KINETICS AND MECHANISMS OF SUBSTRATE REMOVAL BY BIOLOGICAL TOWER REACTORS

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KINETICS AND MECHANISMS OF SUBSTRATE REMOVAL

BY BIOLOGICAL TOWER REACTORS

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Dedicated to my Father

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

Figure | Page

Figure | Page

CHAPTER I

INTRODUCTION

The science and 'art' of wastewater engineering stretches only slightly beyond one hundred years. Trickling filters (or biological tower, to use the preferred modern terminology) have been used in the United States for the purpose of wastewater purification since 1889. In 1973 there were more than 3,500 trickling filter plants (by then little understanding of the system was slowing it in competition) and approximately 3,750 activated sludge plants (60). Biological towers, like activated sludge processes, are principally aerobic processes in which the removal of soluble organics depends on the action of microorganisms. Biological metabolism involves the conversion of the organic waste to new cell material and metabolic end products. Thus, the soluble organics are removed by the synthesis of biomass which can be settled out, and mainly by oxidation to carbon dioxide and water. But there are few primary differences between these two well recognized wastewater treatment processes (35). Biological tower is a fixed-bed growth system, that is, microorganisms are attached to the media and wastewater trickles down over them. The important thing is, for a biological tower the entire mass of attached microorganism is not active in the removal of soluble organics (21, 22, 51). This concept is illustrated in Figure 1. Food and oxygen diffuse through the film until the thickness becomes great enough to impede their

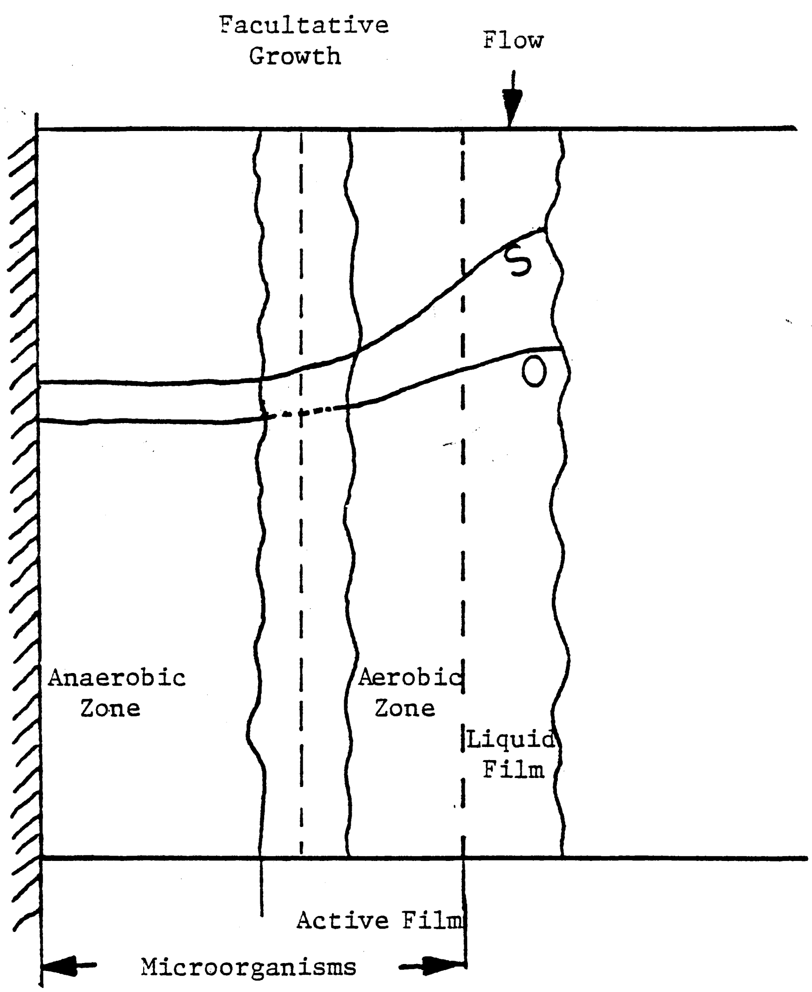

Figure 1. Schematic Drawing of Biofilm Element of Biological Tower

passage to the basal layer. The film is believed to be stratified when oxygen diffusion to the layer is restricted. One layer, the aerobic portion, is characterized by the availability of oxygen, while the other, the anaerobic layer is void, of oxygen.

The primary merits associated with biological towers are their simplicity, ease of operation, production of sludges which can be readily removed, low maintenance and energy requirements and to some extent--ability to survive shock load and toxic wastes. Unfortunately, lack of understanding has hampered its creditability. Little knowledge about the system and probably less need of operational controls caused negligence and overloading which deteriorated the performance. But the energy cry has forced the environmental engineers to look into the potential of the system.

The purpose of this study was to look into the kinetics and mechanisms of substrate removal in a biological tower. Kinetics is a study of how the reaction rate varies with the composition of the reaction mixture. In the biological tower the composition of wastewater changes due to microbial activity as it flows downward and the substrate is removed. Understanding of removal rate kinetics of a system is the most important part for the design model. In this work the reaction mixture is sewage which happens to be very biodegradable but very complex in nature too. Kinetics of removal would change with substrate type, substrate concentration, loading, operation and maintenance, etc. parameters but hopefully, a design model based on understanding of removal rate kinetics along with pilot plant or laboratory-scale study would provide a reliable treatment system.

With an objective to study the kinetics and mechanism of substrate removal by biological tower reactors the following decisions were taken:

1. To critically analyze the performance of pilot plant biological tower in relation to the substrate removal mechanism.

2. To measure a few major compositional constituents to help in looking into their interactions and their effect on substrate removal rate.

3. To see if the first order kinetics or the well proven organic loading concept is more applicable for biological tower.

4. To attempt to find out if the substrate removal kinetics could be reasonably but in simple and more usable form be expressed using any relationships found in literature.

CHAPTER II

LITERATURE REVIEW

Historical Review

Ancient and medieval waste disposal systems were comprised of collection, some sedimentation, and often land disposal filtration (1). As populations became more concentrated, not enough land was available for filtration or sewage farms (2). Methods to artificially biologically treat waste were sought. According to Halverson (3), the first trickling filter, designed by Bailey Denton and built in Birmingham, England, in 1871, used soil as the filtering medium. Development efforts were further promoted through the establishment of organizations, such as England's Royal Commission on Sewage Disposal from 1898 to 1915, the Lawrence Experiment Station in the United States, the Imperial Board of Health and Allied Scientific Institutions in Germany, and later the Water Pollution Research Laboratory in England, and the Robert A. Thaft Sanitary Engineering Center in the United States (4). Trickling filters have been operated in the United States, the United Kingdom, Germany, Netherlands, Australia, New Zealand, India, many in South Africa, Poland, Russia, Argentina, France, Holland, El Salvador and Malaysia, to mention just some of the countries. Though around 1940, 58 percent of all plants in the United States providing secondary treatment utilized trickling filter--the number then decreased as it was misjudged and blamed for being unable to satisfy the required treatment. There was no defined criteria to judge the efficiency with that of activated sludge. But in the mid-1950's a major orientation occured with the advent of modular plastic media a replacement for the conventional stone and slag (51). Plastic media are light in weight, has high surface area to volume ratio and large voidage fraction. This increased the efficiency of the biological tower, conventionally which was known as trickling filter. Now biological towers are comparable to activated sludge (32). There is defined criteria to base on for comparing the performance between activated sludge and biological tower.

Microbial Aspects

Anyone aspiring to gain an understanding of the environment with an eye toward controlling it biologically, must have microbial conceptions. This is responsible mostly for the functional success or failure of the entire array of secondary treatment processes. Under wastewater treatment conditions, bacteria are often in competition for a limited amount of nutrient. Also, the organism-type distribution in any reactor is the result of the particular combination of environmental factors in effect, like--substrate composition, substrate concentration, oxygen availability, inhibitory components, etc. The consequence is that a very efficient regulation mechanism is involved.

Depending on nutritional constituents availability, the community might be heterotrophic organisms--obtaining cellular carbon and energy from the oxidation of the organic compounds, photoautotrophic--using light as energy source and carbon dioxide as the sole source of carbon, chemolithotrophic--using an inorganic compound or element for energy source and carbon dioxide for carbon, etc.

The preparatory stages of catabolism for heterotrophs usually involve degradation of the constituents of the substrate like--polysaccharides, proteins, fats, etc. All these constituents are extracellularly degraded by secreted enzymes to smaller units or monomers. The polysaccharides are broken down into mono- and disaccharides. The different pathways commonly reported for the degradation of glucose to pyruvic acid are: (1) Embden-Meyerhof-Parnes (EMP) pathways, (2) Warburg-Dickens or Hexose Monophosphate (HMP) pathway, and (3) Entner-Doudoroff (ED) pathway.

Each pathway has one or two unique enzymes but other than that often depending on the requirements in many bacteria more than one of the pathways has been observed. The EMP pathway provides the greatest amount of ATP, eight moles aerobically and two moles anaerobically, but does not produce ribose-5-phosphate and erythrose-4-phosphate. The HMP pathway produces all the precursors necessary for purine and pyrimidine biosynthesis but produce only one ATP and is partly capable of producing pyruvate. It is therefore, not surprising that both pathways may be present in those organisms that do possess the HMP pathway. Entner-Doudoroff pathway like HMP produces one mole of ATP and two moles of NADH, and all necessary pentoses but, it also produces pyruvate. Very little is known whether the available oxygen or the nutritional changes or both influence the carbohydrate utilization. Oxygen availability certainly changes the end products formed, but it is uncertain to what extent it influences the pathways. For example, it has been reported that under strict aerobic conditions and low glucose concentration of 0.1 percent HMP pathway and with an increase in glucose EMP pathway has been observed in E. coli (6). Genetic control of pathway, as in Pseudomonas only ED being observed, is common too.

The ability to breakdown proteins to peptones, polypeptides, and amino-acids is not equally shared by all groups of bacteria. Because the majority of these organic nitrogen compounds are at an oxidation level between carbohydrates and fats, however, they are potentially useful as a source of carbon, nitrogen, and energy for both aerobic and anaerobic microorganisms. It has been shown that some protein breakdown accompanies normal exponential growth (7). For E. coli rates of 0.5 percent to 2.5 percent of the protein per hour have been suggested. However, under 'shift down' conditions or when growth is stopped by an inhibitor or by the exhaustion of a nutrient, the rate of protein breakdown increases immediately to about 5 percent per hour in E. coli. It was also suggested that during exponential growth, a limited class of proteins are broken down relatively rapidly, while under less favourable conditions a wider range of proteins is degraded. However, protein or amino-acids are most often catabolysed to pyruvates or to the intermediates of the TCA cycle.

Fats and lipids, mostly found as triglycerides, are excellent energy sources, with the potential of producing a far greater yield of ATP than do carbohydrates and proteins. Triglycerides are mostly broken into fatty acids and glycerol. Glycerol is metabolized by conversion to dihydroxyacetone phosphate, which is an intermediate in the EMP pathway. The major pathway for the oxidation of fatty acid is called 'beta-oxidation' which involves repetition of a sequence of reactions that results in the removal of two carbons as acetyl-CoA with each repetition of the sequence. Acetyl-CoA is then metabolized through the TCA cycle.

The complete oxidation of pyruvate, carbocylic acids, acetyl-CoA etc. occurs by oxidative decarboxylation, followed by a series of reactions called either the "tricarboxylic acid cycle" or "citric acid cycle" or "Krebs cycle." In addition to its role in terminal respiration, the TCA cycle also plays an important role in the synthesis of cell material. The TCA cycle yields CO_2, important anabolic intermediates and involves four dehydrogenation steps. Of the four dehydrogenation steps each revolution of the cycle, three are connected to NAD^+, forming three molecules of $NADH+H^+$ and one to FAD. All four molecules donate their electrons to another series of enzymes, which constitute the respiratory chain. It is during this part of the system that ATP are produced as the reoxidation of reduced NAD or FAD occurs through the respiratory chain. The complete oxidation of two moles of pyruvate to carbon dioxide and water forms 30 moles of ATP.

Autotrophic organisms or phototrophic organisms, as stated, obtain energy from inorganic elements or light but they also need the intermediates of TCA cycle. But now the pathways do not function in a cyclic manner, or do not produce energy. The pathway is branched. So, the autotrophs cannot produce as much as energy or ATP as heterotrophs using the TCA cycle. But there is a difference in algae metabolism. The autotrophic algae could show cyclic and/or non-cyclic photophosphorylation but unlike bacteria, the end product is water. Besides, algae could also be heterotrophic, using organic carbon as the carbon source (50). It could possess another metabolic pathway, B-carboxylation which is related to the TCA cycle.

Further, biological tower biota do have facultative and anaerobic bacteria or algae. Facultative or anaerobic bacteria could use the EMP pathway but not the complete cyclic TCA or HMP pathway. The latter two pathways are restricted to those reactions required for the synthesis of building blocks for biosynthesis. Zymomonas, a fermentative bacteria can use the ED pathway which is an exception (38). Now the end products and intermediates are different. Above all, the reaction kinetic or removal rate is different; much slower because the energy efficiency or production is much lower. Under oxygen limited condition or high F/M ratio facultative microbial predominance is very much expected. Again, depending on the environmental conditions, substrate condition and constitutents--there are regulatory mechanisms related to the entry of nutrients in the cell (85). The transport of nutrient could occur by facilitated diffusion, active transport, group translocation system or binding protein. Such a division into different transport systems is based on the type and location of the proteins involved, on the type of energy coupling and type of mechanism by which translocation is accomplished (85, 77). But not all bacteria contain all the different types of transport system, neither are all nutrients transported in all bacteria by the same way. For example, gylycerol was found to be transported by facilitated diffusion, an energy independent process (86). By contrast, the disaccharides maltose, lactose, melibiose pass by several distinct energy-dependent active transport processes (87). Even McGinnis and Paigen proposed that inhibition of carbonhydrate utilization was a manifestation of transport regulation (88). It was found that the galactose specific permease exhibit high affinity for D-glucose. The nutrient transport system in bacteria is very complicated. Simultaneously, bacteria exhibits biochemical regulatory systems for efficient utilization of energy and available substrate. This regulatory mechanism operates in the cell by regulation of enzyme synthesis and the regulation of enzyme activity. An example of the first type is the end product inhibition and that of later type may be enzyme induction or end-product repression. These mechanisms are found elsewhere (5, 38, 39, 40, 77, 85).

Therefore, the removal kinetics of biological tower would very much depend upon the interactions between species and strains of its diverse mixed population which is again dictated by the substrate and environmental condition. Consequently, nutrient transport, regulatory mechanisms, partial or total shift of metabolic pathways, oxygen and substrate availability, predominance change and substrate removal rate are very closely related.

Composition of Sewage

Knowledge of the nature and amount of the organic substance present in sewage and sewage sludge can be of great assistance in the study of sewage treatment processes. As always the question of survival has made biological wastewater treatment processes' bioter self-adjusting in character. The composition of the wastewater determines the organism-type distribution and so the removal kinetics. Peter and his co-workers (75) found that as the influent COD was increased, the concentration of protozoa and associated heterotrophic bacteria increased in the upper zone of the trickling filter. With decreasing influent COD, the diversity and number of heterotrophs and protozoa decreased resulting in change of habitat and decreased in the zone responsible for COD removal. Apparently, this correlated to the development of nitrifiers which can survive at lower COD concentration and less competition for oxygen. Any studies on the biota and removal kinetics of wastewater would suggest a very close relationship between them and composition of wastewater. But, unfortunately, always the task of obtaining a representative sample of sewage has been complicated due to the inherited variable nature like flow, strength and constituents varying from hour to hour, day to day, and season to season.

Hunter and Heukelekian (8) found that sewage consisted of approximately 30 percent organic carbon in soluble solid fraction and 80 percent organic carbon in particulate fraction. The sewage filtrate obtained by Painter et al. (9) had a crystal-clear yellow color. The analyzed carbohydrate portion was reported to contain 51 percent glucose, 16 percent sucrose, 13 percent lactose, and 9 percent galactose of total sugar with smaller proportions of fructose, peutoses, arabinose, and xylose.

A study on soluble organic nitrogen characteristics and removal indicates of some interesting findings (10). The NH_3-N content of the influent sewage was around 26-29 mg/l, organic-N about 8.3 to 12.2, soluble BOD 42-49 mg/l and protein about 8 mg/l. More than one study indicated (36, 37) protein or protein-like combinations as one of the major constitutents of organic nitrogen. On treating the sewage by activated sludge they found that soluble organic nitrogen production could account for up to 50 percent of secondary-effluent soluble organic nitrogen. They suggested that soluble organic nitrogen and soluble COD in untreated wastewater are from 18-38 and 24-29 percent refractory. But analysis specifically for amino acids and proteins indicated that they comprised less than 10 percent of the soluble organic nitrogen in secondary treatment plant effluents.

Kinetics of Biological Tower

Due to the complicated nature of trickling filter/biological tower an in-depth, well documented theory has not been generally accepted. By observing qualitative significance of each of the many variables, independent investigators developed several diverse opinions.

In 1946, the National Research Council published an empirical formula for treatment efficiency based on data from sewage treatment plants in military installations (12). The equation for the efficiency of a single stage filter without recirculation.

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

where

E = percent BOD removed

W = organic load applied (lbsBOD/day)

V = volume of filter medium (acre-feet)

C = constant, equal to 0.0085 for volume in acre-feet or 0.056 for volume in thousands of cubic feet.

Fairall (13) developed empirical formula based on data from twenty-four treatment plants in the Upper Mississippi Valley. Without recirculation the equation is:

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

where

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

V = volume of filter medium (1,000 cu.ft.)

Q = hydraulic flow rate (MGD)

Another empirical formula used for sometime was developed by Galles and Gotass (14). It was derived by multiple regression analysis of data from existing treatment plants. Without recirculation it is:

$$L_e = \frac{1.3\, L_o^{0.98}\, Q^{0.12}}{(1 + D)^{0.66}\, T^{0.15}}$$

where

L_e = BOD concentration remaining

L_o = influent BOD concentration

Q = hydraulic loading (MGD/acre)

D = depth(feet)

T = water temperature °C

Having recognized the need for a more sophisticated approach toward filter design, a number of workers proposed various theoretical relationships to be used. Velz 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 (15). This was expressed as:

$$\frac{L_o}{L} = 10^{-KD}$$

where

L_o = remaining removable BOD at depth D

L = total removal fraction of BOD

D = depth

K = the logarithmic rate of extraction

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

Stack's (16) theoretical formula for trickling filter performance was 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:

$$L_R = xbs + b(L-xbs)[1 + (1-b) + (1-b)^2 + (1-b)^3 + \ldots(1-b)^{D-x-1}]$$

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.

Schulze combined the first order rate equation with empirical relationships to form a new model. This formula is:

$$\frac{L_e}{L_i} = 10^{-b\ K_{20}\ D/Q^n}$$

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 °C

K_{20} = 0.3

D = filter depth (ft)

The exponent n was found to be 2/3 which has been confirmed by Howland (18).

Germain (19) found that the role of BOD removal is a function of the influent BOD, concentration and the adsorption capacity of the biological growth. According to him, waste residence time 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 to be noted that from identical plots of BOD applied (lbs/1000 cu.ft/day) versus BOD removed (lbs/1000 Cu.ft/day), Schulze (17) concluded that filter performance was independent of organic loading and Germain (19) concluded that BOD removal is proportional to the BOD applied at a specific hydraulic loading rate.

Eckenfelder (20) expanding the work of Velz, Schulze and Howland, developed several equations based on first order removal kinetics. In the simplest form:

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

where

L_e = effluent BOD

L_o = influent BOD

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

D = filter depth

Q = hydraulic load per unit surface area

n = constant

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

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

where C, m and n are constants to be determined by multiple regression analysis.

In 1968 and 1969 Kornegay and Andrews (21, 22) published their results of experiments conducted with completely mixed, annular reactors, and developed the following relationship for trickling filter performance:

$$K_s \ln (S_o/S_e) + (S_o - S_e) = \frac{\mu_{max}\ a.d\ HXZ}{FY}$$

where

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

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

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

a = specific surface area of filter media (L)

d = active microbial film thickness

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

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

Z = filter depth (L)

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

Y = yield coefficient, and

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

As a result of this work (21) Kornegay and Andrews determined that d = 70μ, independent of hydraulic or organic loading and dissolved oxygen concentrations, and that x = 95 mg/cm^3, also constant.

Sinkoff et al. (23) 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.

Atkinson et al. utilized film flow in contact with a vertical wall to approximate the flow waste through a trickling filter (24). They concluded among other things that contact time analysis of trickling filter are irrevalent and serve only to cloud the basic issues.

Meltzer (25) showed that a true Gaussian normal distribution curve would result when the lengths of the path were plotted against their number. It was further suggested that this could also explain the difference of opinion held by many workers regarding the effect of organic strength and/or hydraulic load upon the efficiency of trickling filter.

Majer studied on an inclined plane model, using glucose as the substrate (26) and 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.

Moodie and Greenfield suggests that there are different removal mechanisms in the trickling filter process (27). It is apparent from their results that while the efficiency of total COD follows first-order kinetics, the removal of the soluble COD fraction is more closely approximated by zero-order kinetics.

Williamson and McCarty (28) developed an equation based in part on Monod's (29) equation for microbial growth, and in part on the rate of diffusion of oxygen and essential nutrients into the slime layer. The result is a second order differential equation which states:

$$\frac{d^2 S_e}{dZ^2} = \frac{K\ S_e\ X_c}{D_c\ S_e + K_s}$$

where

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

Z = filter depth (cm)

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

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

D_c = diffusion coefficent within biofilm (sq.cm/day)

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

Stack 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 depth will remove a constant fraction of the removable BOD applied to that unit depth (30). If a loading was a magnitude that does not saturate any portion of the filter with BOD, then almost 100 percent of the removable BOD should be removed.

Around 1971, based upon research conducted at Oklahoma State University, Kincannon (31) showed that the performance of a biological tower evaluated as COD(BOD) removal depends on the amount of total COD/BOD lbs/day/1000 cu.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. He proposed a graphical approach based upon it's ability to remove the total organics applied to it.

Kincannon and Sherrard in 1973 proposed using the biological parameters of θ_c or F/M ratio for evaluating biological tower (32). It gave comparable tools for biological tower to activated sludge and hence, helped in evaluating tower kinetics and performance on an equalivalent base.

Harris and Hansford (51) proposed a mathematic model assuming that lack of either organic carbon, oxygen or both simultaneously, can limit the overall rate of process. They used basic chemical engineering principles of interfacial mass transfer, diffusion and biochemical reaction. The substrate equation is:

$$\frac{d^2S}{dx^2} = \frac{\mu X}{YD_s} \left(\frac{S}{K_s + S}\right) \left(\frac{0}{K_o + 0}\right)$$

And for oxygen:

$$\frac{d^2 0}{dx^2} = \frac{\hat{\mu} XF}{YD_o} \left(\frac{S}{K_s + S}\right) \left(\frac{K}{K_o + 0}\right)$$

where

D_o = diffusivity of O_2 in the slime, cm^2s^{-1}

D_s = diffusivity of glucose in the slime, $cm^2 5^1$

F = constant factor relating the quantitus of glucose and O_2 utilized in the aerobic metabolism

K_o, K_s = half velocity kinetic coefficient for substrate and oxygen, respectively, mg cm^{-3}

S = substrate concentration in the slime, mg cm^{-3}

O = oxygen concentration in the saturated liquid film, mg cm^{-3}

X = cell concentration mg cm^{-3}

$\hat{\mu}$ = maximum specific growth rate of organism, S^{-1}

Y = cell yield

Kincannon in 1982, in an attempt to visualize the contemporary theories regarding biological tower proved that organic loading, not the hydraulic loading or influent concentration, matters in the removal of organic matter (62). In the same study it was also shown how the organic removal rate and organic loading rate relationship could be expressed in terms of lbs/day/1000 ft^2, which is more flexible. This organic loading concept was at the same time supported by Stover (33) for rotating biological contractor.

Kincannon and Stover also derived a formulation for biological tower based on the organic loading concept (34). They recognized the fact that currently it is not possible to predict precisely the extent of dispersion, or mass transfer or oxygen diffusion for biological tower and so an attempt to rigorously model the kinetic relationship would be premative. So, based on the mono-molecular theory they derived an empirical relationship which could be said to be an analytical approach for the previously mentioned Kincannon's graphical approach (31). The kinetic model is given as follows:

$$S_e = S_i - \frac{S_i U_{max}}{K_B + \frac{FS_i}{A}}$$

where

S_e = substrate concentration at point of measurement, mg/l

S_i = influent substrate concentration mg/l

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

K_B = proportionality constant, lbs/day/1000 ft.^{2}

A = surface area of volume, 1000 ft.^{2}

Nitrification

Nitrification is that vital part of the nitrogen cycle whereby ammonia is converted to the more oxidized forms of nitrite and nitrate. It has been reported that biological nitrification is mainly performed by the two general groups of bacteria--Nitrosomonas and Nitrobacter. The respective oxidations are carried out as shown in the reactions below:

$$2\ NH_4^+ + 3\ O_2 \xrightarrow{\text{Nitrosomonas}} 2\ NO_2^- + 2H_2O + 4\ H^+$$

$$2\ NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2\ NO_3^-$$

Here, it could be mentioned that Lan isolated an organism which was capable of metabolizing organic carbon as carbon and energy source and nitrifying after depletion of the organic source (89). Presence of the organism was suggested the reason for nitrification when rapid heterotrophic growth ceased with the depletion of TOC.

The substrate conditions required for nitrification are the presence of a salt of ammonia or nitrite, strongly aerobic conditions and the presence of carbonates in the medium. The first step from ammonia to nitrite produces 79,000 cal/mole, while the second step of nitrite to nitrate produces 21,500 cal/mole (based on heat of combustion). But the organisms manage to utilize about 5 percent of the energy released by the reaction and that approximately 95 percent of the energy librated appears as heat (41). It is this fact and as previously mentioned its inability to use the cyclic nature of TCA cycle is responsible for the extremely low growth rate of nitrifying organism.

Most of the literature on the nitrification performance of trickling filter (42-48) indicate that it can bring about nitrification comparable to that of the conventional activated sludge process. But the process variables such as depth of filter, size and type of media, hydraulic loading with other factors like pH, carbonaceous matter in the wastewater etc. can influence nitrification.

Grantham showed that after a definite "lag" depth, during which there is little nitrification, the percent nitrification-depth curve fits the general pattern of the geometric decreament curve (47). It follows that, below a given depth, the rate of oxidation of nitrogen per interval of depth in a filter bed is proportional to the concentration of remaining oxidizable nitrogen. The relation is expressed by:

$$\frac{N_D}{N} = 10^{-Kn} (D - a)$$

where

N_D = oxidizable nitrogen remaining at depth D

N = total oxidizable nitrogen

Kn = reaction rate constant

a = depth lag factor

Grantham and et al. concluded that nitrification in a trickling filter follows the monomolecular reaction pattern and depends to some extent upon the type of filter medium and loading rates employed.

CHAPTER III

MATERIALS AND METHODS

Experimental Apparatus

For this study of the removal kinetics of biological tower, an existing pilot plant treating Stillwater Municipal Sewage was operated. The pilot plant was made of clear plexiglass, in units of one foot square cross-sectional area. Growth modules containing three cubic feet (3 ft. x 1 ft. x 1 ft.) of Enviroquip's plastic media were separated by spacing units of few inches depth, which provided sampling ports and allowed aeration. The configuration was such that it prevented any drop of wastewater from falling far through the media without contacting a surface. The total height of the plant was 18 feet. It was divided into three separate towers, each of six feet depth. The media provided a specific surface area of 38.8 ft^2/ft^3.

The influent was pumped to the top of the first tower, where it was dispersed evenly over the cross-sectional area by a splash plate and allowed to trickle down through two growth modules (separated by spacing units) and collected in a wet well at the bottom. The fluid collected in the wet well was continuously pumped to the top of the second tower, identical in every respect to the first tower. Then it is pumped to the top of the third and last tower, which was also identical in every respect to the other two towers. The trickled down effluent was discarded into the sanitary sewer system at this point.

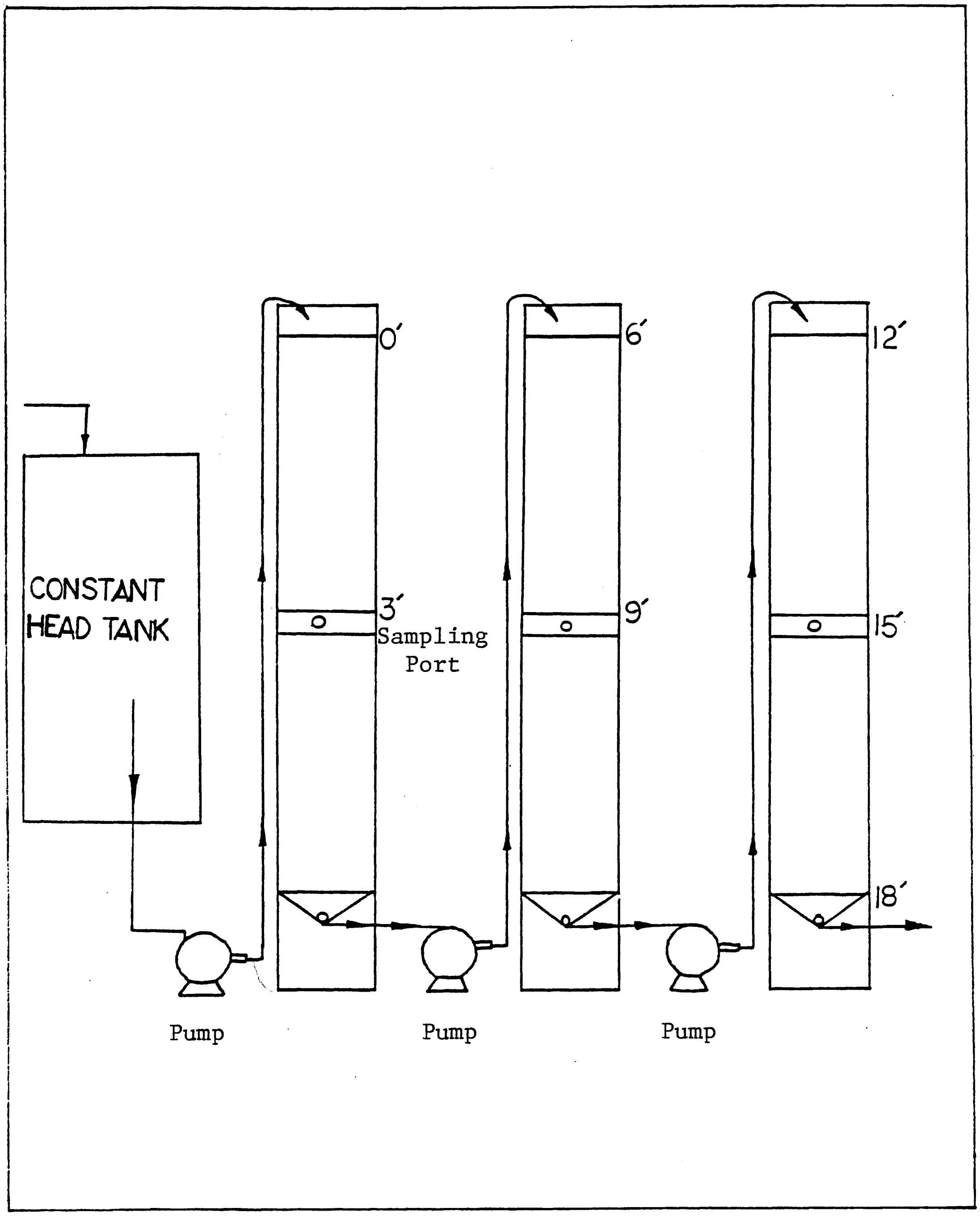

Figure 2. Schematic Drawing of the Experimental Biological Tower Pilot Plant

Hydraulic flow to the tower, that is all pumpings to the top was done by means of constant screw pump. Each pump was driven by a Dayton single speed motor. The control mechanism of the pumps for maintaining the hydraulic flow rate at a desired constant value was manipulated by changing into required size of pulley and belt.

Growth was established on the tower the first time by running sewage through it for two months at the desired hydraulic flow rate.

Experimental Procedure

The pilot plant was operated at four different hydraulic loadings, 820.8 gal./day/ft^2, 1329 gal/day/ft^2, 1440 gal/day/ft^2 and 2880 gal/day/ft^2. During 820.8 gal/day/ft^2, 1440 gal/day/ft^2 and 2880 gal/day/ft^2 loading, samples were collected three times a week for about two months. At 1329 gal/day/ft^2 hydraulic loading, ten sets of samples were collected on daily basis. Each set of samples contained seven samples collected at 0 ft. (influent) 3 ft., 6 ft., 9 ft., 12 ft., 15 ft. and 18 ft. (effluent) depth of the tower. A period of about at least three weeks was allowed in between the change of hydraulic flow rates to let the system approach a steady state condition. The steady state conditions were ascertained by obtaining close values of pH and BOD. It could be mentioned that all of the lines and the pumping systems were chlorinated frequently to prevent excessive microbial growth which could alter flow rates. Though it was expected that the hydraulic flow rate would remain constant, it was measured at every sampling time. Maintaining a constant hydraulic loading rate was not a problem, a constant organic loading was impossible due to the inherited variation of sewage composition and concentration. In order to minimize this organic loading variation, the experiments were arranged with the Oklahoma State University schedule. Because it was found that during the semester the sewage concentration is around 60-114 mg/l BOD and during breaks it drops to about 40-65 mg/l of BOD. So, hydraulic loading was so arranged that samples could be collected for required time at one flow rate and without much variations in sewage concentration.

A sampling wand was used for the collection of samples. This was a piece of PVC pipe with upper portion of about half the length being cut out to form a sort of trough. This wand was inserted into a sampling port and liquid dripped from the growth module above into the trough to run out through the tubing portion into a collection flask. The wand was moved from side to side to obtain a representative sample.

Analytical Procedures

Substrate Removal

In order to study the removal mechanism of sewage, the modified BOD test and COD test were performed on the collected filtrate of the sample. The filtrate was collected by filtering the sample through glass-fiber filter immediately after collecting sample. The samples were already analyzed on the same day as collected.

The BOD analysis was done according to Stover, et al.'s modified method (53). Dissolved oxygen values were measured with a Orion dissolved oxygen analyzer. For the loading where nitrification was observed (820.8 gal/day/ft^2) a nitrification inhibitor, nitrapyrin, was added to the BOD bottle. The concentration of nitrapyrin in the BOD bottle was 10 mg/l (54, 55).

COD analyses were performed on one set of samples once every week or for every third set of sample. The procedure as listed in "Standard Methods for the Examination of Water and Wastewater" for the determination of COD was followed (55).

Substrate Constituent Utilization

The amount of carbohydrate, protein and NH_3-N remaining at different depths of the tower was determined to observe the relation between the utilization of these constituents to the sewage removal rate kinetics of the tower. All these tests were performed at the same time as COD test.

The quantitative determination of carbohydrate was done by the 'Anthrone Test for Carbohydrate' (56). Reagent grade anhydrous dextrose was used for the standard sugar solution.

For protein analysis Bio-Rad Protein Assay was performed (57). The Bio-Rad Protein Assay Kit was used. It consists of Dye Reagent Concentrate and lyophilized bovine gamma globulin.

The ammonia-nitrogen was determined in accordance to Nessler Method for water, wastewater and sea water (58). Since the range of the test was 0-2 mg/l of ammonia-nitrogen, de-ionized water was used to dilute the sample.

All these tests are colorimetric, so HACH DR/2 Spectrophotometer was used to read the results at 540 nm, 595 nm and 425 nm for carbohydrate, protein and ammonia-nitrogen respectively.

Nitrate-Nitrogen

Nitrate-nitrogen was determined quite often for all the experimental runs (except for 820.8 gal/day/ft^2) to see if nitrification was occuring. At 820.8 gal/day/ft^2 hydraulic loading nitrate-nitrogen was analyzed routinely for every three sets of samples or once a week (as COD, carbohydrate, protein, and NH_3-N). During this loading nitrification was observed at the latter few feet of the depth of the tower. This analysis was made in accordance to the method outlined as "Cadmium Reduction Method Using Nitraver 5 Nitrate Reagent for Water and Wastewater; High Range: 0-30 mg/l" (58).

Biological Solids

The weight of biological solids in mixed liquor suspended solid was determined gravimetrically by filtration of the samples through glass filter. Then the method was followed as described in "Standard Methods for the Examination of Water and Wastewater" (55). The active biomass was determined theoretically as shown later.

pH

The pH was monitored for every sample filtrate immediately after the collection. An ORION Model pH meter which was standardized every time at pH 7 and pH 9.0 was employed for the pH determination.

Method of Data Analysis

The data obtained from different experimental techniques and methods are presented in the following Chapter IV, 'Results.' The variation in sewage composition and strength is inherited which varies from time to time, day to day, and season to season. Again, the biological tower microbial population is very diverse in nature. So, it was found convenient and the more representative of the system when grab samples collected over a definite hydraulic loading (since this was the only controlled parameter) for reasonable length of period be averaged and analyzed.

Since quite a few researchers derived removal rate relationships of biological tower based upon first-order kinetics (15, 17, 18, 20, etc.) it was decided to apply this approach to the observed data. Opatken (59) assumed second order reaction rate kinetics for substrate removal with reactor contact time per stage of rotating biological tower. As the organic loading concept is more impressive and reasonably accepted it was used. The concept is based on substrate saturation kinetics which according to Monod's expression is:

$$L_R = \frac{L_{R_{max}} L_0}{K_S + L_0}$$

where

L_0 = Applied BOD loading lbs BOD/day/1000 ft^2

L_R = BOD removed, lbs BOD/day/1000 ft^2

$L_{R_{max}}$ = Maximum BOD removed, lbs BOD/day/1000 ft^2

K_S = Applied BOD loading rate at which the rate of BOD removal is one-half the maximum rate, or the saturation content

Percent efficiency was calculated according to the following expression:

$$E = \frac{(S_i - S_e)\ 100}{S_i}$$

where

E = efficiency of substrate removal, percent

S_i = influent substrate concentration, mg/l

S_e = effluent substrate concentration, mg/l

Food to microorganism (F/M) is operationally defined as the amount of substrate applied per total amount of microorganisms in the system. As applied to a biological tower, food to microorganism ratio is defined as (32):

$$\frac{F}{M} = \frac{S_o\, Q}{X_T}$$

where

$\frac{F}{M}$ = food to microorganism ratio, time^{-1}

$F = S_oQ$ = substrate applied during a finite period of time, mass/time

S_o = influent substrate concentration, mass/volume

$M = X_T$ = dry weight of active microbial mass in the filter volume/mass

X_T can be further defined as:

$$X_T = VAtX$$

where

V = volume of filter medium

A = surface area per unit volume of filter medium, area/volume

t = active film thickness of the biological layer, length

X = dry weight of microorganisms per unit volume, mass/volume

The dry weight of active microbial mass in the reactor volume was obtained by assuming that the active film thickness of the biological layer was 70μ, and that the dry weight of microorganisms per unit volume was 95 mg/cu. cm (22).

The obtained results are analyzed and studied under different sub-sections of Chapter IV. The results are sectioned more or less based on different measured parameters not experimental runs. But the results for 820.8 gal/day ft^2 are presented separately under 'nitrification.' Because this run showed nitrification and was subject to minimal wetting effect.

CHAPTER IV

RESULTS

The results obtained are tabulated and conveniently presented under different sub-sections. Since hydraulic flowrate was the only controlled parameter the results are referred accordingly.

Evaluation of BOD Removal Kinetics for the Total Depth

The values obtained as BOD in mg/l for the samples collected at different depth of the tower are given in Table I. Plot 3 shows BOD remaining (mg/l) versus depth in feet. This plot indicates the concentration of the waste found at different depth of the tower. Plot 4 shows percent BOD remaining versus depth in feet. Both are semi-logarithmic plots in order to see if the removal rate is of first order. It is seen that both the 1440 gal/day/ft^2 and 1329 gal/day/ft^2 loadings show two removal rate constants. The reaction rate constants at different flowrates are shown in Table II.

TABLE I

OBSERVED BOD, mg/l AT DIFFERENT DEPTHS OF THE BIOLOGICAL TOWER AT DIFFERENT FLOWRATES

F gal/day/ft	INFLUENT mg/l	CUMULATIVE DEPTH-FEET 3	6	9	12	15	18
2880	91	75	60	55	41	33	24.4
	138	123	104	90	78	56	44
	85	65	54	46	-	38	32
	96	78	55	58	38	31	26
	87.8	73	60	50	43	36	30
	90	75	58.4	51.3	40	35	26
	112	89	76	62	59	43	41
	76	61	50	38	31	25	18
	114	98.2	83.2	72	60.4	50.5	43.2
	52.6	40	30	24	18.7	16.5	13.8
	85	70	60	50	40	34.4	28.7
	72	65.4	48	41	35	30.6	28.2
	91.8	74.5	61.7	58.6	50	46	40
	88.2	75	65	56	48	43.5	38
	72	58	48.2	40	33.8	28	24.6
	54	48	44.3	38	29	28	25
	81.4	68.2	-	28.7	24.3	16	12
1440	90	42	38	26.2	22.6	17.8	14.3
	65.2	32	28	26.2	23.8	14.2	12.8
	82	59.2	38.3	33.6	28.2	26.1	22.17
	98	48	32.2	27.8	25	21	18.5
	86.3	50.3	45.9	38.1	30	19.8	14.8
	84.5	52.9	41	27.2	25	22.4	16.3
	81	60.6	40.2	36	26	19.2	18.8
	78.2	52.6	39.3	27.6	23	20.5	13.5
	82	49.8	29.9	32	26.3	24	22.1
	92	56.6	48	39.6	29.9	27.4	24.6
	71	58.2	43.5	39.8	25	20	16.4
	82.8	53.1	48.2	32	26.3	24.8	26.8
	91	58	48.5	38	30	26	24
	88	60.1	40.5	35.9	25	27	27.4
	72.8	43	32	21.5	17.1	15.4	14
	60.3	38.8	30.2	25.7	20	-	-
	90.2	65.6	42.2	34.2	30.2	24.2	16.8
	77.6	49.1	35.2	30.2	20	18.8	13.8
	99.5	69.6	38.2	30	-	21.8	17.2
	96.5	49.5	39.8	30.1	24.3	20.6	13.8
1329	65.2	36	25	20	14	10	7
	42	23	15	12	8	5	3.6
	63.7	34	26	20	16	13	11

Table I (Continued)

	69.3	30	20	16	13	11.2	8.4
	55	29	20	16	13	10	8
	66	39	29	23	20	16.8	13.2
	46	25	17	11	9	5	3
	58.4	30.5	21	17.8	14.1	11	8.9
	60	30	26	24	20	17	15
Average							
2880	88	73	60	51.3	43	36	30
	87	57	39.4	31.6	25	19	18
	58	31	22	17.8	14	11	9

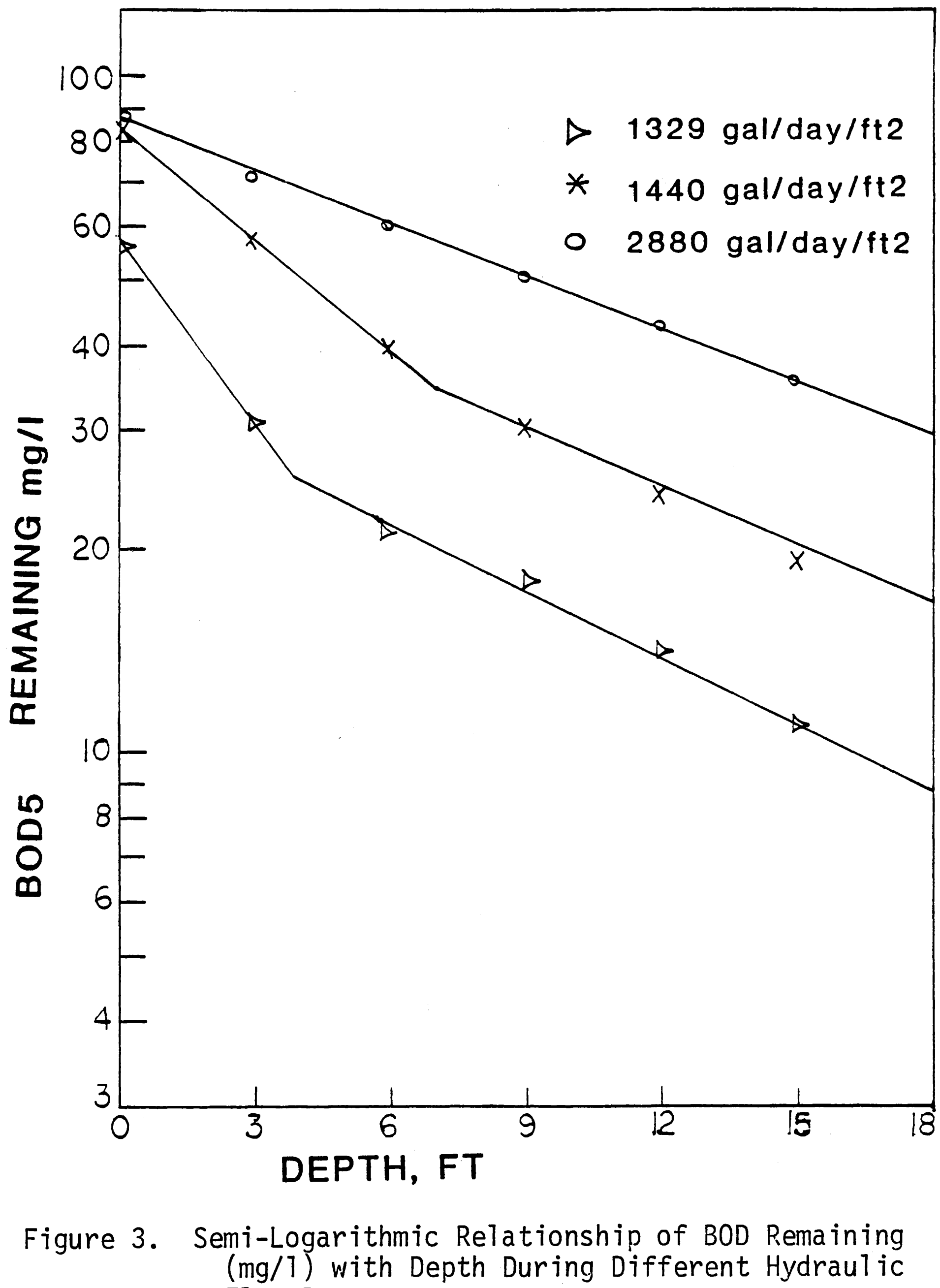

Figure 3. Semi-Logarithmic Relationship of BOD Remaining (mg/l) with Depth During Different Hydraulic Flow Rates

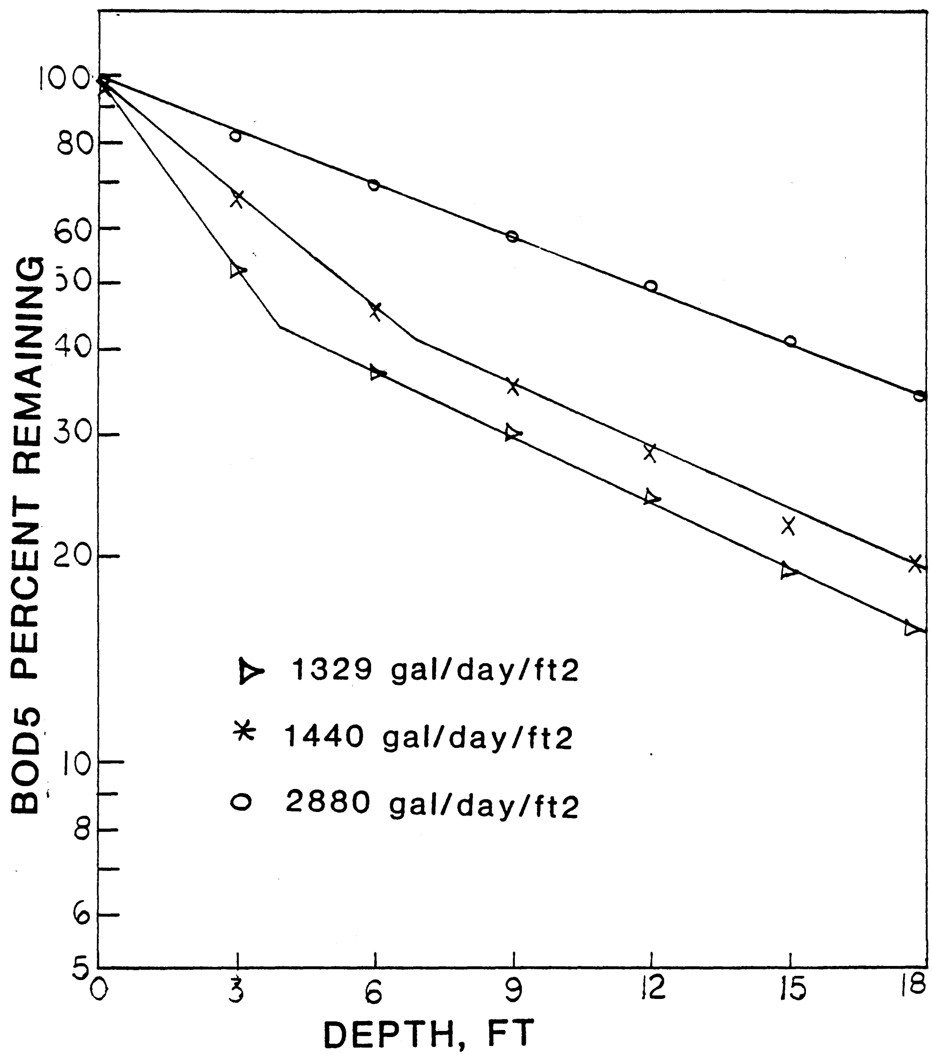

Figure 4. Semi-Logarithmic Relationship of Percent BOD Remaining with Depth During Different Hydraulic Flow Rates

TABLE II

REMOVAL RATE CONSTANTS WITH DEPTH DURING DIFFERENT HYDRAULIC FLOWRATES

Hydraulic Flowrate gpd/ft^2	Organic Loading $lbs/day/1000ft^2$	S_i mg/l	Phase I K_1 ft^{-1}	Phase II K_2 ft^{-1}
1329	0.927	58	0.216	0.071
1440	1.49	87	0.133	0.069
2880	3.03	89	0.062	-

So it is seen that the removal rate constant is more or less the same value for Phase II, that is for the later part of the depth of the tower. According to Kincannon (62) the Phase I reaction rate constant (K_1) vary with influent concentration, hydraulic loading and type of wastewater. It was also said that Phase II reaction rate constant ($K_2 \sim .07$ for domestic wastewater) vary only with type of wastewater. Table II reveals the same fact. As expected, the reaction rate constant K_1 for 1329 $gal/day/ft^2$ is the highest. Because it had the lowest hydraulic load and concentration. It also shows change of phase earlier than the other values. Because naturally it went into substrate limiting condition faster and had predominance change or metabolic shift. The cause of Phase II that is, decrease in removal rate could also be due to production of secondary metabolites or lysis as the more biodegradable forms were used up. The figures further indicate that the majority of the substrate was removed during Phase I. The results for the 2880 $gal/day/ft^2$ loading show a single removal rate. Apparently there was sufficient food to support the thriving microbial population throughout the depth of the tower. As seen, first order decreasing rate removal does occur but the presence of more than one kinetic constant through the depth of the tower would hinder the general expression for the total depth of the tower.

Figures 5 and 6 are plots made to see if the removal rate through the depth could be expressed by other kinetic orders. Plot 5, an arithmatic graph of BOD mg/l remaining versus depth, indicates that substrate removal rate did not follow zero order kinetics with respect to depth.

Second order removal as a function of hydraulic retention time has been used for rotating biological contactors (59). Later Stover and Kincannon (33) showed that the approach could be used for RBC only within certain limit. Here, this approach is attempted for biological tower. It is difficult to determine the hydraulic retention time or contact time for the biological tower. Depth is indirectly related to the hydraulic retention time for a specific flowrate. Therefore, Figure 6 is plotted as reciprocal of BOD, mg/l, remaining versus depth. It is important to recognize that this is an approximate approach. In Figure 6 the data plots as a curve, however a straight line could be fit to the data indicating that second order removal theory for biological tower could be approximated. However, it is seen that a new constant would be required for each flowrate. This would make it difficult to use as a design model.

All plots, 3 through 6, indicate that hydraulic flow rate alone or substrate concentration do not dictate the removal kinetics of the pilot plant biological tower. This is thought to be natural because

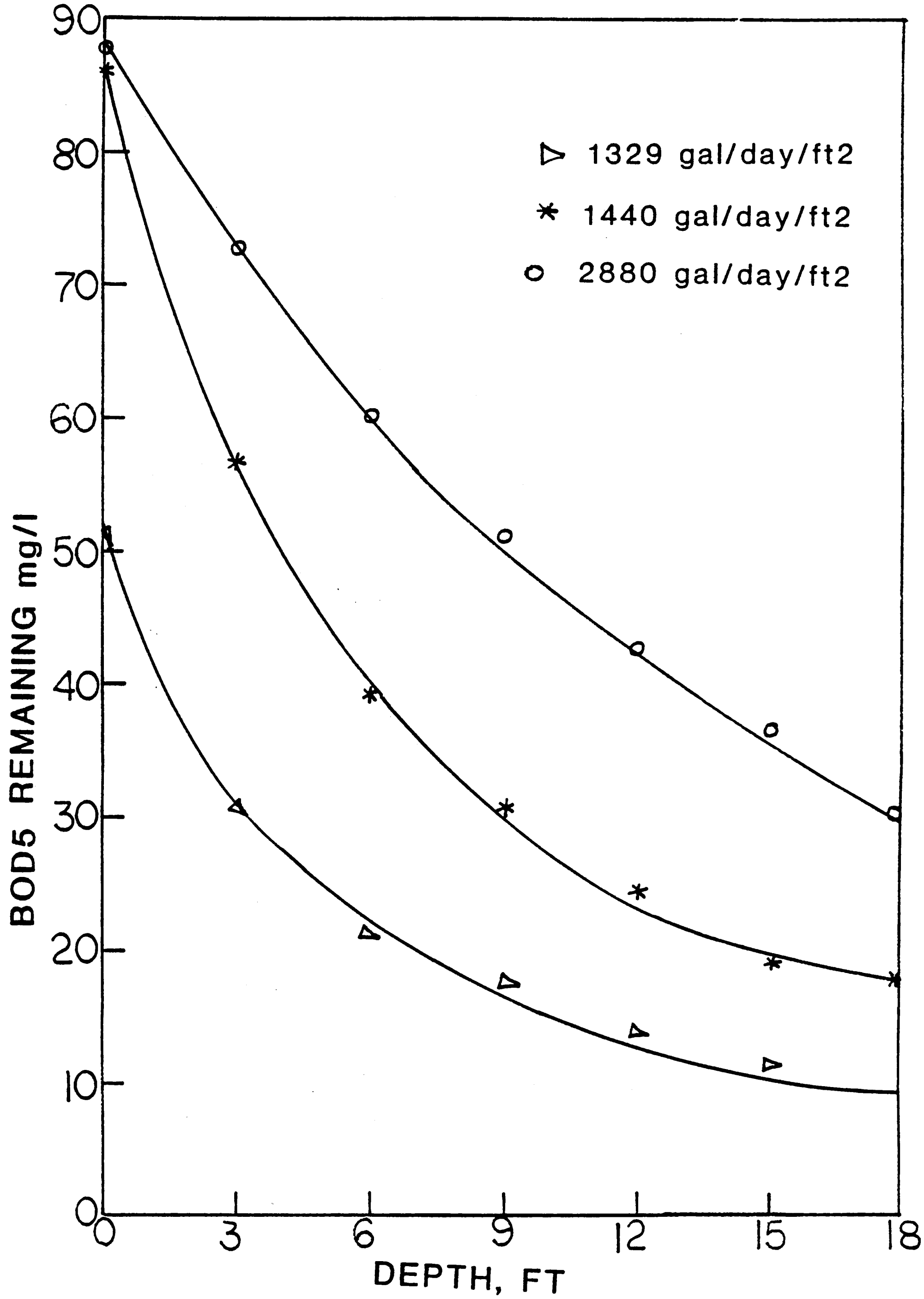

Figure 5. Arithmatic Relationship of BOD Remaining (mg/l) as a Function of Depth

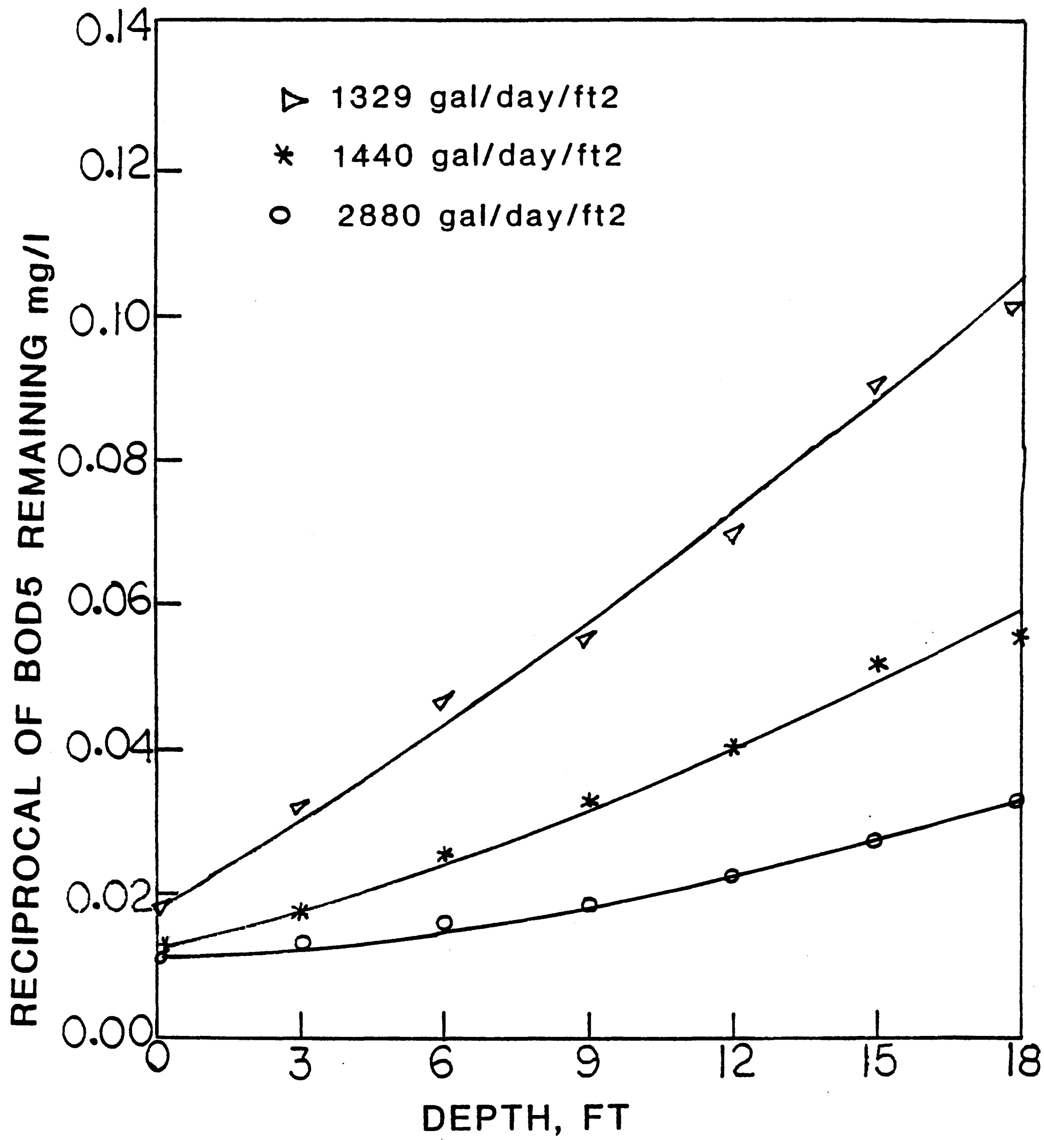

Figure 6. Reciprocal of BOD Remaining (mg/l) as a Function of Depth

with substrate removal, simultaneously compositional and concentration change occurs. This change in environment or of medium would effect the microbial community. Consequently, there could be predominance change, metabolic shift, lysis, secretion of metabolites, regulartory enzymic activity etc., life process activity or activities occuring as the sewage flow through the depth of the tower. All these reaction rates would affect the removal rate of substrate and so there is a change of kinetics within the same tower. But unless the removal rate follows a defined pattern no biokinetic constant can be determined to express or predict the performance of the system.

The total organic loading relationship for designing biological tower has been used with varying degrees of acceptance since the early 1970's (31). BOD or 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. Accordingly, Kincannon derived a graphical relationship based upon the ability of biological tower to remove the total organics applied to it. Figure 7 shows the plot of percent removal efficiency versus organic loading. This figure indicates that the relationship is not a first order type. This approach indeed describes the performance of the tower descriptively as expected. This shows that the relationship is a function of only the type of wastewater and the total organic loading. For a required treatment efficiency, there is an allowable organic loading in lbs BOD/day/1000 ft^2. This approach has been successfully used for design purposes. Later Kincannon and Stover (34) derived an

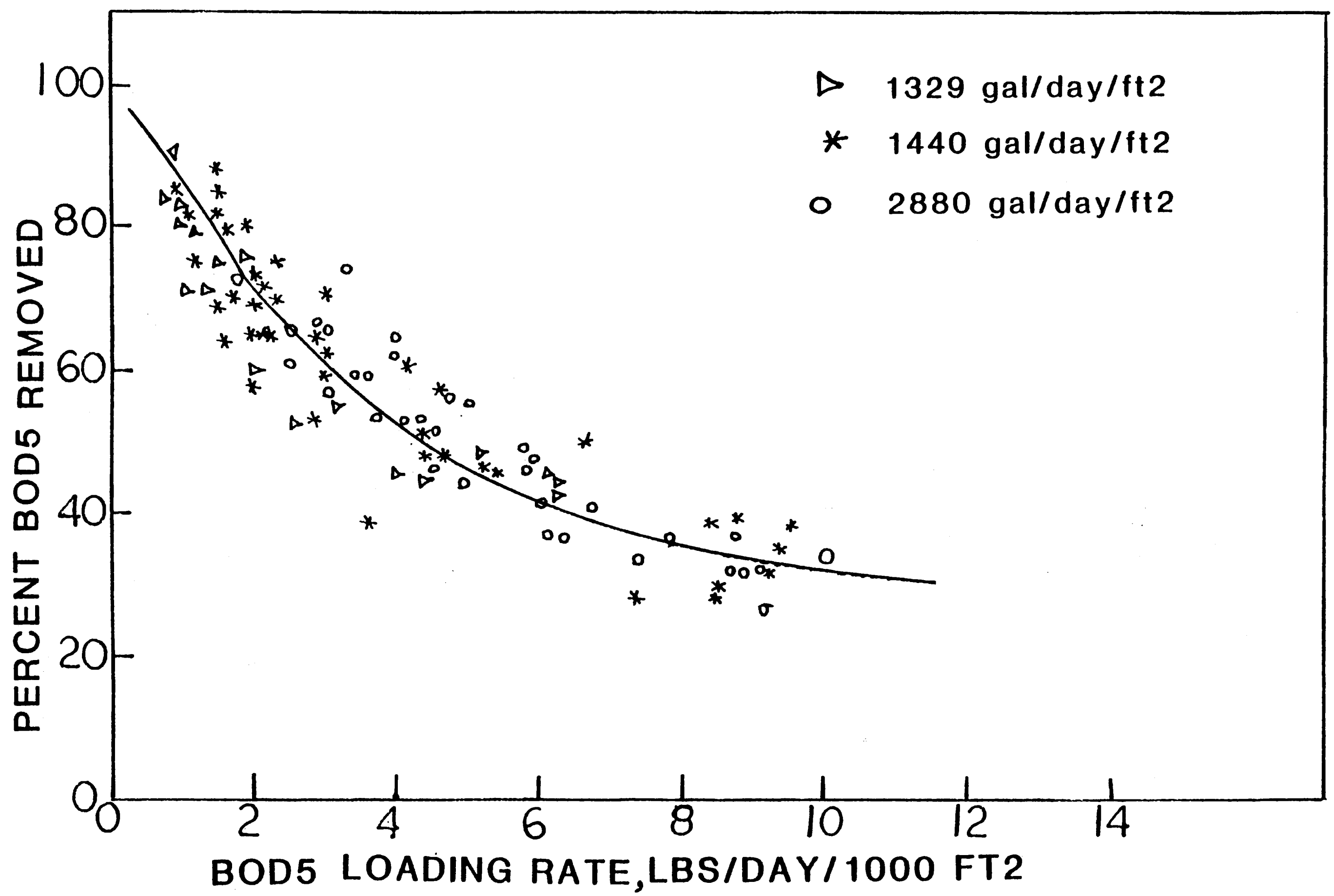

Figure 7. Treatment Efficiency (Percent BOD Removed) as a Function of Loading Rate (lbs/day/1000 ft^2)

analytical solution of the concept. Using this relationship precise biokinetic constants can be obtained. The equation is:

$$S_e = S_i - \frac{S_i\ U_{max}}{K_B + \frac{FS_i}{A}}$$

where

S_e = substrate concentration at point of measurement, mg/l

S_i = influent substrate concentration, mg/l

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

K_B = proportionality constant, lbs/day/1000 ft^2

A = surface area of volume, 1000 ft^2

Here U_{max} and K_B are the biokinetic constants which describes the removal mechanism.

The removal mechanism could be graphically presented as in Figure 8. The organic loading rate and organic removal rate were determined as follows:

$$\text{Organic loading rate, lbs/day/1000 ft}^2 = \frac{F(S_i)}{A}$$

$$\text{Organic removal rate, lbs/day/1000 ft}^2 = \frac{F(S_i - S_e)}{A}$$

Figure 8 shows that substrate removal rate follow a rectangular hyperbolic pattern with organic loading rate. It is seen that the organic removal rate approaches a maximum value. It further indicates that zero order kinetics applied at loadings greater than approximately 5 lbs BOD/day/1000 ft^2. At loadings below that the kinetics are neither zero order nor first order. This removal mechanism definitely

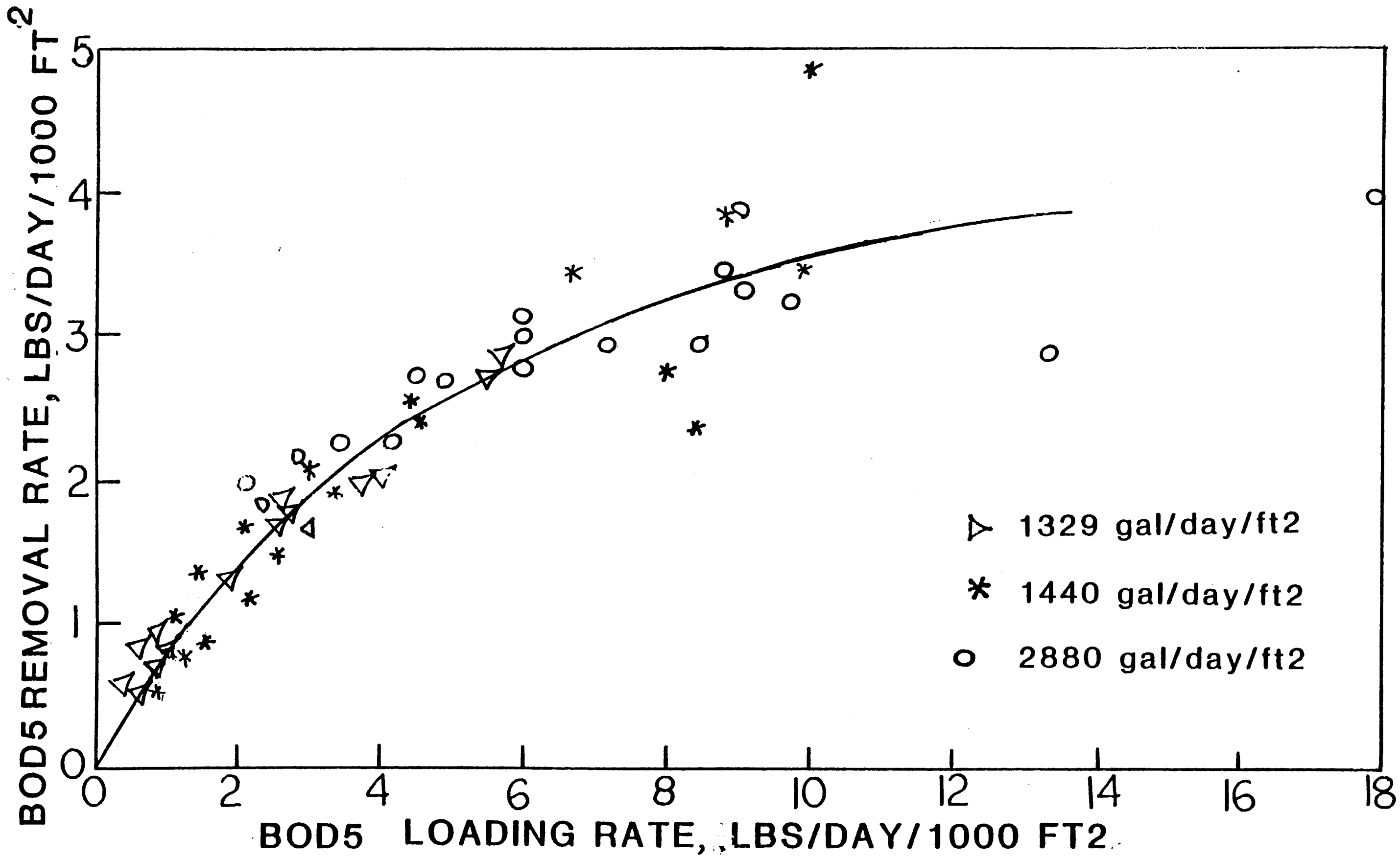

Figure 8. Relationship of BOD Removed Rate (lbs/day/1000 ft^2) as a Function of BOD Loading Rate (lbs/day/1000 ft^2)

exhibits saturation phenomenon. This type of relationship has been expressed after Monod's equation as:

$$\frac{F(S_i - S_e)}{A} = \frac{U_{max} \cdot \frac{FS_i}{A}}{K_B + \frac{FS_i}{A}}$$

Rearranging the equation:

$$\frac{1}{\frac{F(S_i - S_c)}{A}} = \frac{K_B}{U_{max}} \cdot \frac{1}{\frac{FS_i}{A}} + \frac{1}{U_{max}}$$

So, U_{max} and K_B can be determined from the intercept and slope as follows:

$$U_{max} = 1/\text{Intercept}$$

$$K_B = U_{max} \cdot \text{Slope}$$

Figure 9 shows the linearized form of Figure 8. This gives the value of maximum substrate utilization rate as 5.26 lbs BOD/day/1000 ft^2, which is supposed to correspond to the predicted loading rate where the actual zero order kinetics occur.

In order to check how an oxygen limited situation could effect the removal kinetics Figure 10 is plotted as reciprocal of organic loadings less than or equal to 3 lbs BOD/day/1000 ft^2 versus reciprocal of corresponding organic removal rate to determine the required biokinetic constants. Three lbs BOD/day/ 1000 ft^2 organic loading was selected because Figure 8 showed that the curve tends to bend after that loading. Figure 10 gives potential maximum substrate utilization rate of 7.14 lbs BOD/day/1000 ft^2 and K_B = 7.68 lbs BOD/day/1000 ft^2. Curve 2 of Figure 11 is plotted with U_{max} = 7.14 lbs BOD/day/

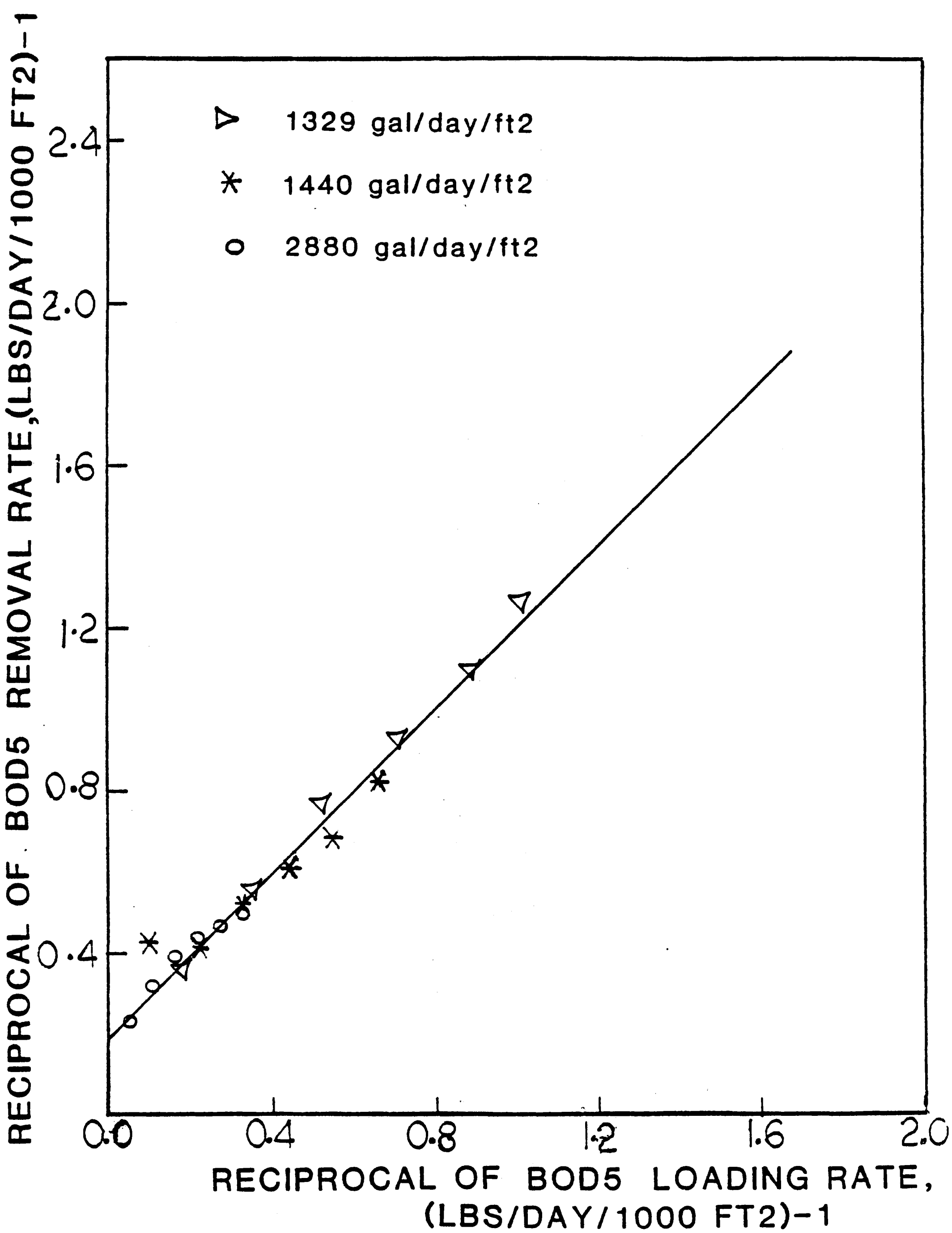

Figure 9. Reciprocal Plot of BOD Removal Rate (lbs/day/1000 $ft^2)^{-1}$ vs. BOD Loading Rate (lbs/day/1000 $ft^2)^{-1}$ for Total Range of Loadings

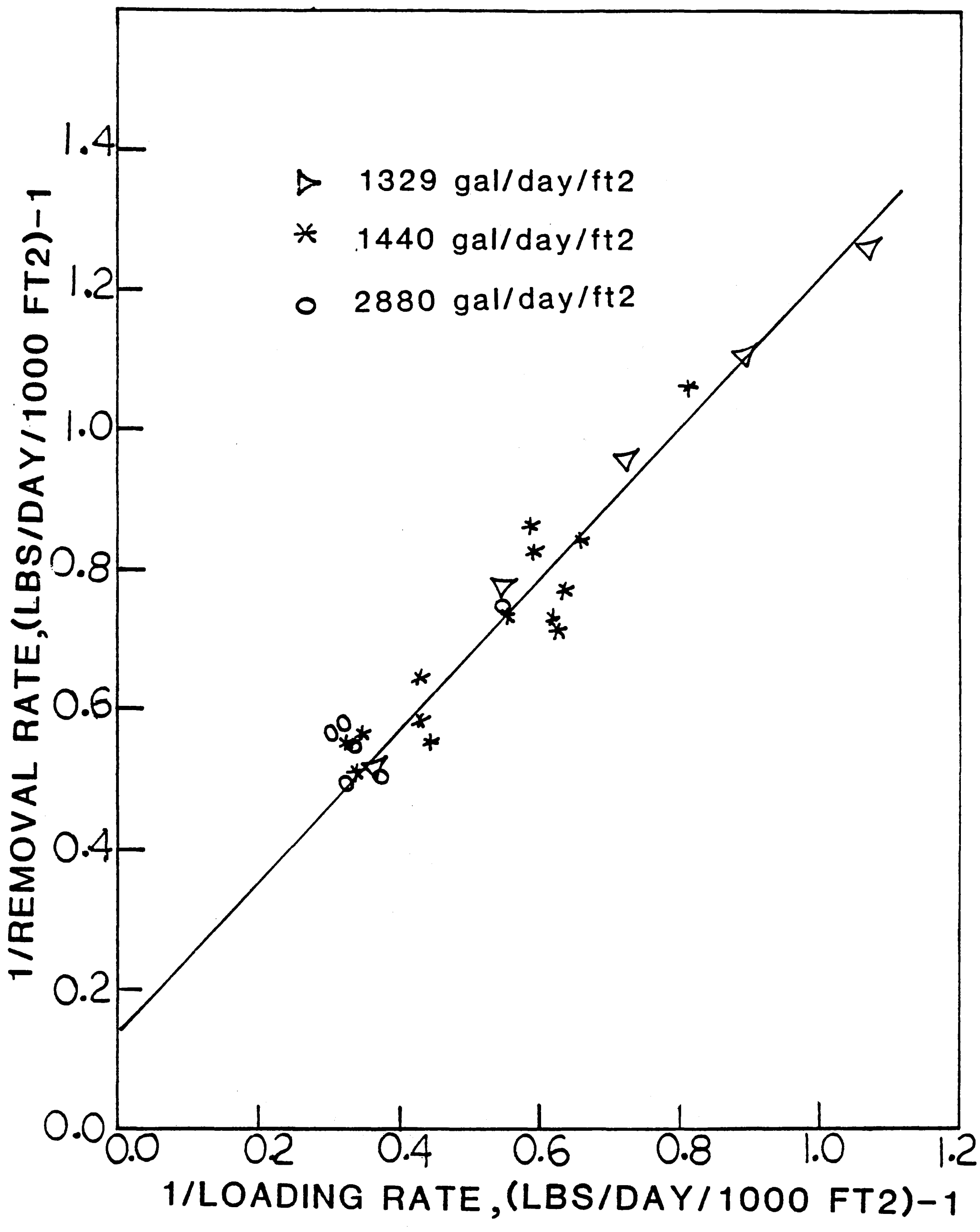

Figure 10. Reciprocal Plot of BOD Removal (lbs/day/1000 ft^2)$^{-1}$ Vs. BOD Loading (lbs/day/1000 ft^2)$^{-1}$ for Less Than Equal to 3 lbs/day/1000 ft^2 Loadings

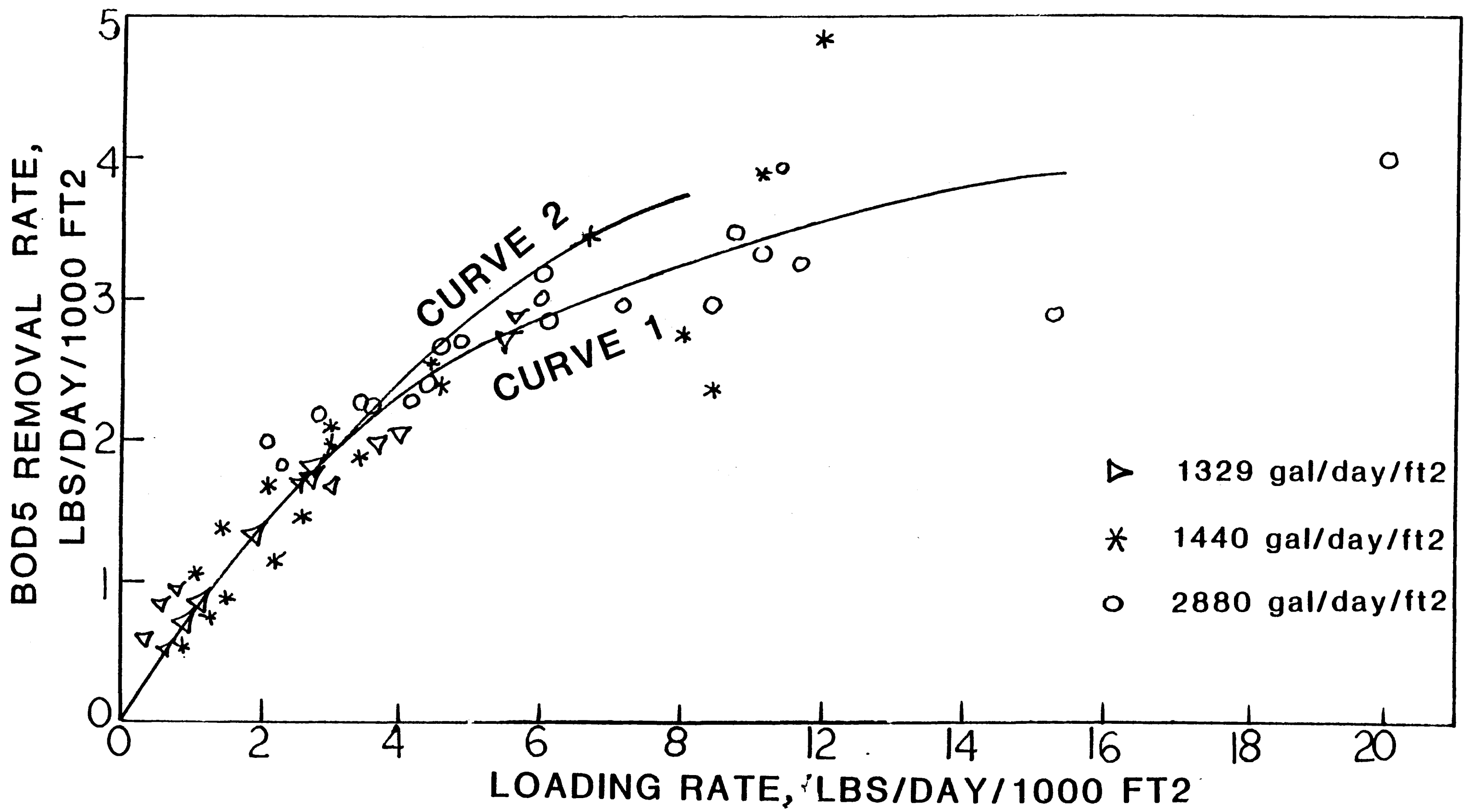

Figure 11. Relationship of Removal (lbs/day/1000 ft^2) Vs. Loadings (lbs/day/1000 ft^2)

1000 ft^2 and K_B = 7.68 lbs BOD/day/1000 ft^2. Curve 1 is plotted with K_B = 5.26 lbs BOD/day/1000 ft^2 and K_B = 5.37 lbs BOD/ day/1000 ft^2. As expected, they deviated around 3 lbs/day/1000 ft^2 loading. However, Table III is computed to check the predictability of the biokinetic constants. S_{e_1} are the predicted values of effluent by using the biokinetic constants obtained from the whole range of applied loading, that is, U_{max} = 5.26 lbs BOD/day/1000 ft^2 and K_B = 5.37 lbs BOD/day/1000 ft^2. S_{e_2} are the predicted values of effluent using U_{max} = 7.14 BOD/day/1000 ft^2 and K_B = 7.68 lbs BOD/day/1000 ft^2. And S_e are the actual obtained values. Table IV presents the results of statistical analysis. It clearly indicates that biokinetic constants obtained from less than equal to 3.0 lbs BOD/day/1000 ft^2 has better predictability of the performance of the tower.

Therefore, organic loading approach (Figure 8), as expected, gave an elaborate and decisive picture of the kinetic changes that occured during substrate removal mechanism and provides method to determine effective biokinetic constants as required.

Evaluation of Carbohydrate Removal Kinetics

Carbohydrate is one of the major components of the soluble organic concentration of domestic wastewater. The measured values of carbohydrate are presented in Table V.

Figures 12 and 13 are plotted to observe the removal rate of carbohydrate with depth. Figure 12 shows the amount of carbohydrate remaining (mg/l) plotted versus depth of the tower. And Plot 13 shows percent carbohydrate remaining with depth. Like the BOD versus depth plots (Figures 4 and 5) these curves also incidate presence of more

TABLE III

COMPARISON OF BIOKINETIC CONSTANTS PREDICTABILITY

S_i mg/l	F gal/day/ft^2	F S_i/A lbs BOD day/1000 ft^2	S_{e_1} mg/l	S_{e_2} mg/l	S_e mg/l	$\lvert S_e-S_{e_1}\rvert$ mg/l	$\lvert S_e-S_{e_2}\rvert$ mg/l
90	1440	1.55	21.6	20.38	14.3	7.5	6.08
65.2	1440	2.246	20.17	18.3	26.2	6.03	7.9
82	1440	2.025	23.67	21.6	21	2.67	0.6
86.3	1440	1.486	20.1	19.1	14.8	5.3	4.3
71	1440	1.223	14.35	14.06	16.4	2.05	2.34
91	1440	1.567	22	21	24	2.0	3.0
99.5	1440	1.714	25.58	23.87	17.2	8.38	6.67
90	1440	4.65	42.76	37.9	38	4.76	0.1
65.2	1440	6.73	36.86	32.9	32.0	4.86	0.9
86.3	1440	8.9	54.5	49.1	50.25	4.25	1.15
114	2880	3.93	49.5	43.9	43.2	6.3	0.7
87.8	2880	3.03	32.8	29.3	30	2.8	0.7
90	2880	3.1	34.11	30.4	26	8.11	4.4
91	2880	3.13	34.7	30.9	24.4	10.3	6.5
76	2880	2.618	26	23.3	18	8.0	5.3
85	2880	2.92	31	27.75	28.7	2.3	0.95
88.2	2880	9.114	56.18	51	65	8.82	14
76	2880	7.85	41.06	45.77	50	8.94	4.23
85	2880	4.39	39	34.72	40.1	1.1	5.38
46	1329	0.73	6.13	6.9	3	3.13	3.9
63.7	1329	3.03	23.67	22	29	5.33	7
58.4	1329	1.76	15.32	14.3	21.5	6.18	7.2
69.3	1329	6.6	38.8	34.5	30.1	8.7	4.4
65.15	1329	1.03	11.78	11.74	7	4.78	4.74

S_{e_1} = Determined using biokinetic constants for total loading.

Se2 = Determined using biokinetic constants for < 3.0 lbs BOD/day/1000 ft^2.

S_e = Observed effluent concentration.

TABLE IV

STATISTICAL COMPARISON OF PREDICTED EFFLUENT CONCENTRATIONS USING DIFFERENT BIOKINETIC CONSTANTS

Statistical Analysis	S_{e_1} U_{max} = 5.26 BOD/day/1000 ft^2 K_B = 5.37 BOD/day/1000 ft^2	S_{e_2} U_{max} = 7.14 BOD/day/1000 ft^2 K_B = 7.68 BOD/day/1000 ft^2	Actual
Mean	30.068	27.7	27.9
Sum of Square Deviation From Actual Values	890.1	671.6	-
Percent Deviation From Actual Mean	7.7	0.78	-
Student t-Test	0.0158	0.00176	-

TABLE V

CARBOHYDRATE REMAINING mg/l AT DIFFERENT DEPTHS OF TOWER

Flowrate gal/day/ft	0 ft	3 ft	6 ft	9 ft	12 ft	15 ft	18 ft
2880	20.7	17.3	12.6	12	9.3	8.4	8.6
	17.3	15	13.2	11	11	7.0	6.3
	13	11	10	8.6	8.0	7.0	6.7
	12	10	8	6	5.3	4.2	4
	13.5	12	9	6.3	4.6	4.0	3.33
	25.5	19	17.3	12	9.33	8	5.22
	26.7	19.3	16.3	14	12	8.2	6.67
1440	13.33	6.2	4.0	3.0	2.0	3.2	4
	16.7	5.3	0.0	1.3	2.0	4.5	6.0
	10	8.0	6.0	5	6	6.2	6.0
	19.8	15.8	6.6	4.3	3.0	1.34	1.33
	26.0	19.2	15.4	12.8	10	6.8	4.2
	27	26.1	22.2	17.33	13.52	7.86	3.88
1329	44	30	20	13.33	12	10.60	10.0
	34.67	29	17.33	15.33	14.6	15.3	15.6
	21.33	17.0	14.7	9.33	10.33	12.66	10.66
Average							
2880	18.386	14.8	12.35	10	8.4	6.69	5.83
1440	18.81	13.443	9.53	7.3	6.1	5.0	4.24
1329	33.33	25	17.34	12.66	12.31	12.87	12.33

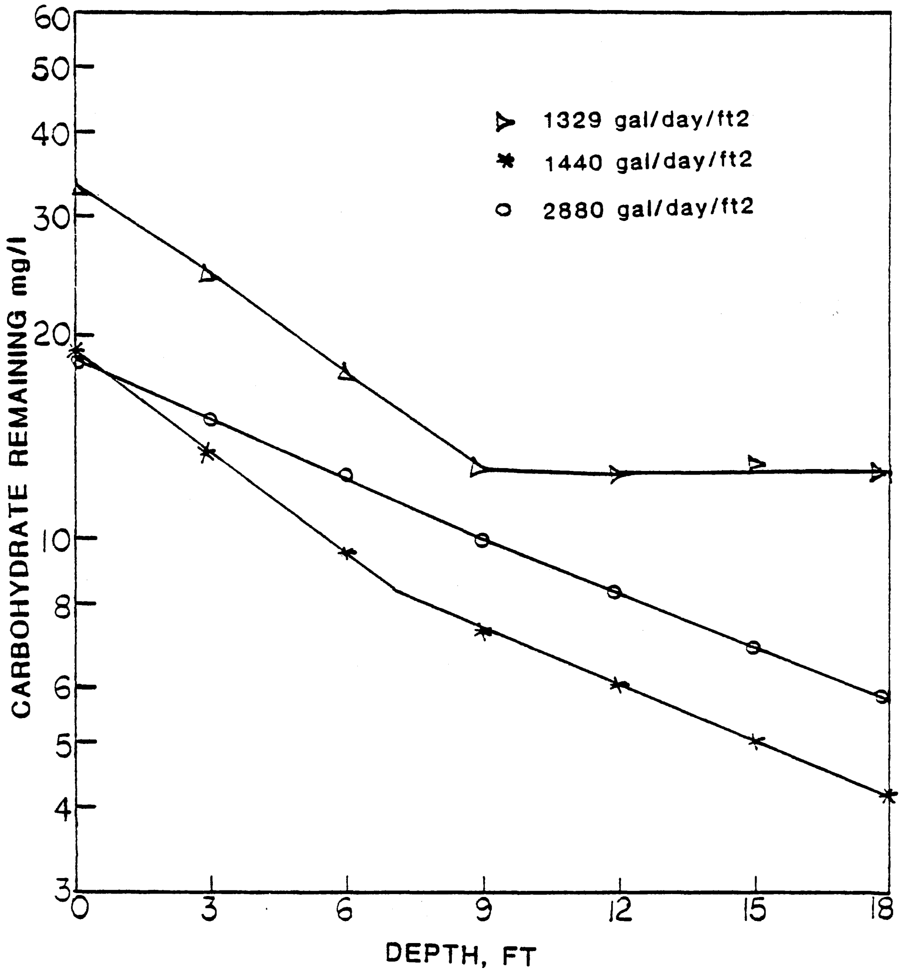

Figure 12. Semi-Logarithmic Relationship of Carbohydrate Remaining (mg/l) with Depth

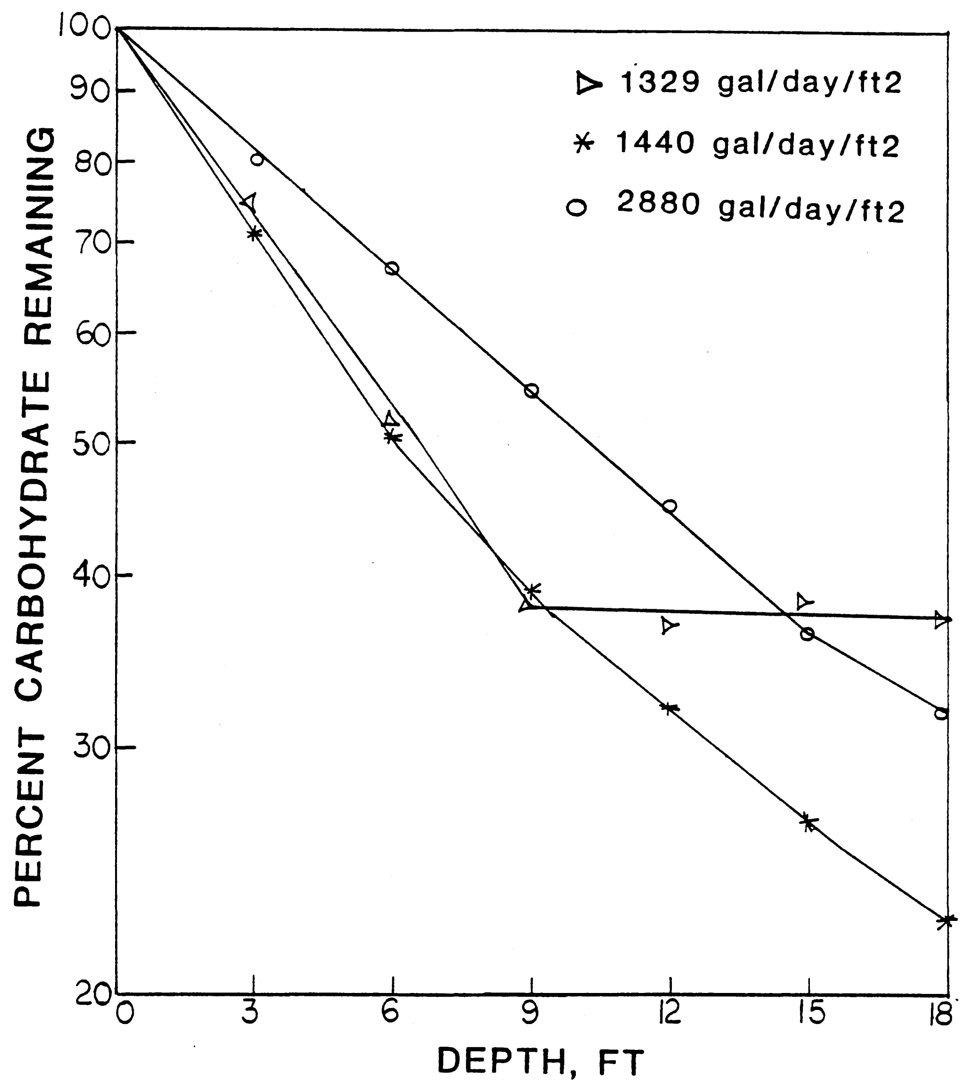

Figure 13. Semi-Logarithmic Relationship of Percent Carbohydrate Remaining (mg/l) with Depth

TABLE VI

KINETIC RATE CONSTANTS FOR CARBOHYDRATE REMOVAL

F gal/day/ft^2	Influent Carbohydrate mg/l	Phase I K_1 ft^{-1}	Phase II K_2 ft^{-1}
1329	33.33	0.16	0.0
1440	18.81	0.1156	.067
2880	18.386	.06	.06

than one removal rate. The kinetic constants as obtained from Figures 12 and 13 are presented in Table VI. Interestingly, kinetic constant for carbohydrate removal is more or less the same as those for BOD removal kinetics. Like BOD removal, the rate constants for Phase I (K_1) here could also vary because of difference in hydraulic flowrate and concentration. The Phase II kinetic constants are very close to those observed for BOD. This indicates that carbohydrate removal rate for this study of sewage has considerable effect on BOD removal.

The values for 2880 gal/day/ft^2 hydraulic flow rate shows one removal rate constant because there was enough of biodegradable carbohydrate throughout the depth of the tower to support the microbial activity. But during both 1440 gal/day/ft^2 and 1329 gal/day/ft^2 hydraulic loading more than one removal rate constant is observed. The change in removal rate constants observed at 1440 gal/day/ft^2 run was caused due to the exhaustion of major part of removable carbohydrate. In spite of the presence of high carbohydrate during 1329 gal/day/ft^2 hydraulic loading, the system exhibits no removal after first 9 ft. of the depth. There are two probable answers to this situation. First, sewage during this period contained a high proportion of non-biodegradable carbohydrate which was predominate at the later part of the depth of the lower. Secondly, as the system was substrate limiting during that part, the secretion of secondary metabolities and bacterial lysis could contribute to the concentration of carbohydrates.

Figures 14 and 15 are plotted according to the total organic loading concept (34). Figure 14 shows lbs/day/1000 ft^2 of carbohydrate removed versus lbs/day/1000 ft^2 of carbohydrate applied. As expected, Figure 14 (Curve 1) does show saturation kinetics that the removal rate reaches a maximum value beyond which removal rate is not effected by increase in applied loading. Figure 15 is plotted to determine the biokinetic constants. The maximum carbohydrate utilization rate is obtained as 1.043 lbs/day/1000 ft^2. Figure 14 indeed shows that zero-order was approached around that loading. Figure 14 also indicates that at loadings higher than about 1 lb carbohydrate/ day/ 1000 ft^2 the data shows more scattering. From Figure 14 it is seen that at greater than 1 lb/day/1000 ft^2 total carbohydrate loading the values for 2880 gal/day/ft^2 hydraulic flowrate exhibits lower removal rate. Comparing Table I and Table V those greater loadings correspond to organic loading of greater than 4.5 lbs BOD/day/1000 ft^2. It could be mentioned that beyond 5 lbs BOD/day/ 1000 ft^2 the system approached zero order kinetics due to oxygen limited situation. But the values for 1329 gal/day/ft^2 flowrate does not show that effect. Because though the total carbohydrate is high, during this hydraulic loading the total organic loading was not

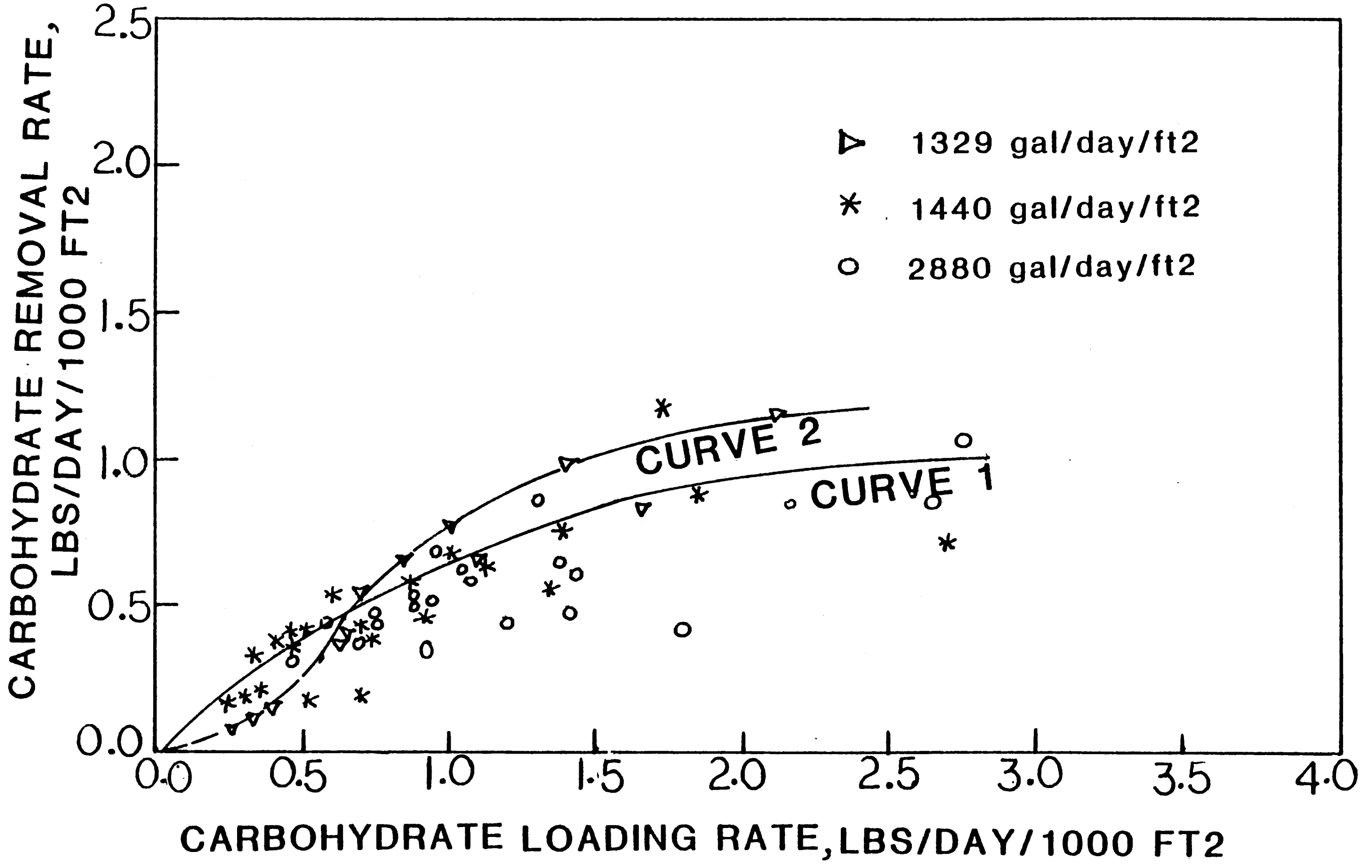

Figure 14. Relationship of Carbohydrate Removal Rate (lbs/day/1000 ft^2) as a Function of Carbohydrate Loading Rate (lbs/day/1000 ft^2)

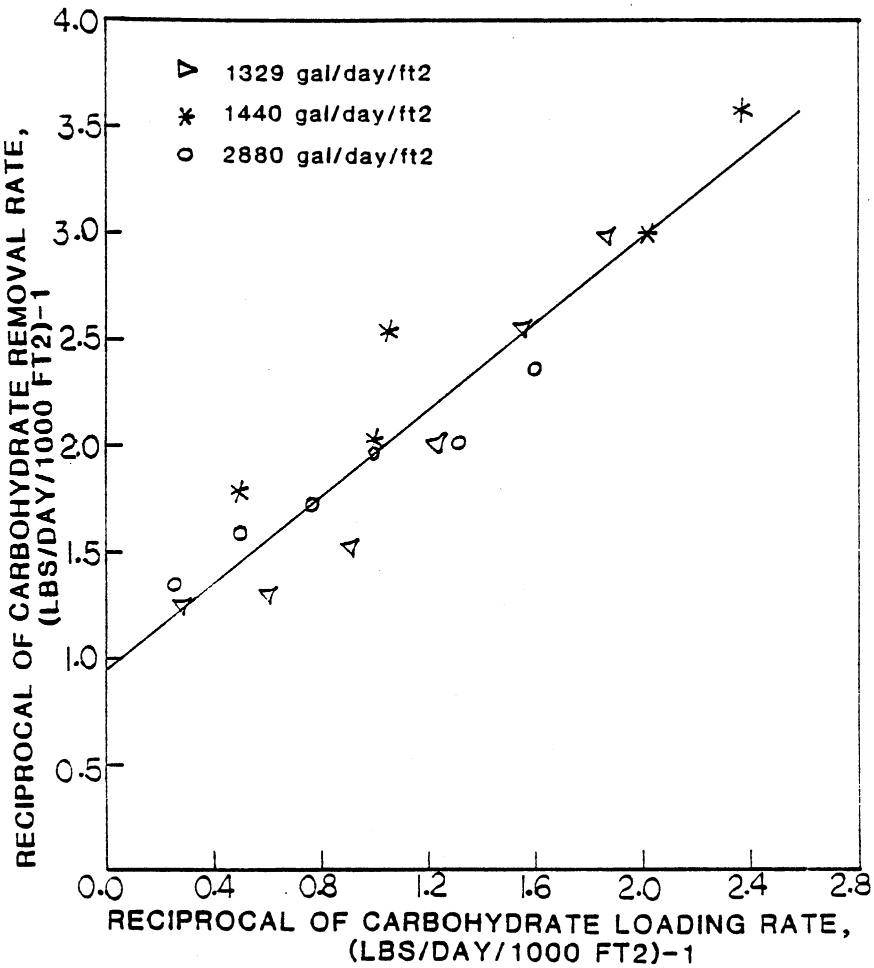

Figure 15. Reciprocal Plot of Carbohydrate Removal Rate (lbs/day/1000 ft^2) Vs. Carbohydrate Loading Rate (lbs/day/1000 ft^2)

so high (about 5.6 lbs BOD/day/1000 ft^2) to be that much oxygen limited.

Curve 2 is drawn along the values obtained only at 1329 gal/day/ft^2 flowrate. It shows (i) a lag in Curve 2 at lower carbohydrate loadings and (ii) higher substrate utilization rate at high loadings. This run was not subject to oxygen limited situation so it shows substrate saturation condition for high loadings. But, the sewage during this run contained non-degradable carbohydrate which significantly effected the removal rate at later depth of tower which here corresponds to tower loadings, therefore the lower loading of carbohydrate shown in Curve 2 shows a lag.

Therefore, carbohydrate and BOD removal mechanism seem to be significantly correlated. It could be noted that though the first order removal kinetics for BOD and carbohydrate more or less agreed, as expected the maximum substrate utilization rate (5.26 lbs BOD/day/1000 ft^2) is much higher than maximum carbohydrate removal rate.

Evaluation of Protein Removal Kinetics

Protein is classified as the second category of biodegradable organic matter in wastewater (76). The oxidation level of protein is between carbohydrate and fat. Bioenergetically it is less preferrable by most aerobic bacteria than many carbohydrates, like glucose, sucrose, maltose, etc. But depending on type of bacteria and the concentration and availability of carbohydrate and other organic-nitrogen compounds like urea, amino-acids, nuclic acis, peptids, etc. Protein can be used by bacteria as an energy source or both carbon and energy sources.

The results obtained on protein analysis of different samples at different depth and during various hydraulic flowrates are tabulated in Table VII.

Figure 16 and 17 are plotted with the average values of protein remaining at different depth of the tower. Figure 16 shows protein concentration mg/l remaining versus depth. Figure 17 shows percent protein remaining versus depth. During the first few feet of the depth of the tower, removal rate of protein is slow. It could be reminded that the first few feet of tower exhibited high removal rate of carbohydrate. Literature suggests that so-called "glucose-effect" which causes repression of certain enzymes is not confined to glucose, any readily utilizable carbon source may exert a similar effect (68). This fact can be more clearly observed by comparing the removal pattern observed for carbohydrate (Figure 12) and that for protein (Figure 16) during 2880 gal/day/ft^2 hydraulic loading. At this run the pilot plant tower was subjected to the highest organic loading (3.03 lbs BOD/day/1000 ft^2) and highest carbohydrate loading (0.63 lbs carbohydrate/day/1000 ft^2). The system was exhibiting high food-to-microorganism ratio. It is most likely that the catabolic repression occured and severely effected the removal rate of protein during the 2880 gal/day/ft^2 hydraulic loading rate. The curve drawn to the 2880 gal/day/ft^2 experimental run shows negligible removal for protein. The curve through the results obtained at 1329 gal/day/ft^2 hydraulic flowrate during which carbohydrate concentration was high, also indicates the repression effect on protein. The removal rate of protein increased only after the carbohydrate removal dropped to

TABLE VII

PROTEIN MEASURED AT DIFFERENT DEPTHS OF THE TOWER

Flowrate	0'	3'	6'	9'	12'	15'	18'
2880	11.5	9.0	9.0	12	11.5	12.5	12.5
	12.5	10	9.5	12	13	12.5	11
	11.5	11.5	10.8	10.4	10.8	7.8	7.5
	11	12.5	13.5	13.0	12.5	11	9.5
	11.8	13	12	13	12	11.5	10.5
	11.5	12.7	12	11.6	11	12	11.5
Avg. 2880	11.6	11.45	11.13	12	11.8	11.21	10.4
1440	10.5	9.5	8.2	6.0	4.4	3	2
	13	11.5	9.0	7.3	5	4	3.5
	17.5	15.6	12.8	9.5	4.15	4.4	3.6
	14.5	10.9	8.7	8.3	8.0	6.9	5.2
	13	11.5	11.2	10	9.2	8.6	7.0
	16.5	13.6	10	9.2	8.0	7.95	6.8
Avg. 1440	14	12.8	9.98	8.38	6.8	5.81	4.68
1329	10	9.25	9.0	8.5	8.0	7.0	6.0
	8.5	9.4	9.5	8.5	7.0	2.0	1.0
	10	9.0	9	8.05	7.0	6.0	3.5
Avg. 1329	9.5	9.2	9.17	8.33	7.33	5.0	3.5

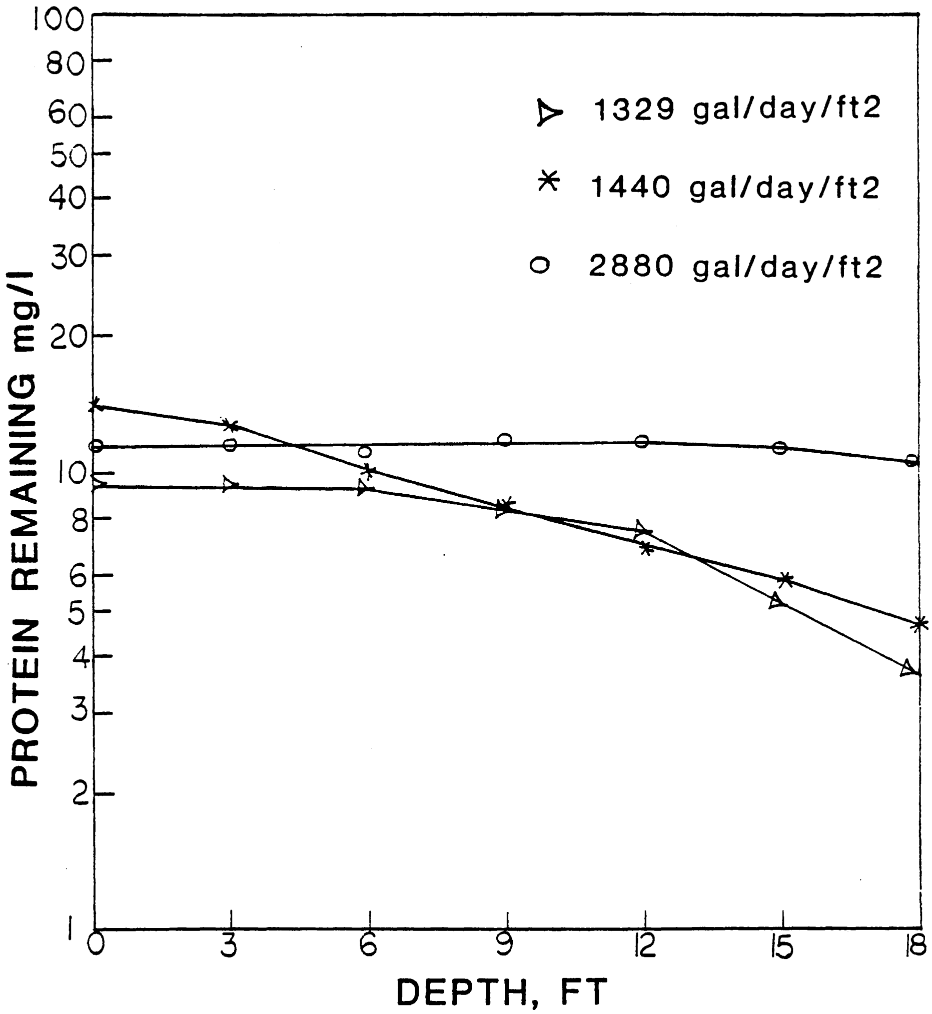

Figure 16. Semi-Logarithmic Relationship of Protein Remaining (mg/l) with Depth

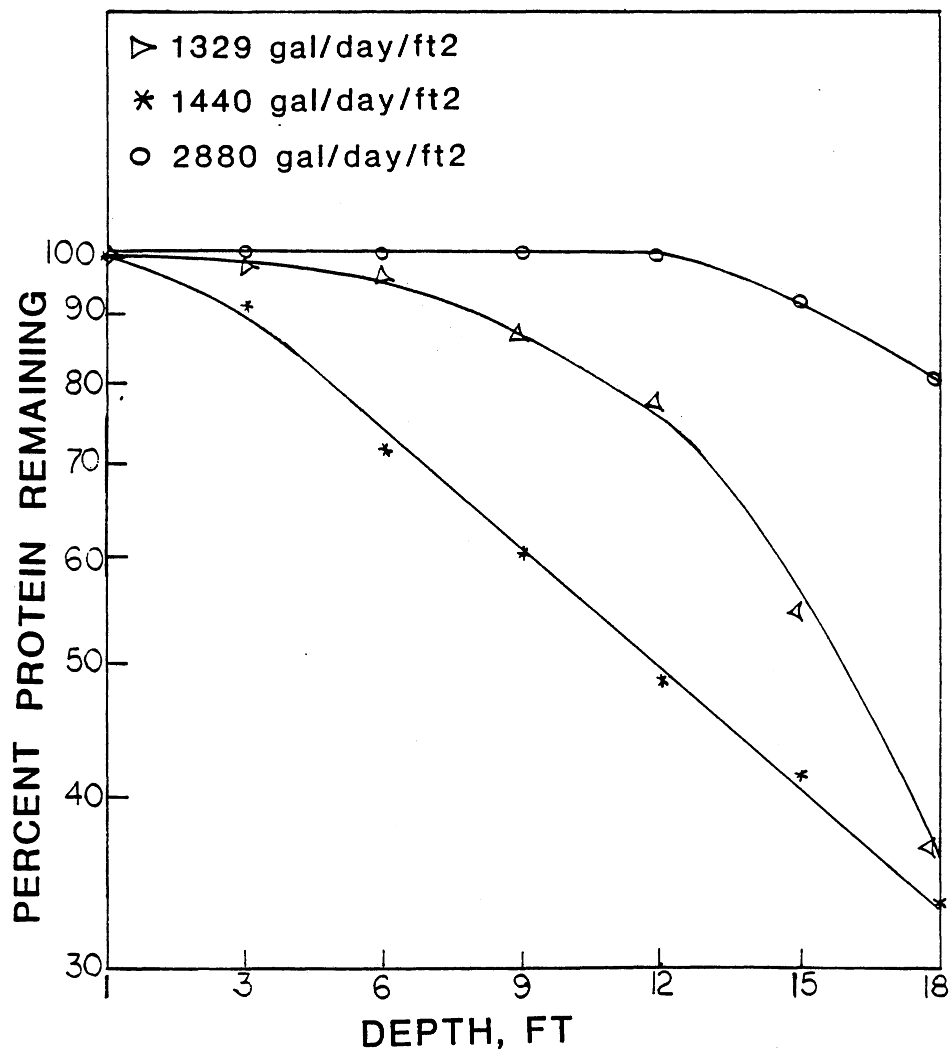

Figure 17. Semi-Logarithmic Relationship of Percent Protein Remaining with Depth

negligible value. Here the protein removal is thought to be an enzyme induced mechanism.

Of course, the removal mechanism of protein during 1440 gal/day/ft^2 is confusing. This curve shows that increased protein biodegradation started after only 3 feet depth of the tower. It could be explained by one or both of the following reasons: (i) Table V indicates that at 1440 gal/day/ft^2 flowrate the total carbohydrate loading applied was only 0.324 lbs/day/1000 ft^2, which is the least amount of carbodhydrate among three loadings (2880 gal/day/ ft^2 applied equals 0.63 lbs carbo/day/1000 ft^2; 1440 gal/day/ft^2 applied equals 0.324 lbs carb/day/1000 ft^2; and 1329 gal/day/ft^2 applied equals 0.53 lbs carb/day/1000 ft^2). Most likely the total amount of carbohydrate was not enough to support the growth or cause catabolitic repression, (ii) protein utilization is effected by the presence of other organic nitrogenous compound like urea, peptides, etc. Maybe during 1440 gal/day/ft^2 there was less amount of these organics and so enhanced the protein utilization.

The application of the organic loading concept is observed in Figure 18. It is found to be unsuccessful in describing any definite removal rate pattern. But it indicates about the complexity involved in the removal pattern of protein for this type of study.

Though protein study could not be directly evaluated or generalized in terms of definite removal kinetic or mechanism, but the observed facts could help in understanding the removal mechanism.

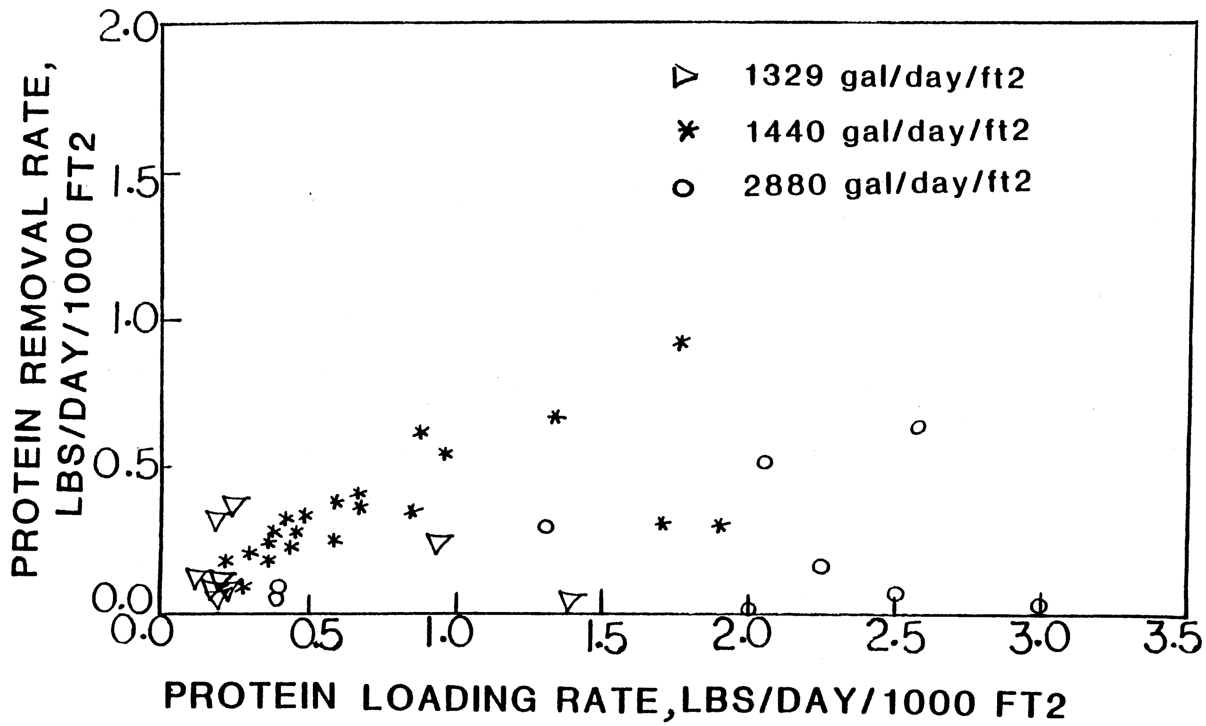

Figure 18. Relationship of Protein Removal Rate (lbs/day/1000 ft^2) as a Function of Protein Loading Rate (lbs/day/1000 ft^2)

Evaluation of COD Removal Kinetics

The results obtained on measuring COD for different experiments are tabulated in Table VIII. More or less similar approach to COD removal kinetic has been applied as it was done for the evaluation of BOD removal kinetics. Figures 19, 20, 21 and 22 are all plotted for COD remaining versus depth according to first order, zero order and second order reaction kinetics respectively. The removal rate kinetics according to Figures 19 and 20 are as follows:

TABLE IX

REACTION RATE CONSTANT FOR COD REMOVAL

F gal/day/ft^2	S_i,COD mg/l	K_1 ft^{-1}	K_2 ft^{-1}	K_3 ft^{-1}
2880	142	.07	.025	-
1440	118	0.148	.066	.015
1329.12	143.67	0.101	.044	.005

Unlike BOD remoal rate these removal rates do present difficulty in explanation. It may be because COD measures both degradable and non-degradable oxygen demand of the wastewater. The analysis of removal kinetics based on COD could be little complicate because it is not a ΔCOD (biodegradable COD).

Figures 19 and 20 show that removal rate constant changes more than observed for BOD or carbohydrate. This could be expected due to

TABLE VIII

COD mg/l OBSERVED AT DIFFERENT DEPTHS OF THE BIOLOGICAL TOWER

Flowrate	0 ft	3 ft	6 ft	9 ft	12 ft	15 ft	18 ft
1329	146	102	76	60	50	54	56
	125	85	70	65.5	60	57	55
	160	115	94	90	72.5	64.5	63
1440	120	86	72	60	42	40	38
	182	126	120	98	82	70	42
	98	45	35	30	20	25	40
	110	72	63.6	52	40	38	39
	98	60	47	42	40	38	32
	100	65	46	24	27	25	-
2880	155	126	120	110	111	96	90
	130	111	88	70	61	55	50
	135	110	86	80	65	55	53
	140	115	88	74	72	68	64
	130	106	88	76	68	60	49
	140	92	87	76	80	77	62
	160	140	111	102	96	102	110
	146	120	105	88	78	60	60
Average							
1329	143.67	100.67	78.33	70.8	60.5	59.8	58
1440	118	75.67	63.9	51.02	41.8	39.3	38.2
2880	142	115	96.6	84.5	78.88	71.6	67.25

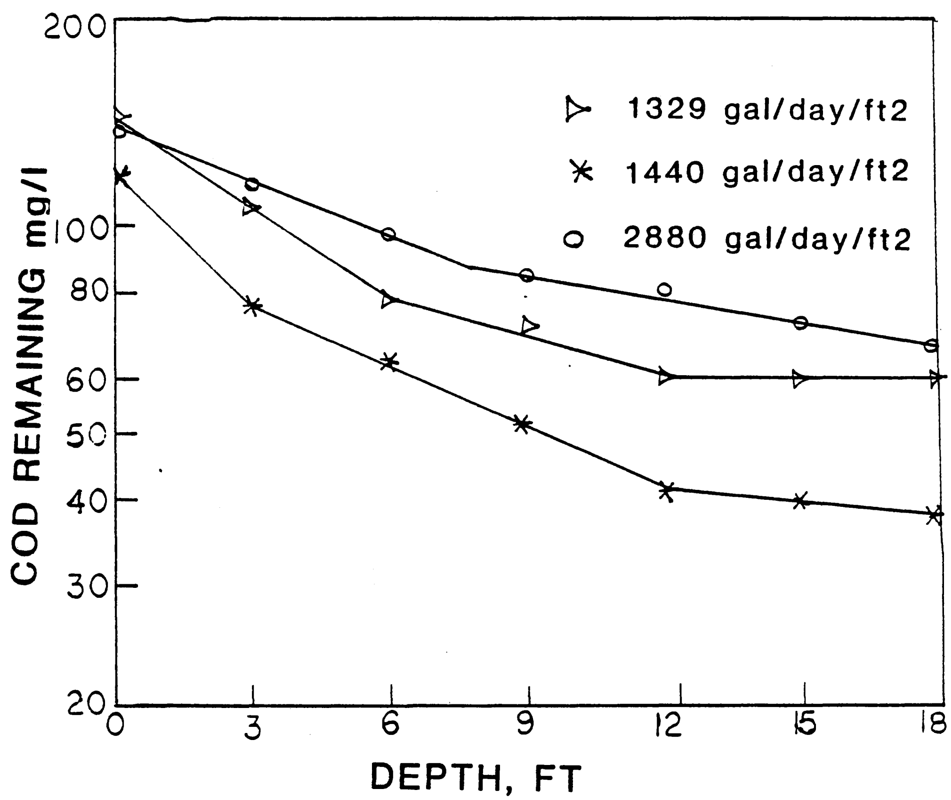

Figure 19. Semi-Logarithmic Plots of COD Remaining (mg/l) with Depth

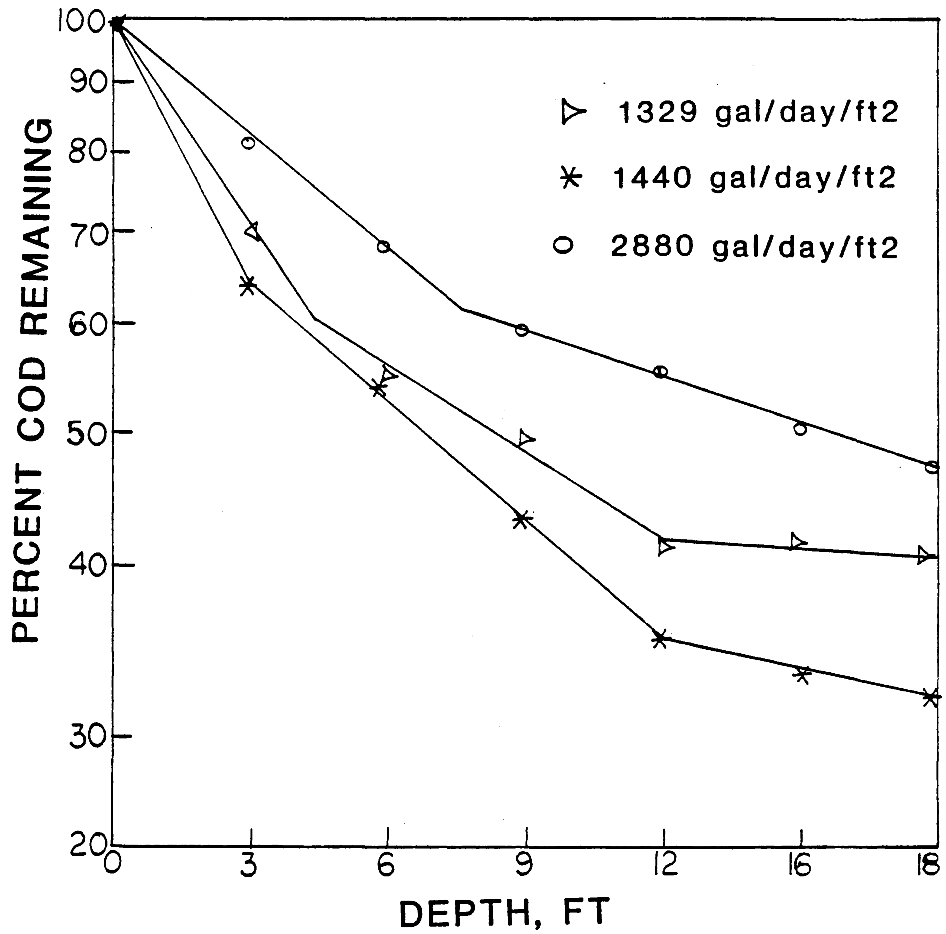

Figure 20. Semi-Logarithmic Plots of Percent COD Remaining with Depth

the nature of the test. The values during 2880 gal/day/ft^2 show phase I removal rate constant of 0.07 ft^{-1}, which is close to its removal rate constant obtained for BOD. then the removal rate decreased may be because the ratio of non-biodegradable organic carbon increased enough to show up in results. That same reason may also stand for three gradual decreases in removal mechanism at 1440 gal/day/ft^2 and 1329 gal/day/ft^2 flowrate. It is also seen from Table VIII that COD loading for 1329 gal/day/ft^2 hydraulic loading (2.28 lbs COD/day/1000 ft^2) is higher than that for 1440 gal/day/ft^2 (2.03 lbs COD/day/1000 ft^2). But the removal rate at 1329 gal/day/ft^2 hydraulic loading is lower than that observed at 1440 gal/day/ft^2. This is because the carbohydrate results showed that during that 1329 gal/day/ft^2 run the sewage had higher amount of non-degradable carbohydrate. But, the most interesting point is carbohydrate and COD removal kinetic shows little or no removal at the last 6 ft. depth but protein and BOD shows removal. This might be confusing. The possible explanation seems to be that production of secondary metabolites, lysis, secretion of polysacharides and capsules etc. occured at that substrate limited situation and that contributed to the COD concentration.

Figure 21 plotted as percent COD remaining versus depth in arithmetic paper shows that removal kinetic do not follow zero order. Figure 22 showing reciprocal of COD remaining versus depth indicates same type of difficulty for use in design as it was observed for BOD.

Figures 23 and 24 are plotted to apply Kincannon and Stover's model. According to Figure 24 maximum substrate utilization rate is 7.41 lbs COD/day/1000 ft^2. Figure 23 also indicates that around 7.41 lbs COD/day/1000 ft^2 the removal rate approached zero order.

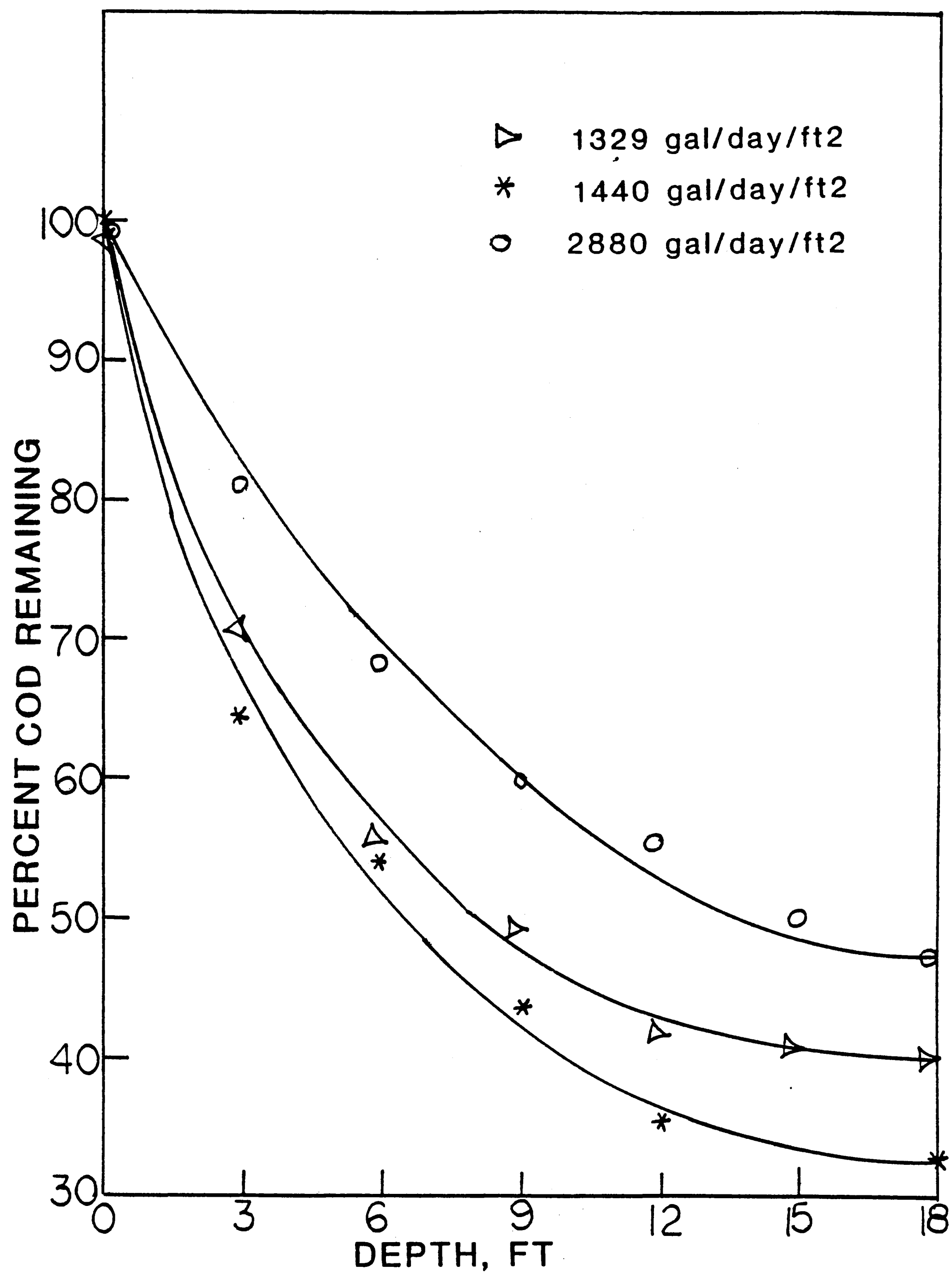

Figure 21. Arithmatic Relationship of Percent COD Remaining with Depth

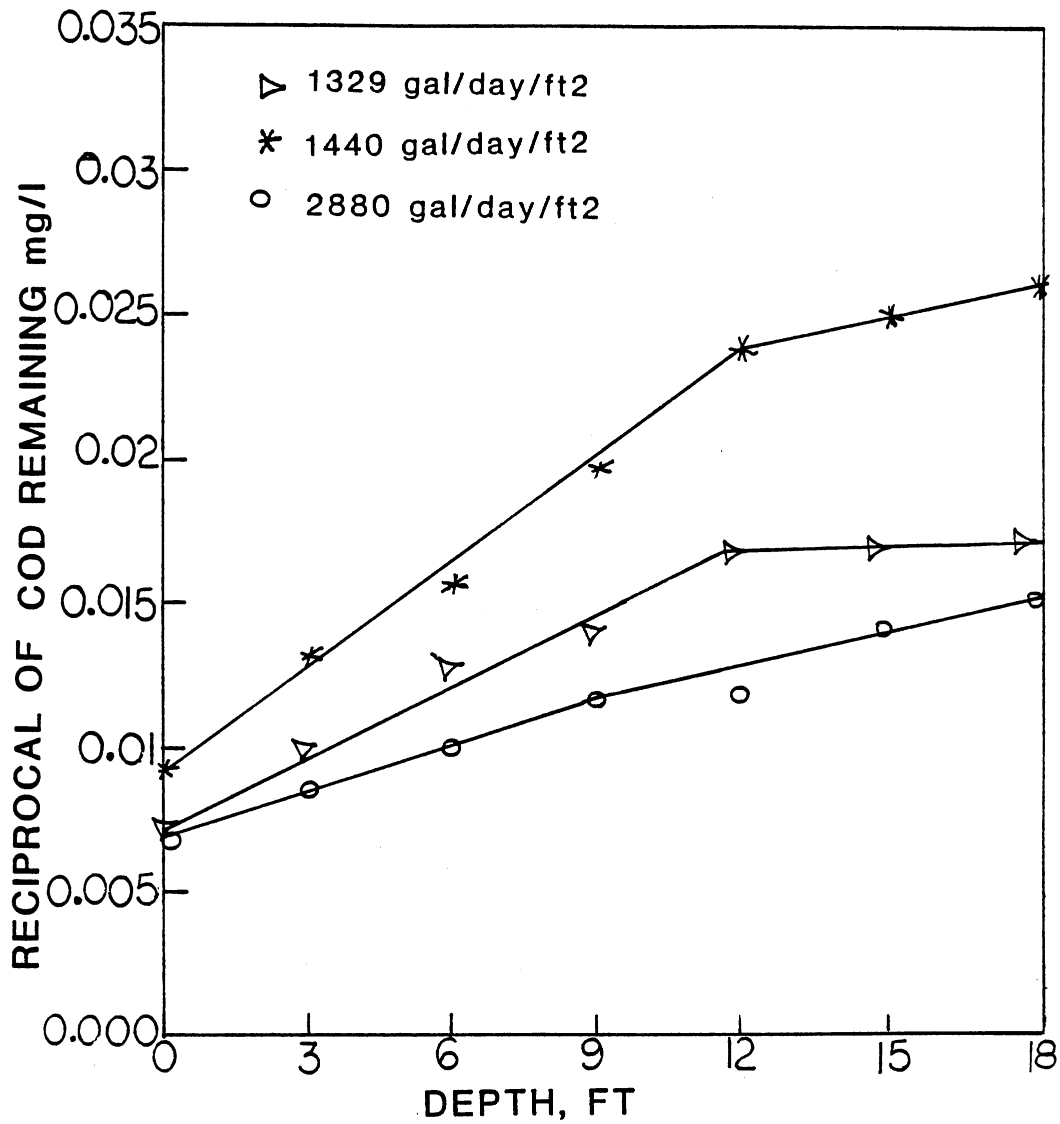

Figure 22. Reciprocal Plots of COD Remaining (mg/l) as a Function of Depth

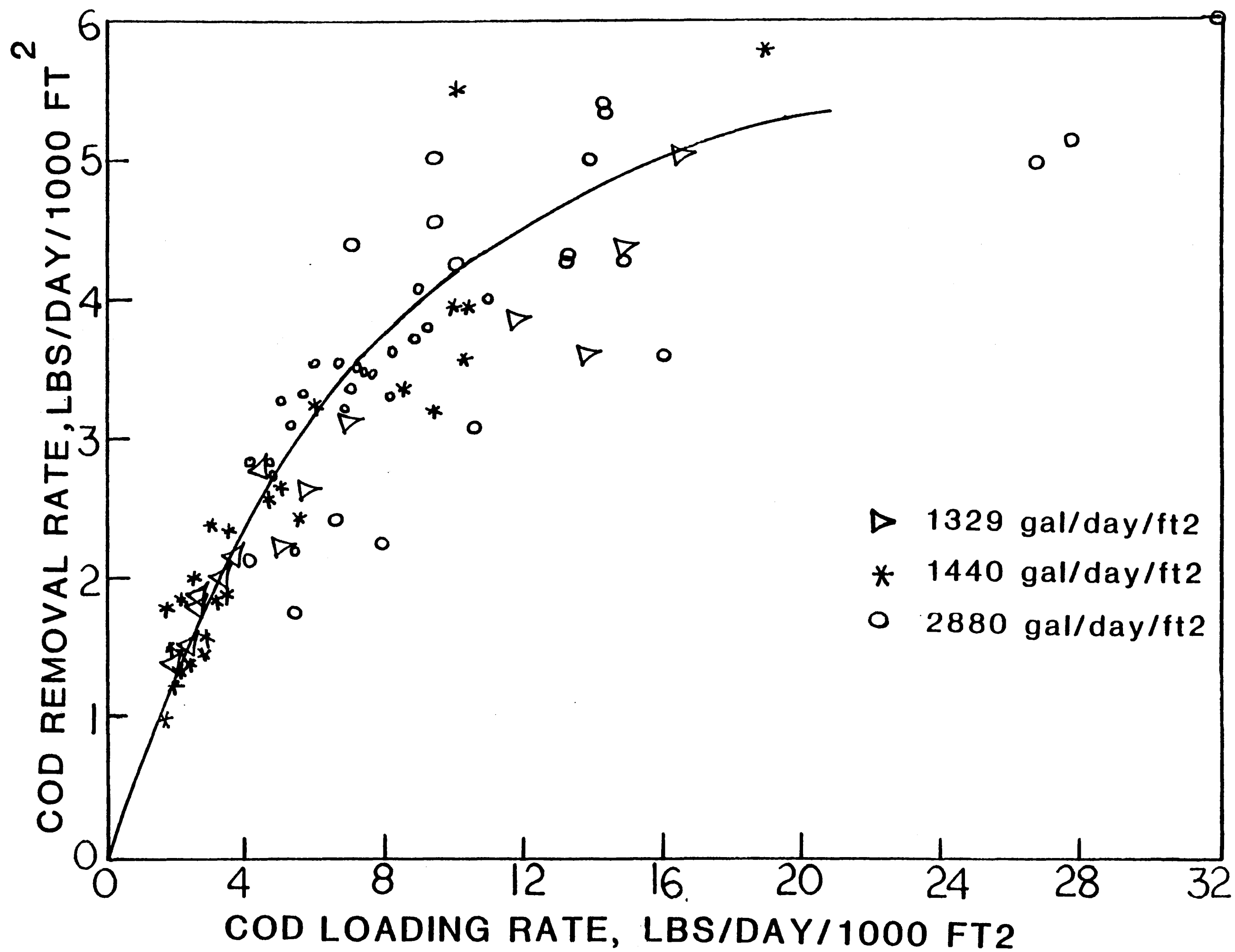

Figure 23. Relationship of COD Removal Rate (lbs/day/1000 ft^2) as a Function of COD Loading Rate (lbs/day/1000 ft^2)

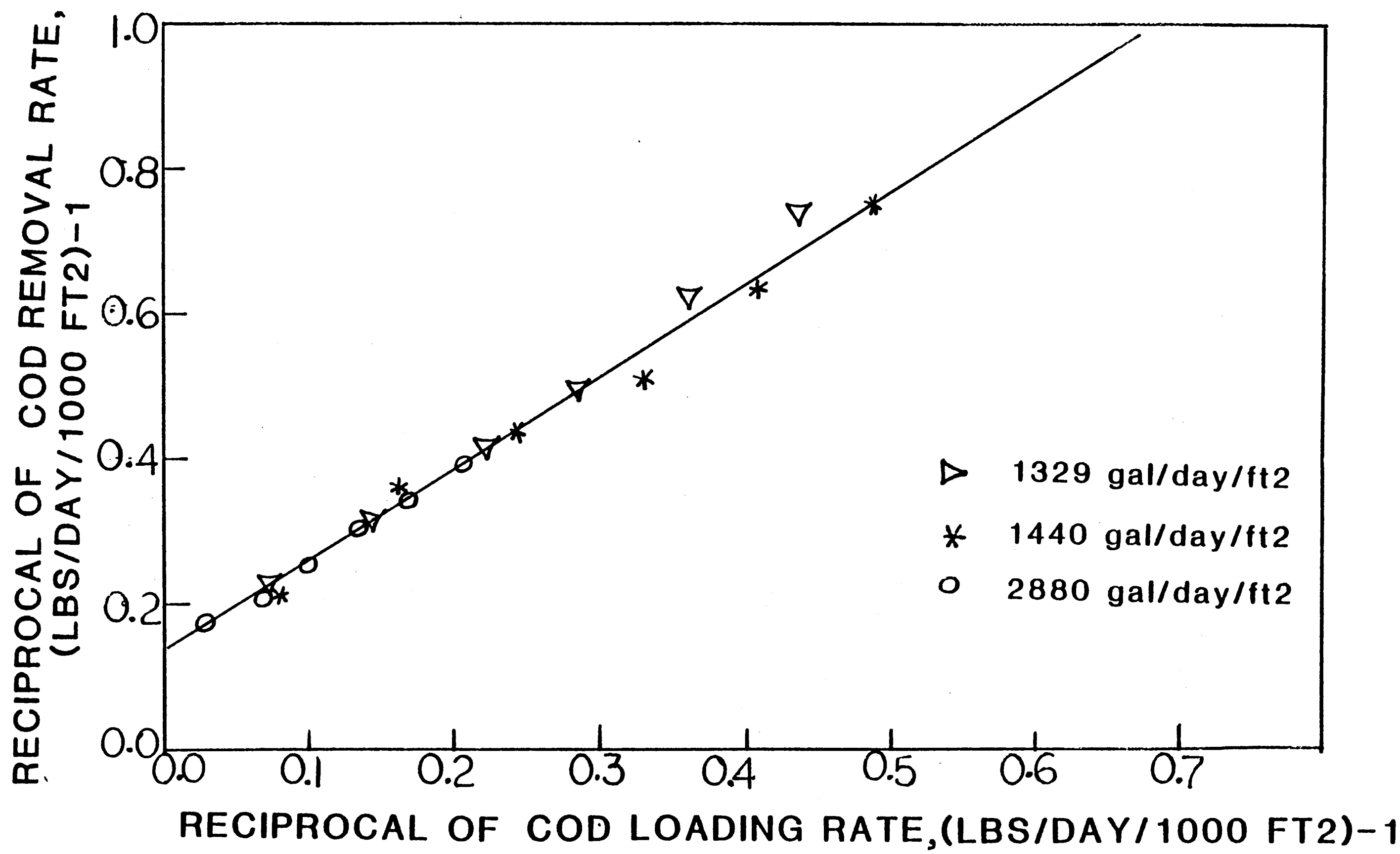

Figure 24. Reciprocal Plot of COD Removal (lbs/day/1000 ft^2)$^{-1}$ Vs. COD Loading Rate (lbs/day/1000 ft^2)

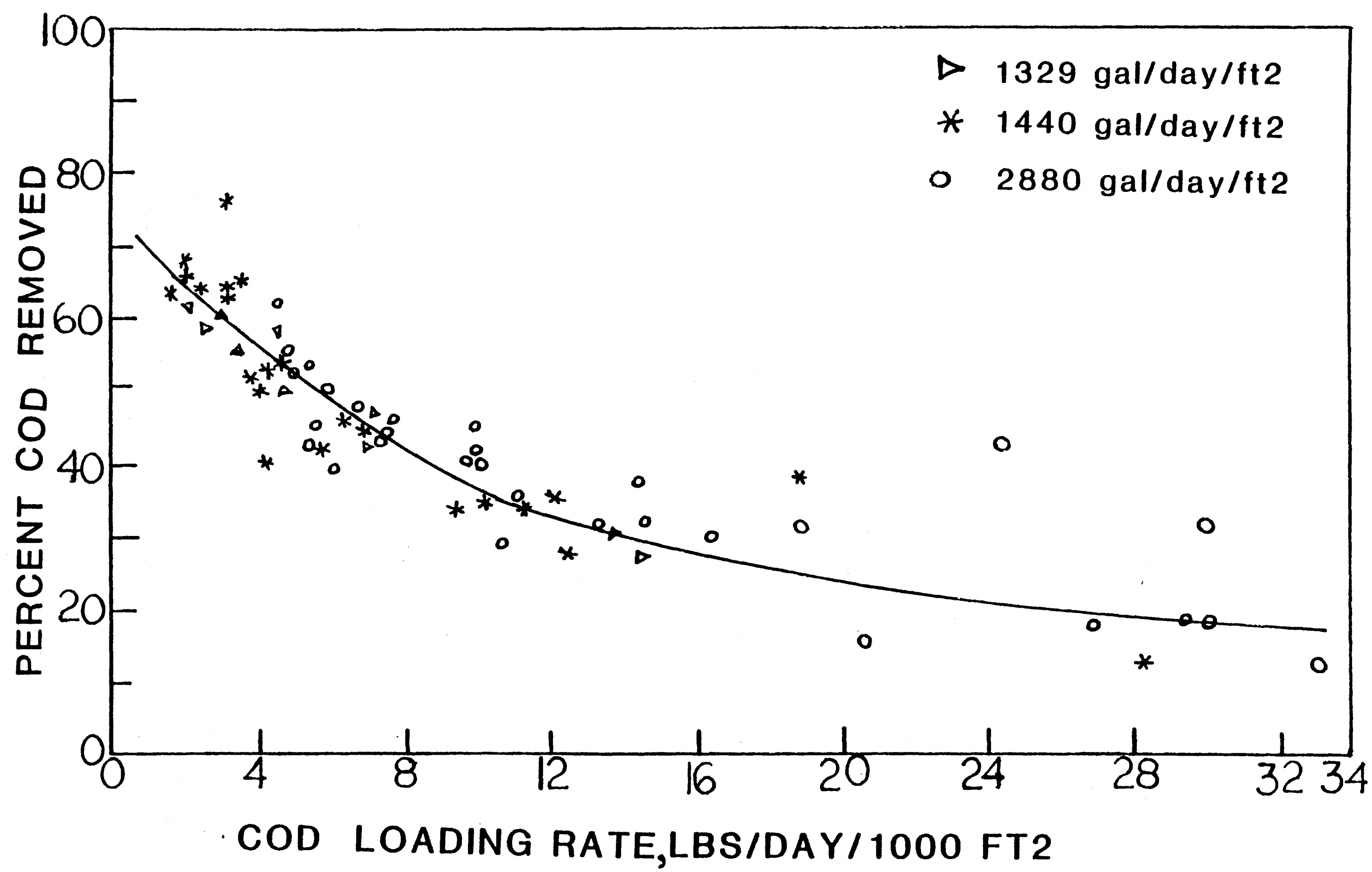

Figure 25. Treatment Efficiency (Percent COD Removed) as a Function of Loading Rate

Figure 25 is plotted as removal efficiency of COD versus COD organic loading. It indicates a removal efficiency of about 68 percent being obtained whereas BOD removal efficiency was more than 90 percent (Figure 7). This discrepancy is due to the nature of the test. COD efficiency curve is also little flatter than BOD efficiency curve at lower loadings. It indicates presence of less or non-degradable organic compounds.

Evaluation of Removal Kinetics for Each Three Feet Segments

The removal kinetic analysis of segments is attempted to see how it is related to the overall performance of the biological tower. It is known that sewage composition and diverse microbial populations mask the segmented performance into a very general form of the tower. Because due to microbial activity the concentration of sewage constituents would change and feedback that to the microbial regulatory mechanisms. Removal kinetics based on stages when applied for rotating biological contactor were unsatisfactory (34). Here analysis based on stages is made to study the removal kinetics obtained per segment for biological tower.

For convenience the segments are numbered as Stage 1, Stage 2, Stage 3, Stage 4, Stage 5, and Stage 6 respectively for 0-3 ft., 3-6 ft., 6-9 ft., 9-12 ft., 12-15 ft., 15-18 ft. depth.

Figures 26 through 32 are plotted to analyze the BOD removal mechanism for each three feet segments. Figure 26A shows percent BOD removed versus stages and Figure 26B shows total amount of BOD, lbs/day/1000 ft^2 removal rate versus depth. Figure 26A indicates that

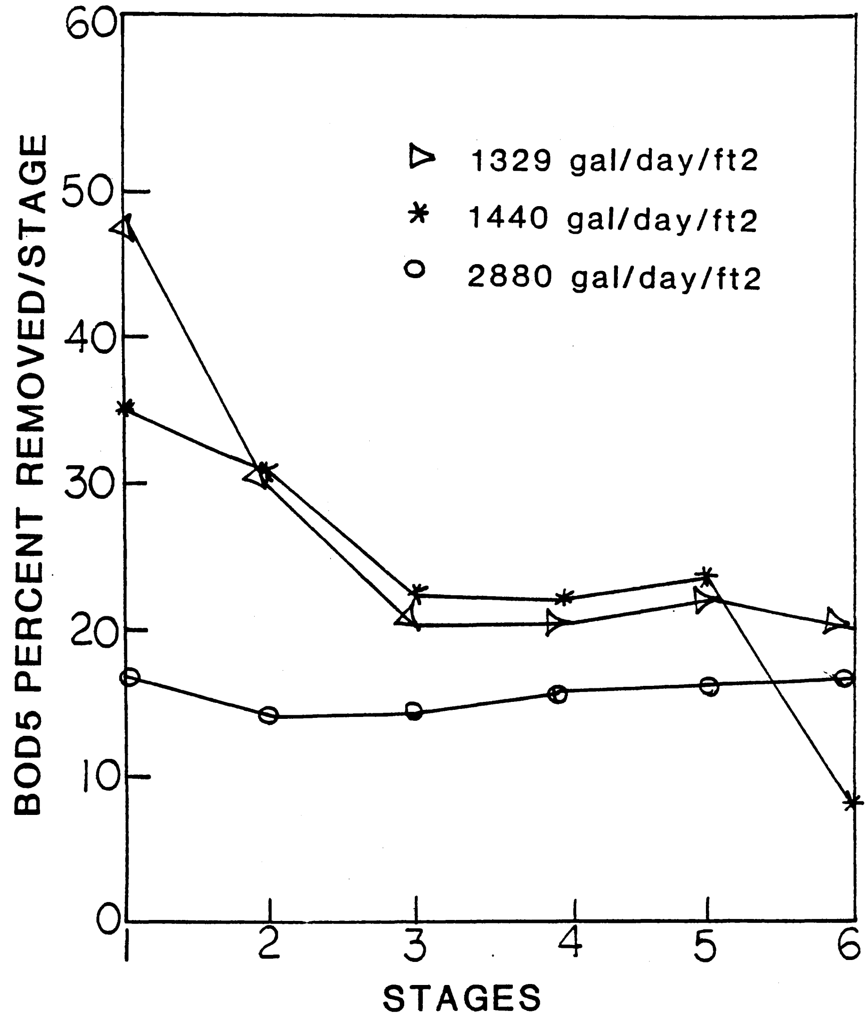

Figure 26A. Percent BOD Removed Per Stage Vs. Stages

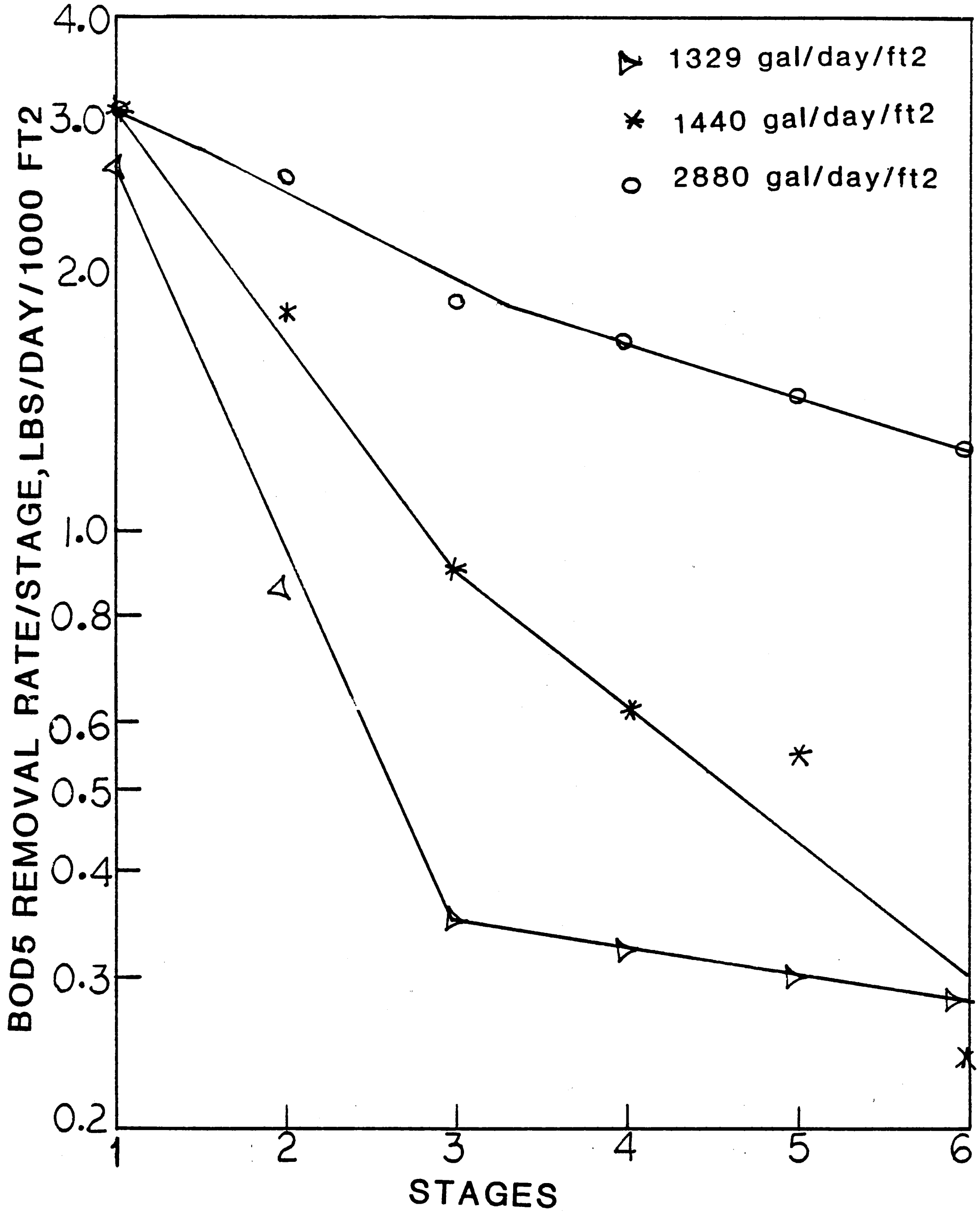

Figure 26B. Semi-Logarithmic Plots of Removal Rate of BOD (lbs/day/1000 ft^2) Per Stage as a Function of Stages during 2880 gal/day/ft^2 hydraulic loading the percent removal was more or less the same for all states. Even 1440 gal/day/ft^2 and 1329 gal/day/ft^2 exhibits same efficiency for few stages. But, Figure 26B shows the amount of removal rate was decreasing per segment. This indicates that the amount of removable total substrate was decreasing with succeeding stages. The removal mechanism was approaching substrate limited condition from substrate saturation. With exhaustion of substrate the presence of non-degradable portion and secondary metabolities (which could even be inhibitory) caused decrease in total BOD removed, lbs BOD/day/1000. Because, with decrease in rate the percent BOD removed of incoming influent concentration could still appear to be the same since it is only related to the concentration. Figure 26A shows highest removal rate at the first stage. Figure 26B gives a better picture of how the removal rate is changed at the later stages. Both the curves show change in removal rate constant. Easily oxidizable compounds probably account for the high removal. The remaining stages took out more complex compounds which are not as readily removed from the waste as preceeding ones. Another interesting notification is Figure 26B indicates that all the loadings exhibit more or less the same amount of organic removal rate for the first stage. This is expected when the system is provided with enough food for the survival of active mass. Because, active mass is said to have constant thickness under optimal condition. It could also be pointed out that the removal rate obtained by considering cummulative depth for the 2880 gal/day/ft^2 plot in Figure 26B is 0.056 ft^{-1} which is close to 0.06 ft^{-1}, observed at the Figures 3 and 4 for BOD removal versus depth. Maybe if substrate saturation condition is maintained throughout the stages the removal rate per stage would work. But nothing definite is commented.

In order to apply Kincannon and Stover's approach (total organic loading concept) to the stage analysis, the following Figures 27 through 32 are plotted to show the removal pattern and to find out the biokinetic constants. The results obtained can be tabulated as in Table X.

TABLE X

BIOKINETIC CONSTANTS PER STAGE OF BIOLOGICAL TOWER

Stages	Depth ft.	U_{max} lbs/day/1000 ft^2	K_B lbs/day/1000 ft^2	Correlation Coefficient
1	0-3	4.9505	4.982	0.577
2	3-6	4.0561	6.407	0.553
3	6-9	1.89	6.2407	0.505
4	9-12	1.765	6.782	0.52
5	12-15	0.8	1.87	0.487
6	15-18	0.8	2.35	0.4

The correlation coefficent results indicate that the scattering of point increases with stage. This could also be observed from the figures.

When the flow moves down the tower and substrate becomes limited, many complicate and interrelated biological processes are triggered. This would result in different rates of substrate removal. For

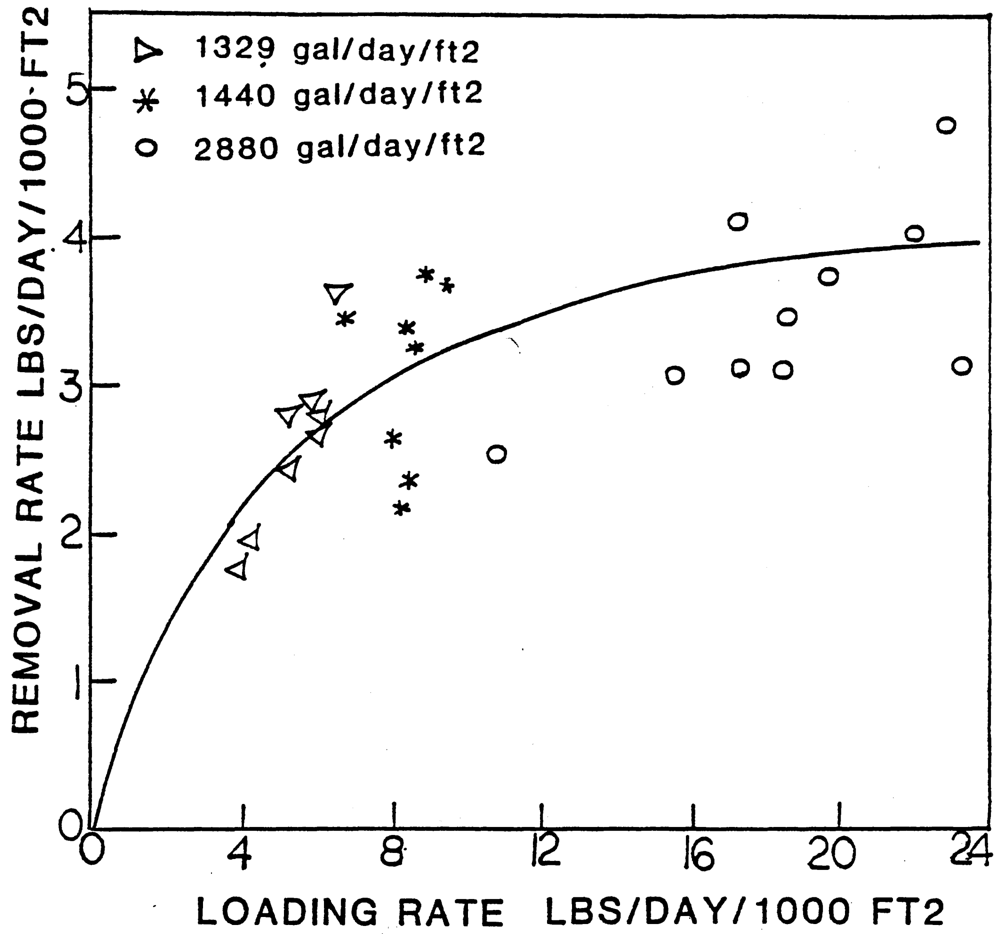

Figure 27A. Relationship of BOD Removal Rate (lbs/day/1000 ft^2) as a Function of BOD Loading Rate (lbs/day/1000 ft^2) for Stage 1 (0'-3')

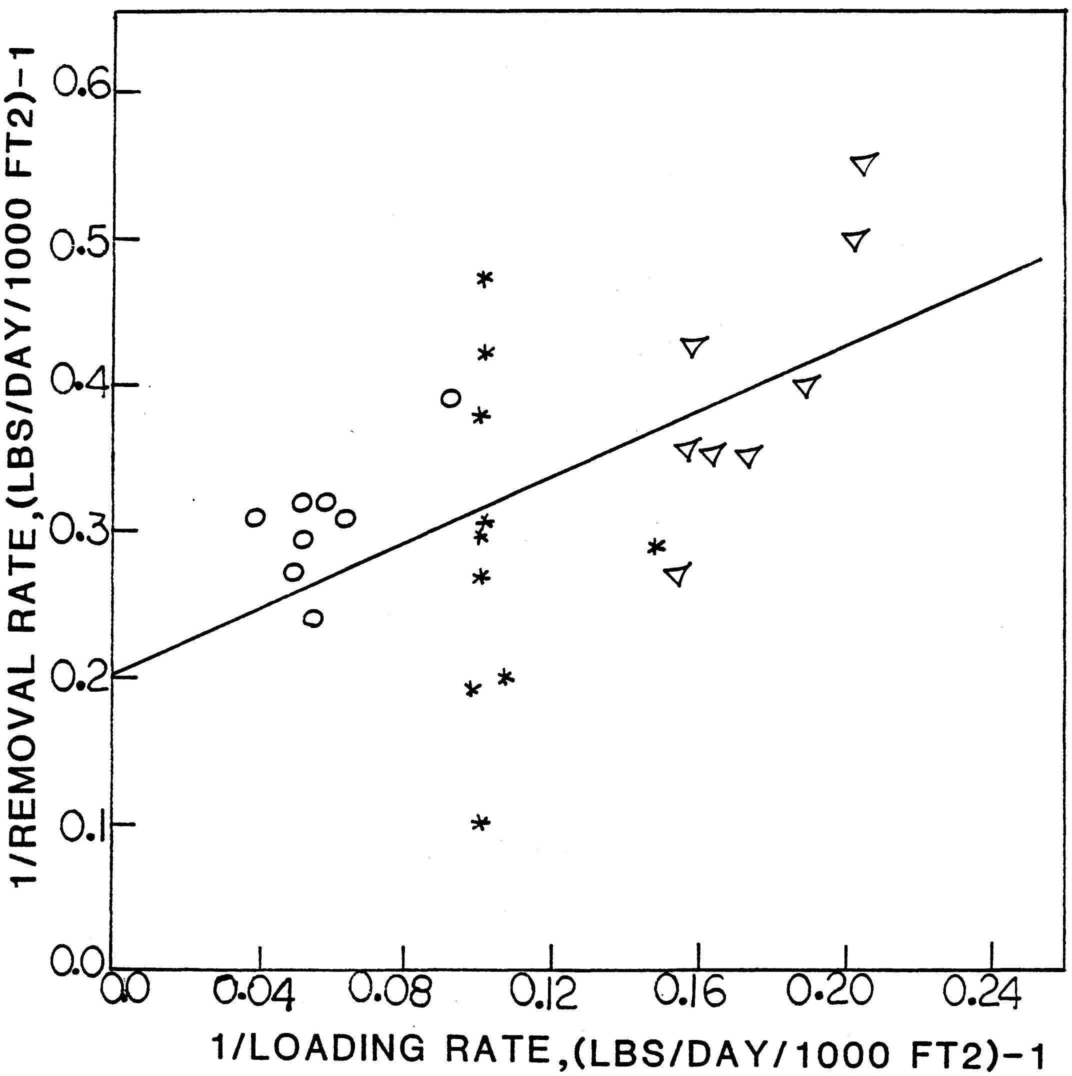

Figure 27B. Reciprocal Plot of BOD Removal Rate (lbs/day/1000 ft^2) Vs. BOD Loading Rate (lbs/day/1000 ft^2) for Stage 1

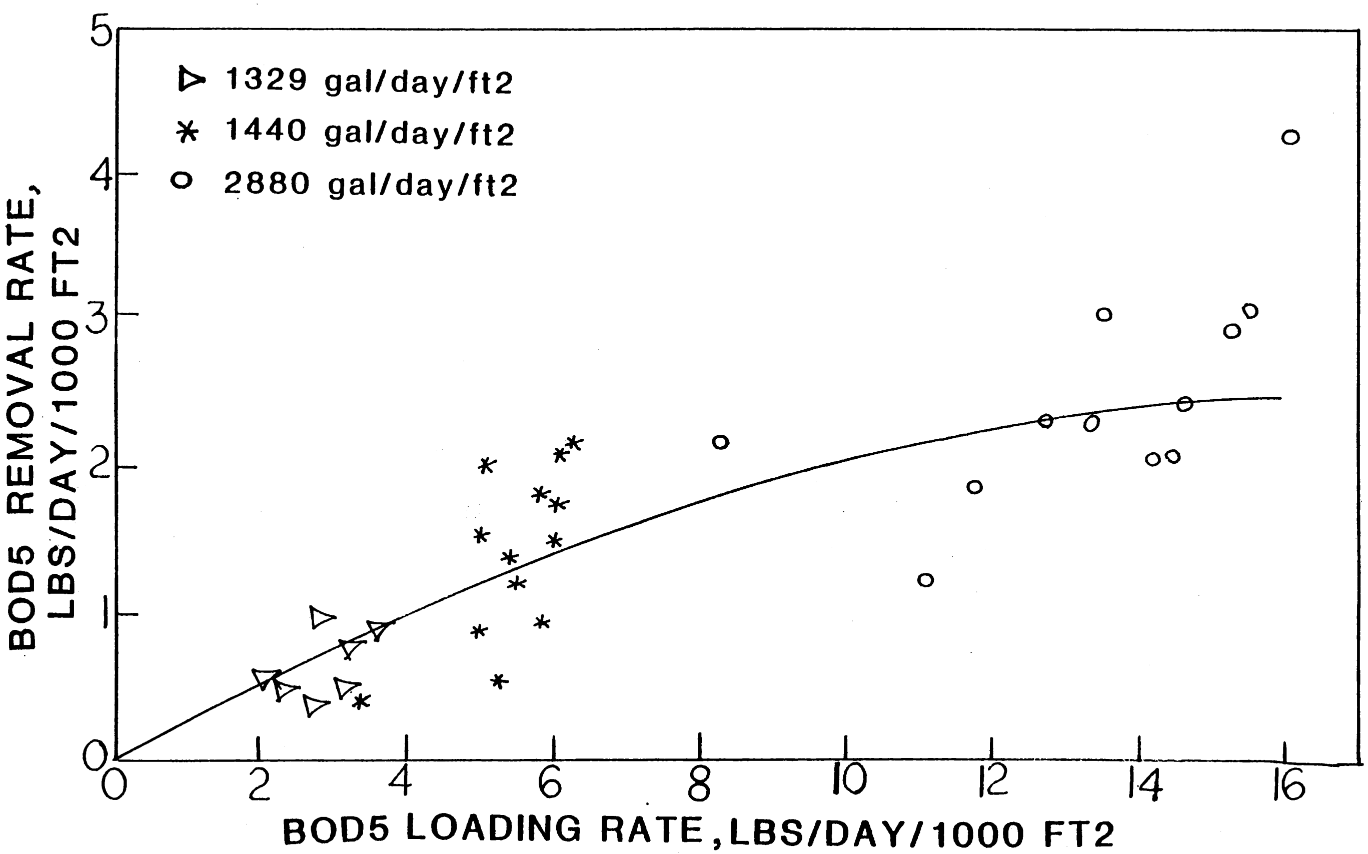

Figure 28A. Relationship of BOD Removal Rate (lbs/day/1000 ft^2) as a Function of BOD Loading Rate (lbs/day/1000 ft^2) for Stage 2 (3'-6')

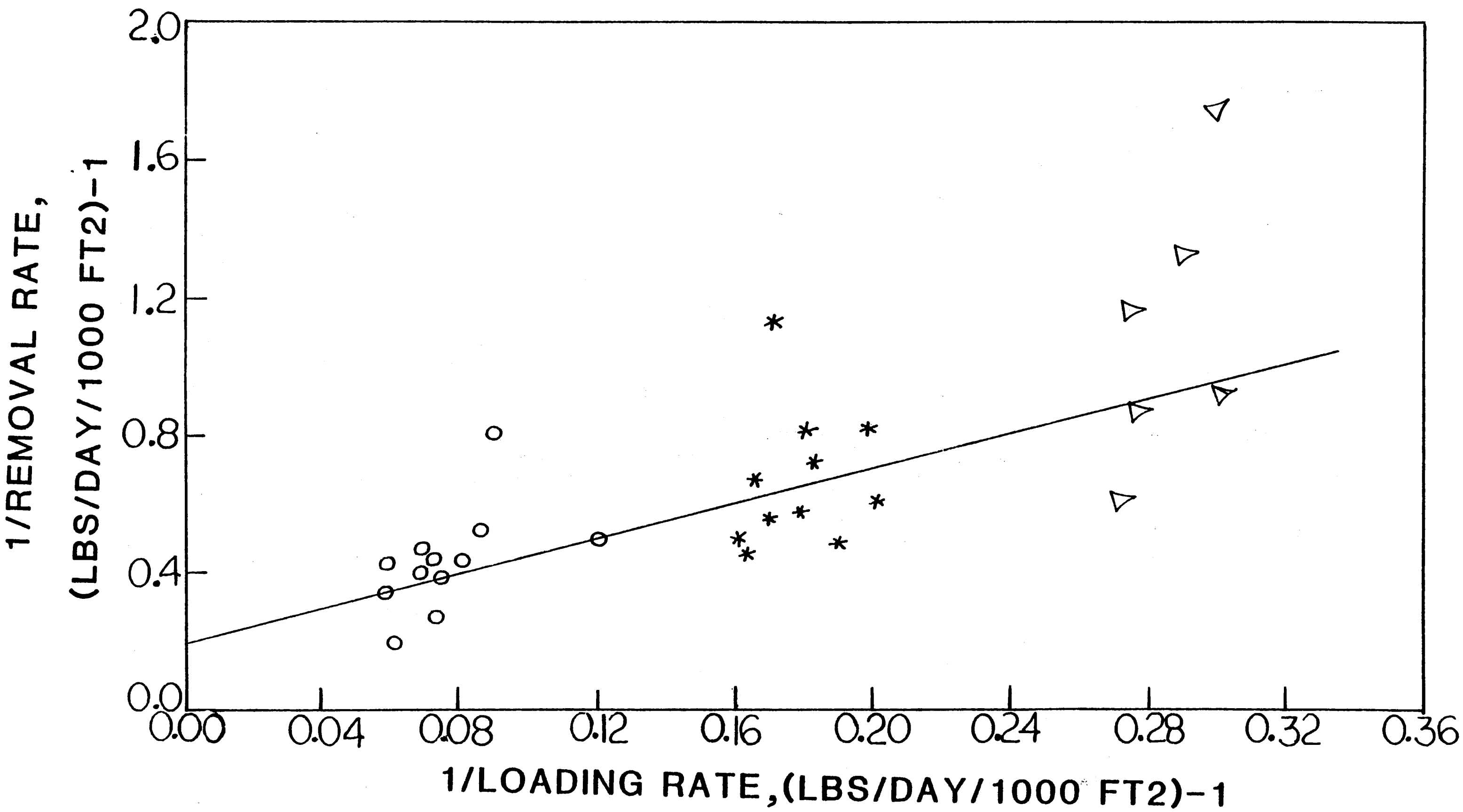

Figure 28B. Reciprocal Plot of BOD Removal Rate (lbs/day/1000 ft^2) Vs. BOD Loading Rate (lbs/day/1000 ft^2) for Stage 2

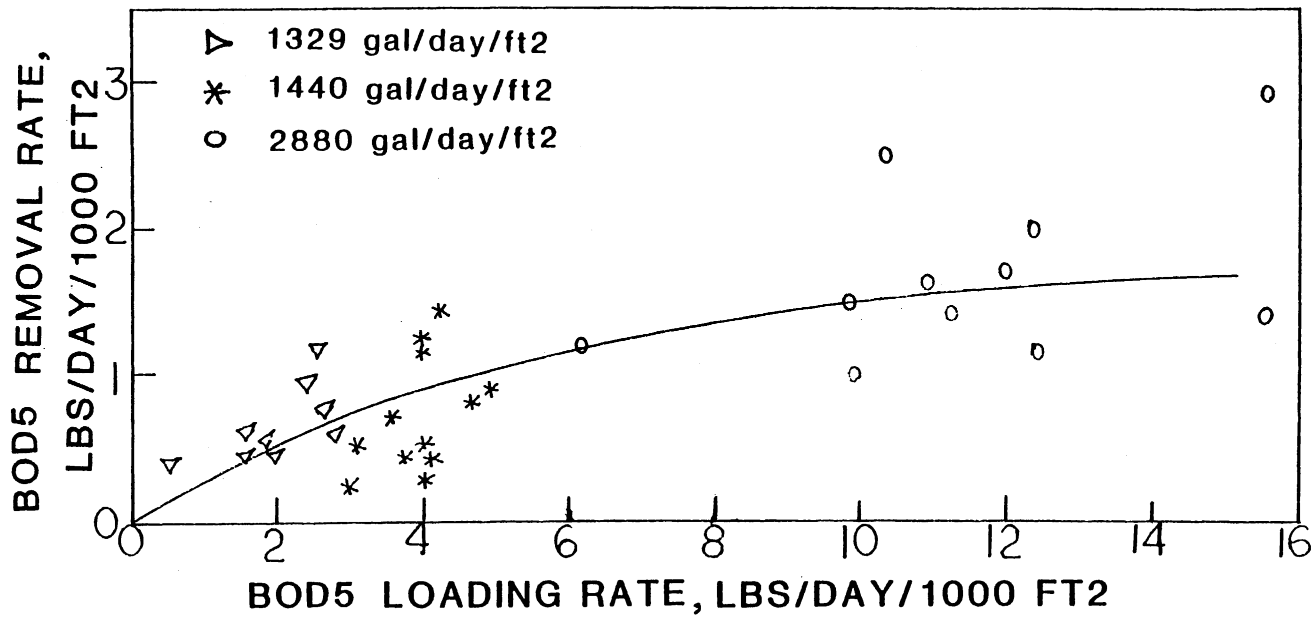

Figure 29A. Relationship of BOD Removal Rate (lbs/day/1000 ft^2) as a Function of BOD Loading Rate (lbs/day/1000 ft^2) for Stage 3 (6'-9')

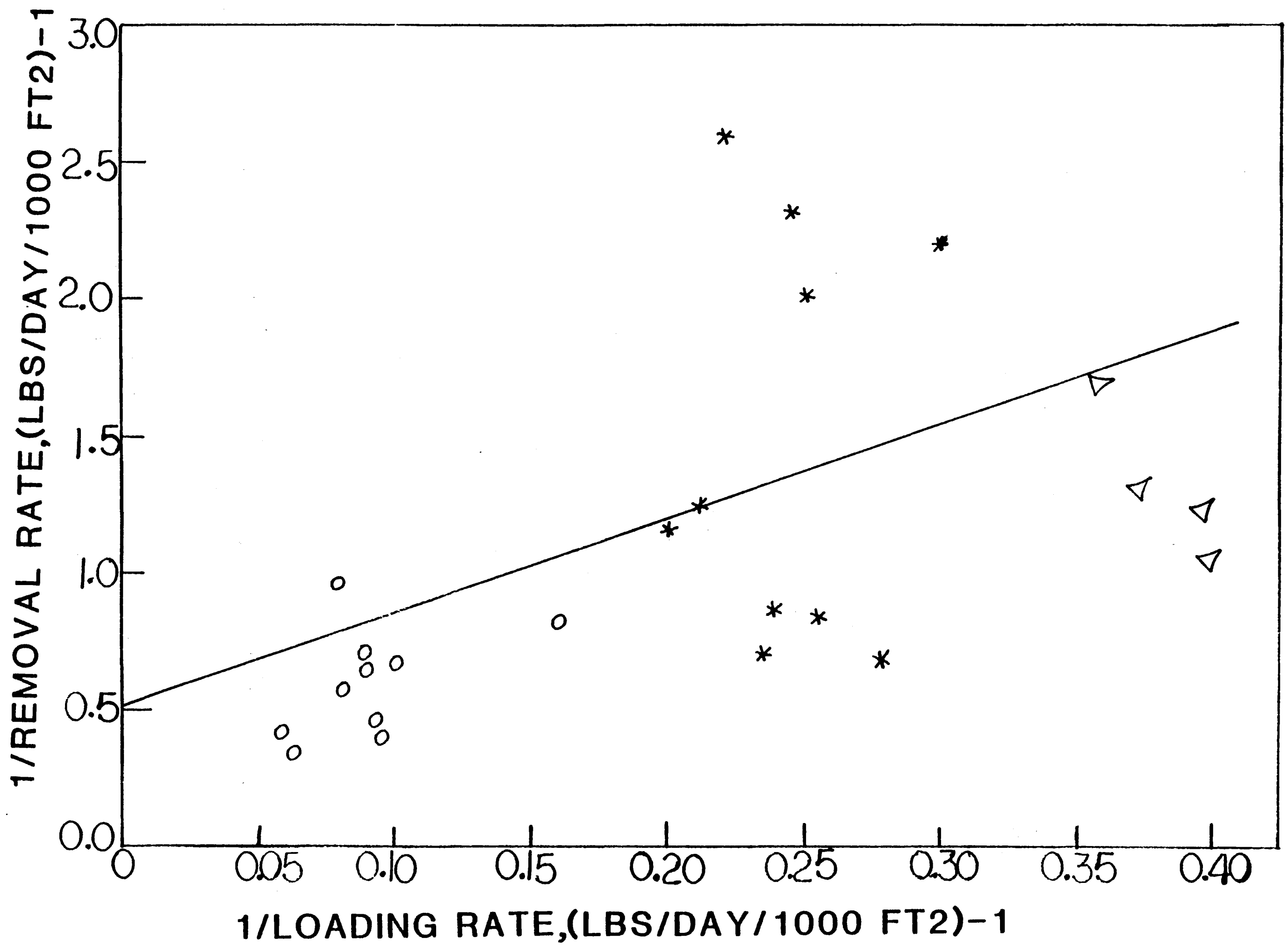

Figure 29B. Reciprocal Plot of BOD Removal Rate (lbs/day/1000 ft^2) Vs. BOD Loading Rate (lbs/day/1000 ft^2) for Stage 3

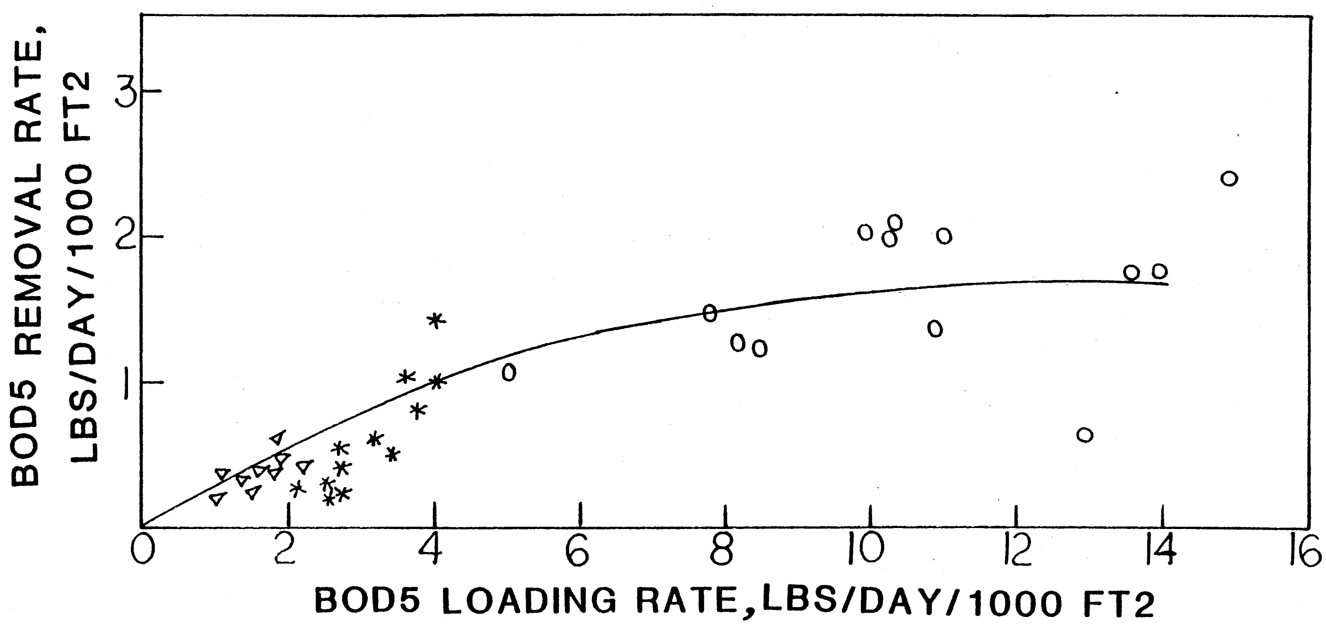

Figure 30A. Relationship of BOD Removal Rate (lbs/day/1000 ft^2) as a Function of BOD Loading Rate (lbs/day/1000 ft^2) for Stage 4 (9'-12')

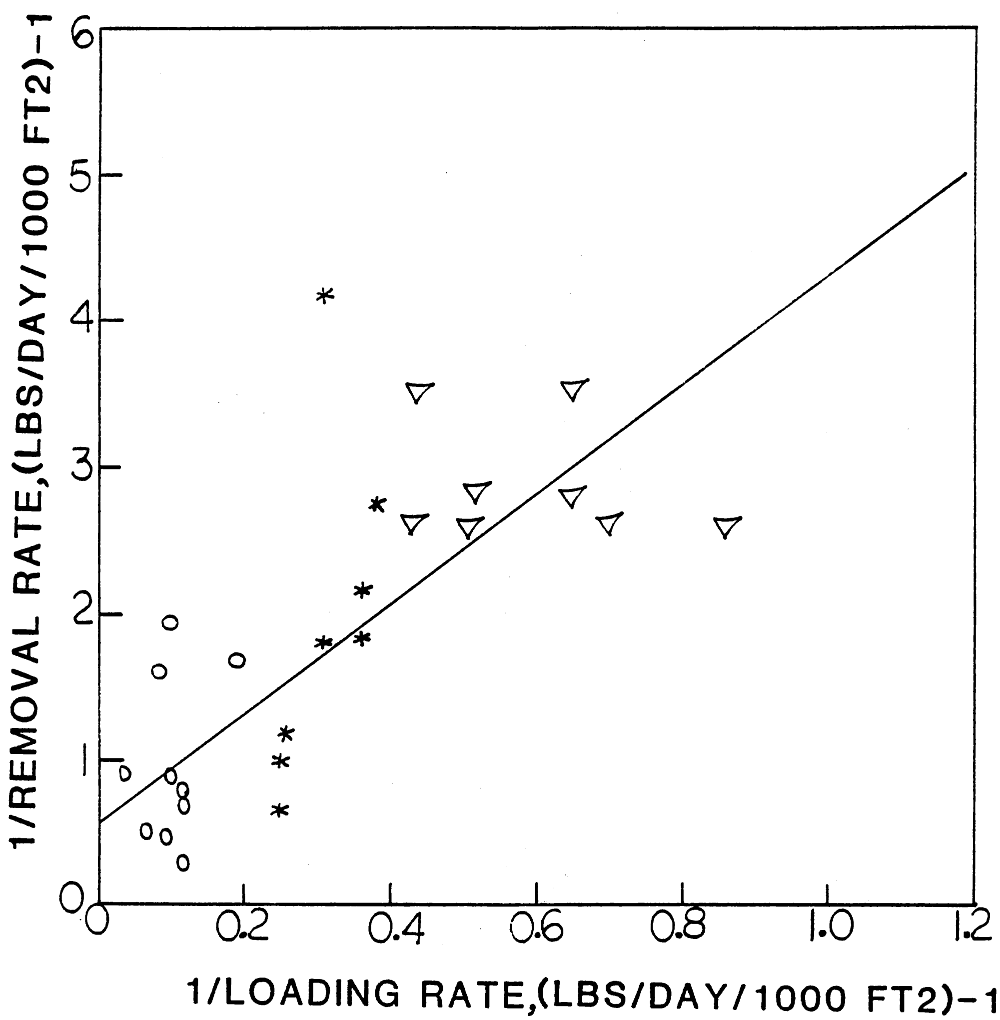

Figure 30B. Reciprocal Plot of BOD Removal Rate (lbs/day/1000 ft^2) Vs. BOD Loading Rate for Stage 4

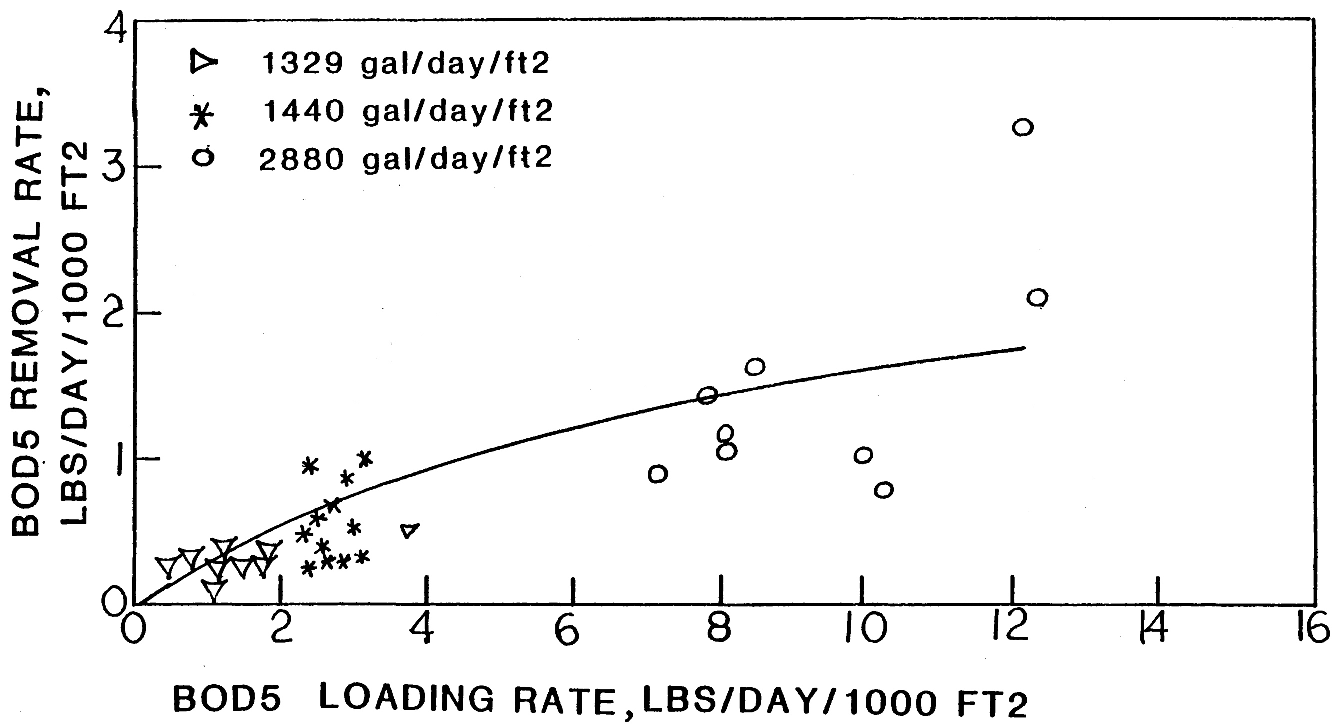

Figure 31A. Relationship of BOD Removal Rate (lbs/day/1000 ft^2) as a Function of BOD Loading Rate (lbs/day/1000 ft^2) for Stage 5 (12'-15')

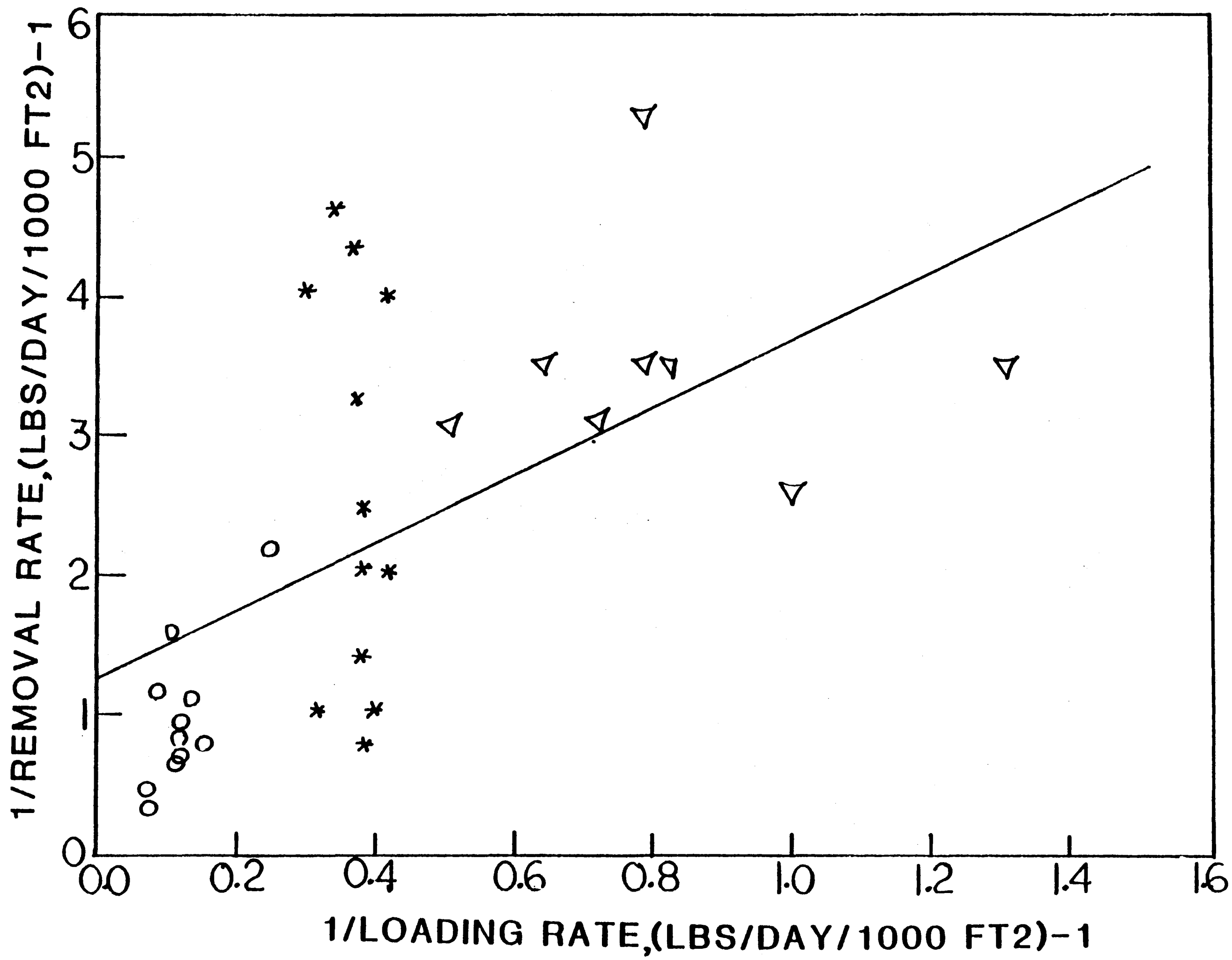

Figure 31B. Reciprocal Plot of BOD Removal Rate (lbs/day/1000 ft^2) Vs. BOD Loading Rate (lbs/day/1000 ft^2) for Stage 5

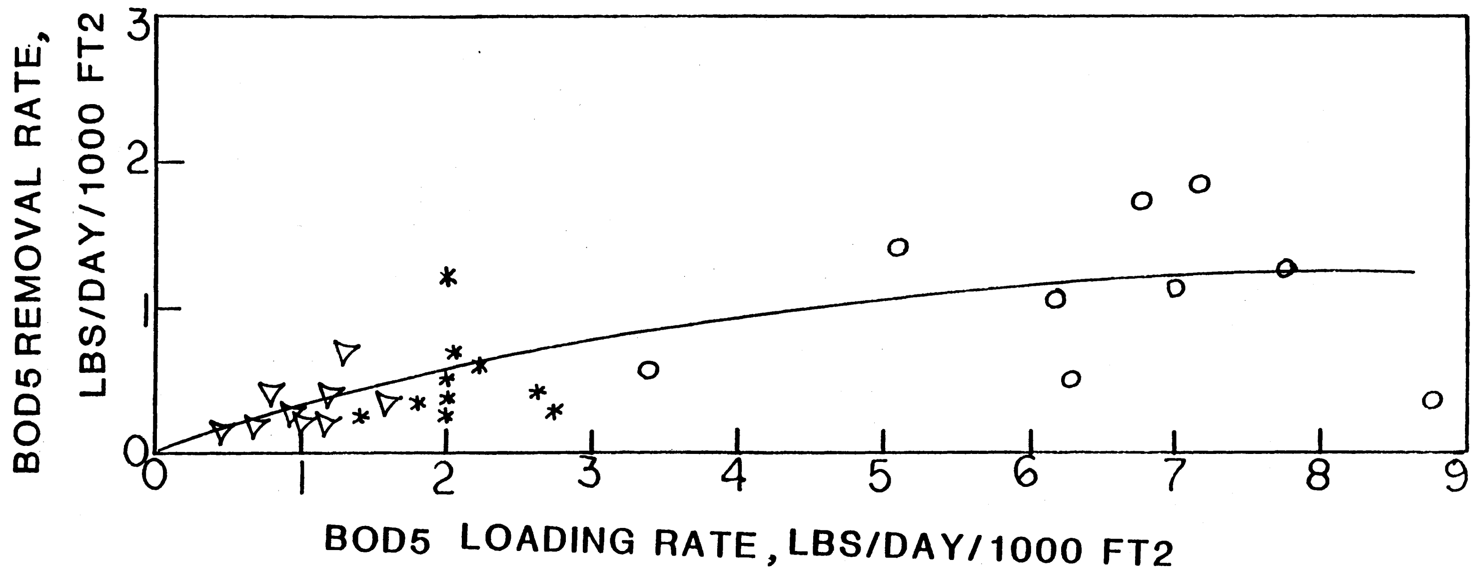

Figure 32A. Relationship of BOD Removal Rate (lbs/day/1000 ft^2) as a Function of BOD Loading Rate (lbs/day/1000 ft^2) for Stage 6 (15'-18')

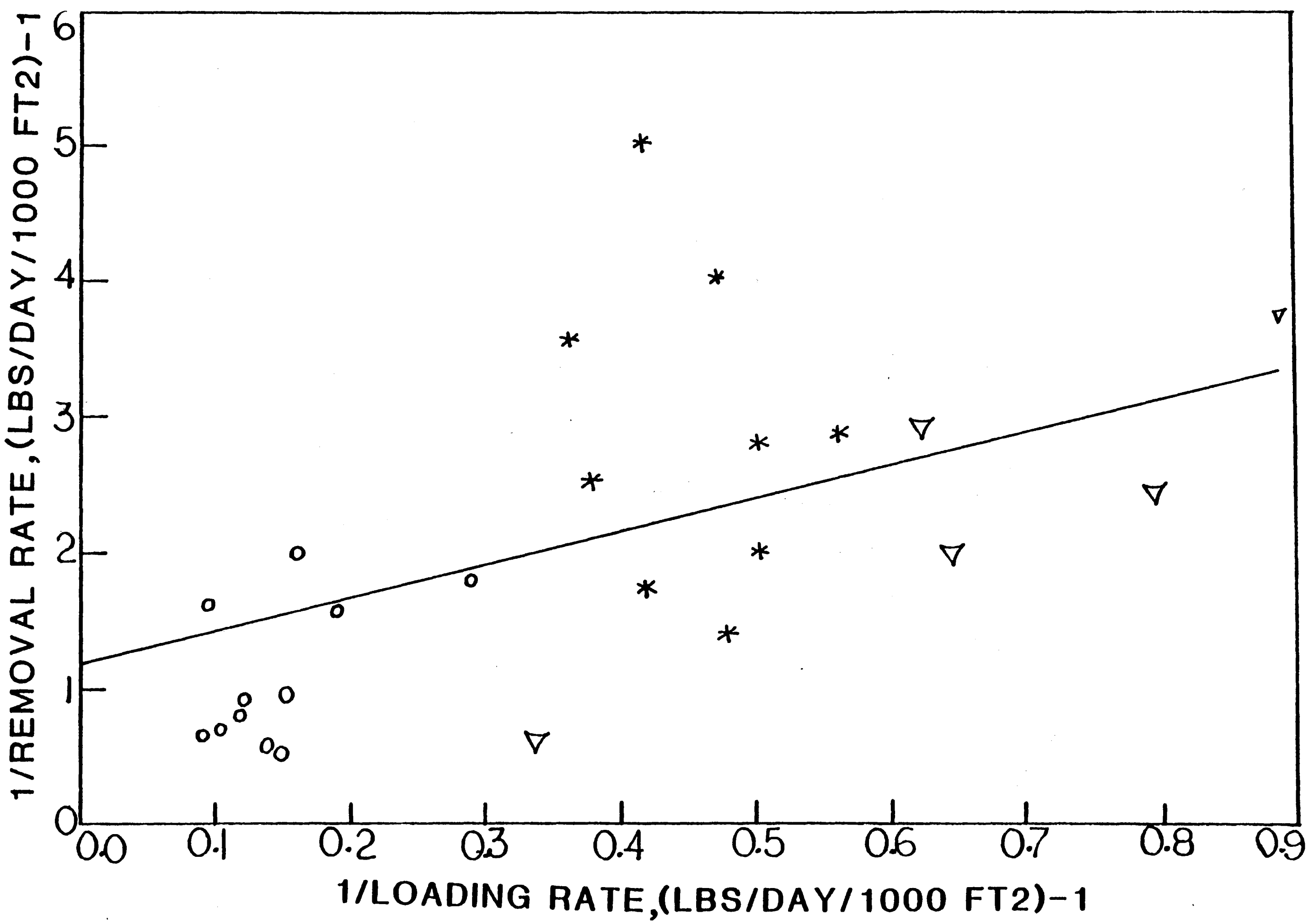

Figure 32B. Reciprocal Plot of BOD Removal Rate (lbs/day/1000 ft^2) Vs. BOD Loading Rate (lbs/day/1000 ft^2) for Stage 6

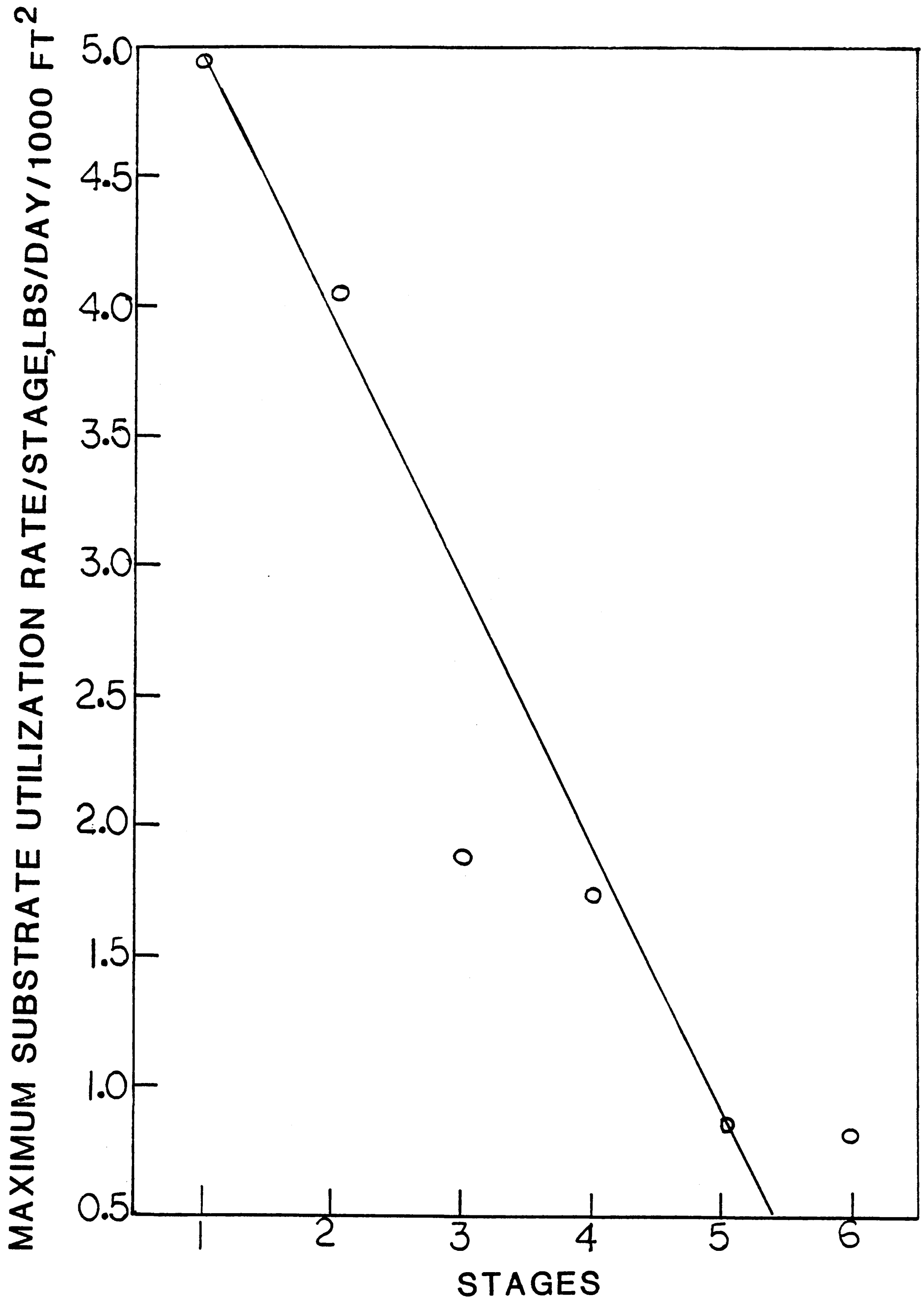

Figure 33. Maximum Substrate Utilization Rate of BOD Per Stage as a Function of Stage

example, during 2880 gal/day/ft^2 the system was subjected to much higher organic loading than the other two cases. It was not going through the same substrate limited condition as the others. It could be remembered that at 2880 gal/day/ft^2 flowrate values did not show change of kinetics with depth (Figures 3 and 4). Most important that the influent concentration entering stage was always changing. So, all these affect the computation of U_{max} and K_B. However, Table X and Figure 33 do indicate a tendency to decrease substrate removal rate as sewage passes through stages. Figure 33, a plot of U_{max} versus stage, also shows inconsistency at later stages.

So, this clearly indicates that a representative biokinetic constant of the whole tower BOD removal mechanism cannot be obtained by segmentation.

Figures 34A and 34B are plotted for COD removal mechanism per stage. Both the Figures 34A and 34B show a sudden drop of COD at the fourth stage during 2880 gal/day/ft^2 hydraulic loading. This could be because of the inhibitory effect of secondary metabolites produced due to the microbial activity. Then at the later stage it may be that enzyme induction caused an increase in removal as the metabolite was then being biodegraded. Further, both the plots in Figure 34 exhibit general decrease in removal rate pattern per stage.

Figures 35A, 35B, 36A, and 36B are plotted for carbohydrate and protein analysis per segments. This analysis for protein and carbohydrate seems very confusing. Because we have seen that the removal of these two constituents of sewage are interrelated and interdependent. Besides, these parameters are also a measurement of direct function of relative biodegradability and preference of the biomass.

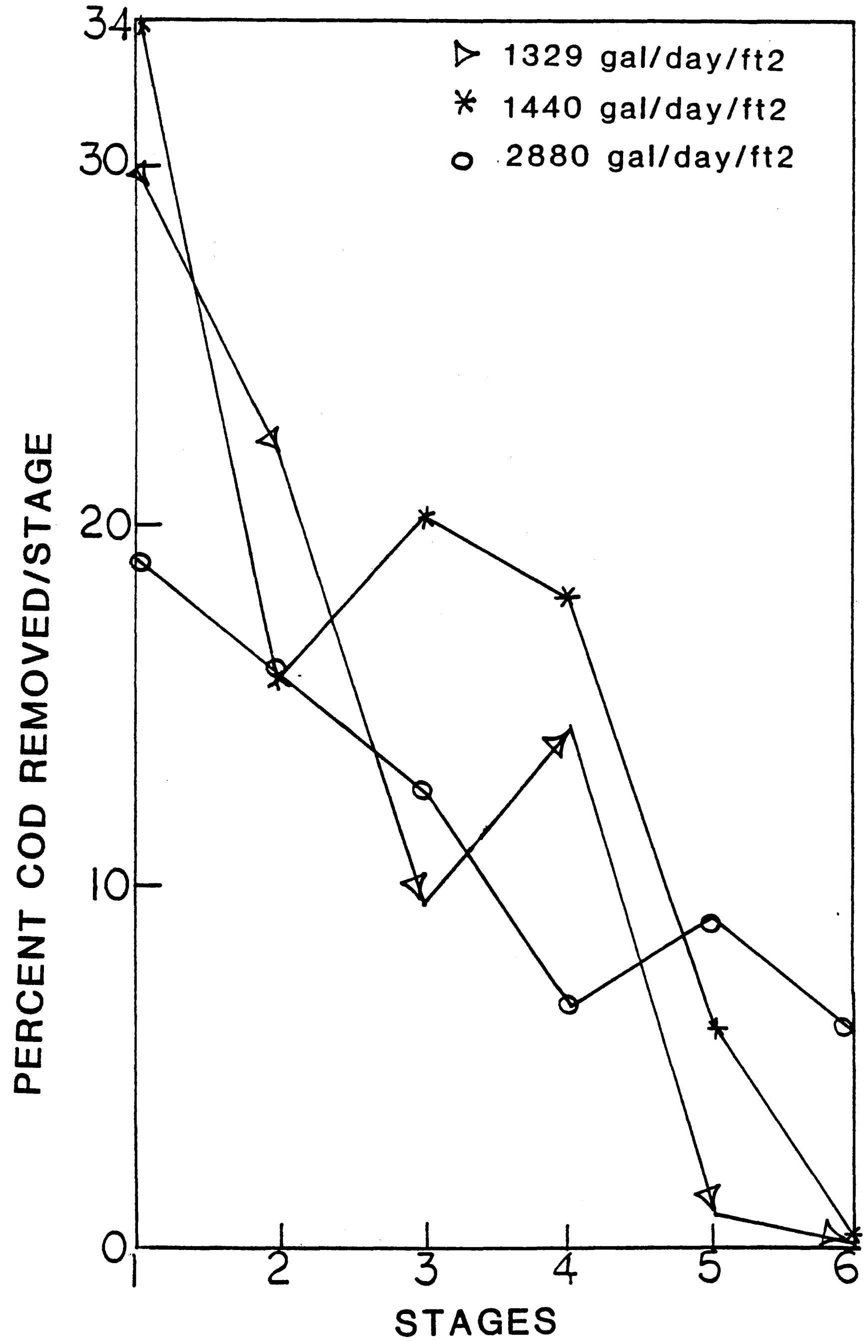

Figure 34A. Percent COD Removed Per Stage Vs. Stages

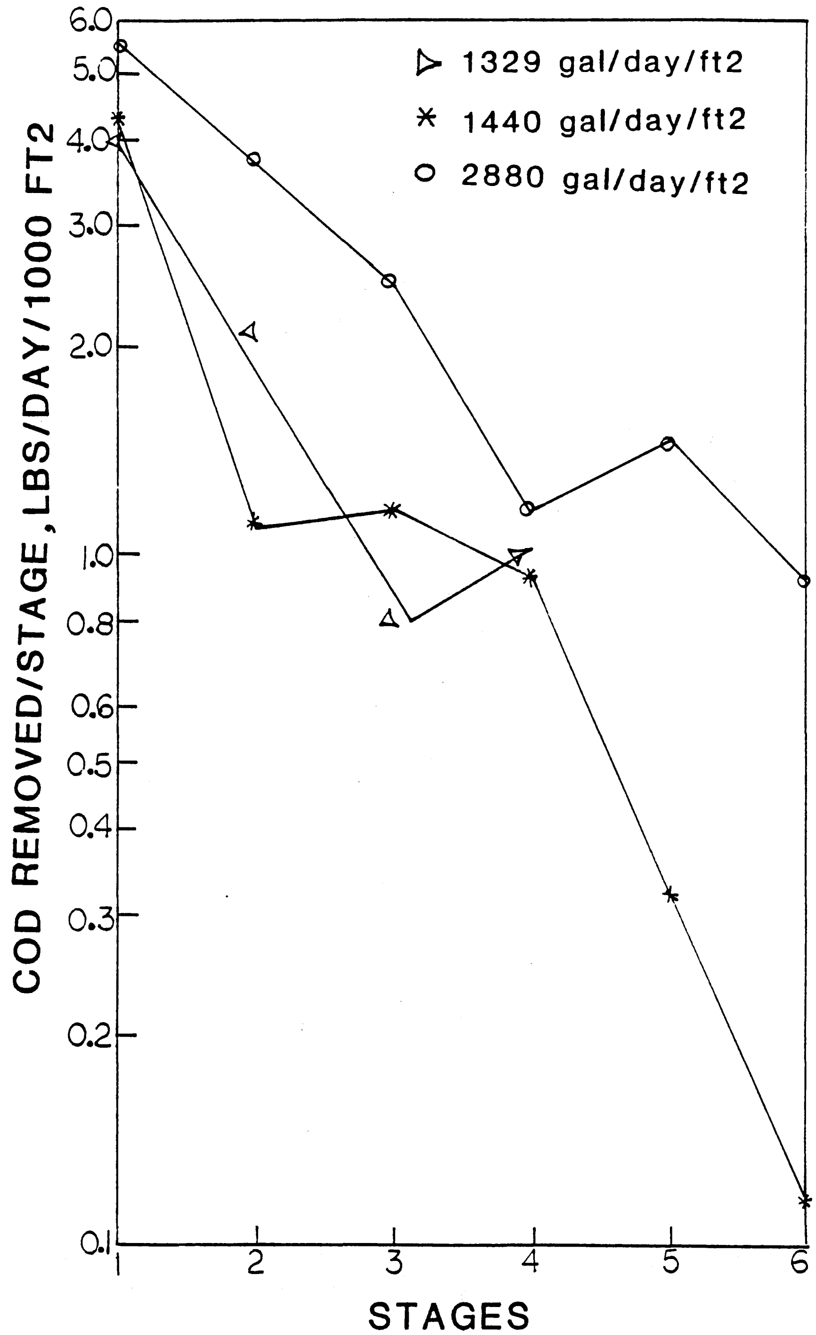

Figure 34B. Semi-Logarithmic Plots of COD Removal Rate (lbs/day/1000 ft^2) Per Stage as a Function of Stages

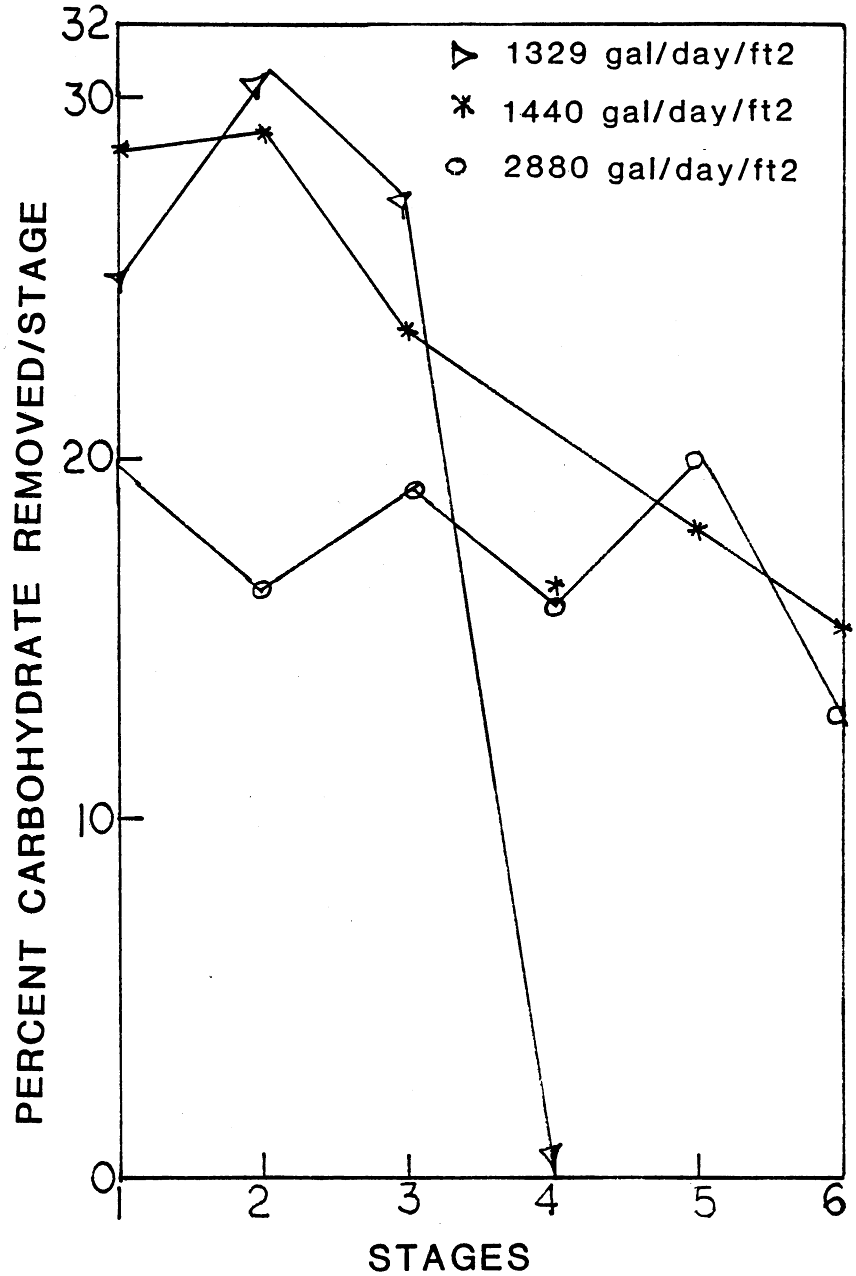

Figure 35A. Percent Carbohydrate Removed Per Stage Vs. Stages

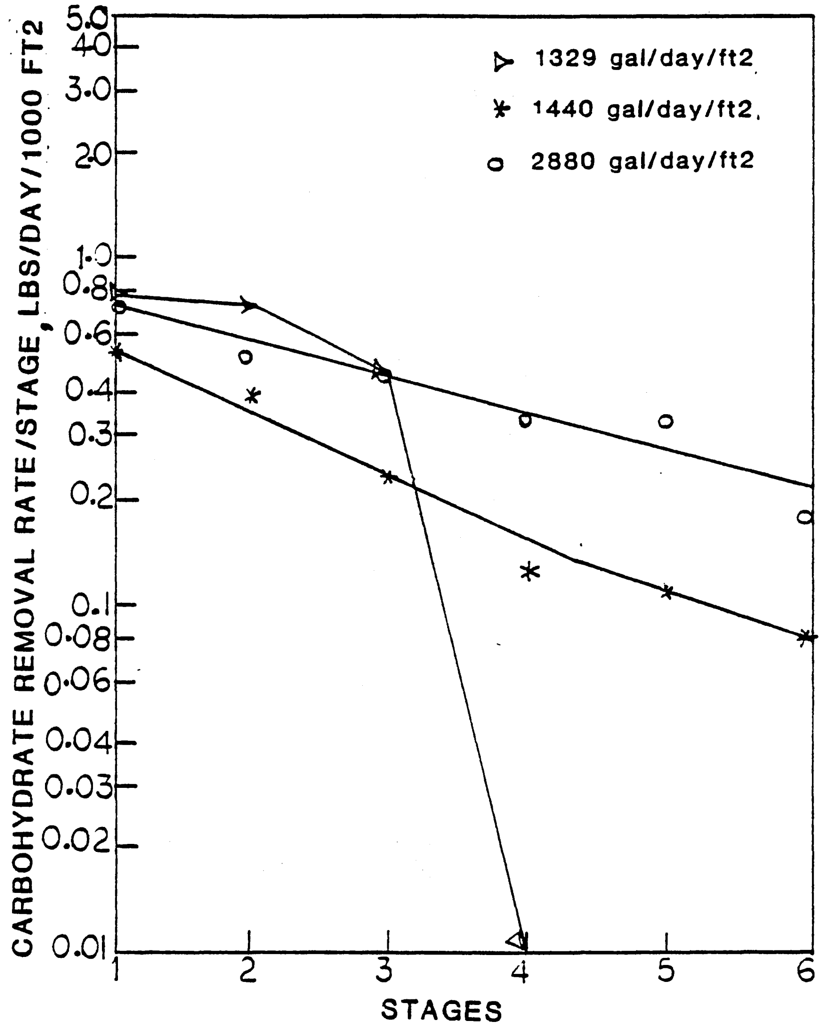

Figure 35B. Semi-Logarithmic Plots of Removal Rate of Carbohydrate Per Stage as a Function of Stages

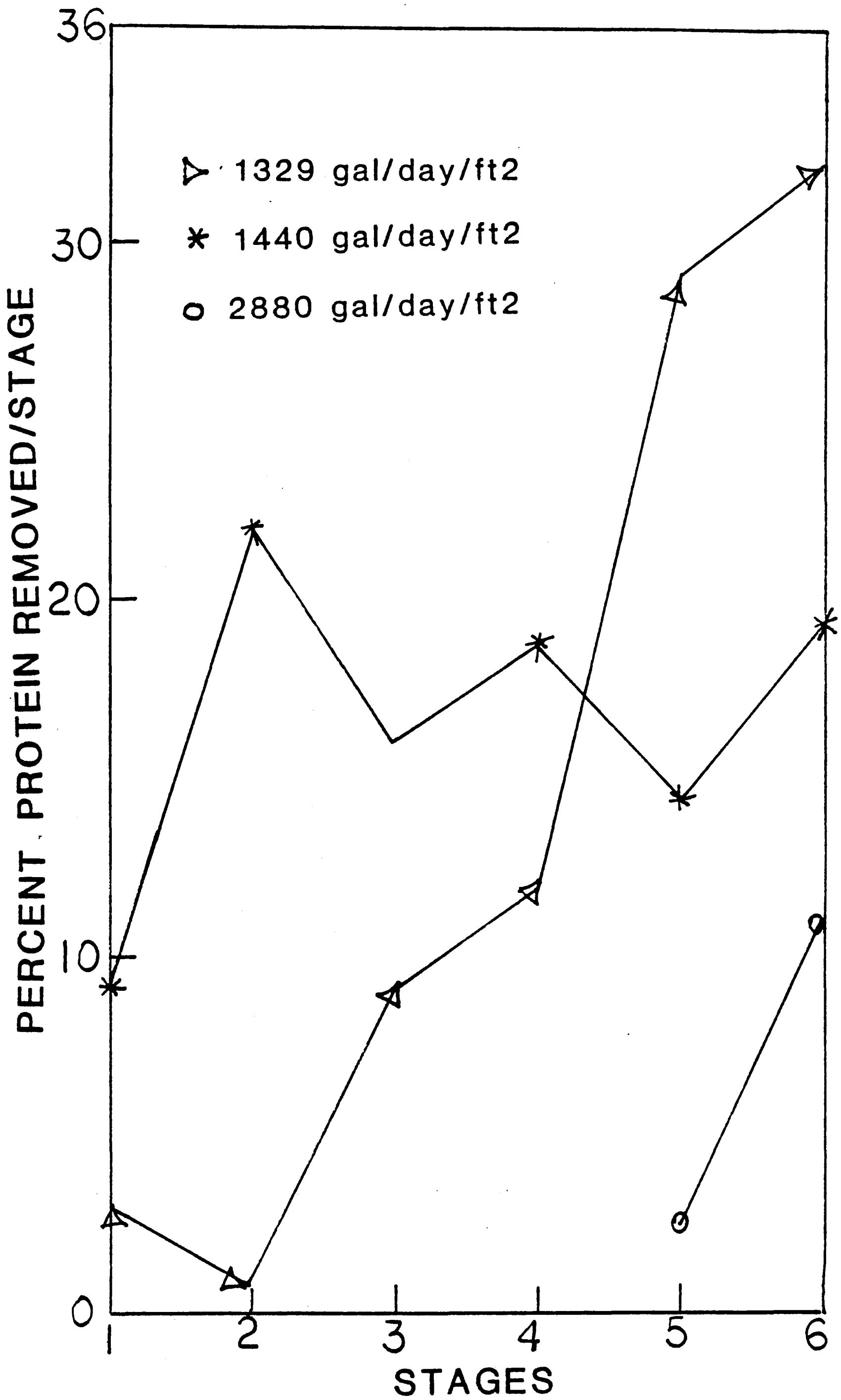

Figure 36A. Percent Protein Removed Per Stage Vs. Stages

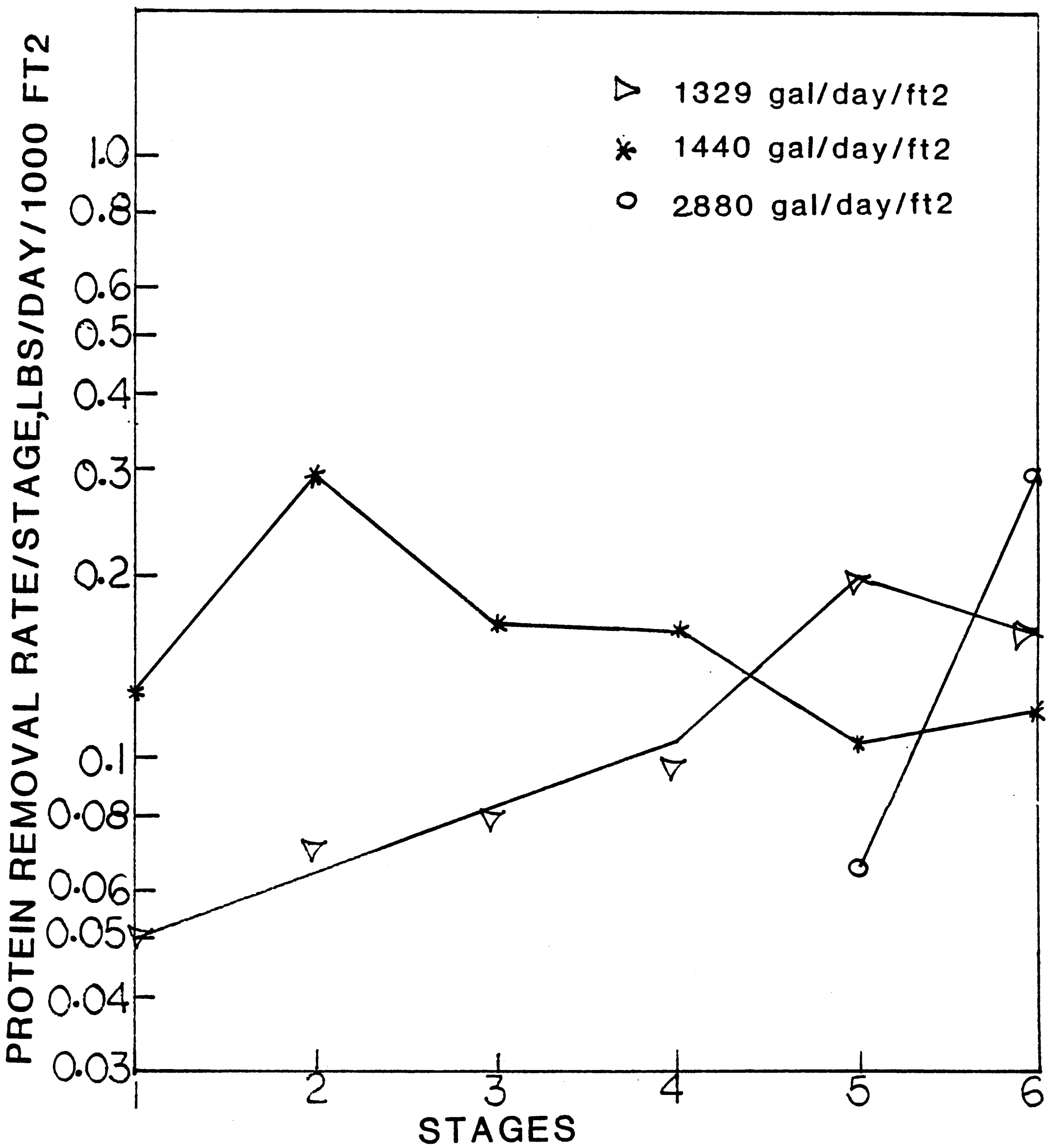

Figure 36B. Semi-Logarithmic Plots of Protein Removal Rate Per Stage as a Function of Stages

However, Figure 35B shows removal rate of carbohydrate per stage versus stages indicates that during 2880 gal/day/ft^2 and 1440 gal/day/ft^2 hydraulic loadings the removal pattern exhibits gradual decrease in removal pattern. During 1440 gal/day/ft^2 the decrease in removal pattern with successive stages show presence of more than one removal rate. Therefore, both 2880 gal/day/ft^2 and 1440 gal/day/ft^2 study coincides with the pattern obtained for BOD (Figure 27B). Unfortunately, the removal rate of protein is very confusing to the author. In general, the figures (36A and 36B) do indicate an increase in protein removal rate at the later stages of the tower. But during 1440 gal/day/ft^2 flowrate the removal rate exhibits oscillatory pattern.

In essence, it could be said that when a biological tower is segmented the removal mechanism becomes very confusing. Because, biological tower is a continuous interrelated and interdependent biological sequential reaction process. Under this situation it is not possible to effectively segment biological reactions or substrate loading. So any attempt to divide the removal mechanism based on depth would lead to erroneous conclusion for the total system.

Evaluation of Ammonia-Nitrogen Removal Without Nitrification

The results of ammonia-nitrogen remaining mg/l, at different depth for various loadings are presented in Table XI.

Figure 37 is plotted as ammonia-nitrogen remaining mg/l versus depth. Though with such small removal it is hard to be specific in analysis, but the reason for small removal could be explained. The

TABLE XI

AMMONIA-NITROGEN CONCENTRATION AT DIFFERENT FLOWRATES

	Depth Ft.						
Flow gal/day/ft^2	0 mg/l	3 mg/l	6 mg/l	9 mg/l	12 mg/l	15 mg/l	18 mg/l
1329	26.3	26	26	24	23.3	22.4	22
	25	24	23.2	22	21	20.5	20
	26	25.7	25	24	24.2	23	22
1440	22	21.2	20	20	20	19.5	19.2
	20	20.5	20	19.5	19	19	18.5
	26.3	26	25.5	25	24	24	23.7
	21.3	20.6	19.8	18.9	18.5	18	17.25
	22	20.5	21	20	19.6	19.2	18.6
	24.6	25	23.2	22.4	21.5	2.5	20
2880	26.2	25	25	24.6	24.2	24	23.6
	38	37.2	36.8	35.3	34	33.6	33.8
	27.5	26.4	26	25.3	25	24.4	24
	29	28	27.2	27	26.5	26	25
	34	33	32	31.5	31	30.4	30
	33.25	32	31.5	31	30	30	30
	24.5	24.2	23.5	23	22.4	22	21
Average							
1329	25.74	25.23	24.7	23.33	22.83	21.96	21.5
1440	22.7	22.3	21.58	20.96	20.33	20	19.425
2880	30.35	29.34	28.64	28.1	27.91	27.36	26.97

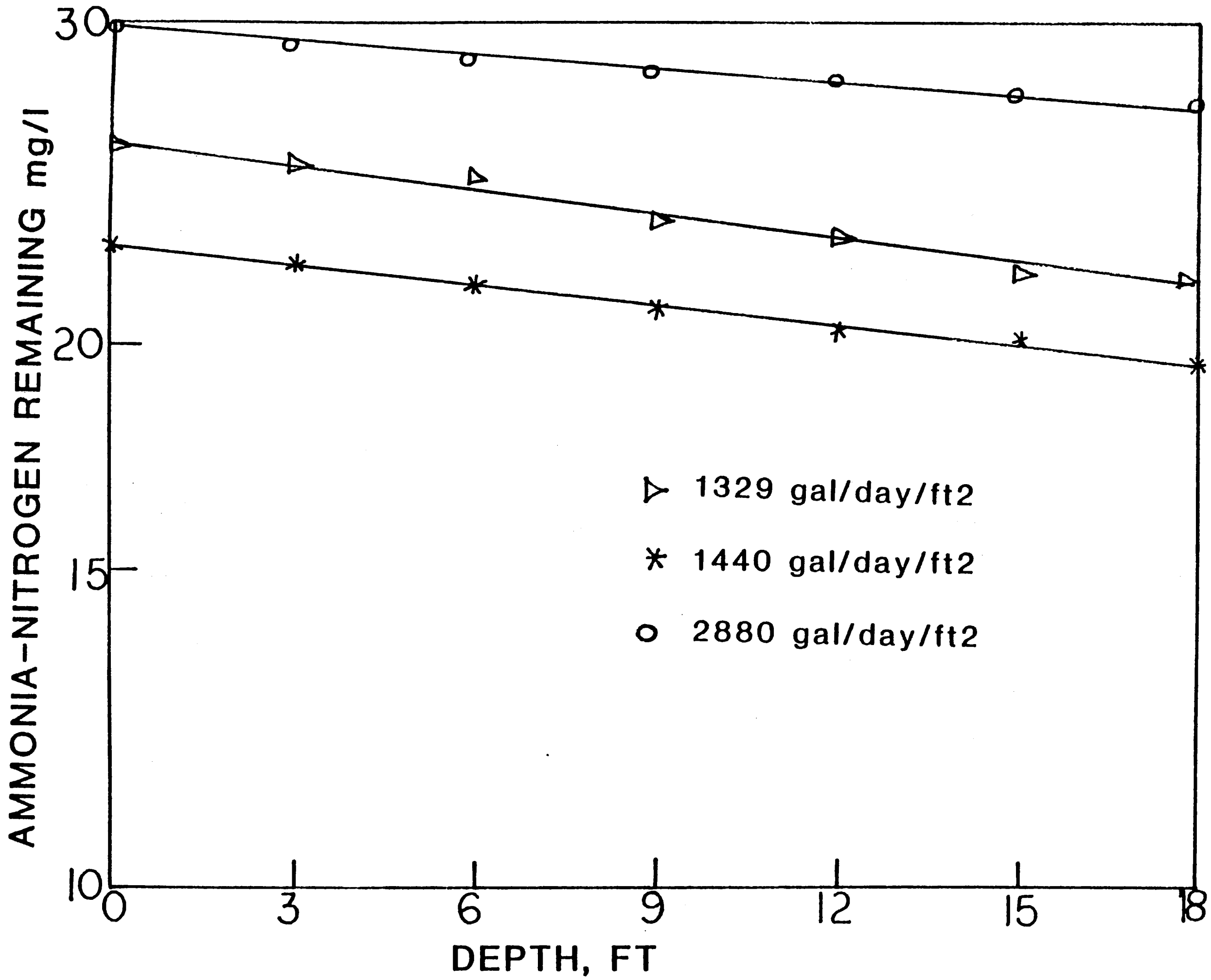

Figure 37. Semi-Logarithmic Plots of Ammonia-Nitrogen Remaining (mg/l) with Depth

nitrate and nitrite test indicated that there was no production of any of these compounds during these three hydraulic loadings. According to literature (90) less than 25 lbs BOD/day/1000 ft^3 organic loading is required for nitification. but, the least organic loading exhibited during the above three experimental runs was 35.8 lbs BOD/day/1000 ft^3. Therefore, the removal of ammonia-nitrogen was definitely due to growth. Generally, BOD:N of 20:1 is required for growth. According to Table XI and Figure 37 an average of 3.35 mg/l, 3.3 mg/l and 4.mg/l of ammonia-nitrogen was respectively removed during 2880 gal/day/ft^2, 1440 gal/day/ft^2 and 1329.12 gal/day/ft^2 hydraulic loading rate. The corresponding BOD removal was approximately 58 mg/l, 69 mg/l and 50 mg/l, respectively. Therefore, it clearly indicates that the removal was mainly due to the growth requirement of biomass.

Evaluation of Removal Kinetics During 820.8 gal/day/ft^2 Hydraulic Loading

This study of 820.8 gal/day/ft^2 hydraulic flowrate is studied separately for two reasons: (1) it was the only set that showed nitrification and (2) the analysis show minimal wetting effect (Curve 2 of plot 48). This wetting of the tower below required minimum flowrate impaired the efficiency of tower--both in respect to carbonaeous removal and ammonia-nitrogen removal. But, as it was the only study showing nitrification it was decided to evaluate the kinetics. The results are given in Table XII.

Figure 38 is a semilogaraithmic plot of average concentration of measured specific parameters versus depth. It is seen that both BOD

TABLE XII

OBSERVED SPECIFIC PARAMETERS REMAINING AT DIFFERENT DEPTHS OF TOWER DURING 820.8 gal/day/ft^2 HYDRAULIC LOADING

Parameters	Cumulative Depth In Feet 0	3	6	9	12	15	18
Inhibited BOD	51.6	35.2	22	17.9	14.0	12.35	8.6
	46.8	30.2	20.2	14.8	12.6	10.2	8.0
	39.2	24.7	16.6	13.4	10.2	8.6	5.8
	36.71	17.28	9,2	5.25	2.8	1.2	0
	38.2	20	12.8	8.6	6.0	5.2	3.8
	45.5	23.1	18.6	12.8	8.2	5.2	4.0
	51.0	38.1	20	16.9	8.42	5.06	3.14
	41.1	27.7	15.4	12.0	6.9	4.0	2.1
	46.8	27.2	14.6	10.2	8.7	6.0	4.1
	35.58	20.2	13.2	6.2	3.3	2.0	0.75
	30	17.8	12.2	8.4	5.0	3.2	1.7
	40.1	21.2	14.8	8.0	5.2	3.8	2.0
	41.6	22.8	15.6	9.2	7.0	5.6	3.2
	44.36	29.4	18.2	12.0	8.6	5.3	3.5
	38.5	24.12	16.2	14.12	9.3	7.2	5.1
	46.5	27.2	14.7	9.0	5.6	3.4	2.0
	41.36	30.26	18.9	12.6	9.87	6.0	3.4
	36.8	17.75	12.2	8.2	5.0	2.9	1.5
Avg.	41.75	25.23	15.86	11.1	7.58	5.4	3.58
Unhibited BOD	56.8	37.8	22.36	20.4	16.8	10.66	10.25
	35.5	18.5	8.8	7.7	7.2	4.0	2.3
	50.6	28.9	19.8	17.2	12.6	9.83	6.0
	44.6	33.45	20.1	13.0	7.54	5.0	3.2
	39.45	22.9	15.2	16.8	9.1	8.6	8.75
	47.6	28.1	16.1	8.8	7.2	6.0	3.8
Avg.	45.76	28.275	17.06	14.0	10.07	7.35	5.72
COD	73	53	39	34	30	28	29
	56	42	38	36	28	20	18
	68	39	30	26	25.5	20	20.5
	70	56	46	38	30	28	27
	60	44	40	42	40	36	40
	71	48	36	32	26	22	23
Avg.	66.33	40.33	38.17	34.67	29.92	25.67	26.25

Table XII (Continued)

Carbo-hydrate	11.2	7.8	5.6	2.0	2.0	4.2	4.0
	9.4	6.2	4.6	2.2	0	0	3.2
	9.2	5.2	3.0	0	0	1.2	2.0
	11.8	7.6	5.4	2.8	1.5	0.8	1.0
	13.33	10.2	7.0	5.2	3.2	2.0	2.6
	17.2	11.33	8.0	7.2	5.5	3.6	3.0
Avg.	12.02	8.06	5.6	3.23	2.03	1.97	2.6
Protein	13.2	11	7.4	4.0	1.6	0	0
	10.7	6.6	4.2	1.4	0.8	0	0
	12.6	9.2	5.6	4.8	2.0	1.2	0
	14.2	12.8	10.4	6.8	4.0	3.0	0.8
	12.2	7.8	4.0	1.2	0	0	0
	11.0	10	5.85	5	3.6	1.0	0
Avg.	12.32	9.6	6.24	3.87	1.33	0.87	0.133
Ammonia-Nitrogen	31.25	30.3	30	29.2	28.2	25	24.5
	24.2	23.0	22	21	19.2	17.6	16.5
	30	29.5	30	28	26.5	26	25
	35.2	35	33.5	32	30.75	28	26
	24.2	25	23.5	20	18	16.5	15
	26.6	26	25	23.5	21	19.0	17.6
Avg.	28.575	28.13	27.33	25.62	23.94	22.02	20.77
Nitrate Nitrogen	-	-	-	1.0	2.0	3.2	5.0
	-	-	0.2	3.2	6.5	8.5	9.0
	-	-	-	0.5	1.6	3.0	5.2
	-	-	0.2	1.2	3.6	5.0	6.0
	-	-	0.3	2.0	4.5	6.25	7.6
Avg.	-	-	0.2	1.58	3.64	5.19	6.56

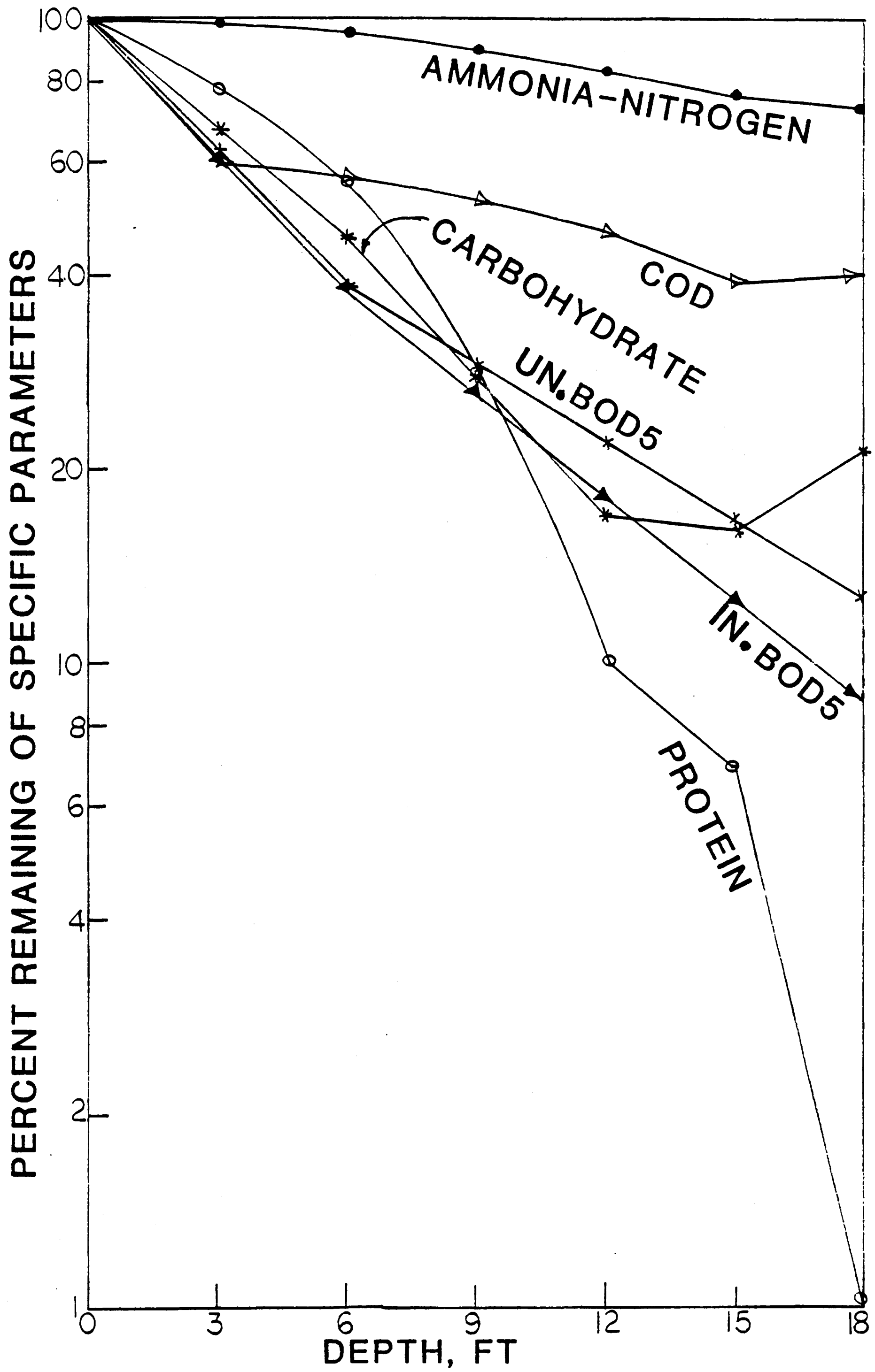

Figure 38. Semi-Logarithmic Plots of Specific Parameters Remaining (mg/l) During 820.8 gal/day/ft^2 Hydraulic Loading Vs. Depth

curves (inhibited and uninhibited) are first order decreasing function of depth but the removal rate is not constant throughout the depth. Both the curves indicate presence of more than one removal rate. The Phase I removal rate is, $K_1 = 0.16\ ft^{-1}$ and Phase II removal rate constant is $K_2 = 0.124\ ft^{-1}$ for the nitrification inhibited BOD curve. This does not agree with the previously obtained kinetic rate constants ($K_2 = .07\ ft^{-1}$) obtained for carbonaceouc removal. The reason for this discrepancy is not clearly understood by the author. The uninhibited BOD curve exhibits Phase I reaction rate, $K_1 = 0.164\ ft^{-1}$ and Phase II kinetic rate constant $K_2 = .09\ ft^{-1}$. The COD and carbohydrate curves show frequent change of removal rate with depth. The increase of carbohydrate concentration and COD at the last few feet of depth indicates production of secondary metabolites, secretion of polysaccharides, lysis, etc. The protein curve shows that it was being utilized throughout the depth of the tower, though the removal rate increased as carbohydrate concentration became low. Figure 38B also demonstrates that ammonia-nitrogen utilization was higher during this 820.8 gal/day/ft^2 loading than it was for any of the previously studied loadings. Results for nitrate-nitrogen list (Table XII) indicates that nitrate-nitrogen has been produced. When the BOD loading decreased, nitrification started.

Figure 39 shows percent of protein, carbohydrate, inhibited BOD, and COD removed and percent of nitrate nitrogen production versus depth. Figure 40 shows percent protein, carbohydrate and BOD removed versus organic loading, lbs BOD/day/1000 ft^2. This indicates that nitrification started at about 1.23 lbs BOD/day/1000 ft^2 loading.

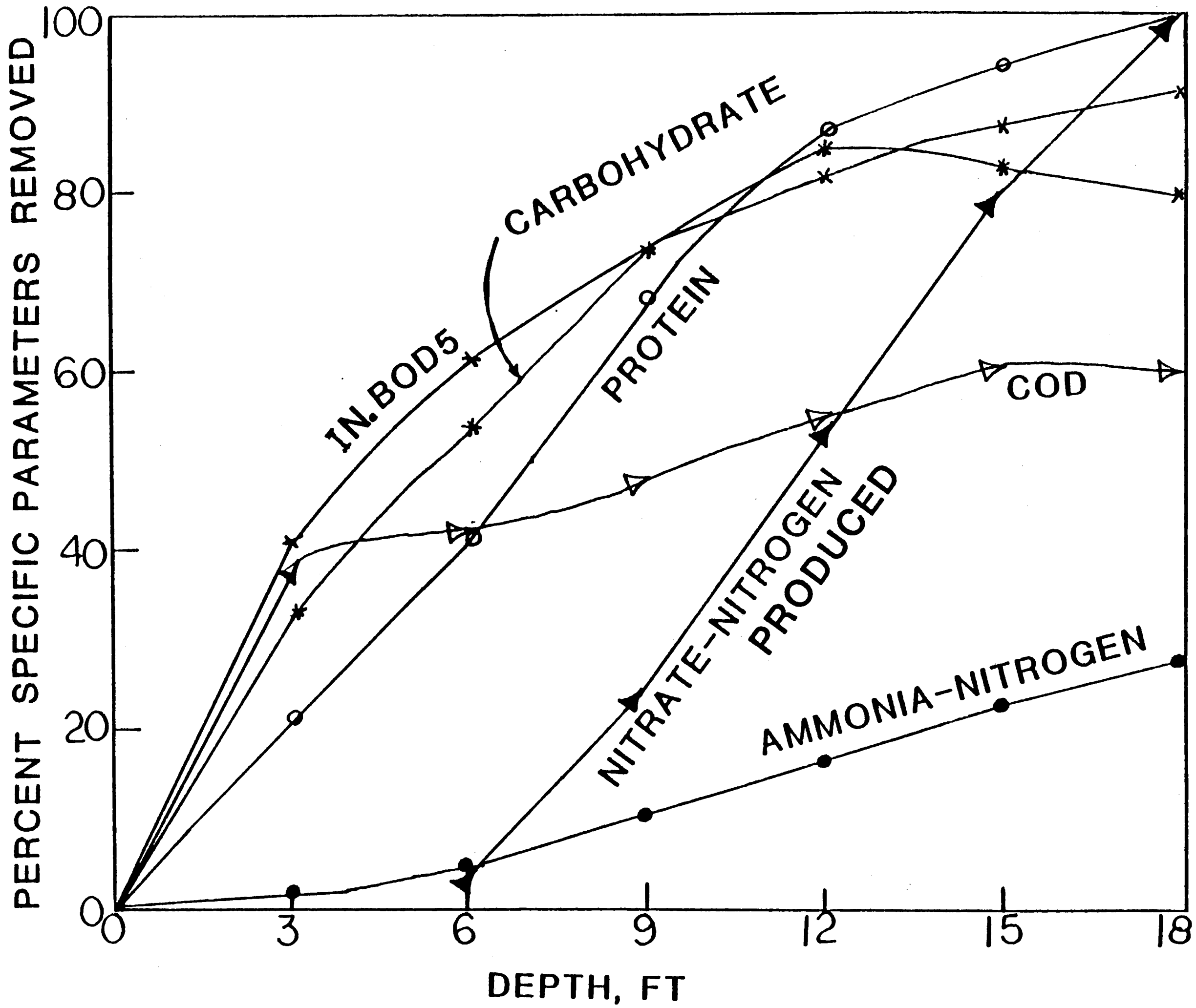

Figure 39. Percent Removed of Specific Parameters During 820.8 gal/day/ft^2 Hydraulic Loading as a Function of Depth

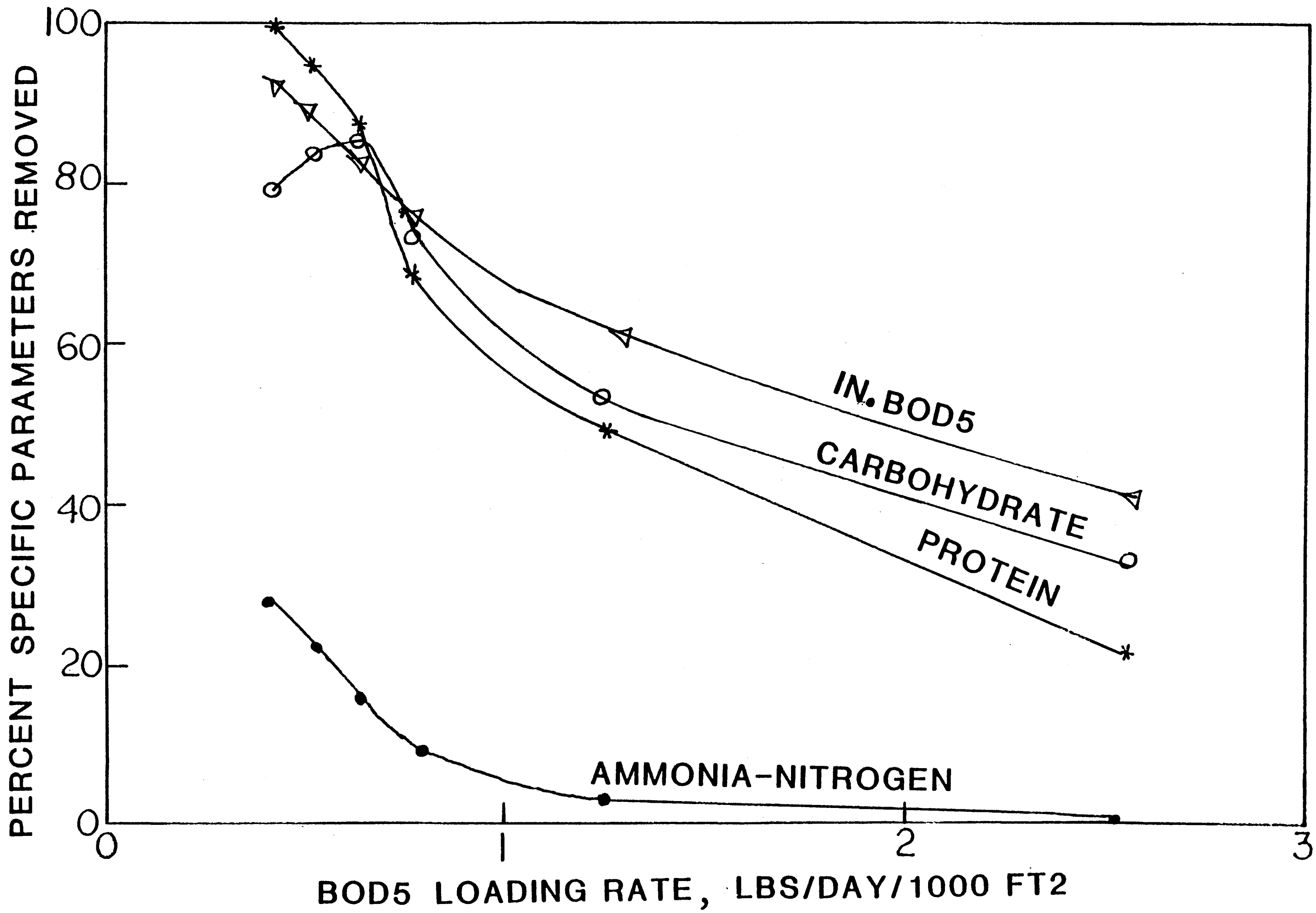

Figure 40. Percent Removed of Specific Parameters During 820.8 gal/day/ft^2) Flow Rate Vs. BOD Loading (lbs/day/1000 ft^2)

Figures 39 and 40 also indicates that by the time nitrification was significant, most of protein and carbohydrate has been utilized.

Figure 41 is plotted as NH_3-N removal rate, lbs/day/1000 ft^2 and NO_3-nitrogen production rate, lbs/day/1000 ft^2 versus ammonia-nitrogen loading rate, lbs/day/1000 ft^2. It shows that below a given depth when carbonaceous loading is low enough, the rate of oxidation of ammonia-nitrogen is proportional to the remaining oxidizable nitrogen upto certain loading and then the removal rate follows saturation kinetics. Figures 40 and 41 further indicate that the maximum ammonia-nitrogen utilization occured at an average of 0.49 lbs BOD/day/1000 ft^2 that is equivalent to 19.01 lbs BOD/day/1000 ft^3. According to the study done in Stockton plant (90) less than 25 lbs BOD/day/1000 ft^3 is required for nitrification in plastic media. As the total available surface area or biomass was not used due to minimal wetting the efficiency was effected. According to literature (51) about 1130 gal/day/ft^2 is the lower limit to flowrate for commercial packings of 38.8 ft^2/ft^3 specific surface area.

Evaluation of pH Study

The pH of a biological system is very important both as a controlling parameter and as an effect of removal reactions. For this study pH was within the biological activity range. There was little change in pH values as the wastewater passed through the depth of the tower. The observed values are given in Table XIII.

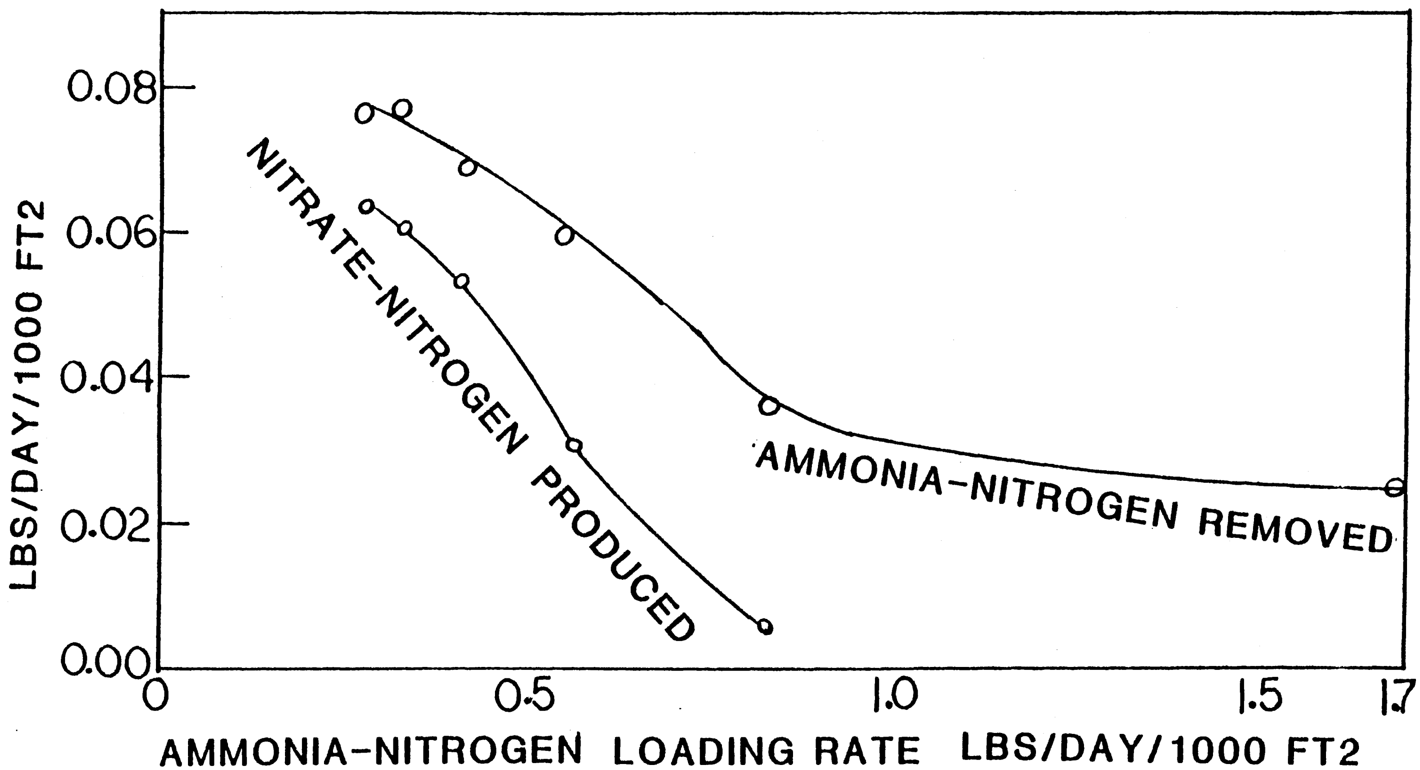

Figure 41. Relationship of Ammonia-Nitrogen Removal Rate (lbs/day/1000 ft^2) and Nitrate Nitrogen Production Rate (lbs/day/1000 ft^2) Vs. Ammonia-Nitrogen Loading Rate (lbs/day/1000 ft^2)

TABLE XIII

pH AT DIFFERENT DEPTHS OF TOWER DURING DIFFERENT LOADINGS

F gal/day/ft^2	Depth 0	3	6	9	12	15	18
820.8	7.44	7.67	7.85	7.9	7.86	7.7	7.54
1440	7.58	7.74	7.84	7.92	7.98	8.0	7.92
1329	7.63	7.7	7.8	7.9	7.85	7.8	7.78
2880	7.72	7.79	7.86	7.9	7.87	7.86	7.85

The overall change in pH is not very significant. The observed pattern of change in pH was more or less similar during all the discussed three hydraulic loadings, 1329 gal/day/ft^2, 1440 gal/day/ft^2 and 2880 gal/day/ft^2. But the results obtained for 820.8 gal/day/ft^2 exhibits different pattern. This occured due to nitrification and that is discussed later. Figure 42 plotted as pH versus depth shows that pH increased during the first part of the tower. This could be because of the breakdown of urea:

$$\text{Urea} \xrightarrow[U_{rease}]{H_2O} NH_4^+ + CO_2$$

Since, urea content of sewage was not measured the reason may not seem specific. Unfortunately, literature search on sewage treatment indicated no work done (to the author's knowledge) on the evaluation of pH change in tower. But, this assumption is justifiable because Urea is one of the major nitrogenous organic compound found in sewage. Urea is easily broken down by U_{rease} into ammonium ion, which when liberated in solution would increase pH.

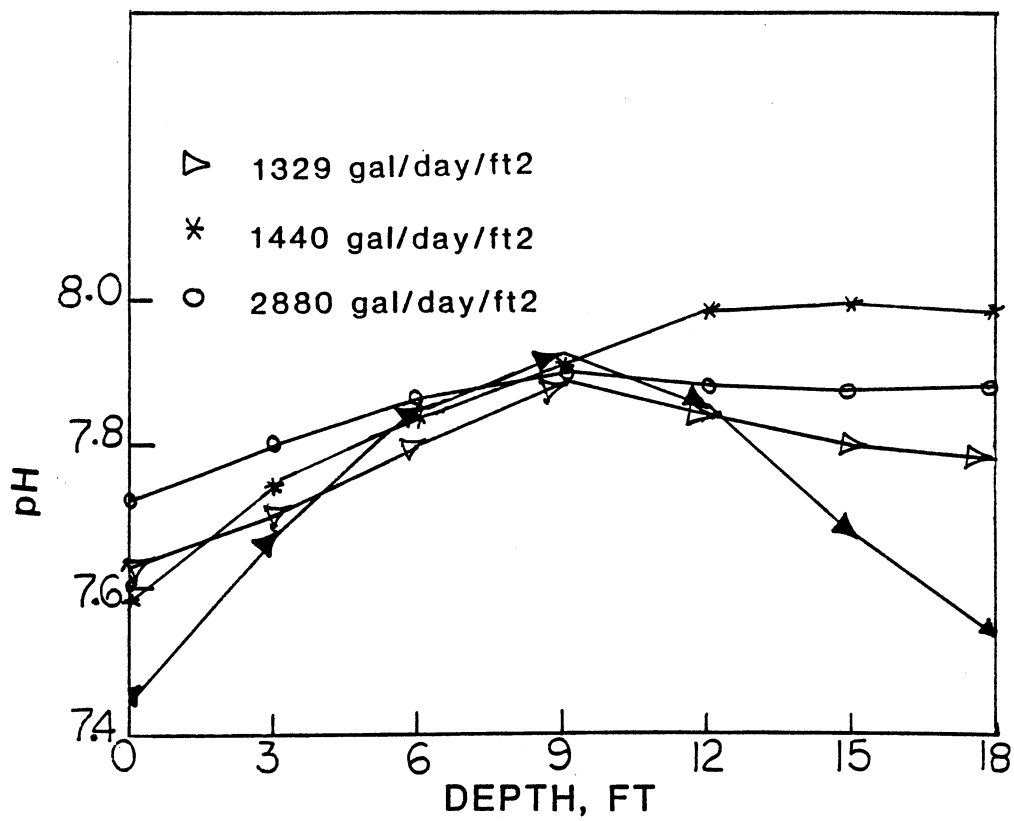

Figure 42. Relation of pH as a Function of Depth

The curve for 820.8 gal/day/ft^2 shows sharp decrease in pH after 12 ft. It could be reminded that around that depth nitrification was predominating from the reaction. Literature (53) indicates about 7.14 mg/l of alkalinity was destroyed for the oxidation of one mg/l of NH_4^+-N to NO_3^--N.

CHAPTER V

DISCUSSION

Domestic sewage is inheritedly very complicated in nature, mainly due to variations in constituents, strength and flowrate with time, place and season. Knowledge of the nature and amount of the organics present in sewage is of basic importance in the study of sewage treatment processes. For this study, the substrate concentration varied from 60 to 114 mg/l of BOD (Avg. ≈ 87 mg/l) during the time school was in session and from 40 to 65 mg/l of BOD (Avg. ≈ 55 mg/l) during breaks. The influent pH was approximately 7.6 and BOD:NH_3-N ratio averaged approximately 4:1. Phosphorus was approximately 25 mg/l. Carbohydrate content was between 10.0 to44 mg/l and protein between 9 to 17 mg/l. The observed results clearly indicated that the biological tower was subjected to compositional changes as well as a change in the organic loading. A constant hydraulic loading was assumed to be providing steady-state condition to the biomass. Strictly speaking, that is not possible. Mentioned variations actually was subjecting the biological tower to transient conditions. To adjust the environmental changes the biological solids must be going through all kinds of metabolic pathway shiftings, enzyme regulations, enzyme inductions, and predominance changes, and definitely these adjustments and changes affects the removal mechanism of tower. According to literature (71, 72, 76, 82, 83) some of the dominating organisms for biological tower treating sewage are Aehromobacter, Alcaligenes, Bacillus, Flavobacterium, Acetobacter, Zymomones and Pseudomonas. The respiratory dissimilation of sugars alomst always takes place for Pseudomonas and Acaligenes through the Entner-Doudoroff pathway. Alcaligenes exhibit another metabolic route, the β-ketoadipate pathway for the dissimilation of organic compounds. Gluconobacter and Acetobacter can oxidize glucose through pentose phosphate pathway or a second, nonphoshorylative pathway resulting in the accumulation of partly oxidized products--gluconate and ketoacids. Bacillus species can ferment, starch, monosaccharides and pectins but for some species the principal substrate of respiratory metabolisms are amino-acids and organic acids. Besides most of the species of Pseudomonadaclose are facultative in nature. Under oxygen limited situation a metabolic shift occurs. Again, there are photosynthetic bacteria which shows different growth requirements. Nitrifiers predominate when organic concentration is low. Lan isolated a heterotroph which could nitrify under cetrain circumstances (89). Since biological tower is an attached film system the biomass is very diverse in nature and it is surprising to find out how many possibilities there are for substrate utilization. Pilot plant study of biological tower irrigated with sewage could lead to the removal mechanism evaluation up to certain limit, but there is no way it could be specific. Biological activities, oxygen diffusion, mass transfer, nutrient uptake by biomass, etc. provide too many factors which are associated with the removal mechanism. Even molecular properties of the constituents of sewage, like molecular size, stereochemistry, length of chain, type etc., can affect the removal mechanism. Since enzymes initiate and catalyze degradation sequences, enzymes capable of attacking the organic molecule and subsequent degrading products must be present, or inducible, and free of inhibition and repression.

For the purpose of evaluation of removal mechanism general indirect parameters, which measures the effect of removal kinetic is more helpful. Analysis of specific compound can give an understanding of the removal mechanism to some extent but it is subject to many factors. During this study BOD was found to be the most effective parameter for studying removal mechanism. COD could be an effective parameter if it had been possible to express it in ΔCOD, that is, removable COD form. The usual procedure for determining non-biodegradable COD is by batch study. This procedure was thought to be not applicable for this study. Because the conditions under batch study are quite different than that exhibited by the biological tower system as the wastewater passes through the depth of the tower.

Carbohydrate, protein and ammonia-nitrogen evaluations did give ideas about the mechanism of removal for the specific compound but it cannot be used for obtaining removal kinetics. Because, the removal kinetics for carbohydrate and protein was interrelated and interdependent. Similarly, ammonia-nitrogen study provide understanding about the growth condition of the bacteria. However, when there is nitrification ammonia-nitrogen study is immensely important. It is to be admitted that evaluation of the removal mechanism for major compositional compound can be accounted, to some extent, for the change of removal kinetics with depth. Literature (62) and this study showed change of removal kinetic constants with depth. This change can now be definitely said to be very closely related to the removal mechanism of major utilizable substrates. The change was more or less observed around the depth where carbohydrate utilization was exhausted and protein utilization started. Literature survey confirms the fact that removal mechanism of carbohydrate is faster than that of protein. Then with the uptake or biodegradation of protein metabolic shifts and predominance change would also effect the removal rate. Besides there is other easily removal organic nitrogen sources.

In order to visualize the above mentioned conditions, Figures 43, 44 and 45 are plotted. These figures could be said to be summarized forms of the removal pattern observed with depth for studied experimental runs. Only the important facts will be mentioned. Figure 43 shows the measured parameters with depth during the 2880 gal/day/ft^2 hydraulic loading. BOD and carbohydrate removal plots show the same single removal kinetic constant. This situation indicates the availability of sufficient carbohydrate, that is, one type of substrate throughout the depth of the tower. Presumably, carbohydrate removal mechanism was predominating and significantly effected the BOD removal rate. This is supported by the observation that protein was not utilized until the very end of the tower, which could be because by then the amount of carbohydrate was getting closer to being an insufficient substrate.

Figure 44 summarizes the removal pattern at 1440 gal/day/ft^2 flowrate. Protein and carbohydrate both are showing more than one removal rate kinetics. So, this could be a reasonable explanation for the change in removal kinetics of BOD.

Figure 45 shows the removal plots during 1329 gal/day/ft^2 hydraulic loadings. BOD, carbohydrate and protein, all are showing

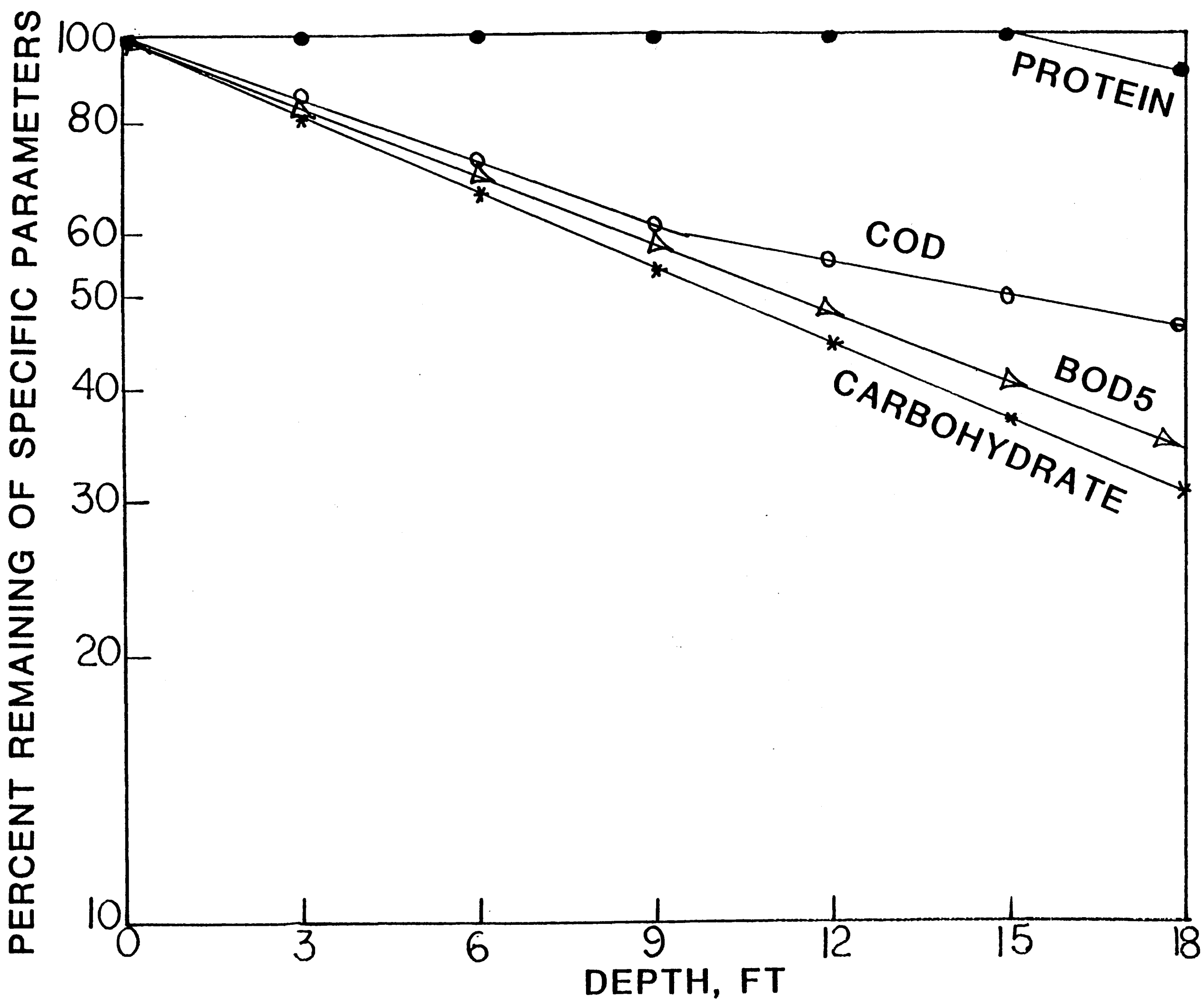

Figure 43. Semi-Logarithmic Plots of Percent Specific Parameters Remaining Vs. Depth During 2880 gal/day/ft^2 Flowrate

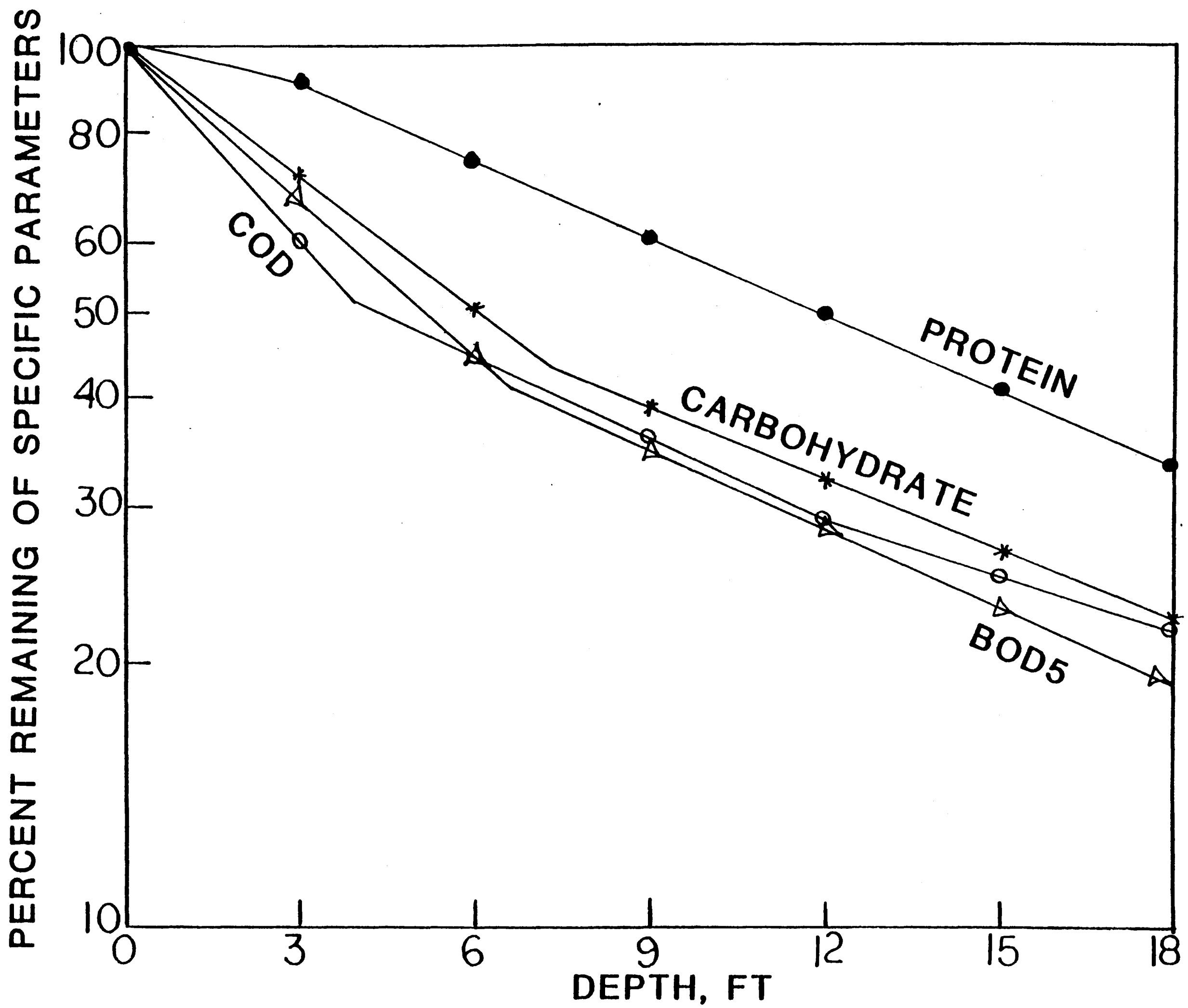

Figure 44. Semi-Logarithmic Plots of Percent Specific Parameters Remaining Vs. Depth During 1440 gal/day/ft^2 Flowrate

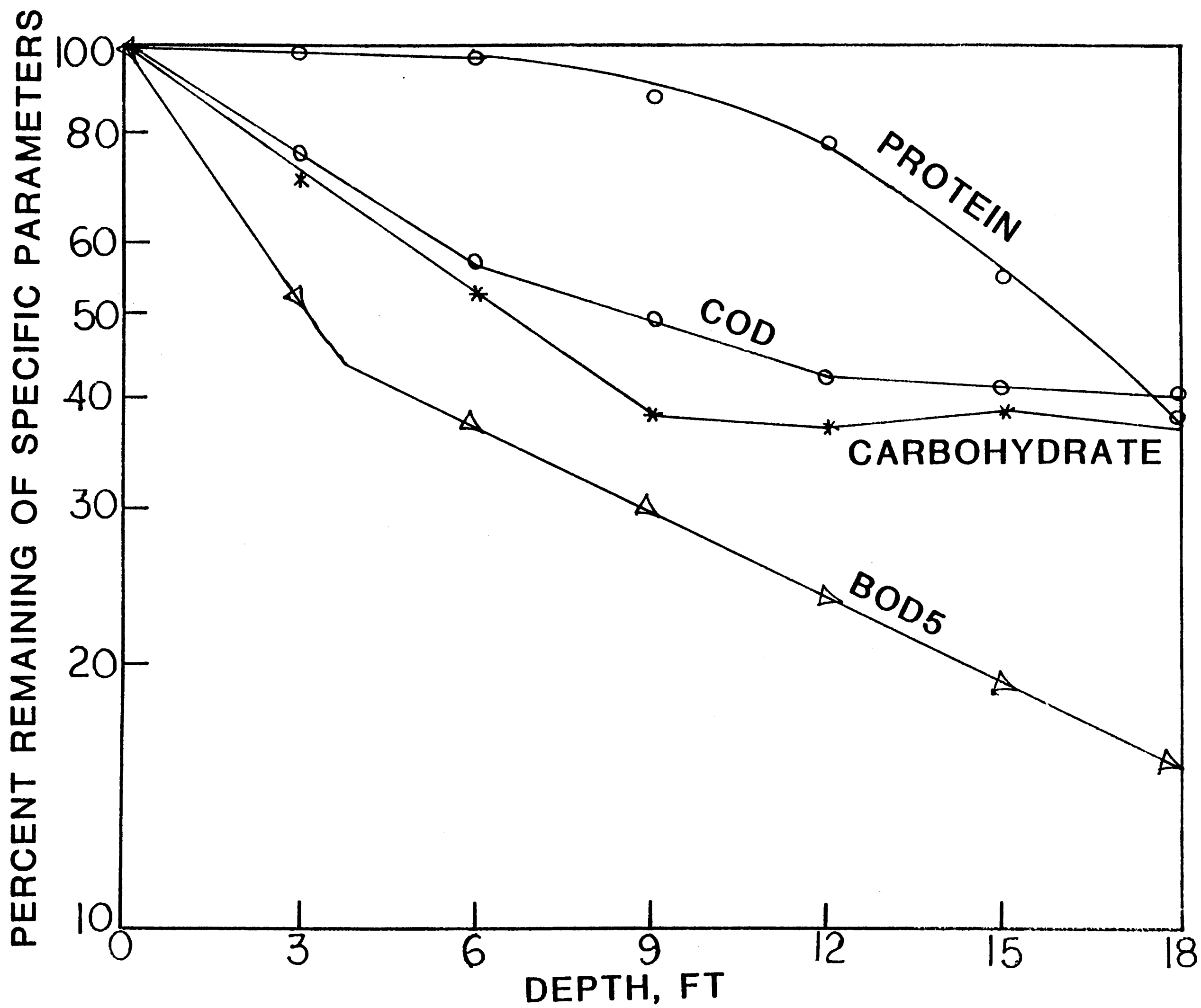

Figure 45. Semi-Logarithmic Plots of Percent Specific Parameters Remaining Vs. Depth During 1329 gal/day/ft^2 Flowrate

more than one removal kinetic constant with protein utilization increasing after exhaustion of carbohydrate utilization.

The interesting observation from Figures 43, 44 and 45 is during 2880 gal/day/ft^2 hydraulic loadings (the organic loading was 3.03 lbs BOD/day/1000 ft^2) there was no BOD removal rate change. During 1440 gal/day/ft^2 hydraulic loading (the organic loading was 1.5 lbs BOD/day/1000 ft^2) the change in BOD removal kinetic occured around 6 ft. depth and during 1329 gal/day/ft^2 hydraulic loading (the organic loading was 0.93 lbs BOD/day/1000 ft^2) the BOD removal kinetic changed near 3 ft. depth. This is better understandable from organic loading concept than hydraulic loading concept. The difference in values as 3.03 lbs/day/1000 ft^2, 1.5 lbs/day/1000 ft^2, and 0.93 lbs/day/1000 ft^2 is more significant and meaningful for the above situation than 2880 gal/day/ft^2, 1440 gal/day/ft^2, and 1329 gal/day/ft^2 or substrate concentration as 88 mg/l BOD, 87 mg/l BOD and 58 mg/l BOD, respectively.

The better applicability of total loading concept has been once again proved by the BOD, COD, carbohydrate and ammonia-nitrogen results. It only failed for the evaluation of protein removal mechanism. This happened because protein utilization was an effect of enzyme induced regulatory metabolism. But, Monod's equation is limited for multiple component substrate when situations like enzyme induction, inhibition, etc. are predominating.

Kinetic analysis based on segment or stage of biological tower showed that when divided into small units none of the approaches--first order decreasing theory or total organic loading concept could be successfully applied. Because the biological treatment of wastewater by biological tower involves many complicate, interreacting, interrelated reactions. The biocommunity of tower is very diverse in nature. It is not possible to bound or express these activities or composition of sewage within limit and then use them efficiently to describe the system.

The nitrification part was not satisfactory in respect of ammonia-nitrogen removal but it provided reasonable understanding of removal mechanisms that could occur during nitrification. Indeed, it was not possible to do solid evaluation of the removal mechanism with only one loading showing nitrification. However, the study indicated the compatibility in removal pattern between carbonaceous removal and ammonia-nitrogen removal.

Now, at the end of kinetic analysis it is thought to be interesting to find out how the performance of the pilot plant biological tower compares wtih that of an efficient activated sludge. In order to do so food-to-microorganism ratio of biological tower was computed by using information from literature (64-68, 21). The dry weight of active biomass microbial mass is assumed to be 95 mg/cu.cm. The above studies showed different active film thickness, 70μ was found to be aggreeable to most of the studies. Using specific surface of the media as 38.8 ft^2/ft^3, the dry weight of active microbial mass is computed as 1.35 lbs/1000 ft^2.

Table XIV gives the calculated food to microorganism ratios (F/M) and corresponding applied organic loading in lbs BOD/day/1000 ft^2 for various flowrates of the experimental biological tower.

TABLE XIV

FOOT TO MICROORGANISM RATIO (F/M) AND CORRESPONDING APPLIED ORGANIC LOADING

F/M	Applied Organic Load lb/day/1000 ft^2
1	1.35
2	2.7
3	4.05
4	5.39
5	6.74
6	8
7	9.33
10	13.33

Figure 46 shows the calculated relationship of food to microorganism ratio versus BOD loadings (lbs/day/1000 ft^2) at different flowrates. Figure 47 shows the removal efficency of the tower versus calculated food-to-microorganism ratio. Curve 1 is plotted with data obtained during 1329, 1440 and 2880 gal/day/ft^2 flowrates. Curve 1 of this figure indicates that at an F/M of 0.5 day^{-1} BOD removal efficiency was about 98 percent, which is quite acceptable as efficient performance. Because activated sludge also shows more or less similar performance at that F/M value (32). Further, Curve 2 of Figure 47, plotted with data obtained at 820.8 gal/day/ft^2 flowrate, clearly indicates that 820.8 gal/day/ft^2 hydraulic loading was less than required minimal wetting for the experimental biological tower.

Lastly, it should be mentioned that attempts were made to analyze the removal mechanism by using some existing models in literature. Models based on first-order removal kinetics in terms of depth of

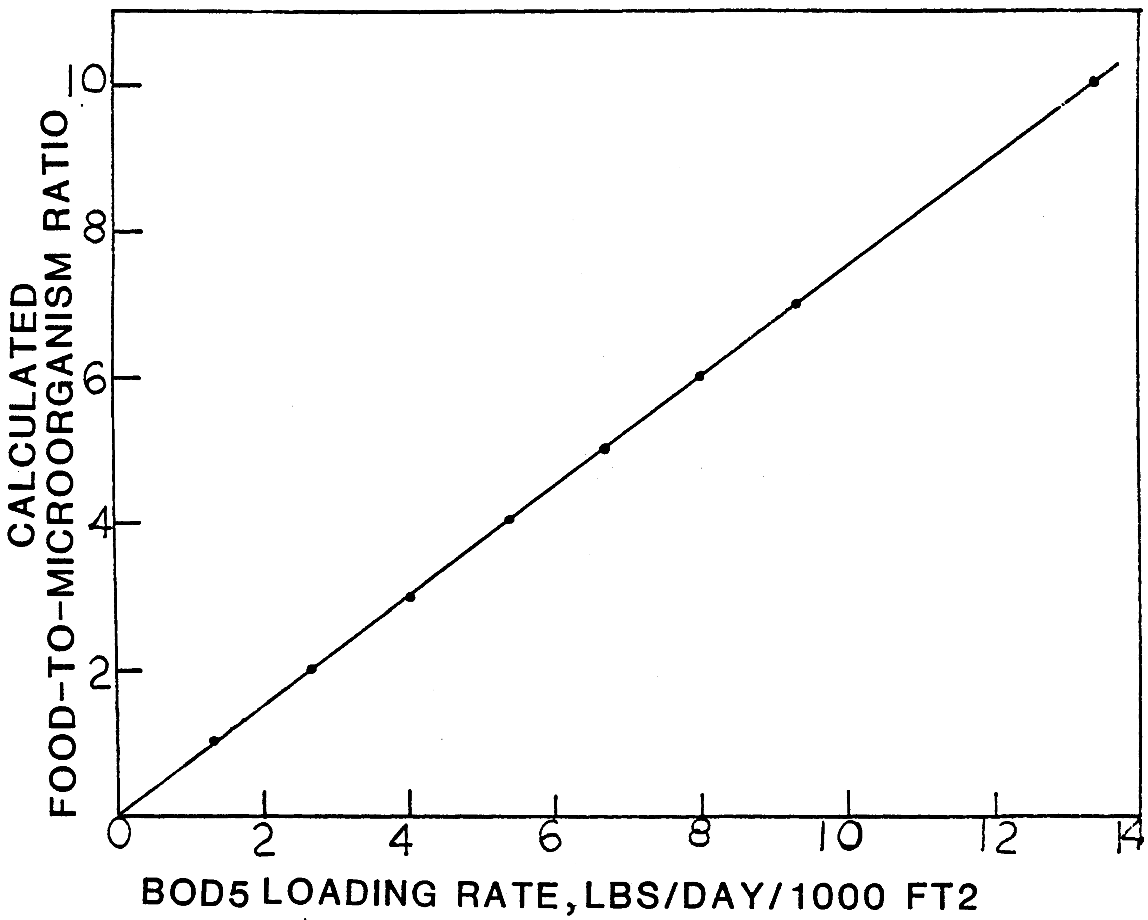

Figure 46. Relationship of Calculated Food-to-Microorganism Ratio Vs. Loading Rate (lbs/day/1000 ft^2)

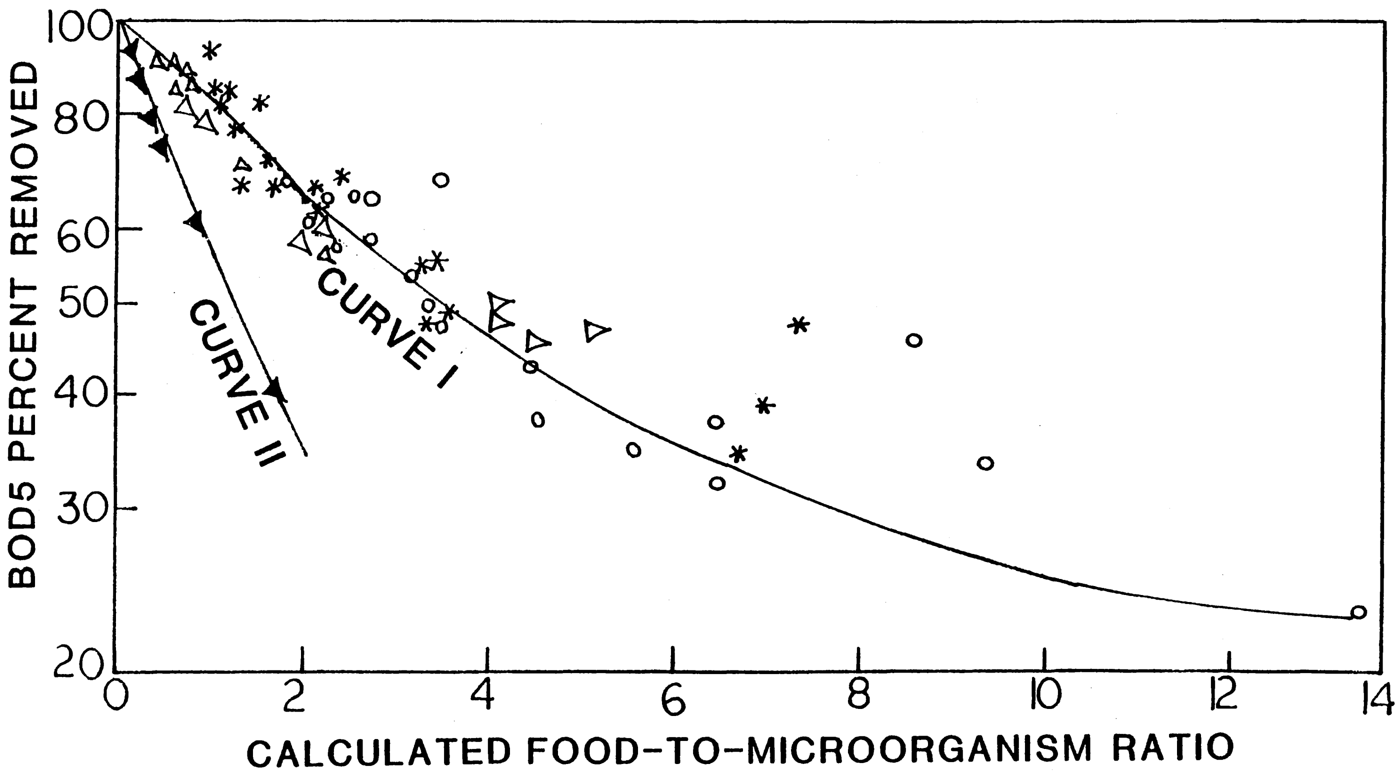

Figure 47. Relationship of Percent BOD Removal Efficiency as a Function of Calculated Food-to-Microorganism Ratio

filter or contact time are not feasible for the study. Because, the removal kinetics exhibit more than one removal rate constant. Unfortunately, the applicability of most of the existing total organic loading models for this study seemed to be poor. NRCF equation could not be used because the constants were derived using rock filters (12). Gallo-Gattas based their multiple regression on data obtained from rock filters (14). And the recent mathematical models not only involves complicate equations, these formulations contain factors like oxygen diffusion coefficient, mass-transfer co-efficient, solids, etc. Oxygen diffusion coefficients and mass-transfer coefficients change with substrate and substrate concentration. Many of the researchers like Williamson and McCarty (28), Harris et. al. (67), Atkinson and Doud (74) worked with synthetic waste made of pure single compound glucose. Literature survey could provide with the required values for glucose but the author could not find any work done on oxygen diffusion or mass transfer through fixed bed reactor with sewage. Sewage is a multiple component wastewater which shows variation in concentration of its components from time to time. Factors like mass-transfer coefficient, oxygen diffusion, etc. could effect the removal mechanism but without reasonable value there is no use in applying a model with erroneous assumptions. The work done at Oklahoma State University by Cook (73) resulted in a model based on total organic loading without mass transfer or oxygen transfer coefficients. But this model could not be applied for study too. Because, it involved parameters like solid produced, etc. which cannot be obtained for this study. The influent contained solids which was sometimes higher than the solids measured from the mixed-liquid suspended-solids. The only model found to be applicable for the study was the one derived by Kincannon and Stover (34). This model has been applied in the result section. Table X indicates that within certain limit the predictability of the model is in excellent coordination with the actual values. That means, the removal rate kinetics obtained by using the model was good representative of the system. It is simple and does not involve less understood factors like mass-transfer coefficient, oxygen duffision. May be the avoidance of this factor has put limitation to the applicability of the model after certain loadings. In any case, according to this study in the present situation this model was once again found to be the most aplicable and reasonable for describing removal kinetics when used justifiably and efficiently.

CHAPTER VI

CONCLUSIONS

1. Application of first order kinetics to biological tower in terms of depth shows presence of more than one removal rate constant.

2. As expected the mechanism and kinetics of removal of substrate is more related to the amount of total substrate applied to the filter rather than its concentration or flowrate.

3. Carbohydrate concentration of sewage could show repression effect on protein utilization rate. Carbohydrate removal showed close relation to the BOD removal mechanism of sewage.

4. Protein analysis is more complicated. None of the approaches could be reasonably applied for the evaluation of protein removal kinetics.

5. Analysis of removal kinetics of major constituents of wastewater could help in understanding of the removal mechanism expressed as BOD or COD. These could be accounted for the change in removal kinetics of BOD or COD.

6. Study of the removal mechanism of tower is more meaningful and representative of the general performance of tower when analyzed as a whole system than segmentation.

7. Minimal wetting effect as usual hindered the removal efficiency of tower during 820.8 gal/day/ft^2 hydraulic loading.

8. The performance of the experimental tower was comparable to activated sludge performance.

9. Kincannon and Stover's model (34) once again proved more applicable for the study of removal mechanism of biological tower.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

In consequence to this study of kinetics and removal mechanisms of biological tower the following suggestions are made:

1. The effect of sewage or complex substrate at various hydraulic flowrates and organic loadings concentration on active biomass should be studied. Even various filter media possessing various specific surface area could be used for better understanding of active film theory.

2. Since total organic loading concept is mainly limited to oxygen concentration at higher loadings, oxygen diffusion and concentration in wastewater flow demands investigation.

3. Analysis of major constituents of substrate is very helpful in understanding the system if it is more or less complete. So for complete study of sewage, along with carbohydrate, protein and ammonia-nitrogen, organic nitrogen, total kjeldahl nitrogen and oil and grease could also be measured.

4. Microbial isolation at the point of kinetic change could lead to supporting evidence of predominance change or metabolic change for compositional change.

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VITA 2

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