A MICRO-MODEL FOR DESIGN AND STUDY OF TRICKLING FILTERS

By

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A MICRO-MODEL FOR DESIGN AND STUDY OF TRICKLING FILTERS

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CHAPTER I

INTRODUCTION

In 1858 the Royal Sewage of Towns Commission of England (1) concluded that

> The increasing pollution of the rivers and streams of the country is an evil of national importance, which urgently demands the application of remedial measures; that the discharge of sewage and of the noxious refuse of factories into them is a source of nuisance and danger to health; that it acts injuriously not only on the locality where it occurs, but also on the population of the districts through which the polluted rivers flow; that it poisons the water, which in many cases forms the sole supply of the population for all purposes, including drinking; that it destroys the fish; and generally that it impairs the value and the natural advantages derived from rivers and streams of waters.

This 115-year-old assessment is still just as valid today as when it was written. What has changed, however, is public awareness of this age-old problem. Study and observation of this problem has shown that "impairment of value and natural advantages" occur when the dissolved oxygen in surface waters is seriously depleted. The cause of this depletion is primarily that of aerobic and subsequent anaerobic metabolism of microorganisms feeding upon the organic, domestic and industrial wastes (food) mentioned above.

Man has treated these wastes in a variety of ways. The most widely used methods employ the same biological processes that caused the problem originally. These processes, controlled and accelerated, are employed before these wastes are discharged to the streams and rivers. The object of this treatment is to reduce or eliminate the organic "food" prior to reaching the streams, thus preventing the serious depletion of dissolved oxygen in natural bodies of water by biological action.

In 1870, Dr. E. Frankland, an early sanitary researcher in England and member of the Rivers Pollution Commission, formulated a theory of "intermittent downward filtration" in which "a field of porous soil irrigated intermittently virtually performs an act of respiration, copying on an immense scale the lung action of a breathing animal, for it is alternatively receiving and respiring air and thus dealing as an oxidizing agent." This intermittent application of sewage to land for the destruction of its organic impurities by bacterial oxidation was tested (1) both in Merthyl Tydfil (Wales), and at Lawrence, Massachusetts, and was the forerunner of the contact filter, a bed of broken stones filled and drained intermittently with sewage. A logical follow-on was the trickling filter, a bed of stones or other media to which microorganisms could attach through which the liquid waste is percolated. The medium of the filter provides the support for a growing biological slime layer of microorganisms and their capsular material. Periodically, portions of this layer slough away and are carried away by shear and gravitational forces.

The microorganisms attached to the trickling filter remove the organics contained in the waste flow for use as nutrients for biological metabolism. This process converts the organic carbon in the waste into carbon dioxide, energy, and new cell constituents. Most of the carbon dioxide passes into the atmosphere and the microorganisms manufacture new cells utilizing the energy for synthesis.

Many investigators have gathered data and developed the relationships relative to design of trickling filters. Many different empirical design equations have resulted, each of which suggests a different design size for identical removal efficiencies. The dimensions of each of the design parameters vary also. This dilemma is particularly confusing when the engineer begins a treatment plant design. How can one logically size a trickling filter with such a diverse array of facts presented in the literature? Since most studies have been made on relatively weak domestic sewage, another uncertainty is introduced when the waste to be treated is an industrial waste far stronger than sewage and possessing different chemical components. Some designs performed under these circumstances have met with success despite the uncertainties involved and others have not.

A logical procedure to employ in treatment plant design is to study, on a micro-scale, the process in the laboratory using the particular waste to be treated. Definitive design parameters and expected efficiencies may be determined from these studies. The engineer then has a sound basis from which to design and the ultimate success of the design may be reasonably assured.

Laboratory modeling of the trickling filter process is not an easy task. Scale models of the trickling filter itself have several shortcomings. The smallest successful laboratory designs may require hundreds of gallons of waste per day. The cyclic nature of intermittent wetting followed by atmospheric exposure without significant drying is difficult to maintain. Other styles of models that simulate the conditions in trickling filters have been tried from time to time. One such model, an inclined rotating tube, had considerable merit. A biomass contained within the tube and fed metered amounts of synthetic waste theoretically possesses many of the characteristics of a trickling filter biomass. It is intermittently wetted and exposed to the atmosphere. Resultant washing action and the cyclic nature of gravitational forces during tube rotation simulate the forces involved in filter sloughing. The model is very flexible. Speed of tube rotation, angle of inclination, and hydraulic flow are capable of infinite variation. Credit for the concept of this model goes to P. N. J. Chipperfield (Brixham Research Laboratory, Imperial Chemical Industries Ltd., England), who spoke of using such a model in his laboratory during a discussion with American colleagues (2) in 1972 at New Orleans, Louisiana.

A four-unit inclined rotating tube model was designed and built in the Oklahoma State University laboratories. This report includes the initial results obtained in studies using this rotating tube laboratory model. Organic wastewater removel characteristics of this model are compared to the characteristics of scale model pilot plants and actual trickling filter characteristics. Wastewater requirements are far less using this model. The results obtained suggest that a simple first order relationship of percent removal efficiency to organic loading rather than hydraulic loading exists. Organic loading is defined as the total mass of organic matter applied per unit of washed filter surface per unit time. Hydraulic loading is similarly defined as volume of carrier water for the organic matter above per unit time. The concept of using statistical variability in trickling filter design parameters is also advanced.

An independent development of the rotating tube model has been found. Pictures of a device known as a "Renn Trickling Filter" (3) are attributed to Dr. Charles Renn, Johns Hopkins University. The pictured apparatus is strikingly similar to the design developed in the Oklahoma

State University laboratories. Results of treatability studies on detergents (4) and photographic industrial wastes were reported.

CHAPTER II

LITERATURE REVIEW

The trickling filter process has been variously described as a "film flow reactor," "fixed bed reactor," or "fixed film biological tower." Each process reported is described, however, as a function of many different parameters.

Phelps

In 1925, Phelps (5) proposed that "the rate of biochemical oxidation of organic matter is proportional to the remaining concentration of unoxidized substance, measured in terms of oxidizability."

This describes the monomolecular reaction:

$$\frac{-dL}{dt} = KL \qquad (1)$$

which, when integrated, becomes

$$\frac{L'}{L} = e^{-kt} \qquad (2)$$

where

L' = final oxidizability in terms of oxygen demand mg/l

L = initial oxidizability in terms of oxygen demand mg/l

k = reaction rate constant (dependent on character of organic matter and temperature)

t = elapsed time in days.

Velz

In 1948, Velz (6) presented a theory applicable to biological beds and high and low rate trickling filters that was very similar to the Phelps formulation. Velz concluded that "The rate of extraction of organic matter per interval of depth of a biological bed is proportional to the remaining concentration of organic matter, measured in terms of its removability."

This relationship can be expressed as

$$\frac{-dL}{dD} = KL \tag{3}$$

which integrates to

$$\mathrm{Ln}\,\frac{L_D}{L} = -KD$$

or

$$\log \frac{L_D}{L} = -.0.434\ KD = -kD \tag{4}$$

which can be rearranged to yield

$$f = \frac{L_D}{L} = 10^{-kD} \tag{5}$$

where

f = fraction remaining oxidizable organic

K = reaction rate constant (naperian logarithm)

k = reaction rate constant (common base logarithm)

D = depth of filter bed in ft

L_D = final oxidizability in terms of oxygen demand in mg/l

L = initial oxidizability in terms of oxygen demand in mg/l.

In forming this relationship, Velz did not consider how the reaction occurs or whether the limiting controls on the reaction are biological in nature or dependent on diffusion of oxygen through a liquid film, biological slime, or the organisms themselves.

Swilley and Atkinson

Swilley and Atkinson (7) addressed themselves to these questions and developed, utilizing fluid mechanics and mathematical techniques, a reaction controlled model that can be expressed as:

$$f = \exp[-1.50\ \eta k] \tag{6}$$

where

$\eta = .9084\ Sc\ Re^{\frac{1}{3}}\ Ra^{\frac{1}{3}}$

$k = 2.932\ Sc^{-1}\ Re^{-\frac{1}{3}}\ Ra^{\frac{1}{3}}$

Sc = Schmidt number

Re = Reynolds number

Ra = reaction number;

and two diffusion controlled models with the form:

$$f = f(\eta,\ k). \tag{7}$$

These theoretical mathematical models all degenerate back to Velz's Equation (5) with appropriate adjustment of the accounted parameters.

National Research Council

Another significant step in seeking appropriate design criterion was the effort of the National Research Council Committee on Sewage Treatment (8, 9) at the conclusion of World War II. Their comprehensive survey of filter performance at military installations provided the empirical relationship:

$$E = \frac{100}{1 + 0.0085\sqrt{\frac{W}{V}}} \tag{8}$$

where

E = percent BOD removed

W = organic load applied in lb BOD/day

V = volume of filter medium in acre ft.

The NRC summary report (9) published two years later included a graphical presentation of all trickling filter efficiencies versus filter loading. This significant graph (Figure 1), not in the original publication, depicts the same first order relationship that will be discussed in Chapter V.

Eckenfelder

Eckenfelder (10) has advanced several equations for filter design, the latest being

$$\frac{S_e}{S_o} = e^{-k \frac{D}{Q^n}} \tag{9}$$

where

S_e = effluent oxygen demand in mg/l

S_o = influent oxygen demand in mg/l

k = reaction rate constant

D = depth, ft

Q = hydraulic loading in gal/min-ft^2

n = constant related to specific surface and configuration.

Galler and Gotaas

Galler and Gotaas (11) analyzed data from worldwide existing plants by using multiple regression techniques and a digital computer. They compared each known parameter against each other parameter statistically

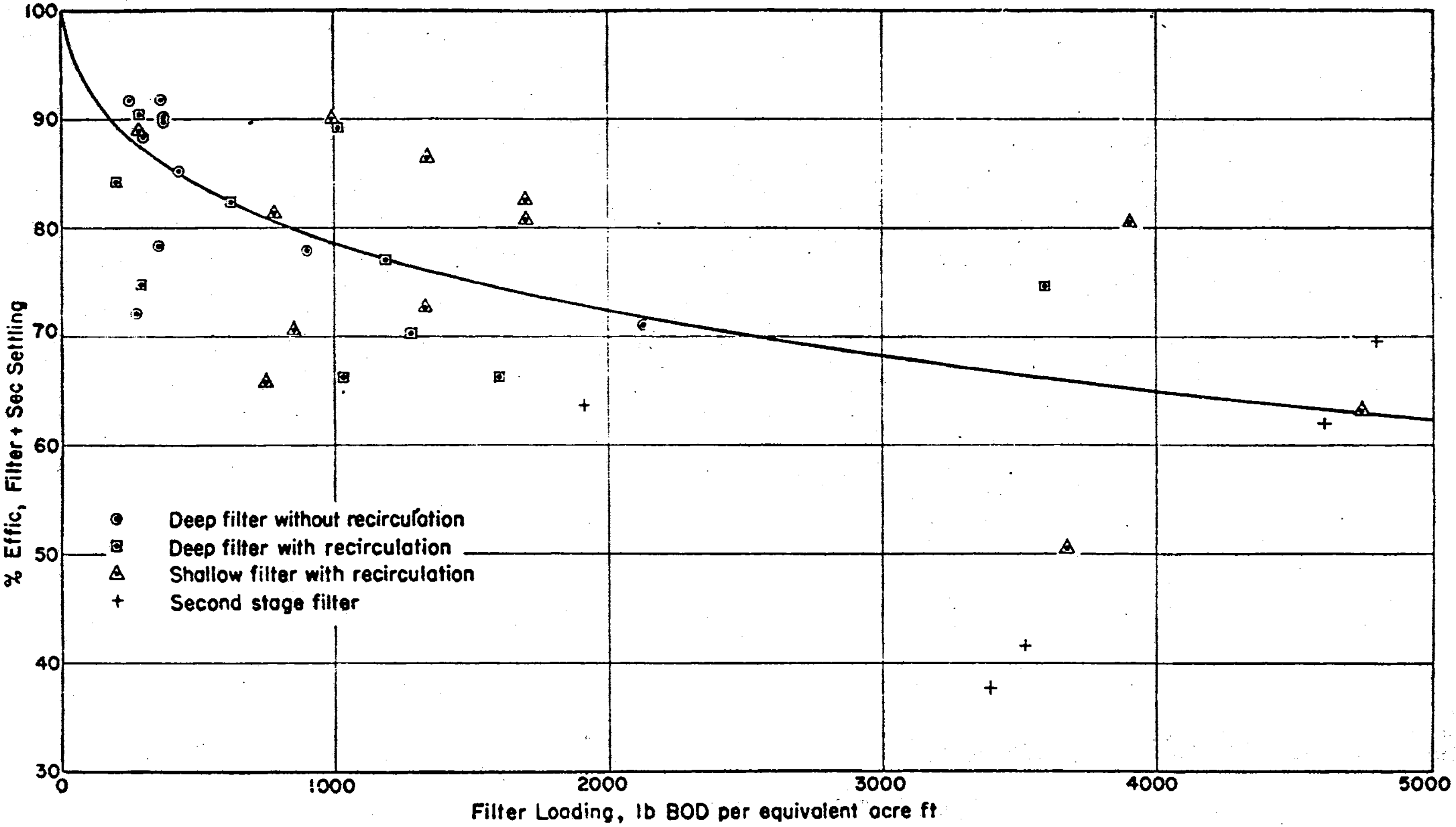

Figure 1. Relation Between Filter Loading and Efficiency for All Filter Plants of NRC Summary of Sewage Treatment at Military Installations

to determine the effect on filter performance. Their conclusions discounted hydraulic loading but considered applied BOD, depth of filter, and temperature as the most significant factors governing concentration of BOD remaining in a trickling filter effluent. Their equation for a filter without recirculation is:

$$L_e = \frac{1.298\ L_o^{0.98}\ Q^{0.12}}{(1 + D)^{0.66}\ T^{0.15}} \qquad (10)$$

where

L_e = concentration of BOD remaining in mg/l
L_o = concentration of influent BOD in mg/l
Q = hydraulic loading, mgd/acre
D = depth, ft
T = temperature of waste water, °C.

Cook (13) substantiates the conclusion that hydraulic loading does not affect filter performance. However, the main disagreement with Galler and Gotaas (12) was that of the influence of hydraulic loading rate.

Cook and Fleming

Cook (13) concluded that the amount of microorganism surface area is the prime factor in the removal of organics in trickling filters. He also summarized the conflicting ideas of the relative importance of hydraulic loading versus organic concentration in trickling filter performance. He operates a scale model pilot plant through a wide range of hydraulic flow rates and organic concentrations. His data substantiates that the combination of organic concentration and hydraulic flow rate, or total organic loading, affects filter performance. This data is used in Chapter V for comparison with the rotating tube model data. Cook also discusses the relationship of trickling filter removal efficiency to the basic microbial kinetic constants. He concluded that the Monod relationship is valid for trickling filters.

Fleming (14) continued the scale model pilot plant operation and reported increased acidity of effluent as organic loading increased and filter efficiency decreased. He hypothesized that increased anaerobic respiration and intermediate organic acid production resulted from increased loadings. Fleming also observed and concluded that although available surface area of a filter medium has a definite bearing on removal rates, there is an upper boundary condition at approximately 27 ft^2/ft^3 beyond which the removal rate and efficiency increase tapered off.

Gaudy

The extreme variability of kinetic constants when measured in heterogeneous microbial populations has been discussed in detail in Gaudy and Ramathan (16), Gaudy and Gaudy (17), and Peil and Gaudy (18). A possible biochemical basis is discussed and the concept of reporting the statistical parameters of variability is proposed.

CHAPTER III

MATERIALS AND METHODS

Apparatus

The rotating tubes used in this model (Figure 2) are two-foot lengths of three-inch inner diameter polyvinylchloride pipe. Four such lengths were supported on an array of four-and-one-half-inch diameter wheels and driven by means of a chain drive to the support wheels. The chain drive was energized by a 1/24 horsepower variable speed electric motor and 1/3600 gear reduction drive. By use of a laboratory "variac" variable voltage transformer, constant tube rotational speeds of 0-24 revolutions per minute could be selected. Axial thrust was supported by grooving the tube exterior at the point of contact with the drive and support wheels. The wheels were appropriately shaped to fit these grooves. The entire assembly was fitted with a variable length adjusting screw on the influent end to provide a means of varying the tube inclination with respect to the horizontal.

The feed apparatus consisted of a Milton Roy 4-gang positive displacement Mini-Pump, model MM-4, capable of moving 0-12 ml/min connected with a tubing and feed bottle manifold to enable common or separate tube feeds. The biomass in the inside surface of the rotating tubes was fed through 1 mm diameter drawn glass discharge nozzles placed at the upper (influent) end approximately 1/4 inch from the inner wall. Total wetted surface per tube was 1.57 square feet. The effluent end of the tubes

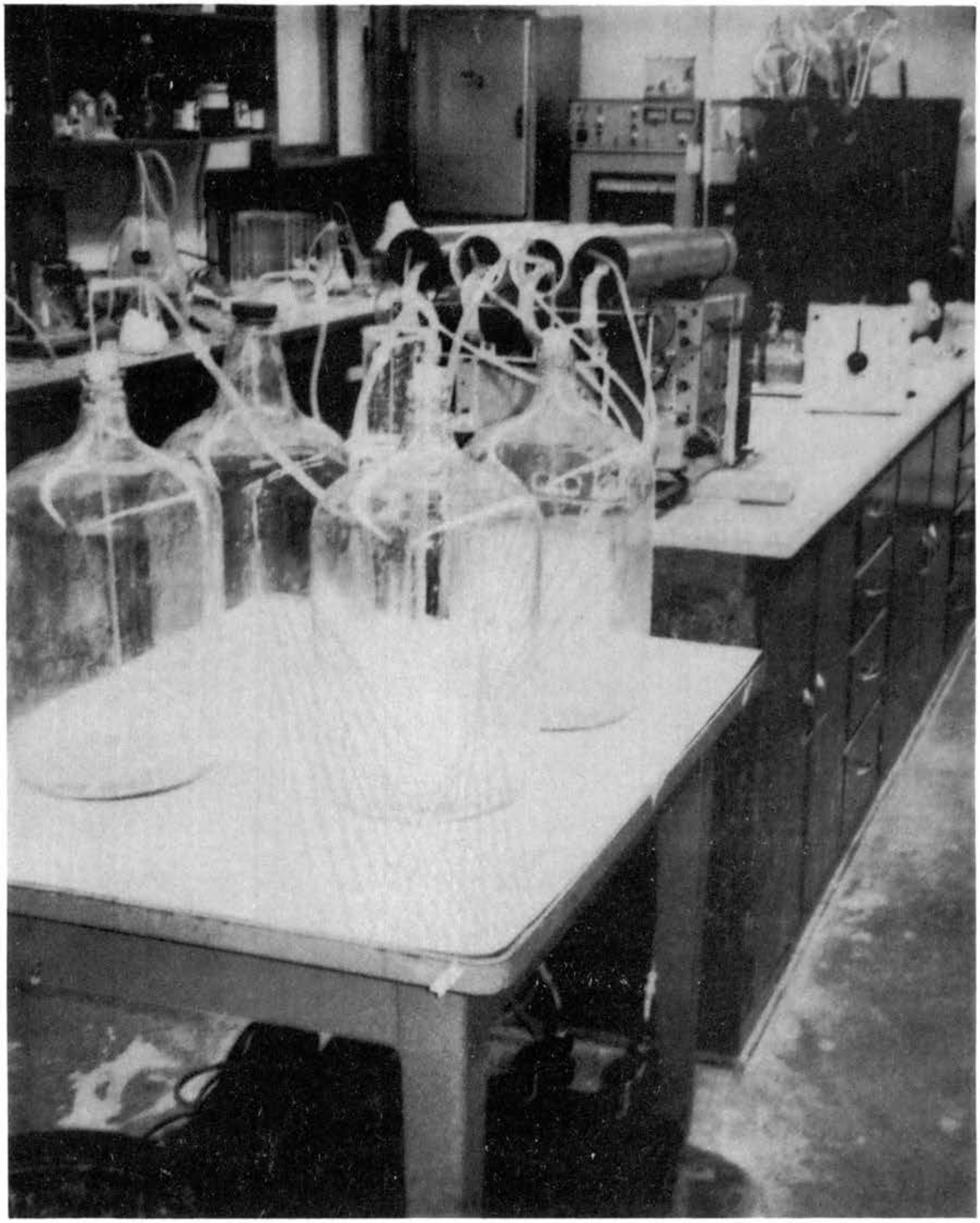

Figure 2. Rotating Tube Trickling Filter Micro-Model

discharged to a sheet metal trough (for recirculation at initial seeding) or to a rack holding 3½ Pyrex glass funnels. The entire apparatus was located on a laboratory workbench over a sink so that effluent could easily flow into the collection system when samples were not being taken.

Experimental and Analytical Procedures

Initial startup and subsequent restarts were made by seeding one liter of raw settled sewage from the primary clarifier of the Stillwater Sewage Treatment Plant with three liters sucrose synthetic waste (Table I) in a four-liter catch basin. The basin was replenished from a sheet metal trough placed under the effluent end of the rotating tubes. A supplementary recycling pump, a 220 V "Little Giant" centrifugal pump, recirculated the seeded feed water from the catch basin, utilizing separate tubing and nozzles through the rotating tubes. After 24 hours of recirculation, the primary feed system was activated and fresh sucrose synthetic waste was introduced. The respective rates were:

Recirculation = 50 L/hr
Feed = 300-500 ml/hr
Detention time = 3.3 hrs (seed basin).

A one-day period of recirculation only followed by a two-day period of recirculation and feed flow provided a thin shiny gelatinous-appearing translucent biological slime inside each tube. After approximately three additional days of feed operation alone, the COD values between successive daily samples and between tubes approached a common steady value.

A varied selection of feed concentrations was run, changing values after two successive equal COD effluent values were achieved. Influent samples were taken from the feed discharge nozzles. A time clock and

TABLE I

COMPOSITION OF SUCROSE SYNTHETIC WASTE PER 100 MG/L COD EQUIVALENT INCREMENT[1]

Constituent	Concentration (mg/l)
Sucrose	87
$Mn\ SO_4 \cdot H_2O$	1
$Mg\ SO_4 \cdot 7H_2O$	10
$Fe\ Cl_3 \cdot 6H_2O$	.05
$Ca\ Cl_2$	.75
$(NH_4)_2\ SO_4$	100
$K_2\ H\ PO_4$[2]	6
$K_2\ H\ PO_4$	1070
$K\ H_2\ PO_4$[3]	527

[1] Carbon is the growth limiting nutrient.

[2] Phosphorus nutrient added when buffer not used.

[3] Buffer concentration for 1M.

graduated cylinders were used to rate the hydraulic loading at each sampling. Periodic routine analyses of the influent and effluent Chemical Oxygen Demand (COD) were made using the dichromate reflux method (15). Samples of effluent were taken, allowing 30 minutes to 1 hour of quiescent settling prior to decanting for tests. Occasional checks were made on COD of filtrate of this same settled effluent after passing through white plain 47 mm millipore filter paper, pore size 0.45μ.

Gross estimates of influent and effluent acidity were made with pHydrion paper (Micro Essential Laboratories, Brooklyn, New York). After the growth and the data phase began, pH adjustments of feed water became necessary. These pH adjustments were made with 2N NaOH and 36N H_2SO_4.

Processing and Analysis

All analytical results were recorded in card form and an IBM 1620 digital computer with CALCOMP 565 plotter was used for data reduction, regression analysis, plotting and printing. The IBM 1620 FORTRAN II-D programming system was used throughout.

Values for flow rates, influent and effluent COD's, removal efficiencies, organic loading, logarithms of removal efficiencies, and the change in COD values of each tube for each run were calculated. Each variable was compared graphically with every other variable to ascertain if dependent relationships could be easily defined.

CHAPTER IV

RESULTS

Experimental Results

Forty experimental data runs were made during the course of this model study to assess organic removal efficiencies. The results of the COD analyses are displayed in Figures 3 and 4. Many difficulties were experienced that highlighted some of the shortcomings of biological treatment in general and trickling filters in particular.

Phosphorus Deficiency

During the initial startup and preliminary runs, considerable difficulty was experienced in maintaining satisfactory biological growth. The feed pump valves clogged repeatedly with hard water scale at flow rates of 5 ml/min. Subsequent operation under the same chemical conditions but at higher flow rates were satisfactory. The buffer was discontinued and feed make-up water switched from tap to distilled in an attempt to solve the scaling problem. Within two days efficiency fell off and the biological slime layer became mottled and dark brown. When supplemental phosphorus was again added to the waste and reseeding completed, the efficiency returned to expected levels.

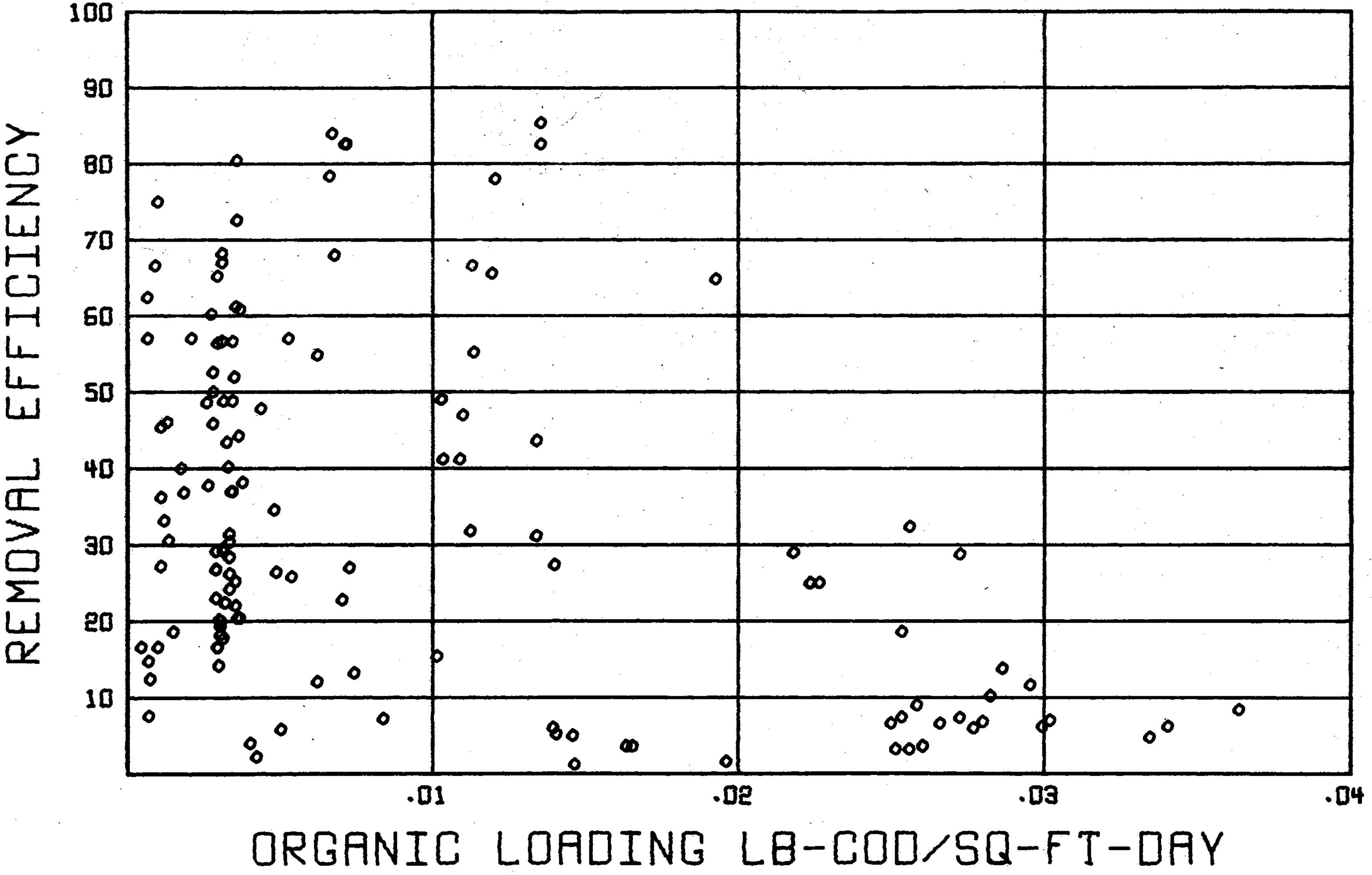

Figure 3. Removal Efficiency Versus Total Organic Loading. Raw Data

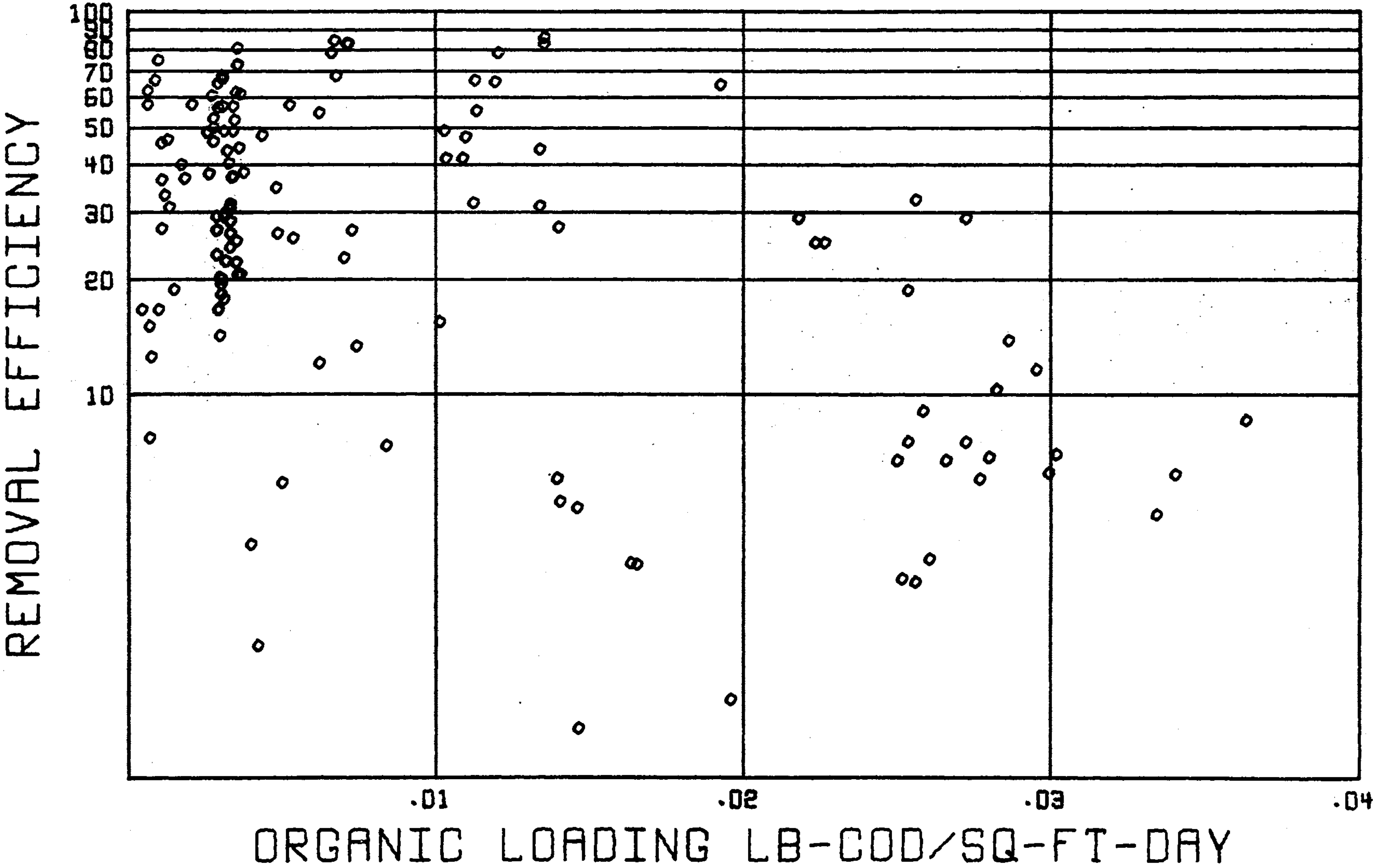

Figure 4. Removal Efficiency Versus Total Organic Loading. Raw Data

Iron Excess

Concentrated feed solutions were prepared and stored for several days' use. One such preparation contained a $FeCl_3$ concentration inadvertently stronger than normal in the order of magnitude of ten. A gradual deterioration of removal efficiency resulted when this feedstock was used with large blocks of biological slime sloughing.

Temperature Effect

A problem in the heating system occurred in the laboratory of several days duration and the resultant loss in efficiency closely paralleled the van't Hoff rule (19) of twofold increase or decrease with 10°C increase or decrease.

pH Control

Soon after the buffer was discontinued and supplemental phosphorous added, the removal efficiency began to fall off once again and the effluent began to take on a yellowish-orange color. Investigation revealed that the distilled water used for feed make-up had a pH of 5.5 and that the unbuffered synthetic waste ran between pH 6.5 and pH 6.0. Effluent pH readings of 5.0 were not uncommon during this period. Gross microscopic examination of the effluent showed small clumps of tiny yellow cocci. The clumps would not settle out but would filter out on the previously mentioned .45μ millipore filter paper.

The buffer supplement was resumed and the apparatus reseeded once more. Again, the expected removal values were reached in three days. Influent pH remained constant at 7.0 and the effluent pH ranged from 6.5 - 7.0.

Insufficient Hydraulic Flow

A curious phenomenon peculiar to the rotating tubes soon became apparent. Whenever the biological film was allowed to dry only slightly, during feed system sterilization or shutdown for repairs, resumption of the normal feed flow rate produced a spiral "rifling" pattern. This pattern tended to stabilize and cut down the surface area wetted by the synthetic waste. A distilled water wash procedure was instituted at start-up after any significant drying had occurred. No further difficulty was experienced.

General Results

The switches from tap water to distilled water and then later in the experiment back to tap water were monitored carefully. Other than the pH difficulty and phosphorus deficiency mentioned above, no discernible effect was observed in removal efficiency. Biological growth frequently contaminated the feed system. The contamination was presumed to be that caused by airborne bacterial debris or trace contamination from the chemical feed bottles and glassware. As the experiment progressed, however, the contamination was almost always observed first in the feed discharge nozzles adjacent to the bacterial film inside the rotating tubes. The turbid-appearing growth would then progress upstream against the flow of synthetic waste to eventually contaminate the entire 20 liter feed storage bottle. When the feed rate was doubled at the end of the experiment, the duration between required cleaning for contamination also doubled in time. Regular flushing with 10% (by volume) commercial Clorox bleach through the pump and tubing and acid dichromate washing of the glassware controlled the problem.

The spontaneous sloughing of biomass so characteristic of trickling filters and expected of this model failed to occur. Only at extremely large organic loadings far in excess of any known trickling filter application did sloughing occur. Since removal efficiency would fall off without sloughing, it was done periodically by hand. Some variation in removal efficiencies was observed after each mechanical sloughing. Poor settling and turbid effluent would be discharged for approximately two hours after each such disruption.

The normal settled effluent COD's seldom tested higher than 5% over the filtrate COD's of the same samples. If the difference was more than 10% the run was not recorded in the raw data. Other than the yellow effluent mentioned above, good settling and clear effluents were the rule during the five-month experimental period.

The raw COD's and flow rates were processed approximately weekly as each COD titration was completed. The computed data was transferred to IBM cards and then reprocessed at the end of the experimental phase. The plotted results are shown in Figures 3 and 4. Note that all points including known low points are retained. These points represent the occasional behavior in the field in trickling filter performance using heterogeneous microbial populations. They also affect the statistical analyses described later.

Analytical Results

The raw COD data taken during the course of the experimental presented a dilemma. Prior to each one of the biological setbacks and catastrophes previously mentioned, the removal efficiencies would fall off. Occasional premature readings would be taken before a "steady state" balance or psuedo-equilibrium was reached. The problem of separating the erroneous from the valid data was treated first.

Each set of calculated values from the initial data was compared graphically against each other set of values. A linear dependent relationship could be observed between the logarithm of removal efficiency and organic loading indicating a relationship

$$\frac{S_e}{S_o} = \exp[-KZ] \tag{11}$$

where

S_e = effluent COD in mg/l

S_o = influent COD in mg/l

K = reaction rate constant

Z = organic loading.

Since the data points were so widely dispersed, a tool of statistical quality control was used to separate the data. The Shewart Control Chart method (20) could be applied to a linear regression line to eliminate excessively low data points. This method is based on the point of view that for a normal distribution, a "stable system of chance causes" exists such that variations outside this stable pattern may be discovered and corrected.

A linear regression analysis of the processed data and subsequent application of 99% confidence limits identified the abnormally low removal efficiency logarithms and provided a logical basis for their elimination. Subsequent analysis of the "purified" data (Table II) provide a removal rate constant k and standard deviation σ for the experimental data. The semi log plot is included in Figure 5. Figure 6 is an arithmetic plot of the same data.

TABLE II

PROCESSED DATA FROM REGRESSION ANALYSIS AFTER STATISTICAL ELIMINATION PROCEDURES

DATE-RUN	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
10 NOV 7-2	346	149	56	.00349	1.75359	196	2
10 NOV 7-3	346	217	37	.00347	1.56953	128	3
10 NOV 7-4	346	135	60	.00370	1.78408	210	4
12 NOV 8-1	278	121	56	.00295	1.75135	157	5
12 NOV 8-2	278	139	50	.00280	1.69896	139	6
12 NOV 8-4	278	96	65	.00298	1.81547	182	8
14 NOV 9-1	264	142	45	.00280	1.66224	121	9
14 NOV 9-2	264	164	37	.00266	1.57792	100	10
14 NOV 9-3	264	135	48	.00264	1.68707	128	11
14 NOV 9-4	264	124	52	.00282	1.72183	139	12
16 NOV 10-1	328	167	48	.00348	1.68942	160	13
16 NOV 10-2	328	196	40	.00331	1.60441	132	14
16 NOV 10-3	328	185	43	.00329	1.63827	142	15
16 NOV 10-4	328	157	52	.00351	1.71745	171	16
19 NOV 11-1	317	217	31	.00337	1.49776	100	17
19 NOV 11-2	317	246	22	.00320	1.35164	71	18
19 NOV 11-3	317	224	29	.00318	1.46558	92	19
19 NOV 11-4	317	199	37	.00340	1.56912	117	20
29 NOV 12-1	336	262	22	.00357	1.34449	74	21
29 NOV 12-1B	336	251	25	.00357	1.40248	85	22
29 NOV 12-2B	336	241	28	.00339	1.45364	95	23
29 NOV 12-2B	336	234	30	.00339	1.48467	102	24
29 NOV 12-3B	336	248	26	.00337	1.42021	88	25
29 NOV 12-3B	336	255	24	.00337	1.38400	81	26
29 NOV 12-4B	336	92	72	.00360	1.86112	244	27
29 NOV 12-4B	336	92	72	.00360	1.86112	244	28
3DEC 13-1B	297	244	17	.00315	1.25181	53	29
3DEC 13-2	297	255	14	.00300	1.15490	42	30
3DEC 13-2B	297	237	20	.00300	1.30616	60	31
3DEC 13-3	297	248	16	.00298	1.22184	49	32
3DEC 13-3B	297	248	16	.00298	1.22184	49	33
3DEC 13-4	297	209	29	.00318	1.47366	88	34
3DEC 13-4B	297	152	48	.00318	1.68850	145	35
4DEC 14-1	290	237	18	.00308	1.26227	53	36
4DEC 14-1B	290	234	19	.00308	1.29030	56	37
4DEC 14-2	290	205	29	.00293	1.46639	85	38
4DEC 14-2B	290	212	26	.00293	1.42860	78	39
4DEC 14-3	290	223	23	.00291	1.36493	67	40
4DEC 14-3B	290	212	26	.00291	1.42860	78	41
4DEC 14-4	290	92	68	.00311	1.83437	198	42
4DEC 14-4B	290	95	67	.00311	1.82654	195	43
6 DEC 15-1	1029	603	41	.01091	1.61643	425	44
6 DEC 15-2	1029	603	41	.01037	1.61643	425	45
6 DEC 15-3	1029	524	49	.01031	1.69053	504	46
6 DEC 15-4	1029	544	47	.01102	1.67316	485	47
7 DEC 16-1	1128	386	65	.01196	1.81815	742	48
7 DEC 16-2	1128	504	55	.01137	1.74243	623	49
7 DEC 16-3	1128	376	66	.01130	1.82390	752	50
7 DEC 16-4	1128	247	78	.01208	1.89248	881	51
13 DEC 17-EF	1089	742	31	.01127	1.50267	346	52
15 DEC 18-1	960	811	15	.01018	1.18931	148	53
15 DEC 18-2	742	643	13	.00748	1.12493	99	54
15 DEC 18-4	336	267	20	.00360	1.31361	69	56
7 DEC 19-4	1306	1227	6	.01399	.78251	79	59
23 DEC 22-1	2613	2455	6	.02771	.78251	158	66
23 DEC 22-3	2534	2059	18	.02539	1.27300	475	67
23 DEC 22-4	2336	2178	6	.02501	.83120	158	68
26 DEC 23-1	2138	1603	24	.02267	1.39793	534	69
26 DEC 23-2	2217	1663	25	.02235	1.39793	554	70
26 DEC 23-3	2178	1544	29	.02182	1.46375	633	71

TABLE II (Continued)

DATE-RUN	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
26 DEC 23-4	1801	633	64	.01929	1.81181	0	72
3 JAN 24-1	590	266	54	.00626	1.73908	323	73
3 JAN 24-2	438	228	47	.00441	1.67966	209	74
3 JAN 24-3	533	228	57	.00534	1.75696	304	75
3 JAN 24-4	285	228	20	.00305	1.30103	57	76
8 JAN 25-1	676	117	82	.00717	1.91702	558	77
8 JAN 25-2	676	215	68	.00681	1.83324	460	78
8 JAN 25-3	676	107	84	.00677	1.92457	568	79
8 JAN 25-4	676	117	82	.00724	1.91702	558	80
11 JAN 26-1	2666	2392	10	.02827	1.01258	274	81
11 JAN 26-2	2705	2501	7	.02727	.87715	203	82
11 JAN 26-3	1352	235	82	.01355	1.91702	0	83
11 JAN 26-4	1254	862	31	.01343	1.49485	392	84
11 JAN 27-1	2666	2392	10	.02827	1.01258	274	85
11 JAN 27-2	2705	1921	28	.02727	1.46218	784	86
11 JAN 27-3	1352	196	85	.01355	1.93200	0	87
11 JAN 27-4	1254	705	43	.01343	1.64097	549	88
11 JAN 28-1	294	127	56	.00311	1.75332	166	89
11 JAN 28-2	186	117	36	.00187	1.56634	68	90
11 JAN 28-3	78	68	12	.00078	1.09690	9	91
11 JAN 28-4	127	88	30	.00136	1.48811	39	92
15 JAN 29-1	3428	3135	8	.03635	.93224	293	93
15 JAN 29-2	3279	3119	4	.03345	.68824	160	94
15 JAN 29-3	2967	2780	6	.02996	.79865	186	95
15 JAN 29-4	2773	2582	6	.02800	.83683	190	96
17 JAN 30-2	3441	3227	6	.03406	.79337	213	97
17 JAN 30-3	3049	2693	11	.02956	1.06775	356	98
17 JAN 30-4	2930	2732	6	.02663	.82973	198	99
18 JAN 32-1	6780	6697	1	.07121	.09200	83	100
18 JAN 32-2	2514	2285	9	.02589	.95860	228	101
18 JAN 32-3	2514	2323	7	.02539	.87942	190	102
20 JAN 33-1	6438	5561	13	.06839	1.13384	876	104
20 JAN 33-2	2990	2780	7	.03020	.84549	209	105
20 JAN 33-3	2895	2495	13	.02865	1.14037	400	106
20 JAN 33-4	2819	1904	32	.02562	1.51097	914	107
22 JAN 34-1	660	509	22	.00706	1.35902	150	108
22 JAN 34-2	698	509	27	.00733	1.43179	188	109
22 JAN 34-3	622	547	12	.00628	1.08354	75	110
22 JAN 34-4	584	433	25	.00543	1.41172	150	111
25 JAN 35-1	462	301	34	.00485	1.54025	160	112
25 JAN 35-3	367	292	20	.00371	1.31202	75	114
25 JAN 35-4	449	330	26	.00491	1.42276	118	115
27 JAN 36-2	74	62	14	.00074	1.17609	11	117
27 JAN 36-3	64	27	57	.00065	1.75696	37	118
27 JAN 36-4	55	46	16	.00049	1.22184	9	119
8 FEB 37-1	58	39	33	.00123	1.52287	19	120
8 FEB 37-2	44	14	66	.00090	1.82390	29	121
8 FEB 37-3	53	29	45	.00114	1.65757	24	122
8 FEB 37-4	58	14	74	.00101	1.87506	44	123
8 FEB 38-1	53	39	27	.00113	1.43572	14	124
8 FEB 38-2	102	44	57	.00212	1.75696	58	125
8 FEB 38-3	53	34	36	.00114	1.56066	19	126
8 FEB 38-4	39	14	62	.00067	1.79587	24	127
8 FEB 39-1	176	34	80	.00363	1.90609	142	128
8 FEB 39-2	78	63	18	.00153	1.27300	14	129
8 FEB 39-3	63	34	46	.00133	1.66420	29	130
8 FEB 39-4	58	49	16	.00102	1.22184	9	131
8 FEB 40-1	401	372	7	.00841	.86433	29	132
-8 FEB 40-2	722	524	27	.01401	1.43788	198	133
-8 FEB 40-4	411	88	78	.00668	1.89526	323	134

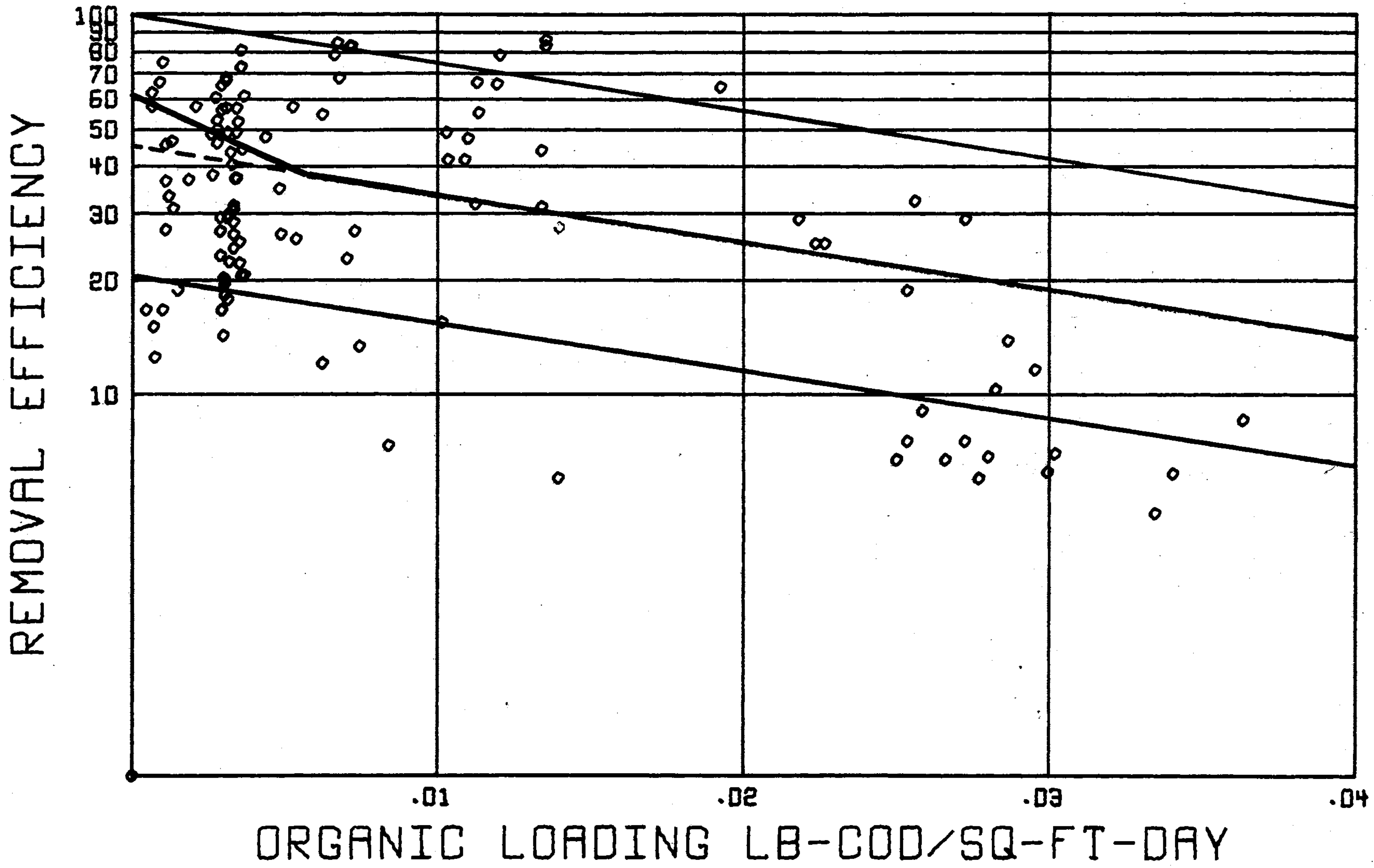

Figure 5. Removal Efficiency Versus Total Organic Loading. Purified Data

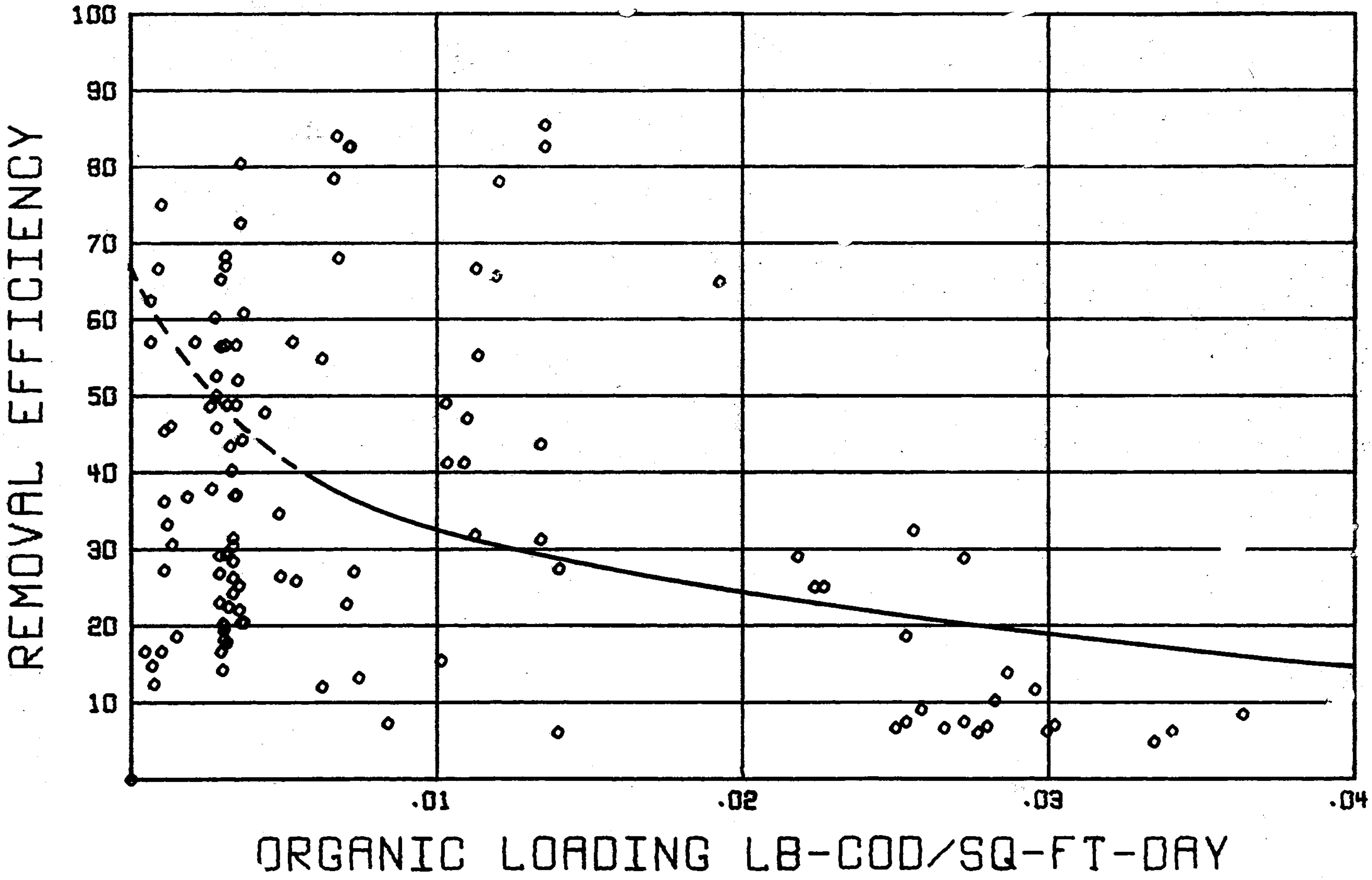

Figure 6. Removal Efficiency Versus Total Organic Loading. Purified Data

The next phase of the investigation dealt with a comparison of this data with known trickling filter data. Cook (12) and Fleming (13) have reported a considerable number of closely controlled experiments with pilot size plastic media trickling filters. Precise values for washed biomass surface area, hydraulic and organic loading rates and temperatures were readily available. Identical synthetic waste formulations were also used. Identical values that were calculated above for the experimental data were also calculated for Cook's and Fleming's data taken at Oklahoma State University. The Cook and Fleming experiments had carefully sampled at each foot of depth in their pilot studies. Each of these unity volumes provided a separate set of values in analysis. A total of 453 data sets were developed (Table III and Figure 7). The same regression analysis techniques were applied as described above for the rotating tube analysis. Since linear regressions were available for the inclined rotating tube model data ($k = -16.3$ and psuedo-intercept 1.6) and the composite Oklahoma State University data ($k = -12.5$ and psuedo-intercept of 1.6), comparisons of the two could be made. A covariance analysis (21) of the two simple regressions was made at the five percent level. The hypothesis that the two slopes and the two intercepts were equal for more than ninety-five percent of all expected samples was <u>not rejected</u>.

The dimensions of the organic loadings in the Cook and Fleming data differed from the initial model loadings. A common or normalized unit of organic loading per unit area of washed biomass was developed. The dimensions of this unit are

$$Z = \frac{\text{lb COD applied}}{\text{sq ft-day}} \; . \qquad (12)$$

TABLE III

PREVIOUS OKLAHOMA STATE UNIVERSITY COMPOSITE DATA

FLOW RATE GAL/DAY	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
100	88	10	88	.00048	1.94761	78	2
100	88	10	88	.00036	1.94761	78	3
100	33	15	54	.00055	1.73675	18	4
100	33	10	69	.00027	1.84321	23	5
100	33	10	69	.00018	1.84321	23	6
100	15	10	33	.00025	1.52287	5	7
100	15	10	33	.00012	1.52287	5	8
150	97	31	68	.00242	1.83277	66	9
150	97	19	80	.00121	1.90532	78	10
150	97	11	88	.00080	1.94772	86	11
150	97	14	85	.00060	1.93230	83	12
150	31	19	38	.00077	1.58781	12	13
150	31	11	64	.00038	1.80966	20	14
150	31	14	54	.00025	1.73908	17	15
150	19	11	42	.00047	1.62433	8	16
150	19	14	26	.00023	1.42021	5	17
200	107	58	45	.00356	1.66081	49	18
200	107	27	74	.00178	1.87370	80	19
200	107	20	81	.00118	1.91013	87	20
200	107	23	78	.00089	1.89489	84	21
200	58	27	53	.00193	1.72793	31	22
200	58	20	65	.00096	1.81635	38	23
200	58	23	60	.00064	1.78064	35	24
200	27	20	25	.00090	1.41373	7	25
200	27	23	14	.00045	1.17069	4	26
250	110	54	50	.00458	1.70679	56	27
250	110	23	79	.00229	1.89812	87	28
250	110	20	81	.00152	1.91284	90	29
250	110	13	88	.00114	1.94537	97	30
250	54	23	57	.00225	1.75896	31	31
250	54	20	62	.00112	1.79908	34	32
250	54	13	75	.00075	1.88039	41	33
250	23	20	13	.00095	1.11539	3	34
250	23	13	43	.00047	1.63827	10	35
250	20	13	35	.00083	1.54406	7	36
300	110	60	45	.00550	1.65757	50	37
300	110	37	66	.00275	1.82193	73	38
300	110	18	83	.00183	1.92239	92	39
300	110	18	83	.00137	1.92239	92	40
300	60	37	38	.00300	1.58357	23	41
300	60	18	70	.00150	1.84509	42	42
300	60	18	70	.00100	1.84509	42	43
300	37	18	51	.00185	1.71055	19	44
300	37	18	51	.00092	1.71055	19	45
600	95	57	40	.00950	1.60205	38	46
600	95	43	54	.00475	1.73827	52	47
600	95	28	70	.00316	1.84835	67	48
600	95	21	77	.00237	1.89150	74	49
600	57	43	24	.00570	1.39025	14	50
600	57	28	50	.00285	1.70652	29	51
600	57	21	63	.00190	1.80042	36	52
600	43	28	34	.00430	1.54262	15	53
600	43	21	51	.00215	1.70895	22	54
600	28	21	25	.00280	1.39793	7	55
100	204	118	42	.00340	1.62486	86	56
100	204	50	75	.00170	1.87789	154	57
100	204	31	84	.00113	1.92841	173	58
100	204	27	86	.00085	1.93834	177	59
100	118	50	57	.00196	1.76062	68	60
100	118	31	73	.00098	1.86763	87	61

TABLE III (Continued)

FLOW RATE GAL/DAY	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
100	118	27	77	.00065	1.88715	91	62
100	50	31	38	.00083	1.57978	19	63
100	50	27	46	.00041	1.66275	23	64
100	31	27	12	.00051	1.11069	4	65
150	220	111	49	.00550	1.69500	109	66
150	220	63	71	.00275	1.85347	157	67
150	220	29	86	.00183	1.93861	191	68
150	220	23	89	.00137	1.95204	197	69
150	111	63	43	.00277	1.63591	48	70
150	111	29	73	.00138	1.86849	82	71
150	111	23	79	.00092	1.89915	88	72
150	63	29	53	.00157	1.73213	34	73
150	63	23	63	.00078	1.80271	40	74
150	29	23	20	.00072	1.31575	6	75
200	212	106	50	.00707	1.69896	106	76
200	212	87	58	.00353	1.77057	125	77
200	212	57	73	.00235	1.86399	155	78
200	212	28	86	.00176	1.93848	184	79
200	106	87	17	.00353	1.25344	19	80
200	106	57	46	.00176	1.66489	49	81
200	106	28	73	.00117	1.86678	78	82
200	87	57	34	.00290	1.53760	30	83
200	87	28	67	.00145	1.83133	59	84
200	57	28	50	.00190	1.70652	29	85
250	205	134	34	.00854	1.53950	71	86
250	205	87	57	.00427	1.76012	118	87
250	205	55	73	.00284	1.86433	150	88
250	205	34	83	.00213	1.92124	171	89
250	134	87	35	.00558	1.54499	47	90
250	134	55	58	.00279	1.77052	79	91
250	134	34	74	.00186	1.87289	100	92
250	87	55	36	.00362	1.56563	32	93
250	87	34	60	.00181	1.78475	53	94
250	55	34	38	.00229	1.58185	21	95
300	211	139	34	.01055	1.53305	72	96
300	211	100	52	.00527	1.72104	111	97
300	211	54	74	.00351	1.87161	157	98
300	211	35	83	.00263	1.92123	176	99
300	139	100	28	.00695	1.44804	39	100
300	139	54	61	.00347	1.78640	85	101
300	139	35	74	.00231	1.87401	104	102
300	100	54	46	.00500	1.66275	46	103
300	100	35	65	.00250	1.81291	65	104
300	54	35	35	.00270	1.54635	19	105
500	190	117	38	.01584	1.58456	73	106
500	190	101	46	.00792	1.67063	89	107
500	190	62	67	.00528	1.82845	128	108
500	190	51	73	.00396	1.86426	139	109
500	117	101	13	.00975	1.13593	16	110
500	117	62	47	.00487	1.67217	55	111
500	117	51	56	.00325	1.75135	66	112
500	101	62	38	.00842	1.58674	39	113
500	101	51	49	.00421	1.69464	50	114
500	62	51	17	.00517	1.24900	11	115
100	316	181	42	.00527	1.63064	135	116
100	316	98	68	.00263	1.83876	218	117
100	316	66	79	.00175	1.89825	250	118
100	316	37	88	.00131	1.94591	279	119
100	181	98	45	.00301	1.66139	83	120
100	181	66	63	.00150	1.80301	115	121

TABLE III (Continued)

FLOW RATE GAL/DAY	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
100	181	37	79	.00100	1.90068	144	122
100	98	66	32	.00163	1.51392	32	123
100	98	37	62	.00081	1.79410	61	124
100	66	37	43	.00110	1.64285	29	125
200	312	199	36	.01040	1.55892	113	126
200	312	156	50	.00520	1.69896	156	127
200	312	100	67	.00346	1.83218	212	128
200	312	50	83	.00260	1.92414	262	129
200	199	156	21	.00663	1.33461	43	130
200	199	100	49	.00331	1.69678	99	131
200	199	50	74	.00221	1.87433	149	132
200	156	100	35	.00520	1.55506	56	133
200	156	50	67	.00260	1.83218	106	134
200	100	50	50	.00333	1.69896	50	135
250	316	242	23	.01317	1.36954	74	136
250	316	196	37	.00658	1.57949	120	137
250	316	150	52	.00439	1.72042	166	138
250	316	91	71	.00329	1.85249	225	139
250	242	196	19	.01009	1.27894	46	140
250	242	150	38	.00504	1.57997	92	141
250	242	91	62	.00336	1.79516	151	142
250	196	150	23	.00817	1.37050	46	143
250	196	91	53	.00408	1.72893	105	144
250	150	91	39	.00625	1.59476	59	145
100	417	245	41	.00695	1.61539	172	146
100	417	149	64	.00347	1.80799	268	147
100	417	66	84	.00231	1.92517	351	148
100	417	33	92	.00173	1.96419	384	149
100	245	149	39	.00408	1.59310	96	150
100	245	66	73	.00204	1.86368	179	151
100	245	33	86	.00136	1.93716	212	152
100	149	66	55	.00248	1.74589	83	153
100	149	33	77	.00124	1.89127	116	154
100	66	33	50	.00110	1.69896	33	155
150	412	293	28	.01030	1.46064	119	156
150	412	229	44	.00515	1.64755	183	157
150	412	163	60	.00343	1.78130	249	158
150	412	108	73	.00257	1.86797	304	159
150	293	229	21	.00733	1.33931	64	160
150	293	163	44	.00366	1.64707	130	161
150	293	108	63	.00244	1.80030	185	162
150	229	163	28	.00572	1.45970	66	163
150	229	108	52	.00286	1.72294	121	164
150	163	108	33	.00407	1.52817	55	165
250	399	264	33	.01663	1.52936	135	166
250	399	244	38	.00831	1.58935	155	167
250	399	160	59	.00554	1.77742	239	168
250	399	127	68	.00415	1.83359	272	169
250	264	244	7	.01100	.87942	20	170
250	264	160	39	.00550	1.59542	104	171
250	264	127	51	.00366	1.71511	137	172
250	244	160	34	.01017	1.53688	84	173
250	244	127	47	.00508	1.68079	117	174
250	160	127	20	.00667	1.31439	33	175
100	511	303	40	.00852	1.60964	208	176
100	511	211	58	.00426	1.76870	300	177
100	511	138	72	.00284	1.86328	373	178
100	511	79	84	.00213	1.92706	432	179
100	303	211	30	.00505	1.48234	92	180
100	303	138	54	.00252	1.73604	165	181

TABLE III (Continued)

FLOW RATE GAL/DAY	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
100	303	79	73	.00168	1.86880	224	182
100	211	138	34	.00351	1.53904	73	183
100	211	79	62	.00175	1.79629	132	184
100	138	79	42	.00230	1.63097	59	185
200	514	322	37	.01714	1.57233	192	186
200	514	295	42	.00857	1.62948	219	187
200	514	223	56	.00571	1.75292	291	188
200	514	198	61	.00428	1.78872	316	189
200	322	295	8	.01074	.92350	27	190
200	322	223	30	.00537	1.48777	99	191
200	322	198	38	.00358	1.58556	124	192
200	295	223	24	.00984	1.38751	72	193
200	295	198	32	.00492	1.51694	97	194
200	223	198	11	.00743	1.04963	25	195
300	480	373	22	.02401	1.34814	107	196
300	480	315	34	.01200	1.53624	165	197
300	480	255	46	.00800	1.67094	225	198
300	480	207	56	.00600	1.75492	273	199
300	373	315	15	.01866	1.19171	58	200
300	373	255	31	.00933	1.50017	118	201
300	373	207	44	.00622	1.64839	166	202
300	315	255	19	.01576	1.27984	60	203
300	315	207	34	.00788	1.53511	108	204
300	255	207	18	.01276	1.27470	48	205
100	986	834	15	.01644	1.18796	152	206
100	986	810	17	.00822	1.25163	176	207
100	986	720	26	.00548	1.43100	266	208
100	986	753	23	.00411	1.37347	233	209
100	834	810	2	.01391	.45904	24	210
100	834	720	13	.00695	1.13573	114	211
100	834	753	9	.00463	.98731	81	212
100	810	720	11	.01351	1.04575	90	213
100	810	753	7	.00675	.84738	57	214
100	175	113	35	.01216	1.54935	62	1
100	175	105	40	.00608	1.60205	70	2
100	175	64	63	.00405	1.80228	111	3
100	175	48	72	.00304	1.86076	127	4
100	113	105	7	.00785	.85001	8	5
100	113	64	43	.00392	1.63711	49	6
100	113	48	57	.00261	1.75983	65	7
100	105	64	39	.00729	1.59159	41	8
100	105	48	54	.00364	1.73468	57	9
100	64	48	25	.00444	1.39793	16	10
200	198	145	26	.02752	1.42761	53	11
200	198	126	36	.01376	1.56066	72	12
200	198	111	43	.00917	1.64285	87	13
200	198	76	61	.00688	1.78969	122	14
200	145	126	13	.02015	1.11738	19	15
200	145	111	23	.01007	1.37011	34	16
200	145	76	47	.00671	1.67748	69	17
200	126	111	11	.01751	1.07572	15	18
200	126	76	39	.00875	1.59859	50	19
200	111	76	31	.01542	1.49874	35	20
200	290	239	17	.04031	1.24517	51	21
200	290	210	27	.02015	1.44069	80	22
200	290	185	36	.01343	1.55879	105	23
200	290	157	45	.01007	1.66145	133	24
200	239	210	12	.03322	1.08400	29	25
200	239	185	22	.01661	1.35399	54	26
200	239	157	34	.01107	1.53541	82	27

TABLE III (Continued)

FLOW RATE GAL/DAY	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
200	210	185	11	.02919	1.07572	25	28
200	210	157	25	.01459	1.40205	53	29
200	185	157	15	.02571	1.17998	28	30
400	429	394	8	.11926	.91161	35	31
400	429	374	12	.05963	1.10790	55	32
400	429	349	18	.03975	1.27063	80	33
400	429	329	23	.02981	1.36754	100	34
400	394	374	5	.10953	.70553	20	35
400	394	349	11	.05476	1.05771	45	36
400	394	329	16	.03651	1.21741	65	37
400	374	349	6	.10397	.82506	25	38
400	374	329	12	.05198	1.08034	45	39
400	349	329	5	.09702	.75820	20	40
100	90	47	47	.00278	1.67922	43	1
100	90	29	67	.00139	1.83108	61	2
100	90	19	78	.00092	1.89701	71	3
100	90	16	82	.00069	1.91498	74	4
100	47	29	38	.00145	1.58317	18	5
100	47	19	59	.00072	1.77506	28	6
100	47	16	65	.00048	1.81926	31	7
100	29	19	34	.00089	1.53760	10	8
100	29	16	44	.00044	1.65154	13	9
100	19	16	15	.00058	1.19836	3	10
200	117	76	35	.00722	1.54459	41	11
200	117	64	45	.00361	1.65608	53	12
200	117	51	56	.00240	1.75135	66	13
200	117	44	62	.00180	1.79513	73	14
200	76	64	15	.00469	1.19836	12	15
200	76	51	32	.00234	1.51712	25	16
200	76	44	42	.00156	1.62433	32	17
200	64	51	20	.00395	1.30776	13	18
200	64	44	31	.00197	1.49484	20	19
200	51	44	13	.00315	1.13752	7	20
300	121	87	28	.01121	1.44869	34	21
300	121	70	42	.00560	1.62478	51	22
300	121	57	52	.00373	1.72339	64	23
300	121	50	58	.00280	1.76847	71	24
300	87	70	19	.00806	1.29092	17	25
300	87	57	34	.00403	1.53760	30	26
300	87	50	42	.00268	1.62868	37	27
300	70	57	18	.00648	1.26884	13	28
300	70	50	28	.00324	1.45593	20	29
300	57	50	12	.00528	1.08922	7	30
200	213	141	33	.01315	1.52895	72	31
200	213	131	38	.00657	1.58543	82	32
200	213	116	45	.00438	1.65839	97	33
200	213	95	55	.00328	1.74350	118	34
200	141	131	7	.00871	.85078	10	35
200	141	116	17	.00435	1.24872	25	36
200	141	95	32	.00290	1.51353	46	37
200	131	116	11	.00809	1.05881	15	38
200	131	95	27	.00404	1.43903	36	39
200	318	247	22	.01964	1.34883	71	41
200	318	211	33	.00982	1.52695	107	42
200	318	169	46	.00654	1.67075	149	43
200	318	133	58	.00491	1.76474	185	44
200	247	211	14	.01525	1.16360	36	45
200	247	169	31	.00762	1.49939	78	46
200	247	133	46	.00508	1.66420	114	47
200	211	169	19	.01303	1.29896	42	48

TABLE III (Continued)

FLOW RATE GAL/DAY	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
200	211	133	36	.00651	1.56781	78	49
200	169	133	21	.01044	1.32841	36	50
300	318	250	21	.02946	1.33008	68	51
300	318	227	28	.01473	1.45661	91	52
300	318	193	39	.00982	1.59448	125	53
300	318	172	45	.00736	1.66192	146	54
300	250	227	9	.02316	.96378	23	55
300	250	193	22	.01158	1.35793	57	56
300	250	172	31	.00772	1.49415	78	57
300	227	193	14	.02103	1.17545	34	58
300	227	172	24	.01051	1.38433	55	59
300	193	172	10	.01788	1.03666	21	60
800	195	167	14	.04818	1.15712	28	61
800	195	133	31	.02409	1.50235	62	62
800	195	119	38	.01606	1.59077	76	63
800	195	97	50	.01204	1.70119	98	64
800	167	133	20	.04126	1.30876	34	65
800	167	119	28	.02063	1.45852	48	66
800	167	97	41	.01375	1.62238	70	67
800	133	119	10	.03286	1.02227	14	68
800	133	97	27	.01643	1.43245	36	69
800	119	97	18	.02940	1.26687	22	70
400	443	373	15	.05473	1.19869	70	71
400	443	339	23	.02736	1.37062	104	72
400	443	297	32	.01824	1.51794	146	73
400	443	240	45	.01368	1.66109	203	74
400	373	339	9	.04608	.95977	34	75
400	373	297	20	.02304	1.30910	76	76
400	373	240	35	.01536	1.55214	133	77
400	339	297	12	.04188	1.09304	42	78
400	339	240	29	.02094	1.46543	99	79
400	297	240	19	.03669	1.28311	57	80
800	212	197	7	.03822	.84975	15	1
800	212	175	17	.01911	1.24186	37	2
800	212	152	28	.01274	1.45181	60	3
800	212	149	29	.00955	1.47300	63	4
800	197	175	11	.03552	1.04795	22	5
800	197	152	22	.01776	1.35874	45	6
800	197	149	24	.01184	1.38677	48	7
800	175	152	13	.03155	1.11868	23	8
800	175	149	14	.01577	1.17193	26	9
800	152	149	1	.02740	.29527	3	10
400	443	404	8	.03994	.94466	39	11
400	443	337	23	.01997	1.37890	106	12
400	443	312	29	.01331	1.47086	131	13
400	443	279	37	.00998	1.56844	164	14
400	404	337	16	.03642	1.21969	67	15
400	404	312	22	.01821	1.35740	92	16
400	404	279	30	.01214	1.49052	125	17
400	337	312	7	.03038	.87031	25	18
400	337	279	17	.01519	1.23579	58	19
400	312	279	10	.02813	1.02435	33	20
400	685	609	11	.06176	1.04512	76	21
400	685	538	21	.03088	1.33162	147	22
400	685	507	25	.02058	1.41472	178	23
400	685	470	31	.01544	1.49674	215	24
400	609	538	11	.05490	1.06664	71	25
400	609	507	16	.02745	1.22398	102	26
400	609	470	22	.01830	1.35839	139	27
400	538	507	5	.04850	.76057	31	28

TABLE III (Continued)

FLOW RATE GAL/DAY	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
400	538	470	12	.02425	1.10172	68	29
400	507	470	7	.04571	.86319	37	30
1400	210	190	9	.06626	.97881	20	31
1400	210	179	14	.03313	1.16914	31	32
1400	210	163	22	.02208	1.34987	47	33
1400	210	156	25	.01656	1.41017	54	34
1400	190	179	5	.05995	.76263	11	35
1400	190	163	14	.02997	1.15261	27	36
1400	190	156	17	.01998	1.25272	34	37
1400	179	163	8	.05648	.95126	16	38
1400	9	156	12	.02824	1.10887	23	39
1400	163	156	4	.05143	.63291	7	40
100	100	26	74	.00166	1.86923	74	1
100	100	23	77	.00083	1.88649	77	2
100	100	19	81	.00055	1.90848	81	3
100	100	22	78	.00041	1.89209	78	4
100	26	23	11	.00043	1.06214	3	5
100	26	19	26	.00021	1.43012	7	6
100	26	22	15	.00014	1.18708	4	7
100	23	19	17	.00038	1.24033	4	8
100	23	22	4	.00019	.63827	1	9
200	102	70	31	.00340	1.49654	32	10
200	102	53	48	.00170	1.68159	49	11
200	102	43	57	.00113	1.76225	59	12
200	102	34	66	.00085	1.82390	68	13
200	70	53	24	.00233	1.38535	17	14
200	70	43	38	.00116	1.58626	27	15
200	70	34	51	.00077	1.71120	36	16
200	53	43	18	.00176	1.27572	10	17
200	53	34	35	.00088	1.55447	19	18
200	43	34	20	.00143	1.32077	9	19
300	123	74	39	.00615	1.60029	49	20
300	123	62	49	.00307	1.69542	61	21
300	123	52	57	.00205	1.76135	71	22
300	123	42	65	.00153	1.81857	81	23
300	74	62	16	.00370	1.20994	12	24
300	74	52	29	.00185	1.47319	22	25
300	74	42	43	.00123	1.63591	32	26
300	62	52	16	.00310	1.20760	10	27
300	62	42	32	.00155	1.50863	20	28
300	52	42	19	.00260	1.28399	10	29
200	207	139	32	.00690	1.51653	68	30
200	207	118	42	.00345	1.63341	89	31
200	207	76	63	.00230	1.80130	131	32
200	207	54	73	.00172	1.86872	153	33
200	139	118	15	.00463	1.17920	21	34
200	139	76	45	.00231	1.65632	63	35
200	139	54	61	.00154	1.78640	85	36
200	118	76	35	.00393	1.55136	42	37
200	118	54	54	.00196	1.73429	64	38
200	76	54	28	.00253	1.46160	22	39
200	316	230	27	.01054	1.43481	86	40
200	316	163	48	.00527	1.68500	153	41
200	316	146	53	.00351	1.73076	170	42
200	316	112	64	.00263	1.80994	204	43
200	230	163	29	.00767	1.46434	67	44
200	230	146	36	.00383	1.56255	84	45
200	230	112	51	.00255	1.71015	118	46
200	163	146	10	.00543	1.01826	17	47
200	163	112	31	.00271	1.49538	51	48

TABLE III (Continued)

FLOW RATE GAL/DAY	COD-IN MG/L	COD-OUT MG/L	PCT-EFF	LOADING LB/FT2D	LOG-EFF	DELTA-COD MG/L	CODE
200	146	112	23	.00487	1.36712	34	49
300	324	266	17	.01621	1.25288	58	50
300	324	224	30	.00810	1.48945	100	51
300	324	217	33	.00540	1.51883	107	52
300	324	169	47	.00405	1.67978	155	53
300	266	224	15	.01331	1.19836	42	54
300	266	217	18	.00665	1.26531	49	55
300	266	169	36	.00443	1.56189	97	56
300	224	217	3	.01120	.49484	7	57
300	224	169	24	.00560	1.39011	55	58
300	217	169	22	.01085	1.34478	48	59
800	190	159	16	.02535	1.21260	31	60
800	190	130	31	.01267	1.49939	60	61
800	190	111	41	.00845	1.61887	79	62
800	190	96	49	.00633	1.69437	94	63
800	159	130	18	.02121	1.26100	29	64
800	159	111	30	.01060	1.47984	48	65
800	159	96	39	.00707	1.59794	63	66
800	130	111	14	.01734	1.16481	19	67
800	130	96	26	.00867	1.41753	34	68
800	111	96	13	.01481	1.13076	15	69
400	454	365	19	.03029	1.29233	89	70
400	454	310	31	.01514	1.50130	144	71
400	454	238	47	.01009	1.67739	216	72
400	454	196	56	.00757	1.75456	258	73
400	365	310	15	.02435	1.17806	55	74
400	365	238	34	.01217	1.54151	127	75
400	365	196	46	.00811	1.66559	169	76
400	310	196	36	.01034	1.56554	114	77
400	310	238	23	.02068	1.36597	72	78
400	238	196	17	.01587	1.24667	42	79

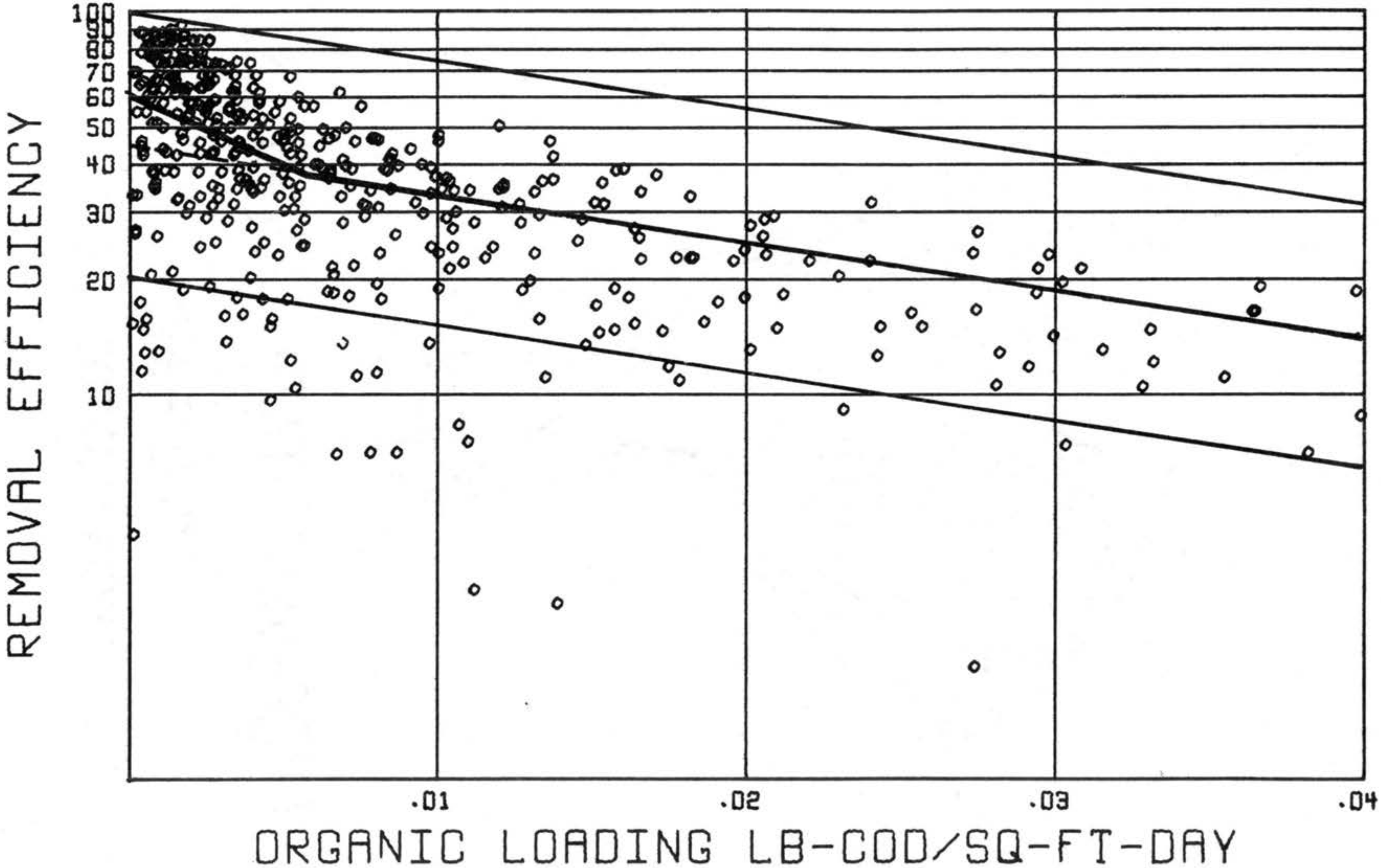

Figure 7. Removal Efficiency Versus Total Organic Loading. Previous O.S.U. Composite Data

This dimension also facilitates a comparison of these experiments with others reported in the literature.

Examination of other sources of data was now begun. Figure 8 compares data supplied for B. F. Goodrich and Ethyl Corporation plastic media, with the incline rotating tube data. An approximation of the average line from the NRC summary data (Figure 1) is also included. The relationship of each of these intermittent wetted, partially exposed biological systems is now more visible. Note the similarity of slopes between the Ethyl Corporation (Flocor), B. F. Goodrich, and the NRC with the rotating tube lines. Also note the Cook data only line and the similarity of slope with the rotating tube model line at extremely low organic loadings.

CHAPTER V

DISCUSSION

Model Correlation

A primary objective of the study was to determine whether the inclined rotating tube model would actually simulate the removal characteristics of other known accurate models of trickling filters. The covariance analysis established that a significant correlation does exist between the removal characteristics of this model and the previous Oklahoma State University scale model pilot removal characteristics. The actual reaction rate constants and intercepts were found to be "statistically equal" at the five percent level.

Amount of Waste Required

The nominal amounts of waste used in the study (7.2 - 12 liters/day) for the inclined rotating tube model represent a considerable savings in bulk handling. Furthermore, the small amounts involved make a detailed laboratory study far more feasible. The size and flow rate of the model were chosen to match available laboratory equipment. The ultimate size of the tube and the flow rates of waste material may be scaled down even further, given reliable pumping apparatus.

Mathematical Model

The linear relationships shown in Figures 5, 7, and 8 indicate that a first order reaction is occurring. Figure 8 also shows a slope (reaction rate constant) relationship between data reported for various media. Further investigation revealed that when each body of data was converted using the normalized unit of organic loading, Z, the slope of each was indicative of the waste being metabolized. Thus the reaction rate constant obtained from the inclined rotating tube model combined with the psuedo-intercept give a reliable removal efficiency when applied in the formulation

$$\frac{S_e}{S_o} = 10^{-kZ} + I \tag{13}$$

where

S_e = influent COD in mg/l

S_o = effluent COD in mg/l

$$\left.\begin{array}{l} k = \text{reaction rate constant} \\ I = \text{psuedo-intercept} \end{array}\right\} \text{determined from model study.}$$

Dimensional analysis of this relationship gives

$$\frac{S_e}{S_o} = \exp[\text{-proportionality constant}_1 \text{ x f (mass, area, time)}]. \tag{14}$$

Dimensional analysis of the other first order relationships previously reported are:

From Equation (2):

$$\text{Phelps: } \frac{S_e}{S_o} = \exp[\text{- proportionality constant}_2 \text{x f (time)}] \tag{15}$$

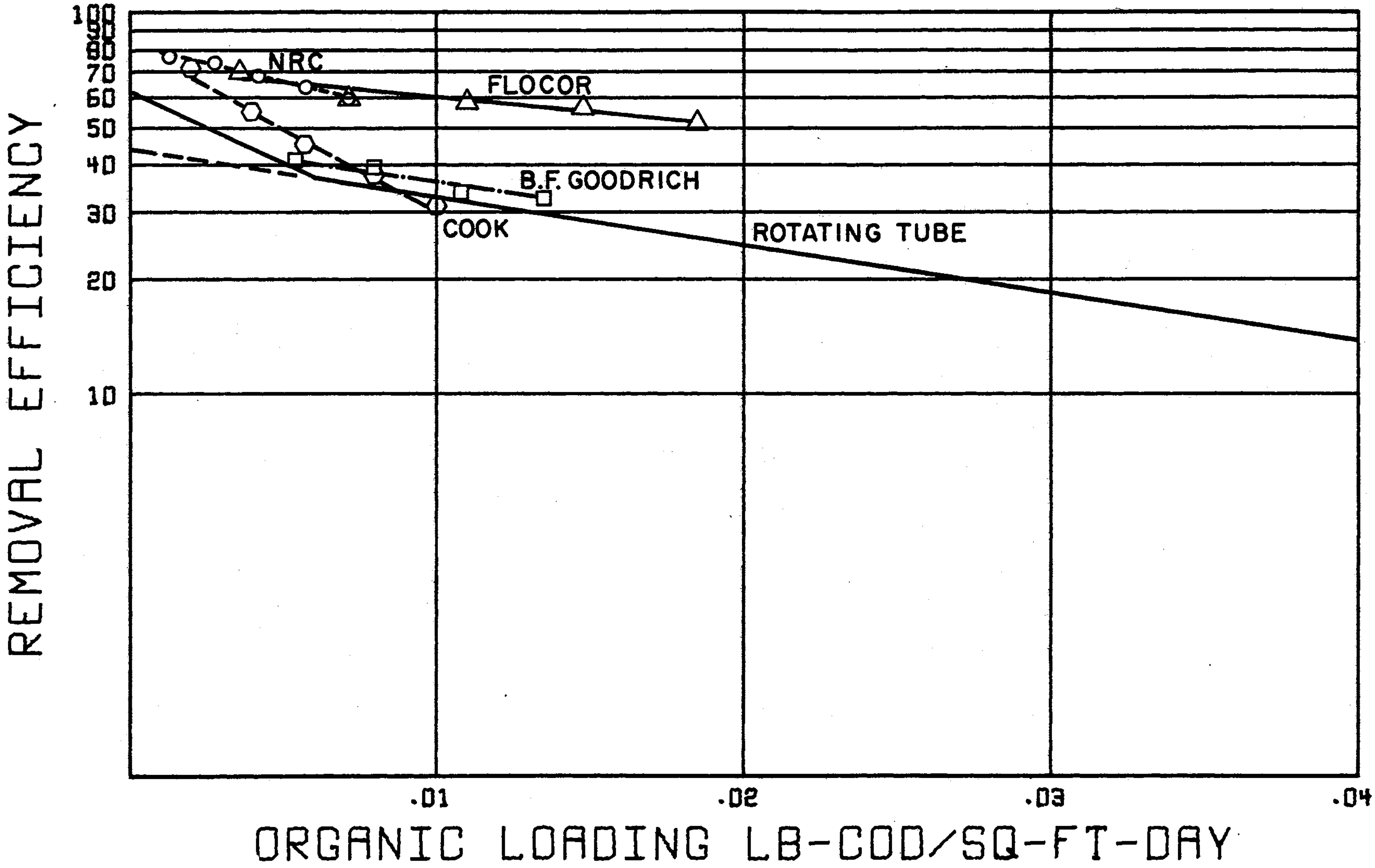

Figure 8. Removal Efficiency Versus Total Organic Loading. Selected Sources

From Equation (5):

$$\text{Velz: } \frac{S_e}{S_o} = \exp[-\text{proportionality constant}_3 \text{x } f\text{ (vol)}] \tag{16}$$

And from Equation (9):

$$\text{Eckenfelder: } \frac{S_e}{S_o} = \exp[-\text{proportionality constant}_4 f\text{ (area, time)}]. \tag{17}$$

Lower Boundary

Plots of the experimental data (Figures 5 and 7) reveal a "break" in the first order relationship toward lower organic loadings. Simple extrapolation of the regression lines as $Z \to 0$ gives a predicted removal efficiency somewhat less than those obtained in the experiments described. Indeed, the molecular point of view would support the hypothesis that

$$\lim_{Z \to 0} \frac{S_e}{S_o} = 1.0 \tag{18}$$

All of the 576 calculated values (Tables II and III) were then reexamined to ascertain whether a left boundary condition would apply to the newly developed design formulation. The apparent "break" appeared at approximately $Z = 0.05$. This point was chosen and all data to the left rerun through regression analysis. A new regression line $k = -35.5$ with $Z = 0$ intercept 1.78 was obtained. This new line, when plotted, intercepts the original line at:

$$Z = 0.0085 \frac{\text{lb COD}}{\text{sq ft - day}}$$

The extrapolation of the original reaction rate constant to the intercept point at $Z = 0$, although not depicting actual removal rate and accordingly referred to as a "psuedo" intercept, is a useful tool in data handling.

The lower boundary condition would seem to apply to the mathematical model (Equation (13)). The region beyond this boundary represents extremely small organic loadings. This region corresponds to the organic concentration levels that have been associated with favorable conditions for the nitrifying microorganisms. Further study in this area is particularly needed. Also note the break in Figure 8 also occurs close to other experimental plots emphasizing the rotating tube model correlation.

Statistical Variation

Variation in removal efficiency was demonstrated throughout this experiment. Similarly, the Cook and Fleming data was also extremely variable. The regression analyses provided the normal statistical parameters to describe the variability precisely. The removal efficiencies predicted by the use of Equation (13) are conservative at the outset because of the analysis itself. The regression line seeks an "average" or lower value rather than the optimum as indicated by Figures 5, 7, and 8. The engineer may enhance his treatment design analysis by allowing for this statistical variation.

CHAPTER VI

CONCLUSIONS

Based on this investigation, the following conclusions are presented:

1. The rotating tube micro-model of a trickling filter does simulate the pilot plant plastic media trickling filter.

2. Treatability studies and design studies may be run simultaneously using far smaller amounts of waste material than previously thought possible.

3. The first order relationship of removal efficiency as an exponential function of loading (time, area, and mass) may be used to design trickling filters.

4. Statistical chance variation (mean expected efficiency and confidence interval data) must be included in any design formulation whenever heterogeneous microbial populations are used.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

As a result of this investigation, the following suggestions are made for future study with the rotating tube trickling filter:

1. Pure culture studies to reinforce the concept of statistical description of the variability of heterogeneous microbial population metabolism.

2. Investigation of lower boundary removal kinetics and nitrification studies.

3. Studies on effect of residence or contact time by varying tube length, apparent path length (varying rotation rate), and angle of inclination.

4. Further refinements to improve sloughing. An increased inclination angle may improve this important feature.

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