# THE EFFECT OF SURFACE AREA ON THE PERFORMANCE OF A FIXED BED REACTOR

By

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# THE EFFECT OF SURFACE AREA ON THE PERFORMANCE OF A FIXED BED REACTOR

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# CHAPTER I

# INTRODUCTION

Within the past few years the word "pollution" has become common in the vocabulary of the general public. This public interest has generated action within private companies as well as the government to take a real look at the environmental problems and find some means to alleviate them. Waste waters from many industries and municipalities present a direct threat to the water quality and aquatic life of the streams, lakes and oceans of the world. The preservation of our water resource can be accomplished only by careful management and treatment of our waste waters.

Biological processes have been employed for many years as a means to treat waste water. One of the oldest unit operations still in use today is the fixed bed reactor or trickling filter. The filter bed is usually circular in shape, about eight feet in depth, with a diameter that depends upon the volume necessary for the designed loading. The filter medium provides a porous fixed bed on which a biological slime growth exists. The organic portion of the waste flow is assimilated and thus removed by the biological organisms during their life processes.

It has been shown in the past, as reported in the literature review, that as the specific surface of a filter medium was increased so was the removal efficiency. However, in the literature that was reviewed, it was found that no investigation had been carried out under controlled organic and hydraulic conditions. The temperature of the waste flow was nearly always noted to have an effect because the performance of the filter varied as the seasonal changes occurred. Also, in many investigations the specific surface area had to be estimated for the filter medium that was used.

The investigation that is reported herein was undertaken to eliminate the different operational factors which affect the performance of a trickling filter. The single parameter which was varied was the specific surface area within the filter. This was accomplished by changes in the filter medium itself.

# CHAPTER II

## LITERATURE RESEARCH

The removal efficiency of a fixed bed reactor (trickling filter) has been professed to be a function of one or more parameters of the filter. One of the first design formulations for trickling filters was developed from actual data obtained from treatment facilities by the National Research Council. This design involved the parameters of applied loading, volume of the filter, and a recirculation factor. Since only conventional stone medium was in use at the time, the volume of the filter was a direct indication of the total surface area provided by the filter. The existence of a standard medium also afforded a consistency in the contact or retention time of the waste water in the filter.

Even though a standardized medium of stone has evolved through the years, there has been considerable investigation of other types of material that could be utilized in the biological filtration process. Also, the development of a commercial plastic packing within the past ten years has caused a real probing of the parameters that affect the performance of trickling filters.

In 1936 Levine (1) reported the results of his investigations using different types of media. In a preliminary study using a synthetic substrate consisting of a mixture of dried sheep manure and powdered skim milk, two different media were investigated. A ceramic type material known as Raschig rings and one to three inch crushed granite were used as the filter media. Three different feed concentrations of 117, 567, and 999 mg/l BOD at a hydraulic flow rate of two million gallons per acre per day were investigated. The filter medium was placed into iron tanks six feet in depth. Composite samples were taken and analyzed for BOD and nitrates. It was found that the larger surface area provided by Raschig rings resulted in the best removal at all organic concentrations. The most significant difference in removal was observed at the 999 mg/l concentration. At this concentration the rings also produced the greatest nitrate content in the effluent.

Further investigations using domestic sewage as a substrate were undertaken. In these experiments five different medium sizes were studied ranging in specific surface area from 19 to 75 square feet per cubic foot. Crushed granite, four different sizes of Raschig rings, and a type of building block provided the wide range of surface areas and percent voids. Hydraulic loadings of two, four, eight, and sixteen million gallons per acre per day were applied to the different filters. Except for the eight million gallons per acre per day flow rate, the best removal efficiencies were obtained by 3/4 and 1 inch Raschig rings which provided the two highest surface areas of 75 and 52 square feet per cubic foot. The highest nitrate production was also afforded by the 3/4 inch Raschig rings.

In 1943 Goldthorpe (2) summarized the results of Levine (1) and the results obtained from the Dorking experiments of the Royal Commission. Both of these reports point to the fact that increasing the surface area per unit volume will in turn increase the percentage of removal, but a linear relationship between the two did not exist.

Rudolfs (3) investigated crushed stone and slag each in two gradations: 3/4 to 1 1/2 inch referred to as the "Small" medium and 2 to 3 inch gradation size called "Large." The filters received a settled sewage influent with an average concentration of 175 mg/l. The stone and slag in the small gradation gave a better removal efficiency than either material in the larger size. Nitrate production was also higher with the smaller medium. It was also observed that the fine material in either size attained a 10 to 20 percent better removal efficiency than the coarser medium.

A dimensionless product was proposed by Gerber (4) which is dependent upon filter depth, dosing rate, and BOD reaction rate. He claimed that no filter or its efficiency can be explained by one variable.

Schulze (5) claims that efficiency is based upon two main factors: (1) the amount of active film per unit of filter volume which is dependent upon the surface available and the supply of substrate and oxygen and (2) the contact time which is a function of filter depth and hydraulic loading. Therefore, he concludes that one way to improve the removal efficiency is to increase the amount of active film.

Using two plastic media, Dowpac and Polygrid, Egan and Sandlin (6) report removal efficiencies of 27 and 25 percent, respectively, in treating a pulp and paper mill waste. In previous data collected the Dowpac had afforded an efficiency of 40%, but due to a structural failure, and therefore a reduction in original surface area, the removal capabilities of the medium had been reduced. The maximum removal was observed at a temperature of $55^{o}$ C.

Minch et al. (7) reported an average 43% reduction in BOD from two filter units twenty feet in height containing Surfpac and Polygrid. The efficiency of the filters remained at a constant level for a range of 200 to 800 pounds of BOD per 1000 cubic feet per day applied loading. Temperatures of the paper waste had a considerable effect upon the efficiency of the filters. The efficiency of the units increased substantially when the temperature of the waste exceeded 45° C. A third medium, Koroseal, was also reported to attain efficiencies of 45% or better under similar loading conditions of the previous two media.

In 1963 Truesdale and Eden (8) reported the results of a pilot plant study involving eight media which gave a range of surface areas between 19.7 and 61.5 square feet per cubic foot. During a two year investigation two dosing rates of three and six minutes were applied to the filters, the greater film accumulation occurring at the smaller dosing interval. The winter weather was noted to have a definite effect on the performance of the filters. The best all-around efficiency during the entire period of study was provided by the one inch clinker which had the greatest specific surface area of the media investigated. The effect of depth was shown by comparing the percent BOD remaining at different depths. This relationship indicates that a depth greater than six feet will not remove a residual BOD of four to nine percent of the influent BOD of the sewage.

Filter media of asbestos (25 $ft^2/ft^3$) and Polygrid (30 $ft^2/ft^3$) were studied by Eckenfelder (9) using a black liquor feed concentration of 400 mg/l as the substrate. Results indicated that as the hydraulic loading was increased from 0.75 $gpm/ft^2$ to 1.5 $gpm/ft^2$ the efficiency of the Polygrid medium dropped approximately 20%. The increased hydraulic loading had very little effect on the removal efficiency of the asbestos medium. At the flow rate of 0.75 gpm/$ft^2$ the Polygrid provided a 20% better removal efficiency than did the asbestos. The higher hydraulic loadings resulted in a heavy accumulation of slime on both types of media. This excessive slime growth lead to a decreased efficiency of both filters.

Chipperfield (10) in 1964 reported that polyurethane foam cubes with about the same specific surface area as a coke medium could operate as efficiently as the coke at a 50% higher hydraulic loading using sewage as the substrate.

A theory presented by Meltzer (12) said that "the cardinal factor controlling efficiency is the hydraulic surface loading." He states that there exists an optimum hydraulic surface loading which results in maximum removal efficiency. The detention time is also noted to be a physical characteristic dictated by the surface area of the filter medium and that an increase in detention time will improve the efficiency of the filter.

Eden et al. (13) made a comparison of 2 1/2 inch rounded gravel (19.7 $ft^2/ft^3$) and a plastic medium (25 $ft^2/ft^3$) using sewage with a 250 mg/l BOD as a carbon source. After five months of operation at a flow rate of 500 gal/$yd^3$/day the better effluent on the average was being produced by the granite which had the smaller surface area of the two packings investigated.

Two plastic packings with surface areas of 25 and 50 $ft^2/ft^3$ were found by Chipperfield (14) to produce similar removal efficiencies in the BOD loading range of 50 to 250 kg/$m^3$/day. The removal percentage was observed to approach a constant value as the applied organic loading was increased. The constant removal percentage was explained by referring to Schulze's theory (15) and Chipperfield (18) (20) which state that the filter is operating in a manner similar to an adsorption process.

A pilot plant study conducted by Gerlich (16) involving Surfpac lead to the design of a filter to treat a combination of municipal and industrial wastes. Because of the organic design loading of 157 lb/1000 $ft^3$/day only two plastic packed filter units were required compared to fourteen rock filters which would have been necessary if the Ten State Standards design criteria of 50 lb/1000 $ft^3$/day had been used. Operational data of the plastic medium showed a 10% better efficiency than that of the pilot unit. It was also noted that the dissolved oxygen content was higher in the effluent from the new plastic filter than from the existing rock filters.

Pearson (17) investigated the treatment of eight different industrial wastes using Flocor as the filter medium. The minimum efficiency reached was 55% when treating a molasses waste stream.

Berridge and Brendish (19), using Surfpac as a filter medium and a mixture of sewage and sludge liquor from a heat treatment process as the substrate, developed a formula to describe the efficiency which was based on the half-life of BOD within the filter and percent tracer recovered. An optimum wetting rate or hydraulic loading was said to exist and to attain the maximum removal of BOD the feed concentration must be increased.

Chipperfield (20) states that the ideal medium should have "the greatest practical area of surface on which bios can grow per unit weight of material." BOD removal is reported to be a function of the biological film present which is dependent upon the surface area of the filter medium. This relationship is said to exist provided that there is an adequate oxygen supply and the percentage of voids is such to prevent clogging.

Bryan and Moeller (22) using phenol as a substrate reported a twenty percent higher efficiency for Dowpac 10 as compared to stone. The calculated surface areas of the two media differed only by 1 1/2 square feet, but the percent voids of Dowpac was 94% as compared to 37% voids for the stone.

Cook and Kincannon (23), using corrugated fiberglass sheets, which provided a surface area of 50 $ft^2/ft^3$, and a substrate of sucrose, reported that the substrate removal rate approached a constant value at high total organic loadings. This observation agrees with the findings of Chipperfield (14), (18), (20) in that a constant percentage of removal is attained above a given BOD loading for a particular waste.

Audoin et al. (24) reported in 1970 the results of pilot studies involving a synthetic medium "Cloisonyle." Three different filter depths of two, four, and six meters were employed. Using settled sewage as the carbon source the hydraulic loading was varied to produce different total organic loadings on each filter. All three filters maintained a constant relationship between BOD removed and BOD applied. This relationship revealed itself in a common removal rate for all three filters.

Rincke and Wolters (25), using sugar molasses as a carbon source, show that from four different media the better efficiency was produced by the two media with the larger surface areas.

Investigations made by Bruce (26) involving four different plastic packed filters and two aggregate filters showed a definite correlation between surface area and removal characteristics. Sewage was the carbon source used in this investigation and the surface areas ranged from 12 to 67 $ft^2/ft^3$. Bruce states that with the exception of one filter "the average proportion of the applied BOD remaining in the settled filter effluents was essentially a simple inverse logarithmic function of the specific surface of the medium." The one filter that varied in behavior was Cloisonyle which had the highest surface area of 67 $ft^2/ft^3$. The reason for its lower efficiency is explained by the geometric design of the media which consisted of continuous vertical tubes.

# CHAPTER III

## MATERIALS AND METHODS

The pilot filter units employed in this study consisted of four plexiglass compartments each enclosing a volume of one cubic foot. The particular filter medium to be studied was placed inside the plexiglass compartments. The four one foot filter boxes were then placed on top of one another with a three inch spacer between boxes to allow room for samples to be collected.

Four filter packings with different known surface areas per unit of volume were used in this investigation. Two of the plastic packings were of the commercial type and the other two were fabricated from corrugated fiberglass sheets. The plastic medium Flocor was developed by the Imperial Chemical Industries Limited in England and is being distributed by the Ethyl Corporation in the United States. The Flocor medium provides 27 $ft^2/ft^3$ specific surface area with a 97 percent void ratio. The other commercial medium used was Koroseal Vinyl Cor which is produced by the B. F. Goodrich Industrial Products Company. A surface area of 37 $ft^2/ft^3$ and a 97 percent void space is reported (27) for the Koroseal medium. The two fabricated plastic packings were constructed out of corrugated fiberglass sheets. Two different surface areas of 12 and 50 $ft^2/ft^3$ were obtained by placing six or twenty-five fiberglass sheets respectively within the plexiglass compartments. The spacing in the 50 $ft^2/ft^3$ filter was such that any free-fall of the waste flow was prevented. Because of the wider spacing of the fiberglass sheets in the 12 $ft^2/ft^3$ medium, five L-shaped pieces of aluminum were placed so as to direct the waste flow onto the sheets of fiberglass and thus to prevent any free-fall through the gaps between the sheets.

The waste used in this investigation was derived from a carbon source of sucrose. The composition of the substrate (see Table I) was such that the carbon source was the limiting growth factor. To obtain the desired organic feed concentration a twenty liter carboy of concentrated substrate was prepared. This concentrated substrate solution was such that when mixed with the flow of tap water the desired filter feed concentration was obtained. The above procedure was accomplished by calculating the required amount of each synthetic waste constituent for a particular feed concentration and hydraulic flow rate for a 24 hour period. This amount was then placed in the carboy and diluted with tap water to a volume of twenty liters. Approximately fifteen milliliters of concentrated sulfuric acid was also added to the concentrated feed solution to suppress any biological growth and to help keep the salts in solution.

The hydraulic flow rate was controlled by the use of a constant head tank connected to a rotameter by which the flow was measured. However, before the water entered the constant head tank, it was heated so that a constant temperature of 20° C ± 1 was maintained in the wet well. The heating was accomplished by the flow of tap water through a coil of copper tubing which was immersed in a water bath. As shown in Figure 1 the flow from the rotameter went directly into a wet well. The function of the wet well was to provide a place where the tap water coming from the constant head tank and the concentrated waste from the

## TABLE I

## COMPOSITION OF GROWTH MEDIUM FOR 100 mg/l SUCROSE AS THE GROWTH-LIMITING NUTRIENT AT A FLOW RATE OF 100 GPD/SQ. FT.

| Constituent | Concentration |
|---|---|
| Sucrose | 100 mg/l |
| $Na_2HPO_4 \cdot 12H_2O$ | 12 mg/l |
| $MgSO_4 \cdot 7H_2O$ | 10 mg/l |
| $FeCl_3 \cdot 6H_2O$ | 0.05 mg/l |
| $CaCl_2 \cdot 2H_2O$ | 0.75 mg/l |
| $MnSO_4 \cdot H_2O$ | 1.0 mg/l |
| $(NH_4)_2 SO_4$ | 25 mg/l |

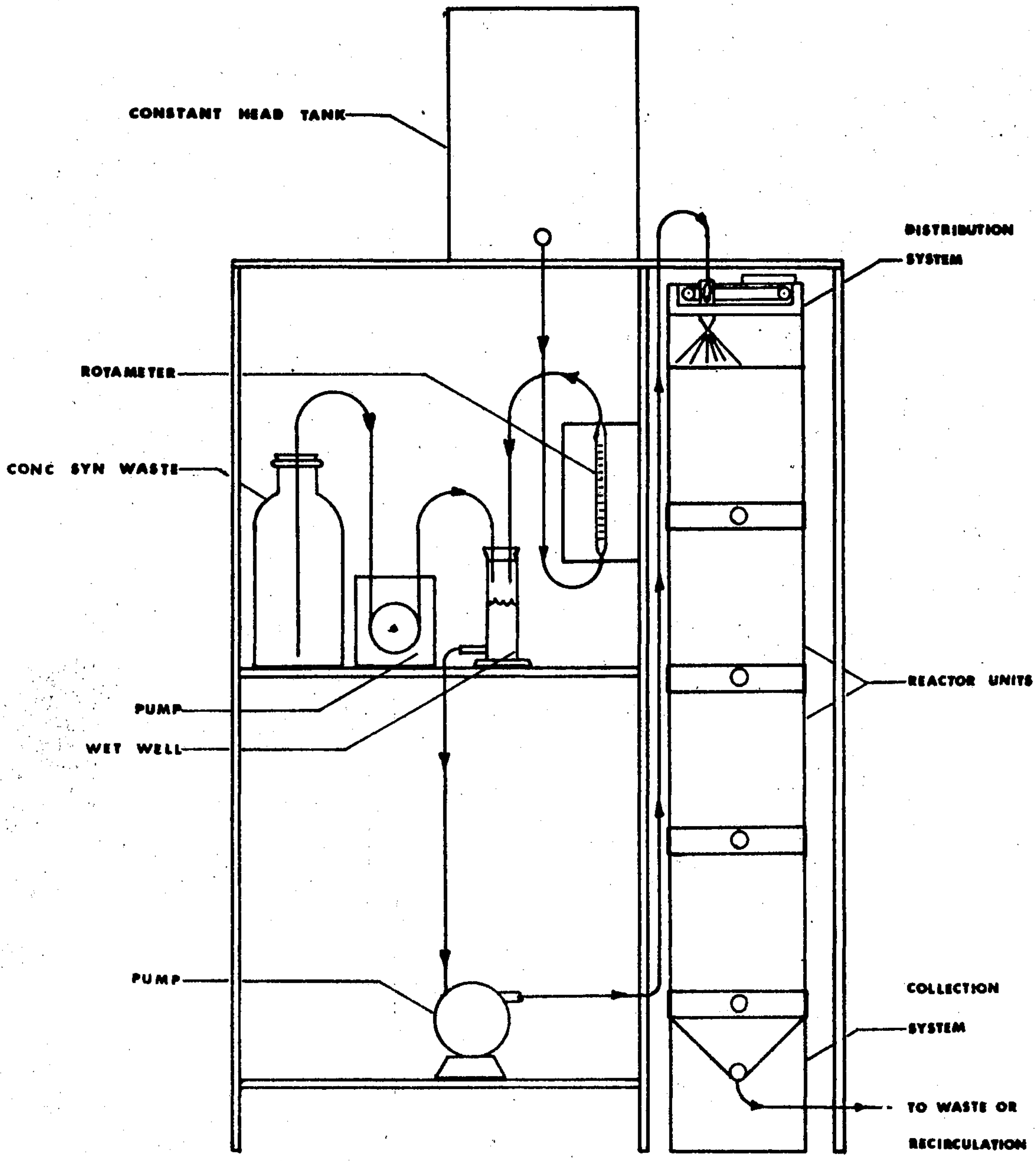

Figure 1. Laboratory Filter Unit.

twenty liter carboy could be mixed. Since rotameters provided the proper flow into the wet well, the pumps were adjusted so that a constant level in the wet well was maintained and thus the desired flow rates were applied to the filters.

The mixed feed was pumped by means of a "progressing-cavity" type pump. The pump was driven by a constant speed electric motor with a "pulley-fan belt" type connection between the two. The pump was modified with a recirculation line and valve so that a portion of the discharge could be recirculated. The valve enabled the amount of recirculation to be controlled and thus the actual output of the pump to the filter units was also controlled.

The feed was distributed on the filter by means of a spray nozzle connected to a reciprocating mechanism. This mechanism was powered by an electric motor with a sprocket type drive which enabled the spray nozzle to be driven back and forth across the filter. The combination of the spray from the nozzle and its movement provided a complete and even distribution of the feed to the filter's top surface.

Only two complete filter units as previously described were available. Since four different filter media were to be investigated the filter units were broken down and the plastic media replaced during this experimentation. The first two plastic media tested were Flocor (27 $ft^2/ft^3$) and the fabricated medium with 50 $ft^2/ft^3$ of surface area. The units were assembled and set into operation on December 6, 1970. The seeding of the units was accomplished by using the effluent of the primary clarifier from the Stillwater sewage treatment plant. The settled sewage was introduced into the system by allowing it to flow into the wet well where it was mixed with the feed and pumped to the filter. The seeding process was continued for four days until a definite growth could be observed in the filters. During the initial start up period many mechanical problems were encountered and therefore the filter units were not operating under equilibrium conditions. A period of approximately four weeks was needed before the biological film appeared to reach a growth equilibrium at a feed concentration of 200 mg/l and flow rate of 200 gpd. The equilibrium condition was established when consistent removal characteristics were observed for a three day period.

The feed at the spray nozzle was sampled immediately before collecting samples from the filter so that the exact feed concentration would be known. Samples were taken after each foot of filter depth with the aid of a plexiglass tube which had a portion of its wall removed to form a trough. The sampling tube was moved back and forth so that a random sample was obtained.

The pH of the samples was immediately determined using a Beckman pH meter and then recorded. Each sample was then filtered using HA 0.45μ Millipore filters. A chemical oxygen demand of the filtrate was then determined by the procedure outlined in Standard Methods (28) using a twenty milliliter sample size.

A minimum of three days was allowed for the filter to acclimate to a particular feed concentration and flow rate before any samples were taken. To assure that the filter had reached equilibrium, samples were taken once a day and analyzed until the results of a consecutive three day period were nearly identical. The COD's of the feed and of the four sampling depths were then averaged. From this data the percent COD remaining was calculated and plotted versus depth in feet on semi-logarithmic graph paper. The substrate removal rate "k" was then determined from this graph. The substrate removal rate "k" for each combination of feed concentration and flow rate was plotted versus the actual applied organic load measured in $gm/hr/ft^2$ of horizontal filter surface area. The COD removal efficiency was also plotted versus the actual applied loading ($gm/hr/ft^2$) on arithmetic graph paper.

The procedure previously outlined was carried out for each of the four filter media. The media which provided surface areas of 27 and 50 $ft^2/ft^3$ were subjected to eight different experimental runs of various flow rates and feed concentrations, while the other two media of 12 and 37 $ft^2/ft^3$ were tested at only four different loadings. The conditions of each experimental run are shown in Table II.

## TABLE II

### DATA SUMMARY OF TOTAL APPLIED LOADING, SUBSTRATE REMOVAL RATE "k" AND REMOVAL EFFICIENCY FOR THE FOUR SELECTED MEDIA AT VARIOUS FLOW RATES AND FEED CONCENTRATIONS

| Flow (gal/day) | Desired Feed Conc. (mg/l) | Actual Applied Feed Conc. (mg/l) | Applied Loading (gm/hr/ft$^2$) | Amount Removed (gm/hr/ft$^2$) | Percent COD Remaining | Substrate Removal Rate "k" | Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|
| 50 Ft$^2$/Ft$^3$ Medium | | | | | | | |
| 100 | 100 | 100 | 1.58 | 1.29 | 22 | 0.257 | 78 |
| 200 | 100 | 120 | 3.79 | 2.71 | 28 | 0.113 | 72 |
| 300 | 100 | 123 | 5.82 | 3.83 | 34 | 0.117 | 66 |
| 200 | 200 | 207 | 6.53 | 4.83 | 26 | 0.142 | 74 |
| 200 | 300 | 316 | 9.97 | 6.43 | 35 | 0.120 | 65 |
| 300 | 300 | 324 | 15.33 | 7.33 | 52 | 0.071 | 48 |
| 800 | 200 | 190 | 23.97 | 11.86 | 51 | 0.077 | 49 |
| 400 | 400 | 454 | 28.64 | 16.28 | 43 | 0.093 | 57 |
| 27 Ft$^2$/Ft$^3$ Medium | | | | | | | |
| 100 | 100 | 90 | 1.42 | 1.17 | 18 | 0.188 | 82 |
| 200 | 100 | 117 | 3.69 | 2.30 | 38 | 0.104 | 62 |
| 300 | 100 | 121 | 5.72 | 3.36 | 41 | 0.096 | 59 |
| 200 | 200 | 213 | 6.72 | 3.72 | 45 | 0.082 | 55 |
| 200 | 300 | 318 | 10.03 | 5.84 | 42 | 0.095 | 58 |
| 300 | 300 | 318 | 15.04 | 6.90 | 54 | 0.067 | 46 |
| 800 | 200 | 195 | 24.60 | 12.36 | 50 | 0.076 | 50 |
| 400 | 400 | 443 | 27.95 | 12.81 | 54 | 0.062 | 46 |
| 12 Ft$^2$/Ft$^3$ Medium | | | | | | | |
| 100 | 200 | 175 | 2.76 | 2.00 | 27 | 0.140 | 73 |
| 200 | 200 | 198 | 6.25 | 3.85 | 38 | 0.097 | 62 |
| 200 | 300 | 290 | 9.15 | 4.20 | 54 | 0.067 | 46 |
| 400 | 400 | 429 | 27.06 | 6.31 | 77 | 0.029 | 23 |
| 37 Ft$^2$/Ft$^3$ Medium | | | | | | | |
| 800 | 200 | 212 | 26.75 | 7.95 | 70 | 0.040 | 30 |
| 400 | 400 | 443 | 27.90 | 10.35 | 63 | 0.050 | 37 |
| 400 | 700 | 685 | 43.20 | 13.56 | 69 | 0.044 | 31 |
| 1400 | 200 | 210 | 46.37 | 11.92 | 74 | 0.034 | 26 |

# CHAPTER IV

## RESULTS

The results of this investigation are shown in tabular form in Tables II and III.* It is important to realize that all values shown in these tables are averages of at least three experimental runs or are the results of calculations involving average values. The desired applied organic loading, which is a function of flow rate and feed concentration, was not always maintained due to the changing characteristics of the tygon tubing used in the Masterflex pump to pump the concentrated feed to the wet well (see Figure 1). As the characteristics of the tubing varied with age, so did the flow of the concentrated feed and thus the concentration of the feed to the filter. The flow rate to the filter was considered to be the desired quantity due to the methods of controlling it as described previously. The desired and actual applied organic loadings are shown in Table II. The actual loading to the filter was calculated using the COD of the feed sample at the spray nozzle and the flow rate which was indicated by the rotameter. The total amount of organics removed from the initial feed was determined in the same manner as the applied loading except that the COD of the filter effluent was used. The removal capabilities of each foot of filter depth are shown in Table III in terms of gm COD/hr/ft$^2$ that were removed and percent COD remaining.

## TABLE III

## DATA SUMMARY OF COD, PERCENT COD REMAINING AND pH AT DIFFERENT FILTER DEPTHS FOR THE FOUR SELECTED MEDIA AT VARIOUS FLOW RATES AND FEED CONCENTRATIONS

| Filter Feed | | | | Depth (Ft.) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | | | | 2 | | | | 3 | | | | 4 | | | |
| Flow (gal/day) | COD (mg/l) | Loading (gm/hr/$ft^2$) | pH | COD (mg/l) | Removal (gm/hr/$ft^2$) | % Remaining | pH | COD (mg/l) | Removal (gm/hr/$ft^2$) | % Remaining | pH | COD (mg/l) | Removal (gm/hr/$ft^2$) | % Remaining | pH | COD (mg/l) | Removal (gm/hr/$ft^2$) | % Remaining | pH |
| 50 $Ft^2/Ft^3$ Medium | | | | | | | | | | | | | | | | | | | |
| 100 | 100 | 1.58 | 7.2 | 26 | 1.17 | 26 | 7.6 | 23 | 0.05 | 23 | 7.8 | 19 | 0.06 | 19 | 8.0 | 22 | 0.05 | 22 | 8.0 |
| 200 | 120 | 3.79 | 7.6 | 70 | 1.58 | 58 | 7.4 | 53 | 0.54 | 44 | 7.5 | 43 | 0.31 | 36 | 7.5 | 34 | 0.29 | 28 | 7.8 |
| 300 | 123 | 5.82 | 7.6 | 74 | 2.32 | 60 | 7.5 | 62 | 0.57 | 50 | 7.6 | 52 | 0.47 | 42 | 7.7 | 42 | 0.47 | 34 | 7.8 |
| 200 | 207 | 6.53 | --- | 139 | 2.15 | 67 | --- | 118 | 0.66 | 57 | --- | 76 | 1.33 | 37 | --- | 54 | 0.69 | 26 | --- |
| 200 | 316 | 9.97 | 7.6 | 230 | 2.70 | 73 | 7.1 | 163 | 2.12 | 52 | 7.1 | 146 | 0.53 | 46 | 7.3 | 112 | 1.07 | 35 | 7.4 |
| 300 | 324 | 15.33 | 7.6 | 266 | 2.75 | 82 | 7.1 | 224 | 1.98 | 69 | 7.1 | 217 | 0.33 | 67 | 7.3 | 169 | 2.47 | 52 | 7.3 |
| 800 | 190 | 23.97 | 7.6 | 159 | 3.91 | 84 | 7.4 | 130 | 3.66 | 68 | 7.4 | 111 | 2.40 | 58 | 7.5 | 96 | 1.89 | 51 | 7.5 |
| 400 | 454 | 28.64 | 7.2 | 365 | 5.61 | 80 | 6.9 | 310 | 3.47 | 68 | 7.0 | 238 | 4.55 | 52 | 7.0 | 196 | 2.65 | 43 | 7.1 |
| 27 $Ft^2/Ft^3$ Medium | | | | | | | | | | | | | | | | | | | |
| 100 | 90 | 1.42 | 7.2 | 47 | 0.68 | 52 | 7.5 | 29 | 0.28 | 32 | 7.7 | 19 | 0.16 | 21 | 7.9 | 16 | 0.05 | 18 | 8.0 |
| 200 | 117 | 3.69 | 7.2 | 76 | 1.29 | 65 | 7.5 | 64 | 0.38 | 55 | 7.5 | 51 | 0.41 | 44 | 7.6 | 44 | 0.22 | 38 | 7.8 |
| 300 | 121 | 5.72 | 7.4 | 87 | 1.60 | 72 | 7.6 | 70 | 0.81 | 58 | 7.7 | 57 | 0.61 | 47 | 7.8 | 50 | 0.33 | 41 | 7.9 |
| 200 | 213 | 6.72 | --- | 141 | 2.27 | 66 | --- | 131 | 0.32 | 62 | --- | 116 | 0.47 | 54 | --- | 95 | 0.66 | 45 | --- |
| 200 | 318 | 10.03 | 7.2 | 247 | 2.24 | 78 | 7.3 | 211 | 1.13 | 66 | 7.4 | 169 | 1.33 | 53 | 7.4 | 133 | 1.14 | 42 | 7.5 |
| 300 | 318 | 15.04 | 7.3 | 250 | 3.21 | 79 | 7.3 | 227 | 1.09 | 71 | 7.3 | 193 | 1.61 | 61 | 7.3 | 172 | 0.99 | 54 | 7.3 |
| 800 | 195 | 24.60 | 7.6 | 167 | 3.53 | 86 | 7.5 | 133 | 4.29 | 68 | 7.5 | 119 | 1.77 | 61 | 7.5 | 97 | 2.77 | 50 | 7.5 |
| 400 | 443 | 27.95 | 7.2 | 374 | 4.36 | 84 | 7.1 | 339 | 2.20 | 77 | 7.0 | 297 | 2.65 | 67 | 7.0 | 240 | 3.60 | 54 | 7.0 |
| 12 $Ft^2/Ft^3$ Medium | | | | | | | | | | | | | | | | | | | |
| 100 | 175 | 2.76 | 6.8 | 113 | 0.98 | 65 | 6.9 | 105 | 0.12 | 60 | 7.0 | 64 | 0.65 | 37 | 7.1 | 48 | 0.25 | 27 | 7.2 |
| 200 | 198 | 6.25 | 6.9 | 145 | 1.68 | 73 | 6.9 | 126 | 0.60 | 64 | 7.1 | 111 | 0.47 | 56 | 7.1 | 76 | 1.10 | 38 | 7.2 |
| 200 | 290 | 9.15 | 6.9 | 239 | 1.61 | 82 | 7.1 | 210 | 0.92 | 72 | 7.0 | 185 | 0.78 | 64 | 7.0 | 157 | 0.89 | 54 | 7.0 |
| 400 | 429 | 27.06 | 7.2 | 394 | 2.21 | 92 | 7.4 | 374 | 1.26 | 87 | 7.3 | 349 | 1.57 | 81 | 7.3 | 329 | 1.27 | 77 | 7.2 |
| 37 $Ft^2/Ft^3$ Medium | | | | | | | | | | | | | | | | | | | |
| 800 | 212 | 26.75 | 7.2 | 197 | 1.90 | 93 | 7.3 | 175 | 2.77 | 83 | 7.3 | 152 | 2.90 | 72 | 7.3 | 149 | 0.38 | 70 | 7.3 |
| 400 | 443 | 27.90 | 7.2 | 404 | 2.46 | 91 | 7.2 | 337 | 4.23 | 76 | 7.0 | 312 | 1.58 | 70 | 7.0 | 279 | 2.08 | 63 | 7.1 |
| 400 | 685 | 43.20 | 7.0 | 609 | 4.79 | 89 | 6.9 | 538 | 4.48 | 79 | 6.6 | 507 | 1.96 | 74 | 6.6 | 470 | 2.33 | 69 | 6.6 |
| 1400 | 210 | 46.37 | 7.3 | 190 | 4.42 | 90 | 7.4 | 179 | 2.43 | 85 | 7.3 | 163 | 3.53 | 78 | 7.3 | 156 | 1.55 | 74 | 7.3 |

The substrate removal rate "k" was determined for each applied load and filter medium from the semi-logarithmic plots of percent COD remaining versus filter depth which are shown in Figures 2 through 5. The removal rates are equal to the slope of the lines that are shown in these graphs. Figures 2A and 2B show the plots of percent COD remaining versus depth for the filter media which provided 50 $ft^2/ft^3$ of surface area. It was noted from these same plots that two distinct removal rates in the filter did occur at the three lowest applied loadings. The same relationship between percent COD remaining and depth for the 27 $ft^2/ft^3$ media is shown in Figures 3A and 3B. The two removal rates were noted to occur at five of the lowest applied loadings. In Figure 4, the removal rates for the Koroseal medium (37 $ft^2/ft^3$) are shown for four applied loads above 26.75 $gm/hr/ft^2$. At these high loadings only a single rate of removal was observed for the entire filter. The removal rates for the 12 $ft^2/ft^3$ medium were determined from the plots in Figure 5. Two distinct removal rates were not observed for any of the four loadings that were employed. In the event of two removal rates, the overall filter removal rate was determined by calculating a weighted average which agreed closely to those rates which had been previously determined from a single line of best fit. When two removal rates occurred they were in the same depth-of-filter region in all cases. The first rate occurred in the first foot of depth and was always slightly greater than the second rate which was observed through the remaining three feet. The graphs also show that in the cases of diphasic removal at least fifty percent of the entire filter's removal occurred within the first foot of filter depth. In general it can be

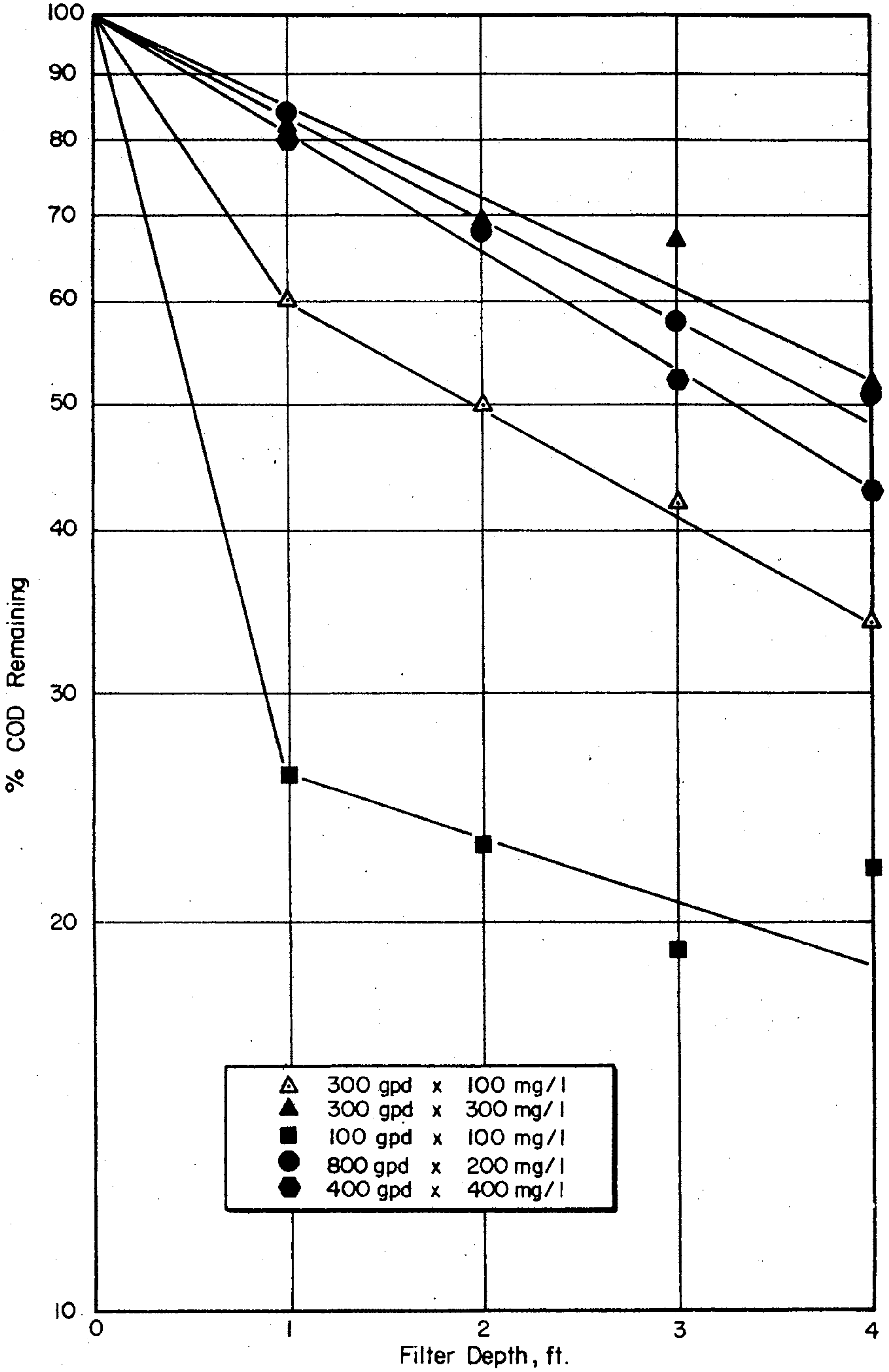

Figure 2A. Relationship of % COD Remaining with Depth at Various Organic Concentrations and Flow Rates Utilizing a Filter Medium Providing 50 $ft^2/ft^3$ of Specific Surface Area.

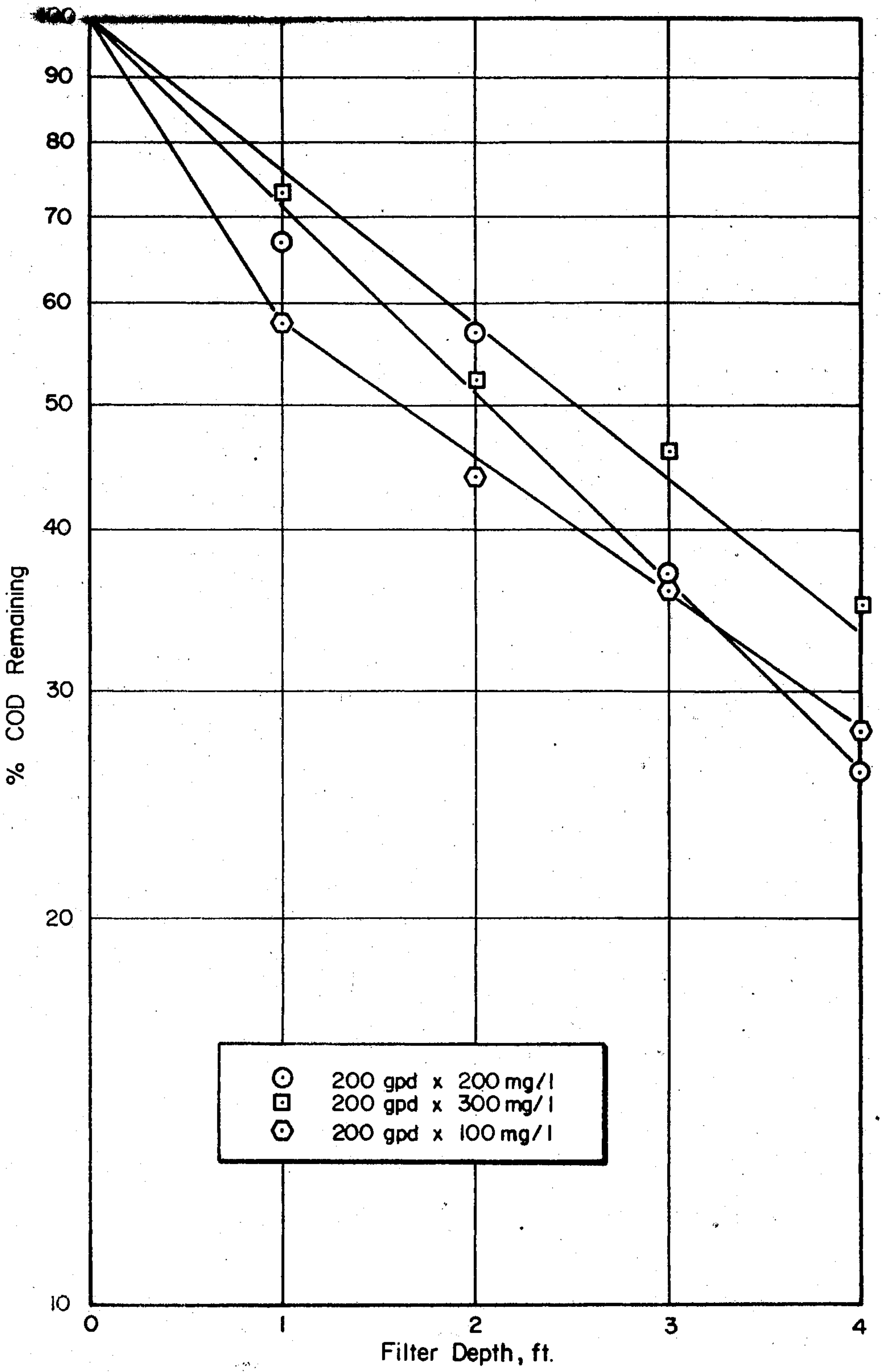

Figure 2B. Relationship of % COD Remaining with Depth at Various Organic Concentrations and Flow Rates Utilizing a Filter Medium Providing 50 $ft^2/ft^3$ of Specific Surface Area.

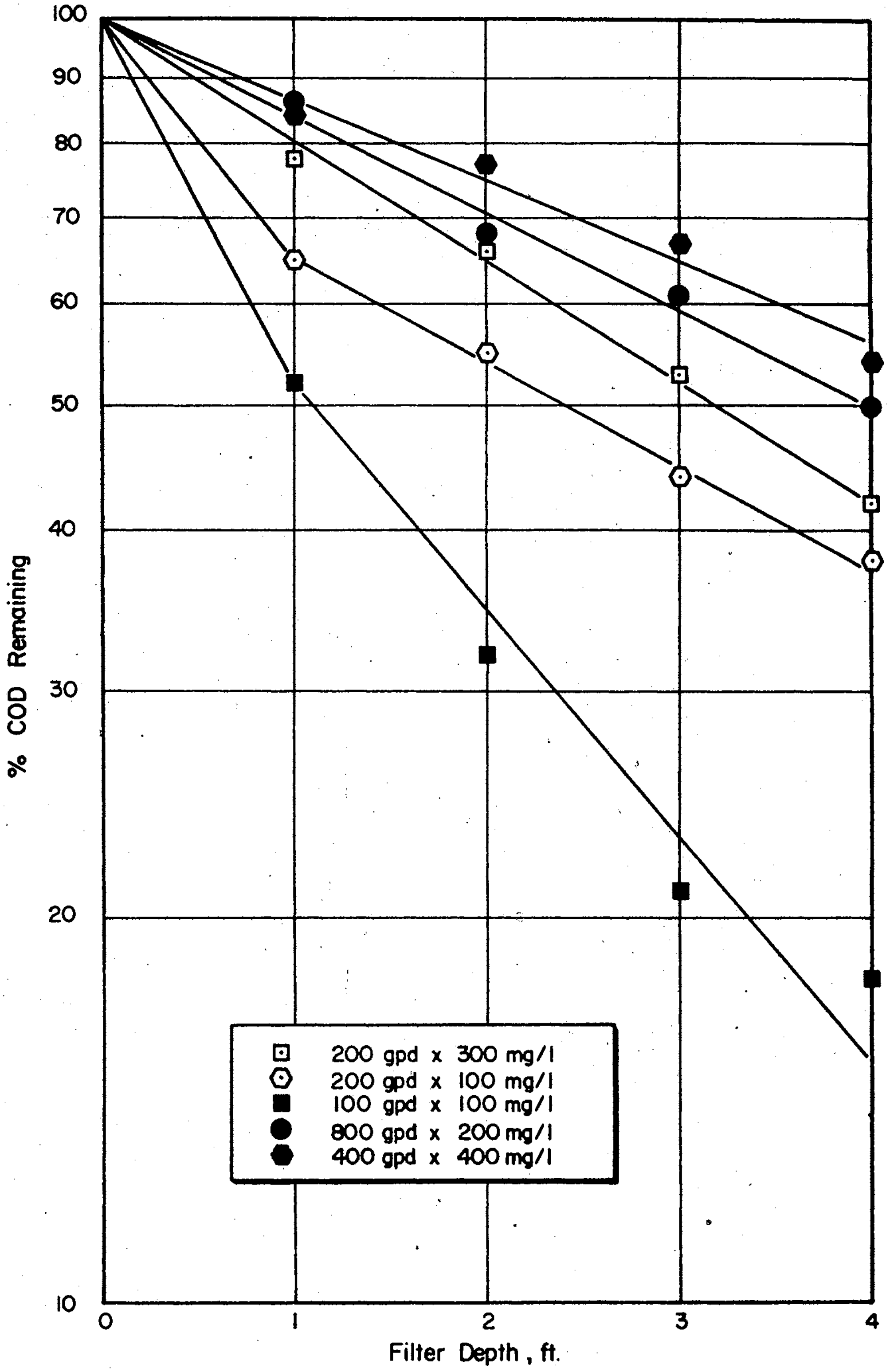

Figure 3A. Relationship of % COD Remaining with Depth at Various Organic Concentrations and Flow Rates Utilizing a Filter Medium Providing 27 $ft^2/ft^3$ of Specific Surface Area.

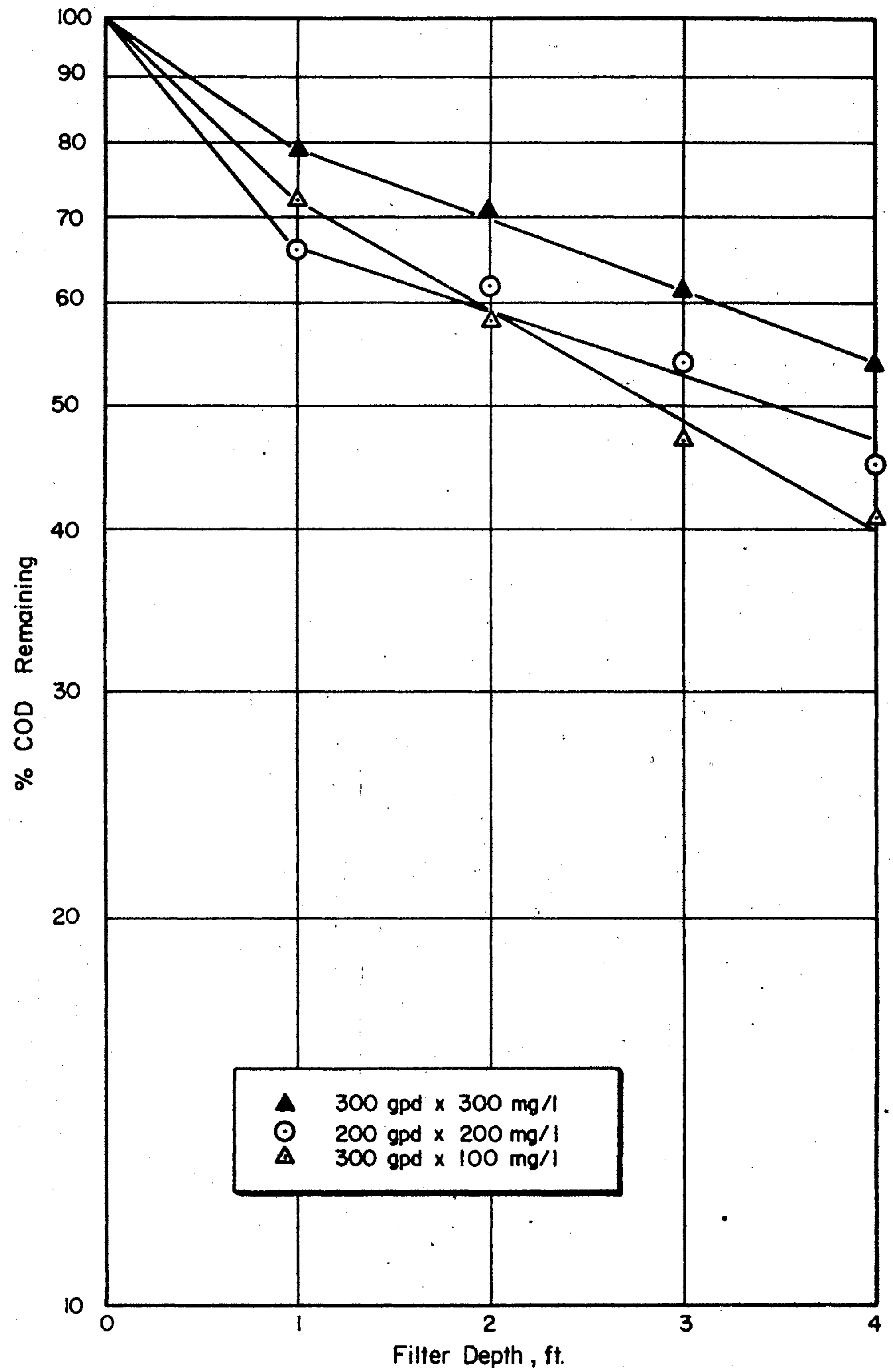

Figure 3B. Relationship of % COD Remaining with Depth at Various Organic Concentrations and Flow Rates Utilizing a Filter Medium Providing 27 $ft^2/ft^3$ of Specific Surface Area.

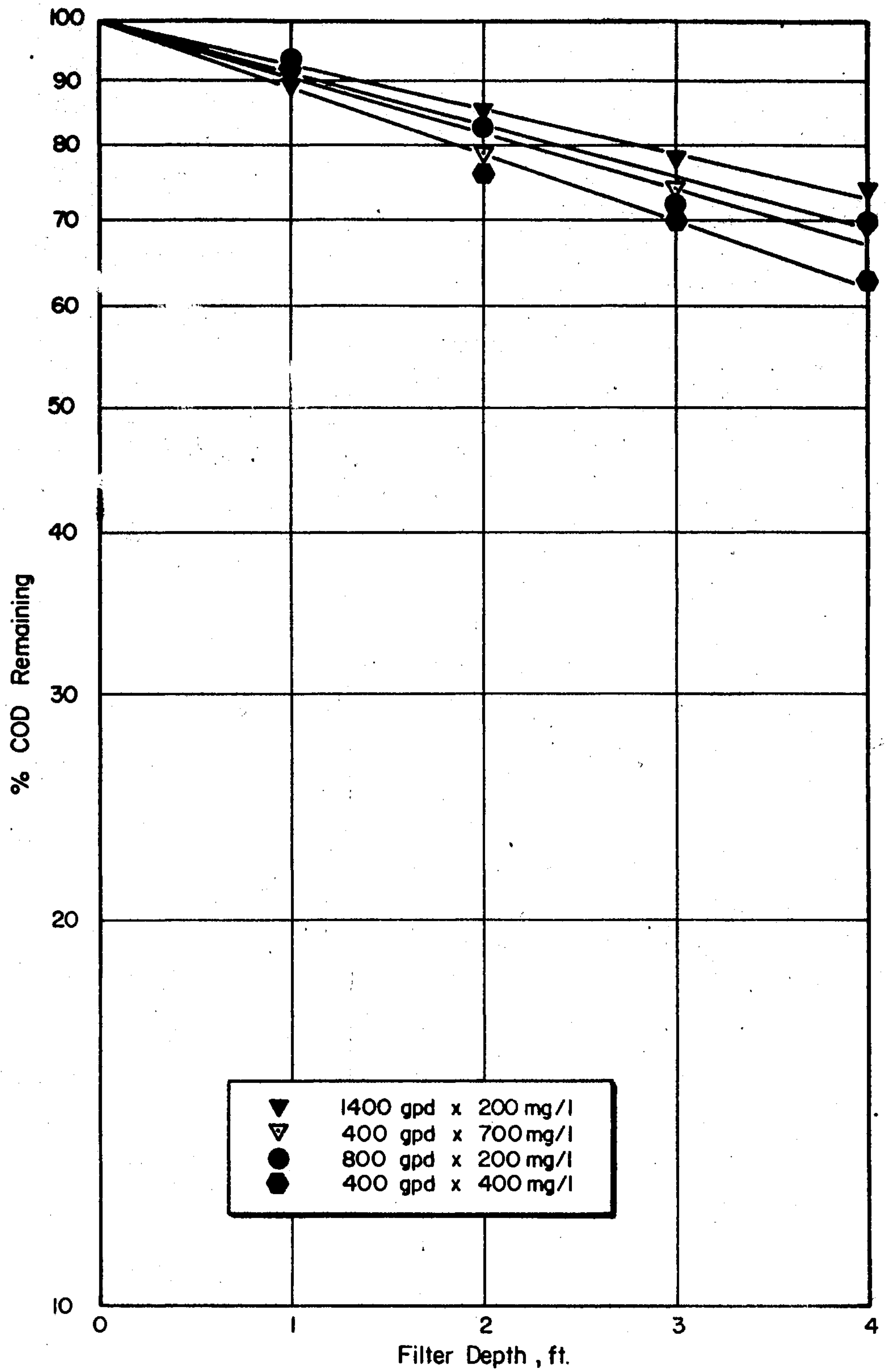

Figure 4. Relationship of % COD Remaining with Depth at Various Organic Concentrations and Flow Rates Utilizing a Filter Medium Providing 37 $ft^2/ft^3$ of Specific Surface Area.

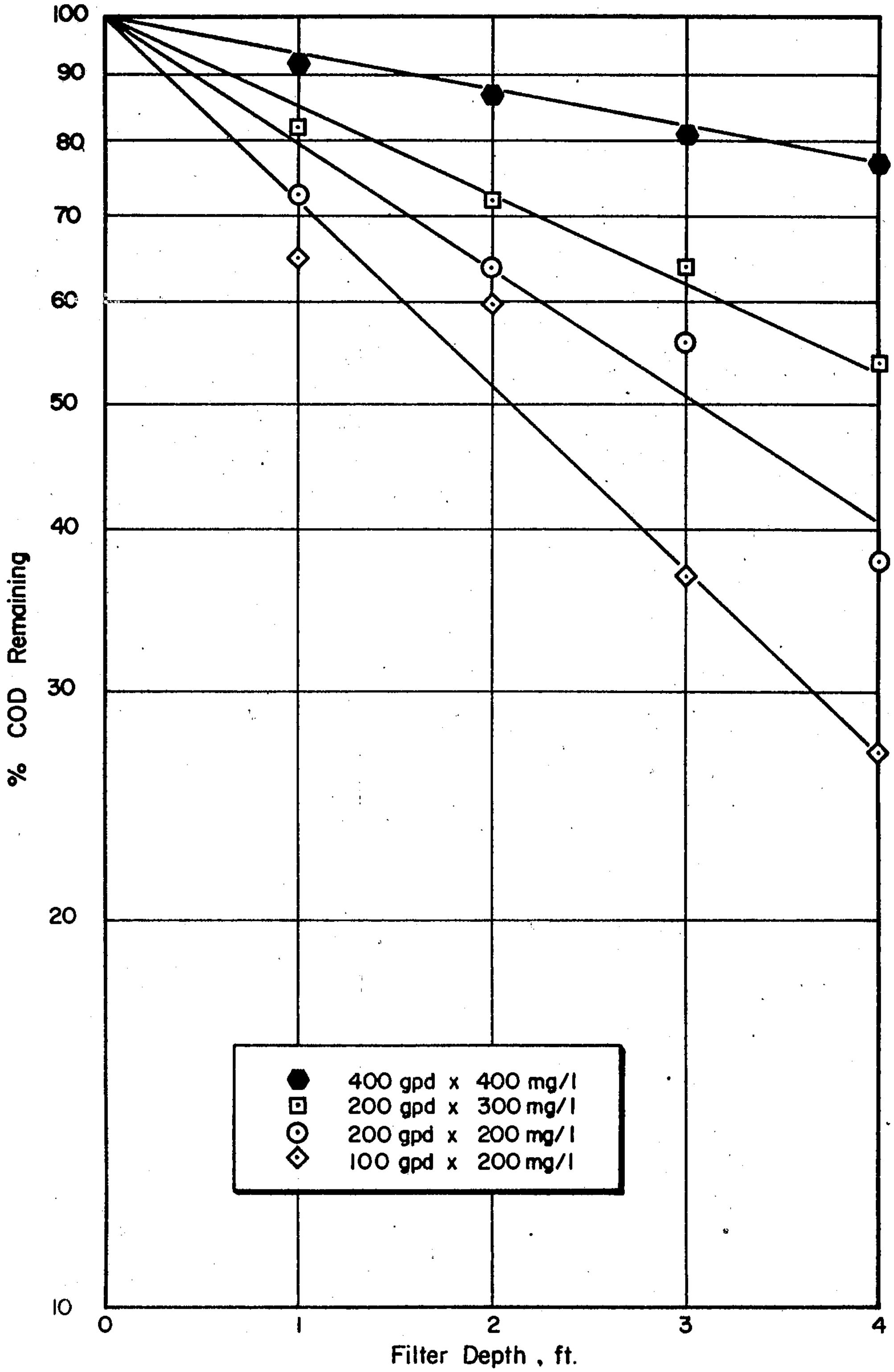

Figure 5. Relationship of % COD Remaining with Depth at Various Organic Concentrations and Flow Rates Utilizing a Filter Medium Providing 12 $ft^2/ft^3$ of Specific Surface Area.

noted that as the applied load increased, the removal rate decreased, as did the total amount removed and the efficiency.

In Figure 6 the relationship between efficiency and applied organic loading (gm/hr/ft$^2$) can be seen. The performance of the filters is shown to decrease as the applied load increases. The efficiency is observed to approach a minimum value as the organic loading is increased to the point that a condition of "saturation" is reached. In other words, any additional applied loading will not cause a decrease in efficiency. The figure also suggests that an increased efficiency will result if more surface area is available for biological slime growth. One exception to this relationship was the Koroseal medium which produced an efficiency lower than that of Flocor even though it provided a greater surface area.

The relationship between substrate removal rate "k" and applied loading (gm/hr/ft$^2$) is shown for the four filter media investigated in Figure 7. The resulting plots indicate that as the total applied organic load is increased the substrate removal rate decreases and approaches a constant value. This indicates that, within the range of loadings utilized in this experimentation, the removal rate reaches a minimum value and increasing the loading to the filter does not change the rate of substrate removal. The data points for the medium affording 37 ft$^2$/ft$^3$ of surface area show that it was subjected only to the loadings in the higher range where "k" had reached a constant value. With the exception of one medium, the graph shows that as the surface area of the filter media increased the minimum removal rate also increased. The Koroseal medium which provided 37 ft$^2$/ft$^3$ of surface area did not exemplify this relationship. The reason for this was due

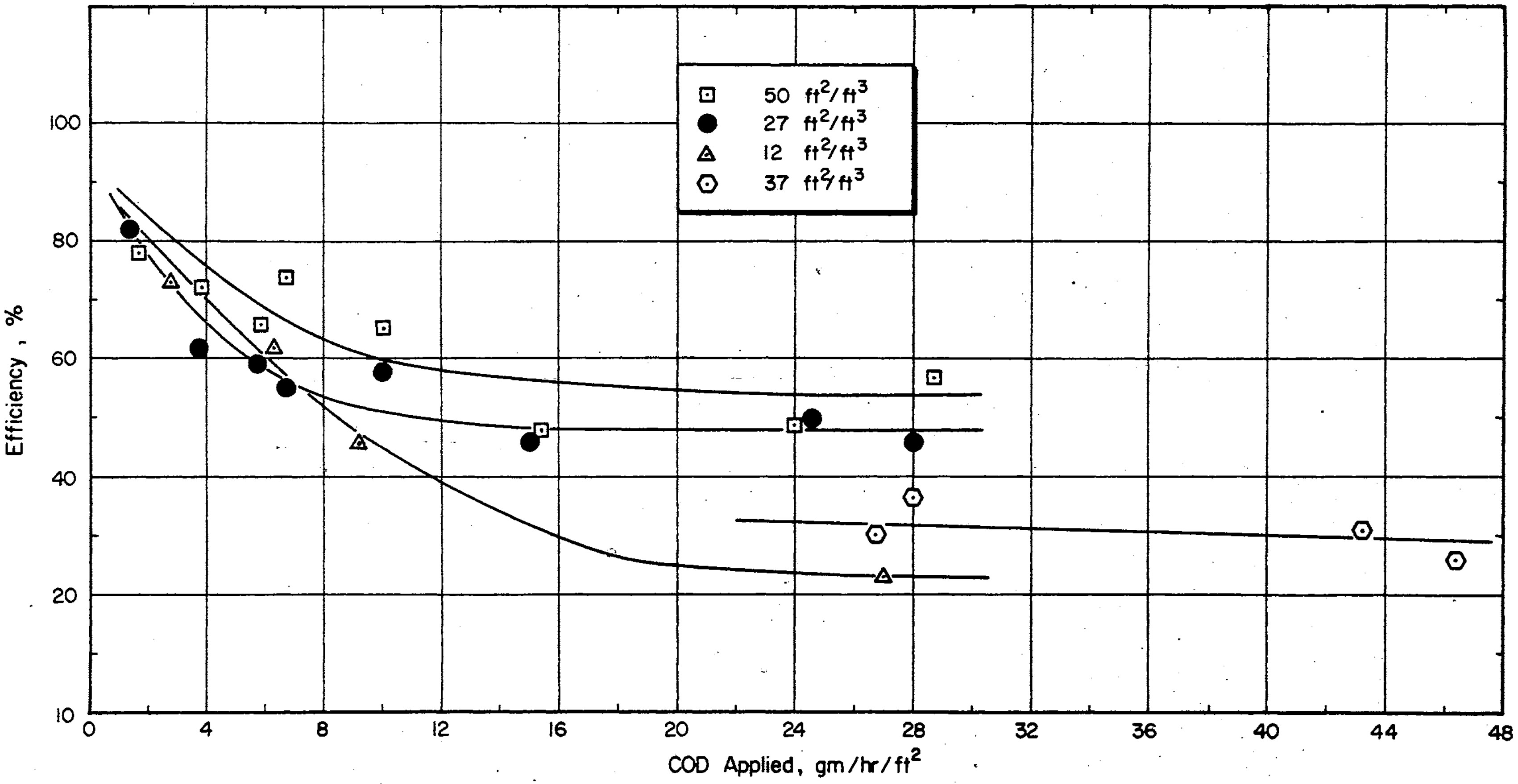

Figure 6. Relationship of Efficiency with COD Applied (gm/hr/ft$^2$) for Four Filter Media Providing Different Specific Surface Areas.

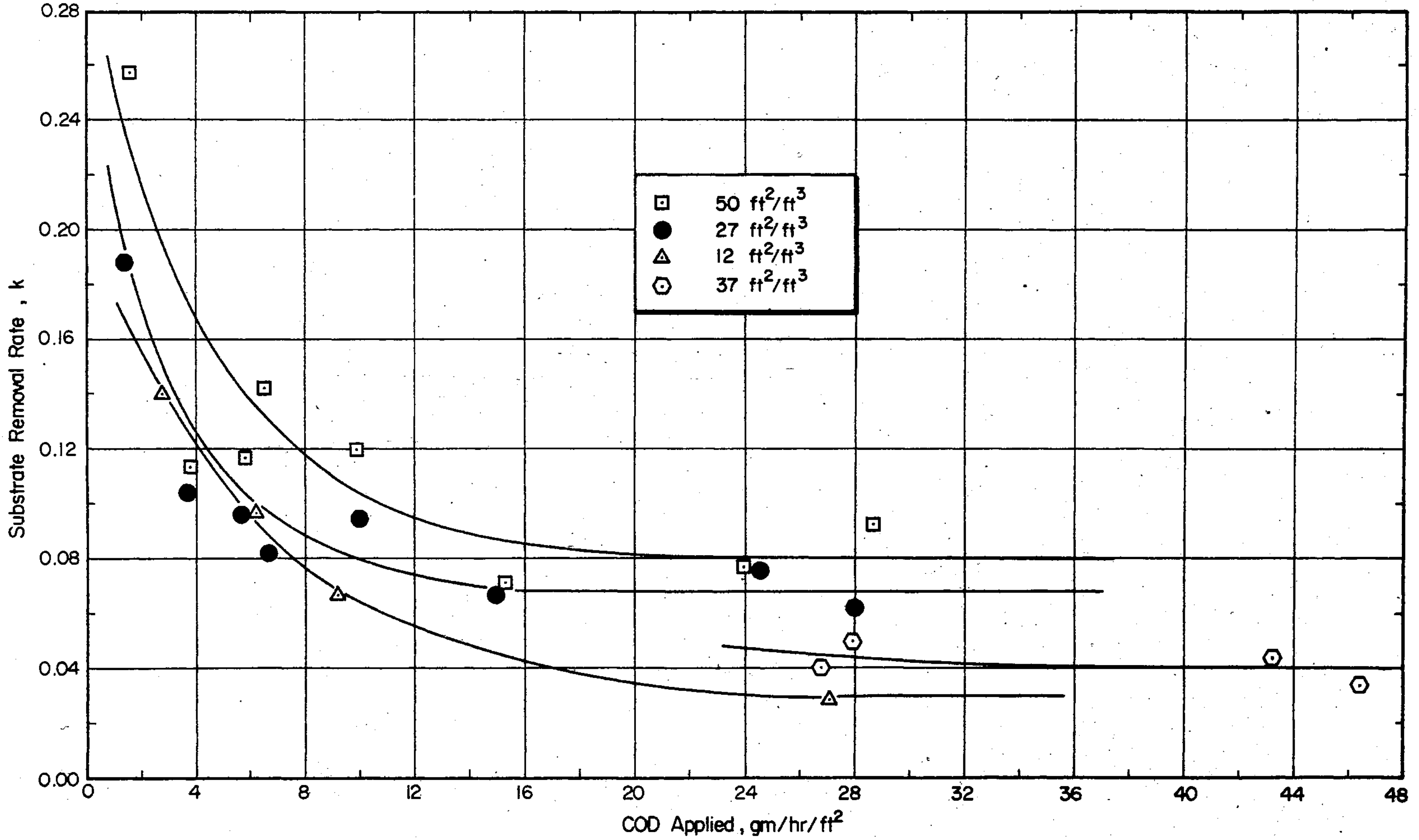

Figure 7. Relationship of Substrate Removal Rate with COD Applied (gm/hr/ft$^2$) for Four Filter Media Providing Different Specific Surface Areas.

to the basic design of the medium and how it was utilized in this experiment which will be discussed in the next chapter. The graph also appears to indicate that the Flocor medium reaches its minimum removal rate at a lower applied loading than do the other media.

The pH of most samples did show a slight indication of how the filter was performing. As can be seen in Table III, the effluent samples tended to become more acidic as the filter efficiency dropped and showed an increase in alkalinity as the filter efficiency increased. The pH increase or decrease was not related to the amount of substrate removed but was related to the percentage of substrate removed.

Figure 8 shows the relationship of the minimum removal rate and efficiency which was observed for each medium and the surface area that the particular medium provided. As shown in the graph there seems to be a nearly constant increase in "k" of approximately 0.01 for each additional increase of 4.0 $ft^2/ft^3$ in specific surface area up to 27 $ft^2/ft^3$. A constant 10% increase in efficiency is also observed for each additional 5.5 $ft^2/ft^3$ of surface area up to approximately 27 $ft^2/ft^3$. The data point of the Koroseal medium was not considered because of the observed poor performance which will be discussed later. The increase in surface area beyond 27 $ft^2/ft^3$ is observed to increase the removal rate and efficiency, but at a much slower rate. Approximately 25 $ft^2/ft^3$ of additional surface area is needed to increase the removal rate 0.01 as compared to the 4.0 $ft^2/ft^3$ of surface area in the range below 27 $ft^2/ft^3$. An efficiency increase of only 5% resulted when the specific surface area was increased from 27 $ft^2/ft^3$ to 50 $ft^2/ft^3$.

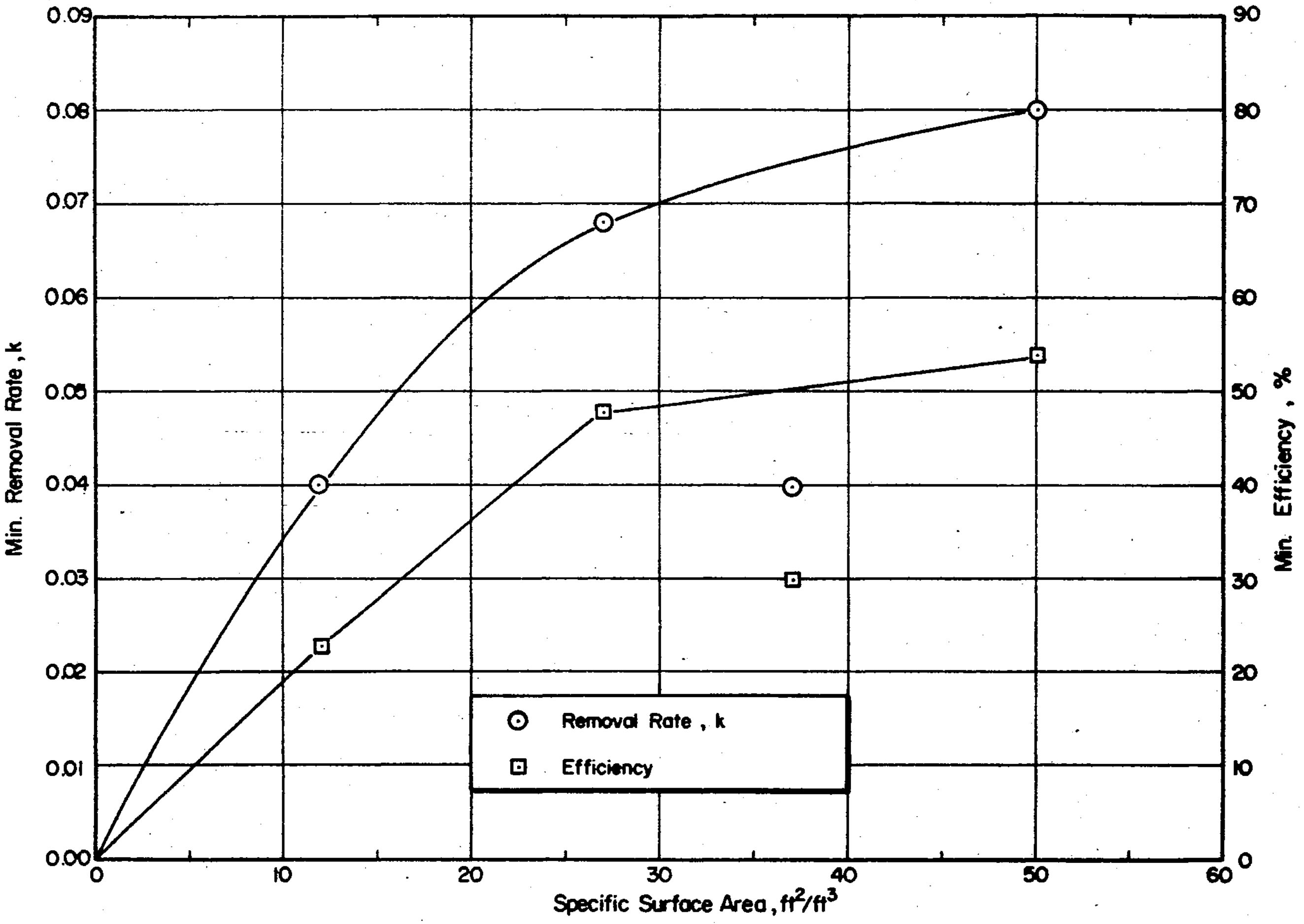

Figure 8. Relationship of the Minimum Removal Rate and Efficiency with the Specific Surface Area Provided by the Filter Medium.

# CHAPTER V

# DISCUSSION OF RESULTS

The results reported in the preceding chapter provide new and definite observations about the performance of trickling filters under controlled conditions. The design and operational capabilities of the filter units enabled the investigation to be carried out under controlled conditions. The utilization of sucrose as the growth limiting nutrient provided a carbon source that did not vary qualitatively, but at the same time the quantity or strength could be adjusted to a desired amount. The hydraulic flow rate was also a controlled experimental parameter. Temperature of the waste flow was not a factor affecting the performance because it was held within a constant range, and the surface area of the medium utilized was known exactly. These factors provided a system in which the performance of a filter could be investigated in a controlled experimental environment.

The diphasic removal characteristics that existed at most applied loadings of less than 15.04 gm/hr/ft$^2$ were probably due to the limited supply of substrate remaining after the first foot. This explanation is supported by the fact that as the applied load to the filter was increased the two removal rates approached a single rate for the entire depth of the filter.

In Figures 6 and 7, the removal efficiencies and rates of removal were shown to decrease and approach a constant value as the applied load (gm/hr/$ft^2$) was increased. Similar observations have been reported and explained by Chipperfield (14), (18) and Schulze (15). The results of Figure 6 show that as the surface area of the medium was increased from 12 $ft^2/ft^3$ to 27 $ft^2/ft^3$ the minimum efficiency was increased from 23% to 48%, respectively. A 6% increase in the minimum efficiency occurred if the surface area was increased from 27 $ft^2/ft^3$ to 50 $ft^2/ft^3$. As noted previously, the 37 $ft^2/ft^3$ (Koroseal) medium produced a poorer efficiency than did the 27 $ft^2/ft^3$ (Flocor) medium. This poor efficiency was due to a portion of the waste flow that was observed to "free-fall" completely through parts of the filter without coming into contact with the filter medium. The occurrence of the free-fall resulted in little or no contact between the waste and the biological film. Therefore, even though a greater surface area was present, it was not utilized because the filter design allowed some free-fall of the waste to occur. Thus the samples collected at each foot of filter depth contained a fraction of the untreated waste. Another filter medium of similar design (vertical tubes) as that of Koroseal was reported by Bruce (26) to yield a poor effluent. Minch et al. (7) reported an efficiency of 45% when Koroseal was used to treat a paper waste as compared to approximately 30% reported in this investigation. The discrepancy in the two reports can be explained by the fact that a twenty foot filter was used by Minch while a filter depth of four feet was utilized in this investigation. Any free-fall that occurred in the twenty foot filter had sufficient depth remaining when it made contact again that a relatively good over-all efficiency resulted. Samples at different depths were not taken by Minch, but one could expect that the lower portions of his filter removed a higher percentage of organics as compared to a filter medium that would prevent free-fall and consequently remove the organics in the upper portion of the filter. The four foot filter depth did not provide enough additional treatment after the free-fall occurred to produce a good removal efficiency.

The increased acidity of the waste as the efficiency dropped was most likely caused by an insufficient supply of oxygen. This efficiency drop also corresponded to the increased loading of the filter. As the loading was increased a greater portion of the organic material was oxidized by means of organic electron acceptors and thus the production of some organic acids may have resulted. Very high efficiencies corresponded to an increase in alkalinity which indicates that a greater portion of the oxidization was accomplished utilizing oxygen as the final electron acceptor and therefore smaller quantities of acid were produced.

Within a certain range, the removal capabilities of a filter appear to be the sole function of the surface area provided by the medium. This same relationship was shown by Levine (1) and others (3), (6), (8), (25), (26). However, above approximately 27 $ft^2/ft^3$, an increase in surface area does not yield the constant increase of the minimum removal rate, as shown in Figure 8, and as was also reported by Chipperfield (14). This indicates that the performance of the filter has been limited by some factor other than available surface area.

During the operation of the 50 $ft^2/ft^3$ filter medium it was noted that a heavy slime growth bridging between the fiberglass sheets at the surface of the filter did occur at times. This caused a slightly uneven distribution of flow over the filter medium and thus the entire surface was not being utilized. The heavy growth and the bridging which resulted emphasizes the importance of void space, which was reported by Chipperfield (10) and others (16), (22). The greater percentage of voids in the medium was reported by Gerlich (16) to produce an effluent with a higher dissolved oxygen content. At the same time growth within the medium and thus ponding or routing of the flow is less likely to occur if the void space is large. Therefore, a combination of high surface area and void space in a medium with a geometric design that prevents any liquid free-fall is necessary to produce the best efficiency within a trickling filter.

# CHAPTER VI

## CONCLUSIONS

From the results of this investigation, the following conclusions can be made:

(1) Within the range of loadings (gm/hr/$ft^2$) employed in this investigation, the substrate removal rates "k" and removal efficiencies decrease and approach constant values as the loading (gm/hr/$ft^2$) is increased.

(2) The available surface area of a filter medium has a definite bearing on the removal capabilities of the filter, providing that the geometric design of the medium does not allow any free-fall of the waste stream. In the range of loadings (gm/hr/$ft^2$) utilized in this study, the removal rates and efficiencies showed an appreciable increase as the surface area was increased, but there appeared to exist an upper limit after which the increase in the removal rate and efficiency was not as great as before.

(3) The change in pH between the influent feed and the effluent is an indication of the filter's performance.

# SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are made for future study involving nonconventional media:

(1) Investigation of filter media with a variety of geometric designs and surface areas

(2) The role of void space in the filter medium

(3) The monitoring of dissolved oxygen at various filter depths.

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# VITA 2

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