APPLICATION AND COMPARISON OF ACTIVATED SLUDGE DESIGN AND OPERATIONAL CONTROL PARAMETERS TO AN EXPERIMENTAL FIXED-BED REACTOR

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

CHAPTER I

INTRODUCTION

Trickling filters (fixed-bed reactors) have been used in the United States for the purpose of wastewater purification since 1889. The removal of organic wastes is accomplished primarily by microorganisms which are attached to the medium contained in the filter bed. The filter bed is normally composed of crushed stone, but other materials such as plastic can be utilized successfully. In reality filtration, as normally defined, does not occur in the filter. The primary purpose of the unit is to provide a location for biological oxidation to occur.

Biological wastewater treatment is also accomplished by the activated sludge process. Activated sludge treatment is similar to trickling filtration in the respect that both 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 a bio-mass which can be settled out, and by oxidation to carbon dioxide and water. The activated sludge process is a fluidized bed system in which flocculated biological growths are held in suspension in the presence of an injected air supply. In contrast, the biological growth in a trickling filter is attached to the filter bed surfaces and required oxygen is obtained from the surrounding environment.

Since the trickling filter and the activated sludge processes are both microbial systems, it should be possible to explain and describe the corresponding removals of soluble organics and the growth of microorganisms by similar procedures. Comparison of the two processes should be performed by using an equivalent basis of evaluation. In 1946, G. M. Ridenour (1) proposed that the load applied to each type of biological unit was equal to the BOD (biochemical oxygen demand) applied per unit time divided by the effective active biological concentration present. The effective biological concentration in a trickling filter was stated to be a function of effective surface area. At the time of his presentation, Ridenour observed that few biological treatment plants were evaluated as he suggested. Current evaluations of the trickling filter process normally tend to neglect the consideration of the microbial population present in the filter.

The primary purpose of this investigation was to establish design and operational control parameters for a biological fixed-bed reactor. These parameters were applied to an experimental laboratory unit for the purpose of determining the relationships between them. Representative values of results were then used for comparison to corresponding activated sludge parameters. Of secondary interest to this investigation was the observation of the production of biological solids. A knowledge was desired as to whether solids production was dependent upon the hydraulic flow to the system or the organic load which was applied. Various investigators have proposed design formulations for the trickling filter process. Mixed opinions exist, however, concerning the variables involved and their relative importance. The author expresses his desire that this investigation will give additional insight to the understanding and control of fixed-bed reactor systems.

CHAPTER II

LITERATURE REVIEW

A. Introduction

Current investigations of the activated sludge process normally describe it as a continuous culture of mixed microorganisms and attempts are made to analyze the system as microbiologists would. Past design formulations for the trickling filter process have been chiefly concerned with obvious physical aspects and empirical equations; there has been a definite lack of research regarding the biological nature of the treatment process. The literature reviewed in this chapter includes not only the results of research pertaining to trickling filters, but is also composed of the application and development of various activated sludge parameters. The purpose of this chapter is to present literature which will be beneficial in the analysis of a fixed-bed reactor system.

B. Suggestions for the Similar Evaluation of Biological Processes

Several researchers have suggested that the trickling filter and activated sludge processes may be evaluated by using similar methods. Ridenour (1) believed that the load applied to each type of process could be described in terms of the BOD applied per unit time divided by the effective active biological concentration. He observed that the common expressions which were used to describe trickling filter loadings were gallons per acre per day, gallons per acre-foot per day, population per acre-foot per day, and pounds of BOD per day per 1000 cubic feet of filter. The only expression which approached the method of evaluation as he suggested was pounds of BOD per day per 1000 cubic feet of filter. Any expressions for the load applied to the two types of biological processes should differ only with respect to the physical state of the biological populations.

In 1961, W. W. Eckenfelder (2) in a study of filter performance indicated that "BOD removal is related to the surface area of active film per unit volume of filter media. This is analogous to the concentration of mixed liquor solids in the activated sludge process." The surface area of mean active film was incorporated into his design formulations. He defined the quantity of active biological film as being dependent on the depth of film through which oxygen could be available for aerobic conditions to be maintained. Eckenfelder's study was significant to the present investigation in the respect that he acknowledged the biological nature of a filter and its resemblance to the activated sludge process.

In 1973, Kincannon and Sherrard (3) proposed a basis for the comparison of the two biological processes. They expressed the opinion that a rational procedure is needed for the purpose of selecting which type is best suited for a particular wastewater treatment objective. They believe that many traditional advantages and disadvantages of either process have normally been defined in vague terms which are not valid for comparison. The concept of mass loading rate of organic material per mass of microorganisms (food to microorganism ratio, F/M) was suggested as being a valid basis of comparison. The authors developed a procedure for the determination of food to microorganism ratios for trickling filters. Sludge age, Θ_c, was also suggested as an equitable parameter for comparison. Thus, food to microorganism ratio and sludge age are parameters by which process comparisons and selections may be evaluated.

The continuous culture theory of microorganisms has been used in the study of trickling filter process kinetics. Kornegay and Andrews (4) utilized an annular reactor comprised of a rotating drum inside an outer vessel for the purpose of analyzing the kinetics which apply to fixed biological films. With the aid of Monod's (5) growth kinetics, they developed a steady state equation which adequately predicted substrate removal for a single stage reactor. The equation is expressed as follows:

$$F(S_o - S_1) = \frac{\hat{\mu}}{Y} (A)(X)(d) \frac{S_1}{K_s + S_1} \tag{1}$$

where

S_o = influent concentration of the essential nutrient (M/L^3)
S_1 = effluent concentration of the essential nutrient (M/L^3)
$\hat{\mu}$ = maximum specific growth rate (T^{-1})
F = hydraulic flow rate (L^3/T)
Y = yield constant
A = area of biological film (L^2)
X = concentration of organisms in the biological film (M/L^3)
d = thickness of the active biological layer (L)
K_s = essential nutrient concentration where = $\frac{1}{2}\,\hat{\mu}$ (M/L^3)

Glucose was employed in their studies as the growth-limiting nutrient, and the annular reactors were seeded with mixed cultures of microorganisms obtained from domestic wastewater. The temperature of the influent hydraulic flow was maintained at $25 \pm 0.5^{o}C$. Film thickness was found to vary prior to the attainment of steady state conditions, but eventually stabilized. Steady state conditions were obtained when the biological film thickness measured 70μ. At this thickness, values for dissolved oxygen and substrate utilization became constant. The authors also observed that film thickness in excess of 70μ did not provide a greater substrate removal rate. The active thickness was found to not be a function of the dissolved oxygen present in the film. Steady state parameters which were determined are:

$Y = 0.26$ g of volatile suspended solids/g of glucose utilized
$X = 95$ mg/cucm, dry weight
$K_s = 121$ mg/l
$\hat{\mu}^s = 0.28\ hr^{-1}$

Cook (6) in 1970, studied the performance of a fixed-bed reactor system employing sucrose as the growth-limiting nutrient and a filter media composed of vertical fiberglass plates. He derived a material balance equation which was identical to the equation developed by Kornegay and Andrews (4) to describe fixed film performance. Cook evaluated the equation by using the data obtained from his experimental reactor. He concluded that "the material balance equation is valid at steady state conditions in a trickling filter."

Kornegay and Andrews (7) later expanded their use of the continuous culture theory in the evaluation of fixed-film reactors. They developed an equation to describe substrate removal in a plug-flow reactor, and modified their equation for single stage removal for the purpose of predicting performance through a series of reactors. They utilized six annular reactors in their experimental investigations. Their experimental results showed that both the plug-flow model and the series reactor model could be used to predict reactor performances.

C. Activated Sludge Parameters

This section of the literature review will be devoted to the presentation of published literature pertaining to the activated sludge process. This literature will be limited to suggestions and formulations of various parameters which can be used in the description and evaluation of biological wastewater treatment processes. The parameters being studied will be those which are applied in this investigation to fixed-bed biological reactor systems.

In 1952, Garrett and Sawyer (8) studied the kinetics of the removal of soluble BOD in the activated sludge process. They believed that a term identified as "biological loading" would be beneficial in process descriptions. This loading was defined as "the pounds BOD applied per day per pound aeration solids." The growth rate of microorganisms was stated to be directly related to this loading.

Garrett (9) in 1958, proposed a method for the operational control of activated sludge plants. Sludge growth rate was found to be a parameter which controlled the operating condition of a treatment plant. Growth rate could be hydraulically regulated by the wastage of solids to an excess sludge settling tank. The reciprocal of growth rate was termed "sludge age." Sludge age was defined as the "total pounds of solids in a plant divided by the solids wasted from the system each day."

McKinney (10) recommended the use of a concept labeled "food: microorganism ratio." This ratio (F:M) could be explained in terms of the food which was available per unit of microorganisms. McKinney suggested that F:M ratios could be related to microorganism growth rate and to excess sludge production. High F:M values were stated to produce larger amounts of excess sludge than would lower F:M values. The flocculation ability of sludge particles was believed to be increased when F:M ratios were decreased.

Jenkins and Garrison (11) indicated that the operation of activated sludge facilities should be based on the mean cell residence time (Θ_c) of activated sludge particles in the system. Control of the mean cell residence time will enable the regulation of the soluble COD (chemical oxygen deman) quality of the system effluent. The authors also discussed the ability to maintain specific organisms in the system, such as those responsible for nitrification, by the control of mean cell residence time. They concluded that this parameter can be rationally used for the design, control, and operation ot activated sludge wastewater treatment plants.

In 1970, Lawrence and McCarty (12) presented mathematical formulations of parameters applicable to biological treatment processes. Their purpose was to develop unifying relationships which could be used in the description of various processes utilizing bacteria as the primary organism. Models were developed for complete-mix systems with and without recycle and for a plug-flow system with recycle. They suggested that biological solids retention time (Θ_c) be used as an independent parameter for design and operational control purposes. Various parameters were related to Θ_c for use in the description of the three models. The concept of minimum biological solids retention time (Θ_c^m) was recognized as being important to the maintenance of a biological population. At lower Θ_c values than Θ_c^m, organisms will be removed from a system faster than they can be synthesized.

Metcalf and Eddy, Inc. (13) recommend that the concept of mean cell residence time be used in the design and operational control of the activated sludge process. They apply biological kinetics to treatment systems, and mean cell residence time is used as a principal parameter in their derivation of equations which describe system performance. Their procedures incorporate mean cell residence time as a rational design basis as shown by its inclusion in an example design problem. Mean cell residence time is suggested because of its basic relation to microbial growth and ease of regulation and control.

Sherrard, Schroeder, and Lawrence (14) developed a mathematical model for a continuous flow completely mixed activated sludge process employing cell recycle. Equations were derived by performing material balances for microbial growth and substrate utilization. The use of a variable observed yield coefficient facilitated the development of the various equations. The parameters of mean cell residence time (Θ_c), observed yield coefficient (Y_{obs}), specific utilization (U), food to microorganism ratio (F/M), and treatment efficiency were used to show graphically the relationships existing for a laboratory system. Mean cell residence time was shown to be a major parameter in the prediction of sludge production and system performance.

D. Studies of Fixed-Bed Reactor Systems

1. Total Organic Loading

In a biological system, the amount of substrate utilized should be related to the amount of substrate provided to the microbial population. The total organic loading applied to a fixed-bed reactor system is a product of the influent organic concentration and the hydraulic loading.

It is the purpose of this section of the literature review to show the results of several investigators who have analyzed the performance of fixed-bed reactor systems by using the concept of total organic loading.

Members of the Committee on Sanitary Engineering of the National Research Council (15) performed an extensive analysis of sewage treatment at various military installations. From the operational data which were obtained, a statistical analysis was made to characterize trickling filter performance. The Committee was able to conclude that of the two types of loading, organic and volumetric, the former has the greater effect on efficiency. The Committee proposed an empirical design formula which combines the hydraulic and organic loadings into one term which represents the total organic load applied to the filter per day.

Sorrels and Zeller (16) in 1953, studied trickling filter performance with the aid of a pilot plant using settled domestic sewage. They observed that BOD removal varied with the organic load which was applied. The removal of soluble BOD was found to be more dependent upon the organic load applied than upon the hydraulic rate of application.

In 1959, Ingram (17) reported on the results of a study using settled sewage as the substrate and a filter composed of six sections, each three feet in depth and twelve inches in diameter. Air was supplied at a controlled rate to the bottom of each section. Ingram stated that "hydraulic flow rate was not the limiting factor" controlling the efficiency of the reactor. He believed that the BOD loading of a filter is a parameter of more importance than the hydraulic loading. BOD removal was observed to be approximately at the same efficiency with the same applied organic loadings. It made no difference whether the organic loading was accomplished by a high flow rate of weak sewage or by a low flow rate of strong sewage.

Deen (18) studied the effects of various organic and hydraulic loadings on an experimental fixed-bed reactor. His investigations used a synthetic substrate with sucrose as the limiting nutrient and carbon source. He concluded that total organic loading provides a better means of evaluation than does the organic concentration or the hydraulic loading considered separately. Equal total organic loadings were found to produce similar substrate removals throughout the depth of the filter.

In 1971, Cook and Kincannon (19) evaluated the performance of an experimental trickling filter which employed sucrose as the growth-limiting nutrient, and a filter medium composed of vertical fiberglass plates. They found that substrate removal efficiency was dependent on the amount of total COD (g/hr/sq ft) applied rather than the COD concentration or the hydraulic flow rate. For their range of hydraulic and organic loadings used in the investigation, residence time or contact time was found to be irrelevant to the COD removal. This was true because removal was dependent upon the total loading applied, regardless of the hydraulic load which was used to achieve a given COD loading.

Richard and Kingsbury (20) studied the treatment of milk wastes using plastic medium biological towers. The plastic medium which they used in their investigations was Flocor. They suggest that the two most important things to consider in tower design are the relation of organic load to performance, and the irrigation rate. For Flocor, they recommend that a continuous and uniform hydraulic loading should be maintained at rates between 864 gpd/sq ft and 2880 gpd/sq ft.

2. Observations of Sludge Production

A secondary purpose for this present investigation was the observation of biological solids production in a fixed-bed reactor system. The results will now be presented of various researchers who have reported information pertaining to the production of solids. The literature is limited to studies which used Flocor plastic medium for the reactor bed in their investigations. This limitation is imposed because Flocor was the medium used in the experimental investigations of the current study.

Chipperfield (21) in 1967, discussed several conclusions concerning the use and performance of plastic medium towers. He reported that the production of biological solids increases when the applied BOD load is increased. The proportion of the applied organic matter converted to solids tends to decrease with increasing organic loads. He observed that in actual practice, twenty to forty percent of the BOD is converted to biological solids.

Askew (22) in an analysis of high rate biofiltration indicated that the proportion of BOD converted to sludge varies with the type of substrate being treated and the loading rate. The conversion ratio for carbohydrate wastes was found to be twenty to thirty percent. Higher values may be obtained if the biological system is not allowed to reach equilibrium. Lower sludge conversion ratios can be expected for wholly soluble substrates than for wastes containing both soluble and insoluble components.

In 1970, Bruce and Merkens (23) reported several findings resulting from pilot plant studies in which six types of filter media were used. Settled domestic sewage was the substrate which they utilized for the purpose of comparing the different media. They found that total sludge production increased with the amount of BOD removed. The weight of sludge produced per unit weight of BOD removed increased with the degree of BOD removal. The average ratio of sludge produced per BOD removed was found to be 0.485 for the Flocor filter bed.

Richard and Kingsbury (20) in their study of the biological treatment of milk wastes observed that sludge is constantly sloughed in proportion to the incoming substrate. The sludge produced in the fixed-bed towers was found to be in their opinion relatively old. The average sludge age of voided sludge was observed to be one day.

CHAPTER III

MATERIALS AND METHODS

A. Experimental Approach

To apply and compare activated sludge design and operational control parameters to a fixed-bed reactor, two model fixed-bed reactors were used in this investigation. The two reactors were operated in series with intermediate clarifiers and a final clarifier to obtain results for total filter depts of four and eight feet. The effect of hydraulic loading on biological solids production was studied by collecting data at various flow rates (500, 1000, and 1250 gpd/ft^2). Biological solids production as a function of total organic load was determined at each flow rate by varying the organic load which was applied. The experimental units were operated under closely controlled conditions in which the influent temperature was held constant and influents and effluents were monitored daily.

Data were collected by determining influent and effluent COD values and by measuring the amounts of biological solids produced per day. These data were then used in the analysis and comparison of various parameters.

B. Experimental Apparatus

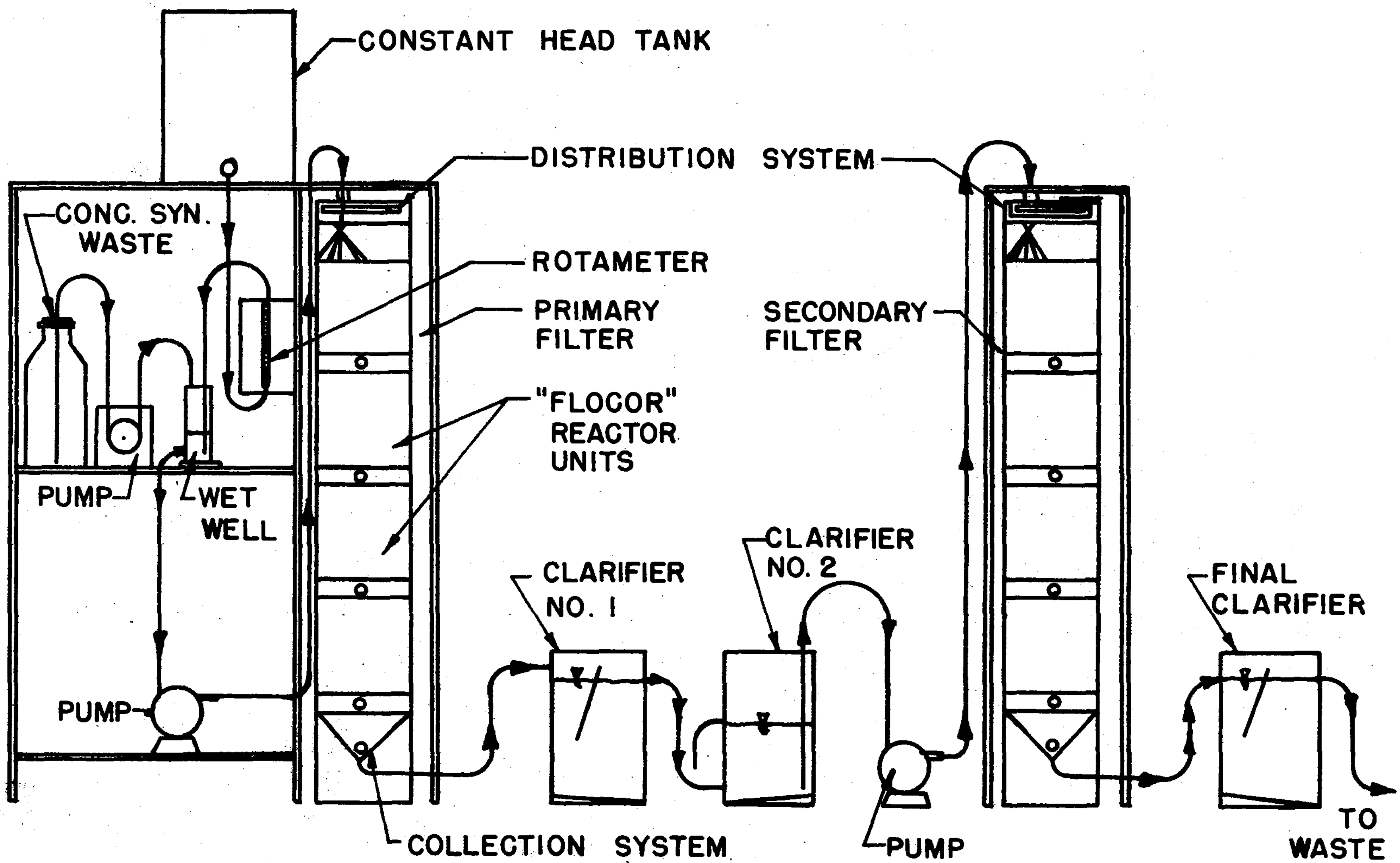
The two fixed-bed reactors employed in this investigation (see

Figure 1) consisted of plexiglass towers which were approximately eight feet in height. Each tower contained four one-cubic foot (1.0 ft x 1.0 ft x 1.0 ft) modules of Flocor rigid PVC plastic medium as the contact bed. The Flocor medium was developed by the Imperial Chemical Industries, Ltd., London, England, and has previously been licensed in the United States by the Ethyl Corporation. Flocor has 2¼-inch triangular openings, and each cubic foot provides a maximum of 27 ft^2 of surface area which can be utilized for biological activity. A void ratio of 97 percent provides ample opportunity for oxygen to react with microorganisms. Approximately four inches of void space existed between adjacent medium units to allow samples to be taken at various depths. The waste stream in each tower was channeled by collection troughs into plexiglass clarifiers.

Effluent from the primary tower was discharged into two plexiglass intermediate clarifiers in series and the secondary tower effluent was discharged to a final clarifier. Intermediate clarifier no. 2 was used as a wet well for pumping the wastewater to the secondary tower. The dimensions of each clarifier were 1.0 ft x 1.0 ft x 2.0 ft; however, the actual effective volumes of liquid were 1.29 ft^3 (36.56ℓ) for intermediate clarifier no. 1, 0.83 ft^3 (23.62ℓ) for intermediate clarifier no. 2, and 1.16 ft^3 (32.85ℓ) for the final clarifier. Clarifier no. 1 and the final clarifier each contained a plexiglass baffle which measured 1.0 ft x 1.0 ft x 0.25 in. The baffles allowed for the flocculation and settling of biological solids entering each clarifier. Wastewater flowed from intermediate clarifier no. 1 into intermediate clarifier no. 2 by gravity through flexible tubing.

Hydraulic flow to the system was maintained by means of a constant

Figure 1. Diagram of the Two-stage Fixed-bed System with Intermediate and Final Clarification


CONSTANT HEAD TANK
DISTRIBUTION SYSTEM
CONC. SYN. WASTE
ROTAMETER
PRIMARY FILTER
SECONDARY FILTER
"FLOCOR" REACTOR UNITS
PUMP
WET WELL
CLARIFIER NO. 2
CLARIFIER NO. 1
FINAL CLARIFIER
PUMP
COLLECTION SYSTEM
PUMP
TO WASTE

head tank which received a continuous flow of tap water from the Stillwater distribution system. Prior to entering the constant head tank, the tap water was passed through two coils of copper tubing which were immersed in water baths. The temperatures of the water baths could be controlled and enabled the primary reactor influent to be stabilized at $25^{o}C \pm 1.5^{o}$. The flow rates to the primary and the secondary reactors were regulated by means of rotameters. Before distribution to the primary unit occurred, the flow was discharged into a wet well, where mixing with a concentrated synthetic waste took place.

Sucrose ($C_{12}H_{22}O_{11}$) was employed as the carbon source and the growth-limiting nutrient for the prepared synthetic waste used for this investigation. The composition of the synthetic waste, relative to a sucrose concentration of 100 mg/l, is presented in Table I. The waste was prepared in quantities of twenty liters in concentrated form 47,310 mg/l). Approximately 35 ml of 16 N sulfuric acid was added to the feed during each preparation to repress biological growth and to assist the dissolution of the waste constituents. The concentrated feed therefore possessed a low pH, but when mixed with the large quantities of tap water, pH values for the flow entering the reactors were within proper ranges for biological growth to occur. The concentrated waste was stirred constantly to maintain a homogenous feed. Transfer and regulation of feed to the wet well was accomplished by a variable speed Cole-Parmer Masterflex Tubing Pump (Model WZ IR031). Desired organic concentrations could therefore be obtained by varying the amounts of waste transferred to the wet well.

Desired mixed feed concentrations were conveyed from the wet well to the primary reactor distribution system by means of a Teel Rotary -

Screw Pump (Model IP610). The pump was driven by a Dayton single speed motor (Model KS55JXBJB-913). Output of the pump was regulated by a valve-controlled recirculation system. The output could be adjusted so that it was equal to the flowrate through the rotameter. Hydraulic flow to the secondary reactor distribution system was accomplished by a pumping system identical to the one for the primary unit. All of the feed lines and the pumping systems were chlorinated frequently to prevent excessive microbial growth which could alter flowrates.

TABLE I

COMPOSITION OF THE SYNTHETIC WASTE FOR 100 mg/l SUCROSE AS THE GROWTH-LIMITING NUTRIENT

Constituent	Concentration
$C_{12}H_{22}O_{11}$ (sucrose)	100 mg/l
$(NH_4)_2SO_4$	25 mg/l
$MgSO_4 \cdot 7H_2O$	10 mg/l
K_2HPO_4	6 mg/l
$MnSO_4 \cdot H_2O$	1 mg/l
$CaCl_2$	0.75 mg/l
$FeCl_3 \cdot 6H_2O$	0.05 mg/l

The distribution of the synthetic wastewater across the 1.0 ft^2 of horizontal surface area of each reactor was achieved by the use of a reciprocating spray nozzle system. The oscillating motion of the spray nozzle was controlled by an electrically-motorized, chain-driven mechanism. Nozzle tip sizes were changed with corresponding changes in flow rate to maintain even and equal distribution of the wastewater across all of the contact surfaces which were provided.

As previously mentioned, the wastewater from the primary reactor was channeled into two intermediate clarifiers, and the secondary reactor effluent was channeled into a final clarifier. Effluent from the total system was discharged into the local sanitary sewer.

C. Experimental and Analytical Procedures

Seeding the reactor system with microorganisms was not required, since it had been used by previous investigators. Original seeding was accomplished with settled sewage from the primary clarifier of the Stillwater, Oklahoma, sewage treatment plant.

This laboratory investigation covered a time span of six and one-half months, and consisted of fifteen exprimental runs. The first five runs were concerned with the determination of the most accurate and practical methods of data collection. Once these techniques were established, actual data were recorded beginning on September 14, 1973, with a feed concentration of 174 mg/l and a hydraulic loading of 500 gpd/ft^2. Each experimental run was initiated with an acclimation period of at least four days for the purpose of obtaining steady state conditions. Once stead state conditions existed, sets of values were recorded for pH, COD, and biological solids concentrations for a minimum of three days. To ensure representative measurements of solids concentrations, daily samples were taken in triplicate. Each set of data was collected during an experimental run was averaged, and the resulting values were used in the evaluation of system performance.

To maintain results which would be valid for comparison, a sampling scheme was established and utilized throughout the investigation. The system influent temperature was monitored constantly with a thermometer which was placed in the mixed feed wet well. Samples for COD determination were collected in each reactor at the nozzle influent and immediately following the last cubic foot of plastic medium. A 100-ml sample was collected at each sampling location in a 250-ml Erlenmeyer flask. The effluent sample from each unit was collected with the aid of a PVC pipe which had the upper half of its wall removed and was attached to a small length of latex tubing. The sampler was moved back and forth horizontally to obtain representative samples. Determinations of pH at each sampling point using approximately 50 ml of sample were made with a Beckman Expandomatic SS-2 pH-meter. The remainder of each sample was filtered through a membrane filter (0.45 μ pore size, Millipore Filter Corp., Bedford, Mass.). The chemical oxygen demand (COD) of the filtrate was then determined in accordance with Standard Methods (24), using a 20-ml sample size. Samples which were anticipated to have low COD values were analyzed by using the dilute COD method as given in Standard Methods (24).

Biological solids measurements were taken for the purpose of determining the amount of solids produced by each reactor and by the total system for various applied organic loads. The total biological solids produced for a given time period consisted of the solids retained in the clarifiers plus the solids discharged in the final effluent. Intermediate clarifier no. 2 did not have a daily accumulation of solids as did the other clarifiers and, therefore, was not included in the solids measurements. The solids generated by the primary reactor were composed of those retained in the primary clarifier plus those which were discharged in the primary clarifier overflow. For convenience, solids determinations were made for a time period of twenty-four hours. This was accomplished by first cleaning the clarifiers while diverting the wastewater flow and then allowing the system to operate under normal conditions for the desired time limit.

The calculation of solids discharges per day in the effluents required a knowledge of the solids concentrations existing at all times. Preliminary studies were performed to determine if solids concentrations after an elapsed time of twenty-four hours were identical to those present at smaller elapsed times. It was found that concentrations could be assumed to remain constant.

The sampling scheme for biological solids was started by taking 50-ml effluent samples from the clarifier overflows. Hydraulic flow was then bypassed around the clarifiers. The influent and effluent to each clarifier was plugged, Psychoda flies and larvae were skimmed from the clarifier surfaces, and baffles were then cleaned of biological growth and removed. The clarifiers were then mechanically mixed with a motor-driven impeller assembly. Mixing was continued until the sludge had been broken into small particles and completely mixed conditions were obtained. Twenty five-ml samples were collected and then centrifuged prior to the determination of the solids concentrations present.

All biological solids concentrations were gravimetrically determined by filtering the sample volumes through membrane filters (0.45 μ pore size, Millipore Filter Corp.). The filters were previously placed in aluminum tare pans and dried for two hours at a temperature of $103^{o}C$. Immediately following cooling to room temperature, the pans were tared by using a Mettler Instrument Corporation balance (No. 1-910). Appropriate volumes of sample were filtered through the membrane filters. Filters with the corresponding pans were replaced in the drying oven for two hours at $103^{o}C$, cooled in the desiccator, and again weighed to find the weight of the solids present in each given sample.

D. Methods of Data Analysis

In this section, various design and operational control parameters which are commonly applied to activated sludge processes will be developed for application to biological fixed-bed reactors. The parameters under study have been described principally by Lawrence and McCarty (12), Metcalf and Eddy, Inc. (13), and Sherrard, Schroeder, and Lawrence (14).

Treatment efficiency or percent COD reduction can be calculated according to the following expression:

$$E = \frac{(C_o - C)100}{C_o} \qquad (2)$$

where

E = efficiency of COD removal, percent

C_o = influent substrate concentration, mg/l

C = effluent substrate concentration, mg/l

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

$$\frac{F}{M} = \frac{(C_oQ)8.34}{X_T} \tag{3}$$

where

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

F = $(C_oQ)8.34$ = substrate applied during a finite period of time, lb/day

C_o = influent substrate concentration, mg/l

Q = hydraulic flowrate, mgd

M = X_T = dry weight of active microbial mass in the filter volume, lbs

X_T can be further defined as

$$X_T = VAdX \tag{4}$$

where

V = volume of filter medium

A = surface area per cubic foot of filter medium

d = active film thickness of the biological layer

X = dry weight of microorganisms per unit volume

Food to microorganism ratio and following parameters assume that steady state conditions are maintained in the filter volume and that incoming substrate is distributed evenly over the filter medium surface area. It is also assumed that the reactor is a once-through system, i.e., there are no solids in the influent flow, and recycle is not employed. Additional similar equations are readily attainable if recycle is desired.

An additional parameter is one which is commonly named sludge age, mean cell residence time, or biological solids retention time (Θ_c):

$$\Theta_c = \frac{X_T}{(\Delta X/\Delta t)_T} \tag{5}$$

where

Θ_c = mean cell residence time, days

X_T = dry weight of active microbial mass in the filter volume, lbs

$(\Delta X/\Delta t)_T$ = total quantity of microbial mass wasted from the system each day, lbs per day

For a system composed of a fixed-bed reactor followed by a clarifier, Θ_c as defined in equation (5) becomes:

$$\Theta_c = \frac{X_T}{V_c X_c + (Q_{eff} X_{eff})8.34} \tag{6}$$

where

V_c = volume of daily accumulated biological solids in clarifier, liters

X_c = concentration of biological solids accumulated in clarifier per day, mg/l $X(2.205 \times 10^{-5})$

Q_{eff} = hydraulic flowrate of effluent, mgd

X_{eff} = concentration of biological solids in the system effluent, mg/l

Another useful parameter is the observed yield coefficient (Y_{obs}). It is defined as the mass of waste solids produced per unit time divided by the mass of substrate utilized by the system per unit time:

$$Y_{obs} = \frac{(\Delta X/\Delta t)_T}{(\Delta F_t/\Delta t)_T} \tag{7}$$

where

Y_{obs} = observed yield coefficient

ΔF_t = total quantity of substrate utilized, lbs

Y_{obs} can be operationally defined as:

$$Y_{obs} = \frac{V_c X_c + (Q_{eff} X_{eff}) 8.34}{(C_o - C)\ Q\ 8.34} \tag{8}$$

If solids production per unit time is represented by the term P_x, and equations (2) and (3) are used for substitution purposes, the following equation is obtained:

$$Y_{obs} = \frac{P_x}{F(E \times 10^{-2})} \tag{9}$$

This equation demonstrates that solids production per unit time can be determined from a knowledge of the observed yield coefficient, the applied organic load, and the system removal efficiency.

$$P_x = Y_{obs}(E \times 10^{-2})F \tag{10}$$

Specific utilization, (U), represents the mass of substrate utilized by the active microbial reactor mass during a finite time period. This parameter can be operationally defined as:

$$U = \frac{(\Delta F_T/\Delta t)_T}{X_T} \tag{11}$$

Specific utilization can be additionally defined in terms of previously described parameters:

$$U = \frac{(\Delta F_T/\Delta t)_T}{X_T} = \frac{1}{\frac{(\Delta X/\Delta t)_T}{(\Delta F_T/\Delta t)_T}} \cdot \frac{\frac{1}{X_T}}{(\Delta X/\Delta t)_T} = \frac{1}{Y_{obs}\Theta_c} \tag{12}$$

Also, since $(\Delta F_T/\Delta t)_T$ is equal to $F(EX10^{-2})$:

$$U = \frac{F(EX10^{-2})}{X_T} = \frac{F}{M}(EX10^{-2}) \tag{13}$$

Mean cell residence time is shown to be a function of specific utilization, yield constant, and maintenance energy coefficient with a plot of specific growth rate ($1/\Theta_c$) vs. specific utilization rate (U). The equation of the resulting line can be determined by using the least squares method of statistical analysis (25). The equation describes the following relationship:

$$\frac{1}{\Theta_c} = YU - b \tag{14}$$

where

b = maintenance energy coefficient, days $^{-1}$

Y = a yield constant, mass of microorganisms/mass of substrate utilized and the other terms are as previously defined

Several design and control parameters have been mathematically described in this section. Following chapters will present the use of these parameters to describe the performance of an experimental fixed-bed reactor. Relationships between these parameters will be presented graphically, and applications will be discussed.

CHAPTER IV

RESULTS

The results of this experimental investigation are presented in tabular form, and various relationships are shown graphically. All values which are tabulated for a specific experimental run represent an average of at least three consecutive days of sampling. Data were collected at hydraulic flow rates of 500, 1000, and 1250 gpd/ft^2. Total organic loadings were varied for each of the flow rates in such a manner as to provide an adequate spread of data for the purpose of graphical comparison. The results will be presented in various sections to better evaluate individual parameters.

A. Evaluation of COD Removal Performance

The performance characteristics of the primary filter, the secondary filter, and the total reactor system are presented in Tables II, III, and IV, respectively. Values are given for hydraulic flow rates, pH, COD, and performance characteristics. Figure 2 represents an evaluation of COD removal efficiency obtained with the use of both the primary reactor system and the overall reactor system. Results are not plotted for the secondary reactor, since its influent contained biological solids. The percent COD removal can be related to the applied total organic loading, as shown in Figure 2. Removal efficiency increases when the applied load is decreased. This relationship appears

TABLE II

DATA SUMMARY OF pH, COD, AND PERFORMANCE CHARACTERISTICS FOR THE PRIMARY FILTER VARIOUS FLOW RATES AND INFLUENT COD CONCENTRATIONS

	System Influent			Primary Filter Performance Characteristics					
Run No.	Flow Rate (gpd/ft^2)	COD Conc. (mg/l)	pH	COD Loading ($lbs/day/1000\ ft^3$)	Effluent COD Conc. (mg/l)	Effluent COD Discharged ($lbs/day/1000\ ft^3$)	Effluent pH	COD Load Removed ($lbs/day/1000\ ft^3$)	% COD Removed
1	500	174.0	7.2	181.4	89.3	93.1	7.4	88.3	48.7
2	500	150.2	7.3	156.6	55.6	58.0	7.4	98.6	63.0
3	500	255.4	7.7	266.2	136.6	142.4	6.8	123.8	46.5
4	1000	107.7	7.3	224.6	50.1	104.5	7.4	120.1	53.5
5	1000	78.2	7.5	163.0	39.0	81.3	7.6	81.7	50.1
6	1000	129.2	7.2	269.4	71.8	149.7	7.3	119.7	44.4
7	1250	101.2	7.5	263.8	60.4	157.4	7.6	106.4	40.3
8	1250	75.4	7.5	196.5	45.7	119.1	7.4	77.4	39.4
9	1250	58.7	7.4	153.0	45.4	118.3	7.5	34.7	22.7

TABLE III

DATA SUMMARY OF pH, COD, AND PERFORMANCE CHARACTERISTICS FOR THE SECONDARY FILTER VARIOUS FLOW RATES AND INFLUENT COD CONCENTRATIONS

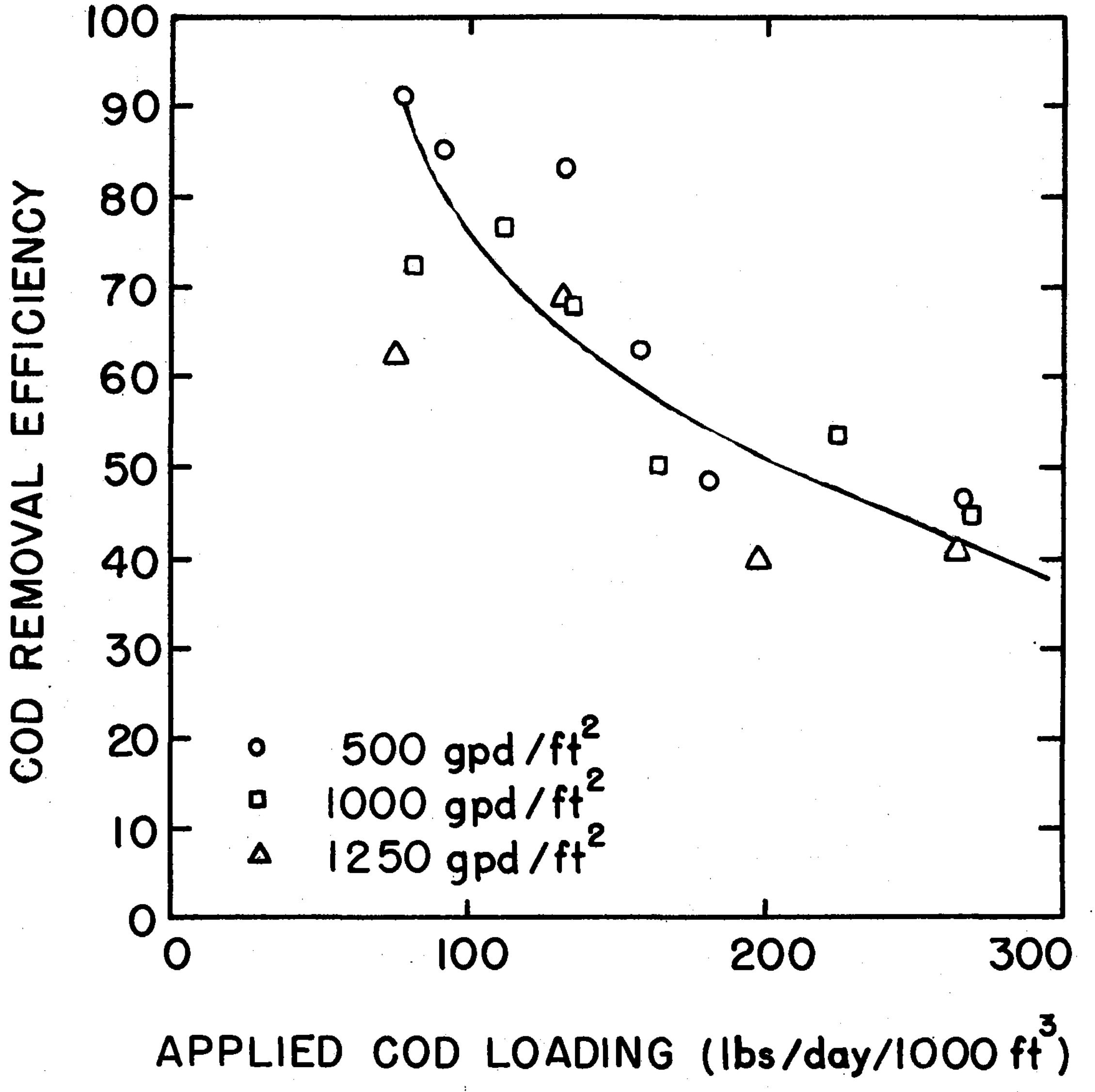
	Filter Influent			Secondary Filter Performance Characteristics					
Run No.	Flow Rate (gpd/ft^2)	COD Conc. (mg/l)	pH	COD Loading (lbs/day/1000 ft^3)	Effluent COD Conc. (mg/l)	Effluent COD Discharged (lbs/day/1000 ft^3)	Effluent pH	COD Load Removed (lbs/day/1000 ft^3)	% COD Removed
1	500	66.0	7.4	68.8	25.3	26.4	7.2	42.4	61.7
2	500	36.0	7.4	37.5	13.2	13.8	7.3	23.7	63.3
3	500	102.7	7.0	107.1	43.1	44.9	7.7	62.2	58.0
4	1000	37.9	7.5	79.0	25.1	52.3	7.3	26.7	33.8
5	1000	35.6	7.6	74.2	21.7	45.2	7.7	29.0	39.0
6	1000	62.3	7.1	129.9	41.6	86.7	7.2	43.2	33.2
7	1250	45.8	7.6	119.4	31.6	82.4	7.5	37.0	41.0
8	1250	35.5	7.4	92.5	24.5	63.9	7.5	28.6	31.0
9	1250	30.6	7.5	79.8	21.9	57.1	7.6	22.7	28.4

TABLE IV

DATA SUMMARY OF pH, COD, AND PERFORMANCE CHARACTERISTICS FOR THE TOTAL REACTOR SYSTEM VARIOUS FLOW RATES AND INFLUENT COD CONCENTRATIONS

System Influent				Total System Performance Characteristics								
								Including Clarification		Without Clarification		
Run No.	Flow Rate (gpd/ft^2)	COD Conc. (mg/l)	pH	COD Loading (lbs/day/1000 ft^3)	Effluent COD Conc. (mg/l)	Effluent COD Discharged (lbs/day/1000 ft^3)	Effluent pH	COD Load Removed (lbs/day/1000 ft^3)	% COD Removed	COD Load Removed (lbs/day/1000 ft^3)	% COD Removed	% COD Removed by Clarifiers
1	500	174.0	7.2	90.7	25.3	13.2	7.2	77.5	85.5	65.4	72.1	13.4
2	500	150.2	7.3	78.3	13.2	6.9	7.3	71.4	91.2	61.2	78.2	13.0
3	500	255.4	7.7	133.1	43.1	22.5	7.7	110.6	83.1	93.0	69.9	13.2
4	1000	107.7	7.3	112.3	25.1	26.2	7.3	86.1	76.7	73.4	65.4	11.3
5	1000	78.2	7.5	81.5	21.7	22.6	7.7	58.9	72.3	55.4	68.0	4.3
6	1000	129.2	7.2	134.7	41.6	43.4	7.2	91.3	67.8	81.4	60.4	7.4
7	1250	101.2	7.5	131.9	31.6	41.2	7.5	90.7	68.8	71.7	54.4	14.4
8	1250	75.4	7.5	98.3	24.5	31.9	7.5	66.4	67.5	53.0	53.9	13.6
9	1250	58.7	7.4	76.5	21.9	28.5	7.6	48.0	62.7	28.7	37.5	25.2

Figure 2. Percent COD Removal vs. COD Applied (lbs/day/1000 ft^3) at Various Flow Rates


100
90
80
70
60
50
40
30
20
10
0
COD REMOVAL EFFICIENCY
500 gpd/ft²
1000 gpd/ft²
1250 gpd/ft²
0
100
200
300
APPLIED COD LOADING (lbs/day/1000 ft³)

valid for all hydraulic flows which were utilized.

Figure 3 represents an additional method for the analysis of COD removal performance. Increased applied loads result in increased amounts of COD removal. It appears that the amount of COD removed may reach some saturation value at high applied COD loadings. Both Figures 2 and 3 establish the concept of total organic loading as a better means of system performance evaluation than either hydraulic flow or influent organic concentration.

B. Biological Solids Production

A summary of the production of biological solids is presented in Table V. The data enable solids production to be related to hydraulic loading, organic concentration, and total applied organic loading. Figures 4 and 5 are plots showing the relationship between influent COD concentration and the corresponding solids wastage for each flow rate. A family of curves develops both for the primary and the total reactor systems. Thus, it is seen that solids production is not constant for a particular influent organic concentration or hydraulic flow rate.

Biological solids production can be better predicted by the method shown in Figure 6. Solids wastage is directly related to the applied total organic loading in the fixed-bed reactor system. Increased organic loads produce greater amounts of solids, as shown by the straight-line relationship. This relationship seems to be valid regardless of the hydraulic loading. The production of solids can therefore not be attributed to a scouring action of the hydraulic flow in the range of this investigation. The total applied organic loading and its utilization in the synthesis of new microbial cells are the controlling factors.

Figure 3. COD Removed (lbs/day/1000 ft^3) vs. Applied COD Loading (lbs/day/1000 ft^3) at Various Flow Rates

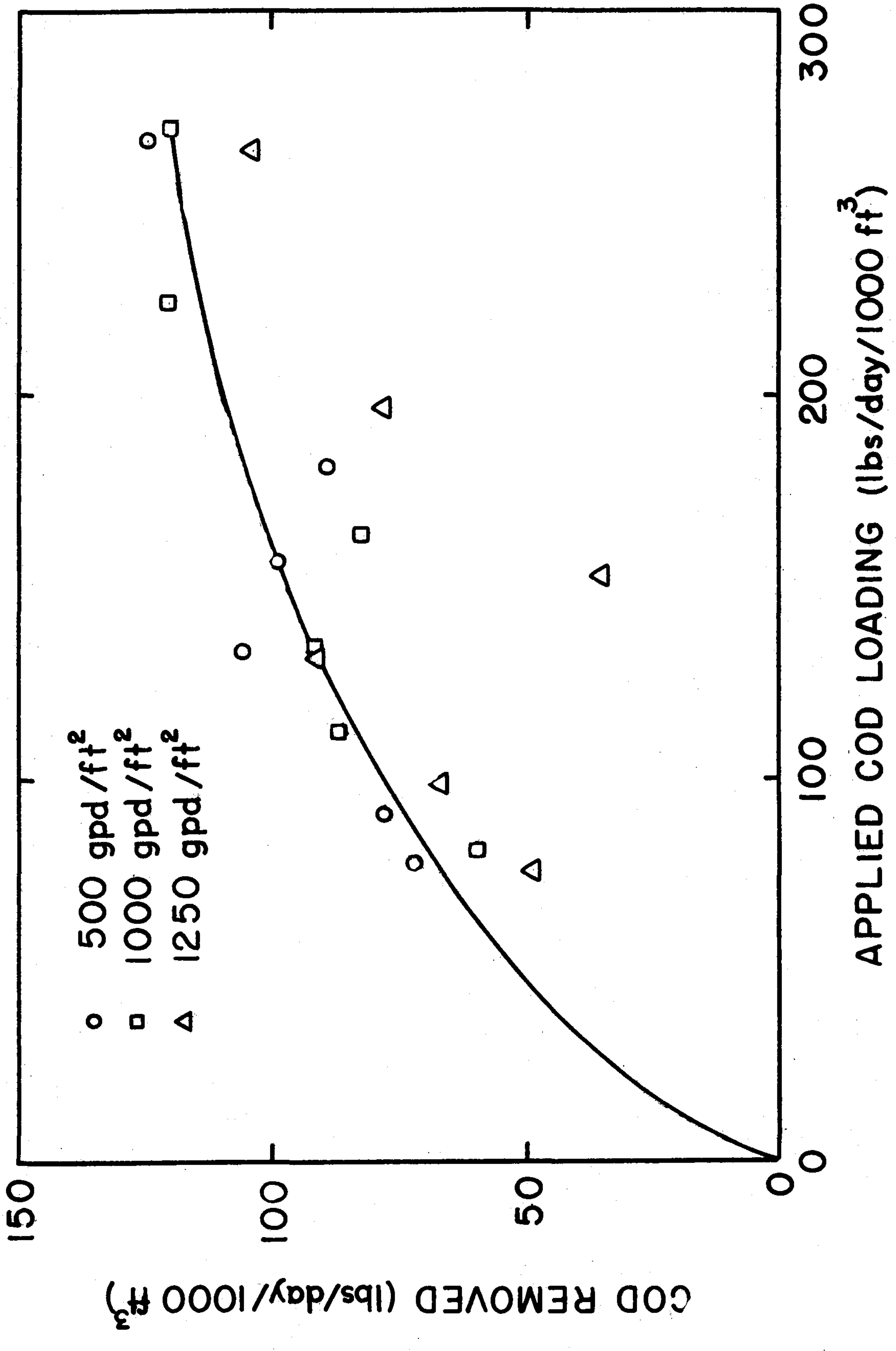
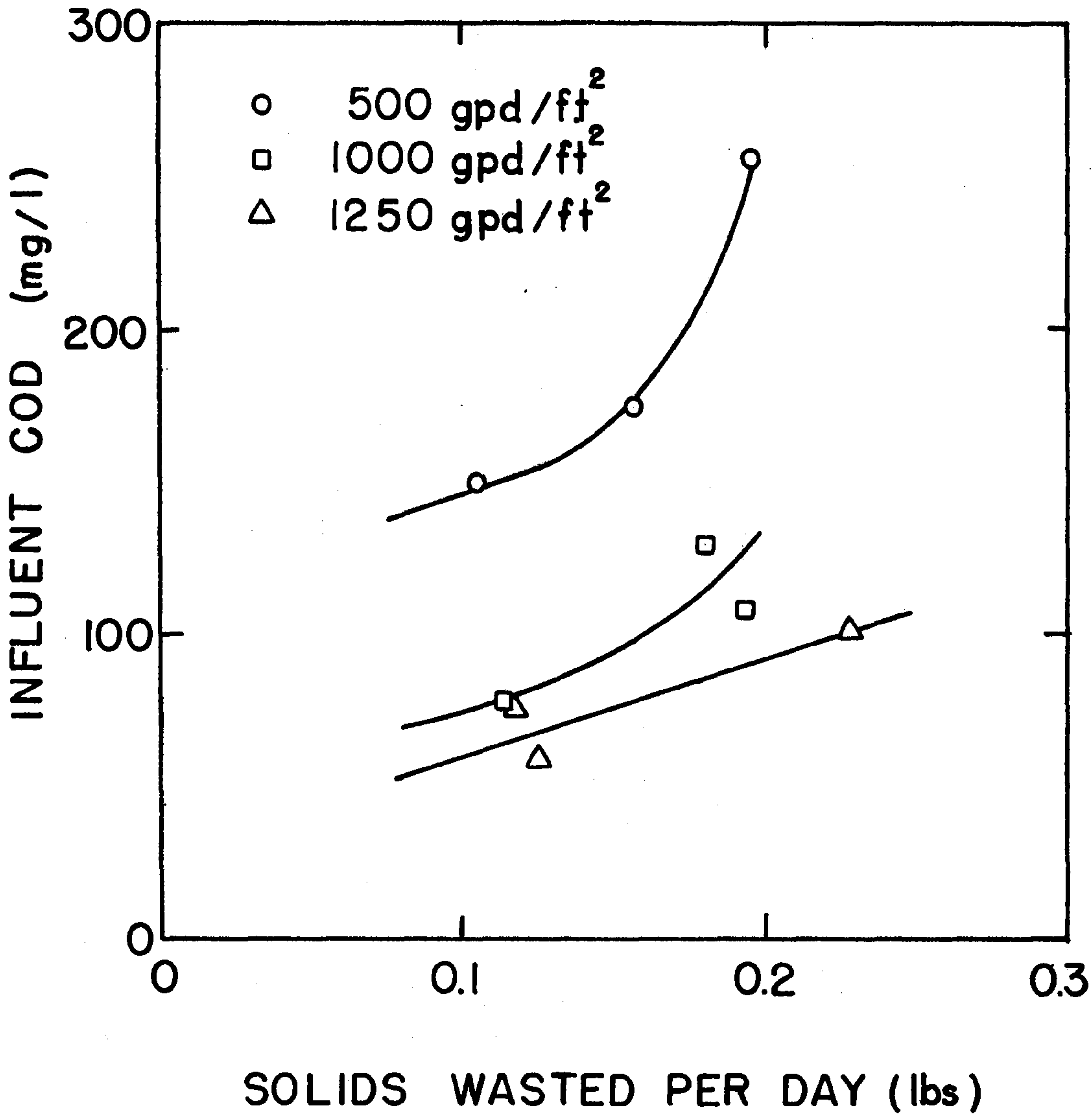

500 gpd/ft²
1000 gpd/ft²
1250 gpd/ft²
APPLIED COD LOADING (lbs/day/1000 ft³)
COD REMOVED (lbs/day/1000 ft³)
0
100
200
300
0
50
100
150

TABLE V

SUMMARY OF BIOLOGICAL SOLIDS PRODUCTION DATA FOR THE EXPERIMENTAL REACTOR SYSTEM
VARIOUS FLOW RATES AND ORGANIC LOADINGS
PRIMARY AND TOTAL SYSTEMS

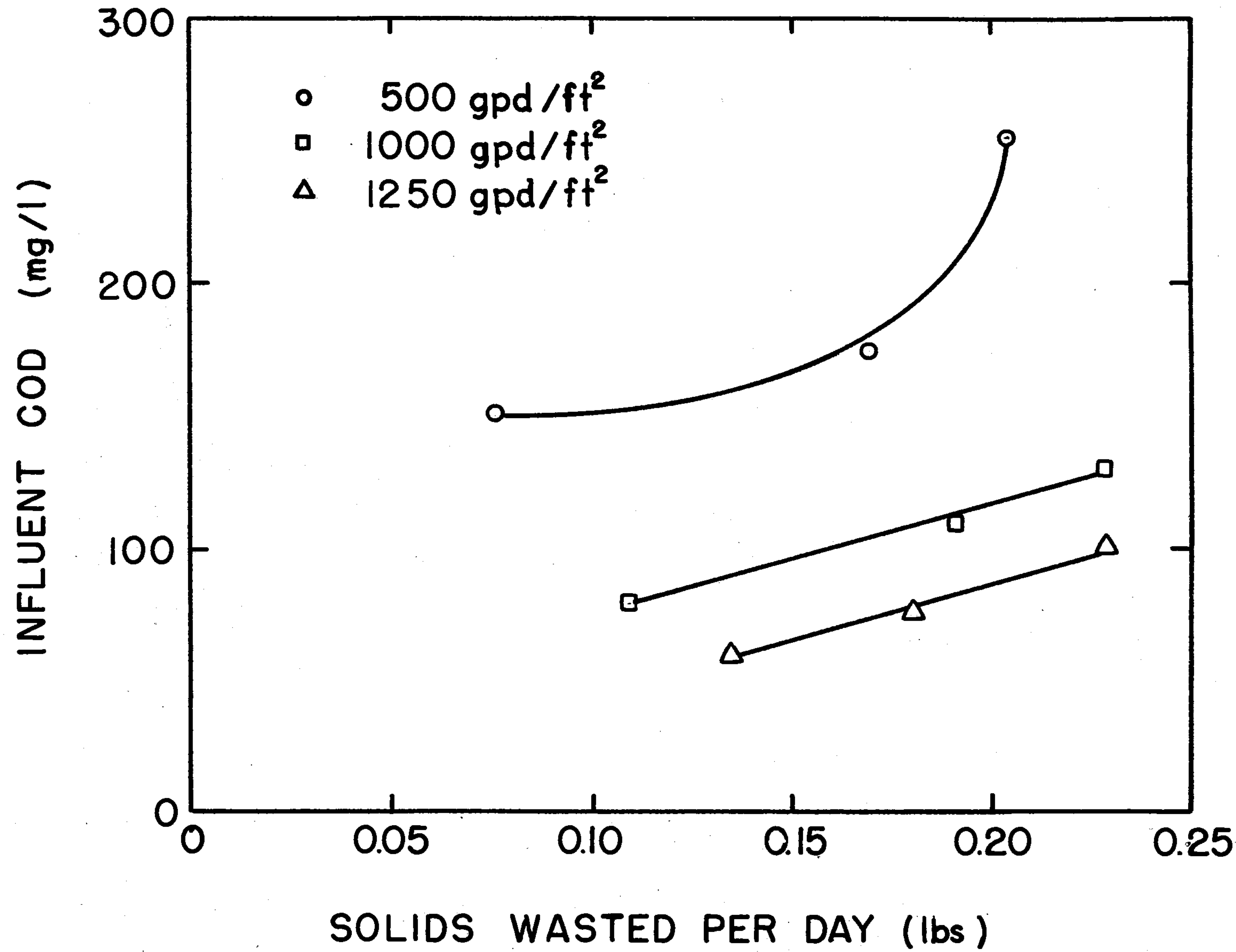
		Primary Reactor System					Total Reactor System				
Run No.	Flow Rate (gpd/ft)	Overflow Effluent (mg/l)	Overflow Effluent (lbs/day/ 1000 ft^2)	Primary Clarifier (mg/l)	System Solids (lbs/day)	System Solids (lbs/day/ 1000 ft^3)	Overflow Effluent (mg/l)	Overflow Effluent (lbs/day/ 1000 ft^3)	Final Clarifier (mg/l)	System Solids (lbs/day)	System Solids (lbs/day/ 1000 ft^3)
1	500	18.15	18.92	996.17	0.156	39.00	15.80	8.24	325.02	0.170	21.25
2	500	13.90	14.49	568.80	0.104	26.00	3.68	1.92	212.28	0.076	9.50
3	500	24.60	25.65	1153.50	0.196	49.00	16.25	8.47	592.05	0.204	25.50
4	1000	12.10	25.23	1126.05	0.192	48.00	7.50	7.82	518.25	0.191	23.88
5	1000	5.80	12.09	807.16	0.113	28.25	2.40	2.50	338.82	0.110	13.75
6	1000	9.43	19.66	1255.50	0.179	44.75	9.14	9.53	703.76	0.228	28.50
7	1250	5.78	15.05	1492.03	0.180	45.00	6.00	7.82	628.84	0.228	28.50
8	1250	4.20	10.95	912.20	0.117	29.25	6.50	8.47	539.20	0.180	22.50
9	1250	6.50	16.94	699.40	0.124	31.00	5.00	6.52	374.20	0.136	17.00

Figure 4. Influent COD Concentration vs. Solids Wasted per Day (lbs) for the Primary Reactor System at Various Flow Rates



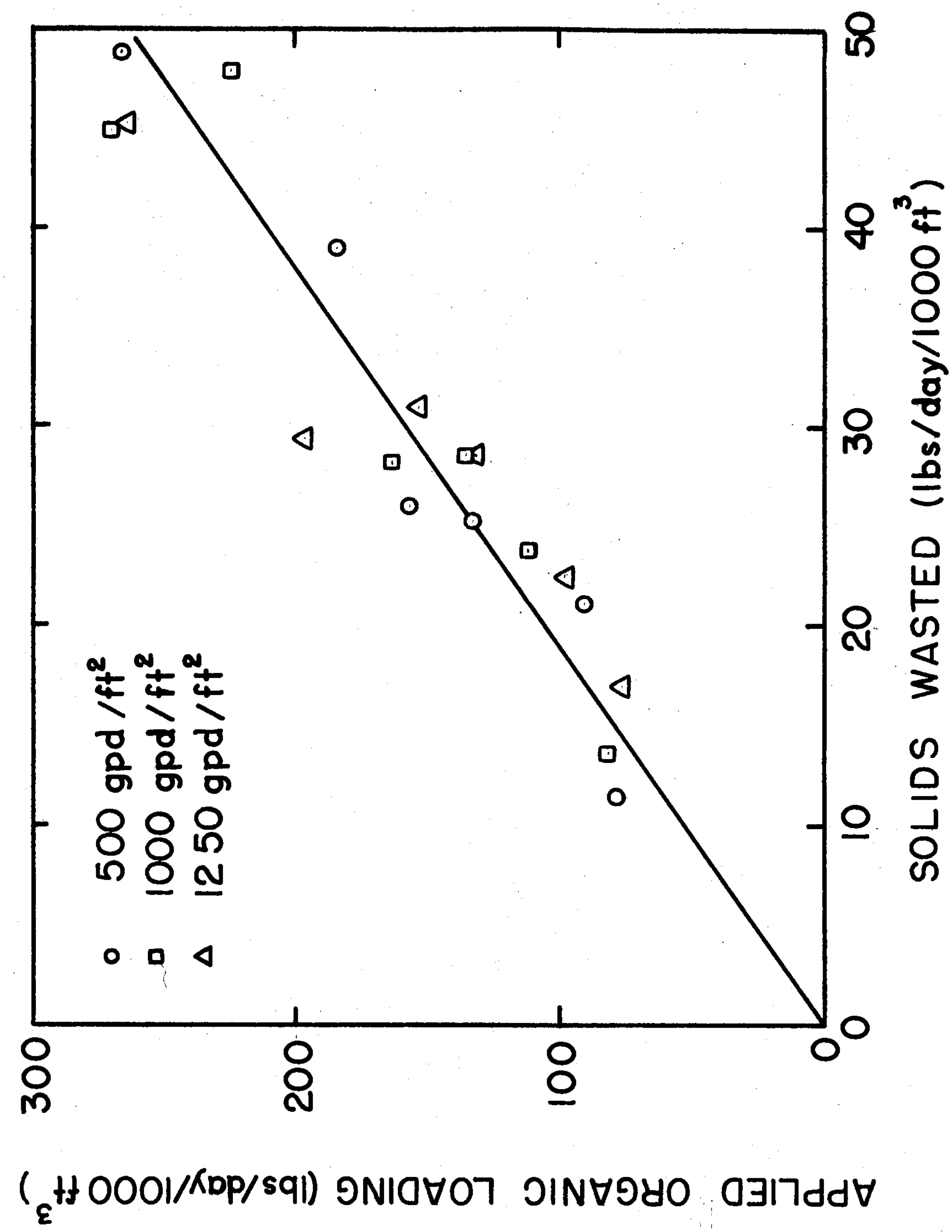
300
200
100
0
0
0.1
0.2
0.3
INFLUENT COD (mg/l)
SOLIDS WASTED PER DAY (lbs)
500 gpd/ft²
1000 gpd/ft²
1250 gpd/ft²

Figure 5. Influent COD Concentration vs. Solids Wasted per Day (lbs) for the Total Reactor System at Various Flow Rates



500 gpd/ft²
1000 gpd/ft²
1250 gpd/ft²
INFLUENT COD (mg/l)
300
200
100
0
0
0.05
0.10
0.15
0.20
0.25
SOLIDS WASTED PER DAY (lbs)

Figure 6. Applied Organic Loading (lbs/day/1000 ft^3) vs. Solids Wasted per Day (lbs/day/1000 ft^3) at Various Flow Rates



500 gpd / ft^2
1000 gpd / ft^2
1250 gpd / ft^2
SOLIDS WASTED (lbs/day/1000 ft^3)
APPLIED ORGANIC LOADING (lbs/day/1000 ft^3)
0
10
20
30
40
50
100
200
300

C. Application of Developed Parameters

The parameters for food to microorganism ratio and mean cell residence time can be applied to fixed-bed reactor systems with the methods of data analysis which were developed in Chapter III. The dry weight of active microbial mass in the reactor can be obtained with the aid of information which has been reported by Kornegay and Andrews (4). They found that the effective thickness of the biological layer was 70 μ, and that the dry weight of microorganisms per unit volume was 95 mg/cm^3 in a system which was operated at approximately the same temperature and with similar substrate as the system used in the present investigation. Using a specific surface area of 27 ft^2/ft^3 for Flocor plastic medium results in a dry weight of active microbial mass of 36.5 lbs/1000 ft^3 of medium. This value is used for the calculation of food to microorganism ratios and mean cell residence times.

Presented in Table VII are calculated food to microorganism ratios (F/M) and corresponding applied organic loadings for the experimental fixed-bed reactor system. The relationship between these values is shown in the plot of Figure 7. Higher COD loadings are equivalent to higher F/M values. Calculated values of mean cell residence time (θ_c) for various biological solids wastage rates are listed in Table VII. Figure 8 shows the relationship which exists between the two terms. As the amount of solids wasted decreases, the mean cell residence time increases. Figures 7 and 8 are valid for all hydraulic flow rates and can be applied to any volume of filter media.

Table VIII is a summary of parameter values which were obtained for the experimental system. The percent COD

TABLE VI

FOOD TO MICROORGANISM RATIO (F/M) AND CORRESPONDING APPLIED ORGANIC LOAD*

F/M	Applied Organic Load (lb/day/1000 ft^3)
1	36.5
2	73.0
3	109.5
4	146.0
5	182.5
6	219.0
7	255.0
8	292.0

*Applicable for all flow rates, primary and total reactor systems

TABLE VII

MEAN CELL RESIDENCE TIME (Θ_c) AND CORRESPONDING SOLIDS WASTAGE*

Θ_c (days)	Solids Wastage (lb/day/1000 ft^3)
1	36.50
2	18.25
3	12.17
4	9.12
5	7.30
6	6.08

*Applicable for all flow rates, primary and total reactor systems

Figure 7. Calculated Relationship of Food to Microorganism Ratio vs. Applied COD Loading (lbs/day/1000 ft^3) at Various Flow Rates

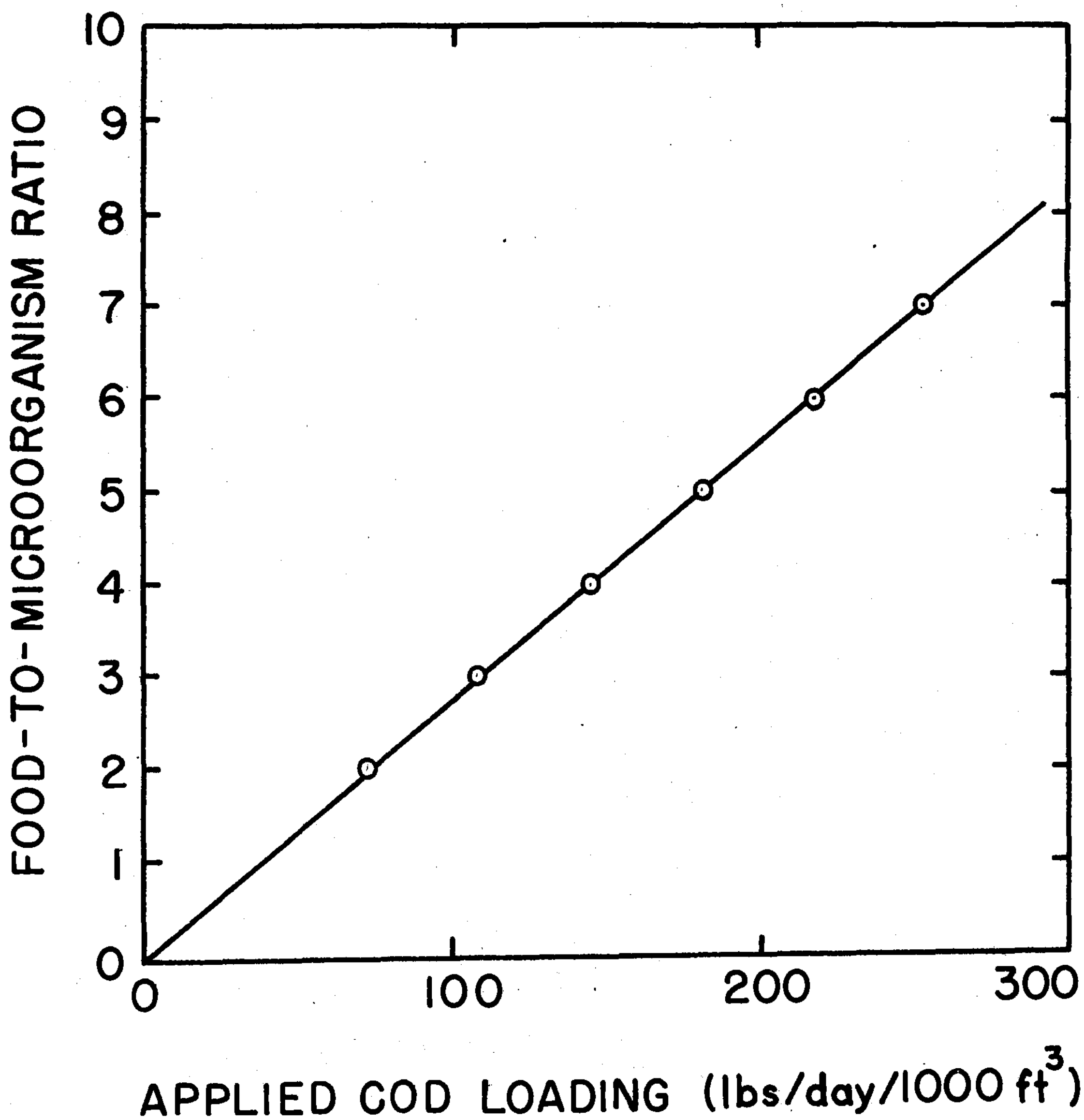
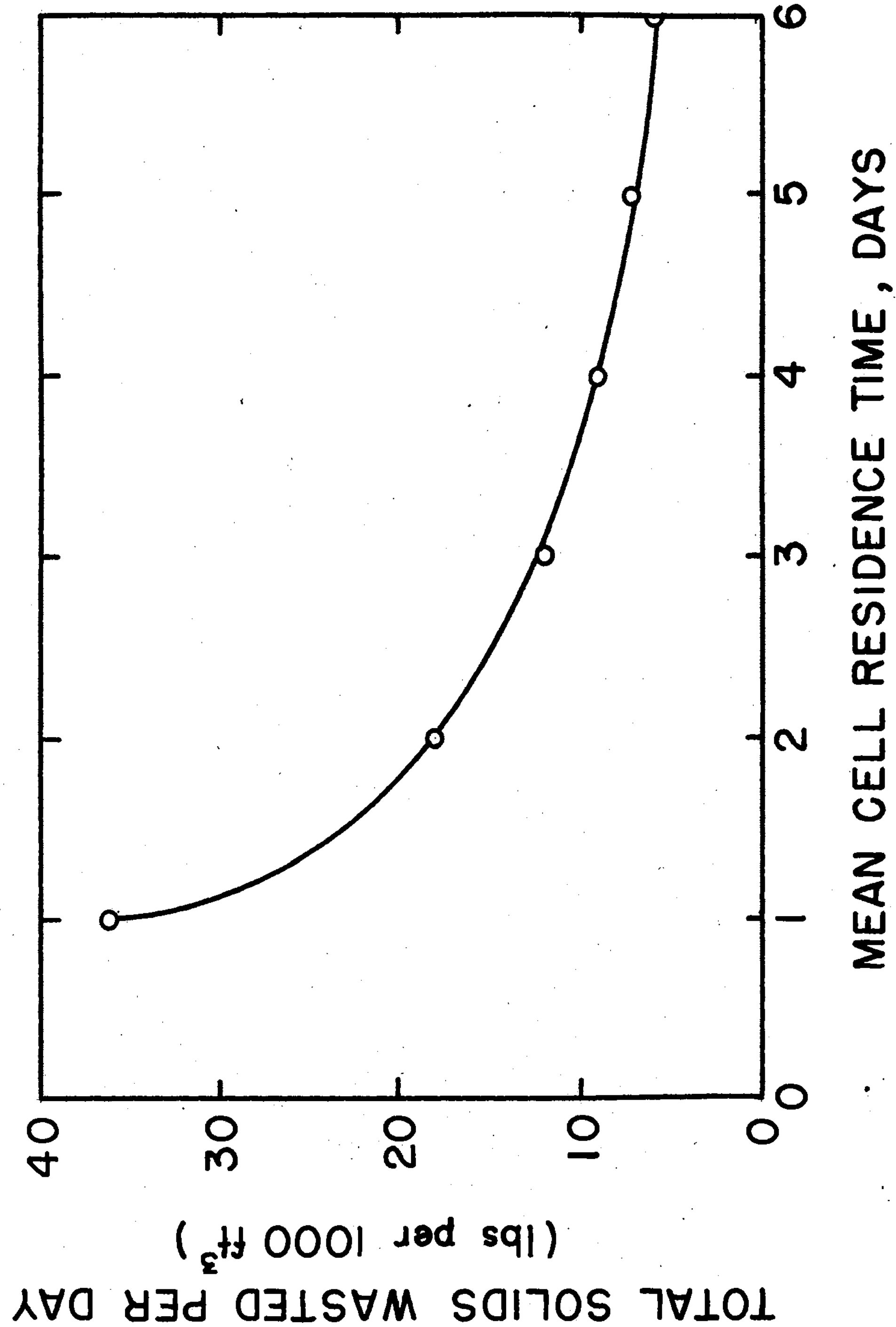

FOOD-TO-MICROORGANISM RATIO
10
9
8
7
6
5
4
3
2
1
0
0
100
200
300
APPLIED COD LOADING (lbs/day/1000 ft^3)

Figure 8. Calculated Relationship of Total Solids Wasted per Day (lbs per 1000 ft^3) vs. Mean Cell Residence Time at Various Flow Rates



TOTAL SOLIDS WASTED PER DAY
(lbs per 1000 ft^3)
0
10
20
30
40
MEAN CELL RESIDENCE TIME, DAYS
0
1
2
3
4
5
6

TABLE VIII

SUMMARY OF PARAMETER VALUES FOR THE EXPERIMENTAL REACTOR SYSTEM
VARIOUS FLOW RATES AND ORGANIC LOADINGS
PRIMARY AND TOTAL SYSTEMS

		Primary Reactor System				Total Reactor System			
Run No.	Flow Rate (gpd/ft^2)	COD Removal (%)	Θ_c (days)	U (days^{-1})	Y_{obs}	COD Removal (%)	Θ_c (days)	U (days^{-1})	Y_{obs}
1	500	48.6	0.94	4.97	0.44	85.4	1.72	2.12	0.27
2	500	62.9	1.41	4.29	0.26	91.1	3.82	1.96	0.13
3	500	46.5	0.75	7.29	0.39	83.1	1.43	3.04	0.23
4	1000	53.1	0.76	6.15	0.40	76.2	1.53	2.36	0.28
5	1000	50.1	1.29	4.47	0.35	72.2	2.67	1.61	0.23
6	1000	44.1	0.81	7.38	0.38	67.8	1.28	2.50	0.31
7	1250	40.1	0.81	7.22	0.42	68.8	1.28	2.48	0.31
8	1250	39.1	1.25	5.38	0.38	67.5	1.62	1.82	0.34
9	1250	22.1	1.18	4.19	0.90	62.6	2.15	1.31	0.35

reductions, food to microorganism ratio, mean cell residence time, observed yield coefficient, and specific utilization are tabulated for both the primary and total reactor systems. The remainder of this chapter will be devoted to the relationships which can be shown to exist between these parameters.

1. COD Removal Performance

The parameters of food to microorganism ratio and mean cell residence time can be related to the removal of COD. The relationship between percent COD removal and food to microorganism values is shown in Figure 9. A family of curves is produced in which efficiencies vary within a limited range for F/M values greater than three. At F/M values greater than five, the removal efficiency becomes a constant minimum value. Decreasing efficiencies which are present at the lower F/M values are probably a result of the residual COD in the wastewater which is not biodegradable in the experimental system.

Figure 10 represents the variation of percent COD removal as a function of mean cell residence time. In general, the efficiency increases when Θ_c is increased. However, at higher values of Θ_c, the efficiency decreases for the flow rates of 1000 and 1250 gpd/ft^2. At the lower values of Θ_c, the percent removal increases within a fairly constant range for all flow rates. The decreases in efficiency at the higher Θ_c values can probably be attributed to the residual COD of the wastewater as was suggested for Figure 9.

Figure 9. Percent COD Removal vs. Food to Microorganism Ratio at Various Flow Rates

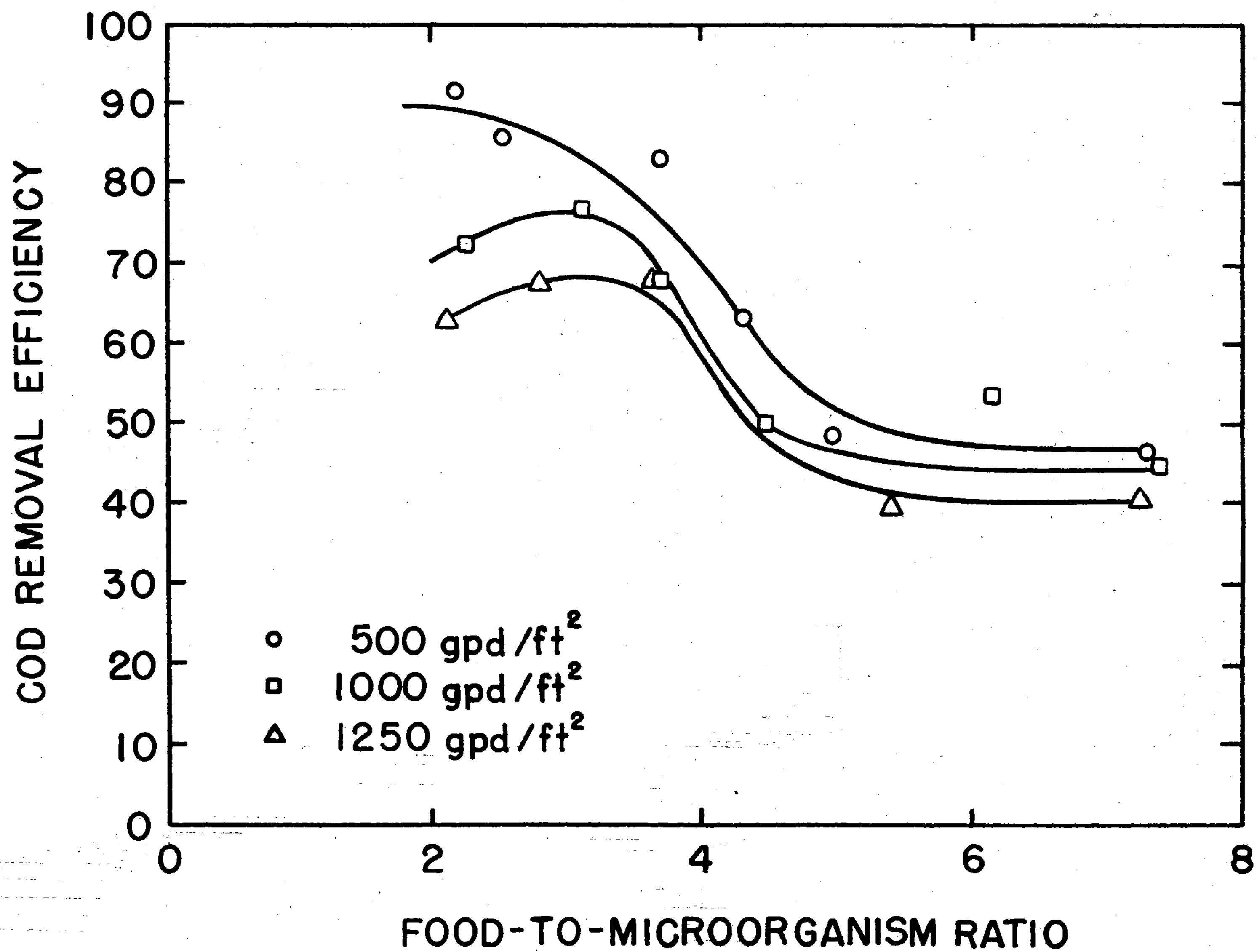
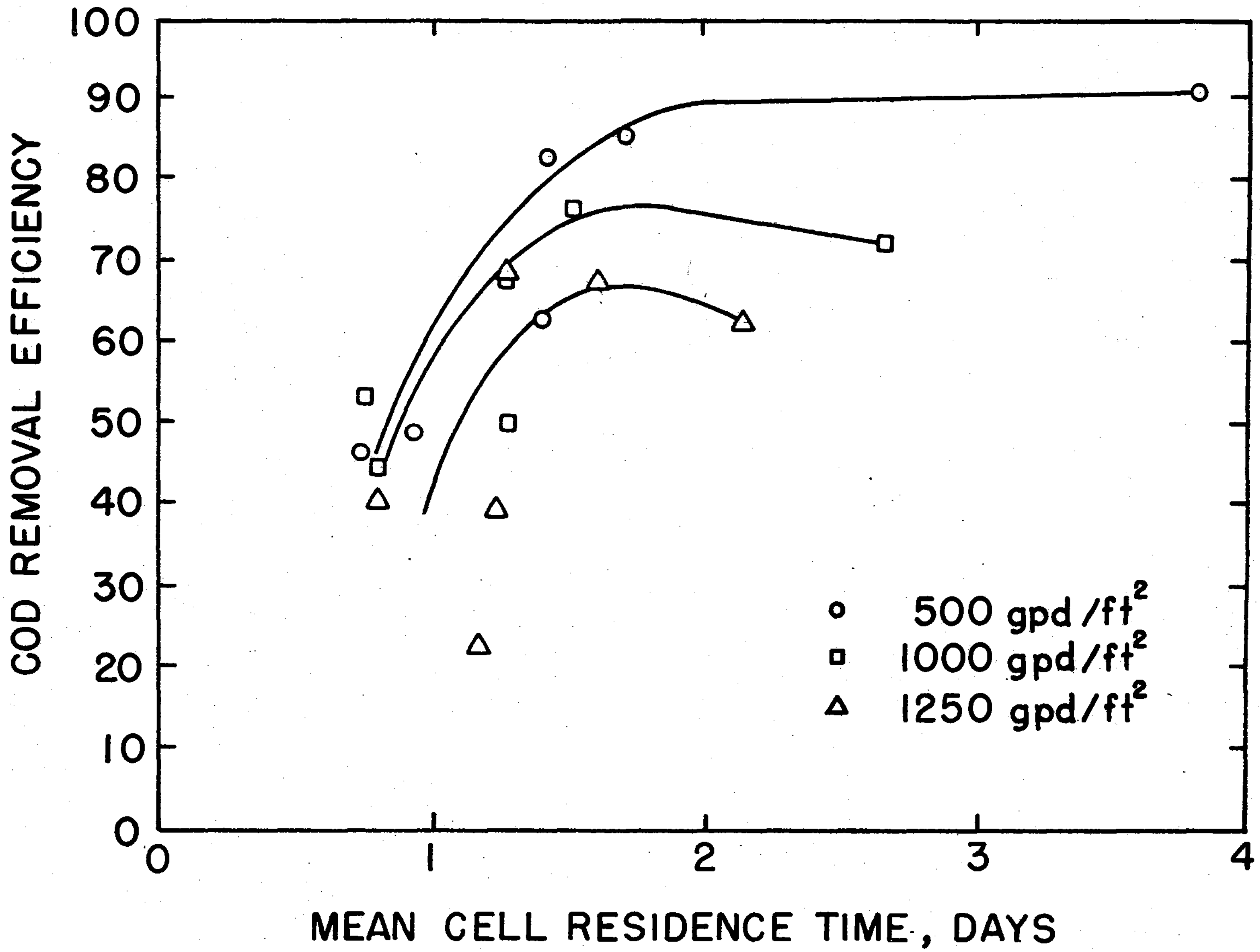

COD REMOVAL EFFICIENCY
FOOD-TO-MICROORGANISM RATIO
500 gpd/ft2
1000 gpd/ft2
1250 gpd/ft2
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8

Figure 10. COD Removal Efficiency vs. Mean Cell Residence Time at Various Flow Rates



COD REMOVAL EFFICIENCY
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
MEAN CELL RESIDENCE TIME, DAYS
500 gpd/ft²
1000 gpd/ft²
1250 gpd/ft²

2. Food to Microorganism Ratio vs. Mean Cell Residence Time

A valuable correlation for describing system performance is shown in Figure 11. When applied COD loading is related to Θ_c, a smooth curve is developed. This curve does not have a spread of data points which is dependent upon flow rate. High applied COD loads represent low Θ_c values, and low applied COD loads represent high Θ_c values. This curve enables values of Θ_c to be predicted when the applied COD loading for a given volume of filter media is known.

Applied COD loads can be converted to corresponding food to microorganism ratios. The use of Figure 7 facilitates the conversion to F/M because calculations do not have to be performed. The relationship between food to microorganism ratio and mean cell residence time is shown in Figure 12. A high F/M is equivalent to a low Θ_c, and a low F/M is equivalent to a high Θ_c. Mean cell residence times and food to microorganism ratios appear to reach some minimum limiting value for a particular system.

3. Effluent Evaluation

The quality of the reactor system effluent can be shown to be a function of mean cell residence time. The relationship between COD discharged in the effluent (lbs/day/1000 ft^3) and Θ_c is shown in Figure 13. The amount of COD discharged per day is directly related to Θ_c. At high values of Θ_c, less COD is discharged from the fixed-bed system. The effluent quality can also be evaluated in terms of the biological solids discharged, Figure 14. Less biological solids (lbs/day/1000 ft^3) are

Figure 11. COD Applied (lbs/day/1000 ft^3) vs. Mean Cell Residence Time at Various Flow Rates

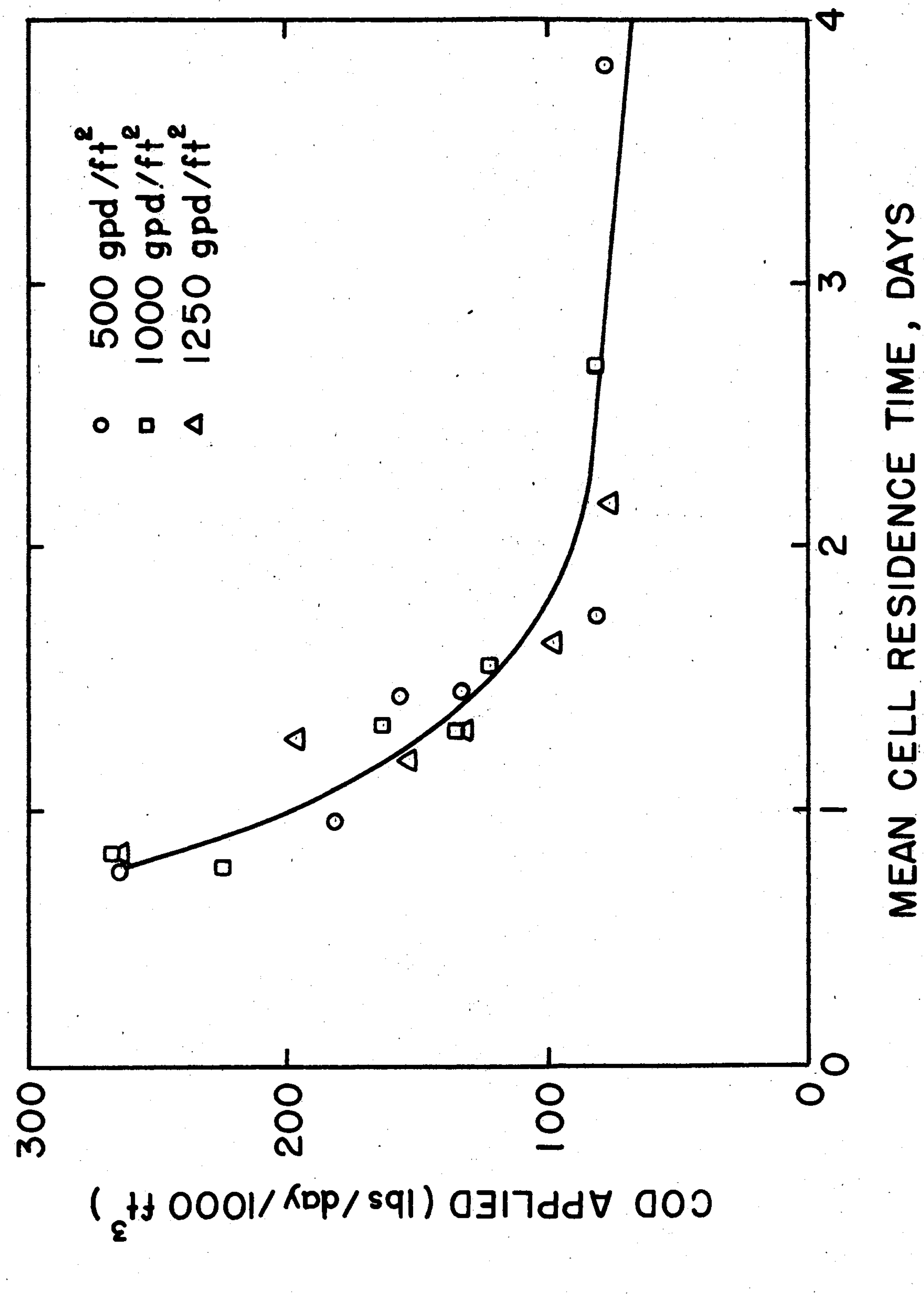

500 gpd/ft^2
1000 gpd/ft^2
1250 gpd/ft^2
MEAN CELL RESIDENCE TIME, DAYS
COD APPLIED (lbs/day/1000 ft^3)
0
1
2
3
4
100
200
300

Figure 12. Food to Microorganism Ratio vs. Mean Cell Residence Time at Various Flow Rates

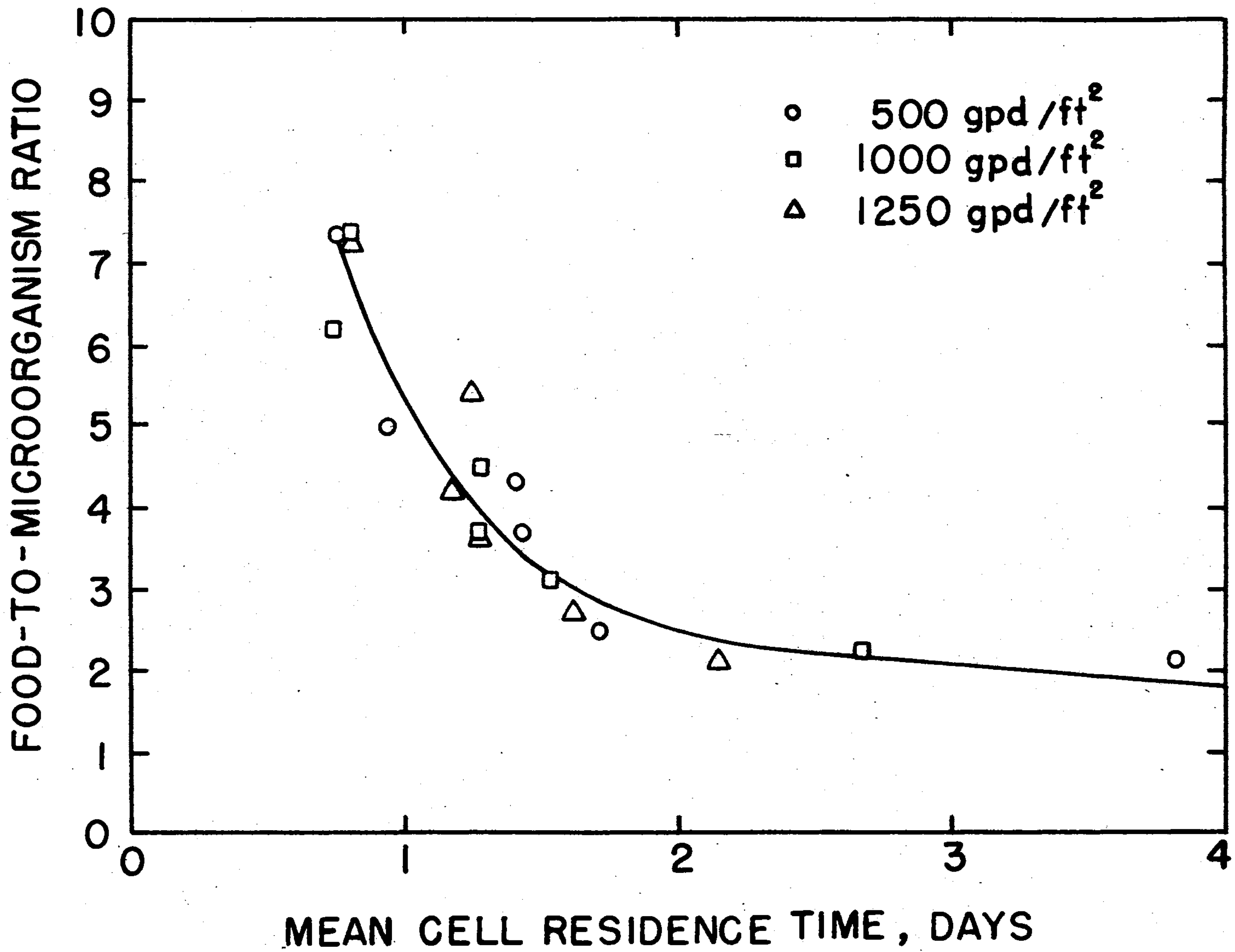

FOOD-TO-MICROORGANISM RATIO
MEAN CELL RESIDENCE TIME, DAYS
500 gpd/ft^2
1000 gpd/ft^2
1250 gpd/ft^2
0
1
2
3
4
5
6
7
8
9
10
0
1
2
3
4

Figure 13. Overflow Effluent COD (lbs/day/1000 ft^3) vs. Mean Cell Residence Time at Various Flow Rates

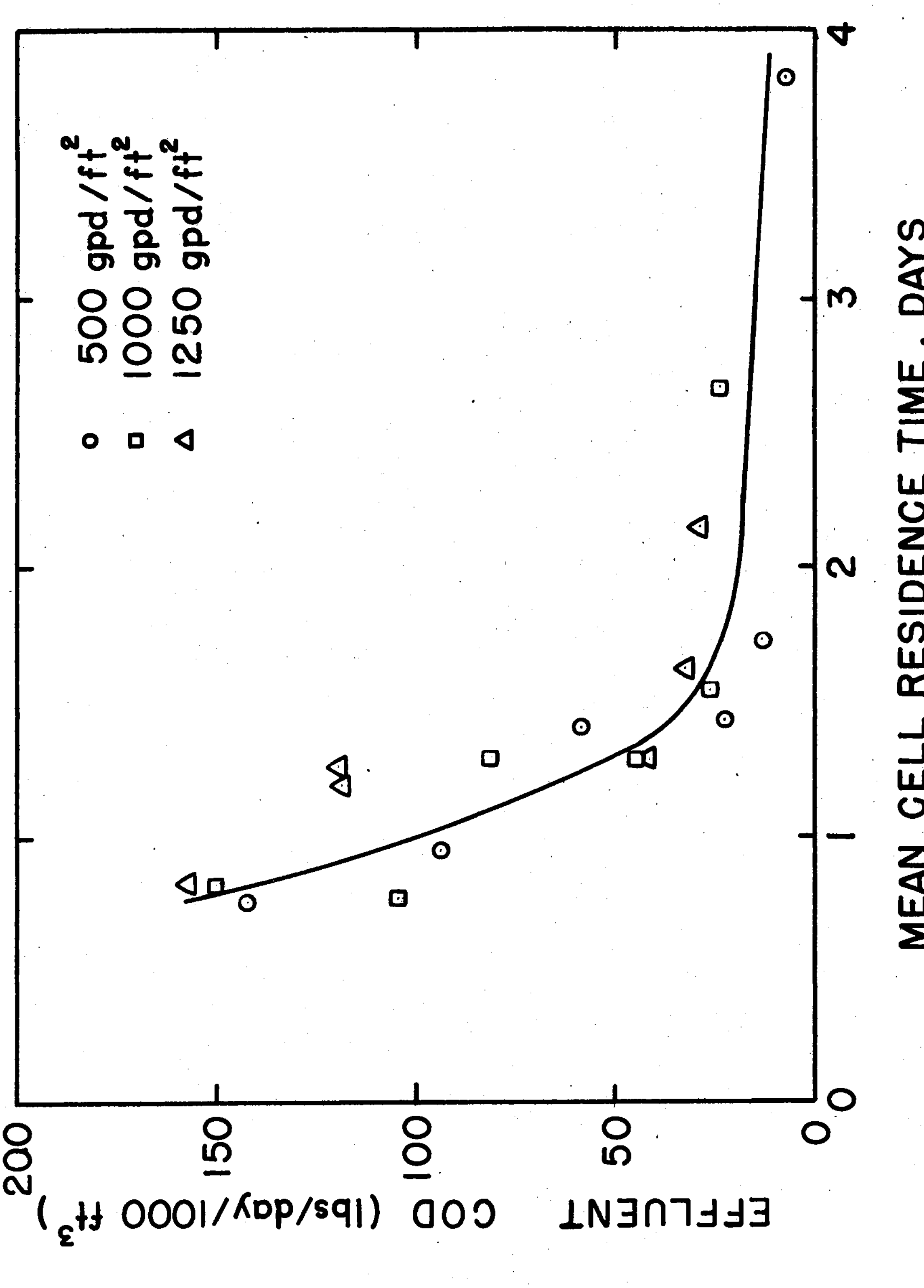
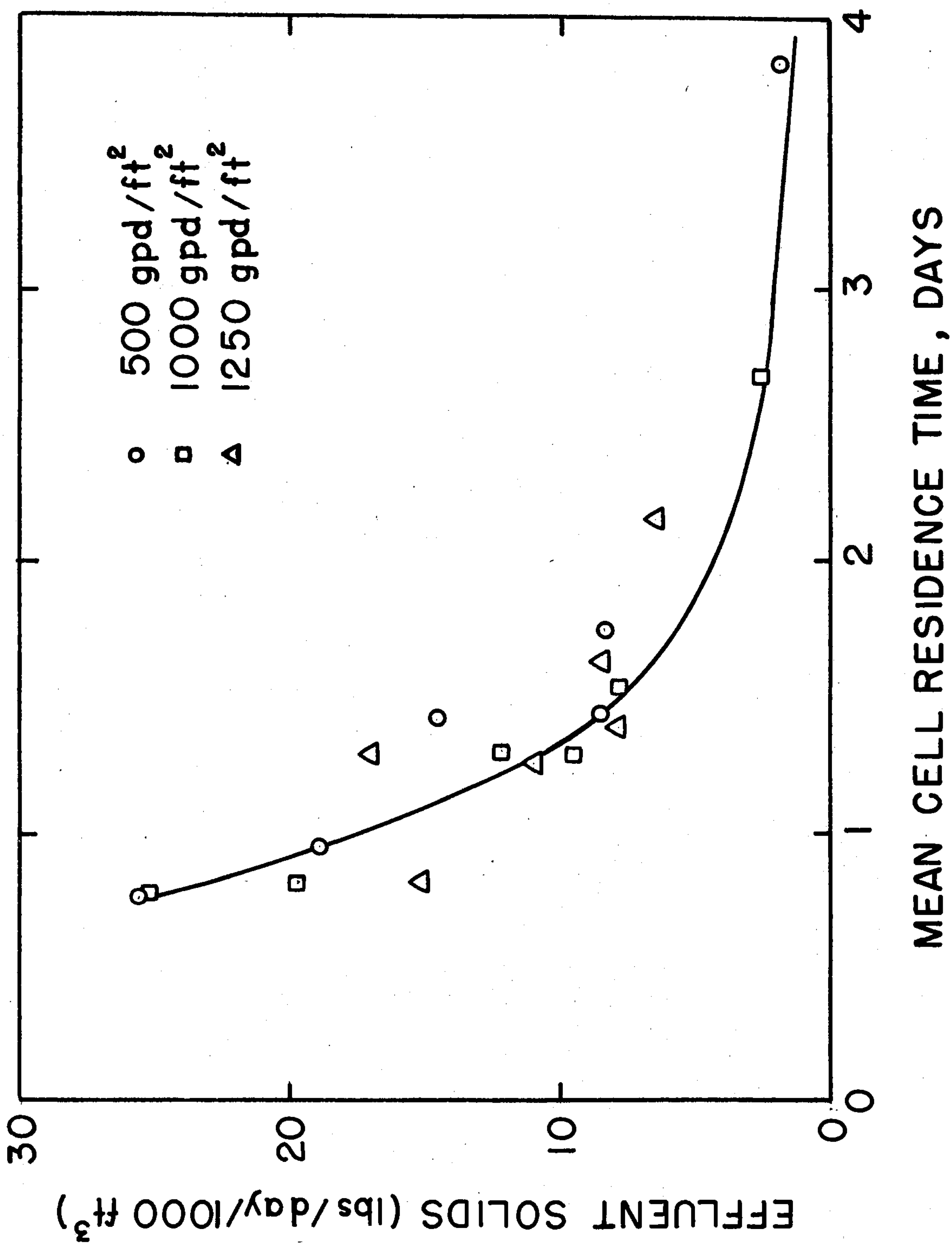

500 gpd/ft²
1000 gpd/ft²
1250 gpd/ft²
0
1
2
3
4
MEAN CELL RESIDENCE TIME, DAYS
0
50
100
150
200
EFFLUENT COD (lbs/day/1000 ft³)

Figure 14. Overflow Effluent Solids (lbs/day/1000 ft^3) vs. Mean Cell Residence Time at Various Flow Rates


500 gpd/ft²
1000 gpd/ft²
1250 gpd/ft²
MEAN CELL RESIDENCE TIME, DAYS
EFFLUENT SOLIDS (lbs/day/1000 ft³)
0
1
2
3
4
0
10
20
30

discharged as Θ_c is increased. Thus, a given quality of effluent can be obtained by operation at a given value of Θ_c. Mean cell residence times greater than two days produce the best effluent quality.

4. Yield Coefficients

The observed yield coefficient can be related to mean cell residence time. The variation of the observed yield coefficient as a function of Θ_c is shown in Figure 15. For the range of mean cell residence times in this investigation, Y_{obs} decreases as Θ_c increases. The observed yield coefficient varied between 0.13 and 0.44.

Mean cell residence time can also be related to constant yield by a plot of specific growth rate vs. specific utilization rate as shown in Figure 16. An equation of the form

$$\frac{1}{\Theta_c} = YU - b \tag{15}$$

is obtained. In this case, the linear relationship is described by the equation

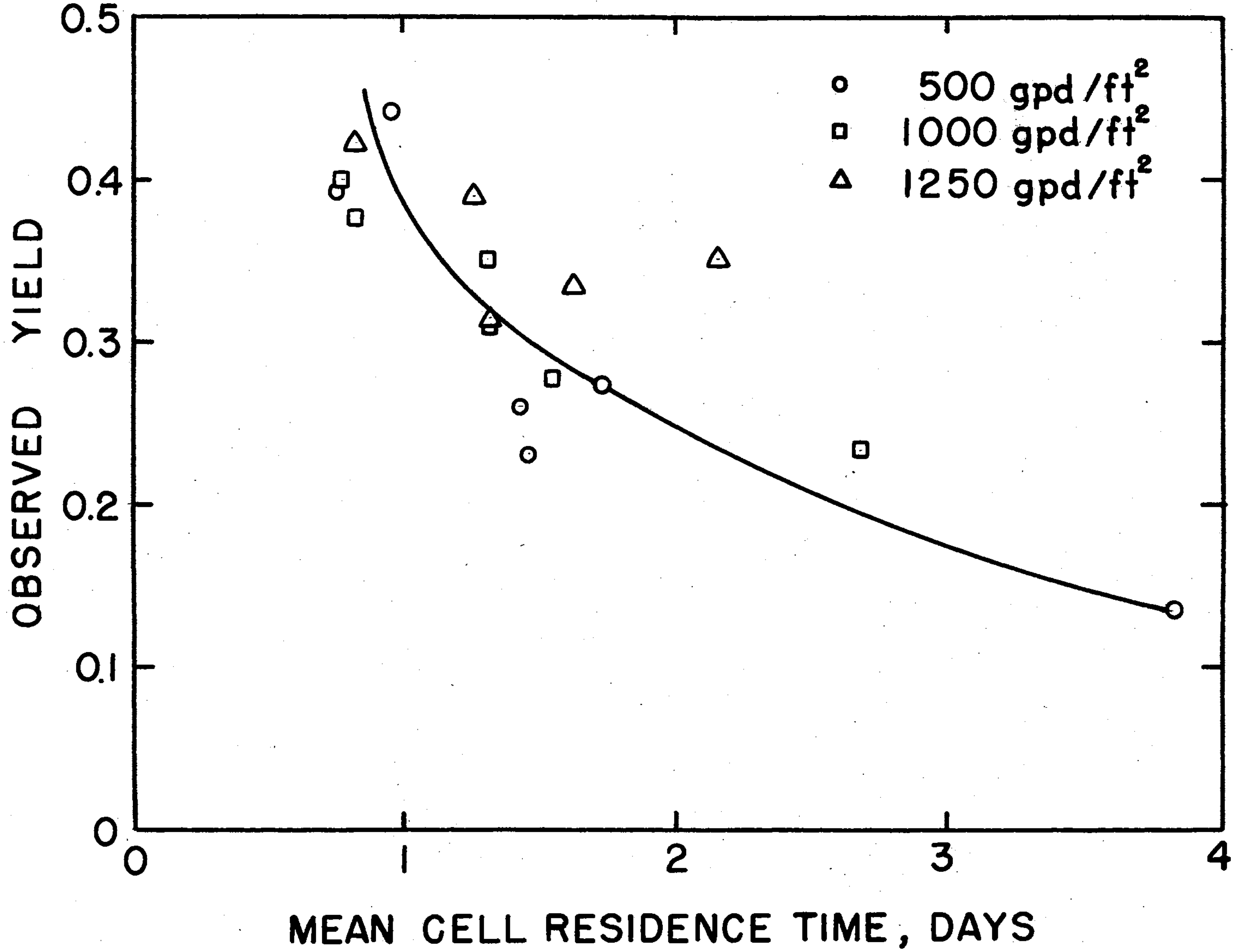
$$\frac{1}{\Theta_c} = 0.447U - 0.286 \tag{16}$$

The solution of equation (15) provides the values of $Y_{max} = 0.447$ and $b = 0.286$ days^{-1}. The correlation coefficient for equation (16) is 0.83.

5. Specific Utilization

The relationship between specific utilization and mean cell residence time is shown in Figure 17. Decreasing values for specific

Figure 15. Observed Yield vs. Mean Cell Residence Time at Various Flow Rates



OBSERVED YIELD
MEAN CELL RESIDENCE TIME, DAYS
500 gpd/ft²
1000 gpd/ft²
1250 gpd/ft²
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4

Figure 16. Specific Growth Rate vs. Specific Utilization at Various Flow Rates

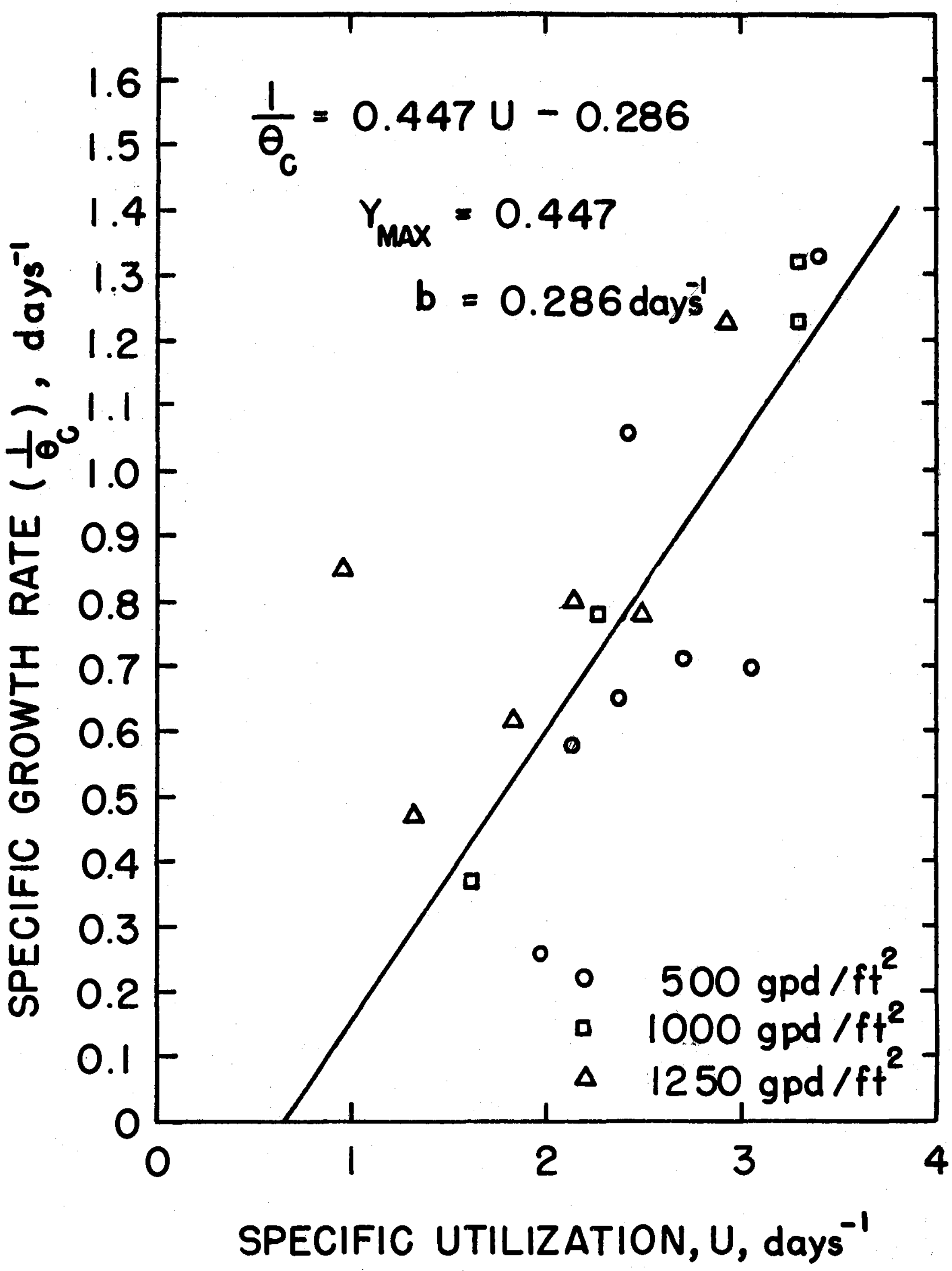
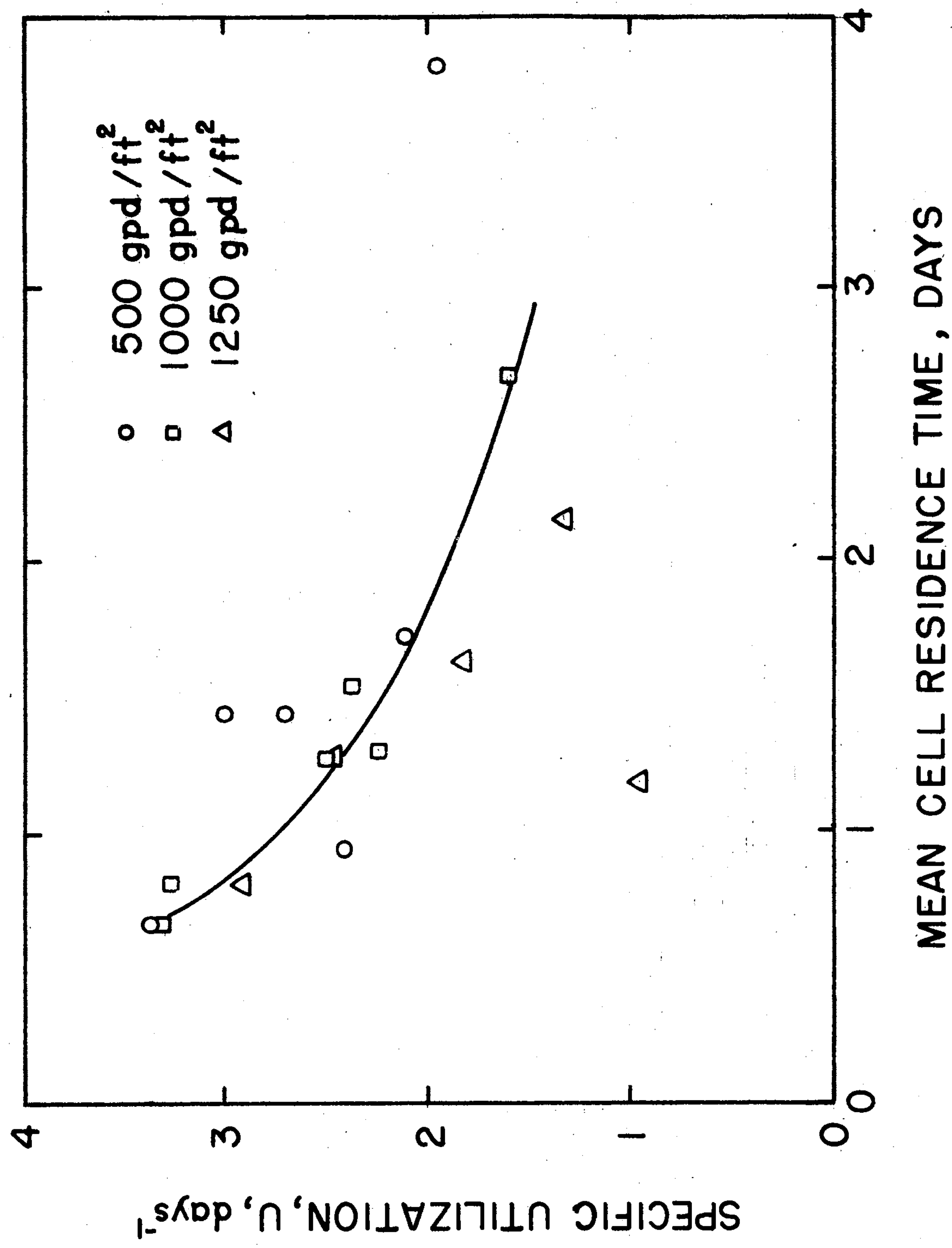

$\frac{1}{\theta_c} = 0.447\,U - 0.286$
$Y_{MAX} = 0.447$
$b = 0.286\ days^{-1}$
SPECIFIC GROWTH RATE ($\frac{1}{\theta_c}$), $days^{-1}$
SPECIFIC UTILIZATION, U, $days^{-1}$
500 gpd/ft^2
1000 gpd/ft^2
1250 gpd/ft^2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
0
1
2
3
4

Figure 17. Specific Utilization vs. Mean Cell Residence Time at Various Flow Rates



500 gpd/ft^2
1000 gpd/ft^2
1250 gpd/ft^2
MEAN CELL RESIDENCE TIME, DAYS
SPECIFIC UTILIZATION, U, days^{-1}
0
1
2
3
4

utilization are obtained as mean cell residence time is increased. The specific utilization appears to decrease rapidly at lower mean cell residence times, and approaches a minimum value at higher residence times. The range of specific utilization values for this investigation was 1.31 to 3.38.

After the main investigational phase of this research was concluded, a secondary study was undertaken. The purpose of the study was to determine if additional insight could be gained as to the existence of a minimum or critical value for food to microorganism ratio. A minimum value may exist based upon an analysis of Figure 12. Such a value would correspond to a system in which sufficient substrate would not be present to maintain the microbial system throughout the depth of filter media.

The experimental reactor system was operated at a hydraulic flow rate of 1250 gpd/ft^2 and an influent COD of 52.5 mg/l. This corresponded to a F/M value of 1.5 for the overall system. Measurements of COD removal revealed that COD was being removed only in the primary reactor. Subsequent testing indicated that the secondary reactor was functioning as a nitrifying system.

CHAPTER V

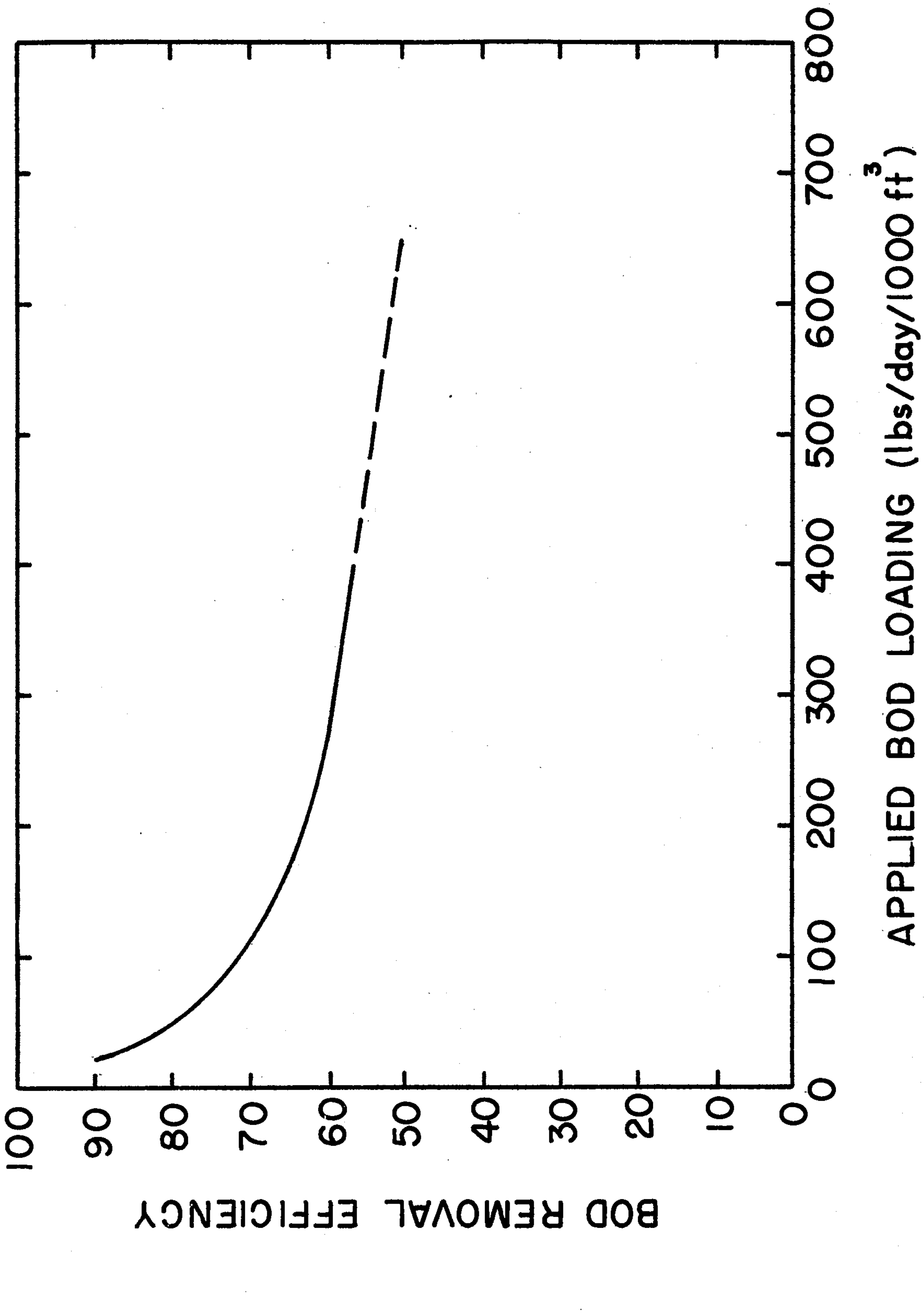
DISCUSSION

A. Design Applications

A primary purpose of this investigation was to propose valid methods of design applicable to fixed-bed biological reactors. These methods of analysis could be extended to any type of medium which has a known specific surface area. Organic removal which occurred in the experimental reactor resembles the results which have been published by several other researchers. The relationship between percent COD removed and COD applied (Figure 2) compares favorably to corresponding plots by the National Research Council (15) and the Ethyl Corporation (18)(26). Particularly important in the comparison to the experimental results is the graph from the Ethyl Corporation, because it was developed from systems using Flocor medium and employing carbohydrate substrates. The relationship which was found to exist between COD removed and COD applied (Figure 3) agrees with graphs presented by Cook and Kincannon (19). Existence of similar performance curves shows that the removal which occurred in the experimental reactor was not peculiar to this investigation.

Results of this investigation suggest several concepts which are of importance to design applications. Parameters which were developed and then applied to the experimental reactor have been shown to be valid in the description of system performance. Production of

Figure 18. BOD Removal Efficiency vs. Applied BOD Loading (lbs/day/1000 ft^3) With Strong Carbohydrate Feed Using Flocor Plastic Medium as Published by the Ethyl Corporation (26)


BOD REMOVAL EFFICIENCY
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
APPLIED BOD LOADING (lbs/day/1000 ft^3)

biological solids for the range of organic loadings used is directly related to the organic loading applied. Increased total organic loadings produce increased amounts of solids independently of the hydraulic flow rate. This increase in solids production with increased organic loadings compares with the findings of Richard and Kingsbury (20) and Chipperfield (21).

The relationship between food to microorganism ratios and mean cell residence times is described by a smooth curve for all hydraulic flows. A low F/M corresponds to a high Θ_c, and a high F/M corresponds to a low Θ_c. This relationship results from low solids wastage at low applied organic loadings, and high solids wastage at high applied organic loadings.

The quality of the system effluent is a function of mean cell residence time. The quality in terms of COD and quantity of biological solids discharged is shown to improve with increasing mean cell residence time values for the particular waste used in this investigation. Thus, effluent quality can be predicted for any given value of mean cell residence time. Mean cell residence times can be predicted from a knowledge of the applied organic loading to the system.

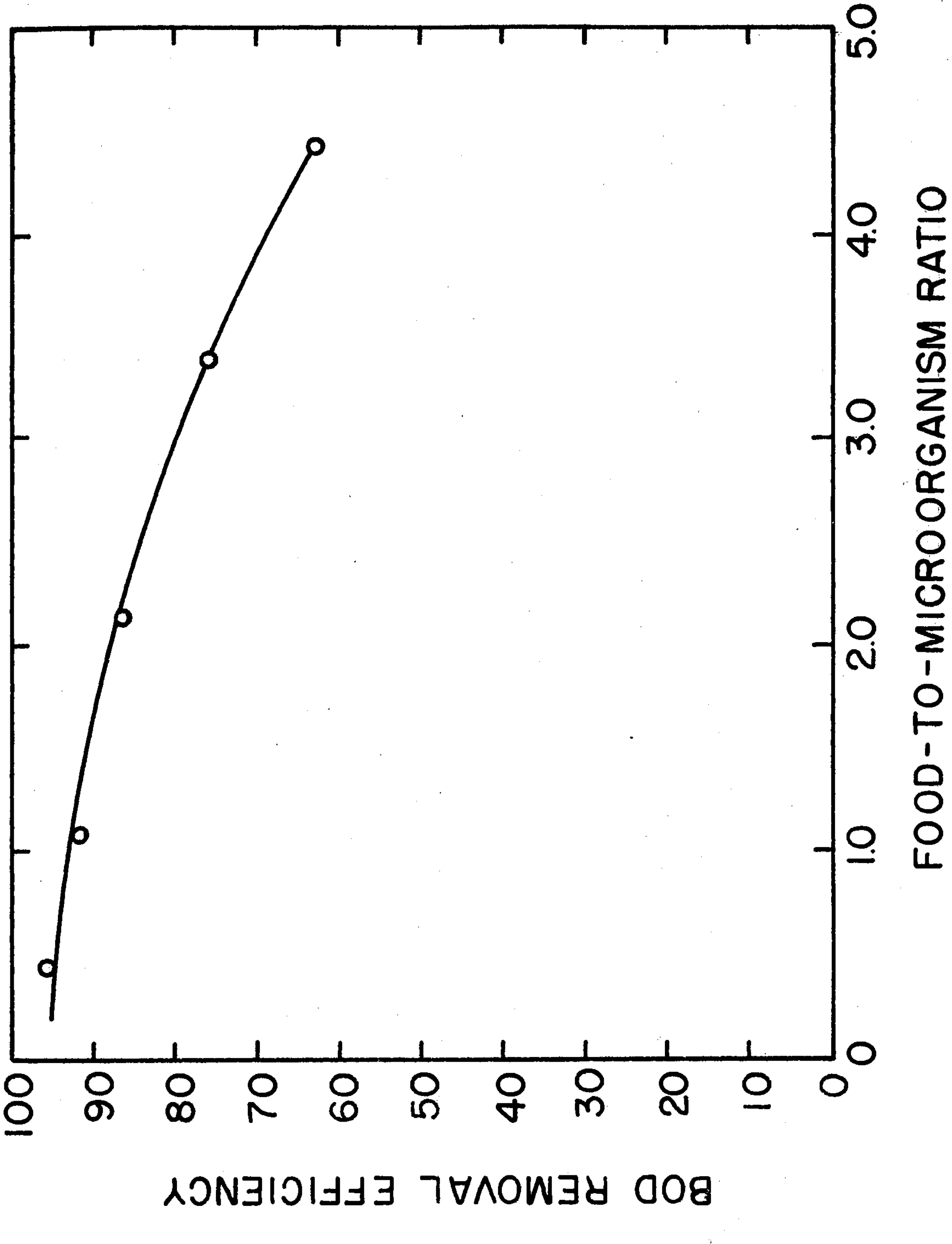
Values obtained for observed yield coefficient and specific utilization are dependent upon the specific growth rate of the microorganisms in the reactor system. This is true, since specific growth rate is mathematically equal to the reciprocal of mean cell residence time. The observed yield coefficient varied between 0.13 and 0.44 in this investigation. This compares to conversion ratios of twenty to thirty percent for carbohydrate wastes, as reported by Askew (22). Chipperfield (21) observed that in actual practice, twenty to forty percent of the BOD is converted to biological solids for various substrates. Bruce and Merkens (23) found an average yield value of 0.485 from studies using domestic sewage. Thus, since all of the yield values were obtained with Flocor medium, values can be expected to vary depending upon the substrate utilized, the mean cell residence time of operation, and the reporting of the yield as being observed or constant.

A pilot plant study by Brown and Caldwell Consulting Engineers (27) may be used to show that the parameters which were developed for fixed-bed systems may be applicable to systems other than the experimental system of this investigation. Reported values of organic loadings and corresponding BOD removals can be used to plot the relationship between percent BOD removed and food to microorganism ratio (Figure 19). The resulting curve is very similar to the curves shown in Figure 9 for the experimental system. Dow Surfpac plastic medium, which has the same specific surface area as Flocor plastic medium (27 ft^2/ft^3), was used in the pilot plant study. The waste being treated was principally from food canning industries.

Fixed-bed reactors are normally classified as being high-rate or low-rate, depending upon the values of hydraulic and organic loadings. Typical ranges of loadings as determined from values listed by Metcalf and Eddy, Inc. (13) for low-rate reactors are: hydraulic loadings of 23-92 gpd/ft^2 and organic loadings of 7-23 lb $BOD_5/1000\ ft^3/day$. Values determined for high-rate reactors are as follows: hydraulic loadings of 230-920 gpd/ft^2 and organic loadings of 23-115 lb $BOD_5/1000\ ft^3/day$.

This investigation was not operated in the range of loadings which could conventionally be classified as low rate. It was, however, operated in or above the range of accepted loadings classified as high-rate.

Figure 19. Percent BOD Removed vs. Food to Microorganism Ratio From Stockton, California, Pilot Plant Study by Brown and Caldwell, Consulting Engineers (27) Using Dow Surfpac Plastic Medium



BOD REMOVAL EFFICIENCY
100
90
80
70
60
50
40
30
20
10
0
FOOD-TO-MICROORGANISM RATIO
0
1.0
2.0
3.0
4.0
5.0

Using a representative high-rate organic loading of 100 lb COD/1000 ft^3 /day, a removal efficiency of 79.5 percent was achieved. This resulted in a wastage of biological solids of 19 lb/1000 ft^3/day and a corresponding mean cell residence time of 1.68 days.

For Flocor plastic medium, a minimum wetting rate of 864 gpd/ft^2 is recommended by the manufacturer. This minimum hydraulic flow rate approaches the maximum hydraulic loading conventionally used for high-rate systems and suggests that the classifications of high-rate and low-rate systems necessitate modification to be applicable to plastic media reactors. A better means of classification would employ the concept of food to microorganism ratio. This was suggested by Kincannon and Sherrard (3) and is upheld in this investigation.

Past descriptions of the loadings applied to fixed-bed reactors have not actually been valid for comparison between fixed-bed reactors or for comparison to activated sludge processes. As observed by Ridenour (1), fixed-bed loadings are normally given in terms of pounds BOD per day per 1000 cubic feet of filter, gallons per acre per day, and gallons per acre-foot per day. Actual surface area of media available for biological activity and the quantity of microorganisms which is present are neglected. These additional reasons also indicate that the loading applied to a fixed-bed reactor should be described by the use of a food to microorganism ratio.

The parameters which have been developed in this investigation and the relationships which have been shown to exist between them can be used in the design of full-scale treatment facilities. A suggested design procedure resulting from the findings of this investigation is outlined as follows:

1. The desired amount of organics to be removed should be expressed as a percentage of the applied organic loading (Figure 2). Applied organic loading is in terms of 1000 cu ft of filter medium and can therefore be used to determine the volume of filter medium which is required.

2. Organic loading can be converted to a corresponding food to microorganism ratio with the aid of Figure 7.

3. Food to microorganism ratio can be related to mean cell residence time by the use of Figure 12. The design mean cell residence time can thereby be determined.

4. Design mean cell residence time can be used to predict the total amount of solids wasted from the system each day (Figure 8).

5. Quality of the system effluent can be predicted in regard to COD and biological solids which are discharged per day. This is accomplished by the use of Figures 12 and 13.

The design method which has been outlined can be applied to other types of media and to different substrates. Relationships between the design parameters can be expected to be similar for different systems, but values of the individual parameters will probably vary. Therefore, pilot plant studies should be undertaken for specific treatment situations. Use of the parameters which have been developed in this study will enable system performances for different fixed-bed systems to be compared on a more equitable basis.

B. Comparison With Activated Sludge Parameters

Parameters which have been developed can be used for comparison purposes with activated sludge parameters. These parameters form the basis for equitable methods of comparison. Kincannon and Sherrard (3) have suggested that food to microorganism ratios and mean cell residence time values can be used in the comparison of the two processes. This study has supported their conclusions, and additional parameters have been shown to also be applicable.

The relationships which have been observed to exist between parameters of the experimental fixed-bed system can be compared to the corresponding relationships generally obtained with activated sludge systems. Several similar relationships which can be expected to hold true for both type processes, follow. High values of F/M correspond to low Θ_c values, and low values of F/M correspond to high Θ_c values. The production of biological solids is dependent upon the Θ_c of operation. Solids production is high at low values of Θ_c, and solids production is low at high values of Θ_c. Effluent quality is shown to improve with increasing mean cell residence times. Observed yield coefficients and specific utilizations are dependent upon the mean cell residence times of operation. As Θ_c increases for a particular system, the values of observed yield coefficient and specific utilization decrease. High sludge production at low values of Θ_c corresponds to higher specific utilizations and observed yield coefficients.

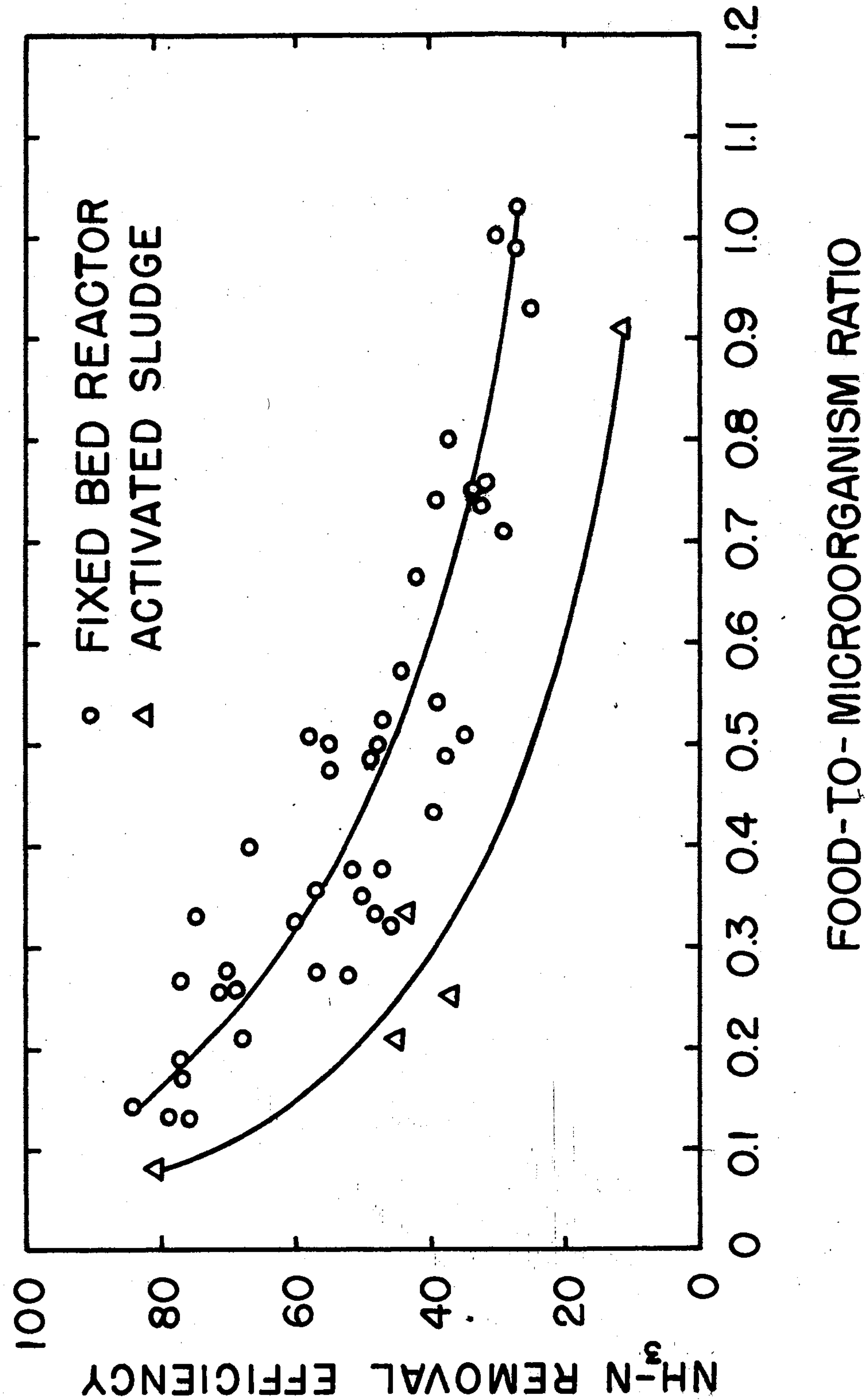
When the data for this investigation were linearized, values were obtained of Y_{max} = 0.447 and b = 0.286 days^{-1}. These values which were determined for a fixed-bed system, can be compared to results which have been reported for an activated sludge system. Stall (28) in a study using a bacto-peptone substrate, determined Y_{max} = 0.446 and b = 0.096 day^{-1} for his laboratory activated sludge unit. The Y_{max} value compares favorably to the value determined in this investigation;

however, an extreme difference exists between b values. This difference explains the higher observed yield coefficients which Stall obtained as compared to those in this study. Since similar Y_{max} values were found, the lower observed yield coefficients for the fixed bed system can be related to the larger microorganism-decay coefficient.

The parameters which have been applied to fixed-bed systems can also be used to describe ammonia removal. Stover (29) showed that the concepts of food to microorganism ratio and mean cell residence time may be valid concepts to be used in the comparison of ammonia removal in fixed-bed and activated sludge processes. He used food to microorganism (ammonia-nitrogen to microorganism) ratios to compare the two processes in terms of ammonia-nitrogen to synthesis removal (Figure 20). The resulting curves for the two processes are parallel with the fixed-bed reactor removing larger percentages of ammonia-nitrogen. Differences in removal percentages can probably be attributed to the fixed-bed system being operated at lower mean cell residence times than the activated sludge unit. One experimental run was made in a nitrifying system (consisting of <u>Nitrosomonas</u> and <u>Nitrobacter</u> autotrophic bacteria) and compared with a curve from an activated sludge unit. Food to microorganism values were compared at mean cell residence times of 5.0 days. Values of 0.046 and 0.055 were obtained for the fixed-bed and activated sludge systems, respectively. Thus, the concepts of food to microorganism ratio and mean cell residence time can be used to equitably compare ammonia removal in the two types of systems.

Fixed-bed systems are normally evaluated in terms of the efficiency of substrate removal for given applied loadings. Fixed-bed systems are usually thought of as being less efficient than activated

Figure 20. Percent Ammonia-Nitrogen to Synthesis Removal vs. Food to Microorganism Ratio for Laboratory Activated Sludge and Fixed-bed Units as Reported by Stover (29)



FIXED BED REACTOR
ACTIVATED SLUDGE
FOOD-TO-MICROORGANISM RATIO
NH$_3$-N REMOVAL EFFICIENCY
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
20
40
60
80
100

sludge processes. This investigation has stressed the importance of properly describing applied loadings. When loadings are described in terms of food to microorganism ratios, poor efficiencies resulting from organic overloadings can be related to those ratios. It is generally found that as F/M values increase, removal efficiencies decrease. When the experimental reactor was operated at lower F/M values, efficiencies as high as 91.2 percent were obtained. The organic loading curve published by the Ethyl Corporation (26) can be related to corresponding food to microorganism ratios. Removal efficiencies in the range of eighty to ninety percent can be obtained when F/M values less than one are used. An analysis of Figure 19 which was developed from a pilot plant study, shows that for a F/M value of 0.5, removal efficiencies of ninety-five percent can be expected for that particular pilot plant. Removal efficiency of ammonia-nitrogen can also be related to food to microorganism ratios, as shown by Stover (29). Higher removal efficiencies were obtained for the fixed-bed system than for the activated sludge system at identical food to microorganism ratios. Therefore, similar substrate removals may result in activated sludge and fixed-bed systems when the fixed-bed systems are designed and operated with food to microorganism ratios usually found to exist for activated sludge systems.

CHAPTER VI

CONCLUSIONS

Based upon the results of this investigation using an experimental fixed-bed reactor, the following conclusions are made:

1. Various design and operational control parameters which previously have been applied primarily to activated sludge processes, can be used successfully in the description of fixed-bed biological processes.

2. The production of biological solids in the laboratory system was dependent upon the total applied organic loading and independent of the hydraulic flow rate.

3. The concept of food to microorganism ratio provides a better means of describing fixed-bed system loadings than conventionally used terminology.

4. High food to microorganism ratios correspond to low mean cell residence times, and low food to microorganism ratios correspond to high mean cell residence times.

5. High biological solids production can be expected at low mean cell residence times, and low biological solids production can be expected at high mean cell residence times.

6. The quality of a fixed-bed system effluent is a function of mean cell residence time. The quality in terms of COD and quantity of biological solids discharged improves with increasing mean cell

residence times.

7. Observed yield coefficients and specific utilization rates are dependent upon net specific growth rate, hence mean cell residence time, of the microorganisms in a reactor system.

8. The parameters which are developed in this study form the basis of an equitable method for comparison between activated sludge and fixed-bed biological treatment systems.

9. Fixed-bed biological reactors should be operated at food to microorganism ratios normally suggested for activated sludge processes to obtain similar substrate removal efficiencies.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are presented for future studies involving the application of activated sludge parameters to fixed-bed biological reactors:

1. Conduct studies to determine the relationships between shock loadings and the various developed parameters.

2. Additional investigations which will apply parameters to existing wastewater treatment facilities and to pilot plant reactors should be initiated. Various substrates and types of media should be utilized.

3. Conduct studies relating nitrification and phosphorous removal to mean cell residence time in fixed-bed biological processes.

4. Perform studies employing biological solids recycle and analyze the corresponding effects of increased total system solids on the parameters which have been presented in this current investigation.

5. Studies should be undertaken for the purpose of determining minimum mean cell residence times for fixed-bed reactors for comparison to values obtained for activated sludge systems.

6. Conduct additional studies to determine minimum food to microorganism ratios.

7. Values for active biological film thicknesses for various substrates should be obtained.

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