

THE EFFECT OF HYDRAULIC LOAD ON AN
EXPERIMENTAL TRICKLING FILTER

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Keith Fry

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This is to certify that the

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Keith Fry

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of the requirements for

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EXPERIMENTAL TRICKLING FILTER

by

Keith Fry

AN ABSTRACT

Submitted to the College of Engineering of Michigan State
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The efficiency of removal of BOD from a waste in a trickling filter has usually been related to the organic load applied per day but, recently, several investigations have suggested that the hydraulic load actually controls the efficiency. In order to establish which of the two concepts is most correct an experimental filter was constructed and operated with the effluent from the primary settling tanks at the East Lansing, Michigan sewage treatment plant. The filter consisted of a plastic screen wound spirally in an angle iron frame. The filter depth was five feet. Two such units were built, one with a one-half inch screen spacing and one with a one inch screen spacing. The one-half inch screen spacing provided 57.7 square feet of surface area per unit filter volume, and the one inch spacing provided 26.3 square feet of surface area per unit filter volume.

The variables measured during the study were BOD, dissolved oxygen, temperature, pH, suspended solids, nitrate and nitrite concentration. Using the one-half inch spaced screen the filter was operated at hydraulic loads ranging from 10.3 to 24.0 mgad and the efficiency was found to increase from 57.6 to 62.4 per cent. However, it was noted that considerable clogging had occurred so the one inch spaced screen was used in an attempt to eliminate the clogging factor.

The new filter was subjected to hydraulic loads ranging from 10.3 to 80.0 mgad and the resulting efficiencies ranged from 80.3 to 61.3 per cent. At hydraulic loads from 10.3 to 30.8 mgad the efficiency remained practically constant at 80 per cent and it was again noted that a portion of the filter was clogged. At flows of 30.8 mgad and up the efficiency decreased with increasing hydraulic load. Plotting the organic load

removed versus the organic load applied per unit filter volume, for any given hydraulic load, resulted in straight lines which passed through the origin for the one-half and one inch screen spacing. The difference between the slopes of the lines at the higher hydraulic loads could be shown to be statistically significant. This indicates that hydraulic rather than organic load controlled the removal efficiency up to at least 335 pounds of BOD per 1000 cubic feet per day.

The one inch spaced screen was also operated at recirculation ratios of 1:1 through 4:1 using 10 mgad incoming flow. Plotting the data again provided straight lines passing through the origin. Related to incoming BOD the efficiencies obtained for the various recirculation ratios remained essentially constant between 88 and 84 per cent. Related to incident BOD the efficiencies showed a consistent and statistically significant decrease from 76 to 50 per cent with increasing incident hydraulic load.

A theoretical equation of the monomolecular type was used for both single pass and recirculation experiments to evaluate the K constants. The results of the application of this equation were compared to the expected results using the NRC formula and the new Ten State Standards. The Ten State Standards were found to give more comparable results than did the NRC formula for both single pass operation and recirculation related to incident flow. In all cases the experimental efficiencies were substantially greater than those predicted by either the NRC formula or the Ten State Standards.

The concentration of nitrate and nitrite nitrogen in the final effluent appeared to vary inversely with the hydraulic load. The over-

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ABSTRACT

all reduction of suspended solids appeared to be increased by recirculation but the per cent ash was not materially changed.

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SECTION I

INTRODUCTION

The efficiency of trickling filters has usually been related to the organic load applied. The NRC-formula (1) or the old Ten State Standards (2) have generally been the basis for design.

Recently work has been done on the effects of temperature, filter media, recirculation, organic and hydraulic load as the governing factors of the process. Obviously the process is not dominated by any one variable but rather by the interaction of all the contributing physical and chemical conditions. The removal of organic material from a waste is accomplished both by biochemical oxidation and by physical capture on the part of the zoogloea mass. Schulze (3) has shown that the biological growth is capable of removing as much as 7.5 lbs-BOD/cu yd/day and that the efficiency was related to the hydraulic rather than the organic load.

To further investigate the effect of hydraulic load an experimental filter was built and operated at varying hydraulic loads under single pass and recirculation conditions. The filter was so constructed as to provide visual examination of the growth. The variables measured during the year and three months of the study were:

- | | |
|---------------------------------|---------------------|
| 1. Biochemical Oxygen Demand | 4. Dissolved Oxygen |
| 2. Nitrite and Nitrate Nitrogen | 5. Temperature |
| 3. Suspended Solids | 6. pH |

SECTION II

LITERATURE REVIEW

Organic load has been used as the design criteria for trickling filters for about 40 years. Two relationships, the NRC formula and the Ten State Standards, for defining the efficiency of a filter in terms of the organic load per unit volume of filter have emerged from the statistical study of operating sewage treatment plants. Most state control agencies require the loads on any trickling filter to be within the values found by the application of one or both of the above methods regardless of the resulting hydraulic load.

The theory that hydraulic load may have a greater influence on the efficiency of the filter than does the organic load has been put forth in the past 10 years.

A. Detention Time in the Filter.

Sorrels and Zeller (4) in a plant study discuss the reduction of contact time with increasing hydraulic load. Howland (5) and Bloodgood, Teletzke, and Pohland (6) have shown by experiment that the time the waste is in contact with the growth is a function of the two-thirds power of the hydraulic load. Sinkoff, Porges and McDermott (7) have shown that the power of the hydraulic load can vary from 0.83 for glass spheres to 0.5 for porcelain spheres. Schulze (3) found the value of 0.67 in a small pilot plant study. Howland, Pohland and Bloodgood in their paper at the 1960 Manhattan College Conference (8) concluded that for conventional filters $Q^{2/3}$ is probably correct.

Assuming Howland's (5) theory to be correct, the contact time is directly proportional to the depth of the filter and inversely propor-

tional to the two-thirds power of the hydraulic load. Velz (9) has shown the importance of filter depth in his work but is still relating the efficiency of removal to the organic load rather than the hydraulic load.

B. Removal of BOD in the Filter.

Velz (9) and Phelps (10) have both shown in general terms that the rate of extraction of organic matter per unit depth of a biological bed is proportional to the remaining concentration of the organic matter. This is analogous to the conditions found by Katz and Rohlich (11) in the activated sludge type treatment where they have shown the removal to be best described by a monomolecular equation. Velz further states that the removal is dependent on the treatability of the waste. In fact, he holds that there is a certain fraction of the BOD which can not be removed. Howland (5) maintains the same position but expresses some doubt about the complete lack of removability of any fraction. Schulze (3) holds that all BOD is theoretically removable. This study will be based on the idea of complete removability but some fractions being more difficult to remove than others.

C. The Effect of Organic Load on Filter Efficiency.

Velz (9), Gerber (12), the NRC formula (1), The Ten State Standards (2) (13) and many others state that the organic load governs efficiency. Fairall (14) in a statistical study of conventional trickling filter plants indicates that the hydraulic load has more influence on efficiency than does the organic load. Rumpf (15) shows a plot of BOD remaining versus BOD applied for various hydraulic loads on deep filters in Germany. The results show the relationship to be best described by a straight line for each hydraulic load up to about 180

mg/l applied BOD. This indicates that efficiency is governed by the hydraulic load rather than the organic load because the efficiency is defined by 100 times 1 - slope of the line resulting from such a plot. Rigbi, Amramy and Shuval (16) show a plot of BOD removed versus BOD applied in terms of lbs-BOD/cu yd/day. If organic load is the governing factor in efficiency the points of such a plot would not fall in a straight line for each of the hydraulic loads applied to the filter. Schulze (3) and Becher and Bryan (17) have used this type of plot to show that hydraulic load controls the efficiency of removal. It is interesting to note that the new Ten State Standards "design" curve (13) makes use of the same plot but draws the opposite conclusion.

D. The Effect of Clogging.

Abdul-Rahim, Hindin and Dunstan (18) and Grantham, Phelps, Calaway and Emerson (19) are among many who have experienced increased efficiency with increasing hydraulic load. The conventional filter with its many small openings tends to retain a great deal of biological growth and as a result a considerable number of the smaller openings become clogged. The clogging causes the flow to be channeled through the larger voids. When the flow is increased the additional forces applied tend to open up new passages through which the sewage flows. The natural result is an increase in efficiency per unit volume of the filter.

Egan and Sandlin (20), Becher and Bryan (17) and Schulze (21) (3) have worked with new type media for trickling filters which tend to eliminate the clogging problem. This thesis will also introduce a new media.

E. The Effect of Recirculation on Filter Efficiency.

According to the NRC formula (1), the new Ten State Standards (13) and Rankin (22) the organic load on a trickling filter under recirculation is determined only by the BOD of the settled sewage applied. Fairall (14) and the old Ten State Standards (2) include the BOD of the recirculation flow. For plant operation and overall efficiency of treatment the first method appears to provide satisfactory results. Sorrels and Zeller (4) point out that when this is done the filter is credited for doing more work than it actually does.

Rankin (22) in a comparative study of operational efficiency of several plants found that the application of the old Ten State Standards formula (2) more closely approximated the actual data than did the application of the NRC formula. The NRC formula recognizes the decrease in treatability of the recycle by the use of a conversion factor. The old Ten State Standards recognizes an increase in plant efficiency due to recirculation as does the NRC formula. The Ten State Standards use the incident BOD load and in the NRC formula the incoming BOD load times a factor of recirculation is used. Moore, Smith and Ruchoft (23) in a study of a trickling filter plant in Elizabethtown, Kentucky pointed out that the efficiency of the recirculating filter was higher than that found in a comparable single pass unit and that efficiency increased with increasing recirculation ratios.

Schulze (3) has shown that theoretically recirculation does not materially change the overall efficiency. Rumpf (15) stated that recirculation should be regarded mainly as a means of bringing microorganisms into applied sewage and to freshen raw sewage which is in danger of becoming septic. He gives no credit to recirculation in the reduction of the BOD of the final effluent.

SECTION III

EXPERIMENTAL APPARATUS AND MATERIAL

A. Material

Primary effluent from the East Lansing, Michigan sewage treatment plant was used as feed to the filter. The sewage treated by this plant is strictly of a domestic nature. During the summer months the plant operates on a decreased volume because the number of students attending the university is reduced by about two-thirds. The collection system is a combined one, thus during periods of rain the strength of the waste is reduced considerably and the sewers also experience more than the usual amount of ground water infiltration. Naturally all of the factors mentioned have a marked effect on the strength of the primary effluent with respect to BOD and suspended solids, the result being a random loading on the filter.

During the term of this study the highest BOD found was 155 mg/l and the lowest was 16 mg/l based on 24 hour proportionate and composite samples.

B. Apparatus

1. Pumps

The pump used to bring the sewage from the primary settling tank to the sampling box in front of the filter was a 75 gallon per minute unit made by the Chicago Pump Company. A by-pass was connected into the line to reduce the flow before entering the sampling box and an overflow pipe allowed for the removal of the excess from the box.

The pump which fed the waste to the filter was a positive displacement unit made by the Continental Pump Company with a capacity of 14

gallons per minute at 1750 RPM. The pump was driven by a Graham Company variable speed motor with speeds from 0 to 3000 RPM. The variable speed motor provided a convenient means of controlling the flow rate to the filter.

The pump used in the recirculation line was also a positive displacement Continental Pump driven by a second Graham Company variable speed motor.

2. The Samplers

The two samplers used in the collection of the 24 hour proportionate and composite samples consisted of a plastic scoop attached to a one RPM clock motor as shown in Figures 1 and 2. The sample size was adjusted to about 4 ml per minute by control of the water level in the sampling box. The samplers were cleaned daily to ensure constant volume and to prevent plugging. The samples were collected in plastic bottles and analyses were run daily. The bottles were thoroughly cleaned each time.

3. The Sampling Boxes

Figures 1 and 2 show the construction of the sampling box for the incoming flow (A). The level of the waste in the box was controlled by an overflow pipe (C) and the intake for the filter was screened (B) to keep grease particles from plugging the nozzles of the distributor. The screen was cleaned daily to ensure proper flow to the filter both in quantity and in the suspended solids concentration.

The sampling box at the outlet of the final settling tank also had an overflow pipe to control the water level for the sampler. Both

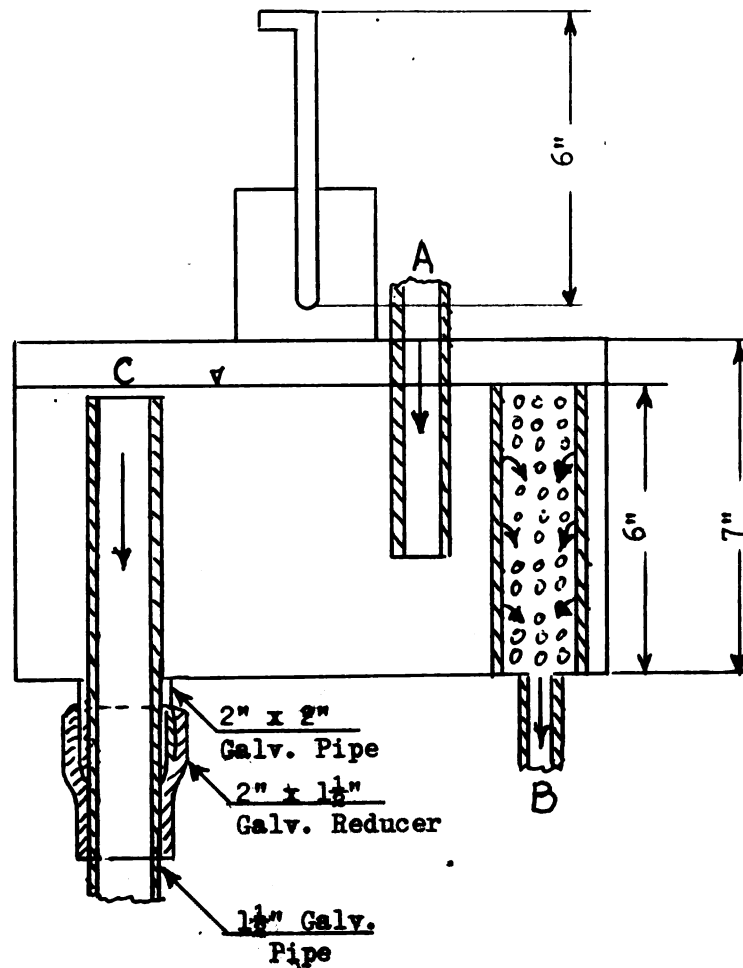


Figure 1. Details of Sampler

boxes were cleaned regularly to prevent the accumulation of organic material on the bottom.

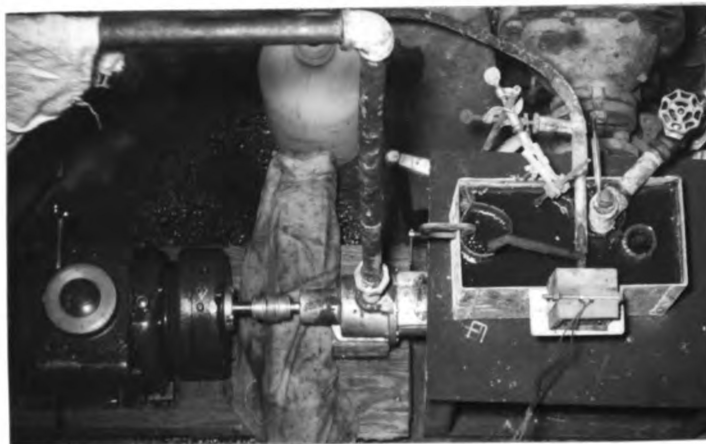


Figure 2. View of the Sampling Box for Incoming Flow.

4. Flow Control

Since the hydraulic load was of primary interest in this study, the control arrangements were such that the flow did not vary more than 0.05 gallons per minute from the desired rate. Fisher-Porter rotameters were used to measure the flow and the speed of the variable speed motors was used as the control. The flow was not allowed to pass through the meters constantly because they tended to become clogged with organic material. The flow diagram, Figure 3, shows how the connections were made for both the single pass and the recirculation study. The head loss through the flow meter system was greater than that through the normal system, therefore the pressure at the distributor was used as a reference point. Reductions were made in the speed of the motor until the pressure was the same at the distributor when the flow metering system was taken out of service as when it was in the line.

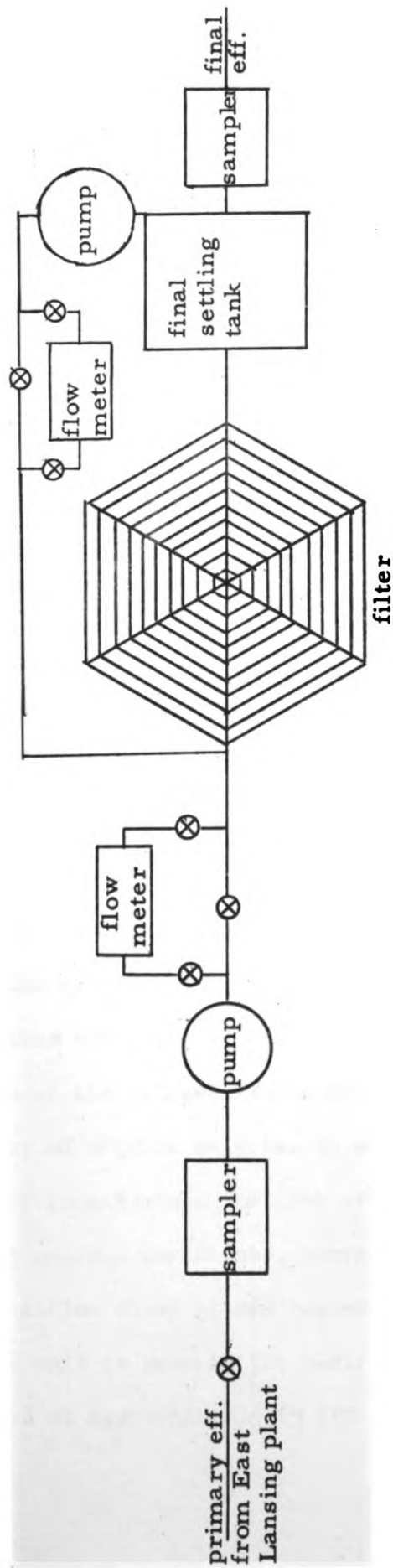


Figure 3. Schematic Flow Diagram of Pilot Plant

To protect the system from high pressures developed when the nozzles of the distributor became plugged, a pressure switch was connected in series with the pumps.

5. The Distributor

Figure 4 shows the detail of the four arm distributor used in most of the experiments. The bearing came from a lawn sprinkler (Sears, Roebuck and Company). The existing arms and nozzles were removed and one-quarter inch pipe unions attached to the bearing with a threaded copper nipple one inch in length. Three-eighths inch copper pipe was threaded into the pipe unions to provide the extended arms shown. The use of the pipe unions provided greater versatility to the distributor under the different hydraulic loads and copper pipe allowed for some bending. By adjusting the angle of spray and by changing nozzle sizes, hydraulic load and distribution of the sewage on the filter could be controlled.

The nozzle tips used were 95° flat atomizing nozzles made by Spraying Systems Company. The size of the tip was so selected as to cause the system to operate at pressures from 7 to 15 psi from minimum to maximum hydraulic load and to distribute the waste evenly over the surface of the filter. The nozzles were cleaned daily to prevent the build up of organic material in and around the tip.

Figure 5 shows the four arm distributor in action at the flow rate of 4.5 gallons per minute, corresponding to a hydraulic load of 30.8 mgad. At low flows it was necessary to change the distributor to a two-arm unit to provide the desired pressures. The distributor was operated at approximately 60 RPM for all hydraulic loads.

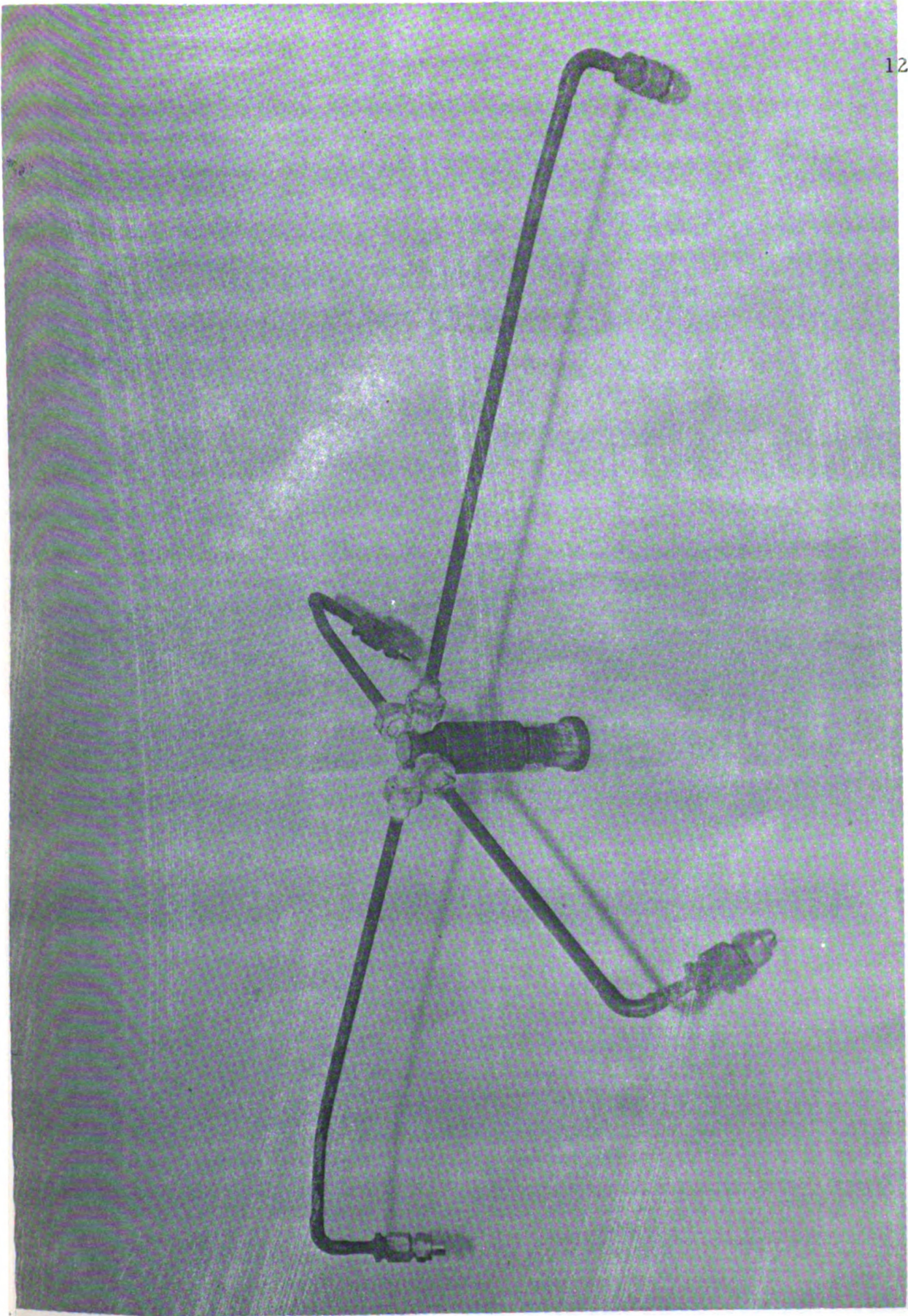


Figure 4. Distributor Made from a Modified Lawn Sprinkler.

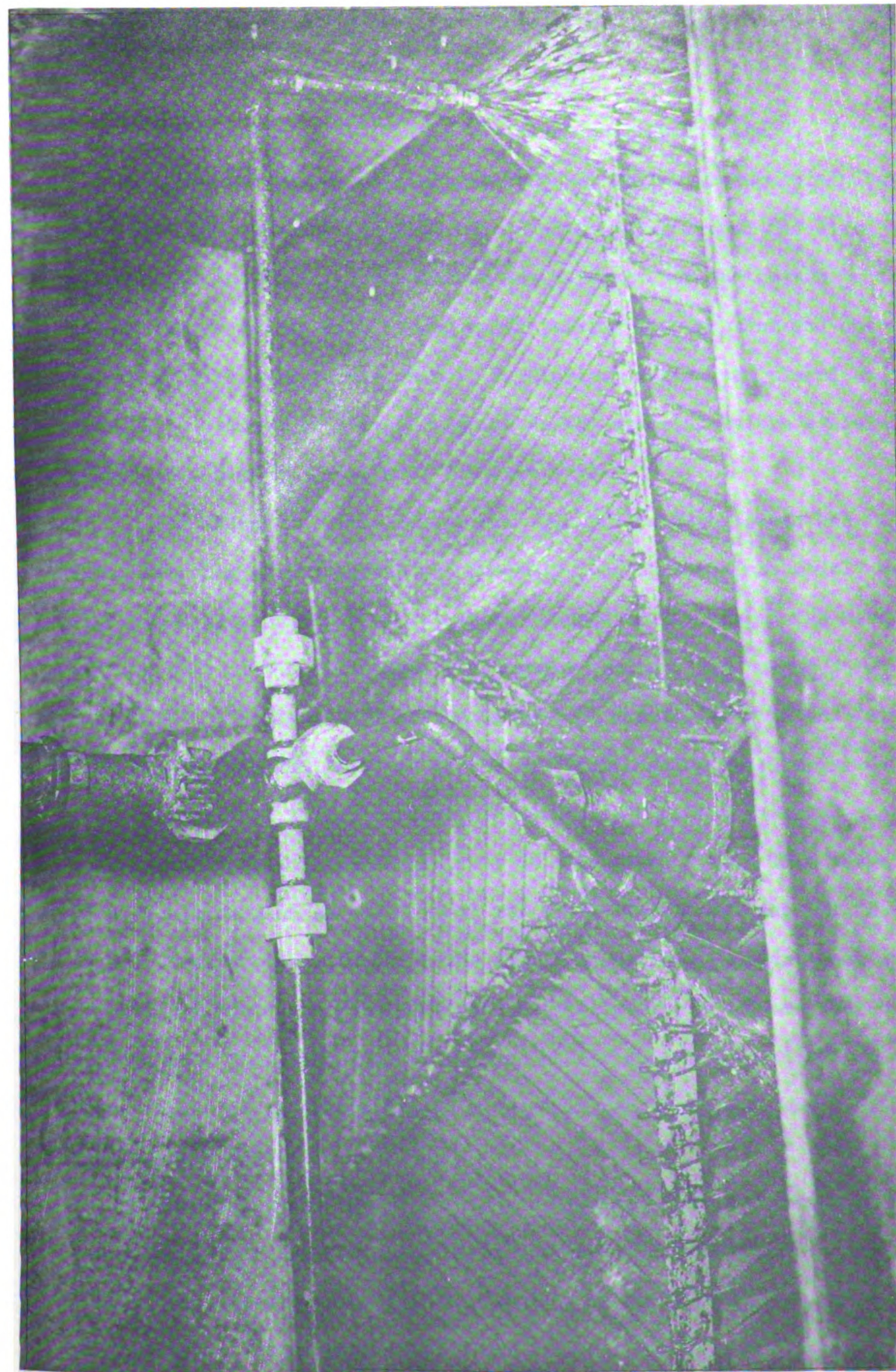


Figure 5. Screen Filter Installed in Plywood Housing with Sprinkler in Operation.

6. The Filter

The details of the filter are shown in Figure 6 and 7. Figures 8 and 9 show the method of construction. Fiberglass window screening (Chicopee by Owens and Corning) was wound spirally around the wire supports of the filter. The screen was attached top and bottom by the use of brass eyelets with copper wires passing through them and subsequently tightened to the frame. An aluminum washer was placed on each side of the screen to prevent ripping of the material by the eyelet. Figure 10 shows the details of the connections.

The diameter of the filter was four feet and the depth was five feet. Spacing of the screen was one-half inch in the first model, but due to clogging the spacing was later changed to one inch. The horizontal surface area of the filter was 9.17 square feet and its volume 45.85 cubic feet. The length of screening used in the filter with one-half inch spacing was 280 feet and in the one inch spacing the length was 121 feet. A vertical filter surface of 2800 or 1210 square feet was theoretically available for the development of biological film. This amounts to 57.7 square feet per cubic foot for the half-inch spacing and 26.3 square feet per cubic foot for the one inch spacing. Conventional stone trickling filters are assumed to theoretically have 35 square feet of surface area per cubic foot of volume. Under actual operational conditions this area is substantially reduced by the filling of small voids with organic matter.

Figure 11 shows the filter in the housing. Note the large space below the filter for the movement of the waste as well as air. The housing was supported on $2\frac{1}{2}$ inch pipe nipples to allow the entrance of air about the entire perimeter of the filter. The bottom of the housing

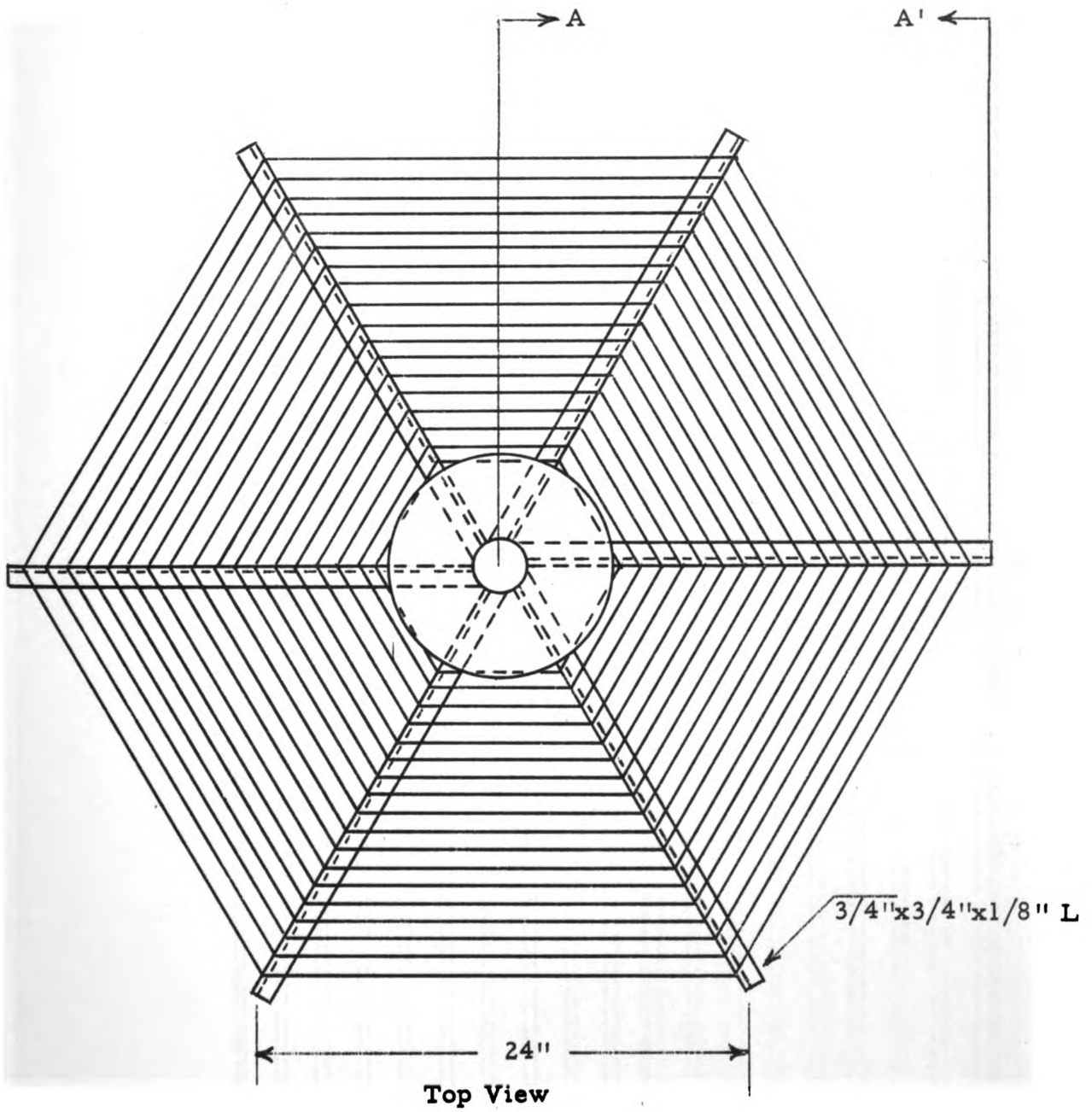
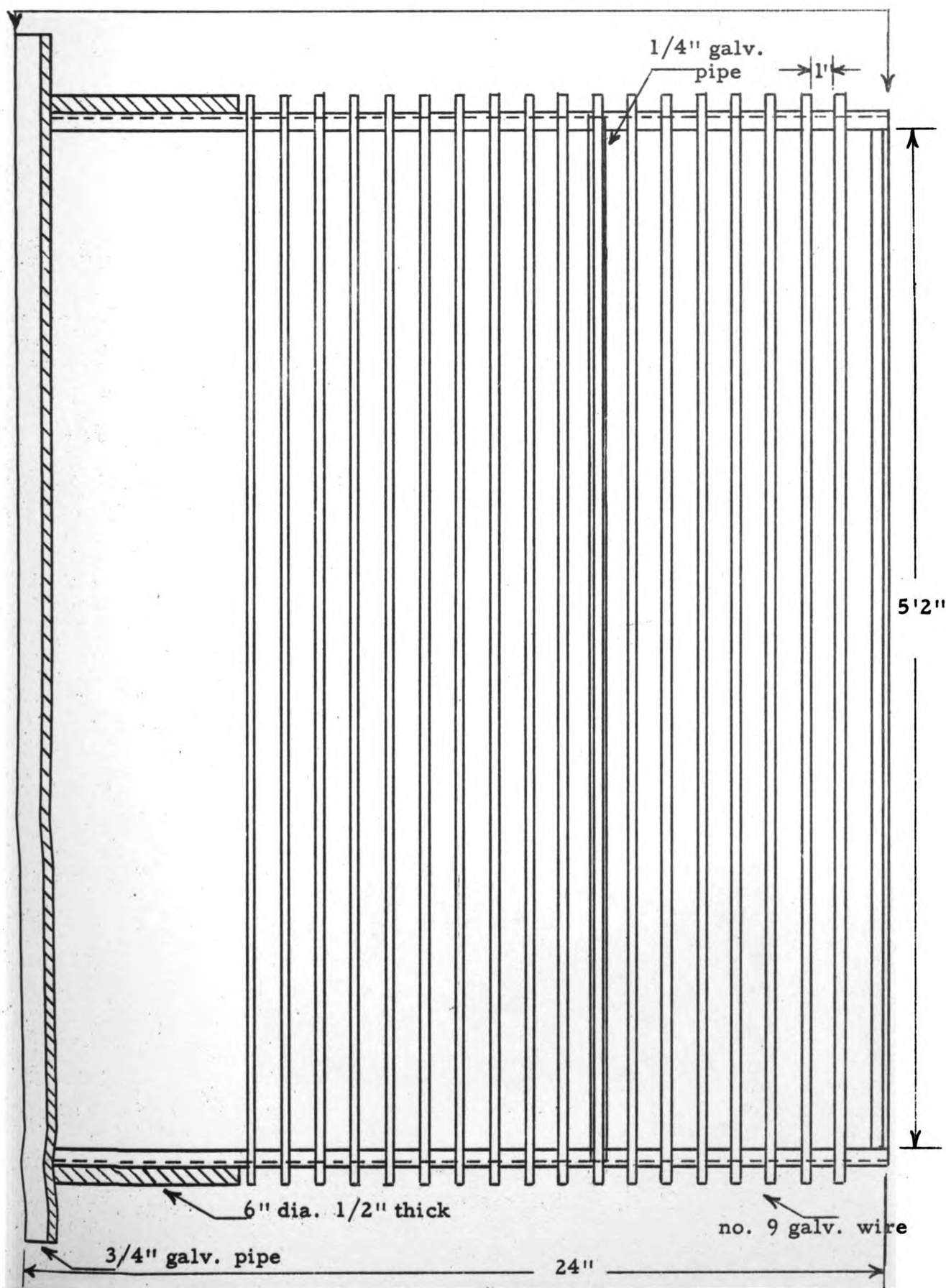


Figure 6. Experimental Filter

Figure 7. Experimental Filter, Section A-A' of Figure 6.

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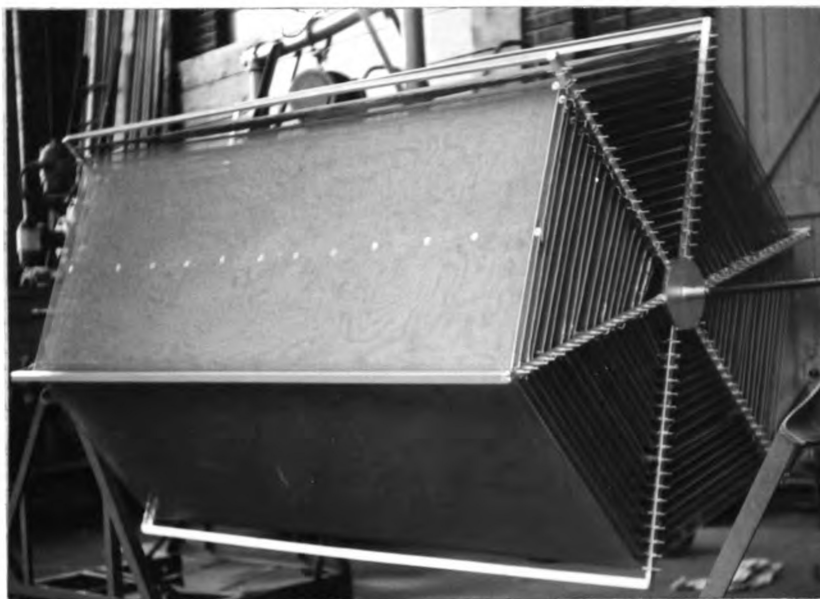


Figure 8. Plastic screen mounted in angle iron frame.

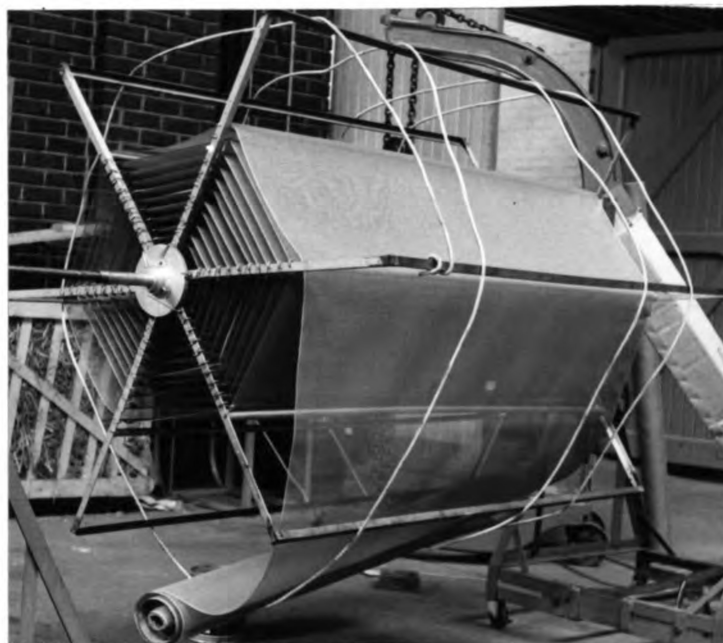


Figure 9. Method of construction for experimental filter.



Figure 10. Detail of Filter Bottom.

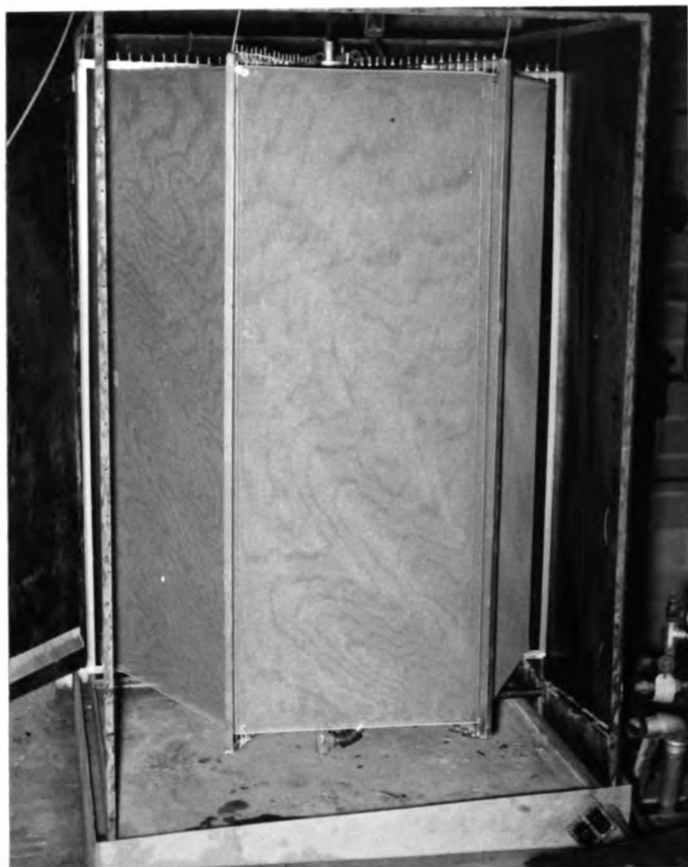


Figure 11. Filter Placed in Plywood Housing Prior to Enclosure.

was one inch above the water level in the collection pan and the pan was built so the filter housing had a half-inch clearance on all sides.

7. The Final Settling Tank

The flow from the filter was collected in an underdrain pan and subsequently passed to the final tank through a $2\frac{1}{2}$ inch pipe. The flow entered the tank at about one half the depth and it was directed to the wall to destroy the forward momentum. A scum plate was provided at the outlet weir and a valve for sludge drainage was provided at the floor of the tank. The tank was skimmed daily and the sludge removed twice each day by moving a scraper slowly over the bottom of the tank.

The settling tank had a fixed volume of 27.5 cubic feet. The unit was one and one-half times as long as it was wide and its depth was approximately equal to the width.

The fixed volume of the final tank presented a problem because the settling times decreased with increasing hydraulic loads. For example, the settling time at 10.3 mgad was 2.3 hours and at 30.8 mgad only 0.77 hours. In an attempt to correct this situation, a by-pass system was set up at the inlet for the final tank. The by-pass system consisted of a pipe inserted into the inlet end of the tank with a valve in the line to control the discharge. The flow over the outlet weir was determined by the elevation of the water surface in the final sampling box. The flow through the by-pass system was adjusted until the elevation in the sampling box stayed at a predetermined level corresponding to a hydraulic load of 13.7 mgad. The settling time for this hydraulic load was 1.73 hours. This system allowed the overflow rate for the weir at the far end of the tank to be controlled. It was felt that if the overflow rate was held constant in this manner, the final effluent would

have approximately the same settling time regardless of the hydraulic load entering the tank. This assumption held true for the lower hydraulic loads but at the hydraulic loads of 60 and 80 mgad the turbulence in the tank was very great and additional settling was required to provide a sample which could be compared to those collected at lesser hydraulic loads. The additional settling took place in the sample collection bottle. At the lower hydraulic loads very little material appeared at the bottom of the bottle and it was thoroughly mixed into the rest of the sample prior to analysis. At high hydraulic loads there was a considerable amount of material at the bottom of the sample bottle and it was felt that the majority of this material would have settled out in a properly sized tank. Therefore the sample was not mixed prior to analysis at these loads.

SECTION IV

PROCEDURE AND RESULTS

A. Procedure

1. Dissolved Oxygen Analysis

The sodium azide modification of the standard Winkler test as described in Standard Methods (24) was used except that the measurement of the free iodine was made by a colorimeter. The Hach Chemical Company colorimeter used for water analysis proved to be as reliable as the titration with sodium thiosulfate. Periodic checks were made throughout the study to ensure that proper results were being obtained.

The colorimeter was equipped to measure high (0-16 mg/l) and low (0-4 mg/l) ranges of dissolved oxygen. To maintain reliable results it was necessary to use only the high range.

2. Biochemical Oxygen Demand

The standard five day BOD test as described in Standard Methods was used throughout the investigation. Duplicate samples were set up on each sample. The temperature was controlled by means of a water bath in which the bottles were completely submerged.

3. Suspended Solids

The suspended solids were determined by filtration through a Gooch crucible. The volume filtered depended on the amount of suspended solids in the waste. The volume used for the incoming flow varied from 100 ml to 200 ml and for the final effluent from 400 ml to 800 ml. Suspended solids, volatile suspended solids and ash were determined 4 or 5 times for each 14 day run.

4. Nitrate Nitrogen

Nitrate nitrogen content of the final effluent was determined by the Brucine Method as developed by the Hach Chemical Company. The Brucine Method for nitrate is much easier to carry out than the Phenoldisulfate acid method, because it is not necessary to evaporate the water sample to dryness. The method registers both nitrate and nitrite as does the phenoldisulfonic acid method, therefore, it is desired to obtain the nitrate content alone, it is necessary to also run a nitrite test, and subtract the nitrite value from the nitrate value obtained by the Brucine test. In some cases the nitrate and nitrite content of the sewage was above the range of the colorimeter scale and it was necessary to dilute the sample with ammonia-free water before adding the reagents. The results were then determine by multiplying by the dilution factor. The nitrate content of the final effluent was determined 4 times in each 14 day run.

5. Nitrite Nitrogen

The nitrite nitrogen content of the final effluent was determined by the standard sulfanilic acid-1, naphthylamine method. The two chemicals were used in the combined stable powder form developed by the Hach Chemical Company. This test is valid for the nitrite nitrogen content up to 0.2 ppm. Above this a precipitate begins to form and inaccurate results are obtained. Therefore, in cases where the nitrite nitrogen content exceeded this value dilutions were made with ammonia free water to bring the content within the range of the test. The nitrite test was run on the same set of samples as the nitrate test.

6. Temperature and pH

The temperature of the incoming flow and the final effluent was

observed twice daily at the points of sampling. The average temperature between the two readings was recorded as the mean temperature of the sewage.

A Beckman, model H2, pH meter was used to measure the pH of each sample daily.

7. Statistical Technique

The lines shown on the plots of the data were obtained by the method of least squares in accordance with the procedures outlined by Youden (25). When plotting lbs-BOD removed versus lbs-BOD applied per cubic yard per day, Schulze (3) has shown that the line is straight and passes through the origin. Examination of the plotted data from this study shows that they also fit a straight line which passes through the origin. The lines take the form $y' = bx'$ where:

$y' = \text{Lbs-BOD Removed/cu yd/day,}$

$x' = \text{Lbs-BOD Applied/cu yd/day and}$

$b = \text{slope of the line or } b \times 100 = \% \text{ efficiency.}$

Using the method of least squares the slopes of lines were found by:

$$b = \frac{\sum x'y'}{\sum (x')^2} \quad (1)$$

The primary purpose of this study was to show the effect of hydraulic load on the performance of the trickling filter, thus a statistical comparison of the slopes for the various hydraulic loads was required. The t-test was used to determine the probability of the slopes being the same. The following equations express the statement of the test:

$$t = \frac{b_1 - b_2}{s_b} \quad (2)$$

$$s_b^2 = s_p^2 \left[\frac{1}{\sum (x_1')^2} + \frac{1}{\sum (x_2')^2} \right] \quad (3)$$

$$s_p^2 = \frac{s_1^2 + s_2^2}{n_1 + n_2 - 2} \quad (4)$$

$$S = \sum (y')^2 - \frac{(\sum x'y')^2}{\sum (x')^2} \quad (5)$$

where

t = the value of t in the t -distribution using two sided test.

$b_1 - b_2$ = the difference between the two slopes under examination.

s_b^2 = the variance of the difference between the slopes.

s_p^2 = an estimate of the variance available from each of the individual slopes.

S = deviation of the experimental points from the straight line.

The organic load applied per unit volume of filter is given by:

$$\text{lbs-BOD Applied/cu yd/day} = \frac{Q \times 8.34 \times \text{BOD Applied}}{V \times 10^6} \quad (6)$$

and the organic load removed per unit volume of filter is given by:

$$\text{lbs-BOD Removed/cu yd/day} = \frac{Q \times 8.34 \times \text{BOD Removed}}{V \times 10^6} \quad (7)$$

where

Q = the flow rate in gal/day,

V = the volume of filter in cubic feet and

BOD = concentration in mg/l.

For a given hydraulic load all the terms in equations 6 and 7 remain constant except the BOD concentration. It is the variance of this variable which must be subjected to the statistical test.

Let us suppose that a BOD concentration of 100 ± 10 mg/l is applied to the filter at the hydraulic loads of 10.3, 30.8 and 60.0 mgad. The constant terms ($Q \times 8.34 / V \times 10^6$) for the above mentioned hydraulic loads are 0.0106, 0.0318 and 0.0622 respectively. When multiplying the BOD concentration times the constant term the variation of the BOD concentration is also multiplied. In the example given above, the organic load applied would be 1.06 ± 0.106 , 3.18 ± 0.318 and 6.22 ± 0.622 lbs BOD/cu yd/day respectively. This multi-

plying effect can be eliminated by working with BOD concentrations only. The equation for the regression line resulting from the plot of the data becomes $y = bx$ where:

y = BOD Removed in mg/l,

x = BOD Applied in mg/l and

b = slope of the line.

Figure 12 shows the slopes of the lines for the flow rates of 10.3, 30.8, 60.0 and 80.0 mgad obtained in this manner.

If it can be shown that the slopes of the lines are statistically different with 95 per cent confidence then the difference shall be considered demonstrated. The following is an example of the computations necessary to establish the value of t for the t -distribution.

EXAMPLE I

Compare the slopes of the regression lines for the hydraulic loads of 30.8 and 60.0 mgad. Table A-I shows the experimental results in terms of BOD concentrations for the 30.8 and 60.0 mgad hydraulic loads. Let the subscripts 1 and 2 represent the 30.8 and 60.0 mgad data respectively.

$$\begin{aligned}
 S &= \sum y^2 - \frac{(\sum xy)^2}{\sum x^2} \\
 S_1 &= 32,913 - 41,602^2/53,544 = 678 \\
 S_2 &= 81,324 - 114,648^2/162,305 = 340 \\
 s_p^2 &= \frac{S_1 + S_2}{n_1 + n_2 - 2} = \frac{678 + 340}{26} = 39.15 \\
 s_b^2 &= s_p^2 \left[\frac{1}{\sum x_1^2} + \frac{1}{\sum x_2^2} \right] \\
 &= 39.15 (1.8676 + 0.6162) \times 10^{-5} = 9.811 \times 10^{-4} \\
 t &= \frac{b_1 - b_2}{s_b} = \frac{0.777 - 0.706}{(9.811 \times 10^{-4})^{1/2}} = 2.270
 \end{aligned}$$

The critical value for t for 95 % confidence is 2.040. It is concluded that the slopes of these lines are different.

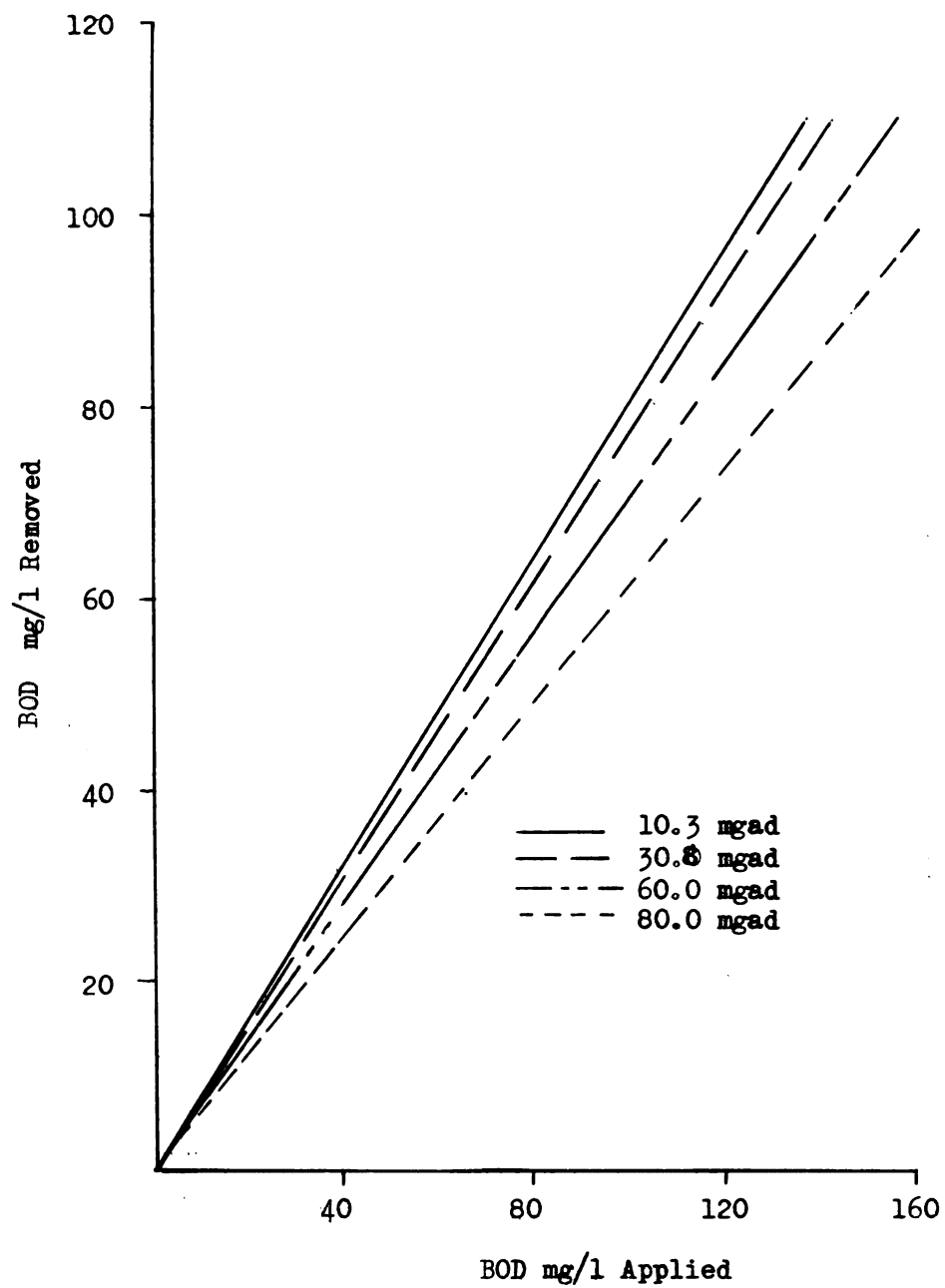


Figure 12. Plot of BOD Removed Versus BOD Applied for Statistical Comparison.

TABLE A-I Experimental Values for the Hydraulic Loads of 30.8 and 60.0 mgad in terms
of BOD Concentrations for Statistical Evaluation.

Day	30.8 mgad					60.0 mgad				
	x_1^*	y_1^*	$x_1 y_1$	x_1^2	y_1^2	x_2	y_2	$x_2 y_2$	x_2^2	y_2^2
1	50	39	1950	2500	1521	84	54	4536	7056	2916
2	44	35	1540	1936	1225	76	54	4104	5776	2916
3	41	32	1312	1681	1024	89	55	4895	7921	3025
4	32	19	608	1024	361	125	55	11875	15625	9025
5	47	37	1739	2209	1369	70	48	3360	4900	2304
6	28	21	588	784	441	78	61	4758	6084	3721
7	26	20	520	676	400	78	56	4368	6084	3136
8	50	36	1800	2500	1296	110	85	9350	12100	7225
9	74	59	4366	5476	3481	135	95	12825	18225	9025
10	81	65	4941	6561	4225	140	100	14000	19600	10000
11	90	75	6750	8100	5625	135	95	12825	18225	9025
12	89	68	6052	7921	4624	130	95	12350	16900	9025
13	76	61	4636	5776	3721	97	66	6402	9409	4356
14	80	60	4800	6400	3600	120	75	9000	14400	5625
SUM	808	627	41602	53544	32913	1467	1034	114648	162305	81324

* BOD in mg/l ** BOD in mg/l

B. Results

1. Single pass, one-half inch screen spacing.

The first model of the filter had a screen spacing of one-half inch and was operated at flow rates of 10.3, 17.1 and 24.0 mgad for periods not less than 14 days. Visual examination of the filter showed that a considerable portion of it was clogged. Figures 13, 14 and 15 show plots of the data obtained in terms of lbs-BOD/cu yd/day applied and removed. The slope of the regression lines times 100 is equal to the efficiency of operation. The slope was found according to the least squares method as previously described. The resulting lines pass through the origin and the slopes are constant. The efficiency is therefore independent of the organic load. It was noted that the efficiency increased with hydraulic load from 57.6 per cent at $Q = 10.3$ mgad to 62.4 per cent at $Q = 24.0$ mgad.

The first 3 or 4 days after the hydraulic load was increased, the quantity of sludge removed increased sharply indicating the release of growth by the filter. Re-examination of the filter showed that it had become less clogged with increasing hydraulic load. It was estimated that at least 65 per cent of the filter volume was clogged at the flow rate of 24.0 mgad. The data collected for the first five days were not used as it was felt that this represented the period of re-adjustment for the filter and should not be considered typical of the results. Table I shows the average data on suspended solids, nitrate and nitrite nitrogen concentration as well as those for the temperature of the incoming flow, pH and dissolved oxygen in final effluent.

The per cent of suspended solids removed showed an increase from 70.0 to 82.0 per cent with increasing hydraulic load. The nitrate con-

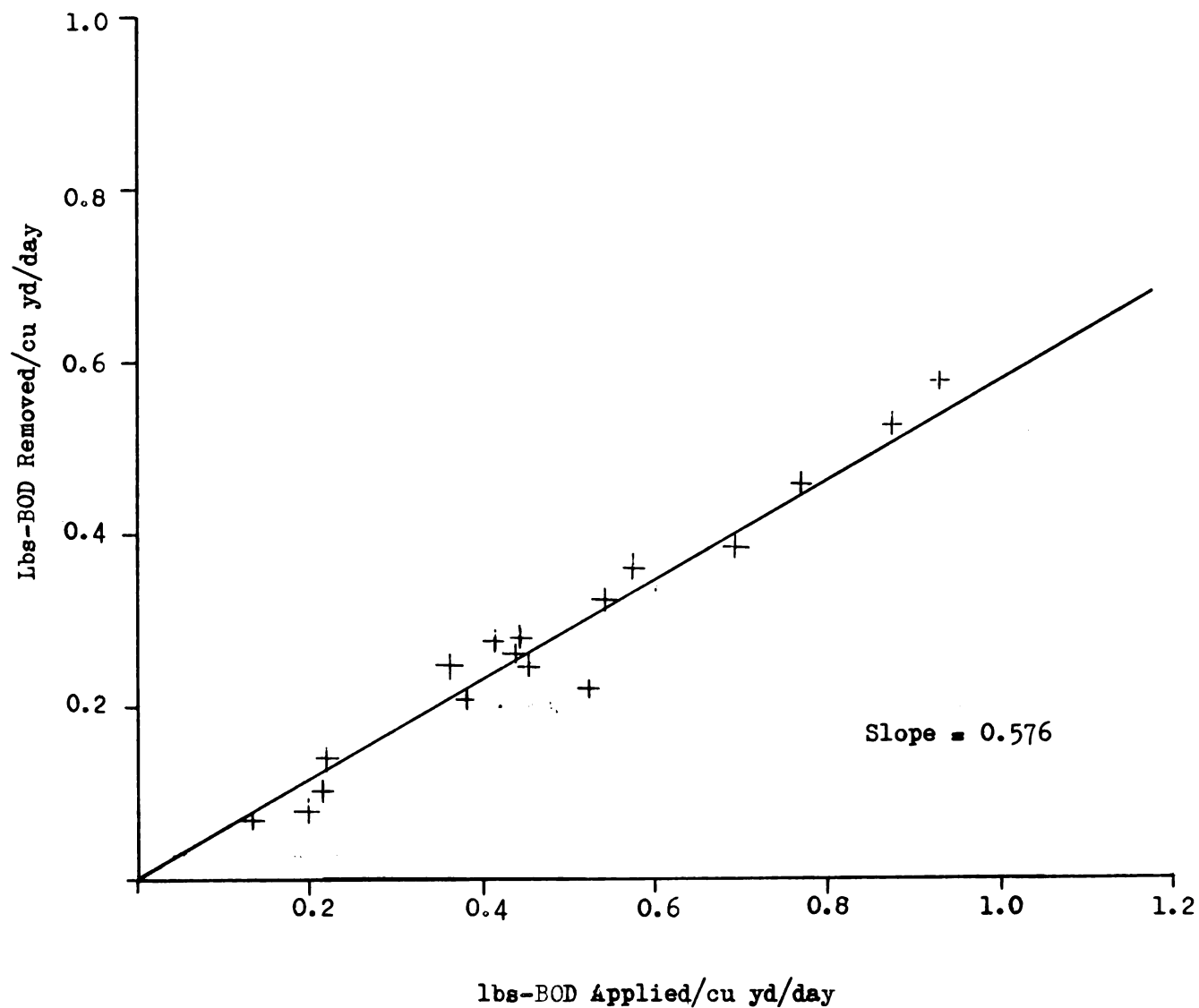


Figure 13. Relationship Between Organic Load Applied and Removed at $Q = 10.3$ mgad.

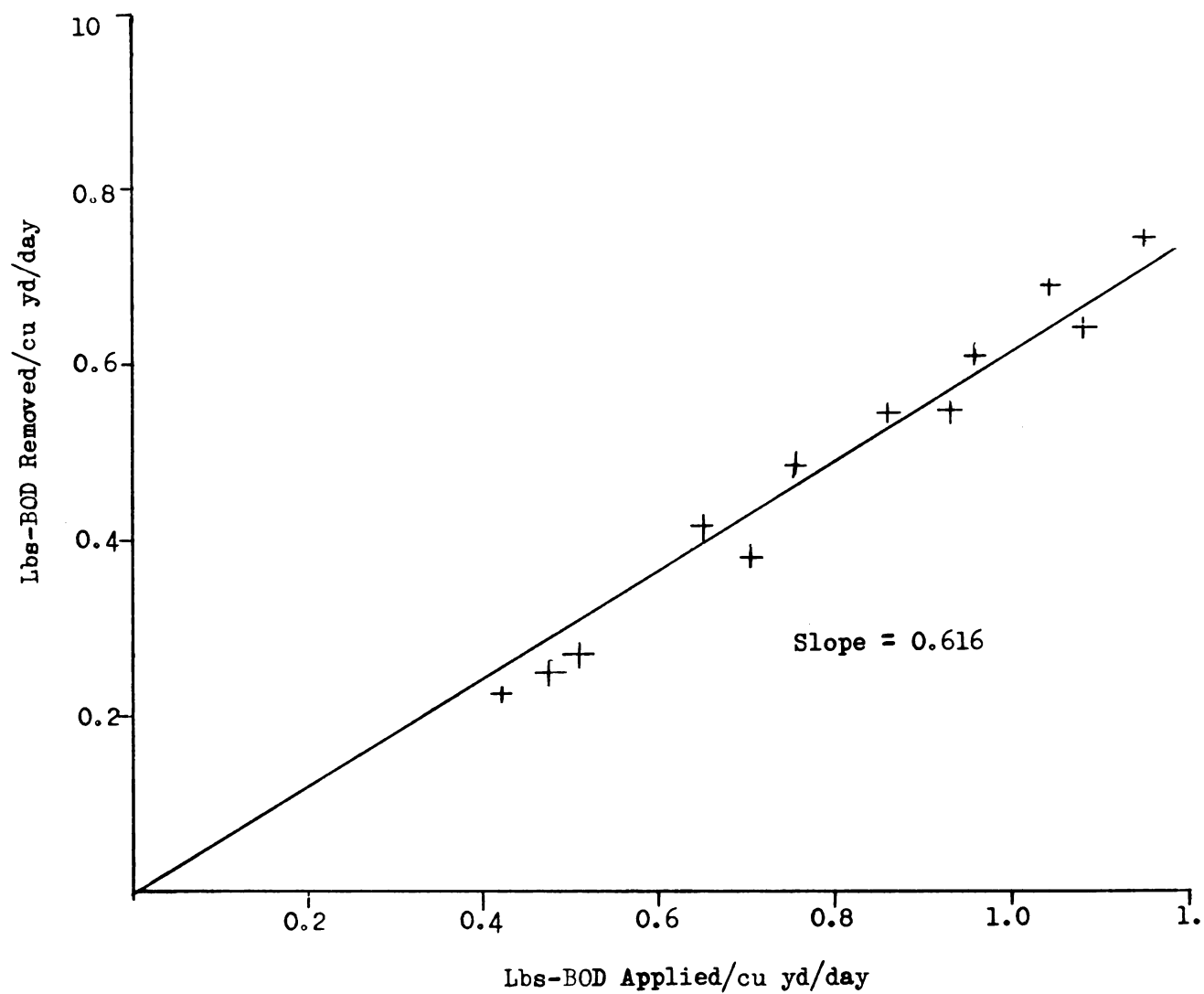


Figure 14. Relationship Between Organic Load Applied and Removed at $Q = 17.1$ mgad.

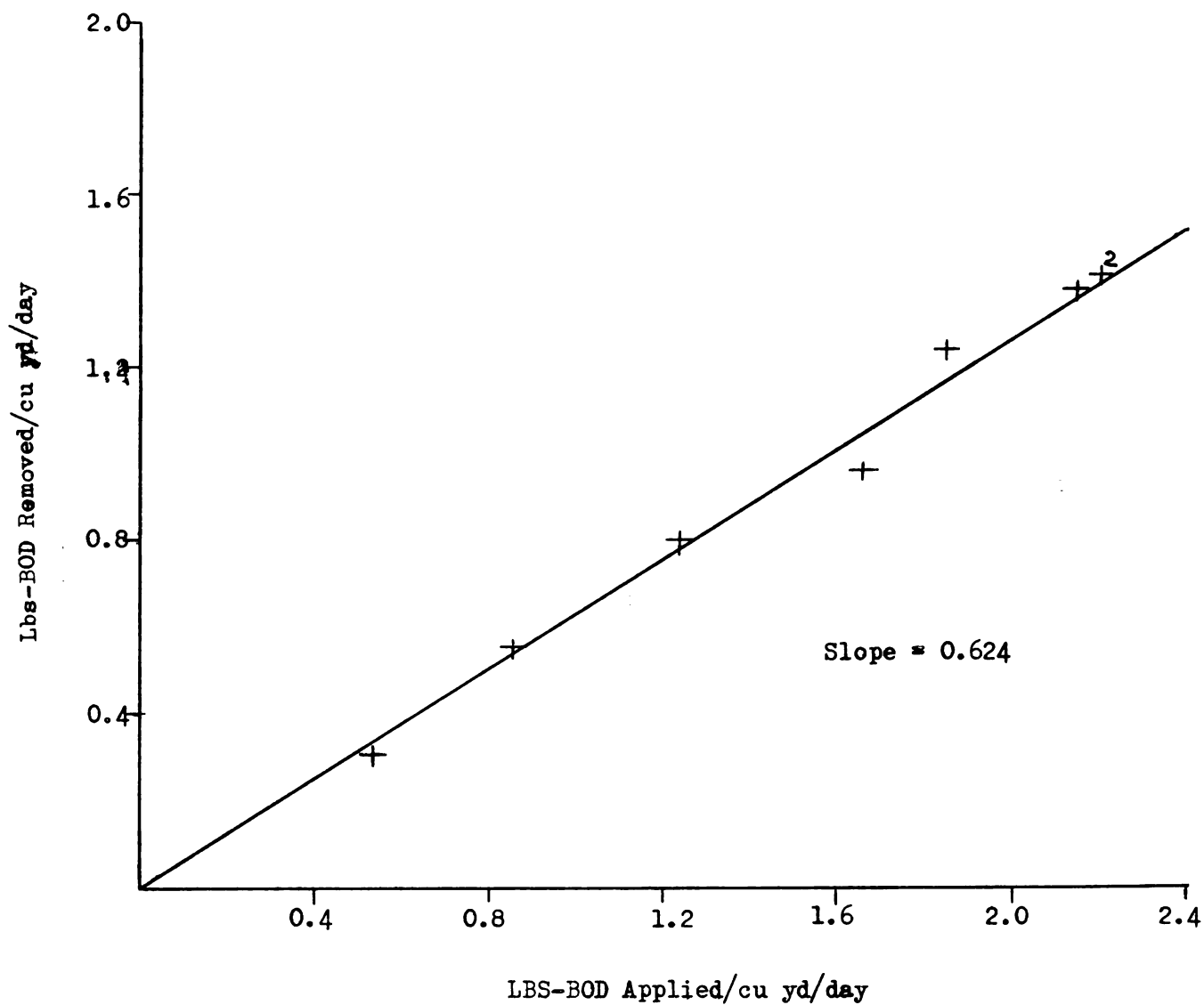


Figure 15. Relationship Between Organic Load Applied and Removed at $Q = 24.0$ mgad.

Table I. Data Collection for One-Half Inch Screen Spacing, Single Pass.

Hydr. Load mgad	Ave. Temp. Co	pH		DO in final Effluent mg/l	Nitrogen in final Effluent*		Total Suspended Solids mg/l		Fixed Suspended Solids as % of Dry Weight	
		in	out		NO ₂	NO ₃	in	out	removed in	out
10.3	21.9	7.45	7.61	3.11	1.60	3.20	96	29	70.0	27.0
17.1	22.1	7.50	7.60	1.94	1.68	7.89	82	25	70.0	36.5
24.0	22.5	7.60	7.68	4.70	1.95	7.50	120	22	82.0	31.6

*In terms of N mg/l.

centration increased from 3.20 to 7.89 mg/l with the maximum at the flow rate of 17.1 mgad. The nitrite concentration increased from 1.60 to 1.95 mg/l with the maximum at the flow rate of 24.0 mgad. The temperature of the incoming flow varied from 21.9° C at 10.3 mgad to 22.5° C at the flow rate of 24.0 mgad. The pH of the incoming flow varied from 7.45 to 7.60 and that of the final effluent varied from 7.61 to 7.68. The dissolved oxygen concentration of the final effluent ranged from 1.94 to 4.70 mg/l.

The increase in efficiency with increasing hydraulic load, the change in the percentage of suspended solids removed and the increase in the concentration of nitrate and nitrite nitrogen were not expected. It was felt that the cause was the varying degree of clogging in the filter. Dissolved oxygen and pH did not appear to change with hydraulic load.

In an attempt to reduce the possibility of clogging, a second filter with a screen spacing of one inch was constructed.

2. Single pass operation with one inch screen spacing

After the construction of the new filter it took approximately 2½ weeks to develop a significant growth. The one inch spacing did not resolve the clogging problem completely. Visual inspection indicated that 30 to 35 per cent of the vertical surface area was plugged at the flow rate of 10.3 mgad. As the hydraulic load was increased to 30.8 mgad the percentage of active free surface area increased to approximately 90 per cent. At the hydraulic loads of 60 and 80 mgad the filter was practically free from clogging and all the vertical surface area was active.

Figure 16, area 2, shows the thickness of the growth developed on the screen at $Q = 10.3$ mgad. Area 1 of the same figure shows a region of recent sloughing of the heavy growth. The quantity of material and the surface area exposed were generally large when sloughing occurred.



Figure 16. Growth on the Screen at the Hydraulic Load of 10.3 mgad.

The small mesh of screen provided an excellent bonding surface for the growth. The thickness of the film approached three-quarters of an inch during periods of high BOD concentrations (100 mg/l) in the incoming flow. The thickness of the film varied considerably during any given hydraulic load and it apparently was dependent on the concentration of the incoming BOD.

When the growth was thin the sloughing took place almost entirely in the anaerobic layer between the screen and the aerobic layer. As the growth sloughed it appeared to travel as a wave down the screen. Figure 17 shows schematically how the sloughing of the anaerobic layer proceeded. Generally from two to three days were required for this type of sloughing in contrast to the instantaneous sloughing of the heavy growth.

Figures 18 and 19 show the difference in the degree of clogging at the hydraulic load of 24.0 and 30.8 mgad by the reduction of the formation of massive stalactites. These stalactites were typical of clogged areas. The clogging generally started directly above the angle iron supports of the filter frame and spread vertically and laterally. When the hydraulic load was low the flushing action was not sufficient to carry the loosened material past the restriction formed by the angle iron supports. When the concentration of the incoming BOD was high the growth became so thick in areas that the space between the screens would fill up completely. Figure 20 illustrates schematically the sequence of events leading to clogging in a section of the filter. At high hydraulic loads (60 to 80 mgad) the flushing action was sufficient to carry the loosened material past the angle iron restriction. In addition these high hydraulic loads also tended to keep the thickness of the growth minimal so that clogging was not a problem.

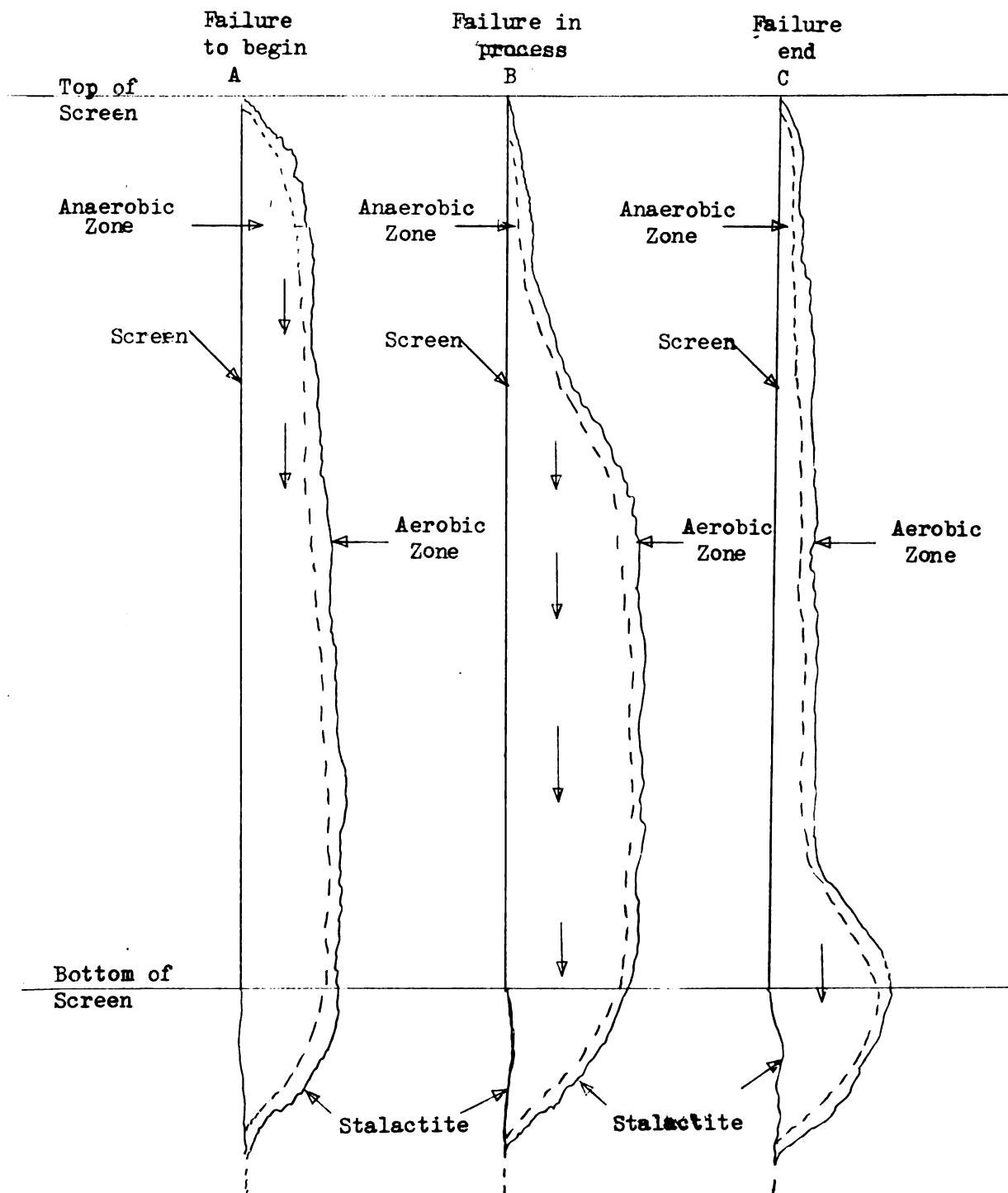


Figure 17. An Illustration of how the Anaerobic Layer Moves out from under the Aerobic Layer when Growth is Thin on Screen.



Figure 18. The Under Side of the Filter at the Hydraulic Load of 24.0 mgad.



Figure 19. The Under Side of the Filter at the Hydraulic Load of 30.8 mgad.

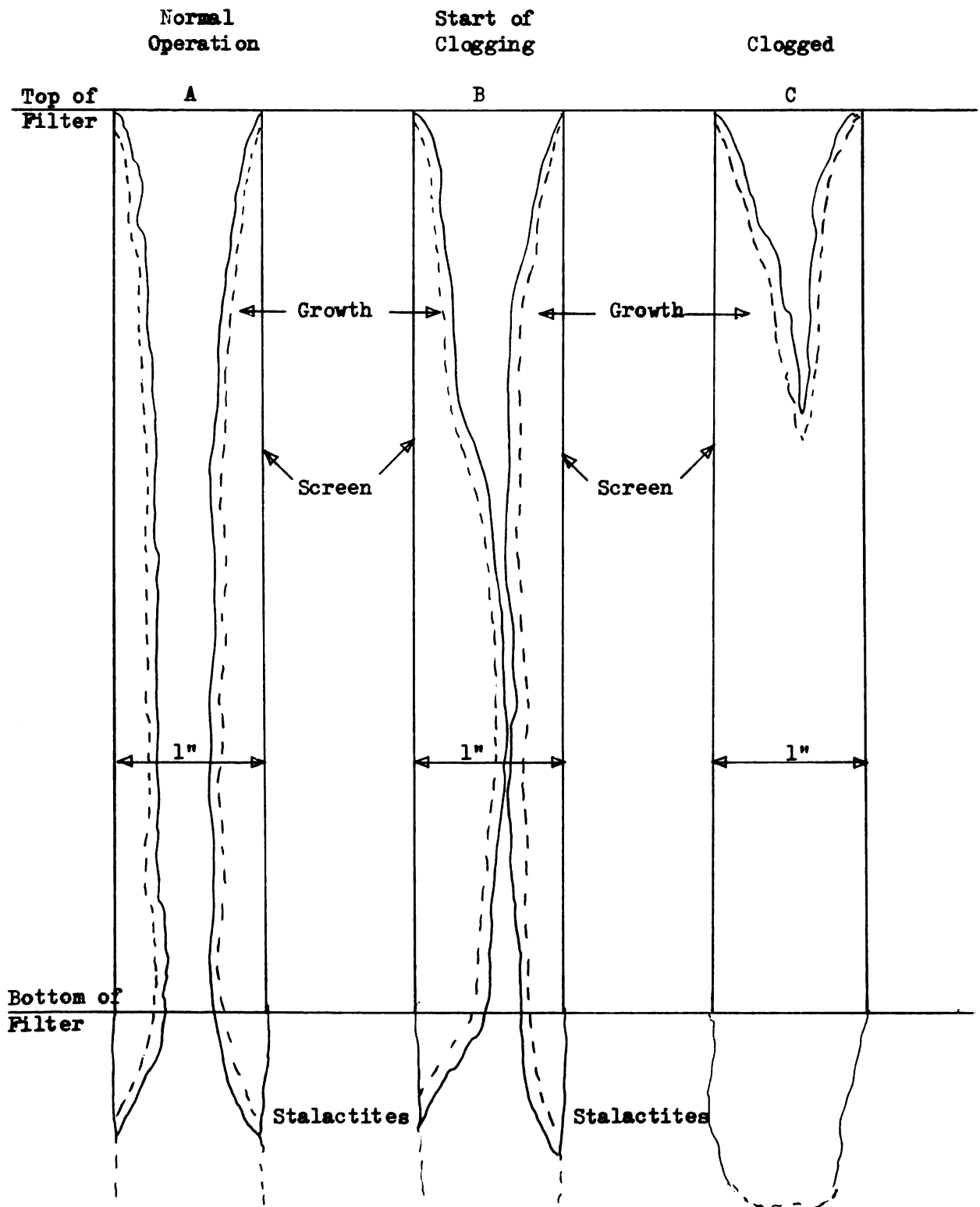


Figure 20. Development of Clogging in a Screen Filter.

The surface or the aerobic layer of the growth was light brown to brownish-gray in color. In cross section the growth showed a gradual transition to the anaerobic layer which was black in color. The anaerobic material appeared grainy and loose in contrast to the aerobic layer which was smooth and firm. It was estimated that the thickness of the aerobic layer at the hydraulic load of 30.8 mgad was 0.4 mm at high BOD concentrations.

Figures 21 through 26 show the relationship between organic load applied and removed at the hydraulic loads indicated. The slope of the line, which has been placed by the method of least squares, times 100 is equal to the per cent BOD removed or the efficiency of operation. The resulting lines are straight and pass through the origin. The efficiency is therefore not a function of the organic load up to the limits shown. The efficiencies obtained from the slopes were 80.5, 80.7, 80.3, 77.7, 70.6 and 61.3 per cent for the hydraulic loads of 10.3, 13.7, 24.0, 30.8, 60.0 and 80.0 respectively and are listed in Table II.

Table II shows that the organic load applied varied from 0.83 to 6.55 lbs-BOD/cu yd/day and that the organic load removed varied from 0.66 to 4.58 lbs-BOD/cu yd/day. The table also shows the results of a statistical comparison of the slopes of the various hydraulic loads by the t-test. The standard deviation of the efficiency line varied from 0.62 per cent to 2.60 per cent. This is a small standard deviation for this type of study. The application of the t-test to the data for 10.3, 13.1 and 24.0 mgad shows that the values for t did not reach the 5 per cent critical level. The differences in efficiencies at these lower hydraulic loads were therefore statistically not significant. The value of t (1.840) approached the 5 per cent critical level in the comparison

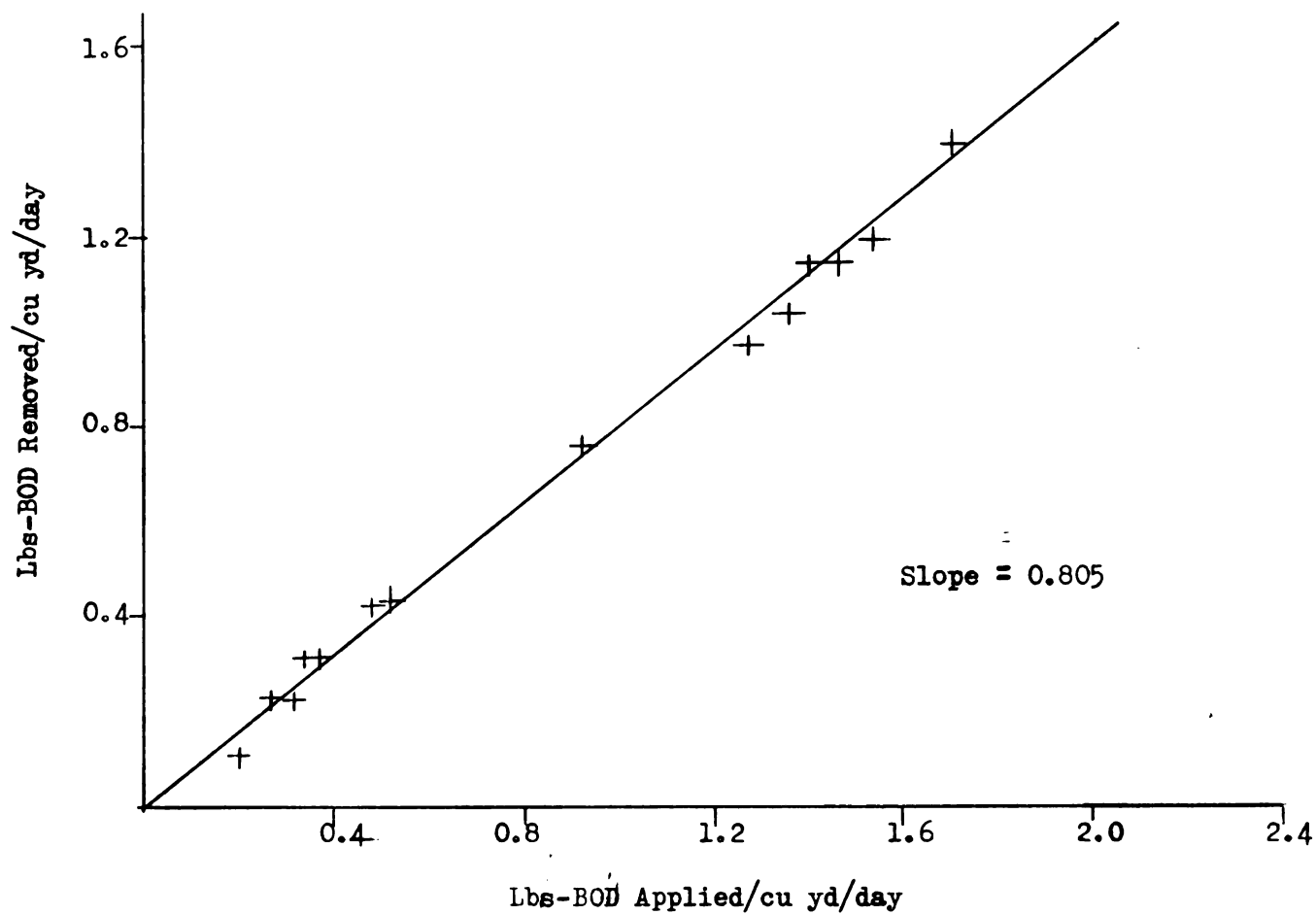


Figure 21. Relationship Between Organic Load Applied and Removed at the Hydraulic Load of 10.3 mgad, Single Pass.

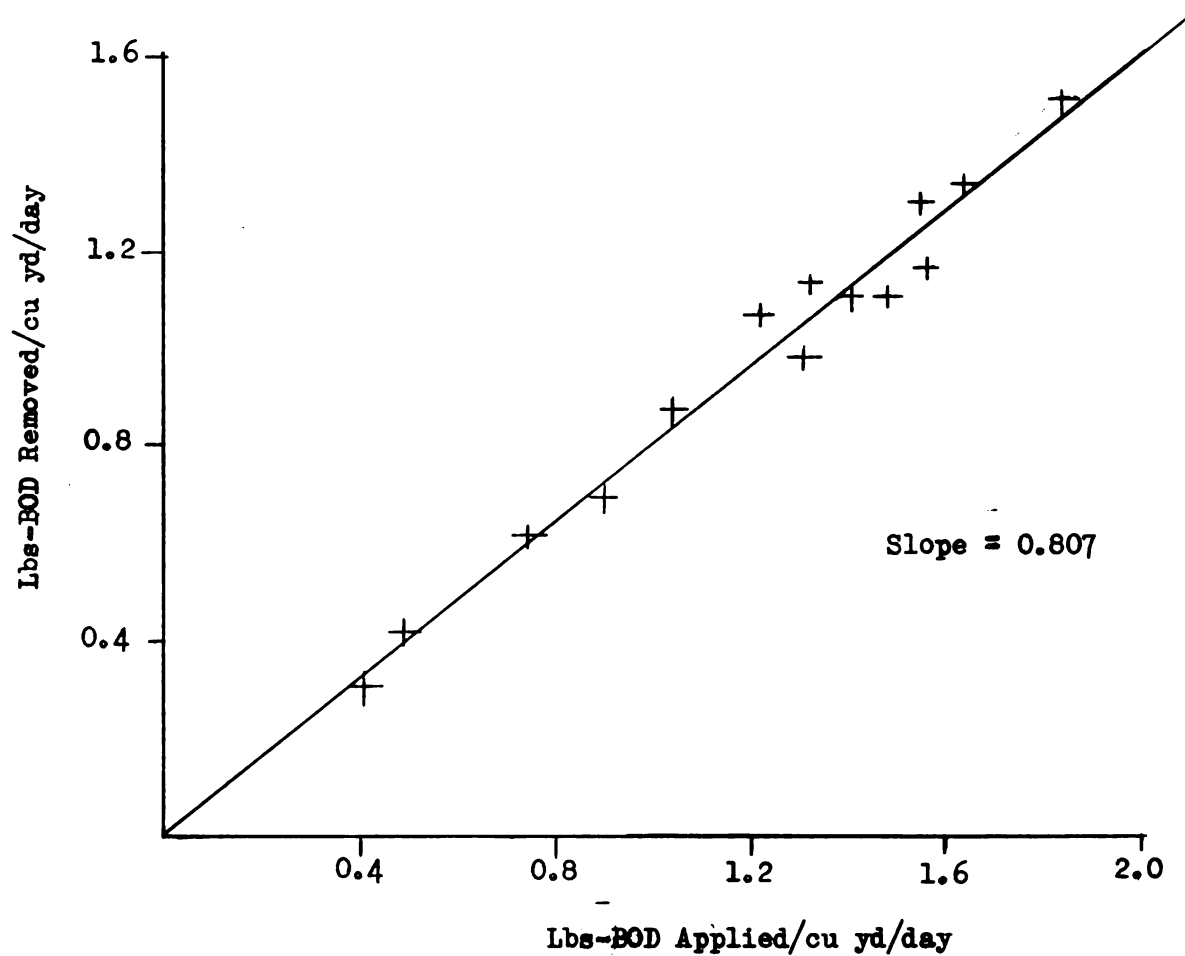


Figure 22. Relationship Between Organic Load Applied and Removed at the Hydraulic Load of 13.7 mgd single pass.

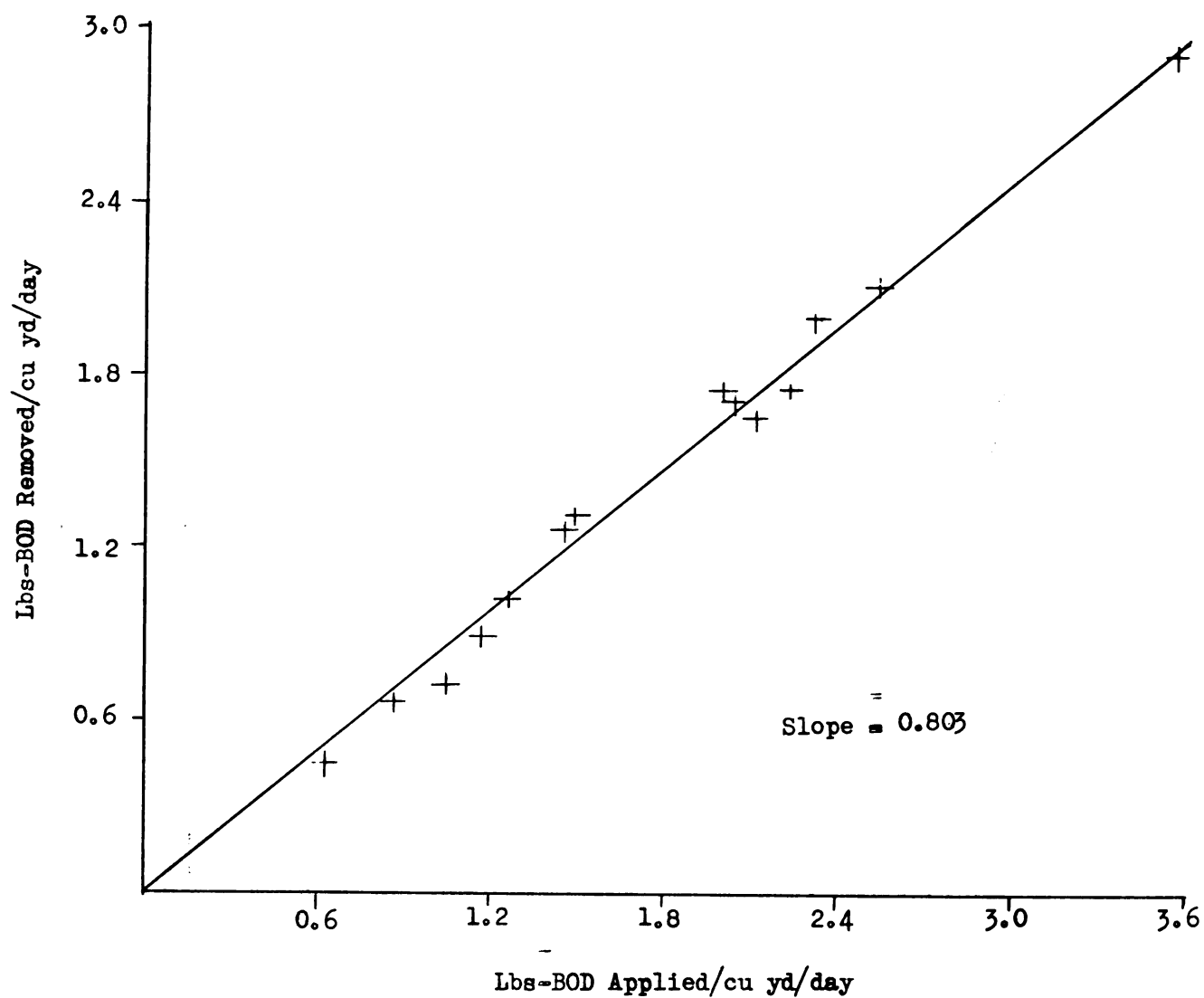


Figure 23. Relationship Between Organic Load Applied and Removed at the Hydraulic Load of 24.0 mgad, Single Pass.

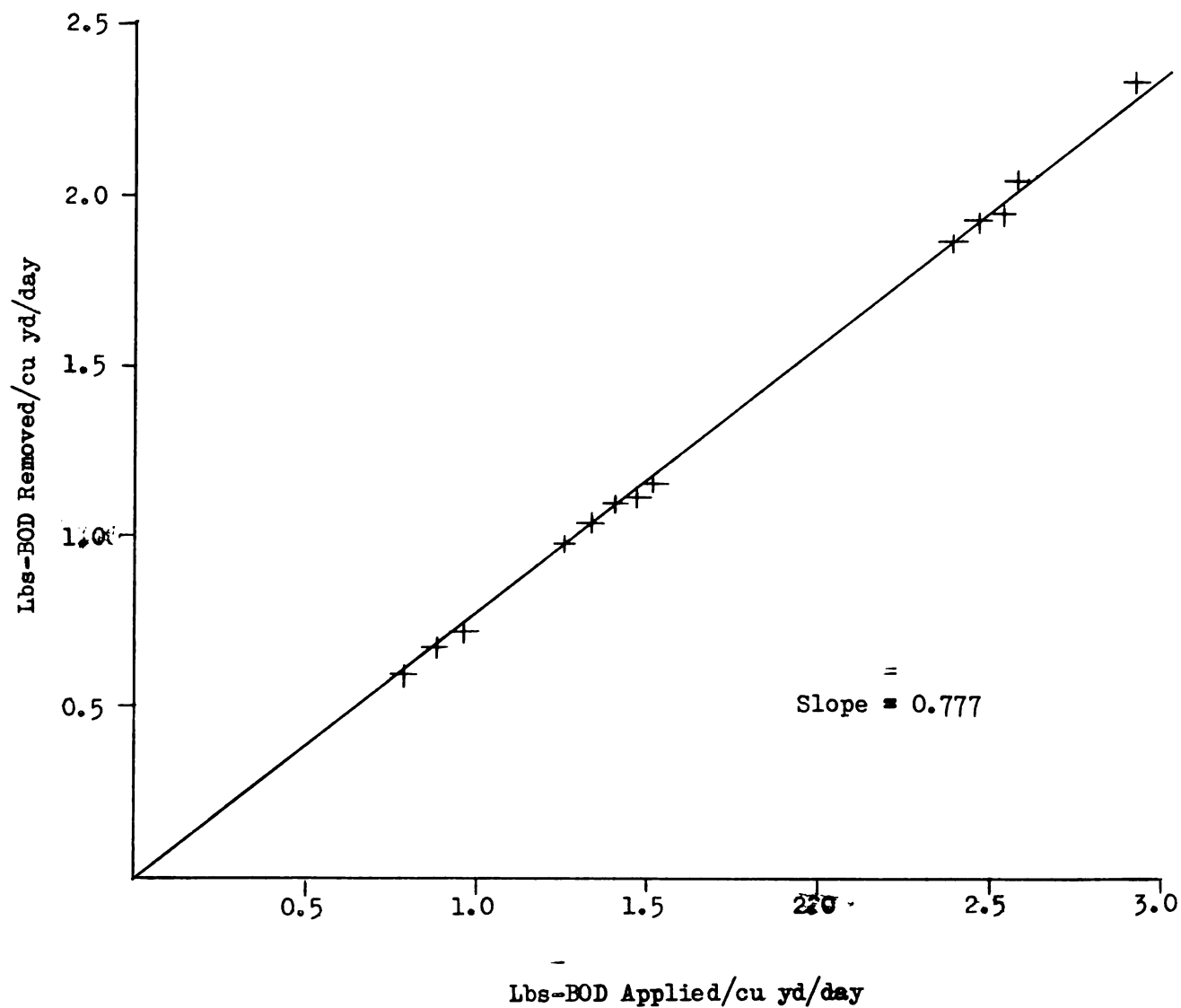


Figure 24. Relationship Between Organic Load Applied and Removed at the Hydraulic Load of 30.8 mgad, Single Pass.

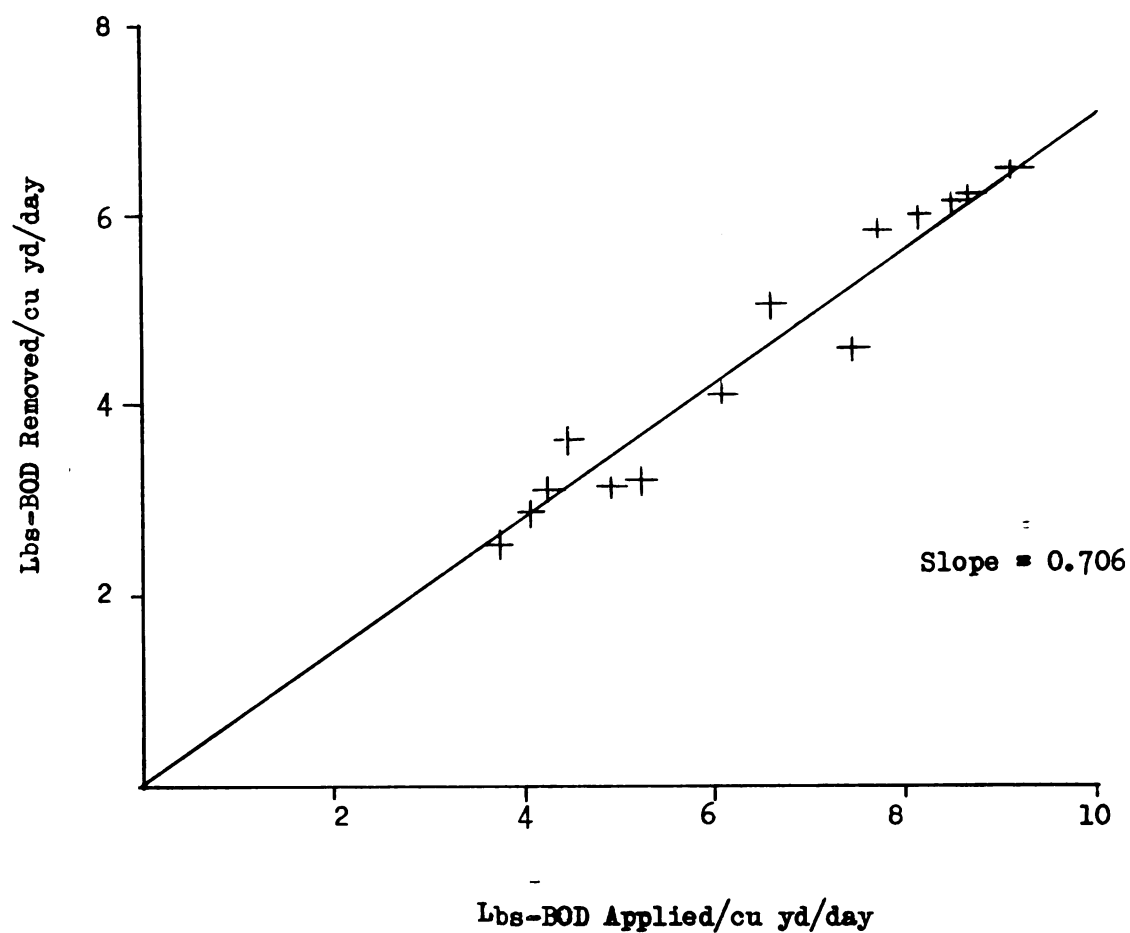


Figure 25. Relationship Between the Organic Load Applied and Removed at the Hydraulic Load of 60.0 mgad, Single Pass.

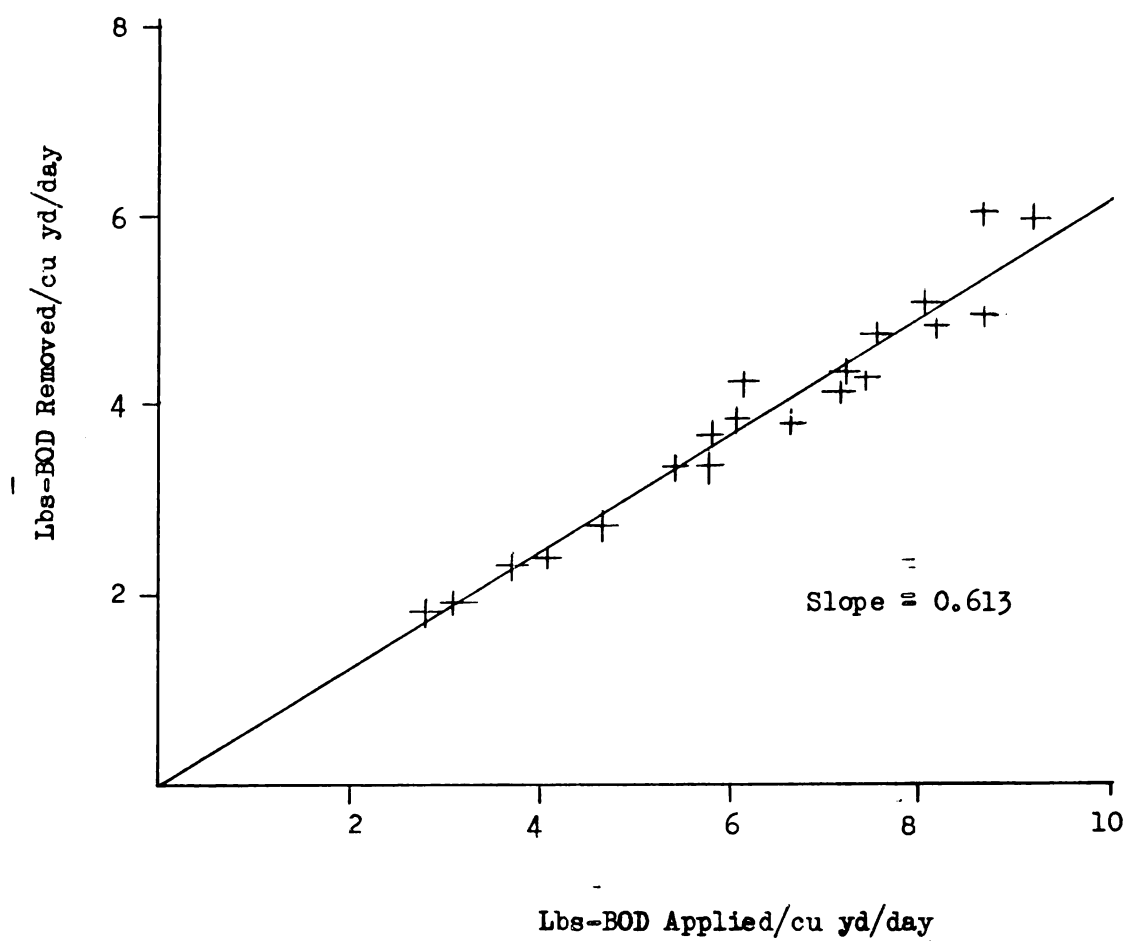


Figure 26. Relationship Between Organic Load Applied and Removed at the Hydraulic Load of 80.0 mgad, Single Pass.

Table II. Effect of Hydraulic Load on One Inch Spaced Screen Under Single Pass Conditions.

Groups	Avg. Hydr. Load (mgd/acre)	Avg. BOD Load (lb/day/ cu yd)	Avg. Efficiency (per cent BOD removed)	No. of Data	Groups Compared	Degrees of Freedom	t	5 per cent Crit Value for t
A	10.3	0.83	80.5 ± 0.62	14	A to B	26	0.114	2.056
B	13.7	1.13	80.7 ± 2.60	14	B to C	26	0.331	2.056
C	24.0	1.23	80.3 ± 1.34	14	C to D	26	0.829	2.056
D	30.8	1.83	77.7 ± 0.90	14	A to D	26	1.840	2.056
E	60.0	6.55	70.6 ± 1.27	13	D to E	25	2.270	2.060
F	80.0	6.30	61.3 ± 1.32	20	E to F	31	4.916	2.040
					D to F	26	5.434	2.056

of the 30.8 and 10.3 mgad flow rates where the critical value of t was 2.056. In contrast the comparison between the 30.8, 60.0 and 80.0 mgad flow rates resulted in t -values which exceeded the 5 per cent critical level. The difference in the efficiencies of 77.7, 70.6 and 61.3 per cent respectively were therefore statistically significant. This demonstrates a decrease in efficiency with increasing hydraulic load.

The fact that the efficiency did not decrease as expected for $Q = 10.3, 13.7$ and 24.0 mgad can probably be explained by recalling that the filter was more or less clogged at the lower hydraulic loads. The clogging decreased as the hydraulic load increased, thus providing more active vertical surface area. At the flow rate of 30.8 mgad the clogging was minimal and for all practical purposes the vertical surface area remained constant for the higher hydraulic loads. The theory that the efficiency is controlled by the hydraulic load presupposes that the active filter surface area remains constant at all hydraulic loads. Obviously this constant condition did not exist at the lower hydraulic loads.

It is reasonable to assume that the removal accomplished in a filter is a function of the length of time the waste is in contact with the biological growth. According to Howland (5) contact time is directly proportional to the depth of the filter and inversely proportional to the two-thirds power of the hydraulic load.

$$t' = D/Q^{2/3} \quad (8)$$

where

t' = factor representing contact time,

D = depth of filter in feet and

Q = hydraulic load in million gallons per acre per day.

The value of t' is not an absolute quantity but it is a function, in part, of the vertical surface area over which the sewage may flow. Schulze (3) found that nearly a straight line relationship existed when log per cent BOD remaining was plotted versus the time factor t' . Figure 27 is a plot of the same variables for the data collected in this study. The points do not fall on a straight line but it must be remembered that the filter was clogged at the lower hydraulic loads. The vertical active surface area was therefore changing until the 30.8 mgad flow rate was exceeded. For the purpose of discussion the dashed line shown in Figure 27 will be assumed to represent the filter performance when the entire vertical surface was being used. The expected values of the per cent BOD remaining are shown for the lower hydraulic loads. An equation of the monomolecular type can be written for the line shown. Schulze (3) has developed such an equation:

$$\frac{Le}{Li} = 10^{-KD/Q^{2/3}} \quad (9)$$

where

Le = final effluent BOD (mg/l),

Li = BOD of flow to the filter (mg/l),

Q = hydraulic load in mgad,

D = depth of filter in feet and

K = the slope of the line with respect to t' .

It follows:

$$K = \frac{\log(Li/Le)}{D/Q^{2/3}}$$

Assuming the straight line shown in Figure 27 to be correct, the value of the slope is $K = 1.49$ and a plot can be made of the theoretical efficiency of the filter unit. Figure 28 shows this curve with the

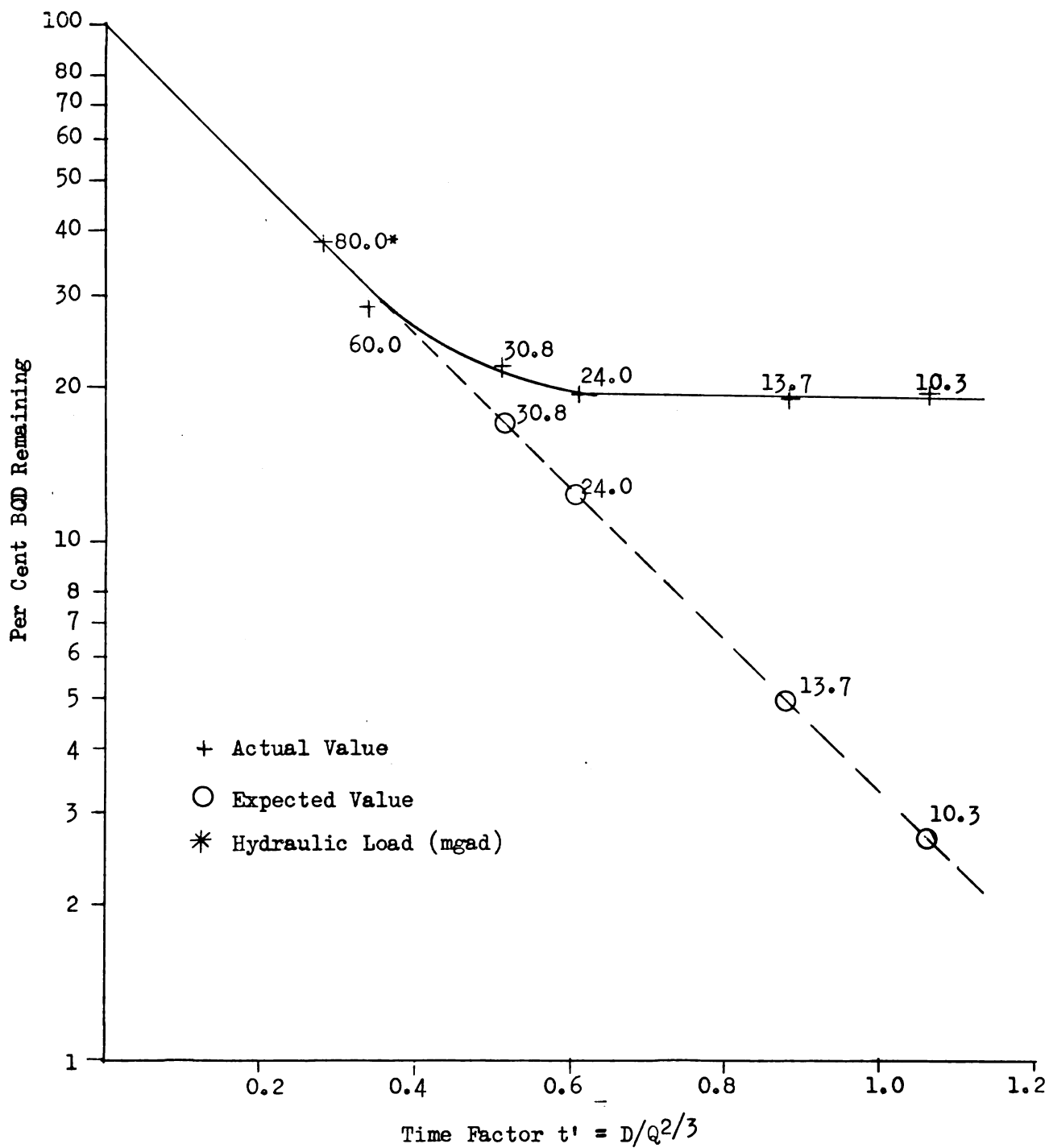


Figure 27. Relationship Between Per Cent BOD Remaining and Time Factor t' Under Single Pass Conditions

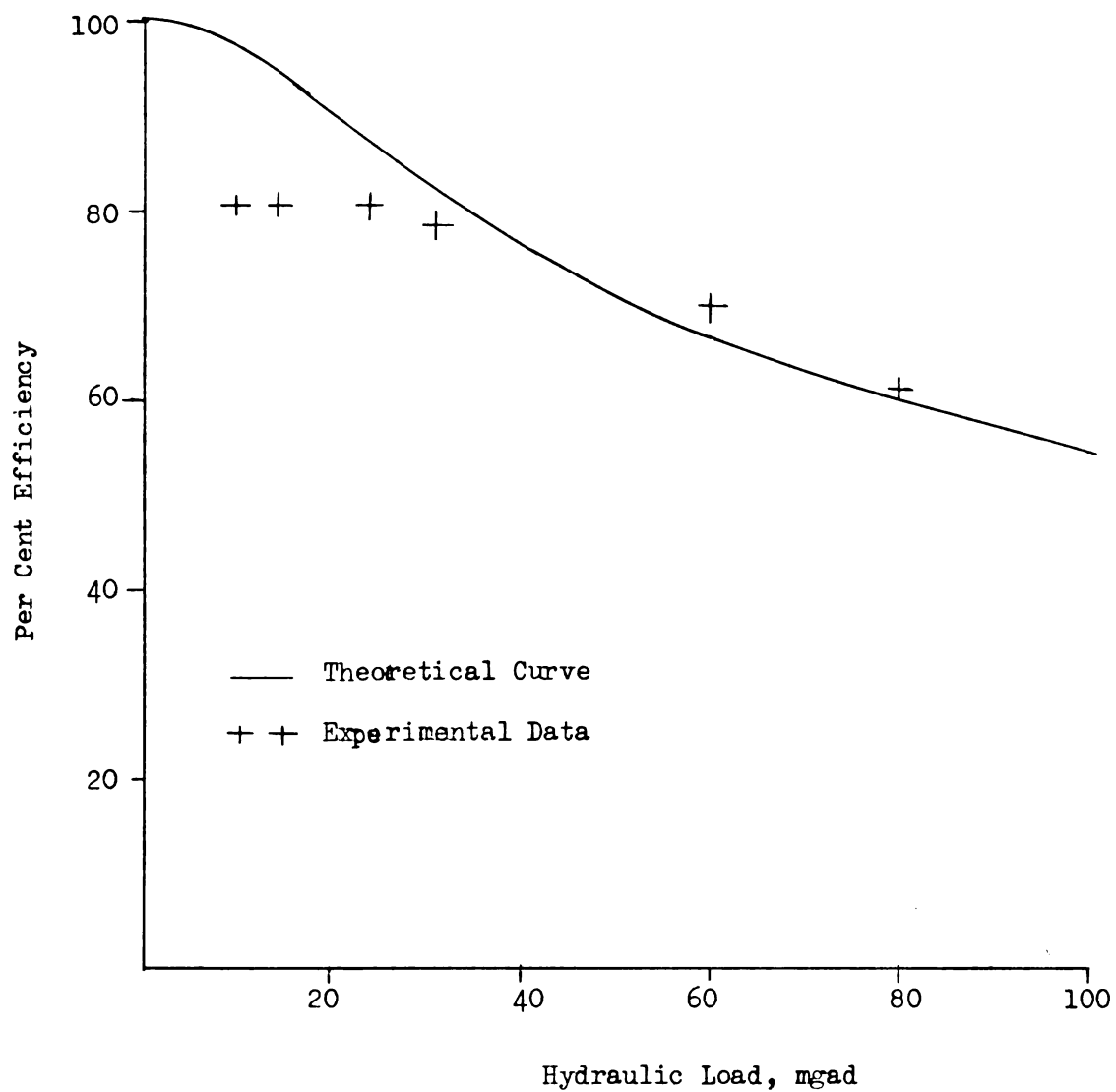


Figure 28. Relationship Between Hydraulic Load and Efficiency,
D = 5 feet, K = 1.48, one inch screen.

experimental data for comparison. At hydraulic loads from 30.8 mgad on up the data fit the curve within reasonable limits but at the lower loads the efficiency drops off rapidly. The value of K for the low hydraulic loads was very much smaller than that at the higher loads because of clogging in the filter with the resulting decrease in active vertical surface area. Figure 29 shows a plot of the K value for each of the experimental hydraulic loads. It appears that K is a function of the hydraulic load for the experimental filter and that a maximum value is reached at 60 mgad.

Table III shows the average data on temperature of the incoming waste, the pH of the incoming flow as well as the final effluent, the dissolved oxygen of the final effluent and the nitrate and nitrite concentration of the final effluent.

The pH of the waste increased from 0.12 to 0.26 points in the process of passing through the filter. The maximum average pH was 7.60 and the minimum was 7.36 for the incoming flow and 7.81 and 7.54 respectively for the final effluent. Apparently the increasing hydraulic load had no effect on the pH of the final effluent.

The nitrification of the final effluent decreased as the hydraulic load increased. The nitrate concentration varied from 5.43 mg/l at 10.3 mgad to 0.60 mg/l at 80.0 mgad. The nitrite concentration which was always less than the nitrate concentration varied from 3.00 mg/l at 10.3 mgad to 0.04 mg/l at 80.0 mgad. This result was expected as the degree of nitrification is a function of the time the waste is in contact with the biological film. The nitrate concentration was always greater than the nitrite concentration because it is the more stable form of the two.

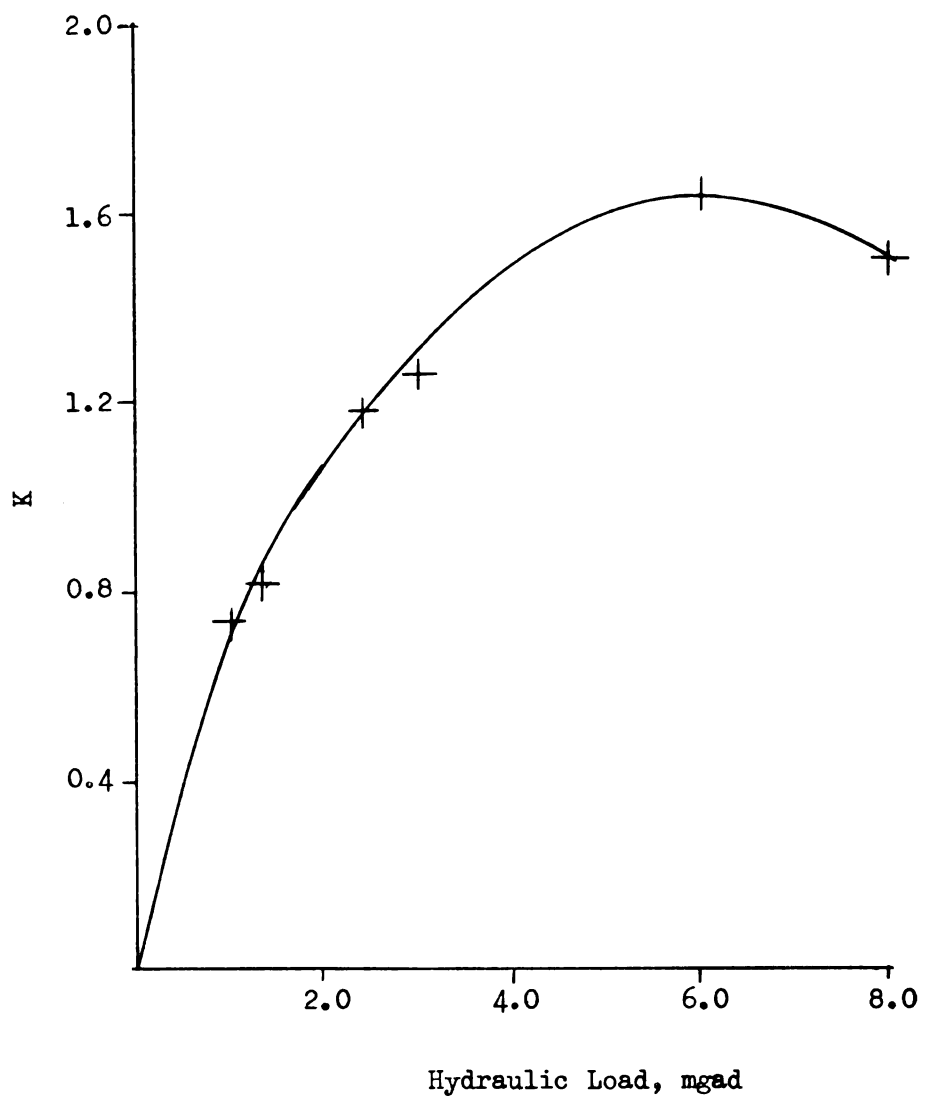


Figure 29. Values of K at Various Hydraulic Loads

TABLE III. Data for Single Pass Operation, One Inch Screen Spacing.

Hydr. Load mgad	Ave. Temp. C°	pH		DO in Eff. mg/l	Nitrogen in final Eff. mg/l	
		in	out		NO ₂	NO ₃
10.3	19.7	7.50	7.66	2.08	3.00	5.34
13.7	17.1	7.42	7.54	1.67	2.32	5.00
24.0	14.8	7.55	7.81	2.00	1.73	4.65
30.8	14.0	7.55	7.76	3.82	0.49	2.20
60.0	13.0	7.60	7.80	0.57	0.10	0.75
80.0	14.0	7.36	7.61	0.40	0.04	0.60

The average dissolved oxygen concentration in the 24 hour composite samples of the final effluent varied between 1.67 and 3.82 mg/l except in the case of the 60 and 80 mgad flow rates. The low dissolved oxygen concentrations at the latter two hydraulic loads were probably caused by the fact that these samples contained a relatively high concentration of suspended solids which were carried over from the final settling tank. These solids depleted the dissolved oxygen during the 24 hour sampling period.

Periodic grab samples were taken from the final sampling box at all hydraulic loads and there was always at least 6.5 mg/l dissolved oxygen in the final effluent. Checks were also made of the dissolved oxygen concentration of the liquid samples taken directly from the screens and the results were always within 75 per cent of saturation for the temperature of the waste at the time of sampling. The average temperature of operation ranged from 13.0° C to 19.7° C as shown in column 3.

The results of the suspended solids measurements are shown in Table IV. The per cent suspended solids removed varied from 67.0 to 81.0. The average removal for the single pass study was 74.0 per cent. A comparison of the composition of the incoming and outgoing suspended solids with respect to the fixed solids in per cent dry matter shows that in most cases the outgoing suspended solids had a higher ash content (30.0 to 50.0 per cent) than the incoming solids (21.6 to 42.2 per cent). In general the data indicated that the varying hydraulic load had no effect on the removal of suspended solids.

3. Operation under recirculation.

Recirculation has been used for many years to improve the quality

Table IV. Suspended Solids Data, One Inch Spacing, Single Pass Conditions.

Hydr. Load mgad	Total Suspended Solids mg/l			Fixed Solids % Dry Matter	
	in	out	% removed	in	out
10.3	83	21	75.0	36.0	38.0
13.7	83	27	67.0	21.6	48.0
24.0	129	37	71.0	31.0	46.0
30.8	108	20	81.0	40.8	30.0
60.0	88	23	74.0	41.0	52.0
80.0	121	30	75.0	42.2	50.0

of the effluent from sewage treatment plants. The basic concern has been the overall efficiency of the filter unit. Most designers have treated recirculation as part of a closed system and thus have compared the flow coming from the primary settling tanks to the final effluent using the flow through the plant as the hydraulic loading rate. The organic load has been computed on the basis of the incoming flow regardless of the rate of recirculation.

In this study the incoming flow was maintained at 10 mgad and the efficiency of operation under the recirculation ratios of 1:1, 2:1, 3:1 and 4:1 was determined.

There are two methods of evaluating filter performance under recirculation conditions. Method 1 relates the incoming BOD concentration to the BOD concentration of the final effluent which defines the overall efficiency of the operation. Method 2 relates the BOD concentration of the mixed flow (incoming flow plus recirculation flow) to the BOD concentration of the final effluent. According to this method the filter is visualized as a single pass filter treating the BOD of the incident mixed flow. The following example is given to demonstrate the difference in the efficiencies obtained:

Example:

Given: Q = incoming flow of 10 mgad at a BOD of 100 mg/l.

R = recirculation flow of 20 mgad - final eff. BOD
30 mg/l.

Method 1: Efficiency related to incoming BOD

$$\% \text{ Efficiency} = \frac{100 - 30}{100} \times 100 = 70.0\% \text{ for 10 mgad flow rate.}$$

Method 2: Efficiency related to incident BOD

$$\text{Incident flow} = R + Q = 20 + 10 = 30 \text{ mgad}$$

Incident BOD concentration =

$$\frac{100 \times 10 + 30 \times 20}{30} = 53.3 \text{ mg/l BOD}$$

$$\% \text{ Efficiency} = \frac{53.3 - 30}{53.3} \times 100 = 43.8\% \text{ for 30 mgad incident}$$

flow.

Figures 30 through 33 show the efficiencies obtained according to Method 1. The efficiencies ranged from 88.4 to 83.7 per cent regardless of the recirculation ratio. This is in contrast to general experience where recirculation should increase the efficiency.

The lower part of Table V shows a statistical comparison of the differences between the efficiencies, the average BOD load in lbs-BOD/cu yd/day, the value of t from the t-test and the 5 per cent critical value of t. Column 3 shows that the efficiency at 4:1 recirculation is less (83.7 per cent) than at 2:1 recirculation where the efficiency was 88.4 per cent. The application of the t-test showed the difference to be statistically significant. The efficiencies at the 1:1 and 3:1 recirculation ratios were 86.8 and 86.2 respectively and the differences were statistically not significant. The organic load per unit volume of the filter varied from 1.18 to 0.77 lbs-BOD/cu yd/day as shown in column 4. The standard deviation of the efficiency line varied from 0.71 to 0.47 per cent which is small for this type of study.

Figures 34 through 37 show the efficiencies obtained according to Method 2. The slopes were placed by the method of least squares and the resulting lines were straight and passed through the origin. The efficiencies obtained from the slopes together with a statistical comparison by the t-test are shown in the upper part of Table V. The efficiencies decreased steadily with increasing hydraulic loads from 76.0 to 50.3

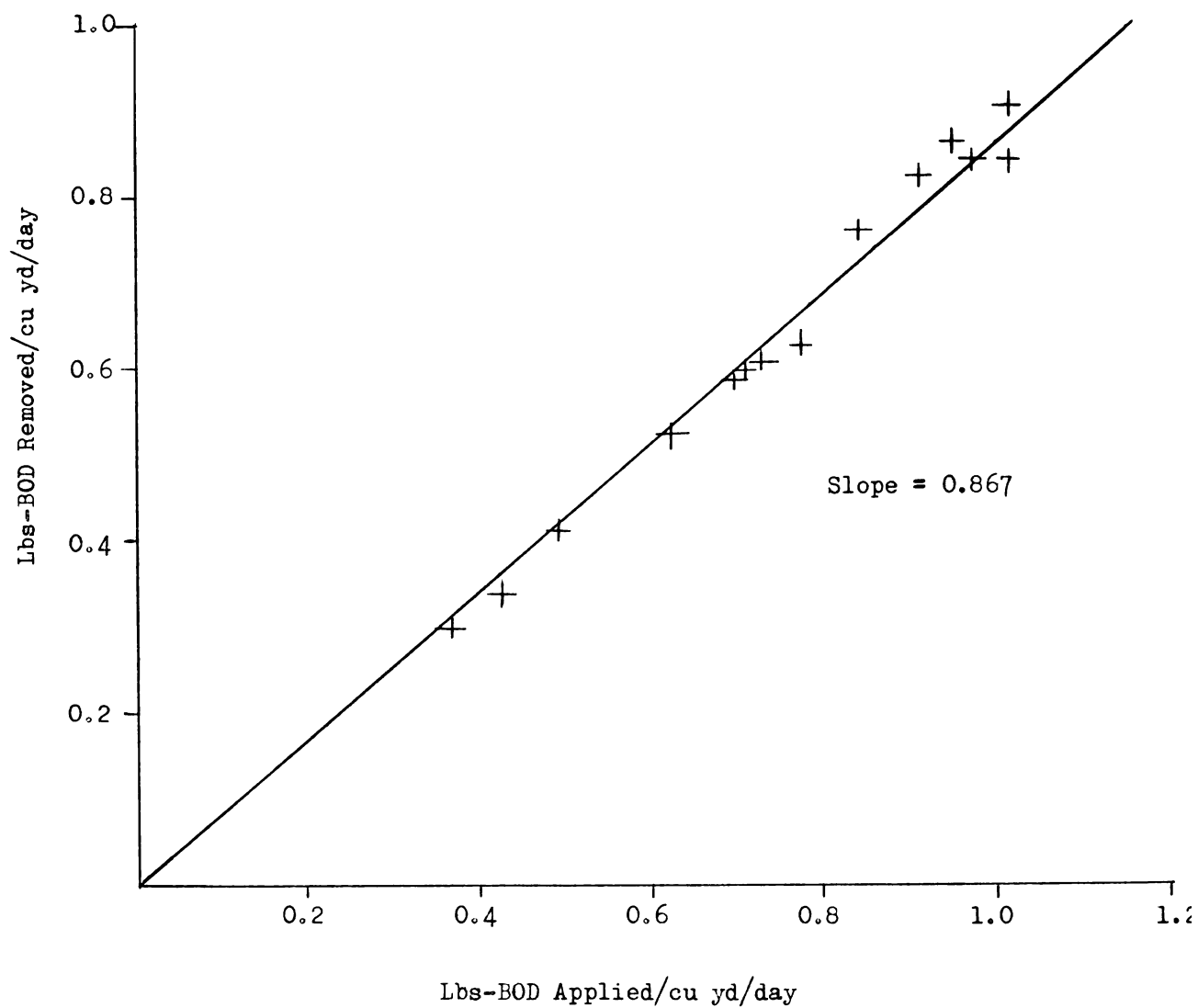


Figure 30. Relationship Between Organic Load Applied and Removed for mgad Incoming Flow and 1:1 Recirculation.

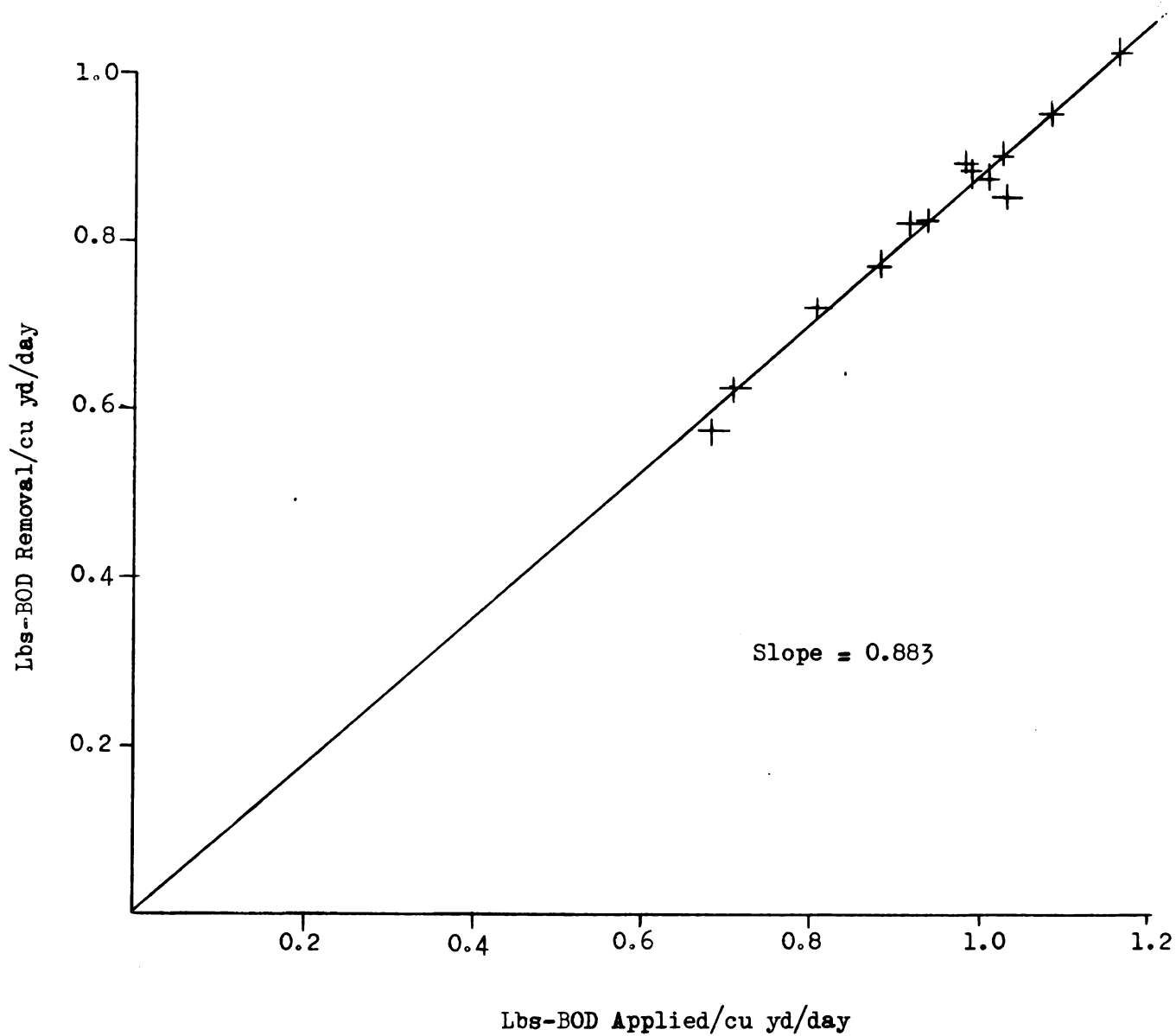


Figure 31. Relationship Between Organic Load Applied and Removed for 10 mgad Incoming Flow and 2:1 Recirculation.

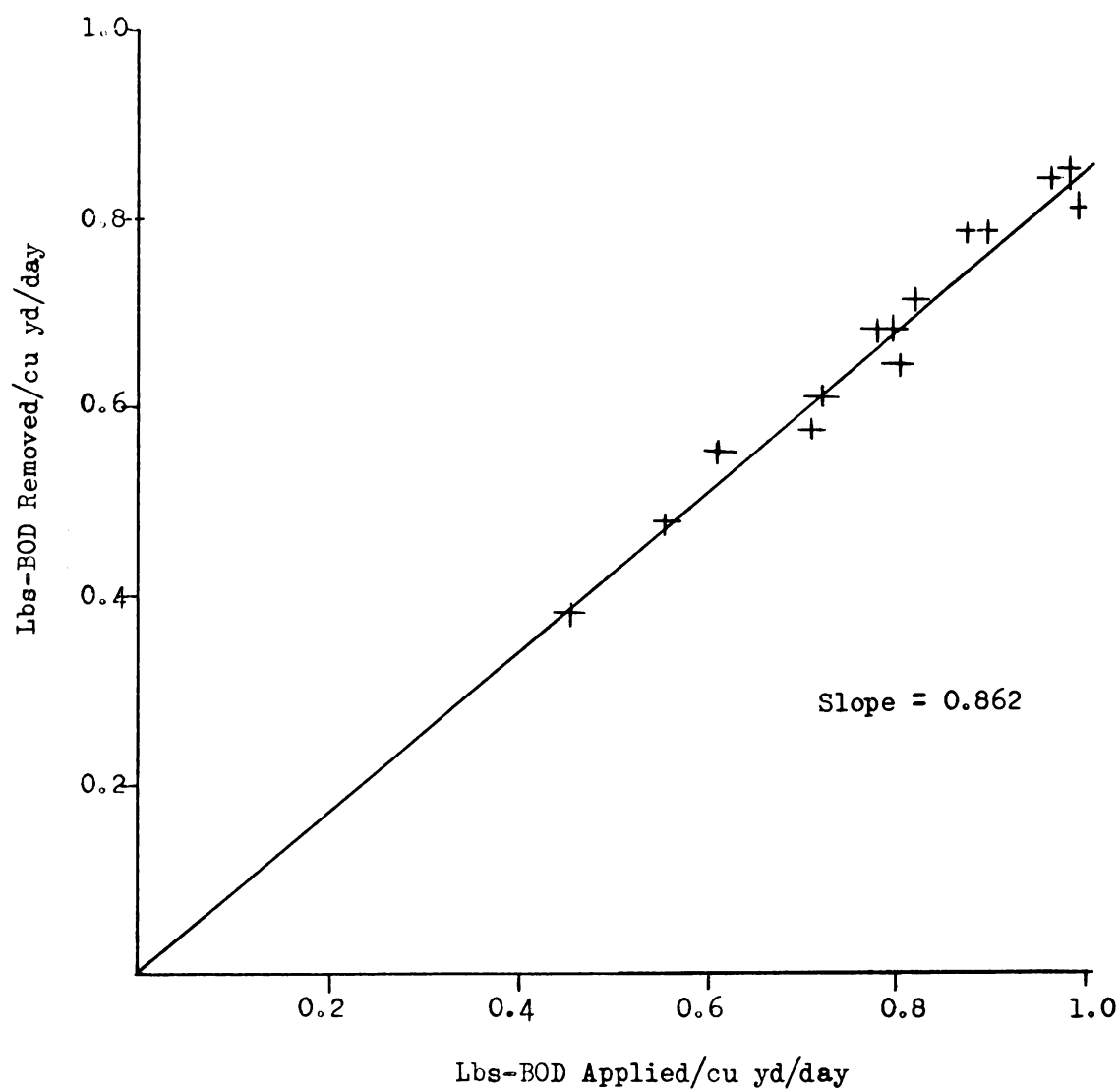


Figure 32. Relationship Between Organic Load Applied and Removed for 10 mgad Incoming Flow and 3:1 Recirculation.

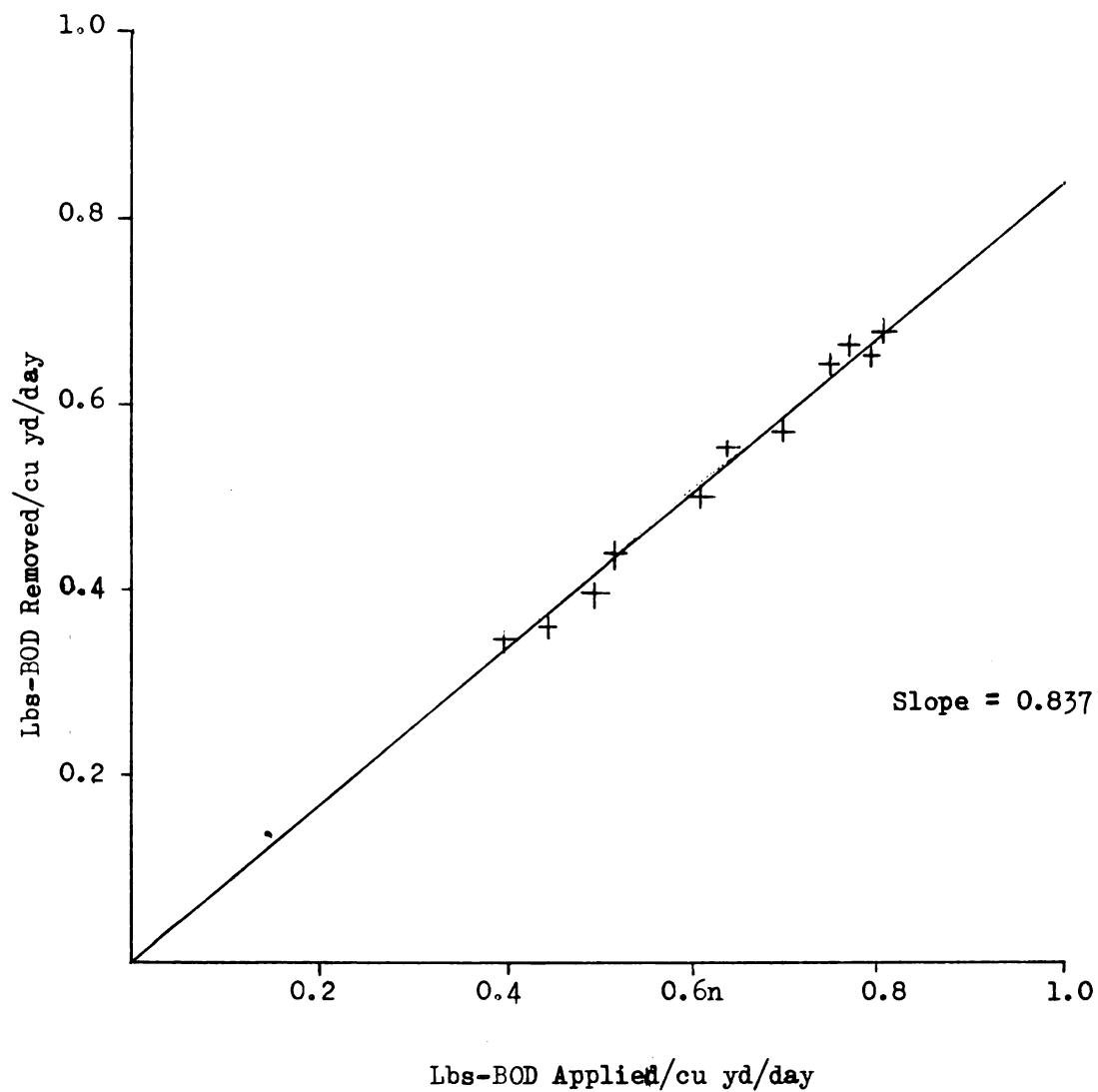


Figure 33. Relationship Between Organic Load Applied and Removed for 10 mgad Incoming Flow and 4:1 Recirculation.

Table V. Effect of Recirculation as Related to Incident Flow and Incoming Flow.

Group	Rec. Ratio r	Avg. Hydr. Load (mgd/acre)	Avg. BOD Load (lb/day/ cu yd)	Avg. Efficiency (per cent) BOD removed)	No. of Data	Groups Compared	Degrees of Freedom	t	5 per cent crit. value for t
G	1	20.0	0.85	76.0 $\pm$ 1.64	18	G to H	29	1.999	2.045
H	2	30.0	1.18	73.5 $\pm$ 1.34	13	H to I	23	3.986	2.069
I	3	40.0	1.13	61.7 $\pm$ 1.84	14	I to J	25	4.459	2.060
J	4	50.0	0.77	50.3 $\pm$ 1.22	11	G to H	27	5.324	2.052
K	1	10.0	0.85	86.8 $\pm$ 0.52	18	K to L	29	1.194	2.045
L	2	10.0	1.18	88.4 $\pm$ 0.47	13	L to M	23	1.734	2.069
M	3	10.0	1.13	86.2 $\pm$ 0.63	14	M to N	25	1.825	2.060
N	4	10.0	0.77	83.7 $\pm$ 0.71	11	L to N	27	2.473	2.052

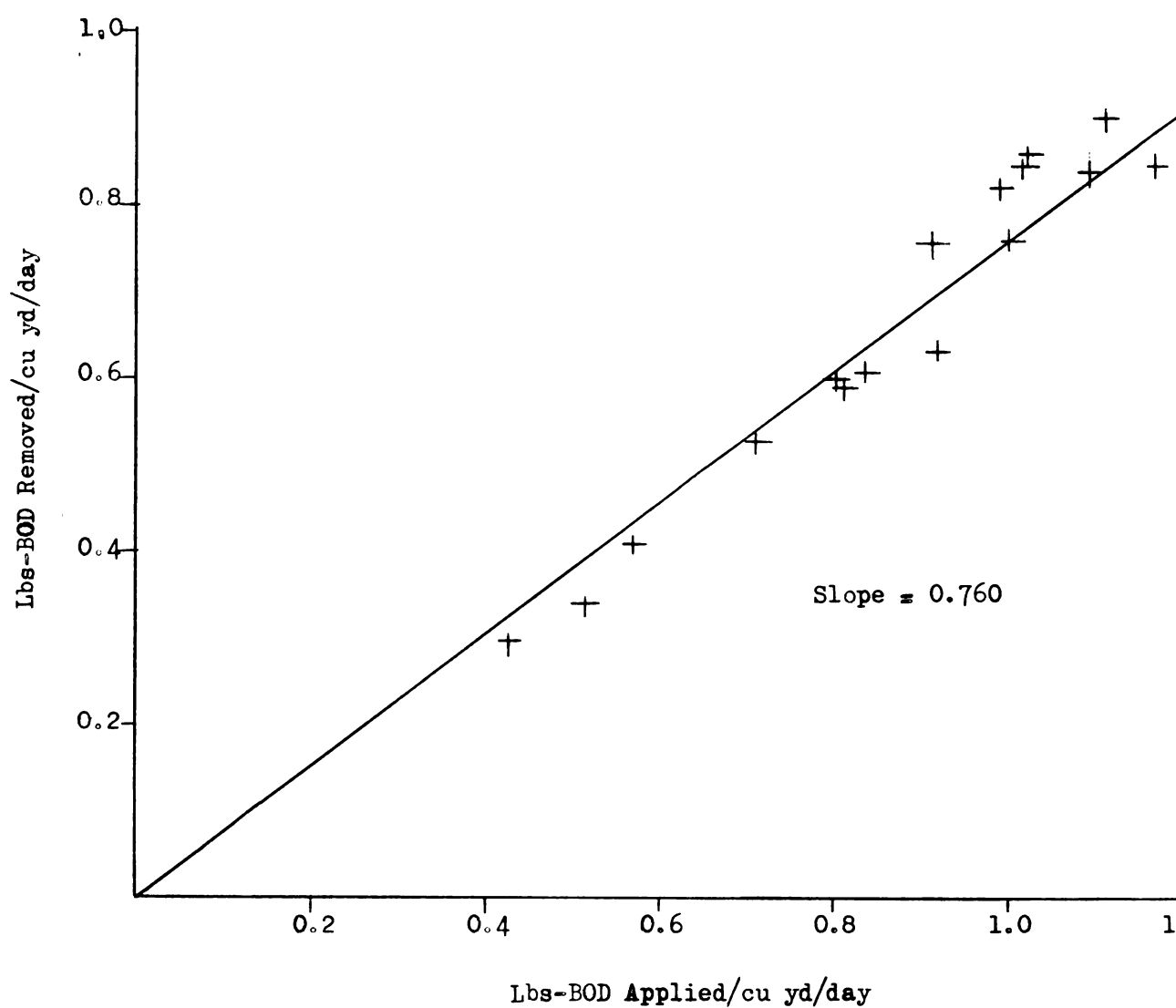


Figure 34. Relationship Between Organic Load Applied and Removed at 1:1 Recirculation Based on Mixed Flow.

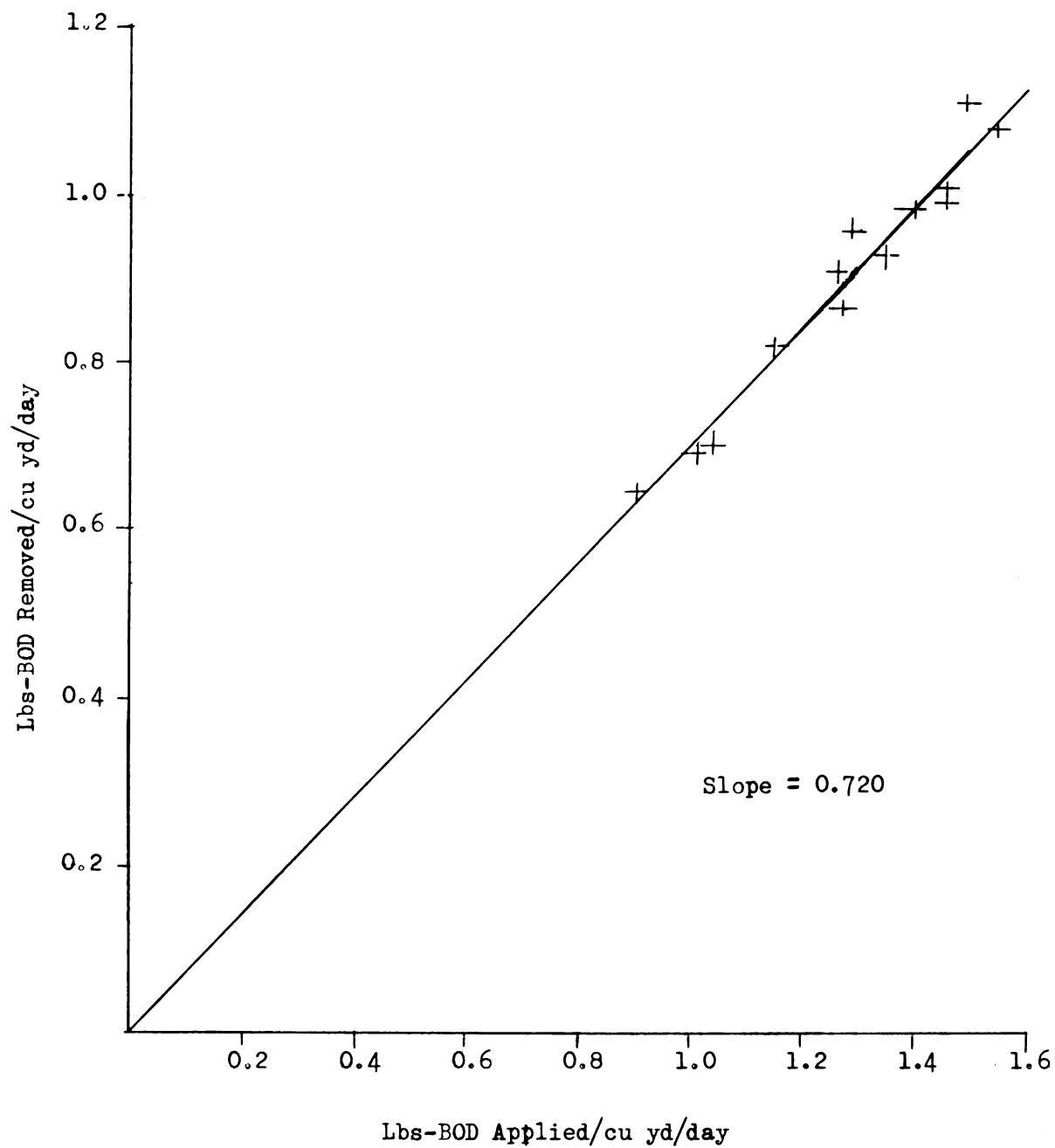


Figure 35. Relationship Between Organic Load Applied and Removed at 2:1 Recirculation Based on Mixed Flow.

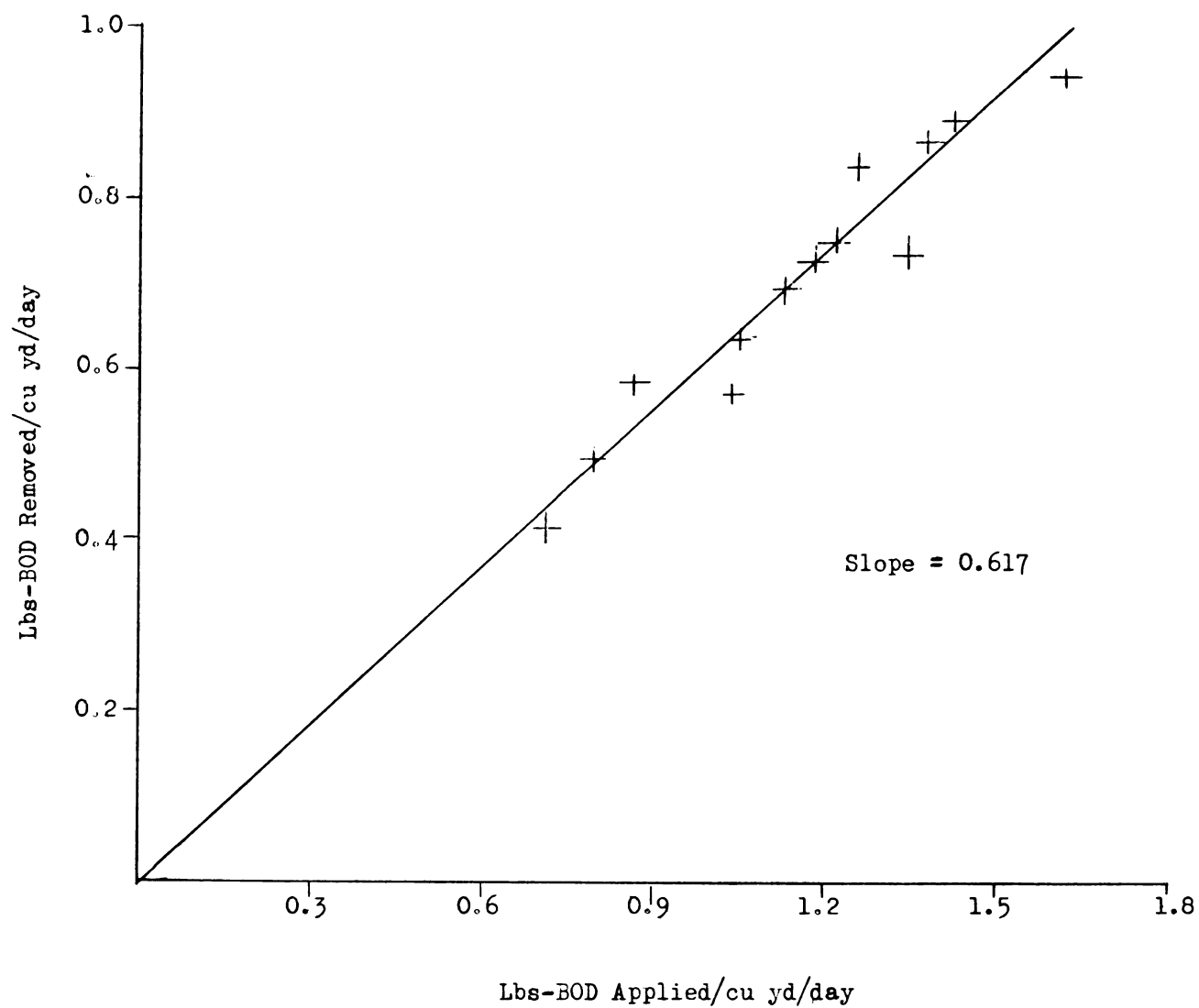


Figure 36. Relationship Between Organic Load Applied and Removed at 3:1 Recirculation Based on Mixed Flow.

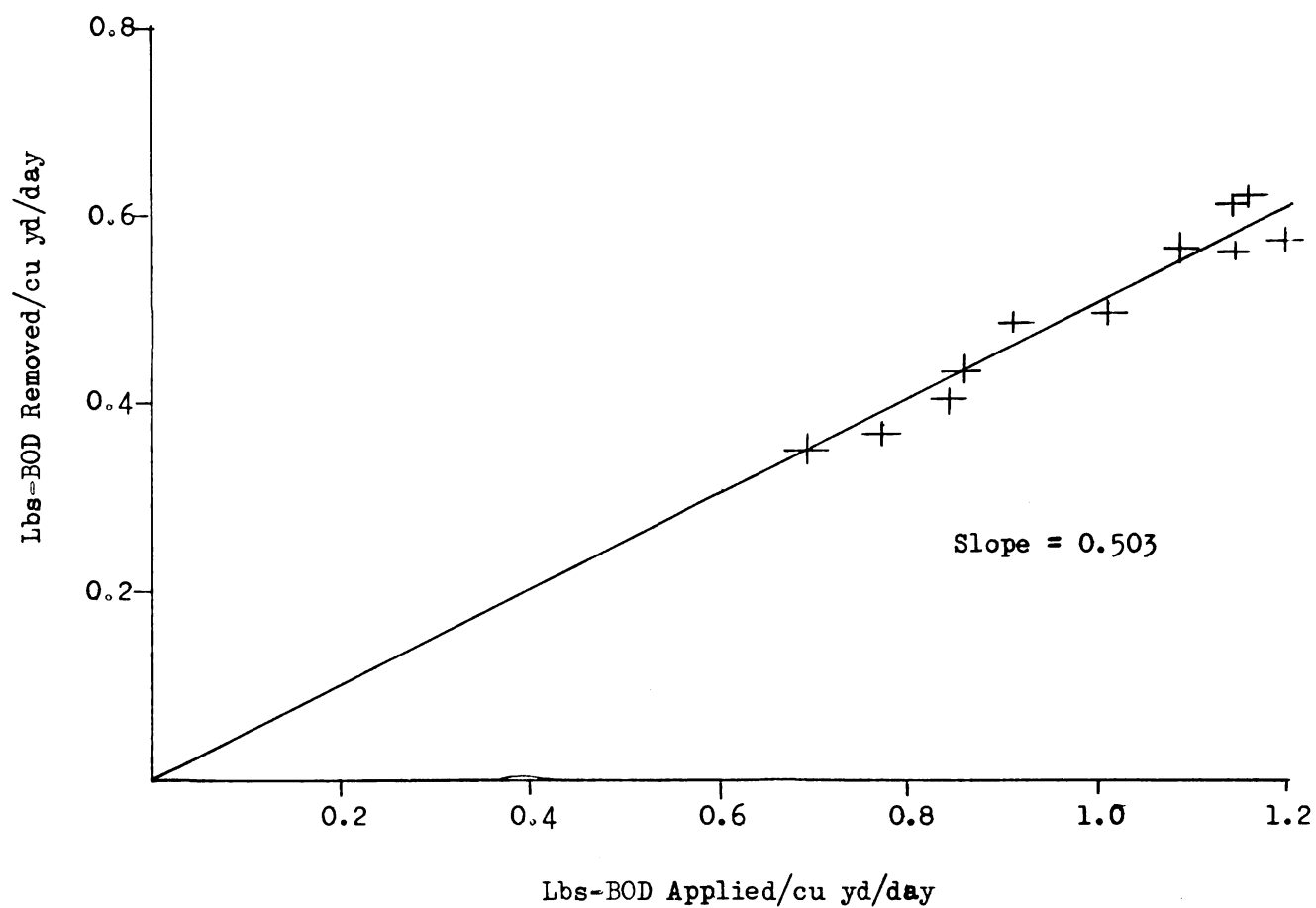


Figure 37. Relationship Between Organic Load Applied and Removed at 4:1 Recirculation Based on Mixed Flow

per cent in contrast to the results given by Method 1. The standard deviation of the efficiency line varied from 1.84 to 1.22 per cent as shown in column 5. Columns 9 and 10 show the result of the statistical comparison of the efficiencies obtained for the four recirculation ratios. A statistically significant difference between efficiencies can be shown in all cases except between the 1:1 and 2:1 recirculation ratios which correspond to the incident flows of 20 and 30 mgad. Since it was observed that a certain degree of clogging occurred at the 1:1 recirculation ratio it is felt that a statistically significant difference would have been found had the filter operated clog free. The value of t in this case was 1.999 and very close to the 5 per cent critical value of 2.045.

The thickness of the biological film was considerably less than that under single pass conditions. The total thickness was 1 cm or less compared to 2.5 to 1.0 cm found for single pass conditions. Apparently this difference was caused by the reduction of the BOD concentration as the result of the diluting effect of the recirculation.

The efficiencies obtained according to Method 2 can be plotted in the same manner as those obtained under single pass conditions. Figure 38 is a semilogarithmic plot showing the relationship of the per cent BOD remaining versus the time factor $t' = D/Q_2^{2/3}$. In this case the resulting line is a straight one. The reason is probably given by the fact that under recirculation no clogging occurred except for a small amount at the 1:1 or 20 mgad flow rate. A similar equation to that used for single pass operation can be written for recirculation related to incident flow:

$$\frac{L_e}{L_m} = 10^{-K_r D / Q_2^{2/3}} \quad (10)$$

where:

L_e = BOD concentration in final effluent (mg/l),

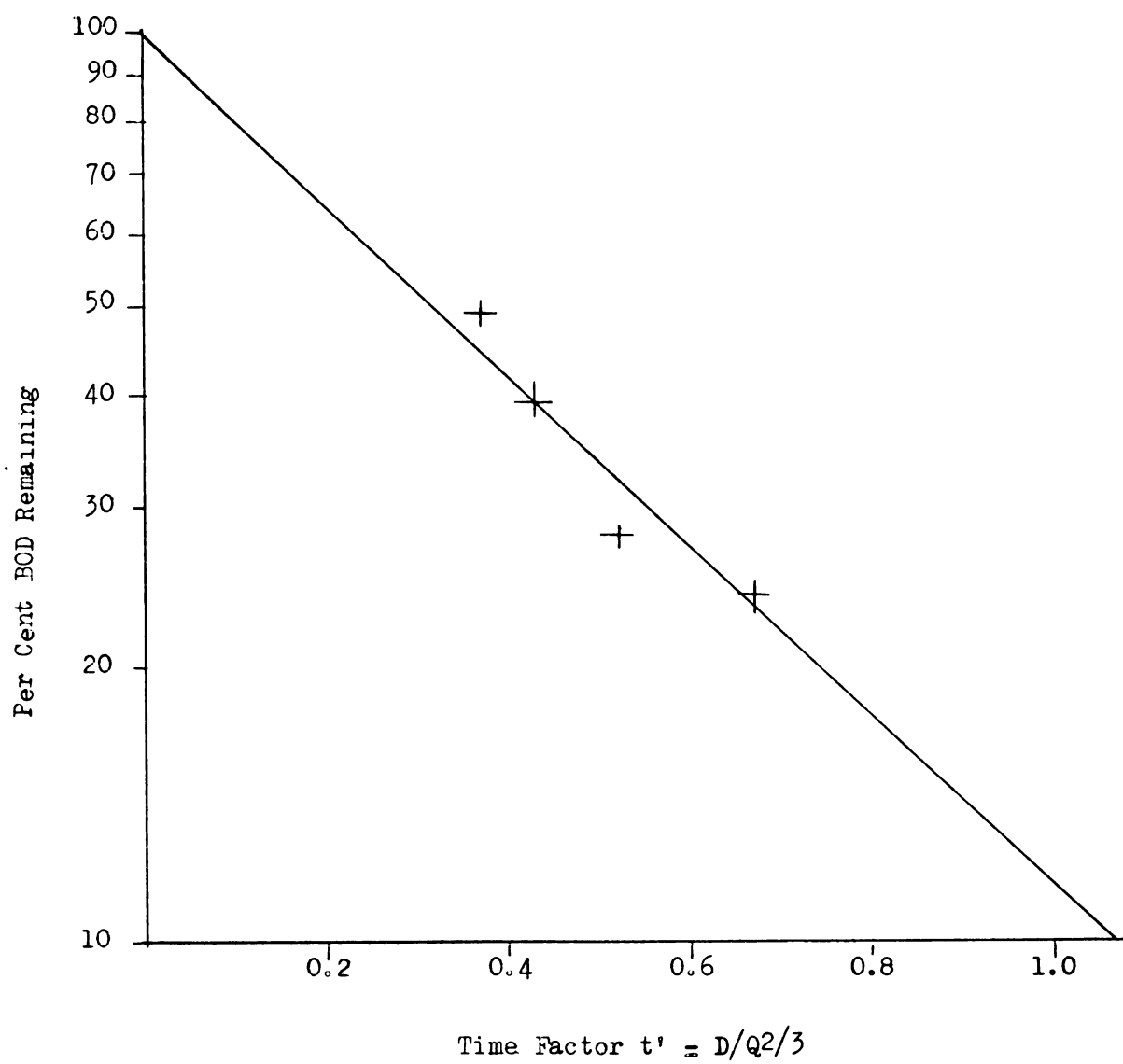


Figure 38. Relationship Between Per Cent BOD Remaining and Time Factor t' under Recirculation.

L_m = BOD concentration of incident flow $R + Q$ (mg/l),

Q_2 = incident hydraulic load ($R + Q$), mgad,

D = depth of filter in feet and

K_r = a constant.

The value of the constant K_r from Figure 38 was found to be 0.943. This value is lower than the maximum K value found for single pass conditions. The value of K found in the single pass study fluctuated considerably because of the clogging effect. Figure 39 shows a plot of K_r versus hydraulic load. The points appear to scatter about the line shown for a constant K_r of 0.943. Apparently the value of K is not a constant for a given filter under all conditions. Such factors as BOD concentration, treatability of the waste, pH, temperature and evenness of distribution all may have an effect on K even if the vertical surface area remains constant. It is felt that the concept of the K value is sound but so far not enough data are available to evaluate the relationship between K and the above mentioned factors.

Figure 40 shows the theoretical efficiency curve, using equation (10) with K_r equal to 0.943 for a filter of five foot depth. The experimental values were also plotted and there appears to be good agreement.

As shown in Table VI the final effluent contained from 0.81 to 1.10 mg/l dissolved oxygen. The concentration was not as high as that found in the single pass study. The grab samples taken directly from the bottom of the filter and from the final settling tank were again found to be within 75 per cent of saturation for the temperature of operation. There was no apparent correlation between the hydraulic load and the dissolved oxygen of the final effluent in the case of recirculation.

Table VI also shows that the nitrification of the final effluent

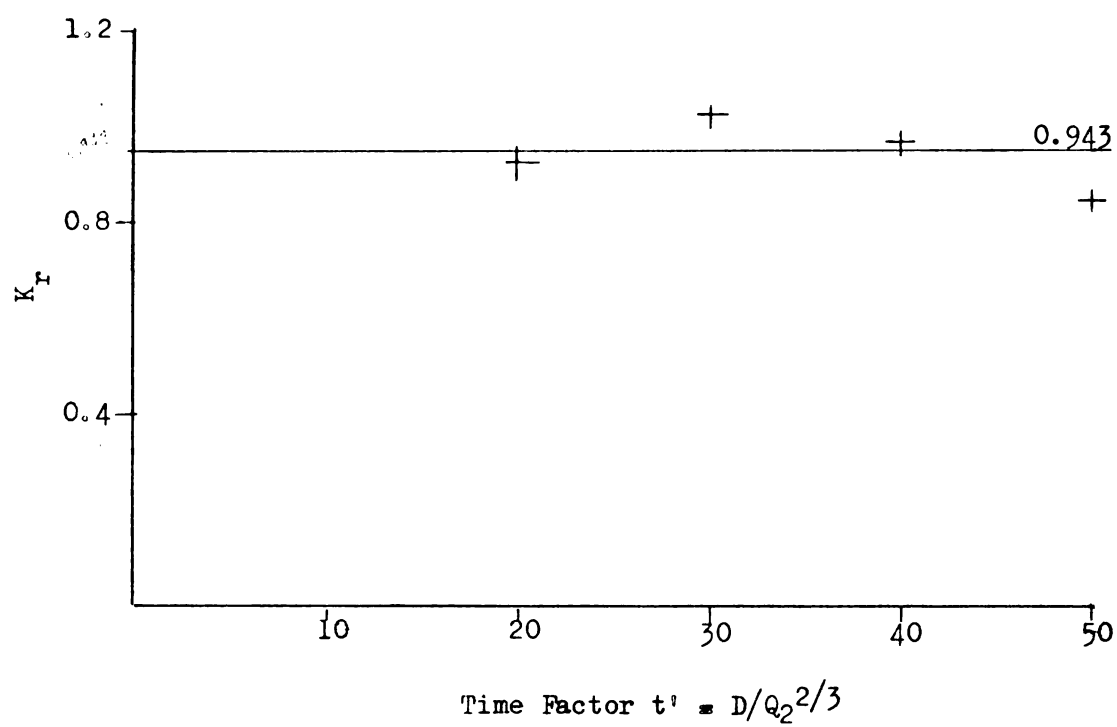


Figure 39. Relationship Between K_r and Incident Hydraulic Load.

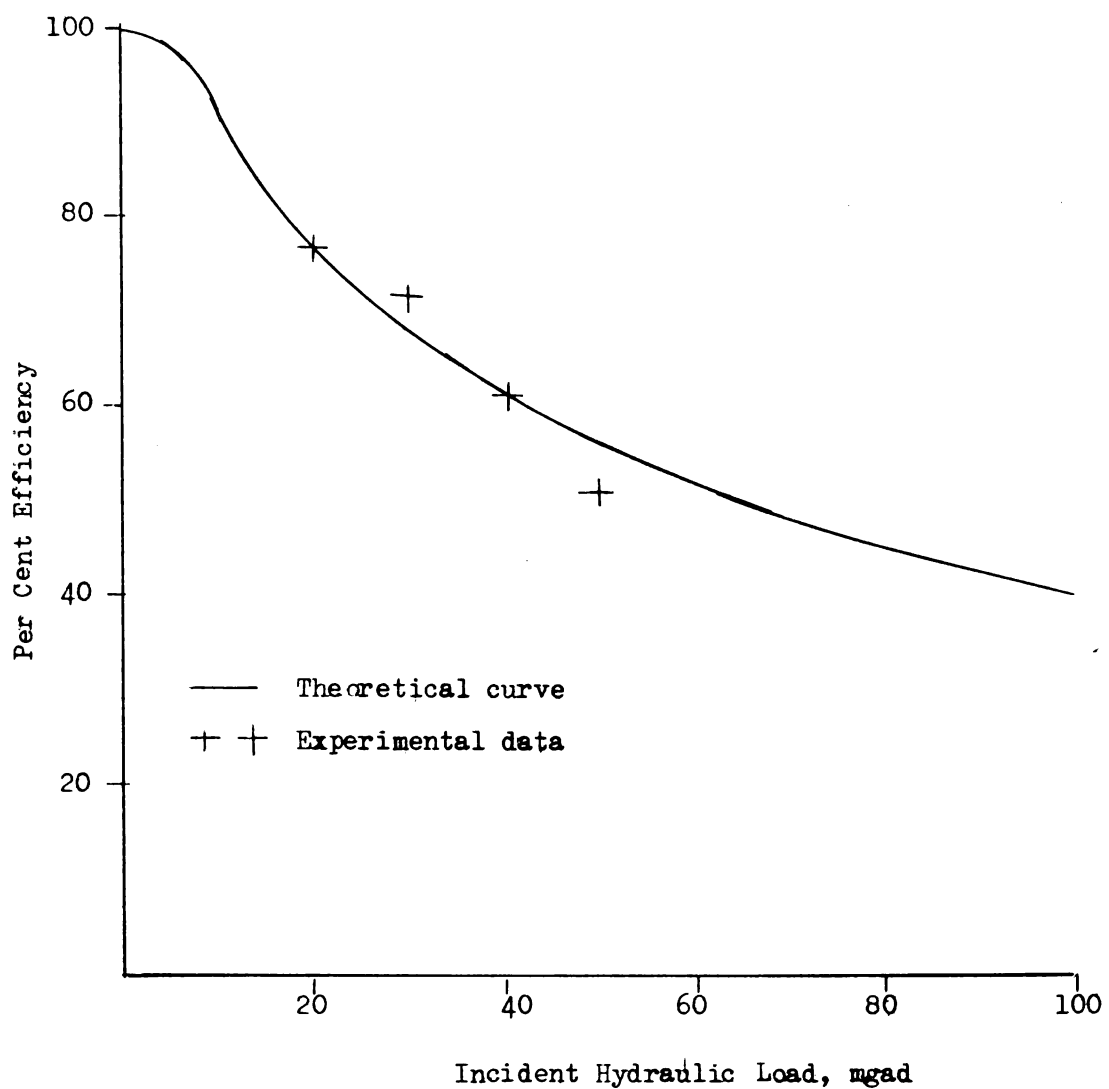


Figure 40. Theoretical Plot of Efficiency Versus Incident Hydraulic Load. $D = 5$ feet, $K = 0.943$, Under Recirculation.

Table VI. Data for Recirculation, One Inch Screen.

Rec. Ratio r*	Hydr. Load mgad	Ave. Temp. C°	Ave. pH		DO in eff. mg/l	Nitrogen in final eff. mg/l	
			in	out		NO ₂	NO ₃
1	20.0**	18.1	7.43	7.69	1.10	1.55	4.80
2	30.0	17.0	7.35	7.78	0.87	1.22	2.62
3	40.0	16.3	7.34	7.71	1.00	0.34	0.84
4	50.0	14.5	7.45	7.73	0.81	0.06	0.60

* Recirculation ratio is return flow over incoming flow.

** Including recirculation.

decreased as the hydraulic load increased. The nitrate concentration varied from 4.80 at 1:1 to 0.60 at 4:1 recirculation ratios. The nitrite concentration varied from 1.55 at 1:1 to 0.06 at 4:1 recirculation ratios. The nitrate was always greater than the nitrite concentration because the nitrate is the more stable form of nitrogen. The degree of nitrification decreased with increasing incident hydraulic load as it did in the single pass study. In general it appears that recirculation does not increase the nitrification of the final effluent as compared to single pass operation.

The pH of the waste was increased in the process of passing through the filter from 7.34 to 7.78. The average temperature of the incoming flow showed a gradual decrease from 18.1 to 14.5° C.

The removal of suspended solids as shown in Table VII was about 75 per cent of the incident concentration (based on computed values) which was approximately the same percentage found under single pass conditions. Under single pass conditions the suspended solids removal ranged from 67.0 to 81.0 per cent and under recirculation related to incident flow the per cent removal varied from 51.0 to 86.0. With recirculation the overall per cent removal of suspended solids, when related to incoming flow, was 94.7 to 83.8 per cent. The data indicate that recirculation improves the overall suspended solids removal as compared to single pass operation.

The ash in per cent dry matter of the suspended solids incoming to the filter ranged from 29.0 to 34.7 per cent and the final effluent contained from 40.0 to 68.5 per cent as shown in Table VII, columns 6 and 7. The increase in ash varied from 10.6 to 23.8 per cent and the percentage difference appeared to increase with increasing hydraulic load. The same comparison can be made with regard to the incident suspended solids results as they are based on computation of incoming and final effluent values.

Table VII. Suspended Solids Data as Related to Incident and Incoming Hydraulic Load.

Rec. Ratio r	Hydr. Load mgad	Total Suspended Solids mg/l			Fixed Solids	
		in	out	% removed	% Dry in	Matter out
Incident Flow						
1	20.0	50	14.0	72.0	30.0	42.8
2	30.0	35	5.0	86.0	28.5	40.0
3	40.0	22	5.0	77.0	33.4	50.0
4	50.0	15	7.3	51.0	46.8	68.5
Incoming Flow						
1	10.0	86	14.0	83.8	29.0	42.8
2	10.0	95	5.0	94.7	29.4	40.0
3	10.0	72	5.0	94.5	30.5	50.0
4	10.0	46	7.3	84.3	34.7	68.5

The percentage of dry matter incident to the filter ranged from 28.5 to 46.8 per cent and the final effluent, as stated above, varied from 40.0 to 68.5 per cent. The data indicate that recirculation increases the percentage of volatile suspended solids removed.

SECTION V

DISCUSSION

The plot of BOD removed versus BOD applied/cu yd/day resulted in a straight line relationship regardless of the organic load for any given hydraulic load. The efficiency of BOD removal for the experimental filter has been shown statistically to be a function of hydraulic load up to at least 334.5 lbs-BOD/1000 cf/day. Schulze (3) in a similar study found the foregoing to be true up to 403 lbs-BOD/1000 cf/day. Fairall (14) in a statistical study of operating plants found a closer relationship between hydraulic load and efficiency than between organic load and efficiency.

The NRC formula (1) for efficiency uses as its basis the organic load applied to the filter:

$$E = \frac{100}{1 + 0.085 \sqrt{\frac{W}{VF}}} \quad (11)$$

Where

E = per cent efficiency,

W = applied load in pounds BOD per day from incoming flow,

F = recirculation factor = $\frac{r + 1}{(0.1r + 1)^2}$,

r = recirculation ratio R/Q and

V = volume of filter in acre feet.

According to the monomolecular type reaction concept the theoretical efficiency for a filter can be computed by the following equation:

$$E = (1 - 10^{-KD/Q^{2/3}}) \times 100 \quad (12)$$

where

E = efficiency as percent BOD removed,

D = depth of filter in feet,

Q = hydraulic load in mgad and

K = a constant for the filter under a given set of conditions.

This equation can also be used for recirculation data if efficiency is related to incident BOD concentration.

Table VIII shows a comparison between the experimental efficiencies and those obtained by the application of equation (12) using $K = 1.49$ ($D = 5$ feet) for single pass conditions, the NRC formula and the new Ten State Standards (13). The NRC formula indicates the efficiency should vary from 26.0 to 50.5 per cent. In the case of the new Ten State Standards the expected efficiency ranged from 70.9 to 67.0 per cent. At higher hydraulic loads the organic load, which varied from an average of 30.87 to 258.51 lbs-BOD per 1000 cubic feet per day, was beyond the range of the Ten States Standards curve (Figure 41). The experimental efficiency was substantially higher than that predicted by either the NRC formula or the new Ten State Standards. There was agreement only insofar as all efficiencies decreased with increasing hydraulic load. As mentioned previously the theoretical efficiencies found by using equation (12) were much higher than the experimental values for the low hydraulic loads. Agreement existed only at hydraulic loads from 30.8 mgad on up.

Table IX shows a comparison for recirculation conditions between the efficiencies based on incoming flow (computation Method 1) and those found by the application of the NRC formula and the Ten States Standards curve. The NRC formula recognizes an increase in efficiency due to recirculation but does not consider the additional organic load introduced by recirculation. The New Ten State Standards (13) also use only the organic load coming from the primary tanks but do not recognize any

Table VIII. Comparison of Efficiency for Single Pass Conditions

Flow Rate mgad	Exp. eff. %	Theor. eff. eq. (12) %*	Lbs-BOD app/1000 cf/day	NRC formula eff. %	Ten State Standards Efficiency %
10.3	80.5	98.0	30.87	50.5	70.9
13.7	80.7	95.0	41.69	46.6	68.7
24.0	80.3	87.0	49.51	44.5	67.0
30.8	77.7	82.0	67.91	40.6	**
60.0	70.6	67.0	258.51	26.0	**
80.0	61.3	61.0	217.31	27.7	**

* Single pass $K = 1.49$

** Beyond the loading range of the Ten State Standards Curve.

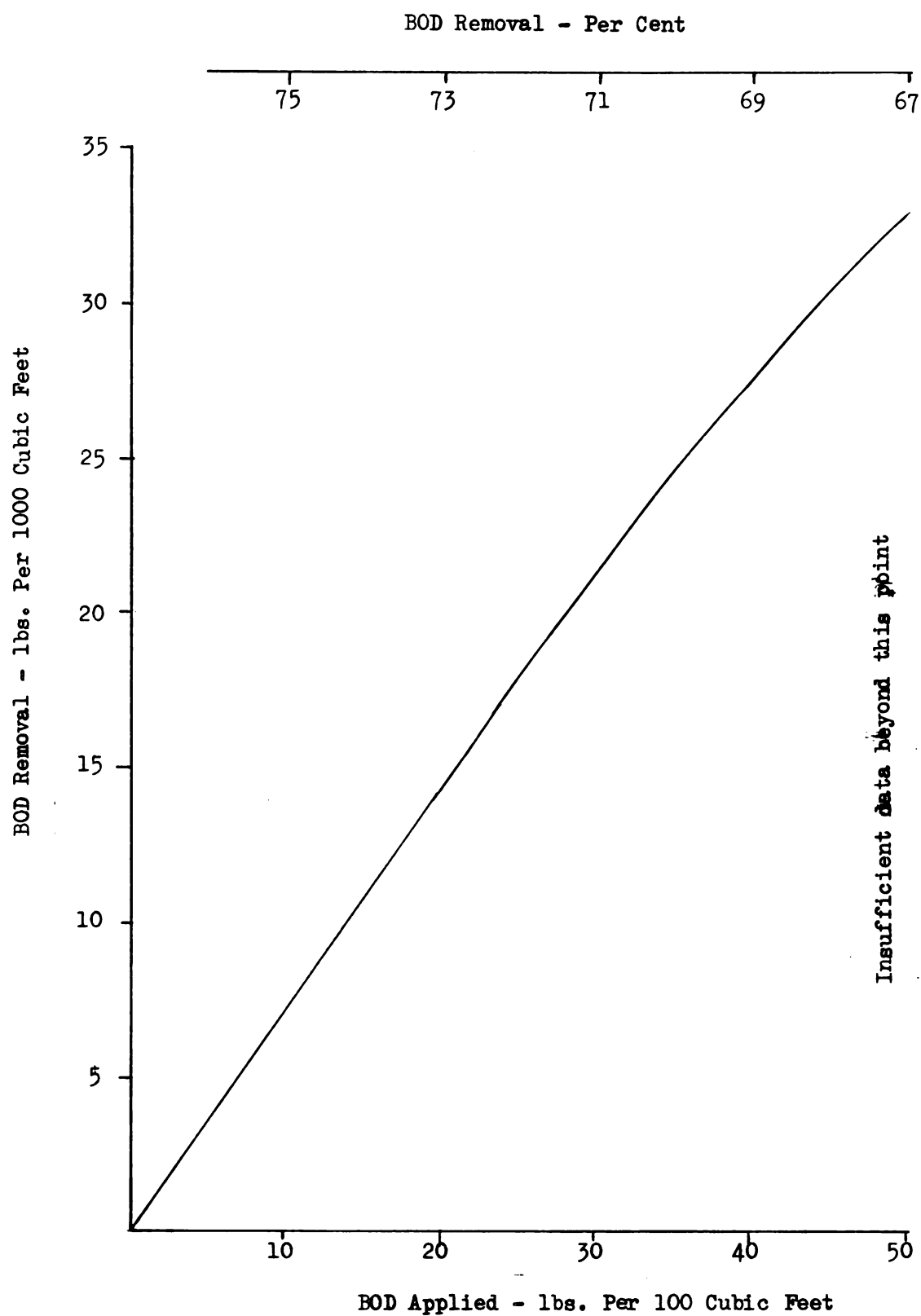


Figure 41. BOD Removal of Trickling Filter Unit Including Final Settling (Ten State Standards, 1960).

Table IX. Comparison of Efficiencies Related to Incoming Organic Load.

Rec. Ratio r	Flow Rate mgad	Experimental Efficiency %	Lbs-BOD app/ 1000/cf/day	NRC formula eff. %	Ten State Standards eff. %
1	10	86.8	31.60	58.7	70.0
2	10	88.4	42.75	60.0	68.4
3	10	86.2	42.00	61.7	68.6
4	10	83.7	36.27	65.2	69.7

increase in efficiency by recirculation. This is a change from the old Ten State Standards recommendations (2) where recirculation was credited for an increase in efficiency.

The experimental efficiency varied from 83.7 to 88.4 per cent and did not appear to increase with increasing recirculation ratios. In fact it was shown in Table V that at the 4:1 recirculation ratio the efficiency decreased significantly. The average organic load applied ranged from 31.60 to 42.75 lbs-BOD per 1000 cubic feet per day. The NRC formula gave expected efficiencies which increased from 58.7 to 65.2 per cent with increasing recirculation ratios. The Ten State Standards curve (Figure 41) provided efficiencies which ranged from 70.0 to 68.4 with no apparent relationship between the efficiency and the recirculation ratio. The efficiencies given by both the NRC formula and the Ten State Standards were lower than the experimental results. The Ten State Standards provided results which were closer to the experimental results and showed the apparent constant efficiency under recirculation.

Table X compares the experimental efficiency based on incident flow (computation Method 2) to the theoretical efficiency according to equation (12) when $K_r \approx 0.943$ and $D \approx 5$ feet. The experimental efficiency decreased steadily from 76.0 per cent at 1:1 recirculation to 50.3 per cent at 4:1 recirculation. According to the theoretical equation (12) the efficiency also decreased consistently with increasing recirculation ratios from 80.0 per cent at 1:1 to 55.0 per cent at 4:1 recirculation. The experimental data show good agreement with the theoretical values. This supports the concept that hydraulic load controls the efficiency of a trickling filter.

Table X. Comparison of Efficiencies Related to Incident Load

Res. Ratio r	Flow Rate mgad	Experimental Efficiency %	Theoretical Efficiency According to eq (12) %
1	20	76.0	80.0
2	30	73.4	72.0
3	40	61.7	61.0
4	50	50.3	55.0

The NRC formula and the Ten State Standards have both been developed by the statistical evaluation of operational data from a large number of plants and for that reason they are of great value in the design of filters presently being built in this country. This study and that of Schulze (3) indicate with considerable statistical argument that the hydraulic load and not the organic load controls efficiency. The studies of Rigbi, Amramy and Shuval (16) and Becher and Bryan (17) also support this concept.

The differences between the experimental and theoretical efficiencies were discussed in Section IV and it was shown that clogging was prevalent at the lower hydraulic loads. Clogging reduces the active surface area per unit filter volume. For the purpose of this discussion the active surface is defined as the surface area of aerobic growth per unit filter volume which is in contact with the waste.

The removal that can be realized in a filter is a function of the time the waste is in contact with the active surface. The active surface area of the free filter was 26.3 square feet per cubic foot of filter volume. When the filter was partially clogged the amount of active surface per unit filter volume could not be determined. As mentioned previously Howland (5) has shown that from a hydraulic point of view the contact time is a function of the two-thirds power of the hydraulic load to the surface. The time factor $D/Q^{2/3}$ has been used in this study because it is independent of the vertical surface area.

The trickling filter as it is known today is actually operated under much higher hydraulic loads than is shown by the design computations for two reasons. (1) The speed of the distributor arms is very slow and therefore the instantaneous hydraulic load is high. (2) The

growth on the media clogs a considerable number of the voids between the media. The flow is probably channeled into a relatively few passages which make up the active surface area.

Increasing the hydraulic load on a conventional filter would probably result in a similar reduction in clogging as that observed in the experiments reported here. Grantham, Phelps, Calaway and Emerson (19) and Ingram (26) have shown cases where the efficiency increased with increasing hydraulic load on conventional as well as experimental filters.

A comparison between the two filter models used in this study may serve to illustrate this point. The theoretical vertical surface area of the first model at one-half inch screen spacing was 57.7 square feet per cubic foot whereas the second model at one inch screen spacing provided only 26.3 square feet per cubic foot of filter volume. The filter with the largest surface area per unit volume should produce the higher efficiency but such was not the case. For equal hydraulic loads of 24.0 mgad the filter with only 26.3 square feet per cubic foot produced an efficiency of 80.3 per cent compared to 62.4 per cent for the filter with the greater vertical surface area. This difference of 17.9 per cent is very significant when consideration has been given to the fact that the ratio between the theoretical surface areas is approximately 1:2. The logical explanation for the low efficiency of the first model appears to be the fact that the active surface area of the first model was reduced by clogging to a value below that for the second model.

Recently attempts have been made to develop new trickling filter media which will prevent clogging and thus maintain a given active surface area per unit volume. Egan and Sandlin (20) discussed three of these new type media (Dowpac, Polygrid and Mead-Cor). So far the

efficiencies for these new media did not appear to be much better than those given by the conventional filter.

Schulze (3) did not experience clogging as the screens used in his experiments were two inches apart providing 12 square feet of active surface area per unit volume of the filter media. The value of K obtained in this study under single pass conditions at the hydraulic loads of 60 to 80 mgad was almost 5 times greater (1.49 compared to 0.3) than the value found by Schulze. This is attributed mostly to the larger active surface area provided by the one inch screen spacing.

The value of K found for recirculation was about 37 per cent lower than that found for single pass conditions. One reason for the decline of K under recirculation may be the decrease in the incident BOD concentration at the higher recirculation ratios. In addition it is possible that the value of K is influenced by the treatability of the waste. Howland (5) concluded from his results that there may be two fractions of BOD of which one is more resistant to treatment than the other. If this is so then a filter which is operating under recirculation would have a lower K value because a greater percentage of the BOD incident to the filter is comprised of the more resistant fraction.

Ingram (26) found that the nitrate and nitrite nitrogen concentrations of the final effluent of an experimental filter were a function of the hydraulic load. At the hydraulic load of 40 mgad he found 4.5 mg/l of nitrate nitrogen and 0.8 mg/l of nitrite nitrogen. As the hydraulic load was increased the concentration of the nitrate and nitrite nitrogen decreased steadily until only traces of each could be found at a load of over 100 mgad. The nitrate and nitrite concentrations (Table II) in the final effluent in this study followed the same trend. The reduction

of the nitrate and nitrite nitrogen in the final effluent may be related to the time the waste is in contact with the biological growth and thus it too may be a function of the hydraulic load.

SECTION VI

CONCLUSIONS

Based on experimental results from a vertical screen trickling filter under single pass and under recirculation conditions the following conclusions were reached:

1. The efficiency of a trickling filter at a given hydraulic load is constant and independent of the organic load up to at least 335 pounds of BOD per 1000 cubic feet per day.
2. Increasing the hydraulic load results in a decrease of efficiency as long as the vertical active surface area of the filter remains constant.
3. At one-half inch screen spacing the voids between the screens became severely clogged by the biological growth. Increasing hydraulic loads reduced the clogging and therefore improved the efficiency. At one inch screen spacing the active surface remained constant from the hydraulic load of 30.8 mgad on up. Accordingly the efficiency decreased consistently at hydraulic loads above 30.8 mgad.
4. The application of the equation $E = (1 - 10^{-KD/Q^{2/3}}) \times 100$ does not result in a constant K factor under single pass conditions because the active surface area changes with changing hydraulic loads.
5. Under recirculation conditions a constant K factor is obtained if the hydraulic load and efficiency are related to incident flow rather than incoming flow.
6. Recirculation in itself does not improve the efficiency of trickling filters except in those cases where clogging is reduced due to the higher incident hydraulic load.

7. Comparison between the experimental efficiencies and efficiencies predicted by the equation $E = (1 - 10^{-KD/Q^{2/3}}) \times 100$, the NRC formula and the new Ten State Standards showed that the theoretical equation approximated the actual results more closely than did the Ten State Standards or the NRC relationship. The Ten State Standards provided a closer approximation than did the NRC formula.

8. The overall reduction of suspended solids appeared to be increased by recirculation. The ash in per cent dry matter of the suspended solids was not materially changed by recirculation.

9. The concentration of nitrite and nitrate nitrogen in the final effluent appeared to be a function of the hydraulic load.

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