THE USE OF BASIC MICROBIAL KINETICS FOR THE DESIGN OF A TRICKLING FILTER WASTE TREATMENT PROCESS

By

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1974

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
December, 1976

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ACKNOWLEDGEMENTS

Foremost, I wish to thank Dr. Don F. Kincannon, my principal adviser, for the guidance, understanding, and endless patience he showed me during the course of my study.

I also wish to thank Dr. Anthony F. Gaudy, Jr., Dr. Richard N. DeVries, and Dr. Marcia Headstream for their excellent instruction and relaxed, friendly attitudes.

I am particularly grateful to Kenneth Norman Bartle and to all of my fellow students for their companionship and stimulating conversation.

I am grateful to my parents, brother and sisters for their moral support, not only during this period, but over my entire life. Their love renews the soul.

I wish to thank my typist, Mrs. Grayce Wynd, for her careful typing of this manuscript.

This thesis was made possible, in part, by Training Grant No. T-900078 from the Environmental Protection Agency.

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CHAPTER I

INTRODUCTION

As the need for high quality water increases in our society, water reuse, either direct or indirect, becomes more common. This reuse results in an increased need for effective, reliable wastewater treatment.

Much research effort has been devoted to understanding the activated sludge process, and this research has resulted in an evolution of design procedures. Modern design methods, such as the "Mean Cell Residence Time Method" of Lawrence and McCarty (1) and the "Constant Sludge Recycle Concentration Method" of Ramanathan and Gaudy (2) are based on basic microbial kinetics. These methods have been used highly successfully in the Oklahoma State University bioenvironmental laboratories to analyze data and explained observed phenomena.

In a paper comparing the activated sludge and the trickling filter processes (3), Kincannon and Sherrard found that the two processes display similar characteristics with regard to treatment efficiency, sludge production, presence or absence of nitrification, removal of inorganic nutrients, and stability under shock loads when compared at equivalent sludge ages or food-to-microorganism ratios.

In view of these facts, it is reasonable to assume that trickling filter design based on laboratory studies and appropriately applied microbial kinetics should be successful, and that many of the

techniques used in the design of activated sludge treatment plants could be modified for use in trickling filter design.

The purpose of this study was to develop a method for trickling filter design based on kinetics of microbial growth.

CHAPTER II

LITERATURE REVIEW

A. Design by Parameters

Imhoff (4) recommended basing the filter volume on the population to be served, and Ingram (5) set ranges for parameters such as volumetric and surface flow rates, and organic volumetric and surface loadings. These design methods are equivalent, in essence, to designing activated sludge for a certain detention time, BOD loading per unit volume, or pounds BOD per pound aeration solids per day.

B. Design by Empirical Formulas

In 1946, the National Research Council published an empirical formula for treatment efficiency based on data from sewage treatment plants in military installations (6). The equation without recirculation is:

$$E = \frac{1}{1 + C\left(\frac{W}{V}\right)^{0.5}} \qquad (1)$$

where

E = fraction of BOD removed

W = organic load applied (lbs BOD/day)

V = filter volume (1000 cu ft)

C = 0.0561

In 1956, Fairall (7) developed another empirical formula based on data from forty-four treatment plants in the Upper Mississippi Valley. Without recirculation, the equation is

$$\frac{L_e}{L_i} = 1.102 \left(\frac{V}{Q}\right)^{-0.322} \tag{2}$$

where

$\frac{L_e}{L_i}$ = fraction of influent BOD remaining in the settled effluent

V = folume of filter medium (1000 cu ft)

Q = hydraulic flow rate (MGD)

In 1964, Galler and Gotaas (8) published an empirical formula based on multiple regression analysis on data from existing treatment plants which states

$$L_e = \frac{0.464\ L_o^{1.19}\ (1 + R)^{0.28} \left(\frac{Q}{A}\right)^{0.13}}{(1 + D)^{0.67}\ T^{0.15}} \tag{3}$$

where

L_e = effluent BOD

L_o = influent BOD

C. First Order or Simple Kinetic Models

In 1944, Phelps (9) published an equation based on first order removal of BOD, which states

$$\frac{L_t}{L} = 10^{-kt} \tag{4}$$

where

L_t = BOD remaining at time t

L = initial BOD

k = rate constant

t = contact time

In 1948, Velz (10) developed a similar expression, based on filter depth rather than contact time, which states

$$\frac{L_D}{L} = 10^{-kD} \tag{5}$$

where

D = depth

all other terms as previously defined

Gerber (11) proposed lumping hydraulic dosing rate (H, ft/day), BOD rate constant (K_1, day^{-1}) and depth (D, ft) into one dimensionless constant (H/DK_1), and found a linear relationship between efficiency (BOD at depth D/BOD applied) and H/DK for values of H/DK_1 up to 50 with wastes having 120 to 140 mg/1 initial BOD.

In 1960, Schulze (12) found that

$$\frac{L_e}{L_i} = 10^{-kD/Q^{2/3}} \tag{6}$$

where

L_e = effluent BOD (mg/1)

L_i = influent BOD (mg/1)

k = rate constant

D = filter depth (ft)

Q = hydraulic load (MGD/acre)

In 1961, Eckenfelder (13) developed several equations based on first order removal kinetics. In the simplest form

$$\frac{L_e}{L_o} = e^{-KD/Q^n} \tag{7}$$

where

L_e = effluent BOD

L_o = influent BOD

K = a coefficient incorporating the surface area of active film per unit volume

D = filter depth

Q = hydraulic load per unit surface area

n = constant

If the slime layer is non-uniform, and different components of the waste are removed at different rates, the equation becomes

$$\frac{L_e}{L_o} = \frac{100}{1 + \frac{CD^{(1+m)}}{Q^n}} \tag{8}$$

where C, m, and n are constants to be determined by multiple regression analysis, and all other terms are as previously defined.

In 1957, Stack (14) developed a theoretical equation based on the assumptions that

1) a trickling filter is basically a self-regenerating absorption tower;

2) each unit depth of the filter will remove a constant fraction of the removable BOD applied to that unit depth;

3) removable BOD is the fraction of the observed BOD which can be removed by biosorption, and

4) the quantity of BOD that can be absorbed by one unit volume of a filter has a maximum limit.

If no recirculation is used but if the load of removable BOD is sufficient to saturate a portion of the filter depth, the equation takes the form

$$R = XfS + f(L-XfS)\left[1+(1-f) + (1-f)^2 + (1-f)^3 + \ldots + (1-f)^{D-X-1}\right] \quad (9)$$

where

R = fraction of removable BOD removed

X = number of unit depths that are saturated

f = coefficient of biosorption

S = quantity of removable BOD that must be applied per unit area to completely saturate one unit depth with BOD

L = quantity of removable BOD applied per unit area

D = number of unit depths in the filter

D. Design Based on Microbial Kinetics

In 1968 and 1969, Kornegay and Andrews (15)(16) published their results of experiments conducted with completely mixed, annular reactors, and developed the following equation for trickling filter performance

$$K_s \ell n(S_o/S_e) + (S_o - S_e) = \frac{\mu_{max}\ a\ d\ H\ X\ Z}{FY} \quad (10)$$

where

K_s = saturation constant which varies with flow velocity (M/L^3)

S_o = initial concentration of growth-limiting nutrient (M/L^3)

S = final concentration of growth-limiting nutrient (M/L^3)

μ_{max} = maximum specific growth rate (1/T)

a = specific surface area of filter media (L)

d = active microbial film thickness

H = cross sectional area of the trickling filter (L^2)

X = unit mass of the microbial film on a dry basis (M/L^3)

Z = filter depth (L)

F = hydraulic flow rate (L^3/T)

Y = yield coefficient, and

L, M, and T denote length, mass, and time, respectively

E. Design Based on Diffusivity

In 1976, Williamson and McCarty (17) developed an equation based in part on Monod's (3) equation for microbial growth, and in part on the rate of diffusion of oxygen and essential nutrients into the slime layer. The result is a second order differential equation which states

$$\frac{d^2S_c}{dZ^2} = \frac{KS_cX_c}{D_c S_c + K_s} \qquad (11)$$

where

S_c = concentration of limiting nutrient within the biofilm cellular matrix (mg/l)

Z = filter depth (cm)

k = maximum utilization rate of rate-limiting substrate (mg/day/mg)

X_c = bacterial concentration within biofilm, assumed constant with depth (mg/l)

D_c = diffusion coefficient within biofilm (sq cm/day)

K_s = Monod half-velocity coefficient (mg/l)

Though no general solution to this equation is possible, if certain assumptions are made, boundary conditions may be set and a solution may be calculated by the Runge-Kutta finite difference method.

CHAPTER III

MODEL DEVELOPMENT

To understand the kinetics of a trickling filter, several facts must be kept in mind. Purification of the waste occurs because microorganisms, predominantly attached to the filter media, utilize components of the waste as nutrients. Thus, part of the material is used for energy and part is used to synthesize new cellular material, and the concentration of nutrients in the liquid decrease with depth. This decrease in nutrient concentration causes a decrease in growth rate, a situation similar to that which occurs in a plug flow reactor.

The layer of microorganisms growing on the media will eventually increase in thickness until the physical forces binding the slime layer together and to the media are insufficient, and a portion of the slime layer will slough off. Though this may produce local differences in conditions at a certain depth, it is assumed that the average condition of the biological material at a given depth is constant if the trickling filter as a whole is at steady state (influent and effluent BOD and flow rate are constant).

Kornegay and Andrews (16) developed kinetics based on the fact that the active film thickness, d, is only a portion of the total film thickness, h, and on the following assumptions:

1) Plug-flow is achieved in the liquid phase.

2) Substrate utilization due to sources other than the attached

microbial film is small and may be neglected.

3) The apparent yield, Y_{OBS}, remains constant with depth.

4) Removal is described by a saturation function which incorporates the effect of diffusion and growth rate.

The model developed in this chapter is similar in many respects to that developed by Kornegay and Andrews (15) with the exception that the true yield, Y (which occurs when the microorganisms are growing at the maximum specific growth rate), is used in place of the observed yield, Y_{OBS} (which decreases with decreasing specific growth rate). With this change, assumption 3 now reads:

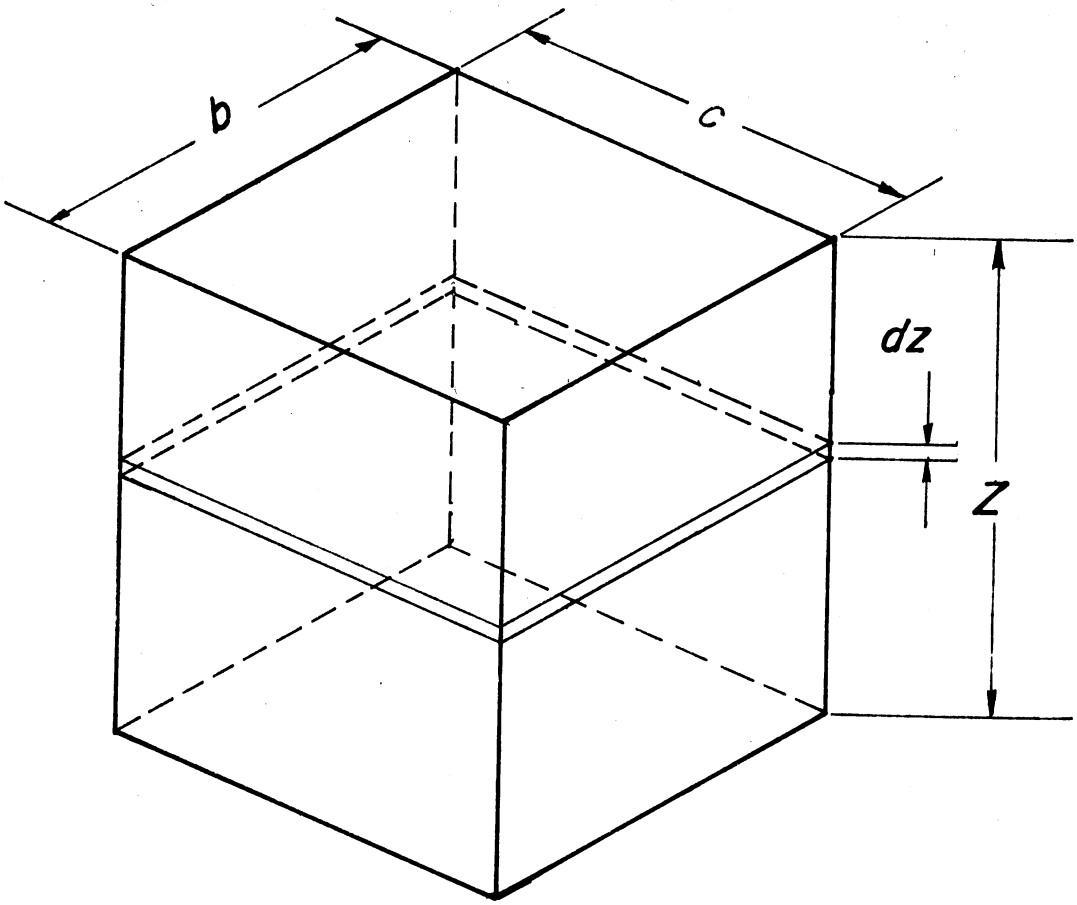
3) The true yield, Y, remains constant with depth.

The substrate available will limit the growth rate. Physical conditions, such as temperature or pH, may limit the maximum growth rate, but the substrate concentration will set the actual growth rate. The material that limits growth in most wastes is carbon. In the case that nitrogen or phosphorous is growth-limiting, these materials may be added so that carbon will be growth-limiting. The oxygen demand of the waste, as biochemical oxygen demand (BOD) or chemical oxygen demand (COD) may be used as measures of substrate where carbon is the limiting nutrient.

Consider the situation in a unit volume of the filter shown in Figure 1. The filter has a cross sectional area, H, and a depth, Z. The unit volume of depth dZ has a substrate concentration, S + dS, entering, and a substrate concentration, S, leaving it. The steady state substrate balance across the differential element, dZ, is then:

$$\text{input} = \text{output} + \text{disappearance by microbial utilization} \qquad (12)$$

Figure 1. Model of Trickling Filter Showing Elemental Volume; Area, H, Depth, Z



$$bc = H$$

The total mass of substrate entering the unit volume is equal to the flow, F, times the substrate concentration. The output is equal to the flow times the substrate concentration leaving the unit volume. The microbial utilization is the change in substrate per unit time. Thus, the substrate balance becomes

$$F(S + dS) = F\ S + \frac{dM_s}{dt} \tag{13}$$

where

F = hydraulic flow rate (ℓ/day)

S = substrate concentration (mg/1)

M_s = mass of substrate (mg)

t = time (days)

The change in the mass of microorganisms is related to the change in mass of substrate by the equation

$$\frac{dM_o}{dt} = Y \frac{dM_s}{dt} - k_d Mo \tag{14}$$

where

Mo = mass of microorganisms (mg)

Y = true yield

k_d = decay coefficient (day^{-1})

Thus

$$\frac{dM_s}{dt} = \frac{dMo/dt + k_d Mo}{Y} \tag{15}$$

The true growth rate, μ ($days^{-1}$), may be defined as

$$\mu = \frac{dMo/dt}{Mo} + k_d \tag{16}$$

so

$$\frac{dM_s}{dt} = \frac{\mu Mo}{Y} \tag{17}$$

By substitution, the balance for substrate becomes

$$F(S + dS) = FS - \frac{\mu}{Y} Mo \tag{18}$$

The microorganisms of interest are not the total mass, but are the active mass in the outer layer of the microbial film. The total active mass in the unit volume may be expressed as a product of the differential depth, dZ, the cross sectional area, H, the specific surface area in the media, a (surface area per unit volume), the mass concentration of microorganisms, X, and the thickness of the active layer, d. Therefore

$$Mo = (a)(X)(d)(H)dZ \tag{19}$$

and the substrate balance becomes

$$F(S + dS) = FS - \frac{\mu}{Y} (a)(X)(d)(H)dZ \tag{20}$$

where

μ = specific growth rate (T^{-1})

Y = yield coefficient

S = concentration of the growth-limiting nutrient (M/L^3)

a = the specific surface area of the media (L^2/L^3)

X = concentration of microorganisms in the film on a dry basis (M/L^3)

d = thickness of the active microbial film (L)

H = cross sectional area of the filter (L^2)

Z = filter depth (L)

F = hydraulic flow rate (L^3/T)

In addition, Monod (18) showed that the specific growth rate may be related to the substrate concentration by the following equation

$$\mu = \frac{\mu_{max} S}{K_s + S} \tag{21}$$

where

μ_{max} = the maximum specific growth rate (T^{-1})

K_s = the substrate concentration at which $\mu = \frac{1}{2} \mu_{max}$, also called the saturation constant or half-velocity constant (M/L^3)

Upon substitution of equation (20) into equation (21), we find that

$$F(S+dS) = FS - \left[\frac{\mu_{max} S}{K_s + S}\right]\left(\frac{1}{Y}\right)(a)(X)(d)(H)dZ \tag{22}$$

which may be rearranged as

$$\left(\frac{K_s + S}{S}\right) dS = \frac{\mu_{max}}{FY} (a)(X)(d)(H)dZ \tag{23}$$

By using plastic or redwood medium, one can construct a trickling filter in which the cross sectional area, H, and the specific surface

area, a, are constant. Kornegay and Andrews (16) found μ_{max}, Y, X, and d to be constant over a wide range of flow velocities, dissolved oxygen and substrate concentrations. The saturation constant, K_s, was found to vary with velocity, but should be constant for a given flow rate. If we assume these parameters to be constant, equation (23) may be integrated to produce

$$K_s \ell n \frac{S_o}{S_e} + (S_o - S_e) = \frac{\mu_{max}(a)(d)(H)(X)}{FY} Z \qquad (24)$$

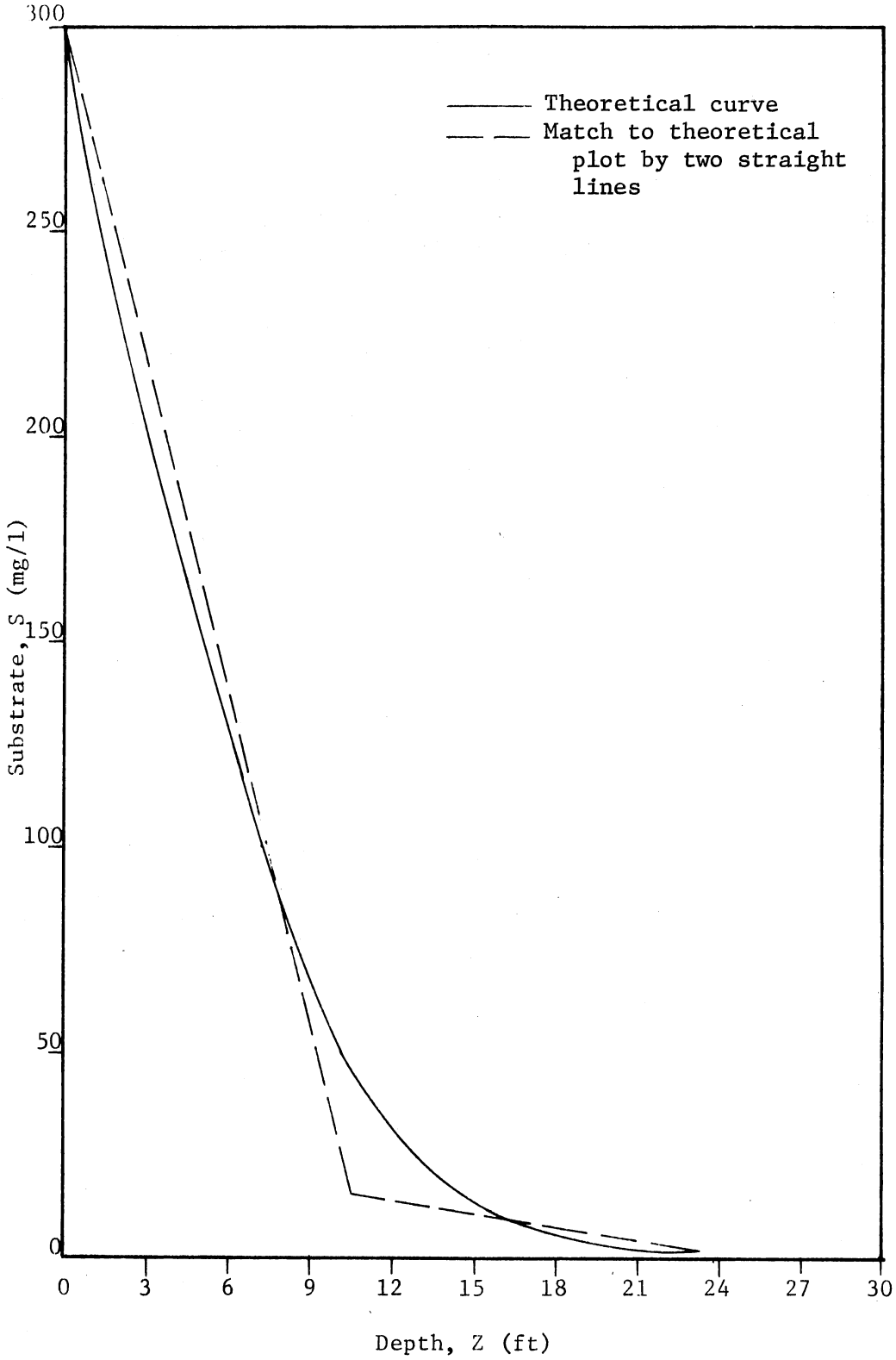
A more useful form of the equation may be developed by rearranging equation (24) in the form

$$Z = \frac{FY\left[K_s \ell n\ (S_o/S_e) + (S_o - S_e)\right]}{(\mu_{max})(a)(d)(H)(X)} \qquad (25)$$

This equation allows one to select the proper filter depth, given a waste of a certain strength and flow, a certain effluent requirement, and values of the various biological constants involved. In addition, the equation may be used to generate a substrate removal profile, by choosing various values of S and calculating the depths at which they occur. One may then change the values of μ_{max}, Y, or K_s, and observe the effect on the substrate versus depth curve.

Kornegay and Andrews found X = 95 mg/cm^3 and d = 7 x 10^{-3} cm (15), and these values are assumed throughout this investigation. In Figure 2, it was assumed that S_o = 300 mg/1, F = 500 gpd, Y = 0.44, K_s = 150 mg/1, μ_{max} = 2.50 day^{-1}, a = 27 ft^2/ft^3, and H = 1 ft^2. Values of depth Z were computed for various values of S down to S = 1 mg/1. The graph shows that the substrate versus depth curve may be approximated

Figure 2. Theoretical Plot of Substrate Concentration Versus Depth by Equation (25)


300
250
200
150
100
50
0
Substrate, S (mg/l)
0
3
6
9
12
15
18
21
24
27
30
Depth, Z (ft)
Theoretical curve
Match to theoretical plot by two straight lines

by two straight lines. This explains results obtained by Little (19) and others.

Figure 3 shows the effect of holding all other values constant and varying K_s to 70 mg/l and 40 mg/l. As K_s is decreased, substrate is removed more rapidly.

The curves in Figure 4 show the effect of varying Y. For K_s = 40 mg/l and all other values as previously stated, curves 4, 5, and 6 may be generated by choosing values of Y = 0.20, Y = 0.44, and Y = 0.60, respectively.

The curves in Figure 5 show the effect of varying μ_{max}. With Y = 0.44, K_s = 40 mg/l, and all other values as in the previous examples, curves 7, 8, and 9 may be generated by choosing values of μ_{max} = 5.50 day^{-1}, 2.50 day^{-1}, and 1.83 day^{-1}, respectively.

The curves in Figures 4 and 5 are identical. Because the term μ_{max}/Y appears in equation (25), any effect on the substrate versus depth curve resulting from an increase (or decrease) in μ_{max} may also be achieved by an appropriate decrease (or increase) in the value of Y (with μ_{max} constant).

A. Determining Biological Constants

Details of data collection will be covered in Chapter V but, basically, the data required for determining values of the biological constants are biological solids production per day, influent substrate concentration (various values or at various flow rates) and effluent substrate concentration. The data presented in the following analysis were gathered by Bently, using a synthetic waste with sucrose as a carbon source (20).

Figure 3. Theoretical Plot of Substrate Concentration Versus Depth by Equation (25); the Effect of Varying K_s

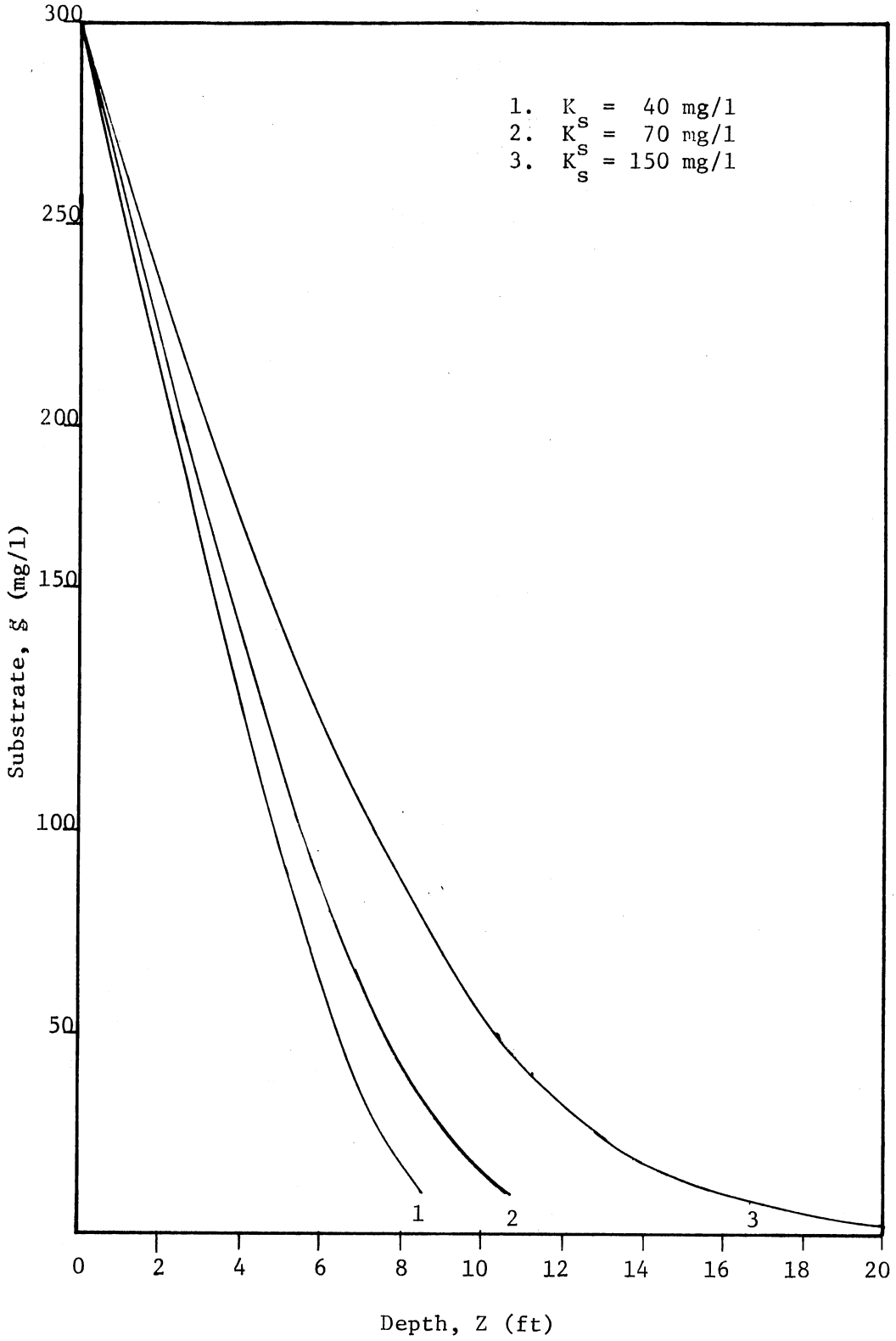

1. K_s = 40 mg/l
2. K_s = 70 mg/l
3. K_s = 150 mg/l
Substrate, S (mg/l)
300
250
200
150
100
50
0
2
4
6
8
10
12
14
16
18
20
Depth, Z (ft)
1
2
3

Figure 4. Theoretical Plot of Substrate Concentration Versus Depth by Equation (25); the Effect of Varying Y

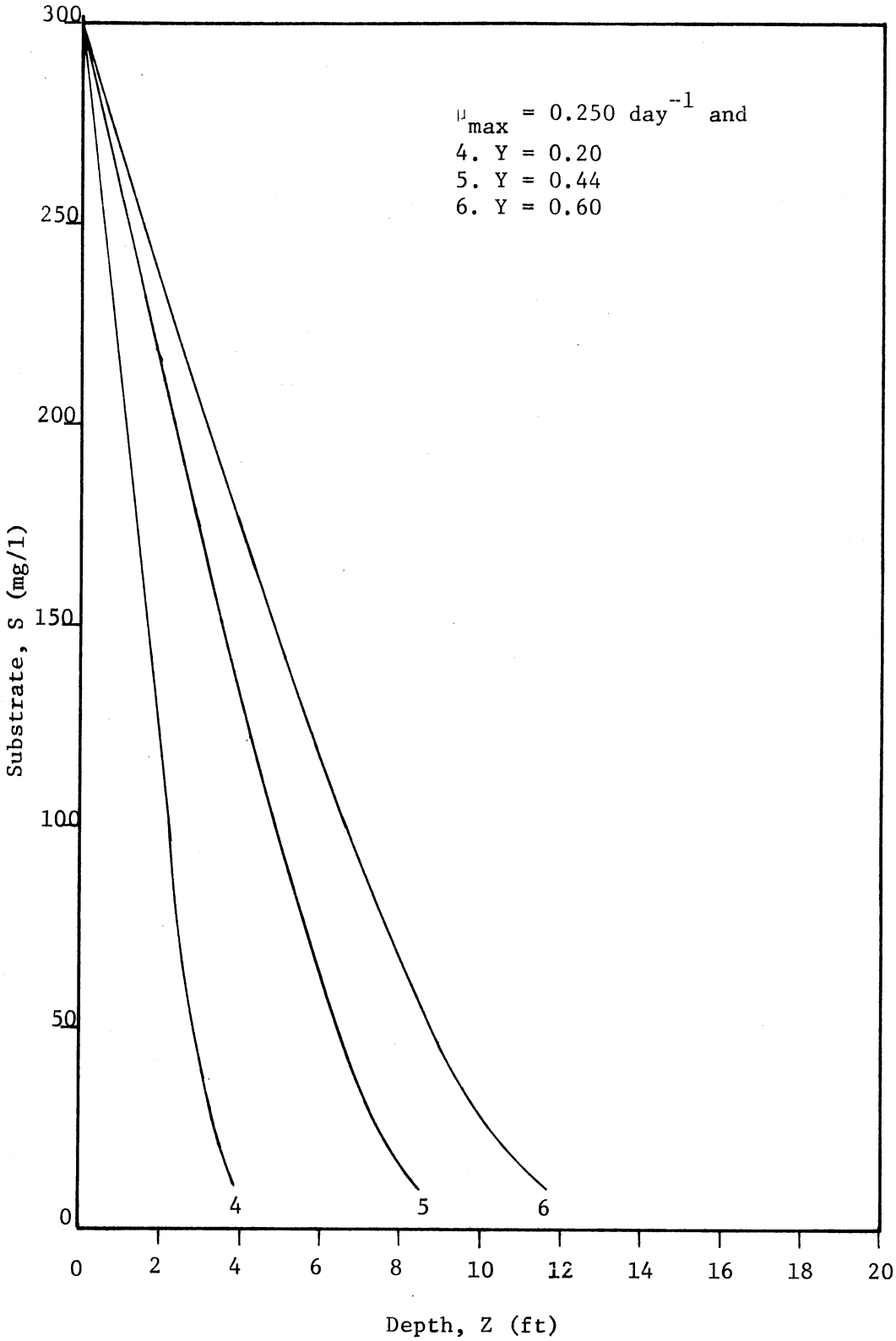
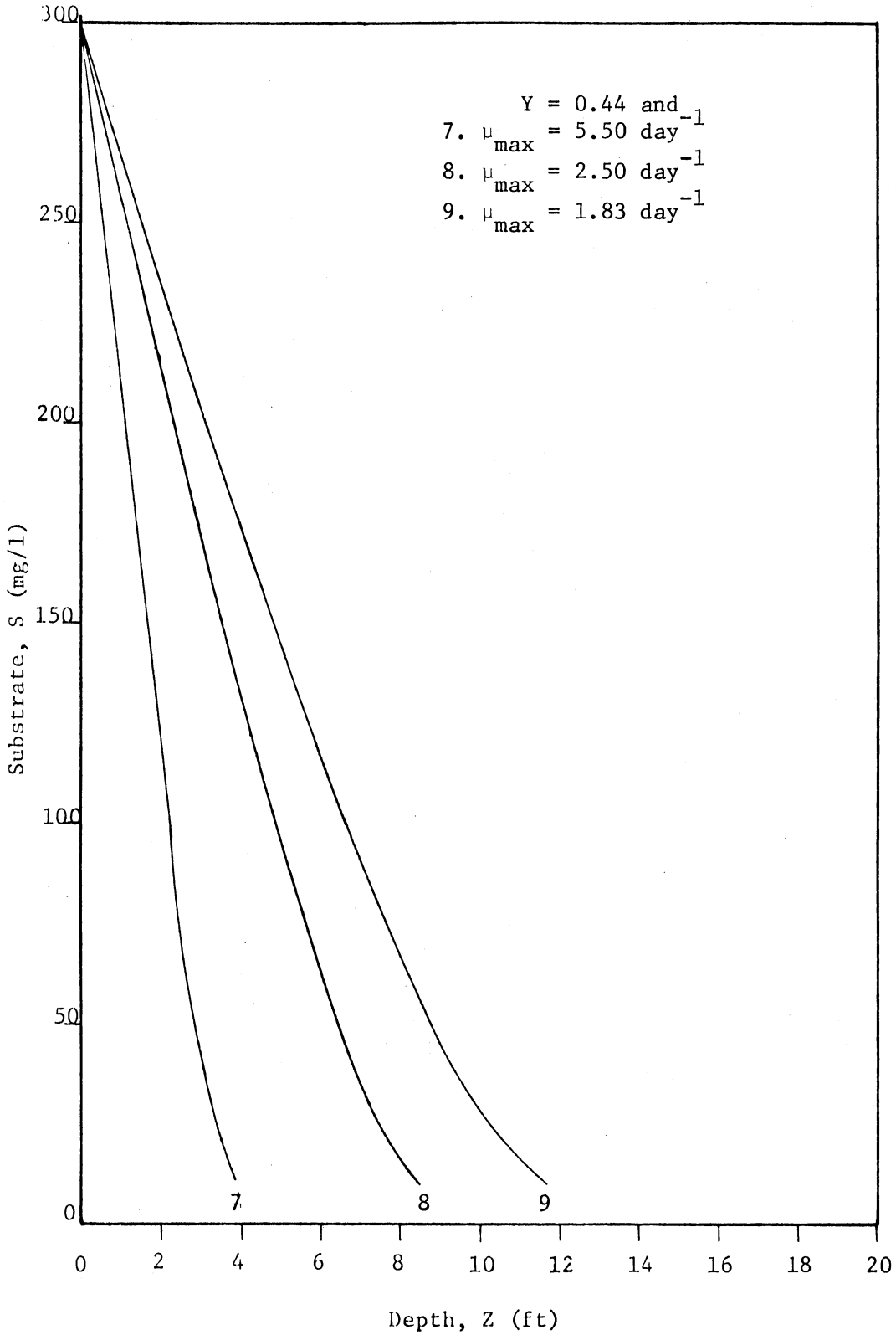

μ_{max} = 0.250 day^{-1} and
4. Y = 0.20
5. Y = 0.44
6. Y = 0.60
Substrate, S (mg/l)
300
250
200
150
100
50
0
4
5
6
0
2
4
6
8
10
12
14
16
18
20
Depth, Z (ft)

Figure 5. Theoretical Plot of Substrate Concentration Versus Depth by Equation (25); the Effect of Varying μ_{max}


Y = 0.44 and
7. μ_{max} = 5.50 day^{-1}
8. μ_{max} = 2.50 day^{-1}
9. μ_{max} = 1.83 day^{-1}
Substrate, S (mg/l)
300
250
200
150
100
50
0
7
8
9
0
2
4
6
8
10
12
14
16
18
20
Depth, Z (ft)

Bently's data measure substrate as COD. A small portion of the total COD is composed of inorganic material or other substances which are not available to the microorganisms as substrate; therefore, a correlation factor of 18 mg/l was subtracted from all values of influent and effluent substrate concentrations. These corrected data are listed in Table I.

TABLE I

CORRECTED DATA BY BENTLY

$F\left(\frac{\text{liters}}{\text{day}}\right)$	S_o (mg/l)	S at 4 ft (mg/l)	Effluent Solids (mg/l)	Clarifier Solids (mg/day)
1893	156	71.3	18.5	996.17
1893	132.2	37.6	13.9	568.80
1893	237.4	118.6	24.6	1153.50
3785	89.7	32.1	12.1	1126.05
3785	60.2	21.0	5.8	807.16
3785	111.2	53.8	9.43	1255.50
4732	83.2	42.4	5.78	1492.03
4732	57.4	27.7	4.20	912.20
4732	40.7	27.4	6.50	699.40

Although the growth rate of the microorganisms in the filter is not

constant with depth, one can use the concept of an average growth rate. Analysis of trickling filter data can be performed using methods developed for activated sludge (21).

The mean cell residence time, Θ_c (days), may be calculated by the following formula

$$\Theta_c = \frac{X \text{ total}}{V_c X_c + F X_E} \tag{26}$$

where

X_T = total active solids on filter surfaces (mg)

V_c = volume of clarifier (liters)

X_c = solids collected in clarifier per day (mg/day)

F = hydraulic flow rate (liters/day)

X_E = solids concentration in the effluent (mg/l)

The total active solids on the filter surfaces are given by

$$X_T = (a)(Z)(H)(d)(X) \tag{27}$$

The observed yield, Y_{OBS}, is given by the formula

$$Y_{OBS} = \frac{V_c X_c + F X_E}{(S_o - S_4)F} \tag{28}$$

where

S_4 denotes the substrate concentration at a 4-ft depth, and all other terms are as previously defined. The specific utilization, U (day^{-1}), is calculated by

$$U = \frac{(S_o - S_4)F}{X_T} \tag{29}$$

Values for the true yield, Y, and the decay coefficient, k_d, may be obtained by two methods. Since

$$\frac{1}{\Theta_c} = YU - k_d \tag{30}$$

a plot of $\frac{1}{\Theta_c}$ versus U will give a straight line with slope, Y, and intercept, $-k_d$. This plot is shown in Figure 6, and the values for the constants are Y = 0.44 and k_d = 0.180 day^{-1}. Also

$$Y_{OBS} = \frac{Y \frac{1}{\Theta_c}}{k_d + \frac{1}{\Theta_c}} \tag{31}$$

which may be inverted to give

$$\frac{1}{Y_{OBS}} = \frac{k_d}{Y} \Theta_c + \frac{1}{Y} \tag{32}$$

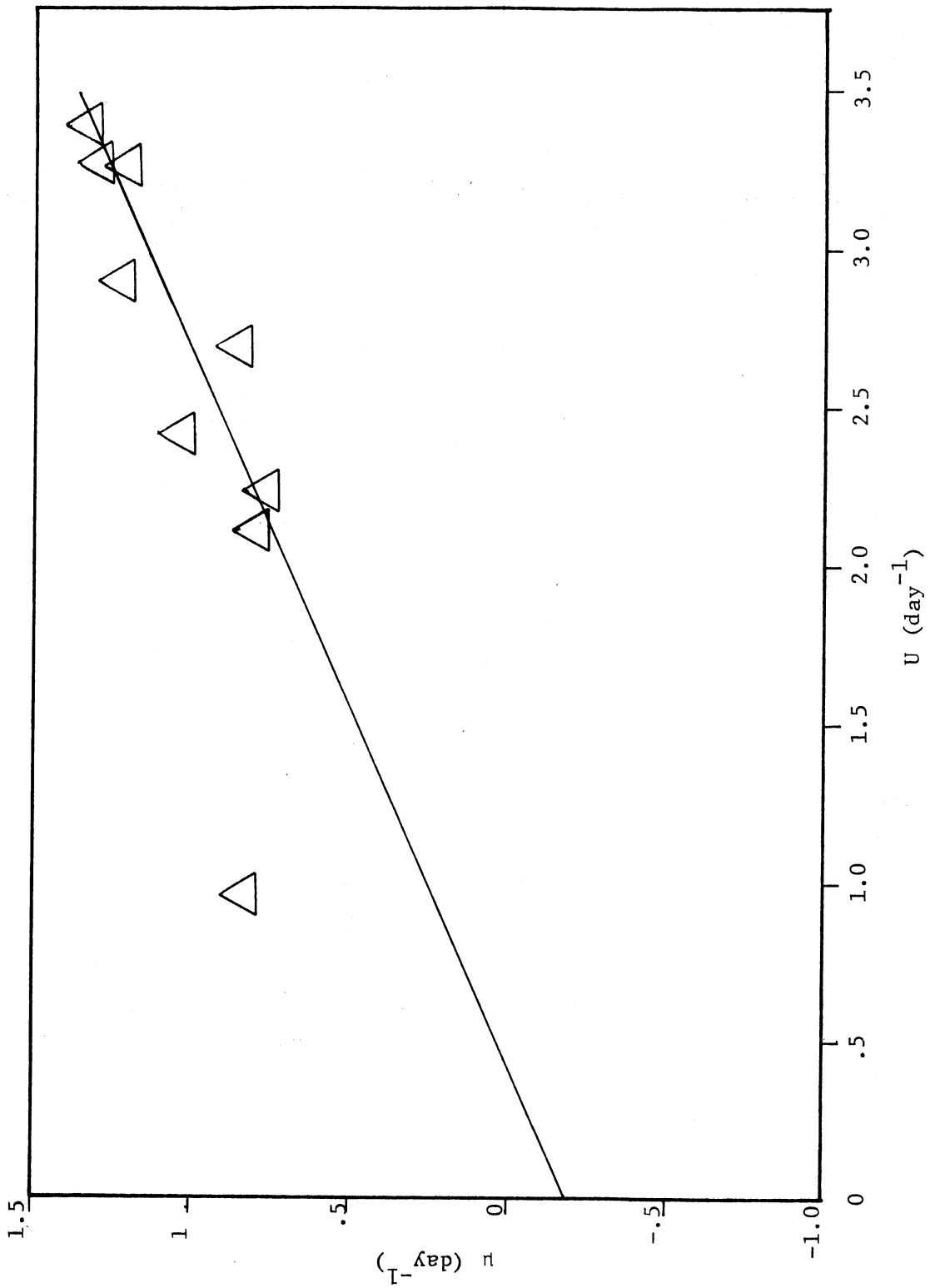
A plot of $1/Y_{OBS}$ versus Θ_c will give a straight line with slope, k_d/Y, and intercept, 1/Y. In this method, the value of k_d is much more sensitive to small changes in slope, and the data did not fit this plot well, so this graph is not included.

Once k_d is known, the true growth rate, μ, may be calculated by the following relationship

$$\mu = \frac{1}{\Theta_c} + k_d \tag{33}$$

The true growth rate, μ, and the substrate concentration, S, are related by the Monod equation

Figure 6. Specific Growth Rate, μ, Versus Specfic Utilization, U, for Bently's Data


1.5
1
.5
0
-.5
-1.0
π (day^{-1})
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
U (day^{-1})

$$\mu = \frac{\mu_{max}\, S}{K_s + S} \tag{34}$$

By inverting, we find

$$\frac{1}{\mu} = \frac{K_s}{\mu_{max}} \frac{1}{S} + \frac{1}{\mu_{max}} \tag{35}$$

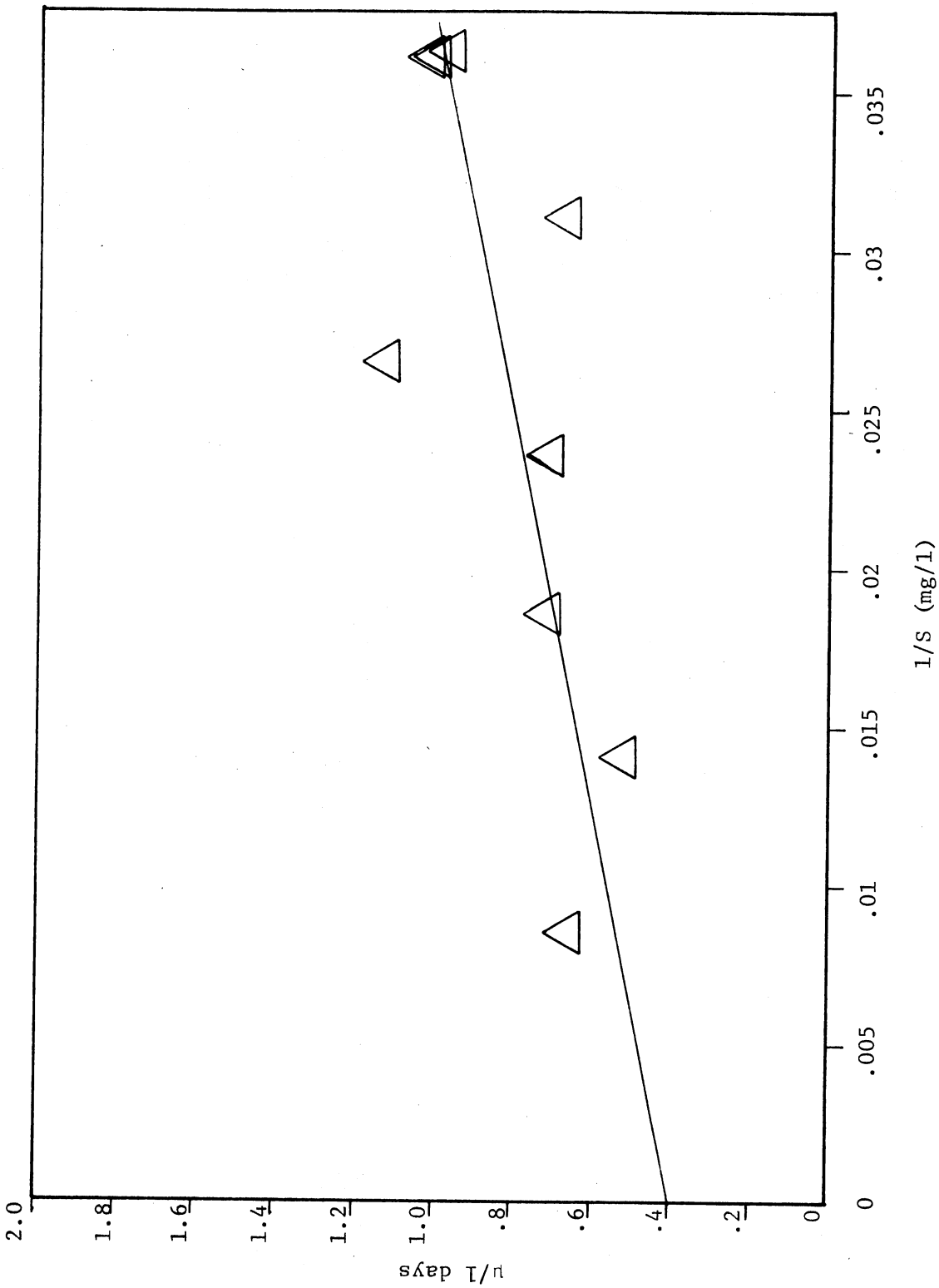
so that a plot of $1/\mu$ versus $1/S$ should give a straight line with slope, K_s/μ_{max}, and intercept, $1/\mu_{max}$. This graph, using adjusted effluent substrate concentrations, is shown in Figure 7. It was found that μ_{max} = 2.50 day^{-1}, and K_s = 40 mg/1. It is interesting to note that the variation in flow velocity produced no obvious variation in K_s, since all data points lie relatively near the line.

Equation (34) may also be rearranged in the form

$$\frac{S}{\mu} = S \frac{1}{\mu_{max}} + \frac{K_s}{\mu_{max}} \tag{36}$$

A plot of S/μ versus S will give a straight line with slope, $1/\mu_{max}$, and intercept, K_s/μ_{max}. Data scatter made this graph unusable, and it is not presented.

Figure 7. Reciprocal of the Specific Growth Rate, $\frac{1}{\mu}$, Versus the Reciprocal of the Substrate, $\frac{1}{S}$


2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
μ/1 days
0
.005
.01
.015
.02
.025
.03
.035
1/S (mg/1)

CHAPTER IV

TESTING THE MODEL

The ultimate value of a kinetic model lies in its ability to predict performance. Therefore, an attempt was made to use the kinetic model and biological constants developed in Chapter II to predict other laboratory data.

The data presented in this section were obtained by Cook on a laboratory trickling filter unit using sucrose as a sole carbon source (22). As with the earlier data, an adjustment for non-biodegradable COD was required, and the value 15 mg/l was subtracted from all substrate concentrations. The corrected data are listed in Table II.

In his study, Cook used media with a specific surface area of 50 ft^2/ft^3. However, a study by Fleming (23) indicated that increasing the media specific surface area above 27 ft^2/ft^3 had little influence on filter performance, so the value of 27 ft^2/ft^3 is used in these calculations.

The values for the biological constants were assumed to be those found by analysis of Bently's data--that is, $\mu_{max} = 2.50\ day^{-1}$, $K_s = 40$ mg/l, and $Y = 0.44$. Using these values, and the actual influent substrate concentrations and flows, substrate versus depth curves were generated using equation (25) for each influent substrate concentration. These curves are shown plotted against the actual data in Figures 8 through 12.

TABLE II

CORRECTED DATA BY COOK

Influent Flow $\left(\frac{\text{liters}}{\text{day}}\right)$	Adjusted Substrate Concentration as COD (mg/1)				
Depth	0 ft	1 ft	2 ft	3 ft	4 ft
1136	465	358	300	240	192
1136	196	124	85	39	20
1893	175	102	86	47	36
1136	95	45	22	3	3
2271	80	42	28	13	6

Figure 8. Theoretical and Actual Substrate Concentration Versus Depth for S_o = 465 mg/l From Data by Cook

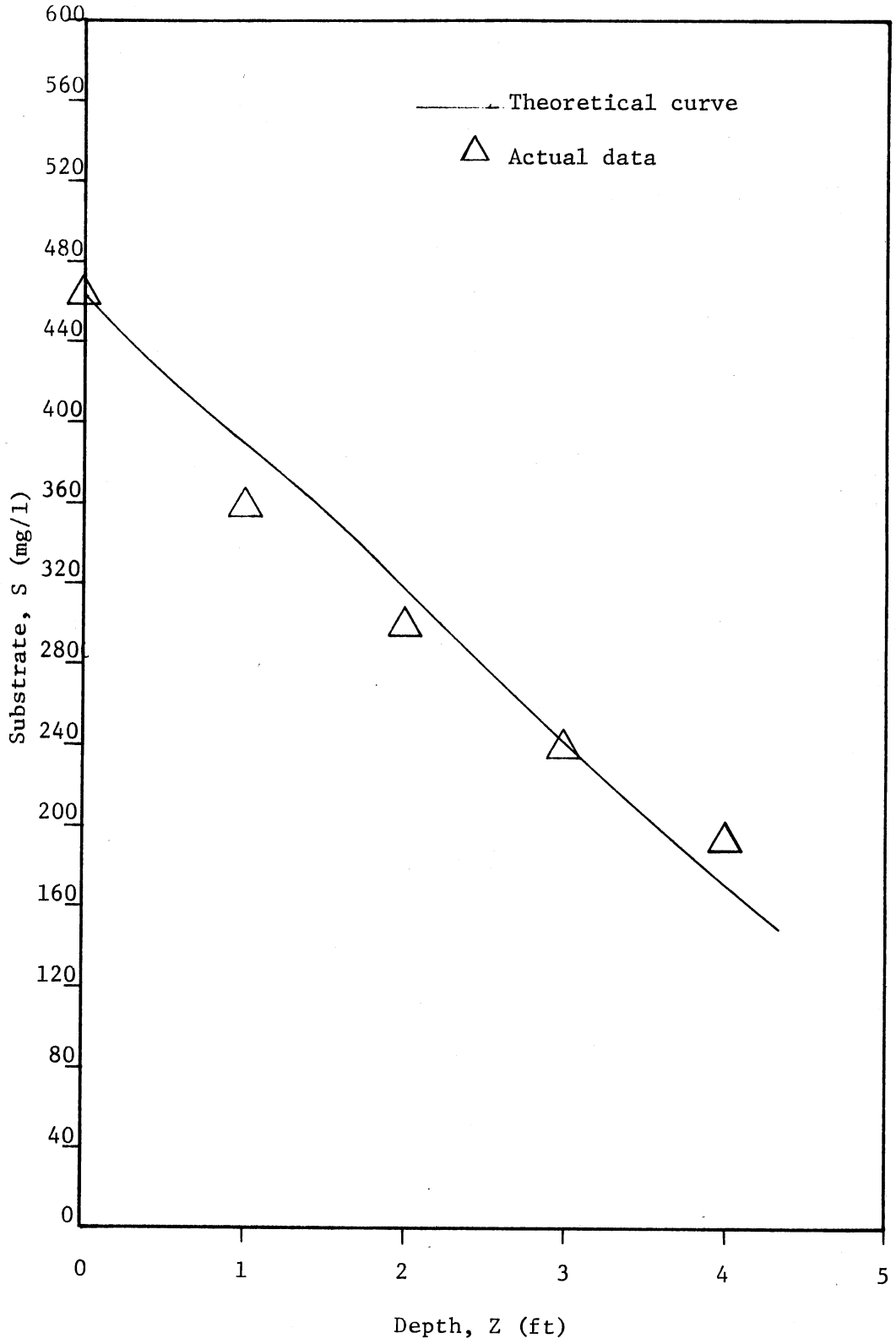

Theoretical curve
Actual data
Substrate, S (mg/l)
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0
0
1
2
3
4
5
Depth, Z (ft)

Figure 9. Theoretical and Actual Substrate Concentration Versus Depth for S_o = 196 mg/l From Data by Cook

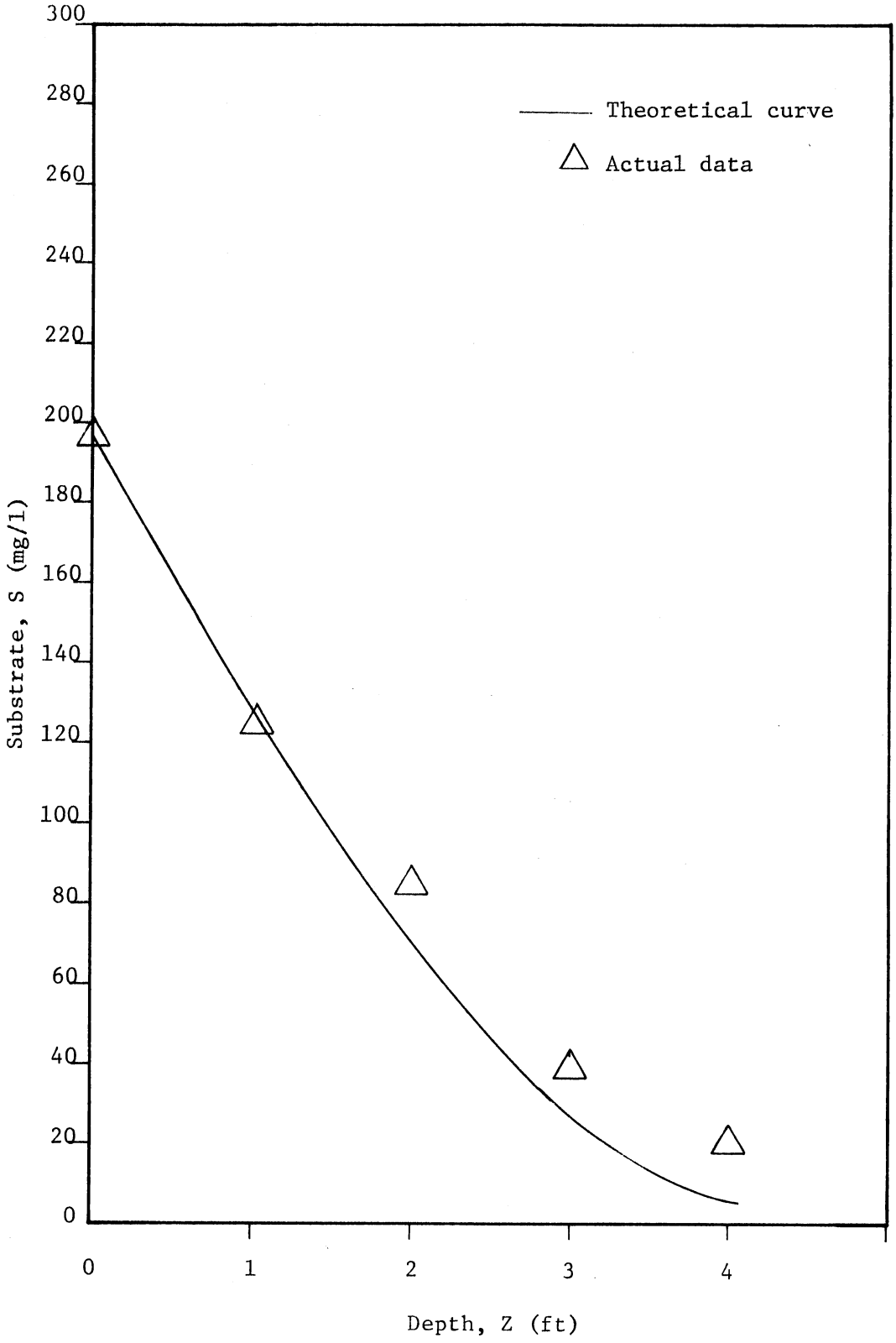

300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
Substrate, S (mg/l)
Theoretical curve
Actual data
0
1
2
3
4
Depth, Z (ft)

Figure 10. Theoretical and Actual Substrate Concentration Versus Depth for S_o = 175 mg/1 From Data by Cook

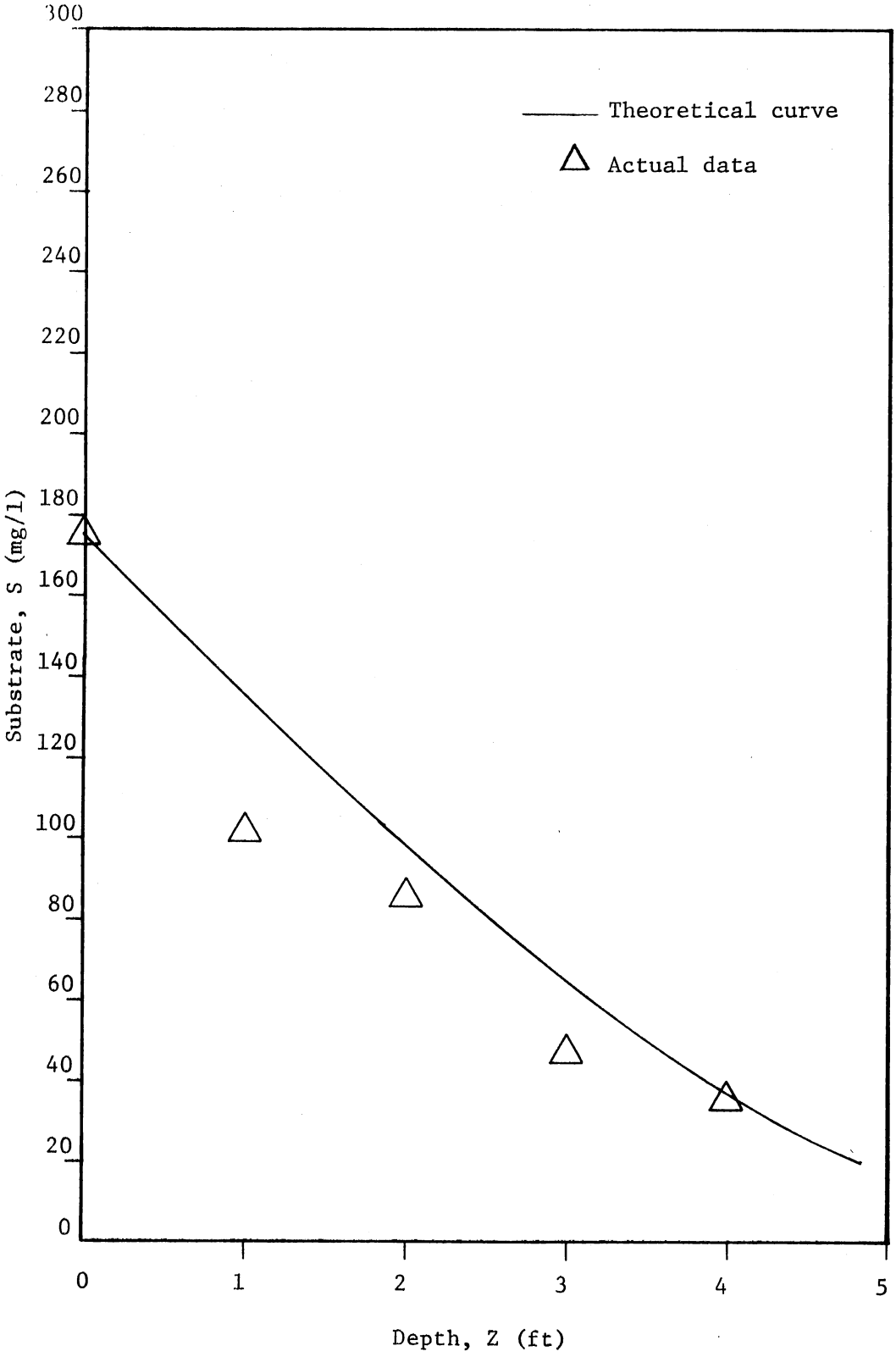

300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
Substrate, S (mg/l)
Theoretical curve
Actual data
0
1
2
3
4
5
Depth, Z (ft)

Figure 11. Theoretical and Actual Substrate Concentration Versus Depth for S_o = 95 mg/1 From Data by Cook

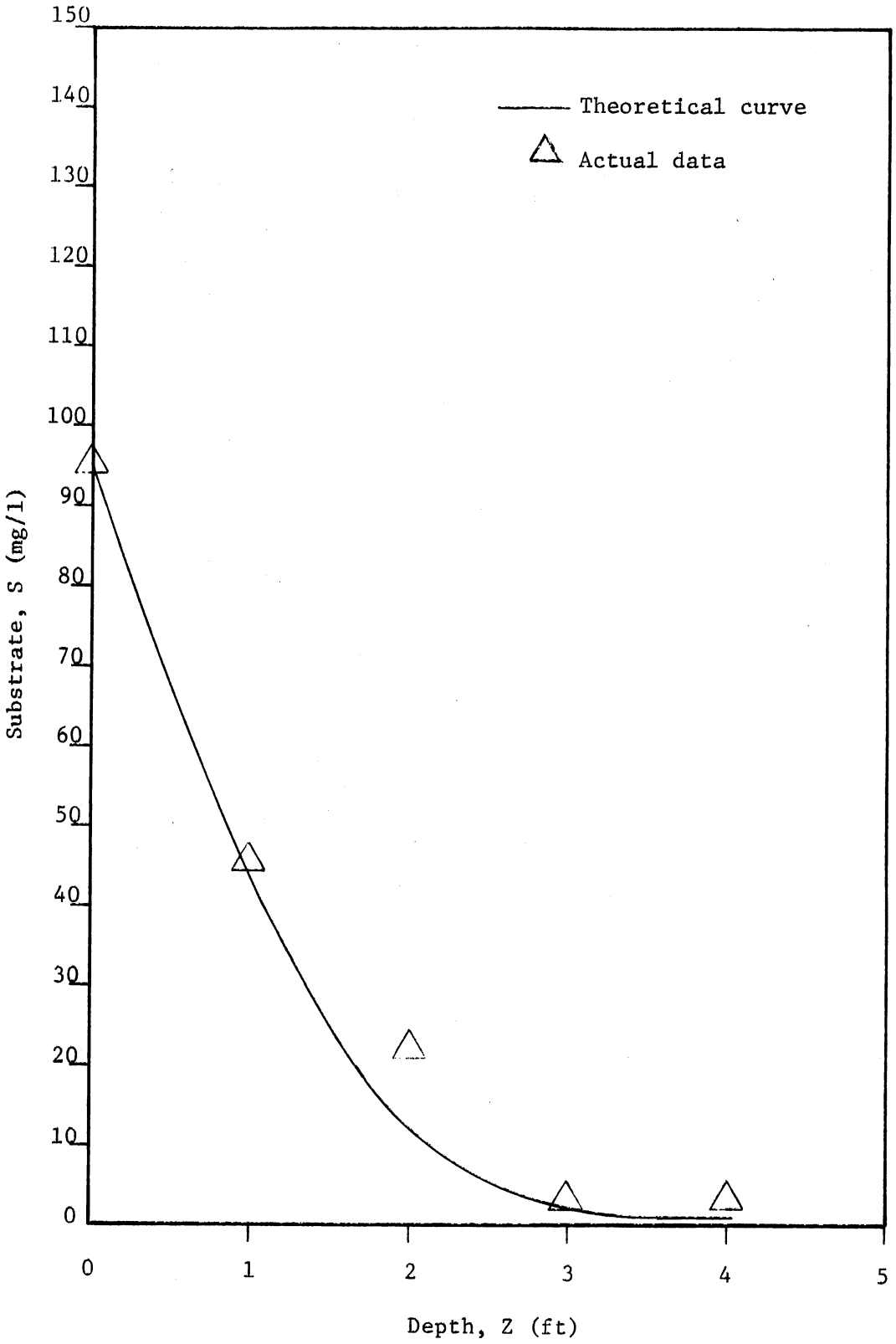
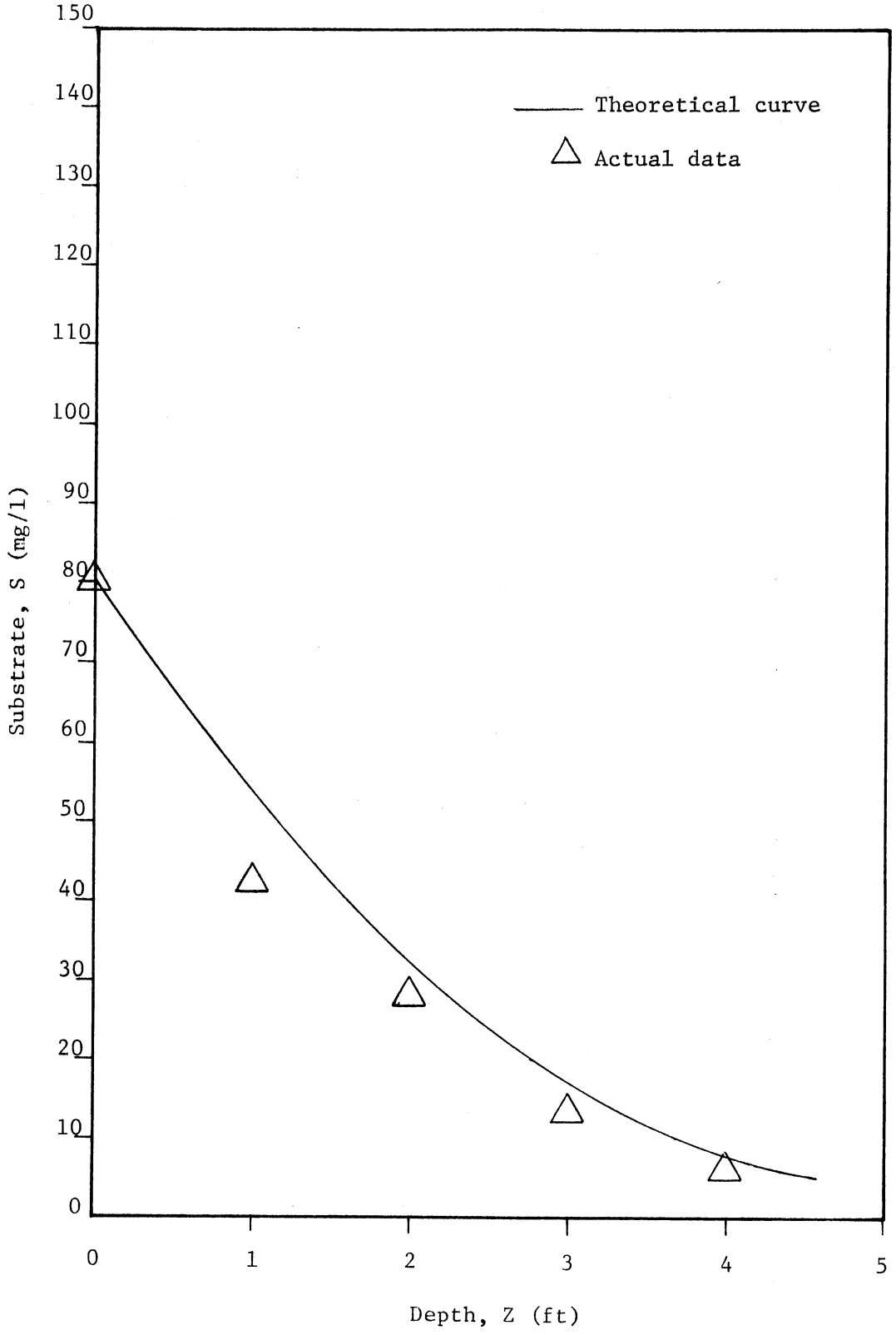

Theoretical curve
Actual data
Substrate, S (mg/l)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
Depth, Z (ft)

Figure 12. Theoretical and Actual Substrate Concentration Versus Depth for S_o = 80 mg/l From Data by Cook


150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Substrate, S (mg/l)
Theoretical curve
Actual data
0
1
2
3
4
5
Depth, Z (ft)

CHAPTER V

DESIGN PROCEDURE

Since the values of the biological constants, μ_{max}, K_s, and Y, will vary with the nature of the waste to be treated and the microbial population that will grow on the waste, it is highly desirable to run a treatability study to ensure that a naturally-occurring microbial population will be capable of purifying the waste, and to collect data in order to determine the values of the constants which characterize that population growing on that waste.

The design procedure is as follows:

Step 1: Characterize the waste as to flow, strength (BOD), and BOD:N:P ratio.

If the variations in flow or strength of the waste are greater than 2:1, serious consideration should be given to the use of an equalization basin. The BOD:nitrogen:phosphorous ratio should be about 100:5:1. If the waste is deficient in nitrogen or phosphorous and supplemental nutrients will be added to the waste, these must be added during the treatability study, also.

Step 2: Set specifications for filter media and choose filter area.

The specific surface area of the media used in the treatability study should lie in the range specified for the treatment plant. Filter cross sectional area may be based on flow rate and media manufacturer's

recommendations. The most important consideration should be to keep the entire filter wet at minimum flow.

Step 3. Choose a range of flow rates for the treatability study.

In order to obtain data at various growth rates, one must vary the organic loading to the filter by varying filter depth, substrate concentration, or flow rate. In most cases, the simplest procedure will be to vary flow rate.

Design will be based on maximum daily flow or, if flow equalization is employed, on average daily flow. Since K_s may vary with flow velocity, it is suggested that the treatability study flow rates be chosen so that the values of flow per unit cross sectional area lie in the range expected in the actual treatment plant.

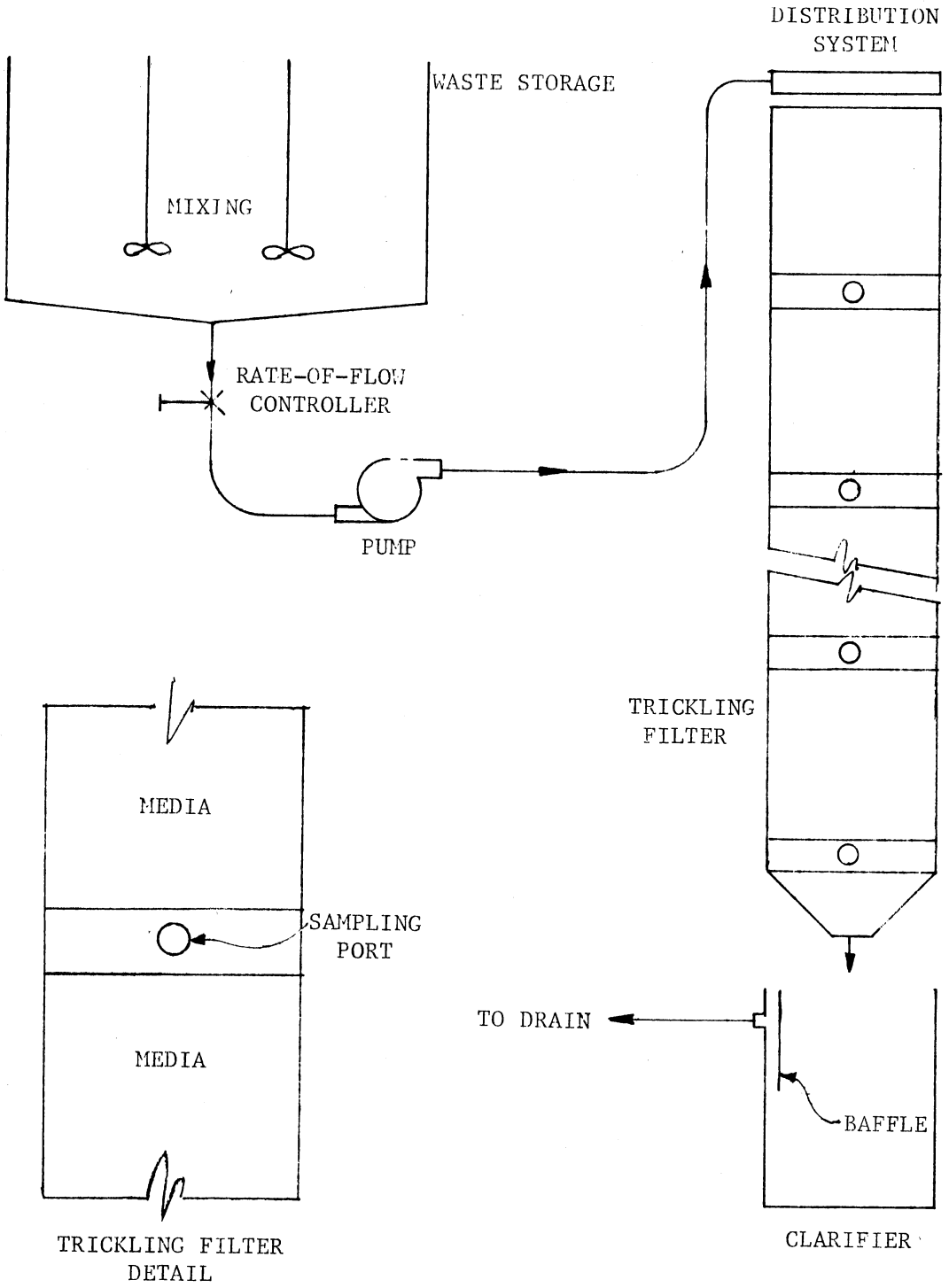
If this variation does not produce adequate variation in growth rate to allow accurate determination of the biological constants, a larger range of flow rates should be chosen or, alternatively, one may extend the range of organic loadings by dilution.

Step 4. Operate a small scale unit and collect data.

If possible, the laboratory unit or pilot plant should be fed the actual waste to be treated. If not possible, a similar waste may be used. A schematic of one possible laboratory unit is shown in Figure 13. This unit allows collection of solids in a clarifier for determining Y and k_d.

The first step in the operation of the unit is to condition the filter by applying the waste until growth is obtained on all surfaces. Once the filter is conditioned, the flow rate should be adjusted to the proper value and the influent substrate concentration adjusted to the maximum observed in the actual waste. The unit should be operated

Figure 13. A Schematic of a Possible Laboratory Unit for use in Determining Design Data


DISTRIBUTION SYSTEM
WASTE STORAGE
MIXING
RATE-OF-FLOW CONTROLLER
PUMP
TRICKLING FILTER
MEDIA
SAMPLING PORT
MEDIA
TRICKLING FILTER DETAIL
TO DRAIN
BAFFLE
CLARIFIER

in this manner until steady state is achieved, at which time data should be taken. Steady state is indicated by constant flow, influent and effluent substrate concentrations. Though BOD may be used in design, it is advisable to monitor the performance of the unit by using COD because results are obtained more rapidly.

As steady state is reached, design data of influent and effluent BOD and COD, and clarifier and effluent solids may be obtained. If substrate removal and solids production are constant for three days' sampling, the flow rate should be changed, a new steady state reached, and design data sampling performed.

It is advisable to operate the unit at a minimum of five different flow rates with a range of at least 5:1 in order to obtain a spread of growth rates for determining μ_{max}, K_s, Y, and k_d.

It is also useful to obtain substrate concentrations from within the filter at various depths, especially at low loadings where the substrate may be exhausted before the bottom of the trickling filter is reached. If this condition does occur, the effective depth of the filter is reduced to the depth at which substrate is exhausted.

Step 5. Determine values for the biological constants.

The constants Y and k_d, and μ_{max} and K_s may each be determined by two graphical methods. All four graphs should be used in order to make the best estimate of the values of these constants. Details of determining these constants were presented in Chapter III, part A, pages 20 to 34 of this thesis.

Step 6. Determine the required filter depth.

Filter depth is given by the formula

$$Z = \frac{FY\left[K_s \ell n \frac{S_o}{S_e} + S_o - S_e\right]}{\mu_{max}(a)(d)(H)(X)} \quad (25)$$

where

Z = required filter depth (ft)

F = design hydraulic flow rate, normally maximum daily flow (liters/day)

Y = true yield (fraction)

K_s = saturation coefficient (day^{-1})

S_o = design influent substrate concentration, normally maximum substrate concentration (mg/l)

S_e = required effluent substrate concentration, normally specified by standards (mg/l)

μ_{max} = maximum specific growth rate (day^{-1})

a = specific area of filter media, normally available from media manufacturer (ft^2/ft^3)

d = thickness of active microbial film, assumed to be 7×10^{-3} cm

X = concentration of biological solids on a dry basis, assumed to be 95 mg/cm^3

H = filter cross sectional area (cm^2)

If the required depth is excessive, the filter may be constructed as two or more units in series.

Step 7. Estimate solids production.

An estimate of the true growth rate, μ, for the trickling filter may be made based on the required effluent substrate concentration and either the graph of $\frac{1}{\mu}$ versus $\frac{1}{S}$ or $\frac{S}{\mu}$ versus S. Solids production is estimated by the formulas

$$\text{Solids production } \frac{mg}{day} = \frac{dX}{dt} = \mu X_t \tag{37}$$

and $$X_T = (a)(Z)(H)(d)(X) \tag{27}$$

A second method for estimating solids production is based on the formulas

$$\text{Solids production} = \frac{dX}{dt} = Y_{OBS} \; F \; (S_o - S_e) \tag{38}$$

and $$Y_{OBS} = \frac{Y(\mu - k_d)}{\mu} \tag{39}$$

Step 7. Including safety factor in design.

The amount of safety factor to be included in the design is a difficult choice, and must be based, largely, on the designing engineer's experience. However, it is possible for that engineer to gain some insight into the effect of a change in the strength of the waste or values of the biological constants, μ_{max}, K_s, and Y, by generating profiles of substrate versus filter depth. Once the designer has chosen values of S_o, μ_{max}, K_s, and Y to be investigated in this scenario, the substrate profile is generated by using equation (25) to calculate filter depth for various substrate concentrations less than S_o. The substrate concentrations chosen are reduced until the predicted depth equals or exceeds the design depth. Now, a graph of S versus Z will allow the designer to estimate the filter depth at which adequate treatment will be achieved for these new conditions of S_o, μ_{max}, K_s, and Y.

CHAPTER VI

DISCUSSION

A. Implications in the Method Used to Determine the Biological Constants

Kornegay and Andrews (16) lump μ_{max} and Y into a constant P, where

$$P = 1/(Y)(\mu_{max})(X)(d) \tag{40}$$

and suggest determining the values of K_s and P by a plot of $S_o - S_e$ versus $\ell n\ S_o/S_e$. This approach has two disadvantages: first, since Y is not determined, no method is available for estimating sludge production. Second, when attempting to use this method, difficulty was encountered due to the sensitivity of the term $\ell n\ S_o/S_e$ to small errors at low values of S_e.

B. Significance of Observed Values for the Biological Constants

An interesting interpretation may be attached to the values of the biological constants observed in this study. For heterogeneous populations of sewage origin grown using a sugar as a carbon source in an activated sludge unit, the values for the biological constants normally encountered are μ_{max} = 3 to 5 days^{-1} (24), K_s = 50 to 125 mg/1, and Y = 0.4 to 0.6 (24)(25). The value of Y = 0.44 is not unusual, nor is

K_s = 40 mg/l very unusual. These values depend only on the microorganisms involved, substrate used, and environmental conditions.

The value determined for μ_{max} = 2.50 $days^{-1}$ depends not only on these factors, but also on the assumptions that d = 7 x 10^{-3} cm and X = 95 mg/cm^3. These assumptions were used to calculate total active biolotical solids, X_T, and X_T was used to calculate sludge age, Θ_c, which was used to calculate specific growth rate μ, which was used to determine, graphically, μ_{max}.

Though not hard proof, the fact that μ_{max} = 2.50 $days^{-1}$, as was found in this study, is not an unusually high or low value, tends to indicate that the values of d and X found by Kornegay and Andrews (15) were similar to those encountered in this study.

An error in the assumed values for d or X would not invalidate the design method, if μ_{max} is determined from actual data. An error in d or X would produce a corresponding error in the value determined for μ_{max}. When applying equation (25), these errors will cancel.

C. A Comparison of the Various Kinetic Models

As was mentioned earlier, the values of S_o, Y, μ_{max}, and K_s can influence the shape of the substrate versus depth curve. Several shapes were observed in the analysis of data obtained by Cook (22). In Figures 8 and 10, the curve is nearly linear. In Figure 12, the curve has a shape similar to that of a first order decreasing function. In Figure 11, the curve might be approximated fairly accurately by two straight lines. All of these shapes have been used in the past to describe data or for filter design.

In light of these similarities, it seems likely that any of the

design methods available, if properly applied, would be adequate in at least some cases. However, the method outlined in this thesis has three basic advantages. First, it may be used to describe sets of data which plot a variety of shapes as substrate versus depth. Second, this method allows one to investigate the effect of a change in the values of influent substrate concentration or biological constants. Third, this method allows an estimate of solids production.

D. Use of ΔCOD in Design

BOD is the standard measure of substrate (strength of the waste or effluent quality) recognized by government pollution control agencies, and it is a logical measurement. However, the BOD test is more variable than is the COD test (25), and use of the COD test is therefore desirable. Since the COD test can measure the oxygen demand of material which is not available to the microorganisms as substrate, a modification of the use of the COD test, known as ΔCOD has been suggested (25).

The non-biodegradable fraction of the COD may be determined by aerating the effluent from the trickling filter in a batch reactor and monitoring the COD. The minimum observed COD is then used as a base line or correction factor which is subtracted from the COD data to obtain ΔCOD. Initial substrate concentration might affect the value for this correction factor, so the correction factor should be determined at each substrate concentration used. The value of the correction factor may be checked by operating a trickling filter at successively lower influent substrate concentrations until a minimum effluent COD is observed or, in a tall tower, by sampling COD at various depths until duplication of COD values indicates that substrate removal is complete.

CHAPTER VII

CONCLUSIONS

1. A design method based on basic microbial kinetics may be applied successfully to a trickling filter.

2. Biological constants for a trickling filter may be determined by using methods of data analysis developed for the activated sludge process.

CHAPTER VIII

SUGGESTIONS FOR FUTURE STUDY

1. Study the effect of flow velocity on K_s.

2. Study the use of biological kinetics to describe nitrification in a trickling filter.

3. Study the possibility of devising a method for determining d and X for a trickling filter.

4. Study the possibility of devising a method for determining μ_{max} for a trickling filter which is independent of the values of d and X.

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