rate of substrate utilization, many different approaches have been presented. Grady and Lim (3) used Monod kinetics based on the concentration of the liquid phase and the specific substrate removal rate. Also, Grady (4) discussed the use of the same type of kinetics but based them on concentration and specific growth rate. The substrate utilization rate in the above cases is presented as the mass of substrate consumed per unit time per unit area of biofilm. Other investigators have presented empirical relationships developed on the basis of first-order kinetics and in

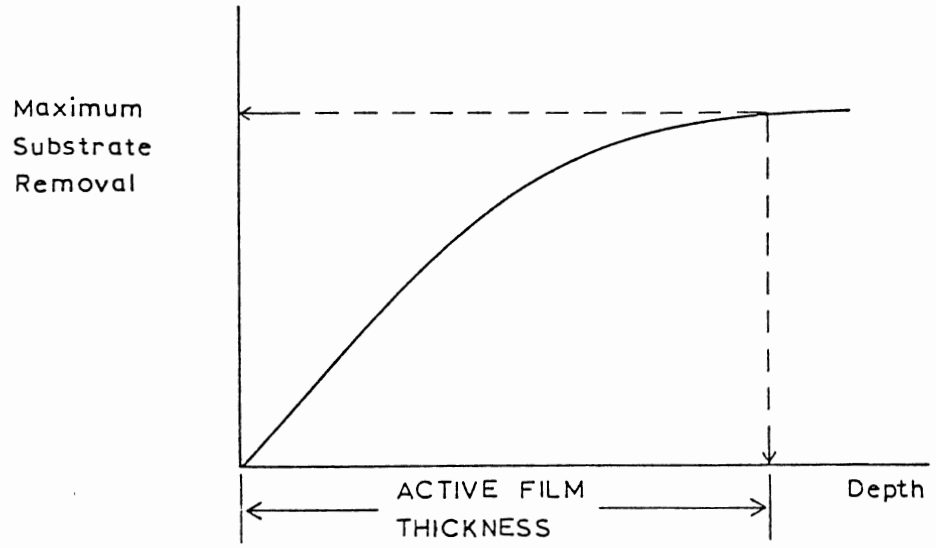

Figure 2. Substrate Utilization Rate as a Function of Depth

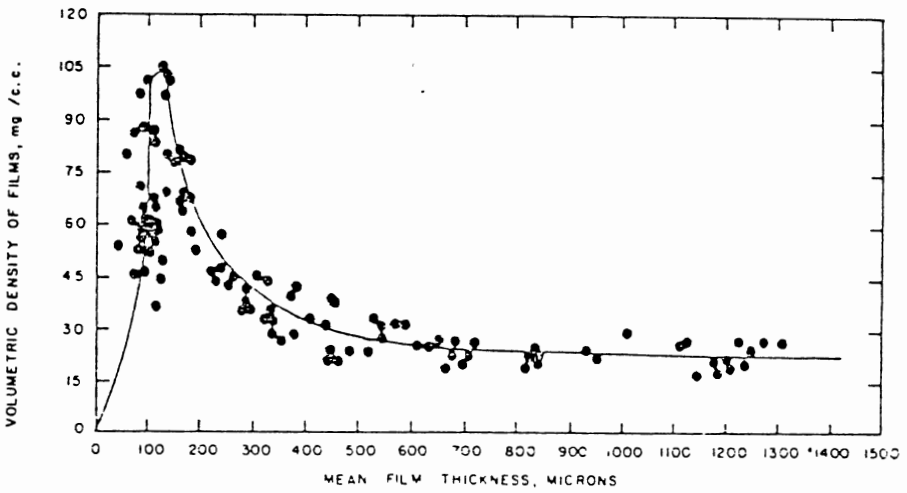

Figure 3. Density as a Function of Film Thickness (Taken From Reference 4)

terms of filter depth or liquid contact time (6).

There has been a controversy among investigators in the field as to whether the performance and efficiency of a fixed-film system depends on the organic concentration of the liquid phase or its hydraulic flow rate. Cook and Kincannon in 1970 (7) indicated that the performance of a biological tower depends upon the organic loading (lbs BOD/day/1000 ft^3) applied to it rather than the concentration or the hydraulic flow rate of the waste. The removal efficiency was the same when the total organic loading was reached by low flow rate and high waste concentrations as when it was reached by high flow rate and low waste concentration. In 1976, Stover and Kincannon (8) reported data indicating that the performance and efficiency of a rotating biological contactor (RBC) also depends upon the total organic loading. In 1982 (9), they presented a kinetic approach, based upon total organic loading, to predict the maximum BOD removal rate observed in RBC's. The relationship used to predict BOD removal was a hyperbolic function similar to the Monod equation. In 1982, Kincannon and Stover (10) presented a design methodology for fixed-film reactors using the total organic loading concept. The following is a discussion of the methodology mentioned above.

A mass balance of substrate into and out of a volume of media from a fixed-film reactor can be made as follows:

Mass of Substrate into the Volume = Mass of Substrate Out of the Volume + Mass of Substrate Consumed

$$FSi = FSe + \left(\frac{dS}{dtA}\right)_{A_G} \qquad (1)$$

where

F = Flow rate

Si = Influent substrate concentration, mg/L.

Se = Effluent substrate concentration, mg/L.

A = Surface area of the volume, 1000 ft^2.

$(\frac{dS}{dtA})_G$ = U = Specific substrate utilization rate, lbs of substrate/day/1000 ft^2.

The surface area represents the active mass of microorganisms. The mathematical expression for the substrate utilization rate is:

$$U = (\frac{dS}{dtA})_G = \frac{U_{max} \frac{FSi}{A}}{K_B + \frac{FSi}{A}} \quad (2)$$

where

U_{max} = Maximum specific substrate removal rate, lbs/day/1000 ft^2.

K_B = Proportionality constant. It is equal to the substrate concentration when the substrate removal rate is half the maximum, lbs/day/1000 ft^2.

Substituting Equation (2) into Equation (1):

$$FSi = FSe + \left\{ \frac{U_{max} \frac{FSi}{A}}{K_B + \frac{FSi}{A}} \right\} A \quad (3)$$

Equation (3) can be solved for A or Se. Solving for A gives,

$$A = \frac{FSi}{\frac{U_{max} \cdot Si}{Si - Se} - K_B} \quad (4)$$

Solving for Se gives,

$$Se = Si - \frac{U_{max}\, Si}{K_B + \frac{FSi}{A}} \qquad (5)$$

Equation (4) can be used to calculate the area required for a given design flow at given influent and effluent substrate concentrations. Equation (5) can be used to predict the effluent quality when given a set flow, area, and influent substrate concentration. The biological kinetic constants, U_{max} and K_B, must be determined experimentally by operating a fixed-film reactor at different substrate loading rates. By plotting the specific substrate utilization, $\frac{F(Si-Se)}{A}$, versus the organic loading applied to the system, $\frac{FSi}{A}$, an exponential type of curve, similar to the Monod equation, is obtained as shown in Figure 4(a). From the reciprocal plot, shown in Figure 4(b), the biokinetic constants, U_{max} and K_B, can be determined. The equation for that line is:

$$\frac{1}{U} = \frac{K_B}{U_{max}} \cdot \frac{1}{\frac{FSi}{A}} + \frac{1}{U_{max}}$$

where $\frac{1}{U_{max}}$ is the Y-axis intercept and $\frac{K_B}{U_{max}}$ is the slope of the line.

Also, a mathematical model is used to predict the sludge production from a fixed-film reactor (10). A solids mass balance for a given segment of the reactor can be written as follows:

Mass of Solids Out of the Volume = Mass of Biological Solids Produced − Mass of Solids Autodigested + Mass of Solids Into the Volume

$$FX_e = [Y_t(\frac{dS}{dtA})_G - Kd']A + FX_o \qquad (6)$$

Substituting Equation (2) into Equation (6) and rearranging

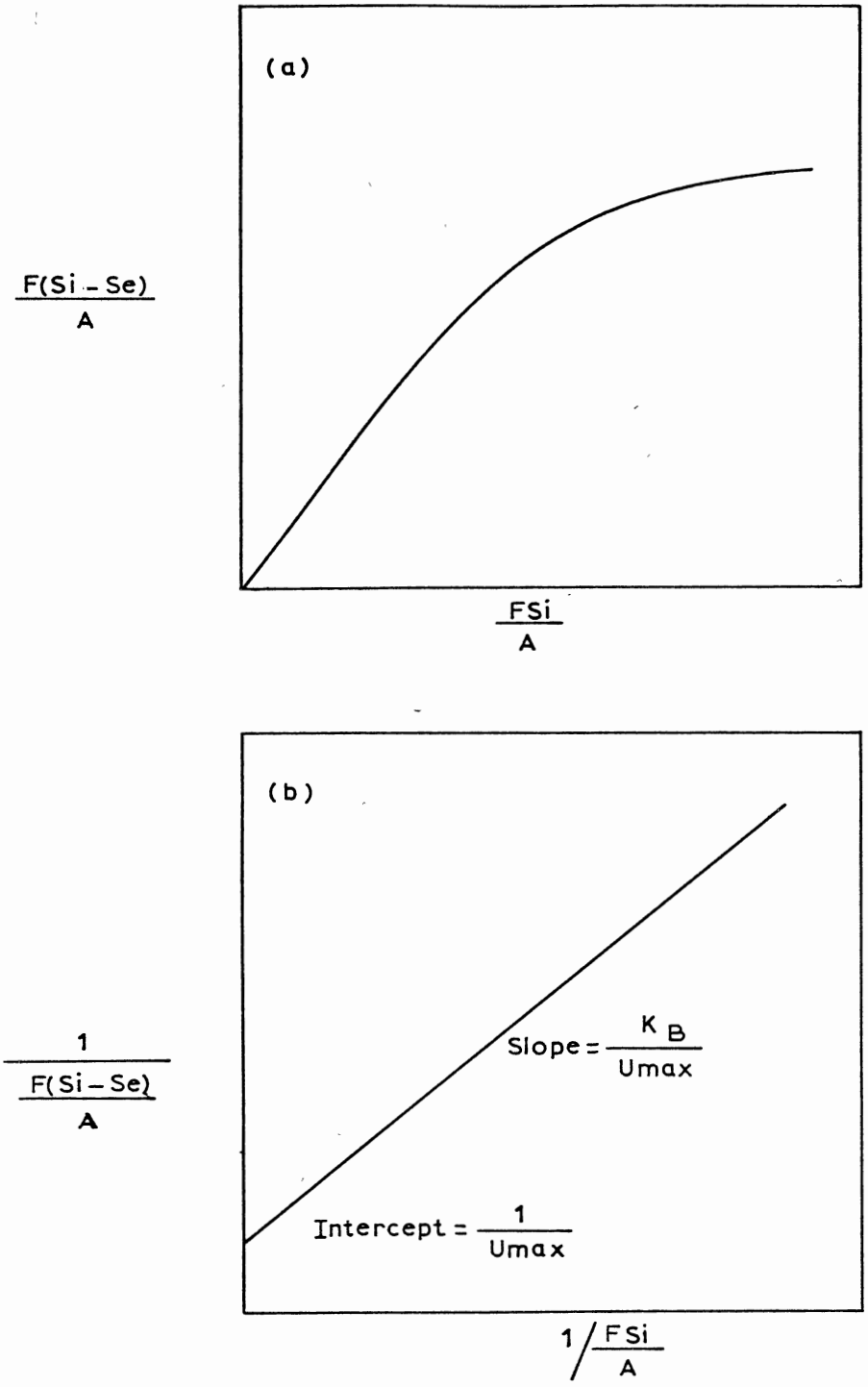

Figure 4. Graphical Determination of U_{max} and K_B

$$\frac{FX_e - FX_o}{A} = Yt \left(\frac{U_{max} \frac{FSi}{A}}{K_B + \frac{FSi}{A}} \right) - Kd' \qquad (7)$$

where

X_e = concentration of solids leaving the reactor, mg/ℓ.

X_o = concentration of solids entering the reactor, mg/ℓ.

Yt = true yield, lbs solids produced/lbs BOD_5 removed.

Kd' = decay coefficient, lbs solids destroyed/d/1000 ft^2.

Also,

$$FX_e = F_e X_{CM} + F_W X_B$$

where

F_e = effluent flow rate, L/d.

X_{CM} = concentration of solids leaving the reactor through the effluent line, mg/L.

F_W = wasted sludge flow rate, L/d.

X_B = concentration of solids in the wasted sludge, mg/L.

Equation (7) can be rewritten:

$$\frac{F_e X_{CM} + F_W X_B - FX_o}{A} = Yt \left(\frac{U_{max} \frac{FSi}{A}}{K_B + \frac{FSi}{A}} \right) - Kd' \qquad (8)$$

Yt and Kd' must be determined experimentally from the plot of lbs of solids produced/day/1000 ft^2, $\frac{F(X_e - X_o)}{A}$ as a function of the specific

substrate utilization rate, $\frac{F(Si-Se)}{A}$. The Y-axis intercept corresponds to Kd' and the slope of the line to Yt (see Figure 11).

CHAPTER III

MATERIALS AND METHODS

A. Experimental Approach

The biological kinetic constants were determined by operating the ASBF reactor at six different loading conditions (0.78, 2.32, 3.11, 4.27, 8.26 and 17.62 lbs/day/1000 ft^2). For each condition, 15 to 20 data points were collected. These data were collected on a daily basis. For every change in loading conditions, a period of one to two weeks was allowed to stabilize the system at that new condition. After steady state conditions were reached the data collection started. The parameters monitored were BOD_5 (influent and effluent), suspended solids and volatile suspended solids (mixed liquor, bottom of the reactor, effluent supernatant and effluent completely mixed), flow rate, dissolved oxygen, and pH. In order to prevent solids accumulation and anaerobic conditions at the bottom of the reactor, a constant volume of sludge (200 mls) was arbitrarly wasted on a daily basis. The different loading conditions were reached by keeping constant the flow rate and changing the substrate concentration. When keeping constant the substrate concentration and changing the flow rate, the same results were obtained. By doing so, it was confirmed one more time that the performance and efficiency of fixed-film systems do not depend only upon the substrate concentration or the hydraulic flow rate but, rather, upon total organic (substrate) loading.

The hydraulic residence time varied from 2 to 4 days during the period of study.

B. The Bench Scale Unit

The aerated submerged biological filter was made of plexiglass (see Figure 5) with a total empty bed reactor volume of 0.42 ft^3 (12.0 liters). The plastic media packing had a specific surface area of 42 ft^2/ft^3 and was contained in 0.33 ft^3 (9.4 liters) of the total reactor volume, yielding a total surface area of 13.9 ft^2. A free board of 0.18 ft^3 (5.1 liters) was provided at the top of the reactor. The void volume was 0.40 ft^3 (11.4 liters), yielding a porosity of 95%.

The influent waste water was pumped into the bottom of the reactor, by using a variable speed Cole-Parmer Masterflex Pump, Model No. 7013, and distributed by a distribution line as shown in Figure 5. The waste water flowed up through the plastic media and out the side of the reactor. The plastic media sat on a plexiglass perforated plate which was located one inch above the bottom of the reactor. Compressed air was supplied to the system to provide aerobic conditions. A set of four four-inch long air diffusors was placed at the bottom of the reactor and underneath the perforated plate. The diffusors array was such that the air was uniformly distributed. The air flow rate was about 2 to 3 liters per minute, which was enough to maintain both a dissolved oxygen level of 1 to 2 mg/L in the mixed liquor and completely mixed conditions. When the reactor is completely mixed, the concentrations of substrate and cells are the same at any point in the reactor. Under this condition, the influent substrate concentration is instantaneously diluted in the reactor. The completely mixed condition was checked by performing a dilute-in study. This study

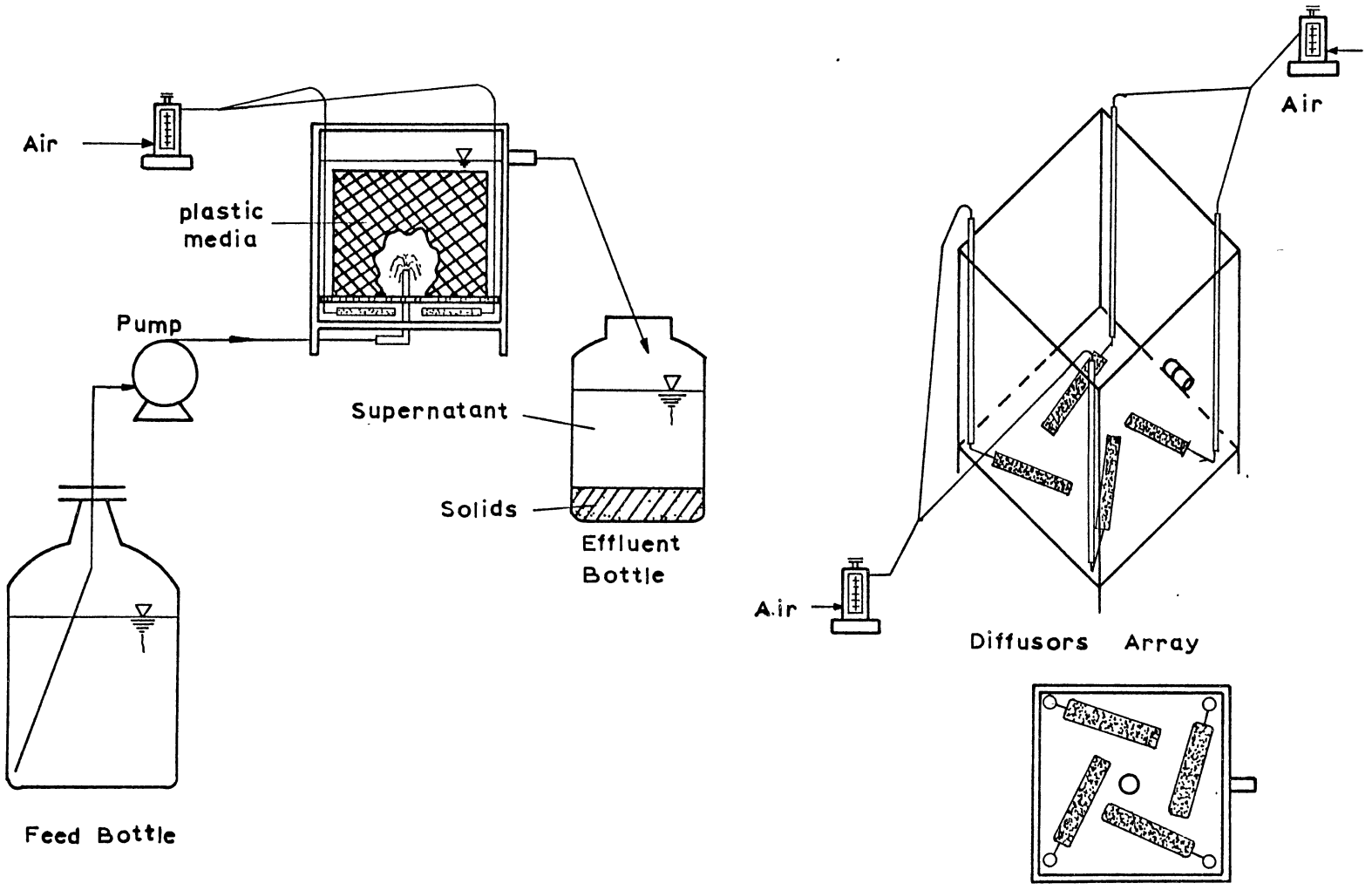

Figure 5. Schematic of the ASBF.

consisted of filling the reactor with clear water and pumping through it a dye solution with a known concentration (Co). The concentration (Ct) in the effluent of the reactor at any time (t) was given by the dilute-in Equation (12):

$$Ct = Co(1 - e^{-Dt}) \tag{9}$$

where D is the dilution factor or dilution rate and is equal to the influent flow divided by the volume of the reactor, $D = \frac{F}{V}$. If complete mixing occurs, the effluent concentration (Ct) will continually increase until it reaches the influente concentration (Co). Figure 6 shows the theoretical and experimental values from the dilute-in test. Since absorbance is directly proportional to highly dilute concentrations of the dye, it was used as the independent variable in this study.

C. The Wastewater

High strength alcohol wastewater, or stillage, was used for this study. The waste was supplied by the Oklahoma State University Agricultural Engineer's 200,000 gallon per year fuel alcohol research facility. Since the stillage came out of the distillation columns at high temperature (around $80^{o}C$), it was allowed to cool down to room temperature and settle before using. Only the supernatant was used to feed the reactor. A series of analyses were performed on the waste in order to characterize it. This characterization was done previous to this study (13). Those analyses included: total solids, total dissolved solids, suspended solids, volatile suspended solids, total and soluble COD, total and soluble BOD_5, soluble TOC, total and soluble P, total and soluble TKN, total

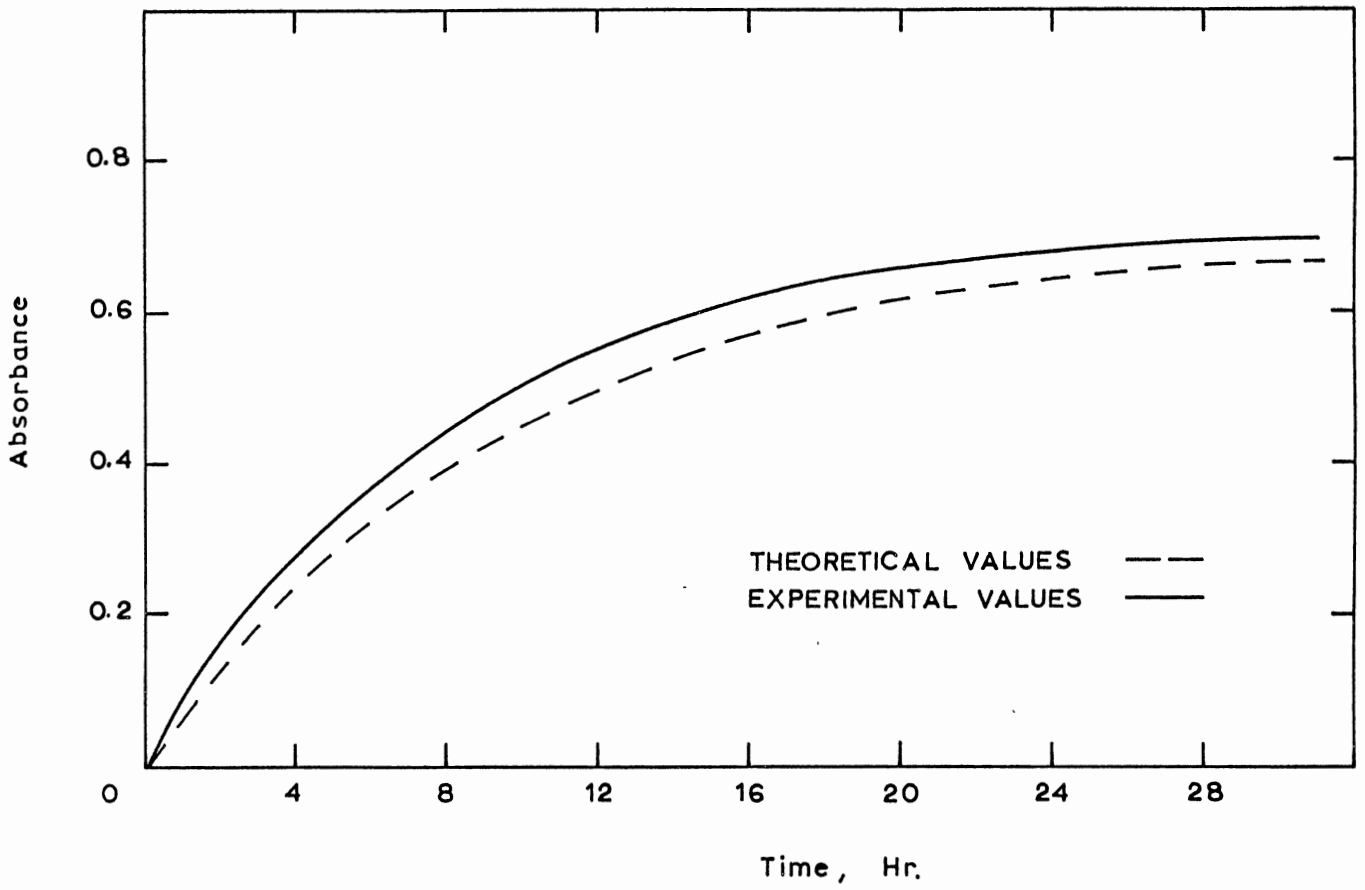

Figure 6. Graphical Representation of the Dilute-In Test

and soluble protein, total and soluble carbohydrate, soluble glucose, and pH. The results are presented in Table I. The waste fed into the reactor was prepared by diluting the raw waste, using tap water, to the desired concentration. Ammonium chloride (NH_4Cl) and phosphoric acid, (H_3PO_4) were added as nutrients to assure adequate conditions for cell growth. Excess of NH_4Cl had to be added during certain loading conditions to stop slimy growth, which yields poor settling characteristics of the sludge. The pH of the feed was adjusted to values between 6.8 and 7.2 by using sodium hydroxide (NaOH). By preparing the feed under the above conditions, the carbon to nitrogen to phosphorus ratio was kept at 100 to 10 to 5 mg/L.

D. Analytical Procedures

D.1. Biochemical Oxygen Demand, BOD_5

The BOD_5 of the samples was determined following the procedure outlined in Standard Methods for the Examination of Water and Wastewater (14). Since the alcohol waste is a very complex industrial waste, seeding of the dilution water with acclimated microorganisms was required and a seed correction factor applied. An Orion Research Oxygen Electrode, Model 97-08-00, was used to measure the dissolved oxygen.

D.2. Suspended Solids, SS and Volatile Suspended Solids, VSS

Suspended solids were determined by filtering the sample through a preweighed glass microfibre filter (Whatman 934-AH, 4.25 cm Dia.), drying it in a oven at $103^{o}C$ for at least one hour, and reweighing. Following

TABLE I

RAW WASTEWATER (THIN STILLAGE) CHARACTERISTICS

Parameter*	Corn Feedstock		Milo Feedstock	
	Mean	Standard Deviation	Mean	Standard Deviation
TS	32,200	9,300	42,800	2,150
TDS	18,600	7,100	20,400	6,800
SS	11,800	3,700	22,500	5,100
VSS	11,300	3,500	19,500	2,600
Total COD	64,500	12,600	75,700	12,100
Soluble COD	30,800	6,200	40,700	9,100
Total BOD_5	26,900	800	34,900	2,000
Soluble BOD_5	19,000	2,100	21,700	1,360
Soluble TOC	9,850	2,200	14,900	2,600
Total P	1,170	100	1,280	100
Soluble P	1,065	75	1,075	150
Total TKN	755	115	--	--
Soluble TKN	480	95	--	--
Soluble NH_3-N	130	60	--	--
Total Protein	4,590	650	--	--
Soluble Protein	2,230	780	--	--
Total Carbohydrate	8,250	750	--	--
Soluble Carbohydrate	2,250	550	--	--
Soluble Glucose	<750	--	--	--
pH (Range)	3.3-4.0	--	3.5-4.0	--

*All units in mg/ℓ except pH.

suspended solids determination, the filter was combusted in a muffle furnace at 550°C for twenty minutes and then reweighed.

D.3. pH

The pH determinations were done by using an Orion Research Model 601A/digital ionalyzer pH meter with an Orion combination pH 91-05 electrode.

D.4. Settling Test

At each loading condition, a settling test was done in order to determine the settling characteristics of the sludge. The tests were performed by transferring 1 liter of mixed liquor from the reactor to a 1000 mls graduate cylinder and reading the sludge blanket height at timed intervals for one hour. Then, the mixed liquor was transferred back to the reactor. A typical settling test curve is presented in Figure 12 for a given loading condition. The Zone Settling Velocity (ZSV) and Sludge Volume Index (SVI) were determined for that particular condition by using the following formulas:

ZSV = slope of the line that represent the clear water, discrete settling, and flocculant settling regions (see Figure 12). Expressed in ft/hr (1000 mls ~1.12 ft.).

$$SVI = \frac{\text{Volume of Sludge Blanket at 30 Min.}}{\text{Mass of Suspended Solids}} \text{ in ml/g} \qquad (10)$$

CHAPTER IV

RESULTS

The aerated submerged biological filter was run for a period of nine months. During this period, six different loading conditions were applied to the reactor in order to develop the biological kinetic constants. These operating conditions of the reactor, as well as the biokinetics, are presented in this chapter.

In Table II, the average values for each operating condition are summarized. Table III is a summary of the loadings applied to the reactor for determination of the biokinetic constants and the substrate removal rates. The first five substrate data points summarized in Table III are presented graphically in Figure 7, where the specific substrate utilization rate is plotted as a function of the applied substrate loading rate in terms of BOD_5. In this graph, the X's represent the average values for each loading condition and the circles represent all the data points. Due to the numerical similarity of several data points, one symbol may represent more than one point. The curve in Figure 7 can be linearized by plotting the reciprocal of the substrate utilization rate as a function of the reciprocal of the applied substrate loading rate. This reciprocal plot is shown in Figure 8. From this plot, the biological kinetic constants U_{max} and K_B can be determined, based on BOD_5. U_{max} and K_B were 32.79 and 31.97 lbs/day/1000 ft^2, respectively. The correlation of the data was very good with a correlation coefficient of 0.9982. The solid

TABLE II

FEED, MIXED LIQUOR, AND EFFLUENT CHARACTERISTICS

Feed			Mixed Liquor						Effluent				
				S.S.		V.S.S.				S.S.		V.S.S.	
Flow (L/d)	Si* (mg/L)	V.S.S. (mg/L)	pH	Top (mg/L)	Bottom	Top (mg/L)	Bottom	D.O. (mg/L)	Se* (mg/L)	Supern. (mg/L)	Mixed	Supern. (mg/L)	Mixed
2.95	1683	359	5.6-7.6	1936	2335	1753	2000	2.5	5	59	414	38	296
3.58	4122	491	6.5-7.1	4507	5253	4076	4742	1.8	22	75	1353	54	1228
3.47	5661	554	6.1-7.0	7533	8880	6457	7551	2.0	20	151	2000	117	1760
4.54	5885	582	6.8-8.0	3847	3919	3679	3780	1.4	85	277	2668	228	2372
5.04	10286	1080	5.8-6.9	3792	3780	3238	3220	1.2	3942	837	2029	696	1758
5.47	20235	980	4.6-4.7	1155	1250	990	1137	1.0	14990	757	1123	705	988

*Si and Se = soluble BOD_5.

TABLE III

SUBSTRATE REMOVALS

Si* (mg/L)	Se* (mg/L)	Loading Rate lbs/d/1000 ft^2	Removal Rate lbs/d/1000 ft^2	% Removal
1683	5	0.790	0.788	99.7
4122	22	2.348	2.335	99.5
5661	20	3.125	3.114	99.7
5885	85	4.251	4.189	98.5
10286	3942	8.248	5.087	62.0
20235	14990	17.610	4.565	26.0

*Si and Se = soluble BOD_5.

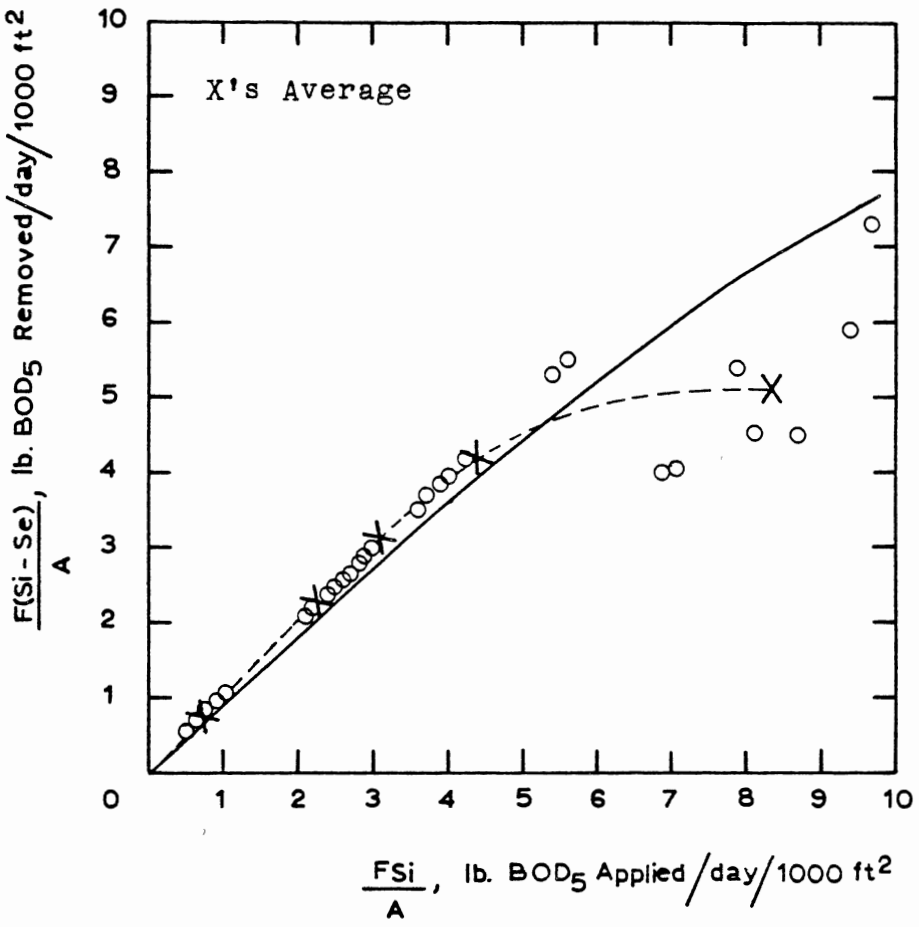

Figure 7. Substrate Utilization as a Function of Mass Substrate Loading (Low Organic Loadings)

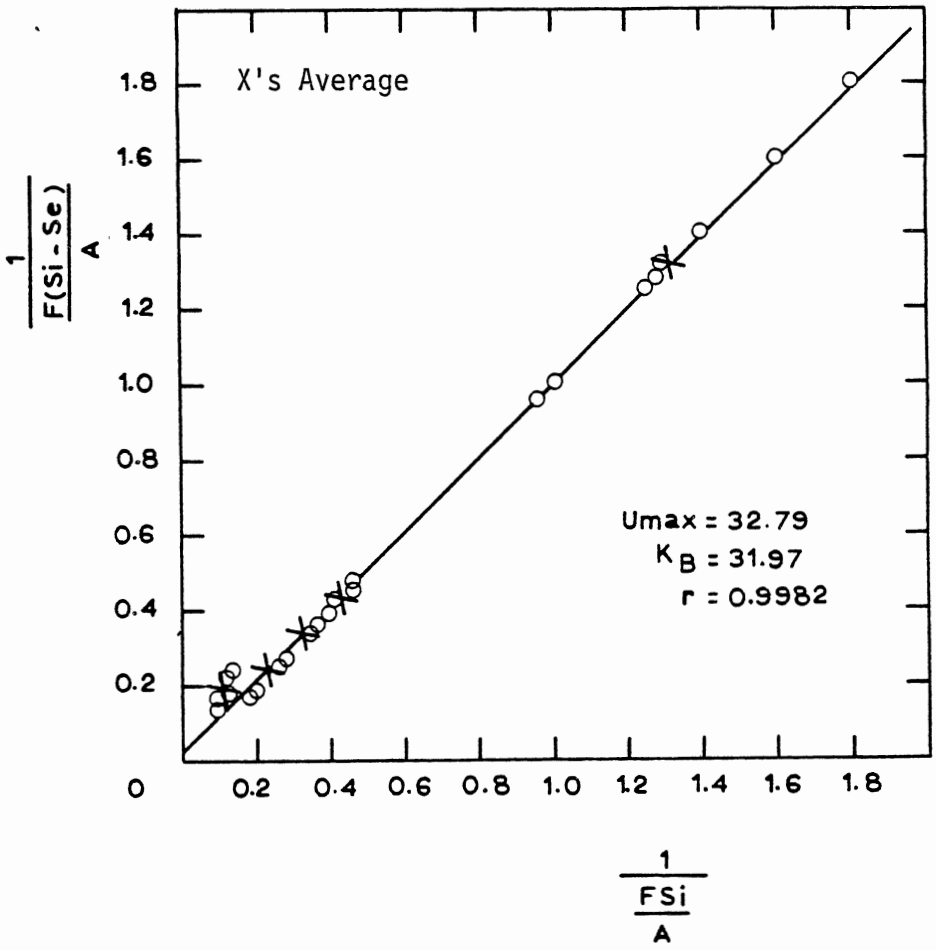

Figure 8. Graphical Determination of U_{max} and K_B in Terms of BOD_5 (for Low Organic Loadings)

line in Figure 7 was drawn using the kinetic constants determined in Figure 8 for loading rates below 8.3 lbs BOD_5/day/1000 ft^2. The broken line was drawn joining the average points corresponding to each loading condition. Both lines were very close up to 5.5 lbs BOD_5/day/1000 ft^2. Above this point, some limitations were present, as seen by the difference between the predicted and actual curve. Oxygen transfer and/or substrate transfer limitations, as well as inhibition, may be present. The calculated maximum substrate utilization rate was much higher (32.79 lbs BOD_5/day/1000 ft^2) than the actual observed rate (approximately 5 lbs/day/1000 ft^2) due to those possible limitations.

All the data from Table III are presented graphically in Figure 9. By linearizing the curve in that figure, the straight line shown in Figure 10 was obtained. U_{max} and K_B were, in this case, 13.51 and 12.47 lbs/day/1000 ft^2, respectively with a correlation coefficient of 0.9910.

Figure 9 was drawn joining the average points for each loading condition. The purpose of this figure is to show the effects of possible oxygen, substrate limitations, and/or inhibition on the performance of the system. At approximately 5.5 lbs BOD_5 applied/day/1000 ft^2, the curve starts bending and at approximately 8.3 lbs BOD_5 applied/day/1000 ft^2, the substrate utilization rate reaches its maximum value, 5 lbs BOD_5/day/1000 ft^2. Between applied loadings of 8 and 14 lbs BOD_5/day/1000 ft^2, the substrate utilization rate remains constant, independent of the applied loading or, in other words, it reaches zero order kinetics. At loadings higher than 14 lbs BOD_5/day/1000 ft^2, the substrate removal rates start decreasing due to possible inhibitions caused by accumulation of intermediate compounds from the incomplete breakdown of the substrate or to pH problems.

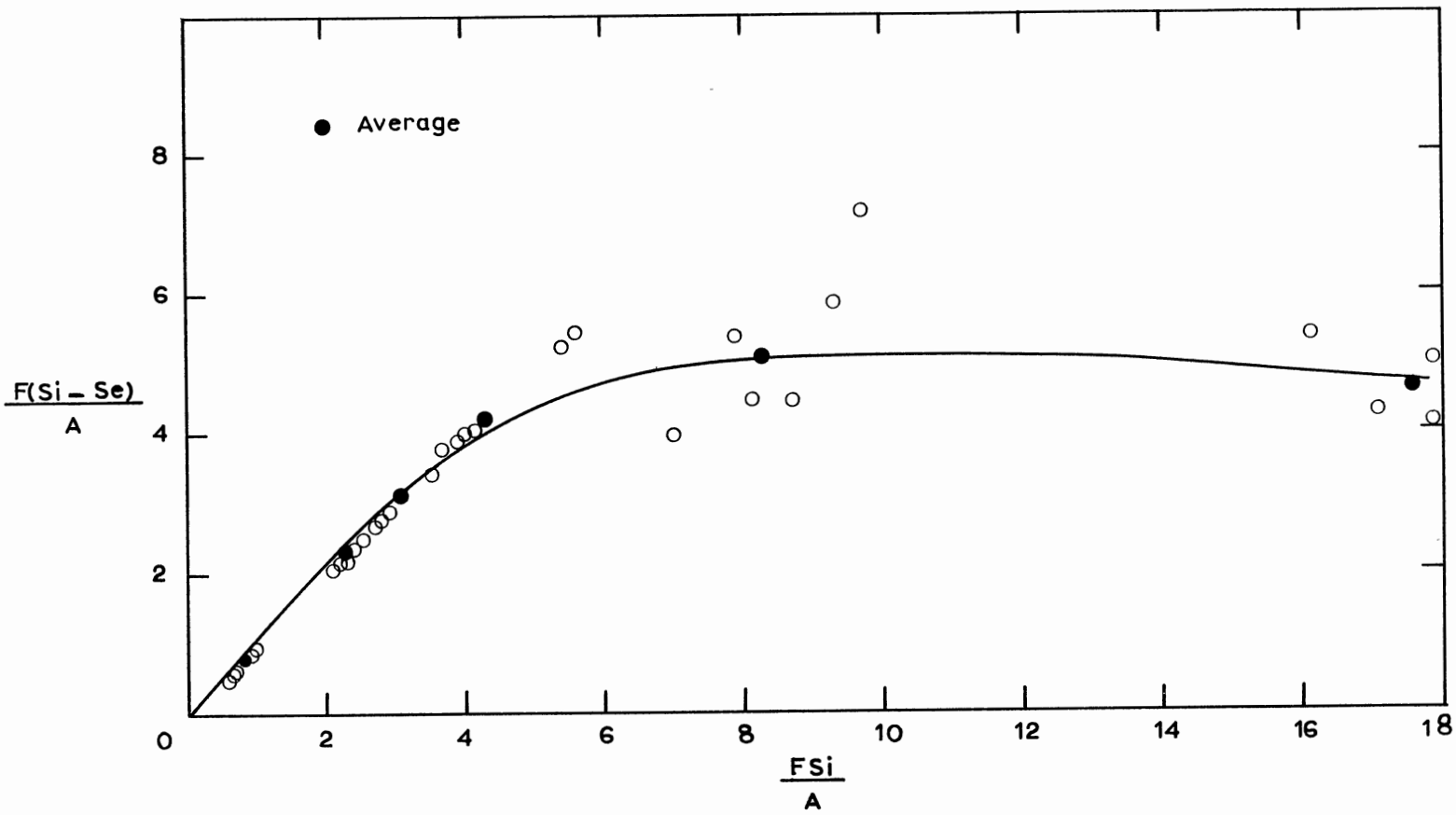

Figure 9. Substrate Utilization as a Function of Organic Loading. High Organic Loadings

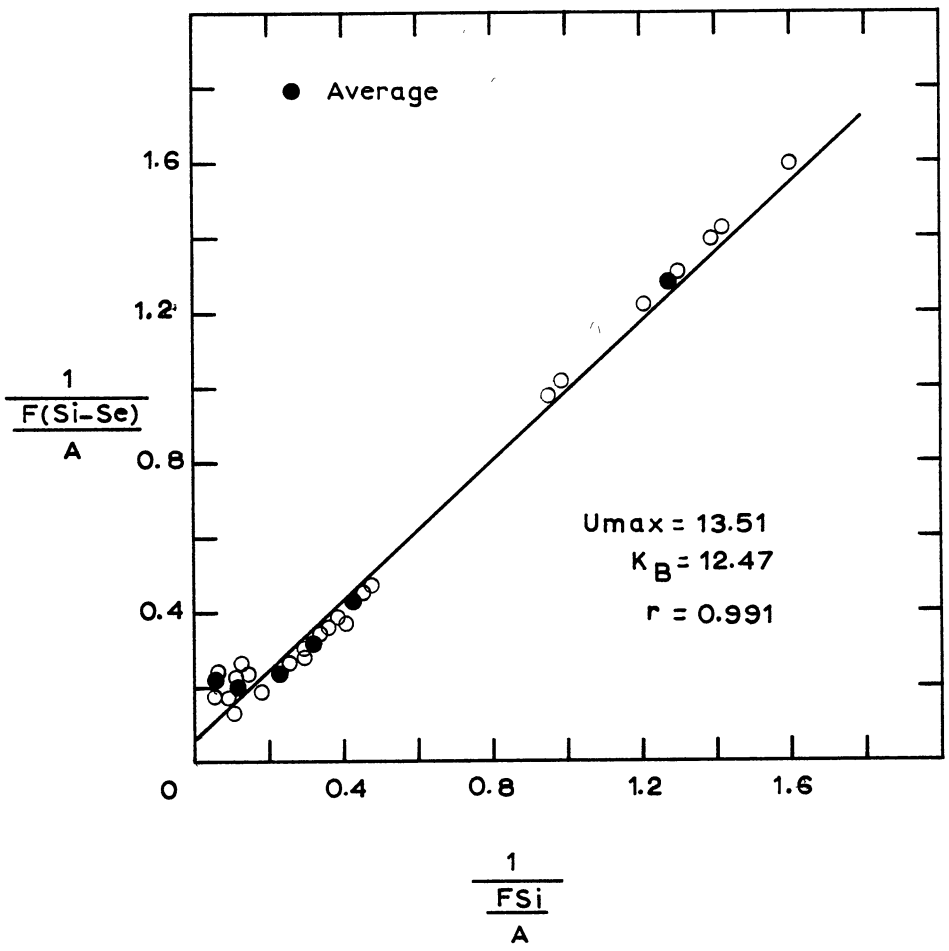

Figure 10. Graphical Determination of U_{max} and K_B for High Organic Loadings

Due to these limitations and/or inhibition, the values of the biokinetic constants vary from 32.79 to 13.51 lbs BOD_5/day/1000 ft^2 for U_{max} and, for K_B, from 31.97 to 12.47 lbs BOD_5/day/1000 ft^2.

In Figure 11, the amount of solids produced per day per 1000 ft^2 is plotted as a function of the specific substrate utilization rate. From this plot the true cell yield (Yt) and the endogeneous decay coefficient (Kd') can be determined. The circles represent the average values for each condition. The true cell yield, in terms of BOD_5, was found to be 0.40 (lbs of solids produced per lb. of BOD_5 removed) and the endogeneous decay coefficient was 0.31 (lbs of solids destroyed per day per 1000 ft^2).

Figure 12 is a typical settling test curve, where the interface is plotted as a function of time. This particular curve represents the settling characteristics of the sludge when a loading of 0.78 lbs of BOD_5/day/1000 ft^2 was applied to the system. The solids concentration at that particular condition was 1400 mg/L. The broken line represents the clear water, discrete settling, and flocculant settling regions. The slope of this line gives the value of the zone settling velocity (ZSV), which in this case was 35.62 ft/hr (53 mls/min). The sludge volume index (SVI) was calculated using Equation (10) and its value was found to be 214 mls/grs of solids.

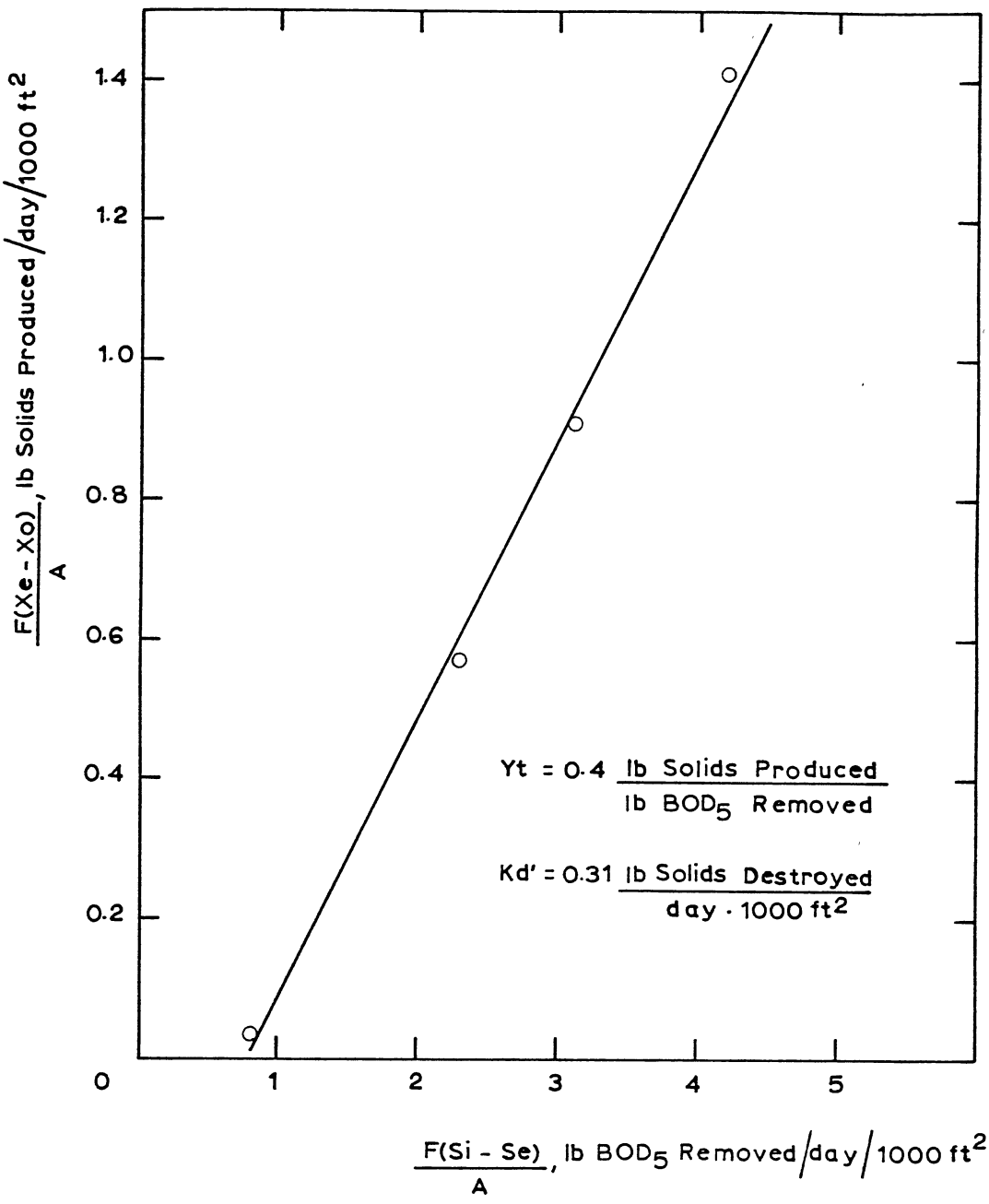

Figure 11. Graphical Determination of Yt and Kd' in Terms of BOD_5

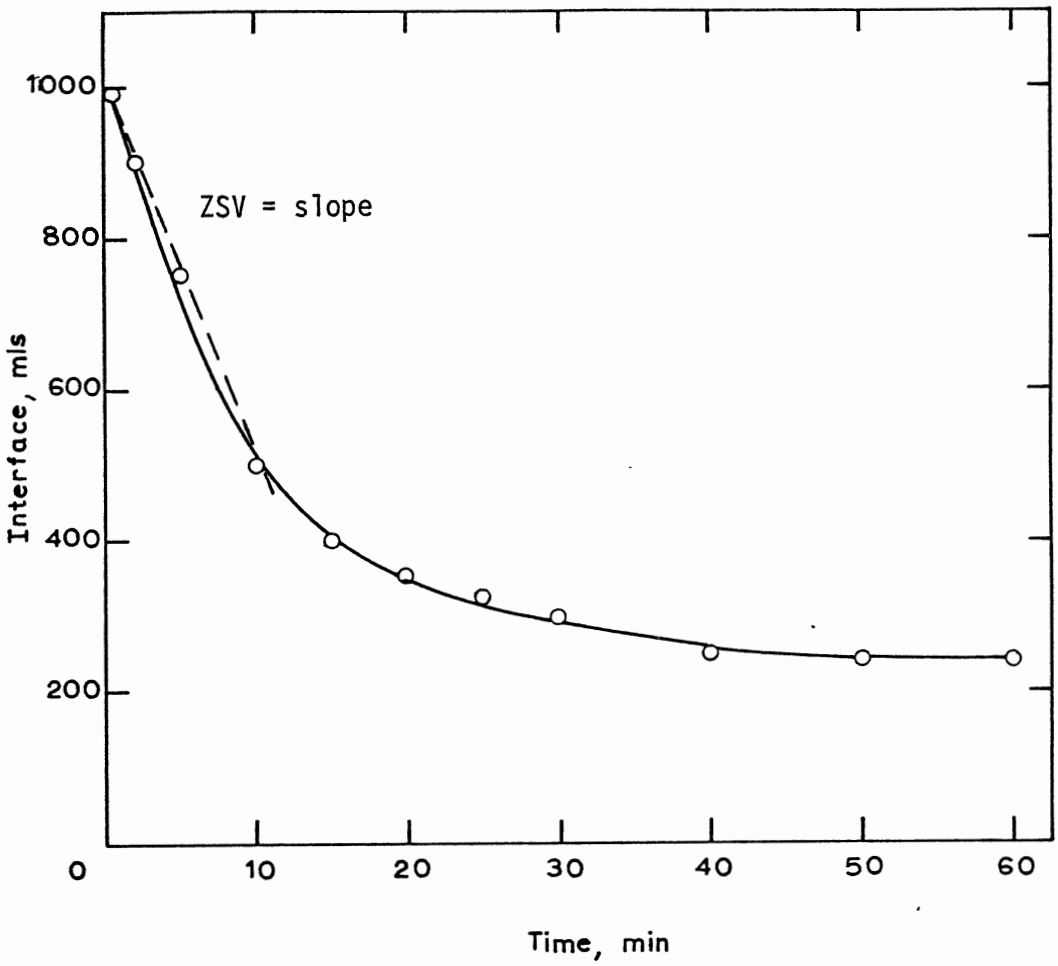

Figure 12. Typical Settling Test Curve

CHAPTER V

DISCUSSION

A. Performance of the System

Biological kinetic constants were developed for organic loading rates up to 8.3 lbs BOD_5/day/1000 ft^2 and, also, for loadings up to 18 lbs BOD_5/day/1000 ft^2. At loadings less than 5.5 lbs BOD_5/day/1000 ft^2, the performance of the system was excellent, with greater than 99 percent removals. At 8.3 lbs BOD_5 applied/day/1000 ft^2, the substrate utilization rate reached its maximum value of 5 lbs BOD_5/day/1000 ft^2, being at this point independent of the applied loading or zero order kinetics. At this loading condition, the system was unable to achieve better removals due to possible physical limitations such as oxygen transfer and/or substrate transfer from the surroundings to the cells. Above, 14 lbs BOD_5 applied/day/1000 ft^2, the removal decreased to 26 percent due to either possible accumulation of substrate or, more likely, intermediate compounds, or low pH which inhibit the microbial activities (see Figure 9).

Because of these possible limitations and inhibitions, the solids concentration in the mixed liquor decreased considerably, from 7533 mg/l to 3792 mg/l and finally to 1155 mg/l. The solids concentration in the effluent supernatant increased as the loading rate increased.

The pH in the mixed liquor decreased to 4.6 when a loading of approximately 18 lbs BOD_5/d/1000 ft^2 was applied to the system. At this

high loading it was difficult to maintain the pH around 7 in the feed bottle and consecutively in the mixed liquor. Fernandez (16) experienced the same type of problem when running an activated sludge unit with external recycle at high total organic loading (F/M of 3.0).

B. Kinetic System Evaluation

The ASBF was evaluated by comparing it to two biological towers fed with a similar wastewater. This comparison was based upon kinetic analysis. A summary of the different operational loading conditions applied to each tower is presented, as well as the values of the biokinetic constants.

Table IV is a summary of the average values for each loading condition applied to the biological tower treating brewery waste (15), and all the conditions applied to the tower treating carbohydrate waste (6).

For low substrate loadings (up to 8.9 lbs BOD_5/d/1000 ft^2), the values of U_{max} and K_B, for the tower fed with brewery waste, were 11.63 and 10.68 lbs/d/1000 ft^2, respectively. Using all the loadings up to approximately 18 lbs BOD_5/d/1000 ft^2 the kinetic constants did not change. The correlation coefficient was 0.999 in both cases.

U_{max} and K_B, for the tower treating carbohydrate waste and for low loadings (up to 8.3 lbs BOD_5/d/1000 ft^2), were 6.29 and 5.44 lbs/d/1000 ft^2, respectively, while for all the loadings up to approximately 18 lbs BOD_5/d/1000 ft^2, the values were almost identical, 6.25 and 5.39 lbs/d/1000 ft^2. The correlation coefficient was 0.991 in both cases.

Table V shows the biological kinetic constants, for the three systems, calculated at low substrate loadings as well as at high substrate loadings.

TABLE IV

SUBSTRATE LOADINGS AND REMOVALS FOR TWO BIOLOGICAL TOWERS USING SIMILAR WASTEWATERS

Brewery Waste*			Carbohydrate Waste**		
Loading Rate	Removal Rate (lbs/day/1000 ft^2)	% Removal	Loading Rate	Removal Rate (lbs/day/1000 ft^2)	% Removal
1.48	1.41	95	1.00	1.00	100
3.70	3.04	82	1.20	1.20	100
5.56	4.00	72	1.30	1.20	92
7.41	4.70	63	1.80	1.40	78
8.90	5.22	59	2.40	1.90	79
11.11	5.93	53	2.50	1.80	72
12.89	6.30	49	2.70	2.00	74
14.81	6.76	46	3.60	2.50	69
17.78	7.41	42	3.60	2.65	74
			4.90	2.90	59
			5.40	3.00	56
			6.00	3.70	62
			8.00	4.20	53
			8.30	4.20	51
			10.60	4.30	41
			16.60	4.40	27

*Taken from Reference (15).

**Taken from Reference (6).

TABLE V

BIOKINETIC CONSTANTS FOR THE THREE REACTOR AT LOW AND HIGH LOADINGS

	Low Loadings Biokinetics (Up to 8 lbs/d/1000 ft^2)			High Loadings Biokinetics (Up to 18 lbs/d/1000 ft^2)		
	ASBF	Biological Tower		ASBF	Biological Tower	
	Alcohol Waste	Brewery Waste	Carbohydrate Waste	Alcohol Waste	Brewery Waste	Carbohydrate Waste
U_{max} (lbs/day/1000 ft^2)	32.79	11.63	6.29	13.51	11.63	6.25
K_B (lbs/day/1000 ft^2)	31.97	10.68	5.44	12.47	10.68	5.39
r	0.998	0.999	0.991	0.991	0.999	0.991

Figure 13 is a plot of the substrate utilization rates as a function of the organic applied loadings for the three systems examined. Curve A corresponds to the ASBF fed with alcohol waste, curve B corresponds to the biological tower fed with brewery waste and curve C the biological tower fed with carbohydrate waste. The kinetics used to plot these curves were obtained with the low loading condition data (approximately up to 8 lbs BOD_5/d/1000 ft^2).

It can be seen clearly from Figure 13 that the ASBF appears to perform much better than the other two systems for substrate loadings below 8 lbs/day/1000 ft^2. For example, at 6 lbs BOD_5 applied/d/1000 ft^2, the removal efficiency for the ASBF was 90% while, for the other two systems, it was 70% (tower fed with brewery waste) and 60% (tower fed with carbohydrate waste). Also, under these conditions, there is a considerable difference in kinetics for the three systems, as can be seen in Table V. The reason for the better performance of the ASBF is the presence of larger amounts of solids, attached and in suspension, as compared to the towers, in which the solids present are only those attached to the media.

Figure 14 is the same type of plot as Figure 13, but the curves were obtained by joining the average points corresponding to each substrate loading condition (up to 18 lbs BOD_5/d/1000 ft^2). It can be seen from this graph that, for loadings greater than approximately 10 lbs/d/1000 ft^2, the three curves get flat or, in other words, they reach zero-order kinetics. Under this condition, the removal efficiency remains constant independent of the organic loadings applied. This situation is due to possible physical limitations of the system such as oxygen and/or substrate transfer.

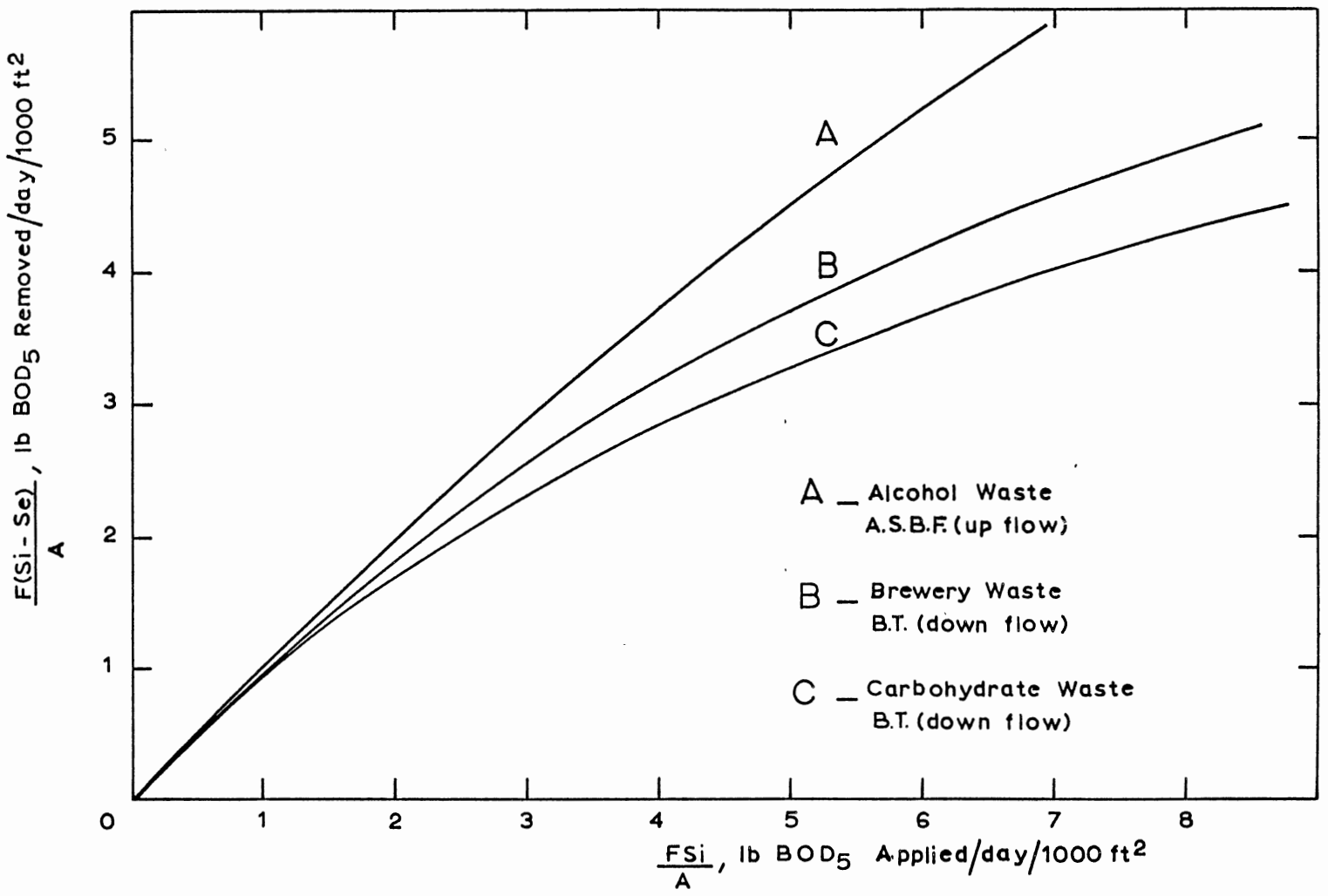

Figure 13. Substrate Utilization Rate as a Function of the Organic Loading for the Three Systems (Low Organic Loadings)

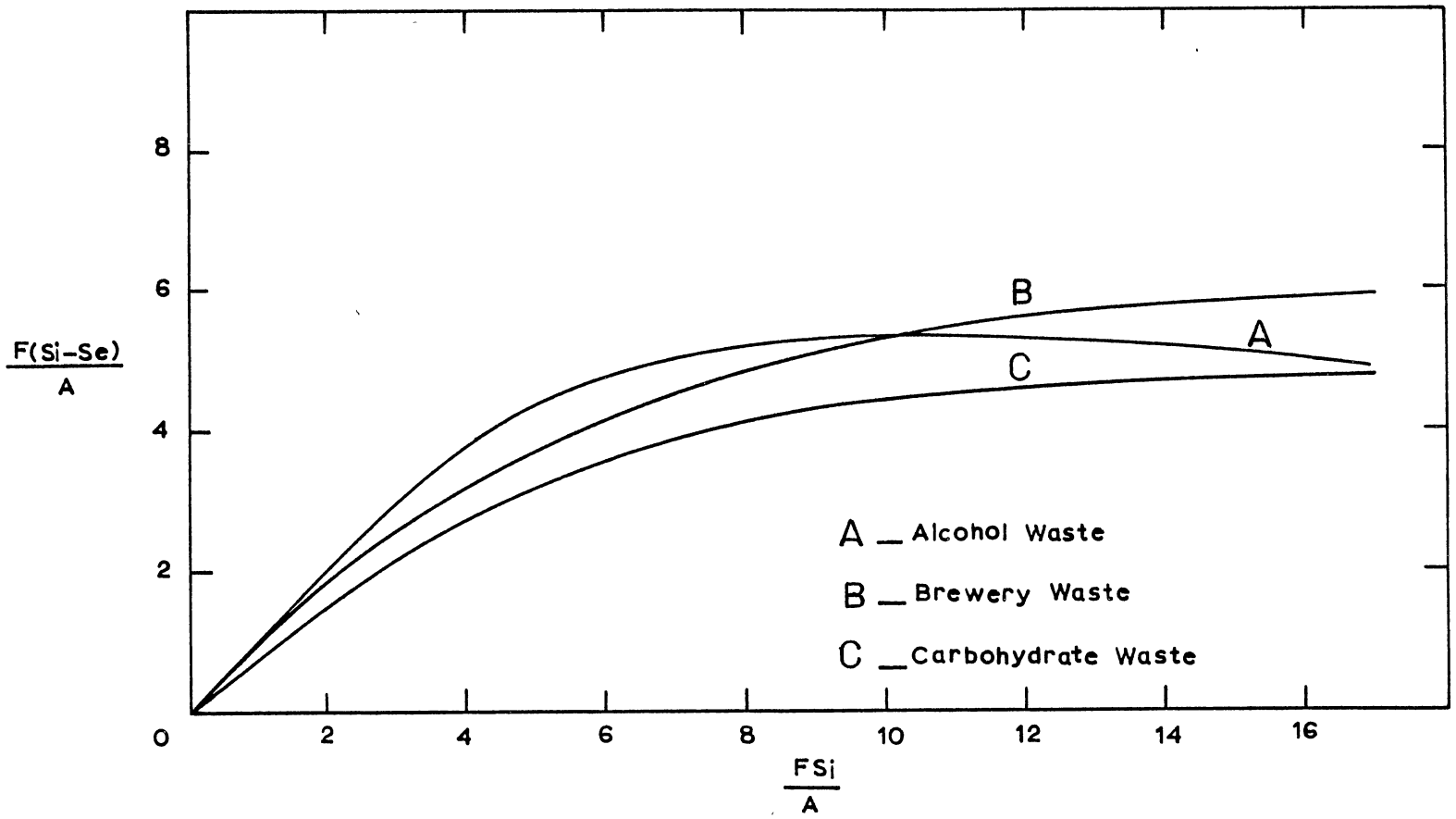

Figure 14. Substrate Utilization Rate as a Function of the Organic Loading for the Three Systems (High Organic Loadings)

At substrate loadings greater than approximately 12 lbs BOD_5/d/1000 ft^2, the substrate utilization rate for the ASBF started decreasing due to possible accumulation of intermediate compounds or low pH. These conditions are toxic to the microorganisms and inhibit their activities. In the case of the biological towers, this situation was not present due to their physical configuration. The towers are down-flow systems while the ASBF is a submerged type of reactor.

At high substrate loading conditions, the biokinetic constants for the ASBF decreased to less than half of their values for low substrate loading conditions. In examining the kinetics of a RBC, Kincannon et al. (17) found similar results. The constants for low stage loading conditions (up to 2.5 lbs BOD_5/d/1000 ft^2) differed from those determined using all loadings up to 6 lbs BOD_5/d/1000 ft^2. For the two towers, the biokinetics remained constant.

The values of the biokinetics for the three systems at high substrate loadings were very close (as seen in Table V). This means that there is not a significant difference in treatment efficiency among them at these high substrate loading conditions.

C. Design Example

A design example is presented to illustrate the use of the mathematical model discussed previously and to compare the areas required for each of the three systems given a set of design conditions.

Given the following design conditions:

$$F = 0.5 \text{ MG}$$

$$Si = 2000 \text{ mg/L } BOD_5$$

$$Se = 20 \text{ mg/L } BOD_5$$

TABLE VI

AREAS REQUIRED FOR THE THREE SYSTEMS AT LOW SUBSTRATE LOADING CONDITIONS

	ASBF Alcohol Waste	Biological Towers	
		Brewery Waste	Carbohydrate Waste
Area (1000 ft^2)	7250	7818	9136

TABLE VII

AREAS REQUIRED FOR THE THREE SYSTEMS AT HIGH SUBSTRATE LOADING CONDITIONS

	ASBF Alcohol Waste	Biological Towers	
		Brewery Waste	Carbohydrate Waste
Area (1000 ft^2)	377857	432710	689030

The area required to achieve the effluent quality is calculated using Equation (4). The kinetic constants used in this calculation are those for low substrate loadings (shown in Table V). The results are presented in Table VI, and from this can be seen that the smallest area required correspond to the ASBF.

Given the following design conditions:

$$F = 10 \text{ MGD}$$

$$Si = 20000 \text{ mg/L } BOD_5$$

$$Se = 4000 \text{ mg/L } BOD_5$$

and using high substrate loading biokinetics, the areas obtained are shown in Table VII. Again, the smallest area is the one corresponding to the ASBF.

Although the use of an ASBF may be more costly than the use of a biological tower due to the air supply, its performance is better (higher removal efficiency) and the area and volume required are smaller. These advantages may compensate the cost of the air supply.

CHAPTER VI

CONCLUSIONS

The following conclusions can be made from this study:

1. The total organic loading concept proposed by Kincannon and Stover, accurately describe the performance of the system.

2. The values of U_{max} and K_B for the ASBF, obtained from low substrate loading conditions (up to 8 lbs BOD_5/d/1000 ft^2) differed from those obtained using all the loadings up to approximately 18 lbs BOD_5/d/1000 ft^2. For the biological towers these values did not change.

3. For substrate loadings greater than approximately 10 lbs BOD_5/d/1000 ft^2, the substrate utilization rate, for the three systems, reached zero-order kinetics. The reason for this was possible oxygen and/or substrate limitations at these high substrate loadings.

4. For loadings greater than approximately 12 lbs BOD_5/d/1000 ft^2, the substrate utilization for the ASBF rate started decreasing due to possible accumulation of intermediates compounds or pH as low as 4.6.

5. For low substrate loadings (up to 8 lbs BOD_5/d/1000 ft^2), the ASBF appeared to perform much better than the biological towers. For high substrate loadings (up to 18 lbs BOD_5/d/1000 ft^2) the performance of the three systems was very similar.

6. The area required for the ASBF was smaller than the ones required for the biological towers.

7. The sludge production of the ASBF was comparable to the sludge

production of an activated sludge system fed with the same type of waste (alcohol waste)(18).

8. The settling characteristics of the sludge from the ASBF were excellent, at low substrate loadings and not very good at high substrate loadings.

9. Even though carbohydrate was the major component of each wastewater examined, variation in the waste composition may have been responsible for the observed differences in the biokinetic constants and performance of the systems when operating at low organic loading conditions (up to 8 lbs BOD_5/d/1000 ft^2).

CHAPTER VII

SUGGESTIONS FOR FURTHER STUDY

1. Measure the void volume of the reactor after each loading condition in order to calculate F/M ratios and mean cell residence times. With these values the ASBF can be properly compared to an activated sludge system.

2. Add more drain lines at the bottom of the reactor, so that the sample taken from there would be more representative. Also, with an improved drain system, accumulation of solids at the bottom of the reactor can be minimized.

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VITA 2

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