

AN ABSTRACT OF THE THESIS

Michael Dan Roach for the Master of Science in Civil Engineering
(Name) (Degree) (Major)

Date thesis is presented March 22 1965

Title Contact Time and Reaction Rates for Trickling Filters

Abstract approved [REDACTED]
(Major Professor)

Three deep experimental filters were used to evaluate the influence of the physical factors of media size, depth of filter, and organic and hydraulic loading on contact time and the rate of removal of organic material by the biological growth on the filters. A further correlation was made between contact time and the COD removal rates.

The experimental filters were three columns, 5.8 inches in diameter and 18 feet in depth. Each column was packed with a constant size, smooth, spherical media. The media used were 9/16-, 7/8-, and 1-1/4-inch diameter marbles.

Tracer studies for contact time were made on the columns at 2-, 4-, 8-, and 16-foot levels and at hydraulic loadings ranging from 15-90 mgad. Sodium chloride was used as the tracer material. Contact time was determined for the three sizes of media without biota and for the 7/8-, and 1-1/4-inch diameter media with biota. Samples of the substrate were taken at the various levels and flow rates for COD determination for the tests run on the media with biota.

A step-wise regression analysis was performed on the data with the use of an IBM computer. Two empirical relationships were established

for contact time, one for the media without biota and the other for media with biota. A further empirical relationship correlated the COD remaining with the contact time.

The results of this analysis showed that contact time on the media without biota is inversely proportional to the 0.76 power of the hydraulic loading, inversely proportional to the 0.50 power of the diameter of the media, and directly proportional to 1.08 power of the filter depth. Contact time on media with biota is inversely proportional to the 1.05 power of the hydraulic loading, and directly proportional to the 1.44 power of the filter depth.

The third empirical equation established a relationship for COD remaining as a function of time, where the fraction of COD remaining is inversely proportional to the 0.19 power of the contact time.

**CONTACT TIME AND REACTION RATES
FOR TRICKLING FILTERS**

by

MICHAEL DAN ROACH

A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1965

APPROVED:

[Redacted Signature]

Associate Professor of Civil Engineering

In Charge of Major

[Redacted Signature]

Head of Department of Civil Engineering

[Redacted Signature]

Dean of Graduate School

Date thesis is presented

8
March 12, 1965

Typed by Kathleen Lewis

TABLE OF CONTENTS

INTRODUCTION	1
PURPOSE	2
SCOPE	2
METHOD OF STUDY	3
THEORY OF FILTRATION	4
General Description of Filter	4
Organic Removal	5
Oxygen Transfer	7
Temperature	8
Contact Time and Reaction Rates	8
EXPERIMENTAL EQUIPMENT AND METHODS	11
Physical Design	11
Equipment	11
Media	14
Application Rates and Distribution	14
Substrate	15
Operating Procedure	16
Experimental Methods	18
Tracer	18
Sample Collection and COD Tests	21
ANALYSIS OF DATA	23
Determination of Median Residence Time	23
Equation of Contact Time	23
Equation of COD Removal	26
DISCUSSION OF DATA	27
Influence of Clean Media on Contact Time	27
Experimental Results	27
General	27
Media	27
Hydraulic Loading	28
Depth	32
Empirical Equation and Experimental Results	32
Influence of Biological Growth on Contact Time	37
Experimental Results	37
General	37
Growth	38

TABLE OF CONTENTS (CONTINUED)

Hydraulic Loading	41
Depth	44
Media	47
Empirical Equation and Experimental Results	47
Effect of Contact Time on COD Removal Rates	49
Experimental Results	49
Empirical Equation for COD Removal	52
SUMMARY	54
CONCLUSIONS	56

LIST OF TABLES

Table		Page
1.	Analysis of Filter Media	14
2.	Analysis of Milk Solids	15
3.	Summary of Statistical Analysis for Contact Time on Media Without Growth	24
4.	Summary of Statistical Analysis for Contact Time on Media With Growth	25

LIST OF FIGURES

Figure	Page
1. Experimental deep trickling filters - laboratory units . . .	12
2. Typical sample ports for filter units	12
3. Flow diagram - experimental filter units	13
4. Flow-through curve using NaCl tracer	20
5. Median time versus hydraulic loading for column I without biological growth	29
6. Median time versus hydraulic loading for column II without biological growth	30
7. Median time versus hydraulic loading for column III without biological growth	31
8. Median time versus depth for column I without biological growth	33
9. Median time versus depth for column II without biological growth	34
10. Median time versus depth for column III without biological growth	35
11. Comparison of empirical equation and experimental data for media without growth	36
12. Biological growth versus filter depth for column II	39
13. Biological growth versus filter depth for column III	40
14. Median time versus hydraulic loading for column II with biological growth	42
15. Median time versus hydraulic loading for column III with biological growth	43
16. Median time versus depth for column II with biological growth	45
17. Median time versus depth for column III with biological growth	46
18. Comparison of empirical equation and experimental data for media with growth	48

LIST OF FIGURES (CONTINUED)

Figure	Page
19. Per cent COD remaining versus depth for column II	50
20. Per cent COD remaining versus depth for column III	51

ACKNOWLEDGEMENT

The author would like to thank the United States Public Health Service for the funds which made this research possible. He further owes his thanks to the many people who advised, encouraged and otherwise influenced the preparation of this thesis, particularly to Professor F.J. Burgess and Dr. D.C. Phillips for their aid in guiding the research program, to Professor Fred Merryfield for inspiration and to his fellow students for their help and suggestions. The painstaking work of the typist, Kathleen Lewis, is sincerely appreciated. A heartfelt thanks goes to my wife, Carole, and my two daughters, Suzanne and Deanna, for their understanding and time in this period of our lives.

Michael D. Roach

CONTACT TIME AND REACTION RATES FOR TRICKLING FILTERS

INTRODUCTION

The trickling filter has been used as a means of biologically treating sewage for more than a half of a century. Much of the design has come from experience and trial and error application of previous knowledge. The determination of basic parameters from controlled laboratory models and pilot plants is relatively young. More recently there has been an attempt to develop mathematical models of the trickling filter.

In either experimental filters or mathematical models the trickling filter may be divided into the physical system and the biological system. A large amount of the experimental laboratory work has been done on either one or the other of the two systems. Many of the small scale laboratory units have been used to define one parameter of either the physical or biological system. While full-scale operating filters may be used to study the biophysical system, they have the disadvantage of not being able to be operated under controlled conditions.

It would seem desirable to study the combined biophysical system of the filter under controlled conditions, correlating the physical factors of media size, depth of filter, and organic and hydraulic loading rates with the biological activity of the filter slime. A controlled study of this nature should give a better knowledge of the mechanisms and performance of a trickling filter.

The degree of purification or removal of organic material from

any substrate is dependent on the chance that the microbial population has to be in contact with the substrate. This time of contact is the time that it takes one particle of fluid to pass through the filter.

The rate of removal of organic material by the filter is essentially a function of the concentration of the organic material, the active biota, the temperature, and the time of retention of the substrate in the filter. Since the rate of removal and the degree of purification are largely dependent on contact time, the correlation of contact time with the rate of removal, while holding the other parameters of media size, temperature, hydraulic and organic loading constant, should give a reliable indication of the overall organic removal or performance that may be expected of a trickling filter.

PURPOSE

The purpose of this thesis is to correlate removal rates of organic material in the laboratory model of a trickling filter with the time of retention of liquid in the filter. The study attempts to provide more basic understanding of the performance of trickling filters and to determine if experimental evidence under controlled conditions will approximate or substantiate previous theoretical derivations.

SCOPE

The scope of this study consists of the determination of contact time and COD removal as a function of flow rate and media size. Initially, contact time will be found on a filter of clean media and a

later correction applied for this same media with microbial growth.

Once the relationship has been established for contact time for a certain size media with growth, a further correlation will be made between COD removal and contact time. This last expression can then be stated in terms of design parameters for the expected COD removal through a filter bed of fixed media size and specified hydraulic loading of sewage or similar liquid waste.

METHOD OF STUDY

To determine contact time a series of tests were run on three sizes of media. The tests for contact time were divided into two phases. The first phase consisted of three data runs for contact time at different flow rates on media without biota. The second phase of tests consisted of three data runs for contact time at different flow rates on two sizes of media with biota.

Each run for both phases consisted of determining the contact time through 2-, 4-, 8-, and 16-foot sections of the filter column. The time of retention was determined by using NaCl as a tracer.

During the second phase of tests, samples for each run were taken from the influent, 2-, 4-, 8-, and 16-foot levels of the filter column and analyzed for temperature, pH, and chemical-oxygen demand (COD). Filter slime samples were taken at each of the sampling levels for determination of weight of growth per unit of surface area.

THEORY OF FILTRATION

General Description of Filter

A trickling filter is essentially a vertical column filled with a loosely packed solid, generally rock. Sewage or other liquid waste is distributed onto the filter intermittently or continuously by a rotary distributor. The sewage trickles down over the filter media by gravity and finally passes through an underdrain system to a secondary settling tank. As the liquid waste flows through the filter it is contacted with biological films on the filter media. Organic (BOD) removal by the microorganisms is accomplished by adsorption of the organic material onto the microbial film.

Aerobic conditions are maintained by the flow of air through the filter. Oxygen from the air in the voids of the filter bed is adsorbed by the liquid and permits aerobic metabolism by the microorganisms.

Generally, trickling filters are classified as low-rate or high-rate filters depending on the hydraulic and organic loading. The design criteria of a low-rate filter is two to four million gallons per acre per day (mgad) with an organic loading of 10 - 20 pounds of five day BOD per 1000 cubic feet of filter stone. The high-rate filter is classed hydraulically at 10 - 40 mgad with an organic loading up to 90 pounds of five day BOD per 1000 cubic feet of filter volume. The depths of low-rate filters range from six to ten feet. The high-rate filter is generally six feet in depth.

Organic Removal

As the liquid waste moves over the filter media, the method of transfer of mass from the fluid to the filter slime has been postulated to occur by biosorption and coagulation from that portion of flow which passes rapidly through the filter and by progressive removal of soluble constituents from the portion of flow with increased residence time (4). Behen et al. (1) states that the original concept of removal and storage is credited to E.B. Phelps (4). Phelps arrived at his conclusions by observing that 75 - 80 per cent BOD reduction seemed to occur in 15 to 20 minutes residence of the waste in the filter while it took seven days for this same reduction in a BOD bottle with excess oxygen.

A mechanism for adsorption is given by McKinney (13). He states that as the liquid flows through the filter bed, the liquid actually flows over the top of the microbial layer rather than through this layer. If the organic concentration of the flowing liquid is greater than that of the bound water on the microbial surface, organic matter will be transferred from the flowing wastes to the bound-water layer. This concentration gradient concept suggests that the most rapid transfer will occur when the incoming organic concentration is high and the bound-water concentration is at a minimum. General observation of trickling filters supports this concept. The upper layers of the filter receive the highest concentration of organic matter which accounts for the observed greater microbial

growth in the top portion of the filter than in the lower portion.

A second mechanism that has been suggested is that the removal of BOD from the waste is due to high rates of oxidation at the surface of the microbial film. This concept has been disputed since experiences with other types of microbial surfaces have not given comparable high rates of oxidation in like aerobic systems (1).

The removal of organic material by adsorption is a function of contact time, the organic concentration of the waste and the microbial surface present. Schulze (17) assumed that the treatment capacity of a filter was essentially determined by two main factors; (a) the amount of active film per unit of filter volume, and (b) the contact time between the waste and this film. The contact time depends on the microbial surface area and hydraulic load. The active film will depend on temperature, the surface area available and the supply of food and oxygen.

The microbial film is also a function of the media size and the depth of the filter. According to McKinney (13), the microbial mass of this film adheres to the media surface by Van der Waal forces of attraction for two surfaces. The microorganisms build one on top of the other. As the layers increase, the lower layers do not receive food or oxygen and these layers shift to an anaerobic endogenous metabolism. As the cells in the lower layers die and lyse, the surface responsible for holding the microbial mass is destroyed. The biota drops or "sloughs" from the media. Organic removal is a minimum when the growth drops from the media and increases to a

maximum when the media is covered with a thin layer of microorganisms.

Oxygen Transfer

Oxygen transfer plays an important role in filter performance along with retention time and the quantity of filter film. According to Eckenfelder (4), oxygen is transferred to the film from the waste liquid passing through the filter. McKinney (13) states that the oxygen is transferred from the void spaces due to the driving force of an oxygen deficit existing in the liquid at the air-liquid interface. In either case the rate of transfer is related to the oxygen deficit and liquid characteristics and may be related by:

$$\frac{dc}{dt} = K(C_s - C) \quad \text{Eq. 1}$$

Where:

- C = actual oxygen present
- C_s = oxygen saturation value
- K = constant for liquid characteristics

The Water Pollution Research Board (7) related the rate of oxygen transfer to the saturation deficit, hydraulic loading, depth and physical characteristic of the filter as:

$$\frac{dc}{dD} = \frac{K'}{Q^{0.5}} (C_s - C) \quad \text{Eq. 2}$$

Where:

- D = filter depth
- Q = hydraulic loading per unit filter surface
- K' = modified rate coefficient

The quantity of active film will depend on the depth to which oxygen can penetrate to maintain aerobic conditions. Research by

Shulze (17) indicates that the maximum aerobic depth is two to three mm.

Temperature

Temperature has an influence on filter performance in that the metabolic activity of the microbial population increases with temperature. This microbial metabolism is a function of the liquid temperature and not of the air temperature (16). Howland (9) has shown the effect of temperature on filter performance by the relationship:

$$E = E_{20} 1.035^{(T-20)} \quad \text{Eq. 3}$$

Where:

E_{20} = BOD removal efficiency at 20°C
 E = BOD removal efficiency
 T = temperature, in °C

Contact Time and Reaction Rates

The degree of purification or organic removal is dependent upon the contact time between the waste and the microbial population of the filter. The residence time of a liquid in turn is dependent upon hydraulic load and the filter surface area. In determining some relationship for the removal of organic material (BOD), Eckenfelder (5) proposed the following approach. He assumes a first order kinetic reaction to relate contact time with organic removal by the same type of equation proposed by Howland (10), and Shulze (18). The variables may be related by:

$$\frac{L_e}{L_o} = e^{-kt} \quad \text{Eq. 4}$$

Where:

- L_e = BOD remaining in the filter effluent
- L_o = BOD applied to the filter
- K = coefficient incorporating the surface area of active film per unit volume

The contact time "t" can be described by the relationship: (17)
(10) (20) (2).

$$t = CD/Q^n \quad \text{Eq. 5}$$

Where:

- t = contact time
- D = filter depth
- Q = hydraulic loading

The constant C , and the exponent n will vary with the type of filter media and hydraulic characteristics of the system.

Eckenfelder (5) further shows that the surface area of the film varies with type and distribution of the filter media and the filter depth, and can be mathematically approximated by:

$$C \sim 1/D^m \quad \text{Eq. 6}$$

in which C is related to the mean active filter film per unit volume throughout the filter depth.

Modification of Equation (4) by Eckenfelder, (5) with Equations (5) and (6) gives:

$$\frac{L_e}{L_o} = e^{(-KD^{1-m})/Q^n} \quad \text{Eq. 7}$$

which presumes all the components of organic waste are removed at the same rate. But evidence shows that BOD removal for sewage decreases with concentration or time (1) (18). To account for this decrease in removal Eckenfelder (5) modified Equation (7) with a retardant

form of the equation for overall removal:

$$\frac{L_e}{L_o} = \frac{100}{1 + \frac{CD(1-m)}{Q^n}} \quad \text{Eq. 8}$$

Determination of the constant C and the exponents (1-m) and n from the various studies yields an equation for the design of rock filters using domestic sewage where:

$$\frac{L_e}{L_o} = \frac{100}{1 + \frac{(2.5)D^{0.67}}{Q^{0.50}}} \quad \text{Eq. 9}$$

Other equations for contact time have been formulated by various authors in the literature. McDermott (11) found contact time on a 23-foot column of 3-1/2 inch balls to be:

$$t = 30.2 D^{1.08} Q^{-0.55} \quad \text{Eq. 10}$$

Sinkoff et al. (20) found residence time for glass spheres as:

$$t = 3.0 D \frac{\nu^{1/2}}{g^{1/3}} \frac{(s)}{(Q)}^{0.83} \quad \text{Eq. 11}$$

and for porcelain spheres as:

$$t = 1.5 D \frac{\nu^{0.20}}{g^{1/3}} \frac{(s)}{(Q)}^{0.53} \quad \text{Eq. 12}$$

Where:

- ν = kinematic viscosity
- g = gravitational constant
- s = specific surface

The specific surface is defined as the surface area of the media divided by the volume occupied by this media. Howland (10) derived a theoretical equation for flow of a liquid over a sphere where:

$$t = 2.6 \frac{(3\nu)^{1/3}}{(g)} \frac{2\pi^{2/3} \nu^{5/3}}{Q^{2/3}} \quad \text{Eq. 13}$$

in which r = radius of the sphere.

EXPERIMENTAL EQUIPMENT AND METHODS

Physical Design

Equipment

Three laboratory deep trickling filters (Figure 1) were erected in the spring of 1962 by Seaders (19). Each filter was a 5.8 inch diameter column 18 feet in height. Each column was filled with a constant-size spherical media. Column I was packed with 9/16 inch diameter marbles. Column II was packed with 7/8 inch diameter marbles and Column III was packed with 1-1/4 inch diameter ceramic spheres. Each column had sampling ports at 1-, 2-, 3-, 4-, 6-, 8-, 10-, 12-, 14-, 16-, and 18-foot levels from the top of the filter. Sampling trays (Figure 2) were inserted in each port for collection of growth samples. Each sample tray contained 40, 15, and 8 marbles for Column I, Column II, and Column III respectively.

The influent feeding apparatus was constructed so the hydraulic loading and organic loading could be controlled to allow the filters to operate at varied flow rates. The flow pattern for feeding is shown in Figure 3. The feeding apparatus consisted of a refrigerated stock-feed tank which was fed into a constant level feed-mixing tank for each filter. A timer and solenoid valve determined operation of pneumatically operated positive displacement pumps which transferred the stock feed to the mixing tanks. Recirculation pumps provided continuous mixing of stock feed with the make up water (tap water)

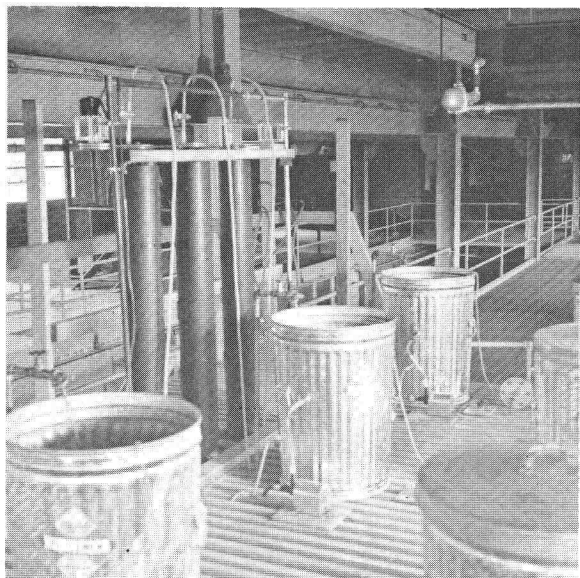


Figure 1. Experimental deep trickling filters-laboratory units.

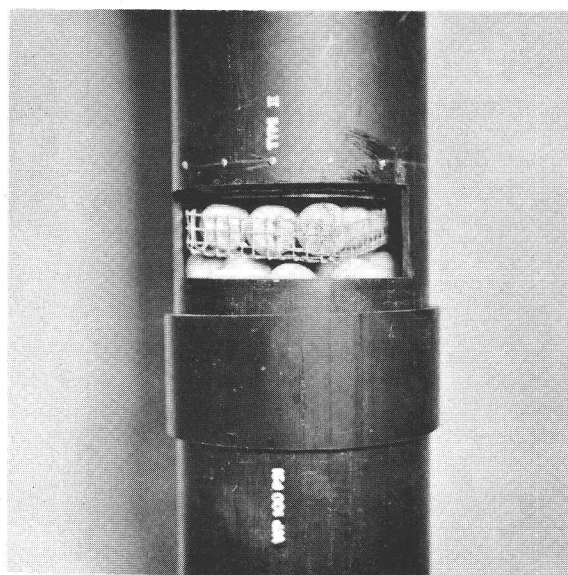


Figure 2. Typical sample ports for filter units.

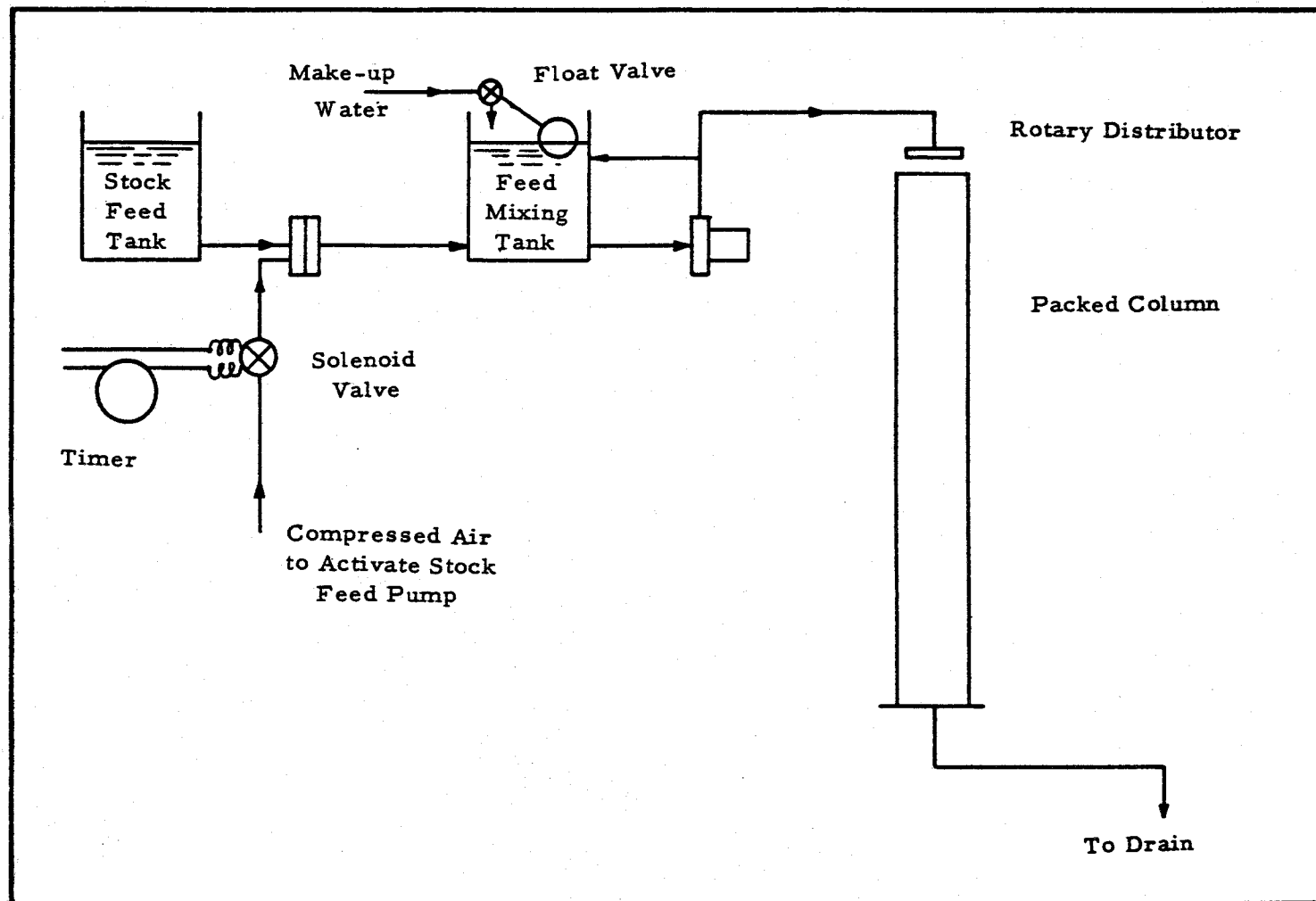


Figure 3. Flow diagram - Experimental filter units

and pumped the resulting feed mixture to rotary distributors at the top of each filter column. A constant strength feed was maintained by proportioning the strength of the stock feed to the flow rate that was being applied to the filters. The flow rate to each filter column was controlled by means of a stopcock located just ahead of the rotary distributors.

Media

In design of the experimental filters it was desired that the media size be known. To meet this criteria glass marbles and ceramic spheres were chosen. The glass marbles were 9/16-inch and 7/8-inch in diameter respectively for Columns I and II. The ceramic spheres were 1-1/4 inch in diameter for Column III. The mean diameter and weight was determined for each size by Seaders (19). A summary of his analysis is shown below in Table 1.

TABLE 1
ANALYSIS OF FILTER MEDIA
Seaders (19)

Nominal size, inches	9/16	7/8	1-1/4
Mean diameter, mm	14.14	23.28	31.43
Mean wt./marble, gms	3.57	16.24	38.25

Application Rates and Distribution

The filters were designed to operate at 5 - 120 mgad. The flow rates were varied by use of stopcock valves ahead of the rotary

distributor. The distributor for each filter was a belt driven four-inch diameter pulley with the feed line freely mounted on the rim. The distributor made one revolution every 30 seconds. It was felt that within a foot from the top of the bed that the flow would be evenly distributed. To minimize wall effects and short circuiting, circular drip rings were installed at each sampling port to redistribute any wall flow.

Substrate

Dry milk solids were used to provide the organic load for the filters. Feed strength of 0.2 grams of milk solids per liter of tap water was used to give a BOD strength of 130 to 140 mg/l and a COD strength of 220 mg/l. The dry milk solids were analyzed by Seaders (19). The results of his analysis are shown in Table 2.

TABLE 2
ANALYSIS OF MILK SOLIDS
Seaders (19)

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

Operating Procedure

The experimental stage of this study was divided into two phases. The first phase was concerned with determination of contact time at different flow rates on clean media. The second phase was concerned with determination of contact time at different hydraulic loading rates on media with microbial growth.

Initially only Column II and III were used in the test series since previous work (19) (15) had shown that the 9/16 inch diameter marbles of Column I were an unsuitable media because of the clogging and ponding associated with this filter for increased loading. Later, in the experimental study when time permitted, contact time tests were conducted on Column I for clean media.

The first phase was started the first week in June 1963, with preliminary testing of different tracers through the filter with the final selection of NaCl as the tracer material. On June 19, 1963 the first data runs were made for a hydraulic loading of 15 mgad. The rest of the data runs for flow rates of 15-, 30-, 45-, 60-, and 90-mgad were run and the first phase was completed on July 2, 1963. Flow rates were checked and adjusted at the beginning of each run and at varying intervals thereafter.

The second phase of the tests was initiated the first week of July, 1963, with seeding of the filter with raw sewage from the Corvallis Sewage Treatment Plant. The milk substrate was introduced to provide food for the microorganisms. Within a week after seeding

the flow rate was set at 90 mgad and the filter allowed to establish growths at this rate. Growths were soon in evidence hanging in finger-like projections from the bottom of the screen used to support the media in each section. The high flow rate (90 mgad) was initiated in hope that the scouring action of the higher flow rates would reduce the build up of layers of inactive growth associated with clogging and ponding encountered by Seaders (19) at the lower flow rates. This hope was realized as no ponding or clogging occurred during the testing period at the lower rates. Subsequent check tests, run later in the fall and starting at the lower rates of flow and proceeding to the higher rates of flow, were troubled considerably with clogging and ponding.

Tracer tests were started on July 23, 1963, at 90 mgad for media with microbial growth. At the end of the tests for each flow rate a new flow rate was set and two weeks allowed for the filter to establish equilibrium conditions at this new rate. Tests at 15 mgad (the final flow rate) for media with growth, were completed on September 19, 1963. Filter flies and red tubiflax worms were noticed the third week in August and appeared to be distributed throughout both columns. The Psychoda larve cleaned the fingerlike growths from screens in each sample port. The adult filter flies became a definite nuisance during sampling. To reduce this nuisance the outside of the columns were sprayed with DDT. The filter flies were still present at the end of the tests.

For each flow rate samplings were made at the 2-, 4-, 8-, and

16-foot levels for each run. These samples were analyzed for COD, pH and temperature. Growth samples were also obtained at corresponding levels for each flow rate.

A check run on contact time determinations for media with growth was made for each flow rate starting October 11, 1963, and ending December 6, 1963. The same procedure was used for these determination as was used for the initial tests except that only one data run was made for each flow rate and the order of the flow rates was reversed going from 15 mgad to 90 mgad.

Final tracer tests were made on Column I, with clean 9/16 inch diameter media, during the spring of 1964. The filters were dismantled the third week of June, 1964.

Experimental Methods

Tracer

To find the residence time of the liquid in the filter different tracers were considered. The criteria for a suitable tracer were that it exhibit the same hydraulic characteristics as the fluid and that it not be harmful or inhibit the microbial growth of the filter. Further requirements were that the tracer be dosed to the filter in small amounts so the flow would not be changed. The tracer also had to be economical and capable of being traced with the equipment available.

Three tracer materials were investigated. These were phosphate,

methylene-blue dye and sodium chloride. Preliminary tests with phosphate showed that the samples (50 ml) needed for analysis by the colormetric Stannous Chloride method (23) required too long a period of collection at the low flow rates. The methylene-blue tracer analyzed by colormetric methods was rejected because the dye adhered to the media causing the apparent time of contact to be greater than actual.

Sodium chloride was selected as the tracer to be used when preliminary tests showed it met the criteria. Evaluation of the tracer was accomplished by conductance measurements with a Serfass Conductance Bridge. A 10 per cent stock NaCl solution gave a good range of conductance values when applied at the rate of one ml per foot of depth of the column.

A series of tracer tests were set up to measure the fluids residence time in 2-, 4-, 8-, and 16-foot sections of the filter column. At these column depths three data runs were made for each of the varied flow rates. To the top of a column an amount of tracer corresponding to one ml per foot of filter depth to be sampled was applied. The frequency of sampling varied according to media size, depth of column and flow rate. A ten ml sample was taken for each time interval. The samples were checked for conductance within 10-15 minutes of sampling. The conductance readings were plotted with time, (Figure 4) and the median residence time determined. The median time is defined as the time at which half the recovered tracer has emerged.

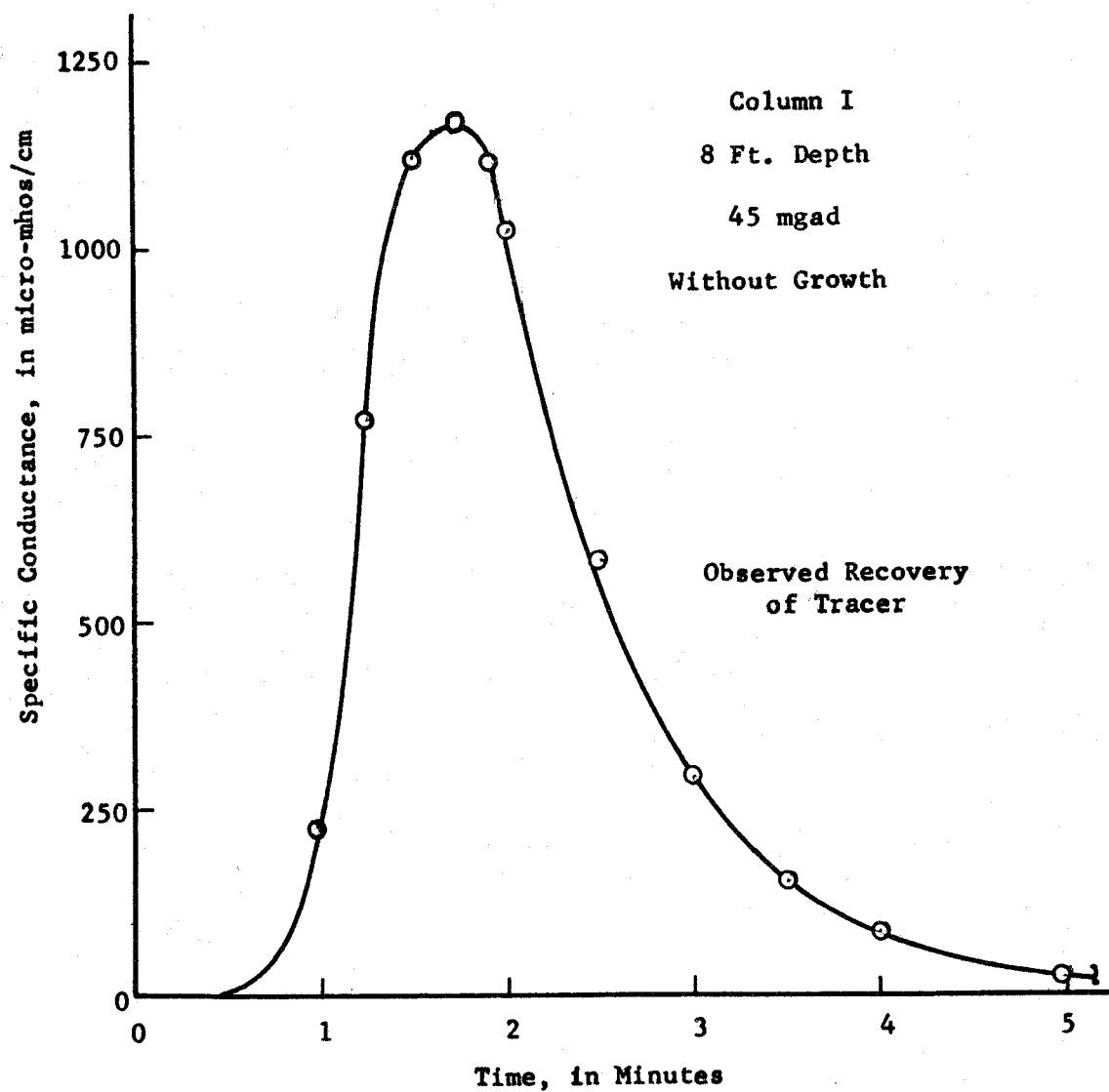


Figure 4. Flow - through curve using NaCl tracer.

Work in Britian (8) has shown that for radioactive tracer studies on trickling filters the percentage of tracer recovered versus time curve can be plotted as a straight line on logarithmic probability paper and the median time taken as the time at the 50 per cent level of recovered tracer.

Sample Collection and COD Tests

To determine organic removal and growth data, samples were taken on the media with growth at the influent, 2-, 4-, 8-, and 16-foot levels. The samples for substrate analysis consisted of three samples for each depth and flow rate which were taken to coincide with the three data runs of the tracer study. These samples were analyzed for COD, pH, and temperature. Growth samples were obtained by removing a prescribed number of marbles from the port of each sampling depth.

Growth analysis consisted of removing the growth from each marble by washing with distilled water. The water was evaporated and the growth dried in an oven at 103°C. The growth was then weighed. The prescribed number of marbles, (15 and 8 for Columns II and III respectively) represented a unit of surface area of approximately 250 cm².

The standard COD test (23) was modified by reducing the dichromate strength from 0.25 N to 0.1 N, and the sample size was increased from 50 ml to 100 ml. The titrant $[\text{Fe}(\text{NH}_4)_2\text{SO}_4]$ was reduced from 0.25 N to 0.1 N also. A digestion time of one hour

was used. Seaders (19) showed that no difference was observed for digestion time ranging from 1/2 hour to two hours. Chloride determinations (23) were made and found to be negligible for correction of COD values.

ANALYSIS OF DATA

Determination of Median Residence Time

In order to evaluate median residence time the value of time at which half the tracer had emerged was determined. This determination was accomplished by finding 50 per cent of the area under the concentration (conductance) versus time curve (Figure 4), which is the value of 50 per cent of the recovered tracer. The area was found by numerical integration where the ordinate values for the approximating trapezoids were successive conductance readings. The abscissa value was the time interval between these readings. The time value corresponding to 50 per cent of the area was recorded as the median residence time.

Equation of Contact Time

The evaluation of a relationship for contact time as a function of flow rate, depth of filter, and media size was determined from the data. A step-wise regression analysis was performed with the use of an IBM 1620 computer after initial plotting showed the data approximated a straight line on logarithmic coordinates. Preliminary investigation showed the equation followed the form:

$$t = K \frac{D^n}{Q^m d^p} \quad \text{Eq. 14}$$

Where:

t = contact time, seconds
D = depth of filter, feet

Q = hydraulic loading rate, mgad
 d = diameter of media, inches
 m, n, p, = exponents

and K is a constant dependent on the characteristics of the system.

Two correlations for contact time were determined from the data. One equation was found for contact time on the media without biota and a second equation for the same media with biota. The equation for media without growth was:

$$t = 207 \frac{D^{1.08}}{Q^{0.76} d^{0.50}} \quad \text{Eq. 15}$$

and the equation for media with growth was:

$$t = 1057 \frac{D^{1.44}}{Q^{1.05} d^{0.09}} \quad \text{Eq. 16}$$

For the clean media a multiple correlation coefficient of 0.99 was found and a T ratio greater than the absolute value of 11 determined for all three variables. An investigation of the T ratio shows all three variables are significant. The T ratio is the value of the exponent divided by its standard error. The summary of these results is seen in Table 3.

TABLE 3

SUMMARY OF STATISTICAL ANALYSIS FOR CONTACT
 TIME ON MEDIA WITHOUT GROWTH

Variable	Exponent	Std. Error	T Ratio
Diameter	-.50024	.04417	-11.32526
Flow Rate	-.75742	.02373	-31.01829
Depth	1.08332	.01877	57.69761

The multiple correlation coefficient for media with biota was 0.98 for the three variables of depth, flow rate, and media size, where depth and flow rate alone had a correlation coefficient of 0.98. This same correlation value suggests that the diameter of the media does not influence contact time. A T ratio of -0.336 (Table 4) further suggests the diameter of the media is not significant. The T value is within the 95 per cent confidence interval for a test of the hypothesis that $T = 0$.

TABLE 4

SUMMARY OF STATISTICAL ANALYSIS FOR CONTACT
TIME ON MEDIA WITH GROWTH

Variable	Exponent	Std. Error	T Ratio
Diameter	-0.08611	.25594	-.33645
Flow Rate	-1.04539	.07977	-13.10411
Depth	-1.43746	.05018	28.64384

Omitting the diameter, the equation for contact time for media with growth is then written as:

$$t = 1072 \frac{D^{1.44}}{Q^{1.05}} \quad \text{Eq. 17}$$

where the value of K has changed from 1057 to 1072 and the coefficients, the standard errors, and the T ratios have changed slightly.

Equation for COD Removal

An initial analysis was made on the COD data on the assumption that removal would follow a first order reaction as given by Equation (4). This assumption proved erroneous as the data did not follow a straight line plot on semi-logarithmic coordinates. Further investigations showed that a plot of per cent COD remaining versus time did approximate a straight line on logarithmic coordinates. An assumption was made that there was no COD removal during the first second of contact which allowed a logarithmic transformation of the data using $t = 1$ instead of $t = 0$ at the time of influent COD loading. A step-wise regression analysis, in this case, a least squares with one independent variable, time, was performed with the IBM 1620 computer. The result of this analysis is an equation for COD removal as a function of time:

$$\frac{P_e}{P_o} = 1.03t^{-0.19} \quad \text{Eq. 18}$$

Where:

P_e = COD remaining
 P_o = COD applied
 t = contact time, seconds

The analysis of the data gave a correlation coefficient of 0.91, a standard error of 0.013 and a T ratio of 14.887. To use Equation (18) a determination of time may be made from Equation (17) and then the expected COD removal calculated.

DISCUSSION OF DATA

Influence of Clean Media on Contact Time

Experimental Results

General. The mean values of the three data runs were compared to find how the variables of media size, hydraulic loading and depth influence the time of contact on smooth, clean, spherical media. Contact time as the dependent variable was plotted separately against depth and against flow rate for each of the columns. These plots gave a series of curves which were helpful in visualizing how the different parameters affect contact time.

It should be noted that other factors beside media size, flow rate, and depth have an influence on the contact time of a liquid through a filter. Temperature, viscosity and density of the fluid, and roughness of the media all affect liquid flow. For the series of tracer tests on clean media the temperature ranged between 19 - 23 °C. No appreciable difference in the experimental results was expected as the viscosity of the tap water would not vary significantly in this small temperature range. The tap water approximated the flow characteristics of a weak settled sewage. If a fluid of different density and viscosity such as some industrial waste were applied to the filter, contact time could change markedly.

Media. The influence of media size on contact time can be seen from Equation (15) where time varies inversely to the 0.5 power of the

diameter of the media. From this it can be seen that contact time decreases as the media size increases because the smaller surface area and greater pore size between the packing offers less resistance to fluid flow. In this study the difference in surface roughness was minimized by using smooth glass marbles and smooth ceramic spheres.

Hydraulic Loading. One of the main variables determining contact time is the hydraulic loading. Plots of contact time versus hydraulic loading at various depths for the three media sizes are shown in Figures 5, 6, and 7. From the family of curves in these plots it is seen that contact time decreases with increased flow rate. These curves approximate a series of straight parallel lines on logarithmic coordinates where $n = 0.76$ as obtained from Equation (15). With an increase in flow rate the curves flatten out indicating the greatest affect on contact time at the lower flow rates. This increase may be assumed to occur from a greater holdup of the liquid around and between the media at the lower flow rates than at the higher rates which may produce a flushing action. The curves indicate that a flow rate may be reached where any further increase would have no influence on the contact time. At this point the physical capabilities of the filter limit the velocity of the fluid and the curve becomes horizontal. Conversely, as the flow rate is decreased the holdup of the liquid due to attractive forces between the liquid and media would predominate and the curves would become asymptotic to the zero flow axis.

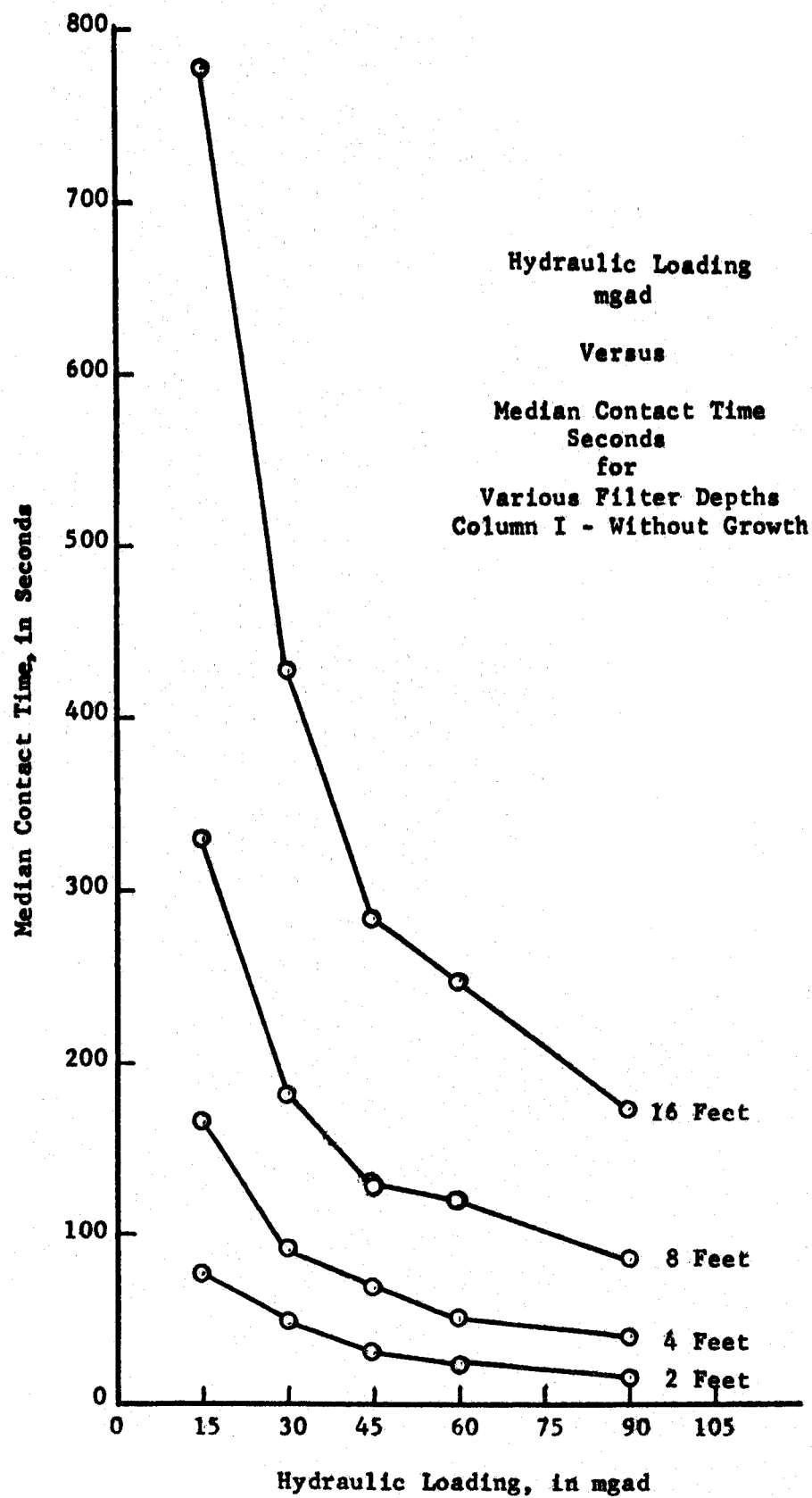


Figure 5. Median Time - Hydraulic Loading

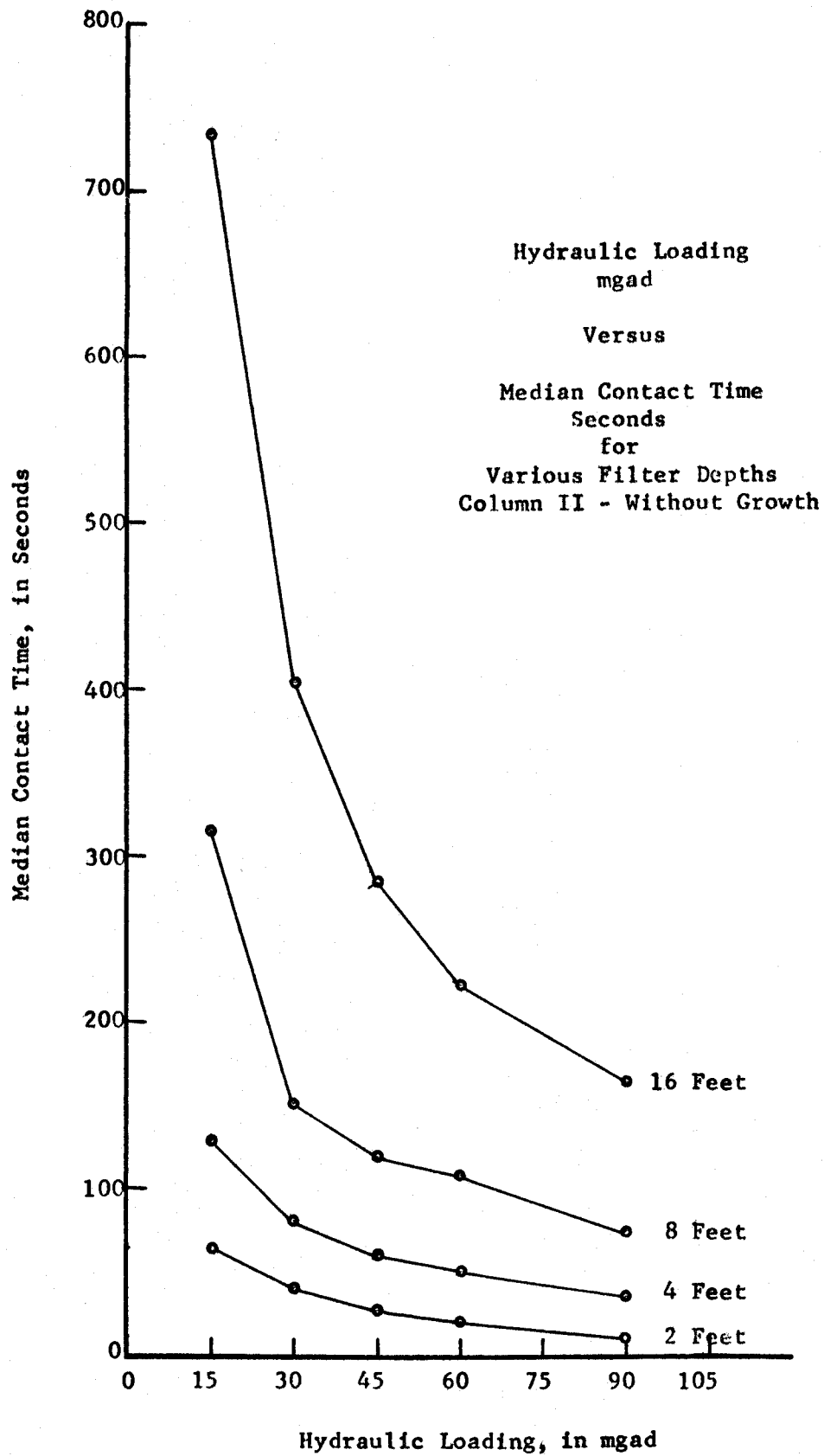


Figure 6. Median Time - Hydraulic Loading

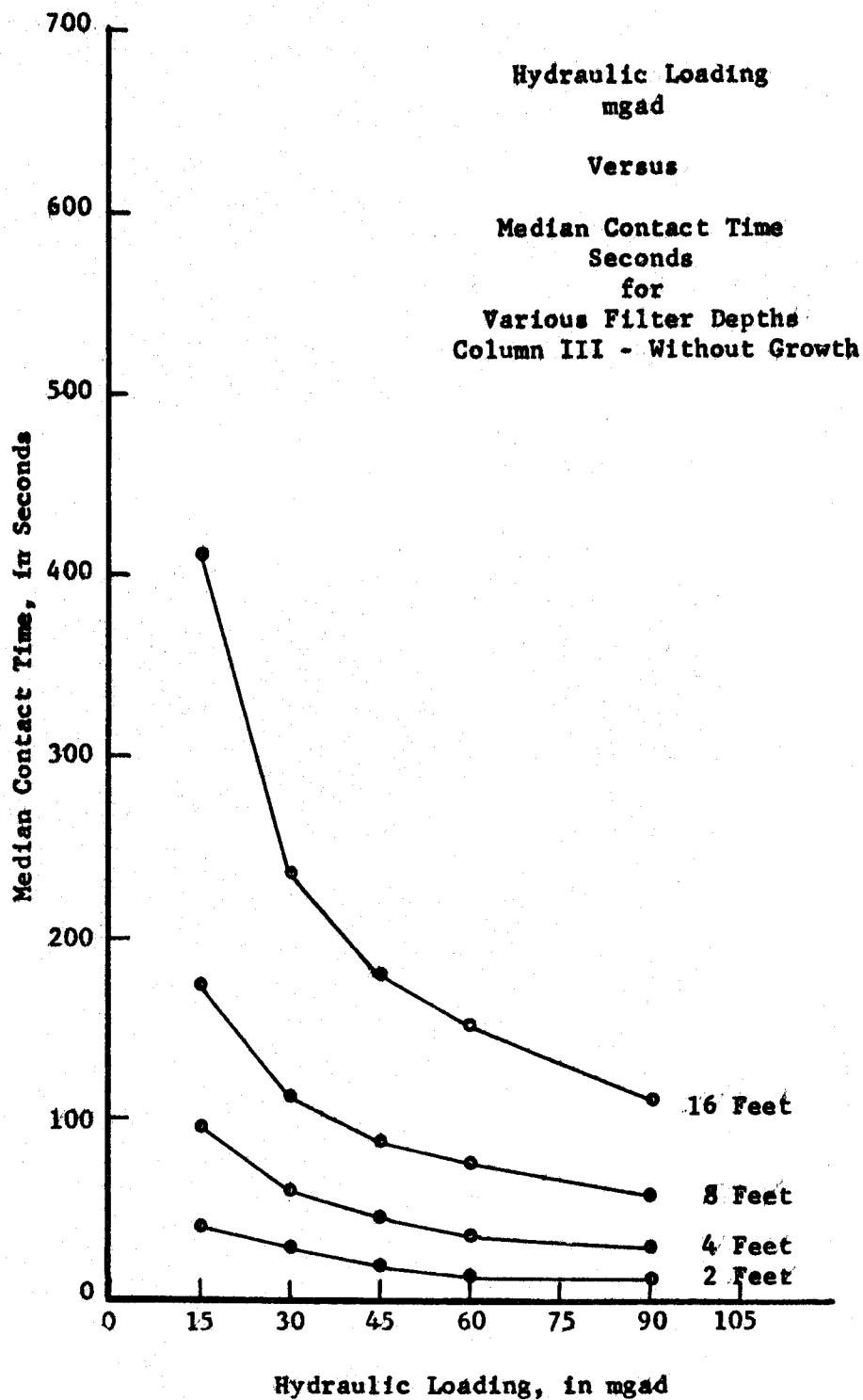


Figure 7. Median Time - Hydraulic Loading

The media size exerts a greater influence at the lower flow rates where the smaller media with the greater surface area provides a more tortuous path for the liquid to travel and greater holdup of the liquid is encountered. At the higher flow rates the effect of holdup is less and the influence of media size decreases.

Depth. Contact time varies with depth as shown in Figures 8, 9, and 10 for the three columns. The contact time increases at a greater rate for the lower flow rates producing a family of curves which approximate a series of parallel lines on logarithmic coordinates with $t \sim D^m$. From Equation (15), m is found to equal 1.08 indicating that contact time increases at a slightly greater rate than would be expected due just to an increase in the amount of media. For deep filters the increased contact time for unit of depth down the filter might be expected due to increased consolidation of the filter bed at lower depths. But for the experimental filters in this study, the media was supported at two-foot intervals and the degree of consolidation should not have been significantly different at any depth. The value of m greater than one then must be considered as characteristic of the system. The value of m equal to 1.08 is the same as that found by McDermott (11) on 3-1/2 inch rubber balls.

Empirical Equation and Experimental Results

A comparison of the experimental data and the solution of Equation (15) is shown in Figure 11. The smooth curves are the solution of Equation (15) for the indicated columns and depths.

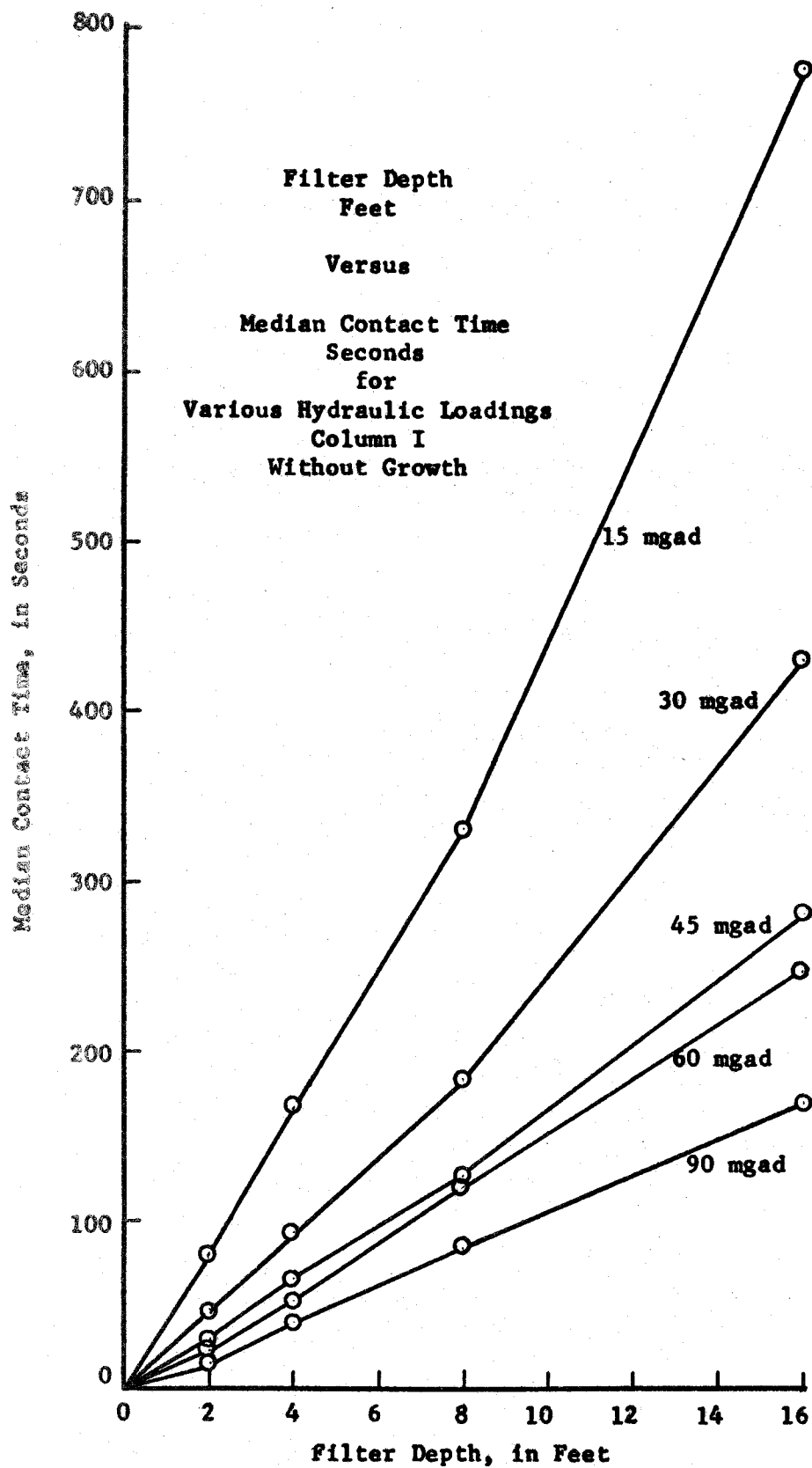


Figure 8. Median Time - Depth

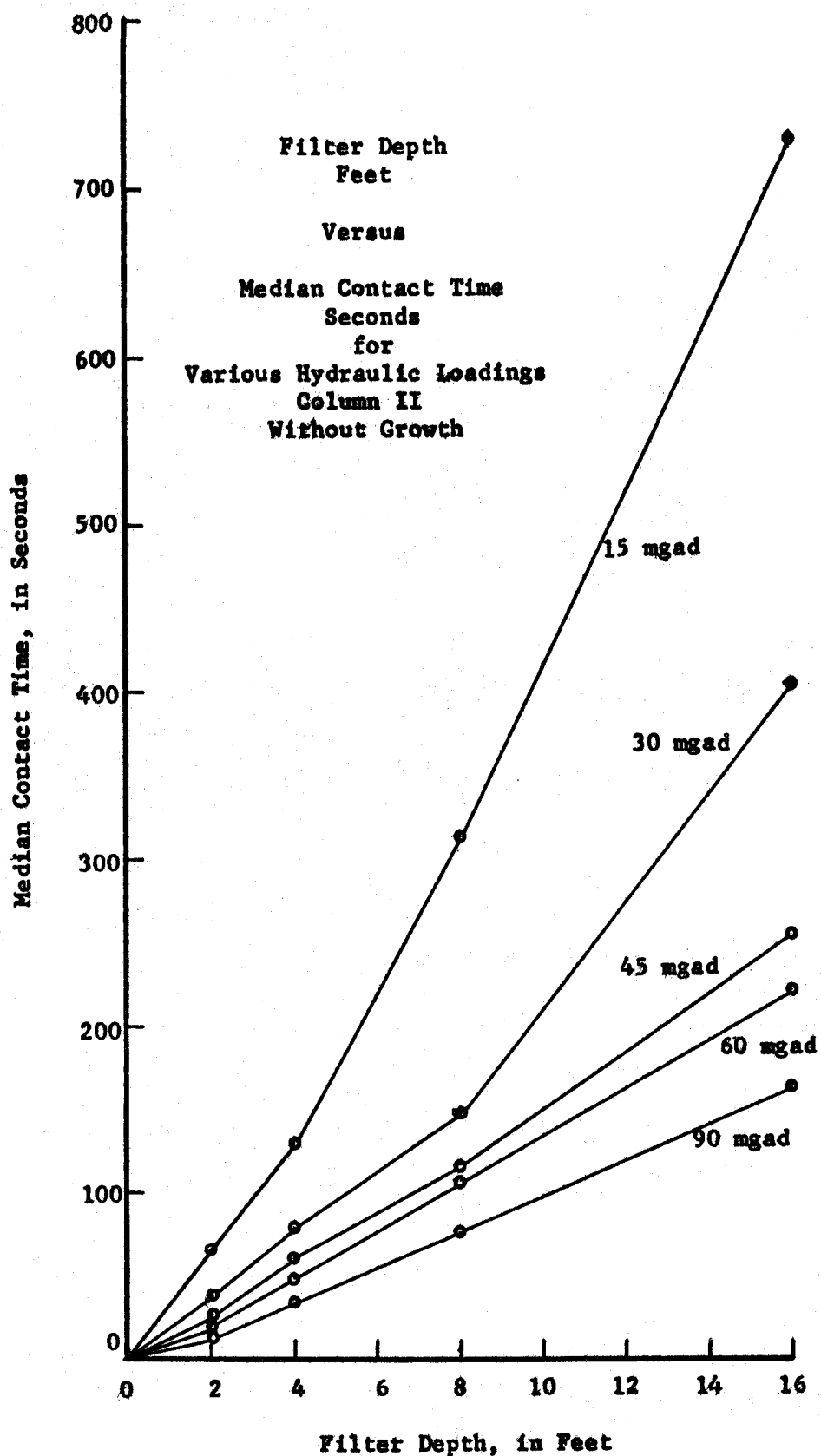


Figure 9. Median Time - Depth

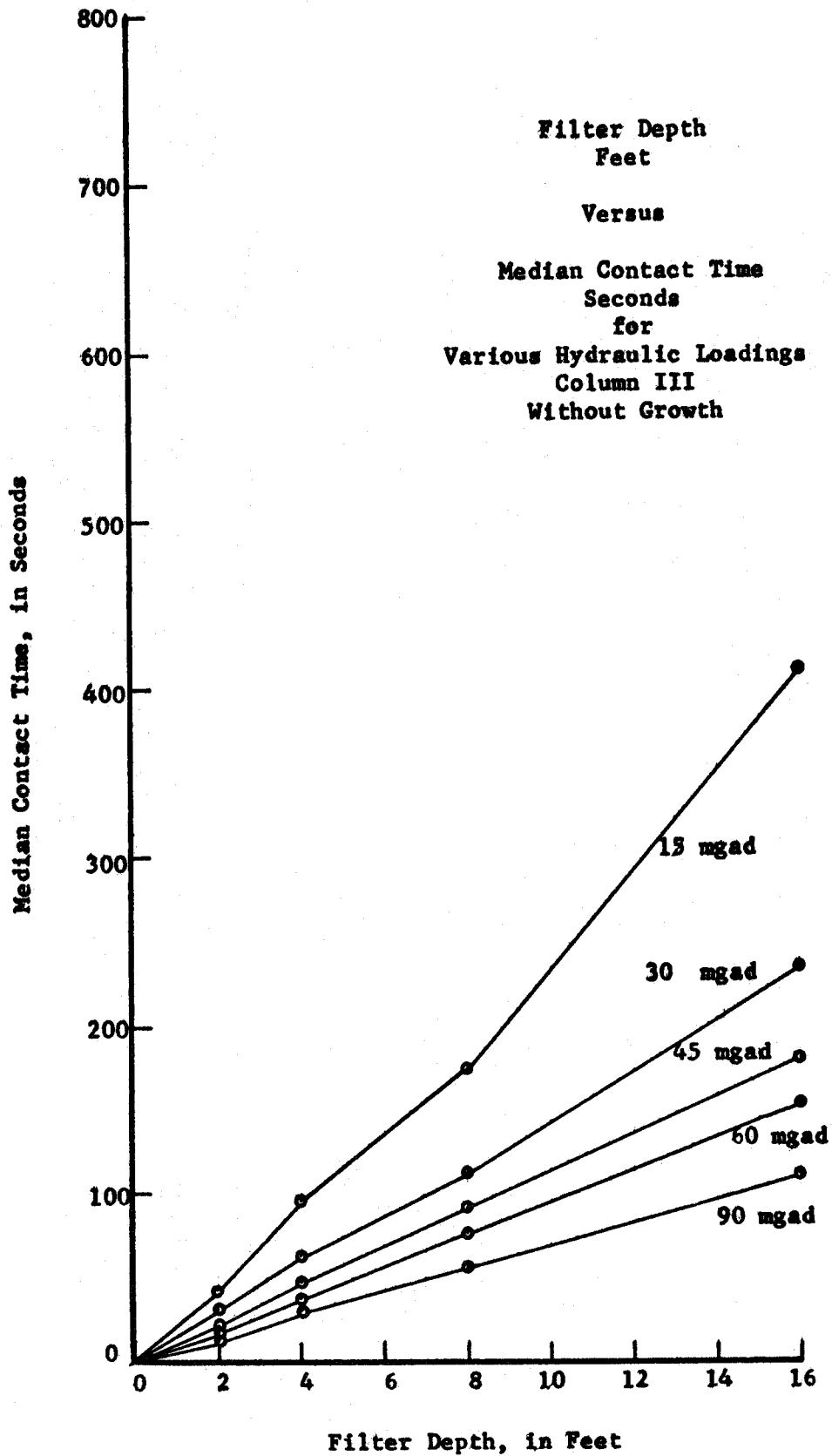


Figure 10. Median Time - Depth

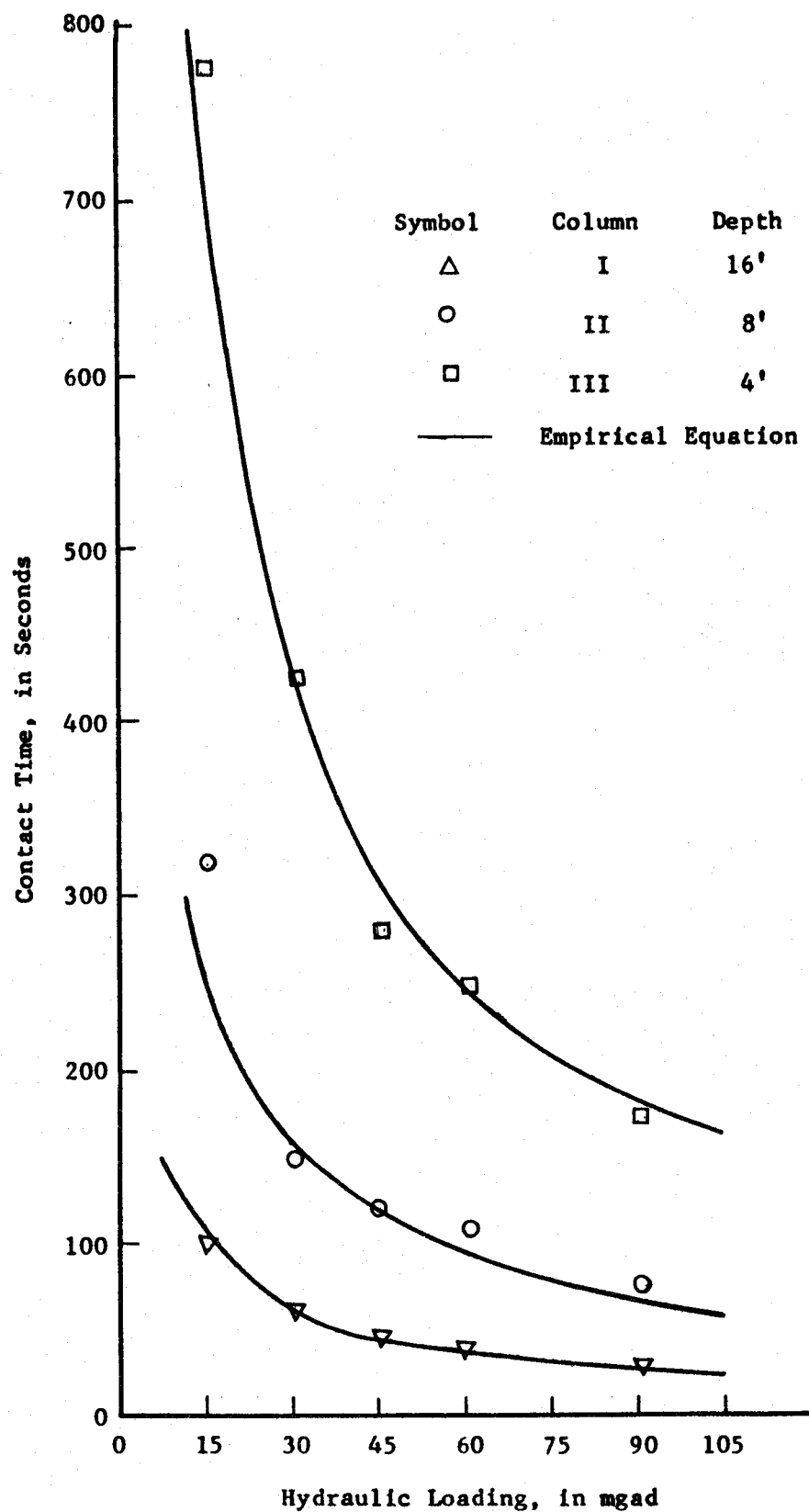


Figure 11. Comparison of empirical equation and experimental data for media without growth.

The plotted points are actual data points found in the experiment. The different depths and columns were chosen to obtain a large range of data values. The majority of data points lie close to the theoretical curve with a greater deviation at the low flow rates and corresponding greater contact time than at the higher flow rates.

Equation (15) is an empirical relationship with defined units. The application of the equation has been limited to describe the action of different variables on a clean media where conditions could be controlled. The form of the equation served as a guide to develop a relationship for contact time on the filter when growths are introduced.

Influence of Biological Growth on Contact Time

Experimental Results

General. Contact time studies were performed on Columns II and III for the filters with biological growth. Column I was not used since previous work (15)(19) showed that operation of the filter with biological growth was difficult due to ponding and clogging associated with the small media. The mean of three data runs were plotted and analyzed the same as the data for contact time on clean media. Equation (16) follows the same form as Equation (15), but the constant K , and the exponents are changed.

Due to biological growth on the media and in the voids of the bed, the contact time was increased from that for clean media. Maintenance

of a uniform biological growth was difficult in that the growth will not only vary from filter to filter, but from day to day in the same filter. To provide some uniformity in formulating the equation, seven data points for median time were rejected on the basis that the stripping action of filter flies on the growth allowed less contact time than would have been encountered under the normally observed growth conditions. These data points were recognized from plots of the data both on arithmetic and logarithmic coordinates.

The other factors beside filter flies that may have affected the biological growth of the filter were temperature and organic loading. The range of temperature for the data runs on the filter with growth was between 20-25 °C. Maintaining the temperature and organic feed fairly constant, the controlling factors both on the biological growth and contact time should be the same variables as for clean media, that is, depth, flow rate, and size of the media.

Growth. Growth samples were taken at each depth for each flow rate. Figures 12 and 13 show the results of this analysis for Columns II and III respectively. There is no general pattern to be determined from the growth analysis, but some observations can be made. At the 90 mgad flow rate the growth appears greater than at other flow rates contradicting the idea that scouring due to the high flow rate would reduce the growth below that found at lower flow rates. Possibly, the greater total organic load available at this rate produced the greater growth. Further examination shows that the growth appears to be heaviest at the 16 foot level in Column II. The

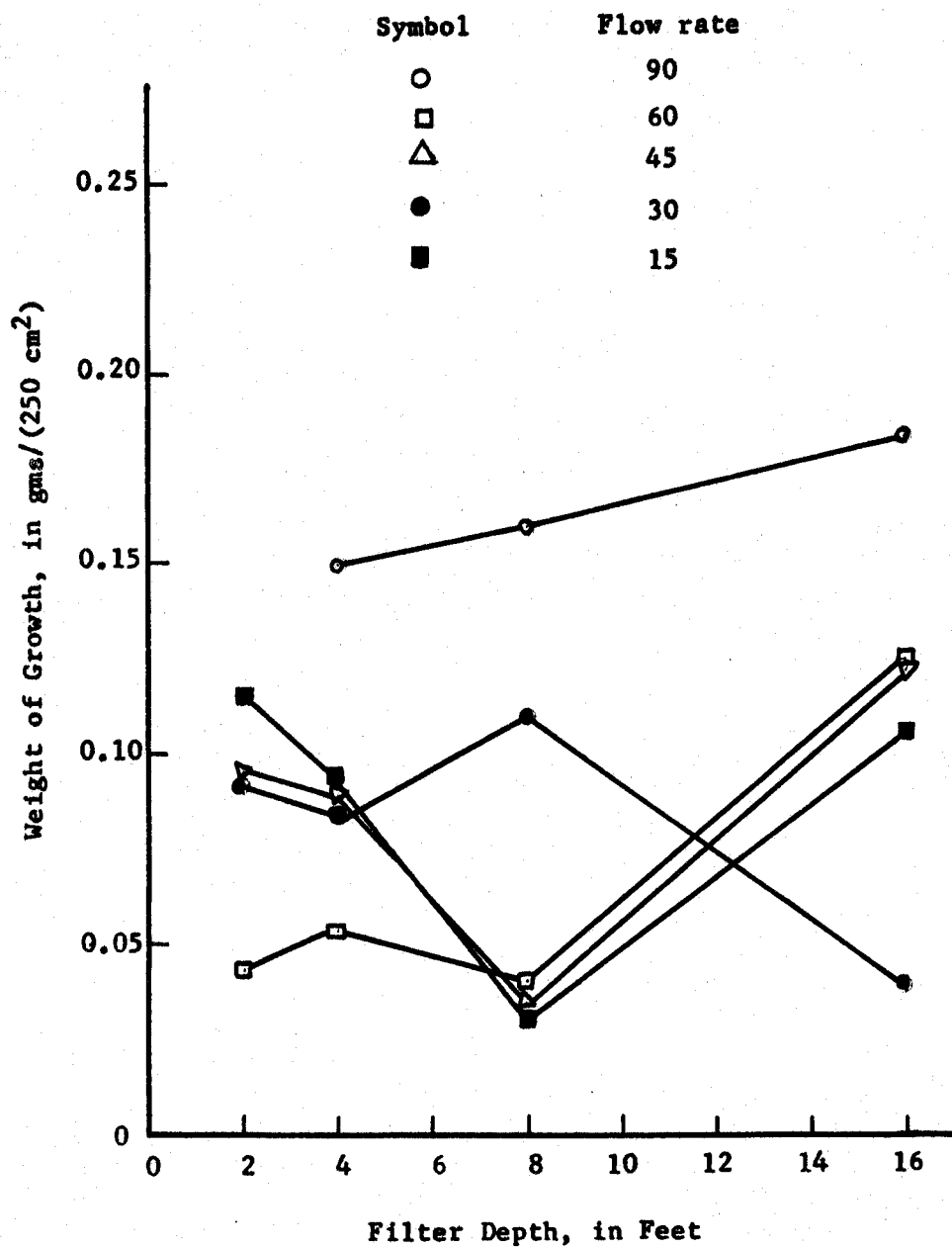


Figure 12. Biological growth versus filter depth for Column II

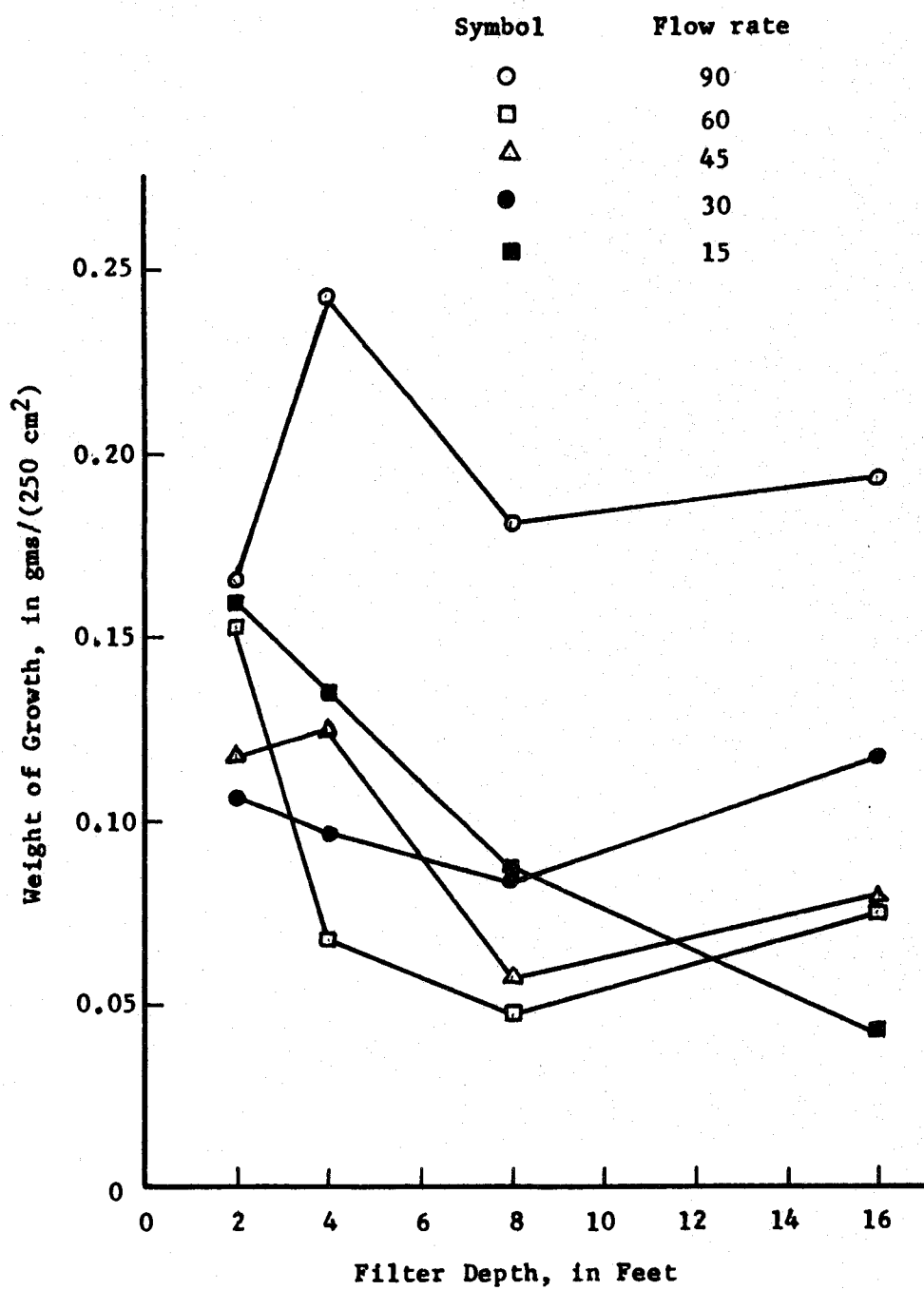


Figure 13. Biological growth versus filter depth for Column III

heavier growth in the bottom levels of the filters is unusual. Generally, more luxuriant growths have been reported to be in the top portions of the filter where food is more readily available. No explanation for the apparent heavier growth in the bottom has been found.

The stripping action of the filter flies can be seen from the growth curves. The fly larvae were first noted at eight-foot level of Column III at the 30 mgad flow rate. From Column III the larvae spread to Column II and permeated the entire depth of both columns at the 15 mgad flow rate. Some larvae were recorded as growth in the growth analysis.

It should be stated that the analysis for growth from a small percentage of the media obtained from the top of a section of the filter may not be a good indication of actual growth conditions in that section. A better indication of the amount of growth would be to mount the filter on a scale and record the change in weight at different flow rates.

Hydraulic Loading. Figures 14 and 15 indicate how contact time varied with hydraulic loading at various depths. From Equation (16) contact time varies inversely with hydraulic loading. A comparison of Equations (15) and (16) shows that the flow rate had a greater influence on contact time for the media with biota than clean media. With clean media the liquid flows through the packing in a defined free space between the media which does not change as

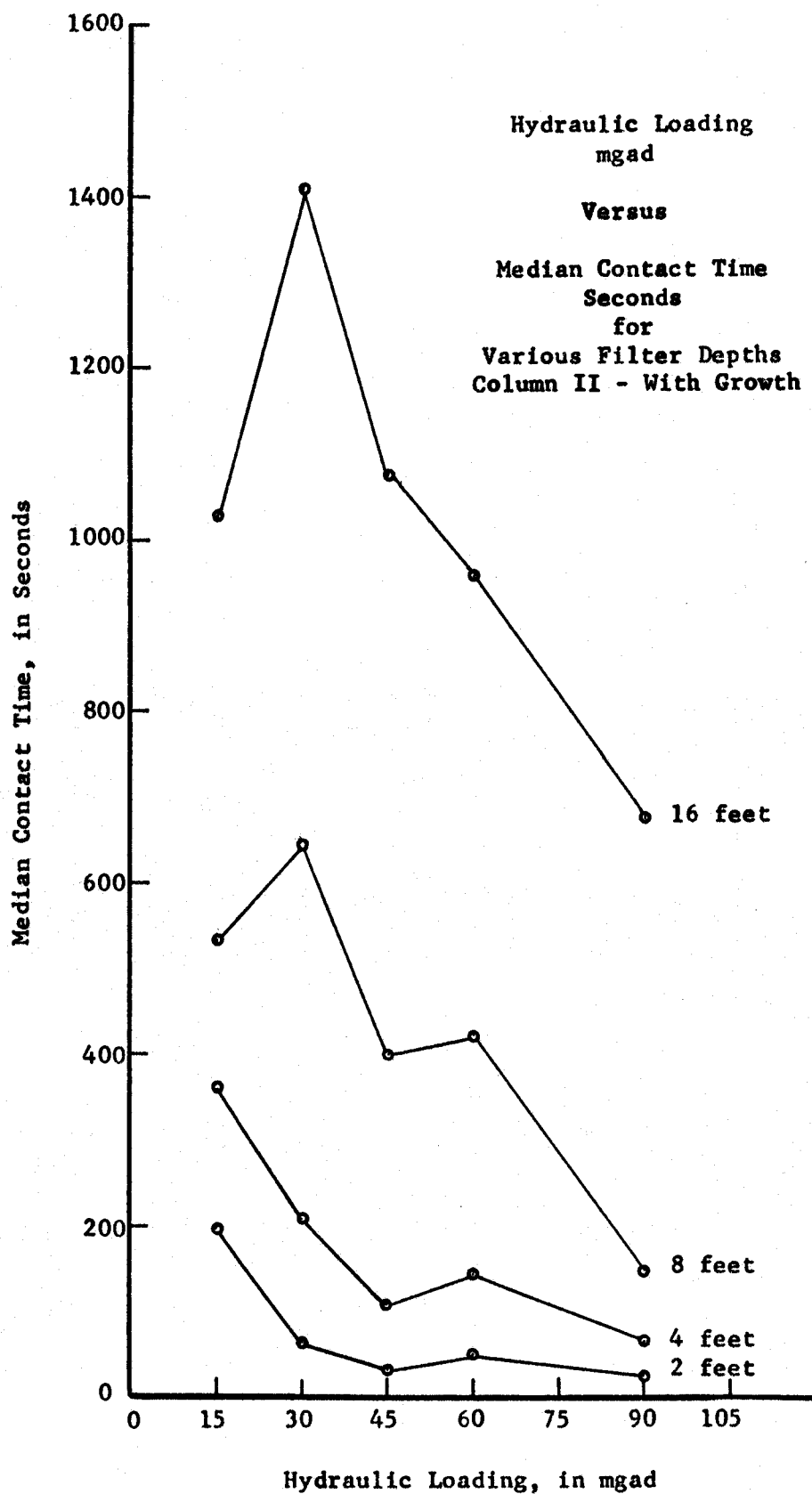


Figure 14. Median Time - Hydraulic Loading

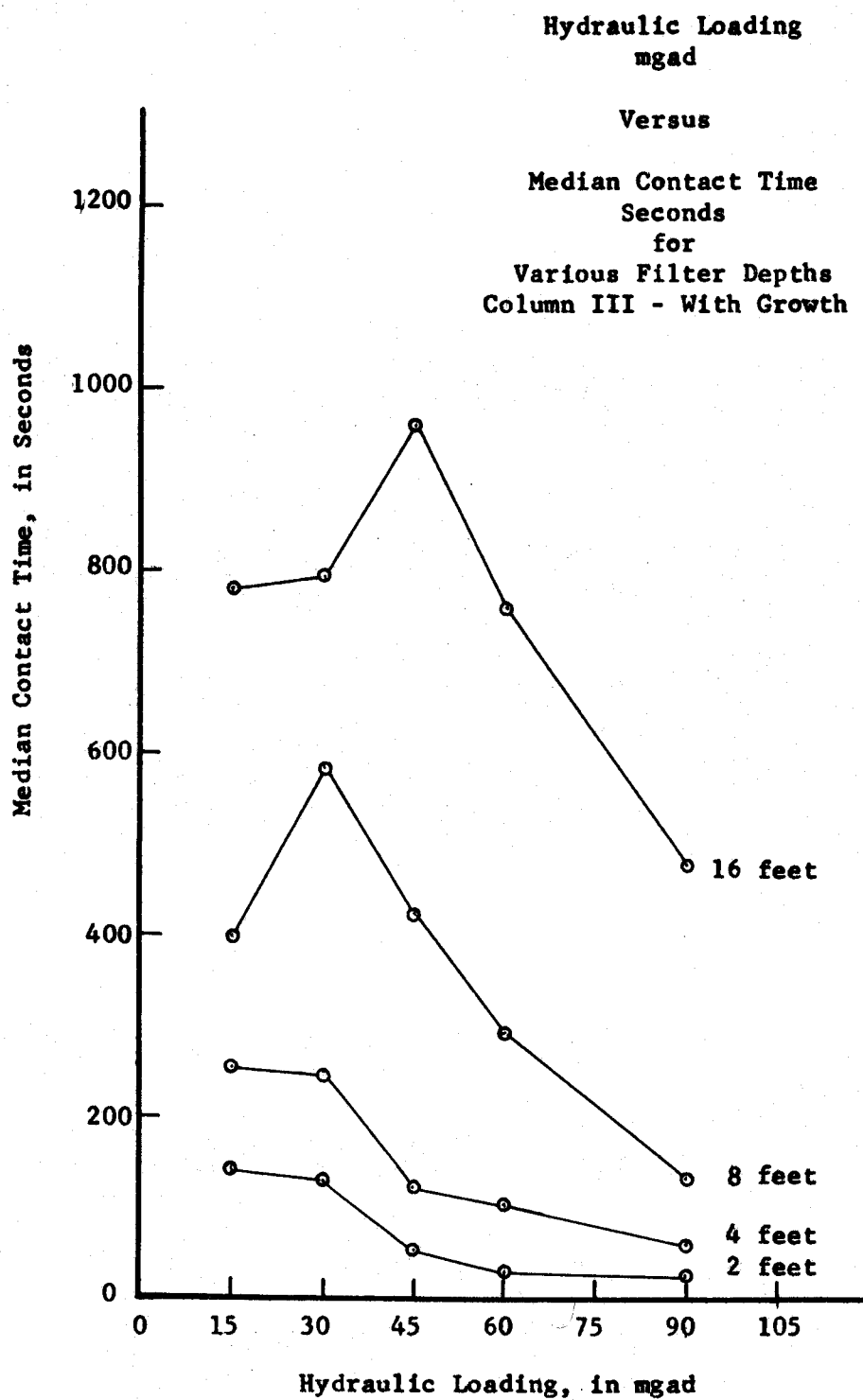


Figure 15. Median Time - Hydraulic Loading

the flow rate is changed. But for the media with growth the space changes as the voids fill with growth. Further, the pattern in which the growth fills the voids depends on the distribution of the liquid in the column. This distribution is dependent on the flow rate and the growth already present. The interplay between flow rate and growth distribution is one explanation of the greater influence of flow rate on the contact time for the media with growth.

A comparison of the exponent m shows an increase from 0.76 for clean media to 1.05 for media with growth. A proportionately larger decrease in contact time results from an increase in flow rate. Channeling is expected where the buildup of growths in the voids divert the liquid to a series of channels in the column. A greater flow through these channels keep the growths scoured and reduces the contact time.

A break in the curves at the 30 mgad flow rate is attributed to the action of the filter fly larvae. The reduction in contact time at 15 mgad resulted from the larvae destroying part of the growths in the voids

Depth. Figures 16 and 17 give an indication how contact time varied with depth at various hydraulic loadings for Columns II and III respectively. Depth had more significance on the determination of contact time than the other variables in either Equation (15) or (16). A comparison between the two equations shows depth has a greater effect on media with growth. The influence of depth as given in

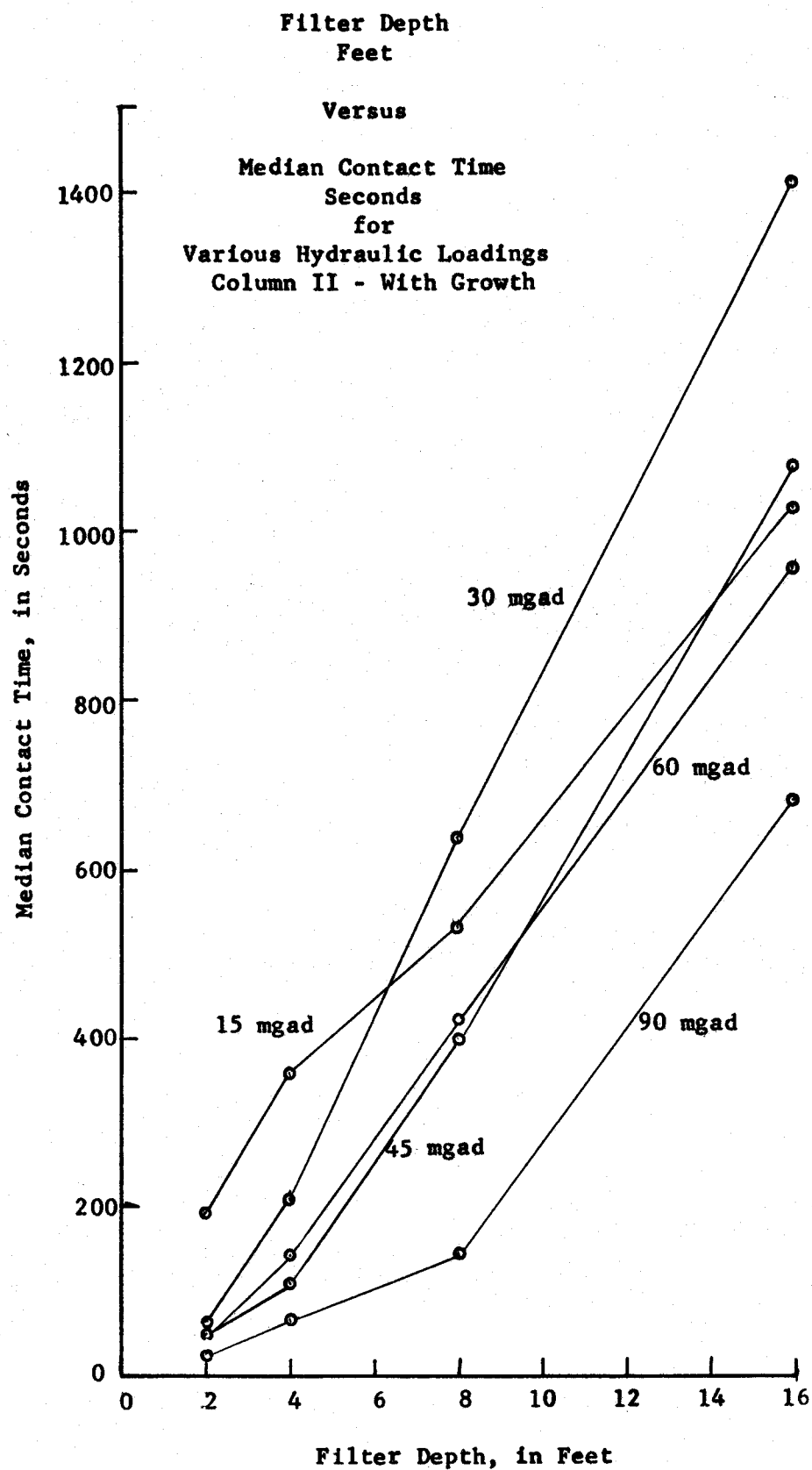


Figure 16. Median Time - Depth

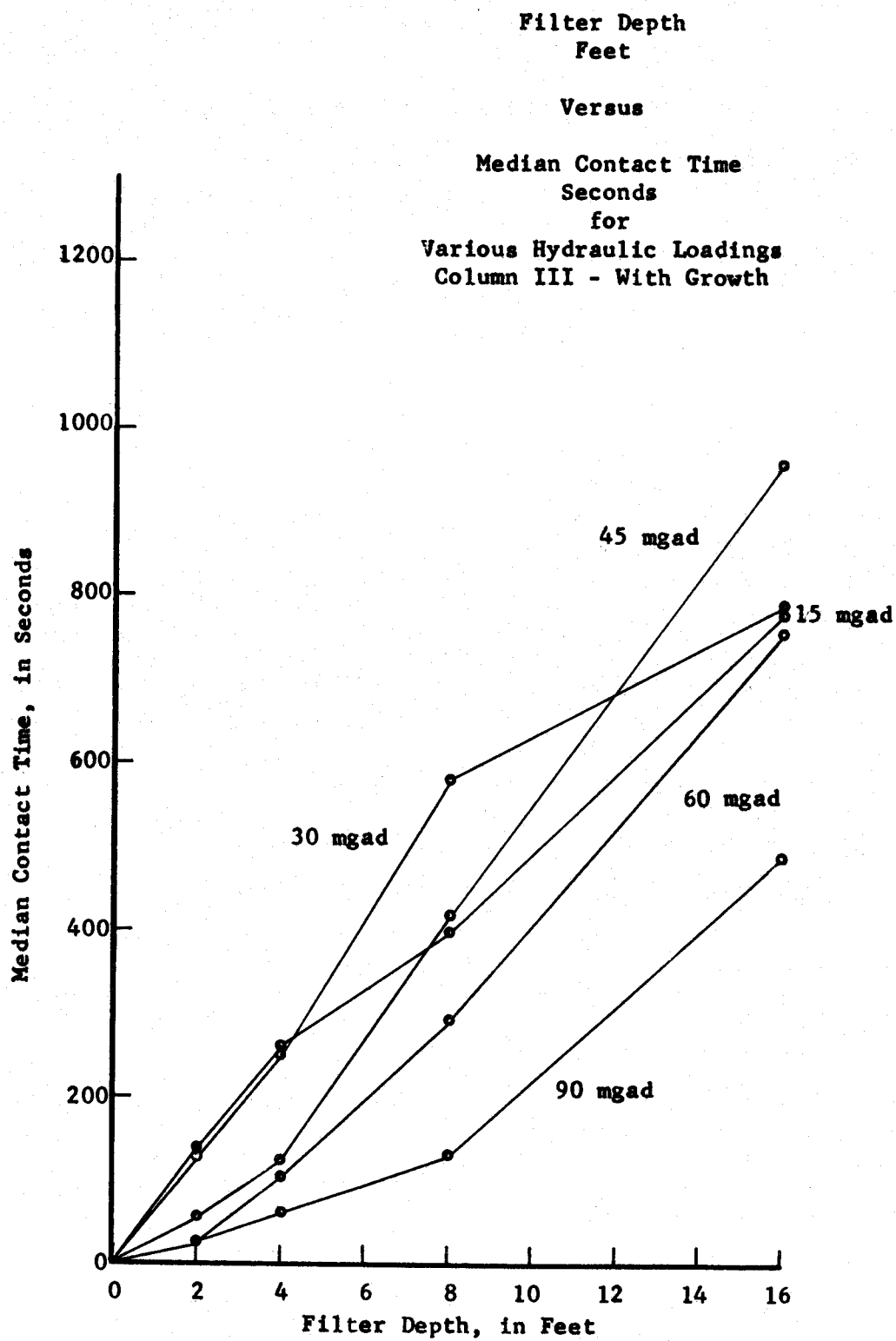


Figure 17. Median Time - Depth

Equation (16) differs from what might be expected. From previous evidence the greater growth would be expected in the top sections of the filters. But from the growth analysis greater growth was encountered at the 16-foot level than at the rest of the levels. If channeling had occurred due to a buildup of growths in the top sections with a better distribution of the liquid at the lower depths a greater contact time could be realized for a section of the column at the lower depths.

Media. As was shown from the analysis of the data, the media size seems to be of little significance as this media becomes covered with a biological slime. A factor that must be considered is that the comparatively small media used in this study provides a general void size such that the growth of the microorganisms could smooth out the effect of the two different media sizes. Whether or not this would be the case for larger media found in present trickling filters would have to be investigated. For this study it is concluded that media size has no influence and this variable will be neglected giving an equation in the form of Equation (17).

Empirical Equation and Experimental Results

A comparison of the curves for the solution of Equation (17) and experimental data is shown in Figure 18. The data points are plotted for both columns since it was determined that the media size does not influence the contact time. The smooth curves are a plot of the

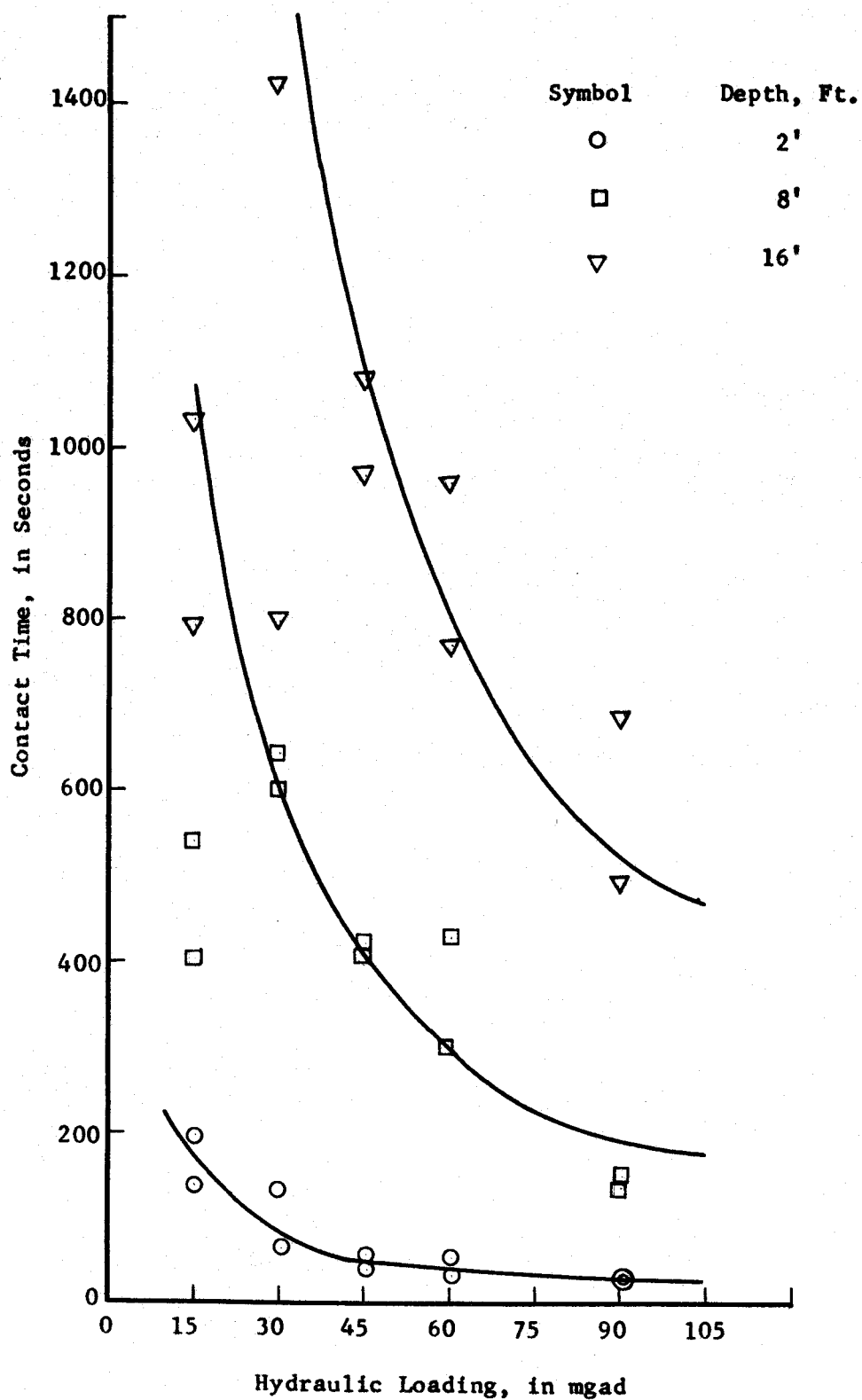


Figure 18. Comparison of empirical equation and experimental data for media with growth.

solution of Equation (17) for the indicated depths. In these plots the experimental data for the 15 mgad at 16-feet and 8-feet have been rejected because of filter flies. The data follows the theoretical curve at lower depths and increasing flow rates closer than at greater depths and lower flow rates.

The useful application of this equation to determine the contact time in any filter will depend on how close the conditions of the biological growths approach the conditions of the growth in this study. It can be seen that the growths can appreciably alter the contact time from that of clean media.

Effect of Contact Time on COD Removal Rates

Experimental Results

Figures 19 and 20 are plots of COD remaining versus filter depth for various hydraulic loadings on the two columns. An examination of the curves show the greatest rate of removal occurs in the top portion of the filter where readily assimilable feed is available. The removal rates then decrease for both columns with increased filter depth as seen by a flattening of the curves past the eight-foot depth.

The greatest effects of flow rate on COD removal rates were observed in the top two feet of the filter. From the plotted values at the two-foot depth the range of COD removal is 57 per cent at 15 mgad for Column II down to 20 per cent at 90 mgad for Column III. As the depth increased the effect of the flow rate on COD removal

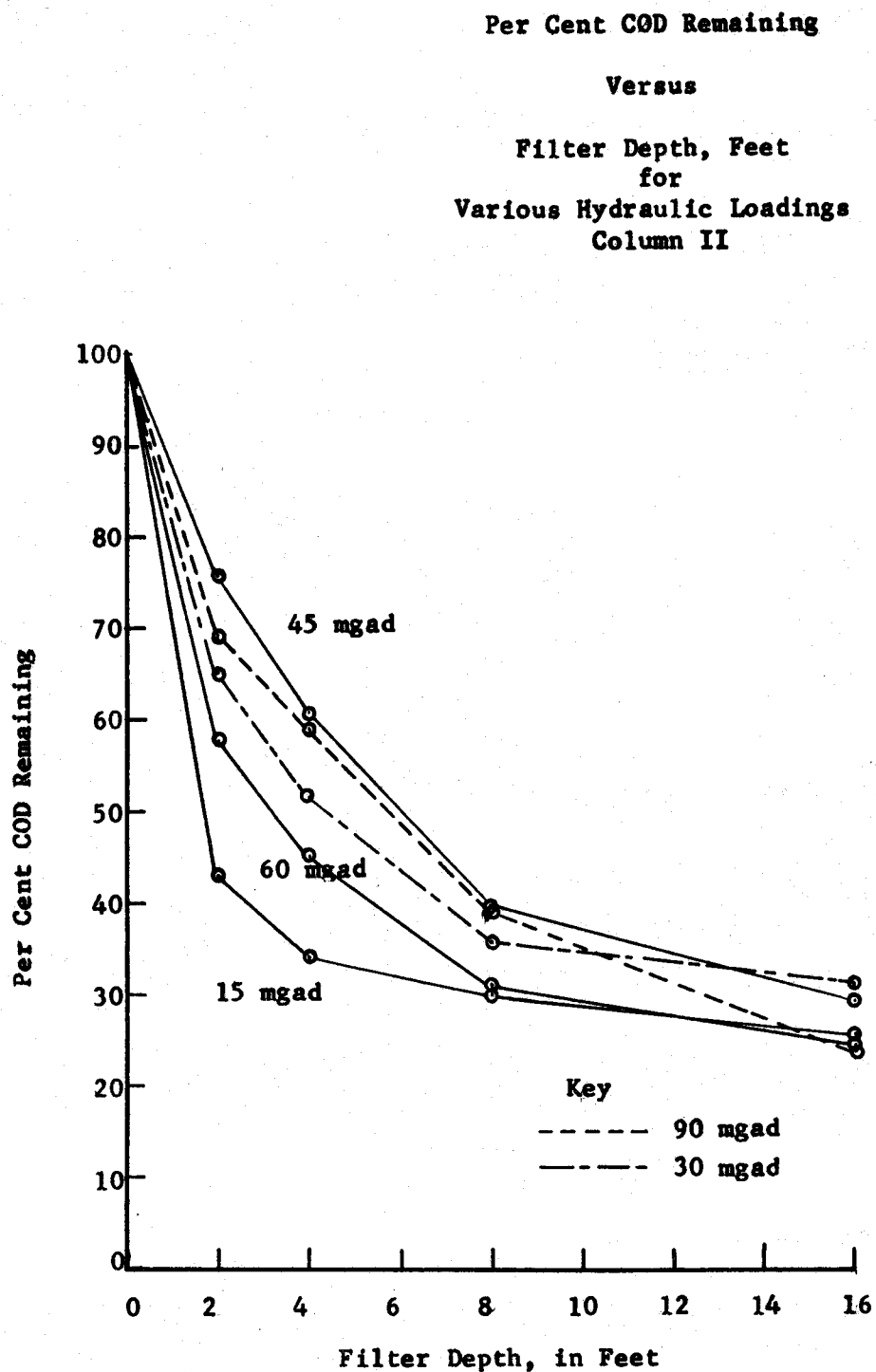


Figure 19. Per Cent COD Remaining - Depth

Per Cent COD Remaining
Versus
Filter Depth, Feet
for
Various Hydraulic Loadings
Column III

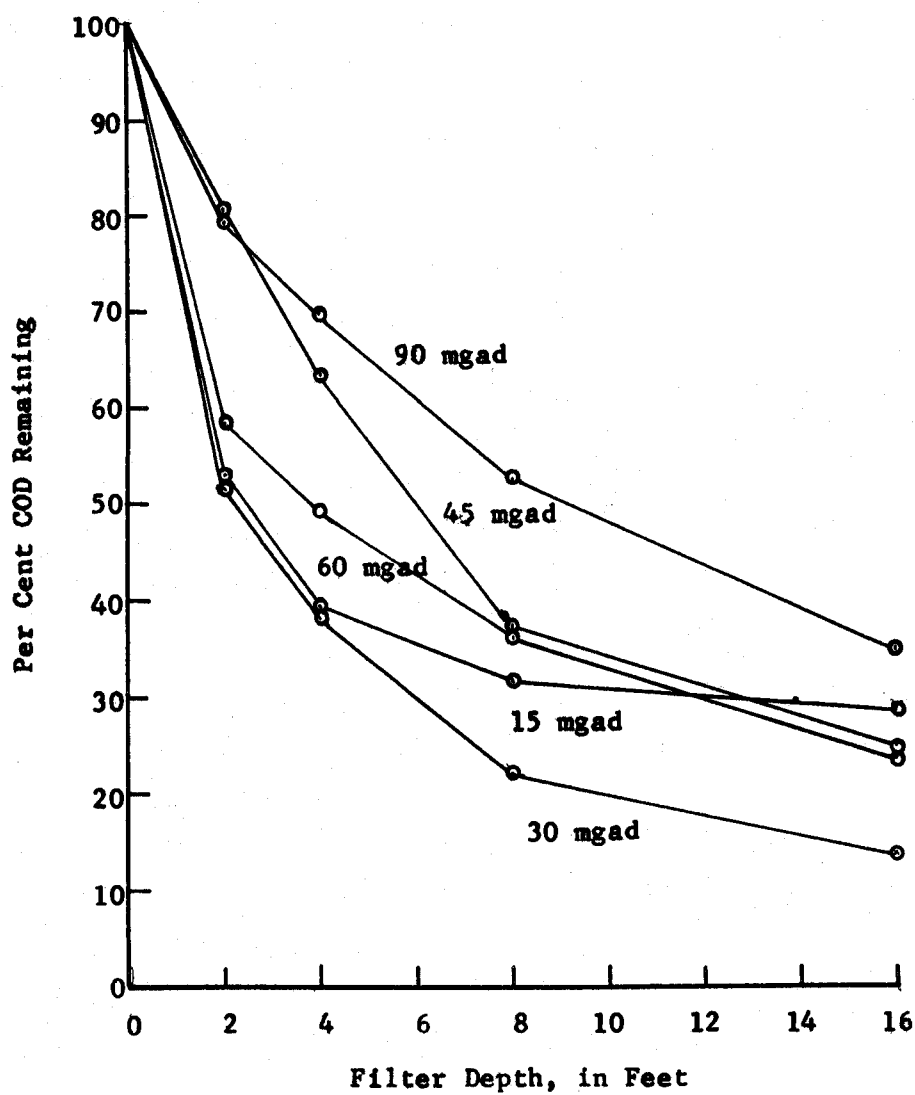


Figure 20. Per Cent COD Remaining - Depth

decreased and the range of values is narrowed down until the COD removal values at 16-feet for Column II are between 69 and 76 per cent. For Column III at 16-feet, the difference in COD removal ranged from 65 to 86 per cent. This narrowing of the range indicates that at higher flow rates greater advantage was taken of the lower depths of the filter for purification. It should also be noted that for Column II at the 16-foot level, six times as many pounds of COD were removed at the 90 mgad flow rate than at the 15 mgad flow rate. This increase in the total pounds of COD removal with increased flow rate was greatest at the lower filter depths.

A comparison of COD removal between the two columns indicates they are generally the same. An exception is that Column II gave better COD removal at the 90 mgad flow rate than Column III. A comparison of the growths at the different flow rates for both columns seems to show little correlation between the amount of growth and the COD removal. It is also difficult to detect from the curves any effect on COD removal due to the filter flies at the 15-30 mgad flow rates. Further examination of the curves indicates in general, that in the top portion of the filters there was a greater COD removal at the lower flow rates than at the higher flow rates.

Empirical Equation for COD Removal

Equation (18) is an empirical equation derived from the analysis of the data of per cent COD remaining as a function of the contact time. The equation does not follow a first order reaction. Most

of the postulated first order kinetic equations are based on BOD removal rather than COD removal. Due to the difference in determination of the two values, there is organic material oxidized in the COD determination that is not accessible for biological degradation. Even for these equations based on BOD removal there is evidence that the reaction is not strictly first order and that the removal rate decreases with concentration or time since the easily assimilable components of the feed are removed more readily. Equation (18) follows this retardant form where the removal of COD becomes more difficult with an increase in time. Further examination of the equation shows that total COD removal is not possible. There will be some fraction or a finite COD value that cannot be removed. This fraction of non-removable organic material seems to be true for BOD values and first order reaction also.

The application of the equation can be approached two ways. Given a deep trickling filter with the physical dimensions known, the contact time through the filter can be computed from Equation (17). This time may be used in Equation (18) to find the COD removal that can be expected of the filter at some hydraulic loading rate. The second approach is to specify the desired COD removal and a solution of Equations (17) and (18) will give the size of the filter needed.

SUMMARY

This research encompassed the study of the combined biophysical system of a deep trickling filter system under controlled conditions. The study attempted to correlate the physical factors of media size, depth of filter, and organic and hydraulic loading rates with the biological activity of the filter slime. This correlation was accomplished by evaluating a relationship between the rates of removal in laboratory models of a deep trickling filter with the time of retention of a liquid substrate in these filters.

The experimental filters consisted of three 5.8-inch diameter columns, 18 feet in depth. Each column was packed with a different size of spherical media. The time of retention of a fluid in these filters, using sodium chloride as a tracer, was evaluated as the median residence time. The contact time and organic removal, measured as COD removal, were determined for different flow rates and at various levels in the columns.

An evaluation of the data by a step-wise regression analysis using an IBM 1620 computer established three empirical relationships. Two equations were determined for contact time as a function of flow rate, depth of the filter and media size. The first equation gave a relationship for contact time on media without growth as:

$$t = 207 \frac{D^{1.08}}{Q^{0.76} d^{0.50}}$$

where the regression analysis yielded a correlation coefficient equal to 0.99. The second equation provided a relationship for

contact time on media with biological growth as:

$$t = 1072 \frac{D^{1.44}}{Q^{1.05}}$$

where the regression analysis gave a correlation coefficient of 0.98.

The useful application of the first equation is limited to describing the action of different variables on a clean spherical media where conditions could be controlled. The form of this equation served as a guide in developing the second equation. The use of this second equation to determine contact time on any filter will depend on how close growth conditions follow those in this study.

The third empirical equation established a relationship for COD removal as a function of time as:

$$\frac{P_e}{P_o} = 1.03t^{-0.19}$$

with a correlation coefficient of 0.91. This equation for COD removal is a retardant form in that organic removal becomes more difficult with an increase in contact time and indicates that there is a fraction of COD which is not removable.

CONCLUSIONS

1. Contact time for a liquid flowing through the filter bed without biota in the range of media size was found to be inversely proportional to the 0.76 power of the hydraulic loading, inversely proportional to the 0.50 power of the diameter of the media, and directly proportional to the 1.08 power of the filter depth.
2. Contact time for a liquid flowing through the filter bed with biota in the range of media size was found to be inversely proportional to the 1.05 power of the hydraulic loading and directly proportional to the 1.44 power of the filter depth.
3. Contact time is not influenced by media size for filter media covered with biota.
4. Flow rate has a greater influence on contact time for media with biota than for the media without biota.
5. Depth has more influence on contact time than any other variable for media both with and without biota.
6. Depth has a greater effect on contact time for the media with biota than the media without biota.
7. The fraction of COD remaining is inversely proportional to the 0.19 power of the contact time.

BIBLIOGRAPHY

1. Behen, V.C., W.F. Ames and K. Keshavan. Trickling filter design and performance. *Journal of the Sanitary Engineering Division, American Society of Civil Engineers* 88 (SA1):31-37. 1962.
2. Bloodgood, Don E., G.H. Teletzke and F.G. Pohland. Fundamental hydraulic principles of trickling filters. *Sewage and Industrial Wastes* 31 (3):243-253. 1959.
3. Burgess, Fredrick J. and Cameron M. Gilmour. Chemical-physical aspects of deep trickling filters. Corvallis, 1962. 25 numb. leaves (Oregon State University. Engineering Experiment Station. Progress report no. 3 on U.S. Public Health Service Research Grant WP 171(C3)).
4. Eckenfelder, W. Westly, Jr. and Donald J. O'Connor. *Biological waste treatment*. New York, Pergamon Press, 1961. 299 p.
5. Eckenfelder, W. Westly, Jr. Trickling filtration design and performance. *Journal of the Sanitary Engineering Division, American Society of Civil Engineers* 87(SA4):33-45. 1961.
6. Fairall, J.M. Correlation of trickling filter data. *Sewage and Industrial Wastes* 28(9):1069-1074. 1956.
7. Gt. Britain. Dept. of Scientific and Industrial Research. Water Pollution Research Board. *Water pollution research*, 1956. London, 1957. 74 p.
8. Gt. Britain. Dept. of Scientific and Industrial Research. Water Pollution Research Board. *Water pollution research*, 1962. London, 1963. 126 p.
9. Howland, W.E. Effect of temperature on sewage treatment process. *Sewage and Industrial Wastes* 25(2):161-169. 1953.
10. Howland, W.E. Flow over porous media as in a trickling filter. In: *Proceedings of the 12th Industrial Waste Conference*, Purdue University, Lafayette, Indiana, 1958. p. 435. (Purdue University, Engineering Extension Department Extension Series no. 94).
11. McDermott, J.H. Influence of media surface area upon the performance of an experimental trickling filter. Master's thesis. Lafayette, Indiana, Purdue University, 1957. 94 numb. leaves.
12. McKinney, Ross E. Biological flocculations. In: *Biological Treatment of Sewage and Industrial Wastes*, ed. by Joseph McCabee and W.W. Eckenfelder, Jr. New York, Reinhold, 1955. p. 88-100.

13. McKinney, Ross E. Microbiology for sanitary engineers. New York, McGraw-Hill, 1962. 293 p.
14. Phelps, E.B. Stream sanitation. New York, John Wiley, 1944. 276 p.
15. Roach, Michael D. The effects of high rate hydraulic loading on small size media for traickling filters. Corvallis 1963. 5 numb. leaves. (Oregon State University. Dept. of Civil Engineering. Research report sponsored by National Science Foundation Undergraduate Research Program).
16. Schroepfer, G.J. et al. Temperature effects on trickling filters. Sewage and Industrial Wastes 24(6):705-722. 1952.
17. Schulze, K.L. Experimental vertical screen trickling filter. Sewage and Industrial Wastes 29(4):458-467. 1957.
18. Schulze, K.L. Load and efficiency of trickling filters. Journal Water Pollution Control Federation 32(3):245-261. 1960.
19. Seaders, John. Kinetics of biological contact beds. Master's thesis. Corvallis, Oregon State University, 1963. 93 numb. leaves.
20. Sinhoff, M.D., R. Porges and J.H. McDermott. Mean residence time of a liquid in a trickling filter. Journal of the Sanitary Engineering Division, American Society of Civil Engineers 85(SA6): 51-78. Nov. 1959.
21. Sorrels, J.H. and P.S.A. Zeller. Two stage trickling filter performance. Sewage and Industrial Wastes 28(8):943-954. 1956.
22. Stack, V.T. Theoretical performance of trickling filtration processes. Sewage and Industrial Wastes 29(9):987-1001. 1957.
23. Standard methods for the examination of water and waste water. 11th ed. New York, American Public Health Association, 1960. 626 p.
24. Velz, C.J. Basic law for performance of biological filter. Sewage Works Journal 20(4):607-617. 1948.