STUDY ON THE PERFORMANCE OF AN EXPERIMENTAL TWO-STAGE TRICKLING FILTER EMPLOYING A PLASTIC MEDIUM

By

GEORGE EDWARD MARCANGELI

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Thesis Approved

Don F Kincannon
Thesis Adviser

Joseph H Sherrard

N N Durham
Dean of the Graduate College

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CHAPTER I

INTRODUCTION

The purification of liquid wastes by fixed-bed reactors, commonly called trickling filters, is a relatively old process which dates to about 1889 in Massachusetts. The word "filter" has been used to denote the process, although the process does not provide filtration in the normally accepted sense. Primary purpose of a biological filter is to provide a locale for biological oxidation, not to filter the waste.

The vast majority of the early trickling filters employed rocks 1½ to 4 inches in diameter as the medium upon which biological growth was established. After distribution over the surface of the filter, the waste advanced downward, contacting the surfaces of the rock medium as it moved along. Microorganisms present in the waste flow attached themselves to the rock surfaces, using these as anchor points from which they could grow and multiply by feeding on the organic material present in the waste. The removal of this organic material from the wastewater was regarded as purification of the waste.

Some of the common problems encountered with rock trickling filters included clogging of the medium, odors due to ventilation problems and poor distribution of the waste over the medium. Rock trickling filters were operated at relatively low BOD loadings because of such problems. They were considered "low rate" systems, operating in the range of 2 to 14 lbs BOD/day/1000 ft^3, at flowrates ranging from 45 to

140 gal/day/ft^2. This necessitated the use of considerably large volumes (and weights) of medium for satisfactory treatment of the waste. Depths had to be restricted to about six feet in order for structures to be built which were capable of supporting the massive amounts of rock. This also meant that a large land area was required for "low rate" systems treating strong domestic and industrial wastes.

In recent years, the development of lightweight plastic media for use in trickling filters has led to many improvements in trickling filter design. The three leading plastic media presently in use are sold under the trade names of Flocor, Surfpac, and Cloisonyle. These have specific surface areas of 27, 56, 66 ft^2/ft^3, respectively, with corresponding void ratios of 97, 94, and 94 percent. Reactors employing plastic media as the contact bed are usually designated as "high rate" filters, operating in the range of 50 to 300 lbs BOD/day/1000 ft^3 at flow rates ranging from 600 to 2000 or 3000 gal/day/ft^2. High rate plastic media filters are capable of treating greater quantities of BOD per unit volume than low rate filters because of their relatively high specific surface areas. Much higher hydraulic loadings can be applied due to the presence of a high percentage of void space. Plastic media trickling filters require much less structural support than conventional rock media filters, and they are cheaper per pound of BOD removed. Due to the modular system of assembling plastic media filters, nearly any desired height, width, or configuration can be obtained without difficulty. Modular design also lends itself nicely to series operation or expansion of existing filter systems.

Although most plastic media have only been used and marketed in the past ten years, a fair amount of research has been conducted on their ability to remove organic matter from wastewaters. However, the majority of this research is centered around single-stage systems and very little has been done which pertains to two-stage or multi-stage filters in series operation. It is the purpose of this study to gain insight into the performance capabilities of a two-stage system employing Flocor plastic medium and utilizing intermediate clarification.

CHAPTER II

LITERATURE REVIEW

Various researchers have studied two-stage and multi-stage trickling filter systems. Attempts have been made by these researchers to predict and explain their behavior under actual operating conditions. It appears that there are disagreements among some as to what is actually taking place, and why. Comparisons of performance between primary and secondary filters differ between studies. Possible explanations for the variations in findings are based on the fact that different substrates are utilized and many different filter configurations are used. It is the purpose of this chapter to present the findings and conclusions of research work conducted on trickling filter systems. The first section of this chapter deals with conventional (rock) multi-stage systems, whereas the second section presents a survey of plastic media systems.

Conventional Multi-stage Systems

In 1952, Heukelekian, et al. (1) conducted studies involving high-rate trickling filters in series and in parallel to compare the efficiency of a cubic yard of filter stone in single vs. double filtration. The experimental filters employed were 5 ft deep and 15 ft in diameter and were subjected to a combined domestic and industrial waste which averaged 580 mg/l of BOD. Effluent from series operation was 39 mg/l

BOD compared with 110 mg/l BOD for parallel operation. The investigators concluded that double filtration systems could handle greater BOD loadings and give lower BOD values in the effluent than could single filtration systems of equal volume. A cubic yard of filter stone was thus found to be more efficient when used in double filtration than when used in single filtration.

Dekema and Krige (2) carried out investigations of two-stage fixed sequence vs. single-stage biological filtration in artificially enclosed and ventilated deep filters in South Africa in 1949. Results using sewage as substrate indicated that 33.8 percent more flow could be applied and 31 percent greater removal of BOD accomplished per cubic yard of stone in two-stage filtration than in single-stage filtration with equal purification.

By utilizing four sets of two-stage trickling filters in series, Sorrels and Zeller (3) discovered that a greater percentage of BOD removal was obtained in the secondary filters at equivalent loadings than in the primary filters. Results using domestic sewage indicated that intermediate sedimentation did not seem to be necessary, since no abnormal sludge was obtained. It was shown that at the same BOD loading, series filtration afforded a higher degree of treatment than did single filtration, even at a higher hydraulic rate. A hyperbolic relation was found to exist between the BOD applied to and removed by the primary filters, whereas a straight line was found to exist for the secondary filters. The authors suggested that there was the possibility that the composition of the zooglea on the two filters was different.

Large-scale studies at Minworth, Birmingham on the treatment of highly industrial sewage by double and alternating double filtration were made by Hawkes and Jenkins (4). Statistical analysis of the results showed no significant difference between the two processes as regards overall removal of organic matter, but the proportion of organic matter removed in the different stages differed for the two processes. In alternating double filtration, the two filters shared the organic load, but in double filtration most of the organic matter was removed in the first filter and nitrification occurred mainly in the second filter. Hawkes and Jenkins indicated that double filtration could have advantages over alternating double filtration because of the nitrification aspect of the former.

In 1963, Sorrels and Zeller (5) operated two experimental trickling filters in series utilizing sewage as substrate. The primary and secondary filters had surface areas of four square feet but the primary was six feet deep as compared to only three feet for the secondary filter. A gravel medium 1.5 to 3 in. in diameter was employed as the contact bed. The filters were submitted to loads ranging from 23 to 120 lbs BOD/day/1000 ft^3. Both filters exhibited a decrease in removal efficiency with an increase in loading, but the decrease was more pronounced in the primary filter. The maximum amount of BOD removal in the primary filter occurred at a loading of 69 lbs BOD/day/1000 ft^3 whereas the maximum absolute BOD removal in the secondary filter was at 115 lbs/day/1000 ft^3. A comparison of primary and secondary filters showed that at any given loading, the secondary filters removed more BOD and a greater percentage of applied BOD. Sorrels and Zeller suggested that this was due to the lack of dissolved oxygen in the sewage applied to the primary filter and to the fact that the primary filter had to flocculate as well as oxidize causing a lag not shown in the secondary filters. They also stated that for equal filter volume, series filtration produces a superior effluent to that of parallel filtration. It was postulated that primary filters function largely by assimilation and synthesis, whereas the secondary filters function largely by oxidation.

D. W. Osborn (6) studied double filtration of domestic sewage on rock media at Johannesburg, South Africa, in 1965. The primary filters under study were six feet deep as compared to secondary filters which were 12 feet deep. A greater amount of nitrification took place in double filtration as compared to single filtration. The results of several experiments showed that the double filtration systems were more efficient in removing BOD.

In presenting an idealized theory for the efficiency of biological filtration, Meltzer (7) claimed that two-stage filtration and effluent recirculation have no theoretical advantage over single-stage filtration in deep filters. He suggested that the controlling factor in filter efficiency was the hydraulic surface loading. Maximum efficiency supposedly occurs at an optimum rate of flow which is specific to the type, size, and configuration of the medium. Meltzer preferred single-stage deep filters to alternating or straight double filtration, but gave no experimental evidence to support his choice.

Design approaches for two-stage trickling filters in series were evaluated by Baker (8) in 1967. Calculations for efficiency and volume were made using Eckenfelder's design formula and the National Research Council (NRC) equations. Results of calculations showed that two-stage plants could be designed and constructed with a great savings in filter volume in most cases over that which would be required for a single-stage plant to achieve the same efficiency with the same depth.

Plastic Media Systems

In a 1967 study by Chipperfield (9) on the performance of plastic media in trickling fiters, various advantages over conventional rock media were cited. These included better performance, absence of clogging, easier construction techniques and more economical treatment of wastes. Ideal requirements for a plastic packing and performance characteristics for Flocor plastic media treating six different trade wastes were given. At BOD loads ranging from 50 to 200 lbs/day/1000 ft^3 the Flocor systems were found to attain removals of up to 95 percent. In multi-stage plants, Chipperfield failed to observe any instances of severe inhibition by the accumulation of less readily treatable products or fractions in the final stages.

Middlebrooks and Coogan (10) investigated a Surfpac filter treating kraft mill wastes in Alabama. The experimental filter was three ft. in diameter and 21.5 ft. deep. At a loading of 250 lbs BOD/day/1000 ft^3, the filter plus a primary and secondary clarifier removed 70 percent of the BOD of the raw waste. Removal efficiencies of greater than 95 percent were obtained at a loading of 65 lbs BOD/day/1000 ft^3.

Attempts have been made in recent years to compare the performances of different plastic media. Bruce (11) made such an investigation in 1968 on partial treatment of domestic sewage. The BOD removal efficiency was found to be related in a fairly consistent manner to the specific surface area provided by the medium. Bruce stated that a major factor contributing to the BOD of the settled effluent was the presence of finely divided and colloidal material, indicating that high-rate filters are not primarily effective in bringing about flocculation and coagulation.

The development of plastic packings for high-rate biofiltration and considerations of the aspects of operation, performance and design were discussed by Askew (12) in 1970. Contrary to the conclusions of Germain (18), Askew contended that research and plant scale operational results in the United Kingdom showed that where units of differing depths are operated at similar loads of BOD/unit volume, similar efficiencies are demonstrated. In other words, deep beds are not necessary for efficiency if the minimum wetting rate is met for shallow filters.

Surfpac plastic media filters with equal volumes and differing depths were operated by Bruce and Merkins (13) to assess the effects of depth on removal efficiency. At depts of seven and 24.5 ft., similar efficiencies were obtained for the same hydraulic and total organic loadings. It was concluded that depth has no significant effect on the efficiency, but rather the volume of media employed.

Audoin, et al. (14) evaluated depth effects by applying sewage to Cloisonyle plastic-filled trickling filters which were 6.5, 13, and 19.5 ft. high, respectively. The filters were loaded at equal hydraulic and organic loads and it was found that the 13 and 19.5 ft. filters removed approximately the same percentage of BOD, while the 6.5 ft. filter removed a lower percentage than the others. A minimum depth of 13 ft. was suggested for use with Cloisonyle pastic media.

In studies on Surfpac plastic media, Germain (18) concluded that depth of plastic medium has a significant effect on the volume of medium required. With increasing heights, decreasing volumes of medium are required. With increasing heights, decreasing volumes of medium are needed for equal purification.

Utilization of plastic media in two-stage or multi-stage systems has been suggested by various researchers, but a very small amount of actual operational data are available for inspection. One such study by Chipperfield, et al. (16) deals with multi-stage plastic media plants treating a variety of trade and domestic wastes. These included whiskey distilling, breweries, dairies, fruit and vegetable processing, synthetic fiber manufacture, pharmaceutical and domestic and industrial wastes combined. All systems studied showed an overall economic advantage over alternative systems. The multi-stage systems were shown to recover rapidly from shock loads or toxic materials. The character of the biomass on successive stages of a multi-stage system was usually different, possibly providing an explanation for the greater effectiveness of a multi-stage plant compared to a single-stage plant to carry out the same duty. From an analysis of the results, Chipperfield, et al. (16) concluded that for removal of a unit weight of BOD, only 0.02 to 0.03 of the land area required for conventional systems was needed.

In 1973, Richard and Kingsbury (15) studied the treatment of high milk BOD wastes with Flocor plastic media towers. At BOD loadings of 200 lbs/day/1000 ft^3, a 60 percent reduction per stage in BOD was achieved without odor or settling problems. Three stages in series were suggested as the most popular for complete treatment (under 20 mg/l) of the waste. Richard and Kingsbury concluded that the two most important things to consider in designing Flocor towers were the relation of organic load to performance and the irrigation rate applied to the medium.

It is evident from the preceding review that there is a large amount of disagreement among researchers regarding both single and multi-stage trickling filters. In the present research, an attempt was made to gain a better understanding of multi-stage trickling filters utilizing plastic media and to compare the findings with findings of previous investigators.

CHAPTER III

MATERIALS AND METHODS

Experimental Approach

Two identical model trickling filters placed in series operation with intermediate clarifiers were employed in this investigation for the purpose of evaluating and comparing the organic removal capabilities of primary and secondary filters at equivalent total organic loadings. To determine the effect of hydraulic loading on reactor performance, experimental runs were conducted employing flowrates both lower and higher than the manufacturer's recommended minimum wetting rate of 864 gpd/ft^2 (0.6 gpm/ft^2). The flow rates investigated were 500, 750, and 1000 gpd/ft^2, respectively.

All experiments were conducted under closely controlled conditions, the only variations applied to the system being the influent organic concentration and the hydraulic loading (gpd/ft^2). The COD (chemical oxygen demand) test was selected as the basis for comparison of the performance characteristics of the individual filters.

Experimental Apparatus

The two pilot reactor units employed in this study (see Figure 1) consisted of plexiglas towers approximately eight feet in height, each tower containing four one-cubic foot (1 ft. x 1 ft. x 1 ft.) modules of

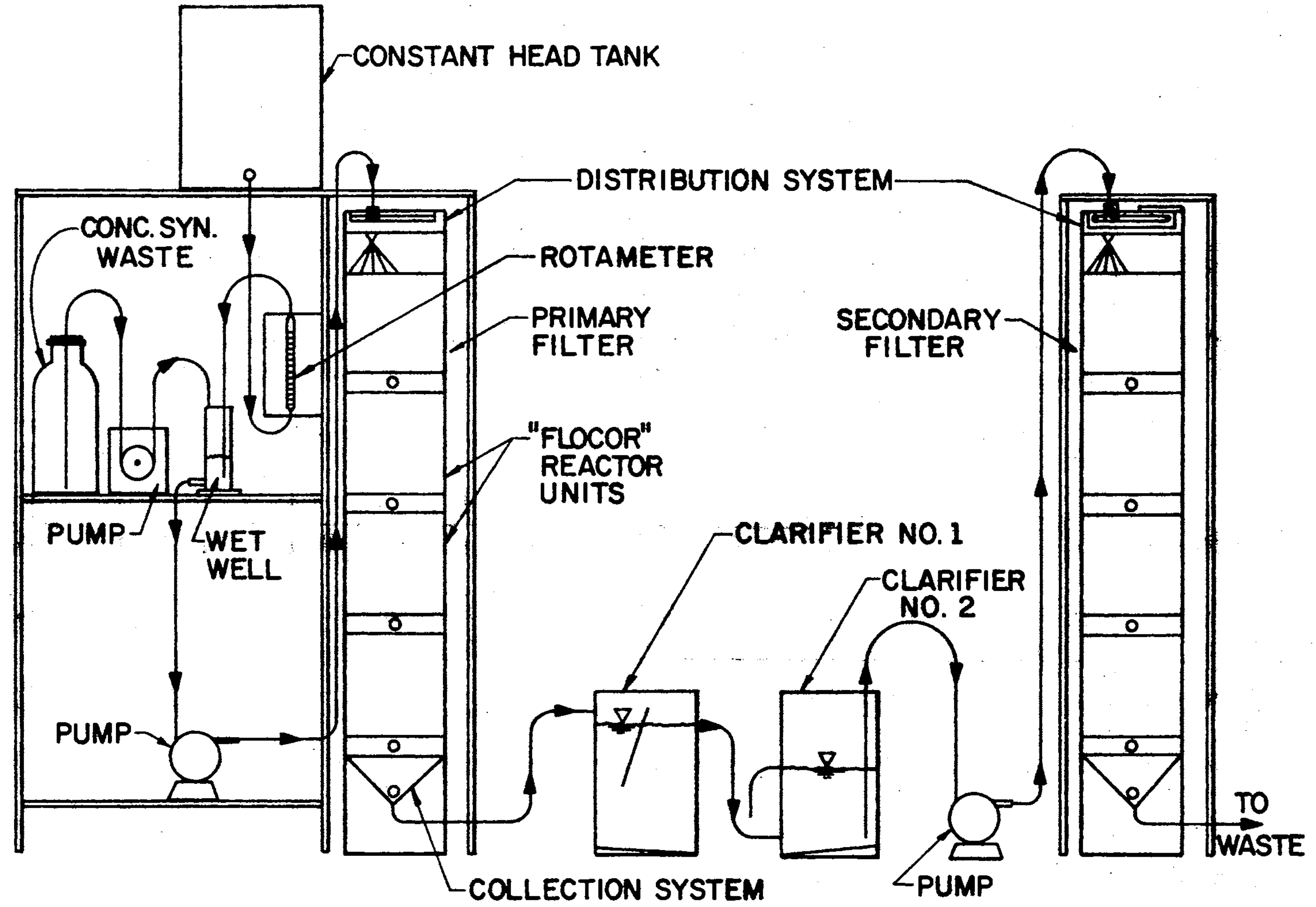

Figure 1. Diagram of Experimental Two-stage Trickling Filter System with Intermediate Clarification

Flocor plastic medium as the contact bed. The Flocor medium was developed by the Imperial Chemical Industries, Ltd., London, England, and is being distributed by the Ethyl Corporation in the United States. The medium has a 27 ft^2/ft^3 specific surface area with a 97 percent void ratio. It is designed to prevent free fall of wastewater through the filter. To permit sampling of the wastewater as it passed through the filters, a void space of approximately four inches was incorporated between the cubic foot modules of Flocor.

The two intermediate clarifiers employed were plexiglas units, each unit measuring 1 ft. x 1 ft. x 2 ft. The bottoms of the clarifiers were sloped gently to facilitate collection and disposal of biological solids which sloughed from the primary filter. The clarifiers were designed with outlets at a given height, such that the total volume of the units was not used for clarification. Actual effective volumes for the clarifiers were 1.29 ft^3 (9.66 gal) for clarifier no. 1 and 0.83 ft^3 (6.24 gal) for clarifier no. 2. Clarifier no. 1 was fitted with a plexiglas baffle to reduce turbulence and allow for flocculation and settling of the sloughed primary filter solids. The waste flow was transported by gravity flow from clarifier no. 1 to clarifier no. 2 through 5/8 in. diameter Tygon tubing. Clarifier no. 2 was utilized principally as a wet well for pumping wastewater to the secondary filter, although a small amount of flocculation and settling did occur due to the carryover of biological solids from clarifier no. 1.

The hydraulic flowrate applied to the system was controlled by means of a constant head tank that received a continuous flow of tap water from the local water supply system. A rotameter connected to the constant head tank was used for regulating the flow to the primary filter. The flowrate to the secondary filter was also regulated by a similar rotameter. To negate the effects of temperature variations on the system, the tap water was passed through a coil of copper tubing immersed in a constant temperature water bath prior to entering the constant head tank. Throughout the duration of the study, the temperature of the influent to the primary filter was held at $25^oC \pm 1.5^o$. After passing through the rotameter, the flow was discharged into a wet well wherein mixing with the concentrated synthetic waste was effected by means of a Sargent magnetic stirring system.

The synthetic waste used in this investigation consisted of a prepared sucrose ($C_{12}H_{22}O_{11}$) solution. The relative composition (Table I) was such that the carbon source (sucrose) was also the growth-limiting nutrient. Sucrose was chosen in preference to other carbon sources because of its relative purity in commercial form and because the large quantities necessary for this study rendered other possible carbon sources economically undesirable. A concentrated solution (47,310 mg/l) of the waste was prepared in either a 20- or 40-liter Pyrex bottle and then conveyed to the wet well by a variable speed Cole-Parmer Masterflex Tubing Pump (Model WZ IR031). The feed solution was supplemented with 30-60 ml of 16 N sulfuric acid during preparation to prevent biological growth in the feed bottle and to assist in dissolving the concentrated waste constituents. The prepared feed solution was stirred slowly and continuously during the feeding period with a magnetic stirring bar to insure that a constant homogeneous solution was always pumped to the wet well for mixing with the tap water. By varying the amount of concentrated waste entering the wet well, the desired organic concentrations (CODs) could be achieved.

TABLE I

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

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

The desired mixed feed concentration was pumped from the wet well to the primary filter distribution system by means of a Teel Rotary-Screw Pump (Model IP610). A valve controlled recirculation system regulated the output of the pump, which was belt-driven by a single-speed electric motor. The output by the pump was adjusted until it equalled the flow rate established by the rotameter. The waste flow to the secondary filter was pumped from clarifier no. 2 and conveyed to its distribution system by a pump identical to the one described above for the primary filter.

Distribution of the waste across the 1.0 ft^2 of horizontal surface area of the two filters was accomplished by utilizing an oscillating spray nozzle. The spray nozzle was powered by an electrically-motorized chain-drive that moved back and forth horizontally across the medium. The rectangular spray pattern of the nozzle and the oscillating movement provided an even distribution of waste to the filter's top surface. Coinciding with a change in the hydraulic loading to the filters, the nozzle tips were changed in order to provide the best possible distribution of waste.

The waste stream was allowed to flow through the four Flocor modules and into a collection device at the bottom of each filter. The effluent from the primary filter was channeled into the intermediate clarifiers, while the effluent from the secondary filter flowed into the local sanitary sewer system.

Experimental Procedures

Since the primary filter had been used by previous investigators, it was not necessary to seed it with microorganisms. However, prior to its initial use, it was seeded with settled sewage from the primary clarifier of the Stillwater sewage treatment plant. The secondary filter was put into operation in February, 1973, the seeding process being accomplished by pumping the clarified effluent from the primary filter. During the period from February to June, the two-stage system was fed sucrose waste at a COD concentration of 200 mg/l and a hydraulic flow rate of 500 gpd. The biological growth was thus allowed to accumulate and equilibrate at this loading on the respective filters. Sloughed solids from the primary filter were removed daily from the intermediate clarifiers during this time and throughout the duration of this investigation. Removal of solids on a daily basis was practiced to prevent anaerobic conditions from developing in the clarifiers.

Actual sampling of the waste flow began on June 3, 1973, with an influent COD of 260 mg/l at a flow rate of 500 gal/day. This was the beginning of a series of 12 runs of one or more week's duration to obtain data. Each time a run was completed, the flow rate and/or feed concentration was changed and a new run initiated. Each run consisted of a minimum four-day equilibration period, followed by a minimum of three consecutive days of sampling at each one-foot depth of the filters.

Steady state conditions were ascertained by obtaining nearly identical values of pH and COD over a three-day sampling period. Results of analyses obtained over the three-day period were averaged and recorded as the values for that particular parameter for that particular run.

Prior to collecting samples for a COD determination, samples of approximately 70 ml were collected in an 80-ml beaker from the influent and effluent of each filter and from the outlet of each clarifier. The temperature of these samples was taken and recorded and the pH determined using a Beckman pH meter. Samples for COD analysis were taken at each foot of depth using a modified PVC tube which had the upper half of its wall removed to form a trough-like sampler. The sampler was inserted into the sampling ports and moved back and forth horizontally across the medium so that a composite sample was obtained at each foot of depth. Approximately 100 ml of sample was collected in a 250-ml Erlenmeyer flask at each sampling point, including samples from the clarifier outlets and the nozzles of each filter. Of this amount, approximately 50 ml was filtered through a HA 0.45 μ Millipore filter. A chemical oxygen demand (COD) of the filtrate was then determined by the procedure outlined in Standard Methods (17) utilizing a 20-ml sample size.

CHAPTER IV

RESULTS

The results of this investigation are given in tabular form. All values listed are averages of at least three experiments or are the results of calculations involving average values for three or more experiments at approximately equal total organic (COD) loadings. The total organic loadings for each experimental run were calculated by multiplying the average influent COD by the flowrate and then converting by use of the proper coefficients into units of lbs COD/day/1000 ft^3. For purposes of clarity, the results are presented separately for each filter and for the combined filter volumes.

Primary Filter

The results for all experimental runs conducted on the primary filter are given in Table II. Values given include the flowrate, COD, pH, and performance characteristics. Seven of the runs were made employing flows of 500 and 750 gpd/ft^2 and five were made at flows of 1000 gpd/ft^2. This allowed for collection of data at flowrates both above and below the minimum wetting rate of 864 gpd/ft^2.

Shown in Figures 2, 3, and 4 are the relationships of COD remaining with depth in the primary filter for the various flowrates and organic concentrations. It is interesting to note that these data plot as a straight line on semi-logarithmic paper. This indicates that the

TABLE II

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

Filter Influent				Depth of Filter Medium (ft)									Performance Characteristics		
				1		2		3		4					
Flow Rate gpd/ft^2	COD Conc. (mg/l)	COD Loading lbs/day/ 1000 ft^3	pH	COD (mg/l)	% COD remain.	COD (mg/l)	% COD remain.	COD (mg/l)	% COD remain.	COD (mg/l)	% COD remain.	pH	COD Load remov. lbs/day/ 1000 ft^3	% COD remov.	Substrate Removal Rate k
500	260	271	7.1	228	87.7	207	79.6	180	69.2	148	56.9	7.0	117	43.1	-.0612
500	421	439	6.9	375	89.1	347	82.4	317	75.3	279	66.3	6.5	148	33.7	-.0447
500	550	573	6.9	492	89.5	449	81.6	410	74.5	375	68.2	6.3	182	31.8	-.0416
750	270	422	7.0	244	90.4	225	83.3	205	75.9	181	67.0	6.9	139	33.0	-.0434
750	213	333	7.0	188	88.3	169	79.3	149	70.0	128	60.1	7.0	133	39.9	-.0553
750	153	239	7.1	128	83.7	115	75.2	98	64.1	82	53.6	7.1	111	46.4	-.0677
750	130	203	7.1	106	81.5	91	70.0	79	60.8	64	49.2	7.2	103	50.8	-.0769
1000	85	177	7.3	71	83.5	62	72.9	48	56.5	43	50.6	7.4	87	49.4	-.0740
1000	111	231	7.2	92	82.9	80	72.1	68	61.3	56	50.5	7.3	114	49.5	-.0743
1000	175	365	7.2	148	84.6	131	74.9	117	66.9	102	58.3	7.3	152	41.7	-.0586
1000	227	473	7.1	198	87.2	180	79.3	162	71.4	141	62.1	7.0	179	37.9	-.0517
1000	297	619	7.1	269	90.6	250	84.2	231	77.8	210	70.7	7.0	181	29.3	-.0376

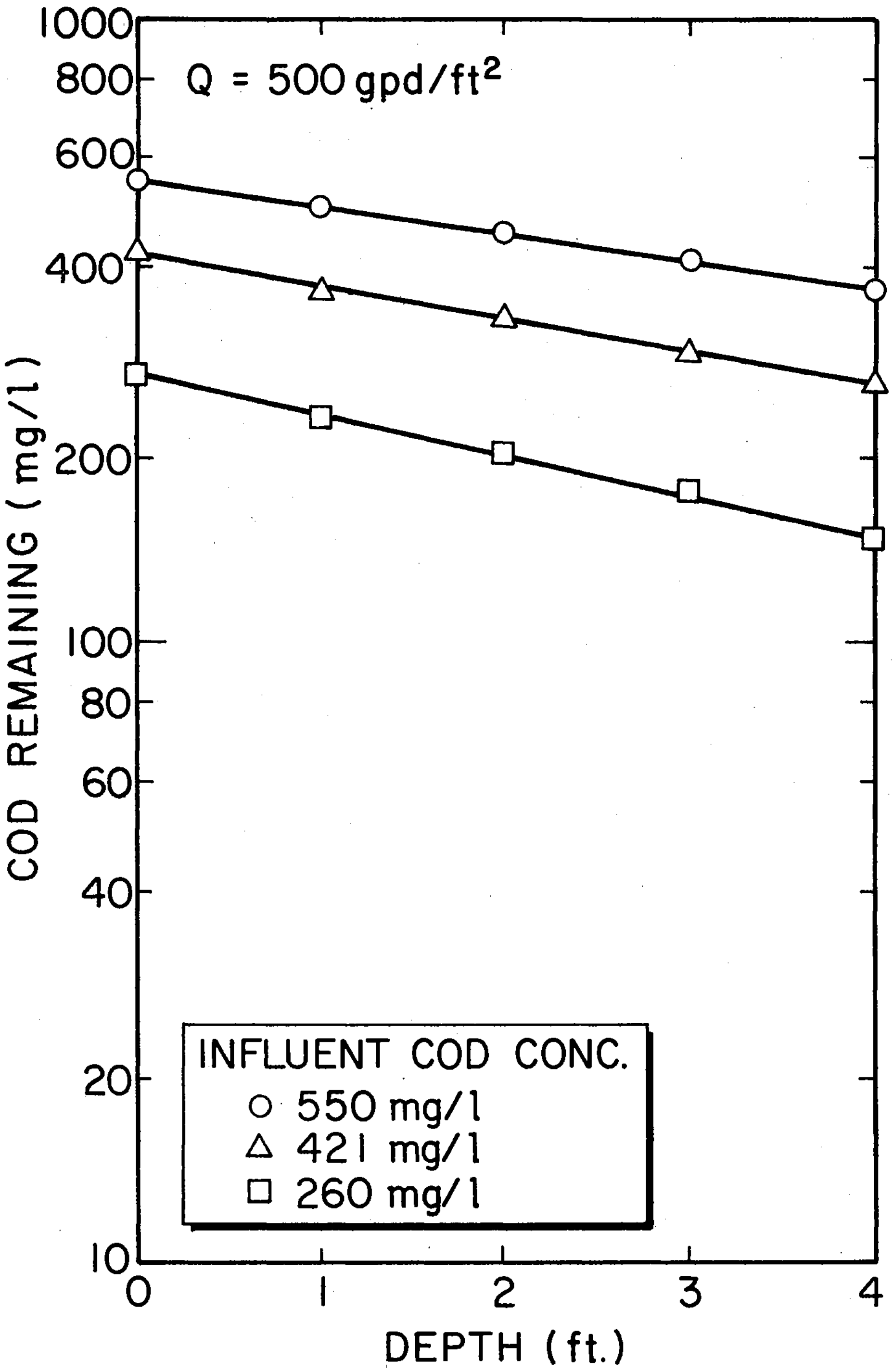

Figure 2. Relationship of COD Remaining with Depth at a Constant Flow Rate of 500 gpd/ft^2 and Varying Organic Concentrations for the Primary Filter

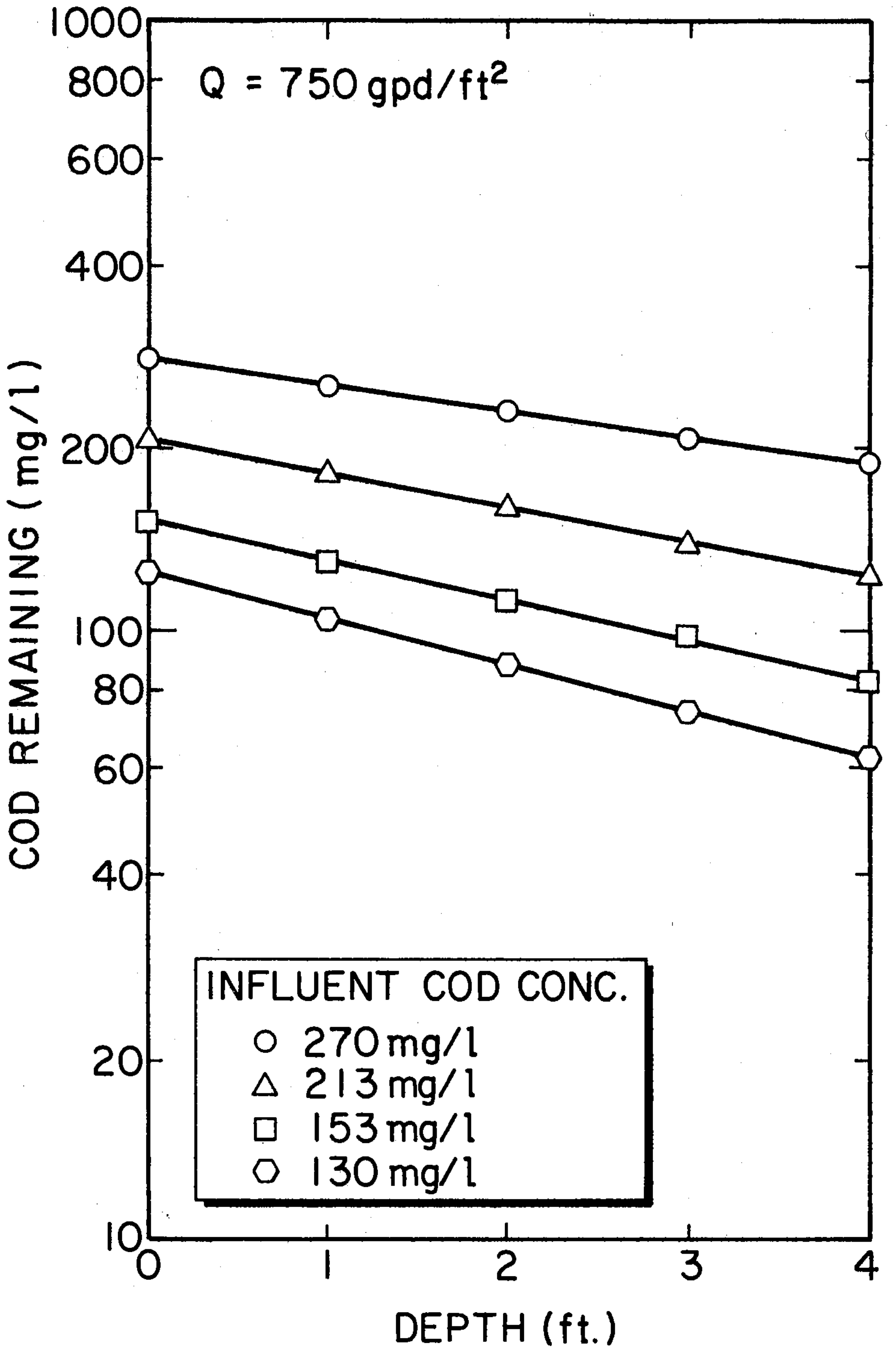

Figure 3. Relationship of COD Remaining with Depth at a Constant Flow Rate of 750 gpd/ft^2 and Varying Organic Concentrations for the Primary Filter

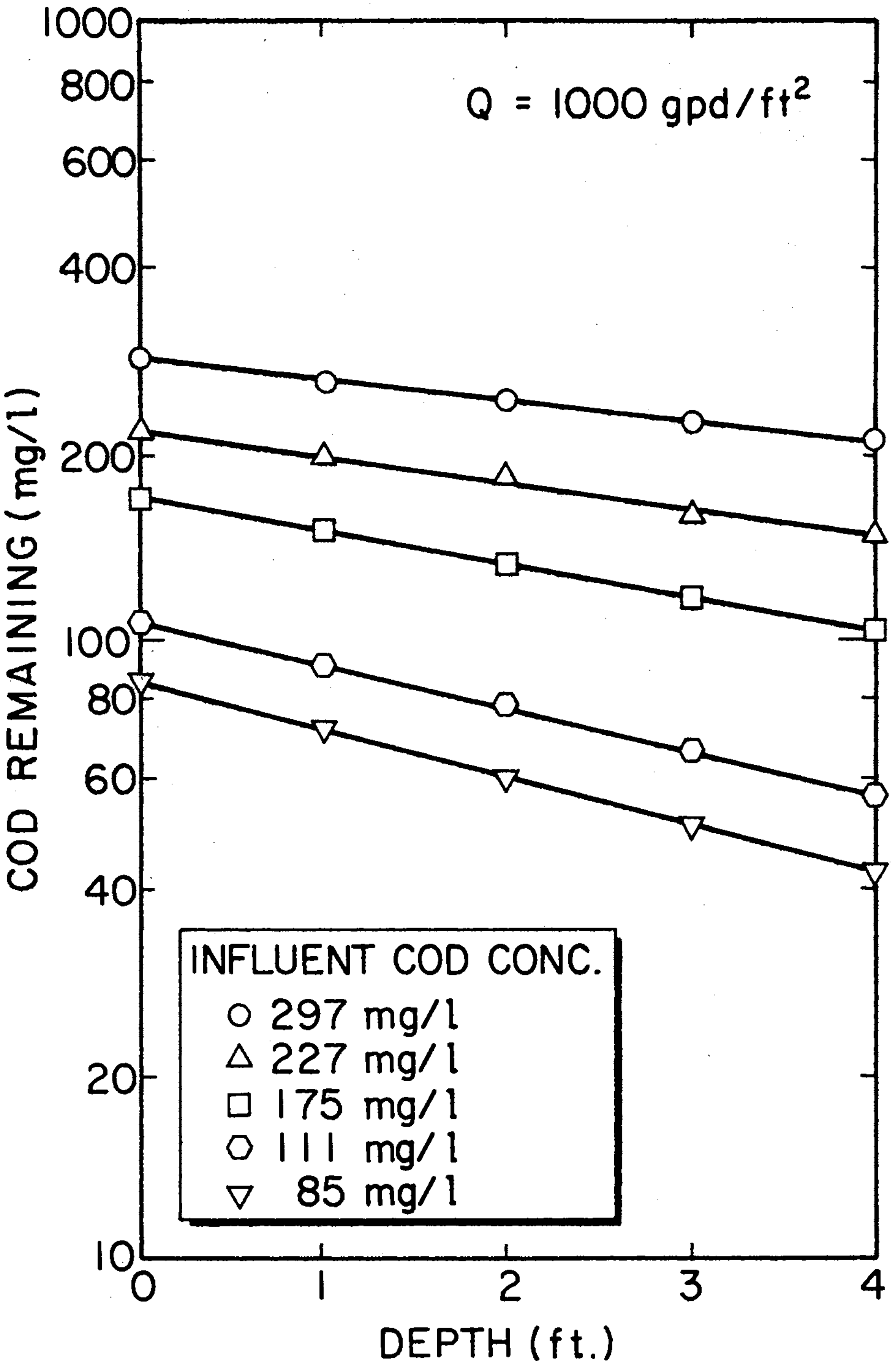

Figure 4. Relationship of COD Remaining with Depth at a Constant Flow Rate of 1000 gpd/ft^2 and Varying Organic Concentrations for the Primary Filter

removal of COD is first-order with respect to depth. This agrees with equations developed by Velz (19) and Eckenfelder on removal in trickling filters.

By calculating the slopes of the lines plotted in Figures 2, 3, and 4, substrate removal rates (k) were obtained for each combination of influent COD concentration and hydraulic loading. These values are shown in Table II. Figure 5 was developed to illustrate the relationship of substrate removal rate with applied COD loading (lbs/day/1000 ft^3) for the primary filter. The two lines shown represent k values at flows above and below the minimum wetting rate. It is evident from the plot that at a flow of 1000 gpd/ft^2, the substrate removal rate is directly proportional to the applied COD loading. For flows of 500 and 750 gpd/ft^2, linearity is not evident but rather a hyperbolic function is shown to exist. The importance of hydraulic loading on the removal rates in a trickling filter can be seen from an analysis of Figure 5. Also of interest is that an increase in applied COD loading results in a decrease in the substrate removal rate.

The relationship of percent COD removed with COD applied (lbs/day/1000 ft^3) for the primary filter is shown graphically in Figure 6. It appears that at the majority of COD loadings utilized, the filter was more efficient in removing COD when operated at a flow of 1000 gpd/ft^2 than at either 500 or 750 gpd/ft^2. This is expected, since at flows below the minimum wetting rate a smaller area of the medium is utilized for biological growth and purification of the wastewater. However, at the extremes of COD loadings studied, this effect was not manifested and nearly equal percentages of COD removal were exhibited at all experimental flow rates. The author can see no apparent reason for this

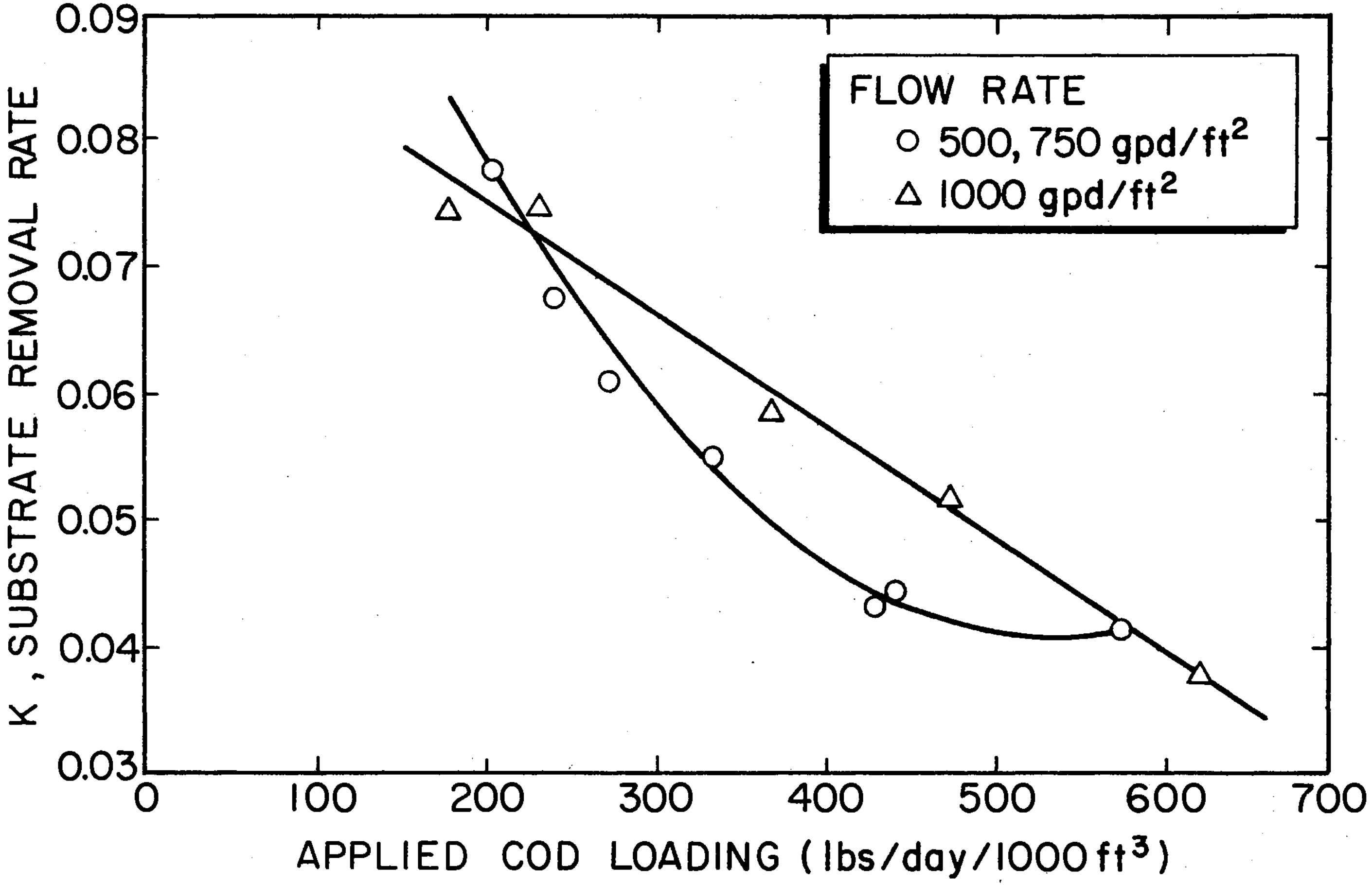

Figure 5. Relationship of Substrate Removal Rate (k) with Applied COD Loading (lbs/day/1000 ft^3) at Various Flow Rates for the Primary Filter

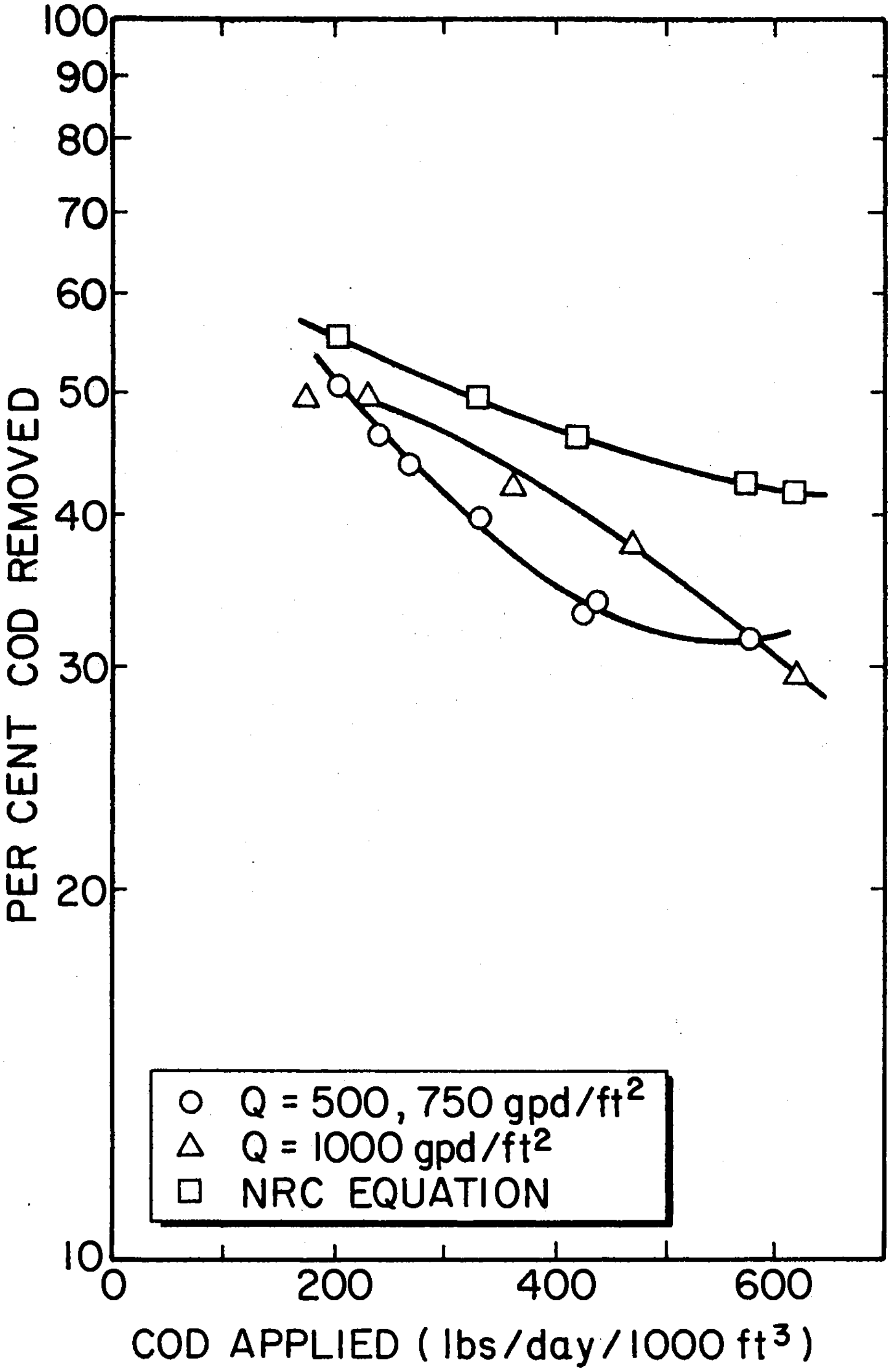

Figure 6. Relationship of Percent COD Removed with COD Applied (lbs/day/1000 ft^3) at Various Flow Rates for the Primary Filter

behavior. Also included in Figure 6 for comparison purposes is a plot made from efficiencies calculated by the National Research Council (NRC) design formula. This equation was developed from extensive studies of sewage treatment at military installations throughout the United States during World War II, and is shown below:

$$E_1 = \text{fraction BOD removed} = \frac{1}{1 + C(\frac{w_1}{VF})^{0.5}} \qquad (1)$$

where

w_1 = organic load, lbs/day

V = volume of media

F = recirculation factor = $\frac{1 + R}{[1 + 0.1R]^2}$

R = fraction of influent flowrate recirculated

C = constant, equal to .0085 for volume in acre-ft or .0561 for volume in thousands of cu ft.

Efficiency values calculated by the NRC equation are seen to be higher than the efficiencies obtained by the experimental filter.

During the operation of the primary filter, various visual observations of possible significance were made. The biomass on the filter was noted as being a light creamy color. Sloughing was slight and erratic at low COD loadings but fairly constant and heavy at higher COD loadings. Filter flies (Psychoda) were evident in abundance during the duration of the study. These flies may have had an influence on the efficiencies observed, but it was beyond the scope of this study to determine the magnitude of this influence, if any.

Secondary Filter

The results of experimental runs on the secondary filter are given in tabular form in Table III. These results correspond to runs on the primary filter made at the same date. Organic loads are lower due to the removal effected by the primary filter and intermediate clarifiers.

Figures 7, 8, and 9 show the relationship of COD remaining with depth for the secondary filter at the various flow rates and organic concentrations. These results vary from those for the primary filter in that two substrate removal rates are exhibited instead of one for most cases. Exceptions are for the runs made at a flow of 1000 gpd/ft^2 which had initial CODs of 81, 121, and 188 mg/l. For these conditions, only one substrate removal rate is exhibited and the lines on Figure 9 are shown as straight continuous lines. Referring back to the other runs, a high substrate removal rate (k_1) is usually exhibited first, followed by a decreased removal rate (k_2) through the remaining depth of the filter. The initial high removal rate (k_1) usually manifests itself in the first foot of the secondary filter, especially at the lower COD loadings, whereas at higher COD loadings, k_1 extends through two or three feet of the filter.

In Figure 10 is shown the relationship of k_1 with the applied COD loading to the secondary filter. It is seen that the k_1 values calculated at a flow of 1000 gpd/ft^2 are directly proportional to the applied COD loading. For a constant increase in loading there is a corresponding decrease in removal rate (k_1). Substrate removal rates for 500 and 750 gpd/ft^2 are much higher than those at 1000 gpd/ft^2 at COD loadings near 100 lbs/day/1000 ft^3, but tend to decrease sharply until they approach the same values shown for 1000 gpd/ft^2 at loadings near 250 lbs/day/1000^3 ft. The second removal rate (k_2) is plotted vs. applied COD loading for the secondary filter in Figure 11. Values are plotted

TABLE III

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

Filter Influent				Depth of Filter Medium (ft)									Performance Characteristics			
				1		2		3		4					Substrate Removal Rates	
Flow Rate gpd/ft^3	COD Conc. (mg/l)	COD Loading lbs/day/ 1000 ft^3	pH	COD (mg/l)	% COD remain.	COD (mg/l)	% COD remain.	COD (mg/l)	% COD remain.	COD (mg/l)	% COD remain.	pH	COD Load remov. lbs/day/ 1000 ft^3	% COD remov.	k_1	k_2
500	126	131	6.8	92	73.0	80	63.5	68	54.0	61	48.4	7.3	68	51.6	-.1366	-.0595
500	242	252	6.2	205	84.7	178	73.6	162	66.9	144	59.5	6.6	102	40.5	-.0721	-.0511
500	341	355	5.7	296	86.8	263	77.1	244	71.6	229	67.2	6.0	117	32.8	-.0564	-.0301
750	156	244	6.7	135	86.5	118	75.6	103	66.0	97	62.2	6.9	92	37.8	-.0601	-.0261
750	103	161	6.9	77	74.8	69	67.0	57	55.3	51	49.5	7.1	81	50.5	-.1264	-.0596
750	57	89	7.1	41	71.9	36	63.2	31	54.4	27	47.4	7.4	47	52.6	-.1431	-.0605
750	44	69	7.2	33	75.0	32	72.7	30	68.2	29	65.9	7.4	23	34.1	-.1249	-.0561
1000	27	56	7.5	22	81.5	24	88.9	20	74.1	21	77.8	7.7	13	22.2	-.0889	-.0202
1000	36	75	7.3	27	75.0	23	63.9	21	58.3	22	61.1	7.4	29	38.9	-.1249	-.0297
1000	81	169	7.2	66	81.5	57	70.4	46	56.8	41	50.6	7.3	83	49.4	-.0739	-
1000	121	252	6.9	102	84.3	90	74.4	79	65.3	67	55.4	7.1	113	44.6	-.0642	-
1000	188	392	6.9	168	89.4	153	81.4	138	73.4	122	64.9	6.9	138	35.1	-.0470	-

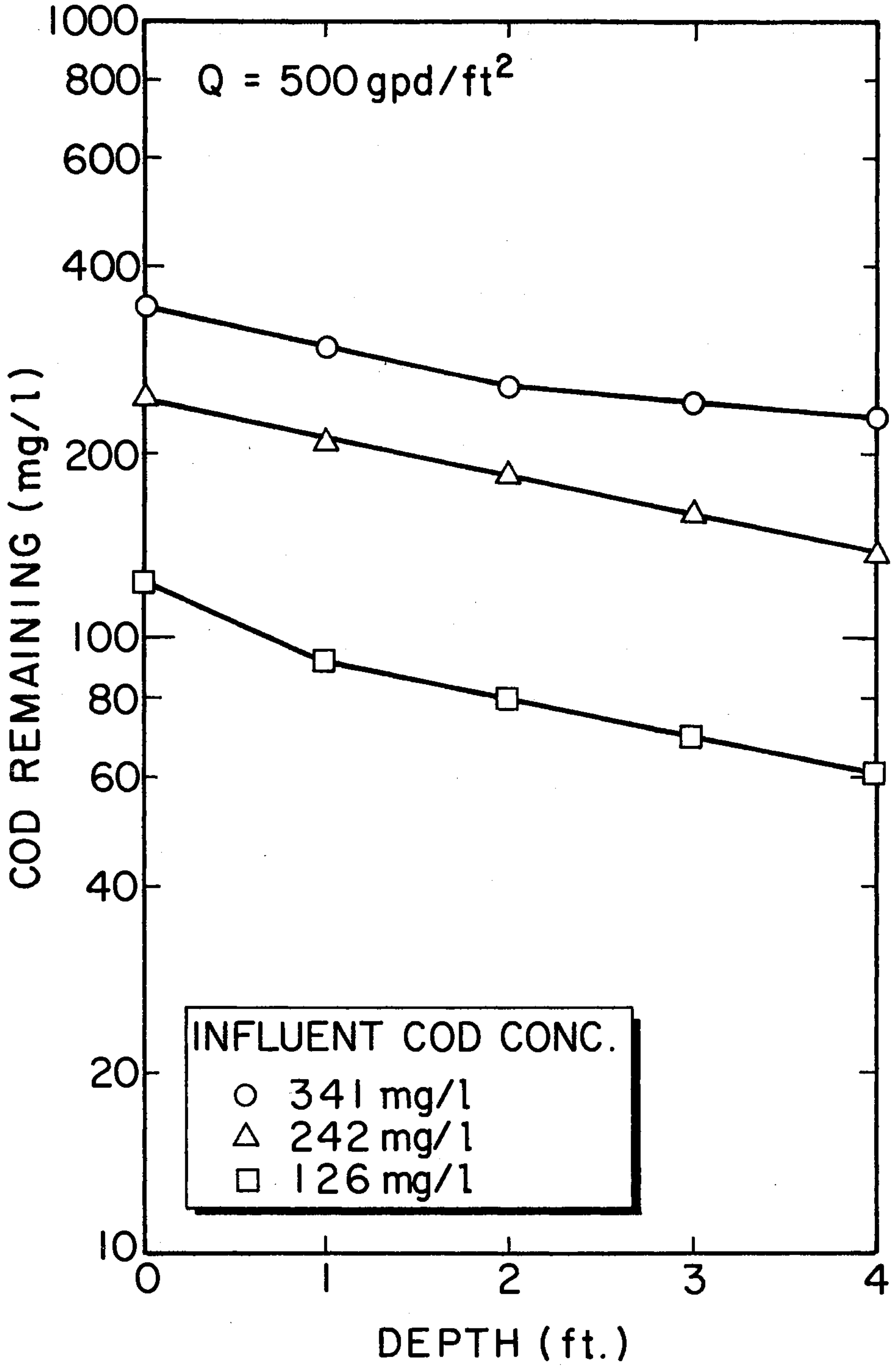

Figure 7. Relationship of COD Remaining with Depth at a Constant Flow Rate of 500 gpd/ft^2 and Varying Organic Concentrations for the Secondary Filter

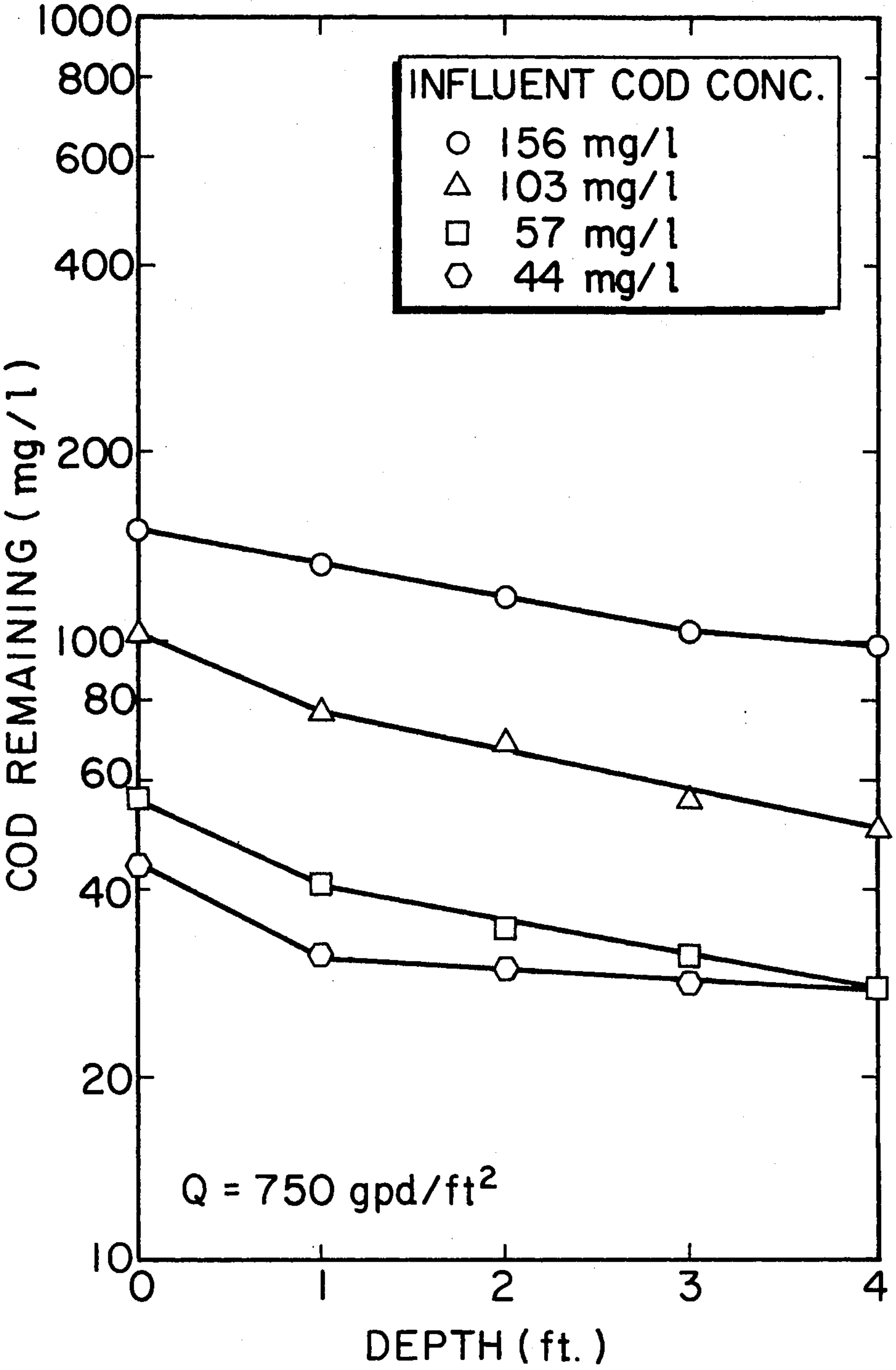

Figure 8. Relationship of COD Remaining with Depth at a Constant Flow Rate of 750 gpd/ft^2 and Varying Organic Concentrations for the Secondary Filter

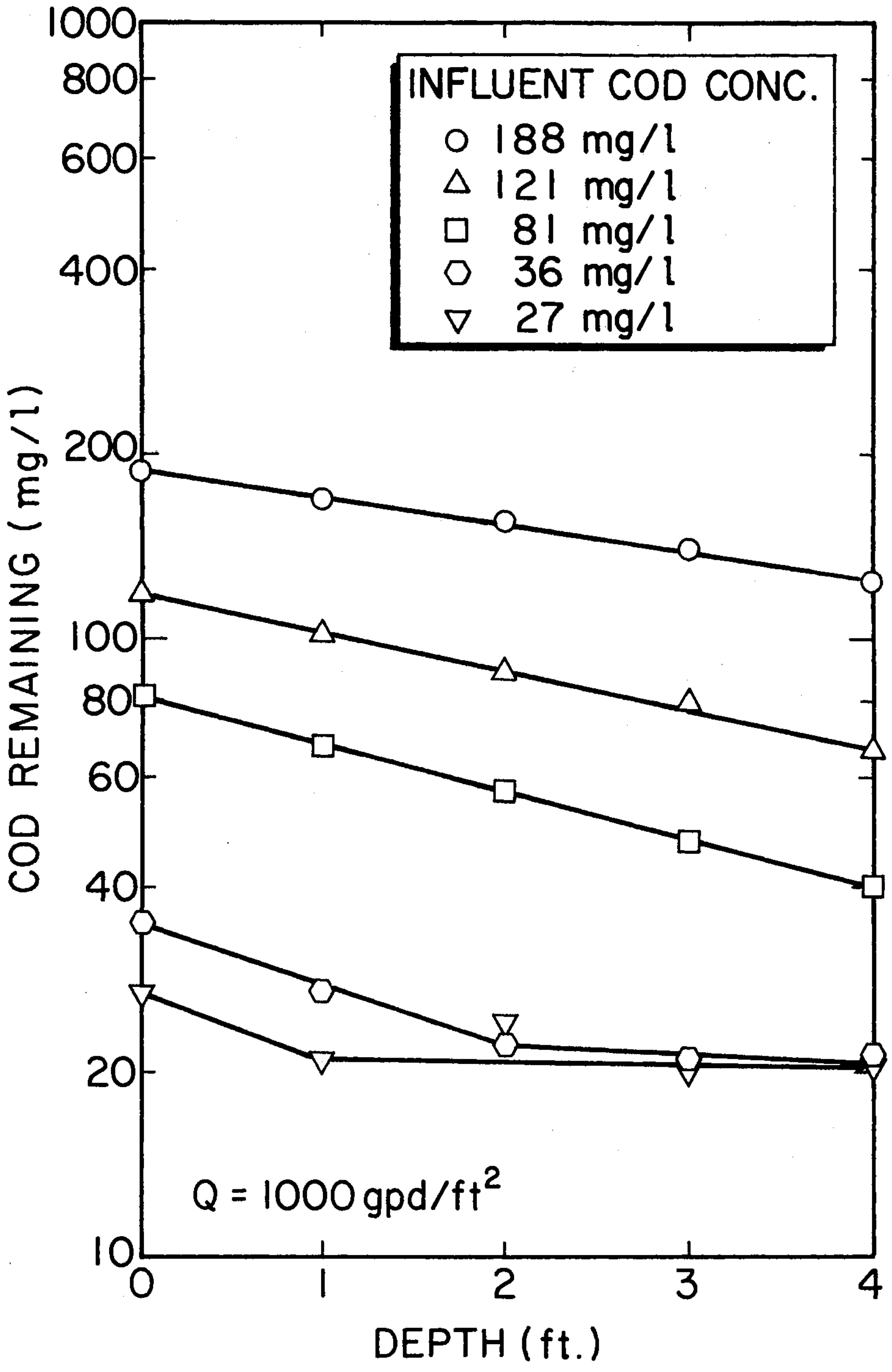

Figure 9. Relationship of COD Remaining with Depth at a Constant Flow Rate of 1000 gpd/ft^2 and Varying Organic Concentrations for the Secondary Filter

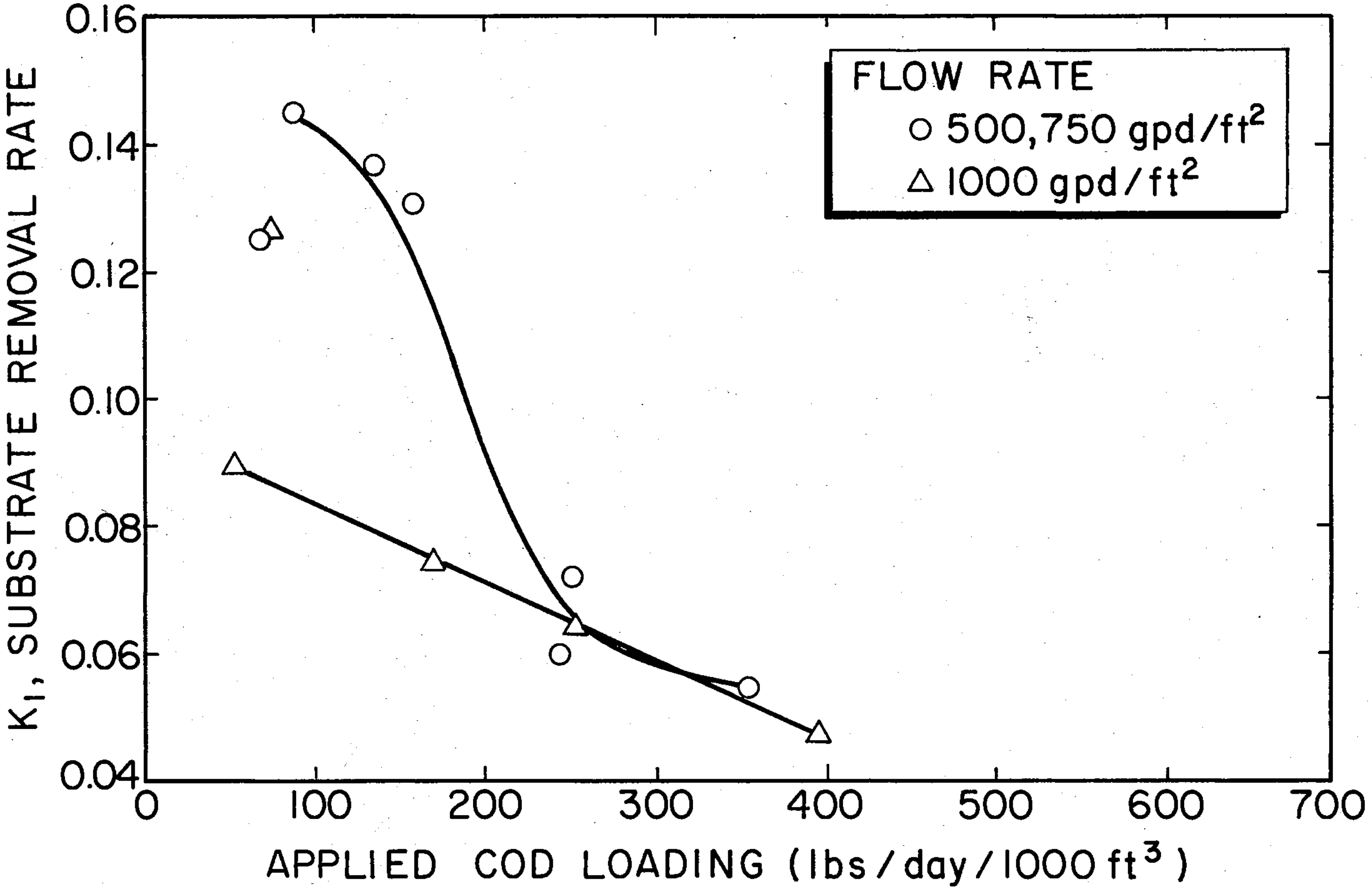

Figure 10. Relationship of Substrate Removal Rate (k_1) with Applied COD Loading (lbs/day/1000 ft^3) at Various Flow Rates for the Secondary Filter

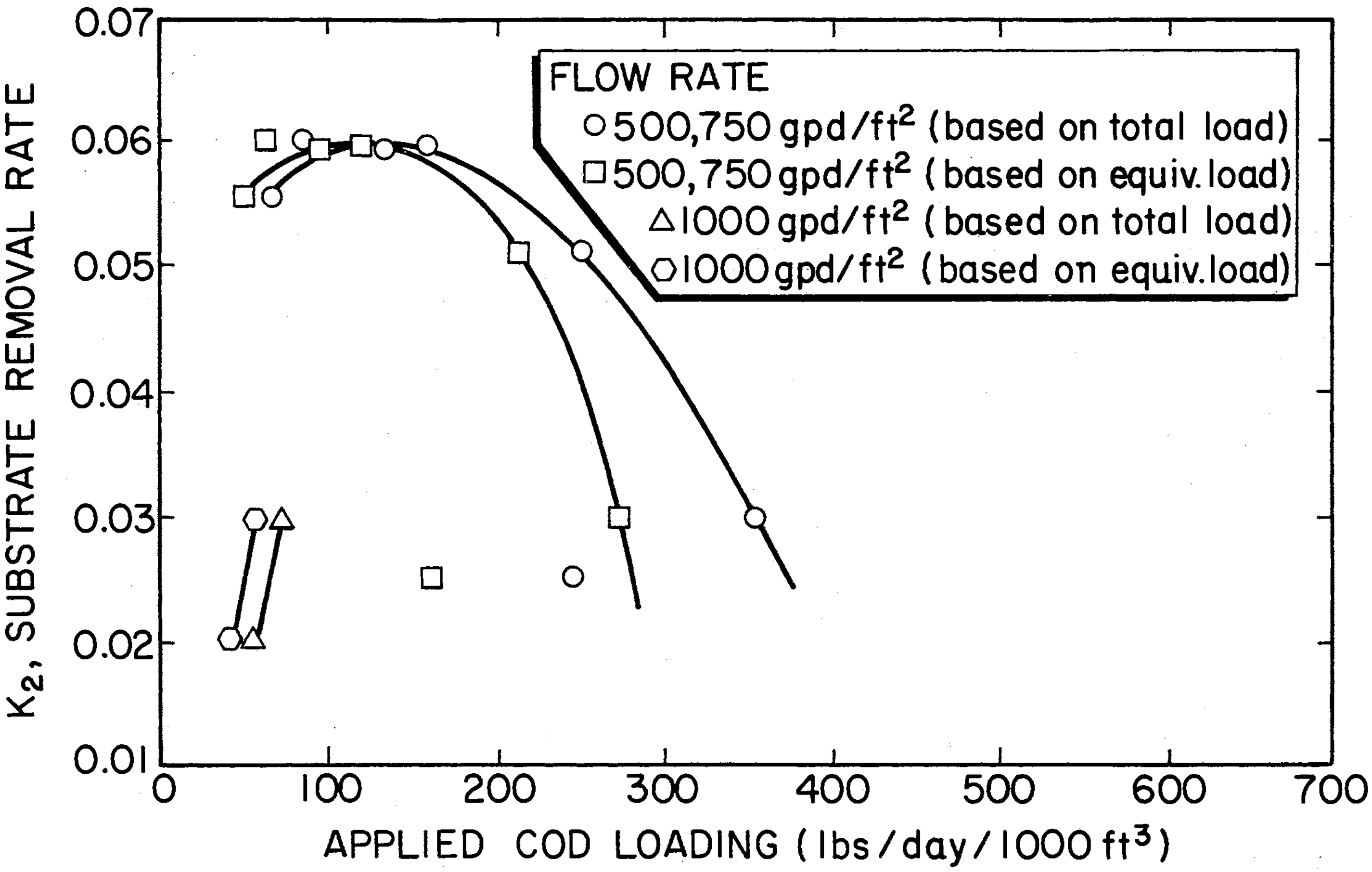

Figure 11. Relationship of Substrate Removal Rate (k_2) with Applied COD Loading (lbs/day/1000 ft^3) at Various Flow Rates for the Secondary Filter

for k_2 vs. both the total COD loading to the filter and the COD loading exhibited on that portion of the filter where k_2 is acting. For flow-rates of 500 and 750 gpd/ft^2, k_2 values appear to be fairly constant at COD loadings ranging from 80 to 150 lbs/day/1000 ft^3. The values then dip sharply for increases in loading up to 355 lbs COD/day/1000 ft^3.

The reltationship of percent COD removed with COD applied (lbs/day/1000 ft^3) for the secondary filter is shown in Figure 12. Maximum efficiencies are seen to exist for COD loadings near 100 lbs/day/1000 ft^3. On either side of this loading, efficiencies tended to decrease. The reason for the decrease in efficiency at COD loadings less than 100 lbs/day/1000 ft^3 is that a residual COD near 20 mg/l was present which could not be biologically reduced. The NRC equation for second-stage filters is also plotted in Figure 12 for comparison with experimental efficiencies. The NRC equation for second-stage filters is as follows:

$$E_2 = \frac{1}{1 + \frac{.0561}{1 - E_1}\left(\frac{w_2}{VF}\right)^{0.5}} \tag{2}$$

where

E_2 = fractional efficiency of BOD removal by the second stage

w_2 = organic load influent to second-stage filter in lbs/day, and

E_1 = efficiency of first-stage filtration expressed as a fraction.

The NRC equation compares fairly closely with experimental data, but shows higher efficiencies at very high and very low COD loadings and lower efficiencies in the intermediate range of loadings.

The biomass growing on the secondary filter was not a light creamy color as in the primary filter, but rather a light brown-to-tan color. It seemed to be distributed over the media better than the biomass in the primary filter. An abundance of filter flies was present on the

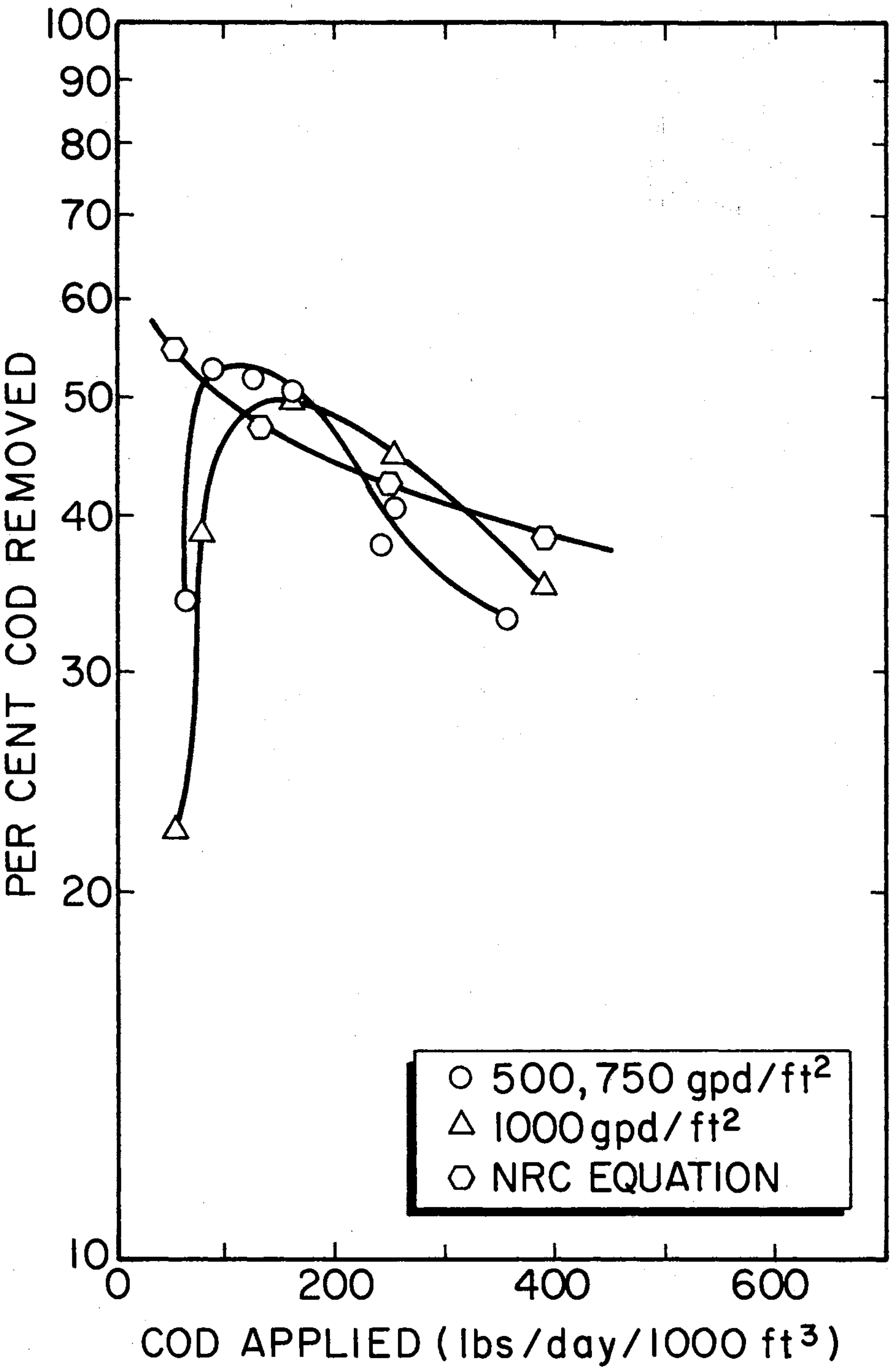

Figure 12. Relationship of Percent COD Removed with COD Applied (lbs/day/1000 ft^3) at Various Flow Rates for the Secondary Filter

secondary filter throughout the duration of this study.

Overall Two-stage System

The results for the entire experimental system, including the intermediate clarifiers, are given in Table IV. Influent and effluent pH values for the overall system plus performance characteristics with and without clarification are listed in the table for all runs. Figures 13, 14, and 15 are utilized to illustrate the relationship of percent COD remaining with successive stages of the overall system. The figures are similar in that lines for the primary filter are linear with one slope, clarifiers are variable, and the secondary filters generally show two slopes, corresponding to the two substrate removal rates calculated previously. In nearly every case, an increase in influent COD to the system resulted in a decrease in the percent COD removed by the system. In only two instances (at the lower loadings for 750 and 1000 gpd/ft^2) did the percent removal increase with an increasing influent COD rather than decrease. This was undoubtedly due to the failure of the secondary filter to remove the low residual COD.

Combined Filter Volumes and Clarifiers

Given in Table V are the results for the individual components of the two-stage system and for the combined filter volumes. The primary filter was shown to remove a greater percentage of the total influent COD than the secondary filter. This is in agreement with results by Hawkes and Jenkins (4). At the high COD loadings (lbs/day/1000 ft^3) to the system, the ratio of percentage removal by primary filters to percentage removal by secondary filters approached a value of 1.0. It is

TABLE IV

DATA SUMMARY OF pH, COD, AND PERFORMANCE CHARACTERISTICS FOR THE COMBINED TWO-STAGE SYSTEM AT VARIOUS FLOW RATES AND INFLUENT COD CONCENTRATIONS

System Influent				Overall Performance Characteristics					
						Including Clarification		Without Clarification	
Flow Rate (gpd/ft^2)	COD Conc. (mg/l)	COD Loading (lbs/day/ 1000 ft^3)	pH	Effluent COD Conc. (mg/l)	Effluent pH	COD Load Removed (lbs/day/ 1000 ft^3)	% COD Removed	COD Load Removed lbs/day/ 1000 ft^3)	% COD Removed
500	260	136	7.1	61	7.3	104	76.5	93	68.1
500	421	220	6.9	144	6.6	145	65.8	125	57.0
500	550	287	6.9	229	6.0	168	58.4	150	52.2
750	270	211	7.0	97	6.9	136	64.1	116	54.9
750	213	167	7.0	51	7.1	127	76.1	107	64.4
750	153	120	7.1	27	7.4	99	82.4	79	66.1
750	130	102	7.1	29	7.4	79	77.7	64	62.3
1000	85	88	7.3	21	7.7	67	75.3	50	56.5
1000	111	116	7.2	22	7.4	93	80.2	72	62.1
1000	175	183	7.2	41	7.3	140	76.6	118	64.6
1000	227	237	7.1	67	7.1	167	70.5	146	61.7
1000	297	310	7.1	122	6.9	182	58.9	160	51.5

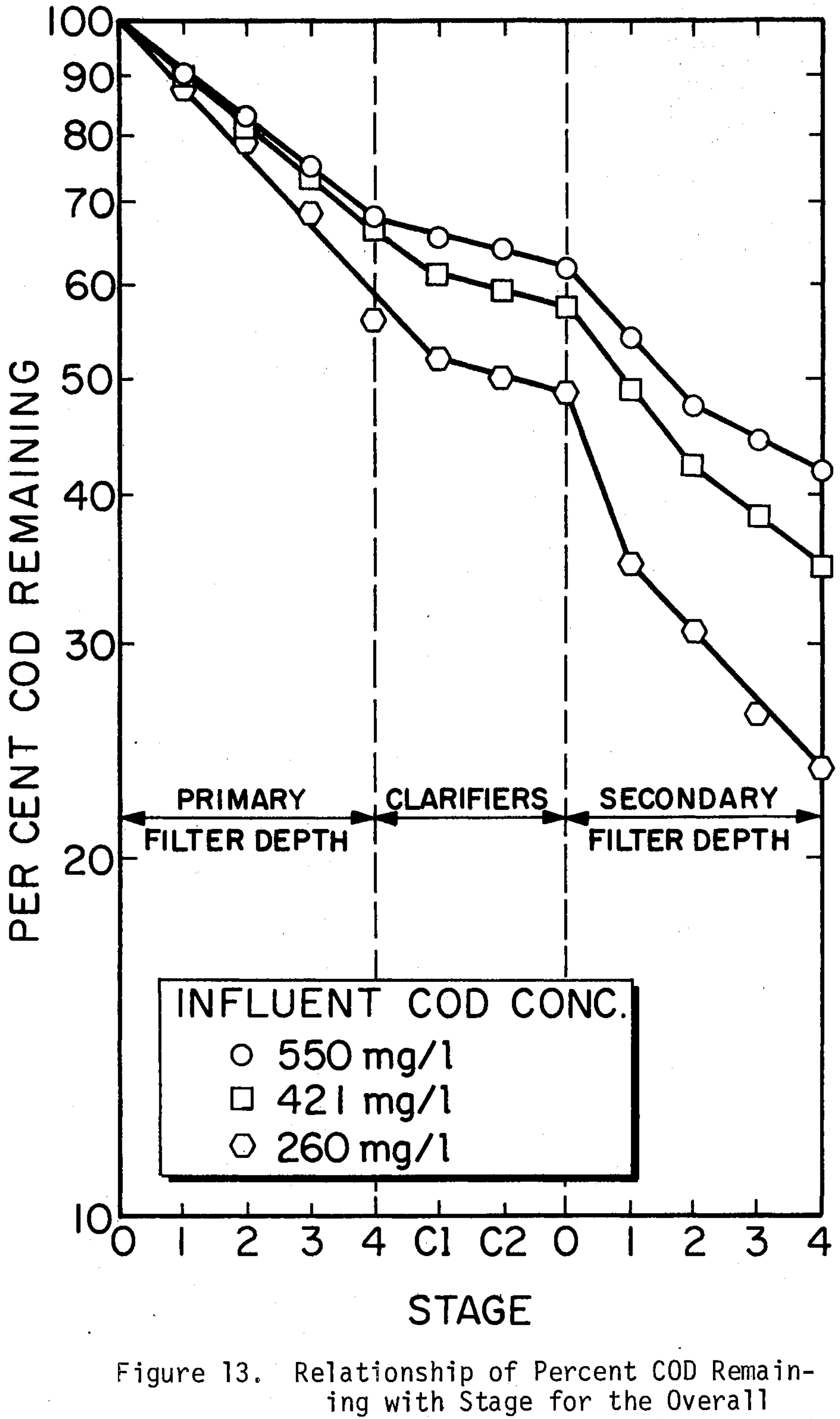

Figure 13. Relationship of Percent COD Remaining with Stage for the Overall System at a Constant Flow Rate of 500 gpd/ft^2 and Varying Influent COD Concentrations

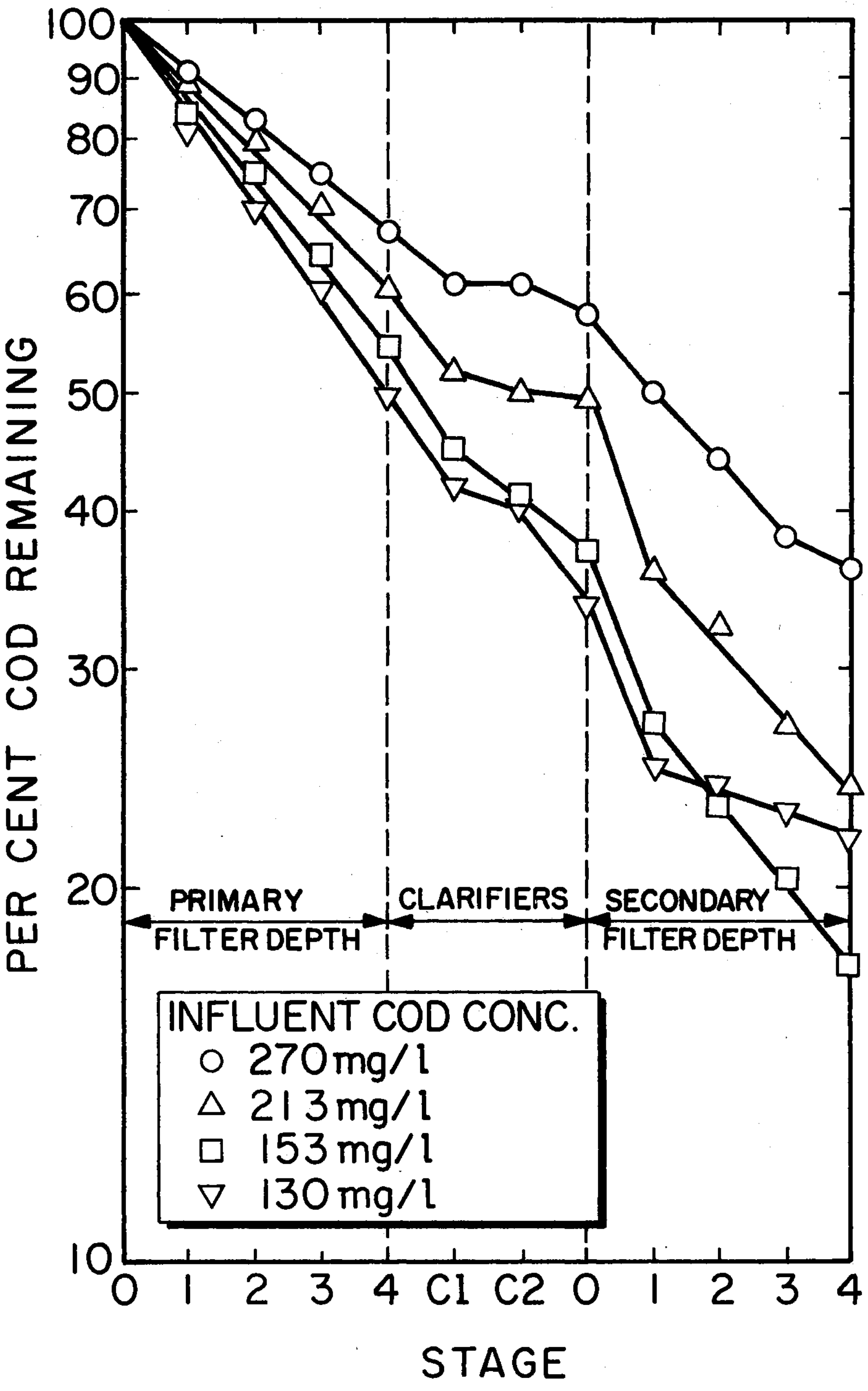

Figure 14. Relationship of Percent COD Remaining with Stage for the Overall System at a Constant Flow Rate of 750 gpd/ft^2 and Varying Influent COD Concentrations

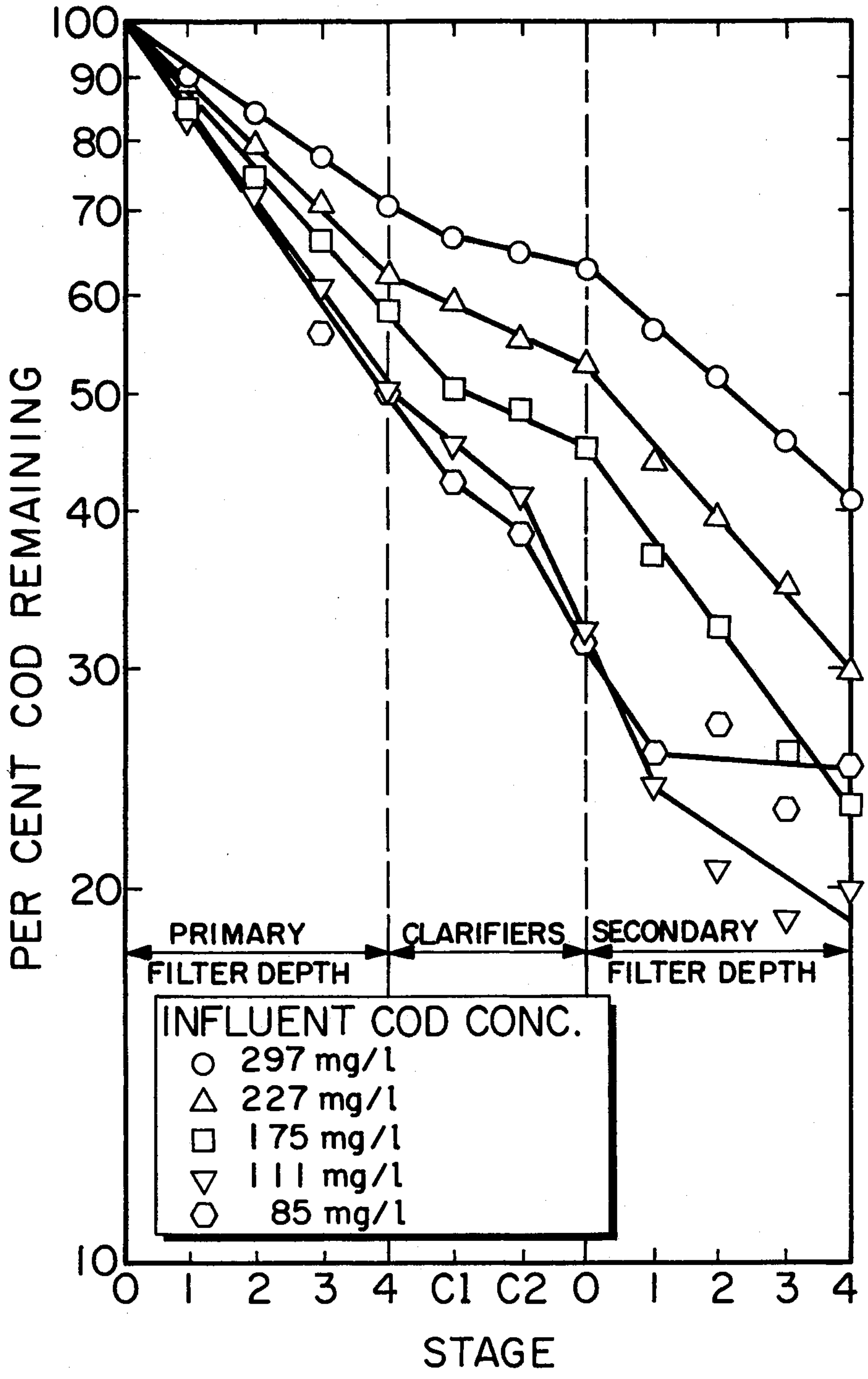

Figure 15. Relationship of Percent COD Remaining with Stage for the Overall System at a Constant Flow Rate of 1000 gpd/ft^2 and Varying Influent COD Concentrations

TABLE V

DATA SUMMARY OF PERCENT COD REMAINING (AS PERCENT OF PRIMARY FILTER INFLUENT COD) FOR THE SECONDARY FILTER AND PERFORMANCE CHARACTERISTICS FOR ALL UNITS OF THE TWO-STAGE SYSTEM

Secondary Filter Influent			Depth of Filter Medium (ft)				Performance Characteristics				
			1	2	3	4					
Flow Rate (gpd/ft^2)	COD (mg/l)	% Primary Influent COD	% COD remain.	% COD remain.	% COD remain.	% COD remain.	Total % COD removed	% Removed by Primary Filter	% Removed by Secondary Filter	% Removed by Combined Filter Vol.	% COD Removed by Clarifiers
500	126	48.5	35.4	30.8	26.2	23.5	76.5	43.1	25.0	68.1	8.4
500	242	57.5	48.7	42.3	38.5	34.2	65.8	33.7	23.3	57.0	8.8
500	341	62.0	53.8	47.8	44.4	41.6	58.4	31.8	20.4	52.2	6.2
750	156	57.8	50.0	43.7	38.1	35.9	64.1	33.0	21.9	54.9	9.2
750	103	48.4	36.1	32.4	26.8	23.9	76.1	39.9	24.5	64.4	11.7
750	57	37.3	26.8	23.5	20.3	17.6	82.4	46.4	19.7	66.1	16.3
750	44	33.8	25.4	24.6	23.1	22.3	77.7	50.8	11.5	62.3	15.4
1000	27	31.8	25.9	28.2	23.5	24.7	75.3	49.4	7.1	56.5	18.8
1000	36	32.4	24.3	20.7	18.9	19.8	80.2	49.5	12.6	62.1	18.1
1000	81	46.3	37.7	32.6	26.3	23.4	76.6	41.7	22.9	64.6	12.0
1000	121	53.3	44.9	39.6	34.8	29.5	70.5	37.9	23.8	61.7	8.8
1000	188	63.3	56.6	51.5	46.5	41.1	58.9	29.3	22.2	51.5	7.4

reckoned that at COD loadings above the range of this study, primary and secondary stages might remove an equal portion of the total applied COD. However, at such high loadings, a poor effluent would be produced which would not be desirable for discharge. Concerning the intermediate clarifiers, it is seen that a surprising percentage of COD was removed. As much as 18.8 percent of the total COD load was removed in one case. Evidently, there was plenty of dissolved oxygen available in the clarifiers for biological growth and oxidation to take place.

Figure 16 shows the relationship of percent COD removed with COD applied (lbs/day/1000 ft^3) for the combined filter volumes (8 ft^3). Efficiencies are approximately equal for 500, 750, and 1000 gpd/ft^2 at COD loadings from 100 to 160 lbs/day/1000 ft^3, but in the range of 160 to 300 lbs/day/1000 ft^3, the system operated at 1000 gpd/ft^2 removes a greater percentage of COD. The NRC equation for an 8 ft^3 filter is plotted in Figure 16 for comparison with the experimental system.

In Figure 17, a comparison is shown among the primary filter, secondary filter, and combined filters at equivalent COD loadings (lbs/day/1000 ft^3). It is seen that the secondary filter is less efficient than the primary filter in removing COD at equivalent loadings. This is possibly due to the fact that the secondary filter is receiving partially treated waste, whereas the primary filter is always receiving an untreated waste. These results differ from results presented by Sorrels and Zeller (5) on domestic waste treated by a conventional rock two-stage filter system. It should be noted that the sewage studied by Sorrels and Zeller contained colloidal particles, whereas the substrate utilized in this study was completely soluble.

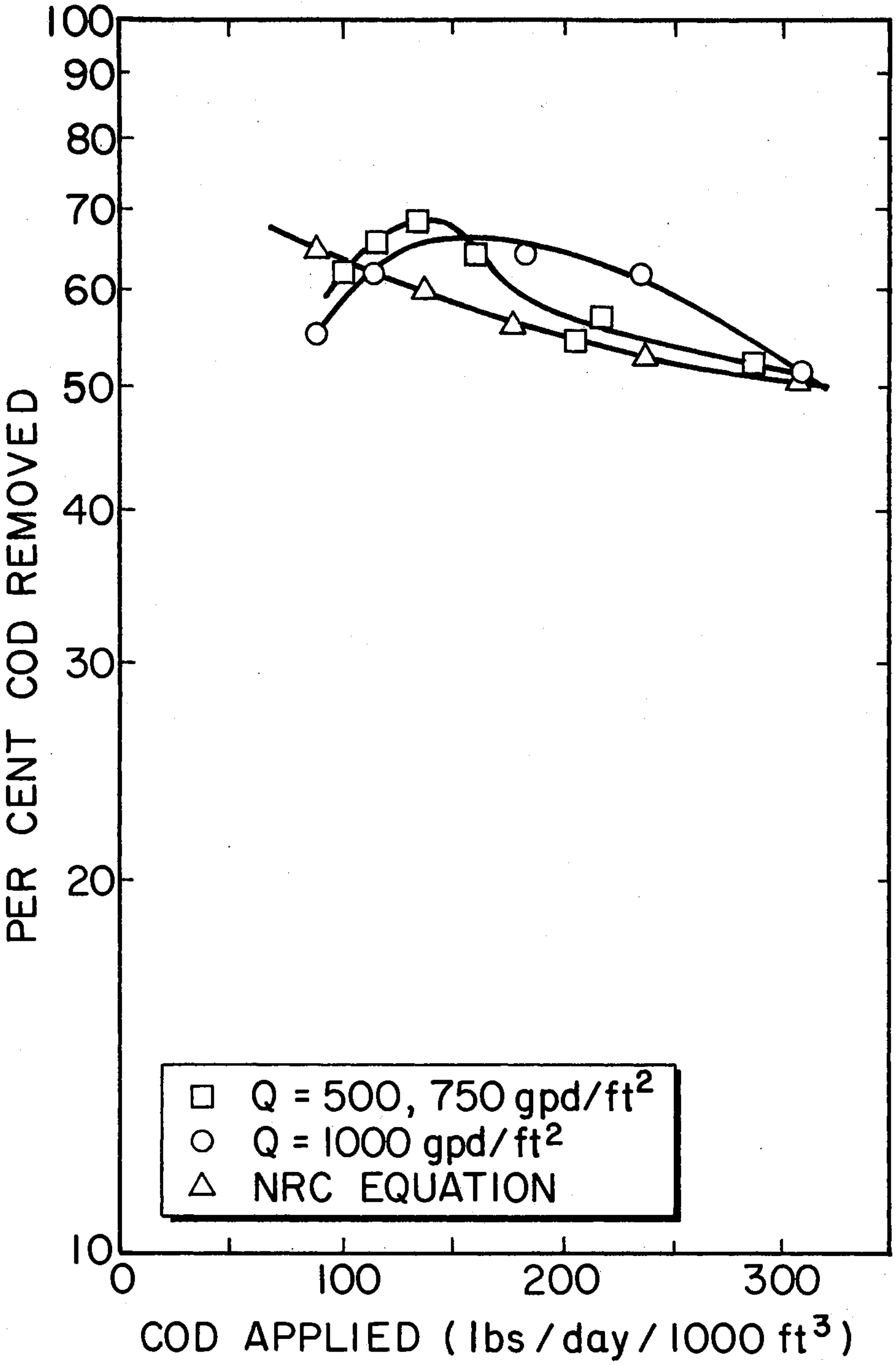

Figure 16. Relationship of Percent COD Removed with COD Applied (lbs/day/1000 ft^3) at Various Flow Rates for the Combined Filter Volumes

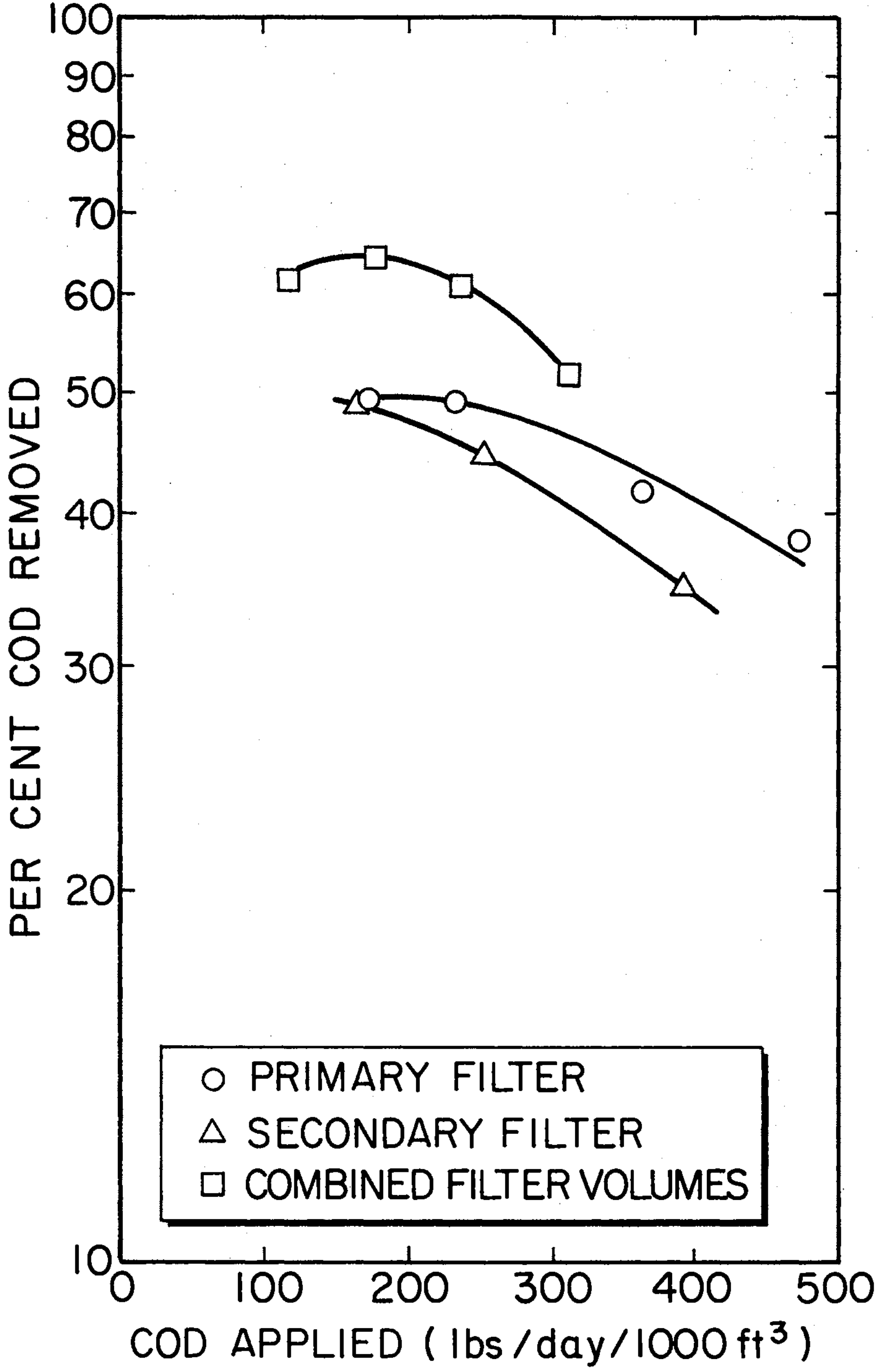

Figure 17. Relationship of Percent COD Removed with COD Applied (lbs/day/1000 ft^3) at a Constant Flow Rate of 1000 gpd/ft^2 for the Primary Filter, Secondary Filter, and the Combined Filter Volumes

CHAPTER V

DISCUSSION

The primary objective of this study was to determine if successive stages of a two-stage trickling filter differed in the amount of COD removed at equivalent total COD loadings (lbs/day/1000 ft^3). An analysis of the results (Figure 17) indicated equal efficiencies for the primary and secondary filters at a COD loading of approximately 175 lbs/day/1000 ft^3. However, for all COD loadings greater than this, a difference in efficiencies was shown which increased with increased loading.

The use of the total COD loading as a basis for comparison was suggested by Cook and Kincannon (20) in 1971. They found that removal efficiency was dependent on the amount of total COD (lbs/day/1000 ft^3) rather than its concentration or flow rate. This is borne out by experimental data collected in this study for varying COD concentrations and flow rates. A slight difference in removal efficiency was seen to exist between runs made at 500 or 750 gpd/ft^2 and 1000 gpd/ft^2. This can be attributed to the fact that 500 to 750 gpd/ft^2 are below the minimum wetting rate, whereas 1000 gpd/ft^2 is above this value. The author would expect equal efficiencies for equal total COD loadings if all flows investigated had been above the minimum wetting rate.

An important question which could be raised concerning the results of this study is, "Are two separate curves necessary for designing successive stages of a plastic media trickling filter?" This question cannot be answered with a definite "yes" or "no." It is apparently dependent on the characteristics of the waste to be treated. In a study on treatment of sewage with a two-stage Flocor plastics filter, Richard (21) developed a curve for the primary filter which received both the soluble and suspended BOD and one for the secondary filter which received only the soluble BOD. These curves varied by about 10 percent at nearly all BOD loadings studied. In this author's study on totally soluble waste (sucrose), curves were obtained for both stages which varied by only about four or five percent at the most.

It would seem, therefore, that the use of separate design curves would depend on whether the waste to be treated was totally soluble or contained a large percentage of suspended BOD as well. For a soluble waste one curve might suffice for design of both stages, assuming a safety factor is incorporated into design. However, for a waste high in suspended matter, such as domestic sewage, this author recommends the use of two separate curves.

It is common with biological systems to experience a certain amount of scatter when gathering operational data. In plotting and evaluating a series of previous trickling filter data, Spurrier (22) found that a fairly large amount of scatter existed at equivalent COD loadings for single stage filters. By employing a statistical regression analysis he was able to develop a line which defined the removal of COD in a trickling filter. The line was a good approximation for any filter studied, but it could not be applied to design a filter for an "exact" percentage of COD removal.

In the present study, a scatter of points was exhibited for data on primary and secondary filters (Figure 17). It is possible that one line instead of two could be drawn through these data points. This would mean that there is essentially no difference in removal of COD between the primary and secondary filters. Assuming this to be the case, a savings might result from the use of only one design curve for both filters instead of two separate curves. The choice of using one or two curves for design is left up to the designing engineer.

The results of this study indicate the importance of operating at the minimum wetting rate. Better removal efficiences are obtained as indicated by Figures 6 and 16. If this minimum flow cannot be obtained in a once-through system, recycle of waste flow can be utilized to meet the flow requirement. However, this results in an added cost of operating the system which may not be justified by the increased removal efficiencies. Where economics control the operation of a system, it may be necessary to sacrifice increased efficiency to keep the system operating.

CHAPTER VI

CONCLUSIONS

Based upon the results of this investigation, the following conclusions are made:

(1) Operation of plastic media filters at flow rates greater than or equal to the minimum wetting rate was more efficient than operation at flow rates less than the minimum wetting rate.

(2) The removal of organic matter from experimental plastic media trickling filters followed first-order kinetics with respect to depth.

(3) In the treatment of a soluble sucrose waste, the primary filter removed a greater percentage of COD than did the secondary filter at equivalent total organic loadings.

(4) The NRC equation was not useful in predicting the performance of the two-stage plastic media filter system.

(5) Hydraulic loading applied to the plastic medium filters affected the substrate removal rate observed at a particular total organic loading.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are made for future studies involving single and multi-stage plastic media trickling filters.

(1) Conduct waste treatment studies utilizing a two-stage system without intermediate clarifiers and compare the results with those obtained in this study.

(2) Study the biological life forms in the successive stages of a multi-stage system to determine if the composition of microorganisms is different.

(3) Make studies on all plastic media at wide ranges of hydraulic loading to determine an optimum flow rate which gives the best efficiency for that particular medium.

(4) Conduct pilot studies on various domestic and industrial wastes and correlate the performance data with lab studies on synthetic wastes.

(5) Subject two-stage plastic media filters to double and alternating double filtration for a comparison of processes.

(6) Carry out an investigation utilizing three or more plastic media filters in series and compare the overall performance with the performance of one filter of equal volume and depth.

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VITA

George Edward Marcangeli

Candidate for the Degree of

Master of Science

Thesis: STUDY ON THE PERFORMANCE OF AN EXPERIMENTAL TWO-STAGE TRICKLING FILTER EMPLOYING A PLASTIC MEDIUM

Biographical:

Personal Data: Born August 18, 1950, in McAlester, Oklahoma, the son of Tullio E. and Marcella Marcangeli; married Scheryl Darlene Lindsey on August 14, 1971.

Education: Graduated from Haileyville High School, Haileyville, Oklahoma, in May, 1968; received the Associate degree in Civil Engineering from Eastern Oklahoma State College, Wilburton, Oklahoma, in May, 1970; received the Bachelor of Science degree in Civil Engineering from Oklahoma State University, Stillwater, Oklahoma, in December, 1972; completed the requirements for the Master of Science degree at Oklahoma State University in December, 1973.

Professional Experience: Environmental Protection Agency Research Trainee, January, 1973, to December, 1973; Graduate Research Assistant, Oklahoma State University, September, 1973, to December, 1973.

Membership in Professional Societies: Water Pollution Control Federation; National Society of Professional Engineers; American Society of Civil Engineers; Oklahoma Society of Professional Engineers; Oklahoma Water Pollution Control Association.