AN INVESTIGATION INTO THE KINETICS OF THE ROTATING BIOLOGICAL CONTACTOR

By

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D E D I C A T E D T O M Y P A R E N T S,

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CHAPTER I

INTRODUCTION

Due to the rising public concern in the last few years over the pollution problems developing in our nation's water resources, the legislative bodies of the state and federal governments have issued increasingly strict water quality standards for wastewater treatment effluents. Private industry, as well as municipalities, are being pressed to meet new standards such as those outlined in Public Law 92-500, in a relatively short amount of time. As a result, there has been a search for new and better processes for purifying wastewater, both industrial and domestic. One of the most recent processes used in this country is the rotating biological contactor process.

The rotating biological contactor consists of a large number of narrow, lightweight plastic discs mounted on a horizontal shaft, which is placed in a semi-circular tank. The discs are rotated with approximately one-half of their surface area submerged in the wastewater. The discs serve to provide a surface area for the growth of a biological film, as well as to ensure contact between the biomass and the wastewater. The rotation of the discs through the air provides oxygen to the disc biomass and also to the wastewater. The shearing forces generated by this rotation cause excess biomass from the discs to slough off into the wastewater, thereby creating a mixed liquor suspended solids concentration.

Proponents of this new process have praised it for its low power consumption, resistance to shock loads, low detention time, resistance to short circuiting, and easy maintenance. Its behavior has been described by some as a combination of fixed film and suspended culture processes. This description is derived from the assumption that the biomass in the mixed liquor, as well as the biomass of the discs, contribute to the removal of exogenous substrate. Although this seems to be a valid possibility, the design methods used for this process treat it as if it were a rotating trickling filter, and any removal contribution by the suspended culture is ignored. It is the purpose of this study to investigate the kinetics of the rotating biological contactor in order to provide some indication of the role played by the mixed liquor suspended solids in the overall performance of the process.

CHAPTER II

LITERATURE REVIEW

Process Development

Origin in Europe

The rotating biological contactor is a relatively new wastewater treatment process. It apparently originated from the "cylindrical filter" developed by a German named Weigan at the turn of the century. This filter consisted of a wooden cylinder with slatted walls which was filled with brushwood, half submerged in wastewater, and then rotated. This type of reactor was very efficient, but sludge accumulation in the spaces between the slats was a constant problem which often resulted in anaerobic conditions (1). The present day rotating disc process has evolved primarily from the research work beginning in 1958 by Hartmann and Popel in West Germany (2). By 1965, the system was well established in Germany and other European countries (3) (2).

Research and Development by Allis-Chalmers/Autotrol

The first American interest was developed in 1965 when Allis-Chalmers began research and development work on the process at a waste treatment plant in the Milwaukee area. Initially, tests were run using primary clarifier effluent. However, due to the variations in flow rates and concentrations of this waste, it was difficult to effectively

examine the desired parameters. As a result, a new set of tests was run using a synthetic waste made up of dairy solids, chemical nutrients, and buffer. Using this synthetic waste, it was possible to evaluate the effects of such system parameters as hydraulic loading, inlet COD concentration, dissolved oxygen content of the mixed liquor, and rotational velocity (4). Later, another series of tests were run using the same pilot plant and synthetic waste for the purpose of determining the effects of intermittent and varying flows, and hydraulic surges. It was found that the test unit could retain a surprising COD removal efficiency of 66% under intermittent flows and could retain steady state or better removal efficiency at cyclic varying flow patterns. In addition, the unit was not seriously affected by hydraulic surges (5).

In 1967, Allis-Chalmers began their first field testing of the rotating biological contactor at a large Midwestern dairy plant. The pilot plant unit was fed a combined waste from several sources, including wastewater from milk tank trucks and cottage cheese processing. Another waste, consisting of whey from cottage cheese processing, was also used in these tests. The primary objective of these tests was to determine whether or not the test unit could treat actual dairy wastes under field conditions as well as it had treated synthetic wastes under controlled conditions. The test unit succeeded in achieving 80% COD reduction of loadings as high as 400 lb COD/day/1000 ft^3 on either waste. This compared favorably with the results predicted by the lab pilot plant (6).

From November, 1969, to August, 1972, Autotrol Corporation, formerly part of Allis-Chalmers, was involved in a research effort for

EPA aimed at evaluating the performance of the rotating biological contactor as a municipal wastewater treatment process. This work was begun using a pilot plant unit at a municipal treatment plant in Wisconsin and terminated shortly after a full scale rotating biological contactor system had been installed at the treatment plant. This installation was the first full scale application of this process for municipal wastewater treatment in the United States. During this period, many variables of operation and design for the process were evaluated, including the effects of staging, rotational disc speed, and hydraulic loading. It was found that a larger number of stages improves residence time distribution and results in increased efficiency of BOD removal. The optimum disc rotational speed in these studies was found to be 60 ft/min peripheral velocity. Ronald Antonie, the head of these investigations, also concluded that the process is first order with respect to BOD removal, and therefore the main design criterion is hydraulic loading. This implied that at any hydraulic loading there will be a given percent BOD reduction regardless of the initial BOD concentration. The BOD removal efficiencies of the pilot plant units were consistently in the 90-95% range when operated at the proper hydraulic flow rates. The full scale field unit achieved 85% BOD removal at 0.04 mgd. In addition to the excellent BOD removal, Antonie found that the rotating biological contactor was very well suited to nitrification, particularly in the latter stages of the unit. It should be noted that Antonie mentioned the possibility of a contribution to the overall removal by the mixed liquor suspended solids, but did not ever actually investigate this phenomena (7) (8) (9) (10).

Research and Development by Other Researchers in the United States

Although Autotrol and Allis-Chalmers have probably performed more research on the process than any other single organization in the United States, there have been many other researchers involved in evaluation of the rotating biological contactor. Garrett (11) investigated the removal characteristics of the process using a synthetic sucrose waste in an attempt to correlate the performance of the contactors with that of the trickling filter. She found that the rotating biological contactor was superior in performance to the rock or plastic trickling filter when compared on the basis of total organic loading. She also found data that led her to believe that the test unit was behaving as a combination fixed film reactor and fluidized reactor.

While Antonie was evaluating the rotating biological contactor system as a municipal wastewater treatment process, Birks and Hynek (12) reported on the first commercial application of the process in the United States. The Eiler Cheese Company in DuPree, Wisconsin installed a rotating biological contactor as part of a treatment system which included septic tank pretreatment, a final clarifier, and a 30-day polishing lagoon. The rotating biological contactor was found to be very satisfactory, as it continuously achieved 85% or better COD reduction even with increased loading caused by poor septic tank performance. It also displayed a high amount of resistance against shock loads.

Several studies of the rotating biological contactor's performance using municipal sewage were made in addition to those mentioned

earlier by Antonie. Borchardt (13) found that the process demonstrated 89-94% removal at nominal loadings with detention times of approximately 20 minutes. He speculated that this excellent performance could be attributed to the disc motion through the wastewater which resulted in excellent transfer of food and oxygen to the biological growth. Torpey, Heukelekian, Kaplovsky, and Epstein (14) investigated not only the carbonaceous removal characteristics of the process on municipal sewage, but also its performance as a nutrient removal process using an illuminated series of discs with algal growth. Hao and Hendricks (15) examined the effects of adding chemicals to improve performance of the process on municipal sewage. They found that chemical addition within the unit decreased rather than improved performance. The effects of temperature, rotational velocity, liquid retention time, degree of immersion, and recycle were evaluated by Ellis and Banaga (3) using municipal sewage. They concluded that optimum conditions for operation are a temperature near 20°C with a liquid retention time of 97 minutes and an immersion of the discs in wastewater equivalent to 26% of the disc area.

In addition to the previously mentioned work using municipal sewage, there has been much research on the rotating biological contactor as an industrial wastewater treatment process. Some of the commercial wastes studied with respect to the rotating biological contactor process include cheese, poultry, bakery, winery, yeast, digestor supernatant, thermally conditioned sludge liquor, and slaughterhouse waste (2). The effectiveness of the contactors in treating slaughterhouse wastes have been reported by Stover (16), Chittenden and Wells (17), and Stover and Kincannon (18). Stover (16)

observed a two-phase removal rate corresponding to the high removal in the first stage compared with a lesser degree of removal in the rest of the unit. Chittenden and Wells (17) examined the effects of hydraulic loading and organic loading on the removal characteristics of the contactors using slaughterhouse anaerobic lagoon effluent. Stover and Kincannon (18) used a slaughterhouse waste and a synthetic waste to observe the relationship of organic and hydraulic loadings and their influence on the removal characteristics. They concluded that the rotating biological contactor performance is not a function of hydraulic loading only, but instead is a function of total organic loading which includes organic concentration and hydraulic loading. They also found that much higher removal efficiencies for a large increase in total organic loading, could be achieved with the synthetic waste, than with slaughterhouse waste.

The rotating biological contactor has been found to be suitable to the treatment of refinery wastes. Efficiencies of 60-75% BOD removal as well as satisfactory removal of toxicity, oil, and grease have been reported. Along with its removal capabilities, the characteristics of short retention time, low power requirements, low volume sludge, resistance to shock loads and low maintenance requirements, made the rotating biological contactor process a very successful method of treatment for the refinery industry (19) (20).

Kinetics

Microbial Growth Kinetics

The relationship between bacterial growth and substrate removal is obviously a very important consideration in the design of any

biological wastewater treatment system. There are two important relationships between growth and substrate removal. The amount of growth obtained for a certain amount of substrate removal is referred to as the cell yield. The other important relationship is the one between the rate of growth and the concentration of substrate. Assuming that all necessary nutrients for cell growth are present, the carbon source is the limiting factor. Therefore, the relationship between the carbon substrate, and the rate of growth is most important to the design and operation of biological treatment systems. It has been found that the biological solids concentration, X, experiences a significant period of exponential growth during substrate removal. This has been described by a first order differential equation stating that the increase in biological solids, dX/dt, is equal to a proportionality constant times the solids concentration X at any instant. This can best be illustrated by a plot of X against time on semi-log paper (See Figure 1). The slope of the resulting line will be equal to the proportionality constant μ which is also called the "specific growth rate constant". It has been found that μ increases with increasing substrate concentration up to a maximum value of μ after which increases in substrate concentration have no effect. The relationship is described by the "Monod Equation" shown below:

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

This equation can be plotted using different substrate concentrations as shown in Figure 2. The value μmax represents the maximum value of μ and is a constant. K_s is the "saturation constant" and

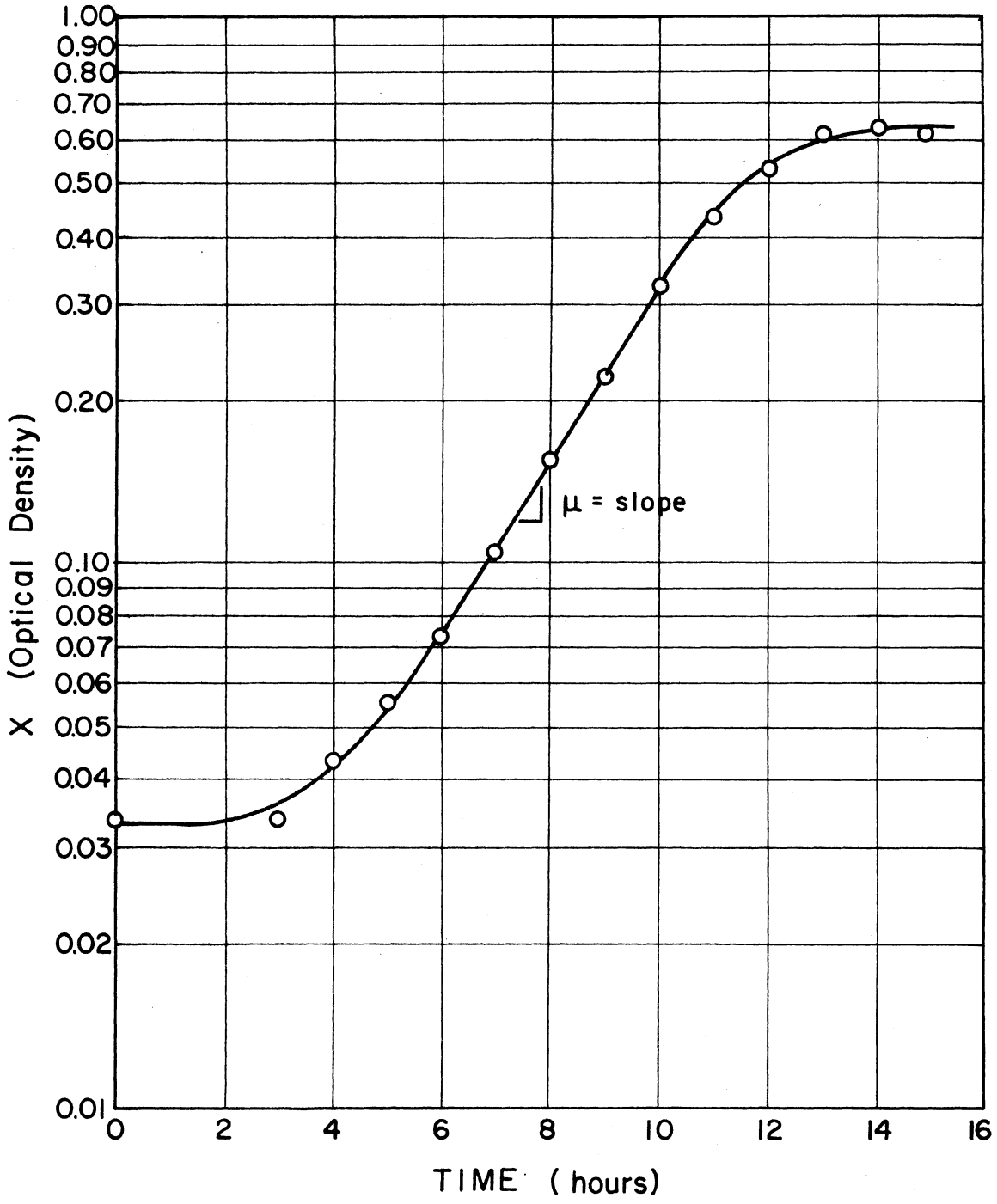

Figure 1. Semi-log Plot of Biological Solids Concentration vs. Time

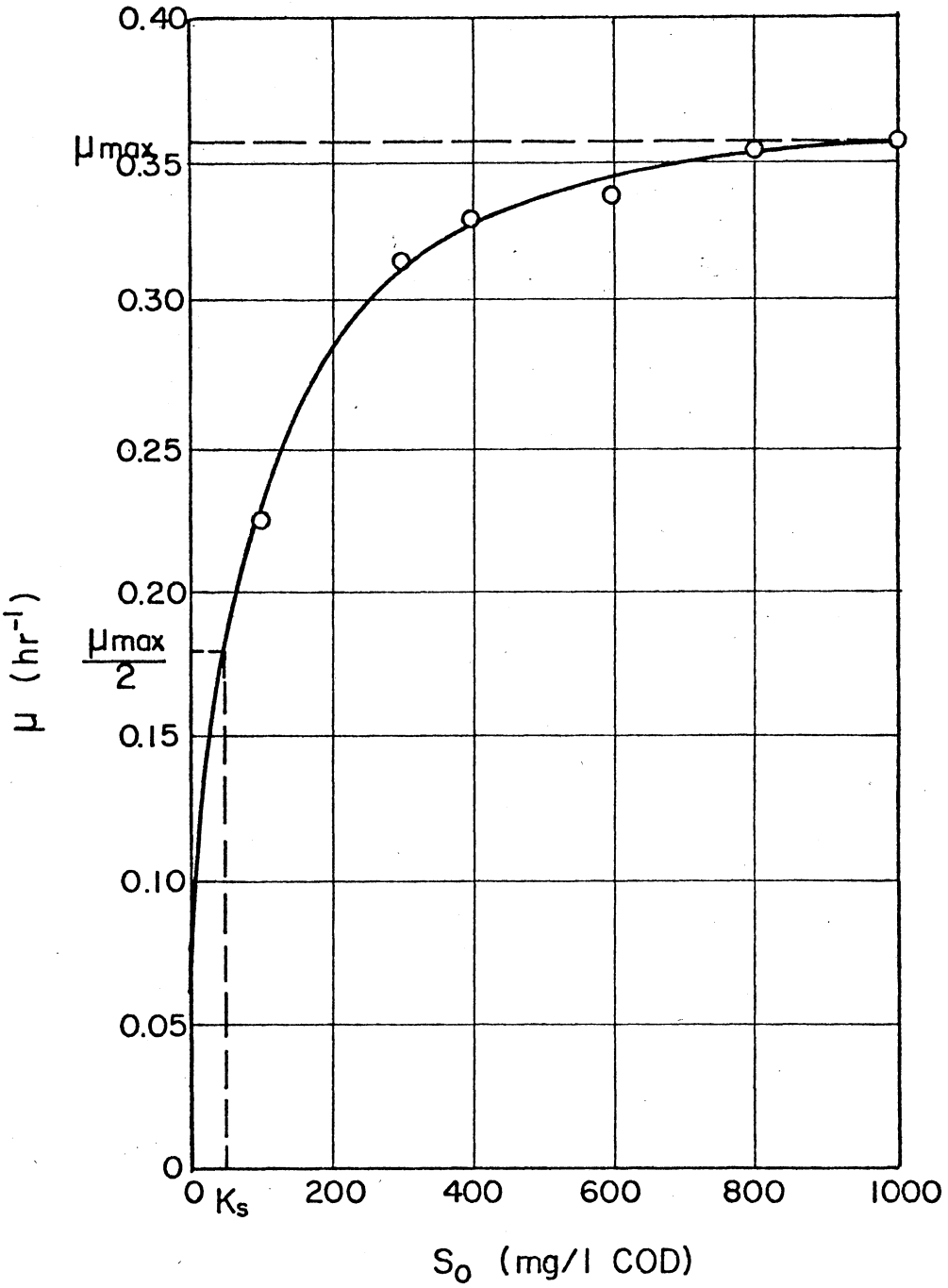

Figure 2. Hyperbolic Plot of Relationship Between Specific Growth Rate Constant and Initial Substrate Concentration

represents the substrate concentration at which the resulting curve intersects 1/2 μmax. K_s can be used to indicate the extent of the dependence of μ on S. The importance of this equation lies in the fact that it can be used as a kinetic description for determining the effect of substrate concentration on the growth rate constant μ, and that it can be used as a description of the behavior of a completely mixed, continuous flow, suspended culture reactor (21).

Fixed Film Kinetics

Unlike the fluidized culture reactors in which substrate removal is accomplished by a liquid suspension of microorganisms, fixed film reactors remove substrate through the action of a mass of cells which are attached to a solid media. As wastewater is passed over this mass or film of cells, organic material and inorganic nutrients are removed from the wastewater by the bacteria. The effectiveness of the fixed film is largely dependent upon the diffusion of metabolic reactants through the biofilm. If diffusion of the metabolic reactants is not complete through the biofilm thickness, then not all of the biofilm mass is utilized.

Sanders (22) has concluded that diffusion of oxygen through the cell mass thickness is limited to approximately 20-60 μm. This implies that only a portion of the biofilm thickness is actively participating in substrate removal.

Maier (23) observed that scraping to remove excess cell mass had no effect on the rate of substrate removal and suggested that the slime layer thickness is not an important variable. He also suggested that changes in substrate removal rates at intermediate

thicknesses are more directly related to the texture of the slime layer surface rather than its thickness.

Kornegay and Andrews (24) derived a mathematical model to describe fixed film kinetics using a mass balance approach and Monod's Equation. In deriving their model, they provided for the effects of changing biomass thickness upon substrate removal. They found that both dissolved oxygen and substrate utilization reached a steady state value after the biological film reached a thickness of 70 μm. Greater film thickness did not improve removal.

McCarty and Williamson (25) (26) developed a mathematical model of substrate utilization kinetics within biofilms by using a mass balance approach which incorporated an expression for the rate of substrate mass transfer (Fick's Law), and an expression for the rate of substrate utilization (Monod's Equation). The researchers also provided a method for determining whether the electron acceptor or the electron donor are rate limiting.

Rotating Biological Contactor Kinetics

While some researchers have speculated that the rotating biological contactor may possess some of the behavioral traits of both the fixed film and suspended culture processes, the majority, if not all, of the design methods developed have discounted the effects of the mixed liquor suspended solids present in the system. As a result, the performance predicted for the rotating biological contactor design is a function of the disc surface area and biofilm characteristics only (27) (28) (29).

CHAPTER III

METHODS AND MATERIALS

Test Unit

The model rotating biological contactor unit used in this study consisted of a plexiglas tank divided into six stages with four polyethylene discs in each stage (See Figure 3). Each disc was approximately 1/8 inch thick and 6 inches in diameter. This resulted in a total disc surface area of 9.43 square feet for the entire unit. To insure complete mixing of the wastewater and to keep the mixed liquor solids in suspension, small plexiglas paddles were placed in between the discs at intervals of approximately 90 degrees. Baffles, with openings at the base to allow flow through the unit, separated the stages. The final stage contained an overflow weir which directed the effluent out of the unit and into the sanitary sewer. Initially, the tank volume was 9.0 liters. This was changed to 7.6 liters when the tank was modified to conform to the shape of the discs after the tests for 2 gpd/ft^2 hydraulic loading had been made. This was done to promote complete mixing in the unit when a smaller motor with less rpm capacity was installed. To account for the change in volume of the tank, possible reduction in oxygen transfer efficiency due to reduction in disc rotational speed, or any other unknown effects on the system, the tests on the initial two hydraulic loadings were

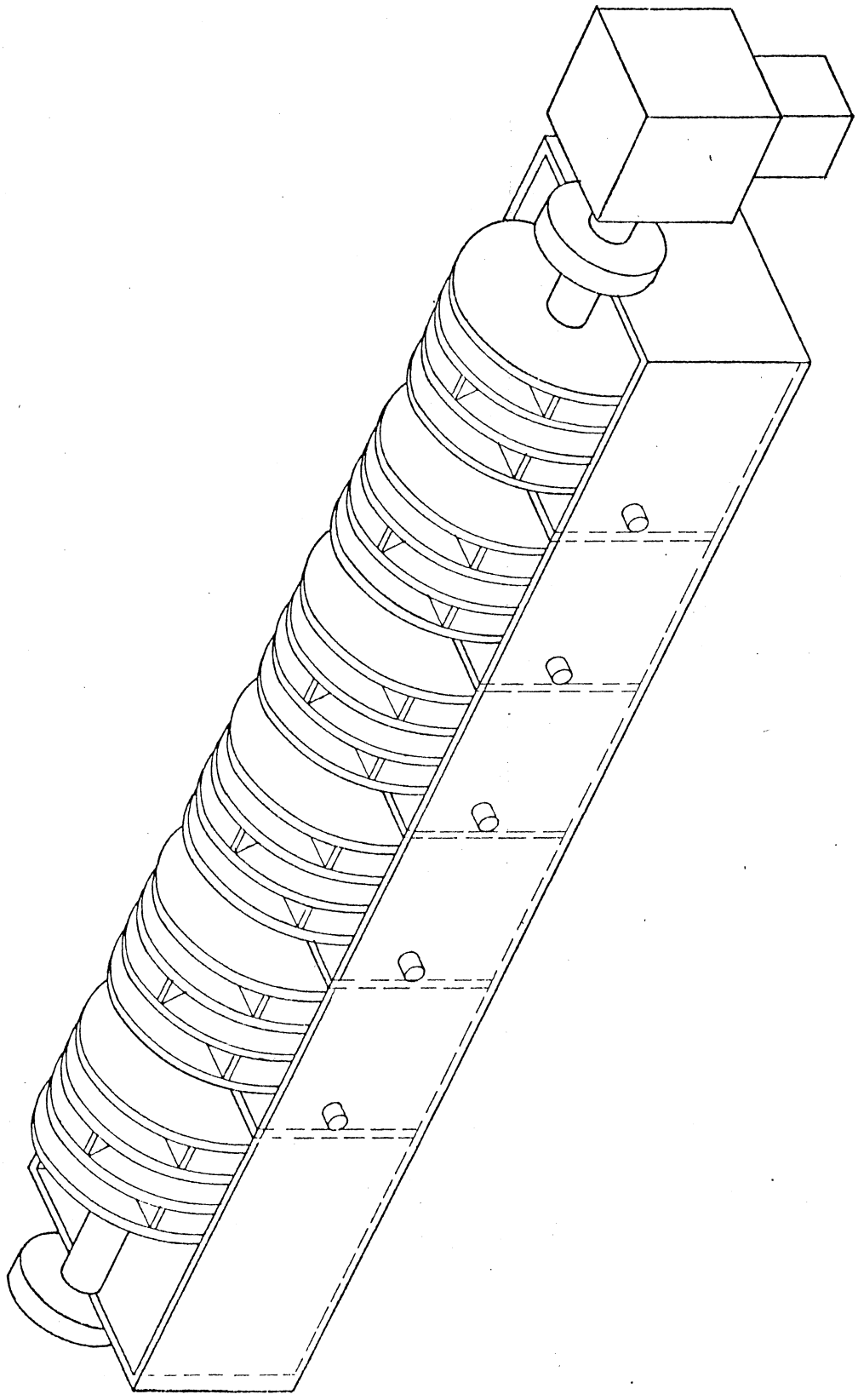

Figure 3. Rotating Biological Contactor Laboratory Unit

repeated. Hydraulic flow rates of 1 gpd/ft^2, 2 gpd/ft^2, 4 gpd/ft^2, 5 gpd/ft^2, and 7 gpd/ft^2 were used in this study. These hydraulic flows were maintained through the use of a constant head tank which received a continuous flow of tap water from a faucet outlet (See Figure 4). The flow from the constant head tank was regulated by a valve combined with a flow meter on the tank outlet line. Water from the constant head tank fed by gravity into a wet well, where it was mixed with the concentrated synthetic waste to achieve the desired organic concentration. The synthetic waste was pumped to the wet well using a Cole-Parmer Masterflex Tubing pump. From the wet well, the mixture flowed by gravity into the first stage of the test unit. The rotational speed of the discs was initially set at approximately 15 rpm using a Dayton 1/15 horsepower motor with a variable speed control. Later in the experiment, this motor failed and was replaced by a Barcol Speed Reducer. The speed reducer had no speed control and was not capable of turning the discs at the previous speed. The slower speed, approximately 8 rpm, was not fast enough to keep the mixed liquor suspended solids in suspension, and this resulted in the tank volume change previously mentioned.

Synthetic Waste

The synthetic waste used in this experiment contained glucose as the carbon source, along with other nutrients and buffer required for microbial growth. The concentrations of the other nutrients and buffer were maintained so that carbon was the limiting growth factor (See Table I). The waste was made up in a concentrated solution and fed into the wet well at a rate which combined with the

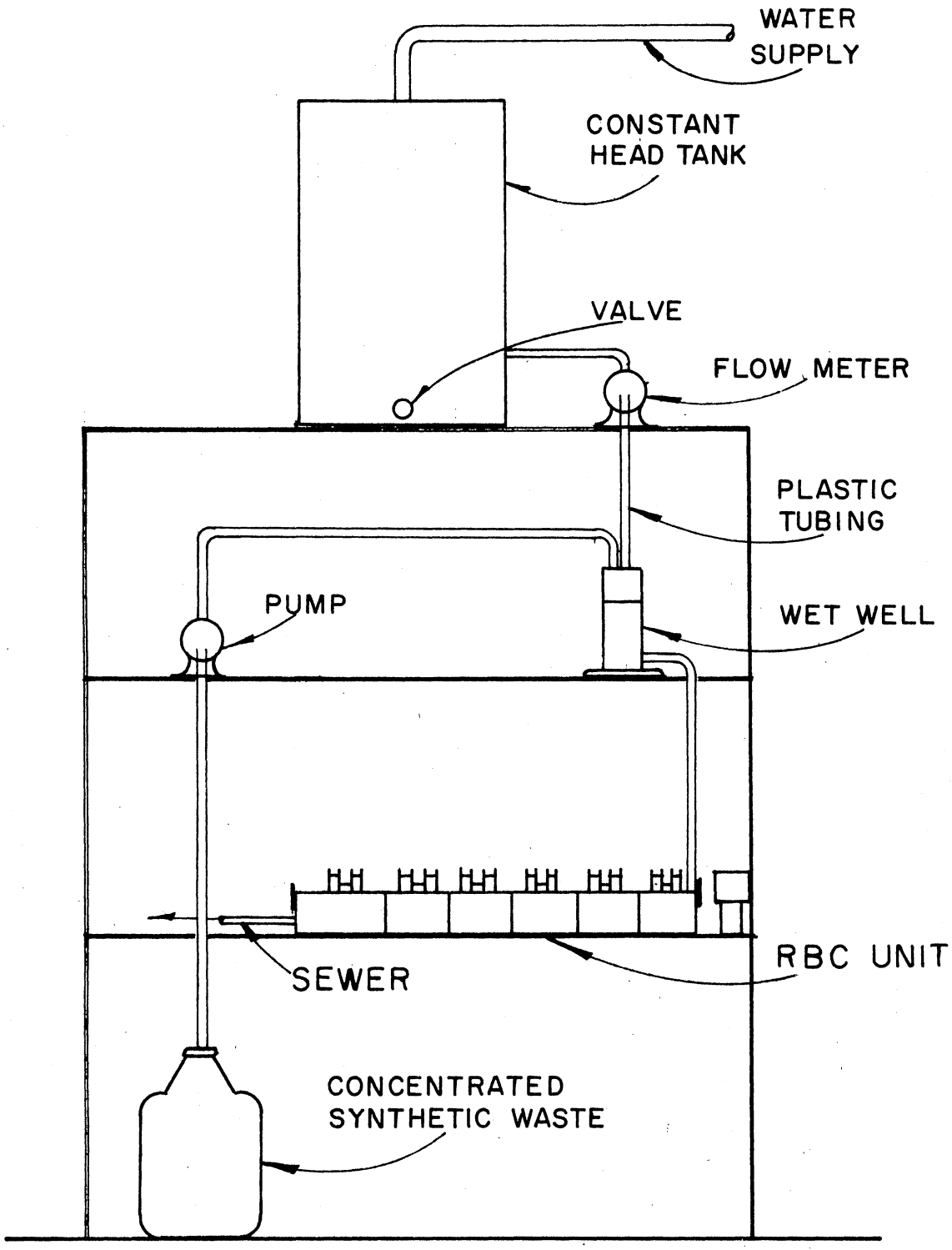

Figure 4. Experimental Apparatus

TABLE I

RELATIVE COMPOSITION OF SYNTHETIC WASTE FOR 1000 mg/l GLUCOSE CONCENTRATION

Constituent	Concentration
Glucose	1000 mg/l
$(NH_4)_2SO_4$	500 mg/l
$MgSO_4 \cdot 7H_2O$	100 mg/l
$FeCl_3 \cdot 6H_2O$	0.5 mg/l
$CaCl_2$	7.5 mg/l
$MnSO_4 \cdot H_2O$	10.0 mg/l
KH_2PO_4	527 mg/l
K_2HPO_4	1065 mg/l

Tap water to volume

flow of tap water to give the desired influent concentration. The influent concentration was maintained at 300 mg/l for all flow rates.

Operational and Sampling Procedures

The test unit was seeded with sewage and fed synthetic waste as a batch process for two to three days before beginning continuous flow operation. The unit was run under continuous flow conditions initially for a period of about two weeks to insure a good growth on the discs. At each flow rate, COD and total solids concentration tests were run until two sets were comparable. It was then assumed that the unit had reached equilibrium, and the values of the two comparable runs were averaged to represent the performance of the unit. Samples were taken at eight locations in the system for each run. These locations were: the influent, beginning of the first stage, end of the first stage, and the end of each of the remaining five stages. The sample from the end of the sixth stage represented the process effluent. Samples were taken from the unit using a 25 ml broken-ended pipette. The broken end served to allow the solids to enter the pipette.

In addition to the COD and solids concentration tests, two other tests were performed at each flow rate. A residual measurement was made using a sample of the effluent from the unit. This test was performed to give some indication of the non-biodegradable organics produced by the cells. The other test made at each flow rate was a batch growth study. Actually, two growth study tests were run at each flow rate since two different seeds for the test were used. Cells from the first and fourth stages, respectively were used to innoculate two separate batch growth experiments. This was done in order to

compare the growth characteristics of the cells at the beginning of the unit where food was plentiful, with those of the cells in the latter part of the unit where organic substrate was less abundant.

Analytical Procedures

Total Biological Solids

The total biological solids concentration was measured gravimetrically by filtering the sample through 0.45 μm Milapore filter papers. The following procedure was used for this analysis: Filter papers were placed in aluminum tare pans which were placed in a drying oven at 103°C for two hours. After removal from the oven, the pans and filters were placed in a dessicator for two hours to cool to a constant weight. The dry weights were then recorded. The 25 ml samples were filtered through the filter papers using a vacuum pump. At the higher flow rates, centrifugation of the samples was required to reduce the filtering time. After filtering, the filters were replaced in the pans and placed in the drying oven at 103°C for approximately two hours. The filters were then cooled in the dessicator, weighed, and the solids concentrations calculated. It should be noted that the accuracy of this test was limited by the fact that the mixed liquor suspended solids in the unit were not homogeneous and in fact were often sucked into the pipette as large clumps of solids.

COD

The COD of the filtrate was measured using the procedure outlined in Standard Methods (30).

Residual

The residual determination experiments were run for the purpose of estimating the non-biodegradable organic matter left in the effluent. This test was performed by bubbling a large sample of the effluent in a large volume glass tube for a period of one week. Samples were taken at the beginning and end of this procedure for COD analysis.

Growth Studies

The batch growth studies were run to determine the kinetic constants μmax, K_s, and Y using methodologies suggested by Gaudy and Gaudy (21). At each flow rate, cells from the first and fourth stages, respectively were used as initial innoculum for the experiments. The medium used contained the same proportions of nutrients and buffer as were present in the synthetic waste, with glucose as the limiting nutrient. The cells from each of the two stages were grown in separate sets of 250 ml Erlenmeyer flasks with glucose concentrations ranging from 100 to 1000 mg/l. The total volume of liquid medium in each flask was 40 ml. Before seeding the flasks, it was necessary to separate the large clumps of filamentous biomass of seed samples into homogeneous mixtures in order to provide accurate instrument readings. This was done by mixing each seed sample in a high speed electric blender for approximately two minutes. The initial innoculum concentration was the same in all flasks, so that initial optical density readings were approximately 0.0458. After initial readings were made, the flasks were placed on an Eberbach oscillating shaker table, which was adjusted to 100-110 oscillations

per minute. The growth curves were derived by measuring the optical density of each of the flasks every hour using a Bausch and Lomb Spectronic 20 set at 540 nm. The cell yield, Y, was determined by measuring the COD and total solids concentrations of the 1000 mg/l flask after the cells had stopped growing. The constants μmax and K_s were determined by plotting the data obtained from the growth study. The plotting and calculation methods for this data are discussed briefly in a previous section of this paper, and in detail by Gaudy and Gaudy (21).

CHAPTER IV

RESULTS

COD Removal

COD removal characteristics at various hydraulic loadings as a function of stage, are shown in Figures 5-9. Figure 5 describes the behavior of the unit at 1 gpd/ft^2. As can be seen from this plot, the initial COD of 365 mg/l is reduced to approximately 34 mg/l by the time it leaves the unit. This apparently represents a removal of 91%. It should also be noted that more than 85% of the removal mentioned above is accomplished in the first stage. Figure 6 represents the removal performance of the test unit at 2 gpd/ft^2. For this hydraulic loading, the majority of the removal is complete at the end of the second stage as evident from the figure. The final COD concentration is approximately 8% of the influent concentration. At a hydraulic loading of 4 gpd/ft^2 (See Figure 7), the COD is reduced from 294 mg/l to 32 mg/l for an apparent total removal of 89%. This removal was complete at the fourth stage. Figures 8 and 9 describe the performance of the unit at 5 gpd/ft^2 and 7 gpd/ft^2, respectively. The unit achieved removals of 86% and 80% for these two flow rates. At 5 gpd/ft^2 the removal appears to be largely complete at the fourth stage. The 7 gpd/ft^2 loading resulted in a distribution of the removal throughout the entire unit, with an effluent COD concentration

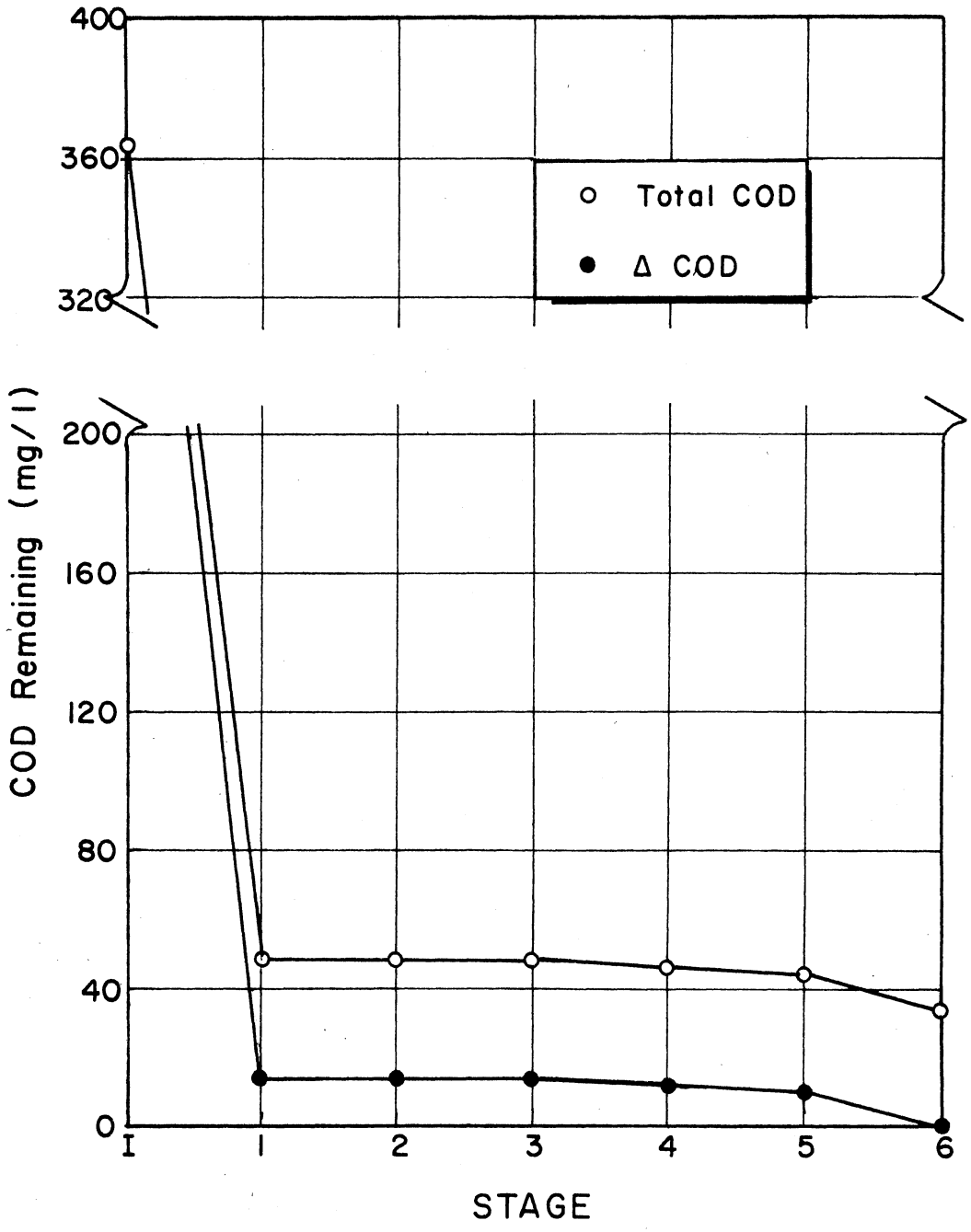

Figure 5. COD Remaining vs. Stage for Hydraulic Loading of 1 gpd/ft^2 Using Total COD and ΔCOD

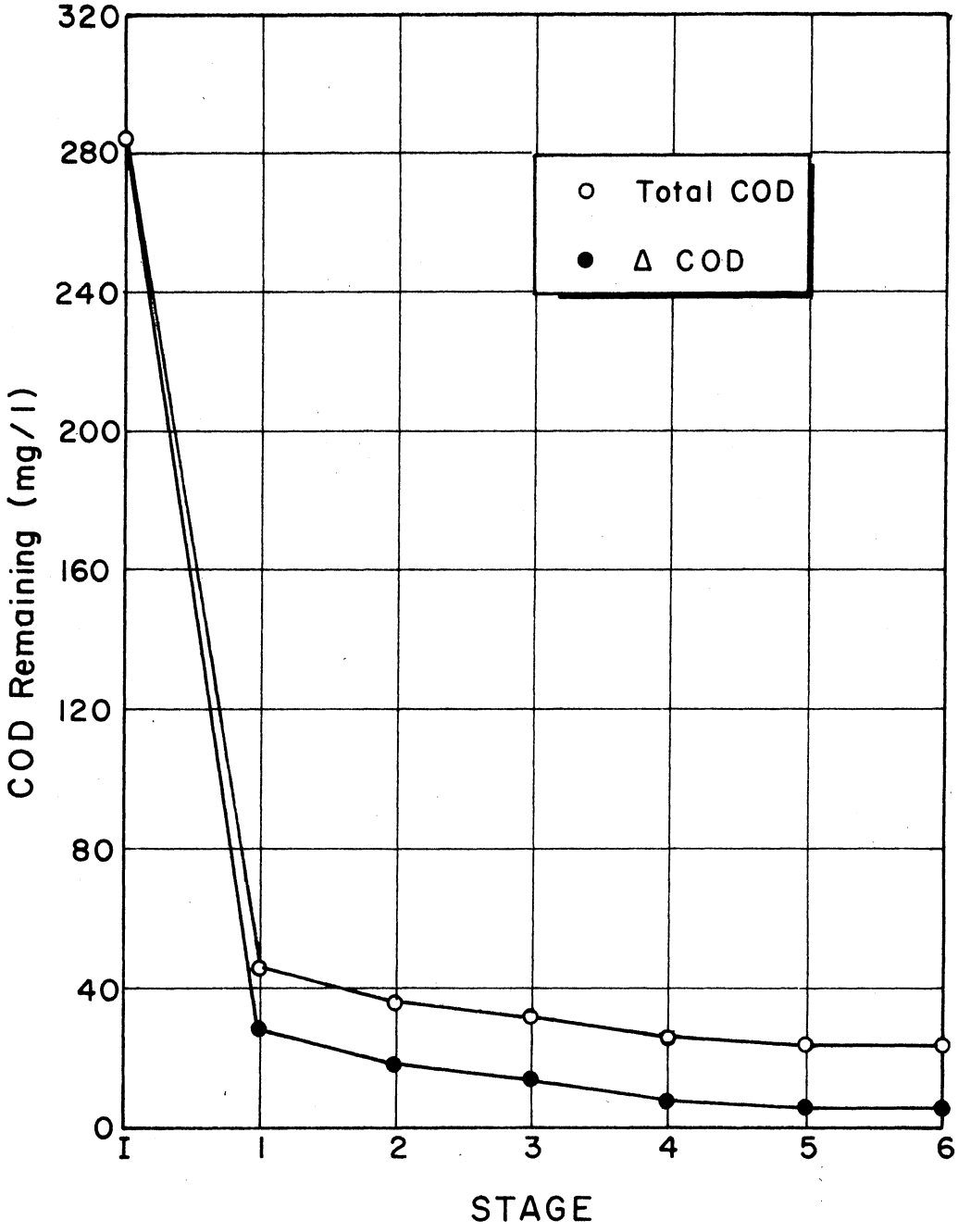

Figure 6. COD Remaining vs. Stage for Hydraulic Loading of 2 gpd/ft^2 Using Total COD and ΔCOD

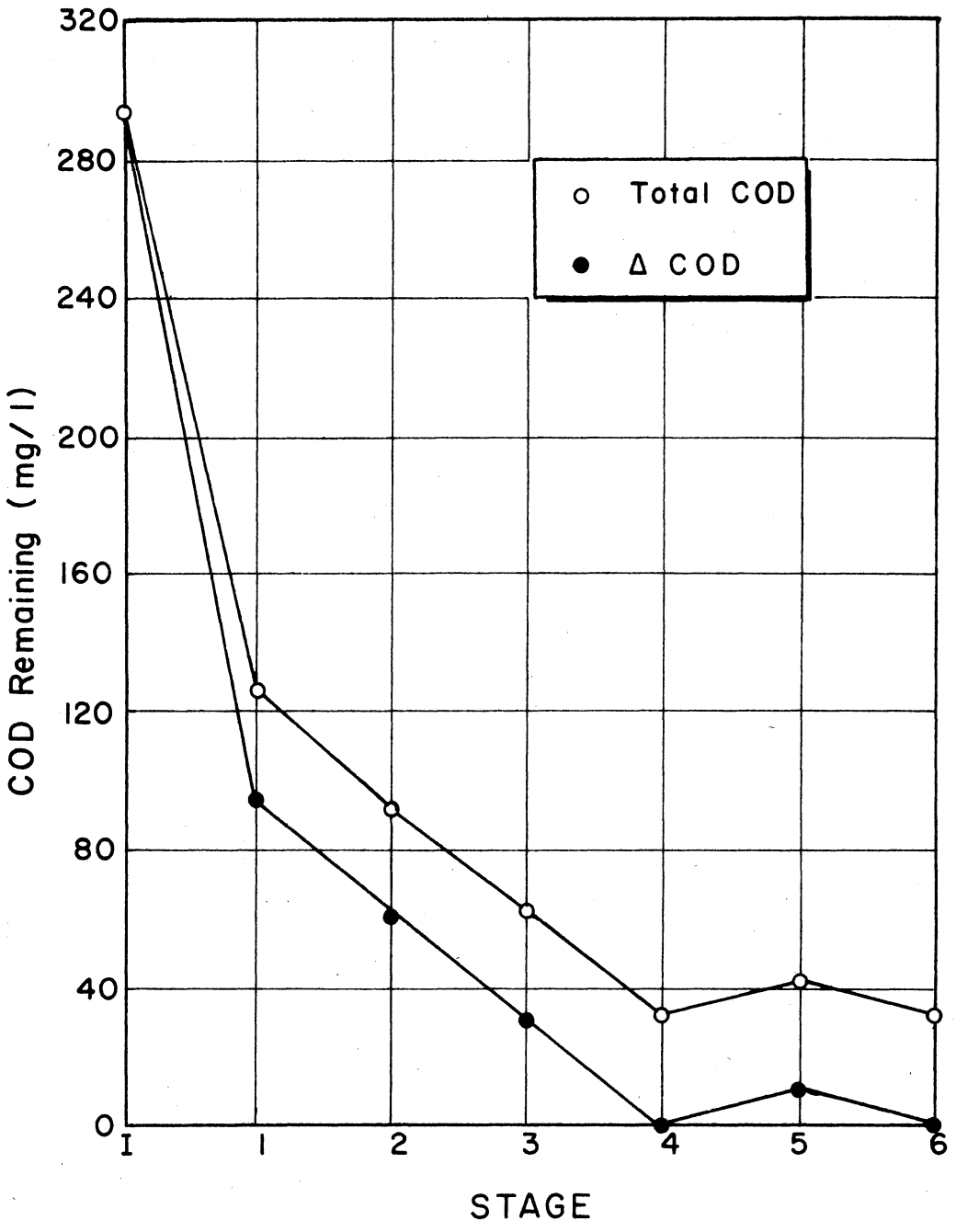

Figure 7. COD Remaining vs. Stage for Hydraulic Loading of 4 gpd/ft^2 Using Total COD and ΔCOD

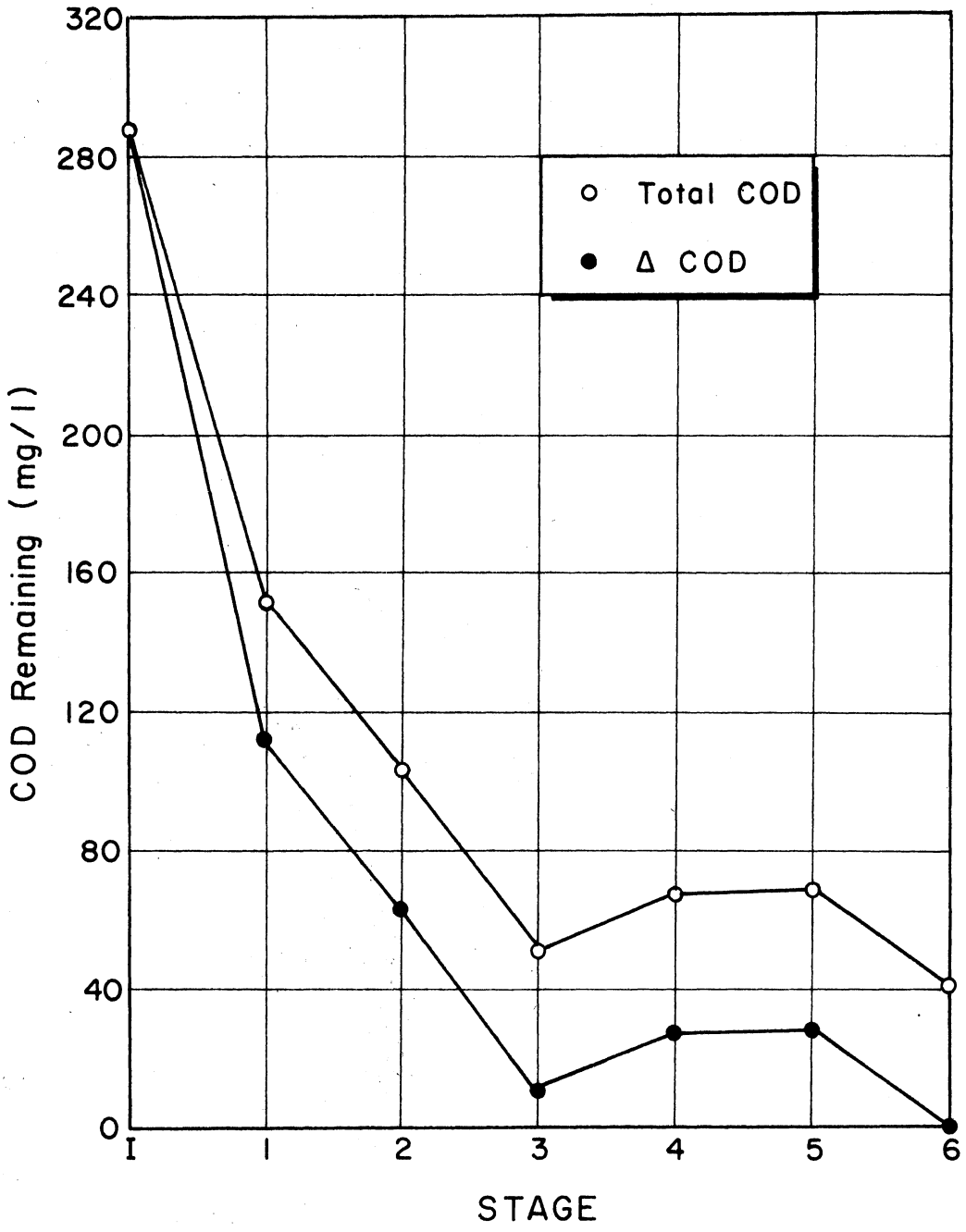

Figure 8. COD Remaining vs. Stage for Hydraulic Loading of 5 gpd/ft^2 Using Total COD and ΔCOD

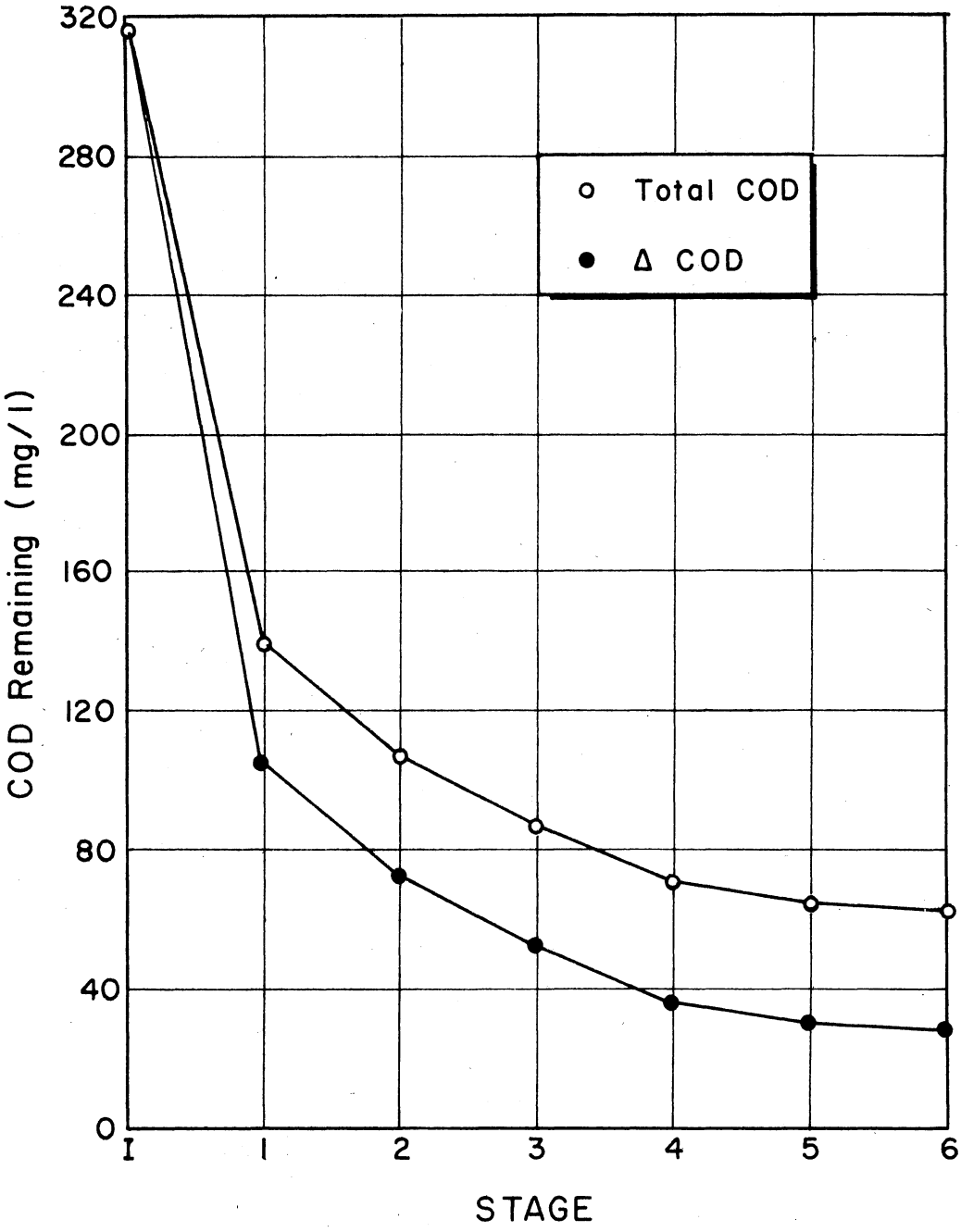

Figure 9. COD Remaining vs. Stage for Hydraulic Loading of 7 gpd/ft^2 Using Total COD and ΔCOD

equal to 62 mg/l. During operation of the test unit, it was noted that the stage at which most of the removal was complete was also the last stage containing extensive growth on the discs. For example, at 1 gpd/ft^2, the discs in the first stage were much more thickly populated with biomass than were the discs in the remaining stages of the unit. This corresponds to the majority of removal taking place in the first stage. At 7 gpd/ft^2, the discs in all of the stages had a large amount of growth which corresponded to the distribution of the COD removal throughout the entire unit.

Table II lists the results of the residual COD experiments. Although the samples taken from the test unit for these experiments were bubbled in batch for approximately one week, the COD of the samples did not always decrease. At times, the COD increased after bubbling of the samples. This increase in COD was attributed to the release of organic material by lysis of the cells after all available substrate in the sample had been removed. As a result, the values selected for the residual COD were taken to be the lowest COD value attained either in the effluent of the test unit, or in the residual batch experiments. The importance of the residual COD is that it represents a portion of the effluent COD which is non-biodegradable by the heterogeneous population of the unit. Since all of the influent COD was biodegradable, the residual COD has to be due to the activities of the cells and should not be included as part of the removal efficiency calculations. Gaudy and Gaudy (21) suggest that if the remaining COD in the effluent cannot be reduced further, the difference between the influent COD and that residual COD can be used to represent the total amount of organic matter available as

TABLE II

SUMMARY OF RESIDUAL COD VALUES AT VARIOUS HYDRAULIC LOADINGS

Hydraulic Loading	Experimental Residual COD	Effluent COD	Selected Residual COD
1 gpd/ft^2	46.4 mg/l	34.3 mg/l	34.3 mg/l
2 gpd/ft^2	18.0 mg/l	24.3 mg/l	18.0 mg/l
4 gpd/ft^2	39.8 mg/l	32.0 mg/l	32.0 mg/l
5 gpd/ft^2	39.8 mg/l	40.4 mg/l	39.8 mg/l
7 gpd/ft^2	34.3 mg/l	62.6 mg/l	34.3 mg/l

substrate to the microorganisms. This difference is called ΔCOD and is used in this study to provide a more accurate estimate of the biodegradable substrate removal performance of the unit. Figures 5-9 show the difference in removal characteristics of the unit using Δ COD and total COD for each hydraulic loading. A constant residual COD was assumed throughout the unit and was subtracted from the effluent COD of each stage to obtain ΔCOD for that stage. It should be noted from the figures that the hydraulic loadings of 1 gpd/ft^2 and 4 gpd/ft^2 have 100% removal using the ΔCOD approximation. The 2 gpd/ft^2 flow rate was expected to also indicate 100% removal, but only indicated approximately 98% using ΔCOD. The higher hydraulic loadings of 5 gpd/ft^2 and 7 gpd/ft^2 have less efficient removal as was expected, but still demonstrated that over 90% of the biologically available organic substrate was being removed by the unit.

Figures 10 and 11 illustrate the efficiencies achieved by the unit as a function of total organic loading at each hydraulic flow rate. The values used in Figure 10 were obtained using total COD, while those in Figure 11 represent ΔCOD. As was expected, the removal efficiency decreased with increasing organic loading in both plots. It can also be seen that the points in the plot for total COD approximate a curve which appears to be asymptotic at 100% on the Efficiency axis. This curve, however, is derived by forcing the curve fit through 100% efficiency. If the curve fit is not forced through 100% on the Efficiency axis, the curve approximates more closely an inverted S-shaped curve. This type curve is similar to those obtained by Garrett (11). The curve intersects the Efficiency

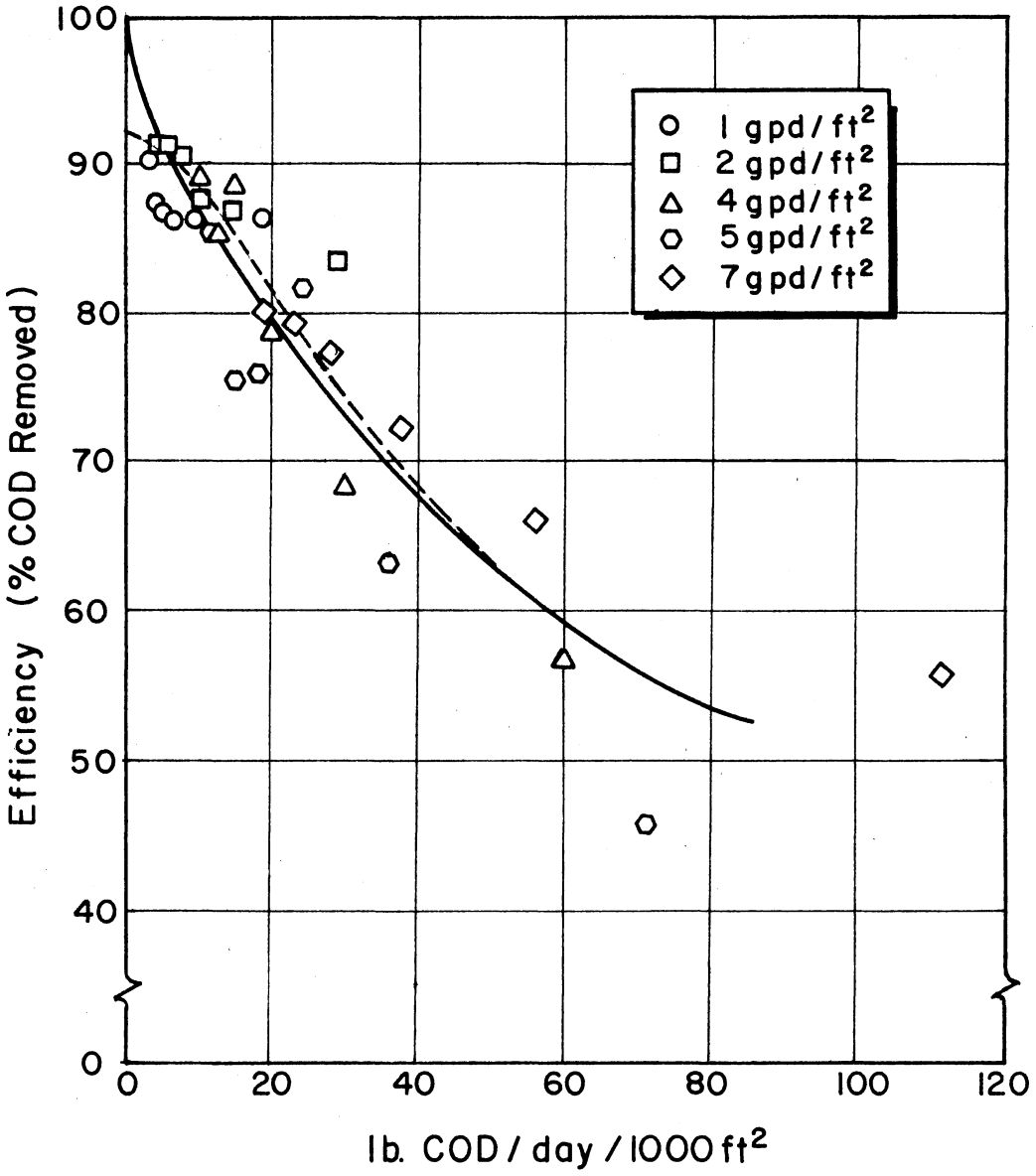

Figure 10. Efficiency (% COD Removed) vs. Total Organic Loading (lb COD/day/1000 ft^2) Using Total COD

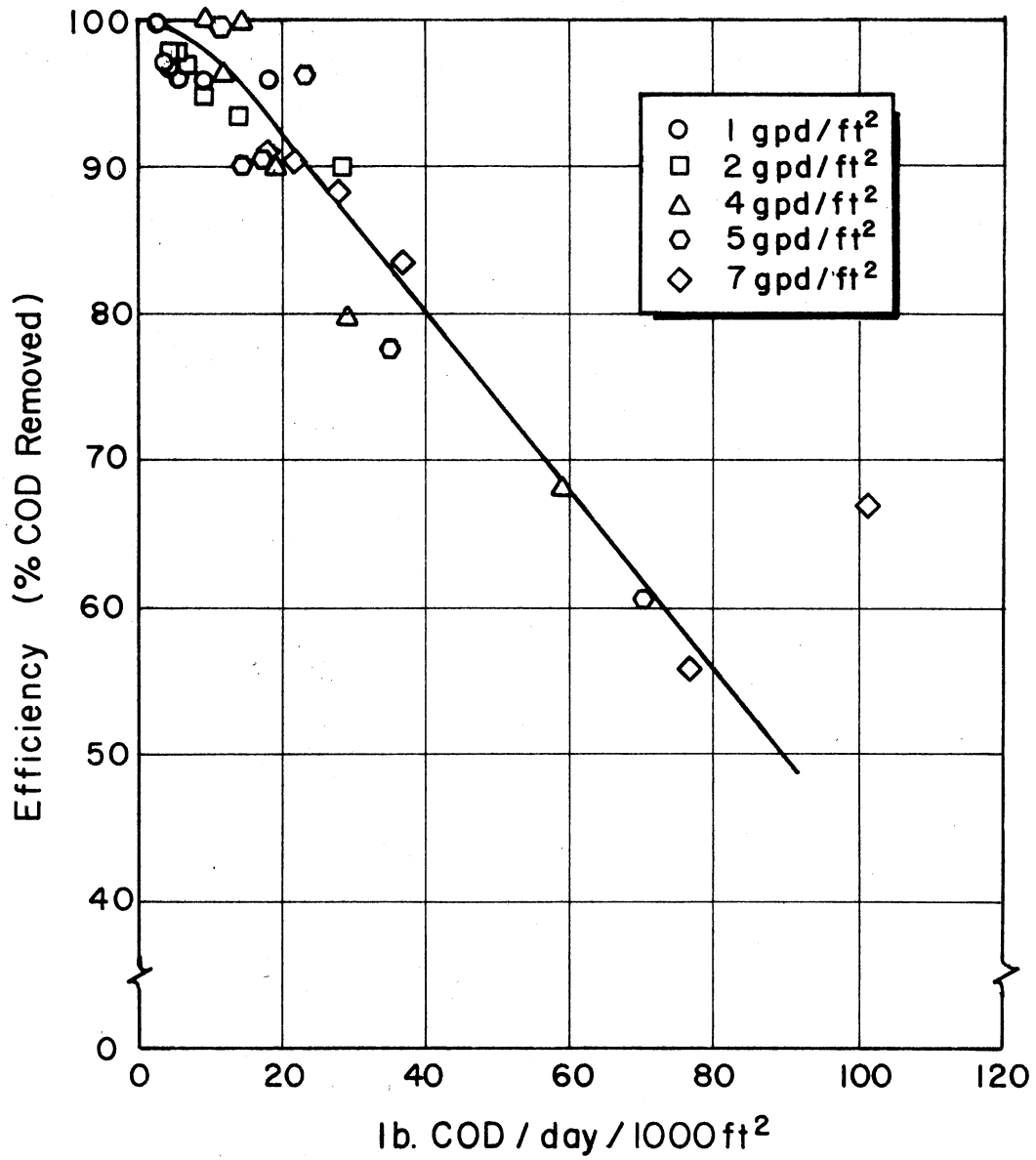

Figure 11. Efficiency (% COD Removed) vs. Total Organic Loading (lb COD/day/1000 ft^2) Using ΔCOD

axis at approximately 92%. This may possibly indicate a maximum attainable removal efficiency for total COD, and will be discussed in more detail later. Figure 11 shows that the points calculated using ΔCOD appear to follow a straight line except at its top where it seems to curve into 100%. The 100% efficiency was expected since the residual non-biodegradable COD was eliminated.

Biological Solids

The biological solids concentrations in the different stages for the various hydraulic flow rates are shown in Figure 12. It should be noted that due to the large masses of sloughed solids present in the mixed liquor and the resulting difficulty in collecting a representative sample, the data obtained is a fairly rough approximation. As can be seen in the figure, there was a general tendency of the solids concentration in the mixed liquor, to decrease with increasing hydraulic loading. This was particularly true in the first two stages, and was visibly noticeable when the unit was in operation. The reason for this decline in solids concentration as the flow rate increased, is thought to be the decreased detention time in the stages at the higher flow rates. The solids were washed out of the unit at a faster rate when the flow rate was increased. The relatively large concentration of solids in the sixth stage, shown in the figure, are a result of the solids' inability to pass over the weir and out of the unit. This resulted in the accumulation of solids in the sixth stage.

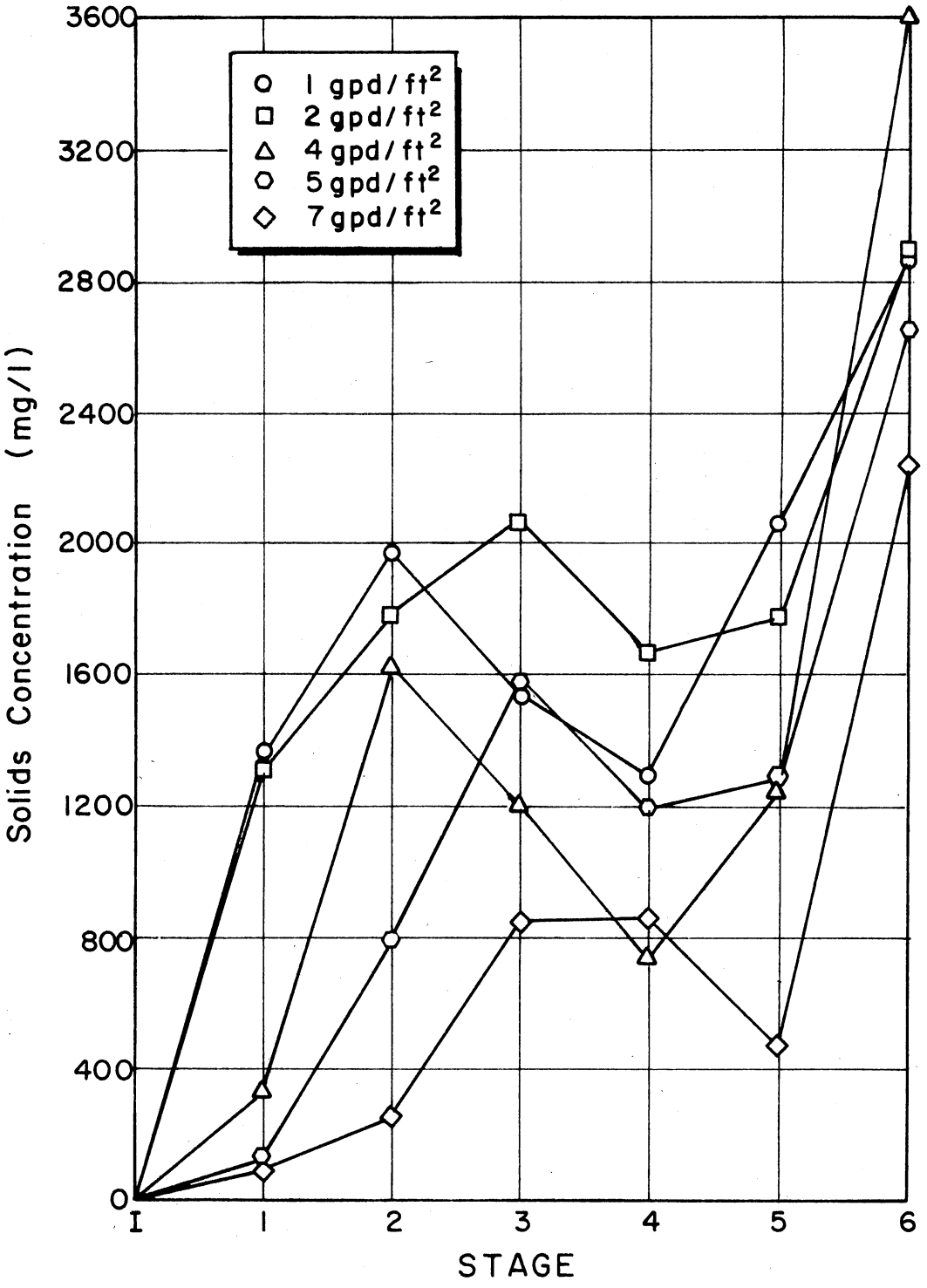

Figure 12. Solids Concentration vs. Stage for All Hydraulic Loadings

Batch Growth Studies

Table III lists the results of the batch growth study experiments. The variable D represents the dilution rate, or reciprocal of detention time. The dilution rate is equal to the flow rate divided by the reactor volume. In this case, the volume of the rotating biological contactor tank was used to calculate D. The dilution rate has been shown to be very valuable as a means of explaining the performance of continuous flow reactors. As can be seen from the table, there are two sets of data for each hydraulic flow rate. This is due to the fact that two different seed samples, one from the first stage and one from the fourth stage, were used to innoculate the batch experiments. As mentioned previously, this was done in order to compare the growth kinetics in two separate regions of the unit. It is evident from the table that the μmax and Y values for the two stages were very close to the same for the various flow rates. The K_s values were comparable, but seemed to indicate a slight difference in the behavior of the microorganisms in the first and fourth stages. With the exception of the first hydraulic loading, K_s for the fourth stage was higher than that of the first stage. Whether or not the K_s values obtained actually represent a significant difference in the behavior of the first and fourth stage microorganisms is a matter for further investigation. The cell yield data at the various flow rates ranged from a high of 0.68 at 1 gpd/ft^2, to a low of 0.27 at 7 gpd/ft^2. This range is comparable with typical values for activated sludge. The μmax values shown in the table begin at approximately 0.2 at the initial flow rate and

TABLE III

KINETIC CONSTANTS AT VARIOUS HYDRAULIC LOADINGS

Hydraulic Loading	Seed	D (hr^{-1})	μ max (hr^{-1})	K_s (mg/l)	Y
1 gpd/ft^2	1st Stage	0.197	0.21	96.1	0.68
	4th Stage	0.197	0.22	79.1	0.53
2 gpd/ft^2	1st Stage	0.393	0.38	42.1	0.48
	4th Stage	0.393	0.39	72.1	0.49
4 gpd/ft^2	1st Stage	0.786	0.53	84.2	0.42
	4th Stage	0.786	0.48	114.4	0.40
5 gpd/ft^2	1st Stage	0.983	0.41	60.5	0.44
	4th Stage	0.983	0.41	66.2	0.51
7 gpd/ft^2	1st Stage	1.376	0.39	56.9	0.32
	4th Stage	1.376	0.36	116.0	0.27

peak out at approximately 0.5 for a flow rate of 4 gpd/ft^2. At higher hydraulic loadings, μ max decreases. This would seem to imply that 4 gpd/ft^2 represents an optimum hydraulic loading for maximum growth of the mixed liquor microorganisms.

The importance of the dilution rate, D, in explaining the performance of the unit was mentioned previously. Gaudy and Gaudy (42) have explained that the relationship between μ and D is very important in maintaining a population of microorganisms in a continuous flow system. In effect, the dilution rate, D, must be less than or equal to the growth rate μ in order to prevent the cells from being washed out of the unit. In other words, the cells must be replaced at a rate, μ, at least equal to the rate at which they are washed out, D. Figure 13 compares the dilution rate with the average maximum growth rate at each hydraulic loading. As can be seen from the figure, the dilution rate of the first two hydraulic loadings, 1 gpd/ft^2 and 2 gpd/ft^2, is less than or approximately equal to the values for μ max. The remaining flow rates have dilution rates much higher than the corresponding maximum growth rates. This suggests that the mixed liquor suspended solids are growing fast enough to maintain a cell population in the unit at the low flow rates, but are washed out faster than they can be replenished at the higher flow rates. As mentioned earlier, the concentration of mixed liquor suspended solids was visibly and graphically observed to decrease as the hydraulic loadings increased. This observation may now possibly be explained by the comparison of μmax and D described above and shown in the figure.

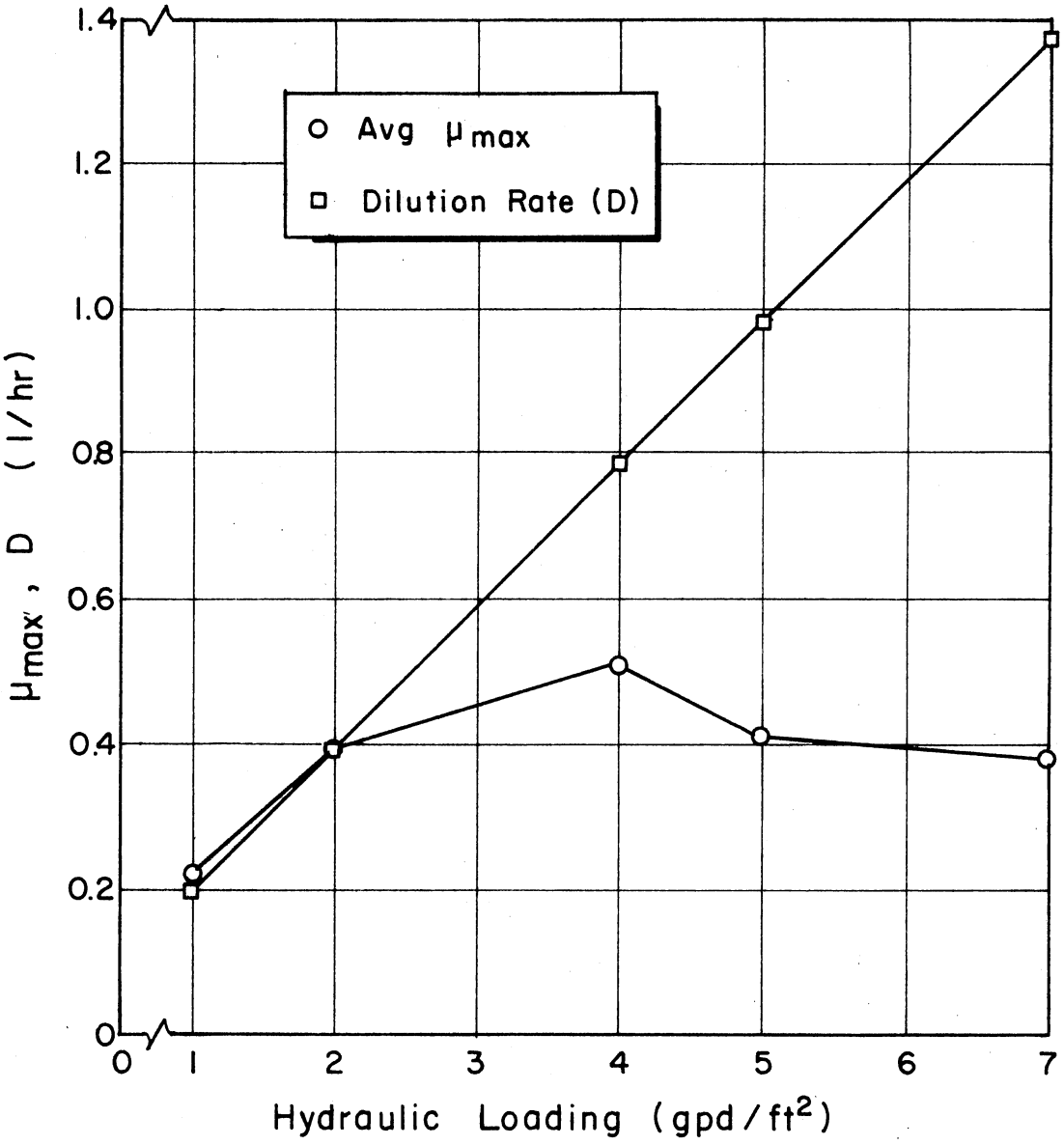

Figure 13. Maximum Specific Growth Rate and Dilution Rate vs. Hydraulic Loading

Substrate Utilization Per Cell

Figures 14 and 15 represent an attempt to describe the substrate utilization of the cells in the unit as a straight line relationship. This is done by plotting $(S_i-S_e)/X$ against S_e. Where S_i-S_e represents the COD removed up to a particular location in the unit, X represents the active portion of the disc surface area microbial population, and S_e is the COD concentration of the effluent at the particular location in the unit. It is evident that an accurate estimate of the amount of biological solids present on the discs and actively participating in the substrate removal, is not easy to make. The X used in these calculations was derived by multiplying the total disc surface area previous to the location at which S_e is taken, times the density of the microorganisms, times the thickness of the substrate removing cells. The active film thickness used in these calculations was 70 μm, while the density of the cells was assumed to be 95 mg/cm^3. Both of these numbers represent experimental values observed by Kornegay and Andrews in their study of fixed film kinetics (24). As can be seen in Figure 14, the data points using total COD appear to approximate two separate straight lines of different slopes. The points corresponding to 1 gpd/ft^2 and 2 gpd/ft^2 seem to fit a straight line with a steep slope, while the data points for the remaining hydraulic loadings more closely fit a straight line with a smaller slope. This implies that the lower hydraulic loadings, 1 gpd/ft^2 and 2 gpd/ft^2, have a much higher removal rate than the higher hydraulic loadings. The points also seem to intersect the S_e axis at approximately 30 mg/l. Since this plot uses total COD rather than

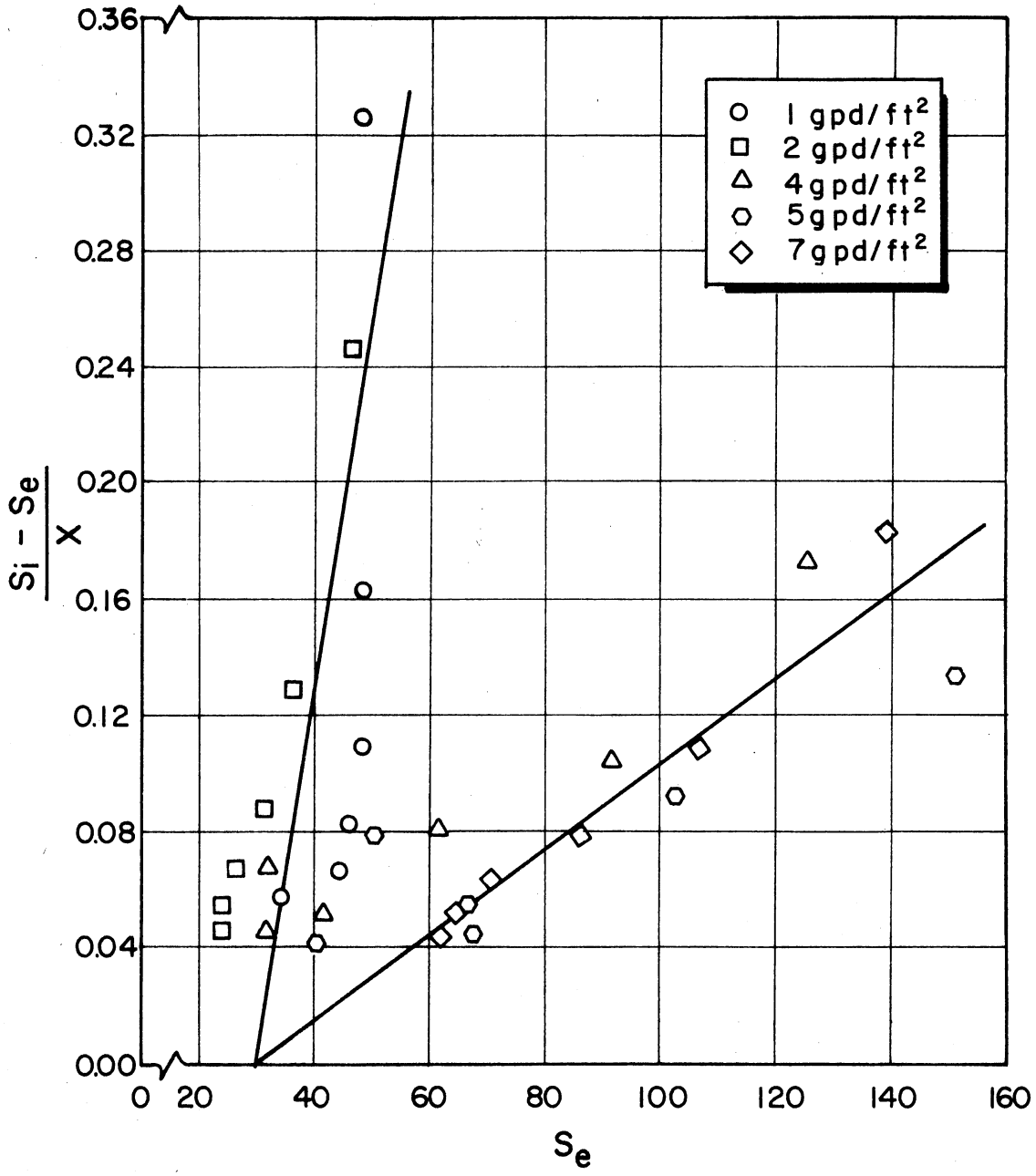

Figure 14. Substrate Utilization Per Solids Concentration vs. Effluent Substrate Concentration Using Total COD

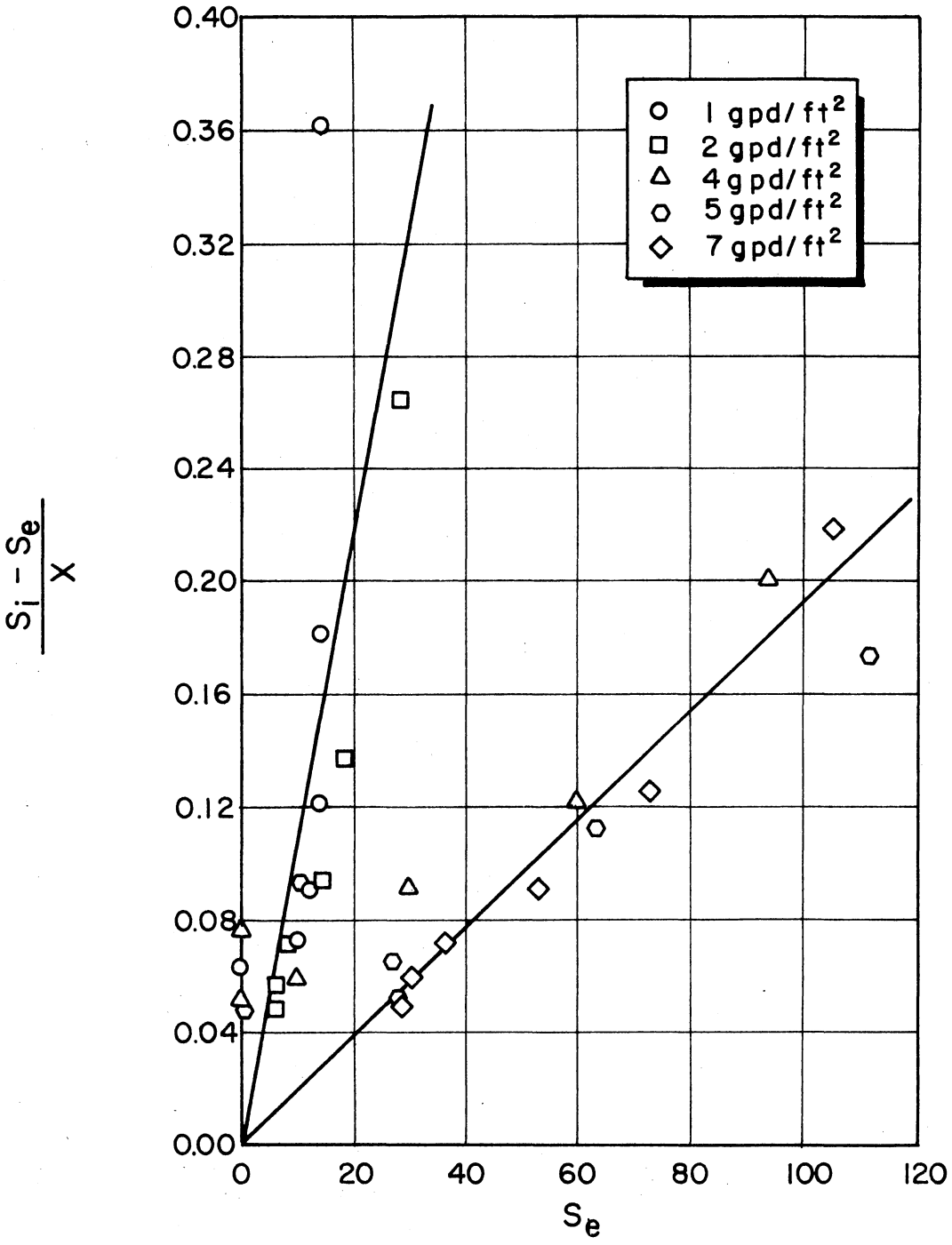

Figure 15. Substrate Utilization Per Solids Concentration vs. Effluent Substrate Concentration Using Δ COD

Δ COD, the S_e value of 30 mg/l may be related to the residual non-biodegradable COD. When the data is plotted up using ΔCOD, (See Figure 15) the two resulting lines appear to intersect the S_e axis at the origin.

Figure 16 shows a modified form of the straight line expression used for Figures 14 and 15. This modified form includes the contribution of the mixed liquor suspended solids by adding a new term to the expression for substrate utlization per solids concentration. The term "X_mV" is now added to the fixed film biological solids, X. Like X, X_mV is a summation of the solids in each stage up to the point where S_e is taken. This new term is the summation of the product of the experimentally determined biological solids concentration and the volume, for each stage. However, since the growth study data and the biological solids data indicate that the mixed liquor suspended solids are not contributing to substrate removal at the higher hydraulic loadings, the term X_mV is only included at 1 gpd/ft^2 and 2 gpd/ft^2. As can be seen from the figure, the data points now appear to approximate a single straight line rather than two separate lines with different slopes. It should be emphasized that this plot is derived using ΔCOD. If total COD had been used, the line would not pass through the origin, but instead would have intersected the S_e axis at some value close to the residual COD value.

Figure 17 shows the same plot as Figure 16, except that now the detention time is included in the substrate utilization per cell term. This was another attempt to obtain a straight line relationship and at the same time, a possible design equation. As can be seen from the

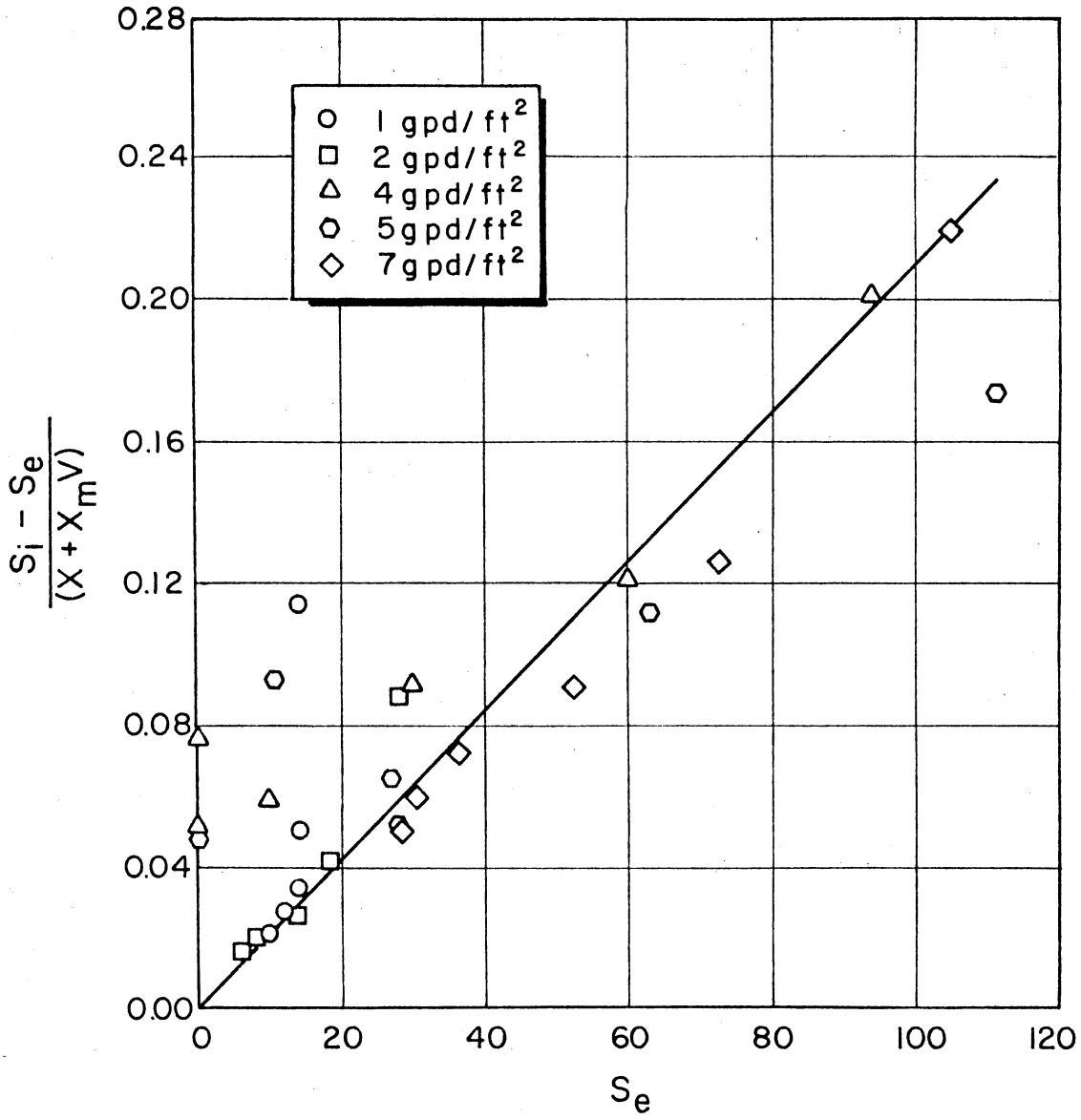

Figure 16. Modified Substrate Utilization Per Solids Concentration vs. Effluent Substrate Concentration Using ΔCOD

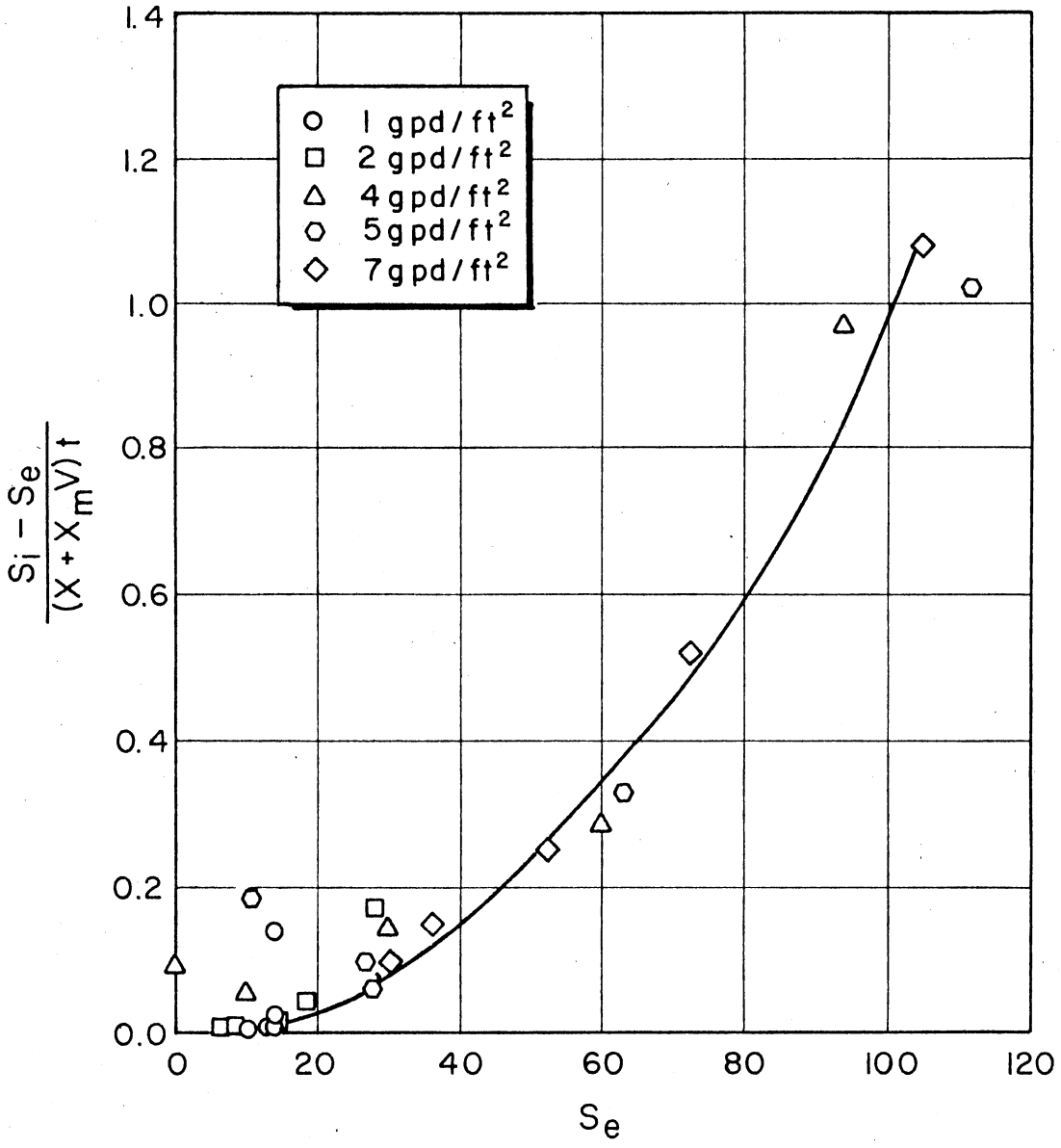

Figure 17. Modified Substrate Utilization Including Detention Time Per Solids Concentration vs. Effluent Substrate Concentration Using ΔCOD

figure, there is not a simple straight line relationship, since the points seem to follow a curve.

CHAPTER V

DISCUSSION

The purpose of this investigation was to acquire some insight into the kinetics of the rotating biological contactor with special attention paid to the contribution of the mixed liquor suspended solids. While a considerable amount of work has been done on the fixed film kinetics of the trickling filter and the suspended culture kinetics of the activated sludge process, very little, if any, research has been conducted on the combination of these two kinetic mechanisms in the rotating biological contactor. In fact, for the most part, the rotating biological contactor has been treated as a moving trickling filter. This study provides indicative results supporting the presence of both kinds of kinetic mechanisms in the process.

Biological Solids Concentration

The behavior of the biological solids during the operation of the unit provided the first indications that they played an active part in the substrate removal. At the initial two hydraulic loadings, the biological solids concentration was observed to be very thick, particularly in the first two stages of the unit. As the hydraulic loadings increased, the solids concentration in the mixed liquor became less dense. This behavior was confirmed in Figure 12. As

noted earlier, this behavior suggested that the solids were being washed out of the unit faster than they could replenish themselves at the higher flows. At the lower flow rates, the solids were able to maintain a dense population in the mixed liquor. This constant microbial population provided an indication that the mixed liquor might be contributing to the substrate removal.

Batch Growth Studies

The second indication of mixed liquor suspended solids substrate removal is evident in the results of the batch growth studies. The μ max values of the suspended cells were found to be greater than or equal to the dilution rates at the 1 gpd/ft^2 and 2 gpd/ft^2 hydraulic loadings (See Table III). This suggested that the cells were growing faster than, or at the same rate as they were being washed out, and therefore were probably metabolizing exogeneous organic substrate in order to maintain their population. This conclusion corroborates the earlier observation of the biological solids concentration behavior.

COD Removal Efficiency

As was seen earlier in Figures 5-9, the best removal efficiencies were achieved at the hydraulic loadings of 1 gpd/ft^2 and 2 gpd/ft^2. While this may be attributable to the low total organic loading, it is possible that the excellent removal capacities at these two flow rates were due in part to the activities of the mixed liquor suspended solids.

The efficiency curves produced in Figures 10 and 11 can also be

used to support the argument of removal by the suspended cell concentration. Figure 10 shows an inverted S-shaped curve (dashed) which intersects the efficiency axis at 92% and may represent the maximum total COD removal possible. It can be seen from the figure that at low total organic loadings the efficiency is less affected by changes in the total organic loading. As the total organic loading increases, the curve becomes steeper and the efficiency is more greatly affected. At the low total organic loadings, the mixed liquor suspended solids are assumed to be participating in the removal, and therefore help maintain the same efficiency. As the total organic loadings increase with increasing hydraulic loadings, the mixed liquor suspended solids are not able to grow due to the high dilution rate, and therefore cease to contribute to the removal. As a result, the efficiency of the unit drops more rapidly as the total organic loading is increased. Figure 11 shows a fit to the data begins as a curve, but then approximates a straight line. The curved portion of this line is also attributed to the effects of the mixed liquor suspended solids for the same reasons mentioned above. The straight line portion of the line indicates that there may be a straight line relationship at higher loadings.

Substrate Utilization Per Cell

Figures 14 and 15 are an attempt to describe the performance of the unit by a straight line relationship using only the fixed film solids, X. As can be seen from the figures, two separate lines were obtained indicating two separate rates of removal. One rate of removal was for the initial hydraulic loadings of 1 gpd/ft^2 and

2 gpd/ft^2 and the other was for the remaining hydraulic loadings. The intersection of these lines at a value of 30 mg/l on the S_e axis in Figure 14 was taken to be a measure of the residual which should be expected. When a comparison was made with the experimental residual values obtained, it was found that the average of the residuals at all of the hydraulic loadings was equal to 32 mg/l, which is very close to the 30 mg/l shown in the figure.

After examining these results, it was decided that a second attempt at the straight line relationship should be made incorporating the mixed liquor suspended solids into the calculations. The results of this change are evident in Figure 16. What was formerly two sets of points corresponding to two separate removal rates is now an approximation of a straight line. The high $(S_i-S_e)/X + X_mV$ values for the lower hydraulic loadings, which constituted the steeper removal rate line, have been brought down in closer correlation with the data from the higher flow rates by including the mixed liquor suspended solids in the calculations. This resulted in all of the hydraulic loadings more closely matching a single removal rate line. The effect of including the suspended solids as part of the active substrate removing microbial population therefore results in a better fit of the data and most important, indicates that they play an active part in the removal kinetics of the unit. Figure 16 therefore apparently represents a fair approximation of a straight line relationship where $(S_i-S_e)/X+X_mV$ is proportional to S_e by a constant.

Figure 17 represents an attempt to utilize this relationship by further modification as a useable design relationship using detention time. As can be seen from the figure, the incorporation of t into

the equation did not result in a simple straight line relationship. The development of a design equation was therefore left as a topic for further investigation.

CHAPTER VI

CONCLUSIONS

The results of this study support the following conclusions:

1. At low hydraulic loadings, it is possible for the rotating biological contactor to behave as a combination of the fixed film and suspended culture type processes. Substrate removal is accomplished by the microorganisms fixed on the discs, and the mixed liquor suspended solids. At higher hydraulic loadings, the effects of the mixed liquor suspended solids are nil and substrate removal is accomplished solely by the disc solids.

2. A simple straight line relationship between substrate utilization per cell and effluent substrate concentration can be approximated by including the mixed liquor suspended solids in the calculations.

3. A non-biodegradable residual COD, presumably metabolic intermediates, is found in the effluent and results in lower removal efficiency values if not accounted for.

CHAPTER VII

SUGGESTIONS FOR FURTHER STUDY

1. Run a chemical analysis to determine the composition of the residual COD.

2. Determine where the metabolic intermediates are formed in the unit by sampling at each stage for residual COD.

3. Derive a design relation which includes the mixed liquor suspended solids as part of the active microbial population at low flow rates.

4. Evaluate the relationship between tank volume and disc surface area at different loadings to obtain an optimum ratio.

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