

OBSERVATIONS ON THE EFFECTS OF BIOLOGICAL
SOLIDS RECYCLE ON THE PERFORMANCE OF
AN EXPERIMENTAL FIXED-BED REACTOR

By

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TABLE OF CONTENTS

Chapter	Page
I. INTRODUCTION	1
II. LITERATURE REVIEW	4
Theoretical Models	4
Investigations With Experimental Filters	6
Full-Scale Field Investigations	9
Summary	12
III. MATERIALS AND METHODS	14
Experimental Approach	14
Experimental Apparatus	14
Experimental and Analytical Procedures	20
IV. RESULTS	24
V. DISCUSSION	37
VI. CONCLUSIONS	40
VII. SUGGESTIONS FOR FUTURE STUDY	41
LITERATURE CITED	42

LIST OF TABLES

Table	Page
I. Relative Composition of Synthetic Waste Employing Sucrose as the Growth Limiting Nutrient	18
II. Comparison of Fixed-Bed Reactor Performance Characteristics as Related to Influent Biological Solids Concentration . . .	25
III. Analysis of Variance Used in Computation and Comparison of Removal Rates	29
IV. Example of Analysis of Covariance Used in Comparing Substrate Removal Rates for the Regressions of COD Concentration Verses Reactor Depth	31

LIST OF FIGURES

Figure	Page
1. Experimental Fixed-Bed Reactor Used in Investigation	16
2. Relationship of COD Remaining Verses Depth of Reactor Medium for Fixed-Bed Reactor Operated With Various Influent Biological Solids Concentrations	28
3. Relationships of Substrate Removal Rate Verses Biological Solids Concentration in Fixed-Bed Reactor Influent	33
4. Relationships of Increase in Substrate Removal Efficiency Verses Biological Solids Concentration in Fixed-Bed Reactor Influent	36

CHAPTER I

INTRODUCTION

The passing of a wastewater through a porous medium, onto which is attached a diverse microbial community, is one of the oldest approaches to the purification of organic-laden wastewaters. Initially, the procedure was to intermittently apply sewage to sand or a porous soil and to allow for its slow passage therein. Such methodology was probably introduced early during the latter half of the nineteenth century, prior to the development of the discipline of bacteriology. Consequently, the process of purification was misconstrued as being entirely physical in nature, i.e., filtration was thought to be the only mechanism involved in the removal of organic matter. The possibility of chemical oxidation being instrumental in waste purification under such conditions was submitted by Franklin in 1870 (1). However, it was not until 1877 that the function of bacteria in the purification of organic wastes was exhibited (1). The perception of some of the important attributes of higher organisms in waste treatment systems was to follow.

The development of contact filters, watertight receptacles filled with stones or rock, succeeded the use of porous soils and sand beds as treatment systems. Commonly, the sequence of events in the cyclic operation of a contact filter included filling the basin with wastewater, allowing time for contact between the wastes and the microorganisms attached to the filter bed, draining the unit, and resting the bed. How-

ever, there were restraints imposed on this system, e.g., the tendency for clogging and the low effective loading it could accommodate. The search to alleviate such shortcomings led to the development of the wastewater treatment procedure customarily known in the United States as trickling filtration.

Since the first trickling filters (fixed-bed biological reactors) were placed in operation near the end of the nineteenth century (2) the use of trickling filters has grown immensely; it is currently the most widely used procedure for aerobic wastewater treatment. As originally designed, these filters had basic structural similarities with the outmoded contact filters, i.e., they were usually basins enclosing a bed of stone, crushed rock, or analogous material. The primary modification was that of continuously spraying the wastewater, via fixed nozzles, over the filter medium and allowing it to percolate through the bed. Assuredly, aside from the development of rotary distribution, many present day filters have retained the essence of early design features.

Although trickling filters have been in existence for over 80 years relatively few advancements have been made to improve their performance. Only two major modifications in basic filter design have been made with possible intent of improving treatment capability: the practice of recirculating a portion of treated wastewater and the use of plastic-media filter packings. The employment of plastic media for contact beds is a somewhat recent procedure which has demonstrated both economic and performance advantages over conventional rock medium (3)(4)(5)(6)(7). Recirculation has been, and continues to be, a commonly applied technique believed to control the performance of biological filters. The recirculation of treated effluent has been utilized since 1912 (8). Neverthe-

less, in spite of the continuing popularity of the process, the significance of recirculation to filter performance appears from published information to be quite a controversial issue.

The purpose of this research was to investigate the possibility that the presence of bacterial in the flow recirculated to trickling filters can exert a positive influence on the degree of treatment afforded by these biological systems. Specifically, experimentation was conducted to determine if biological solids recycle could be employed to enhance the performance of a laboratory-scale fixed-bed reactor.

CHAPTER II

LITERATURE REVIEW

Presented in this chapter are several published findings thought to be pertinent to an analysis of the contribution of recirculation to the trickling filtration process. Capsule discussions of theoretical models, investigations with experimental filters, and full-scale field investigations are considered separately below.

Theoretical Models

A fixed-bed system was modeled mathematically by Howland (9) as an inclined rectangular plate, over which a liquid film passed in laminar flow. It was suggested that the time of flow through a filter medium, i.e., contact time, was an important factor to the purification of an organic waste by trickling filtration. The effect of recirculation could not be resolved, however, when he considered the process in theory.

Meltzer (10) determined mathematically that the detention time of a wastewater in a biological filter is actually increased by recirculation. This increased detention time was offered, along with other factors, as being a possible reason for the improved performance of filters employing recirculation.

In 1963, Atkinson et al. (11) modeled the trickling filter process as film flow in contact with a vertical wall. Only first-order, irreversible reaction kinetics were considered and these were assumed to be lim-

iting, i.e., no concentration gradients were incorporated into the model. Furthermore, all reactions were considered to take place throughout the liquid film. In theory, recirculation was found to improve effluent quality, especially when a transition from laminar to turbulent flow was effected. Because purification was assumed to be occurring everywhere in the liquid film, recirculation increased the reaction volume and, therefore, increased the rate of substrate removal through the filter. Also, it is interesting to note that the investigators concluded that residence time analysis, e.g., Howland (9) and Meltzer (10), were irrelevant and only served to cloud basic issues.

The work of Swilley and Atkinson (12) was fundamentally similar to that of Atkinson et al. (11). However, Swilley and Atkinson considered the biological reactions taking place in a filter to be only occurring at the interface between the microbial film and the liquid film. Consequently, the overall rate of substrate removal in a filter was contemplated to be determined by the relative resistances due to diffusion and biological removal. These surface reaction models predicted progressively lower quality effluents upon increases in recirculation flow rate. Recirculation increased the film thickness making the diffusion of substrate to the reaction surface limiting to the overall rate of removal.

The effect of recirculation on the removal of soluble organic matter in three theoretical film flow models was investigated by Kehrberger and Busch (13). They postulated that recirculation has a detrimental effect on the removal of soluble organic compounds in a fixed-bed reactor, provided that no microorganisms are present in the recycled effluent. The hypothesis being that although recirculation reduces the influent organic concentration, the presiding effect is to decrease both the con-

tact time in the reactor and the mass transfer of organics in the liquid film. However, if microorganisms are present in either the recirculated flow or incoming waste stream (as with domestic sewage), the efficiency of organic removal would increase with an increase in recycle ratio. They felt that information from municipal waste treatment plants tended to support this theory

Investigations With Experimental Filters

Experimental stone medium filters were used by Edwards and Adams (14) to ascertain the effects of recirculation. They found the efficiency of BOD removal to be 67% for the filter with a recirculation ratio of 0.2 and 59% for the filter lacking a recirculated flow.

Schulze (15) used a vertical screen trickling filter to determine the relative contribution of hydraulic and organic loading to the efficiency of biological filters. He found efficiency to be independent of organic loading in the range of 17.4 to 403 lbs BOD/day/1000 ft³. The fraction of BOD in the effluent was proportional to the two-thirds power of the hydraulic load to the filter, i.e., efficiency decreased at a decreasing rate as hydraulic loading increased. Organic load was not considered pertinent as long as it did not achieve a critical limit. Based on these findings, Schulze theorized that no improvement in effluent quality could be predicted to result from the use of recirculation. He did state, however, that there was general agreement in the field that recirculation did increase the efficiency of treatment afforded by trickling filters. Secondary factors associated with recirculation, such as more equalized hydraulic loads, better distribution, and less clogging were mentioned as being open to consideration as possible elements to

increases in efficiency.

In studying the effects of both recirculation and alternating double filtration on the performance of experimental rock-media filters, Stones (16) found that neither process offered an advantage over single filtration. It was reported that the success of these methods was generally believed to result from the ability of each to prevent excessive microbial growths in the surface layers of filters. Because the filters under study were not prone to the development of such growths, he speculated that this was a possible explanation for the lack of success of these processes in his investigation. The mode of sewage distribution over the medium was briefly mentioned as being a potentially important factor to the performance of the experimental filters.

Germain (17) experimented with a 43 feet high plastic medium filter to evaluate a formula for the design of plastic media filters treating domestic sewage. A substantial effort was made to elucidate the effects of recirculation. No statistically significant difference was found between the rate of BOD removal and recirculation ratio, i.e., recirculation of partially treated effluent had no meaningful effect on the effluent BOD. Nevertheless, because a constant hydraulic dosage rate appeared desirable, Germain recommended effluent recycle for such maintenance during periods of low flow.

The influence of recirculation on both a stone-packed and a plastic-packed trickling filter was determined by Wing and Steinfeldt (18). Recycle was found to greatly increase the efficiency of the stone bed, whereas, it had a negligible effect on the efficiency of the plastic medium, except at very high hydraulic loadings and high recycle rates. They concluded that hydraulic loading was the only variable influencing

efficiency of the plastic-packed filter under the conditions studied.

Schaumburg and Lasswell (19) discussed the performance of a pilot plant designed to combine the desirable features of trickling filter and activated sludge processes. The plant recycled a mixed liquor of secondary sludge and filter effluent through a 21 feet tall contact bed composed of horizontal redwood slats. Influent wastewater (of domestic and industrial origin) and the mixed liquor were composited in a distribution box prior to being applied to the redwood medium. Mixed liquor suspended solids concentrations were varied from 3000 to 9500 mg/l during the study. Although the BOD loadings to the experimental plant were considerably higher than those witnessed at the nearby municipal plant with high-rate rock filters, the experimental system gave better performance. When the filter was operated as a high-rate system without solids recycle, the BOD removal efficiency dropped to a level similar to that of the rock filter, yet the BOD load applied to the redwood filter was approximately four times greater. The authors concluded that the redwood filter with solids recycle could be expected to produce a high quality effluent in terms of BOD at loadings up to 200 lbs BOD/day/1000 ft³ and with mixed liquor suspended solids concentrations of 3000 to 6000 mg/l. The higher level of active microorganisms and the improved settleability of solids in filter underflow were cited as probable reasons for the pilot plant with solids recycle giving better treatment than either the rock filter or the pilot plant without recycle. They felt that the hybrid system offers great flexibility, as the filter can be used with or without solids recycle depending upon seasonal waste strength and effluent standards.

Through experimentation with a model filter containing a medium of

corrugated fiberglass plates, and a synthetic waste, Cook and Kincannon (20) found that COD removal was dependent upon the COD loading applied to the filter and independent of either COD concentration or hydraulic loading alone. In other words, the efficiency of the filter was the same for any given COD loading, irregardless of whether this loading was accomplished with a high COD concentration and low hydraulic loading, or vice versa. Although recirculation was not investigated by Cook and Kincannon, their results indicate that recirculation would not have improved efficiency and could have even been detrimental. This would be assuming, of course, that microorganisms in the recycled flow would not have contributed to filter efficiency.

Full-Scale Field Investigations

Moore et al. (21) compared the effect of three recirculation patterns on the performance of the Centralia, Missouri, trickling filter plant. Results from this study indicated that recirculation of final (settled) effluent produced an effluent quality which was similar to that experienced in the absence of recirculation. However, the recirculation of filter effluent and final clarifier underflow resulted in substantial improvements in final effluent quality, with the latter procedure appearing the most influential. The recycle of clarifier underflow also effected a slightly greater degree of nitrification than the other recirculation patterns.

After analyzing operational data from eight single-stage and five two-stage trickling filters located at various plants in the United States, Rankin (22) surmised that dosing rate, loading of the filter, and filter depth had no significant effect on plant performance. The

ratio of recirculation was thought to be the primary factor influencing efficiency.

With the purpose of establishing a method for augmenting the treatment capacity of the trickling filters at the Halifax, England, biological purification plant, Lamb and Eastwood (23) experimented with the "pseudo-recirculation" of final effluent generated by adjacent activated sludge units. Previous small-scale studies indicated that the dilution of inflow to a filter with such effluent yielded a degree of treatment comparable to that produced when the dilution was with purified effluent from either the same filter (true recirculation) or other filters operating without recirculation. Results from the full-scale investigation indicated that "pseudo-recirculation" enabled the filter beds to handle over twice the normal organic loading and still produce an effluent of better quality (except for nitrate level) than that characteristic of the filters without recirculation. Some factors thought to have a bearing on the success of recirculation were forwarded. Of these, the following were offered as being most plausible: (1) the presence of dissolved oxygen in the recirculant, (2) the provision of a greater vehicle for carrying dissolved oxygen while concurrently decreasing the impurity concentration, (3) the continual seeding of the bed with aerobic organisms and beneficial enzymes, and (4) the advantageous effects of greater hydraulic loading, i.e., (a) increased mechanical flushing, (b) better distribution of waste and microorganisms over media surfaces, and (c) extending the biochemical oxidation zone further down the filter bed. Lamb and Eastwood suggested that factor 6(c) may be of considerable importance.

The method of direct recirculation of high-rate filter effluent was

compared by Culp (24) to the more conventional method of recirculating secondary clarified effluent. The investigation was carried out at the Webster City, Iowa, wastewater treatment plant. The plant's two filters were operated in parallel and, after both were found to be giving similar performance, one recycled filter effluent while the other recycled clarified effluent. The recirculation ratio was approximately 1:1 for both filters. Culp found that direct recirculation produced an effluent of quality equal to or slightly better than that created by the other scheme. The filter with direct recirculation had less tendency to pond and consistently yielded a higher nitrified effluent. Furthermore, a greater abundance of higher organisms (e.g., protozoa and stalked ciliates) were found in the filter with direct recycle. Culp remarked that such higher forms are generally associated with systems producing a well stabilized effluent.

Based on data collected at the treatment plant serving Mississippi State University, Archer and Robinson (25) concluded that recirculation definitely improved the overall plant efficiency. They found plant efficiency to be closely predicted by the National Research Council Design Equations.

In India, Hanumanulu (26) investigated the relevance of recirculation to the performance of a deep (12 ft) rock trickling filter. Although both hydraulic and BOD loading were increased due to recirculation, the efficiency of a filter employing recycle was considerably greater than two similar filters without recycle. Additionally, it was stated that the effect of recirculation appeared to be more pronounced as the wastewater increased in strength. The contention was that recirculation improves filter efficiency by distributing the BOD load

throughout the filter, thereby effectively utilizing the entire bed. Lamb and Eastwood (23) had previously suggested this factor as being instrumental to the success of recirculation.

In a most recent investigation, Dye (27) examined under semi-controlled conditions the incorporation of solids recycle in the rock trickling filter plant serving Tucson, Arizona. He experimented with recycling of waste activated sludge alone and in association with various concentrations of filter secondary settled sludge. Waste activated sludge alone was ineffective in improving filter effluent quality. However, the data supplied by Dye indicated that this source of organisms resulted in rather nominal increases in influent solids concentrations, i.e., approximate increases of 150 to 200 mg/l were produced. In contrast, the recycling of filter secondary settled sludge resulted in increases in influent solids levels up to roughly 2000 mg/l. At this highest influent solids concentration biological malfunction occurred and the effluent quality deteriorated greatly. This failure was attributed to the development of anaerobic conditions within the treatment units. But, when the wasting of secondary sludge was regulated such that the influent solids concentration was reduced to about 400 mg/l, treatment efficiency improved above that experienced without recycle and there was also a marked increase in treatment stability.

Summary

The above literature review offered contradictory evidence as to the relevance of recirculation to the performance of the trickling filtration process. Furthermore, when recirculation was found to be complementary, there were divergent opinions on which factor(s) brought about

the additional treatment capacity. Basically, the factors purported to be beneficial resulted from either physical alterations, e.g., dilution and better distribution; or biological changes, i.e., the increased assimilative capacity of the filter due to the presence of active microorganisms in the recycled flow. Without neglecting the possible influence of physical factors, it appears that a very beneficial effect of recirculation may be that of seeding filter influent with microorganisms. The papers of Kehrberger and Busch (13), Schaumburg and Lasswell (19), Moore et al. (21), Culp (24), and Dye (27) allude directly to this possibility. Consequently, it can be surmised that a potential means of augmenting the treatment capability of a trickling filter would be to increase the mass of microorganisms in filter inflow by some sort of secondary sludge recycle scheme. With the intent of gaining insight into the potential of such a procedure the present investigation was undertaken.

CHAPTER III

MATERIALS AND METHODS

Experimental Approach

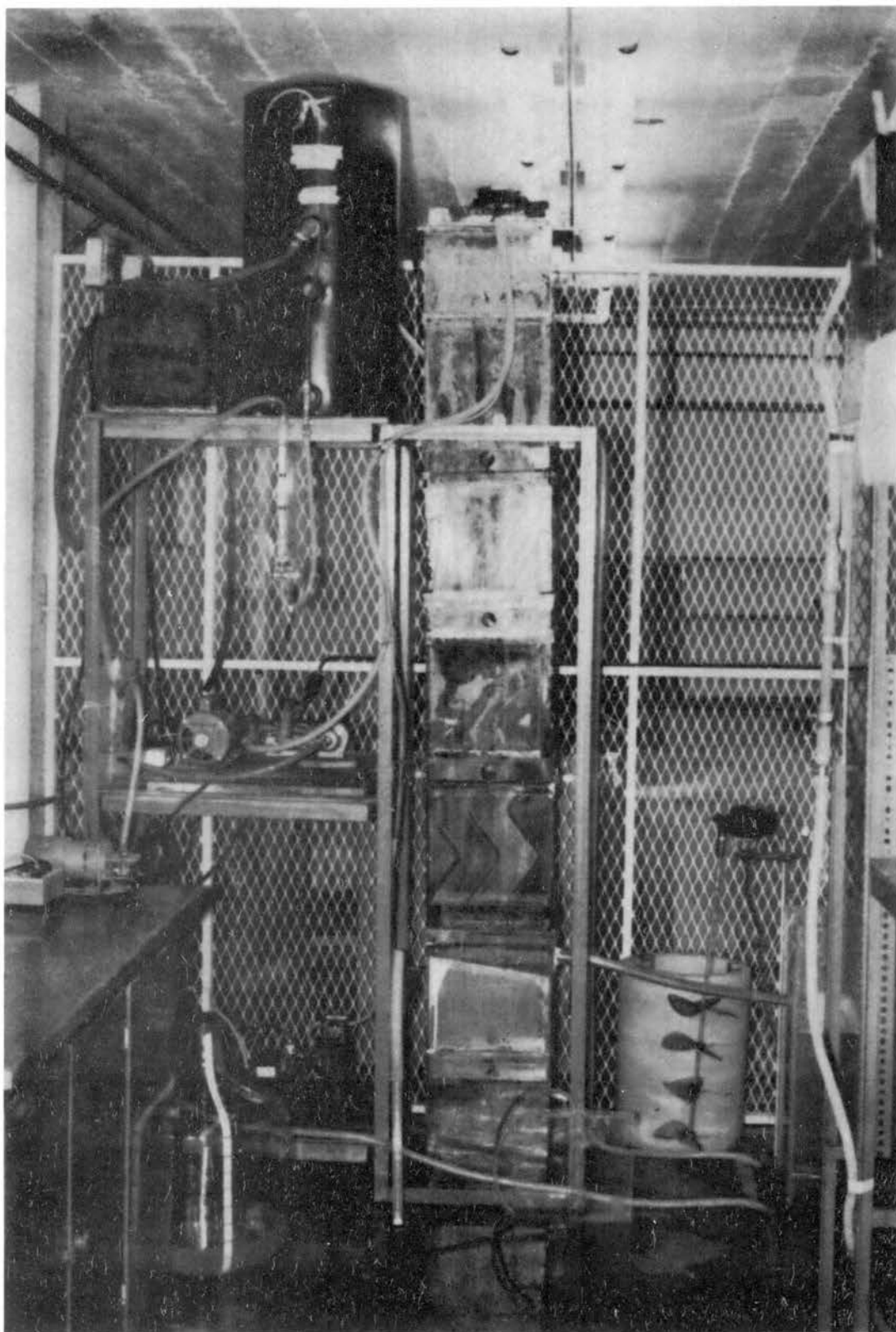
To illustrate the possible effects of biological solids recycle on the performance of a trickling filter a model fixed-bed reactor was operated under closely controlled experimental conditions. The only procedural variation applied to the treatment system was the incorporation of a recycle flow containing various concentrations of microorganisms (sludge) which had been generated by the reactor. The related performance characteristics of substrate removal rate and efficiency of substrate removal were selected as parameters for ascertaining the influence of solids recycle.

Experimental Apparatus

The fixed-bed reactor employed in this investigation (Figure 1) consisted of a plexiglas tower (7.0 ft x 1.0 ft x 1.0 ft) containing four one cubic foot modules of Flocor plastic medium as the contact bed. The Flocor medium was developed by the Imperial Chemical Industries, London, and is currently licensed in the United States by the Ethyl Corporation. A void space of approximately 4 inches in height was reserved between adjacent units to allow for sequential sampling of the waste flow as it passed through the reactor medium.

Hydraulic flow to the system was regulated via a rotameter that

Figure 1. Experimental Fixed-Bed Reactor Used in Investigation



received tap water from a constant head tank. Prior to entering the constant head tank, the water was passed through a coil of copper tubing immersed in a water bath. The temperature of the bath was adjusted such that the water influent to the tower was $20^{\circ}\text{C} \pm 1^{\circ}$. After passing through the rotameter, the flow was discharged into a wet well where mixing with a concentrated, synthetic waste occurred.

Sucrose was employed as the carbon source and growth limiting nutrient for the synthetic wastewater used in this study. The composition of the waste used, relative to a sucrose concentration of 100 mg/l, is given in Table I. A concentrate of the waste was prepared in a forty liter Pyrex bottle and was transferred to the wet well by a variable speed Cole-Parmer Masterflex Tubing Pump (Model WZ 1R031). The concentrated waste was prepared to a strength that allowed five days of uninterrupted substrate dispensation to the reactor biota. Sixty milliliters of 16 N sulfuric acid was added to the waste concentrate at each preparation to repress biological activity and to assist the dissolution of waste constituents. All feed lines and pumps were thoroughly chlorinated periodically to restrict the presence of microbial growth to the reactor tower.

The mixed feed was conveyed from the wet well to the reactor distribution system by means of a Teel Rotary-Screw Pump (Model 1P610). The pump was belt driven by a single-speed electric motor and wastewater output was regulated by a valve controlled recirculation system. Output was adjusted until it was in equilibrium with the rotametrically established flow rate.

Through use of a reciprocating spray nozzle system, the reactor's contact bed was irrigated with the synthetic wastewater. The oscillating

TABLE I
RELATIVE COMPOSITION OF SYNTHETIC WASTE EMPLOYING
SUCROSE AS THE GROWTH LIMITING NUTRIENT

Constituent	Concentration
$C_{11}H_{22}O_{11}$	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
$CaCl_2 \cdot 2H_2O$	0.75 mg/l
$FeCl_3 \cdot 6H_2O$	0.05 mg/l

motion of the nozzle was controlled by an electrically motorized, chain-drive mechanism. By employing the proper spray height and nozzle design it was possible to achieve a spray pattern that provided an even distribution of wastewater across the plastic medium surface. The waste stream was allowed to flow through the four modules of plastic medium and into a collection device. From there the flow was diverted to a baffled plexiglas tank for clarification, prior to discharge.

When biological solids (sludge) recycle experiments were initiated, the settled microorganisms were removed from the clarifier and placed in a circular, plastic tank where the sludge was diluted with tap water and mechanically aerated by way of a motor-driven impeller assembly. (For the first three recycle experiments sludge was transferred to the aeration tank on a bidaily basis. However, the findings from these experiments necessitated a more frequent, daily, removal of sludge. See explanation in results section.) Through baffling the perimeter of the tank and applying an adequate degree of agitation, it was possible to simulate completely mixed conditions within the vessel. The concentration of biological solids in the aeration tank was regulated by varying both the amount of solids transferred to the tank and magnitude of dilution. Following the final solids transference in preparation for an experimental run, a continued aeration period of at least twenty-four hours was provided, for the purpose of promoting the acclimation of the microorganisms to aerobic conditions. By adjusting the mixing rate dissolved oxygen concentrations of 1 mg/l or greater were maintained in the aeration tank at all times.

When a recycle experiment was in progress, the aerated mixture of microorganisms was transposed by a Sigmamotor Pump (Model T-8) from the

mixing tank to the reactor distribution system. The presence of Psychoda larvae in the sludge precluded the interjection of the recirculated organisms ahead of the nozzle assembly, as the larvae would have immediately plugged the nozzle's orifice. Consequently, a plastic spout was devised and attached to the oscillating nozzle to allow for the injection of organisms into the nozzle's spray. The injection was applied to the wastewater as it emerged from the nozzle. Location of solids introduction, design of the recycle line spout, and recycle flow rate all provided for a satisfactory dispensation of biological solids to the waste flow.

Experimental and Analytical Procedures

The fixed-bed reactor was set into operation with a feed concentration of 300 mg/l of sucrose and a hydraulic loading of 600 gpd/ft², corresponding to an organic loading of approximately 400 lbs COD/day/1000 ft³. Seeding the unit at startup was not required as another investigator had previously seeded the reactor with microorganisms contained in the primary, settled effluent from the Stillwater, Oklahoma, treatment plant.

The initial organic loading was comparatively high and, thusly, the efficiency of waste removal was foreseen to be quite low. It was preferred, for the purpose of evaluating the influence of recirculated microorganisms, that the reactor efficiency be somewhere in an arbitrary range of 30 to 50 percent. The desire was to provide a sufficient excess of nutrients for possible assimilation by the recycled solids, and yet, not operate the treatment system at a loading that would promote exorbitantly low efficiencies and unstable performance.

The results of several experimental runs revealed that the reactor was performing somewhat erratically and was yielding COD removal efficiencies (14 to 23%) below those deemed satisfactory. Resultantly, the loading was reduced to approximately 222 lbs COD/day/1000 ft³ by both decreasing the feed concentration to 200 mg/l of sucrose and reducing the hydraulic loading to 500 gpd/ft². After conditioning the reactor for two weeks at this lower loading tests were resumed. Subsequent results indicated that the system was functioning under equilibrium or steady-state conditions and that removal efficiency had increased to a more acceptable level (i.e., 32 to 37%).

Altogether, eight experimental runs were conducted under these conditions for the purpose of establishing reliable standards for operational parameters from which to compare the effects of biological solids recycle. Specifically, the related operational characteristics of substrate removal rate and efficiency of removal were the subjects of comparison.

When sludge recycle experiments were conducted, the treatment system was operated as described previously but with the added condition of an introduction of an aqueous mixture of microorganisms to the influent waste flow. Nine experimental runs were performed, each of which employed a different concentration of biological solids. Both recycle flow rate and recycle substrate concentration were essentially the same for 6 of these experiments, thereby isolating solids concentration as the major variable to the operation of the reactor.

A similar reactor sampling scheme was utilized for all of the experiments transacted in this investigation. The sampling regime and accompanying analyses were performed in triplicate during each experi-

mental run. The first sample collected was from the waste flow after it passed the last cubic foot of plastic medium. The flow was sampled at this location by inserting a trough-shaped receptacle into the reactor. This device was capable of diverting almost the entire flow in the reactor through an incorporated tube to a collection flask. Two separate samples were taken at this depth: the first one was gathered in a 4 liter Erlenmeyer flask and had a volume of equal magnitude, and the second was of 150 ml and was obtained in a 250 ml flask. The larger sample was mixed by magnetic stirrer and a 40 ml aliquot was removed at mid-depth by pipet for gravimetric suspended solids determination. The mixing rate applied was of sufficient magnitude to suspend only the smaller flocs of microorganisms that continuously sloughed from the reactor medium due to growth, i.e., an attempt was made to keep large, irregularly discharged slime masses and Psychoda larvae from influencing solids measurements. A 50-60 ml fraction was removed from the smaller sample (150 ml) immediately after collection for a pH measurement and of the residual, 40 ml was utilized for COD analysis.

Sampling the wastewater passing through the remainder of the reactor was accomplished by inserting an improvised sampler through ports provided in spacers interjacent to the medium modules. The sampling device consisted of a longitudinally sectioned PVC pipe with an attached latex tube. At each depth the sampler was inserted through two ports and moved back and forth in the waste flow, both in an effort to achieve a representative sample for analyses. A 150 ml sample was taken in a 250 ml flask at each depth from which 40 ml was used for obtaining a COD measurement.

The last sample in the regime was of approximately 200 ml and was

collected directly by flask at the spray nozzle. When solids recycle was not engaged, this sample was processed as stated immediately above, but with the added accompaniment of a pH analysis. An additional fraction of 40 ml was used for a suspended solids determination if recycle was employed.

Each sample fraction earmarked for COD determination was first filtered using a 0.45 μ membrane filter. Chemical oxygen demand was assessed by the procedure outlined in Standard Methods (28) using 20 ml of the filtrate.

The membrane filter technique (28) was utilized for gravimetric measurement of suspended solids (i.e., nonfiltrable residue). Subsamples of 40 ml from the reactor influent (during recycle) and effluent were devoted to such an analysis. Also, the pH was determined for sample portions from these locations by means of a Beckman Zeromatic II meter.

CHAPTER IV

RESULTS

A total of 17 experimental runs were conducted during this investigation (Table II). Eight of these experiments were carried out for the purpose of determining the performance characteristics of a fixed-bed reactor in the absence of biological solids recycle. The findings from these initial experiments were used as standards from which the effects of solids recycle could be ascertained in later experiments. The data presented for each experimental run in Table II represents the means of values derived from three sequential reactor samplings and analyses.

The results from the first recycle experiments indicated that the frequency of sludge withdraw from the clarifier was inadequate, in that an anaerobic state was promoted by the delay in translocation. The odorous nature of the sludge and both the increases in influent COD values and decreases in the pH of the waste flow that accompanied recycle attested to the prevalence of anaerobic conditions in the settled sludge. As the predominant bacteria in a fixed-bed reactor are facultative (29), it is quite probable that a buildup of anaerobic metabolic products, e.g., organic acids and H_2S , would occur if reactor organisms were exposed to an anoxic environment.

A more frequent (daily) removal of settled microorganisms from the clarifier, in combination with washing the displaced sludge with tap water, alleviated the problem of recycle flow significantly increasing

TABLE II

COMPARISON OF FIXED-BED REACTOR PERFORMANCE CHARACTERISTICS
AS RELATED TO INFLUENT BIOLOGICAL SOLIDS CONCENTRATION

Reactor Influent						Depth of Reactor Medium (ft)								Overall Performance Characteristics				
						1		2		3		4						
Experi- ment	COD (mg/l)	Flow Rate (gpd/ ft ²)	COD Loading (lbs/day/ 1000 ft ³)	Sus- pended Solids (mg/l)	pH	COD (mg/l)	% COD Remain- ing	COD (mg/l)	% COD Remain- ing	COD (mg/l)	% COD Remain- ing	COD (mg/l)	% COD Remain- ing	Sus- pended Solids (mg/l)	pH	COD Load Removed (lbs/day/ 1000 ft ³)	COD Removal Rate (k)	% COD Removed
1	226	500	236	0	7.3	204	90.3	187	82.7	163	72.1	147	65.0	20	7.3	153	-	35.0
2	234	500	244	0	7.1	212	90.6	193	82.5	173	73.9	149	63.7	25	7.0	156	-	36.3
3	218	500	227	0	7.3	199	91.3	183	83.9	155	71.1	146	67.0	16	7.1	152	-	33.0
4	230	500	240	0	7.5	208	90.4	189	82.2	161	70.0	145	63.0	12	7.4	151	-	37.0
5	239	500	249	0	7.2	214	89.5	198	82.8	174	72.8	157	65.7	21	7.3	158	-	34.3
6	241	500	251	0	7.6	218	90.4	190	78.8	176	73.0	159	66.0	12	7.3	166	-	34.0
7	231	500	241	0	7.4	210	90.9	192	83.1	170	73.6	157	67.9	28	7.4	164	-	32.1
8	239	500	249	0	7.2	220	92.0	200	83.7	172	72.0	153	64.0	27	7.1	153	-	36.0
Mean	232	500	242	0	7.3	211	90.9	191	82.3	168	72.4	152	65.5	20	7.2	157	- 0.04326	34.5
Experiments Employing Biological Solids Recycle																		
9	251	582	-	133	7.3	228	90.8	199	79.3	186	74.1	166	66.1	125	7.2	-	-	33.9
10	270	586	-	274	6.9	243	90.0	223	82.6	205	75.9	176	65.1	260	6.9	-	-	34.9
11	433	574	-	631	6.7	422	97.4	399	92.1	369	85.2	321	74.1	601	6.5	-	-	25.9
12	211	577	241	172	7.4	184	87.2	172	81.5	156	73.9	135	64.0	163	7.3	154	- 0.04597	36.0
13	205	584	247	315	7.2	178	86.8	163	79.5	151	73.6	131	63.9	288	7.2	158	- 0.04602	36.1
14	205	580	247	684	7.3	177	86.3	163	79.5	143	69.7	125	61.0	653	7.4	151	- 0.05223	39.0
15	206	584	254	839	7.0	181	87.9	153	74.2	139	67.5	119	57.8	804	7.0	147	- 0.05915	42.2
16	212	580	256	1165	7.2	175	82.5	155	73.1	134	63.2	114	53.8	1113	7.1	138	- 0.06547	46.2
17	215	575	260	1764	7.3	182	84.6	149	69.3	135	62.8	109	50.7	1688	7.1	132	- 0.07198	49.3

the COD loading influent to the reactor. The COD loading resulting from recycle was in the range of 5.7 to 10.4 lbs COD/day/1000 ft³ for all following experiments. (Recycle loadings were calculated directly through knowledge of recycle flow rates and the COD of aeration tank mixtures.) Such recycle loadings were thought to more accurately simulate conditions of constant sludge withdraw. Therefore, organic loading was sufficiently nullified as a possible influence on reactor performance, allowing for a more unencumbered evaluation of the effects of recycled microorganisms. Only the latter six recycle experiments are considered in subsequent discussions.

To determine the substrate removal rate, k , semi-logarithmic plots of COD remaining verses depth of filter medium were made for the experimental runs not utilizing solids recycle and for each recycle experiment. In each case a straight line relationship existed between these parameters (Figure 2), signifying that the kinetics of substrate removal were first order. Notably, the kinetics of substrate removal were unaltered by the introduction of various biological solids concentrations to the influent wastewater flow. The removal rates are the slopes of these linear regressions as determined by the method of least squares (Table 3). When measured by "t test", each of these regressions displayed a very good fit to the data; there was low probability in each case that a linear relationship did not exist.

As shown in Table II and illustrated in Figure 2, the employment of biological solids recycle (experiments 12 through 17) appeared to result in increases in the rate of substrate removal and the directly related parameter of reactor efficiency. The implied relationship was one whereby increases in the concentration of solids influent to the reactor

Figure 2. Relationships of COD Remaining Verses Depth of Reactor Medium for Fixed-Bed Reactor Operated With Various Influent Biological Solids Concentrations

Experiment Number	Influent Solids Concentration
1-8	0 mg/l
12	172 "
13	315 "
14	684 "
15	839 "
16	1165 "
17	1764 "

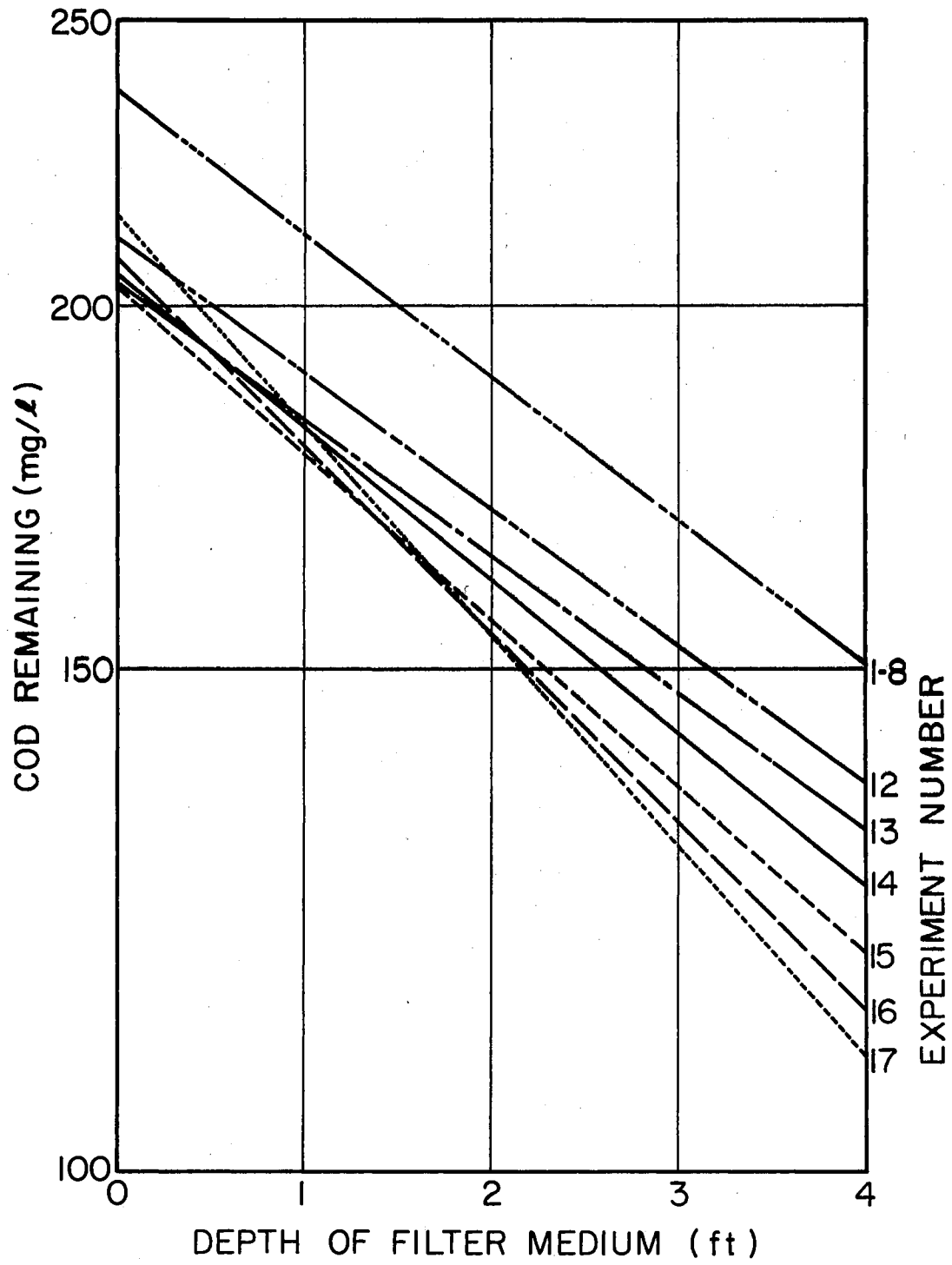


TABLE III

ANALYSIS OF VARIANCE USED IN COMPUTATION AND COMPARISON OF REMOVAL RATES

Experiment Number	d.f.	Deviations from Means		Sum of Products of Deviations	Regression Coefficient	Regression Deviations		
		Sum of Squared Deviations of X	Sum of Squared Deviations of Y			d.f.	Sum of Squares	Mean Square
1-8	39	80	0.18580	-3.4609	-0.04326*	38	0.0360800	0.0009494
12	4	10	0.02143	-0.4597	-0.04597*	3	0.0003016	0.0001005
13	4	10	0.02145	-0.4602	-0.04602*	3	0.0002706	0.0000902
14	4	10	0.02744	-0.5223	-0.05223*	3	0.0001603	0.0000534
15	4	10	0.03516	-0.5915	-0.05915*	3	0.0001718	0.0000572
16	4	10	0.04305	-0.6547	-0.06547*	3	0.0001868	0.0000622
17	4	10	0.05227	-0.7198	-0.07198**	3	0.0004578	0.0001526

*Significant at 0.001 level of probability

**Significant at 0.025 level of probability

were reflected in concurrent increases in reactor performance.

To determine if biological solids recycle had any statistically significant effect on substrate removal rate, an analysis of covariance as described by Snedecor and Cochran (30) was utilized (Table IV) to compare individually each of the k values obtained during solids recycle against that characterizing the standard treatment system, i.e., the system with no recycle. The analyses revealed that only experiments 15, 16, and 17 (influent solids concentrations of 839, 1165, and 1769 mg/l, respectively) yielded removal rates that could be considered distinct from the standard removal rate. The differences were significant at the probability levels <0.25 , <0.05 , and <0.01 , respectively. When the removal rates of these three experiments were compared against each other, experiment 15 differed from 16 ($P<0.25$), 16 from 17 ($P<0.05$), and 15 from 17 ($P<0.01$).

The analyses therefore indicated that biological solids did indeed affect the rate of substrate removal in the reactor, once the influent solids concentration was increased to and beyond 839 mg/l. Furthermore, a dissimilarity existed between each of the removal rates that were found to differ from the standard removal rate, denoting that increases in influent solids concentration beyond 839 mg/l effected significant increases in the rates of substrate removal. And, because the efficiency of substrate utilization is a direct result of the rate at which substrate is metabolized, the findings of the above analyses can also be extended to include reactor efficiency.

The relationship between influent solids concentration and substrate removal rate can be additionally witnessed through an analysis of the plot of solids concentration verses removal rate (Figure 3).

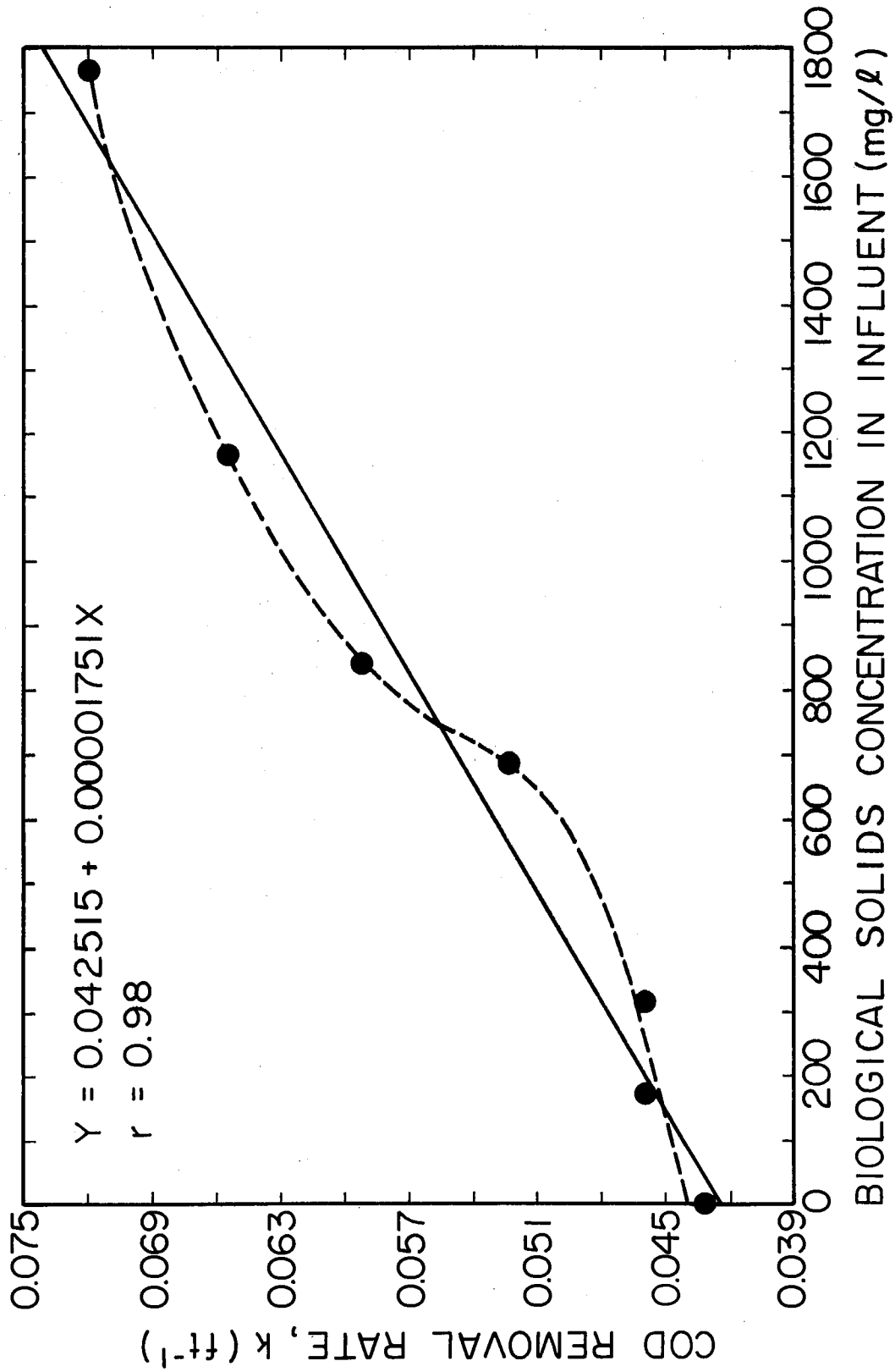
TABLE IV

EXAMPLE OF ANALYSIS OF COVARIANCE USED IN COMPARING SUBSTRATE REMOVAL RATES
FOR THE REGRESSIONS OF COD CONCENTRATION VERSES REACTOR DEPTH

Experiment Number	d.f.	Deviations from Means		Sum of Products of Deviations	Regression Coefficient	Regression Deviations		
		Sum of Squared Deviations of X	Sum of Squared Deviations of Y			d.f.	Sum of Squares	Mean Square
1-8	39	80	0.18580	-3.4609	-0.04326	38	0.0360800	0.0009494
12	4	10	0.02143	-0.4597	-0.04597	3	0.0003016	0.0001005
Summation of Degrees of Freedom and Sum of Squares						41	0.0363816	0.0008873
Pooled Analysis	43	90	0.20723	-3.9206	-0.04356	42	0.0364400	0.0008676
Difference Between COD Removal Rates						1	0.0000584	0.0000584
Comparison of COD Removal Rates				$F = \frac{0.0000584}{0.0008873} = 0.066^*$				

*Highly Insignificant Difference ($P \gg 0.25$)

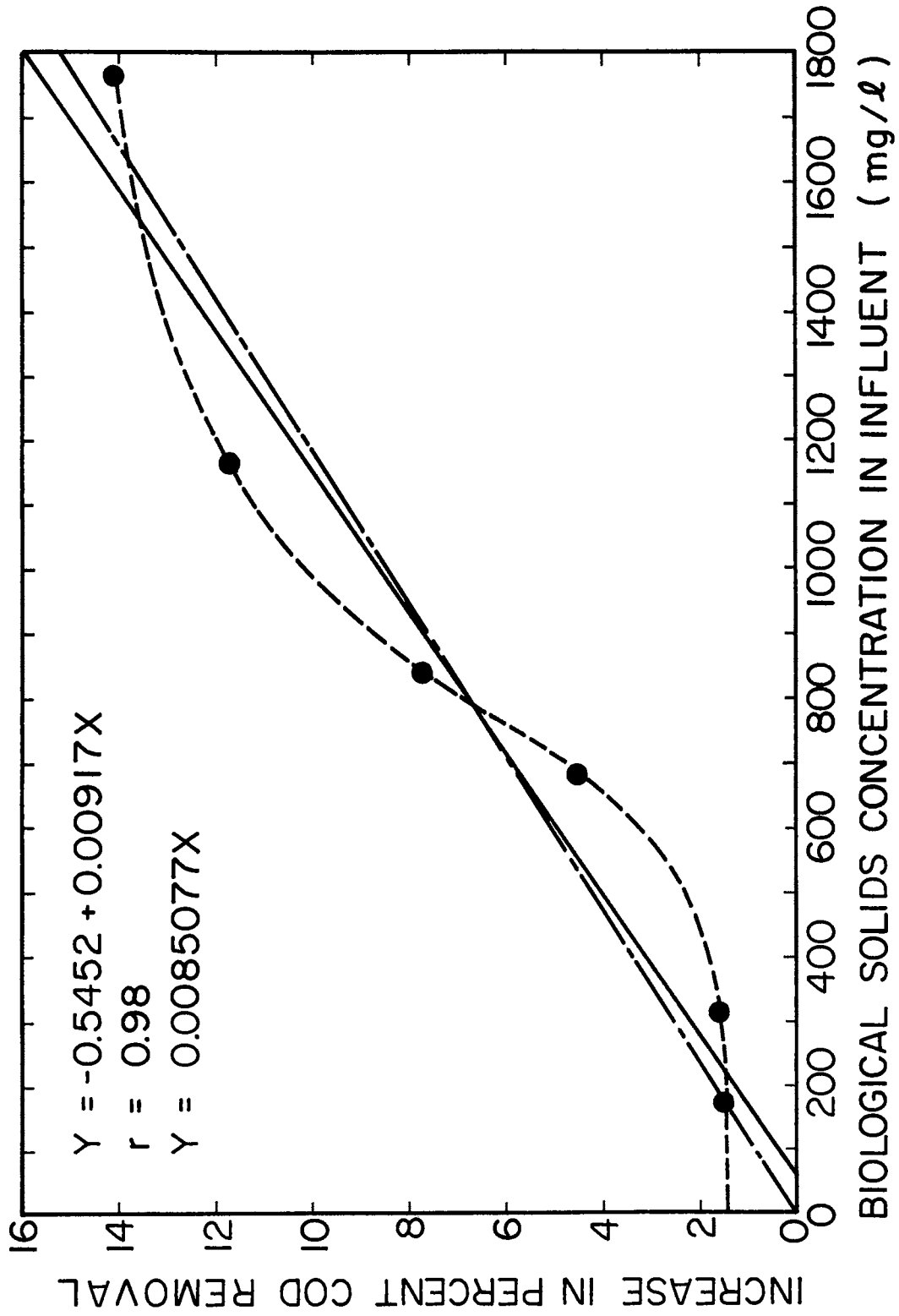
Figure 3. Relationships of Substrate Removal Rate Verses
Biological Solids Concentration in Fixed-Bed
Reactor Influent



This plot can be described very effectively by linear regression, as suggested by the results of both a "t test" for linearity ($P < 0.001$) and a correlation analysis ($r = 0.98$), or one may choose to describe the relationship by an S-shaped curve. As expected, the plot of increase in substrate removal efficiency verses influent solids concentration can be described in similar fashion (Figure 4).

The sigmoid relationships are interesting in that they illustrate to a certain degree the insignificant effect of the lower influent solids concentrations, while at the same time showing the more pronounced effect of higher concentrations. However, the low number of data points available precludes the issuance of any definitive statement on the precise relationship between influent solids concentration and reactor performance. Suffice to say that the same general denotation that resulted from the analyses of covariance are conveyed by Figures 3 and 4, i.e., the presence and concentration of influent biological solids can have a positive influence on fixed-bed reactor performance.

Figure 4. Relationships of Increase in Substrate Removal Efficiency Verses Biological Solids Concentration in Fixed-Bed Reactor Influent — The Second Linear Equation is a Modified Form of the First, and It Predicts a Straight Line Through the Origin



CHAPTER V

DISCUSSION

The purpose of this study was to determine the effects of biological solids recycle on the performance of a laboratory-scale fixed-bed reactor (trickling filter). A plexiglas tower containing four one cubic foot modules of Flocor plastic medium as the contact bed was used in this assessment. Wastewater characteristics of organic (sucrose) concentration, hydraulic flow rate, and temperature were closely controlled. The magnitude of these parameters, as well as pH, remained at nearly constant levels throughout the investigation. Employment of a recycle flow and the concentration of biological solids therein were the only significant operational variations applied to the basic treatment system.

The related performance characteristics of substrate removal rate and efficiency of substrate removal were selected as measures of reactor performance. These were determined initially for the reactor without recycle to establish standards against which findings from subsequent recycle experiments were compared. Through analyses of these comparisons it was found that each of the three highest influent solids concentrations consequent to recycle (839, 1165, and 1764 mg/l) resulted in significant increases in removal rate and efficiency. Therefore, because the recycle flow rate was essentially constant for all recycle experiments, the concentrations of microorganisms in the recycled flows were

responsible for the differences in performance. In other words, the additional hydraulic loading due to recycle was alone inconsequential to reactor performance. The relationship between reactor performance (removal rate and efficiency) and biological solids concentration could be described by both linear and sigmoid relationships; although, statistical validity was afforded only to the former.

Therefore, under the conditions of this investigation, biological solids recycle displayed a definite potential as a process for augmenting the capability of a fixed-bed reactor in the treatment of a soluble, organic waste. This finding is of little value, however, unless operational procedures are developed for the successful implementation of solids recycle in biofiltration technology.

An example of the operational difficulties that may arise in the use of sludge recycle in the trickling filter process is illustrated by Dye's investigation (27). The rather drastic increases in BOD concentrations (and loadings) to the filters during all returns of secondary sludge indicates that anaerobic biodegradation may have been occurring in the sludge during these experiments. Such a situation could possibly be guarded against by close regulation of sludge recycle rates and sludge wasting. Also, a sludge reaeration basin, of similar conceptual design to that utilized in the present investigation, could be used to promote the desired aerobic conditions. This latter remedial measure would raise an important economic consideration.

Another possibility is that trickling filter sludge may possess an inherent characteristic, e.g., the presence of an abundance of microbial capsular material, that could in some manner result in abnormal organic loadings when recycled. If this is found to be the case, the

feasibility of solids recycle could be seriously questioned.

Undoubtedly, the development of procedures for sludge recycle in rock trickling filters will be particularly difficult. The very low percentage of void space within rock filter beds would be expected to make such a medium critically prone to clogging under situations where the wastewater contained high suspended solids concentrations. Furthermore, the low void space undermines ventilative capacity, restricting atmospheric reaeration in rock filters.

Consequently, the greatest promise for the application of solids recycle to the biofiltration process probably lies with the biological towers of modern design. These towers contain media (e.g., plastic packings and redwood slats) possessing such attributes as light weight, high surface area, and a high percentage of void space. Properly designed, these towers are well ventilated and essentially free of the problem of clogging.

A treatment system employing biological solids recycle with a redwood medium bio-tower is currently marketed. Published information on the success of this process (10), along with the results of the present investigation, offers evidence attesting to the potential of solids recycle as a method for increasing the treatment capability of fixed-bed biological reactors. In spite of these findings, however, increased research at both laboratory and full-scale levels is needed before any definite conclusions can be forwarded as to the significance of the process to the water pollution control field.

CHAPTER VI

CONCLUSIONS

Based on the findings in this investigation, the following general conclusions are presented:

(1) The microorganisms cultivated in a fixed-bed reactor possess the capability when recycled of increasing the rate and efficiency of soluble substrate removal within the treatment system.

(2) The concentration of recycled biological solids in the flow influent to reactor must be increased above a "threshold" level before a significant improvement in performance can be expected. Above this level a positive relationship may exist between influent solids concentration and reactor performance.

(3) Biological solids recycle promises potential as an procedure for enhancing the operational control of fixed-bed reactor systems.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

(1) Pilot-plant investigations should be conducted to determine the effects of a wide range of influent biological solids concentrations on the performance of a fixed-bed reactor subjected to several hydraulic and organic loadings.

(2) A special effort should be made to devise and operate a successful solids recycle system that that could be economically simulated by full-scale trickling filter installations.

(3) A detailed study of the biological characteristics of the solids generated by a fixed-bed reactor would be helpful in assessing the potential of solids recycle as a complement of the trickling filtration process.

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