KINETICS AND MECHANISMS OF FIXED BED REACTORS

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CHAPTER I

INTRODUCTION

Fixed bed reactors (trickling filters) are artificial beds of stone or porous medium over which an organic waste is applied. Micro-organisms present in the organic waste (or supplied from other sources) accumulate on the filter medium and, when they come in contact with the waste and air, remove the organics contained in the waste flow for use as nutrients for biological metabolism.

This biological metabolism involves the conversion of the organic waste into carbon dioxide, energy, and new cell material. Most of the carbon dioxide diffuses into the atmosphere and the newly synthesized cells remain attached to the filter medium, later sloughing off and being settled out in the final clarifier. In this manner the soluble organics are converted to a bio-mass which can be settled out thus removing the pollutant and clarifying the waste stream.

This process is one of the oldest methods of biological waste treatment and yet it is probably the least understood of the treatment processes.

Numerous investigators have worked on trickling filters, gathering pertinent data, but in their analysis of this data have only searched the most obvious physical aspects and relationships. Consequently, they all terminate the search at approximately the same point. We now have a wealth of knowledge on the physical aspects but virtually nothing has been researched beyond.

Each investigator has his own manner of data presentation which will prove beyond a doubt that his theories and equations are correct.

The design of trickling filters has been approached by the use of numerous empirical formulations. Each of these formulations has received its share of criticism with justification in most cases. Recently, Baker and Graves (1) made a computer analysis of various trickling filter formulations. The National Research Council (NRC) formula, the Eckenfelder formula, and the Galler-Gotaas formula were compared. It was found that for identical conditions the three formulations suggested three different volumes of filter capacity to produce the same BOD removal efficiency.

A most perplexing problem arises from this dilemma, in that the consultant or sanitary engineer designing a waste treatment plant has no idea which formulation should be used in his design. Most of these formulations have been derived from systems utilizing domestic sewage as a substrate which contains 100 to 250 mg/l of 5 day, 20^{o} C BOD. This is fine for domestic sewage, but these same formulations are being used to design treatment systems for industrial wastes which contain 5 to 20 times the amount of BOD present in domestic sewage. Some have met with success and others have not.

The purpose of this investigation was to look at the basic mechanisms and kinetics found in the trickling filter process during microbial metabolism of a simple substrate.

The goal was to provide a glimpse into a new direction for research on trickling filters. Hopefully, others will begin where this research terminates and eventually elucidate a basic understanding of this poorly understood process.

CHAPTER II

LITERATURE REVIEW

To take advantage of an unprecedented opportunity, brought about by the expansion of military installations during World War II, the Committee on Sanitary Engineering of the National Research Council organized a subcommittee to record operational experiences with different sewage treatment processes found throughout the United States (2).

From these various military installations, a myriad of operational data was obtained and statistical analysis was performed on applicable portions of it in order to determine trickling filter performance. The subcommittee reported that the "degree of treatment" attained in any treatment process depends on: (a) magnitude of the organic load treated per unit of time; (b) amount of biologically active growth, whether sessile or free floating; (c) adequacy of air-liquid interface; (d) time of contact between organic load and biological growth; (e) degree of agitation and turbulence at the interface of growth and sewage; and (f) provision made for settling of agglomerated material and detached excessive growths.

After analyzing the operational data on trickling filters, the subcommittee concluded that of the two types of loading, organic and volumetric, the former has the greater effect on efficiency. The following empirical formula was derived for the efficiency of a single stage filter without recirculation:

$$E = \frac{100}{1+C\left(\frac{W}{V}\right)^{0.5}} \tag{1}$$

where:

E = % BOD removed

W = organic load applied (lbs BOD/day)

V = volume of filter medium (acre·feet)

C = constant, equal to 0.0085 for volume in acre·feet or 0.0561 for volume in thousands of cubic feet.

The subcommittee reported that the more readily degradable organics are extracted first, leaving the less degradable organics to be removed thus causing a definite reduction in the "treatability" of the sewage in a treatment process.

Velz (3) in 1948 developed a formula based on theoretical principles with empirically derived constants. He proposed that in all trickling filters the rate of extraction of organic matter per interval of depth is proportional to the remaining concentration of organic matter, measured in terms of its removability. This is expressed in a differential form as:

$$-\frac{dL}{dD} = KL \tag{2}$$

Integrating,

$$\ln \frac{L_D}{L} = -KD \tag{3}$$

or
$$\log \frac{L_D}{L} = -0.434KD = -kD \tag{4}$$

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

where:

L = total removable fraction of BOD

L_D = remaining removable BOD at depth D

D = depth

k = the logarithmic rate of extraction

k and L must be determined experimentally for any particular type of biological bed.

The values for k and L for a 460 gal/day/ft^2 plant at Englewood, New Jersey, were determined to be 0.1505 and 0.784, respectively.

Since increasing the depth of a filter bed is essentially the same as increasing the contact time between the microbial mass and the organic waste, Velz's expression is nearly identical to that of Phelps (4) which describes basic first-order kinetics of biological oxidation:

$$-\frac{dL}{dt} = KL \tag{6}$$

$$\ln \frac{L_t}{L} = -Kt \tag{7}$$

$$\log \frac{L_t}{L} = -0.434Kt = -kt \tag{8}$$

$$\frac{L_t}{L} = 10^{-kt} \tag{9}$$

where:

L_t = quantity of BOD remaining at time t.

L = initial quantity of BOD

In 1956, Fairall (5) developed an empirical formula from data of 44 plants in the Upper Mississippi Valley. The formula is as follows for a filter without recirculation:

$$\frac{L_e}{L_i} = 1.102 \left(\frac{V}{Q} \right)^{-0.322} \tag{10}$$

where:

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

V = volume of filter medium (1000 cu ft)

Q = plant hydraulic flow rate (mgd)

Stack (6) in 1957 presented a theoretical formula for trickling filter performance based on the assumptions that: (a) a trickling filter is a self-regenerating absorption tower, (b) each unit depth of the filter will remove a constant fraction of the removable BOD applied to that unit depth, (c) removable BOD is the fraction of the observed BOD which can be removed by biosorption, and (d) the quantity of BOD that can be absorbed by one unit volume of a filter has a maximum limit. For a trickling filter operated with no recirculation, the derived equation expressing its performance is:

$$L_R = xbS+b(L-xbS)\{1+(1-b)+(1-b)^2+(1-b)^3+\cdot\cdot\cdot(1-b)^{D-x-1}\} \qquad (11)$$

where:

L_R = fraction of the removable BOD that is removed

L = the applied load of removable BOD

S = the load of removable BOD which must be applied to saturate one unit of depth with BOD

b = coefficient of biosorption

x = the number of unit volumes saturated by a given load of BOD

D = filter depth

The values of removable BOD (L), b, and S must be determined experimentally.

In 1959, Ingram (7) published the results of his studies on controlled filtration. In his research he utilized a filter composed of six sections stacked on top of one another, each having a depth of 3 feet and a diameter of 12 inches. Air was supplied to the bottom of each section at a controlled rate. Settled sewage was the substrate. Ingram concluded that Velz's "non removable" BOD can be removed with depth. The behavior of the filter through the first section followed the theory of Velz reasonably well, but thereafter there were essential differences. The filter throughout the investigation gave consistent average results better than those predicted by the NRC formula. It appeared to Ingram that the BOD loading of a filter is a more important parameter than is the hydraulic loading.

Schulze (8, 9, 10) conducted studies with a trickling filter constructed of a series of one-half-inch mesh vertical wire screens serving as the filter medium. Sewage and whey were used as the nutrient source.

The complete equation relating BOD removal to depth, hydraulic load, and temperature was found to be:

$$\frac{L_e}{L_i} = 10^{-bK_{20}\ D/Q^n} \tag{12}$$

where:

L_e = final effluent BOD (mg/l)

L_i = BOD of flow to the filter (mg/l)

Q = hydraulic load (mgd/acre)

b = $1.035^{(T-20)}$

T = temperature in ^{o}C

K_{20} = 0.3

D = filter depth (ft)

The exponent n was found to be 2/3 which has been confirmed by Howland (11) and in studies performed by Bloodgood, Teletzke, and Pohland (12).

Schulze proposed that efficiency will follow a function such as this which is based primarily on hydraulic loading and will be independent of the organic loading as long as the organic loading remains below a certain critical level which is usually not encountered in trickling filter operation.

In 1961 Eckenfelder (13, 14, 15) expanded the work of Schulze and others. He proposed that BOD removal was primarily dependent on the contact time between the "active mass" of the filter slime and the waste passing through the filter. The mass of active film is related to the surface area of filter slime and to the depth of aerobic activity. The time of contact is primarily related to the hydraulic loading.

The equation expressing the fraction of BOD remaining in the effluent as a function of hydraulic loading is:

$$\frac{L_e}{L_o} = e^{-(KD)/Q^n} \qquad (13)$$

where:

L_e = BOD remaining in the filter effluent

L_o = BOD applied to the filter

D = filter depth

Q = hydraulic load/unit surface area

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

n = constant

Eckenfelder explains that equation (13) presumes that all components of the organic waste are removed at the same rate. Eckenfelder claims there is considerable evidence concerning sewage and other complex wastes that BOD removal decreases with concentration or time, because the components that are more easily removed from the waste water are removed more rapidly. To account for this, a modified equation is required and this is:

$$\frac{L_e}{L_o} = \frac{100}{1+ \frac{CD^{(1-m)}}{Q^n}} \qquad (14)$$

From analysis of filter performance data, Eckenfelder gives the values of the constants as $C = 2.5$, $(1-m) = 0.67$ and $n = 0.50$ (for Q in mgd/acre and D in feet).

Galler and Gotaas (16) in 1964 developed a mathematical model for trickling filter efficiency by making a multiple regression analysis of 322 sets of data from existing treatment plants. For BOD in terms of concentration (mg/l) the equation for a filter without recirculation is:

$$L_e = \frac{1.3\ L_o^{0.98}\ Q^{.12}}{(1+D)^{.66}\ T^{.15}} \qquad (15)$$

where:

L_e = concentration of BOD remaining

L_o = concentration of influent BOD

Q = hydraulic loading, mgd/acre

D = depth, feet

T = temperature of waste water, °C

Germain (17) reported in 1966 that BOD removal by plastic medium trickling filters would follow the equation proposed by Schulze.

In 1968, Kornegay and Andrews (18) utilized a submerged rotating drum inside a reactor for approximation of the trickling filter process. From Monod's (19) kinetics they arrived at an equation describing the relationship of the various parameters acting in the unit:

$$F(S_o - S_1) = \frac{\hat{\mu}}{Y}(A)(X)(d)\left(\frac{S_1}{K_s + S_1}\right) \tag{16}$$

where:

S_o = influent concentration of essential nutrient (M/L^3)

S_1 = effluent concentration of essential nutrient (M/L^3)

μ = specific growth rate (T^{-1})

$\hat{\mu}$ = maximum specific growth rate (T^{-1})

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

Y = yield

A = area of biological film (L^2)

X = concentration of organisms in the biological film (M/L^3)

d = thickness of the active biological layer (L)

K_s = essential nutrient concentration where $\mu = 1/2\hat{\mu}$ (M/L^3)

M, L, and T are, respectively, units of mass, length and time.

Eckenfelder (20, 40) recently modified his trickling filter formulation. The new formula is:

$$\frac{L_e}{L_o} = e^{-.0362 A_v^{.644} L_o^{.54} D/Q^n} \tag{17}$$

where:

L_e = BOD remaining in filter effluent

L_o = BOD applied to the filter

D = filter depth

Q = hydraulic flow rate

n = a constant, characteristic of the filter medium used

A_v = area available for biological growth (sq ft/cu ft)

There are numerous conflicting ideas afforded by the previous investigators and others on the importance of the various parameters and the role they play in trickling filter performance.

Schulze (10), operating a single pass trickling filter using domestic sewage and whey as the waste, found that at a constant hydraulic loading, the efficiency of a trickling filter remains constant for organic loads up to 11 lbs BOD/day/cu yd. He claimed that the efficiency, measured as per cent BOD removed, was not decreased by increased organic loads, and therefore, the hydraulic loading determined the degree of treatment achieved.

Eckenfelder (15) in 1961, investigating trickling filter performance, assumed that BOD removal was related primarily to hydraulic loading and depth following a retardant type reaction and offered an equation based upon these assumptions.

Etzel (21) conducted studies at Purdue University with a model trickling filter and utilized radioactive glucose as the substrate. On the trickling filter studied he concluded that hydraulic loading was the parameter found to influence the efficiency of the filter. He stated that there was no reason to use any parameter other than hydraulic loading in predicting per cent efficiency of operation for the experimental filter studied.

Other investigators have theorized that contact time or residence time which is related to the hydraulic loading and depth of the trickling filter is the controlling parameter in BOD removal efficiency.

Horton et al. (22) claimed it was evident that the degree of purification obtained is largely dependent upon the time of contact between the sewage and the gelatinous film found in the filter bed.

Howland (23) indicated that both theory and experiment support the idea that contact time is a factor determining the removal of BOD in a trickling filter. In his paper he formulated a relationship between this contact time and the determinable hydraulic factors involved.

Eckenfelder (15) proposed that BOD removal can be expected to be proportional to both the mass of the active filter slime and to the time of contact of waste in the filter which is primarily related to the hydraulic loading.

In 1959, Sinkoff (24) et al. joined with others in the belief that the degree of purification obtained in a trickling filter is in some manner proportional to the length of contact time afforded between the waste and the filter slime. A vast study was initiated to determine this relationship.

Atkinson et al. (25) utilized film flow in contact with a vertical wall to approximate the flow of waste through a trickling filter. They concluded among other things that contact time or residence time analyses of trickling filters are irrelevant and serve only to cloud the basic issues.

Sorrels and Zeller (26), in their pilot plant study using domestic sewage, found that soluble BOD removal is more dependent upon the organic loading applied than it is upon the hydraulic rate of application.

Germain in 1966 (17) theorized that the rate of BOD removal is a function of the influent BOD concentration and the adsorption capacity of the biological growth. Waste residence time is considered by him to be an indirect parameter. It does not affect the rate of reaction, but merely defines how close to completion the reaction can proceed within the waste residence time provided. It is interesting to note that from identical plots of BOD applied (lb/1000 cu ft/day) versus BOD removed (lb/1000 cu ft/day), Schulze (10) concluded that filter performance was independent of organic loading and Germain (17) concluded that BOD removal is proportional to the BOD applied at a specific hydraulic loading rate.

Maier (27) utilizing an inclined plane model of a trickling filter and starch as the substrate observed in a colloid system that the maximum rate of carbon removal was highest for the higher feed concentrations, being almost directly proportional to the feed concentration. In earlier studies on the inclined plane model, using glucose as the substrate, Maier (28) found that liquid feed rate had a marked effect on the rate of glucose utilization at low feed rates. However, at high liquid feed rates, glucose removal became independent of feed rate.

Fairall (5) presenting a statistical correlation of trickling filter loading and performance data found that the strength of the sewage in the filter feed is a negligible factor in filter performance when performance is evaluated as percentage BOD removal.

Galler and Gotaas (16) state that their results indicate that, of the variables studied, the BOD in the applied liquor had the highest correlation to the BOD remaining in the filter effluent and that hydraulic rate was not an important factor.

In his controlled filtration studies, Ingram (7) found that BOD removal depends on the amount of BOD applied, rather than its concentration or its hydraulic rate through the filter. He found that BOD removal is at about the same efficiency with the same loading regardless of whether the loading is accomplished by a higher flow rate of weaker sewage or a lower flow rate of stronger sewage.

Kornegay and Andrews (18) observed that the influent BOD concentration did have an effect on the effluent BOD concentration.

In a few of the studies accomplished on trickling filters, researchers have observed a "saturation phenomenon" or a "limiting load" beyond which no further treatment is realized or treatment declines drastically.

Velz (3) states:

> Obviously there must be some limit to the quantity of BOD which can be assimilated by the biological life of the bed. The limiting BOD load, then must be a function of the rate of biological oxidation and the storage capacity for accumulation of BOD within the bed. If the rate of extraction from the applied load exceeds the rate of assimilation, the accumulation will reach a point where bed storage capacity of the Zooglea is exceeded and the excess will be carried through thereby increasing the residual in the effluent.

Sorrels and Zeller (29) observed in their pilot plant studies that the primary filter demonstrated increasing BOD removal with increased loading, to a maximum removal of 32 lb BOD/day/1000 cu ft at a loading of 69 lb BOD/day/1000 cu ft and rapidly decreasing removal beyond that optimum.

Stack (6) in 1957 proposed that there was a maximum limit to the amount of BOD that could be absorbed by one unit volume of a filter and that each unit depth will remove a constant fraction of the removable BOD applied to that unit depth. If a loading was of a magnitude that does not saturate any portion of the filter with BOD, then almost 100 per cent of the removable BOD should be removed.

Using a model filter constructed of wire screens, Schulze (10) concluded that at a constant hydraulic loading, the efficiency of a trickling filter remains constant for organic loads up to 11 lb BOD/day/cu yd. He indicated that the efficiency measured as per cent BOD removed was not decreased by increased organic loads.

In studies conducted by Kornegay and Andrews (18) utilizing a submerged rotating drum as an approximation of a trickling filter, they found that a saturation phenomenon definitely existed in that as the substrate concentration was increased, the rate of substrate removal approached a constant value.

Ingram's studies (7) on controlled filtration resulted in his conclusion that there was exhibited no upper limiting relationship of BOD removal to either organic load or hydraulic load.

CHAPTER III

THEORETICAL CONSIDERATIONS

A. Material Balance

After a period of time, at a given hydraulic and organic loading, steady state conditions should prevail throughout a fixed bed reactor. After steady state is reached, a material balance for substrate can be written for any point at any depth in the filter where:

inflow of substrate - outflow of substrate - consumption of substrate = 0

For development of the material balance equation the following symbols will be used at the point selected:

S_0 = substrate concentration of limiting nutrient arriving at selected point (M/L^3)

S_1 = substrate concentration of limiting nutrient leaving selected point (M/L^3)

Q = flow rate of limiting nutrient (L^3/T)

x = mass of active biological solids at selected point (M)

μ = growth rate of biological solids at selected point ($1/T$)

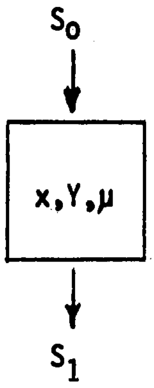
μ_m = maximum growth rate of biological solids at selected point ($1/T$)

K_s = saturation constant at $1/2\ \mu_m$ (M/L^3)

Y = yield of biological solids at selected point

M, L and T are, respectively, units of mass, length and time.

Consider the point at which the material balance is to be written to be a box of infinitesimal size at depth D.



The material balance for the substrate at steady state will be:

Inflow - Outflow - Consumption = 0

in symbol form is:

$$QS_o - QS_1 - \frac{\mu x}{Y} = 0 \tag{18}$$

from Monod (19), $$\mu = \mu_m\left(\frac{S}{K_s+S}\right) \tag{19}$$

then: $$Q(S_o-S_1) = \frac{x}{Y}\mu_m\left(\frac{S_1}{K_s+S_1}\right) \tag{20}$$

or: $$S_o-S_1 = \frac{x}{Y}\mu_m\left(\frac{S_1}{K_s+S_1}\right)\frac{1}{Q} \tag{21}$$

and $$S_1 = S_o - \frac{x}{Y}\mu_m\left(\frac{S_1}{K_s+S_1}\right)\frac{1}{Q} \tag{22}$$

The symbol x can be shown to be equal to x = XAd (23)

where:

X = concentration of active biological solids at selected point (M/L^3)

A = area of the biological film - this becomes the area afforded by the particular filter medium utilized when the feed concentration and flow rate are sufficient to support a prolific slime growth covering all the medium (L^2)

d = thickness of the active biological layer (L)

Substituting equation (23) into equation (20),

$$Q(S_o - S_1) = \frac{XAd}{Y} \mu_m \left(\frac{S_1}{K_s + S_1} \right) \tag{24}$$

one can recognize the resulting equation as the identical equation proposed by Kornegay and Andrews (18) to describe the relationship of parameters found in their submerged fixed film reactor.

B. Data Presentation

There are various methods of data presentation utilized by investigators today. Velz (3) and others plot depth versus log per cent COD remaining and derive their equations describing the relationship of the parameters acting on the unit. Per cent COD remaining seems like a poor design parameter and it appeared to this writer that a better design parameter could be utilized such as designing on merely COD applied.

Consider the three plots shown in Figure 1.

Determining the slope of each plot:

Fig. 1A: $$K_a = \frac{-\left(\log S_4/S_o - \log S_o/S_o \right)}{D} = \frac{-\log \left(\frac{S_4/S_o}{S_o/S_o} \right)}{D} \tag{25}$$

then: $$K_a = \frac{-\log \left(S_4/S_o \right)}{D} \tag{26}$$

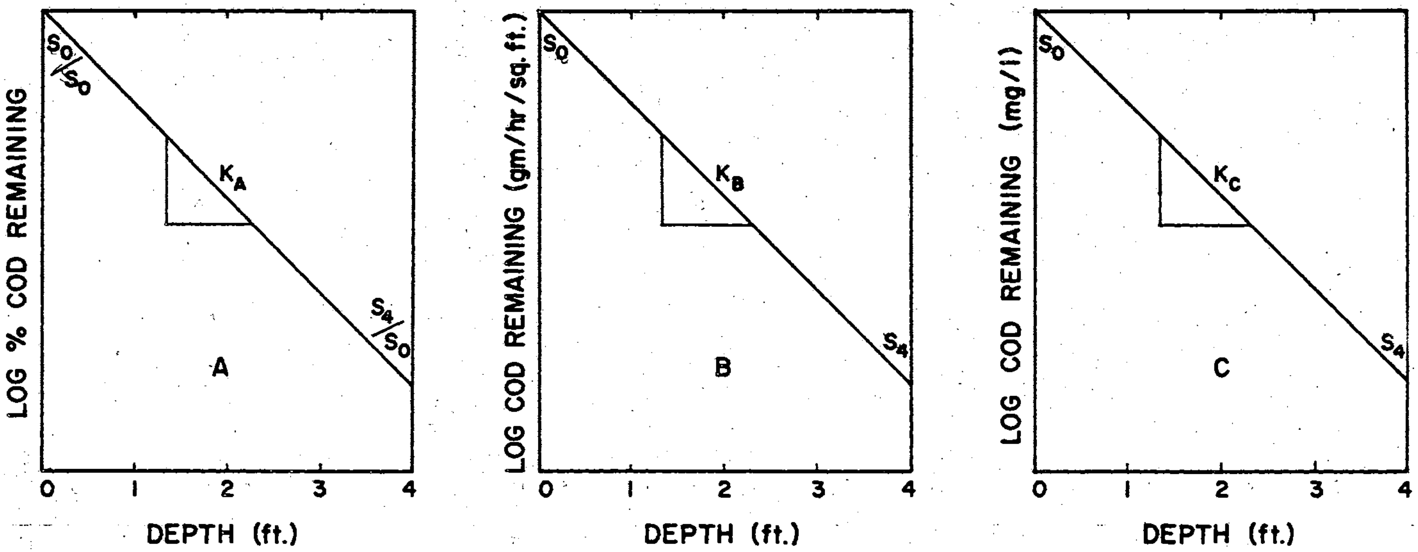


Figure 1. Relationship of Log % COD Remaining and Log COD Remaining with Depth.

Fig. 1B or 1C: K_b or $K_c = \frac{-(\log S_4 - \log S_o)}{D}$ (27)

then: K_b or $K_c = \frac{-\log(S_4/S_o)}{D}$ (28)

As can be seen, the slopes for each of the three plots are the same. Solving for S_{4}/S_{o}:

$$\log S_4/S_o = -KD \tag{29}$$

or $S_4/S_o = 10^{-KD}$ (30)

one can recognize equation (30) as the same equation proposed by Velz in equation (5). Therefore it does not matter which of the three plots one chooses for data presentation as all yield the same slope value, and consequently, the same equation describing the amount of COD remaining at any depth in a fixed bed reactor when the values of S_o and K are known. Note also that it matters not whether S_o and S_4 are expressed in mg/l COD or in gm COD/hr/ft^2.

CHAPTER IV

MATERIALS AND METHODS

A. General

In order to study the kinetics and mechanisms of a fixed bed reactor, an investigator has three possible choices of units on which to accomplish the study. Each has its inherent advantages and disadvantages.

First, he may choose an existing full scale plant treating an industrial or domestic waste. Here, he is limited to the BOD loading and flow rate that is produced by that industry or municipality. Also, the fluctuations of these two parameters throughout the day are great. Therefore, the fixed bed reactor is always in a transient state, seldom reaching the steady state condition long enough to determine with any degree of accuracy what is actually occurring in the fixed bed reactor.

Next, he may desire to build a small scale pilot plant, select a synthetic waste and vary its concentration and flow rate to meet the conditions he desires. The cost of construction and operation even on this small scale becomes excessive for one desiring to operate the unit for any extended period of time.

Another possibility is the construction of a model fixed bed reactor utilizing a synthetic waste at the desired concentration and flow rates selected. This method was selected as the most feasible approach to obtain the needed data for this study. Numerous investigators have described and built various trickling filter models for research and study. After perusing their models, it was determined that none of the existing designs possess the degree of flexibility needed to accomplish valid research on fixed bed reactors. Therefore, a model fixed bed reactor has been designed and built in this laboratory to study selected design parameters of fixed bed reactors. The general arrangement of the experimental fixed bed reactor is shown in Figure 2. Tap water from the city main enters into a constant head tank where the flow from this tank is controlled by a rotameter and flows into a wet well. The concentrated synthetic waste is pumped into the wet well where it is mixed with the tap water to provide the concentration of waste desired. If it is desired to study an industrial waste in order to gain design data, then the constant head tank could be utilized as the reservoir for the soluble waste. Also, in this case the concentrated feed unit would be eliminated. The waste is pumped from the wet well to the distribution system. The waste then flows over the fixed bed reactor into a collection device. At this point the waste water may be wasted or it may be recirculated.

The fixed bed reactor is composed of 1.0 ft^3 units. The individual units are constructed of plexiglas and have dimensions of 1.0 ft x 1.0 ft x 1.0 ft. The units may be stacked to give any reactor depth desired, while the horizontal surface area is 1.0 ft^2. Figure 3 shows an individual unit. This unit is shown with the corrugated fiberglass plates as the reactor medium which was used throughout the duration of this research. The fiberglass plates are placed with 1/2 inch spacings. Since the fiberglass has 9/16 inch deep corrugations, this provides a

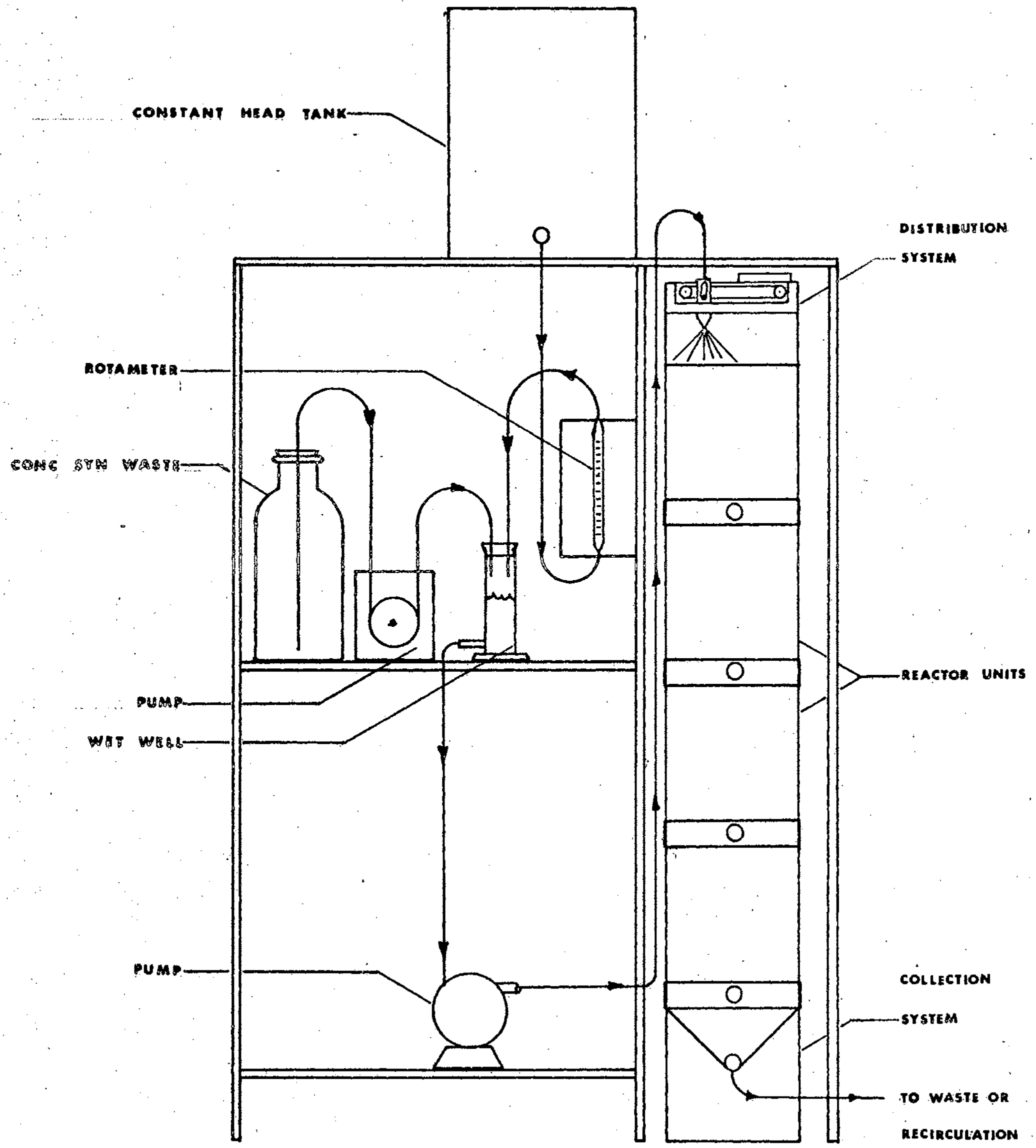


Figure 2. Schematic Drawing of the Experimental Fixed Bed Reactor.

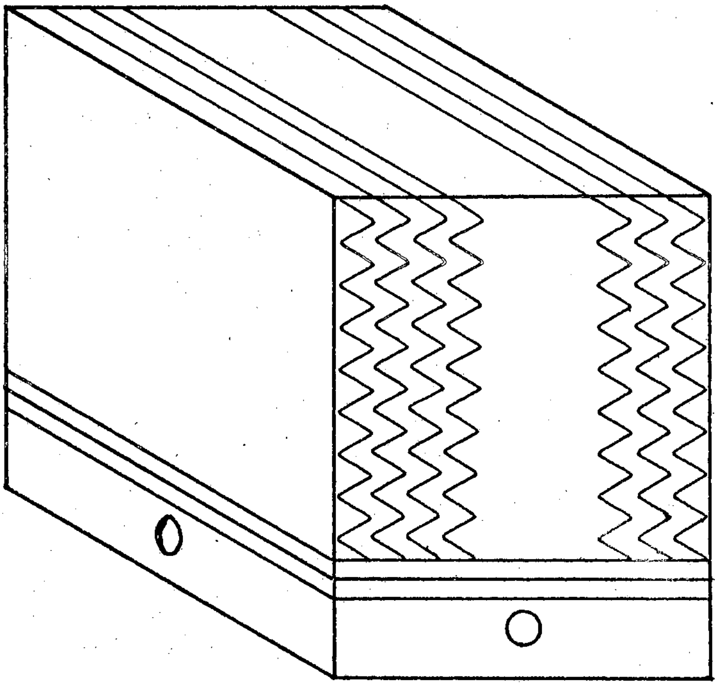


Figure 3. Schematic Drawing of the Individual Reactor Unit.

1/16 inch overlap and prevents the possibility of a free drop of the waste through the reactor.

One of the excellent features of this fixed bed reactor is that any type of medium desired may be used. Thus, the design engineer or researcher may investigate many different types of reactor media.

Figure 4 shows the individual units in a stacked position. The 1 ft^3 units are stacked with a three inch spacer between each unit. This spacer is provided with sampling ports through which samples may be collected for analysis. Sampling is accomplished by utilization of a sampling wand which was made from an 18 inch long, 1.5 inch diameter plexiglas pipe which has been cut in half along the 18 inch dimension. The sampling wand is placed through the sampling port, perpendicular to the bottom of the plates being sampled. In this manner a composite sample was taken from all 24 fiberglass plates simultaneously and collected in a 50 ml beaker. The sample was then filtered through a 45 μ pore size membrane filter and subsequent analyses were run on the filtrate.

The distribution system for applying the waste stream across the 1.0 ft^2 horizontal surface area of the reactor utilizes an oscillating spray nozzle. A sketch of the distribution device is shown in Figure 5. The spray nozzle is powered by an electric motor via chain drive and approximates a constant linear velocity at any selected speed of 20-54 ft/min. The spray pattern is a rectangular band 12 inches long by 3.5 inches wide, whose dimensions may be varied simply by raising or lowering the nozzle to the desired height to achieve the desired spray pattern dimensions. The flow rate through the nozzle may be varied from 75 gpd to 800 gpd while maintaining the desired spray pattern

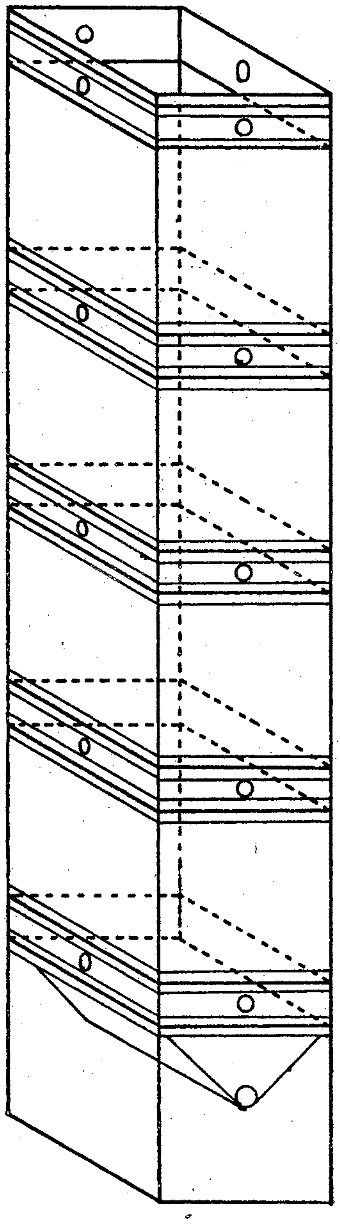


Figure 4. Schematic Drawing of the Stacked Reactor Units.

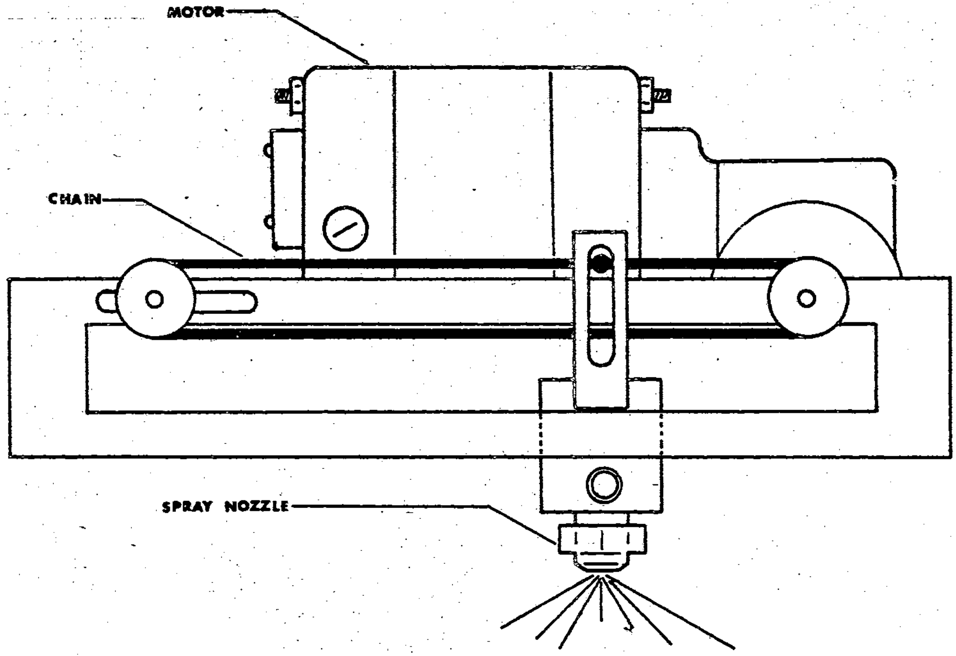


Figure 5. Schematic Drawing of the Distribution System.

dimensions merely by interchanging the nozzle tips and increasing the pump rate.

As stated previously, each 1 foot unit of depth possesses a 1 ft^2 horizontal surface area. There were 24 vertical corrugated fiberglass plates in each 1 foot of depth which afforded 50 ft^2 of surface area on which the microorganisms could adhere and flourish. From preliminary studies utilizing sucrose as the limiting nutrient, it was found that the bulk of organics was removed in the first three feet of the fixed bed reactor. Consequently, four feet was selected as the depth of the fixed bed reactor for these studies.

B. Experimental Protocol

1. Trickling Filter Studies

The synthetic waste in all experiments was such that the carbon source, sucrose, was the growth limiting nutrient. Shown in Table I is the composition of the synthetic waste for a concentration of 100 mg/l sucrose at a flow rate of 100 gpd/sq ft. Note that there was no buffering system provided in the waste as pH change with depth was one of the parameters to be studied. Sucrose was selected as the growth limiting nutrient due to its low cost and degree of purity when bought in commercial (technical) grade. Also sucrose, being composed of the two sugars glucose and fructose joined by an α-1,2 linkage, afforded an opportunity to observe if sequential removal of these two sugars occurred or if they were removed simultaneously in the trickling filter process.

A concentrated synthetic waste was prepared in a twenty liter carboy and pumped into the wet well at a constant rate of 14 ml/min by a Sigmamotor pump. Depending on the concentration or flow rate of the waste applied to the filter for a particular experiment, the

TABLE I

COMPOSITION OF SYNTHETIC WASTE FOR 100 MG/L SUCROSE AS THE GROWTH LIMITING NUTRIENT AT A FLOW RATE OF 100 GPD/SQ FT

Constituent	Concentration
Sucrose	100 mg/l
$(NH_4)_2SO_4$	25 mg/l
$MgSO_4 \cdot 7H_2O$	10 mg/l
K_2HPO_4	6 mg/l
$MnSO_4 \cdot H_2O$	1 mg/l
$CaCl_2$	0.75 mg/l
$FeCl_3 \cdot 6H_2O$	0.05 mg/l

concentration of the synthetic waste in the twenty liter carboy was varied. The concentrated waste was then diluted to the desired concentration in the wet well by tap water from the constant head tank. The waste was then pumped from the wet well through the oscillating spray nozzle by use of a Milton Roy Co. (model R220A) controlled volume pump. This pump is capable of 0 to 300 gpd. In studies requiring a flow rate greater than 300 gpd, two of these pumps were manifolded together realizing a capability of 600 gpd. The Milton Roy pumps were changed and chlorinated weekly and the concentrated feed pumps were chlorinated every other day to prevent biological growth in the pumps and lines.

The distribution system (nozzle) was operated at a linear velocity of 54 ft/min throughout the study. The spray nozzle screens were changed and cleaned daily to prevent biological growth from plugging the spray nozzle.

No method of temperature control was utilized on the system. Consequently, the temperature at which the unit operated varied primarily with the temperature of the tap water which varied between 13 and 20° C during the course of the investigation.

The fixed bed reactor was started up at an initial feed concentration of 200 mg/l of sucrose and at a flow rate of 200 gpd/ft^2. This feed rate and concentration was selected as it provided sufficient feed at a flow rate allowing all the filter medium to be covered with a prolific slime growth but not enough growth to cause "ponding" as seen in filters with high feed concentrations and low flow rates.

Seeding the filter with microorganisms was accomplished with settled effluent from the primary clarifier of the Stillwater, Oklahoma, treatment plant. For a period of 5 days, settled effluent was dripped into the spray of the distribution nozzle to facilitate distribution of the microorganisms over the 1.0 ft^2 horizontal surface area of the fixed bed reactor. After the five day period, it was ascertained by visual inspection that a uniformly distributed growth of microorganisms had been started throughout the filter. The filter continued to be fed at the previously mentioned feed rate and concentration for a period of three weeks. By previous investigation on this fixed bed reactor, three weeks was deemed sufficient time for the reactor to "ripen" or allow all the filter medium to become covered with a prolific growth of microorganisms. Following the three week ripening period, various preliminary tests were run and at the end of the fourth week, the feed concentration was changed to 100 mg/l at a feed rate of 100 gpd/ft^2. This was the beginning of a series of 22 runs of one or more weeks' duration for the purpose of obtaining needed data.

The matrix in Table II shows runs made at the various feed concentrations and flow rates. Each time a run was completed, the feed rate and/or feed concentration was changed and a new run begun. Each run was of one week's duration consisting of a four day acclimation period after a change in flow rate or feed concentration, followed by three consecutive days of sampling at each one foot depth of the filter.

Steady state conditions were ascertained by obtaining nearly identical values of pH, COD, and anthrone COD over the three day sampling period at each one foot depth. If nearly identical values were not obtained in the three day sampling period, the run was continued until the desired reproduction of these parameters occurred on three consecutive days.

The results of analyses of the samples obtained over the three day

TABLE II

MATRIX OF EXPERIMENTS CONDUCTED AT VARIOUS FLOW RATES AND ORGANIC CONCENTRATIONS INDICATING THE TOTAL AMOUNT OF SUCROSE (COD) APPLIED/DAY/SQ FT

Flow Rate gpd/sq ft	Organic Concentration mg/l					
	100	200	300	400	500	1000
100	37.85 gm COD .08 lbs	75.6 gm COD .16 lbs	114 gm COD .25 lbs	151 gm COD .32 lbs	189 gm COD .40 lbs	378 gm COD .833 lbs
150	56.7 gm COD .125 lbs	114 gm COD .25 lbs		226 gm COD .50 lbs		
200	75.6 gm COD .16 lbs	151 gm COD .32 lbs	226 gm COD .50 lbs		378 gm COD .833 lbs	
250	94.5 gm COD .21 lbs	189 gm COD .42 lbs	284 gm COD .158 lbs	378 gm COD .84 lbs		
300	114 gm COD .25 lbs	226 gm COD .50 lbs			568 gm COD 1.25 lbs	
500		378 gm COD .84 lbs				
600	226 gm COD .50 lbs					

period at each one foot depth were averaged and recorded as the values for that particular parameter for that particular run. Steady state conditions with respect to solids could not be ascertained due to the irregular occurrence of sloughing of the microorganisms from the filter medium.

2. Growth Studies

Microorganisms for a growth study were obtained from the bottom of a selected unit of depth. By reaching through the sampling ports of the spacer with a pair of forceps, small pieces of biological growth were removed from 10 randomly selected points and placed in a 250 ml beaker. These were mixed with 150 ml of water containing all the salts that are found in Table I. Mixing was accomplished over a one minute period in a two speed Waring Blender set at the low speed. A 10 ml volume of the resulting cell mixture was placed into 1000 ml growth flasks containing sufficient salts medium and substrate for a final volume of 100 ml. These flasks contained various substrate concentrations of sucrose from 100 mg/l to 500 mg/l. The optical density of each suspension was read immediately after inoculation and the flasks were placed on the shaker apparatus which was oscillating at the rate of 90 oscillations per minute. All growth studies were conducted at room temperature. Optical density readings were taken on each flask on the hour or half hour until no additional change in absorbancy was observed. An Eadie plot (30) of S versus S/μ from which μ_m and K_s were determined was made at the termination of the run.

3. Yield Studies

In some cases, yield studies were run concurrently with growth studies. A 60 ml volume of the cell mixture prepared for growth studies was placed into a 2000 ml flask containing sufficient salts medium and substrate for a final volume of 600 ml. This flask contained 500 mg/l of the sucrose substrate. The biological solids concentration was determined immediately after inoculation by the gravimetric method and the flask was placed on the shaker apparatus along with the growth flasks. Hourly, this flask was sampled for biological solids concentration and the filtrate from this determination was analyzed for the amount of substrate remaining both by the COD test (31) and the anthrone method (32) for anthrone COD. Both biological solids growth and COD remaining were plotted versus time of sampling on arithmetic graph paper. The slope of the straight line portion of the biological solids plot divided by the slope of the straight line portion of the COD removal plot gave the sought-after yield.

C. Analytical Techniques

1. Substrate Removal

Substrate removal was determined by analyzing the membrane filtrate for COD both by the method outlined in Standard Methods (31) and anthrone COD by the anthrone method (32).

2. Substrate Utilization

Nelson's test (32) for reducing sugars was utilized to determine if any free fructose or glucose was present in the filtrate samples obtained at each one foot depth.

3. Biological Solids

Gravimetric determination of biological solids was performed by filtration through membrane filters (0.45 μ pore size, Millipore Filter Corporation, Bedford, Mass.) as described in Standard Methods (31). This type of biological solids determination was utilized when yield values were to be calculated from the data.

4. pH

The pH of the unfiltered samples obtained at each one foot depth of the fixed bed reactor was determined on a Beckman "Zeromatic II" pH meter following standardization of the pH meter at pH 7.0.

CHAPTER V

RESULTS

Twenty-two experiments of varying substrate concentrations and flow rates were made during the course of this investigation to gather data on COD removal characteristics of the fixed bed reactor. The results of the COD, anthrone COD and reducing sugar (Nelson's) analyses are tabulated in Table III for all experiments at each one foot depth. The experimental methods for obtaining these parameter values for each experiment were discussed in Chapter IV.

In all of the following plots involving COD, the COD indicated is actually anthrone COD as determined by the anthrone method (32) rather than COD as determined in Standard Methods (31). The reason for this is threefold. At the low organic loadings when determining COD below 50 mg/l, dilute dichromate (0.10N) had to be used. According to Standard Methods (31) for the COD determination, COD values of around 10 mg/l are inaccurate when using dilute dichromate and may be used only to indicate an order of magnitude. When determining anthrone COD, duplicate samples were run and a high degree of accuracy was obtained. After the first foot, the ΔCOD calculated between the COD values and the anthrone COD values remains relatively constant throughout the remainder of the depths. Consequently, anthrone COD was utilized rather than COD to indicate COD values.

TABLE III

DATA SUMMARY OF COD, ANTHRONE COD AND REDUCING SUGAR CONTENT OF THE WASTE AT EACH UNIT OF FILTER DEPTH AT VARIOUS FLOW RATES AND FEED CONCENTRATIONS

		Depth - Feet														
		0			1			2			3			4		
Feed conc. mg/l	Flow rate gpd/ft^2	COD mg/l	Anthrone COD mg/l	Red. Sugar mg/l	COD mg/l	Anthrone COD mg/l	Red. sugar mg/l	COD mg/l	Anthrone COD mg/l	Red. sugar mg/l	COD mg/l	Anthrone COD mg/l	Red. sugar mg/l	COD mg/l	Anthrone COD mg/l	Red. sugar mg/l
100	100	88	94	0	33	26	0	15	12	0	10	6	0	10	9	0
100	150	97	107	0	31	28	0	19	15	0	11	8	0	14	6	0
100	200	107	111	0	58	48	2	27	18	0	20	12	0	23	7	0
100	250	110	114	0	54	51	2	23	21	3	20	16	1	13	9	0
100	300	110	109	0	60	46	7	37	30	5	18	11	3	18	7	1
100	600	95	97	0	57	57		43	41		28	25		21	16	
200	100	204	190	0	118	75	0	50	23	0	31	9	0	27	6	0
200	150	220	198	0	111	81	2	63	39	1	29	18	0	23	11	0
200	200	212	209	0	106	85	8	87	46	5	57	24	4	28	16	3
200	250	205	220	0	134	128	6	87	89	0	55	45	9	34	24	2
200	300	211	212	0	139	122	16	100	83	11	54	39	10	35	22	4
200	500	190	200	0	117	107		101	91		62	54		51	43	
300	100	316	308	0	181	140	6	98	65	4	66	36	0	37	15	1
300	200	312	307	0	199	159	7	156	117	7	100	68	13	50	31	5
300	250	316	306	0	242	207	0	196	154	0	150	112	1	91	66	0
400	100	417	413	0	245	195	11	149	102	13	66	33	5	33	13	1
400	150	412	402	0	293	237	24	229	165	16	163	103	31	108	62	0
400	250	399	399	0	264	222	9	244	188	6	160	107	10	127	76	10
500	100	511	509	0	303	223	25	211	129	18	138	68	15	79	30	11
500	200	514	524	0	332	279	41	295	223	28	223	148	26	198	121	21
500	300	480	486	0	373	316	2	315	227	2	255	162	2	207	114	1
1000	100	986	920	0	834	480	113	810	319	98	720	183	87	753	165	62

A. Experiments in Which the Organic Loading Was Held Constant and the Hydraulic Loading Varied

In all of the following figures, each figure set consists of 3 semilog plots, A, B and C. Plot A shows COD remaining (mg/l) versus depth in feet. This plot indicates the concentration of the waste found at each unit of depth in the filter. Plot B shows COD remaining (gm/hr/sq ft) versus depth in feet. This plot indicates the total amount of organics remaining at each unit of depth in the filter. Calculation of this COD remaining involves both the concentration of the waste as well as the flow rate of the waste. Plot C shows per cent COD remaining versus depth in feet.

Figures 6A, 6B and 6C are plots made from data obtained at a constant feed concentration of 100 mg/l of sucrose at varying flow rates of 100, 150, 200, 250, 300 and 600 gpd/sq ft. In all three plots, at the low flow rates, two and sometimes three rates of removal are exhibited. This could be due to lack of sufficient food to support the rate of substrate removal by the microbial population as seen in the first foot of depth. As can be seen at a flow rate of 600 gpd/sq ft, one rate of removal is described throughout the depths of the filter. Note also that as the flow rate is increased the slope of the line describing the COD remaining decreases and approaches a limiting value. This may be an indication of filter saturation with COD.

Figures 7A, 7B and 7C are plots made from data obtained at a constant feed concentration of 200 mg/l of sucrose at varying flow rates of 100, 150, 200, 250, 300 and 500 gpd/sq ft. Two rates of removal are ascertained at the low flow rates at the various depths and one rate of removal is observed at the higher flow rates throughout the depths of the filter.

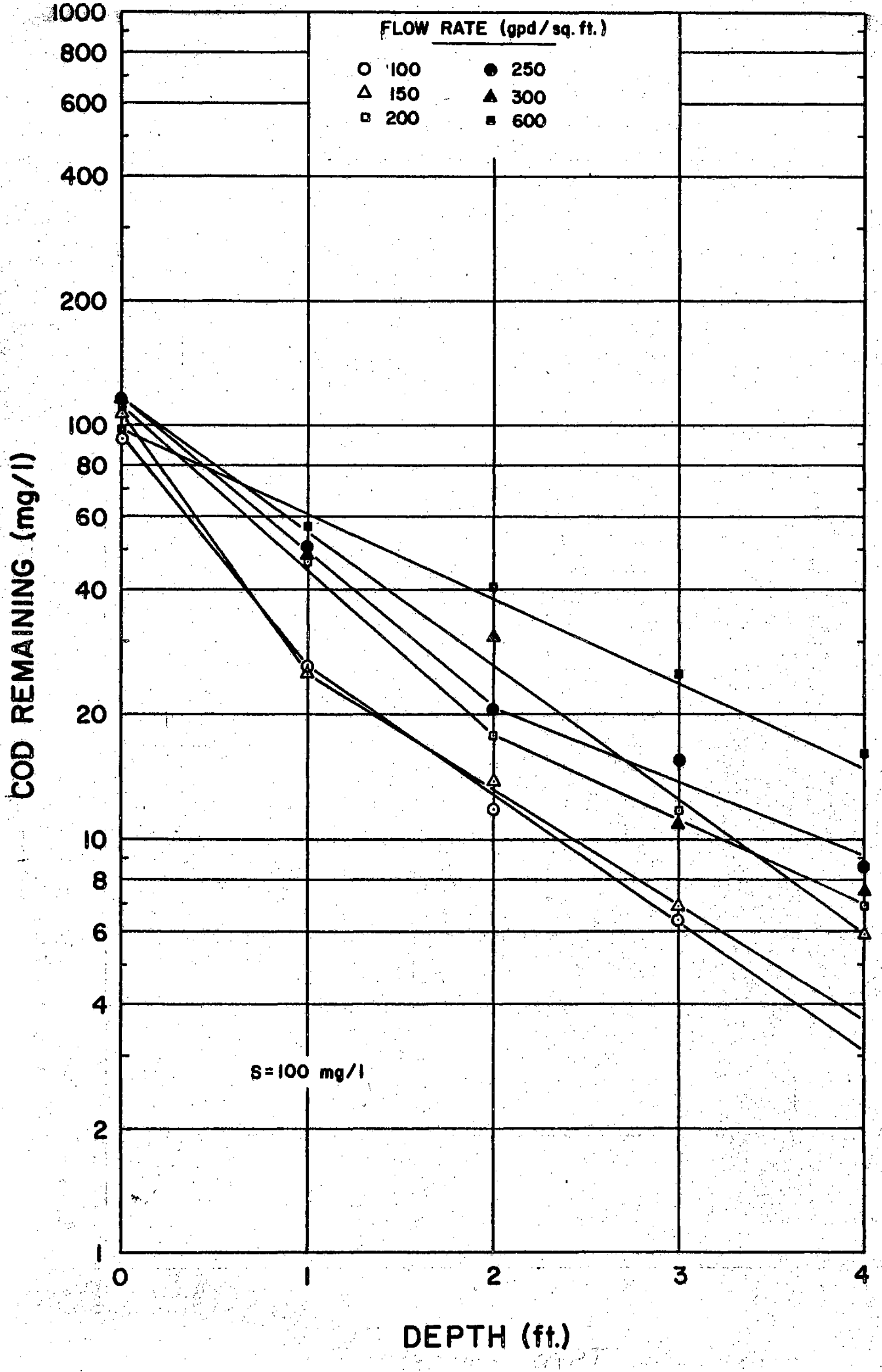


Figure 6A. Relationship of COD Remaining (mg/l) with Depth at a Constant Organic Concentration of 100 mg/l and Varying Flow Rates.

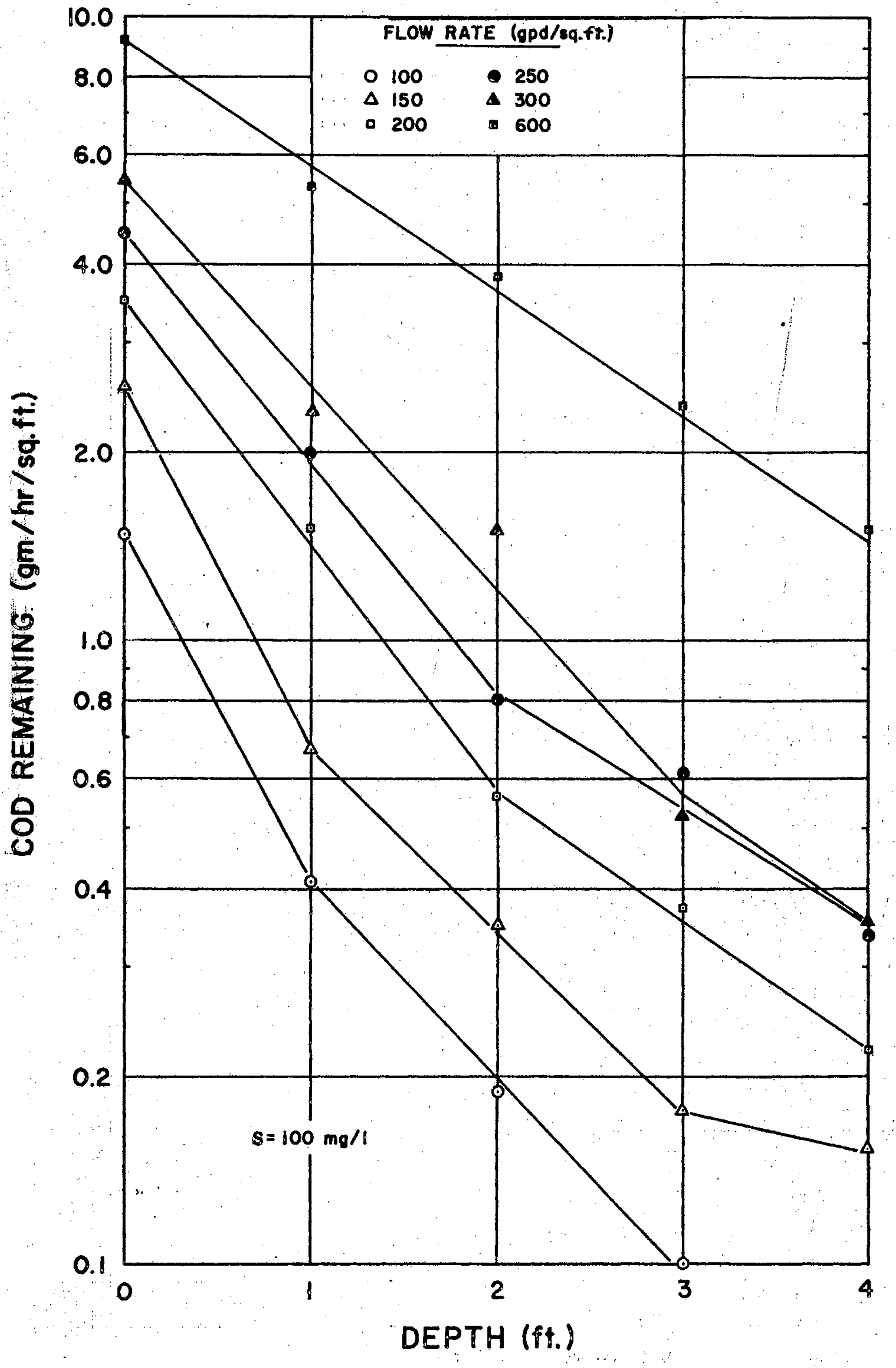


Figure 6B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Organic Concentration of 100 mg/l and Varying Flow Rates.

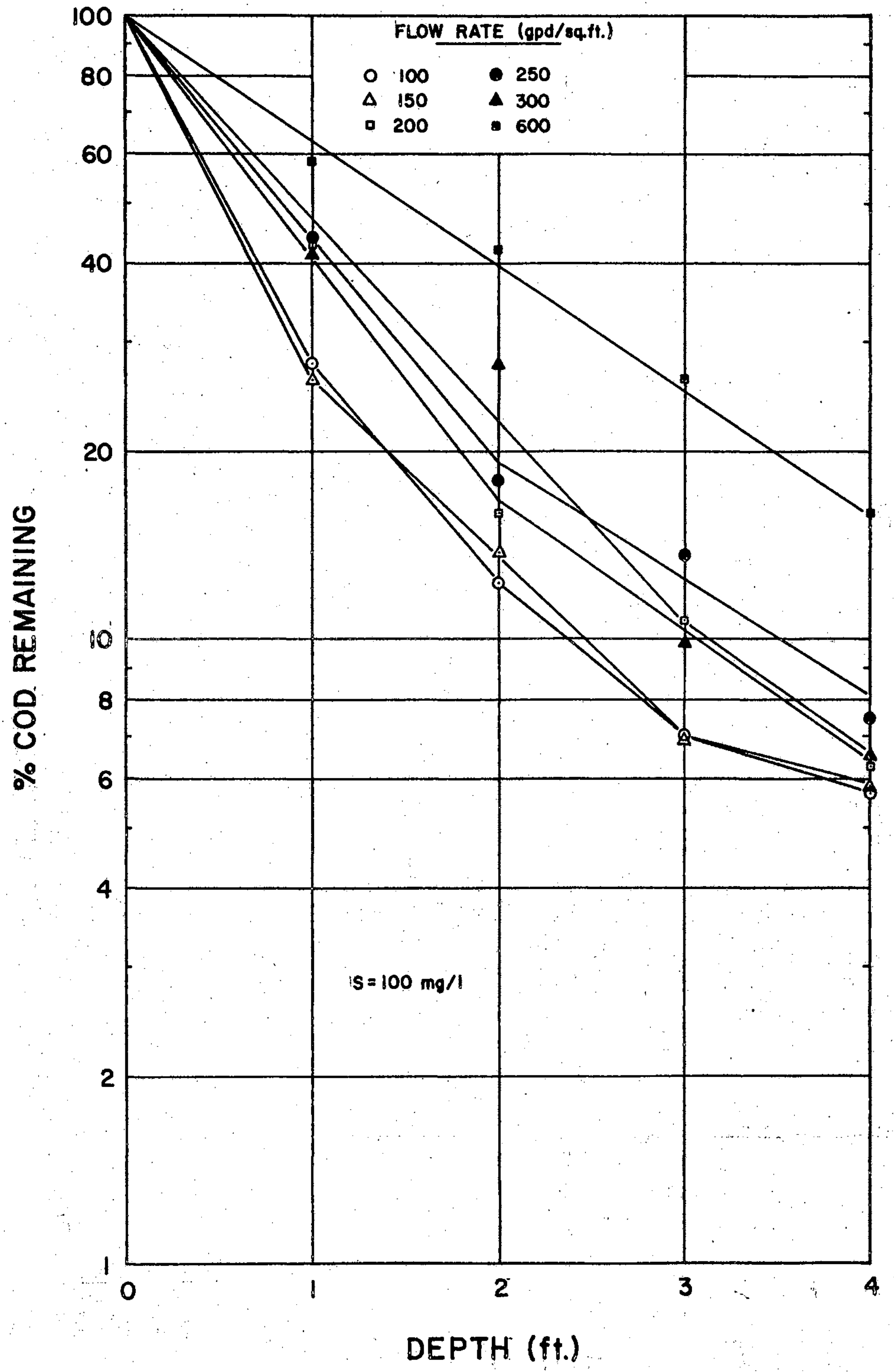


Figure 6C. Relationship of % COD Remaining with Depth at a Constant Organic Concentration of 100 mg/l and Varying Flow Rates.

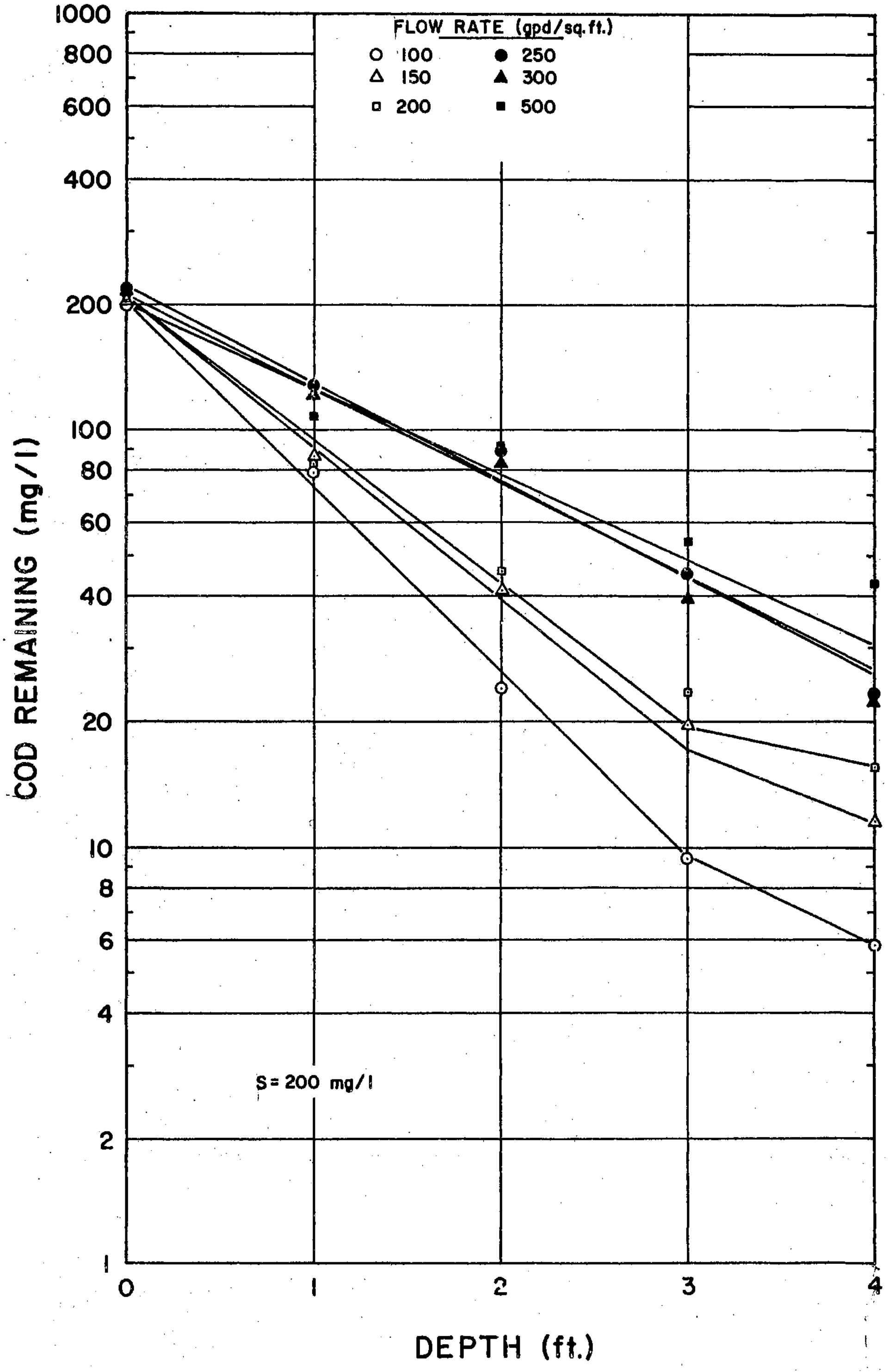


Figure 7A. Relationship of COD Remaining (mg/l) with Depth at a Constant Organic Concentration of 200 mg/l and Varying Flow Rates.

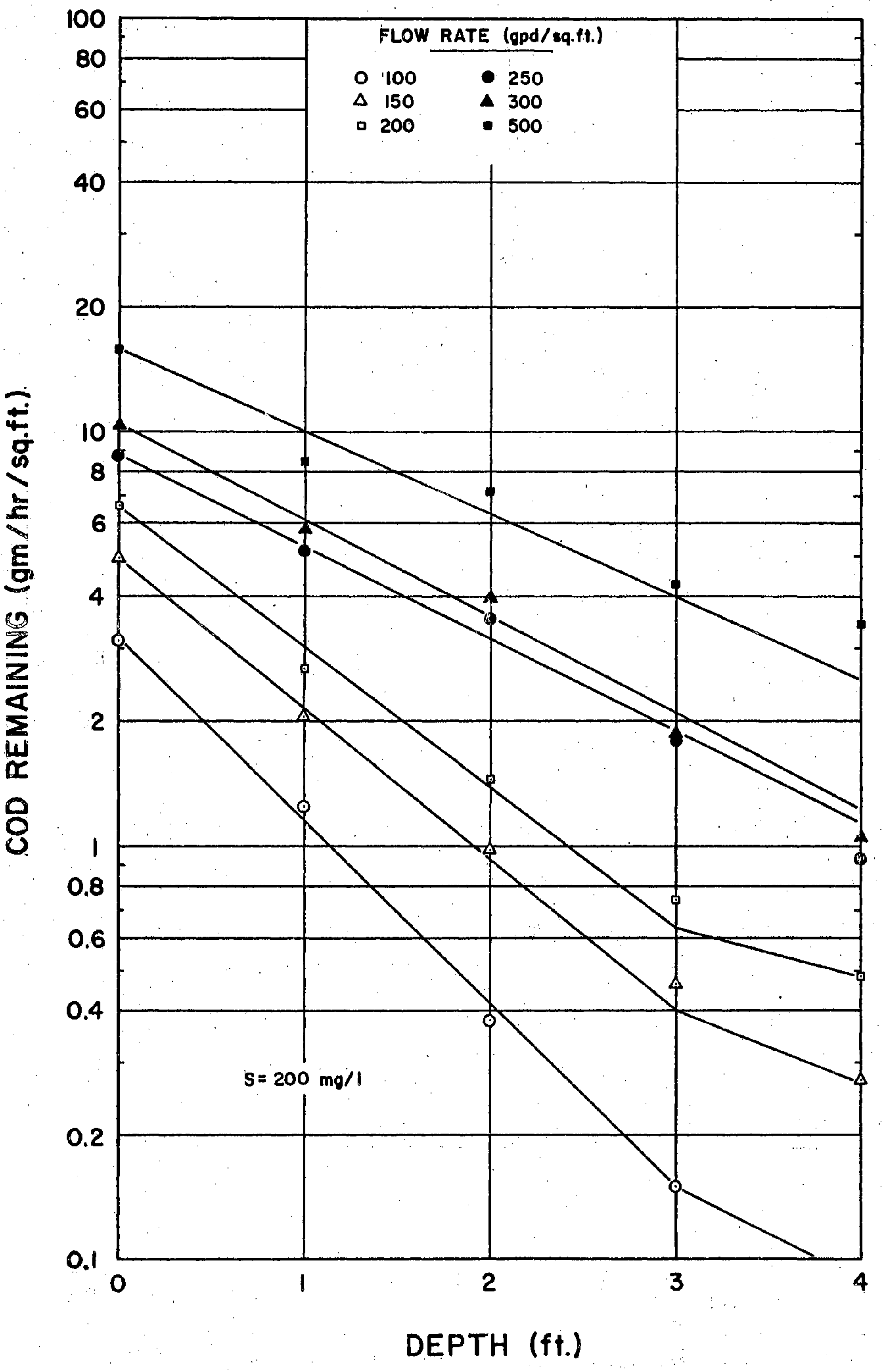


Figure 7B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Organic Concentration of 200 mg/l and Varying Flow Rates.

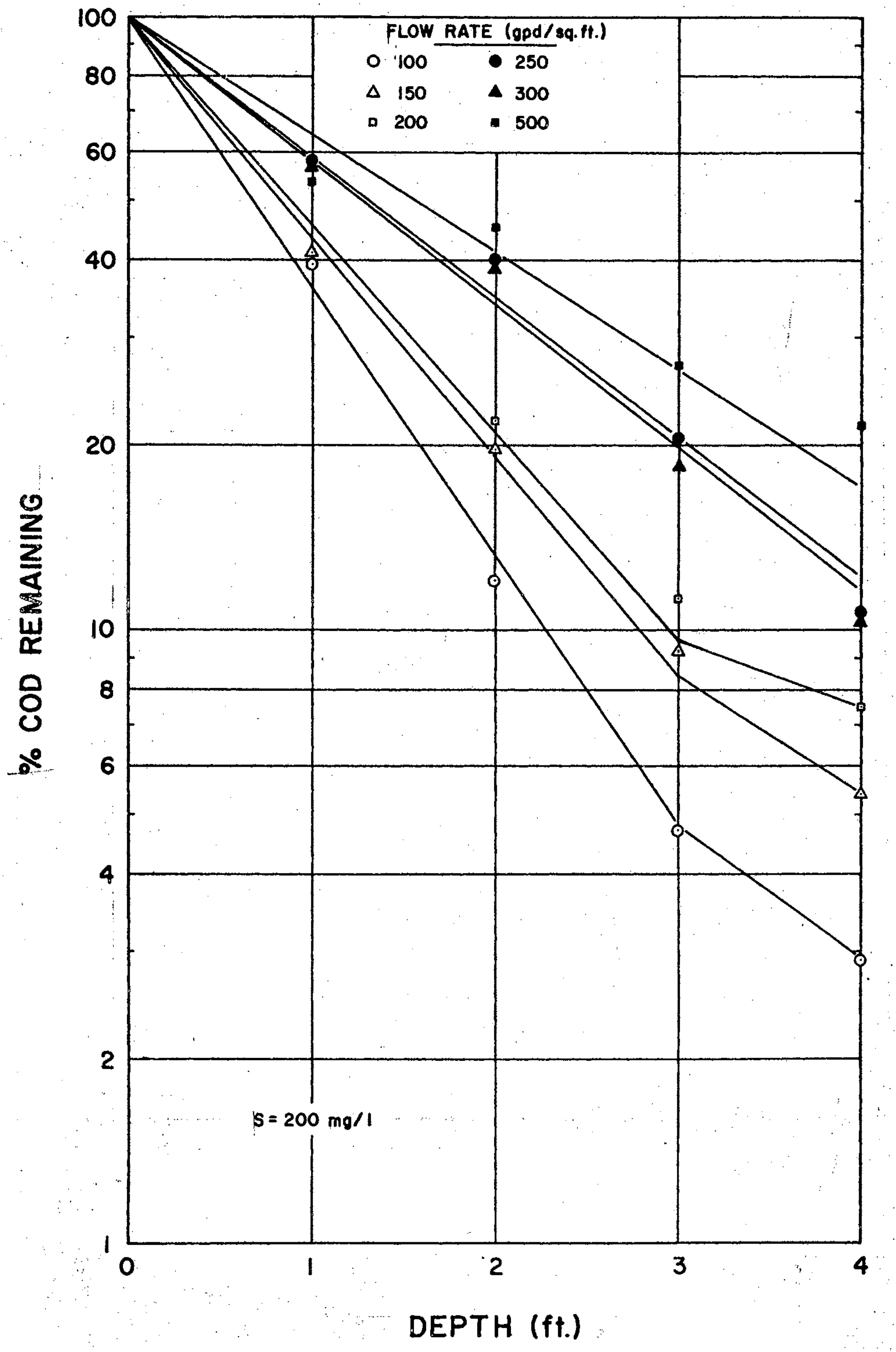


Figure 7C. Relationship of % COD Remaining with Depth at a Constant Organic Concentration of 200 mg/l and Varying Flow Rates.

Figures 8A, 8B and 8C are from data obtained at an organic loading of 300 mg/l at the various hydraulic loadings of 100, 200 and 250 gpd/sq ft. All three of the removal curves describe a single rate of first order organic removal for all depths of the filter. Apparently there was sufficient food present to support a thriving microbial population at each unit depth of the filter.

Figures 9A, 9B and 9C show the results of a constant feed concentration of 400 mg/l of sucrose at flow rates of 100, 150 and 250 gpd/sq ft. Figures 10A, 10B and 10C show the results of a constant feed concentration of 500 mg/l of sucrose at flow rates of 100, 200 and 300 gpd/sq ft. Both cases show similar results to that shown in figure set 8 in which all curves exhibit a single rate of first order organic removal.

All of these figure sets show that as the hydraulic loading is increased, with the organic loading held constant, the rate of COD removal decreases and approaches some limiting rate.

B. Presentation of Data with Hydraulic Loading Held Constant and the Organic Loading Varied

Utilizing the data obtained in the previous set of experiments, the data were regrouped and plotted with the hydraulic loading held constant and the organic loading varied. As in the previous plots the following figure sets consist of three semilog plots A, B and C. Again plot A shows COD remaining (mg/l) versus depth in feet. Plot B shows COD remaining (gm/hr/sq ft) versus depth in feet and Plot C shows per cent COD remaining versus depth in feet.

Figures 11A, 11B and 11C show substrate removal with depth at a constant flow rate of 100 gpd/sq ft and varying substrate concentrations

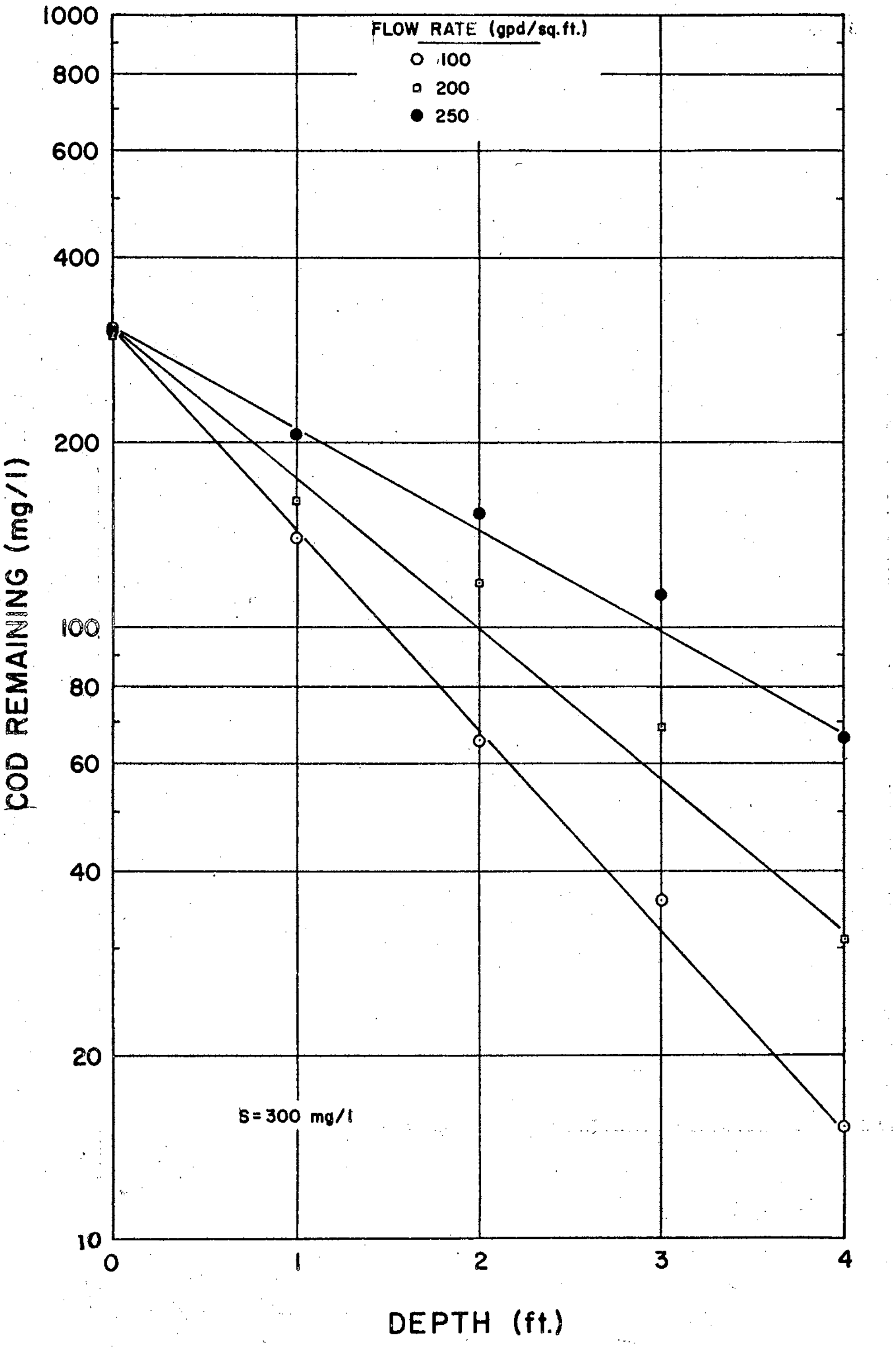


Figure 8A. Relationship of COD Remaining (mg/l) with Depth at a Constant Organic Concentration of 300 mg/l and Varying Flow Rates.

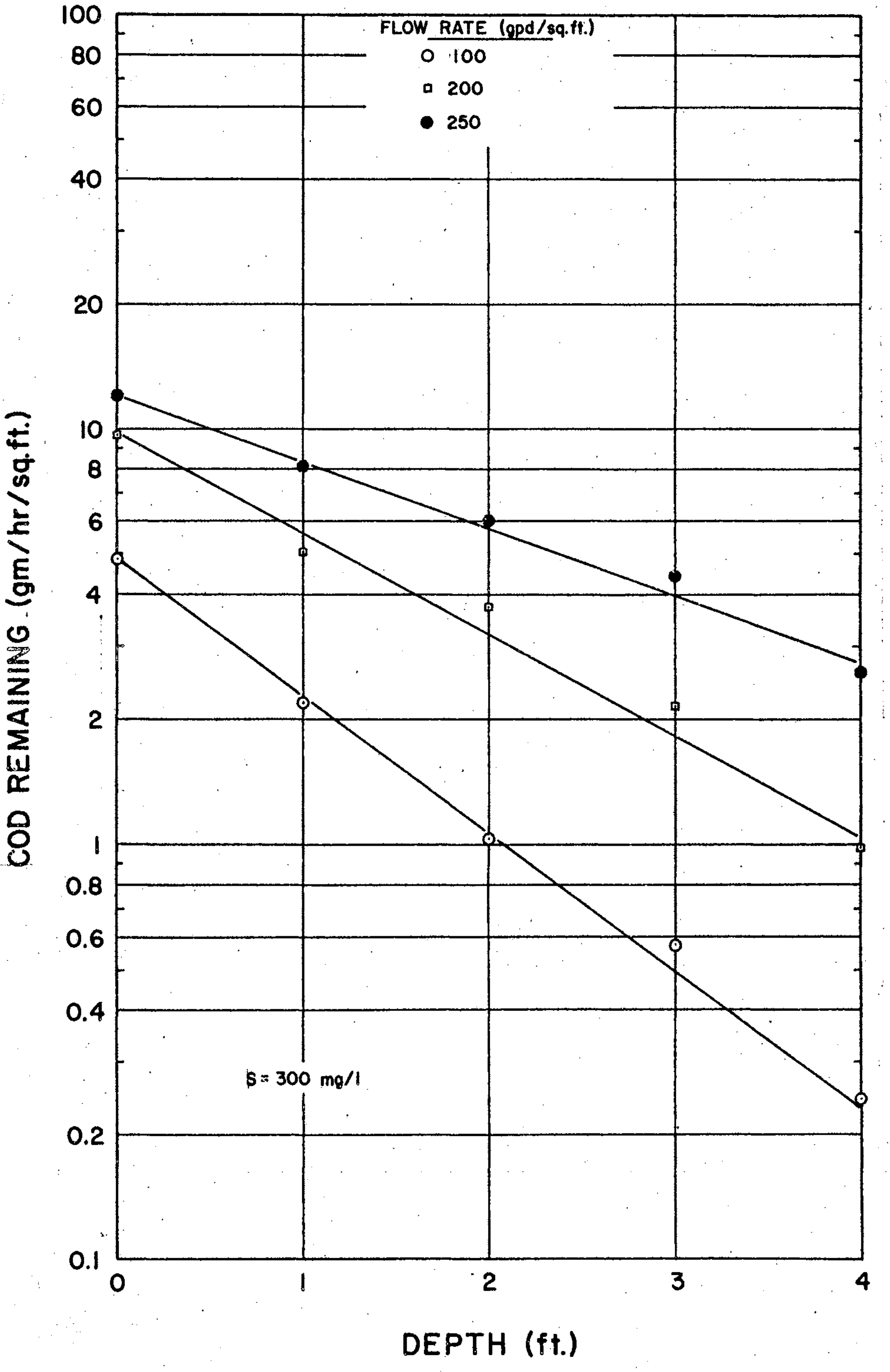


Figure 8B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Organic Concentration of 300 mg/l and Varying Flow Rates.

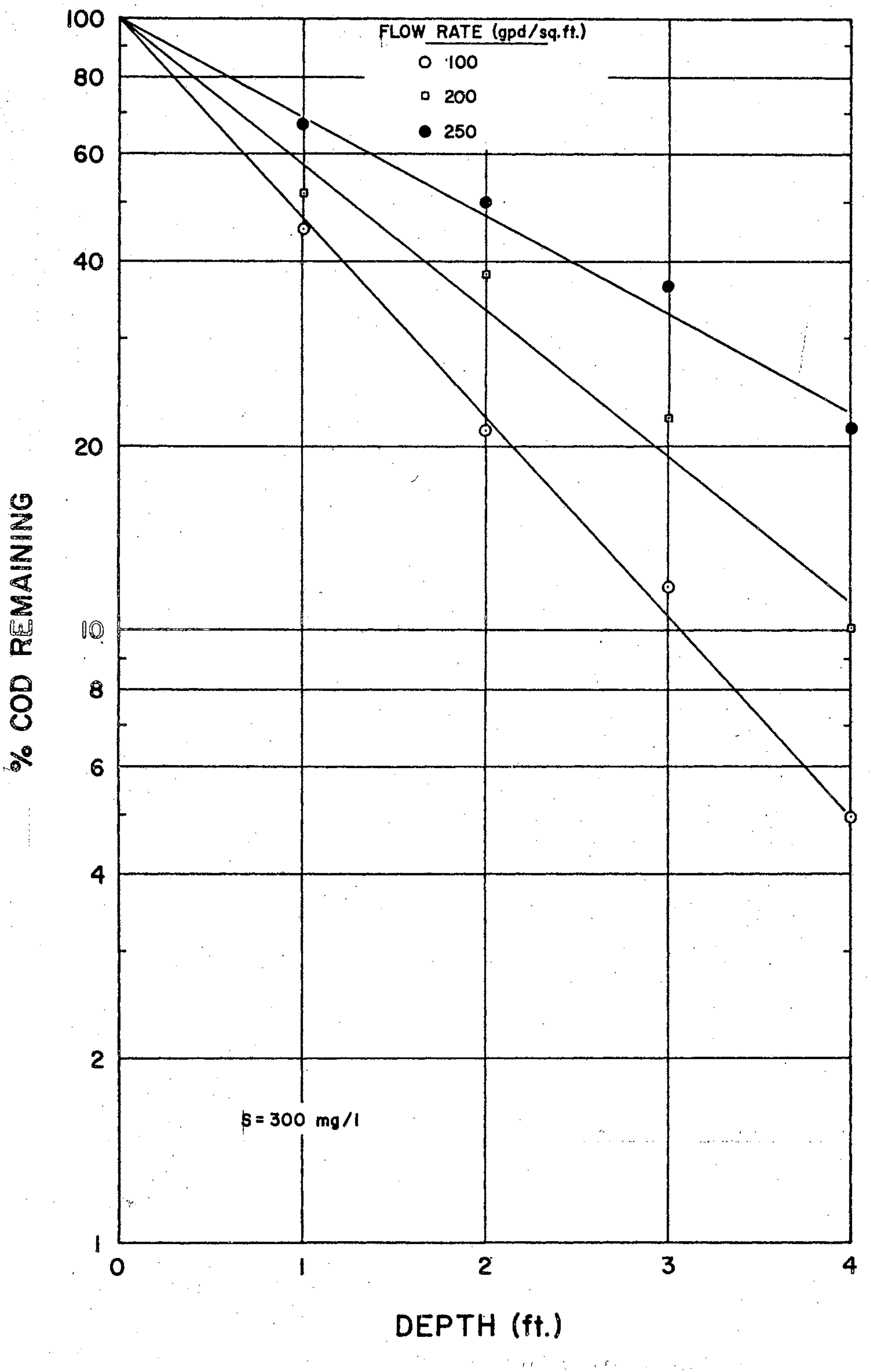


Figure 8C. Relationship of % COD Remaining with Depth at a Constant Organic Concentration of 300 mg/l and Varying Flow Rates.

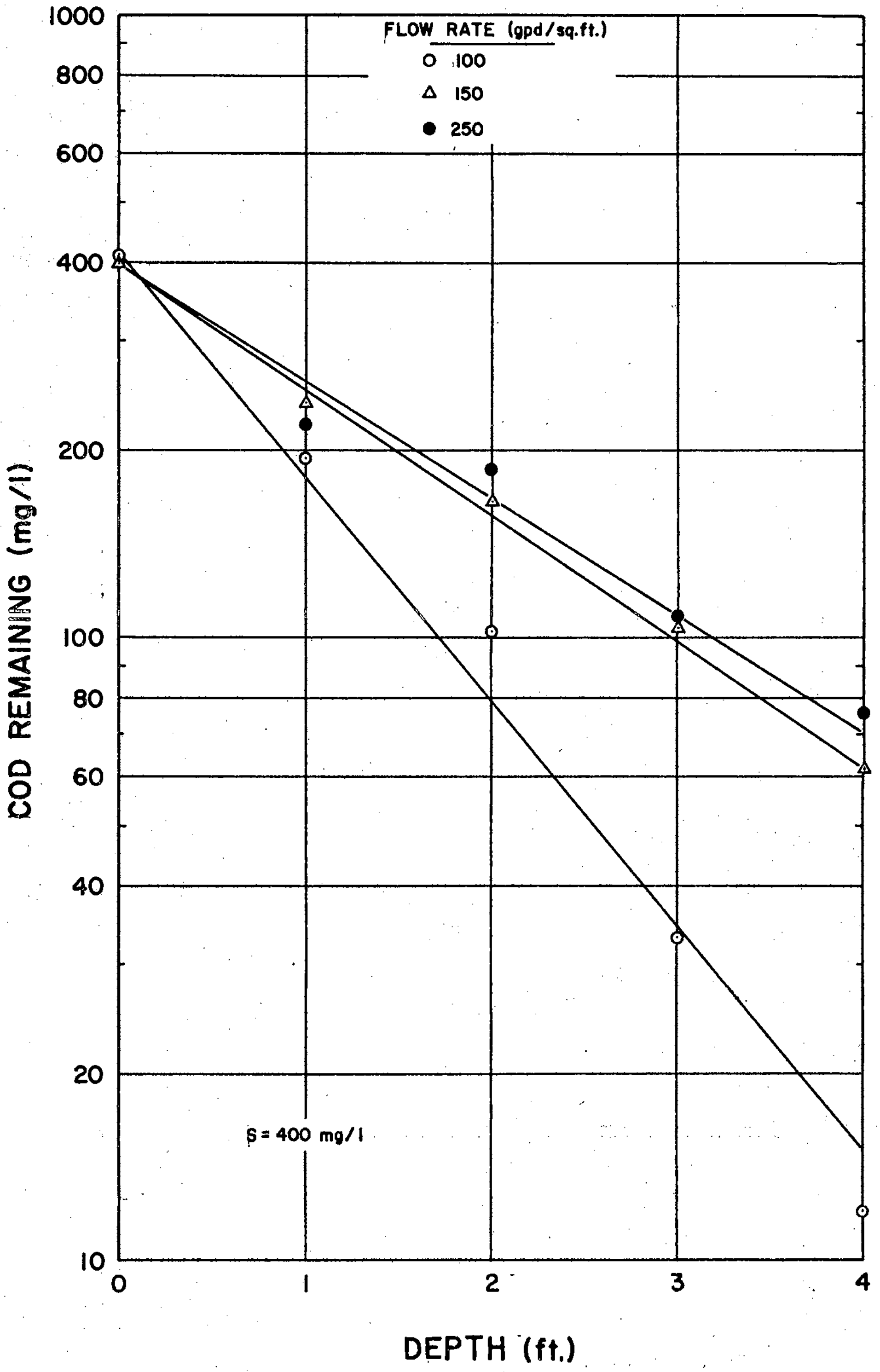


Figure 9A. Relationship of COD Remaining (mg/l) with Depth at a Constant Organic Concentration of 400 mg/l and Varying Flow Rates.

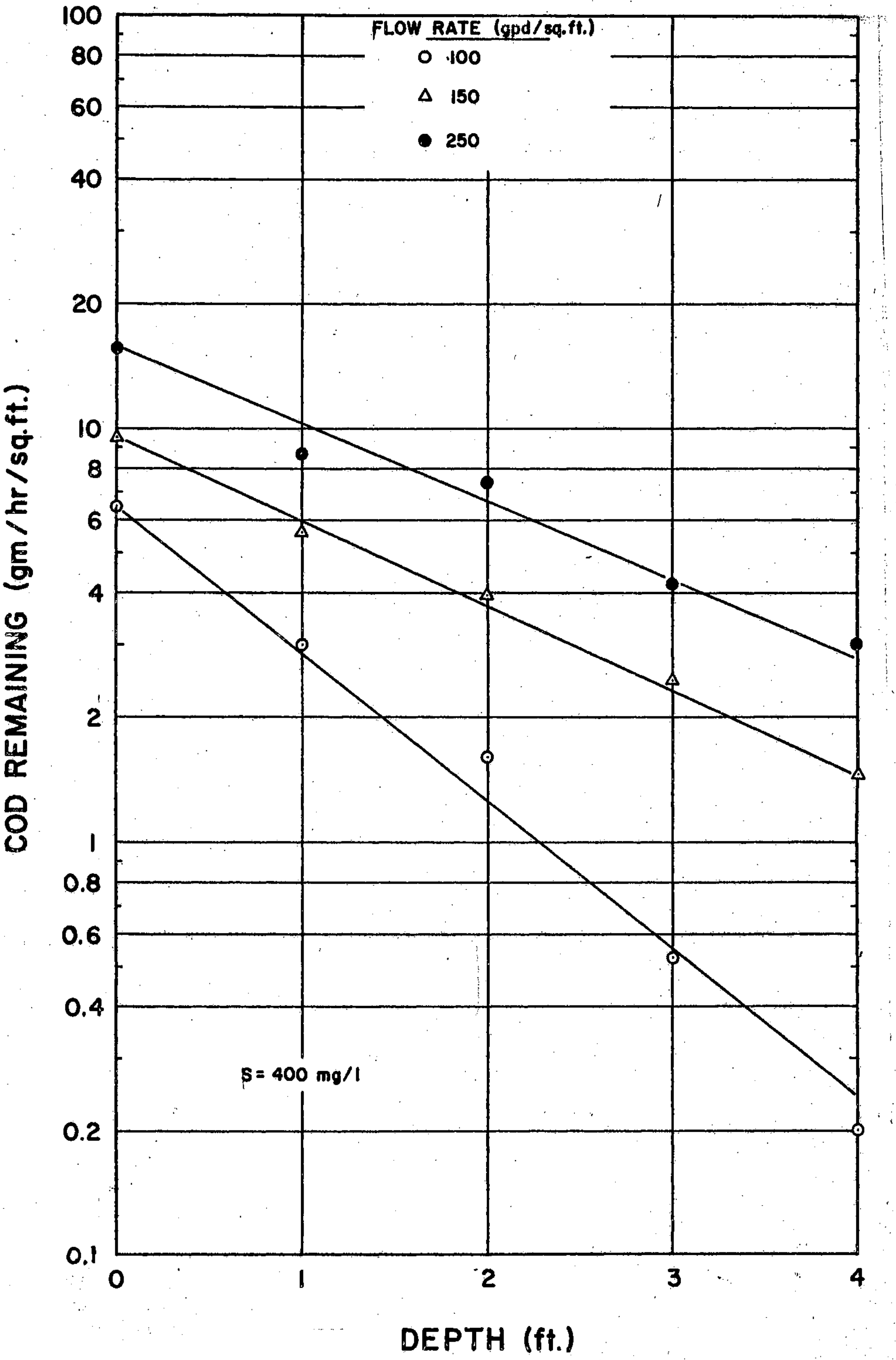


Figure 9B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Organic Concentration of 400 mg/l and Varying Flow Rates.

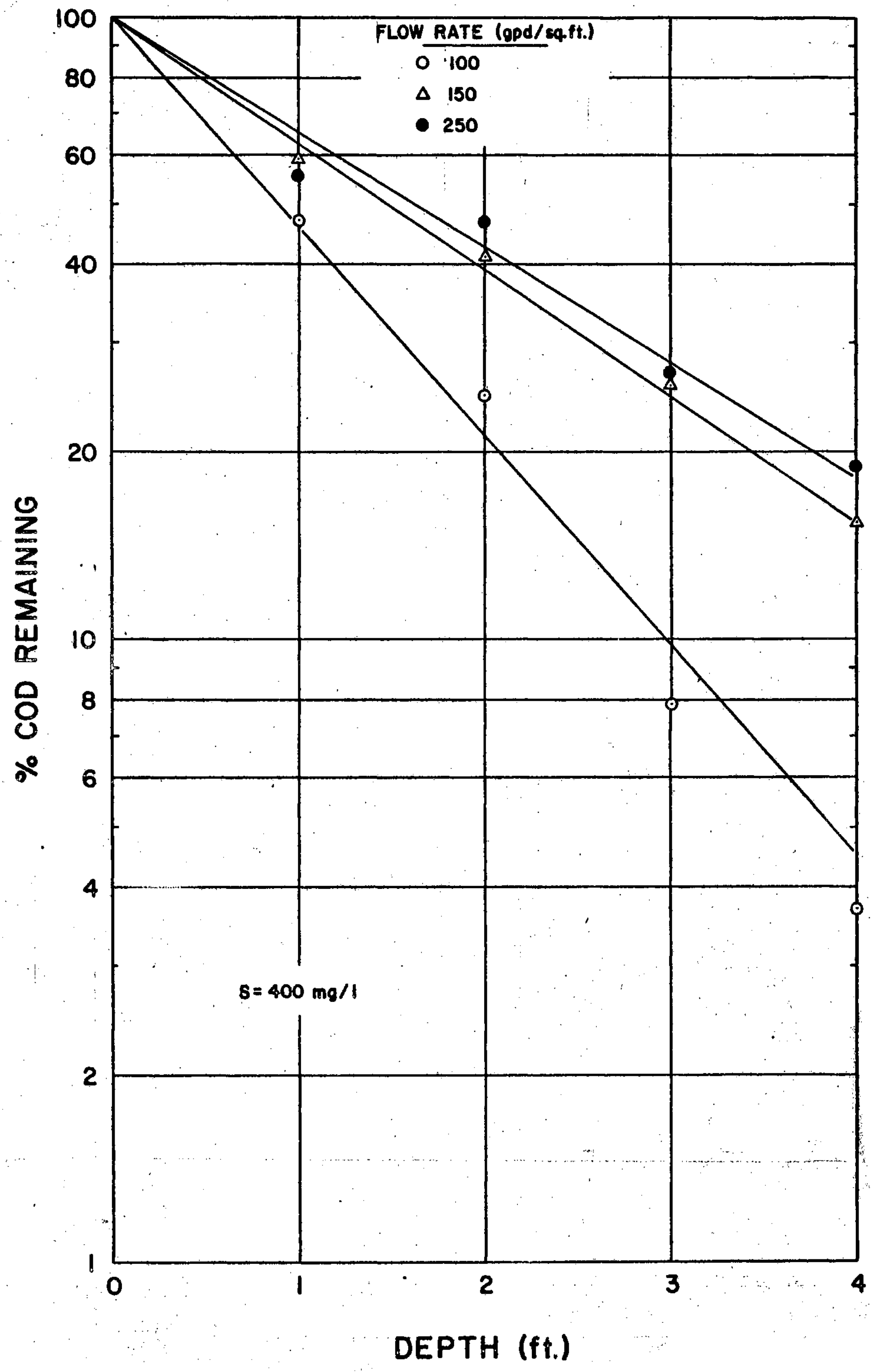


Figure 9C. Relationship of % COD Remaining with Depth at a Constant Organic Concentration of 400 mg/l and Varying Flow Rates.

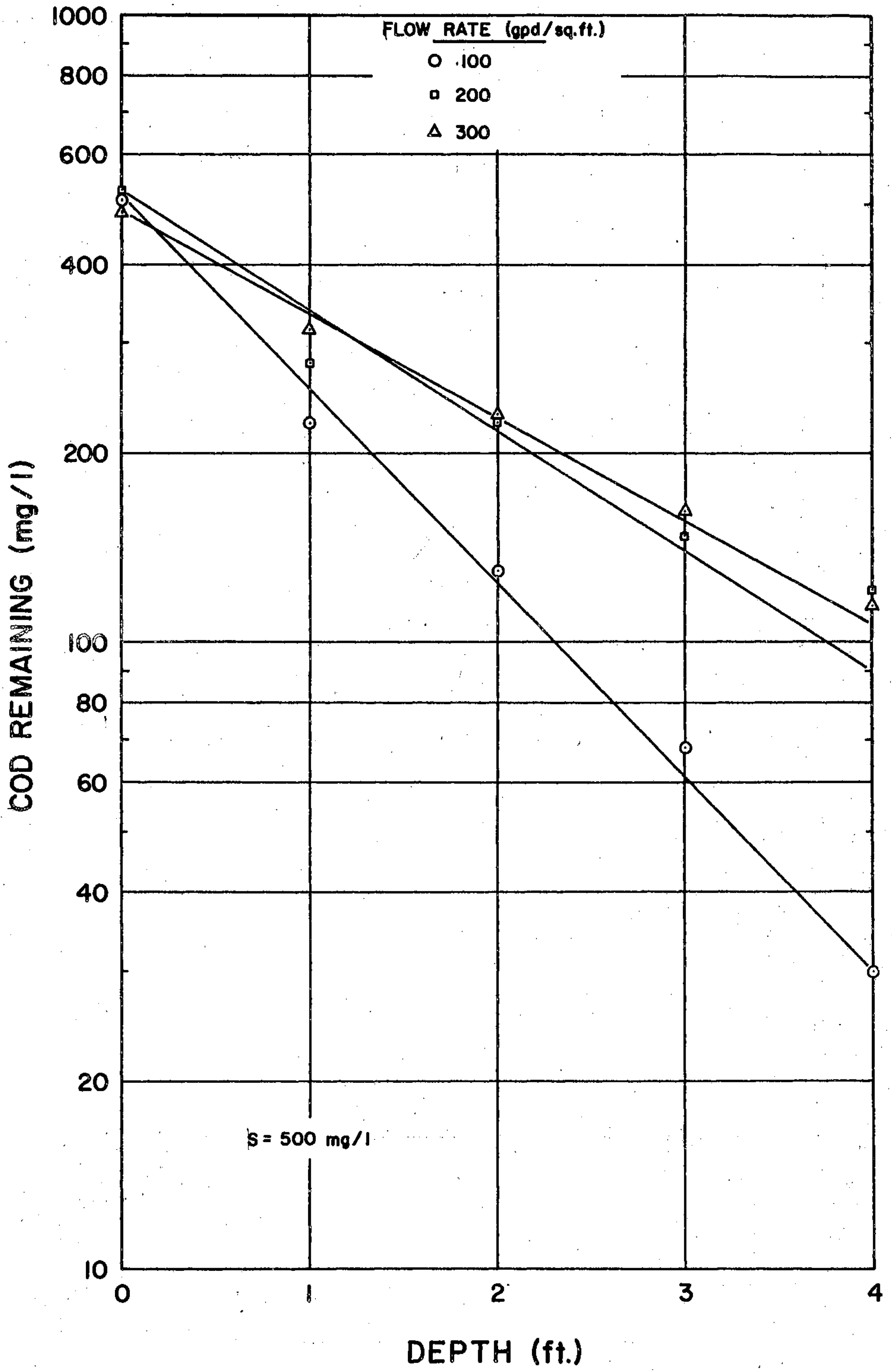


Figure 10A. Relationship of COD Remaining (mg/l) with Depth at a Constant Organic Concentration of 500 mg/l and Varying Flow Rates.

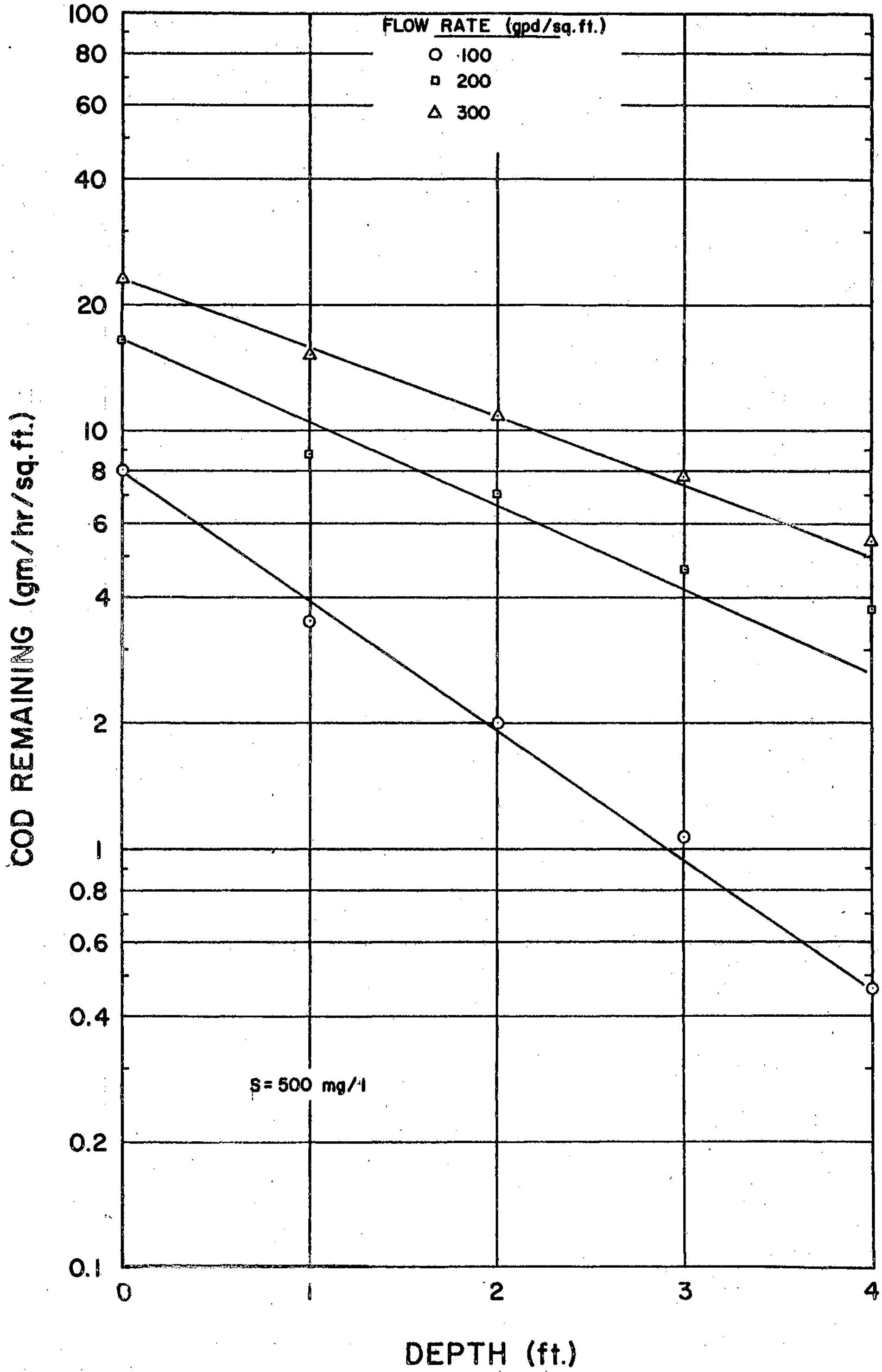


Figure 10B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Organic Concentration of 500 mg/l and Varying Flow Rates.

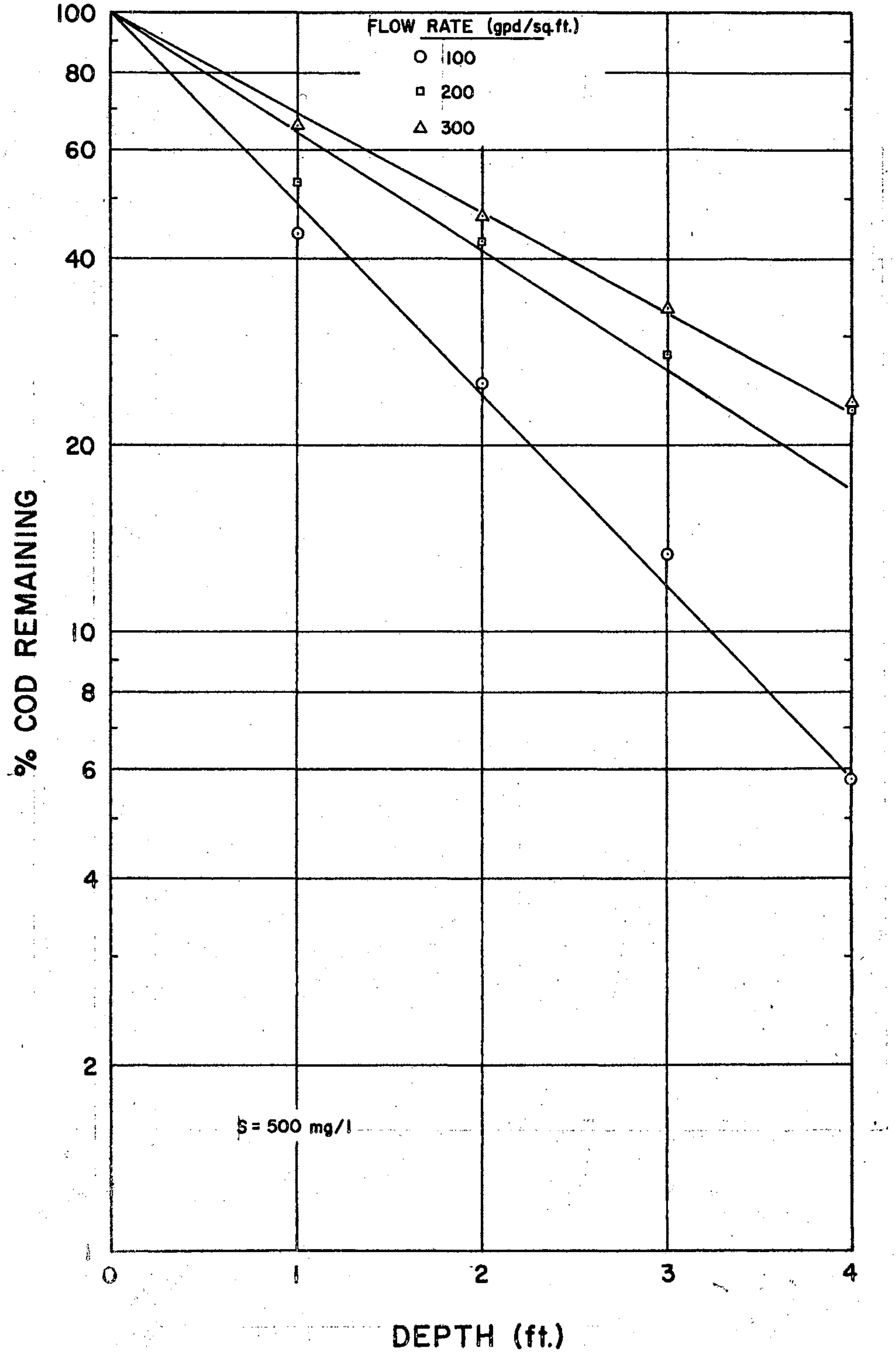


Figure 10C. Relationship of % COD Remaining with Depth at a Constant Organic Concentration of 500 mg/l and Varying Flow Rates.

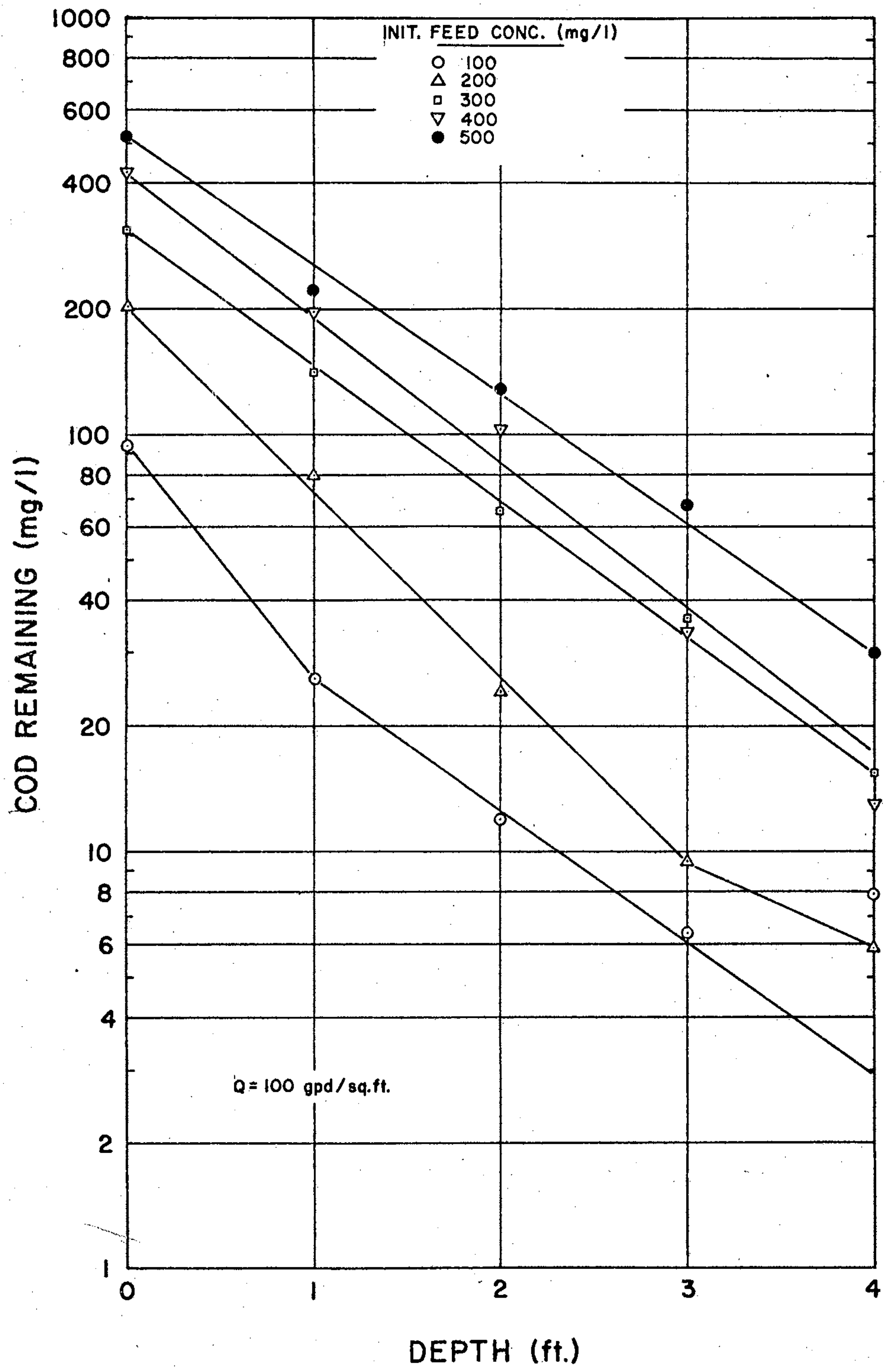


Figure 11A. Relationship of COD Remaining (mg/l) with Depth at a Constant Flow Rate of 100 gpd/sq ft and Varying Organic Concentrations.

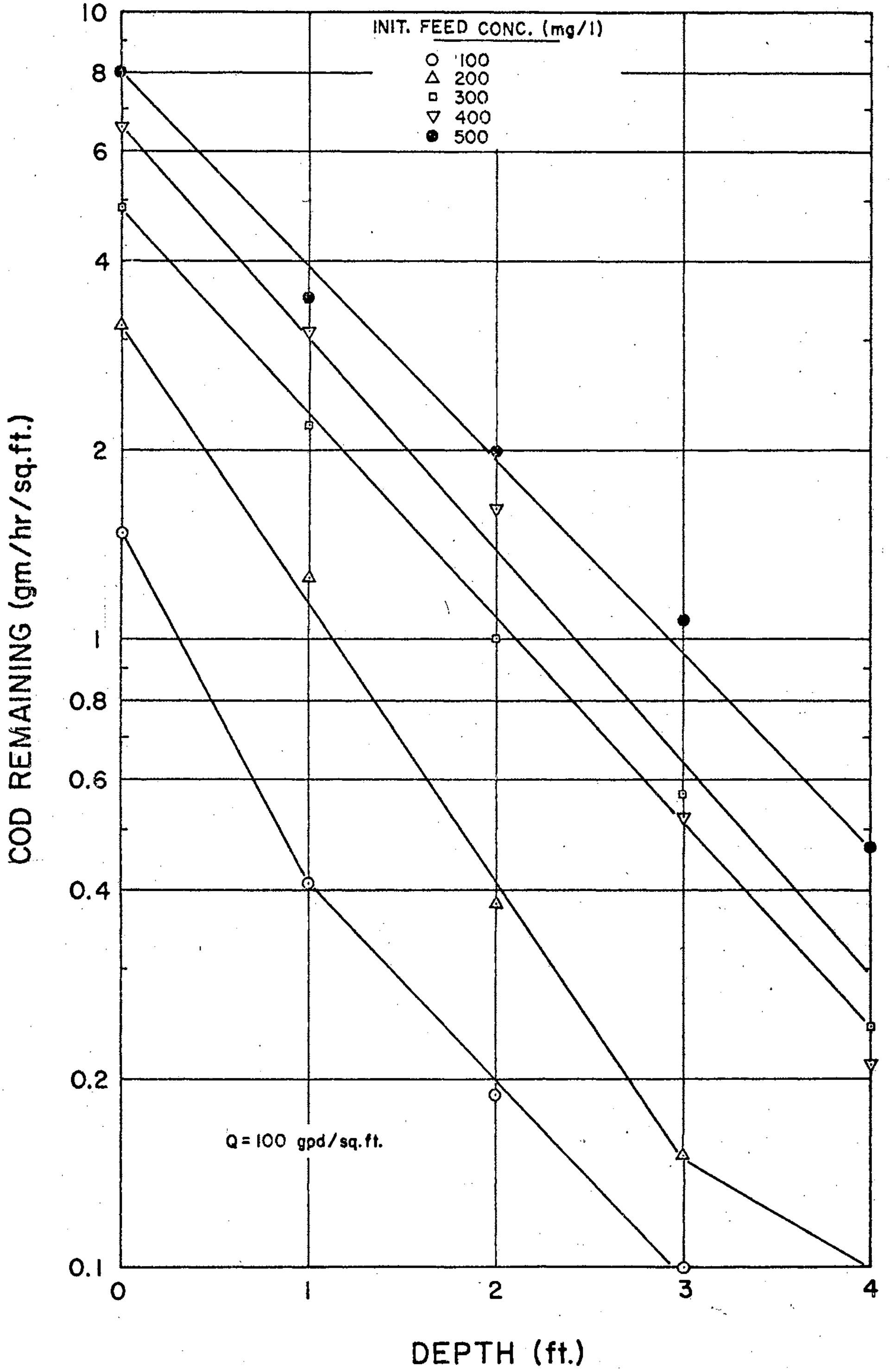


Figure 11B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Flow Rate of 100 gpd/sq ft and Varying Organic Concentrations.

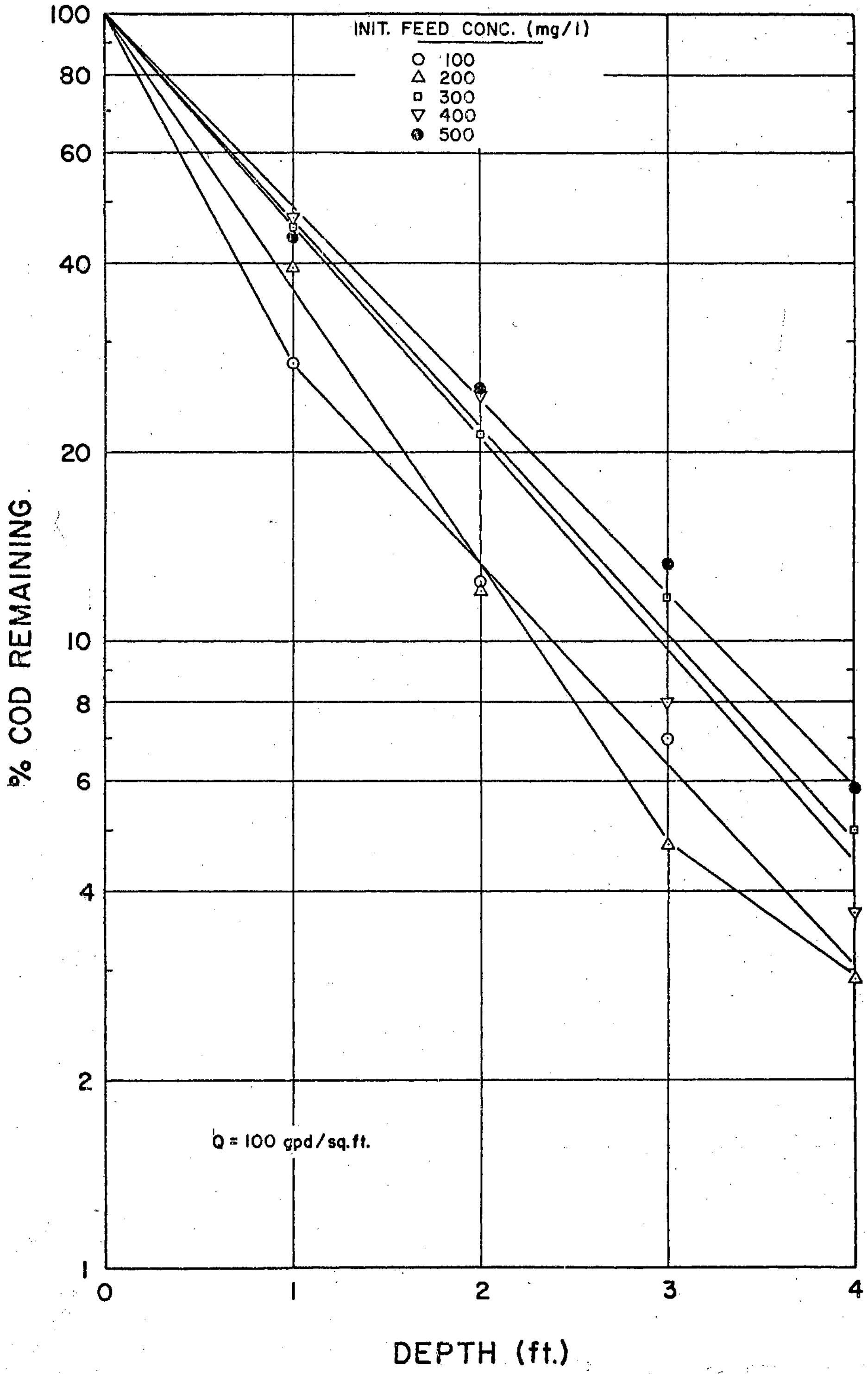


Figure 11C. Relationship of % COD Remaining with Depth at a Constant Flow Rate of 100 gpd/sq ft and Varying Organic Concentrations.

of 100, 200, 300, 400 and 500 mg/l. The curves at the lower organic loadings show two rates of removal, whereas the curves at the higher organic loadings are described by a single rate of removal throughout the depths of the filter. Also at the higher feed concentrations, the slope of the line describing the COD remaining decreases and approaches a limiting value. This too could be considered to be an indication of COD filter saturation.

Figures 12A, 12B and 12C show the results of a constant flow rate of 150 gpd/sq ft at feed concentrations of 100, 200 and 400 mg/l. Figure sets 13, 14 and 15 show similar results obtained at various feed concentrations at the respective flow rates of 200, 250 and 300 gpd/sq ft. In all cases the results obtained were similar to those seen in figure set 11 in which the curves at the higher organic concentrations are described by a single rate of removal throughout the depths. Again at the higher feed concentrations the slope of the line describing the COD remaining decreases and approaches some limiting rate.

C. Presentation of Calculated COD Removal Rates

In the previous two sections, it was seen from the data that COD removal rate decreased as the hydraulic loading was increased with the organic loading held at a constant concentration. Also it was observed that the COD removal rate decreased as the organic loading was increased with the hydraulic loading held at a constant flow rate. In both cases the rate of COD removal appeared to approach some limiting value. In order to better observe the phenomenon of the COD removal rate approaching some limiting value, the COD removal rates were calculated for each COD removal curve from the previously presented data. The removal rate was calculated for each curve from each of three

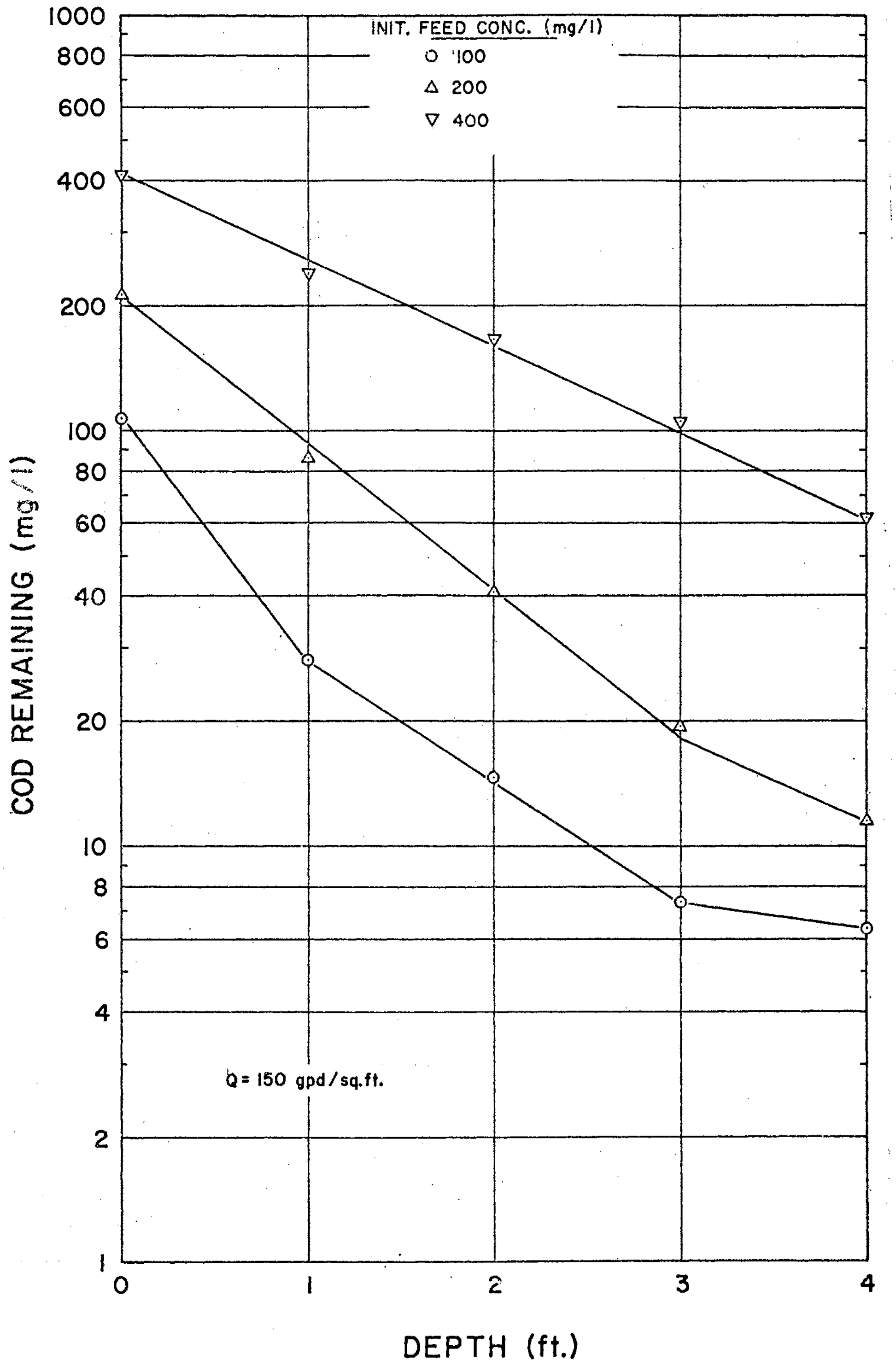


Figure 12A. Relationship of COD Remaining (mg/l) with Depth at a Constant Flow Rate of 150 gpd/sq ft and Varying Organic Concentrations.

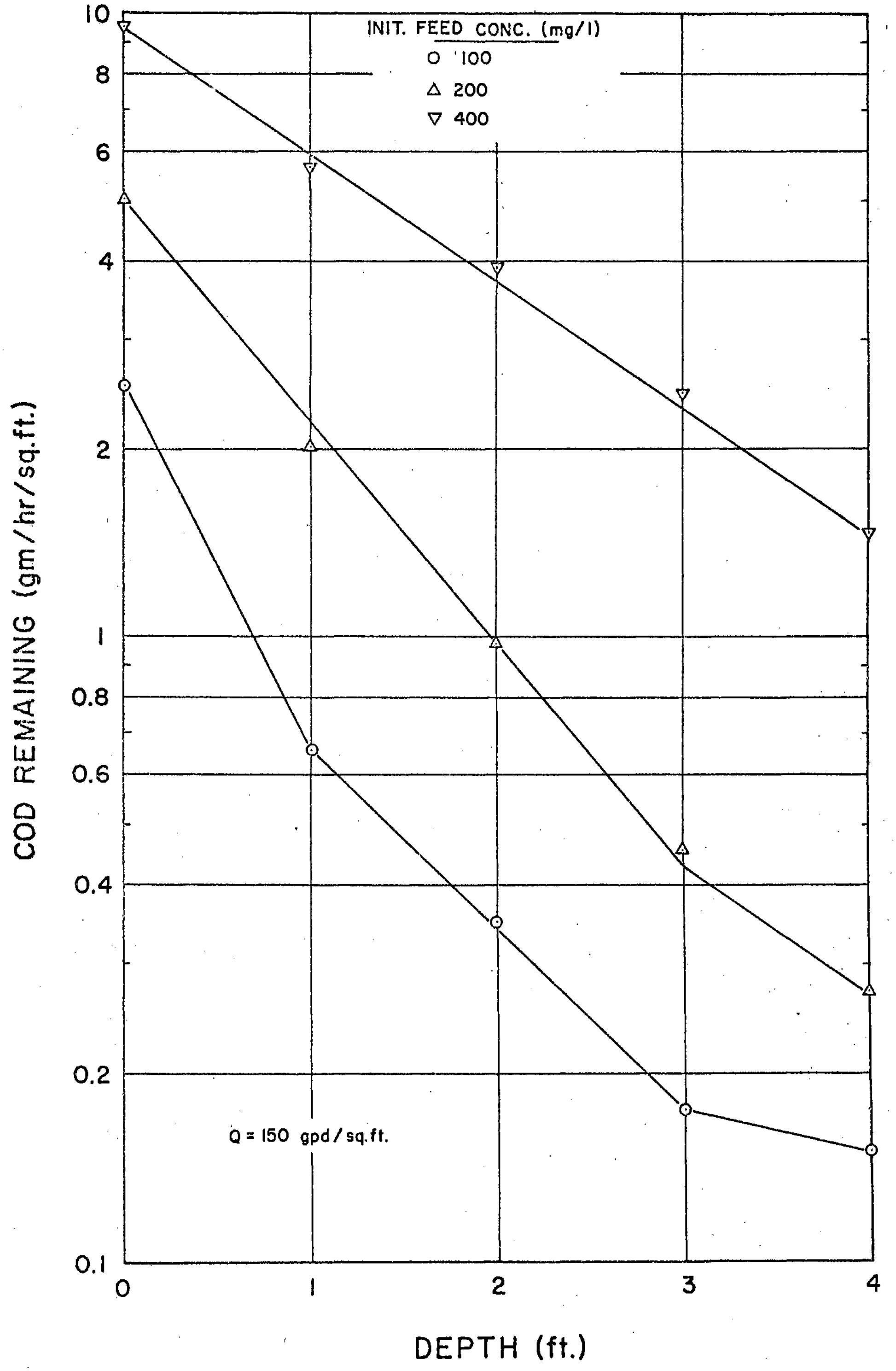


Figure 12B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Flow Rate of 150 gpd/sq ft and Varying Organic Concentrations.

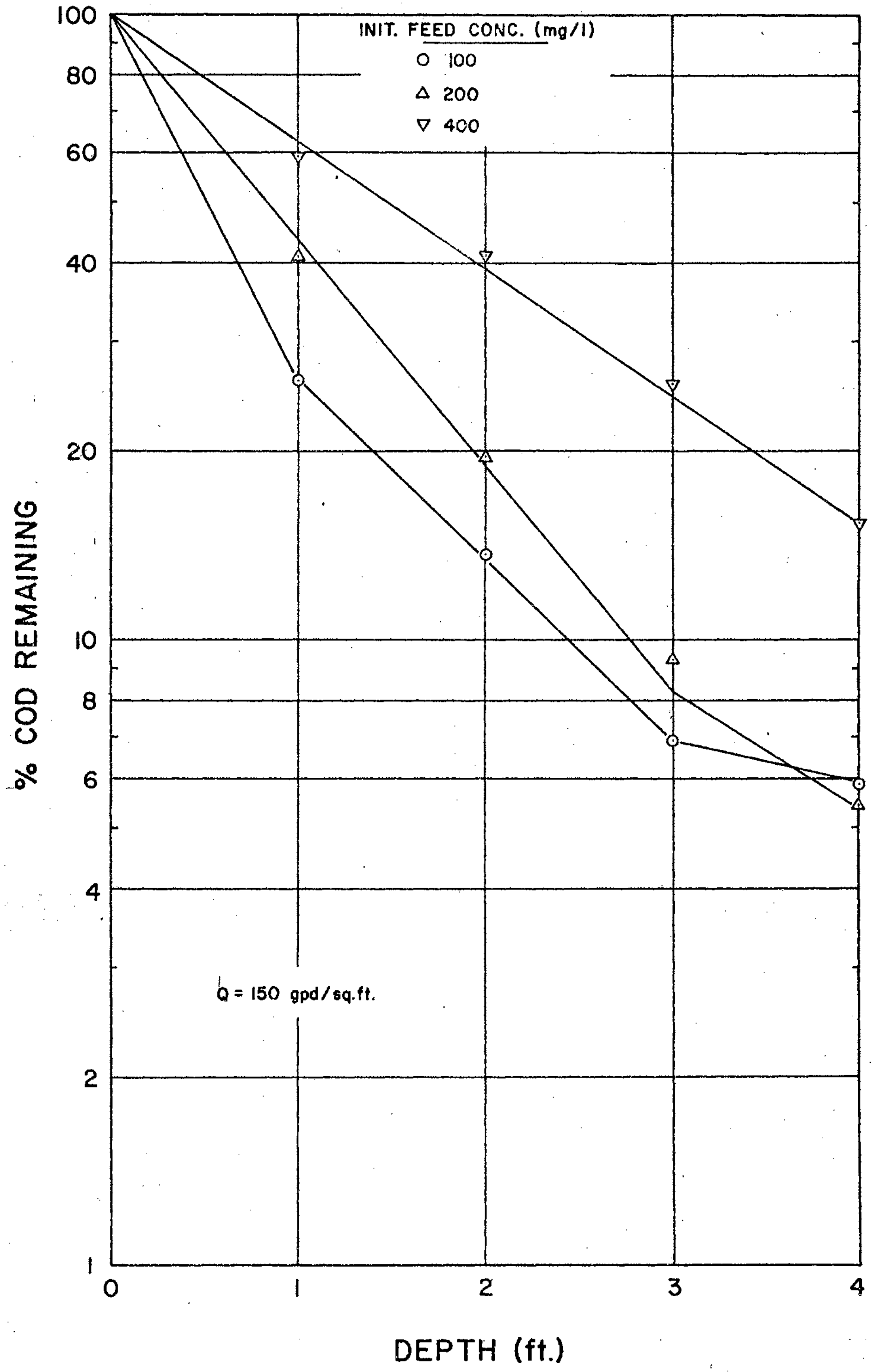


Figure 12C. Relationship of % COD Remaining with Depth at a Constant Flow Rate of 150 gpd/sq ft and Varying Organic Concentrations.

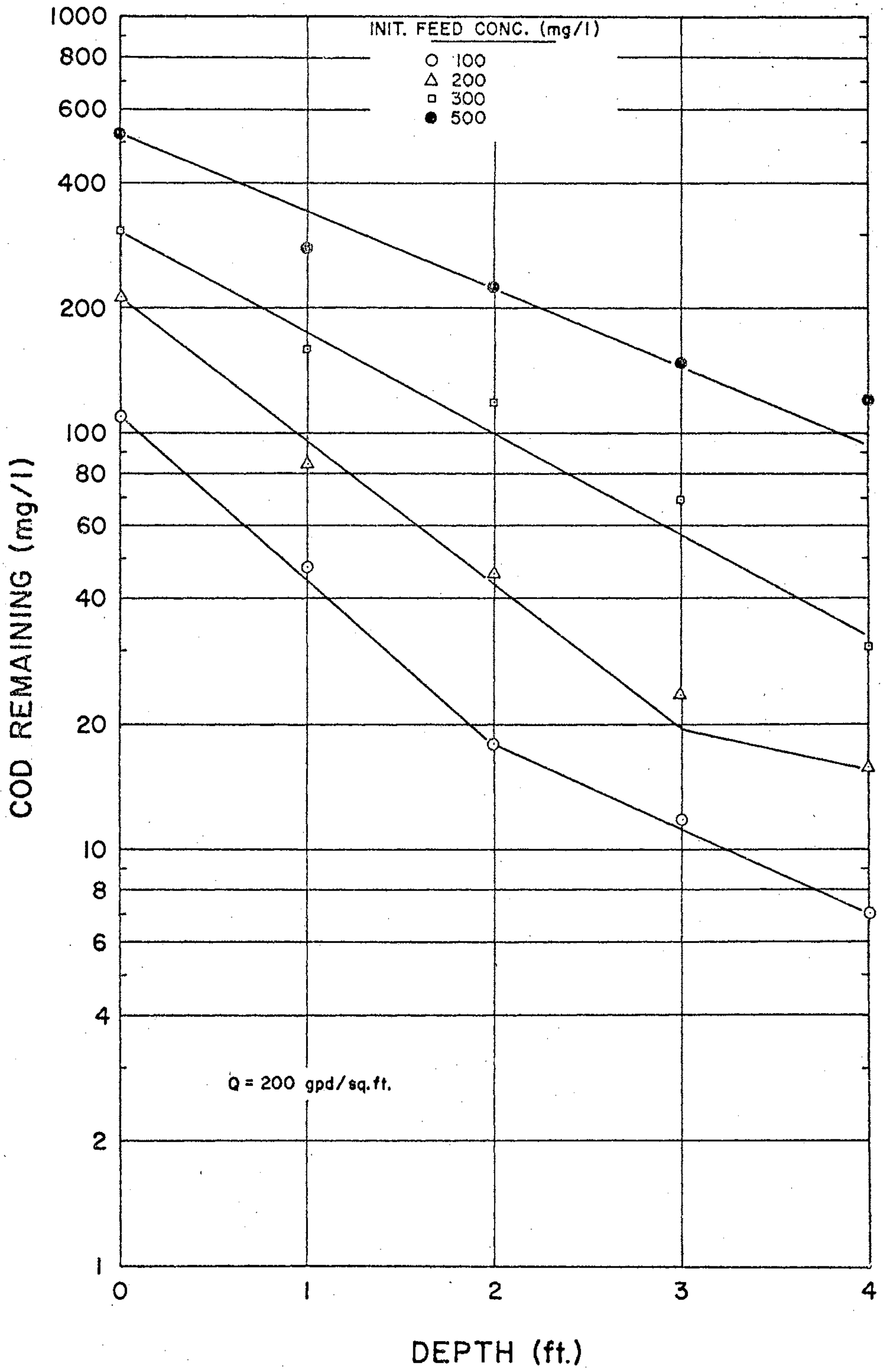


Figure 13A. Relationship of COD Remaining (mg/l) with Depth at a Constant Flow Rate of 200 gpd/ sq ft and Varying Organic Concentrations.

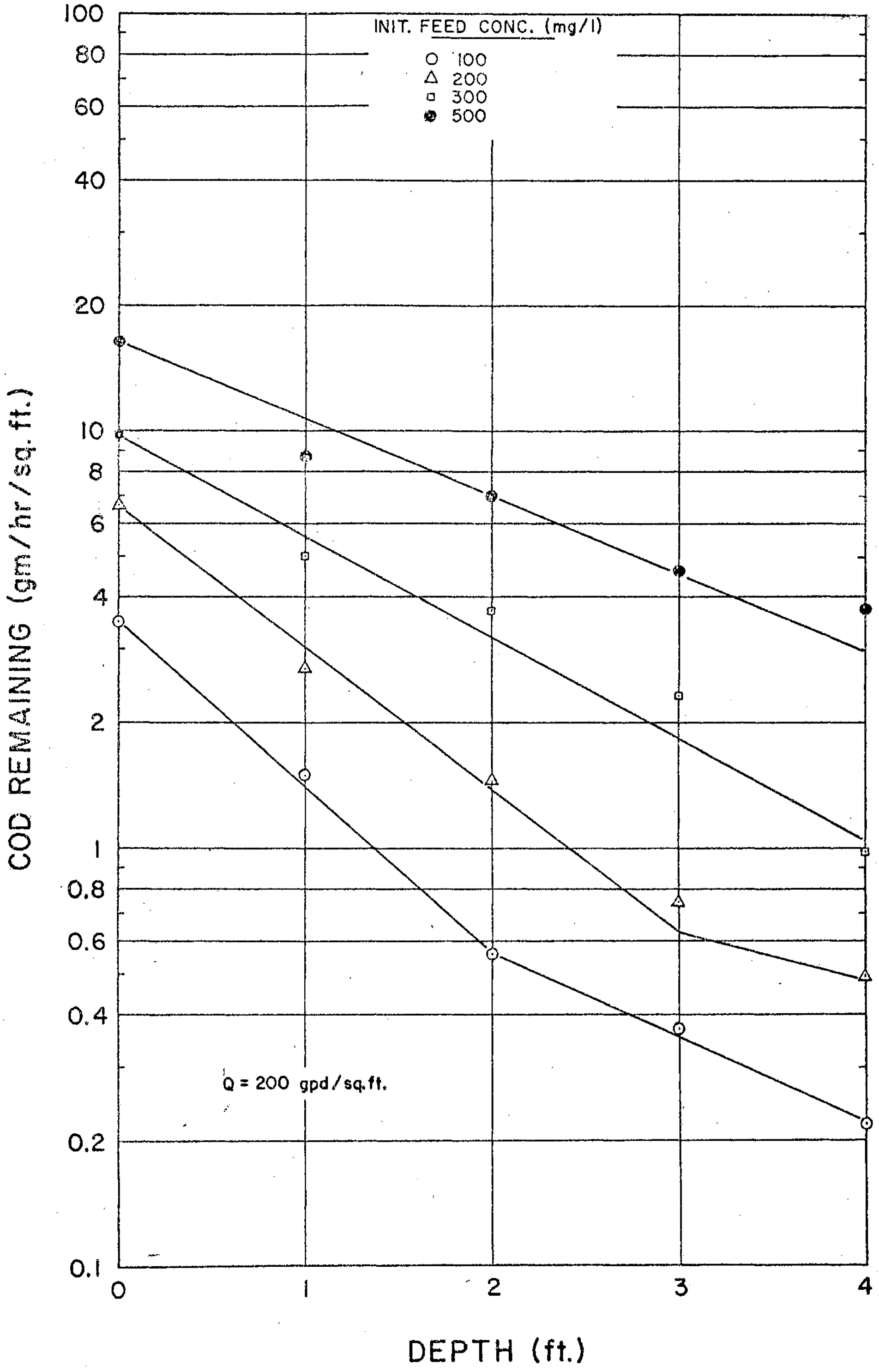


Figure 13B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Flow Rate of 200 gpd/sq ft and Varying Organic Concentrations.

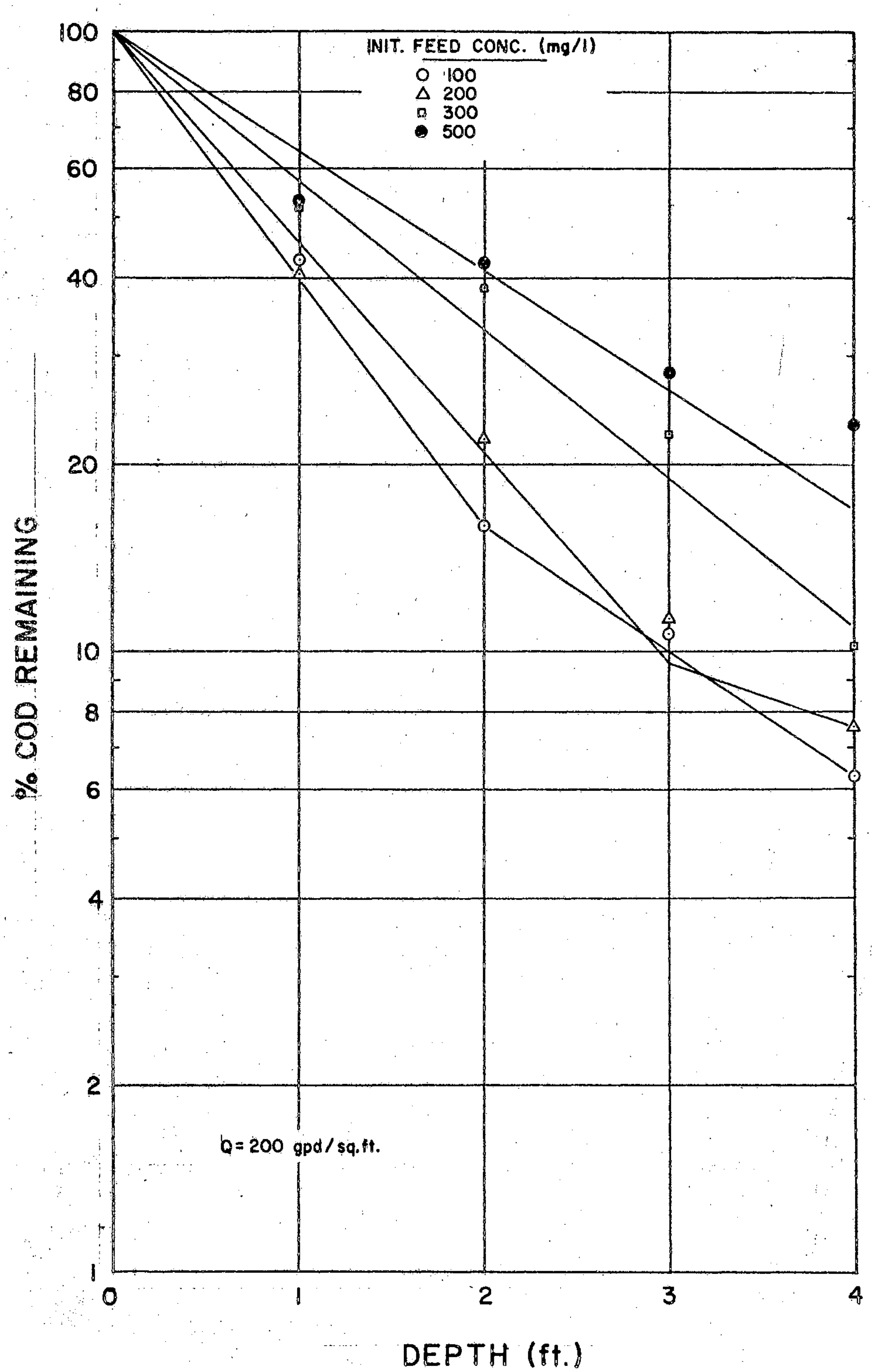


Figure 13C. Relationship of % COD Remaining with Depth at a Constant Flow Rate of 200 gpd/sq ft and Varying Organic Concentrations.

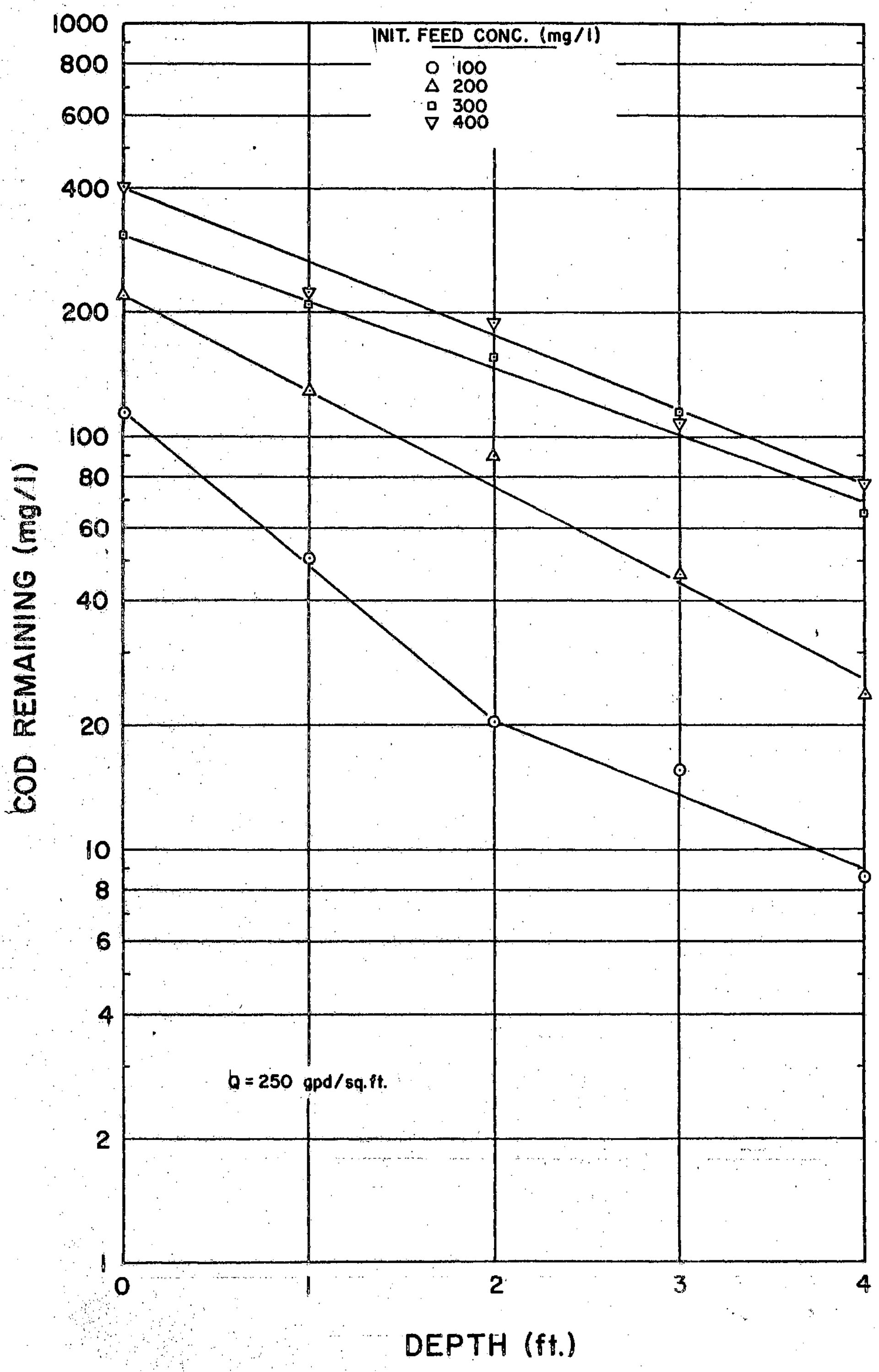


Figure 14A. Relationship of COD Remaining (mg/l) with Depth at a Constant Flow Rate of 250 gpd/sq ft and Varying Organic Concentrations.

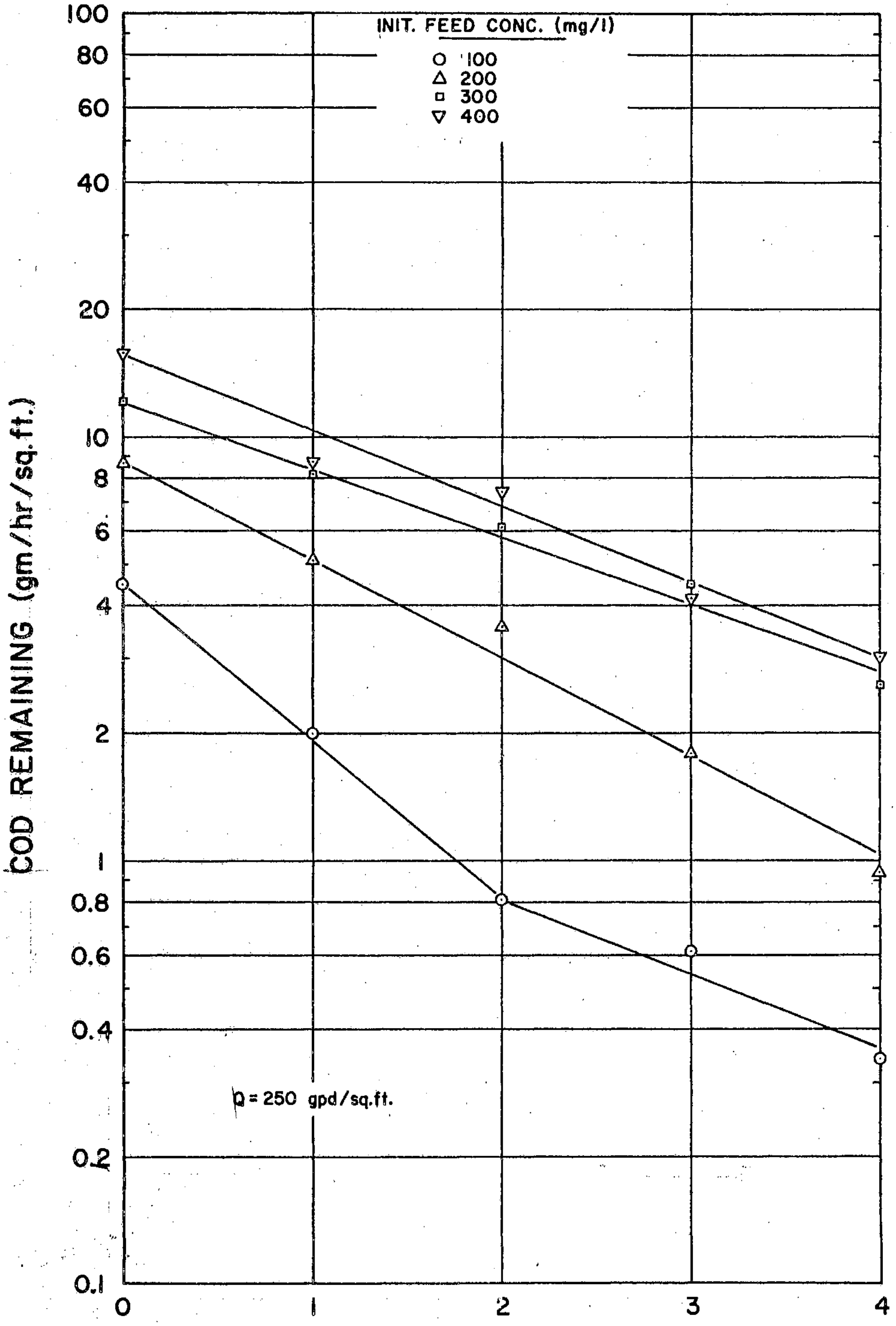


Figure 14B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Flow Rate of 250 gpd/sq ft and Varying Organic Concentrations.

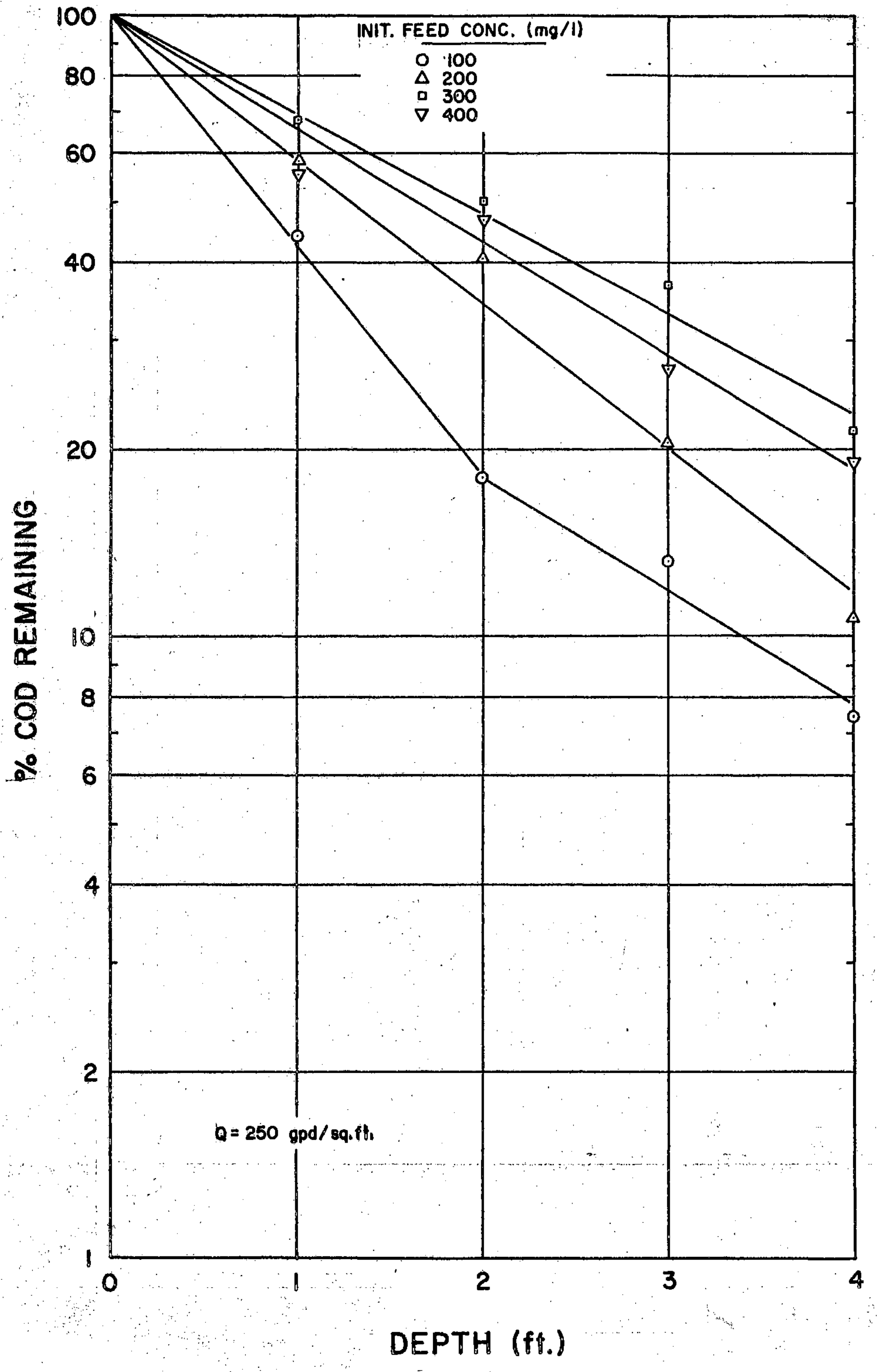


Figure 14C. Relationship of % COD Remaining with Depth at a Constant Flow Rate of 250 gpd/sq ft and Varying Organic Concentrations.

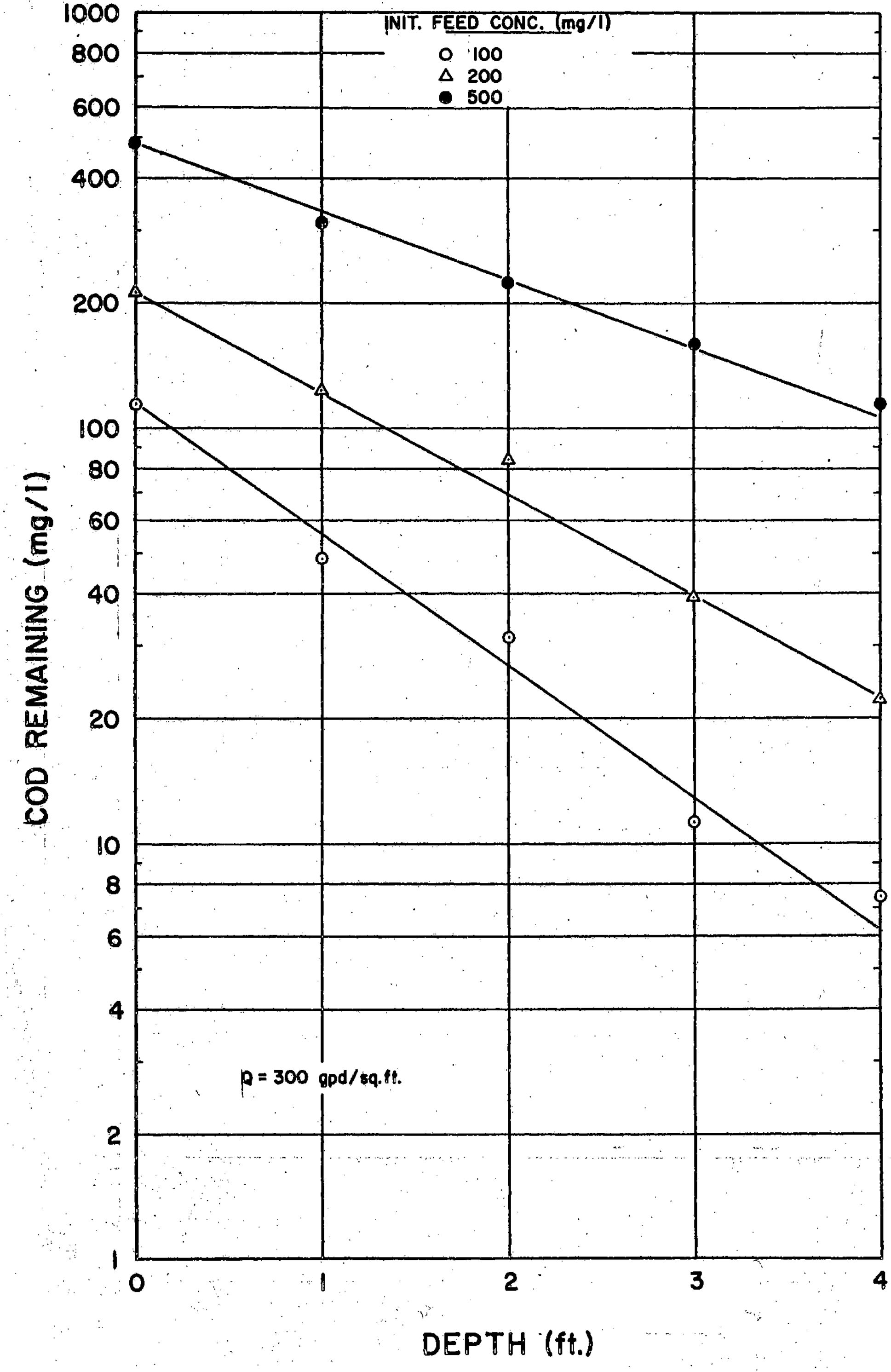


Figure 15A. Relationship of COD Remaining (mg/l) with Depth at a Constant Flow Rate of 300 gpd/ sq ft and Varying Organic Concentrations.

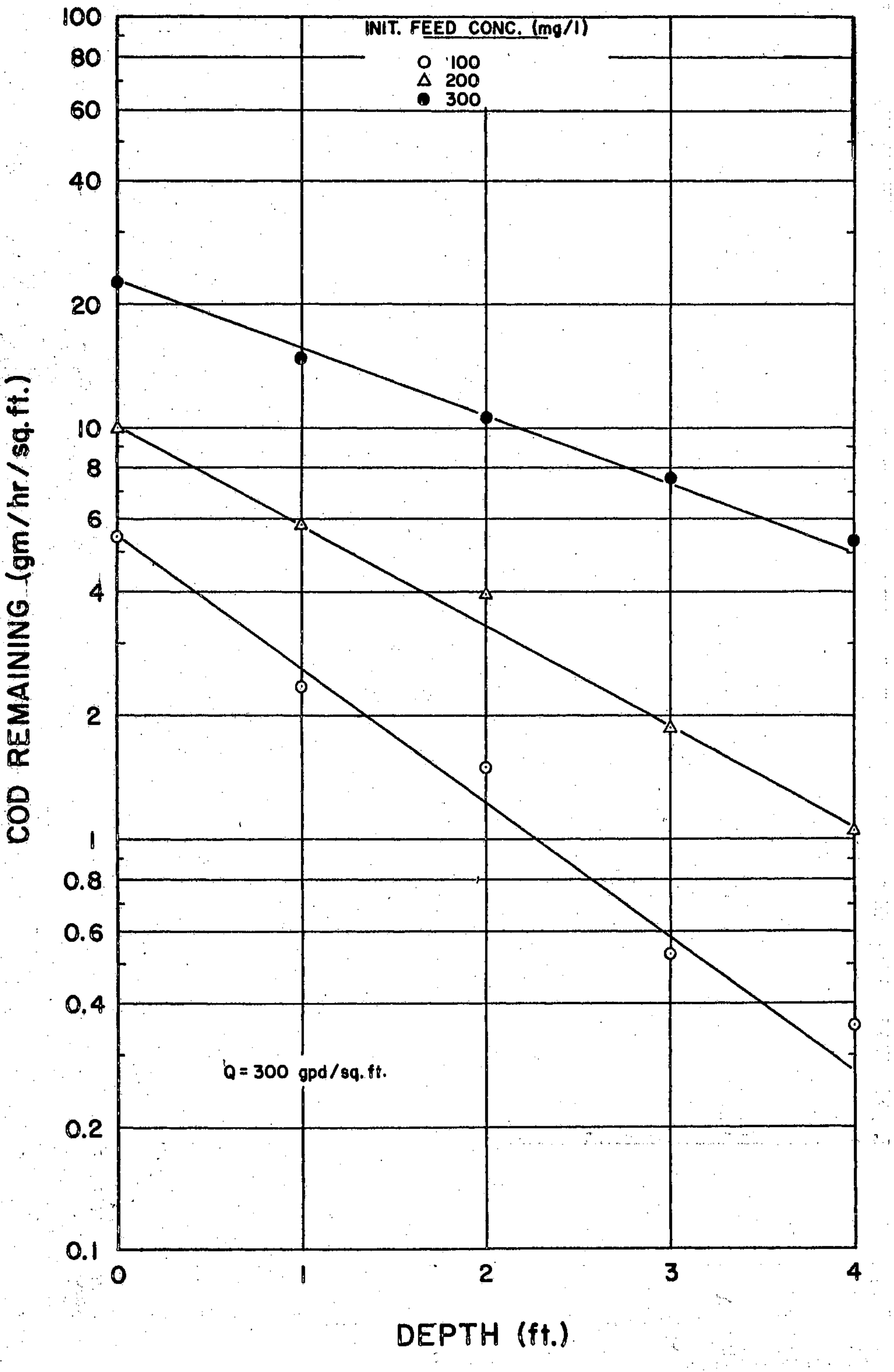


Figure 15B. Relationship of COD Remaining (gm/hr/sq ft) with Depth at a Constant Flow Rate of 300 gpd/sq ft and Varying Organic Concentrations.

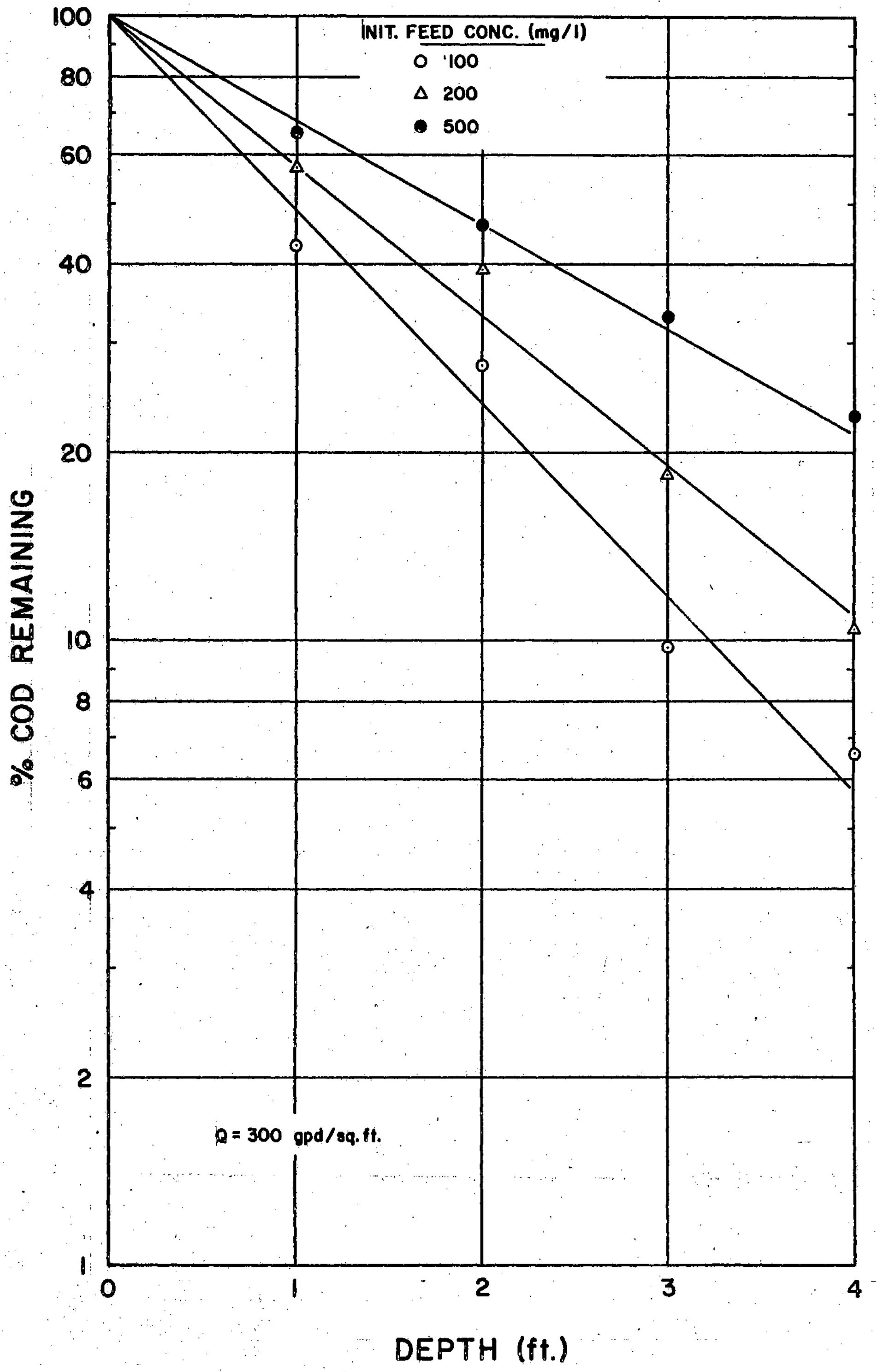


Figure 15C. Relationship of % COD Remaining with Depth at a Constant Flow Rate of 300 gpd/sq ft and Varying Organic Concentrations.

different semilog plots A, B and C in each figure set and presented in Table IV. For removal curves where more than one removal rate was observed, the rate as determined in the first foot of removal was taken as the removal rate for that removal curve. As seen in Table IV the removal rates, when calculated from plots A, B and C for each removal curve, were essentially identical as they should be as pointed out in the section on theoretical considerations.

Figure 16 shows the substrate removal rate of the COD remaining curves plotted versus the concentration (mg/l) of COD at the spray nozzle. Curves are drawn connecting the points obtained from the slopes of the COD remaining curves at each of the various flow rates 100, 150, 200, 250 and 300 gpd/sq ft. As can be seen, a family of curves develop, each approaching a constant value of removal rate as the feed concentration is increased and as the flow rate increases the family of curves tend to approach one another exhibiting a saturation phenomenon or a limiting load beyond which the removal rate does not decrease.

Figure 17 shows the substrate removal rates of the COD remaining curves plotted versus the flow rate (gpd/sq ft). Curves are drawn connecting the points obtained from the slope of the COD remaining curves at each of the various feed concentrations, 100, 200, 300, 400 and 500 mg/l sucrose. Again, a family of curves develop, each approaching a constant value of removal rate as the flow rate is increased and as the substrate concentration increases, the family of curves approach one another exhibiting a saturation phenomenon or a limiting load beyond which the removal rate does not decrease.

Figure 18 shows the removal rates of the COD remaining curves

TABLE IV

DATA SUMMARY OF pH AT EACH UNIT OF FILTER DEPTH AND SUBSTRATE REMOVAL RATES AT VARIOUS FLOW RATES AND FEED CONCENTRATIONS

Feed conc. mg/l	Flow rate gpd/ft^2	Depth - Feet					Initial feed at nozzle gm/hr/ft^2	Removal rate of COD rem. curve A	Removal rate of COD rem. curve B	Removal rate of COD rem. curve C
		0	1	2	3	4				
		pH	pH	pH	pH	pH				
100	100	7.8	7.8	7.9	8.1	8.1	1.48	-.545	-.560	-.558
100	150	7.9	7.7	7.8	8.0	8.1	2.54	-.535	-.577	-.560
100	200	7.9	7.4	7.7	7.9	8.0	3.49	-.393	-.389	-.395
100	250	8.0	7.6	7.8	7.9	8.0	4.50	-.341	-.360	-.372
100	300	8.0	7.6	7.6	7.8	7.9	5.45	-.329	-.325	-.323
100	600	8.0	7.7	7.6	7.7	7.8	9.14	-.202	-.199	-.204
200	100	7.9	7.3	7.5	7.7	7.8	3.17	-.416	-.440	-.442
200	150	8.0	7.4	7.5	7.7	7.9	4.97	-.372	-.358	-.364
200	200	8.0	7.5	7.7	7.8	7.9	6.60	-.339	-.339	-.344
200	250	8.0	7.6	7.6	7.6	7.7	8.68	-.226	-.230	-.232
200	300	8.0	7.4	7.3	7.4	7.5	10.03	-.228	-.235	-.226
200	500	7.8	7.4	7.4	7.5	7.4	15.70	-.200	-.192	-.204
300	100	7.9	7.2	7.4	7.5	7.6	4.86	-.328	-.326	-.328
300	200	7.9	7.2	7.3	7.4	7.4	9.67	-.241	-.237	-.245
300	250	7.9	7.3	7.3	7.3	7.3	12.07	-.162	-.161	-.167
400	100	7.7	7.1	7.2	7.4	7.3	6.50	-.358	-.336	-.360
400	150	7.8	7.1	7.1	7.1	7.1	9.50	-.204	-.202	-.202
400	250	7.9	7.3	7.2	7.2	7.2	15.70	-.188	-.186	-.188
500	100	7.7	7.0	7.1	7.2	7.4	8.00	-.310	-.310	-.310
500	200	7.8	7.1	7.0	7.1	7.0	16.50	-.200	-.192	-.192
500	300	7.7	7.1	7.0	7.1	7.0	23.00	-.163	-.162	-.164
1000	100	7.7	6.0	4.9	4.8	4.7				

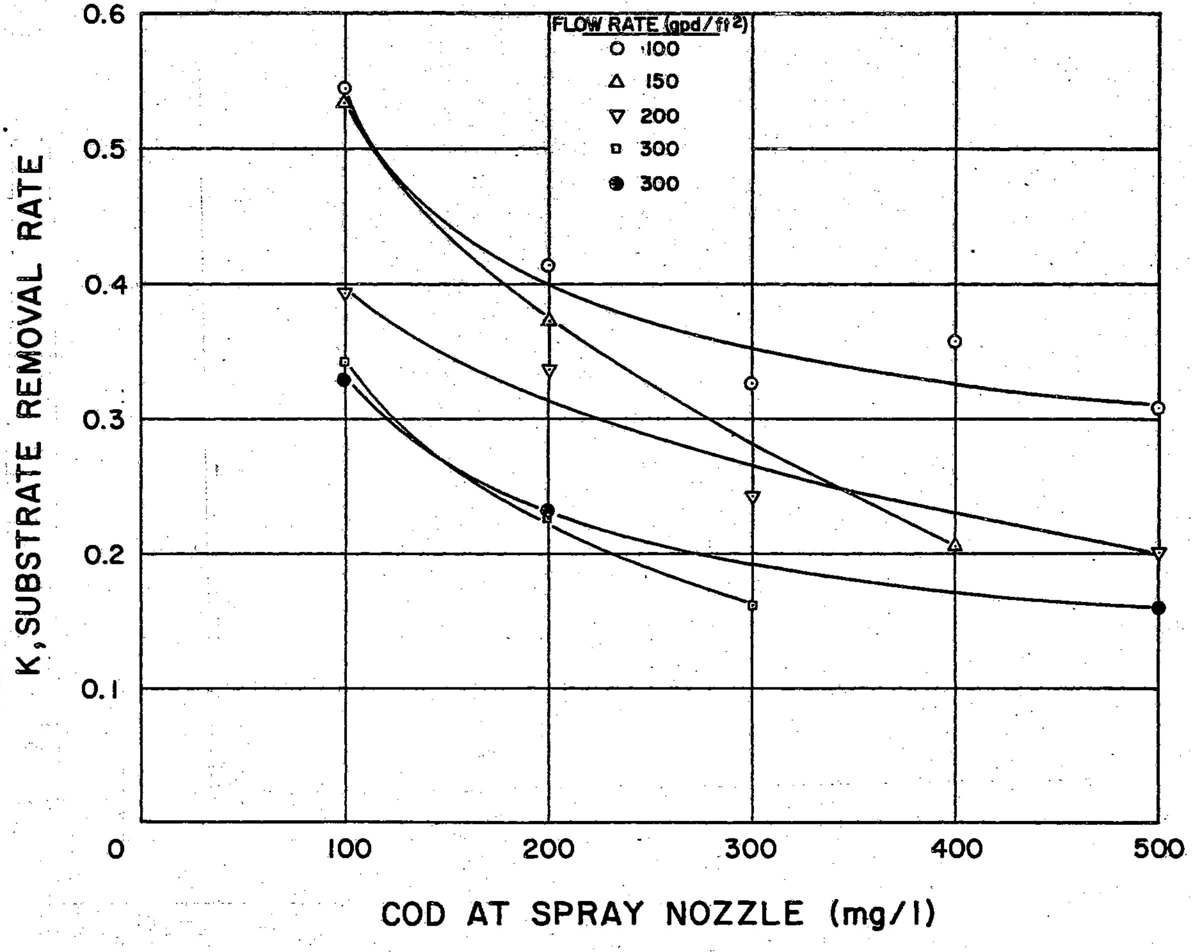


Figure 16. Relationship of Substrate Removal Rate (K) with COD at Spray Nozzle (mg/l) at Various Flow Rates.

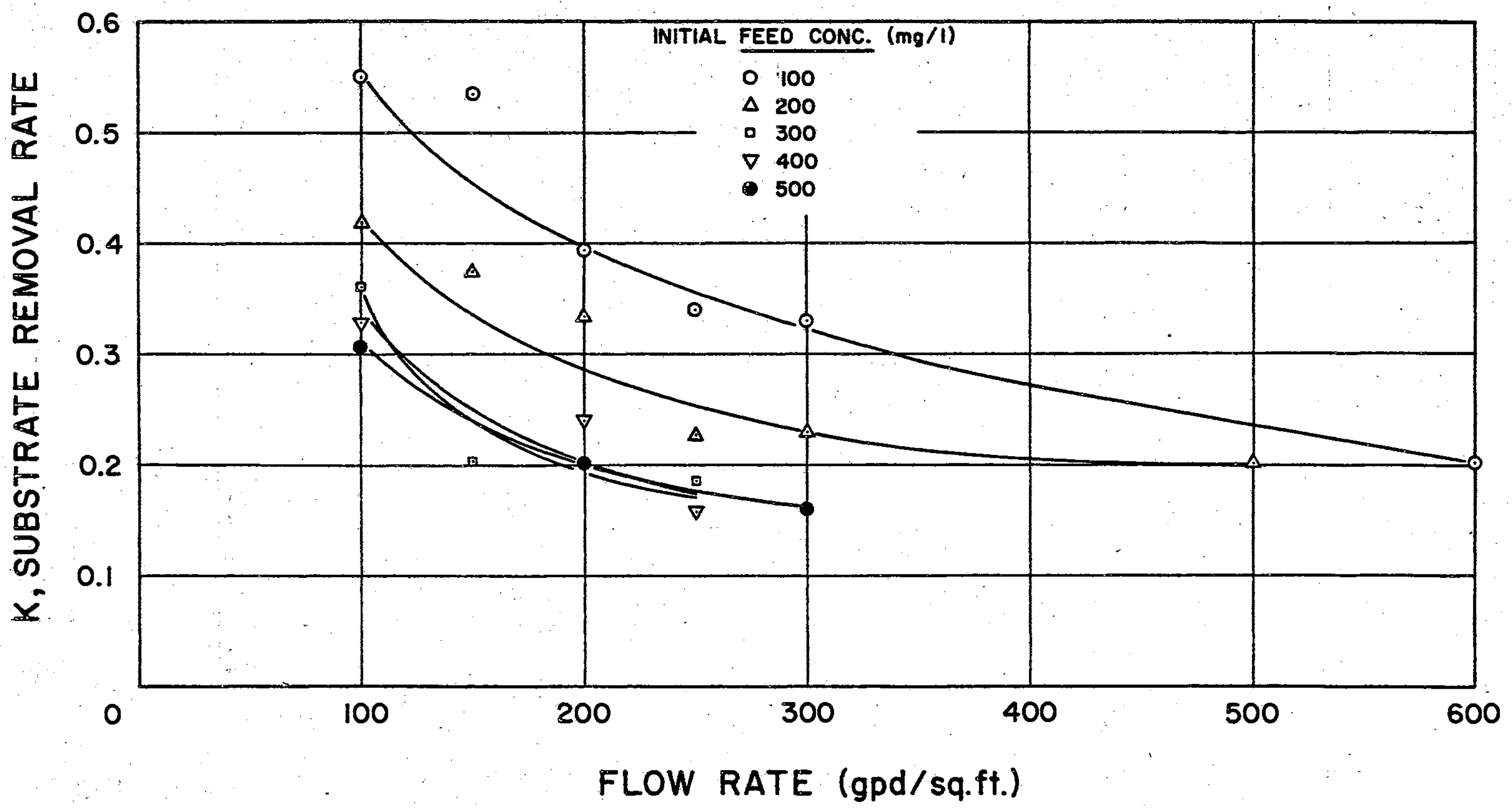


Figure 17. Relationship of Substrate Removal Rate (K) with Flow Rate (gpd/sq ft) at Various Organic Concentrations.

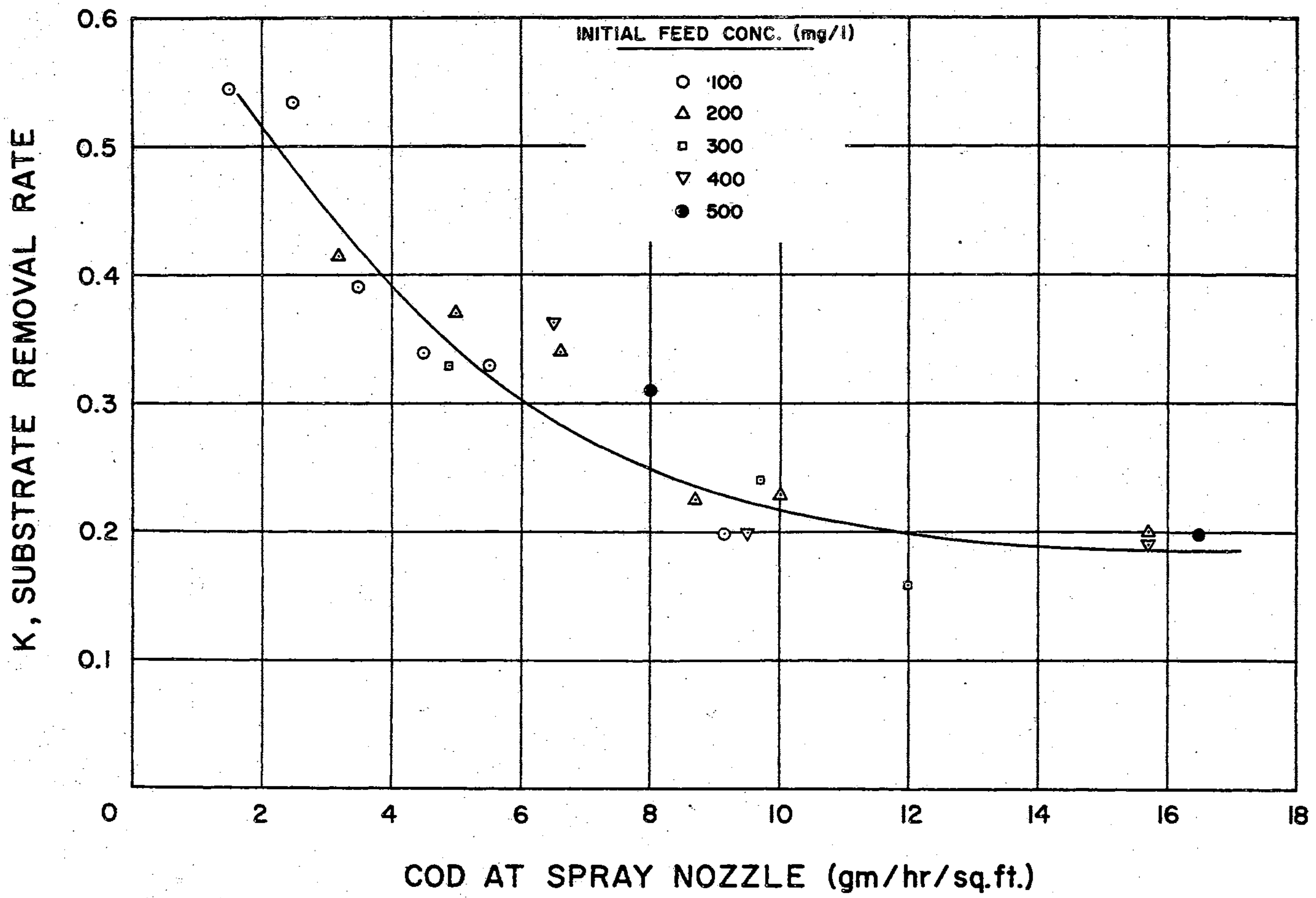


Figure 18. Relationship of Substrate Removal Rate (K) with COD at Spray Nozzle (gm/hr/sq ft).

plotted versus the total amount of COD at the spray nozzle expressed as gm/hr/sq ft. By this method, both the concentration of the waste as well as the flow rate are taken into account. As can be seen, one smooth curve can be drawn through all the points showing that COD removal rate decreases and approaches a constant value as the total amount of organics applied is increased.

D. Presentation of Data at Various Flow Rates and Substrate Concentrations Having the Same Total Organics Applied at the Spray Nozzle

From the previous presentation of data it is seen that an increase in either flow rate or substrate concentration causes a decrease in removal rate and the removal rate approaches a constant value both at the higher flow rates and at the higher substrate concentrations. Both parameters exhibit a definite relationship with substrate removal rate. However, the question may be asked, "Are these parameters independent of one another and does each exert its own influence on organic removal rate or is it rather the two in combination exerting the effect on removal rate?" At a constant hydraulic loading, an increase in substrate concentration naturally increases the total amount of organics applied to the filter. Also, at a constant substrate concentration, an increase in flow rate also increases the total amount of organics applied to the filter. In Table II it can be seen that at a total organics applied of 114 gm sucrose/day/sq ft, there are three experiments of varying substrate concentrations and flow rates. They are: 100 mg/l of sucrose at 300 gpd/sq ft; 200 mg/l of sucrose at 150 gpd/sq ft; and 300 mg/l of sucrose at 100 gpd/sq ft. These three sets of data are plotted in Figure 19 as COD remaining (gm/hr/sq ft) versus depth. Again, COD remaining as gm/hr/sq ft was utilized so that both

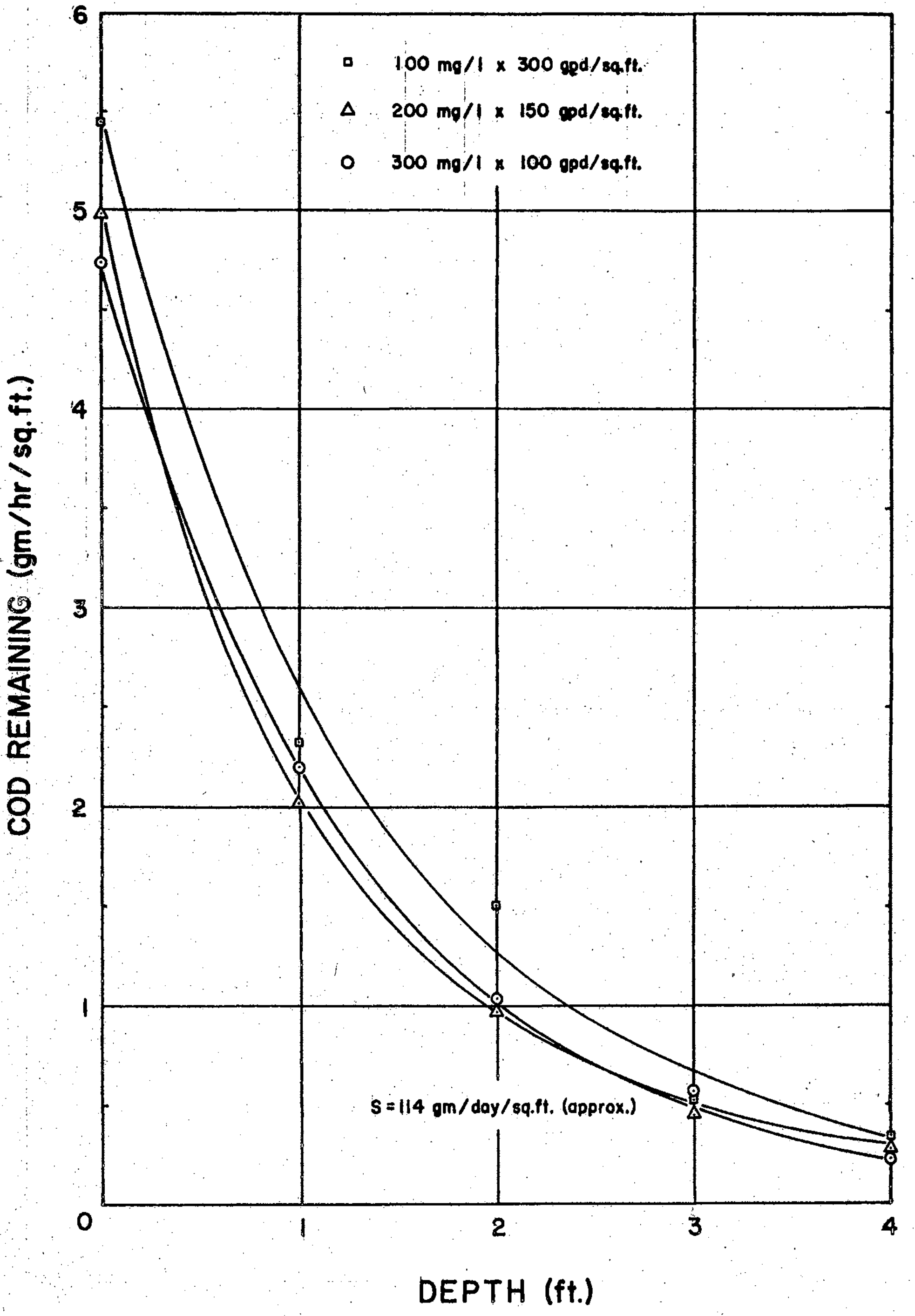


Figure 19. Relationship of COD Remaining (gm/hr/sq ft) with Depth for Various Organic Concentrations and Flow Rates. Resulting Total Organic Load: 114 gm Sucrose/day/sq ft.

the concentration of the waste as well as the flow rate are combined as one parameter. As can be seen from Figure 19 each curve exhibits first order decreasing rate removal and there are no discernible differences in the plots of the respective COD remaining curves. Figure 20 is a semilog plot of per cent COD remaining versus depth for the same data as in Figure 19. Again, there can be seen essentially no differences in the plots of the three sets of data. Since there was such a small difference in flow rates and substrate concentrations in the previous data, it was felt other supporting data at higher total organics applied should be presented.

From Table II at a total organics applied of 226 gm sucrose/day/sq ft there can be found four experiments at this level. They range from 100 mg/l of sucrose at 600 gpd/sq ft to 400 mg/l sucrose at 150 gpd/sq ft. These data are presented in Figure 21 as COD remaining (gm/hr/sq ft) versus depth. As seen in the previous presentation of data, no differences can be ascertained in the plots of the respective COD remaining curves. Figure 22 is a semilog plot of the same data as per cent COD remaining versus depth.

Figures 23 and 24 are plots of data as seen in Figures 21 and 22 except at a higher total organics applied (378 gm sucrose/day/sq ft). Note the same results are obtained at the higher total organics applied as was seen in Figures 19, 20, 21 and 22. Note also that in all the figures COD removal is at the same efficiency with the same total organics applied regardless of whether the total organic loading is accomplished by a high flow rate at a low waste concentration or a low flow rate at a high waste concentration.

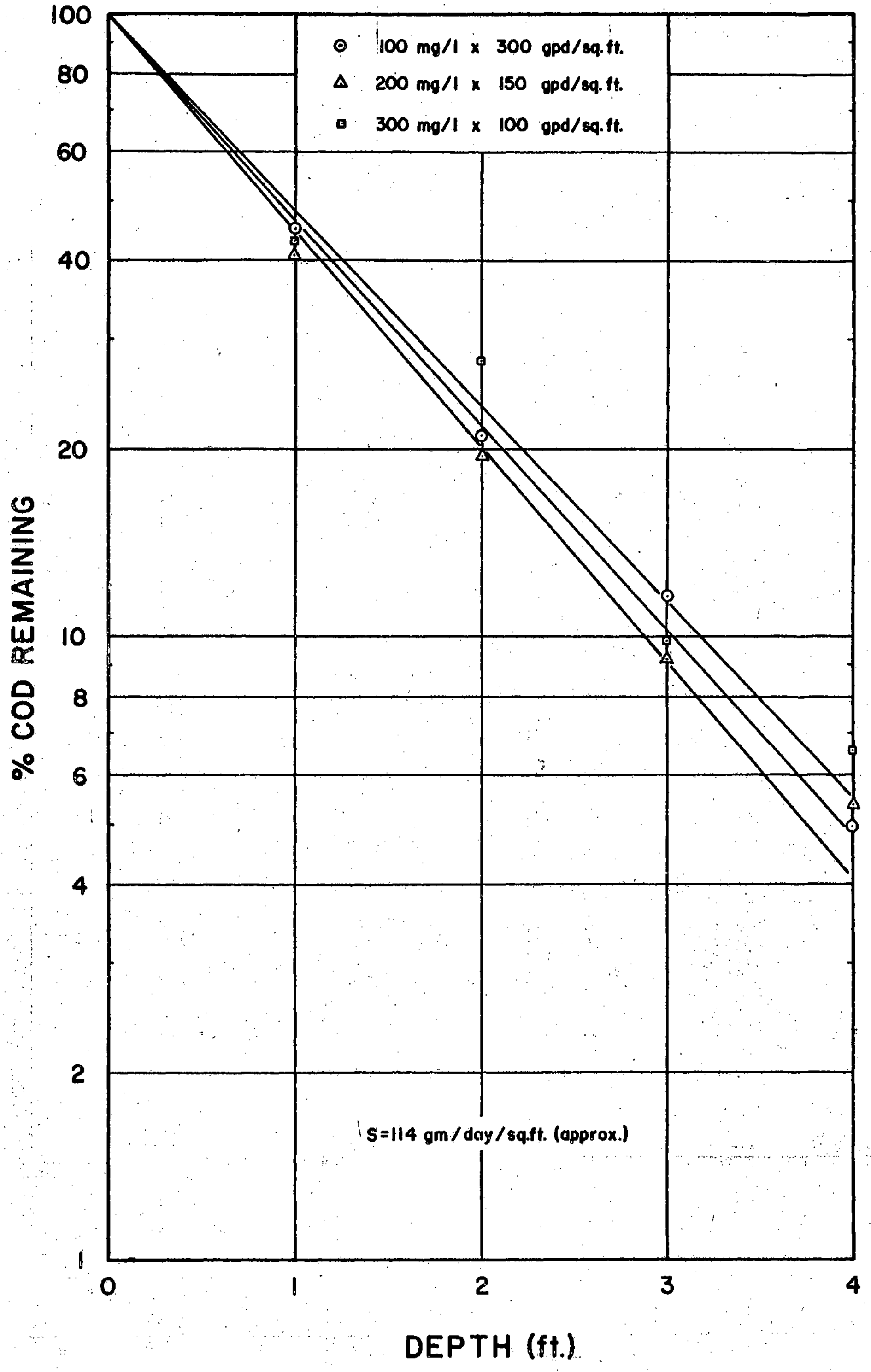


Figure 20. Relationship of % COD Remaining with Depth for Various Organic Concentrations and Flow Rates. Resulting Total Organic Load: 114 gm Sucrose/day/sq ft.

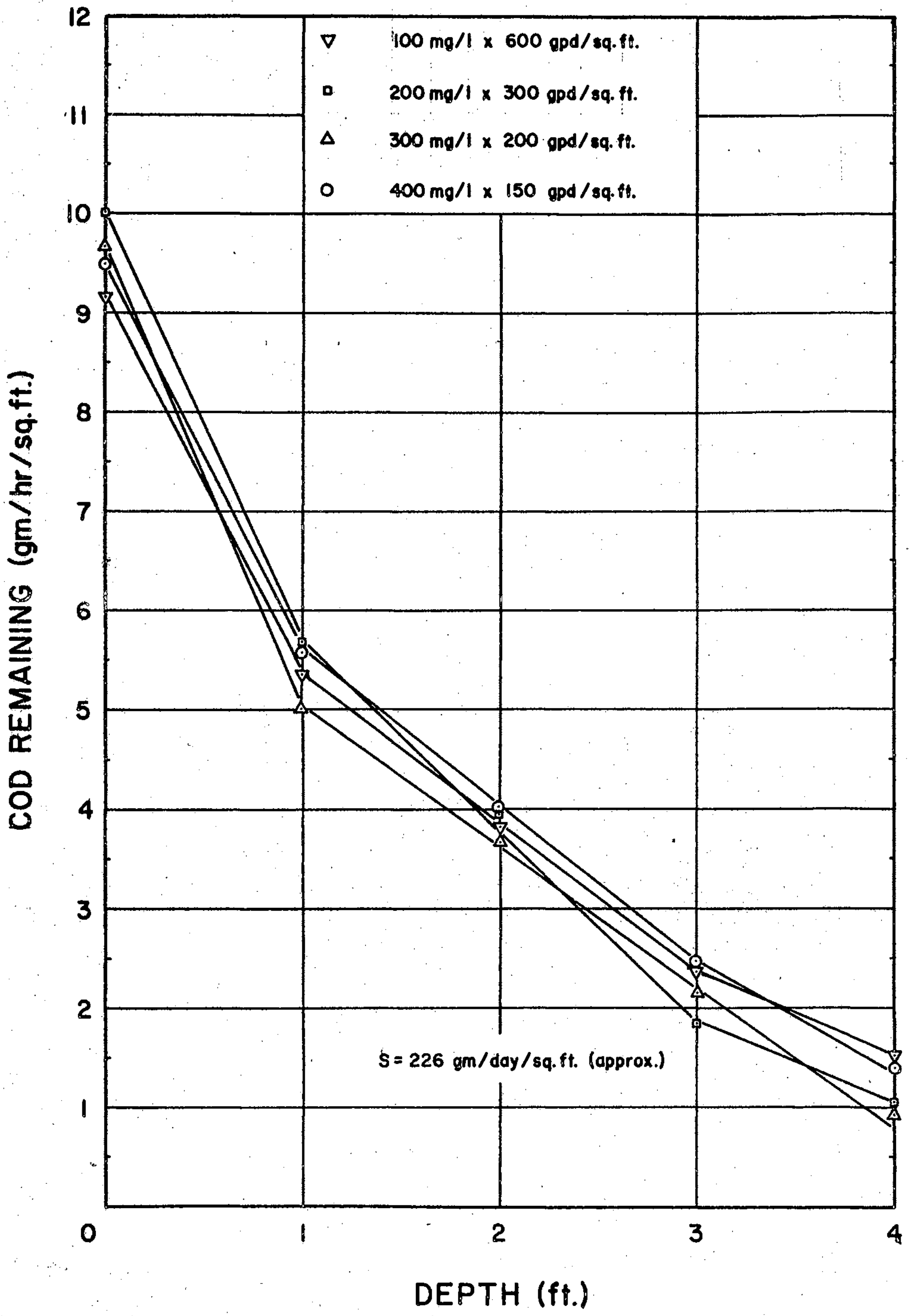


Figure 21. Relationship of COD Remaining (gm/hr/sq ft) with Depth for Various Organic Concentrations and Flow Rates. Resulting Total Organic Load: 226 gm Sucrose/day/sq ft.

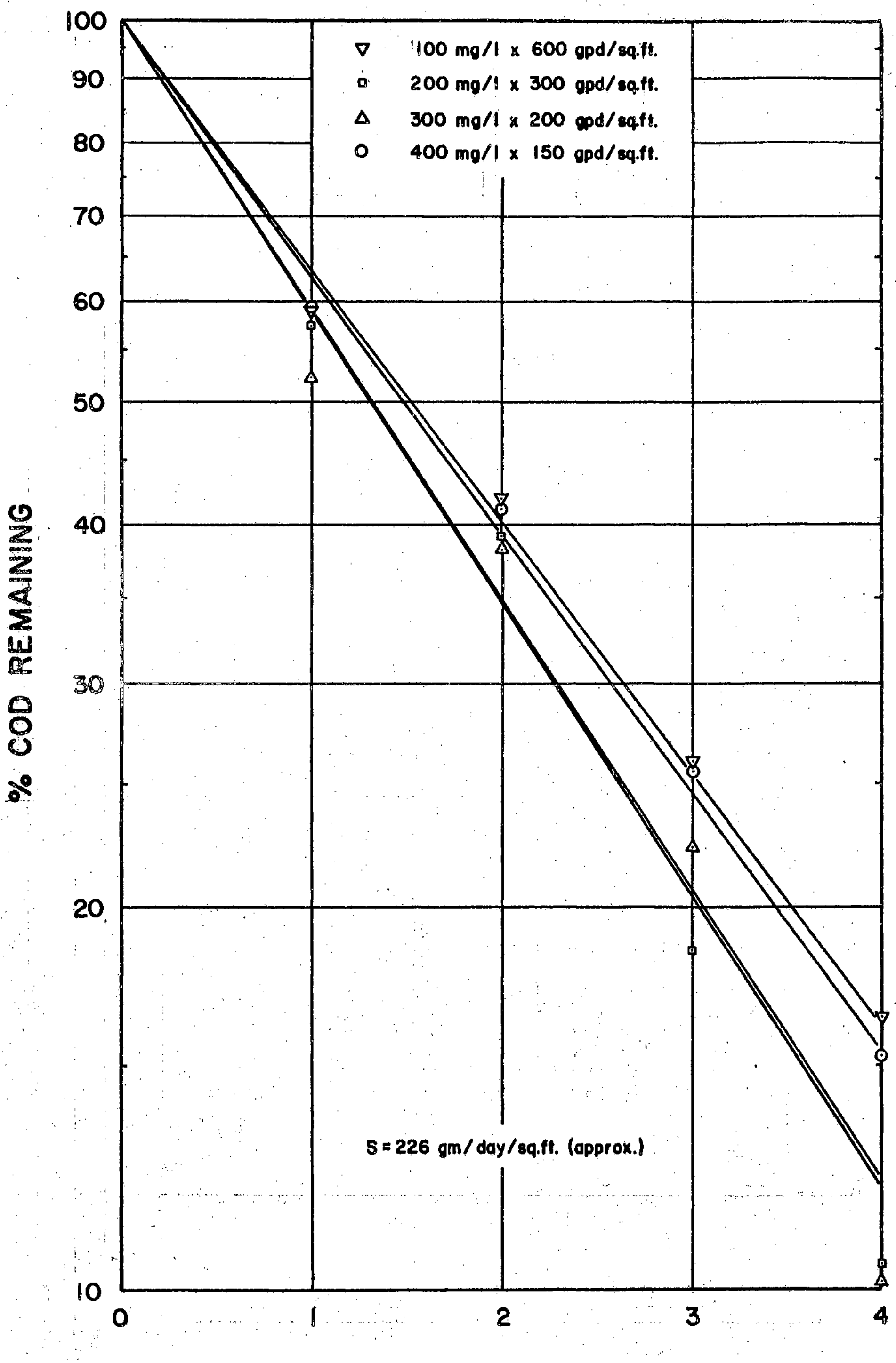


Figure 22. Relationship of % COD Remaining with Depth for Various Organic Concentrations and Flow Rates. Resulting Total Organic Load: 226 gm Sucrose/day/sq ft.

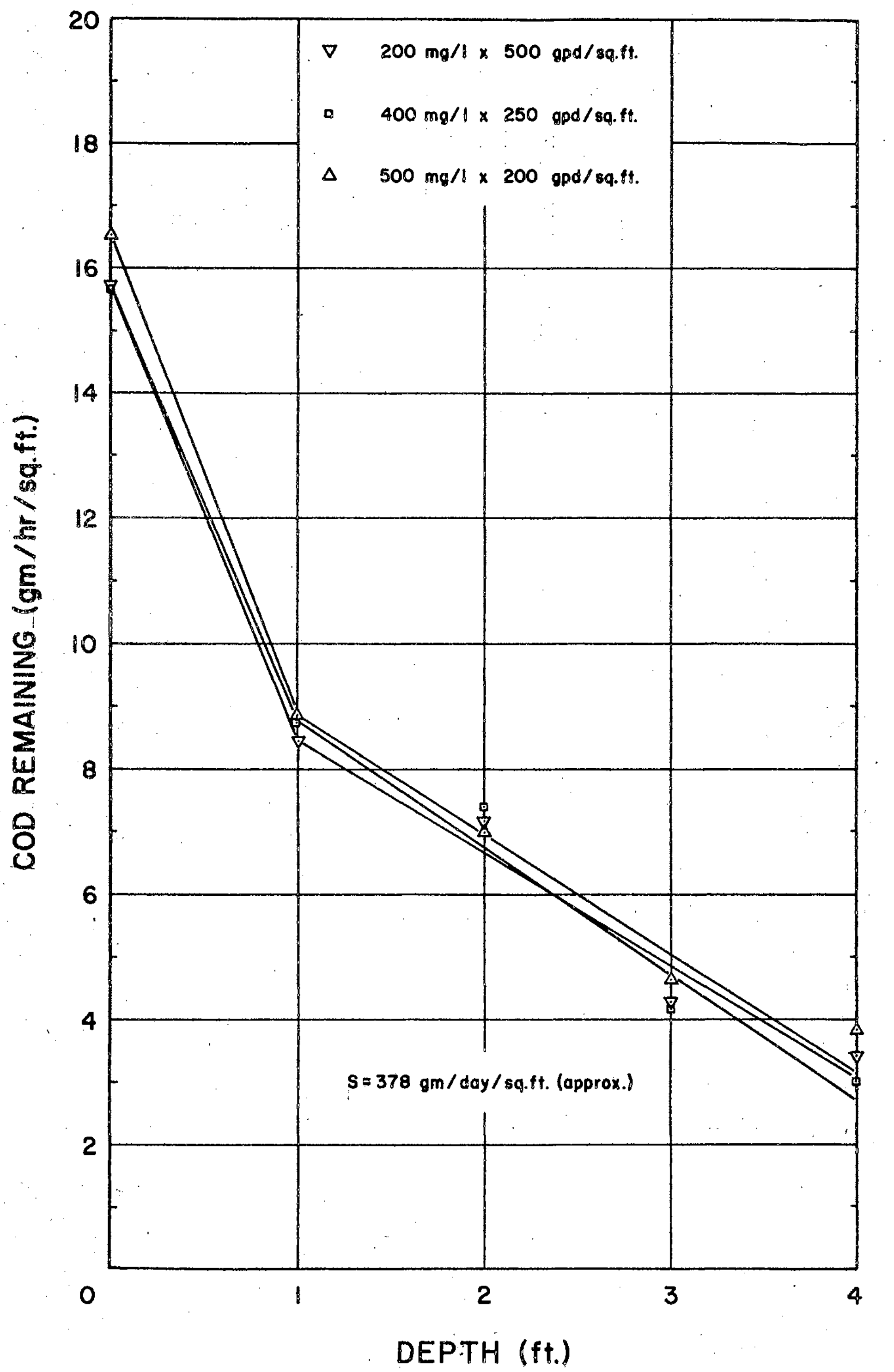


Figure 23. Relationship of COD Remaining (gm/hr/sq ft) with Depth for Various Organic Concentrations and Flow Rates. Resulting Total Organic Load: 378 gm Sucrose/day/sq ft.

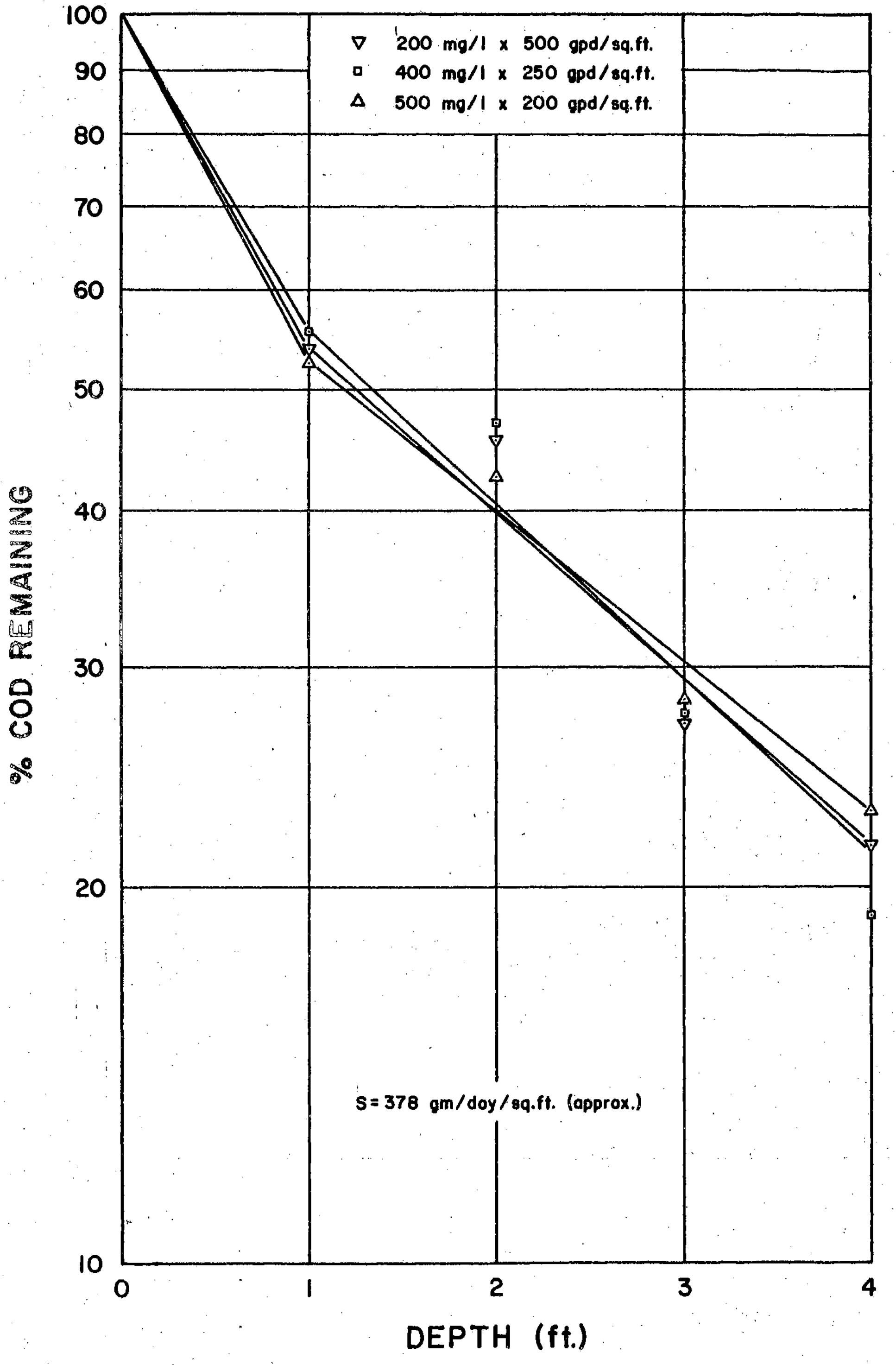


Figure 24. Relationship of % COD Remaining with Depth for Various Organic Concentrations and Flow Rates. Resulting Total Organic Load: 378 gm Sucrose/day/sq ft.

E. Presentation of Data Showing the Amount of Total Organics Removed of the Total Organics Applied at Each Unit of Depth

In the following figures (25, 26, 27, and 28) the total COD removed for a unit of depth was determined by obtaining the difference between the total amount of influent and effluent COD (gm/hr/sq ft) for that particular unit of depth. In these values calculated for a given experiment, the effluent from the first foot of depth becomes the influent to the second foot of depth and so on through the depths of the filter.

Figure 25 shows the amount of total COD removed (gm/hr/sq ft) plotted versus total COD applied (gm/hr/sq ft) for the first foot of filter depth for all of the experiments conducted. Note the curve drawn through the points approaches linearity. The slope of this line is necessarily the efficiency of that unit of filter depth.

Figures 26, 27 and 28 show the same results as Figure 25 for the respective second, third and fourth feet of depth. Consequently, it may be seen that, regardless of the amount of total organics applied to a particular unit of depth, a nearly constant percentage of the total organics applied will be removed by that unit of depth.

F. Presentation of Data Obtained on the Parameters Involved in the Removal Equation

$$Q(S_0-S_1) = \frac{x}{Y} \mu_m \left(\frac{S_1}{K_s+S_1} \right) \qquad (20)$$

Of the parameters involved in the above equation, Y, x, μ_m and K_s are not readily obtainable. Therefore the task was undertaken to determine values for these parameters.

The parameter x is the mass of active biological solids present in a unit of filter depth. Its units are (M). The first method utilized

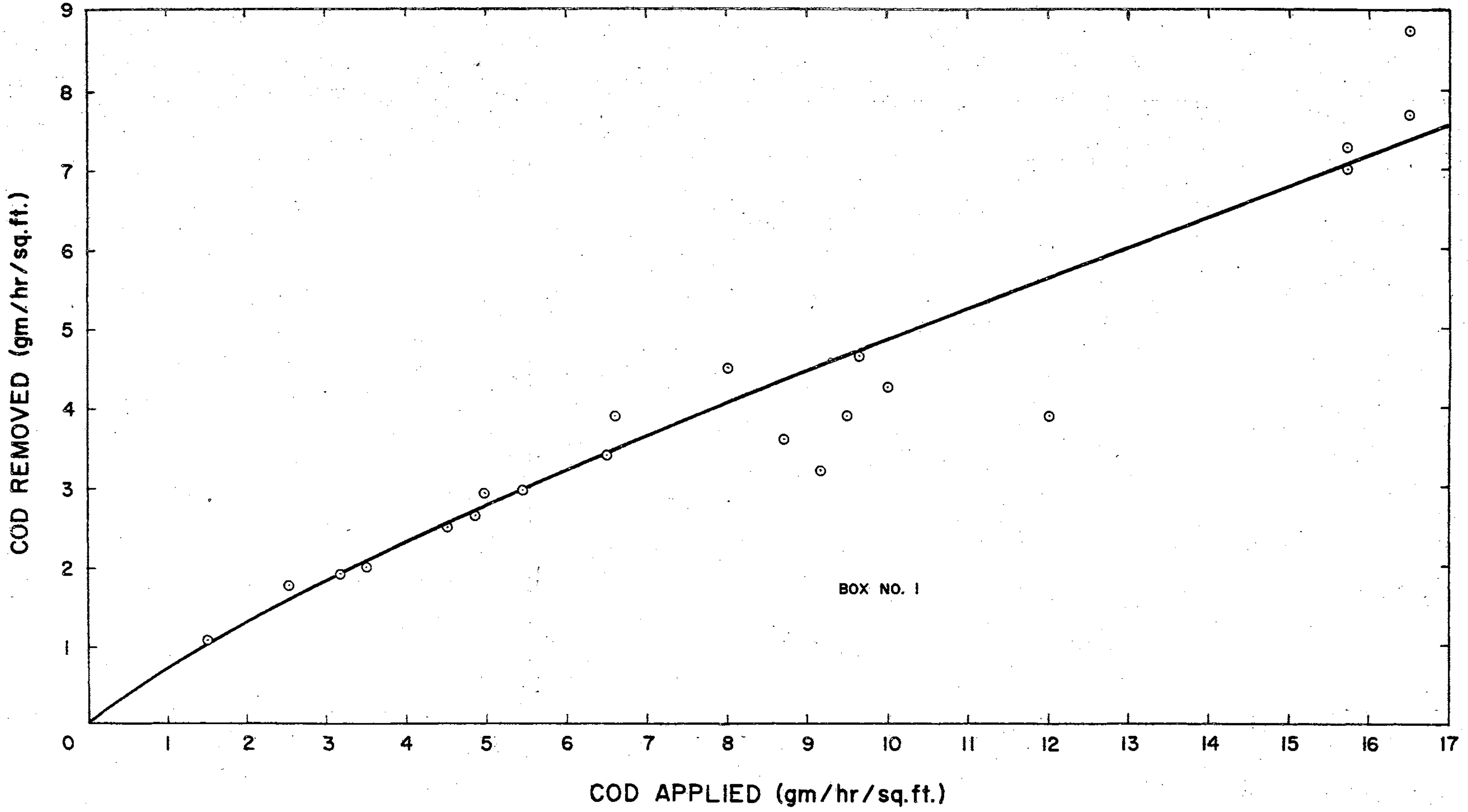


Figure 25. Relationship of COD Removed (gm/hr/sq ft) with COD Applied (gm/hr/sq ft) for the First Foot of Filter Depth.

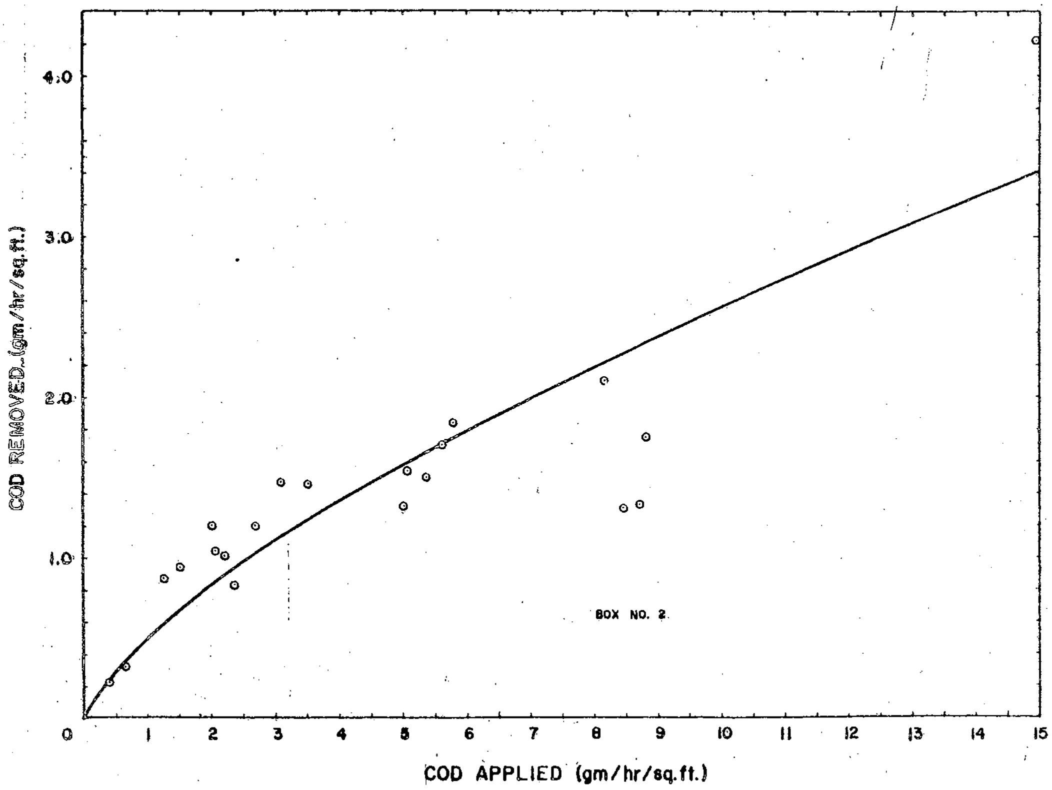


Figure 26. Relationship of COD Removed (gm/hr/sq ft) with COD Applied (gm/hr/sq ft) for the Second Foot of Filter Depth.

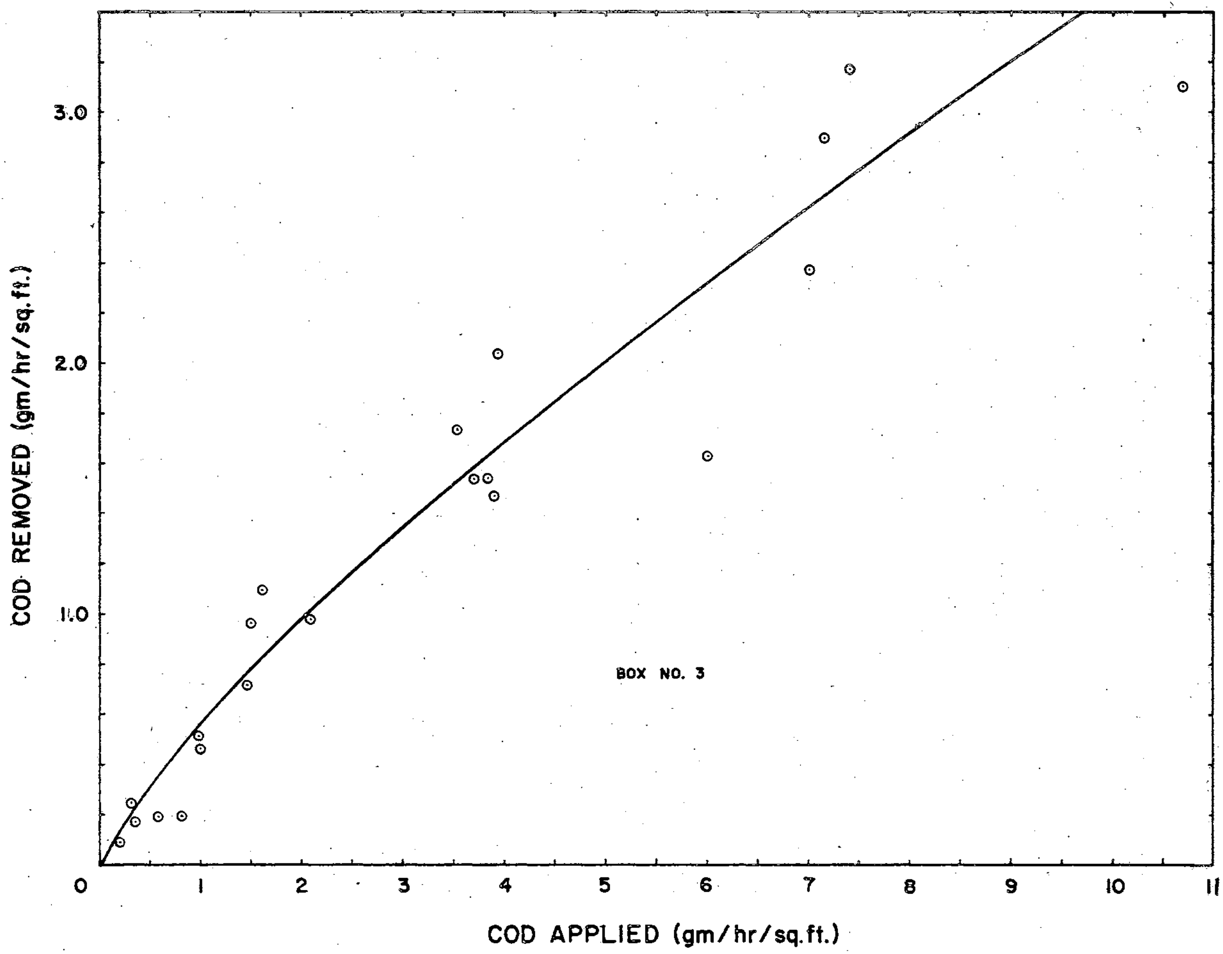


Figure 27. Relationship of COD Removed (gm/hr/sq ft) with COD Applied (gm/hr/sq ft) for the Third Foot of Filter Depth.

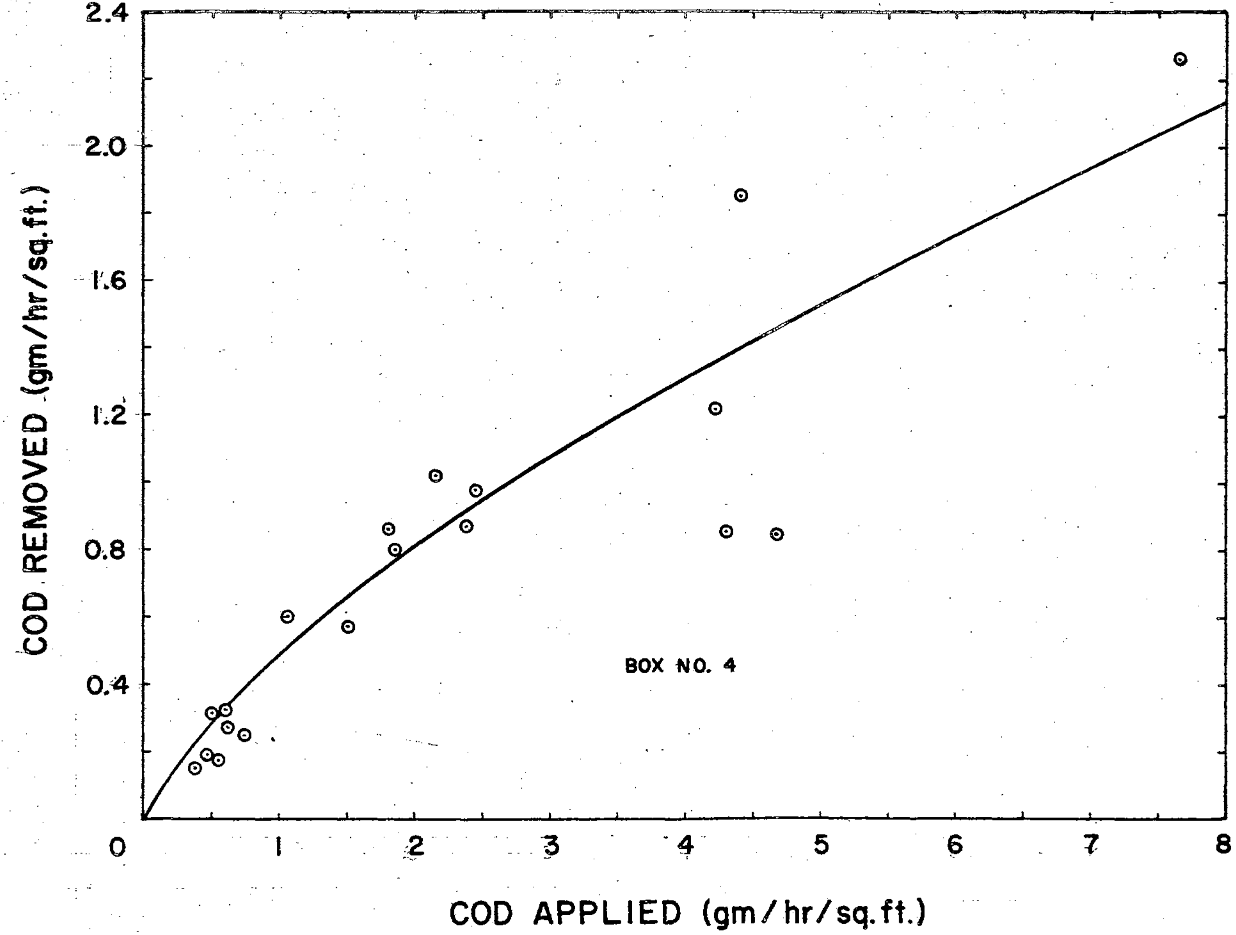


Figure 28. Relationship of COD Removed (gm/hr/sq ft) with COD Applied (gm/hr/sq ft) for the Fourth Foot of Filter Depth.

to attempt the determination of this parameter was to take coupons of known weight and surface area made from the filter medium utilized, insert them into the unit and allow the microorganisms to grow on the coupon. As soon as steady state conditions were reached, (COD removal is constant with time and pH is constant at that given depth for a given organic and hydraulic loading), the coupon would be removed, dried and again weighed. The difference between the initial weight of the coupon and its final weight would be calculated and recorded as dry weight of microorganisms per surface area of coupon utilized. Knowing the surface area afforded by the particular filter medium used and assuming all the available surface area of the filter medium to be covered with a uniform microbial growth, the mass of total biological solids could be determined for that unit of depth. By visual inspection, it was ascertained that a uniform growth of microorganisms was obtained neither on the coupon nor on the filter medium itself. Consequently, this method of determining biological solids was abandoned. Next, a neutron scattering device was utilized to try to determine the mass of active biological solids per unit of depth. Due to the 1/2 inch spacing between the plates of fiberglass medium, the device could not obtain the depth of penetration needed by the fast neutrons to allow one to correlate its readings with the amount of biological solids present. This device has been used with apparent success in rock medium filters (34) for the determination of biological solids. A gamma ray device has been described in the literature (35) which permits the determination of biological solids present on the type of filter medium utilized in this investigation. However, no such device was available to this investigator and its cost prohibited obtaining it for this investigation. Having exhausted all known methods of obtaining a value for this parameter, it was decided to abandon further efforts on this elusive parameter and turn to the study of the remaining parameters Y, μ_m and K_s.

Kornegay and Andrews (18) determined the yield (Y) of their submerged drum, fixed film, completely mixed reactor by measuring the amount of biological solids in the effluent of their reactor. They indicated that after the film thickness and suspended solids reached steady state, the newly formed microorganisms being washed from the wall of the drum represented the mass of microorganisms produced from the observed utilization of glucose. Consequently the yield could be determined by measuring the suspended solids in the effluent.

An attempt was made to obtain cell yield values for each unit of filter depth in a manner similar to that used by Kornegay and Andrews. After the trickling filter reached steady state at a given organic and hydraulic loading, 50 ml samples of effluent were collected from each unit of filter depth. Each sample was filtered through a tared 45 μ pore size membrane filter thus retaining the biological solids on the membrane filter. The filters were dried and weighed and the solids determination made. Knowing the influent and effluent COD of a particular unit of depth, a yield value could be calculated for that unit of filter depth. After a short period of time it became apparent that the sloughing of the filter did not occur at a uniform rate. Hawkes (36) observed the same in a rock medium filter. Therefore, yield values obtained by this method during this investigation were erratic and could not be used.

Consequently, it was decided to determine cell yield values concurrently with growth studies as pointed out in the Materials and Methods section. Gaudy and Rao (37) found in a batch activated sludge unit that cell yield varies for a single substrate and that a statistical range of yields could be employed.

Utilizing the method selected for cell yield determination, the cells suffered a great change in environment. It was realized that yield values obtained in this manner most likely would not be the actual cell yield realized with the cells as a fixed film on the filter medium. Consequently, only two cell yields were determined at each unit of filter depth in order to obtain an idea as to their magnitude. The cell yields obtained the first time from the first, second, third and fourth foot of filter depths were, respectively: 0.67; 0.33; 0.47; and 0.50. The second time cell yields were determined, the respective values obtained were: 0.42; 0.41; 0.396; and 0.425. The cell yield obtained one other time at the one foot depth was 0.29. As can be seen there were great variations observed in the cell yields obtained from one determination to another. The nearly identical values obtained at each unit of depth on the second determinations of cell yields were attributed to mere chance.

Figure 29 is a plot of all the maximum growth rates obtained at each unit of depth throughout the investigation versus the depth at which the determination was made. Note the general decreasing trend of μ_m with depth. A line of best fit was determined by the least squares method to allow selection of μ_m values with depth for calculations to be carried out later.

K_s values were also obtained from the data when determining μ_m. For all depths considered, the range of K_s varied between 21 and 50 mg/l.

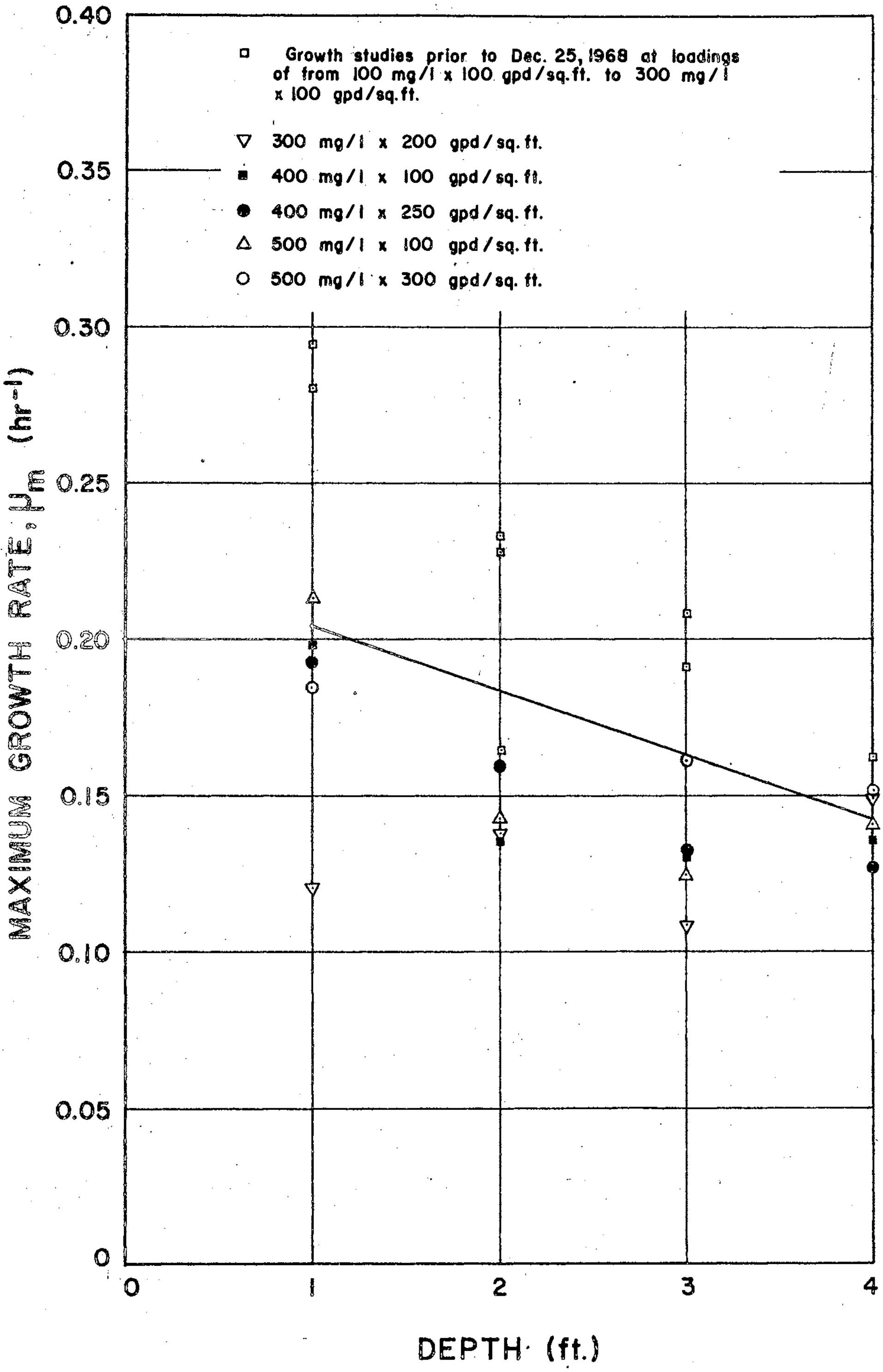


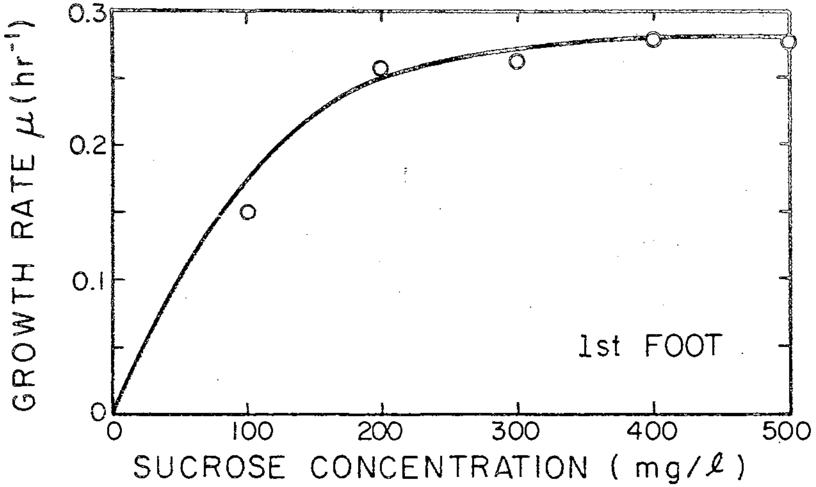
Figure 29. Relationship of Maximum Growth Rate (hr^{-1}) with Depth.

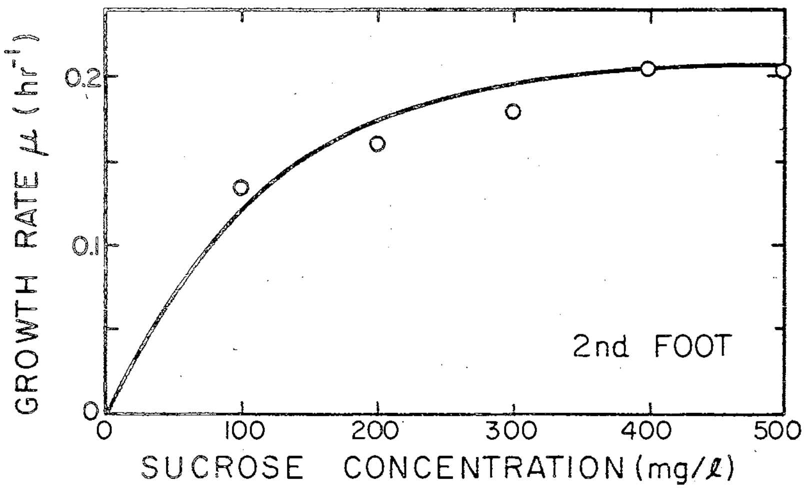
Figure 30 shows typical plots of growth rates versus substrate concentration at each foot of filter depth. The plots provide evidence for the use of the Monod relationship which is a single phase hyperbolic relationship between growth rate and substrate concentration in preference to a linear two phase relationship. This relationship was to be expected, as Peil (38) in earlier work acclimated a sewage seed to sucrose and determined the relationship between growth rate and substrate concentration and concluded that his experimental results provided evidence for application of a single phase hyperbolic relationship between growth rate and substrate concentration in preference to a linear two phase relationship for heterogeneous populations of sewage origin.

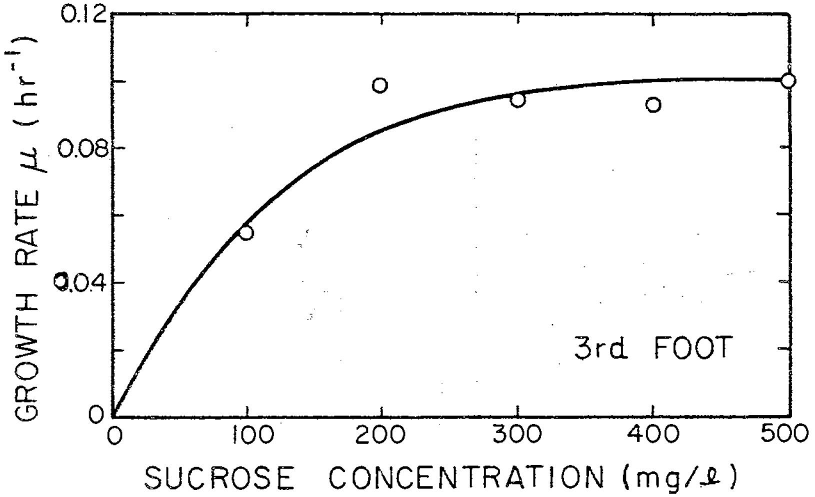
G. Dissolved Oxygen and pH

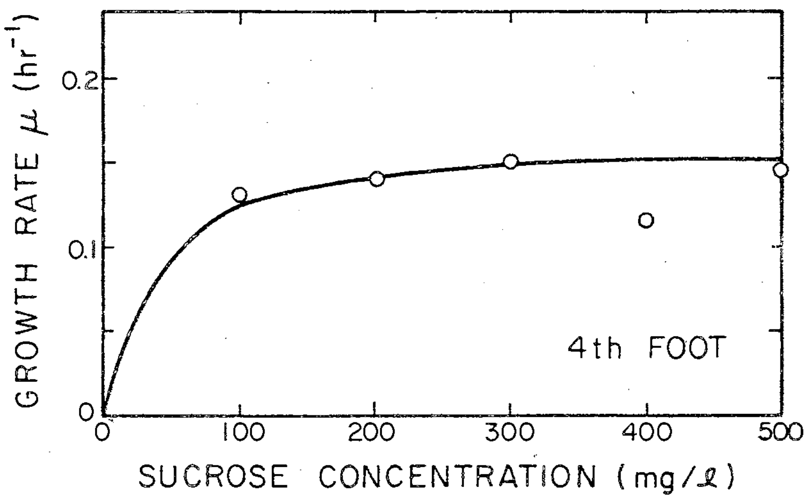
The average effluent D. O. (dissolved oxygen) values obtained at each depth of the filter were, respectively: spray nozzle, 10.6 mg/l; first foot, 7.0 mg/l; second foot, 7.2 mg/l; third foot, 6.8 mg/l; and the fourth foot, 7.1 mg/l. The spray nozzle D. O. was high, due to the fine spray at the nozzle. These levels of D. O. were maintained throughout the course of the investigation except for one experiment at 1000 mg/l of sucrose at 100 gpd/sq ft. For this experiment, the values of the effluent D. O. at each unit of depth were, respectively: spray nozzle, 11.45 mg/l; first foot, 0.3 mg/l; second foot, 4.65 mg/l; third foot, 5.3 mg/l; and the fourth foot, 6.3 mg/l. The pH at each of these respective depths as seen in Table IV was: spray nozzle, 7.72; first foot, 6.0; second foot, 4.93; third foot, 4.78; and the fourth foot, 4.68. It could be that insufficient dissolved oxygen (in total quantity rather than concentration) was present in the waste stream to support

Figure 30. Relationship of Growth Rate μ (hr^{-1}) with Sucrose Concentration (mg/l) at Each Foot of Filter Depth Indicating the Existence of the Monod Relationship at Each Unit of Filter Depth.


GROWTH RATE μ (hr^{-1})
0.3
0.2
0.1
0
0
100
200
300
400
500
SUCROSE CONCENTRATION (mg/ℓ)
1st FOOT


GROWTH RATE μ (hr^{-1})
0.2
0.1
0
0
100
200
300
400
500
SUCROSE CONCENTRATION (mg/ℓ)
2nd FOOT


GROWTH RATE μ (hr^{-1})
0.12
0.08
0.04
0
0
100
200
300
400
500
SUCROSE CONCENTRATION (mg/ℓ)
3rd FOOT


GROWTH RATE μ (hr^{-1})
0.2
0.1
0
0
100
200
300
400
500
SUCROSE CONCENTRATION (mg/ℓ)
4th FOOT

complete aerobic degradation of such a concentrated waste. That is, all the oxygen was depleted in the first foot of depth and the microorganisms became anaerobic, thus elaborating the end products of anaerobic metabolism, namely volatile acids, thus causing a drastic drop in the pH. Note in Table III during this experiment (1000 mg/l feed at 100 gpd/sq ft) there is shown to be a tremendous difference in COD values and anthrone COD values at each unit of depth. Also, for the first time, an appreciable quantity of reducing sugars are present, possibly indicating extracellular cleavage of the α-1,2 bond of sucrose between glucose and fructose. It appears that both D. O. values and pH values observed at various filter depths are a good indication of the degree of treatment achieved by that unit.

Another possibility causing the pH drop with depth could have been a tremendous increase in CO_2 production due to the higher substrate concentrations experienced during the run. The CO_2 would combine with the water forming carbonic acid which, in turn, due to the system's not being buffered, would cause a depression in the pH of the waste. This possibility is unlikely in that looking at Table IV at the runs made at 200 mg/l x 500 gpd/sq ft and at 500 mg/l x 200 gpd/sq ft which are the identical loadings (gm/hr/sq ft) as 1000 mg/l x 100 gpd/sq ft, one can see no drastic change in pH with depth for either of the runs.

In all the other experiments, the pH dropped to its lowest value in the first foot of depth and then increased through the remainder of the depths of the filter. At no time other than in the experiment at 1000 mg/l feed at 100 gpd/sq ft did the pH ever decrease more than 0.8 of a point from the pH determined at the spray nozzle.

CHAPTER VI

DISCUSSION

In the preceding chapters of this report various studies have been described, methods of study have been shown and the results of these experiments were presented. In this chapter, the significance of these experiments and results will be discussed.

A. First Order Decreasing Rate Removal of Organics in a Trickling Filter

Velz (3), Eckenfelder (13, 14) and others (2, 8, 39) claim that the first order decreasing rate removal of organics in a trickling filter occurs due to the change in treatability of the waste with depth. That is, the more easily removable substrates are removed in the upper portions of the filter, leaving the organics which are harder to metabolize for removal in the lower depths of the filter. Consequently, the rate of removal decreases as the more easily assimilable substrates are removed with depth.

As shown in the results section, first order decreasing rate removal was observed for the single substrate sucrose. It was noted that in most experiments at low total organic loadings (gm/hr/sq ft) there was very little difference observed in the COD and anthrone COD values at each unit of depth. Therefore, the same type of substrate (carbohydrate) was applied to each unit of depth and first order decreasing rate removal was observed at all times. From this, it may be reasoned that the first order decreasing rate removal of an organic waste must involve a more complicated causation than that proposed by the previous investigators. At high total organic loadings (gm/hr/sq ft) after the first foot of filter depth, the ΔCOD calculated between the COD values and the anthrone COD values remains relatively constant throughout the remainder of the filter depths. This indicates possibly a non-degradable waste fraction produced in the first foot of filter depth which is never removed by the filter. It is conceivable that this non-degradable waste fraction could affect the organic removal rate realized in the lower depths of the filter.

Another possibility proposed by other investigators (25, 27, 28, 40) is that the trickling filter process is mass transfer limited. That is the concentration of the waste is the driving force for its removal. In the upper portions of the filter, where the concentration of waste is the greatest, the greatest removal rate occurs. As the concentration of the waste decreases with depth, due to removal by the microorganisms in the upper portions, the rate of removal decreases thus giving first order decreasing rate removal with depth. Most of this work has been accomplished by investigators utilizing inclined plane models as an approximation of the trickling filter process.

To test this hypothesis, equation (22) which was derived previously will be used:

$$S_1 = S_o - \frac{X}{Y}\ \mu_m \frac{1}{Q} \left(\frac{S_1}{K_s + S_1} \right) \tag{22}$$

This equation holds for any point at steady state in a trickling filter. For this illustration, the influent COD concentration will be 500 mg/l at 300 gpd/sq ft (47.4 l/hr/sq ft). This high concentration and flow rate was selected since it was observed during the investigation that this was sufficient loading to assure that all levels of the filter were covered with a prolific slime growth. In order to test the hypothesis the biological solids must be assumed to be uniform throughout the depths of the filter. It is recognized that in an actual trickling filter the solids will not remain uniform throughout the depths of the filter but will decrease as the available substrate is decreased. However, if one accepts the theory of mass transfer limitation, it is also necessary to accept that the biological solids are uniform with depth in a trickling filter. Therefore, uniform solids throughout the filter are being assumed here to illustrate a point. Schulze (41) has used this same assumption when he proposed the theory that the trickling filter process is an adsorption process where hydraulic loading and depth determine contact time and this in turn determines the level of efficiency with which the process operates. This theory has been accepted by many and Schulze's assumption of uniform solids throughout the trickling filter has not been questioned by other workers in the field. Eckenfelder (13) has also accepted the idea that in many cases the filter film is uniformly distributed throughout the filter and has reported that the filter film was approximately uniformly distributed in studies conducted by McDermott in a 23 foot column of 3 1/2 inch balls and by Schulze on his screen filter. Therefore, the assumption in this hypothesis that the biological solids remain constant throughout the filter is not being assumed as a fact, but rather as a point to demonstrate that the first order decreasing rate removal of organics in a trickling filter is dependent upon a change in biological solids with depth.

It will also be assumed that μ_m and Y are constant with depth. Therefore the term $(\frac{x}{Y}\mu_m)\frac{1}{Q}$ of equation (22) becomes a constant throughout the filter at all depths for a given flow rate. From Andrews and Kornegay's work (18) it can be calculated that the density of biological solids, 70 μ thick (assuming they are all active) is 616 mg/sq ft. As pointed out previously, each unit of depth of the filter in this investigation afforded 50 sq ft of surface area. Consequently each unit of depth affords 30,800 mg of active biological solids which is the term x. Assume a cell yield of 0.4 and a maximum growth rate of 0.2 hr^{-1}. Substituting these values into the term $(\frac{x}{Y}\mu_m)\frac{1}{Q}$, its numerical value becomes 325.

K_s, as shown previously, varied from 21 to 50 mg/l. The value of K_s will be assumed to be 34 mg/l.

Substituting these values for their respective symbols, equation (22) becomes:

$$S_1 = S_o - 325\left(\frac{S_1}{34+S_1}\right) \qquad (31)$$

which is now an equation in which S_1, the concentration of the effluent COD is dependent entirely on the concentration of the influent COD, S_o. As the amount of solids were figured on one unit of depth, so will the effluent COD value S_1 be figured for each unit of depth over a 4 foot depth. Entering the first foot of the filter, the influent COD assumed was 500 mg/l. Substituting this into equation (31) and solving for S_1, the quadratic equation develops where:

$$S_1^2 - 141\,S_1 - 17000 = 0 \qquad (32)$$

and

S_1 = 219 mg/l at the 1st foot of filter depth

S_1 then becomes the influent COD concentration to the second foot of unit depth and

$$S_2 = S_1 - 325 \left(\frac{S_2}{34+S_2}\right) = 219 - 325 \left(\frac{S_2}{34+S_2}\right) \qquad (33)$$

then: $$S_2^2 + 140\ S_2 - 7446 = 0 \qquad (34)$$

and $S_2 = 41$ mg/l at the 2nd foot of filter depth

S_2 then becomes the influent COD concentration to the third foot of filter depth and it is found that $S_3 = 8.5$ mg/l at the 3rd foot of filter depth and $S_4 = 0.8$ mg/l at the 4th foot of filter depth.

If the trickling filter process is mass transfer limited, then by plotting the values of COD remaining (mg/l) at each unit of depth versus the depth on semilog graph paper, first order decreasing rate removal should be described by a single straight line connecting all the points. In Figure 31, curve 1, which is a semilog plot of the previously calculated COD concentrations at each depth versus their respective depths, such is not the case. Therefore, it appears that according to equation (22), first order decreasing rate removal of COD with depth is not a result of the trickling filter process being mass transfer limited.

In order to determine how K_s would change the amount of COD remaining at each foot of depth, the average of all K_s values determined at each foot of depth during this investigation was calculated and substituted into equation (22). The values of K_s at each of the respective first, second, third and fourth foot of depths were 50 mg/l, 35 mg/l, 24 mg/l and 21 mg/l. All other parameters were held constant at the values previously mentioned and the amount of COD remaining was calculated at each foot of depth: $S_1 = 232.5$ mg/l; $S_2 = 47$ mg/l; $S_3 = 3.7$ mg/l; $S_4 = 0.25$ mg/l.

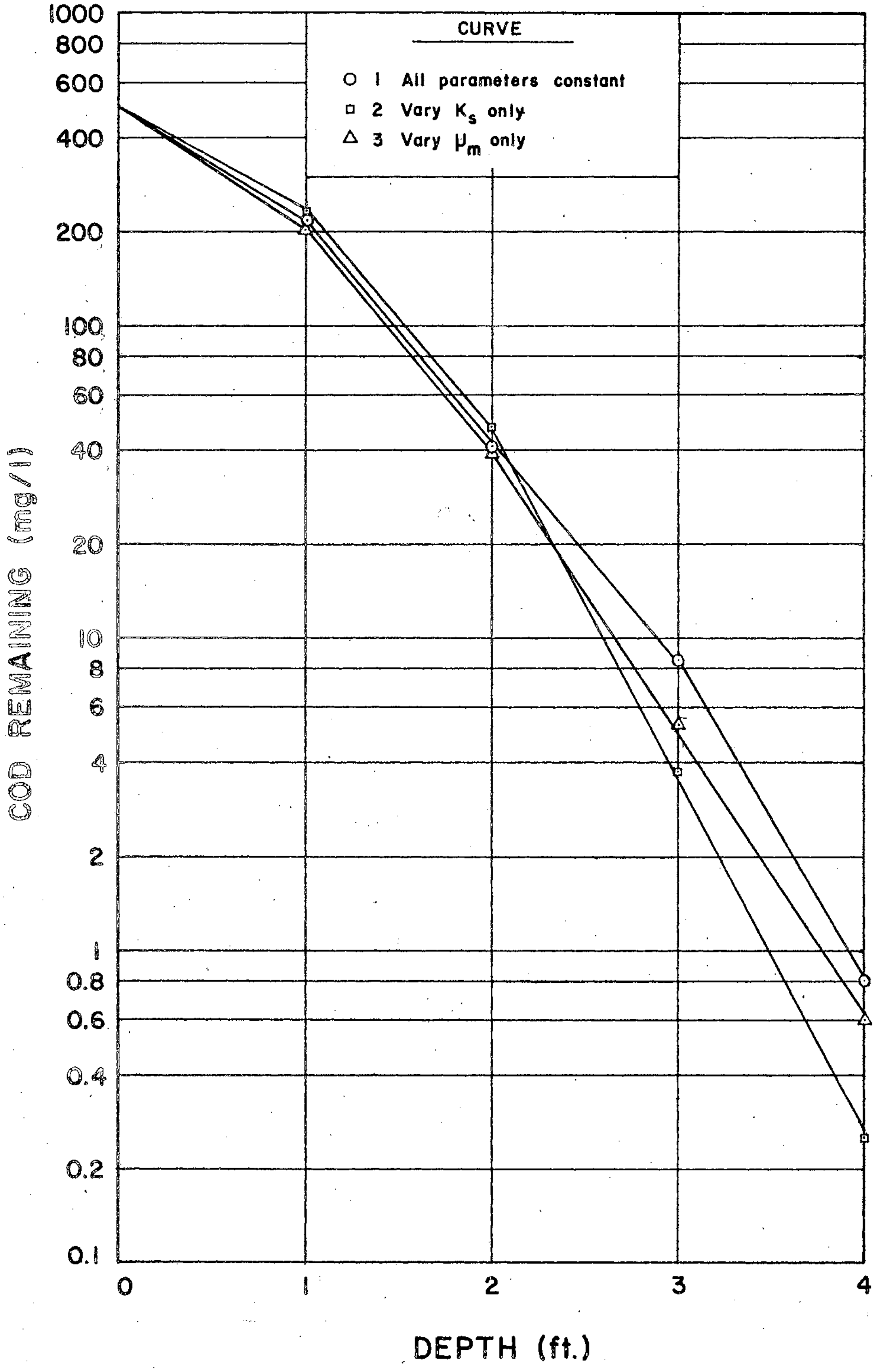


Figure 31. Relationship of Calculated COD Remaining with Depth when Varying Selected Parameters of Equation 22.

These values are shown in Figure 31 plotted as curve 2. As can be seen, varying K_s with depth had little effect on the general shape of the COD remaining curve.

In Figure 29, from the line of best fit (by least squares method) of the data, values for μ_m may be selected at each unit of depth. They are: first foot, 0.204 hr^{-1}; second foot, 0.184 hr^{-1}; third foot, 0.163 hr^{-1}; and fourth foot, 0.143 hr^{-1}. By maintaining all other parameters constant, K_s = 34 mg/l; Q = 47.4 l/hr; Y = 0.4; and x = 30,800 mg solids; S_0 = 500 mg/l and varying μ_m at each depth, the COD remaining at each unit of depth may be calculated from equation (22). The values of COD remaining at each unit depth were: S_1 = 208.5 mg/l; S_2 = 41 mg/l; S_3 = 5.2 mg/l; and S_4 = 0.6 mg/l. These values are shown plotted as curve 3 in Figure 31. Again, it can be seen that varying this parameter (μ_m) has little effect on the shape of the COD remaining curve.

As cell yield is generally considered a constant within a statistical range of values it will not be considered further. Therefore, the only other parameter left in equation (22) to explore is the biological solids x. By varying all the other parameters singly in equation (22) it was seen that no one parameter caused a variation in the shape of the COD remaining curve.

Extracting actual data of COD remaining at each unit of depth from Table III and holding all other parameters in equation (22) constant, the amount of biological solids present at each unit of depth may be calculated where: μ_m = 0.2; Y = 0.4; K_s = 34, and the remainder of the parameters are extracted from Table III at various initial concentrations of substrate and various flow rates. Table V shows the values of

TABLE V

BIOLOGICAL SOLIDS, MICROORGANISM SURFACE AREA AND CUMULATIVE MICROORGANISM SURFACE AREA CALCULATED AT EACH UNIT OF FILTER DEPTH UTILIZING EQUATION 22 AT VARIOUS FLOW RATES AND FEED CONCENTRATIONS

		Depth - Feet											
		1			2			3			4		
Feed Conc. mg/l	Flow rate gpd/ft^2	Solids mg	Solids area - sq ft	Cumulat. area - sq ft	Solids mg	Solids area - sq ft	Cumulat. area - sq ft	Solids mg	Solids area - sq ft	Cumulat. area - sq ft	Solids mg	Solids area - sq ft	Cumulat. area - sq ft
100	300	10609	17.2	17.2	3471	5.64	22.84	7778	12.6	35.44	1947	3.16	38.6
200	300	9901	16.1	16.1	4727	7.7	23.8	7815	12.7	36.5	4106	6.7	43.2
500	300	17890	29	29	9696	15.7	44.7	7431	12	56.7	5909	9.6	66.3
500	200	17422	28.3	28.3	4000	6.5	34.8	5823	9.45	43.25	2183	3.55	46.8
500	100	10400	16.9	16.9	3745	6.08	22.9	2887	4.7	27.6	2559	4.16	31.76

biological solids obtained at each unit of depth for the various organic and hydraulic loadings. Assuming a 70 μ active thickness of microorganisms on the filter and a density of 95 mg/cm^3 (dry weight) (18) for the microorganisms, the surface area of microorganisms present in each unit of filter depth was calculated and also presented in Table V. By adding together the microorganism surface area available at each unit of depth, a cumulative microorganism surface area is obtained which may be plotted versus depth as seen in Figures 32 and 33. Figure 32 shows the cumulative microorganism surface area plotted versus depth for a variety of substrate concentrations at a constant hydraulic loading. As can be seen, an increase in the substrate concentration causes an increase in the cumulative microorganism surface area at each unit of depth.

Figure 33 shows the cumulative microorganism surface area plotted versus depth for a variety of flow rates at a constant substrate concentration. As can be seen, an increase in flow rate causes an increase in the cumulative microorganism surface area at each unit of depth. From visual inspection of the model filter during the course of this investigation, it was observed that the greatest mass of microorganisms appeared in the first foot of the filter and decreased thereafter.

In Figure 31 it was seen that varying μ_m or K_s in turn with depth, in equation (22) did not appreciably change the COD remaining at each unit of depth as compared to the calculated COD remaining at each unit of depth when all parameters were held constant. That is, their effect on the shape of the COD remaining curve when considered over the range of values selected for each in this presentation is negligible.

Figure 32. Relationship of Cumulative Microorganism Surface Area with Depth Calculated from Actual Data Utilizing Equation 22 at a Constant Flow Rate and Varying Organic Concentrations.

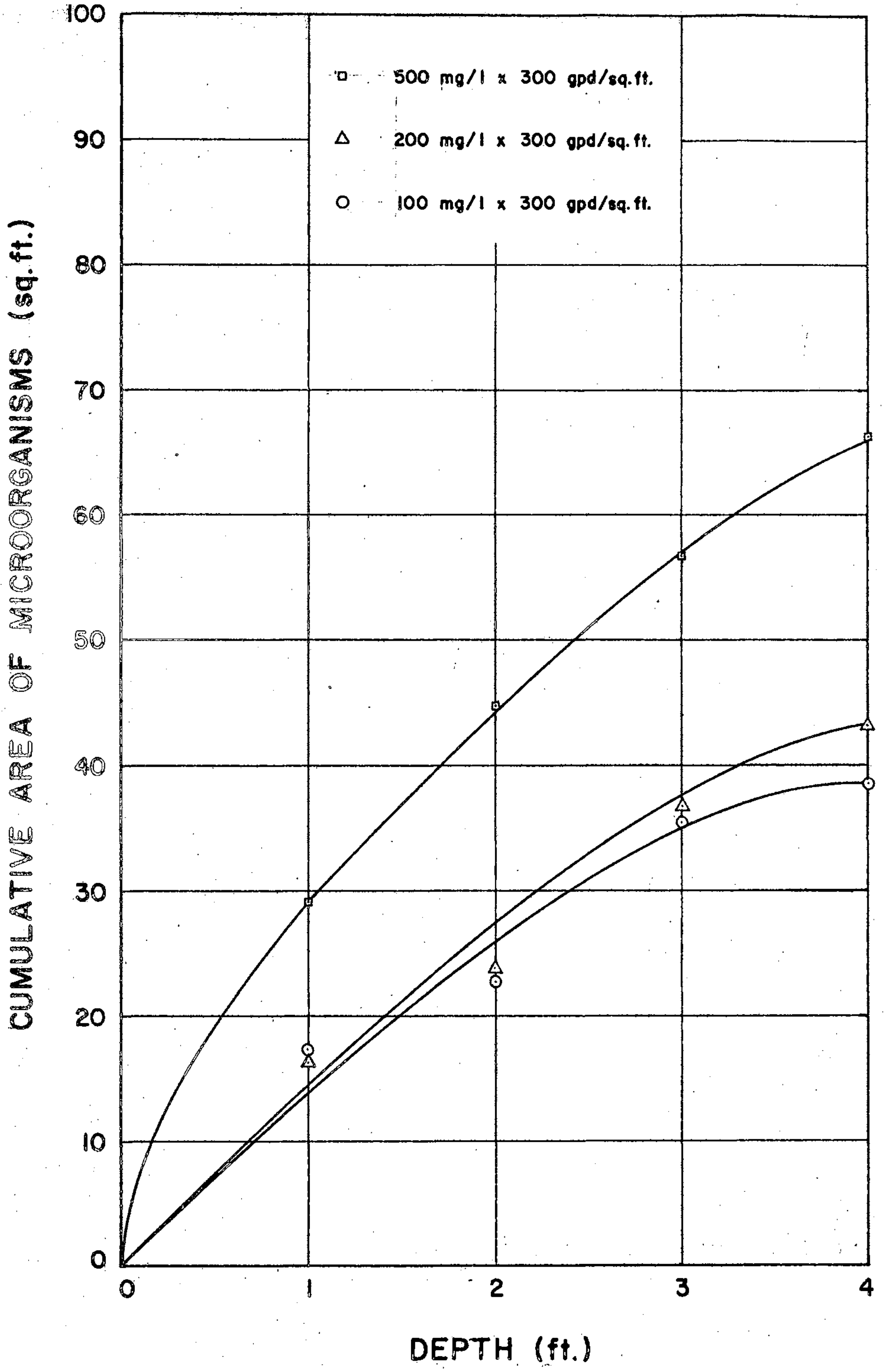
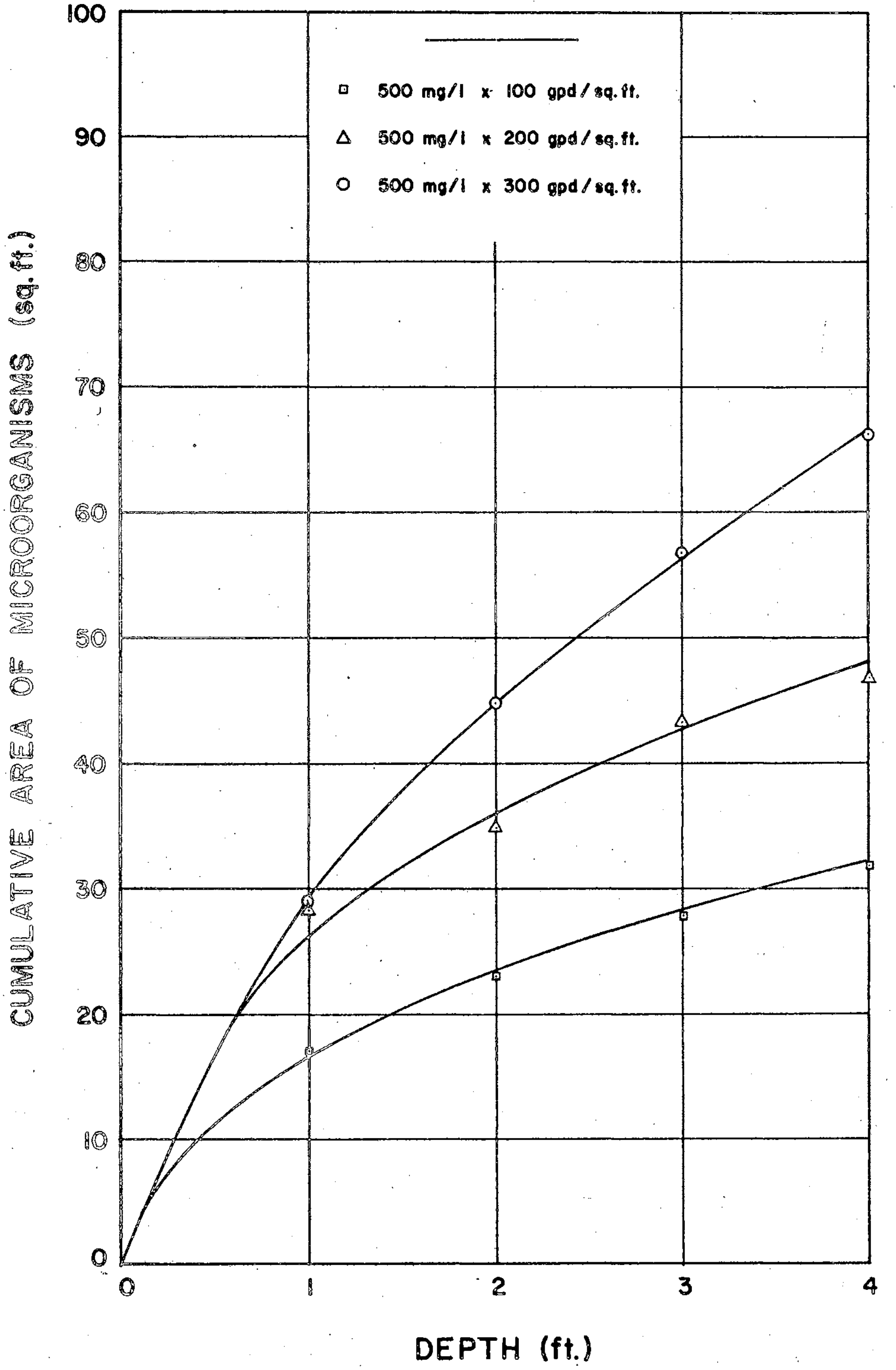

□ 500 mg/l x 300 gpd/sq.ft.
△ 200 mg/l x 300 gpd/sq.ft.
○ 100 mg/l x 300 gpd/sq.ft.
CUMULATIVE AREA OF MICROORGANISMS (sq.ft.)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
DEPTH (ft.)

Figure 33. Relationship of Cumulative Microorganism Surface Area with Depth Calculated from Actual Data Utilizing Equation 22 at a Constant Organic Concentration and Varying Flow Rates.


500 mg/l x 100 gpd/sq.ft.
500 mg/l x 200 gpd/sq.ft.
500 mg/l x 300 gpd/sq.ft.
CUMULATIVE AREA OF MICROORGANISMS (sq.ft.)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
DEPTH (ft.)

Therefore, it must be that the amount of biological solids or the amount of microorganism surface area in a filter is the prime factor in the removal of organics realized in a trickling filter. Also, the biological solids varying with depth must be responsible for the characteristic first order removal of organics encountered in trickling filters.

B. The Role of Organic Loading Versus Hydraulic Loading in the Removal Rate of Organics in a Trickling Filter

As previously mentioned, conflicting ideas are afforded by numerous investigators on the relative importance of these two parameters on trickling filter performance.

Schulze (10), Eckenfelder (15) and others (21, 5) contend that BOD or COD removal is related primarily to the hydraulic loading or flow rate.

Galler and Gotaas (16), Sorrels and Zeller (26), Germain (17) and others contend that the concentration of the waste or organic loading is the controlling factor in the removal of COD or BOD in a filter.

From data previously presented in figure sets 6, 7, 8, 9 and 10, when the hydraulic loading was increased with the organic concentration held constant, the rate of COD removal decreased and approached a limiting value. From figure sets 11, 12, 13, 14 and 15 it was observed that as the organic loading was increased, with the hydraulic loading held constant, the rate of COD removal again decreased and approached a limiting value.

COD removal rates were calculated from the previously mentioned figure sets and plotted versus the concentration of the waste (mg/l) at the spray nozzle in Figure 16 and versus the flow rate (gpd/sq ft) in

Figure 17. In both of these figures a family of curves developed and generally approached one another thus exhibiting a saturation phenomenon or a limiting load beyond which the removal rate did not decrease. Also there was observed a definite relationship between COD removal rate and either of the two parameters, organic loading (mg/l) or hydraulic loading (gpd/sq ft).

Up to this point, it was observed that both organic loading and hydraulic loading were related to the removal of organics in a trickling filter. However, it could not be ascertained if these two parameters were independent of one another, each exerting its own influence on organic removal rate or whether they were acting in combination exerting their effect on organic removal rate.

Figure 18 showed the removal rates of the COD remaining curves plotted versus the total amount of COD at the spray nozzle expressed as gm COD/hr/sq ft. By expressing COD at the spray nozzle in these units, the effect of the combination of the concentration of the waste and its flow rate could be observed. As was seen, rather than a family of curves developing, one continuous relationship was observed indicating that it might be well to consider the effect on COD removal rate of the two parameters in combination rather than each one separately. Also it was seen that the removal rates approached a constant value at the higher total organic loadings (gm/hr/sq ft). This indicated that the filter was becoming saturated and operating at a constant removal rate regardless of the quantity of total organics (gm/hr/sq ft) applied.

Figures 19 through 24 were plotted to determine whether COD removal rate is affected by the two parameters, organic loading (mg/l) and hydraulic loading (gpd/sq ft) acting separately or if their effect is actually caused by the two parameters acting in combination expressed as total organics applied (gm/hr/sq ft). From these figures it was seen that COD removal depends on the amount of total COD applied (gm/hr/sq ft) rather than its concentration or its hydraulic rate through the filter. COD removal is at the same efficiency with the same total organics applied regardless as to whether the total organic loading is accomplished by a high flow rate at a low waste concentration or a low flow rate at a high waste concentration. This is in absolute agreement with Ingram's (7) conclusions.

Figures 25 through 28 are plots at each unit of filter depth showing the amount of total COD removed (gm/hr/sq ft) plotted versus total COD applied (gm/hr/sq ft). In each figure the slope of the curve drawn through the points was seen to be the efficiency of that unit of filter depth. It was pointed out that regardless of the amount of total organics applied (gm/hr/sq ft) to a particular unit of depth, a nearly constant percentage of the total organics applied will be removed by that unit of filter depth.

Schulze (8) made two sets of runs at two different hydraulic loadings and various concentrations of waste on his vertical screen trickling filter. He plotted the data in a manner identical to the above mentioned plots (lb BOD removed/day/cu yd versus lb BOD applied/day/cu yd) and concluded that filter efficiency was independent of the organic loading up to 10.9 lb BOD/day/cu yd. In order to determine if Schulze's conclusions were valid, two flow rates, 100 and 300 gpd/sq ft, were selected and the initial feed concentration was varied for each of these two flow rates. The influent and effluent concentrations of the waste in the 4 foot deep filter were determined and knowing the flow rate, the COD applied (gm/hr/sq ft) was plotted versus the COD removed (gm/hr/sq ft) in Figure 34A. The plot is identical to that obtained by Schulze except that he shows two lines (one for each of the hydraulic flow rates) where actually his data would have fitted one continuous curve, rather than the two straight lines. From this Schulze concluded that filter efficiency was independent of the organic loading (gm/hr/sq ft).

For comparison purposes, two feed concentrations 100 and 500 mg/l were selected. Each in turn was held constant and the flow rate (gpd/sq ft) varied over a selected range. Again the COD applied (gm/hr/sq ft) was plotted versus the COD removed (gm/hr/sq ft) in Figure 34B. The identical relationship was obtained as seen in Figure 34A. Consequently, from this we could conclude that filter efficiency is independent of the hydraulic loading.

Figure 34C shows the data from both Figure 34A and 34B plotted together. As can be seen, all the data from both plots A and B can be represented by one continuous curve indicating they are related.

Schulze (8), by not plotting the data as seen in Figure 33B, formed an erroneous conclusion. What the data actually show as seen in Figure 34C is that regardless of the amount of total organics applied to a filter a slightly decreasing percentage of the total organics applied (gm/hr/sq ft) will be removed by that filter. Also the effect on filter performance of the two parameters organic concentration (mg/l) and flow rate (gpd/sq ft) is exerted by the two in combination as total organics applied rather than the two acting independent of each other.

C. Discussion of Design Formulations

Considered in this discussion will be the formulas proposed by the

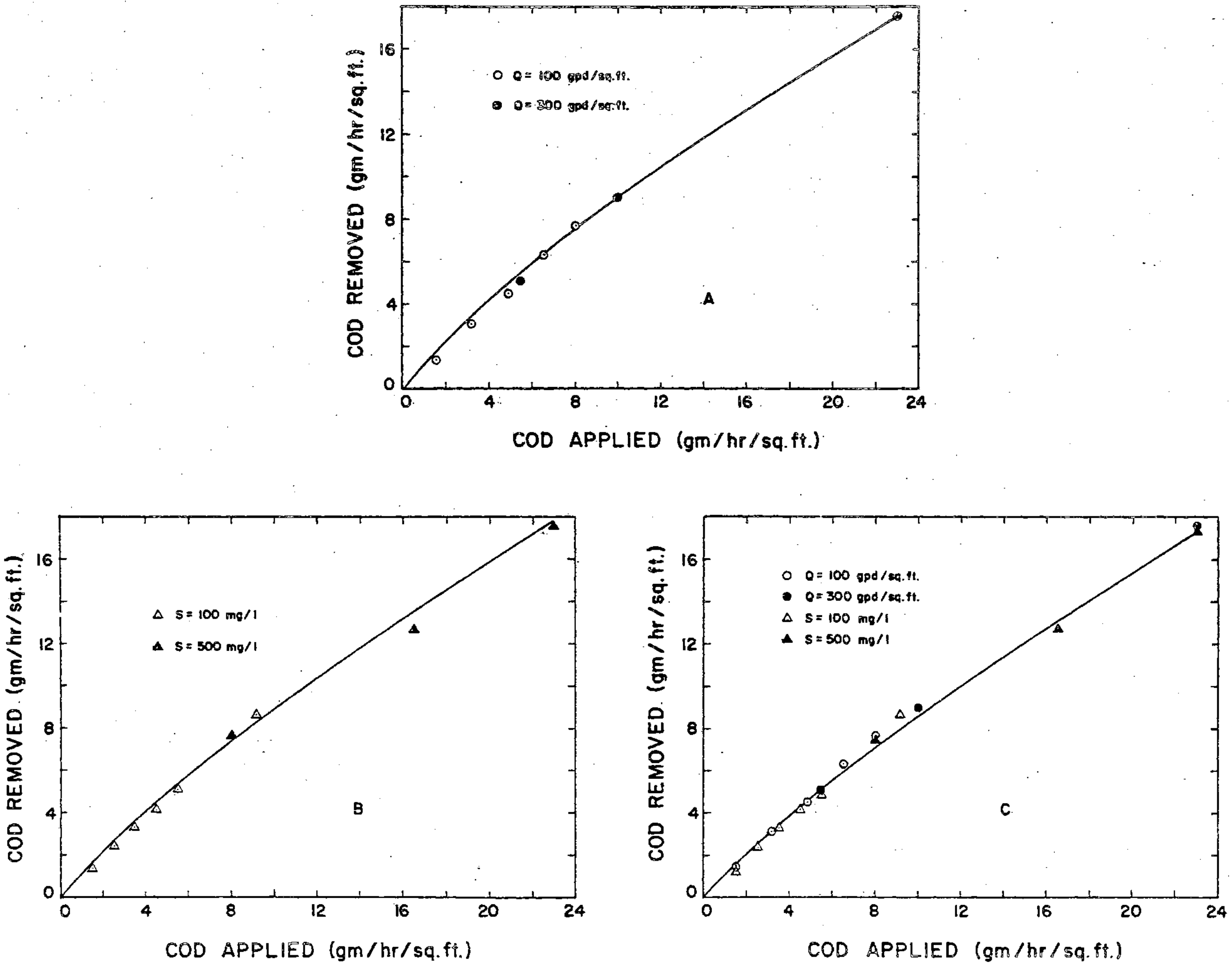


Figure 34. Relationship of COD Removed (gm/hr/sq ft) with COD Applied (gm/hr/sq ft) for the Model Trickling Filter.

following groups or individuals: Galler-Gotaas (equation 15); National Research Council (equation 1); Eckenfelder (equation 14) and Eckenfelder (equation 17).

Each of these equations was used to calculate the filter efficiency expected from a four foot deep filter affording a one square foot horizontal surface area. Filter efficiencies were calculated at various feed concentrations and flow rates and are presented in Table VI for comparison to the actual efficiency achieved in the four foot deep model filter utilized during the course of this investigation.

As can be seen, the Galler-Gotaas equation:

$$L_e = \frac{1.3\, L_o^{.98}\, Q^{.12}}{(1+D)^{.66}\, T^{.15}} \qquad (15)$$

consistently predicted the poorest filter efficiencies. The equation separates the two parameters, organic concentration and flow rate, and indicates that the organic concentration parameter far outweighs flow rate in its effect on organic removal. However, based upon the results of this investigation it was previously concluded that these two parameters should not be separated. Their effect on filter performance is exerted by their combination as total organics applied (gm/hr/sq ft) rather than either of the two acting independently of the other parameter. Also there is no indication of any role played by the microorganisms in the removal of organics from the waste.

The NRC formula:

$$E = \frac{100}{1 + C\left(\frac{W}{V}\right)^{0.5}} \qquad (1)$$

yielded credible filter efficiencies as seen in Table VI. It considers the two parameters organic concentration and flow rate in combination

TABLE VI

FILTER EFFICIENCY CALCULATED AS PERCENT COD REMOVED UTILIZING VARIOUS DESIGN FORMULATIONS AT VARIOUS FLOW RATES AND FEED CONCENTRATIONS

Flow rate gpd/sq ft	100 mg/l feed					200 mg/l feed					300 mg/l feed					400 mg/l feed					500 mg/l feed				
	G	N	E_2	E_1	C	G	N	E_2	E_1	C	G	N	E_2	E_1	C	G	N	E_2	E_1	C	G	N	E_2	E_1	C
100	56	76	54	75	88	56	69	68	75	87	56	65	75	75	88	57	61	81	75	92	58	59	84	75	85
150	54	72	44	71	85	54	65	59	71	90	54	60	65	71		55	56	71	71	74	55	54	75	71	
200	52	69	38	68	79	52	61	50	68	87	53	56	58	68	84	53	53	64	68		54	50	68	68	62
250	51	67	34	66	88	51	59	45	66	84	51	54	52	66	71	52	50	58	66	68	52	47	62	66	
300	50	65	30	64	64	50	56	41	64	83	50	51	48	64		51	47	54	64		51	45	58	64	77

All filter efficiencies are figured on a filter of 4 feet depth with 1 sq ft horizontal surface area.

G = Galler Gotaas - Equation No. 15.

N = NRC Formula - Equation No. 1.

E_2 = Eckenfelder's second formulation - Equation No. 17.

E_1 = Eckenfelder's first formulation - Equation No. 14.

C = Cook's results on experimental filter.

expressed as total organics applied to the filter. Efficiency decreases as total organics applied increases. However, in comparison to the actual efficiencies obtained in the model trickling filter, efficiences as calculated by the NRC formula appear to decrease too rapidly with an increase in total organics applied. Again there is no indication of any role played by the microorganisms in the removal of organics from the waste.

Eckenfelder's formula:

$$\frac{L_e}{L_o} = \frac{100}{1+\frac{CD^{(1-m)}}{Q^n}} \tag{14}$$

appeared to give the best results of all the formulations considered when compared to the actual efficiencies obtained during this investigation. The constant C, Eckenfelder says, is related to the mean active filter film per unit of volume throughout the filter depth. The exponent n is a characteristic of the filter medium used. The deficiency of this equation is that again organic concentration and flow rate are considered as two separate parameters rather than as the two acting in combination as total organics applied. Also the efficiency of the filter obtained by this formulation is completely independent of the concentration of the waste.

After discussion of this equation by Baker and Graves (1), Balakrishnan and Eckenfelder (20) presented the equation:

$$\frac{L_e}{L_o} = e^{-K_s\, D/Q^n} \tag{35}$$

where:

$$K_s = .0362\ A_v^{.644} L_o^{.54} \tag{36}$$

then:

$$\frac{L_e}{L_o} = e^{-.0362\ A_v^{.644} L_o^{.54} D/Q^n} \tag{17}$$

In determining $K_s = .0362\ A_v^{.644} L_o^{.54}$, Balakrishnan and Eckenfelder (20) plotted $\frac{K_s}{L_o^{.54}}$ versus specific surface area, A_v(sq ft/cu ft) on full logarithmic graph paper. Observing the scatter in the data, there appeared to be no reason for plotting the data on full logarithmic graph paper. The same relationship would have existed on semilogarithmic or arithmetic paper as there appeared to be no relationship between the two quantities plotted. On the previously mentioned log-log plot of parameters, the scale on the x axis (A_v) runs from 10 to 400 units of specific surface area. The scale on the y axis runs from 0.01 to 0.10 units of $\frac{K_s}{L_o^{.54}}$. The equation Balakrishnan and Eckenfelder determined from this plot is:

$$\frac{K_s}{L_o^{.54}} = .0362\ A_v^{.644} \tag{36}$$

where .0362 must be the value of the y intercept of the line drawn through the data points at x = 1. From the plot, the line drawn through the data points has a y intercept of less than 0.02 at x = 10. Therefore the value of the y intercept at x = 1 must surely be less than 0.02 and consequently cannot be 0.0362. The authors must have intended to propose 0.00362 as the actual y intercept at x = 1. As this value for the constant was published in two different papers (20, 42), it could not have been a typographical error.

The corrected equation now becomes:

$$\frac{L_e}{L_o} = e^{-.00362\ A_v^{.644} L_o^{.54} D/Q^n} \tag{37}$$

By plotting the slopes of the removal curves (removal rates) versus the flow rate (mgd/acre) on full logarithmic paper as Eckenfelder suggests, the exponent n, which is the slope of this plot for the particular medium used, was found to be 0.699. This plot is shown in Figure 35. Note all the data available from this investigation were plotted by holding the feed concentration constant, varying the flow rate and determining the slope of the resulting removal curve to be plotted versus flow rate (mgd/acre). Note also that at the higher feed concentrations (300 mg/l, 400 mg/l and 500 mg/l) the curves all fall on one another and are represented by one line, indicating saturation. The exponent n appears to approach a constant value for a given filter medium.

By substituting the value obtained for n into equation (37), the following equation developed:

$$\frac{L_e}{L_o} = e^{-.00362\ A_v^{.644} L_o^{.54} D/Q^{.699}} \tag{38}$$

This equation was utilized to compute filter efficiencies for comparison to the actual filter efficiencies obtained in the four foot deep model trickling filter. As can be seen in Table VI filter efficiency decreases with increasing flow rate and increases with an increase in waste concentration. The latter result is hardly plausible.

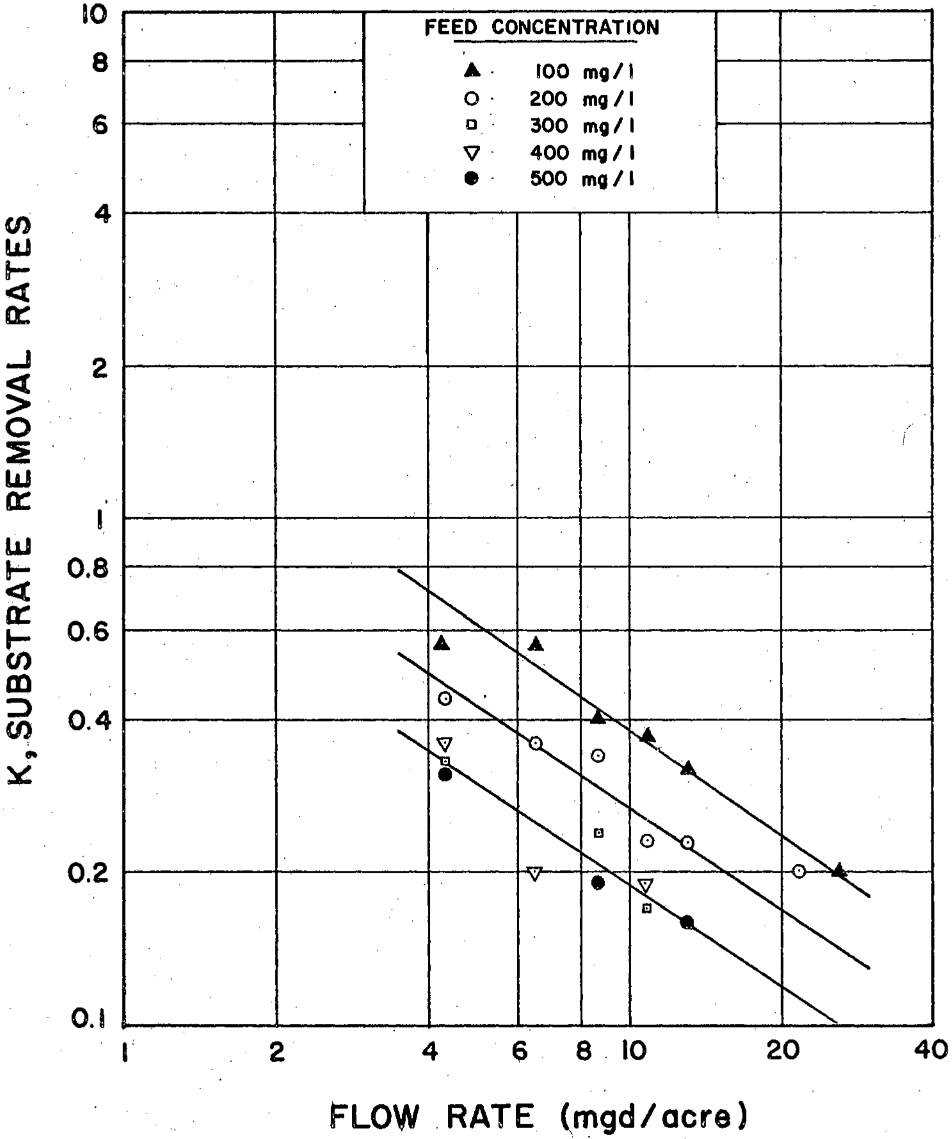


Figure 35. Relationship of Substrate Removal Rates (K) with Flow Rates (gpd/sq ft).

It is no doubt due to the parameter $L_o^{.54}$. Eckenfelder never explains from where the exponent 0.54 is obtained or why it is utilized. However, he does explain that $L_o^{.54}$ is included in the equation when domestic sewage is used because increased flocculation and biosorption occur at higher influent organic concentrations due to a large percentage of the organics in sewage being in suspended or colloidal form. After comparison of filter efficiencies obtained by using equation (37) it becomes apparent that Eckenfelder's first formulation (equation 14) is far superior to his new formula (equation 37).

In equation (36): $K_s = .0362\ A_v^{.644} L_o^{.54}$

Eckenfelder says K_s can be determined by plotting log per cent COD remaining at each unit of depth versus $\frac{D}{Q^n}$. K_s is the slope of the resulting plot and is a constant. This is accomplished at one feed concentration and three different flow rates. In order to check Eckenfelder's values for K_s, the data obtained during this investigation were utilized. The exponent n was previously determined to be 0.699 from the data. The manipulations were carried out at a constant organic concentration and results are shown in Figure 36. As can be seen K_s, if ever a constant, is only so for a given organic concentration. K_s decreases from 4.43 and approaches a limiting value of 2.1 as the organic concentration is increased indicating again some form of saturation. K_s is determined by using logarithms to the base e whereas n is determined by using logarithms to the base 10. This adds confusion to the use of this equation. K_s determined from data during this investigation varied from 2.1 to 4.43 whereas Eckenfelder reports a value of 0.375. As can be seen, great differences exist.

The equation Eckenfelder offers (equation 37) is valid only for

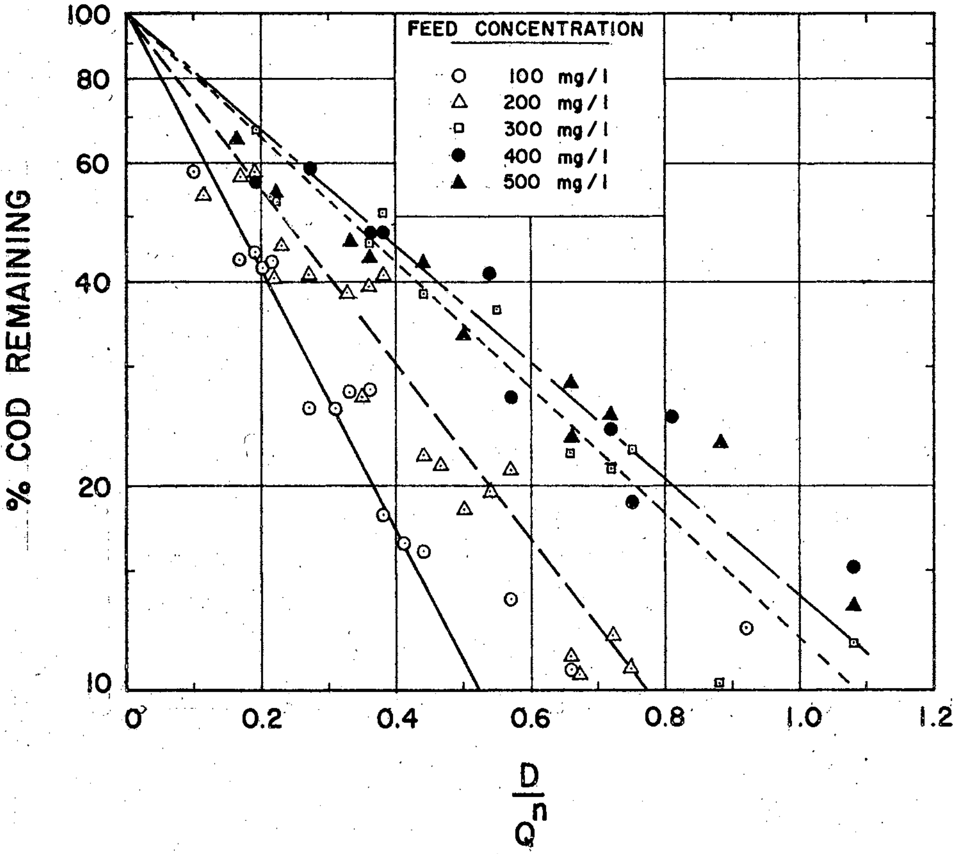


Figure 36. Relationship of % COD Remaining with $\frac{D}{Q^n}$.

one organic concentration and as can be seen from Table VI yields very poor results.

CHAPTER VII

CONCLUSIONS

1. The performance of a filter evaluated as COD removal depends on the amount of total COD (gm/hr/sq ft) applied to the filter rather than its concentration or flow rate. COD removal is at the same efficiency with the same total organics applied regardless of whether the total organic loading is accomplished by a high flow rate at a low waste concentration or a low flow rate at a high waste concentration. Since residence time is a function of flow rate, it is irrelevant to the COD removal realized in a trickling filter when observed over the range of organic and hydraulic loadings encountered during this investigation.

2. All the trickling filter formulations considered in this discussion are of limited value. The material balance equation:

$$(S_o - S_1) = \frac{x}{Y}\frac{1}{Q}\mu_m\left(\frac{S_1}{K_s+S_1}\right)$$

is valid at steady state conditions in a trickling filter. The curves of growth rate versus substrate concentration for each foot of filter depth have been drawn showing the Monod relationship exists for trickling filter biota.

3. In the previously mentioned equation, the biological solids x are the important parameter in determining the amount and type of substrate remaining. All other parameters contribute an insignificant

effect on substrate remaining when considered over the range of values selected for each throughout the duration of this investigation.

4. The removal of organics in a trickling filter follows first order decreasing rate kinetics with depth. This appears to be due to the biological solids which decrease with depth in accordance with the Monod relationship shown to exist at each unit of depth.

5. The saturation phenomenon observed in a trickling filter by some investigators is a result of the substrate removal rate approaching a limiting value at the higher total organic loadings.

CHAPTER VIII

SUGGESTIONS FOR FUTURE STUDY

As a result of this investigation, the following suggestions are made for future study on the kinetics and mechanisms of the fixed bed reactors.

1. Various filter media possessing various available surface areas should be placed in the model fixed bed reactor and their effect on filter performance noted. This would be essentially a study of microorganism surface area or mass which appears to be the controlling factor in trickling filter performance.

2. The equation $(S_0-S_1) = \frac{x}{Y}\frac{1}{Q}\mu_m\left(\frac{S_1}{K_s+S_1}\right)$ should be studied further and smaller increments of filter depth utilized (rather than one-foot increments) in calculating the COD remaining at a given depth when values are assumed for μ_m, Y, Q, K_s, and varying x with depth. This should result in obtaining a removal curve approximating first order decreasing rate removal kinetics.

3. Other substrates should be utilized and combinations of substrates (both soluble and colloidal) should be observed as to their removal characteristics on the fixed bed reactor.

4. The effect of recirculation on filter performance should be studied in depth utilizing varying flow rates, feed concentrations and recirculation ratios.

5. Investigations should be carried out to find a feasible means of determining the amount of biological solids present at a given filter depth.

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APPENDIX

LIST OF SYMBOLS

A = area of biological film

A_v = area afforded by a given filter medium for biological growth (sq ft/cu ft)

b = coefficient of biosorption in equation (11)

b = temperature correction factor in equation (12)

C = constant, equal to .0085 for volume (V) in acre feet or .0561 for volume (V) in thousands of cubic feet

D = depth of filter bed

d = thickness of the active biological film

E = % BOD removed

F = hydraulic flow rate

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

K_s = essential nutrient concentration where $\mu = 1/2\ \mu_m$

K_s = a constant in equation (35)

k = logarithmic rate of BOD extraction

L or L_i or L_o = total removable fraction of BOD or initial quantity of BOD

L_D = remaining removable BOD at depth D.

L_e = remaining BOD in effluent

L_R = fraction of the removable BOD that is removed

L_t = quantity of BOD remaining at time t

m = constant, equal to 0.33 (for Q in mgd/acre and D in feet)

n = constant, characteristic of the filter medium used

Q = hydraulic loading or flow rate (hydraulic load/unit surface area)

R = recirculation ratio

S = the load of removable BOD which must be applied to saturate one unit of filter depth with BOD

S_o = influent concentration of essential nutrient

S_1 = effluent concentration of essential nutrient

S_4 = concentration of essential nutrient at a filter depth of 4 feet

T = temperature in ^{o} C

μ = specific growth rate of microorganisms

$\hat{\mu}$ or μ_m = maximum specific growth rate of microorganisms

V = volume of filter medium (acre-feet or thousands of cubic feet)

W = organic load applied (lb BOD/day)

x = number of unit volumes saturated by a given load of BOD in equation (11)

X = concentration of microorganisms in the biological film

x = mass of biological solids at a selected point

Y = yield of microorganisms or biological solids

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