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The influence of media size upon the effective removal of organic waste from a liquid substrate was studied by the use of three experimental trickling filters under a set of uniform operating conditions. The range of experiments involved hydraulic loadings of increasing magnitude and of constant organic strength.

The trickling filter columns consisted of three 18-foot, 5.8-inch diameter pipes with ports cut at various levels to permit the taking of samples and observation of conditions existing within the media mass.

The media selected for the analysis were 9/16-, 7/8- and 1-1/4-inch diameter marbles which were placed in the columns in such numbers that the surface areas were related in the ratio of the inverse diameter of the marbles.

The data collected for a basis of analysis were COD, BOD, film quantity, pH, ORP and temperature at influent, 1-, 2-, 4-, 8-, 12- and 18-foot or effluent levels. The other variable introduced intentionally was the hydraulic loading rate which started at 15 mgad and was increased to 75 mgad in 15 mgad steps between data test runs. A data test run consisted of five consecutive tests at each sampling point for each of the items selected as data basis.

The performance of the three filter columns was measured in terms of BOD and COD removals. These performance data were subjected to an analysis of variance to detect significant differences between columns. There were observable differences in Columns II and III, but at the 90 percent significance level the analysis of variance showed a similarity in treatment capacity at each level and each rate applied between these filter units.

Failure to pass hydraulic loads above 45 mgad put Column I out of the test series. This left Columns II and III for comparison at the 60 and 75 mgad rates.

The performance of the filter columns showed that the 9/16-inch marbles were not a practical size media for use in a trickling filter, as clogging and ponding made the filter very hard to maintain and operate. COD and BOD removals became less and less, and the filter failed to function satisfactorily above the 45 mgad rate.

The 7/8- and 1-1/4-inch media both maintained treatment capacity at the maximum rates applied. The measurable conditions indicated a much greater removal of organic load in total organic material removed at the higher rates than at the lower rates even though effluent quality deteriorated. The high rates of application favor the creation of a healthy environment for bacterial growth in providing better ORP and pH conditions.

The media size and thus surface area is shown to be of great influence in the establishing of optimum treatment conditions. The media size should be small enough to provide for a large amount of surface area per unit volume of media yet large enough to provide for a pore space giving adequate reaeration and fluid passing channels.

The smallest media tested does not meet these requirements, while the larger size media tested appeared to meet them better at the higher rates of application.

KINETICS OF BIOLOGICAL CONTACT BEDS

by

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Typed by Mary Coslet

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John Seaders

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INTRODUCTION

In the biological treatment of settled domestic sewage by trickling the sewage over a bed of inert media, there are many factors which affect the removal rate of the organic material by the biological contact bed. The major physical factors which are subject to control are: temperature, size and shape of filter media, depth of filter, the organic and hydraulic loading rates, and the air circulation through the filter. For any one combination of these factors there is a rate at which the organic materials are removed from the sewage by the biota in the bed. Each factor has limits beyond which it exerts such influence upon the system that the efficiency of the bed is destroyed.

The media size may be considered to vary from sand to huge rocks. Common sense would suggest a media size somewhere between such extremes. Experience with trickling filters has somwhat limited the range of sizes and the materials used for this purpose. The purpose of the media is to provide a surface upon which the micro-organisms can grow. The lower limit for media size, however,is determined by requirements for flow (food supply and cleaning action) and ventilation and with some types of industrial wastes by the type of organisms in the bed. The limiting depth of a filter would be the depth where the rate of removal is such that it is no longer removing the organic materials from the substrate efficiently in terms of the cost involved in constructing the filter bed.

In doing this work, it is hoped that a conclusion may be made which will enable the prediction of filter performance by analysis of the physical properties of the bed and the organic and hydraulic loads imposed on it.

Purpose and Scope

The purpose of this thesis is to investigate removal rates of organic substrates in sewage as affected by media size and filter depth.

The scope of this work is limited to five data runs. Each run consists of a series of five sets of tests. A single set of tests encompasses the taking of samples from each filter column at the influent, 1-, 2-, 4-, 8-, 12-foot and effluent levels and the analysis of these samples for temperature, pH, oxidation-reduction potential, chemical oxygen demand and five-day, 20° C., biochemical oxygen demand. At the end of a test run bacterial growth samples were taken at each of the sampling levels for determination of weight of growth per unit of surface area. During a five-day test series BOD_5 were obtained for three of the five days.

REVIEW OF LITERATURE

Introduction

A review of the literature shows that trickling filters have had extensive use in the secondary treatment of sewage and industrial wastes. The literature contains numerous articles which report operational data and experimental investigations on high-rate and low-rate trickling filters; however, few articles have referred to the influence of media size *per se* upon the performance of trickling filters.

The literature review which follows was prepared in recognition of the accumulated knowledge and experience of previous investigators. In addition to a section devoted specifically to media type and size, other sections have been provided to indicate the significance of several factors which were considered to be pertinent to this thesis.

Media Type and Size

For the support of the biological mass an inert media is required. A wide assortment of materials has been used and some differences, however minor, have been found to exist between different types. The selection of materials ranges from slag, coke and limestone to wooden slats and prefabricated plastic cells. Location of available materials influences the choice of media in most instances and the process requirements in others. Most commonly, a well-rounded river gravel or crushed stone is used. The general viewpoint about filter media material is that any uniform, inert, hard material is suitable as filter media.

In a thesis presented to Purdue University, J. C. McDermott proposed a design equation for surface area requirements based on a desired degree of purification, in terms of COD and applied hydraulic loads.

The size of the media is as yet an empirical selection; but since it is felt that the best purification is obtained by adequate contact time and that contact time per unit of filter is greatest for the smallest media used, it is best to use the smallest media practical. Investigations with 3/4-inch media at standard rates showed serious problems with clogging even though a positive pressure head was maintained with forced air. Experiments with 3/4-inch Raschig rings, when compared to other types and sizes of materials, gave the best results. Designers favor the use of filter media ranging from two to four inches in size, but the indications are that the smallest practical size is to be preferred to obtain a given contact time at maximum efficiency. However, the literature does not indicate the smallest practical size and the operating conditions which should be used for successful operation. (2, 5, 8, 11, 15, 16, 17)

Depth and Loadings

Filter depth has received prime attention by investigators due to the fact that direct financial benefits were to be gained from the results. Earliest filters were designed empirically. With testing and data becoming available, attempts have been made to obtain some design formulations for depth requirements in terms of loadings and efficiency desired. The thinking with respect to loadings has changed drastically with time. The early experiments at Lawrence Experiment Station in England in 1889 limited hydraulic rates to about two mgad for optimum results. Present testing at high rates indicates that good treatment can be obtained at loadings once considered out of question.

In general, it has been found that increasing BOD and hydraulic loadings results in poorer effluent, but the total removal in number of pounds of BOD or COD is greatly increased. Research, when related to depth, shows that the greater amount of BOD is removed in the upper part of the filters, and the removal rates have been demonstrated to follow a straight-line semilog function when the removal is figured as percent removal of the total amount of removable organic material entering a section of filter.

A limiting depth of eight feet is considered the economic limit for trickling filters how being designed since the extra efficiency obtained does not, in most cases, warrant the added cost of filter construction. When the rate of application is increased and BOD strength maintained constant, the effect on effluent strength has been reported nil up to loadings of 30 mgad. (1, 2, 4, 5, 9, 25)

Film and Contact Time

Differences in film quantity between high-rate and standard filters have been attributed by investigators to incomplete absorption and removal of the load by the high-rate filter because of inadequate contact time. Contact time is the increment of time during which a given part of a bacterial population has the opportunity to remove organic materials from the substrate. Predictable variations in film quantity have been noted with variations in applied BOD load and seasonal temperature variations.

At one time film quantity was considered to be directly proportional to the purification achieved, and design formulas for trickling filters based on film quantity per unit of filter media have been proposed but have not found general acceptance.

The latest indications are that the mass of slime or biota has little or no relationship to contact time or degree of purification. This thought is based upon the consideration that the active area of the slime layer is the outermost layer and that underlying layers are not as active as once was thought. Also, the underlying layers are thought of as a reservoir for fluid storage and not as contributing to increasing the contact time.

Initial experiments with trickling filters showed that for highest efficiency in terms of percent BOD removed, a very thin film of fluid moving very slowly over a film of organisms was the ideal criteria for contact time. BOD is usually defined as the oxygen required by organisms to stabilize organic materials under aerobic conditions. Recently, contact time T has been related to filter depth D and hydraulic loading Q; the contact time was found to vary directly with filter depth and inversely with hydraulic loading according to the equation:

$$T = 30.2\ D^{1.08}\ Q^{-0.515}$$

(1, 2, 3, 7, 9, 10, 23, 25)

Ventilation

There is still a great deal of controversy about ventilation. Investigations on bottom ventilation, side ventilation, forced and top ventilation are reported and the merits of each scheme have their adherents. The mass of evidence as shown by the more closely controlled experiments indicate, however, that adequate ventilation aids substantially in the waste stabilization process. The purpose of ventilation is still controversial; some feel it aids directly in the metabolic processes and in maintaining a positive oxidation-reduction potential, which is the ratio between materials in the reduced form and materials in the oxidized form, conducive to more rapid oxidation of soluble and colloidal waste products, while others think that the main purpose is to remove gaseous waste products. (5, 6, 7, 13, 14, 19)

pH

The pH sensitivity of biological treatment processes has almost been an accepted axiom for years. Experiments with domestic wastes and adjusted pH's have indicated that although the pH affects the treatment plant efficiency, the biological treatment process is not so sensitive that the system is upset to the point of failure. Good treatment efficiency has been obtained with pH between 8 and 9, but at pH 11 the results became poor. However, the filter was able to reduce the pH from 11 to 9. Low pH ranges soon become toxic and can destroy the process. For specific wastes it has been demonstrated that a pH range of 5 to 8 has only a slight effect on the effluent quantity. (21, 27)

ORP

The influence of the oxidation-reduction potential has been under study for some time, and ORP is presently considered to be dependent on two different reactions. One reaction, which is enzymatic, changes the dissolved oxygen into activated oxygen which is then able to take part in biochemical reactions. The second reaction is between this activated oxygen and the reduced waste products from the metabolic processes. In vigorous cultures the second process takes place faster than the first, and the activation rate becomes the limiting process. Particular enzyme systems, as well as the diffusion rate of oxygen from free oxygen to dissolved oxygen and the transfer of dissolved oxygen to the active reactions area, will influence the activation rate. The thinking has been that a high dissolved oxygen content indicated a good ORP; but when the activation process is proceeding rapidly, the stabilization process of reduced products will proceed as fast or faster. This suggests that even though the dissolved oxygen is low because of rapid activation, the process may be in excellent condition in terms of reduced waste products being stabilized. On the other hand, if the activation rate is lagging, the reduced products may increase, causing a sharp drop in ORP even though an excess of dissolved oxygen exists. If there is no source of oxygen available, the medium becomes conducive to the action of anaerobic enzymes which take over, and the ORP remains low. (24)

Temperature

The literature is in agreement that within the limits of the temperature growth range for organisms, it is important to create temperature conditions which fulfill the requirements for optimum growth conditions for a maximum number of organisms. At such temperatures the metabolic activity is nearer optimum for most organisms, and thus cell division takes place at a higher rate, producing a larger cell mass engaged in stabilization of organic materials.

Several reports indicate an increase of 25 percent in BOD removal between summer and winter. However, at depths greater than six feet no difference could be shown. The high-rate filters which have come into use are even less influenced by seasonal variations, as the great influx of liquid mass and the latent heat of this mass prevent the filter mass from cooling to lower efficiency levels. (20, 21, 22)

EQUIPMENT AND METHODS

Equipment

Three trickling filters of 5.8-inch diameter and 18-foot depth were constructed for testing under controlled conditions. Each column was packed with a media of constant size; the size and type media selected for this study were 9/16-inch and 7/8-inch marbles and 1-1/4-inch ceramic spheres.

An analysis of 25 marbles of each size was performed to determine the mean diameter per sphere. The diameter of the spheres was taken in three cartesian coordinate directions. A summary of this analysis is shown in Table 1.

Nominal size in inches	9/16	7/8	1-1/4
Mean diameter in mm. of 25 marbles	14.14	23.28	31.43

In order to load the columns uniformly in each section of column, the weight of five samples of 100 marbles each for the smaller-sized media and five samples of 50 marbles each for the largest media was determined. This permitted loading by weight rather than counting out each marble. The results are given in Table 2.

Size of media	9/16	7/8	1-1/4
Mean wt./marble, gms.	3.57	16.24	38.25

In order to obtain a degree of uniformity between columns, the surface area provided per filter column was based on the ratio of inverse diameters of the media sizes used.

Ratio Calculation:

Diameter	9/16	7/8	1-1/4
Diameter	D_1	D_2	D_3
Area/unit of media	A_1	$A_1\left(\frac{D_2}{D_1}\right)^2$	$A_1\left(\frac{D_3}{D_1}\right)^2$
Volume/unit of media $4/3 \quad D^3$	V_1 total	V_2 total	V_3 total
Number of marbles/section	N	$N\left(\frac{D_1}{D_2}\right)^3$	$N\left(\frac{D_1}{D_3}\right)^3$

From the above tabulation, the following may be set up:

$$A_1 \text{ total} = N\ A_1\left(\frac{D_1}{D_1}\right)$$

$$A_2 \text{ total} = N\left(\frac{D_1}{D_2}\right)^3 \times A_1\left(\frac{D_2}{D_1}\right)^2 = N\ A_1\left(\frac{D_1}{D_2}\right)$$

$$A_3 \text{ total} = N\left(\frac{D_1}{D_3}\right)^3 \times A_1\left(\frac{D_3}{D_1}\right)^2 = N\ A_1\left(\frac{D_1}{D_3}\right)$$

$$\frac{A_{1T}}{D_1} = \frac{A_{2T}}{D_2} = \frac{A_{3T}}{D_3}$$

Then using D_2 as unity, the ratio between surface areas based on the ratio of the inverse diameters becomes:

$$\frac{1}{D_1} : \frac{1}{D_2} : \frac{1}{D_3}$$

$$\frac{1}{\frac{14.14}{23.28}} : \frac{23.28}{23.28} : \frac{1}{\frac{31.43}{23.28}}$$

$$1.645 : 1 : 0.741$$

In both the one- and two-foot sections this ratio of surface areas was maintained.

In the top five feet of the columns, sampling ports were constructed at one-foot intervals and in the remaining part of the column at two-foot intervals. Sampling trays were placed in the ports to aid in the removal of growth samples at various levels (Plate 1). Wall effects were minimized by drip rings at each sampling port to redistribute the flow clinging to the walls. The influent feeding apparatus was constructed so that constant feeding and feed strength could be maintained.

The original setup used three sets of two tanks of 100 L. each, each filter having its own feeding apparatus (Plate 2). The schematic diagram (Fig. 1) shows the flow pattern of the feeding arrangement.

The stockfeed tank contained the concentrated feed which was fed into a feed-mixing tank by a pneumatically operated positive displacement pump. A solenoid valve operated by a timer determined the frequency and rate of stockfeed supply to the mixing tank.

The feed-mixing tank contents were kept at a constant level by a float valve. The constant rates of incoming liquids and outgoing products insured a constant strength feed. Recirculation pumps provided mixing of influents and supplied the feed to rotary distributors.

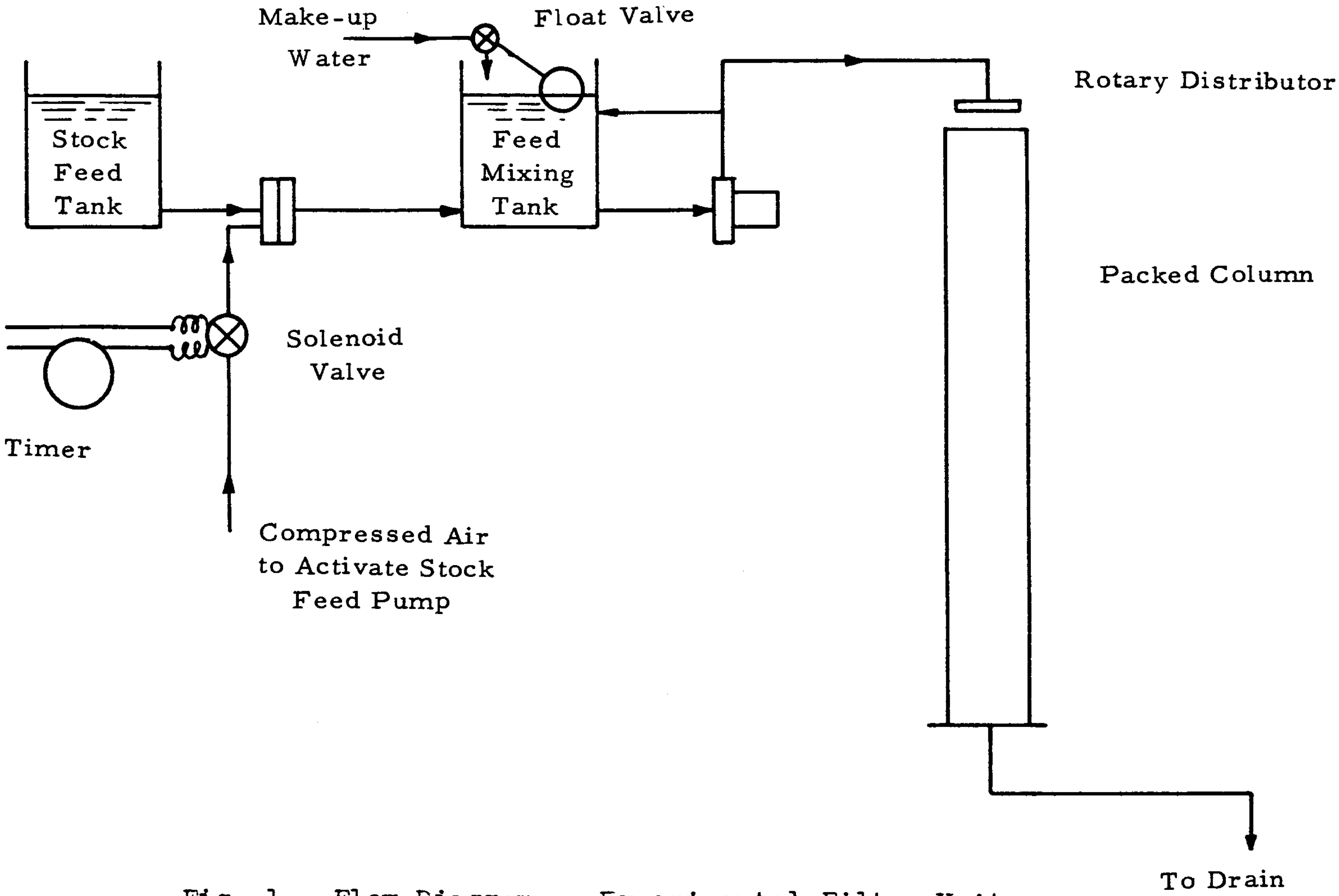


Fig. 1. Flow Diagram -- Experimental Filter Units

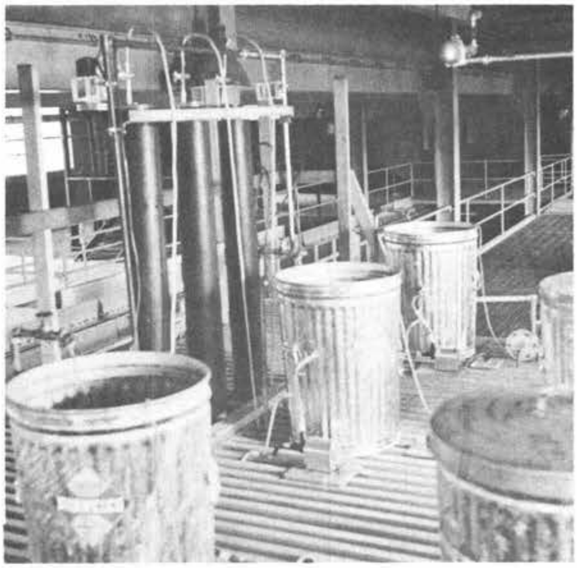


Fig. 2. Loading and Control Platform -- Laboratory Units

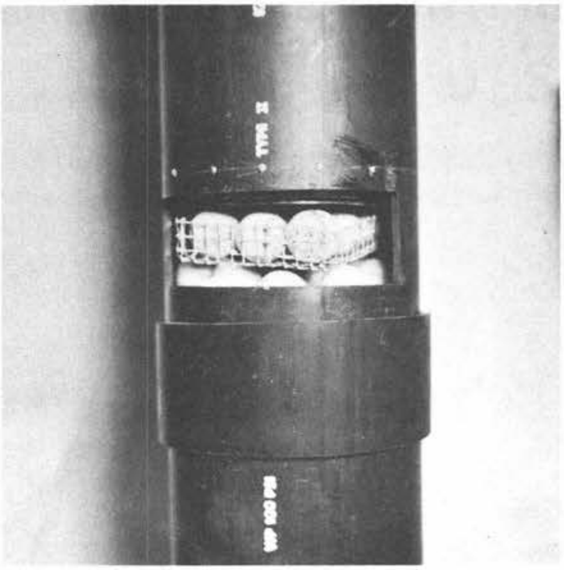


Fig. 3. Typical Sample Ports -- Laboratory Filter Units

The hydraulic rates to the filters were controlled by stop-cock valves. All lines to the feeding mechanisms were cleaned daily and the stop-cock valves adjusted to give the desired rate. The rates were measured before and after cleaning. The average daily rates are recorded in Appendix C.

The design of the filter units allowed for loadings from low rates to rates up to 120 mgad. For a change of loadings from 15 mgad to 30 mgad the rates were stepped up in five increments of three mgad at two-day intervals while maintaining a constant feed strength.

This system was modified in its operational procedure when bacteria growths in the feed lines interrupted continuous flow rates and at time stopped flow altogether.

A rotation procedure was adopted using one set of tanks per day for feeding while the other two sets were cleaned by continuous washing with a diluted "Purex" solution and rinsed with tap water. This system insured cleanliness at every point in the feeding system. During the hot summer days, the stockfeed tanks had to be abandoned as the milk used for substrate stockfeed went sour and curdled. Refrigeration of the stockfeed solved this problem satisfactorily.

Substrate Analysis

The milk solids used for organic load to the filter columns were analyzed for the following:

COD
BOD
Nitrogen as ammonia
organic nitrogen
nitrites
nitrates
Phosphorus as PO_4

For methods of analysis the procedures outlined in the eleventh edition, 1960, of Standard Methods for the Examination of Water and Waste Water published jointly by the APHA, AWWA and WPCF were used. A Bausch and Lomb spectrophotometer was used to analyze the samples. Standard curves for NH_3, NO_3 and PO_4 were prepared.

The results of the analysis, tabulated in Table 3, are recorded as mg. per gm. of dry milk solids.

COD		1075	mg./gm.
BOD		700 - 775	"
Nitrogen:	Organic -- N	50	"
	Ammonia -- NH_3	0	"
	Nitrite -- NO_2	0	"
	Nitrate -- NO_3	0	"
Phosphorus:	Phosphate -- PO_4	29	"

Methods

The intended organic load was approximately 120 to 140 ppm of five-day BOD. Preliminary testing with milk solids showed that a BOD strength of 130 to 140 ppm and a COD strength of 220 ppm would be supplied by 0.2 gm. of milk solids per liter of water. The chemical oxygen demand is the amount of oxygen required by the organic materials if they were participating in a chemical reaction. The 0.2 gm. per liter was used as the standard feed for all operations, and the feed strength was maintained for the major part of the time within ten percent of the desired concentration (Fig. 18).

Data Collection and Sample Preparation

To establish the influence of media size, the substrate quality at various levels was required. Samples were taken at the 0-, 1-, 2-, 4-, 8-, 12- and effluent or 18-foot levels, and analyzed for ORP, pH, temperature, COD and BOD. The ORP, pH and temperature data are tabulated in Appendix B.

The samples were collected by means of channeled trays inserted in the sampling ports and then funneled into BOD bottles. The preparation of all samples from time of sampling until testing was accomplished in two to four hours.

Each sample was filtered through No. 40 Whatman paper to render the effluent comparable to settled trickling filter effluent. For BOD testing no seeding was needed except for the influent.

To obtain growth samples, marbles were lifted out of the trays (Fig. 2) with all growth that adhered or seemed to belong as having grown on that specific marble.

Forty, fifteen, and eight marbles were taken from Columns I, II and III, respectively, at each sampling level except the top. This number of marbles per column represented a unit of surface area approximately 250 cm^2. The marbles were then washed in distilled water and the thus-obtained growth dried in an oven at 103° C.

Preliminary Testing

Because of the weak nature of the waste, the standard COD test method had to be modified in order to employ it as a test for sample analysis.

The dichromate strength was reduced from 0.25 N to 0.10 N. This introduced a constant error of about 5 to 10 percent. Next, the sample size was increased from 50 ml. to 150 ml. This permitted digestion and titration of all samples with the same dichromate and titrant normality. The variation in results due to the different acid percentage was obtained by running a series of tests with samples of 25 ml. diluted to 25, 50, 75, 100 and 150 ml. with varying acid volumes of 25, 50 and 75 ml. per sample. The results of this test are tabulated in Table 4 and are shown in Fig. 4. The difference between the standard method and the modified method was computed to be 1.55. This, then, means that all COD values obtained were to be multiplied by a factor of 1.55, for each COD sample was brought to the same acid percentage by dilution.

Since the number of tests required was large, the possibility of reducing the digestion time was investigated. Samples of like strength and dilution were digested for one-half, one, one-and-a-half and two hours (Table 5). No difference was observed and, therefore, the digestion time of 45 to 60 minutes was employed throughout the testing period.

To ascertain the way in which the BOD samples used available oxygen, two sets of ten-day BOD samples were taken. The main purpose was to ascertain if the nitrification stage had been reached within the five-day period in which the samples taken during the data runs were reported.

The curves taken from this data are shown in Figs. 5 and 6.

Table 4.

Sample Volume	Acid Volume 25		Acid Volume 50		Acid Volume 75	
	% Acid	COD	% Acid	COD	% Acid	COD
25	33.3	157	50.0	221	60.0	254
50	25.0	141	40.0	176	50.0	216
75	20.0	129	33.3	151	43.0	189
100	16.7	126	28.6	141	37.5	160
150	12.5	112	22.2	129	30.0	141

$K_2Cr_2O_7$ Normality -- 0.1

$Fe(SO_4)NH_3$ Normality -- 0.1

Table 5.

Sample Number	Digestion Time Hrs.	Titrant Volume ml.
1	0.5	20.25
2	1.0	20.10
3	1.0	20.10
4	1.5	20.20
5	1.5	20.00
6	2.0	20.20

Method of Data Analysis

To establish significant differences between the media sizes used, the data was subjected to a one-way analysis of variance. In order to use the analysis of variance, all COD data was reduced to percent COD remaining at each level used for testing. Plots of these data are shown in Figs. 7 to 14, where each point represents the average of five tests or ten in some cases.

The hypothesis was that there was no significant difference at the 90 percent significance level. Fisher's F value was used to determine whether the hypothesis was true or false. Then, to compare the filter columns further, the single degree of freedom was used to check for differences between two columns. The results of the analysis of variance are tabulated in Appendix A.

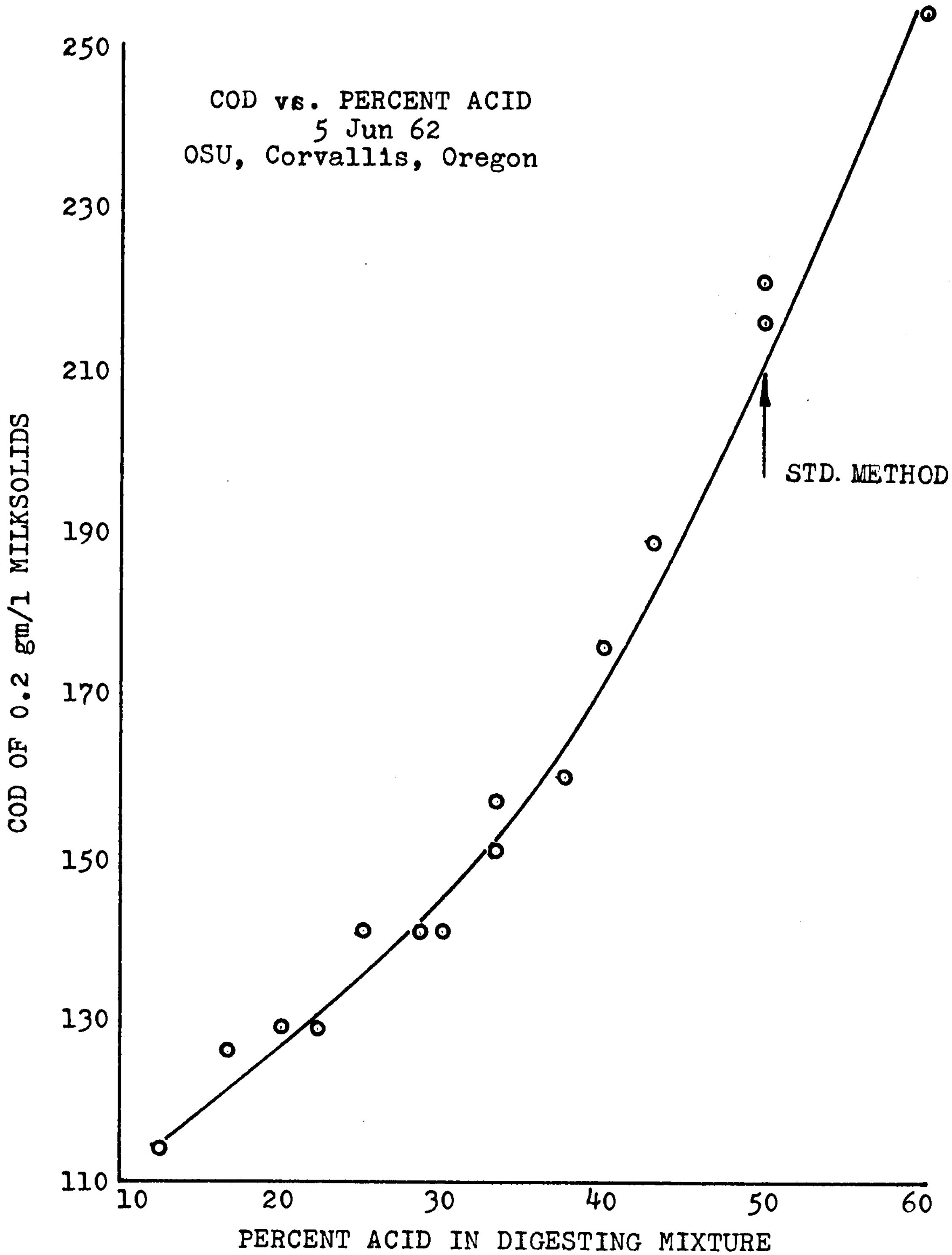

COD vs. PERCENT ACID
5 Jun 62
OSU, Corvallis, Oregon
COD OF 0.2 gm/1 MILKSOLIDS
250
230
210
190
170
150
130
110
10
20
30
40
50
60
PERCENT ACID IN DIGESTING MIXTURE
STD. METHOD

FIG. 4

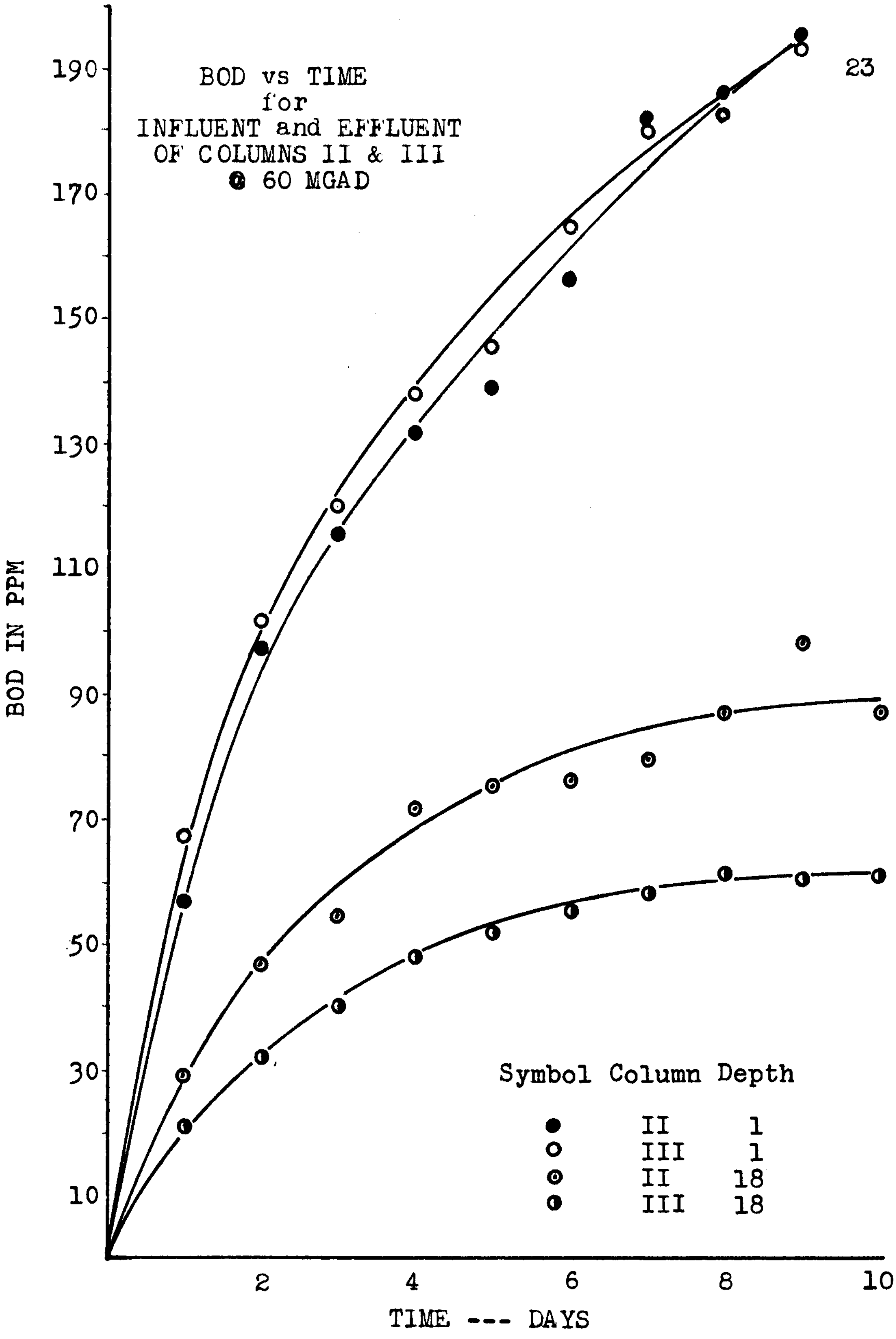
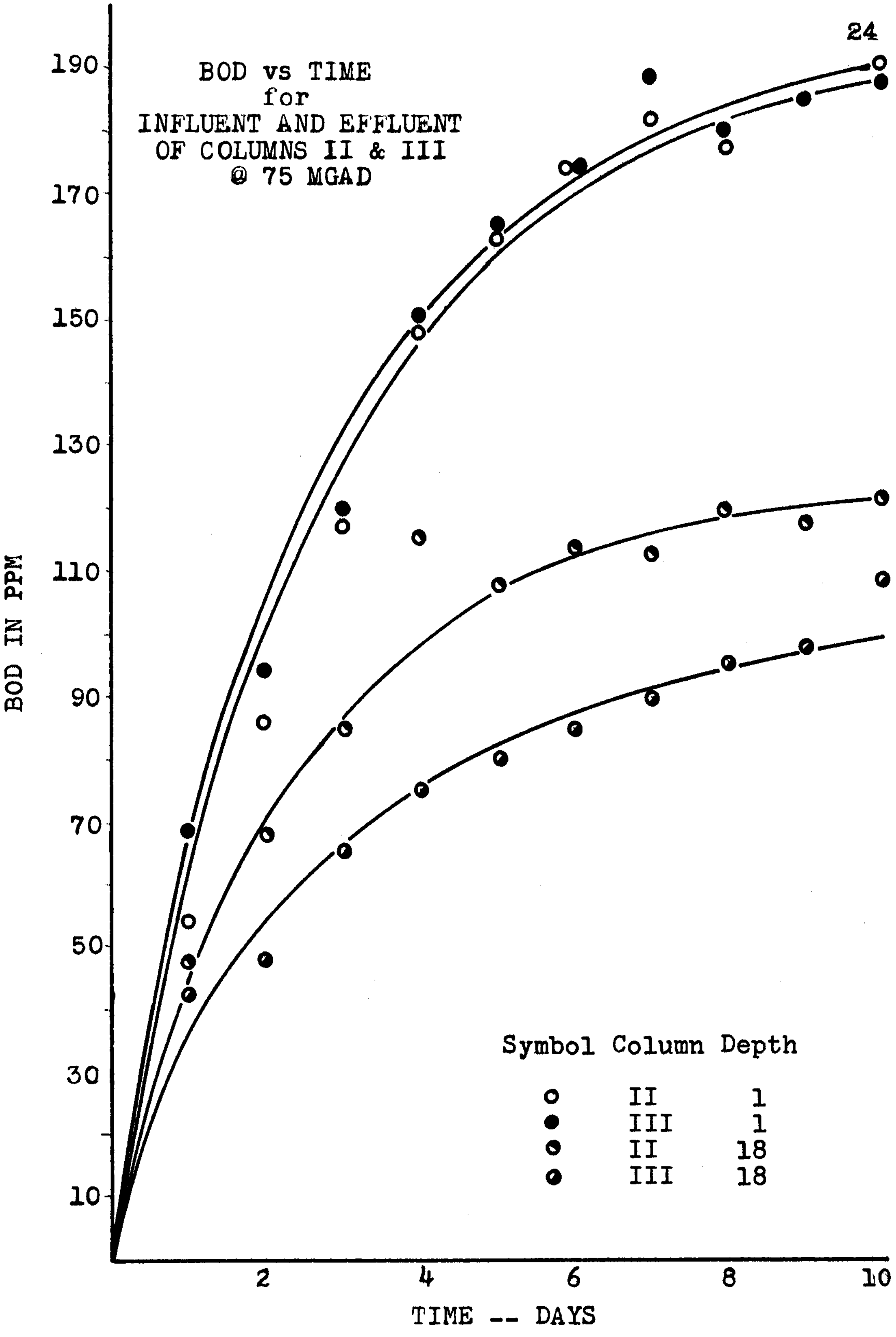

BOD vs TIME
for
INFLUENT and EFFLUENT
OF COLUMNS II & III
@ 60 MGAD
BOD IN PPM
TIME --- DAYS
Symbol Column Depth
II 1
III 1
II 18
III 18
10
30
50
70
90
110
130
150
170
190
2
4
6
8
10

FIG. 5



BOD vs TIME
for
INFLUENT AND EFFLUENT
OF COLUMNS II & III
@ 75 MGAD
24
190
170
150
130
110
90
70
50
30
10
BOD IN PPM
2
4
6
8
10
TIME -- DAYS
Symbol Column Depth
II 1
III 1
II 18
III 18

FIG. 6

Filter Operation Diary

Filter operation started April, 1962, with seeding of settled domestic sewage and the introduction of artificial substrate. The initial rate was set at 15 mgad and a growing period of six weeks was considered adequate for the establishment of equilibrium conditions.

During this period only slight bacterial growth was observed below the eight-foot level in the filter with the smallest media, hereafter to be referred to as Column I, or below the six-foot levels in the filters with 7/8-inch and 1-1/4-inch media, to be referred to as Columns II and III, respectively.

From the bottom of the screens which supported the media in each section, growth occurred repeatedly (after cleaning) in the shape of icicles and of rubbery texture. The icicle shapes developed, no doubt, due to channeling effects within the filter mass. This excess growth was removed at regular intervals. The loss of active organisms can be considered nil, for only the outer layers were in contact with passing liquids.

Ponding and the associated anaerobic conditions were first noted in Column I and to some degree also in Column II at the initial rate. At higher rates, however, when remedial action was applied by draining the section and agitation of the media, aerobic conditions were brought about and persisted. Due to the small diameter of the columns (5.8 inches), wall effects were anticipated to be a problem. The problem was overcome by drip rings which tended to redistribute this flow over the center portion of the column section. Observations showed that the dispersion of liquid through the media after the liquid passed through one foot of filter was no problem.

Filter fly problems were not encountered to any great degree. Filter flies began to show up at the end of June, but as the rates were increased, the flies decreased.

DISCUSSION OF DATA

Media Size Influence upon Effluent Quality (COD)

Figs. 7, 8 and 9 are plots of the percent COD remaining vs. depth for each filter column. The flattening out of the curves indicates that greater use was made of the lower part of the column as the hydraulic rates went up. Even though in Fig. 8 the COD of the effluent increased from 10 percent remaining to 33 percent remaining, the total pounds of COD removed was almost four times greater at 75 mgad than at 15 mgad.

Increase of COD in the effluent but greater removal of applied weight of organic material can also be seen for Column III, while Column I shows this trend only for the upper 12 feet of the column. Almost every curve plotted showed a flat slope at the top of the column. This is probably due to a gradual change-over from aerobic to anaerobic conditions during initial rates of application. Some degree of clogging and insufficient sloughing were noticed in every column. The clogging problem decreased from Column I to Column II. But once the anaerobic condition prevails, it is difficult to reverse the process until aerobic conditions prevail. The anaerobic section also progressed to some extent downwards with increasing rates. See Figs. 7 and 8 for Columns I and II. But after the rates went up to where flushing became substantial, a reversal was indicated.

The analysis of variance of the COD data collected from five data test runs (Appendix A) gave the following indications on the influence of media size upon the effluent quality. At the initial rate of 15 mgad the media size showed a significant influence upon the purification results at almost every level in the columns. At the increased rates this influence diminished, and only the bottom sections of the filters showed significant differences. The choice of which media size is to be preferred at what rate is only arrived at by a comparison between the columns in pairs.

The Analysis of Variance calculations as well as visual inspection of the COD and BOD remaining vs Depth curves, indicate with the exception of Run 1, that Columns I, II and III have the same purification capacity at every hydraulic loading imposed on the systems. If Column 1 had not clogged over most of its length this trend might have been established more firmly. Comparisons between individual columns lead to the same conclusions. The real difference between columns is not their ability to purify the wastes but to remain in operation without the need of remedial action. The analysis of variance, exclusive of data run 1, showed that 90 percent of the F values obtained from the comparison of Columns II and III are below the F value at the 5 percent significance level. This established the hypothesis that Columns II and III are alike and, therefore, that the difference between 7/8-inch and 1-1/4-inch media is of no consequence in the purification of waste when the results are reported in terms of COD.

The smallest (9/16-inch) media began to exert detrimental influence upon the facility soon after operations started. After repeated efforts to keep the system operational at 60 mgad failed, the column was taken out of action. The requirements for growth, aeration and fluid passage could not be met by the smallest media when the rates were increased above 45 mgad. The closure of available channels for fluid flow by growth in the voids most certainly attributed to the failure of the system. The closure of channels did not proceed as rapidly or did not occur at all with the larger media sizes in Columns II and III.

Media Size Influence upon Effluent Quality (BOD)

An analysis of variance was also made of the BOD data at the 4, 8, 12 and effluent levels. The F values obtained from this analysis are shown in Appendix A.

The results of this analysis agree with the COD data analysis in that Columns II and III are shown to have the same degree of variation and are the same in purification capacity at the 5 percent significance level.

As in the COD analysis the columns are quite similar in results produced by the upper section of filter column during the first three data runs. But the lower sections showed marked differences beginning at the 12- and 8-foot depth at 30 and 45 mgad loadings, respectively.

The effluent of Column I in terms of BOD deteriorated rapidly at the higher rates due to poor contact conditions resulting from clogging and ponding.

There is a similar increase in total removal and greater activity in the lower part of the filter columns evident in BOD results as was shown by the COD results. This would indicate that the percent removal of BOD and COD as a percent of removable fraction present at entering a section was decreasing at the higher rates.

This removal rate or K rate is defined as the rate of extraction or organic material per interval of depth of a biological contact bed, and this rate is proportional to the remaining concentration of organic matter measured in terms of its removability.

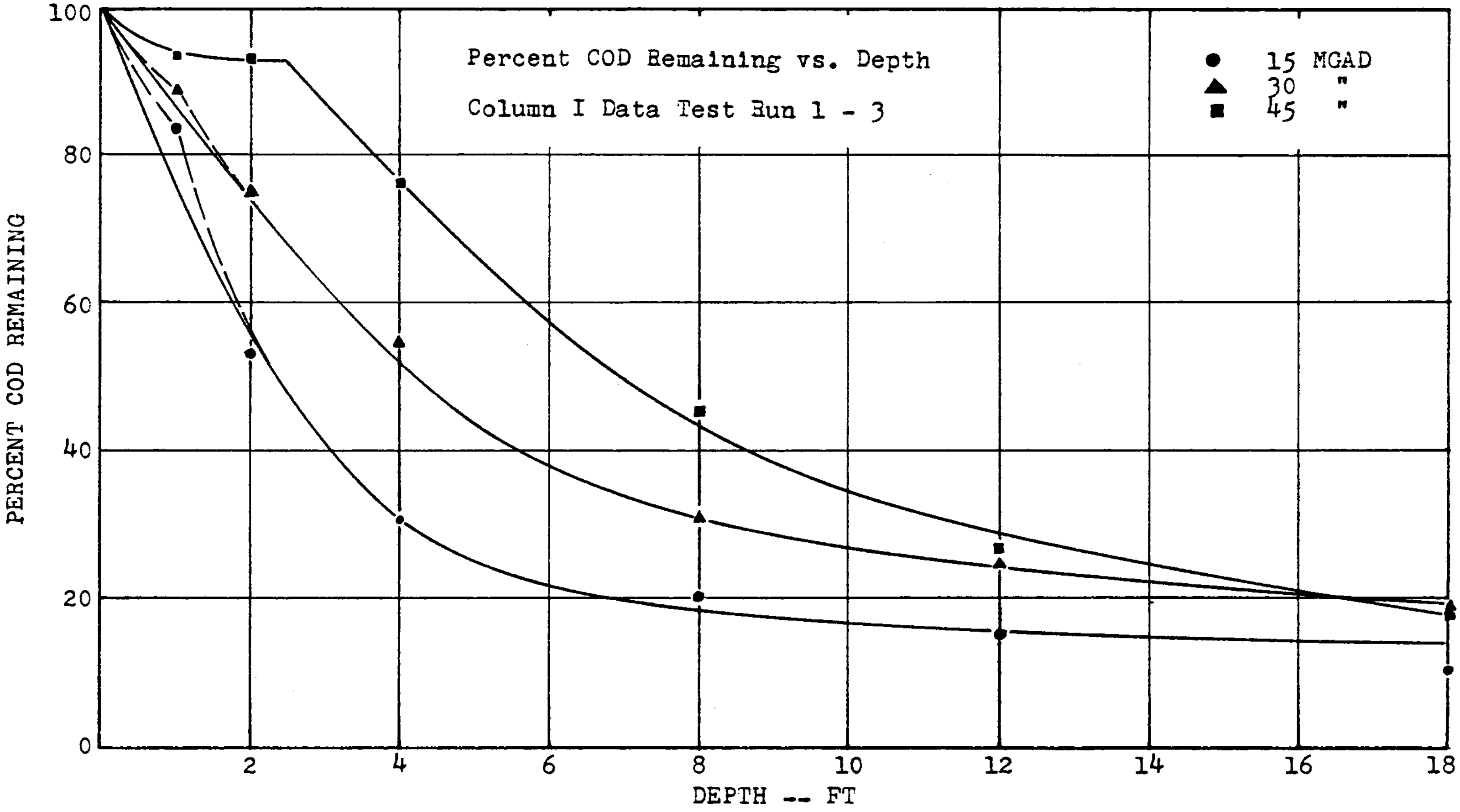
Therefore, the K rates may vary with hydraulic loads.

Biological Growth

The growth patterns as determined by the dry weight of biological mass are shown in Figs. 15, 16 and 17. Despite the scattered pattern, some observations and conclusions may be made.

First, the variation within each column shows that the greater mass of growth occurred in the upper part of the filter column where, according to the percent remaining vs. depth curves, the larger removal was effected. When the rates increased and the bottom part of the columns became more effective, a more even distribution of growth throughout the columns was observed.

Between the 30 mgad and 45 mgad rates there was a build-up of growth within each column. This is clearly indicated in Column I and to a lesser degree in Columns II and III. By the time the 60 mgad was reached, Column I was so thoroughly clogged that most of the fluid was running outside the column. For this reason Column I was taken out of action. Column II began to show less growth at this rate and Column III a great deal less. The flushing and shearing action of the great mass of liquid kept the lush growth which was observed at lower rates from accumulating.



Percent COD Remaining vs. Depth
Column I Data Test Run 1 - 3
15 MGAD
30 "
45 "
100
80
60
40
20
0
PERCENT COD REMAINING
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 7

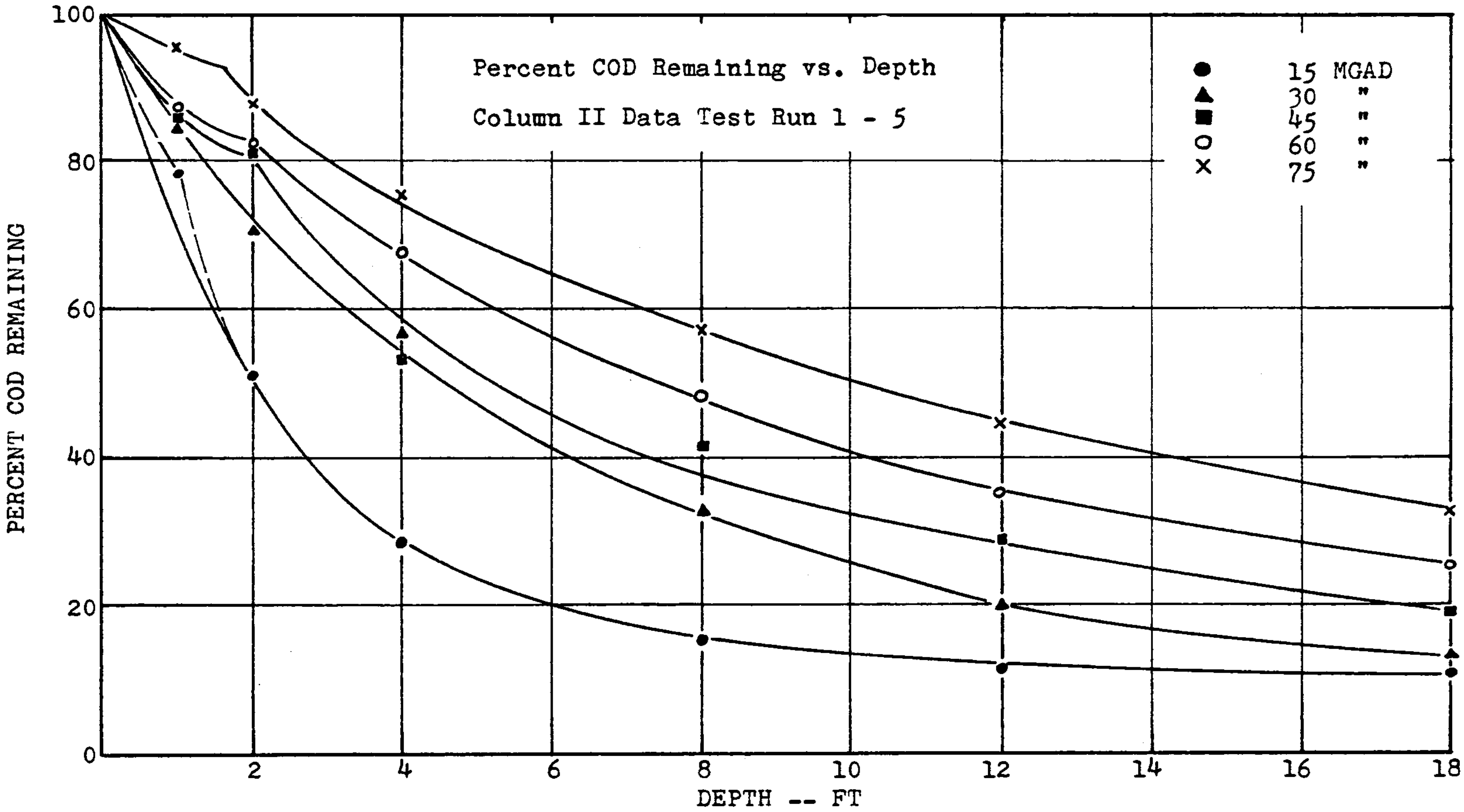

Percent COD Remaining vs. Depth
Column II Data Test Run 1 - 5
15 MGAD
30 "
45 "
60 "
75 "
PERCENT COD REMAINING
0
20
40
60
80
100
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 8

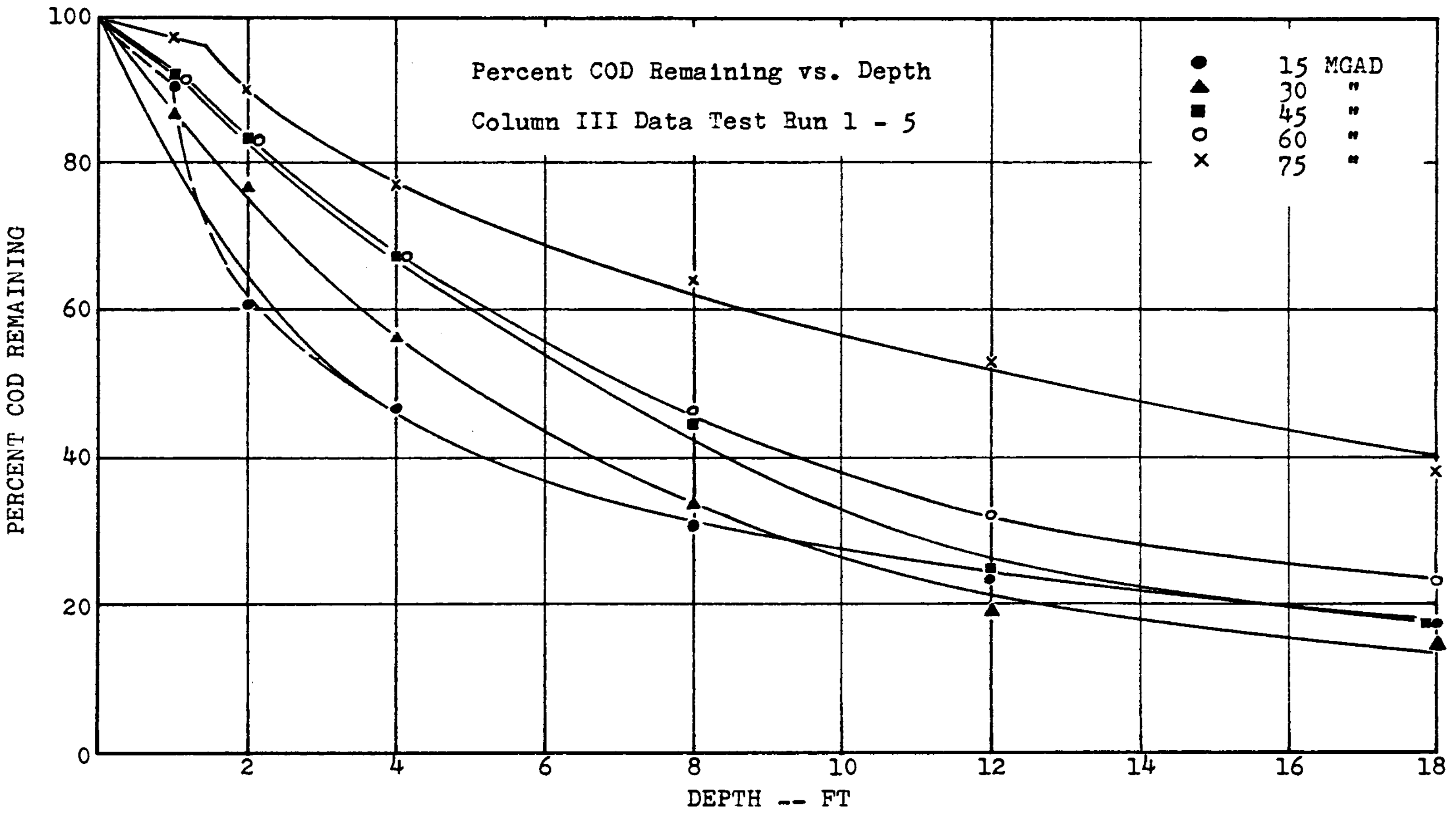

Percent COD Remaining vs. Depth
Column III Data Test Run 1 - 5
15 MGAD
30 "
45 "
60 "
75 "
100
80
60
40
20
0
PERCENT COD REMAINING
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 9

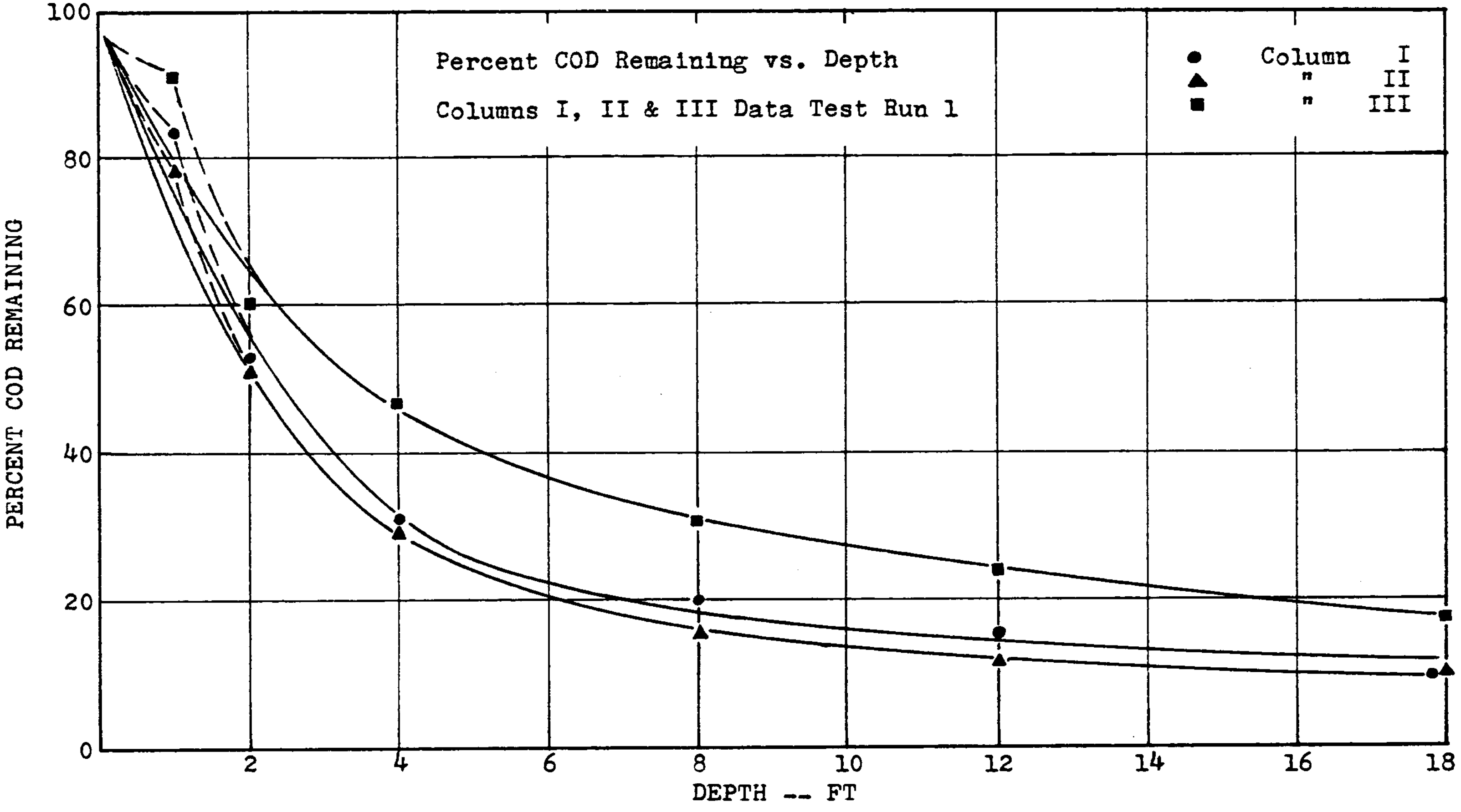

Percent COD Remaining vs. Depth
Columns I, II & III Data Test Run 1
Column I
" II
" III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 10

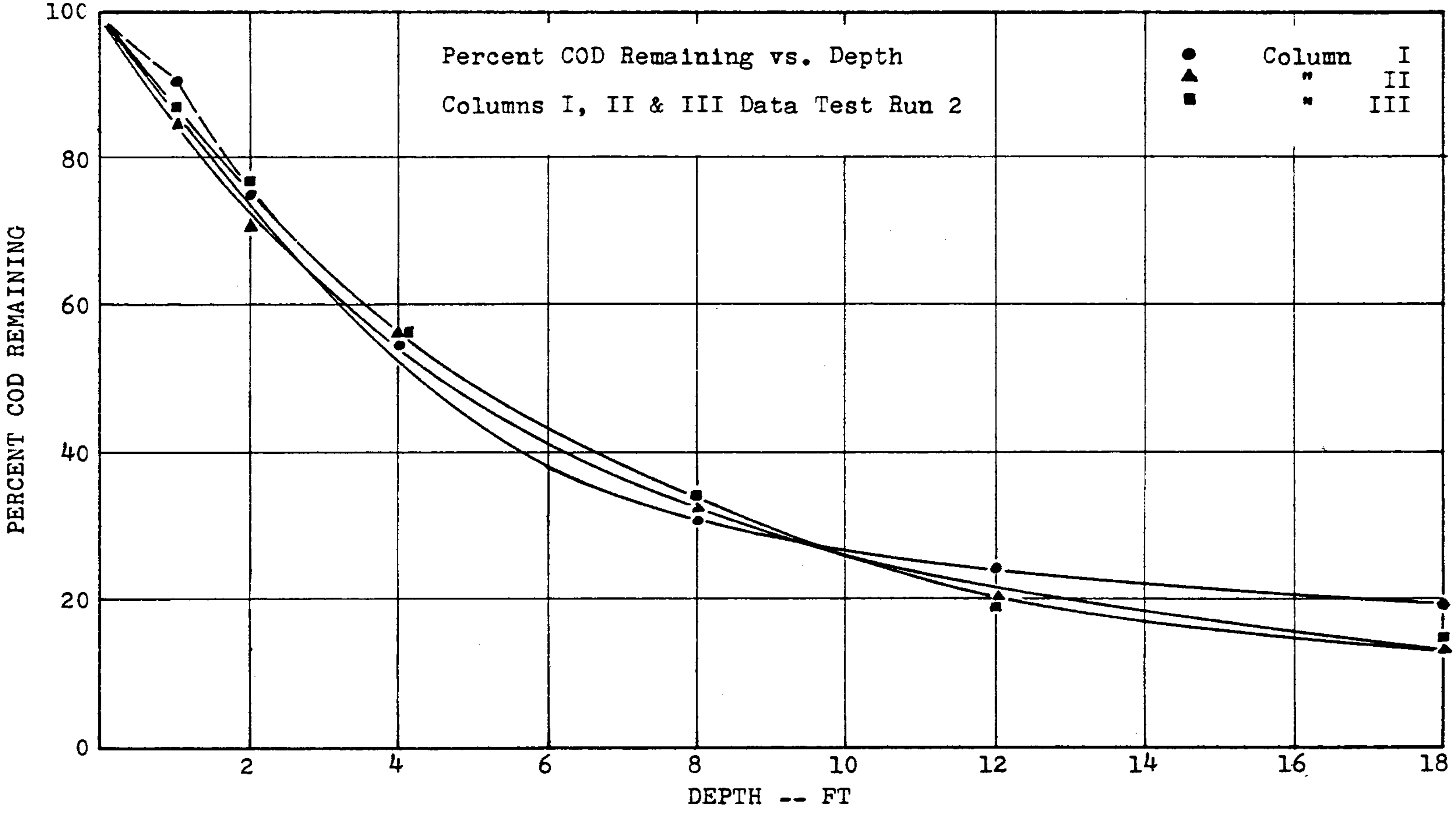

Percent COD Remaining vs. Depth
Columns I, II & III Data Test Run 2
Column I
" II
" III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 11

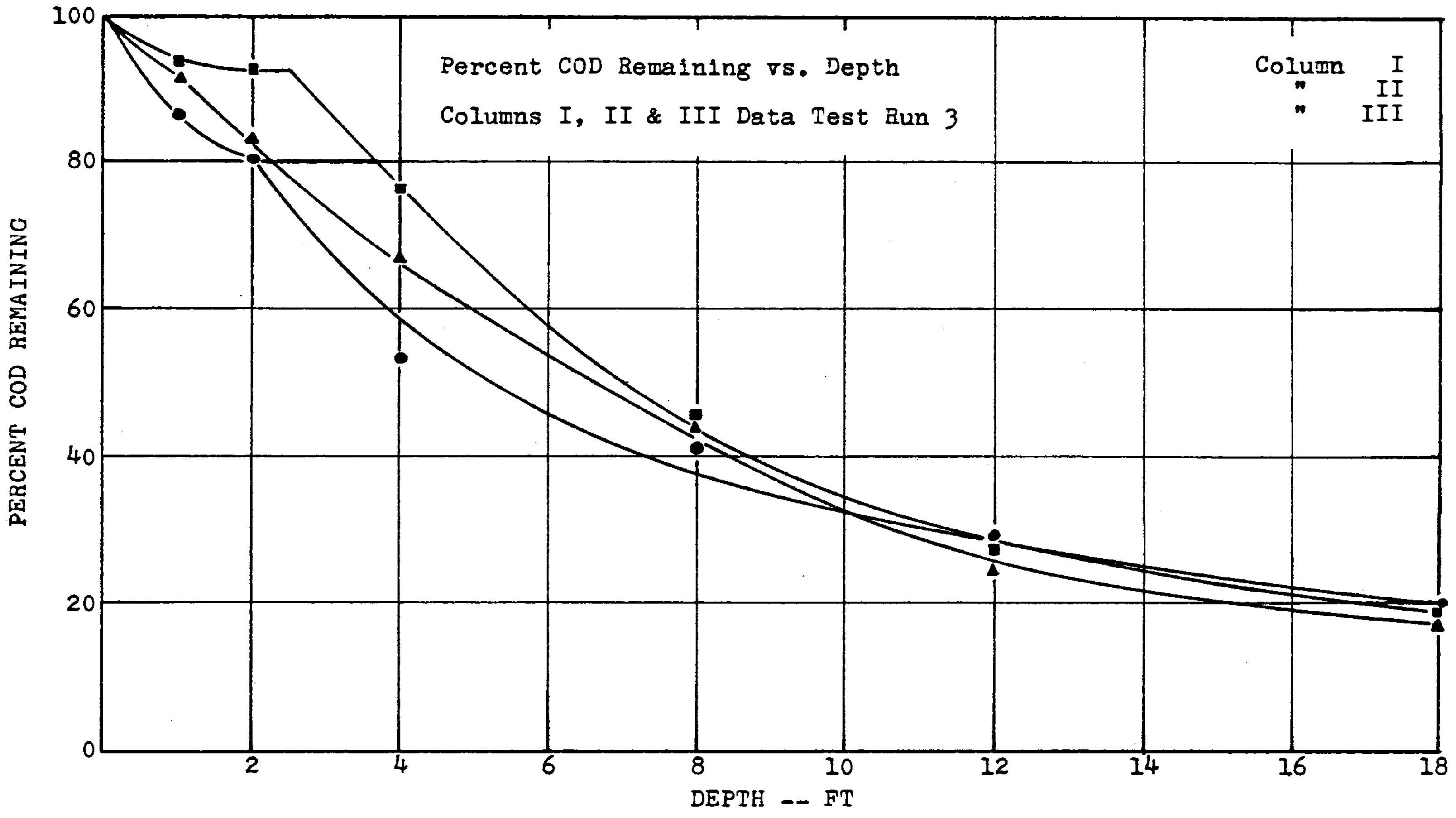

Percent COD Remaining vs. Depth
Columns I, II & III Data Test Run 3
Column I
" II
" III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 12

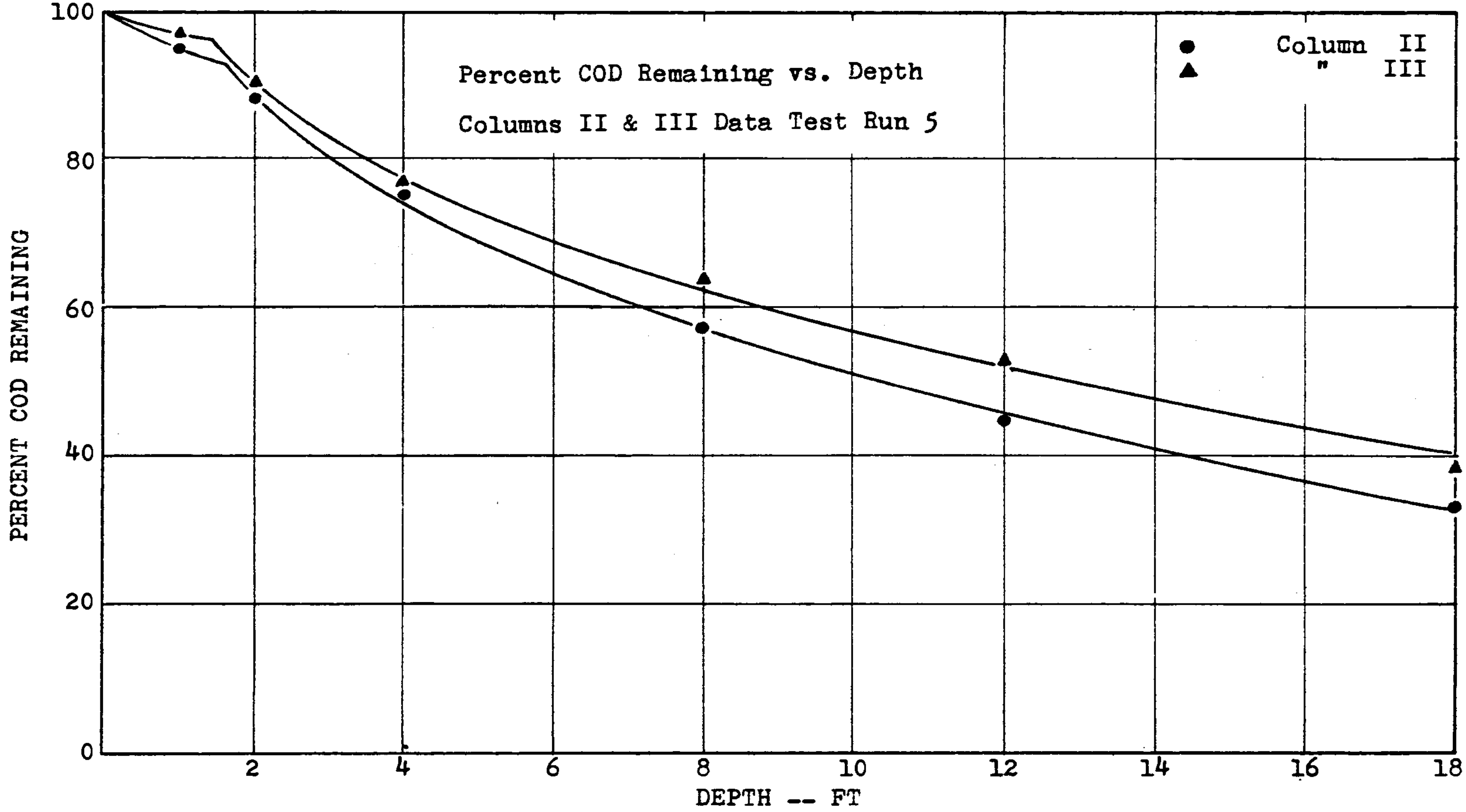

Percent COD Remaining vs. Depth
Columns II & III Data Test Run 5
Column II
" III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 13

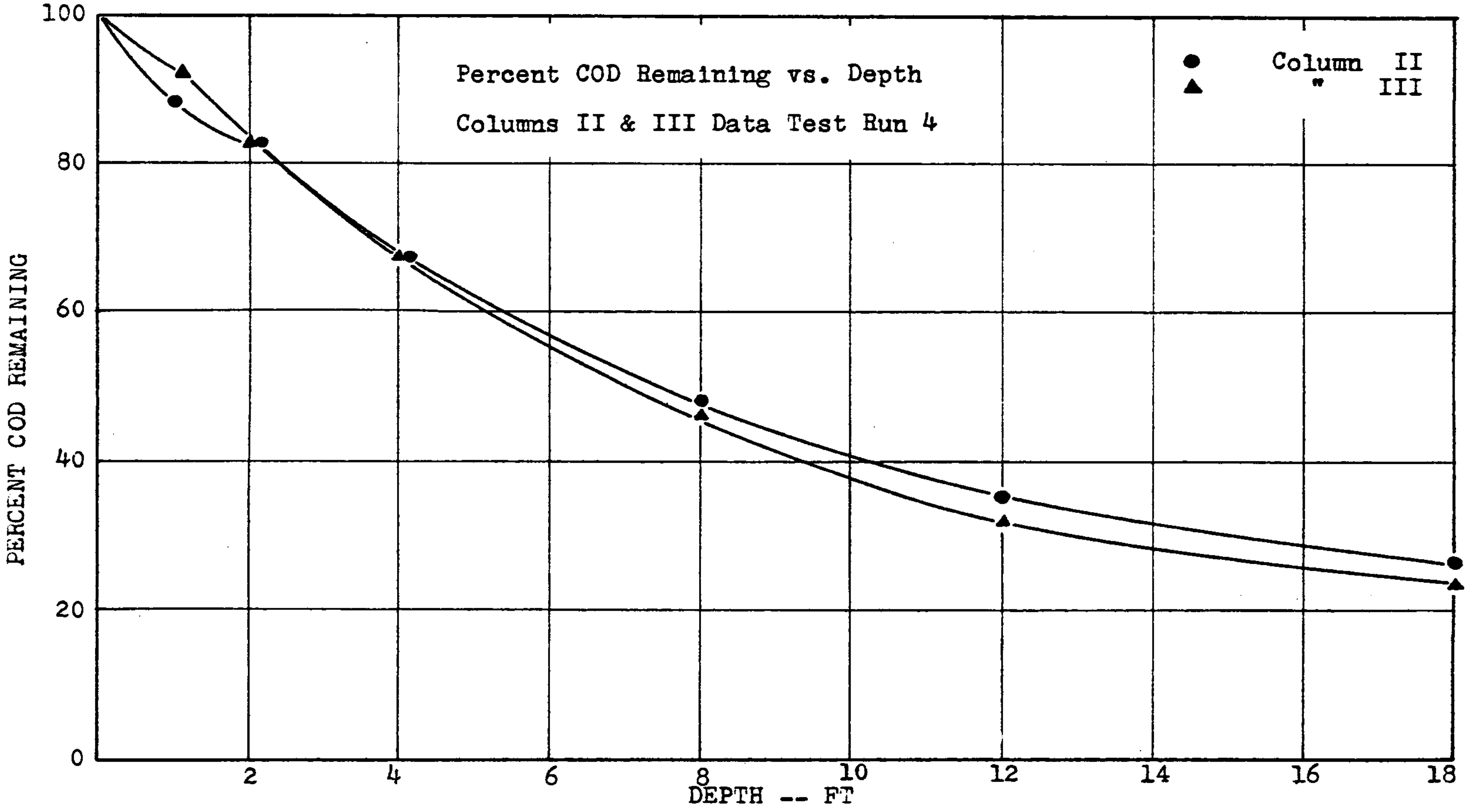

Percent COD Remaining vs. Depth
Columns II & III Data Test Run 4
Column II
" III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 14

This action becomes even more evident at the 75 mgad rate where both Columns II and III have dropped to a relatively small biological mass which is now, however, more uniformly distributed.

From this we can draw the following conclusions. The mass of growth is not indicative of purification achieved. For the treatment effected by the columns at the higher rates in terms of pounds of organic material removed, it is almost four times greater than what was removed by a biological mass which was four times greater in volume. Thus, one-fourth the mass did four times more work. This does not contradict the localized differences in biological mass. The contention is that even though there was a great mass of growth concentrated in the area of great removal effectiveness, a much smaller mass could have effected the same thing. However, sloughing off and washing down of biological mass did not take place at the lower rates but accumulated as inactive sublayers which provided water storage capacity but little else.

The fact that the peaks of growth occur at the places of lowest ORP may bear out the view of Shapiro, which is that a low ORP can be indicative of greatest activity of biological mass. On the other hand, if the mass had come to the point where a lot of it is dead, then anaerobic conditions may be the cause of the low ORP.

Between columns the difference in surface area ratios comes into the picture. The ratios were computed to be 1.65 : 1 : 0.745 for Columns I, II and III, respectively. If this ratio is applied to the reported mass, then the same conclusions pertaining to mass of growth as having no influence on the purification achieved may be arrived at between columns as was done before within the columns.

Thus, the parameter of proper contact conditions seems to come into the foreground as being of greater influence than the relative biological mass which can be cultivated.

pH

In Fig. 18 several curves are plotted to show the pH variation with depth. Although influent and effluent pH are almost the same in most of the tests reported, there occurs a 10-fold increase and subsequent decrease in H^+ ions during the passage of the fluid through the filter column.

Accumulation of soluble waste products is the probable cause for this increase. The action of the CO_2 released during the degradation of the organic material could partially account for this pH increase. The H^+ ions build up during the rapid breakdown of the organic material in the substrate while passing through the upper portions of the filter column. CO_2 is given off and dissolved in the passing liquid, causing a rise in the H^+ ion concentration. Then, when the amount of CO_2 which is dissolving lessens

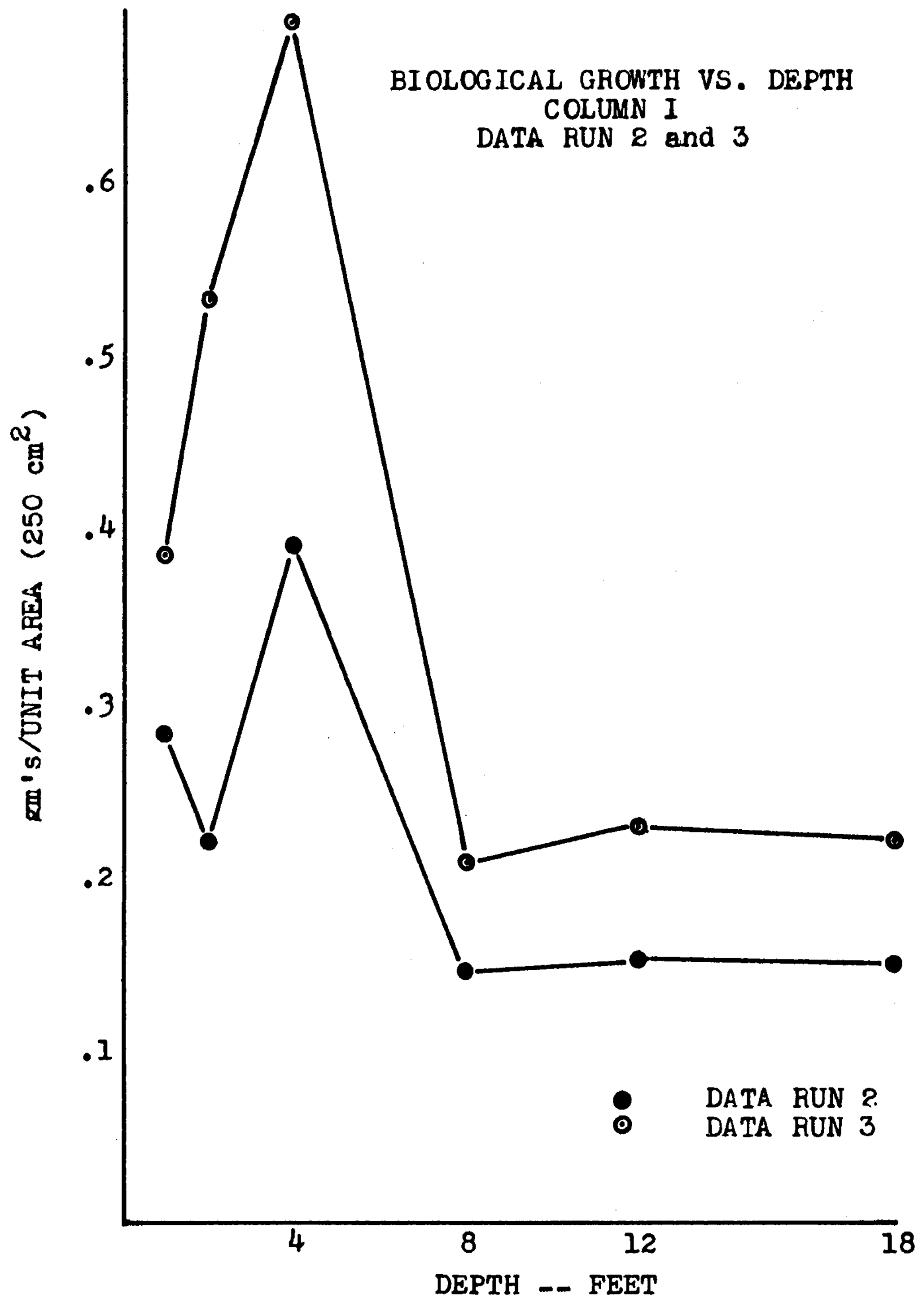

BIOLOGICAL GROWTH VS. DEPTH
COLUMN I
DATA RUN 2 and 3
gm's/UNIT AREA (250 cm2)
.6
.5
.4
.3
.2
.1
4
8
12
18
DEPTH -- FEET
DATA RUN 2
DATA RUN 3

FIG. 15

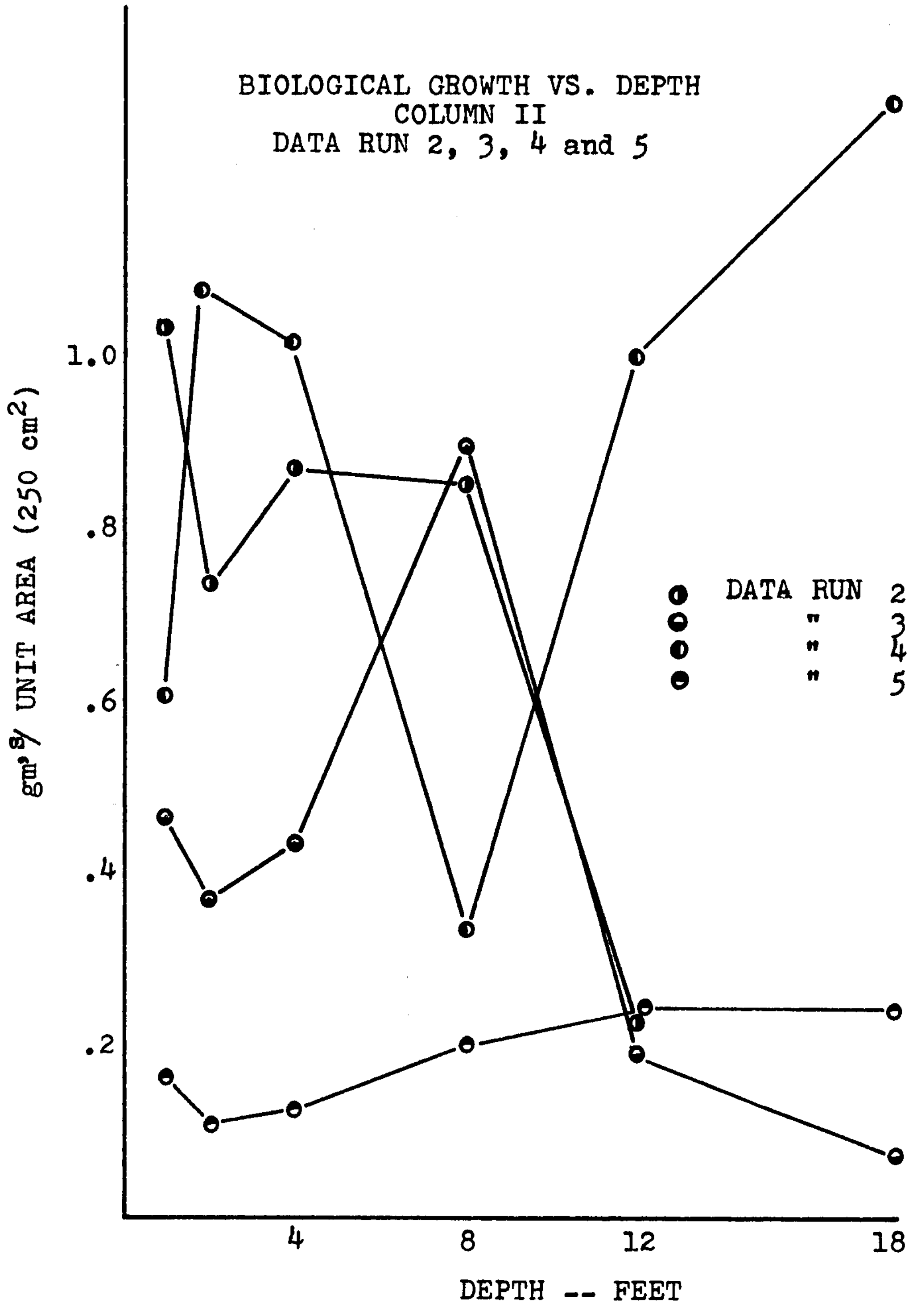

BIOLOGICAL GROWTH VS. DEPTH
COLUMN II
DATA RUN 2, 3, 4 and 5
gm's/ UNIT AREA (250 cm²)
1.0
.8
.6
.4
.2
4
8
12
18
DEPTH -- FEET
DATA RUN 2
" 3
" 4
" 5

FIG. 16

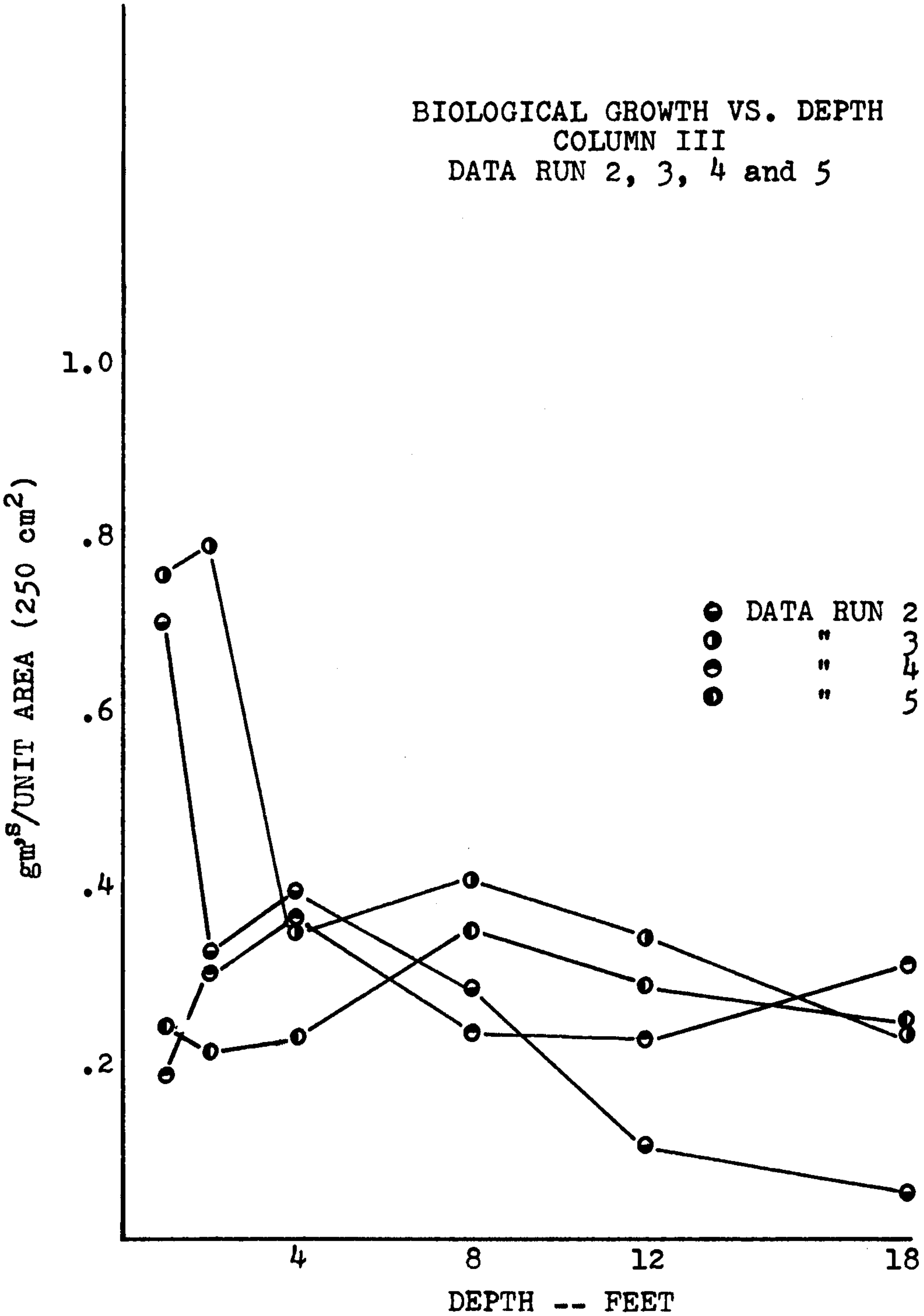

BIOLOGICAL GROWTH VS. DEPTH
COLUMN III
DATA RUN 2, 3, 4 and 5
DATA RUN 2
" 3
" 4
" 5
1.0
.8
.6
.4
.2
gm's/UNIT AREA (250 cm²)
4
8
12
18
DEPTH -- FEET

FIG. 17

and the CO_2 coming free as gas increases, helped by fluid turbulence, the pH rises again to a value comparable to influent pH at the bottom of the filter column.

The difference in pH values between columns can be explained by the relative size of the void spaces through which the fluid passes. In the smaller media the opportunity for the CO_2 to escape is much less than in the larger media where greater dripping and turbulence in contact with air give much better release conditions. The CO_2 thus remains entrained much longer in the filter column with the smaller media, resulting in a lower pH.

ORP

During the entire series of tests ORP readings were taken. The samples were collected and analyzed for ORP with a minimum delay of one to three minutes.

At the low rates a definite sag can be seen in the typical ORP curve, the minimum occurring between the one- and three-foot levels. The incoming substrate had an ORP which seemed to be temperature dependent, as the ORP was higher on the cooler days.

Since the largest part of the waste products is produced in the upper part of the filter column, it is to be expected that the largest amount of waste product oxidation needs to take place here, also.

As the substrate passed through the first section of the filter column, the ORP went down. This fact agrees

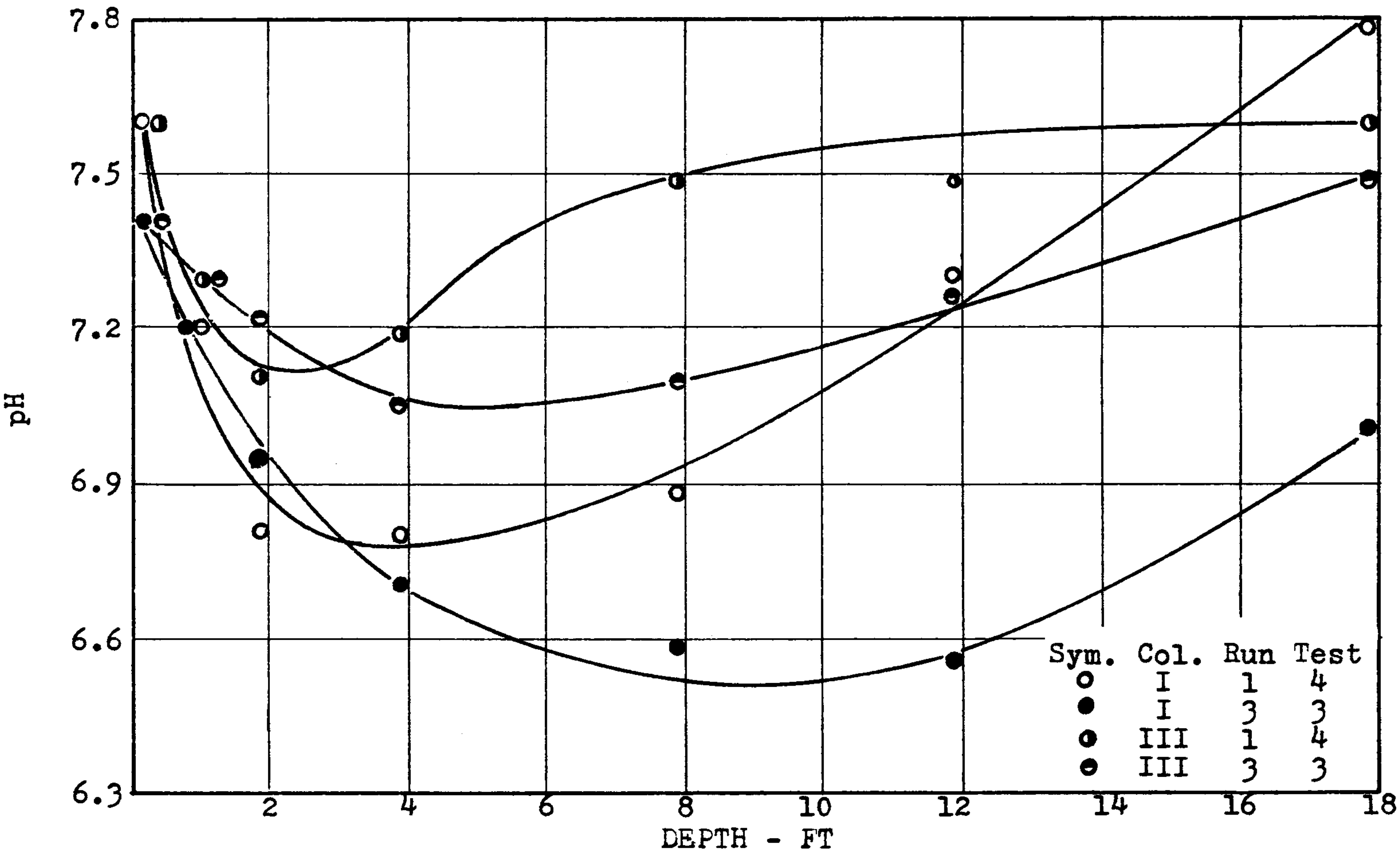


FIG. 18

TYPICAL CURVES
pH VS. DEPTH

with Shapiro's presentation of ORP, which states that the activation rate of dissolved oxygen lags the high production of reduced waste products which need to be oxidized, accounting for the ORP reduction.

Thus, the low ORP readings were not necessarily indicative of a process going anaerobic but more suggestive of a normally proceeding treatment process with a healthy culture. When the production of reduced waste products begin to abate in the middle portion of the filter column, the activation rate of oxygen begins to catch up and the ORP recovers, stabilizing in the bottom part to an equilibrium condition (Fig. 19).

At the higher rates, 60 and 75 mgad, there is less dip to the ORP vs. depth curve than at the lower rates. This is not quite in accord with the foregoing discussion as it might be expected that the relative proportion of the ORP in the substrate would be unaffected by the hydraulic loading rate. An examination of the percent remaining vs. depth curves may answer the problem. At the higher rates the curves are much flatter; thus, the relative proportion of ORP to waste products accumulated is more advantageous in maintaining a higher ORP because of less material to be oxidized vs. the activated oxygen available.

Cyclical fluctuations were noted during the test runs. If Shapiro's discussion of ORP is adhered to, then the reasons for these fluctuations can be limited to two basic parts of the process -- first, enzymes used in activating oxygen and, secondly, oxygen transfer from gaseous to liquid phase. If it is assumed that oxygen transfer during any one day of a test run was the same as any other day, then the enzyme activity is subject to variation. How is as yet a question mark. If, however, enzyme activity was constant, then the cause may lie with unequal aeration conditions. This latter view may have merit inasmuch as during reaeration the substrate (being a milky substance) gave rise to bubble formations in the sampling ports which may well have interferred with the reaeration capacity of the filter as a whole. The build-up of microbial growth may also have caused interference in reaeration within the column by clogging the interstices between the media.

The lack of subsequent reaeration may have diminished the bubble build-up and thus a cycle was established, parts of which were observed during data test runs.

The difference in ORP readings between Column I and Columns II or III may be attributed mainly to the lack of reaeration which in turn results from clogged media.

The lack of dissolved oxygen then retarding the activation of dissolved oxygen to activated oxygen and the progression of anaerobic conditions in the upper part of the trickling filter columns being the final effect and the cause of low ORP readings.

Thus, we may have a manifestation of both causes of low ORP. In Column I anaerobic conditions persist, and in Column III and perhaps also Column II healthy cultures produce reduced waste products in excess of the activated oxygen available.

Temperature

The temperature readings listed in the appendix indicate, more than anything else, the surrounding air temperature. Daily variations of about two degrees were observed during warm summer days.

The effect of temperature on the treatment process requires temperature control which is beyond the scope of the work here reported. The main reason for taking the temperature data was the possibility that there might be significant differences which would help in the analysis of the data.

SUMMARY

The research work reported in this thesis encompasses the testing for the influence of media size on the kinetics of the trickling filter process. The investigations included testing for COD, BOD, film quantity, pH, ORP and temperature. The results of these tests have been used to establish the influence of the media size upon the effectiveness of the biological process. The comparison

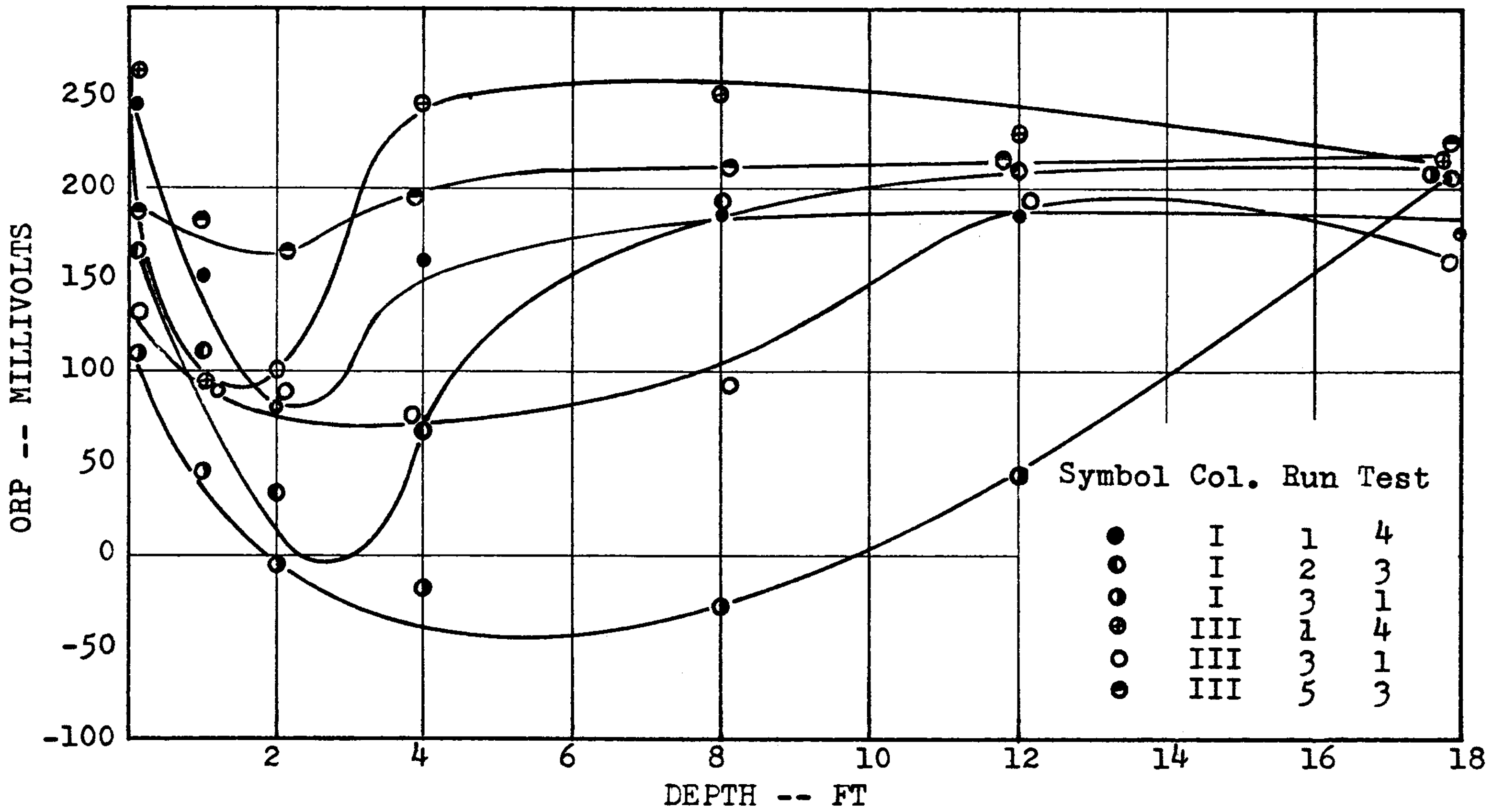


FIG. 19

TYPICAL CURVES
ORP VS. DEPTH

of columns by analysis of variance of the COD and BOD data showed that the largest percent of purification is accomplished in the upper eight feet of the filter columns. As the hydraulic rates are increased, greater use is made of the lower portion of the column. The rate constant K may thus be expected to vary with hydraulic loadings. Column I was shown to have the least capacity to purify the waste used in these tests when the rates were increased. The clogging and ponding which caused near anaerobic conditions made it necessary to discontinue testing of Column I, after 45 mgad rate testing was completed. Columns II and III were almost the same in their capacity to handle the hydraulic and organic loadings and in effecting a degree of treatment. From a general review and acquaintance with the entire project, the author feels that Column III displayed the best filter column characteristics in terms of operational problems encountered.

A problem which has not been mentioned heretofore is the difference between BOD and COD values obtained from tests which were prepared from the same sample. The COD removal effected by any of the filter columns was always greater in terms of percent removed than the BOD removal. The reason for this is not understood except the general conclusion that the COD test does not remove certain constituents which are removed in the BOD test.

Film quantity was shown to be of no influence upon purification capacity. Growth which developed became an inactive mass and only the outer film layers were considered active in the purification process.

A pH drop due to the dissolving of waste products, probably CO_2, was observed throughout the series of tests. The recovery to at least the influent pH was attributed to the release of CO_2 from the fluid mass helped by turbulence in contact with air when the rate of CO_2 uptake and release passed a maximum around the four-foot depth. The difference between media size accounts for the release condition for the CO_2. The larger media size provides better opportunity for turbulence and air surface contact.

The characteristic ORP sag was accounted for by the two reactions which are considered to take place -- first, the activation of dissolved oxygen and, secondly, the oxidation of reduced waste products by the activated oxygen. The rate by which activation lags the oxidation of excess waste products of a healthy culture was considered as causitive of the characteristic ORP drop observed. The rate of activation was considered dependent on enzymatic activity and oxygen transfer from gaseous to liquid state. The ORP differences noted between the three columns appear to be due to the oxygen transfer conditions and the release of gaseous waste products which tend to reduce the ORP. The larger media favored the ORP conditions.

Temperature variation within the range reported was not of such magnitude that conclusions may be made about its influence upon the treatment processes.

CONCLUSIONS

1. The 9/16-inch media is impractical as the clogging and ponding problem will cause system failure at any hydraulic rate. Only regular remedial action permitted continuation of testing.

2. The 7/8-inch and 1-1/4-inch marbles are both effective as media and more so as the hydraulic rates are increased. A maximum hydraulic rate using all the available pore space as fluid passage would be a limiting factor in the rate of application.

3. The difference between the 7/8-inch and 1-1/4-inch media is negligible when the variation of the observations is subjected to analysis of variance and the 90 percent significance level is used.

4. The limiting practical depth at rates below 30 mgad is about eight feet.

5. High rates make greater use of the filter portion below eight feet.

6. The K rates are considered as dependent upon hydraulic rates.

7. Total film quantities are of no influence in the degree of purification achieved. Some stratification with depth will occur, depending upon where the greatest organic removal was effected; i.e., there are no organisms where little is left to be removed.

8. The pH will drop with depth due to uptake of waste products. Release of gaseous waste products will cause pH to recover.

9. A negative or low ORP value is not necessarily indicative of a failing biological process but in healthy cultures represents a lag between activation of dissolved oxygen and oxidation of reduced metabolic waste products.

SUGGESTIONS FOR FUTURE RESEARCH

1. The hydraulic rate limits for a particular media size which will maintain adequate degrees of treatment.

2. The optimum contact and film conditions for a trickling filter system.

3. Further investigations of ORP relating it to dissolved oxygen, metabolic activity of the organisms and gas analysis of the surrounding air mass.

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APPENDICES

APPENDIX A

ANALYSIS OF VARIANCE FROM COD DATA

ANALYSIS OF VARIANCE FROM BOD DATA

VALUES OF FISHER'S F

OBTAINED BY ANALYSIS OF VARIANCE

OF COD DATA FOR FILTER COLUMNS I, II AND III

	RUN		
DEPTH	1	2	3
1	12.97	3.52	0.356
2	0.142	0.222	2.182
4	29.71	0.634	3.32
8	11.33	0.39	2.484
12	7.64	23.07	4.73
18	1.59	7.55	22.12

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1 and 2	3.35	2 and 27	5
3	3.89	2 and 12	5

VALUES OF FISHER'S F

OBTAINED BY ANALYSIS OF VARIANCE

OF COD DATA FOR FILTER COLUMNS I AND II

	RUN		
DEPTH	1	2	3
1	12.25	7.89	0.63
2	0.14	0.42	1.33
4	0.27	1.08	0.006
8	5.61	0.004	3.97
12	7.79	38.88	2.97
18	0.79	13.99	34.93

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1 and 2	4.21	1 and 27	5
3	4.75	1 and 12	5

VALUES OF FISHER'S F

OBTAINED BY ANALYSIS OF VARIANCE

OF COD DATA FOR FILTER COLUMNS I AND III

	RUN		
DEPTH	1	2	3
1	140.83	1.07	0.408
2	0.025	0.04	0.87
4	32.51	0.8	4.92
8	5.71	0.655	3.46
12	0.94	29.7	9.41
18	2.77	7.76	31.34

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1 and 2	4.21	1 and 27	5
3	4.75	1 and 12	5

VALUES OF FISHER'S F

OBTAINED BY ANALYSIS OF VARIANCE

OF COD DATA FOR FILTER COLUMNS II AND III

	RUN				
DEPTH	1	2	3	4	5
1	236.11	2.51	0.025	1.18	0.48
2	2.76	0.72	4.34	1.067	0.25
4	53.94	0.02	5.03	0.02	0.086
8	22.65	0.604	0.17	0.404	4.29
12	14.17	0.61	1.81	1.98	8.16
18	1.91	0.91	0.10	3.416	6.08

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1 and 2	4.21	1 and 27	5
3	4.75	1 and 12	5
4 and 5	5.32	1 and 8	5

VALUES OF FISHER'S F

OBTAINED BY ANALYSIS OF VARIANCE

OF BOD DATA FOR FILTER COLUMNS I, II AND III

	RUN				
DEPTH	1	2	3	4	5
4	1.98	1.27	0.167	1.48	0.107
8	11.38	3.86	37.0	2.44	0.037
12	3.72	20.86	102.83	9.92	0.72
18	0.89	12.2	267.0	2.59	2.48

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1, 2 and 3	5.14	2 and 6	5
4 and 5	7.71	1 and 4	5

VALUES OF FISHER'S F

OBTAINED BY ANALYSIS OF VARIANCE

OF BOD DATA FOR FILTER COLUMNS I AND II

	RUN		
DEPTH	1	2	3
4	3.9	2.18	0
8	22.1	1.69	45
12	4.83	22.3	132
18	0.0234	21.7	392

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1, 2 and 3	5.99	1 and 6	5

VALUES OF FISHER'S F

OBTAINED BY ANALYSIS OF VARIANCE

OF BOD DATA FOR FILTER COLUMNS I AND III

	RUN		
DEPTH	1	2	3
4	1.43	1.45	0.278
8	9.2	7.72	64.2
12	0.107	13.1	173.5
18	1.49	38.5	408.0

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1, 2 and 3	5.99	1 and 6	5

VALUES OF FISHER'S F

OBTAINED BY ANALYSIS OF VARIANCE

OF BOD DATA FOR FILTER COLUMNS II AND III

	RUN				
DEPTH	1	2	3	4	5
4	0.61	0.091	0.278	1.48	0.107
8	2.78	2.2	1.67	2.44	0.037
12	6.3	1.25	2.85	9.92	0.72
18	1.14	2.4	0.161	2.59	2.48

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1, 2 and 3	5.99	1 and 6	5
4 and 5	7.71	1 and 4	5

APPENDIX B

SUMMARY OF EXPERIMENTAL DATA

1. FILM GROWTH
2. pH
3. ORP
4. TEMPERATURE

SUMMARY DATA

GROWTH/UNIT SURFACE AREA

RUN 2

BIOLOGICAL MASS IN gms. (DRY)

	COL. I	COL. II	COL. III
NUMBER OF SPHERES	40	15	8
DEPTH			
1	.2812	.4644	.7055
2	.2198	.3705	.3285
4	.3906	.4359	.3960
8	.1467	.8961	.2879
12	.1502	.1892	.1071
18	.1486	.0732	.0597

SUMMARY DATA

GROWTH/UNIT SURFACE AREA

RUN 3

BIOLOGICAL MASS IN gms. (DRY)

	COL. I	COL. II	COL. III
NUMBER OF SPHERES	40	15	8
DEPTH			
1	.3844	1.0321	.7566
2	.5335	.7383	.7874
4	.6910	.8705	.3503
8	.2084	.8522	.4088
12	.2290	.2261	.3423
18	.2196		.2340

SUMMARY DATA

GROWTH/UNIT SURFACE AREA

Run 4

BIOLOGICAL MASS IN gms. (DRY)

		COL. II	COL. III
NUMBER OF SPHERES		15	8
DEPTH			
1		.6048	.1935
2		1.0755	.3043
4		1.0165	.3696
8		.3354	.2373
12		.9971	.2301
18		1.2968	.3130

SUMMARY DATA

GROWTH/UNIT SURFACE AREA

RUN 5

BIOLOGICAL MASS IN gms. (DRY)

		COL. II	COL. III
NUMBER OF SPHERES		15	8
DEPTH			
1		.1830	.2426
2		.1117	.2152
4		.1283	.2317
8		.2034	.3522
12		.2446	.2905
18		.2418	.2537

SUMMARY DATA

pH VALUES

RUN 1

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0		6.9	7.4	7.6	7.5	7.3		7.5	7.7	7.8	7.2	8.0	7.6	7.6	7.7
1	6.6	7.0	7.2	7.2	6.9	6.8		7.2	7.2	7.5	6.7	7.6	7.4	7.3	7.4
2	6.5	6.7	6.9	6.8	6.6	6.7		7.0	7.1	7.2	6.5	7.3	7.0	7.1	7.3
4	6.4	6.3	6.6	6.8	6.5	6.8		7.0	7.0	7.3	6.5	7.2	7.2	7.2	7.5
8	6.3	6.4	6.9	6.9	6.8	7.1		7.5	7.6	7.8	6.9	7.2	7.5	7.5	7.6
12	6.7	6.9	7.3	7.3	7.2	7.3		7.6	7.7	7.9	7.5	7.3	7.5	7.5	7.6
18	7.0	7.4	7.5	7.8	7.5	7.3		7.9	7.5	7.8	7.4	7.5	7.8	7.6	7.7

SUMMARY DATA

pH VALUES

RUN 2

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	7.8	7.6	7.5	7.8	7.6	7.8	7.6	7.8	7.8	7.6	7.9	7.6	7.6	7.8	7.4
1	7.4	7.5		7.3	7.3	7.4	7.1	7.4	7.4	7.3	7.5	7.3	7.3	7.4	6.8
2	7.2	7.3	6.9	6.9	7.0	7.2	6.9	7.0	7.0	7.1	7.4	7.2	7.1	7.3	7.1
4	7.0	6.6	6.5	6.7	6.8	7.1	6.8	6.8	6.9	7.0	7.4	7.0	6.9	7.1	6.8
8	7.3	6.4	6.5	6.6	6.8	7.1	6.8	6.9	6.8	7.0	7.6	7.2	7.2	7.3	7.2
12	7.4	6.7	6.6	6.9	6.9	7.4	7.3	7.2	7.2	7.3	7.6	7.3	7.2	7.4	7.4
18	7.8	7.4	7.3	7.3	7.4	7.6	7.5	7.9	7.9	7.6	7.5	7.5	7.4	7.6	7.1

SUMMARY DATA

pH VALUES

RUN 3

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	7.7	7.6	7.4	7.6	7.5		7.6	7.4	7.6	7.5	7.7	7.6	7.4	7.6	7.5
1	7.2	7.2	7.2	7.4	7.1		7.3	7.2	7.4	7.2	7.3	7.3	7.3	7.2	7.1
2	7.1	7.0	7.0	7.1	6.9		7.1	7.0	7.3	6.9	7.2	7.2	7.2	7.2	6.9
4	6.9	6.7	6.7	6.9	6.6		6.9	6.9	7.1	6.7	7.1	7.1	7.1	7.2	6.9
8	6.5	6.3	6.6	6.7	6.3		6.8	6.8	6.9	6.6	7.2	7.2	7.1	7.3	7.0
12	6.6	6.5	6.6	6.7	6.4		6.7	7.0	6.9	6.7	7.3	7.4	7.3	7.3	7.2
18	6.8	6.7	7.0	6.8	6.8		7.3	7.2	7.4	7.2	7.5	7.6	7.5	7.5	7.4

SUMMARY DATA

pH VALUES

RUN 4

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		7.4	7.4	7.6	7.7	7.7	7.4	7.4	7.6	7.7	7.7
1		7.3	7.2	7.3	7.3	7.4	7.2	7.3	7.5	7.5	7.4
2		7.1	7.1	7.0	7.2	7.3	6.8	7.2	7.2	7.3	7.2
4		7.0	7.1	6.9	6.9	7.0	6.7	6.9	7.0	7.1	7.0
8		7.0	7.0	6.6	6.8	6.9	6.8	7.0	6.9	7.1	6.8
12		7.2	7.2	6.8	6.9	6.8	7.0	7.0	7.0	7.1	7.0
18		7.5	7.5	7.0	7.0	7.1	7.3	7.3	7.4	7.6	7.8

SUMMARY DATA

pH VALUES

RUN 5

DEPTH	COL. II					COL. III				
	TEST					TEST				
	1	2	3	4	5	1	2	3	4	5
0	7.6	7.6	7.5	7.5	7.7	7.6	7.6	7.5	7.5	7.7
1	7.4	7.5	7.3	7.2	7.6	7.3	7.5	7.5	7.4	7.6
2	7.2	7.3	7.2	7.1	7.3	7.3	7.3	7.3	6.9	7.6
4	6.9	7.0	7.0	6.9	7.2	7.2	7.2	7.2	6.9	7.4
8	6.7	6.9	6.8	6.7	7.0	7.1	7.0	7.2	7.2	7.4
12	6.7	6.8	6.8	6.7	6.9	7.1	7.2	7.3	7.2	7.3
18	7.0	7.0	6.9	6.9	7.1	7.4	7.5	7.3	7.4	7.5

SUMMARY DATA

ORP VALUES

RUN 1

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0		250	260	245	165			240	235	250		245	235	265	255
1		200	200	150	15			160	130	185		220	82	95	140
2		210	140	80	-165			90	165	180		170	45	100	135
4		205	220	160	30			150	140	160		165	120	245	240
8		260	250	190	190			210	235	230		245	175	250	220
12		260	235	185	227			215	220	205		220	200	230	235
18		235	255	175	180			245	195	175		220	225	205	245

SUMMARY DATA

ORP VALUES

RUN 2

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	140	190	165	120	150	185	195	210	205	180	215	190	210	215	130
1	80	65	110	10	90	100	90	150	105	100	185	135	155	100	-35
2	15	25	-5	-90	-80	60	90	175	130	105	205	160	155	90	-55
4	20	-125	65	-70	115	170	140	220	160	155	220	190	205	110	30
8	30	50	190	-95	95	215	165	245	205	170	230	180	230	220	80
12	70	208	210	40	140	215	200	220	215	210	215	225	235	225	175
18	148	230	205	215	208	180	200	190	215	190	200	215	225	215	165

SUMMARY DATA

ORP VALUES

RUN 3

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	110	90	85	55	45	100		80	55	45	130		80	55	40
1	45	40	5	55	-40	20	105	40	90	-40	90	95	65	60	-25
2	35	35	-15	35	-95	0	100	20	80	-55	85	105	70	65	-10
4	-20	0	-85	0	-105	0	100	0	40	-50	70	100	60	65	-15
8	-30	-140	-120	-170	-150	70	90	-5	30	-45	90	85	45	95	-7
12	45	20	-50	25	-125	175	60	85	120	0	195	75	100	120	45
18	205	250	170	175	100	193	175	170	175	105	160	320	170	175	130

SUMMARY DATA

ORP VALUES

RUN 4

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		115	175	170	145	170	115	175	170	145	170
1		95	170	150	120	130	120	140	120	140	120
2		145	170	170	160	120	135	150	160	145	125
4		165	190	195	185	165	140	195	170	160	170
8		185	225	210	190	210	170	205	200	170	200
12		185	245	220	205	225	170	220	210	180	210
18		185	235	220	200	225	170	215	190	180	190

SUMMARY DATA

ORP VALUES

RUN 5

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		210	185	185	145	125	210	180	185	145	125
1		160	130	150	80	20	205	180	180	145	130
2		185	140	115	65	10	215	185	165	160	145
4		175	155	115	75	-100	220	170	195	160	130
8		230	185	155	205	130	230	205	210	190	190
12		265	215	225	200	170	245	205	210	200	200
18		260	220	250	230	215	250	205	215	185	190

SUMMARY DATA

TEMPERATURE VALUES

RUN 1

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0		17.9	18.9	16.0	19.4	20.2		19.6	21.2	19.0	20.7	17.8	21.2	20.2	18.0
1	16.6	18.1	18.9	17.0	19.6	20.1		19.5	21.2	19.0	20.9	18.0	21.3	20.3	18.5
2	17.4	18.2	19.3	18.0	19.6	20.2		19.6	21.2	19.0	21.0	18.2	22.5	20.3	19.5
4	17.8	18.2	19.6	19.5	20.1	20.4		19.6	21.2	19.0	20.9	18.3	22.5	20.5	20.0
8	17.6	18.2	19.6	21.0	20.5	19.7		18.3	21.5	19.3	20.2	18.0	22.5	20.5	21.8
12	17.6	18.2	19.4	20.0	20.7	19.2		18.2	21.1	19.5	19.8	17.1	22.2	20.2	22.0
18	17.6	18.5	18.9	20.0	20.5	19.2		18.1	21.5	19.5	19.3	18.2	22.2	19.8	22.2

SUMMARY DATA

TEMPERATURE VALUES

RUN 2

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	21.0	22.5	21.0	23.5	22.0	22.0	22.5	21.0	20.0	22.0	23.0	22.5	22.5	20.0	23.0
1	21.5	22.5	21.0	23.5	22.0	22.5	22.5	21.0	20.5	22.0	23.0	22.5	22.5	20.0	23.5
2	21.0	22.0	21.0	24.0	22.0	22.5	22.0	21.0	20.5	22.5	23.0	22.5	23.0	20.5	24.0
4	21.5	22.0	21.0	24.0	22.0	22.5	22.0	21.0	21.0	23.0	23.0	22.5	22.5	20.5	24.0
8	21.5	22.0	20.5	24.0	22.0	22.0	22.0	21.0	21.0	23.0	23.0	21.5	22.0	21.0	24.0
12	21.0	21.5	20.0	23.5	21.0	22.0	21.5	21.0	21.0	22.0	22.5	21.5	22.0	21.0	23.0
18	21.0	21.0	20.0	24.0	22.0	21.5	21.0	21.0	21.0	22.0	22.5	21.0	22.5	21.0	24.0

SUMMARY DATA

TEMPERATURE VALUES

RUN 3

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	22.5	22.0	22.0	22.0	23.0	24.5		22.0	22.0	23.0	25.0		22.0	22.0	
1	22.5	22.0	22.0	22.0	23.0	24.5	22.0	22.0	22.0	23.0	25.0	22.0	22.0	22.0	23.0
2	22.5	22.0	22.0	22.0	23.0	24.5	22.0	22.0	22.0	23.0	25.0	22.0	22.0	22.0	23.0
4	22.5	22.0	22.0	22.0	23.0	24.5	22.0	21.5	22.0	23.0	25.0	22.0	21.5	22.0	23.0
8	22.0	21.5	21.5	22.0	22.5	24.5	21.5	21.5	21.5	22.5	25.0	21.8	21.5	21.5	22.5
12	21.5	21.0	21.5	21.5	22.5	24.0	21.5	21.5	21.5	22.5	25.0	21.5	21.5	21.5	22.0
18	21.0	21.0	21.0	21.5	22.0	24.0	21.0	21.0	21.0	22.0	25.0	21.0	21.0	21.0	22.0

SUMMARY DATA

TEMPERATURE VALUES

RUN 4

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		22.0	22.5	23.0	22.0	22.0	22.0	22.5	23.0	22.0	22.0
1		22.0	22.5	23.0	21.5	22.0	22.0	22.5	23.0	22.0	22.0
2		22.0	22.5	23.0	21.5	22.0	22.0	22.5	23.0	22.0	22.0
4		22.0	22.0	23.0	21.5	22.0	22.0	22.0	23.0	22.0	22.0
8		21.5	22.0	23.0	21.5	22.0	21.5	22.0	23.0	22.0	22.0
12		21.0	21.5	22.5	21.5	22.0	21.0	21.5	22.5	22.0	22.0
18		21.0	21.5	22.0	21.5	22.0	21.0	21.5	22.0	21.5	22.0

SUMMARY DATA

TEMPERATURE VALUES

RUN 5

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		20.5	19.5	20.2	20.0	20.2	20.5	19.5	20.2	20.0	20.2
1		20.5	19.5	20.2	20.0	20.2	20.5	19.5	20.2	20.0	20.2
2		20.5	19.5	20.2	20.0	20.2	20.5	19.5	20.2	20.0	20.2
4		20.5	19.5	20.1	20.0	20.0	20.5	19.4	20.1	20.0	20.0
8		20.3	19.4	20.1	19.8	20.0	20.3	19.4	20.1	19.8	20.0
12		20.2	19.2	20.0	19.8	19.8	20.2	19.2	20.0	19.8	19.8
18		20.0	19.2	20.0	19.6	19.8	20.0	19.2	20.0	19.6	19.8

APPENDIX C

STOCKFEED AND HYDRAULIC LOADING RATES AS PERCENT OF INTENDED RATES

1. STOCKFEED AND HYDRAULIC LOADING RATES COMPUTATIONS
2. DAILY STOCKFEED RATES AS PERCENT OF INTENDED RATES
3. DAILY HYDRAULIC LOADING RATES COLUMN I AS PERCENT OF INTENDED RATES
4. DAILY HYDRAULIC LOADING RATES COLUMN II AS PERCENT OF INTENDED RATES
5. DAILY HYDRAULIC LOADING RATES COLUMN III AS PERCENT OF INTENDED RATES

STOCKFEED AND SUBSTRATE LOADING RATE COMPUTATIONS

The stockfeed rates were so adjusted that with proper column hydraulic rates a substrate strength of 0.2 gm/l of milksolids could be maintained. This strength is approximately 215 ppm COD.

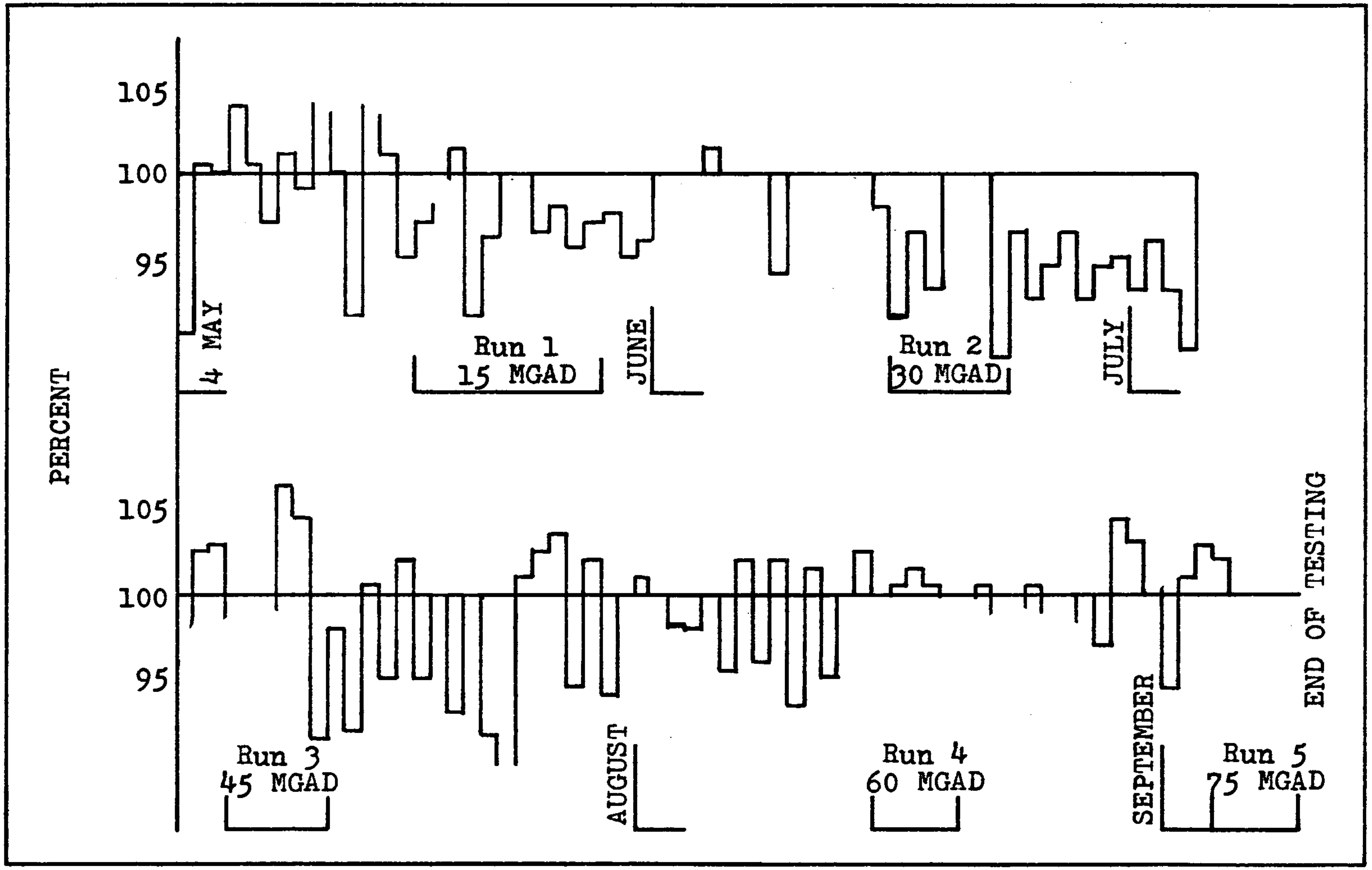
In order to find the pounds of COD applied per acre per day for a column at a given day:

1. Obtain percentage rates for stockfeed rate (a) and column hydraulic rate (b).
2. Determine applicable rate in mgad (c).
3. Compute pounds of COD/acre/day.

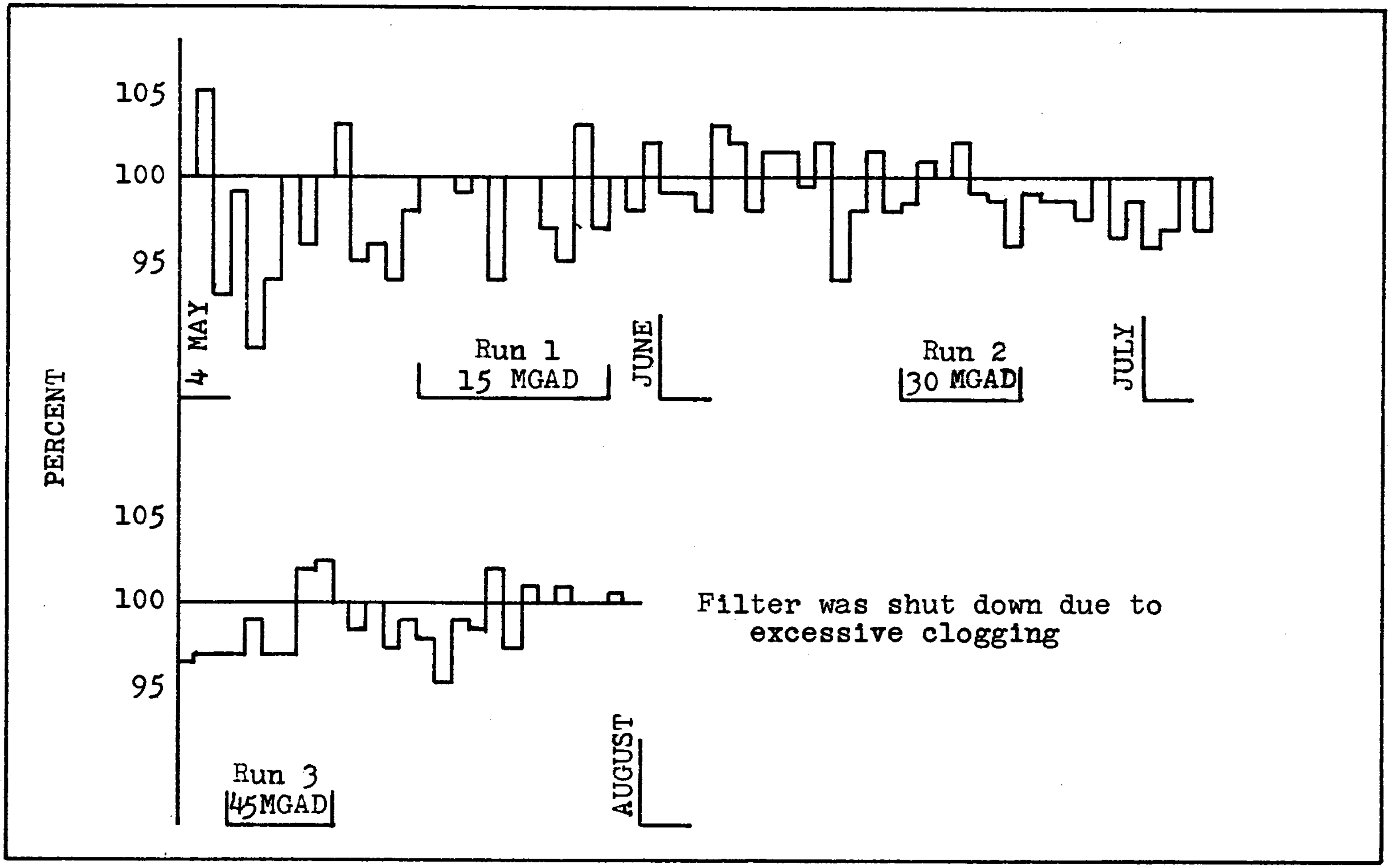
$$(a\ \%)(b\ \%)(c\ \text{mgad})(8.34)\left(\frac{215}{10^6}\right)^{*} =$$

$$abc \times 1.168 \times 10^{3}\ \text{lbs COD/acre/day}$$

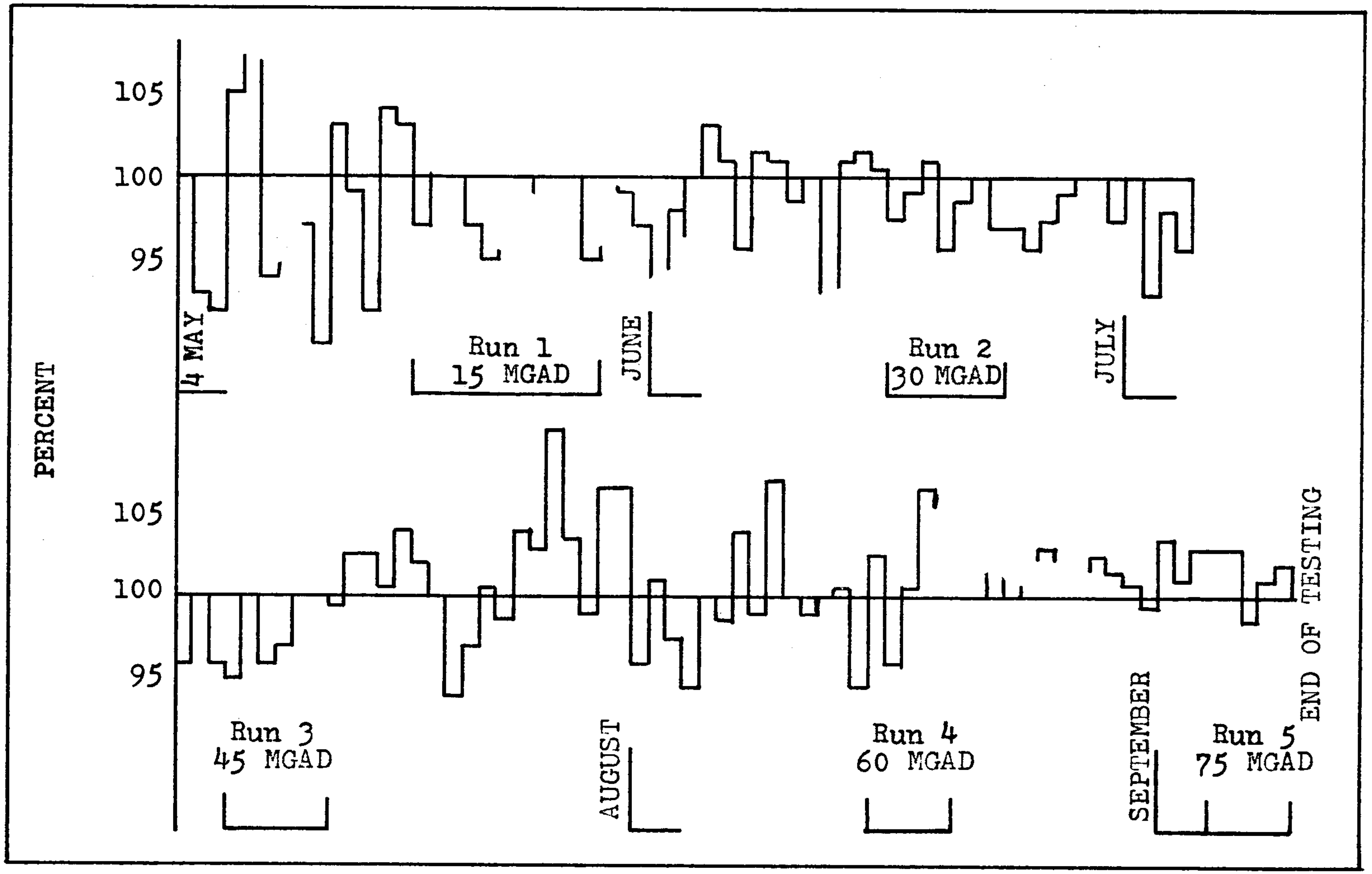
* COD quantity based on modified COD test without 1.55 factor



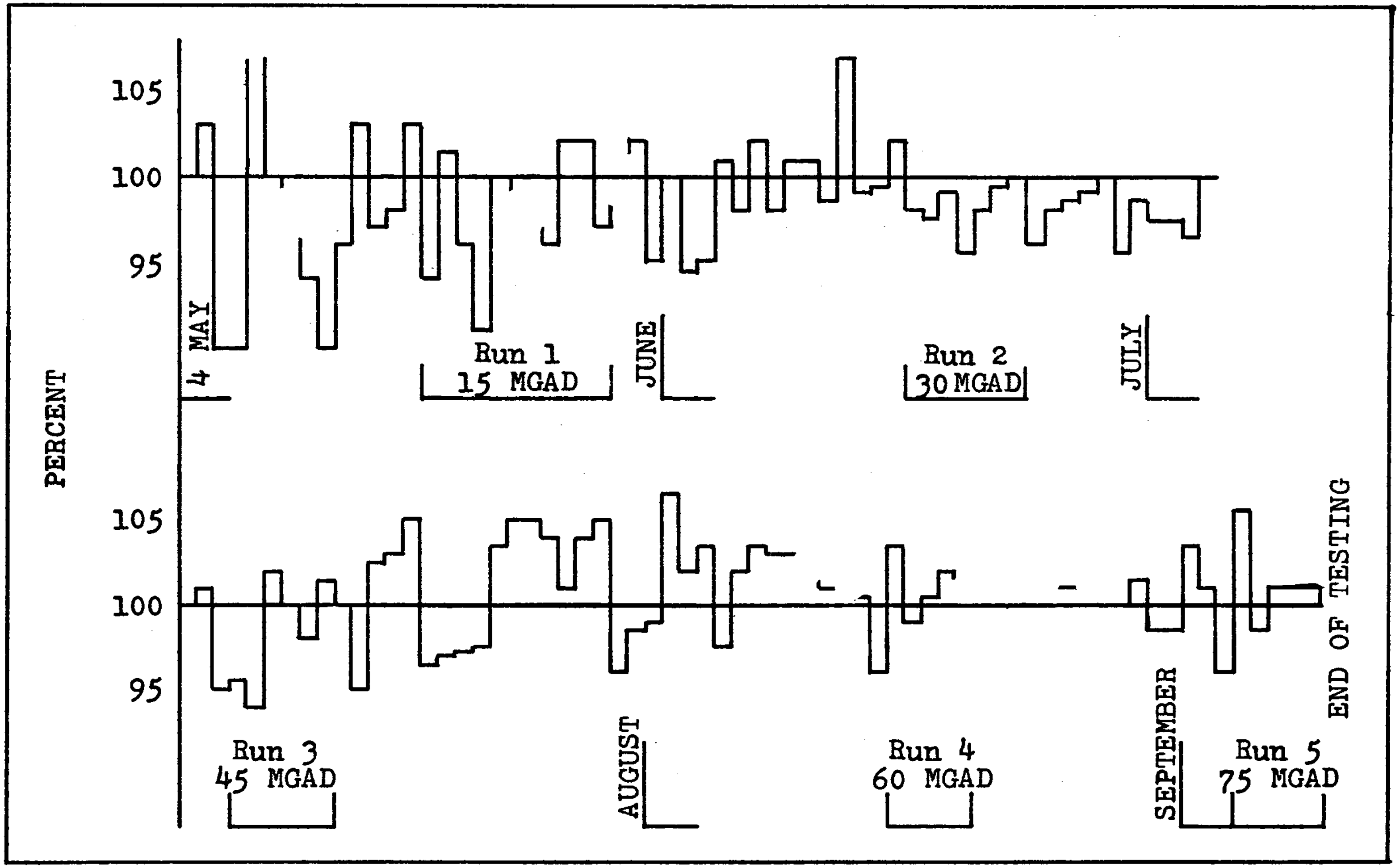
DAILY HYDRAULIC STOCKFEED LOADING RATES
AS
PERCENT OF INTENDED RATES



COLUMN I
DAILY HYDRAULIC LOADING RATES
AS
PERCENT OF INTENDED RATES



COLUMN II
DAILY HYDRAULIC LOADING RATES
AS
PERCENT OF INTENDED RATES



COLUMN III
DAILY HYDRAULIC LOADING RATES
AS
PERCENT OF INTENDED RATES