AN EVALUATION OF RECENT APPROACHES FOR THE DESIGN OF TRICKLING FILTERS

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THE DESIGN OF TRICKLING FILTERS

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CHAPTER I

INTRODUCTION

1. The Trickling Filter in Wastewater Treatment

There are four basic ways in which man disposes of his waste products: by burying them beneath the ground, by carrying them away in air, by carrying them away in water, or by making them reusable. Man has utilized the water medium for waste disposal for centuries; however, the fresh water resource is far from inexhaustible, and when employed as a medium for waste disposal, it must be reclaimed for re-use by some means of wastewater treatment.

Many water-carried wastes of domestic and industrial origin can be removed from the wastewater by biological oxidation. In a wastewater treatment plant, wastes undergo decomposition in two ways: aerobically, and anaerobically. Decomposition by aerobic biological oxidation has traditionally been accomplished by one of two methods: trickling filtration process, or activated sludge process. The difference between these processes is the manner in which the microorganisms come in contact with the wastewater.

The trickling filter, which is the subject of this study, can more adequately be described as a fixed-bed wastewater treatment unit. In reality, filtration as normally defined does not occur. The trickling filter is a tank containing relatively coarse media to which microorganisms are attached. The wastewater is distributed over the surface, and passes (or "trickles") through the pores of the media bed, and the microorganisms extract the oxidizable wastes from the wastewater. Aerobic conditions are maintained by natural ventilation through the voids in the media or by air forced into the filter.

In contrast, the activated sludge process is a fluid-bed system; flocculated biological growths ("activated sludge") are continuously circulated and contacted with the organic waste in the presence of oxygen supplied from air bubbles injected under turbulent conditions.

2. Description of the Trickling Filter and Mechanism of Wastewater Treatment

From the first trickling filters constructed in England in the 1890's, many different types have developed. In general, the trickling filter can be separated into these elements: (1) the media bed, (2) method of application of the wastewater to the surface of the bed, and (3) the underdrains, which collect the treated water from the bottom of the media bed and carry it away from the filter (see Figure 1).

Historically, the media of the filter bed has been crushed stone or gravel. More recently, new plastics and

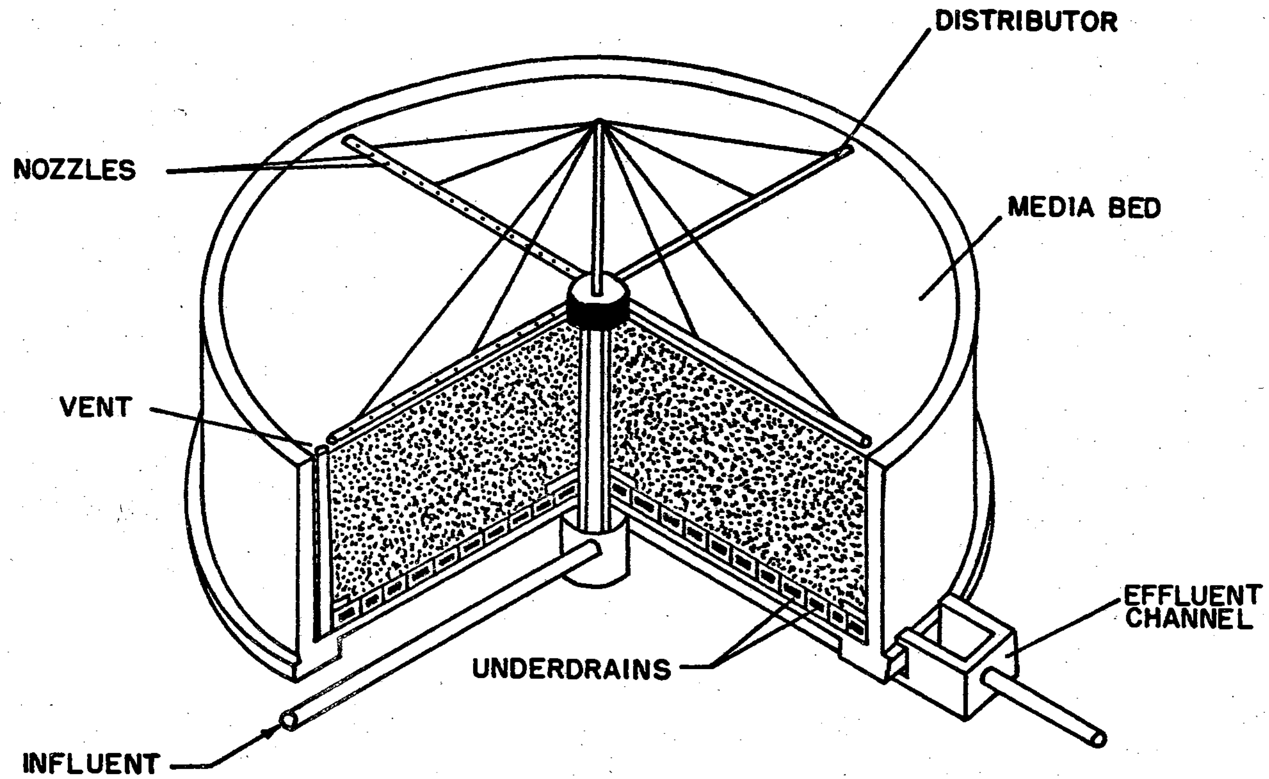

Figure 1 - A Typical Trickling Filter.

related materials have been used. On occasion, hard coal, coke, cinders, slag, wood, and ceramic materials have been used (1). However, the majority of trickling filters in existence have crushed rock media. The main problem encountered in the media bed is clogging, which can be caused by disintegration of the media, or excessive biological growth. Disintegration can be retarded by the use of a proper grade of stone as media.

Early trickling filters were rectangular in shape. Wastewater was applied to the filter through nozzles affixed to the surface of the filter. Flow was regulated by dosing syphons, which caused the flow to be applied steadily for a few minutes, then stopped entirely for a rest period. This was done to assure a regulated application of wastewater to the filter in spite of fluctuations in the plant influent rate and to give the microorganisms rest and aeration periods thought to be necessary between dosing intervals.

In 1921, the first rotary distributor was introduced (2). This type of distributor is mounted on a turntable in the center of a circular filter, and is usually driven by the reaction from the nozzles affixed horizontally to the distributor arms which spread the wastewater over the surface. Intermittent application is maintained by the interval between distributor arm passes. The ease of operation of this type of distribution has caused the old rectangularly shaped filter with fixed nozzle distributors to be almost completely supplanted by the circular type with rotary distributors.

The underdrains collect the treated wastewater and convey it to the filter effluent channel. Today, underdrains are usually specially made filter blocks of vitrified clay or concrete (2). At least 50 per cent of the capacity of these blocks must remain filled with air, to assure proper aeration within the filter at all times. Sometimes vents through the media bed close to the perimeter of the filter or vents from outside the filter are also required to maintain proper aeration. In special cases, and particularly in deeper filters, forced aeration is necessary.

In a typical trickling filter wastewater treatment plant treating municipal sewage, the wastewater first undergoes primary treatment which includes grit removal, comminution of solids, grease removal, and primary sedimentation. A large part of the settleable solid material composing the oxidizable waste is removed from the wastewater in the primary sedimentation process, and is subjected to anaerobic digestion. The effluent from the primary settling chamber flows through the secondary treatment section. This includes trickling filter(s) and the final sedimentation process, which removes remaining settleable solids and humus which may have sloughed off of the trickling filter. This may be the last stage of treatment, or it may be followed by tertiary treatment.

Trickling filters can be classified as first-stage filters or second-stage filters, depending on their location in the sequence of plant treatment units. Second-stage filters follow first-stage filters in the sequence. These filters may receive as influent the unsettled effluent of first-stage filters or may be separated from the first-stage filters by an intermediate sedimentation unit. Final sedimentation follows second-stage filters in a two-stage plant.

The efficiency of a trickling filter is measured in terms of the ability of the unit to remove waste from the wastewater. The established method of determining the strength of the biological waste in wastewater is the 5-day biochemical oxygen demand (BOD) determination, made according to Standard Methods (3). BOD is usually expressed in terms of concentration in milligrams per liter (mg/l). The efficiency of a waste treatment unit such as a trickling filter is usually measured by the ratio of the reduction of BOD concentration in the unit to the concentration of BOD in the influent to the unit.

In the cycle of aerobic decomposition, organic nitrogen is converted successively to ammonia nitrogen, nitrite nitrogen, and to nitrate nitrogen (1). The stage of the decomposition cycle is indicated by the amount of nitrite and nitrate nitrogen in the trickling filter effluent. This is an important indicator of the stability of the effluent, in that a non-nitrified effluent still has a certain amount of oxygen demand needed to complete the cycle.

The applied BOD and the amount removed by trickling filtration are frequently given in pounds per day, which is known as the organic or BOD load. In reality, this quantity is the product of the hydraulic flow rate and the BOD concentration. A formula for this is

$$w = Q \cdot L_i \cdot 8.34 \qquad (1)$$

where

w = organic load, lbs/day

Q = hydraulic flow rate, gal/day x 10^6

L = BOD concentration, mg/l

Frequently, trickling filter loadings are expressed as the organic load per unit of filter surface area or per unit volume of media. The hydraulic loading of a filter is the hydraulic flow per unit of surface area.

The mechanism of waste removal by the microorganisms in a trickling filter bed is described by Eckenfelder (4) in the following manner:

> "As waste passes through the filter, nutrients and oxygen diffuse into the slimes, where assimilation occurs, and by-products and carbon dioxide diffuse out of the slime into the flowing liquid. As oxygen diffuses into the biological film, it is consumed by microbial respiration, so that a defined depth of aerobic activity is developed. Slime below this depth is anaerobic."

According to Schulze (5), "purification" of the waste is accomplished by the biochemical activity of the film which is supported by the media bed. Waste liquid flows over the biological growth as a thin sheet, forming a large contact surface of air and water. The mass of bacteria contained in the biological growth enzymatically splits organic substances such as carbohydrates, fats, and proteins into smaller units which are oxidized or used for cell growth.

An important feature in most modern trickling filter operations is the return of a portion of the filter effluent to be mixed with the influent wastewater to the filter. This is known as recirculation, and is an important parameter of filter efficiency. There are numerous recirculation flow patterns which have been used. Some recirculate settled trickling filter effluent, while others recirculate unsettled effluent. Some schemes recycle the flow through the primary settling tank, while others mix it directly ahead of the trickling filter (see Figure 2). Recirculation is usually expressed quantitatively as the ratio of recirculated flow to influent flow, known as the recirculation ratio or number of recirculations.

3. Historical Review

Many different approaches have been used in attempts to determine the variables involved and a relationship among the variables to describe the operating efficiency of a trickling filter. The problem of determining a mathematical relationship is complicated primarily by the difficulty in separating the variables. Research has proceeded toward (1) attempts to develop empirical formulas based on observations of existing plant operations, (2) attempts to develop theoretical formulas based on fluid flow, waste characteristics, and other factors of trickling filters, (3) combinations of empirical and theoretical approaches.

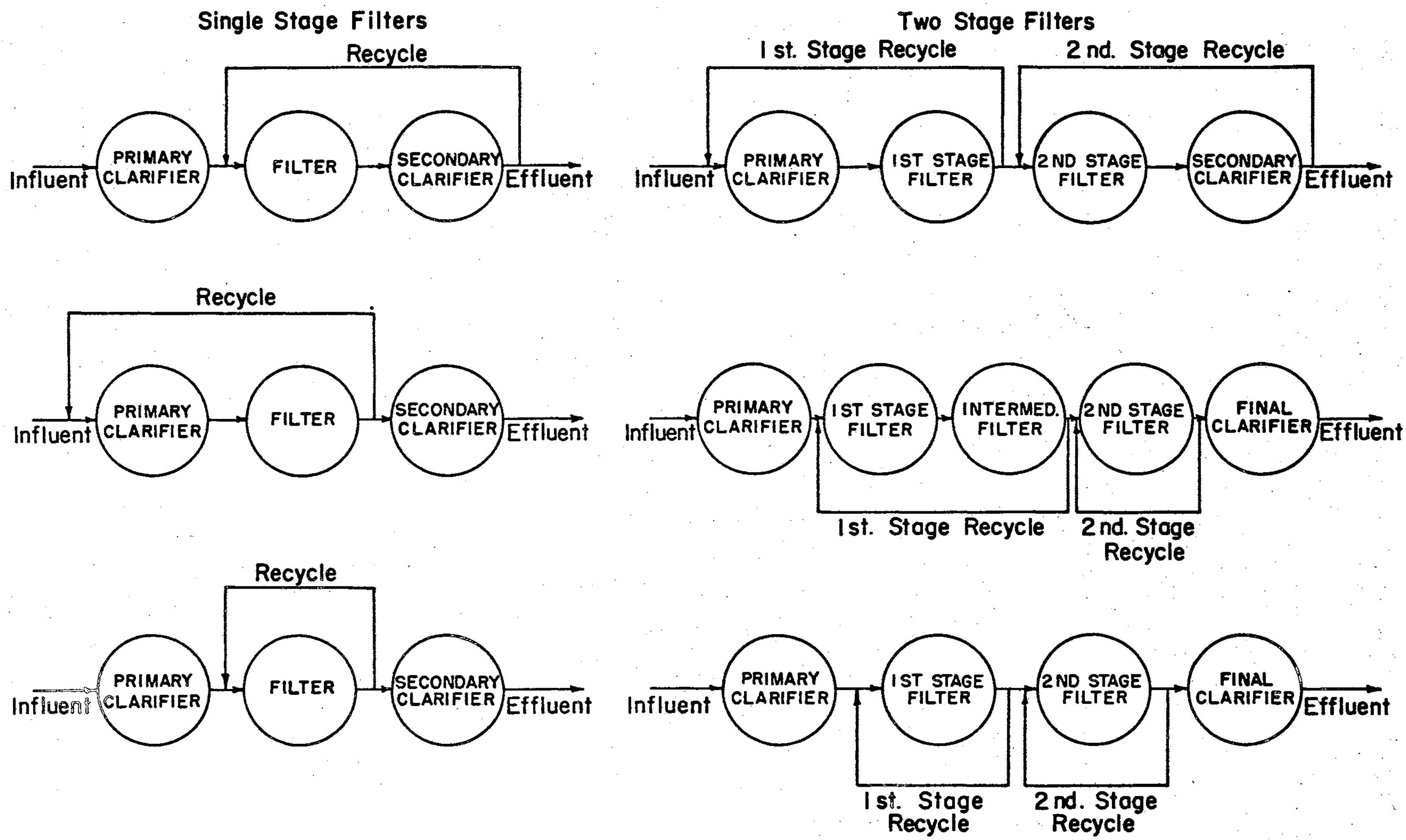

Figure 2 - Trickling Filter Flow and Recirculation Patterns (After Eckenfelder).

Clark and Viessman (6) give as factors to be considered in trickling filter design the following: (1) composition and characteristics of the waste, (2) hydraulic loading on the filter, (3) pretreatment of the waste, (4) organic loading applied to the filter, (5) recirculation ratio maintained and system of recirculation, (6) size and shape of the filter bed, (7) kind of media and its characteristics, (8) aeration of the filter bed, (9) temperature of the air and of the waste. It can be seen that a number of these factors are interdependent. This is one of the most perplexing problems in studies of trickling filter efficiency. It is extremely difficult to relate the effect of independent design variables as parameters of efficiency. There have been many notable attempts to study the variables which control the efficiency of trickling filters.

Early filters were sized on the basis of hydraulic flow rate per unit of surface area. They were usually loaded at the relatively low rate of 34 to 69 gal/day/sq.ft. of surface area, with depth set at 5 to 6 ft. (7). This type of filter is known as a "standard rate" or "low rate" filter and, for example, is restricted in Oklahoma to a maximum loading of 92 gal/day/sq.ft. (8). During the 1930's "high rate" trickling filters began to appear. These filters are characterized by a hydraulic loading of 230-690 gal/day/sq.ft., and have almost continuous discharge with rest periods not exceeding 15 seconds. Early experiments and observations concerning high-rate filters were made by

Mohlman (9), Halvorson (10), and Herrick (11). Their results were summarized by Stanley (7) as showing that the high rate filters produced an inferior BOD removal efficiency and, consequently, inferior effluent quality, to standard rate filters, although the high rate filter was more economical in terms of construction cost because of its comparatively smaller volume. It was also noted that a possible combination of high-rate filters and additional treatment might prove to be economical.

Keefer and Kratz (12) made experiments in 1938-39 on a portion of a large old standard-rate trickling filter with fixed nozzles at Baltimore, which was converted to rotary distributors. The rate of application through the rotary distributors was increased in increments from 150 gal/sq.ft./day to 600 gal/sq.ft./day in the first series, and 150 to 690 gal/sq.ft./day in the second. The incremental increases of the hydraulic loading caused simultaneous increases in the organic loading from 18 to 118 lbs/day/1000 cu.ft. of media in the first series, and from 24 to 104 lbs/day/1000 cu.ft. in the second series. The results indicated that high rate operation was practical and that a 70 per cent BOD reduction could be expected in summer, and 50 per cent in winter. Thus the temperature of the sewage appeared to have an important effect on the filter efficiency. Nitrates in the effluent of the high rate operation were shown to be less than those of the standard rate operation. Their results also indicated that most of the BOD was removed in the top layers of the filter. The total depth was 8.5 ft. These results did not include the effect of final sedimentation following trickling filtration. Keefer and Kratz concluded that as rate of flow increases, an increase in effluent BOD will result, accompanied by a decrease in nitrates in the effluent.

Horton, Porges, and Baity (13) reported in 1942 on the results of an experimental filter in a pilot plant. Their conclusions were that the "degree of purification" or amount of BOD removal is largely dependent on time of contact between the sewage and the microorganisms in the filter bed. With recirculation of unsettled filter effluent, efficiency increased until the recirculation ratio reached 5. Higher ratios gave a decrease in efficiency. It was believed that the effect of recirculation of unsettled filter effluent was to seed the influent sewage and provide solids contact somewhat resembling the activated sludge process. In the studies, time of contact was shown to depend on the hydraulic flow rate through the filter.

During World War II the Committee on Sanitary Engineering of the National Research Council made an extensive study of sewage treatment at military installations throughout the United States (14). From sources of operating data at several military installations a statistical analysis was made for trickling filter performance. The committee reported that the "degree of treatment" depends on (1) magnitude of the organic load treated per unit of time,

(2) amount of biologically active growth, (3) adequacy of air-liquid interface, (4) time of contact between organic load and biological growth, (5) degree of agitation and turbulence at the interface of growth and sewage, (6) provision made for settling of agglomerated material and detached excessive growths. From the results of the operating data analysis the organic loading was believed to have greater effect on efficiency than the volumetric loading. The following formula was derived for the efficiency of a single-stage or first-stage filter:

$$E_1 = \text{fraction BOD removed} = \frac{1}{1 + C \cdot \left(\frac{w_1}{VF}\right)^{.5}} \qquad (2)$$

where

w_1 = organic load, lbs/day

V = volume of media

$$F = \text{recirculation factor} = \frac{1+R}{[1 + (1-p)R]^2} \qquad (3)$$

R = recirculation ratio

p = weighting factor of recirculation, from analysis of data = 0.90

C = constant, equal to .0085 for volume in acre ft. or .0561 for volume in thousands of cu.ft.

The expression for the recirculation factor was developed in the following manner: The average number of passes through the filter is given by the following formula:

$$\frac{Q}{r+Q}\ (1)\ +\ \frac{Q}{r+Q}\left(\frac{r}{r+Q}\right)(2)\ +\ \frac{Q}{r+Q}\left(\frac{r}{r+Q}\right)^2 (3) \tag{4}$$

$$+ - - - - - - = 1 + R$$

where

r = recirculation flow rate

Q = plant influent flow rate

R = recirculation ratio = r/Q

The committee reported that there was a definite reduction in the "treatability" of sewage in the treatment process, which is due to the decrease in the availability of the remaining organic matter which is reduced as the more readily degradable substances are extracted first. To take this into consideration with regard to the organic matter in the recirculated flow, the "weighting factor," p, was introduced into the expression for the average number of passes:

$$F = \frac{Q}{r+Q}\ (1)(1)\ +\ \frac{Q}{r+Q}\left(\frac{r}{r+Q}\right)(2)(p)$$

$$+\ \frac{Q}{r+Q}\left(\frac{r}{r+Q}\right)^2 (3)(p)^2 + - - - - \tag{5}$$

or, as a sum

$$F = \frac{1+R}{(1 + (1-p)\cdot R)^2} \tag{6}$$

The rate of removal of BOD in second stage filters is also retarded because of the decrease in treatability due to the fact that the more easily removable fractions have been extracted in prior treatment units. To account for this, an empirical factor, f, was introduced into the the efficiency formula for first-stage or single-stage filters in the following manner:

$$E_2 = \frac{1}{1 + .0561\left(\frac{w_2}{VF} \cdot f\right)^{0.5}} \tag{7}$$

where

E_2 = fractional efficiency of BOD removal by the second-stage

$$f = \frac{1}{(1-E_1)^2} \tag{8}$$

E_1 = efficiency of first-stage filtration expressed as a fraction

w_2 = organic load influent to second-stage filter in lbs/day, which is equal to the organic load remaining in the first-stage effluent

The formula for second stage-filter efficiency then becomes

$$E_2 = \frac{1}{1 + .0561\left(\frac{w_2}{VF(1-E_1)^2}\right)^{0.5}} \tag{9}$$

or

$$E_2 = \frac{1}{1 + \frac{.0561}{1-E_1}\left(\frac{w_2}{VF}\right)^{0.5}} \tag{10}$$

These formulas for BOD reduction efficiency are based on the BOD in the effluent of settling tanks following the trickling filters. In two-stage plants, intermediate settling between first-stage and second-stage filters must be included, or efficiency will be reduced below that predicted by the formula.

According to the committee's report, the total efficiency of two-stage trickling filters can be predicted by the formula

$$1-E_t = (1-E_1)(1-E_2)* \qquad (11)$$

where E_t is the total efficiency of trickling filtration. It was further shown that the optimum, or minimum, volume combination of first and second-stage filters occurs when the first and second-stage volumes are approximately equal.

The efficiency formulations of the National Research Council were empirical formulas based on the analysis of data from existing treatment plants. In 1948, C. J. Velz (15) developed a formula based on theoretical principles with empirically derived constants. Velz proposed that in all trickling filters the rate of extraction of organic matter per interval of depth is proportional to the remaining concentration of organic matter, measured in terms of its removability. This is expressed in a differential form as

$$-\frac{dL}{dD} = KL \qquad (12)$$

Integrating,

$$\ln \frac{L_D}{L} = KD \qquad (13)$$

or

$$\log \frac{L_D}{L} = -\ 0.434KD = -\ kD \qquad (14)$$

---

*This formula corrected to this form by the writer. As published, it is $E_t = (1-E_1)(1-E_2)$, which is incorrect.

whence

$$\frac{L_D}{L} = 10^{-kD} \tag{15}$$

where L is the total removable fraction of BOD; D is depth; and L_D represents the corresponding quantity of removable BOD at depth D.

Since increasing intervals of depth of contact in the filter bed is essentially increasing the contact time of the sewage with microbiological film, this expression is essentially the same as that of Phelps (16) which describes basic first-order kinetics of biological oxidation:

$$-\frac{dL}{dt} = KL \tag{16}$$

$$\ln\frac{L_t}{L} = Kt \tag{17}$$

$$\log\frac{L_t}{L} = -0.434\ Kt = -kt \tag{18}$$

$$\frac{L_t}{L} = 10^{-kt} \tag{19}$$

L_t = quantity of BOD remaining at time t

In order to apply Velz's formula to determine the efficiency of a trickling filter, the removable fraction of BOD, L, and the logarithmic rate of extraction, k, must be determined empirically. Velz stated that the limiting load, L, is a function of the rate of biological oxidation and the storage capacity for accumulation of BOD in the trickling filter. Since the rate of biological oxidation is temperature-dependent, L is lower in winter and higher in summer, with the exception of "equilibrium" loadings. The values for k and L for a 460 gal/day/sq.ft. plant at Englewood, New Jersey, were determined to be 0.1505 and 0.784, respectively.

Velz proposed that the effect of recirculation around a trickling filter is that of additional passes of the wastewater through the filter and is equivalent to additional depth or addition of a second-stage filter.

In 1953, R. S. Rankin (17) compared the actual performance of several plants to performance calculated by the National Research Council formulas, the Velz formula, and the Tentative Standards. The Tentative Standards were proposed by a joint committee of the Upper Mississippi Board of Public Health Engineers and Great Lakes Board of Public Health Engineers in 1951. Rankin developed formulas based on these standards. For a single-stage trickling filter including final settling, the efficiency of BOD removal is given by

$$L_e = \frac{L_i}{2R+3} \tag{20}$$

where

L_e = BOD of settled filter effluent

L_i = BOD of primary settling effluent

R = recirculation ratio

For a second stage filter, the following formula applies:

$$L_{e_1} = 0.5\, L_i \tag{21}$$

$$L_{e_2} = \frac{L_{e_1}}{R+2} \tag{22}$$

where

L_{e_1} = BOD of first-stage effluent

L_{e_2} = BOD of second-stage effluent

R = recirculation ratio of second stage

With regard to the single-stage plants, Rankin found that the Velz formula gave results closest to the actual performance; the Tentative Standards, the next closest, and the National Research Council, the least close. The performance of two-stage plants was computed according to the Tentative Standards and the National Research Council formulas. The Tentative Standards gave the closest results. Rankin concluded that the ratio of recirculation is the paramount parameter of BOD removal efficiency. He also concluded that dosing rate, loading of the filter, and depth have no significant effect on efficiency within the range of the data used in his analysis.

In 1956, Fairall (18) developed empirical formulas from data of 44 plants in the Upper Mississippi Valley. The formulas are as follows:

For filter without recirculation

$$\frac{L_e}{L_i} = 1.102 \left(\frac{V}{Q}\right)^{-0.322} \tag{23}$$

$\frac{L_e}{L_i}$ = fraction of influent BOD remaining in settled trickling filter effluent

V = volume of filter media (1000 cu.ft.)

Q = plant hydraulic flow rate (mgd)

For filters with recirculation:

$$\frac{L_e}{L_i} = 2.065 \left(\frac{V(1+R)}{Q} \right)^{-0.444} \tag{24}$$

R = recirculation ratio

Stack (19) in 1957 proposed a theoretical formula for trickling filter performance. His derivation is based on the following assumptions: (1) a trickling filter is basically a self-regenerating absorption tower; (2) each unit depth of the filter will remove a constant fraction of the removable BOD applied to that unit depth; (3) removable BOD is the fraction of the observed BOD which can be removed by biosorption; and (4) the quantity of BOD that can be absorbed by one unit volume of a filter has a maximum limit. The equation for a trickling filter having no recirculation is

$$L_R = XbS+f(L-XbS)\left[1+(1-b)+(1-b)^2+(1-b)^3 + - - - (1-b)^{D-X-1}\right] \tag{25}$$

where L is the applied load of removable BOD, S is the load of removable BOD which must be applied to saturate one unit of depth with BOD, b is the coefficient of biosorption, $1-10^{-K}$, X is the number of unit volumes saturated by a given load of BOD, D is filter depth, and L_R is the fraction of removable BOD removed.

The formula for a trickling filter operated with recirculation at an organic loading less than S is

$$L_R = \frac{(R+1)CbL}{1+RCb} \tag{26}$$

where R is the recirculation ratio. The values of removable BOD, f, and S must be experimentally determined.

Several of the investigators previously mentioned believed that the time of flow of the wastewater through a trickling filter or time of contact of the wastewater with the biological film is an important parameter of trickling filter efficiency (13)(14)(15). On this premise an expression for the time of contact or time of flow in a filter will also be an expression of filter efficiency.

Howland (20) reported in 1958 the results of experimental investigations and theoretical studies of trickling filters. A mathematical description was developed for the time of fluid flow over a sphere, which resembles the flow of wastewater through the porous media of a trickling filter. Howland concluded that the time of fluid travel through a trickling filter bed might vary inversely with the two-thirds power of the liquid rate of application, directly with depth and directly with the temperature factor 1.035^{T-20}. An expression for time of travel, x, is

$$x = \frac{\left(1.035^{T-20}\right)(D)}{\left(Q/A\right)^{2/3}} \tag{27}$$

where T is temperature in degrees centigrade, D is depth, Q is hydraulic flow rate, and A is surface area.

The effect of intermittent periods of no discharge between passes of the distributor arm is analyzed in the following manner: if h is the fraction of time that a given portion of the surface receives wastewater, then the time of travel of that portion of wastewater through the filter will be $h^{2/3}$ times the time that it would be if the same average flow were applied with absolute uniformity to the surface. Therefore, increasing the number of distributor arms would increase the time of flow, and would be equivalent to increasing the depth of the filter. However, Howland indicates that intermittent discharge is necessary to maintain proper aeration of the filter.

The effect of recirculation is described as affecting the thickness of the "flowing film" which will vary with recirculation as $(1+R)^{1/3}$ (R = recirculation ratio). The expression of variables for the time of flow when modified for recirculation becomes

$$x = \frac{\left(1.035^{T-20}\right)\ (D)}{(Q/A)^{2/3}} \cdot (1+R)^{1/3} \qquad (28)$$

The effect of Howland's time of flow theory on recirculation may also be stated in another manner. It is assumed that the influent to a trickling filter contains homogeneous organic matter which can be described by an average concentration, L_i. In a like manner, the effluent concentration is L_e. Then the concentration of the influent after mixing with the recirculated flow (at this point, the flow is usually called the "applied" flow) is

$$L_o = \frac{L_i + RL_e}{1+R} \qquad (29)$$

where R is recirculation ratio.

Ingram (21) reported in 1959 on the results of controlled filtration experiments made with special filters of 12 inches diameter and 18 feet of depth. The filters were separated into six sections of 3 feet of depth, and air was supplied to the bottom of each section. Ingram concluded that the "so-called non-removable BOD" can be removed with depth, and that secondary filters treat this non-removable BOD. Ingram's studies also indicated that the BOD loading of a filter is a more important parameter than the hydraulic loading.

Schulze (5)(22)(23) made experimental studies with a trickling filter constructed with a series of one-half inch mesh vertical screens serving as media. Analysis of the data from the experimental filter yielded the following formula for the fraction of influent BOD remaining in the filter effluent:

$$\frac{L_e}{L_i} = K\left(\frac{Q}{A}\right)^c \qquad (30)$$

where

L_e = final effluent BOD (mg/l)

L_i = BOD of filter influent (mg/l)

Q = hydraulic loading (mgd)

A = surface area (acres)

c = constant

K = constant

The exponent c was found to be 0.67, which is the same as that of Howland (20) in his expression for contact time.

This exponent was also confirmed by studies of Bloodgood, Teletzke, and Pohland (24).

Schulze proposed that if it is assumed that the fraction of BOD remaining in the effluent is directly related to contact time, then the fraction remaining is

$$\frac{L_e}{L_i} = e^{-kt} \tag{31}$$

and t can be replaced by $D/(Q/A)^{2/3}$, and the fraction remaining becomes

$$\frac{L_e}{L_i} = e^{-kD/(Q/A)^{2/3}} \tag{32}$$

Converting to base 10 logarithms

$$\frac{L_e}{L_i} = 10^{-KD/(Q/A)^{2/3}} \tag{33}$$

which is similar to that of Velz (15)

$$\frac{L_D}{L} = 10^{-kD} \tag{15}$$

It appeared to Schulze that the constant of Velz, k, included the parameter Q/A and, therefore

$$k = K/(Q/A)^{2/3} \tag{34}$$

Schulze proposed that efficiency will follow a function such as this which is based on the hydraulic loading and will be independent of the organic loading as long as the organic loading remains below a certain critical level which is usually not encountered in trickling filter operation.

In 1961, Eckenfelder (25)(26) expanded the trickling filter theory of Howland (20) and Schulze (5)(22)(23). The equation expressing the fraction of BOD remaining in the effluent as a function of hydraulic loading is

$$\frac{L_e}{L_o} = C(Q/A)^n \tag{35}$$

where L_e is the effluent BOD concentration, L_o is the applied BOD concentration, and coefficient C and exponent n vary with the type of filter media and the hydraulic characteristics of the filter. However, C is proportional to $\frac{1}{D^M}$ where D is depth. Inserting this into the equation of Schulze (23)

$$\frac{L_e}{L_o} = e^{(-K)\left(\frac{1}{D^M}\right)\left(\frac{D}{(Q/A)^n}\right)} \tag{36}$$

or

$$\frac{L_e}{L_o} = e^{(-K)(D^{1-M})/(Q/A)^n} \tag{37}$$

The exponent (1-M) on depth becomes 1.0 when the biological film is approximately uniformly distributed through the filter depth. For a usual situation where activity of the film decreases with depth, the exponent is less than 1.0.

Equation (37) presumes that all components of the organic waste are removed at the same rate. Eckenfelder stated, however, that there is considerable evidence that in sewage and other complex wastes the removal decreases with concentration or time, because the components that are more easily removed from the wastewater are removed more rapidly. To account for this, a modified equation is required, and this is

$$\frac{L_e}{L_o} = \frac{1}{1 + \frac{CD^{(1-M)}}{(Q/A)^n}} \tag{38}$$

From analysis of filter performance data, Eckenfelter gives the values of the constants as C = 2.5, (1-M) = 0.67, and n = 0.50 (for A in acres, D in feet, and Q in mgd). Eckenfelder assumed that the effect of recirculation is to dilute the influent BOD, as previously given by Howland (20):

$$L_o = \frac{L_i + RL_e}{1+R} \tag{29}$$

(symbols as previously defined).

Galler and Gotaas (27) in 1964 developed an empirical formula for trickling filter efficiency by making a multiple regression analysis of 322 sets of data from existing treatment plants. Using the BOD in the effluent of the trickling filter as dependent variable, this equation was formed:

$$\frac{w_e}{A} = K_1 \log\left(\frac{w_o}{A}\right) + K_2 \log (1+R) + K_3 \log (D+1) + K_4 \log T + K_5 \log Q/A + B \tag{39}$$

where

$\frac{w_e}{A}$ = BOD loading of filter effluent, lbs/acre/day

$\frac{w_o}{A}$ = BOD loading applied to filter, lbs/acre/day (including load in recirculation)

R = recirculation ratio

D = depth, ft.

T = temperature of wastewater, °C.

Q/A = hydraulic loading, mgd/acre

B = intercept value

$K_{1- - - 5}$ = partial regression coefficients

Using an IBM 709 computer, the multiple regression analysis was performed and an equation was determined:

$$\frac{w_e}{A} = \frac{0.31 \left(\frac{w_o}{A}\right)^{1.19} (1+R)^{0.28}}{(1+D)^{0.67} T^{0.15} (Q/A)^{0.06}} \tag{40}$$

For BOD in terms of concentration (mg/l)

$$L_e = \frac{0.46 \, L_o^{1.19} (1+R)^{0.28} (Q/A)^{0.13}}{(1+D)^{0.67} T^{0.15}} \tag{41}$$

Galler and Gotaas state that their results indicate that the organic loading has a greater effect on the quality of the effluent than the hydraulic loading. This contradicts those who proposed the hydraulic loading as the controlling parameter (13)(20)(23)(25), but agrees with the conclusions of Ingram (21). Galler and Gotaas propose time of contact between the organisms and the wastewater as the controlling parameter, but with a greater amount of contact time attributed to the organisms in the recirculated effluent flow. Cited are the results of Moore, Smith, and Ruchhoft (28) where efficiency of a trickling filter plant was increased when the underflow of the settling tank following the trickling filters was returned to the plant influent and used as a method of recirculation.

The optimum increase in efficiency occurred at a recirculation ratio of approximately 4, and further increases did not yield any significant improvement. This agrees with the findings of the National Research Council (14). An exponent of 0.67 was obtained on the depth parameter, which agrees with Eckenfelder (25) (26). Temperature was also included as a parameter. Its effect, within the range of temperature of the data (2.3°C. to 32°C.), is to show decreasing efficiency with decreasing temperature.

To develop a formula for design purposes, Galler and Gotaas utilized the recirculation expression of Howland (20):

$$L_o = \frac{L_i + RL_e}{1+R} \tag{29}$$

or

$$\frac{QL_i + QRL_e}{Q+RQ} \tag{42}$$

(Q = hydraulic flow rate, mgd)

Then the equation for effluent BOD concentration becomes

$$L_e = \frac{K(QL_i + QRL_e)^{1.19}}{(Q+QR)^{.78}(1+D)^{.67}a^{.25}} \tag{43}$$

where a is the filter radius in feet, and

$$K = \frac{0.464\left(\frac{43,560}{\pi}\right)^{0.13}}{Q^{0.28}T^{0.15}} \tag{44}$$

In 1966, Galler and Gotaas (29) proposed a method for the optimum design of trickling filters. Utilizing the design formula (43), a mathematical method was used to minimize the cost of the wall, floor, media, distribution system, power for recirculation pumping, pumps, and annual costs. The results of these studies showed that a deep filter up to 20 feet of depth is favored when additional pumping of the influent is not necessary for deep filters. This includes the cost of forcing 2 cu.ft. of air per gallon of wastewater treated into the filter. Also, it was determined that a single filter would yield the optimum design.

Germain (30) reported in 1966 that BOD removal by plastic medium trickling filters would follow the equation proposed by Schulze and Howland. Germain theorized that the rate of BOD removal is a function of the influent BOD concentration and the adsorption capacity of the biological growth. Waste residence time in the filter affects the amount of waste removal by determining how close to completion the reaction can proceed within the waste residence time provided.

Archer and Robinson (31) reported in 1967 the results of studies of the design of trickling filters using the National Research Council formulas (14). With these formulas, the minimum volume of filter media occurs with a two-stage combination, at a point where the volume of the second-stage filter is slightly larger than that of the first-stage filter.

CHAPTER II

STATEMENT OF THE PROBLEM

1. Optimum Trickling Filter Design

The objective in the design of any wastewater treatment facility is to find the most economical solution which will best accomplish the required amount of waste removal. When trickling filtration is selected as the process to be used, the most economical filter design is desired.

The cost of a trickling filter can be separated into the cost of construction and the cost of operation and maintenance. The operation and maintenance costs for trickling filters are usually relatively low. These include the cost of pumping (if required), pump maintenance, and distributor maintenance. Construction costs are usually relatively high compared to the operating costs as well as compared to the construction costs of some alternate treatment processes. The construction cost of trickling filters includes the cost of pumps, piping, distributors, floor underdrains, sidewalls, structural supports, excavation, and filter media. The cost of procuring and placing trickling filter media is frequently one of the greater costs. The cost of the media can be expressed as the cost per unit of volume required. Since a greater volume of media will be required for a filter of greater size, and a filter of greater size will in general have greater distributor, floor, underdrains, excavation, and sidewall costs, the cost per unit volume will, in general, be an indicator of the filter construction cost. It can frequently be assumed that the construction cost of a trickling filter increases as volume increases, and in this situation the most economical design from a construction cost standpoint is the design of minimum volume.

It will be shown, however, that in many situations the required volume may be decreased by increasing the recirculation. Increasing recirculation, however, increases the amount of pumping required, and thus increases operating costs. This poses a choice of alternatives for the designer: to design for higher construction cost with lower operating cost, or for lower construction cost with higher operating cost. Making this choice frequently requires consideration of a large number of factors.

2. Subject of Study

This work is a study of three methods of trickling filter design. The principal question in the design of trickling filters is that of required volume. The required volume is usually calculated from one of the efficiency formulas. In this work three formulas are studied: the National Research Council formula (14); the Eckenfelder formula (25); and the Galler-Gotaas formula (27). These formulas for efficiency may be solved for volume:

NRC

$$V(\text{cu.ft.x}10^{-3}) = .00315 \frac{w_1}{F} \left(\frac{E}{1-E}\right)^2 \qquad (45)$$

$$(w_1 = L_i x Q x 8.34)$$

$$F = \frac{1+R}{(1+.1R)^2} \qquad (8)$$

Eckenfelder

$$V(\text{cu.ft.x}10^{-3}) = \frac{Q}{D^{.33}} \left[\frac{\frac{E}{1-E}}{.379(1+R)}\right]^2 \qquad (46)$$

Galler-Gotaas

$$V(\text{cu.ft.x}10^{-3}) = \frac{\pi D}{1000} \left[\frac{CL_i^{.19} Q^{.13} (1+R(1-E))^{1.19}}{(1-E)(1+D)^{.67}(1+R)^{.78} T^{.15}}\right]^8 \qquad (47)$$

$$C = .464 \left[\frac{43,560}{3.1416}\right]^{.13} = 1.60 \qquad (48)$$

The derivation of these formulas is given in Appendix II.

The objective of this study is to evaluate the effect of the variables of the formulas on the volume requirement. If a design engineer wishes to design by the use of these formulas, an easy method of solution is needed. The design engineer is interested in the optimum or most economical design. The advantage of a two-stage design as opposed to a single-stage filter is also an important question. This study is an effort to present solution to some of these problems of trickling filter design. An IBM 7040 computer was used to make computations necessary for the evaluation of the design formulas. Further discussion of the methods of evaluation are included in succeeding chapters.

CHAPTER III

EVALUATION OF SINGLE-STAGE TRICKLING FILTER DESIGN

1. The National Research Council Method

As previously given, the National Research Council expression for the value of a single-stage or first-stage trickling filter is

$$V(\text{cu.ft.x}10^{-3}) = .00315 \frac{w_1}{F} \left[\frac{E_1}{1-E_1}\right]^2 \tag{45}$$

Volume is a function of organic loading, w_1, efficiency, and recirculation factor, F. Writing the equation to show all of these inherent parameters

$$V = .00315 \cdot Q \cdot L_i \cdot \left[\frac{(1+0.1R)^2}{(1+R)}\right] \cdot \left[\frac{E_1}{1-E_1}\right]^2 \tag{49}$$

Thus, volume varies directly with flow, Q, and influent BOD concentration, L_i, and is a function of recirculation ratio and efficiency attained. The effect of influent BOD and wastewater flow rate on volume is shown in Figures 3 and 4, which were constructed from calculations made by the IBM 7040 computer. The effect of recirculation is quite different, as shown in Figure 5. A sharp decrease in required volume is observed in the initial recirculation increments. The decrease becomes negligible for recirculation ratios

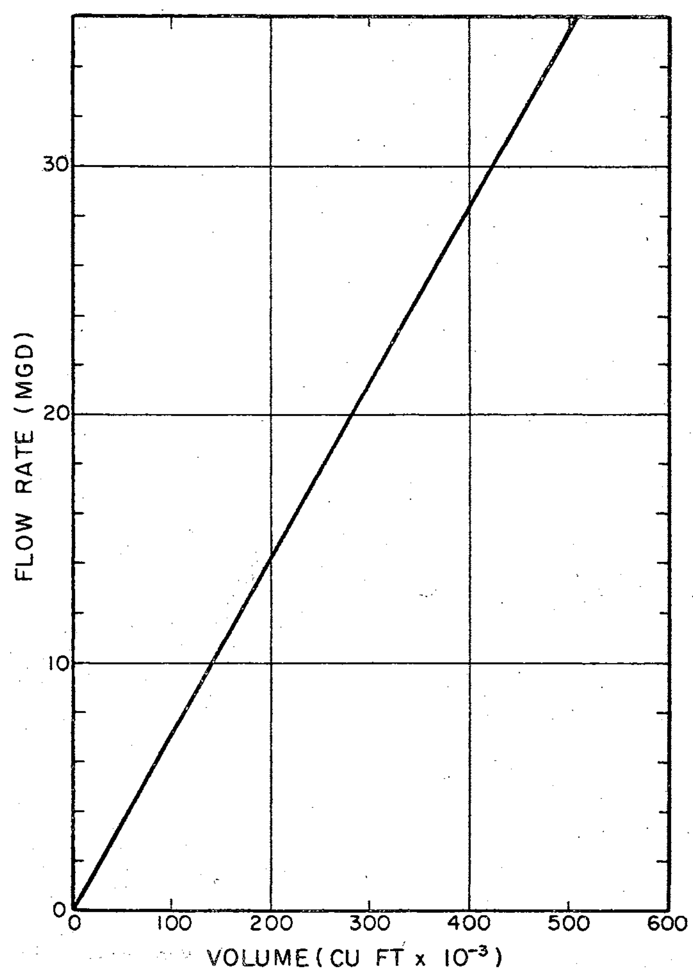

Figure 3 - NRC Formula: Effect of Flow Rate on Volume L_i = 100 mg/1, E = .70, and R = 0.0.

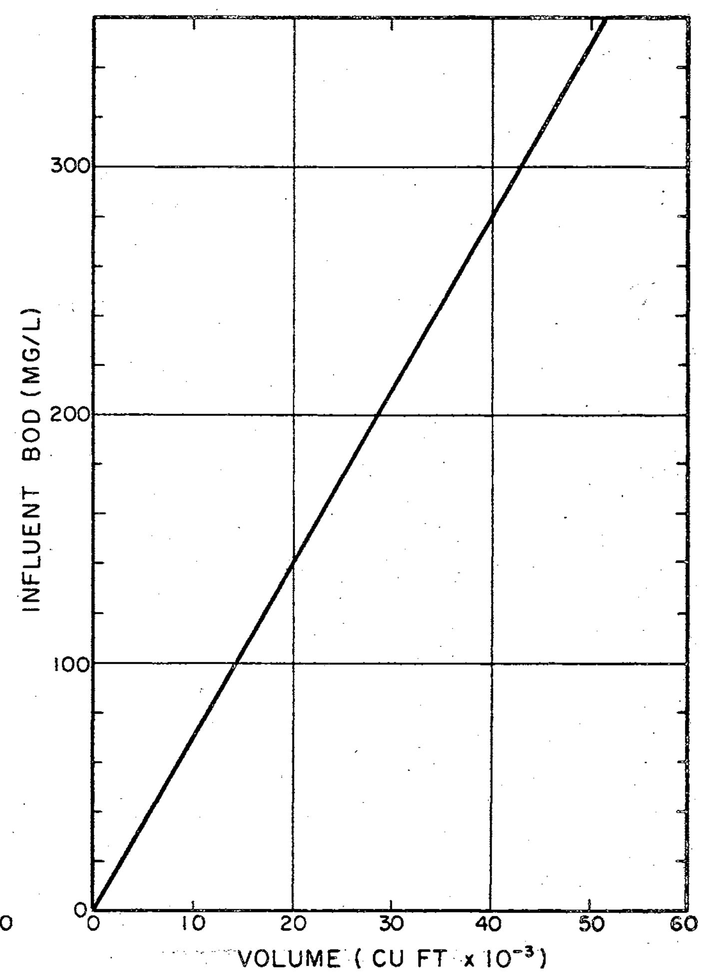

Figure 4 - NRC Formula: Effect of Influent BOD on Volume at Q = 1.0 mgd, E = .70, and R = 0.0.

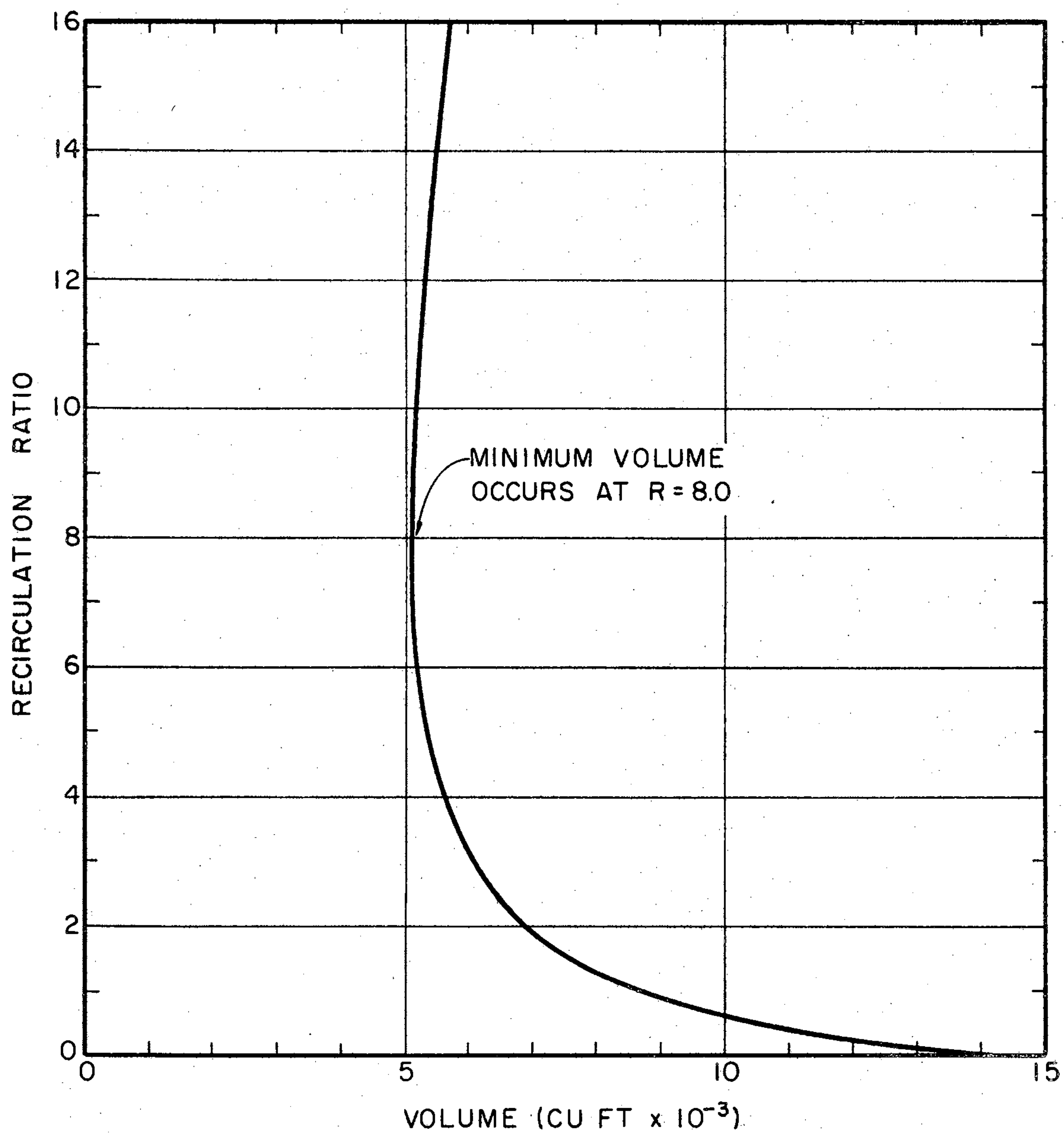

Figure 5 - NRC Formula: Effect of Recirculation on Volume at Q = 1.0 mgd, L_i = 100 mg/l, and E = .70.

greater than 5, and a minimum volume is reached at a recirculation ratio of 8.0.

Figure 6 shows the effect of the efficiency requirement. Volume increases logarithmically with efficiency. The decreasing volume reduction with greater recirculation is illustrated by the recirculation curves.

Design by the NRC formula is simplified by the fact that volume is directly proportional to two of the variables, Q and L_i. Figure 7 is constructed on the base of Q = 1.0 mgd and L_i = 100 mg/l, and may be used for design purposes, as illustrated in the following example. This method is similar to that proposed by Archer and Robinson (31).

Example Problem I. Design of Single-Stage Trickling Filter by NRC Formula:

Known: L_i = 200 mg/l, Q = 0.75 mgd

L_e = 20 mg/l

Required: Filter volume and R

1. Compute efficiency required

$$E = \frac{L_i - L_e}{L_i} = \frac{180}{200} = .90$$

2. From Figure 7, for L_i = 100 mg/l and Q = 1.0 mgd

   At R = 0, V = 215,000 cu.ft.

   At R = 1, V = 127,000 cu.ft.

   At R = 2, V = 102,000 cu.ft.

3. Choose R = 2, V = 102,000 cu.ft.

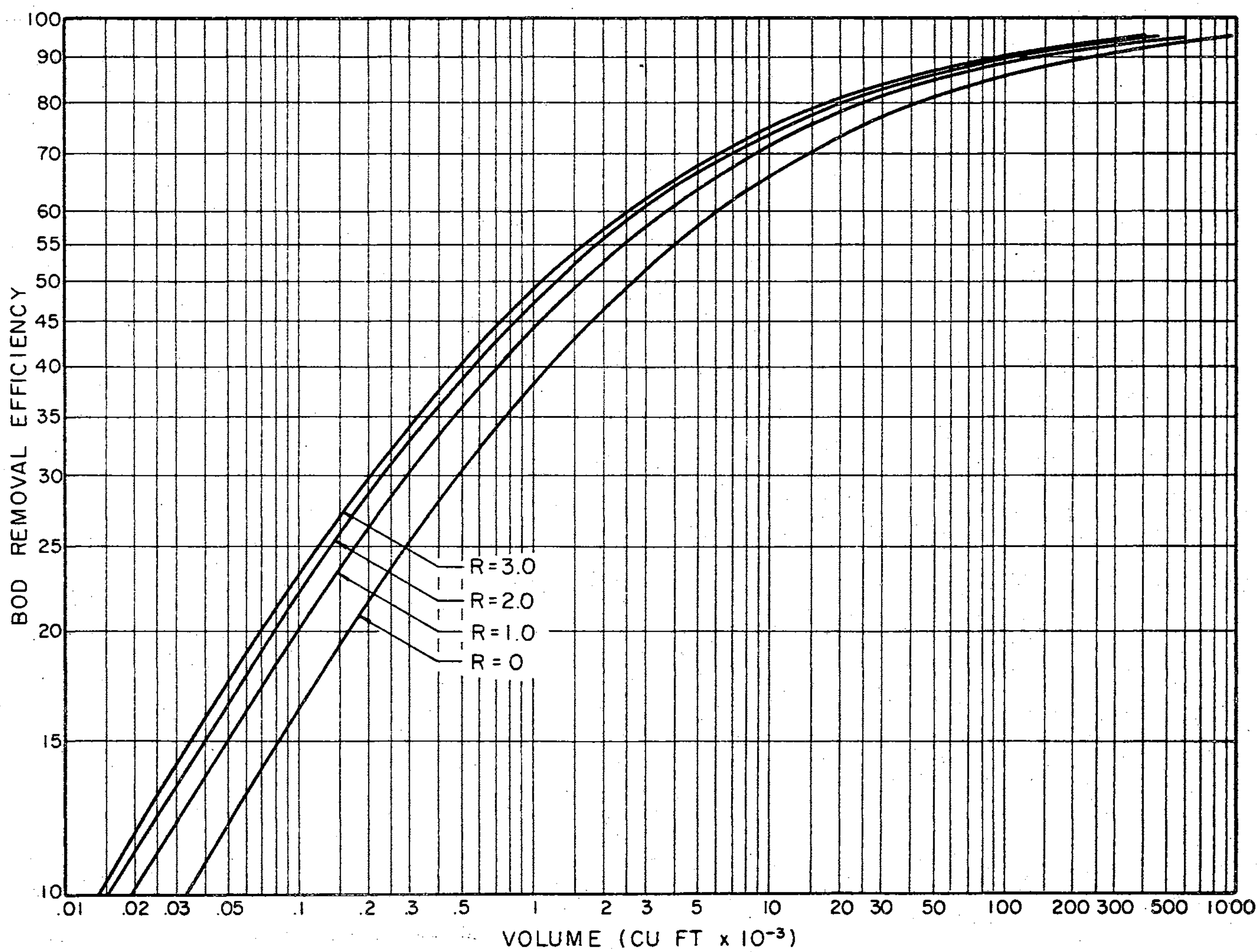

Figure 6 - NRC Formula: Effect of Efficiency on Volume for Recirculation Ratios of 0, 1, 2, and 3 at Q = 1.0 mgd and L_i = 100 mg/l.

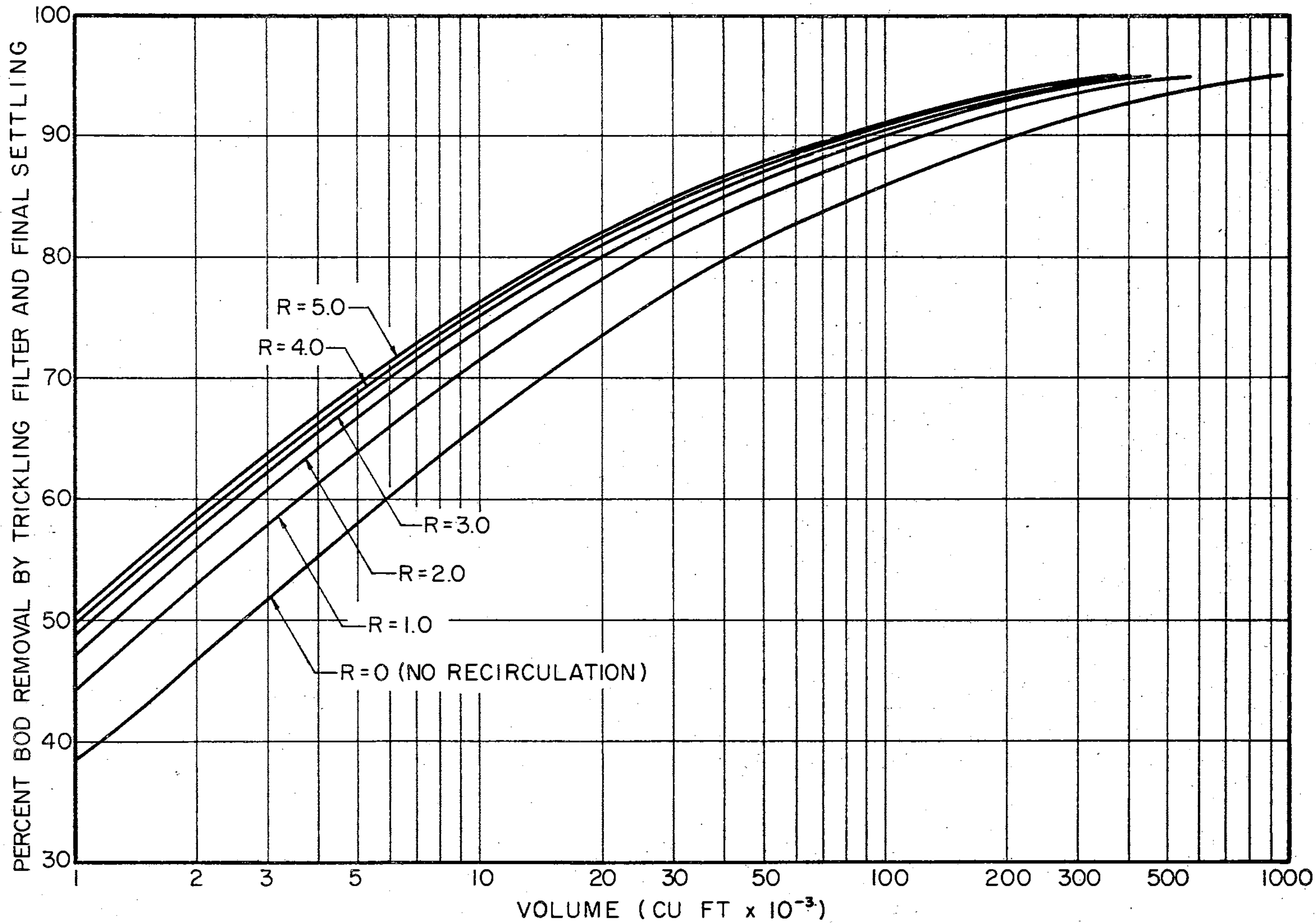

Figure 7 - Chart for Single-Stage Trickling Filter Design by the NRC Formula. Constructed on the Base of L_i = 100 mg/l and Q = 1.0 mgd.

4. Since changes in volume are directly proportional to changes in flow and influent BOD, the required volume is

$$\text{Required volume} = 102{,}000\left(\frac{200\ \text{mg/l}}{100\ \text{mg/l}}\right)\left(\frac{0.75\ \text{mgd}}{1.0\ \text{mgd}}\right)$$

$$= 153{,}000\ \text{cu.ft.}$$

2. <u>The Eckenfelder Method</u>

As previously mentioned, Eckenfelder's (25) equation for the removal of BOD in sewage and complex industrial wastes is

$$L_e = \frac{1}{1+C\cdot\frac{D^{(1-M)}}{(Q/A)^n}} \qquad (38)$$

Solved for volume, and including recirculation, the formula is

$$V(\text{cu.ft.x}10^{-3}) = \frac{Q}{D^{.33}}\cdot\left[\frac{\frac{E_1}{1-E_1}}{.379(1+R)}\right]^2 \qquad (46)$$

Thus, volume is a function of Q, D, E, and R. It is directly proportional to Q and increases with increasing efficiency requirements. Volume decreases with increases in depth and recirculation. The linear relationship of volume and flow rate is shown in Figure 8. The effect of recirculation is to decrease the volume requirement, with the greatest decrease given by recirculation ratios of one and two. The advantage sharply decreases with greater ratios, and becomes negligible with higher recirculation ratios. This is shown in Figure 9.

Figure 10 shows the effect of additional depth. With all other variables held constant, the volume requirement will decrease with increases in depth. According to

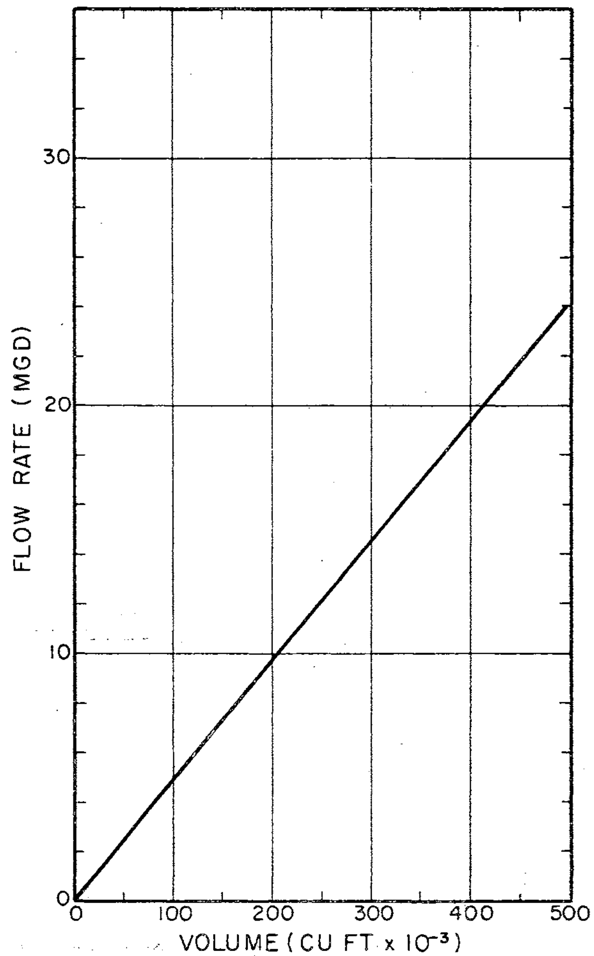

Figure 8 - Eckenfelder Formula: Effect of Flow Rate on Volume at E = .70, R = 0.0, and D = 6.0 ft.

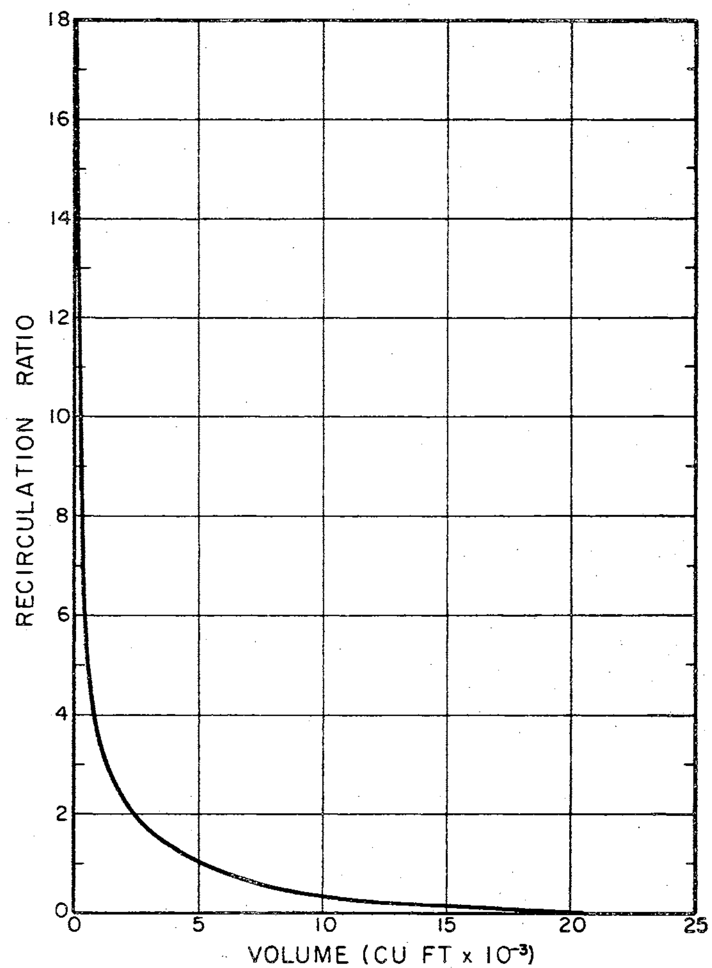

Figure 9 - Eckenfelder Formula: Effect of Recirculation on Volume at Q = 1.0 mgd, E = .70, and D = 6.0 ft.

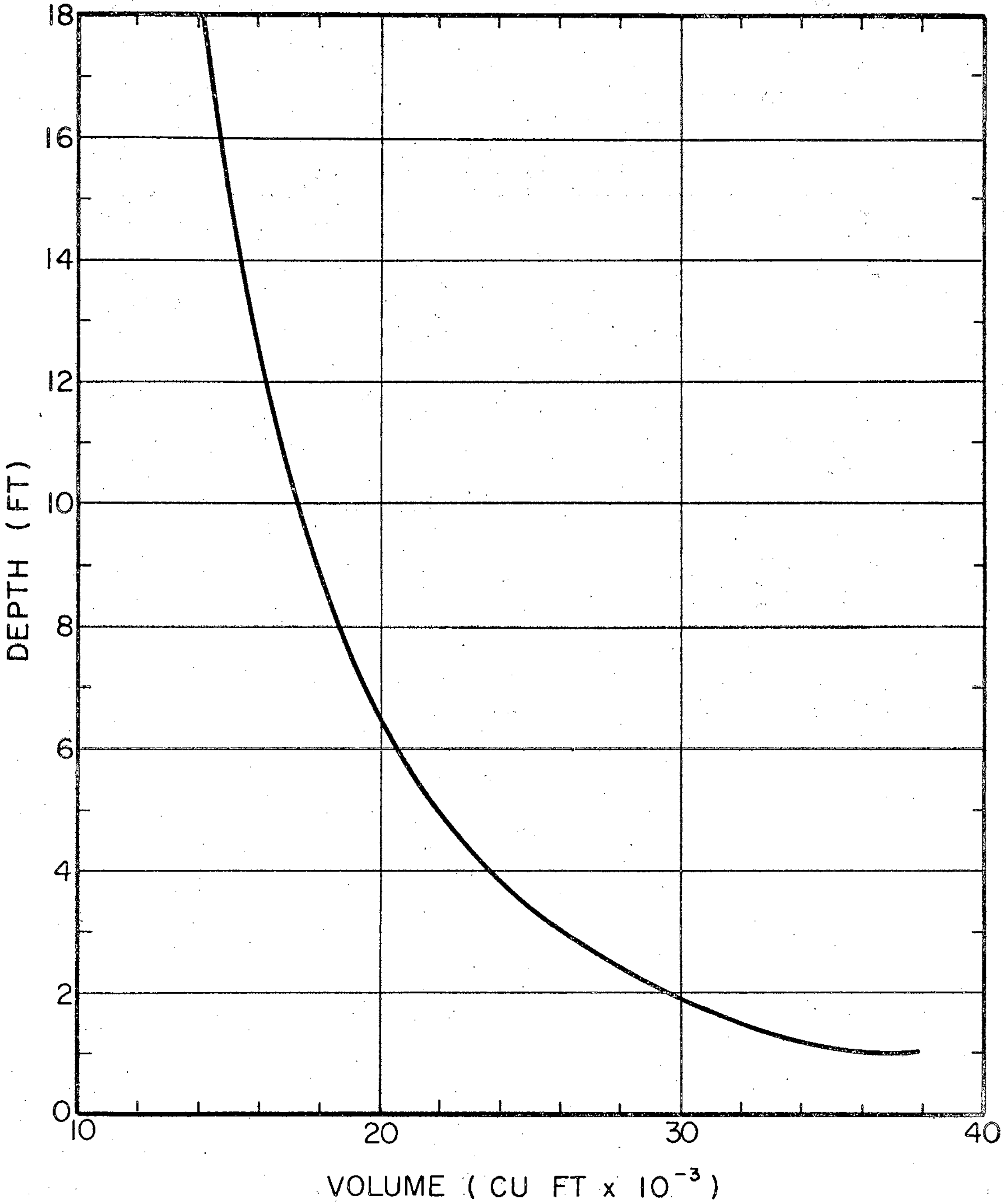

Figure 10 - Eckenfelder Formula: Effect of Depth on Volume at Q = 1.0 mgd, E = .70, and R = 0.0.

Figure 10, a filter with 15 feet of depth will require only half as much total volume as one with 2 feet of depth.

Figure 12 shows the effect of increasing efficiency on volume. This is a logarithmic curve, quite similar in shape to the curves produced by the NRC formula. Eckenfelder states that the effect of temperature on the wastewater is given by a correction of efficiency as developed by Howland (32). This formula is

$$E_T = E_{20}\ 1.035^{(T-20)} \tag{50}$$

where T = temperature of wastewater, $^{\circ}$C.

E_T = efficiency at temperature T

E_{20} = efficiency at T = 20°C.

The effect of this correction of efficiency on volume computed by the Eckenfelder formula for temperatures other than 20°C. is shown in Figure 11. The formula was also applied to volumes computed by the NRC formula, and this effect is also illustrated in Figure 11.

Figures 12 and 13 may be used for the design of single-stage filters according to the Eckenfelder method. The use of these charts is illustrated by the following example:

Example II. Design of Single-Stage Trickling Filter by Eckenfelder Formula:

Known: L_e = 20 mg/l

L_i = 200 mg/l

Q = 0.75 mgd

Required: V, R, D

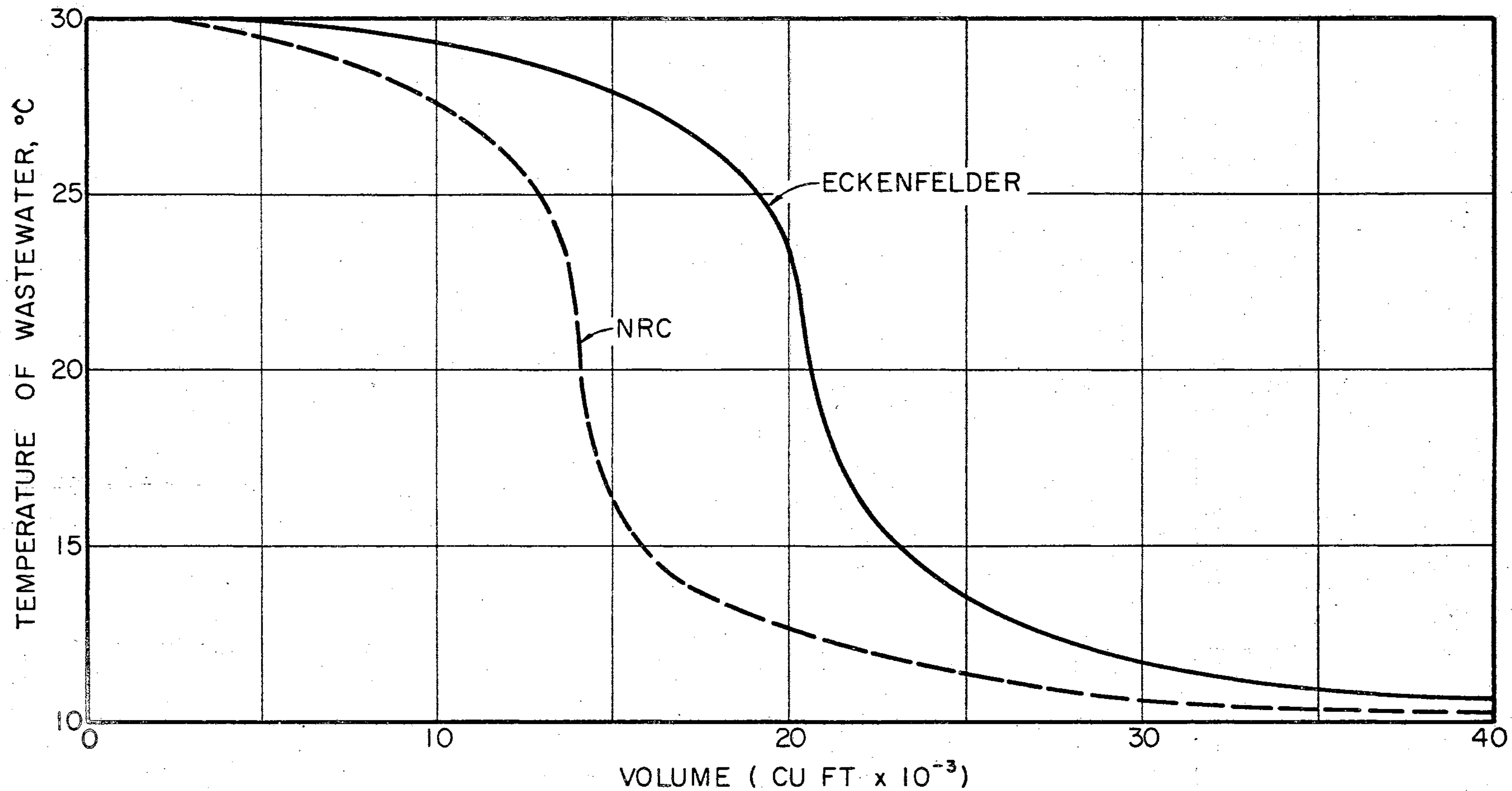

Figure 11 - Effect of Howland's Temperature Correction on Volume Computed by the NRC and Eckenfelder Formulas at L_i = 100 mg/l, Q = 1.0 mgd, E = .70, R = 0.0, and D = 6.0 ft.

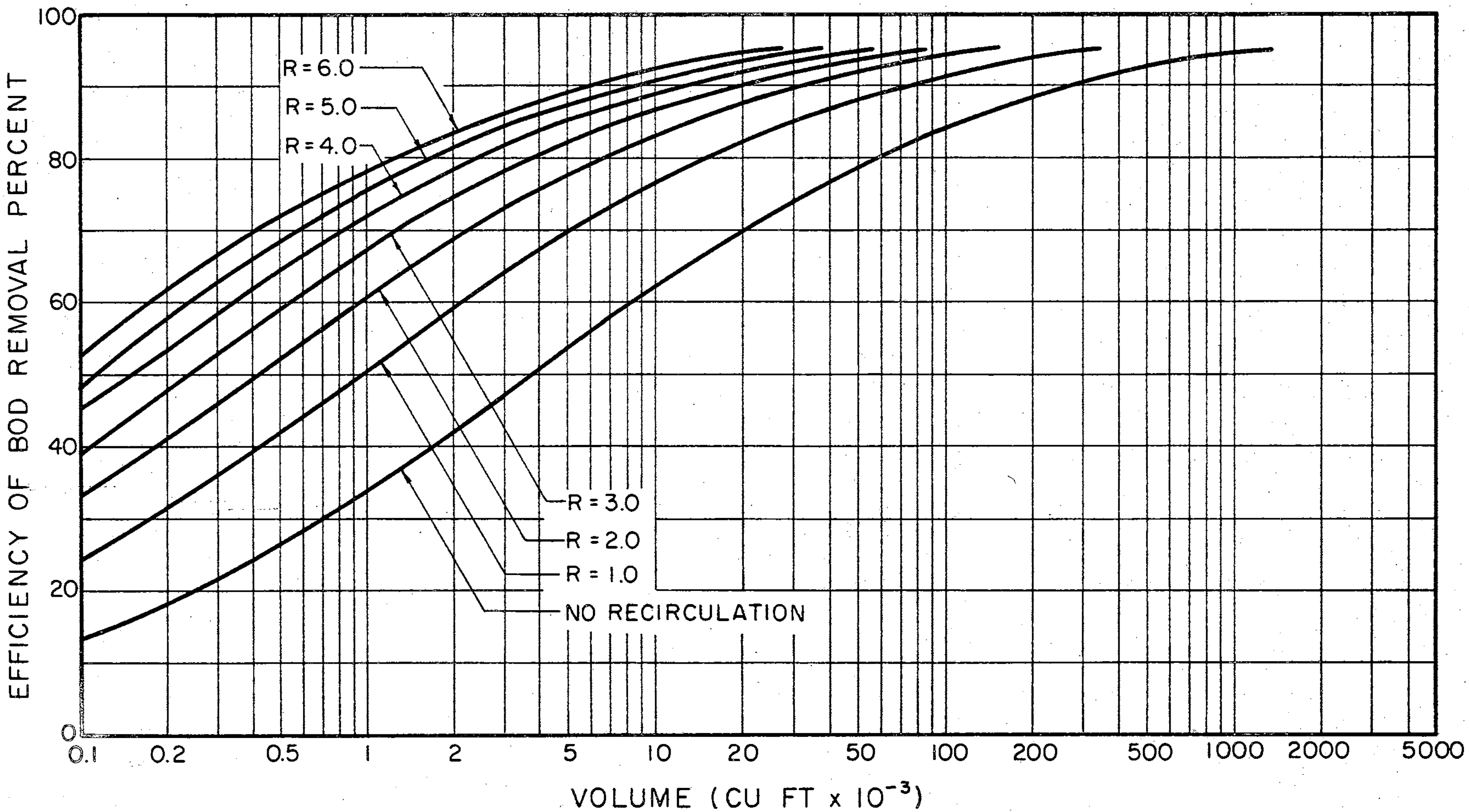

Figure 12 - Chart I for Single-Stage Trickling Filter Design by the Eckenfelder Formula. Constructed on the Base of Q = 1.0 mgd and D = 6.0 ft.

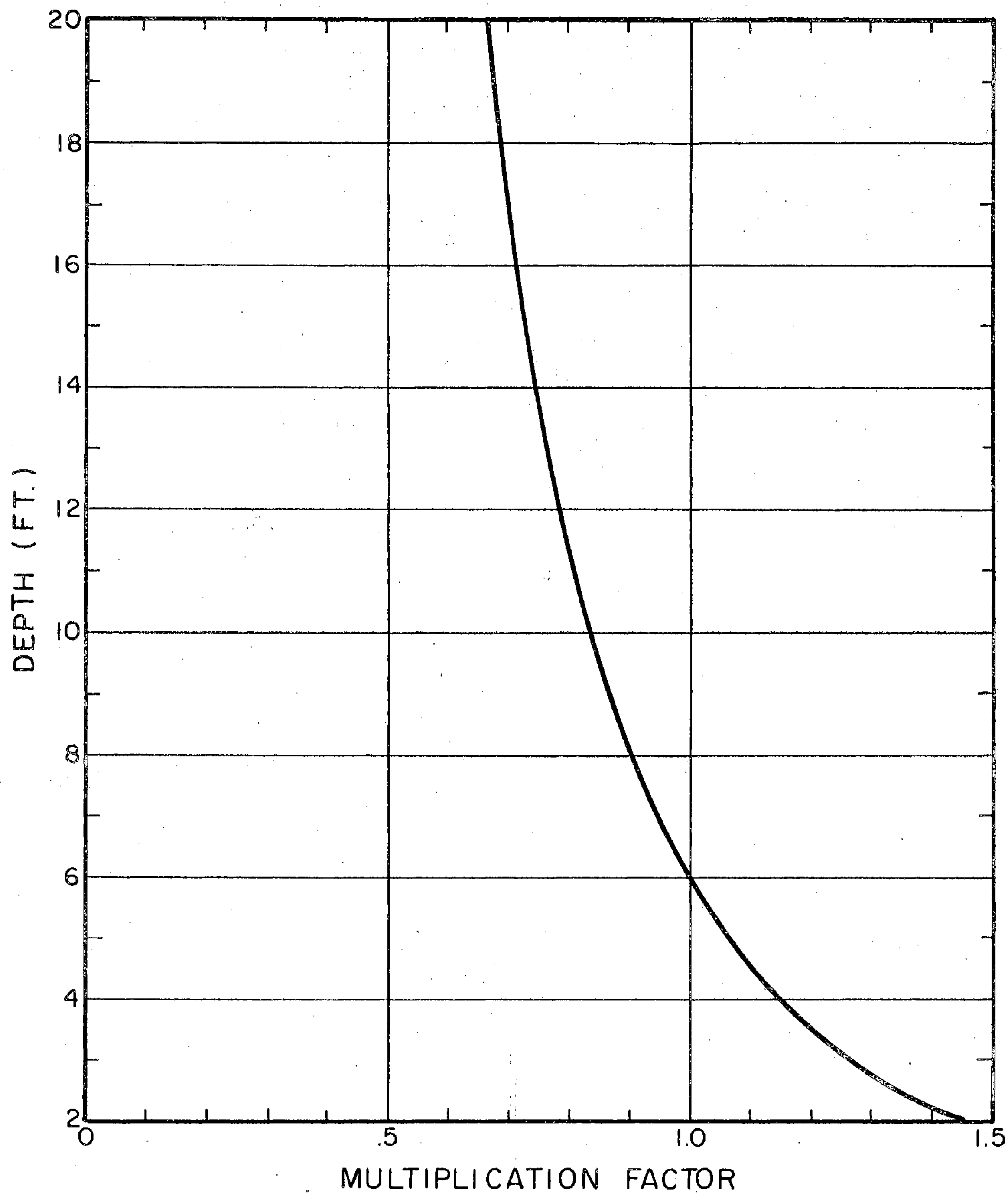

Figure 13 - Chart II for Single-Stage Trickling Filter Design by the Eckenfelder Formula. Multiply Volume Determined from Chart I by Appropriate Factor from Chart II for Filter Depths other than 6 ft.

1. Calculate the required efficiency

$$E = \frac{L_i - L_e}{L_i} = \frac{200-20}{200} = .90$$

2. Assume that the average temperature of the waste-water is 20°C. A correction may be made for temperatures other than 20°C. by the Howland formula (formula 50).

V = 300,000 cu.ft. @ R = 0

V = 76,000 cu.ft. @ R = 1

V = 35,000 cu.ft. @ R = 2

V = 20,000 cu.ft. @ R = 3

Select R = 2 and a depth of 8 feet.

3. From Figure 13,

Find depth factor for 8 feet of depth = .91. Then required volume is found by

$$V = 35{,}000\ (.91)\ \frac{(0.75)\,\text{mgd}}{(1.0)\,\text{mgd}} = 23{,}900 \text{ cu.ft.}$$

It is interesting to note that this volume is only 15.6 per cent of that given for the same conditions by the NRC formula in Example I. Unlike the NRC formula, the Eckenfelder forumla does not include the influent BOD as a parameter, but includes a depth parameter not present in the NRC formula. The differences between these formulas will be discussed at greater length in a succeeding subchapter.

3. <u>The Galler-Gotaas Method</u>

The Galler-Gotaas equation, solved for volume, is

$$V = \frac{\pi}{1000} \cdot \frac{D}{(1+D)^{5.36}} \cdot \left[\frac{C \cdot L_i^{.19} \cdot Q^{.13}}{T^{.15}} \cdot \frac{(1+R(1-E))^{1.19}}{(1-E)(1+R)^{.78}} \right]^8 \qquad (47)$$

$$C = .464 \left(\frac{43,560}{3.1416}\right)^{.13} = 1.60 \tag{48}$$

(V = volume in cu.ft.x 10^3)

According to this formula, volume is a function of depth, D, influent BOD, flow rate, Q, temperature, T, efficiency, E, and recirculation ratio, R. However, efficiency and recirculation ratio are interdependent variables.

The effect of flow rate on volume is shown in Figure 14. This is almost linear, as shown by the small deviation of the curve from a straight line. The effect of influent BOD is shown in Figure 15. The change in slope of the curve decreases for higher BOD's. However, the relationship of volume and influent BOD is clearly not linear for BOD values below 150 mg/l. The relationship of depth to volume is shown in Figure 16. There is a very pronounced reduction in required volume for deep filters. The effect of temperature is shown in Figure 17. A much greater volume is required for wastewater of colder temperatures.

According to the Galler-Gotaas formula

$$V \propto \left[\frac{(1+R(1-E))^{1.19}}{(1+R)^{.78}(1-E)}\right]^{8} \tag{51}$$

Recirculation and efficiency cannot be separated into independent variables; they are interdependent variables and affect the filter volume according to this relationship. This effect is illustrated in Figure 18. The curve of R = 0 shows the effect of efficiency on volume when no recirculation is present. When there is no recirculation, the effect of efficiency on volume is

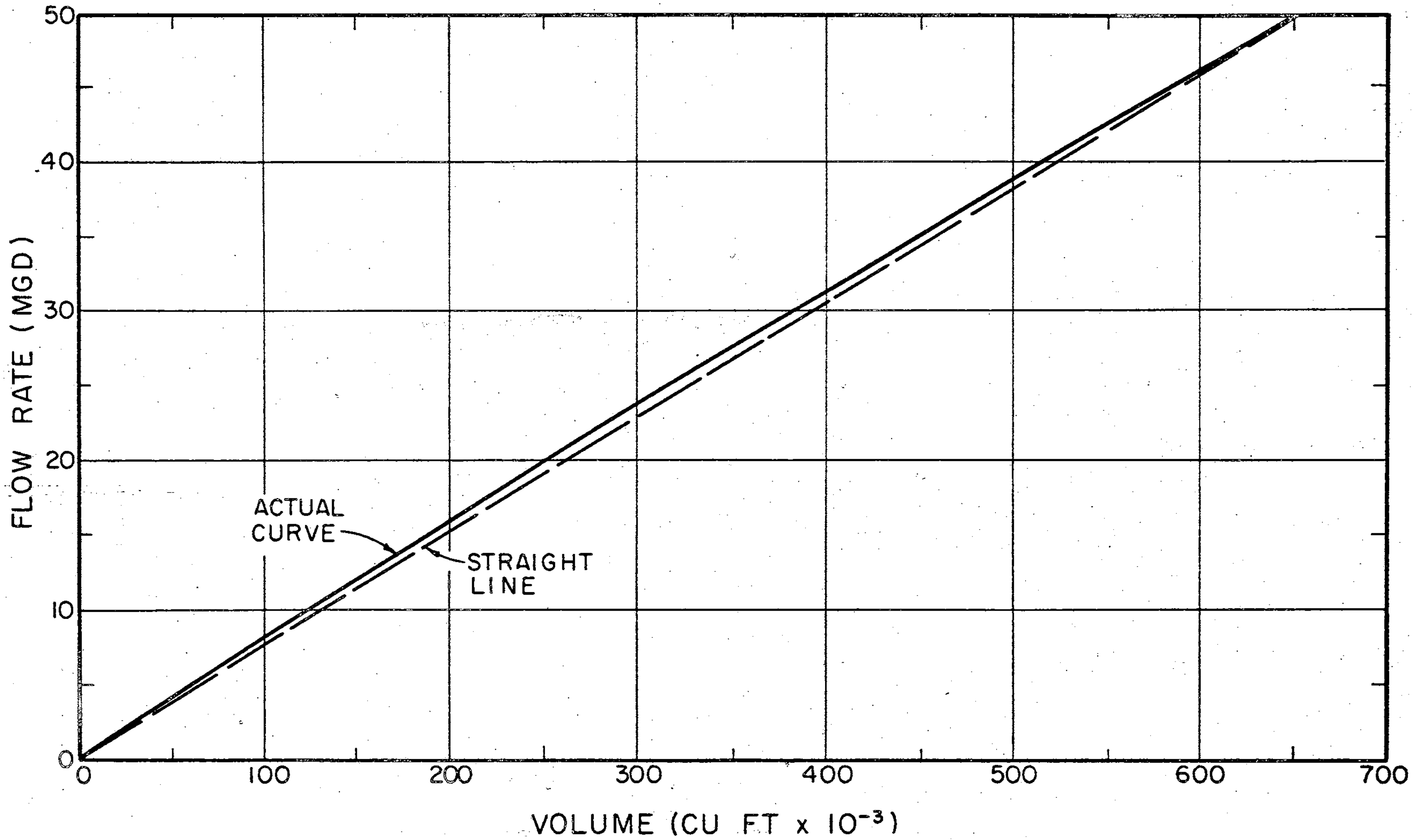

Figure 14 - Galler-Gotaas Formula: Effect of Flow Rate on Volume at L_i = 100 mg/l, E = .70, R = 0.0, D = 6 ft., and T = 20°C.

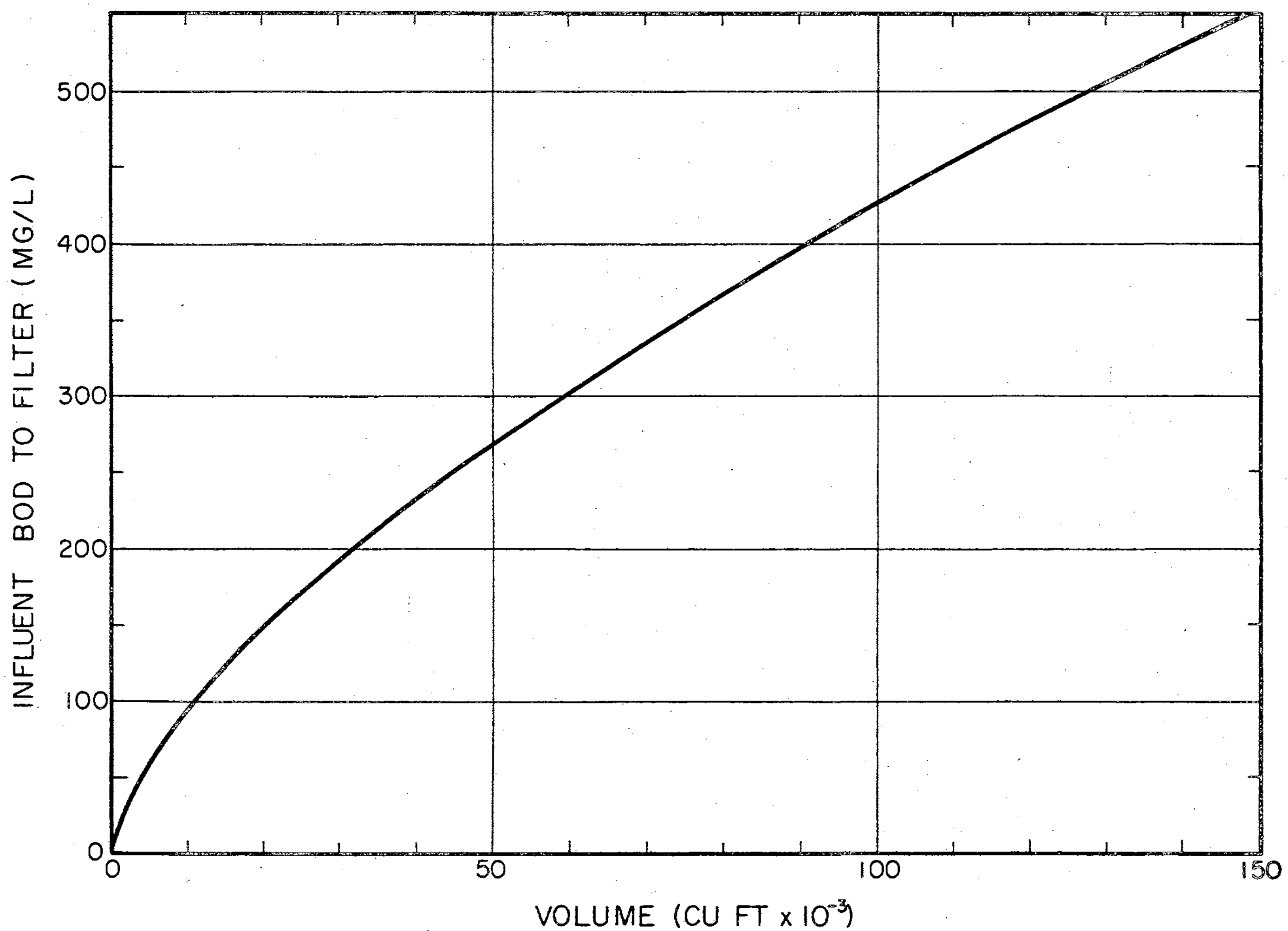

Figure 15 - Galler-Gotaas Formula: Effect of Influent BOD on Volume at Q = 1.0 mgd, E = .70, R = 0.0, D = 6.0 ft., and T = 20°C.

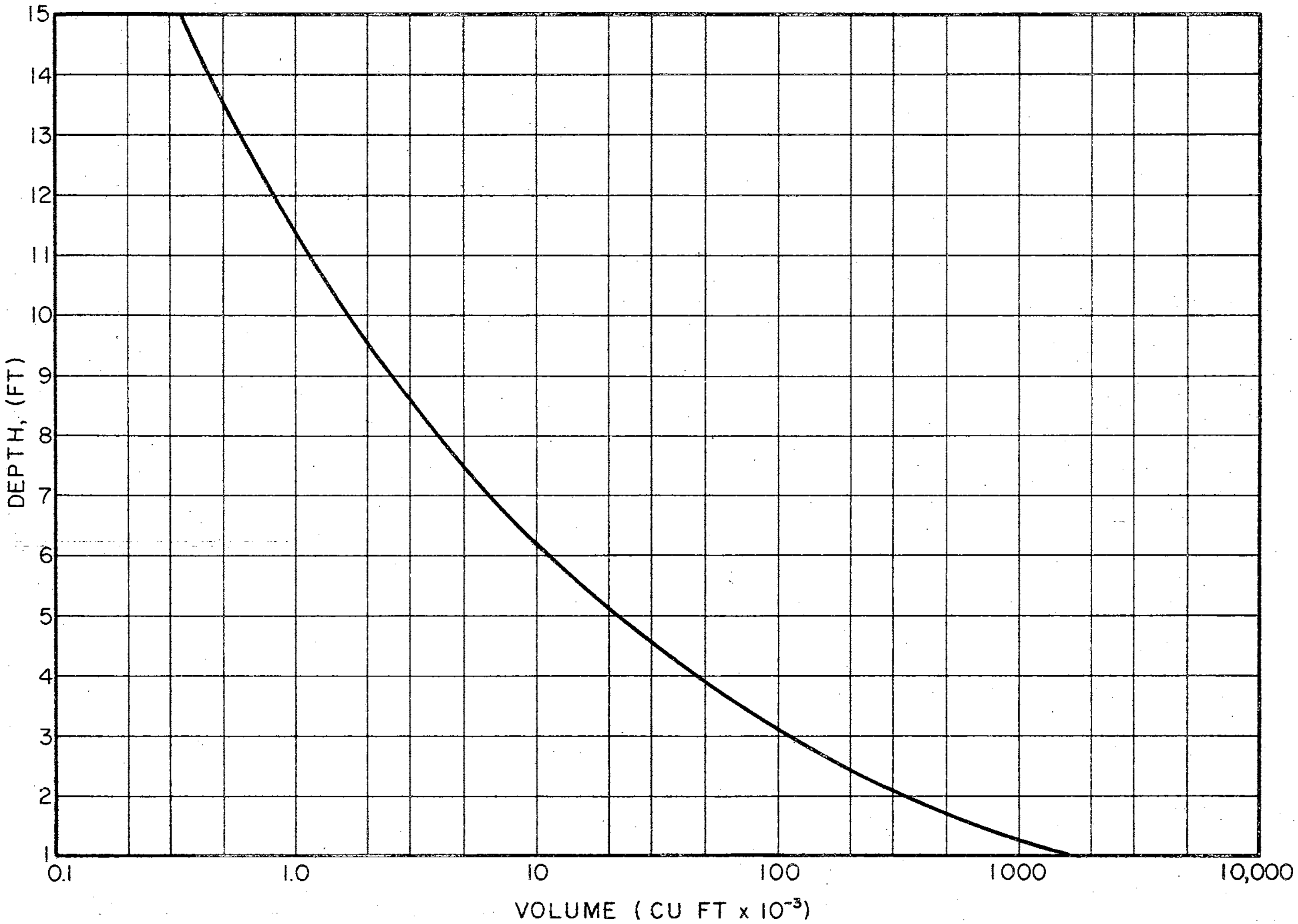

Figure 16 – Galler-Gotaas Formula: Effect of Depth on Volume at L_i = 100 mg/l, Q = 1.0 mgd, E = .70, R = 0.0, and T = 20°C.

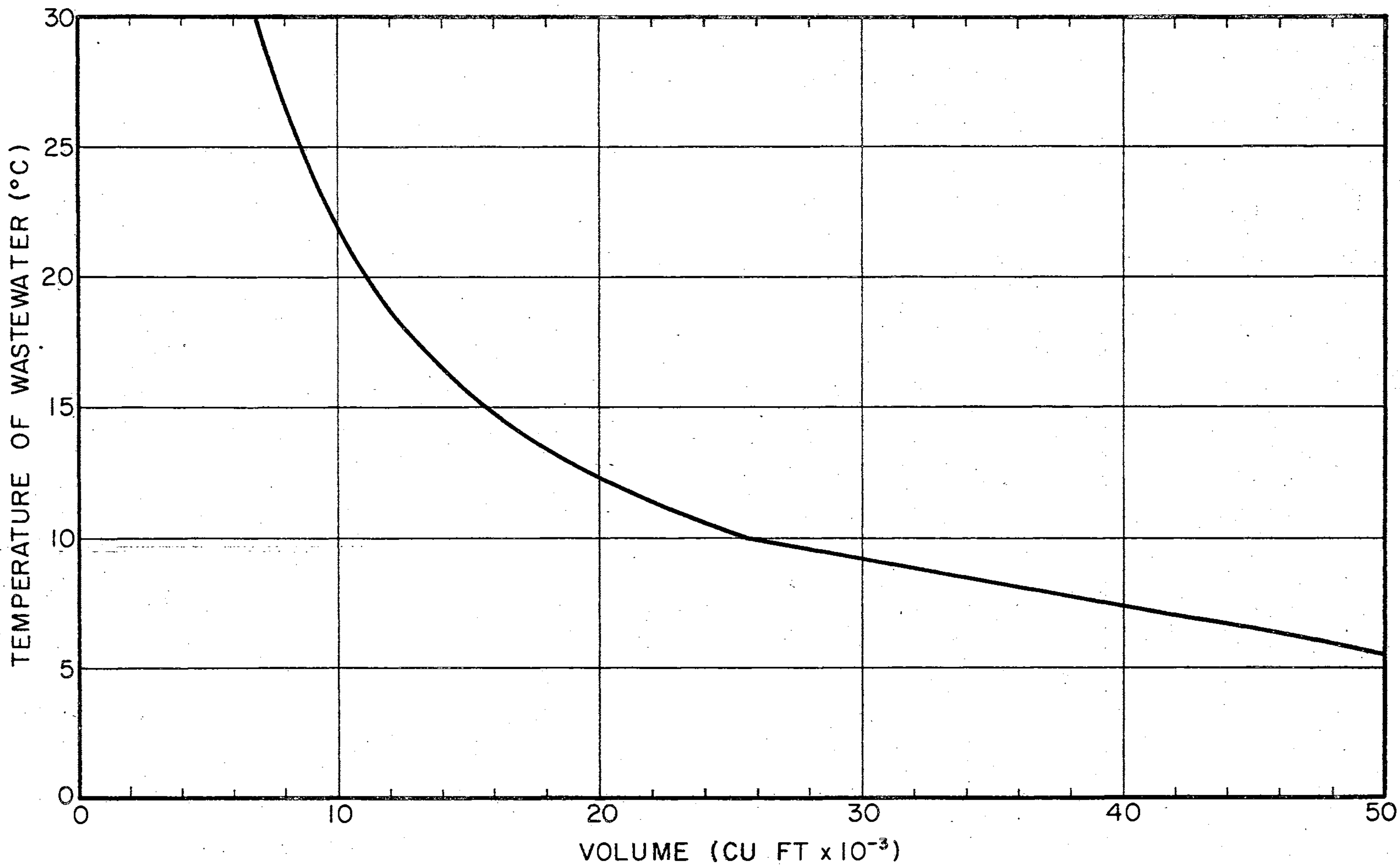

Figure 17 - Galler-Gotaas Formula: Effect of Temperature on Volume at L_i = 100 mg/l, Q = 1.0 mgd, E = .70, R = 0.0, and D = 6.0 ft.

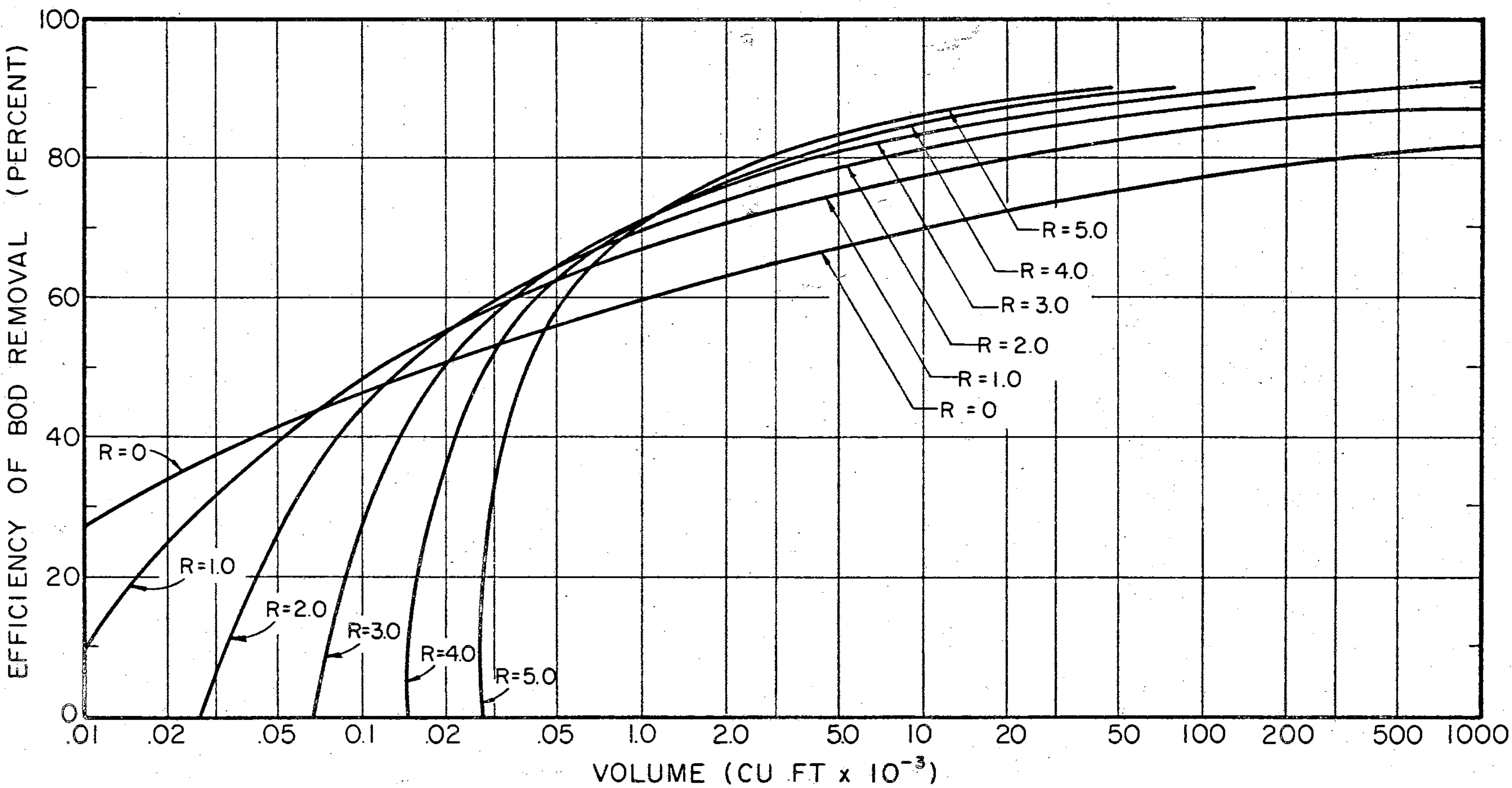

Figure 18 - Galler-Gotaas Formula: Effect of Recirculation on Volume and Efficiency at L_i = 100 mg/l, Q = 1.0 mgd, D = 6.0 ft., and T = 20°C.

$$V \propto \left[\frac{1}{1-E}\right]^{8} \tag{52}$$

It can be seen that recirculation will decrease the required volume above some efficiency and increase the volume below it. The interdependence of recirculation and efficiency on volume present in the Galler-Gotaas formula is due to the construction of the original form of the formula as set forth by Galler and Gotaas (27).

$$\frac{w_e}{A} = \frac{0.31\left(\frac{w_o}{A}\right)^{1.19}(1+R)^{0.28}}{(1+D)^{0.67}T^{0.15}((Q+r)/A)^{0.06}} \tag{40}$$

However

$$w_o = L_o \cdot Q \cdot 8.34, \text{ and}$$

$$L_o = \frac{L_i + RL_e}{1+R} \tag{29}$$

Thus, the organic loading w_o is a function of L_i, R, and L_e, and L_i and L_e determine efficiency E. This interdependence was recognized by Schulze (33), and Blain and McDonnell (34), in discussion of the Galler-Gotaas formula as presented in reference 27.

The variables have been separated as completely as possible in Formula 47. It should be noted that no inference can be made from this separation as to the validity of the statistical methods used by Galler and Gotaas in developing their formula. It can only be stated that the published formula can be reduced to the form of Equation 47.

According to Figure 18, a recirculation ratio of 1.0 will require increased volume below 44 per cent efficiency. No advantage (decrease in required volume) can be gained by recirculation ratio of 2.0 below 55 per cent, or with a higher recirculation ratio of 3.0 below 65 per cent. Higher recirculation ratios will require a volume increase below 75 per cent.

One explanation for this behavior of trickling filters according to the Galler-Gotaas formula, might be that the portion of the effluent BOD of filters of low efficiency returned and mixed with the influent BOD in recirculation increases the applied BOD over that of the case of no recirculation or less recirculation such that the filter efficiency is impaired rather than augmented, requiring an increase in volume to maintain the same efficiency.

Design of a single stage trickling filter by the Galler-Gotaas formula can be made from Figures 19, 20, 21, and 22. The procedure to be followed is illustrated by the following example:

Example III. Design of a Single-Stage Trickling Filter by the Galler-Gotaas Method:

Known: $L_e = 20$ mg/1, $L_i = 200$ mg/1, Q = 0.75 mgd

Required: V, R, D

1. Calculate required efficiency:

$$E = \frac{L_i - L_e}{L_i} = \frac{200-20}{200} = .90$$

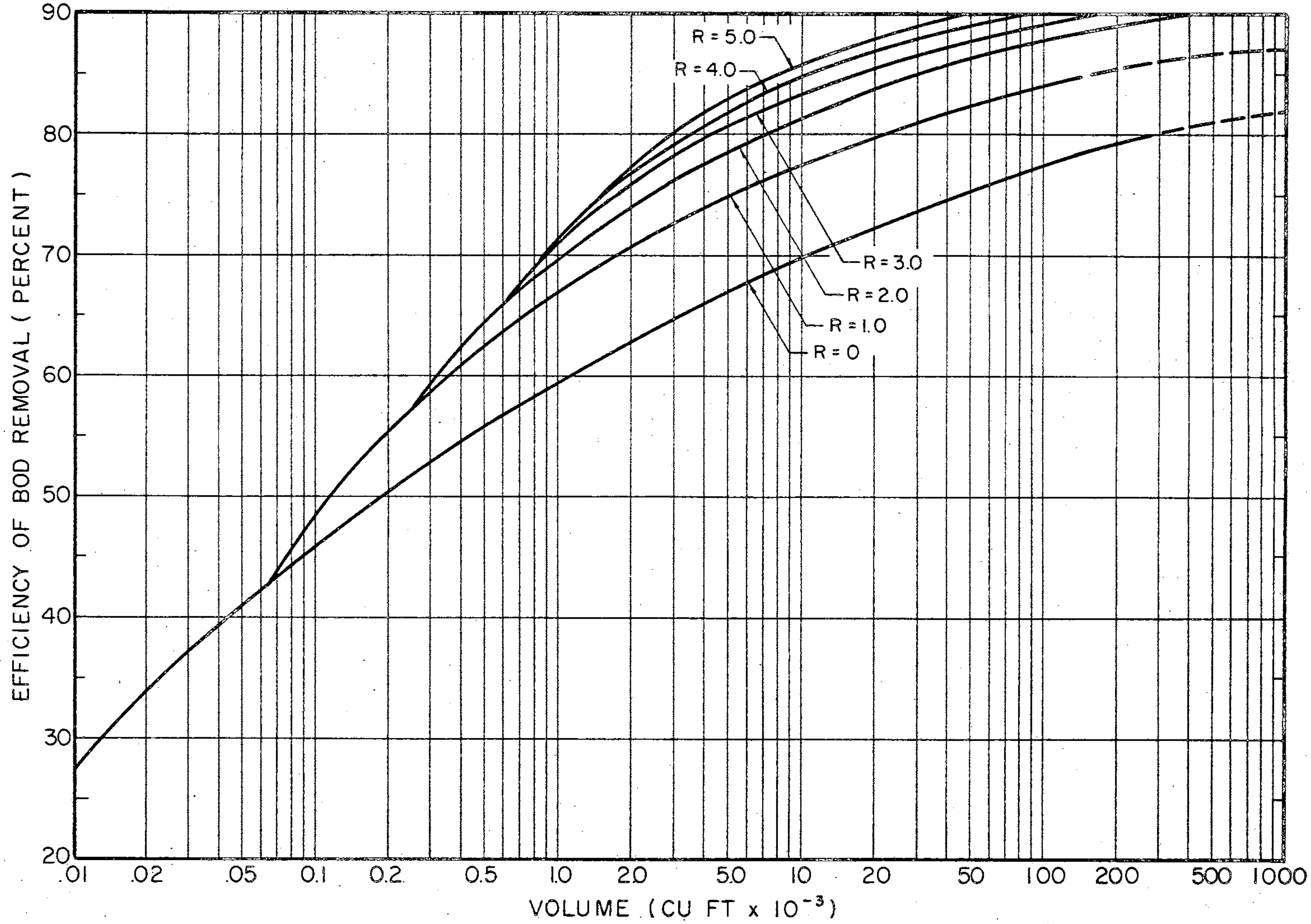

Figure 19 - Chart I for Single-Stage Trickling Filter Design by Galler-Gotaas Formula. Constructed on the Base of L_i = 100 mg/l, Q = 1.0 mgd, D = 6.0 ft., and T = 20°C.

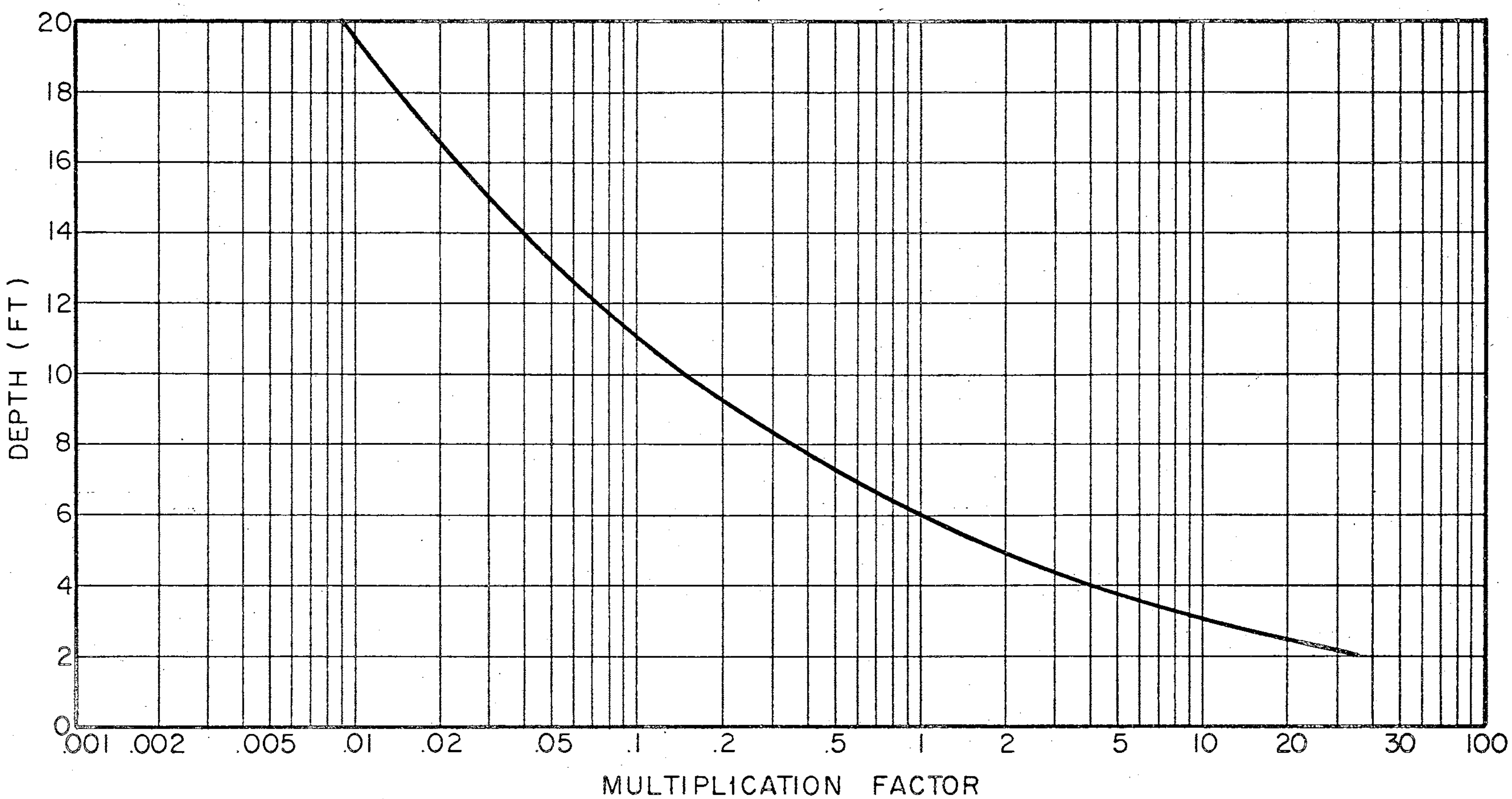

Figure 20 - Chart II for Single-Stage Trickling Filter Design by Galler-Gotaas Formula. Multiply Volume Determined from Chart I by Appropriate Factor from Chart II for Filter Depths other than 6 ft.

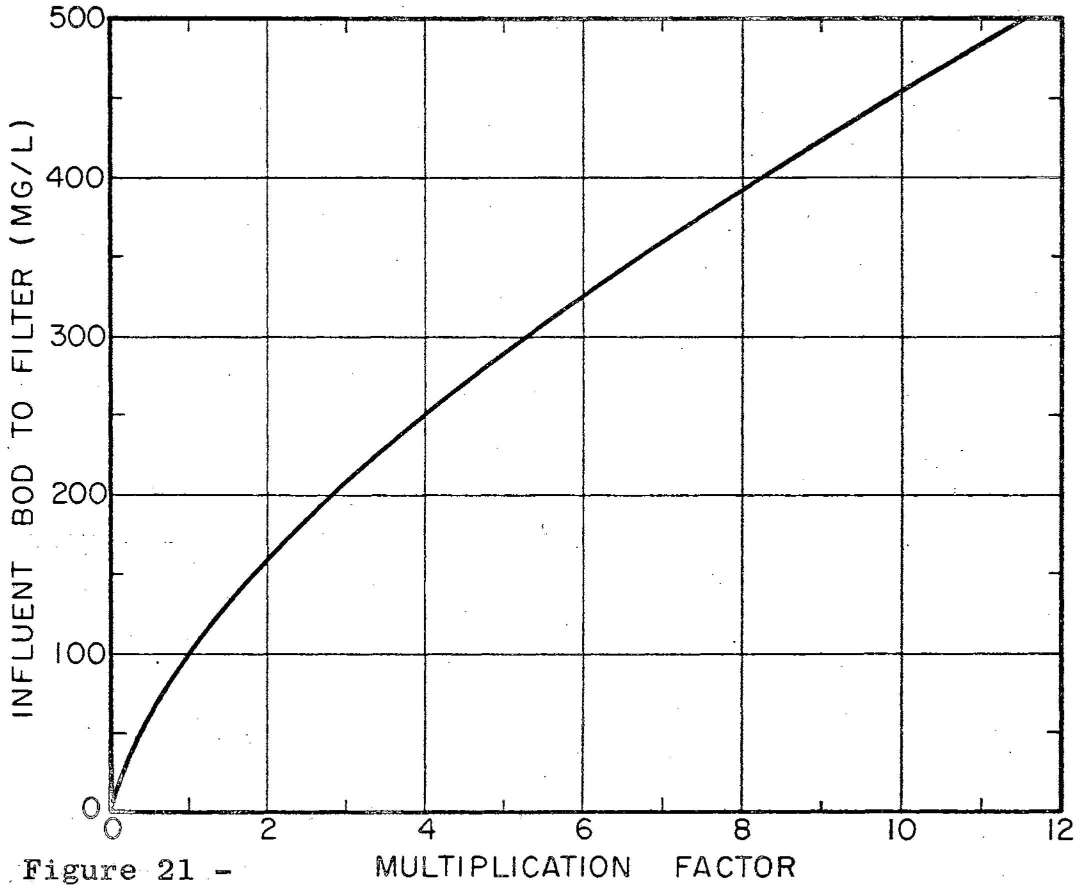

Figure 21 –
Chart III for Single-Stage Trickling Filter Design by Galler-Gotaas Formula. Multiply Volume Determined from Chart I by Appropriate Factor from Chart III for Influent BOD Concentrations Other than 100 mg/l.

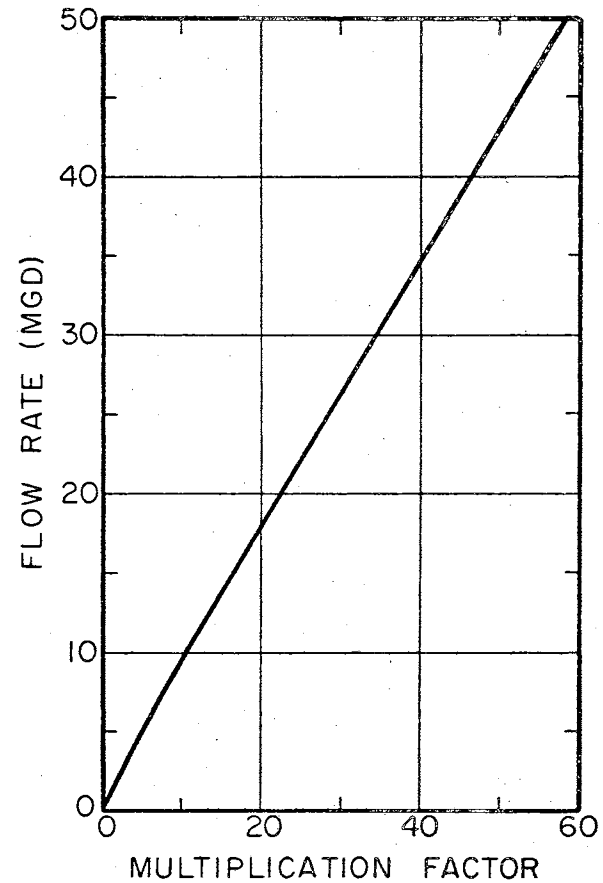

Figure 22 – Chart IV for Single-Stage Trickling Filter Design by Galler-Gotaas Formula. Multiply Volume Determined from Chart I by Appropriate Factor from Chart IV for Plant Flow Rates Other than 1.0 mgd.

2. Assume that the average temperature of the wastewater is 20°C. If it is not, the volume obtained here must be multiplied by the factor $\left(\frac{20}{T}\right)^{.15}$.

3. From Figure 19, it can be seen that

V = 450,000 cu.ft. @ R = 2.0

V = 160,000 cu.ft. @ R = 3.0

V = 80,000 cu.ft. @ R = 4.0

V = 48,000 cu.ft. @ R = 5.0

Select V = 450,000 cu.ft. @ R = 2.0.

4. A depth of 8 feet is selected.

From Figure 20, depth factor = .35 for D = 8 feet

From Figure 21, L_i factor = 2.9 for L_i = 200 mg/l

From Figure 22, Q factor = 0.75 for Q = .75 mgd

5. Compute required volume:

(450,000)(.35)(2.9)(.75) = 342,000 cu.ft.

This volume is 2.24 times that computed by the NRC formula and 14.4 times that computed by the Eckenfelder formula for the same conditions.

4. <u>Comparison of the National Research Council, Eckenfelder, and Galler-Gotaas Methods for the Design of Single-Stage Trickling Filters</u>

The effect of the various parameters in the NRC, Eckenfelder, and Galler-Gotaas formulas on trickling filter volume has been shown. The Eckenfelder formula is based on the expression for time of contact between the wastewater and the microorganisms which carry out the process of BOD removal by biological oxidation in the trickling filter process as developed by Howland (20):

$$t \propto \frac{CD^{.67}(1+R)}{(Q/A)^{0.5}} \tag{53}$$

(neglecting the temperature parameter)

The time of contact has been reported by numerous investigators as an important parameter of BOD removal in a trickling filter. The effect of contact time can be hypothetically explained in this way: The BOD removal in the trickling filter process proceeds according to some rate of removal, dL/dt. This rate of removal is not necessarily constant for any particular trickling filter, and probably is not constant throughout all sections of the filter, due to a wide number of varying factors such as uniformity of biological growth, aeration, wastewater distribution, and undoubtedly many others. However, the amount of removal, dL, depends on the amount of contact time provided, dt. The efficiency of removal is dependent on the amount of removal, since efficiency $E = \frac{\Delta L}{L_i}$, where L_i is assumed to be constant for a certain set of conditions.

Eckenfelder incorporated Howland's expression for contact time into his formula for efficiency in the following way:

$$E = 1 - \frac{1}{1 + \frac{CD^{.67}(1+R)}{(Q/A)^{0.5}}} \tag{38}$$

Since $\left(\frac{CD^{.67}(1+R)}{(Q/A)^{0.5}}\right)$ represents contact time, t, the form of this formula is:

$$E = 1 - \frac{1}{1+t} \tag{54}$$

The NRC formula is

$$E = \frac{1}{1+C\cdot\left(\frac{W}{VF}\right)^{0.5}} \tag{2}$$

or

$$E = \frac{1}{1+C\cdot\left[\frac{Q}{AD}\cdot L_i\cdot\frac{(1+0.1R)^2}{(1+R)}\right]^{0.5}} \tag{55}$$

Dimensionally, the expression

$$C\left[\frac{Q\ L_i\ (1+0.1R)^2}{AD\ (1+R)}\right]^{0.5} \tag{56}$$

is

$$\left(\frac{\frac{L^3}{t}}{L^3}\right)^{0.5} \quad \text{or} \quad (1/t)^{0.5} \tag{57}$$

Apparently, then

$$C\left[\frac{QL_i\ (1+0.1R)^2}{AD\ (1+R)}\right]^{.5} \tag{56}$$

is the reciprocal of contact time.

The NRC formula may then be written as

$$E = \frac{1}{1+1/t} \tag{58}$$

However,

$$\frac{1}{1+1/t}\cdot\left(\frac{t}{t}\right) = \frac{t}{1+t} \tag{59}$$

The Eckenfelder formula for efficiency written in the form of contact time is

$$E = 1 - \frac{1}{1+t} \tag{54}$$

However,

$$\left(1 - \frac{1}{1+t}\right)\left(\frac{1+t}{1+t}\right) = \frac{1+t-1}{1+t} = \frac{t}{1+t} \qquad (59)$$

Therefore, the NRC formula and the Eckenfelder formula are identities in basic form. The expression

$$\frac{1}{.0561}\left(\frac{AD}{QL_i}\,\frac{(1+R)}{(1+0.1R)^2}\right)^{0.5} \qquad (60)$$

can be taken as the expression of contact time in the NRC formula. This expression is similar to that of Howland as adapted by Eckenfelder:

$$.379\ \frac{D^{0.67}(1+R)}{(Q/A)^{0.5}} \qquad (53)$$

The basic similarities and differences between the NRC formula and the Eckenfelder formula can be readily seen by examining these expressions for contact time. The two formulas have been shown to be the same with respect to the relationship of contact time to efficiency of BOD removal. In the NRC formula, the contact time is related as

$$t \propto \frac{1}{C} \cdot \left[\frac{V}{QL_i} \cdot \frac{(1+R)}{(1+0.1R)^2}\right]^{0.5} \qquad (60)$$

and in the Eckenfelder formula

$$t \propto \frac{CA^{0.5}D^{0.67}(1+R)}{Q^{0.5}} \qquad (61)$$

The relationship between t and Q is the same in both the NRC and Eckenfelder formulas:

$$t \propto \frac{1}{Q^{0.5}} \qquad (62)$$

However, in the NRC formula

$$t \propto V^{0.5} \text{ or } t \propto (AD)^{0.5} \quad (63)$$

and in the Eckenfelder formula

$$t \propto A^{0.5} D^{0.67} \quad (64)$$

Eckenfelder introduced this variation of the exponent on D to account for unequal growth of the biological film and consequent decreased activity at greater depths. The NRC formula does not show any decrease in the effect of additional depth to provide additional volume of filter media. Recirculation increases contact time as

$$t \propto (1+R) \quad (65)$$

in the Eckenfelder formula, and as

$$t \propto \frac{(1+R)^{0.5}}{(1+0.1R)} \quad (66)$$

in the NRC formula. A limit is not shown in volume reduction with recirculation increases by the Eckenfelder formula at a recirculation ratio of 8. The reason for this behavior is explained by the differences in the above expressions.

The most noticeable difference between the NRC formula and the Eckenfelder formula is that the NRC formula includes the influent BOD, L_i, as a parameter of efficiency, while the Eckenfelder formula does not. The concentration of BOD in the influent to the filter is a part of the organic load applied to the filter (see formula 1). In reality, the organic load is the amount of biological waste applied per unit of time, and the hydraulic loading is the amount of wastewater applied per unit of time. If biological waste is applied to the filter at some rate dw_i/dt, and removed at some rate dw/dt, then the efficiency of the filter must be

$$\frac{dw/dt}{dw_i/dt} = E \qquad (67)$$

According to this expression, a filter of 100 per cent efficiency would have a rate of BOD removal equal to the rate of BOD application. Therefore, according to this reasoning, the influent BOD, L_i, would be an important parameter of trickling filter efficiency. Howland, Schulze, and Eckenfelder are not incorrect in proposing that the contact time, and therefore efficiency and volume requirements, are governed by the hydraulic flow rate; this would be true for cases where simultaneous changes in flow rate and BOD occur such that the value of the organic load, w_i, remains nearly constant, or in cases where the influent BOD remains constant but the hydraulic flow rate changes. These situations are frequently encountered in the normal operation of trickling filter plants. The controversy over the matter of whether hydraulic loading or organic loading is the governor of trickling filter efficiency seems to be an outgrowth of the failure of investigators to separate the variables involved and examine their individual effects.

The Galler-Gotaas formula for efficiency of trickling filters is

$$E = 1 - \left(\frac{1}{V} \cdot \frac{\pi D}{1000}\right)^{.125} \cdot \frac{CQ^{.13}L_i^{.19}(1+R(1-E))^{1.19}}{T^{.15}(1+D)^{.67}\ (1+R)^{.78}} \qquad (68)$$

The dimensions of this expression, disregarding exponents, are

$$\frac{\frac{L^3}{t}}{L^3} \text{ or } 1/t \qquad (69)$$

The form of this formula with regard to contact time is

$$E = 1-[1/t] \qquad (70)$$

which is a different form from that of the NRC and Eckenfelder formulas:

$$E = \frac{t}{1+t} \qquad (59)$$

Therefore contact time, according to the Galler-Gotaas formula, can be expressed as

$$t \propto \frac{1}{C} \cdot \frac{T^{.15}(1+D)^{.67}}{Q^{.13}L_i^{.19}} \cdot \frac{(1+R)^{.78}}{(1+R(1-E))^{1.19}} \cdot \left(\frac{AD}{\pi}\frac{1000}{D}\right)^{.125} \qquad (71)$$

There is apparent similarity between this expression and the expression for contact time in the NRC and Eckenfelder formulas. In the Galler-Gotaas formula,

$$t \propto \frac{1}{Q^{.13}L_i^{.19}} \qquad (72)$$

compared with $t \propto \frac{1}{Q^{0.5}}$ in the Eckenfelder formula and

$$t \propto \frac{1}{Q^{0.5}L_i^{0.5}}$$

in the NRC formula. In the Galler-Gotaas formula,

$$t \propto T^{.15} \cdot \frac{(1+R)^{.78}}{(1+R(1-E))^{1.19}} \cdot A^{.125}(1+D)^{.67} \qquad (73)$$

The relationships of the NRC formula,

$$t \propto AD^{0.5} \cdot \frac{(1+R)^{0.5}}{1+0.1R} \qquad (74)$$

and of the Eckenfelder formula

$$t \propto A^{0.5}D^{0.67}(1+R) \qquad (75)$$

are similar, but contain apparent differences.

The BOD removal efficiency of a trickling filter is dependent upon the time of contact between the biological waste and the microorganisms provided by the trickling filter process. The efficiency requirement controls the volume requirement of a trickling filter. Therefore, the volume requirement is essentially dependent upon the amount of contact time that can be designed into the unit. The three formulas of this study are relationships between the contact time parameters and filter efficiency. To illustrate the differences and similarities between these parameters of contact time and filter volume requirements, graphical illustrations have been made from data obtained from computations of volume requirements for various combinations of these parameters by use of the IBM 7040. These figures may also be used to find the calculated efficiency with a certain fixed volume within the range of volumes shown.

Figure 23 shows the calculated volume given by the three formulas for the conditions of L_i = 100 mg/l, Q = 1.0 mgd, and no recirculation. The fact that the basic form of the Eckenfelder and NRC formulas is the same is

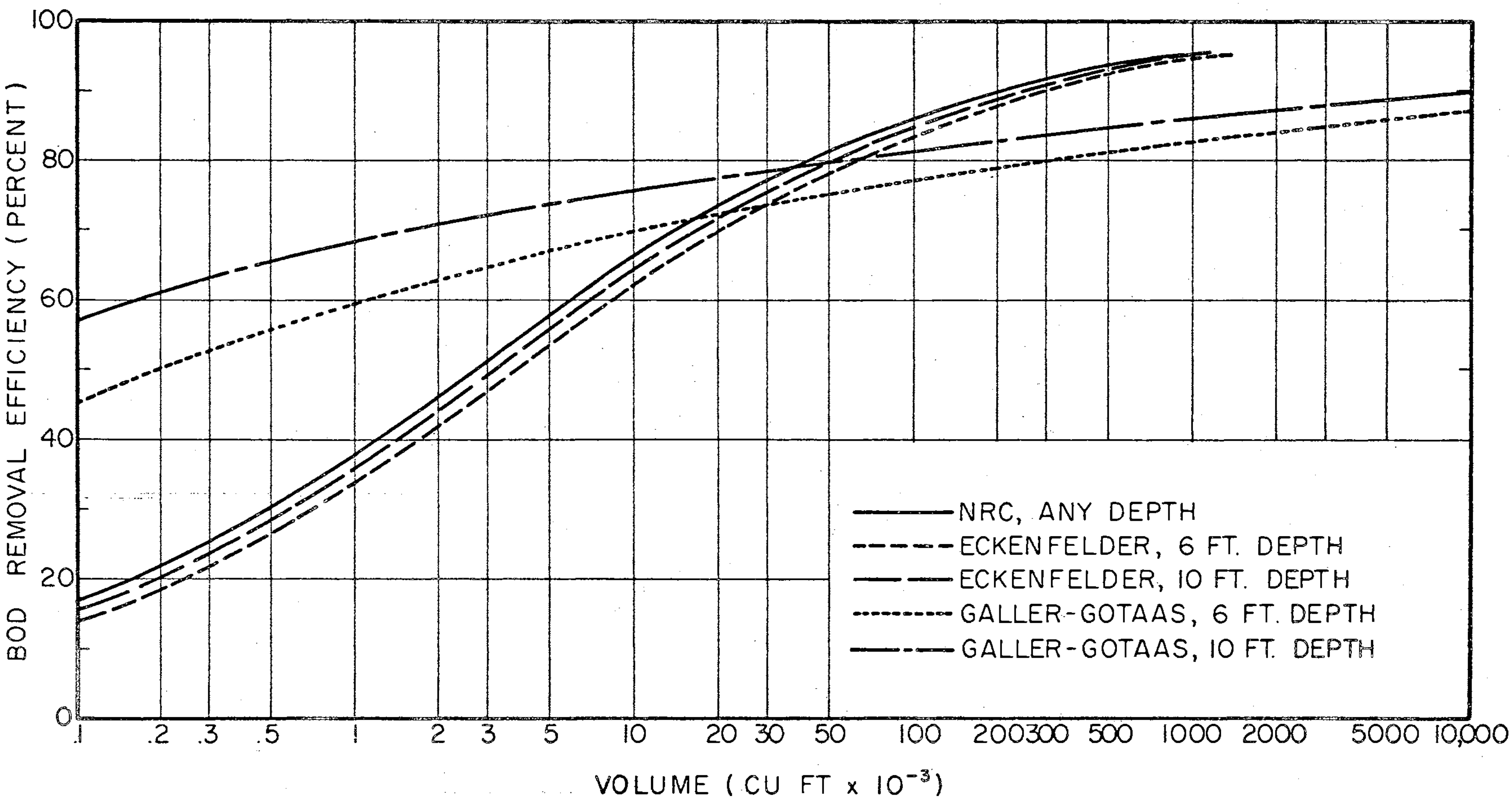

Figure 23 - Volume Comparison at L_i = 100 mg/l, Q = 1.0 mgd, R = 0.0, and T = 20°C.

demonstrated by the parallel curves of these two formulas. The NRC formula, which has an exponent of 1.0 on depth, will generate only one curve, which is presumably valid for any depth. However, the Eckenfelder formula exhibits a decrease in required volume for increases in depth. Two depths are shown to illustrate this: 6 and 10 feet. Both of these curves are relatively close to the curve of the NRC formula. The curves of the Galler-Gotaas formula are clearly of a different form, as previously discussed. The effect of increases in depth to decrease volume is seen to be greater than those of the Eckenfelder formula. The Galler-Gotaas formula gives a much lower volume requirement than either the Eckenfelder or NRC formula for lower efficiencies. Above 73 per cent efficiency, however, the Galler-Gotaas volume is much greater than either the Eckenfelder volume or the NRC volume for 6 feet of depth. The same is true for efficiencies greater than 79 per cent with 10 feet of depth.

Figure 24 shows the effect of a higher influent BOD. Conditions are Q = 1.0 mgd, L_i = 300 mg/l, and no recirculation. The same characteristic curves are present as in Figure 23. However, since the Eckenfelder formula shows no change in volume or efficiency with changes in influent BOD, the curves of Figure 24 with L_i = 300 mg/l are the same as in Figure 23 with L_i = 100 mg/l. The NRC formula curve shows increased volume with increased BOD and gives considerably greater volume than the Eckenfelder formula

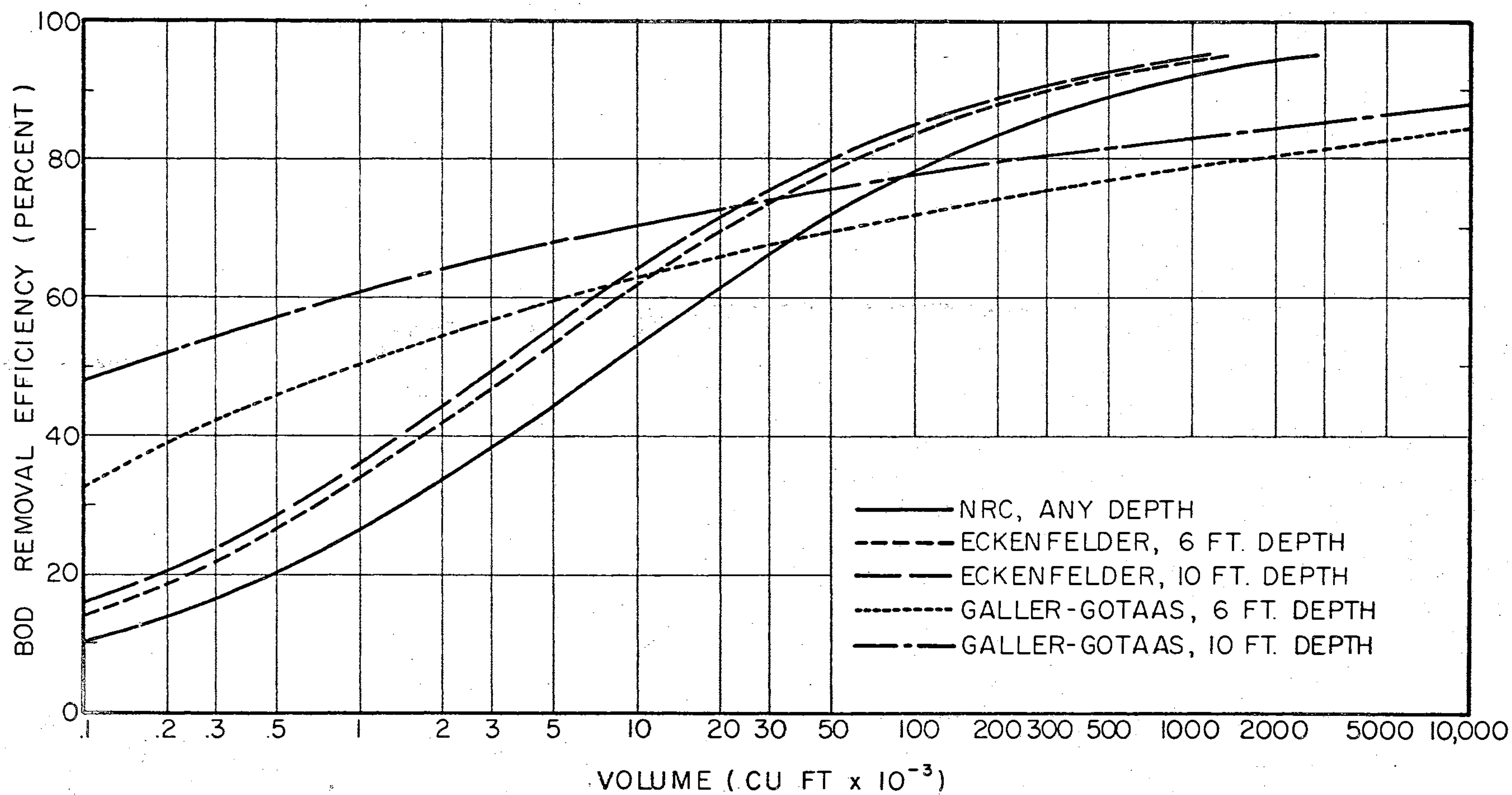

Figure 24 - Volume Comparison at L_i = 300 mg/l, Q = 1.0 mgd, R = 0.0, and T = 20^{o}C.

curve. The Galler-Gotaas formula curves also show an increased volume. The same effect of lower volume at lower efficiencies and higher volume at higher efficiencies given by the Galler-Gotaas formula compared to the other two formulas is exhibited as in the previous case.

In each of the three formulas, increased recirculation has been shown to reduce volume requirements or increase efficiency with a fixed volume. Figure 25 shows that the greatest volume reduction is shown with the Eckenfelder formula and the Galler-Gotaas formula. However, it has been shown that in lower efficiency ranges the effect of increasing recirculation with the Galler-Gotaas formula is to increase the required volume or decrease the efficiency with a fixed volume. This produces the steep parts of the Galler-Gotaas curves in the lower efficiency ranges of Figure 25.

Figure 26 illustrates the conditions of Q = 1.0 mgd, R = 2.0, and L_i = 300 mg/l. The effect of increased BOD gives the Eckenfelder formula an apparent advantage over the other formulas at all efficiencies with 6 feet of depth, and at efficiencies greater than 80 per cent with 10 feet of depth.

The required volume is generally reduced with all formulas in Figure 27, where Q = 1.0, L_i = 100.0 mg/l, and R = 5.0, except in the lower efficiency ranges for the Galler-Gotaas formula, as previously discussed. Again, the Eckenfelder formula gives the lowest volume with 6 feet of depth at all efficiencies, and with 10 feet of depth at

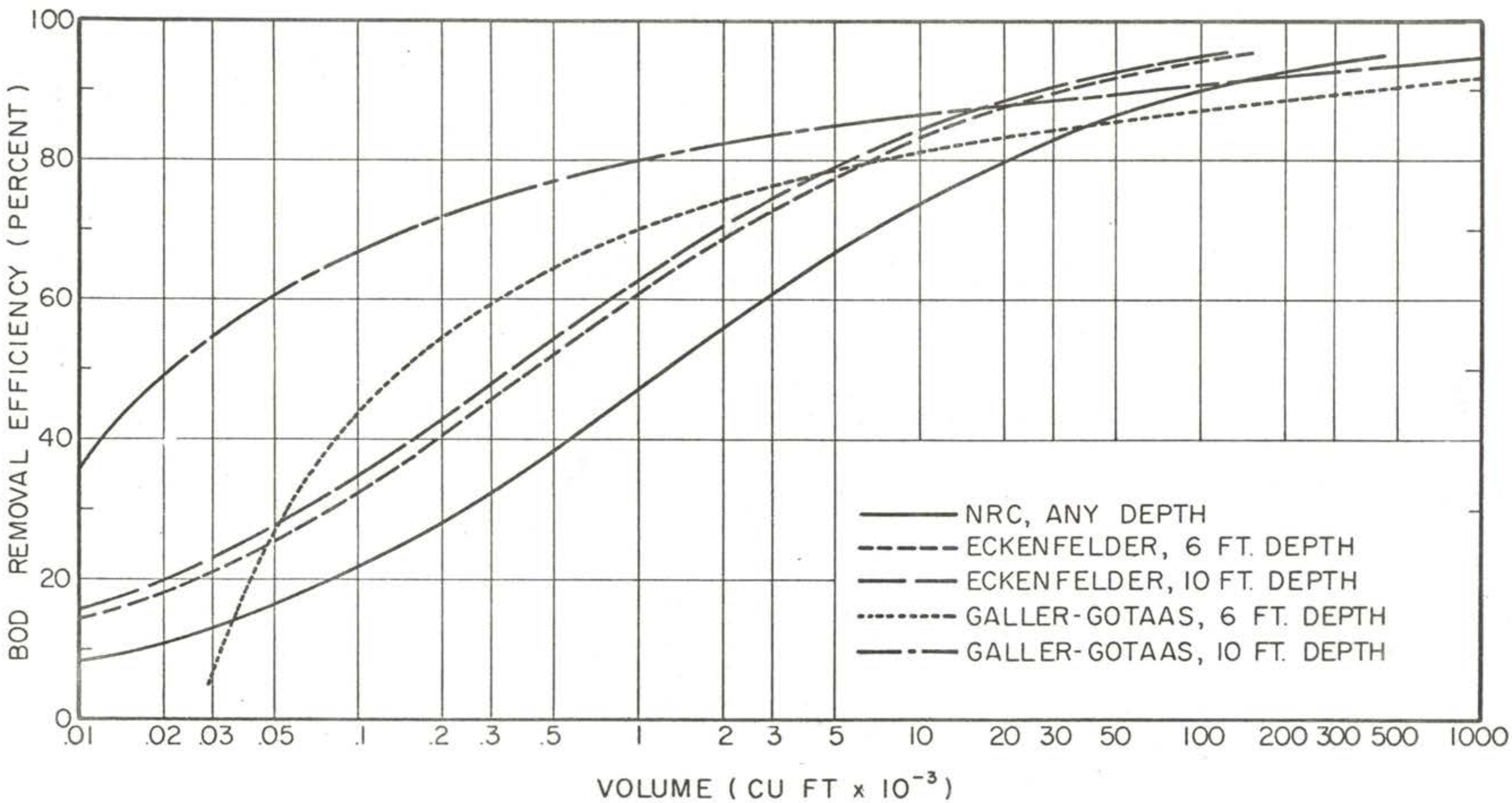

Figure 25 - Volume Comparison at L_i = 100 mg/l, Q = 1.0 mgd, R = 2.0, and T = 20^oC.

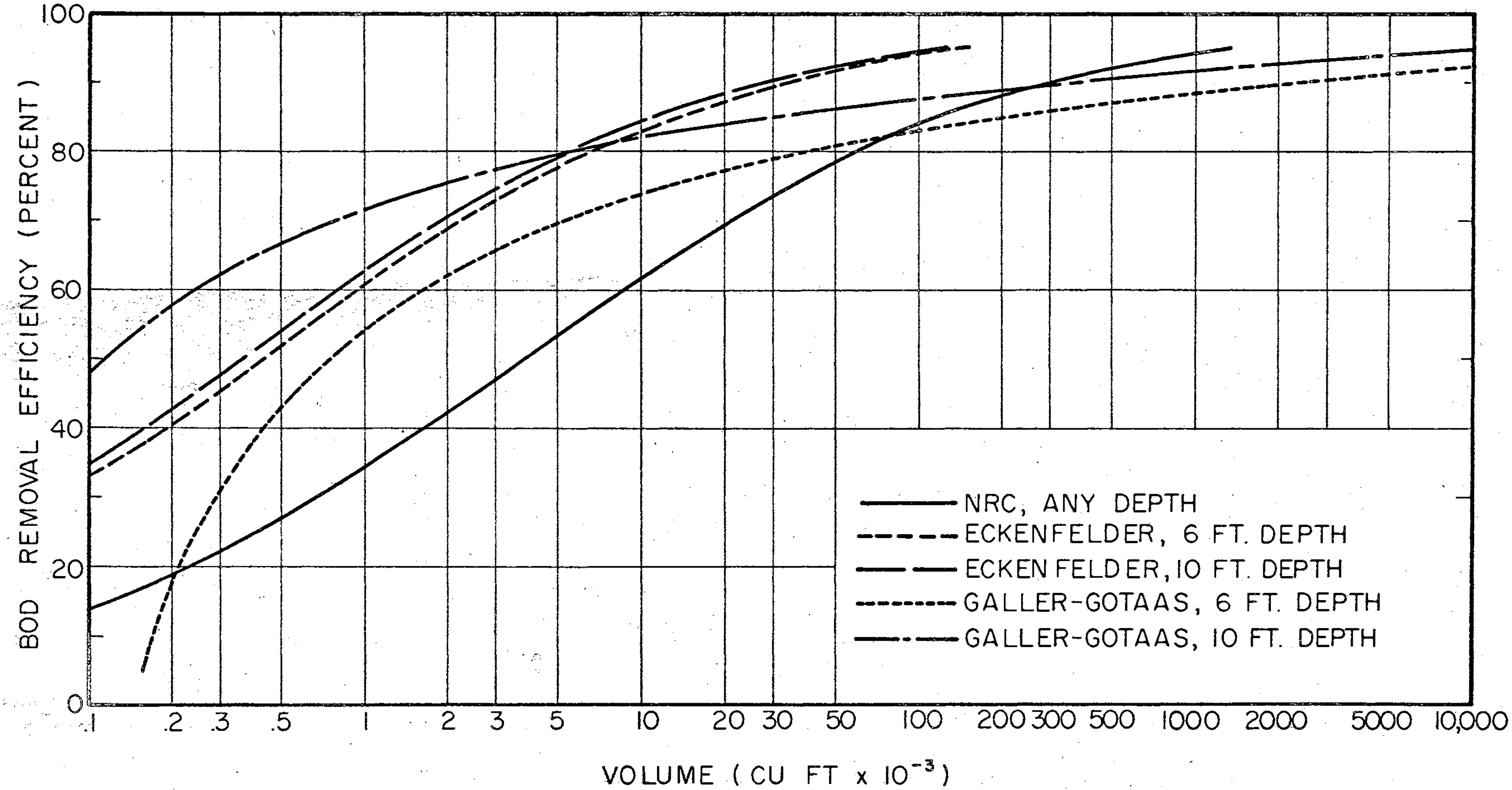

Figure 26 - Volume Comparison at L_i = 300 mg/l, Q = 1.0 mgd, R = 2.0, and T = 20°C.

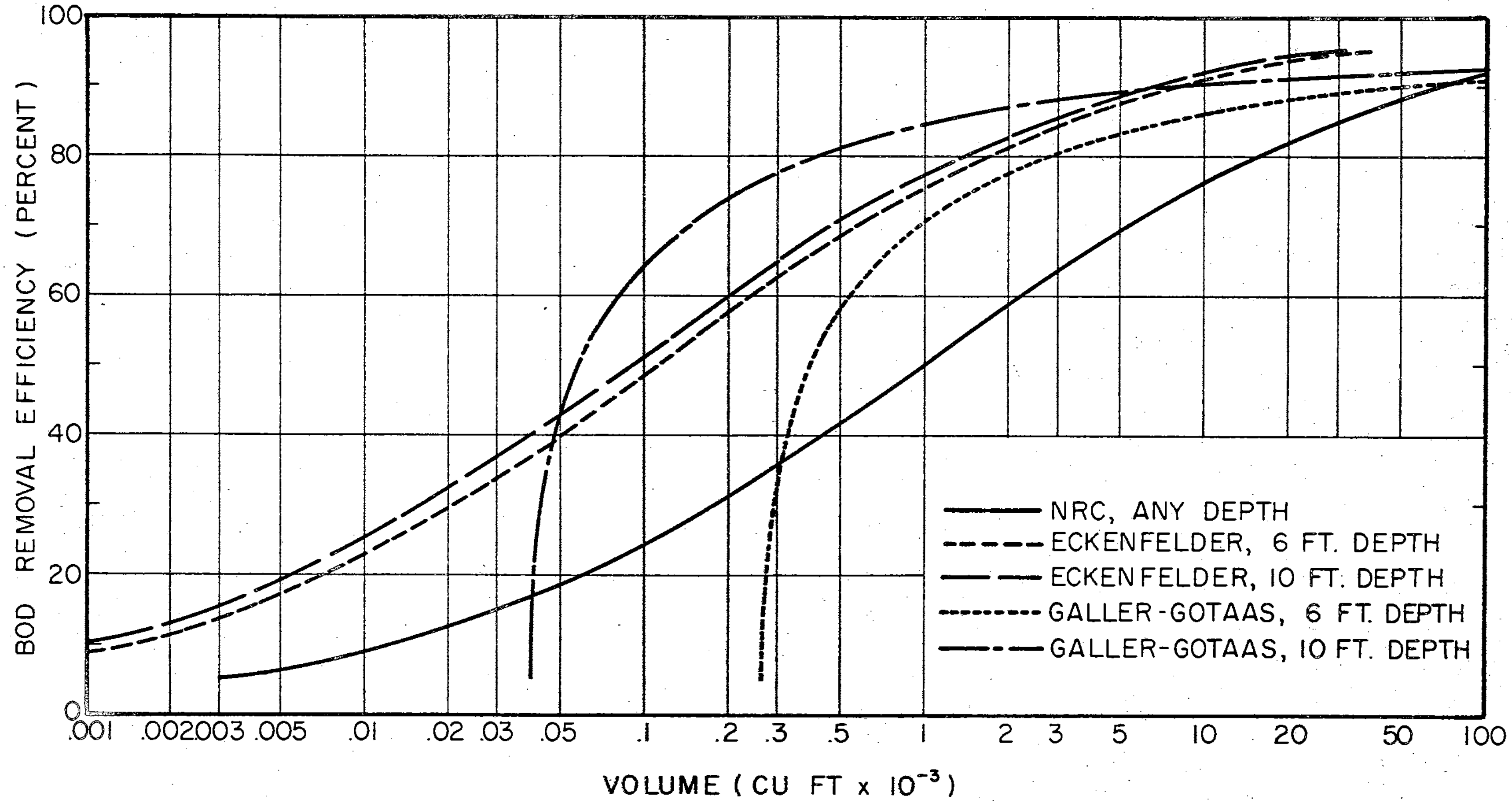

Figure 27 - Volume Comparison at L_i = 100 mg/l, Q = 1.0 mgd, R = 5.0, and T = 20°C.

efficiencies below 43 per cent and above 90 per cent. Between 43 per cent and 90 per cent, the Galler-Gotaas formula gives the least volume for 10 feet of depth.

Figure 28 shows the combined effects of a high BOD (300 mg/l) and a high recirculation ratio (5.0) with Q = 1.0 mgd. Here the Eckenfelder formula gives the least volume with the depth range studied. This is due to the fact that no real limit is reached with recirculation increases, and influent BOD increases do not increase the volume requirements according to the Eckenfelder formula.

It can be concluded from this comparison that the three design formulas under study are somewhat similar, but produce considerably different values of efficiency and volume. It appears that the amount of BOD removal by a trickling filter is a function of the time of contact between wastewater and the microorganisms. The volume of a trickling filter, which is a general parameter of its cost, is one of the parameters of contact time; however, it can be generally stated that the volume required can be determined from the required efficiency of BOD removal, which is dependent on the contact time. The contact time must be provided for BOD to be removed from the wastewater at some rate of removal with time, which is not necessarily constant. The problem of determining the factors which control the efficiency is the problem of determining the parameters of the rate of removal and the contact time. The factors included in the three formulas considered in this study are

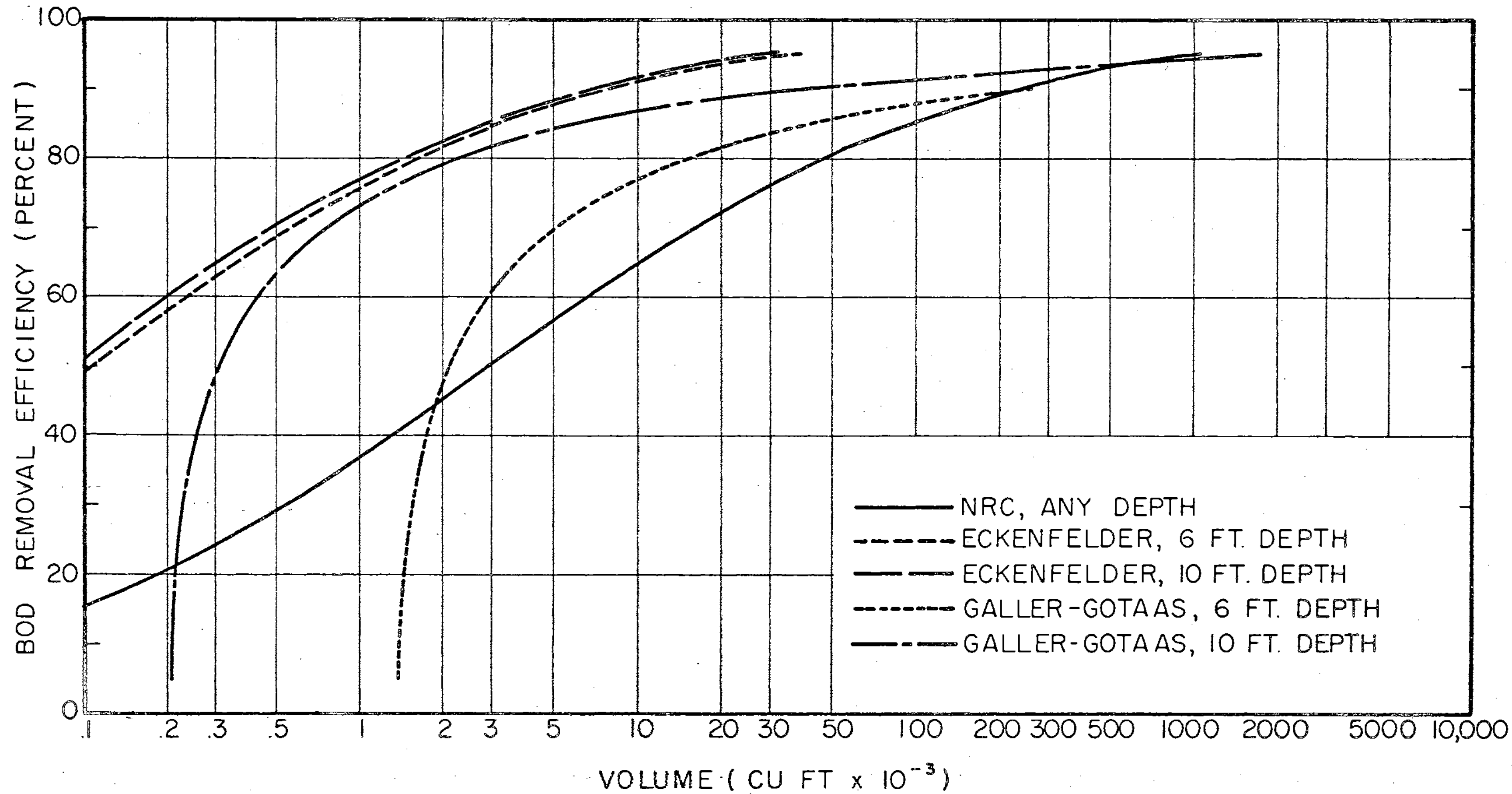

Figure 28 - Volume Comparison at L_i = 300 mg/l, Q = 1.0 mgd, R = 5.0, and T = 20°C.

rate of flow, Q, influent BOD, L_i, recirculation ratio, R, depth of filter, D, surface area of filter, A, and temperature of the wastewater, T. These factors are related in some way to the rate of BOD removal and contact time in a trickling filter; the formulas considered in this study are attempts to relate mathematically variables and filter efficiency.

There are many factors which complicate attempts to develop mathematical formulas for trickling filter efficiency. The difficulty of separating the variables has been previously discussed. Laboratory and pilot plant studies usually attempt to achieve controlled filtration conditions so that the separate effects of the variables will be shown. However, actual trickling filters are frequently subjected to large daily flow and BOD fluctuations, which are generally uncontrollable factors. Studies of existing trickling filter plants have been hindered by the difficulty in separating the effects of numerous differences in flow patterns and recirculation patterns (see Figure 2). None of the three formulas separate the effect of recirculation of unsettled filter effluent or settled effluent. Culp (35) reported from studies conducted at two single-stage trickling filter plants that recirculation taken directly around the filter without passing through either the final or primary settling tanks produced an effluent quality slightly better than or equal to that produced when recirculation was taken from the effluent of the final clarifier. Previously mentioned were the results of Moore, Smith, and Ruchhoft (28) who noted an increase in efficiency with recirculation taken from the underflow of the final clarifier through the primary clarifier.

Another complication is the fact that the effect of settling following trickling filtration has never been clearly evaluated. The National Research Council formula assumed that sedimentation following trickling filtration was a part of the trickling filter process, and the settled effluent BOD and BOD influent to the filter were used to determine the efficiency. Blain and McDonnell (34) pointed out that the data used by Galler and Gotaas included both settled and unsettled effluent BOD[1]. This appears to be the case also with the data used by Eckenfelder.

The type of media used in the filter undoubtedly has some effect on its performance. Only the Eckenfelder formula makes some provision for variations in media characteristics. Eckenfelder (4) states that the constant, C, and the exponent, n, of Equation (38) are related to the specific surface and configuration of the media. However, no factor for variation in media is included in the NRC or Galler-Gotaas formulas.

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[1]Data used by Eckenfelder (25): with unsettled effluent: References 12, 36, and 37; with settled effluent: references 14, 17, 21, and 37. Data used by Galler and Gotaas (27) with unsettled effluent: references 12, 13, and 37; with settled effluent, references 37, 38, and 39.

The effect of wastewater temperature is included as an efficiency parameter by Eckenfelder and Galler and Gotaas, but is not in the NRC formula. However, Howland's formula for the effect of temperature on efficiency (formula 50) could probably be applied to the NRC formula as well as to the Eckenfelder formula (see Figure 11). Due to the fact that the design engineer rarely has available information concerning wastewater temperature, this was not included in this comparison of design methods. This is another area where more study is greatly needed.

5. Optimum Volume Conditions of Single-Stage Filters

It has been shown that the volume requirement for trickling filters is a function of the flow rate, Q, influent BOD, L_i, filter depth, D, recirculation ratio, R, required efficiency, E, and temperature of the wastewater, T. When design of a plant is being considered, the rate of flow, Q, influent BOD, L_i, and temperature, T, are fixed factors.

The efficiency required is fixed by the influent BOD and effluent BOD requirement. The factors which may be varied according to design are depth, D, and recirculation ratio, R. In general, the filter construction cost will vary directly with the volume of filter media required.

The Eckenfelder and Galler-Gotaas formulas show that increased depth will decrease the required volume. However, increased depth will in most situations increase pumping head, which increases the cost of pumping, and may require forced air application. This problem of design has been investigated by Galler and Gotaas (29). Their optimization analysis showed that a shallow filter would be favored for higher efficiencies, while a deep filter would be favored for lower efficiencies. The breakpoint is due to the cost of increased pumping, and the requirement of compressed air in deeper filters when the size must be great enough to meet a high efficiency requirement.

Increased recirculation will decrease volume requirements, reaching a practical maximum ratio of four or five in all three formulas. However, increasing recirculation increases the pumping costs, which offsets the savings from the decrease in volume. There is probably a cost breakpoint on this, similar to the one where the increased pumping cost with a deep filter exceeds the savings of the cost of the volume saved by constructing a deep filter. Galler and Gotaas (29) state that their studies indicated that for recirculation ratios lower than four, the cost of increasing the filter size is greater than the cost of increasing recirculation, to obtain increased BOD removal.

Any cost minimization will depend on local conditions and will vary with each specific plant design problem. The design engineer must consider these factors in order to make the optimum design.

A computer program for the IBM 7040 is given in Appendix III, which will calculate the required volume by each of the three formulas for any given set of conditions of L_e, L_i, Q, D, R, and T. Using this program, the design engineer could calculate trial volumes for variations of R and D to determine the most economical solution.

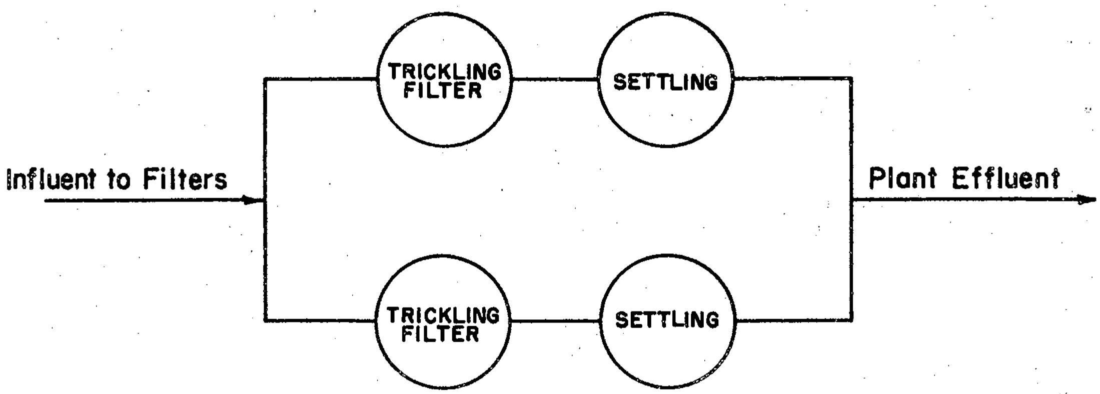
CHAPTER IV

EVALUATION OF TWO-STAGE TRICKLING FILTER DESIGN

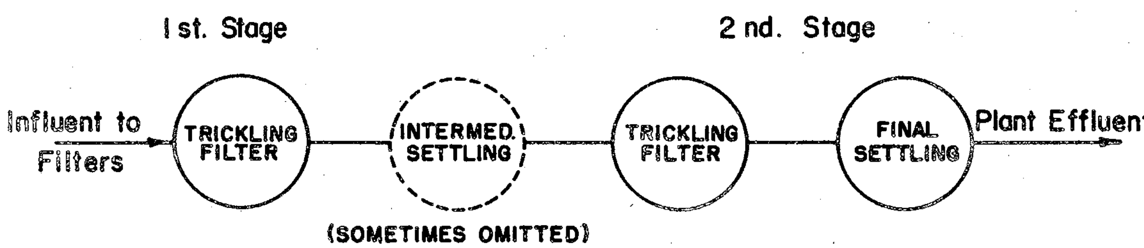
1. History and Advantages of Two-Stage Trickling Filter Design

As existing trickling filter plants become overloaded beyond their designed capacity, a decision must be made concerning plant expansion or replacement. In many cases expansion and modification of existing facilities appears to be the most feasible alternative. In the expansion of trickling filters, more volume must be provided. This is usually accomplished by constructing additional units of the circular type. There is a choice of flow patterns available to the designer: new filter units parallel to existing filters, or addition of second-stage filters. This is illustrated in Figure 29.

A parallel filter system is merely an expanded single-stage filter. Each filter receives a portion of the wastewater influent to the trickling filters. In two-stage filtration the wastewater passes first through the first-stage filters and the effluent from these units, either settled or unsettled, becomes the influent to the second-stage filters.



Single - Stage Parallel Filters



Two - Stage Filters

Figure 29 - Single-Stage Parallel Filters and Two-Stage Filters.

According to the National Research Council (14), the BOD in the effluent of first-stage filters which is applied as influent to second-stage filters is considerably less treatable than the influent to the first-stage filters. This "treatability" factor is dependent upon the amount of removal in first-stage filters. Due to this decrease in treatability, less BOD will be removed per unit of volume in the second stage than by a corresponding unit in the first stage. Consequently, the volume of a second-stage filter required to produce an equal efficiency as that of a first-stage unit will be larger than that of a first-stage unit. In order to take into consideration the added factor of decreased BOD treatability in the design of second-stage units, a modified formula for volume must be used.

The design engineer is primarily interested in making the optimum design, which is usually the design of least rock volume. Two-stage designs may be used for all-new facilities as well as expanded plants, and in many cases, the minimum total volume of rock is required with two-stage filters, as opposed to single-stage filters. Besides the saving in rock volume, two-stage plants frequently have more operating flexibility. For these reasons many two-stage trickling filter plants have been constructed in the United States.

2. <u>The National Research Council Method for Design of Two-Stage Trickling Filters</u>

As previously mentioned, the report of the National

Research Council (14) noted a decrease in treatability of BOD remaining in first-stage filter effluent which is dependent on the amount of BOD removed in the first stage. To account for this retardation of efficiency in second-stage filters, the NRC proposes that the organic loading, w, should be multiplied by the following factor:

$$f = \frac{1}{(1-E_1)^2} \tag{8}$$

Introduced into the NRC formula for efficiency,

$$E_2 = \frac{1}{1+.0561\left(\frac{w_2}{VF(1-E_1)^2}\right)^{0.5}} \tag{76}$$

or

$$E_2 = \frac{1}{1+\frac{.0561}{(1-E_1)}\left(\frac{w_2}{VF}\right)^{0.5}} \tag{77}$$

where

E_2 = fractional efficiency of BOD removal in the second-stage filter

w_2 = organic loading influent to the second-stage filter

Solved for volume, this formula is

$$V = \frac{w}{F}\cdot\left[\frac{.0561\ E_2}{(1-E_1)(1-E_2)}\right]^2 \tag{78}$$

The effect of the retardation factor is shown in Figure 30. Efficiency of BOD removal in the second stage is plotted versus required second-stage volume, at Q = 1.0

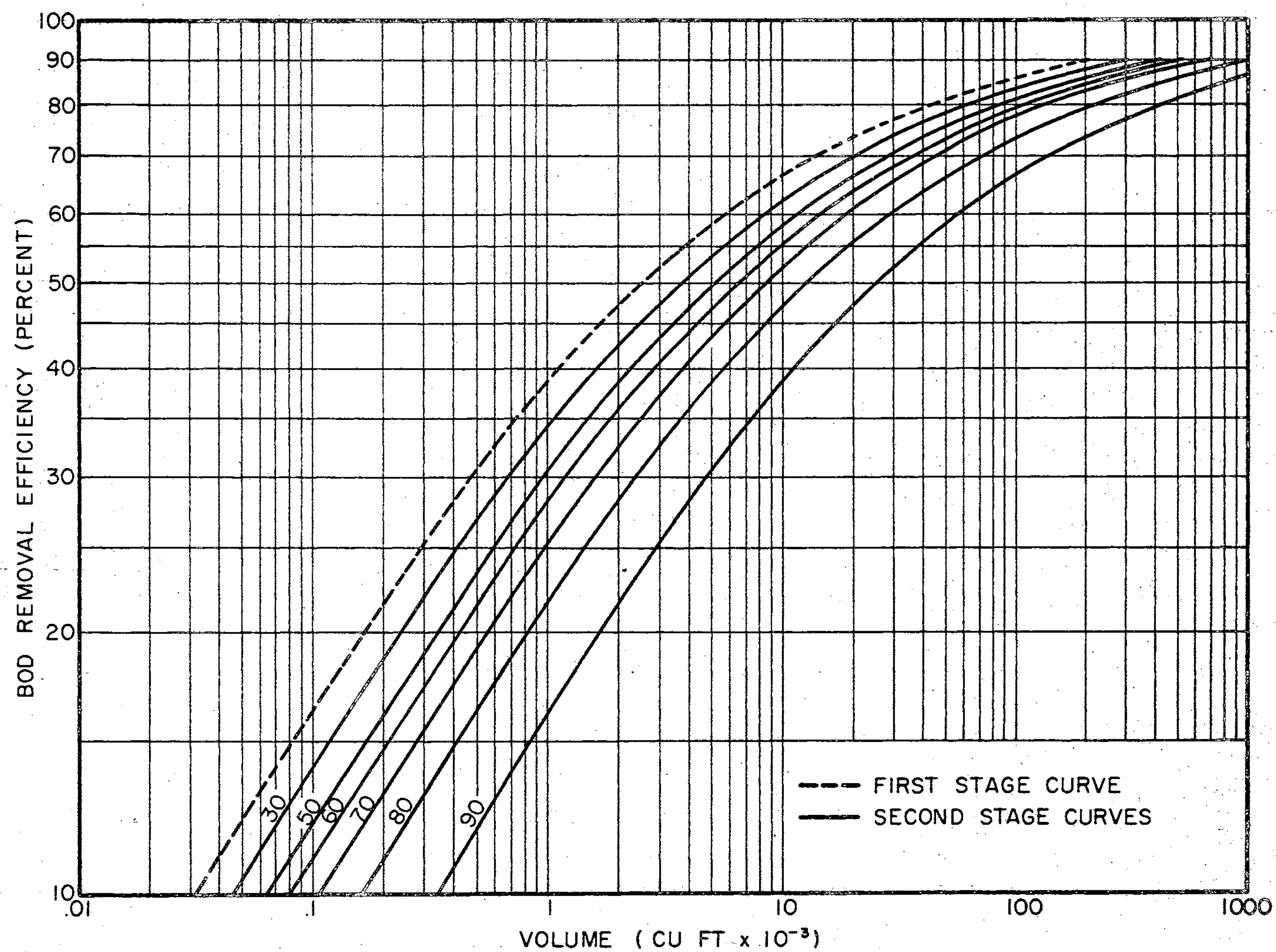


Figure 30 - Chart I for Two-Stage Trickling Filter Design by the NRC Formula. Constructed on the Base of L_i = 100 mg/l, Q = 1.0 mgd, and R = 0.0.

mgd, R = 0.0, and L_i = 100 mg/l. The uppermost curve shows the volume of a first-stage filter as abscissa required to meet the efficiency requirements plotted as ordinate. The series of curves below the first stage curve are curves for second-stage filters. The appropriate curve must be applied according to the efficiency of the first-stage filter. For example, a first-stage filter for Q = 1.0 mgd, R = 0.0, and L_i = 100 mg/l at 60 per cent efficiency would require a volume of 5,800 cu.ft. This would reduce the effluent BOD to only 40 mg/l, however, and a second-stage filter would be necessary to further reduce the BOD to an acceptable maximum, such as 16 mg/l. Since 40-16 = 24, and 24/40 = .60, the efficiency required of the second-stage filter would be 60 per cent. Referring to the E_1 = 60 per cent curve of Figure 30, the required volume for a second-stage filter is 14,000 cu.ft. The total volume required is 19,800 cu.ft., compared to a volume of 70,000 cu.ft. required for a single-stage filter with an equal overall efficiency.

This illustrates the increased volume requirement for the same efficiency in second-stage filters even though the BOD influent to the second stage is lower than the influent to the first stage. The required volume for the second stage is 2.4 times that of the first stage.

As in single-stage filters, recirculation will decrease the required volume up to a maximum recirculation ratio of 8.0. Since Figure 30 is for the case of no recirculation, the volume read from this chart must be divided by the recirculation factor, F, for various recirculation ratios. A plot of F versus recirculation ratio is given in Figure 31.

3. Proposed Design Method for Two-Stage Trickling Filters Using the Eckenfelder Formula

The Eckenfelder formula for trickling filter efficiency is

$$E = 1 - \frac{1}{1 + \frac{.379D^{.67}(1+R)}{(Q/A)^{0.5}}} \tag{38}$$

According to Eckenfelder, the primary parameter of efficiency is the hydraulic loading, Q/A. Although not specifically stated as such by Eckenfelder, this formula was presumably proposed as applicable to single-stage or first-stage filters. The National Research Council formula for single-stage or first-stage filters is

$$E = \frac{1}{1 + .0561\left(\frac{w}{VF}\right)^{0.5}} \tag{2}$$

This formula is modified for second-stage filters to take into account the decrease in treatability of biological waste which has previously been treated by the first-stage filter and is influent to the second-stage filter. The organic load, w, is multiplied by the factor

$$f = \frac{1}{(1-E_1)^2} \tag{8}$$

which retards the effect of the organic load to the second-stage filter. The decrease in treatability of the waste reaching the second stage is dependent upon the fraction of

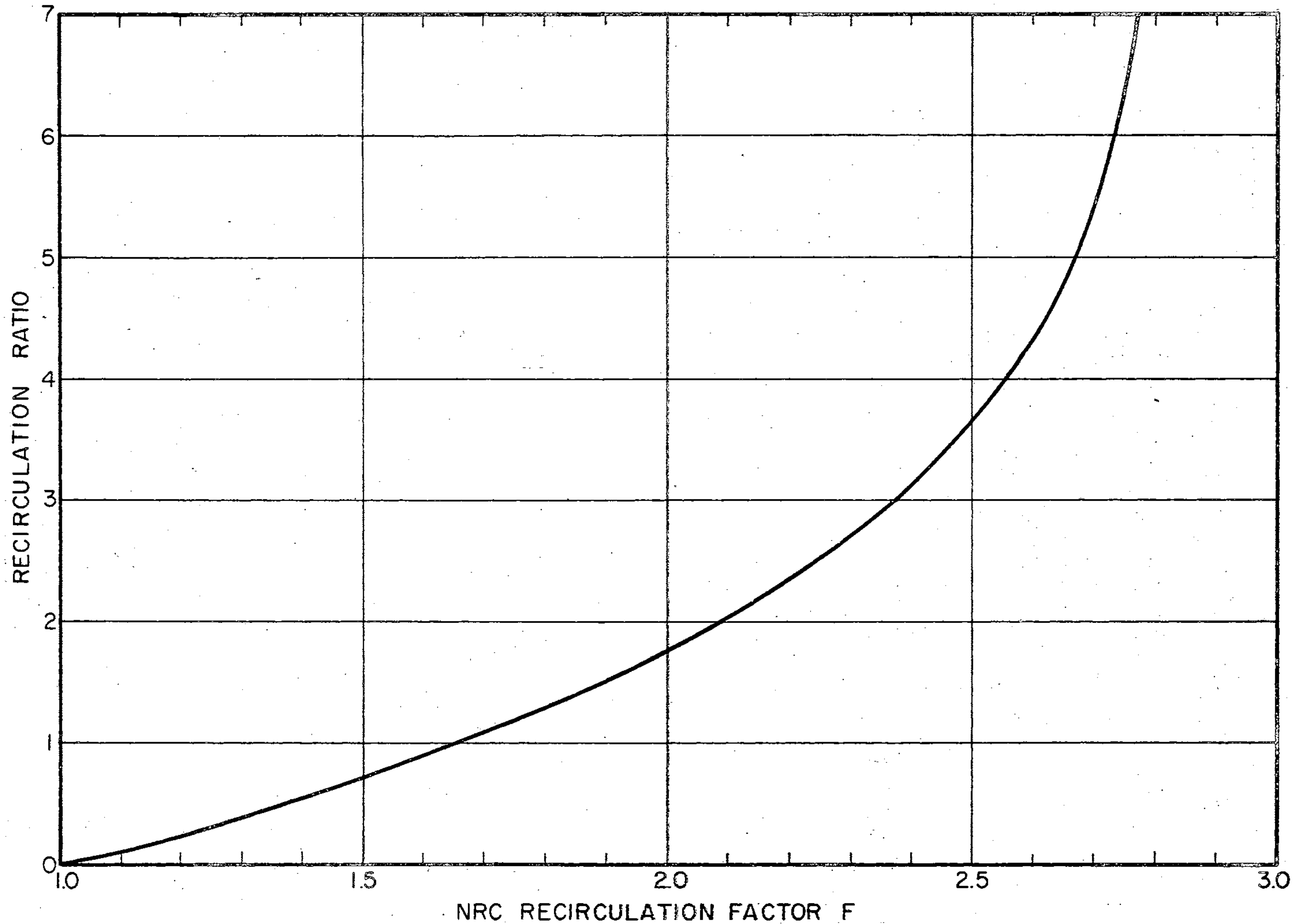


Figure 31 – Chart II for Two-Stage Trickling Filter Design by the NRC Formula. Divide Volume Determined from Chart I by Appropriate Recirculation Factor F for Filters with Recirculation. (Figure 31 by Quintin B. Graves)

BOD removed by the first stage, E_1. The effective organic load becomes

$$\frac{W}{(1-E_1)^2} \tag{79}$$

It seems logical this same factor might be applied to the hydraulic load, Q/A, in the Eckenfelder formula in a manner analogous to that just described in the NRC formula. This incorporates the effect of decreased treatability into the Eckenfelder formula, and creates a modified Eckenfelder formula applicable for predicting the efficiency of a second-stage filter:

$$E_2 = 1 - \frac{1}{1 + \frac{.379D^{.67}(1+R)}{\left(\frac{Q}{A} \cdot \frac{1}{(1-E_1)^2}\right)^{0.5}}} \tag{80}$$

or

$$E_2 = 1 - \frac{1}{1 + \frac{.379D^{.67}(1+R)(1-E_1)}{(Q/A)^{0.5}}} \tag{81}$$

The expression for contact time of the NRC formula including the decreased treatability factor is

$$t \propto \frac{1}{C}\left(\frac{V(1-E_1)^2(1+R)}{QL_i(1+0.1R)^2}\right)^{0.5} \tag{82}$$

By the method just explained, the factor $(1-E_1)^2$ appears in the same manner in the expression of contact time in the Eckenfelder formula,

$$t \propto \frac{CD^{.67}(1+R)(1-E_1)}{(Q/A)^{0.5}} \tag{83}$$

The effect of this factor is shown in Figure 32. As in Figure 30, which illustrates the NRC formula, Figure 32 shows that the effect of the decreased treatability factor is to make a larger volume required to produce the same efficiency with a second-stage filter. The volume requirement for second-stage filters increases as the efficiency of the first stage increases, due to the increased amount of less treatable waste which is influent to the second stage as the more easily treatable fractions are removed by the first-stage filter.

Figure 32 may also be used for design of two-stage filters by the proposed modification of the Eckenfelder formula. For example, a first-stage filter with a plant flow rate of $Q = 1.0$ mgd, $R = 0.0$, and $L_i = 100$ mg/l, at 60 per cent efficiency would require a volume of 8,500 cu. ft. with a filter of 6 feet of depth. To reduce the plant effluent to 16 mg/l, an efficiency of 60 per cent is also required for the second-stage filter. The required volume of the second-stage filter is given for 60 per cent efficiency on the 60 per cent first-stage efficiency curve as 52,000 cu.ft. This makes the total volume 60,500 cu.ft., which is over three times that given by the NRC formula for these conditions. However, according to the Eckenfelder formula, increased depth will reduce the volume requirement. This reduction may be made by a multiplication factor determined from Figure 13. In general, the second stage volume is considerably greater than the first-stage volume accord-

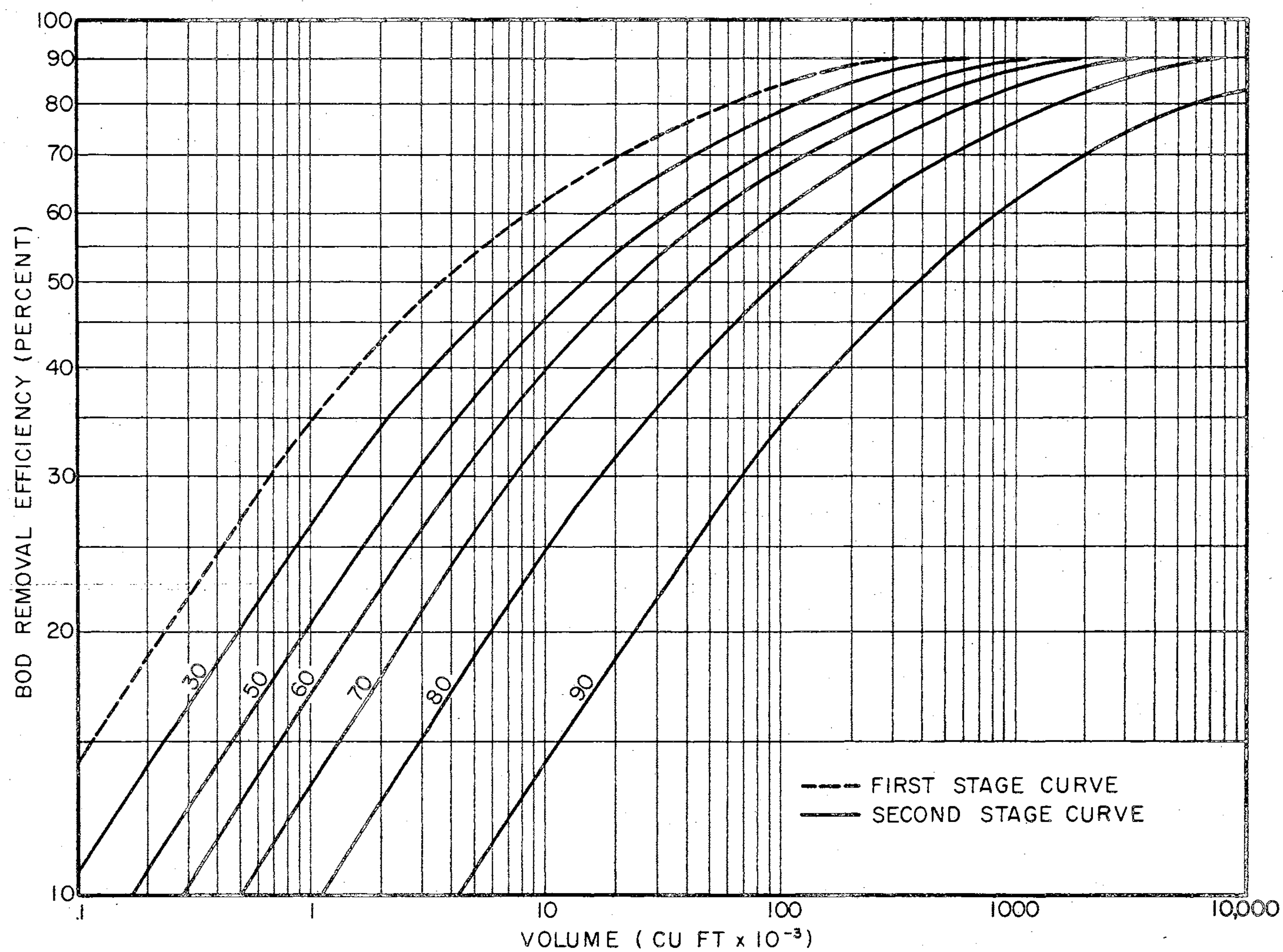


Figure 32 - Chart I for Two-Stage Trickling Filter Design by the Eckenfelder Formula. Constructed on the Base of Q = 1.0 mgd, R = 0.0, and D = 6.0 ft.

ing to the proposed modification of the Eckenfelder formula for second-stage filters. The optimum volume combination will be discussed in a succeeding subchapter.

Recirculation will decrease the required volume in both first and second-stage filters. The volume determined from Figure 32 must be multiplied by the appropriate factor shown in Figure 33 for the recirculation ratio to be maintained.

Variations in rate of flow, Q, are directly proportional to the required volume.

4. Proposed Design Method for Two-Stage Trickling Filters Using the Galler-Gotaas Formula

Examination of the references cited by Galler and Gotaas for the data utilized to make their regression analysis from which the Galler-Gotaas formula was developed, indicated that the data was taken from single-stage filters. An effort was then made to modify the Galler-Gotaas formula to make it applicable to two-stage trickling filters. The Galler-Gotaas formula for efficiency of single-stage or first-stage trickling filters is

$$E_1 = 1 - \left(\frac{1}{V}\,\frac{\pi D}{1000}\right)^{.125} \cdot \frac{CQ^{.13}L_i^{.19}(1+R(1-E))^{1.19}}{T^{.15}(1+D)^{.67}(1+R)^{.78}} \qquad (68)$$

The controlling parameter is the organic loading which is vested in the variables $Q^{.13}$. $L_i^{.19}$. Applying a factor of $1/(1-E_1)^2$ to the organic loading in this form is somewhat difficult. By analyses of calculations made by the IBM 7040 computer using different exponents on $(1-E_1)$, a factor

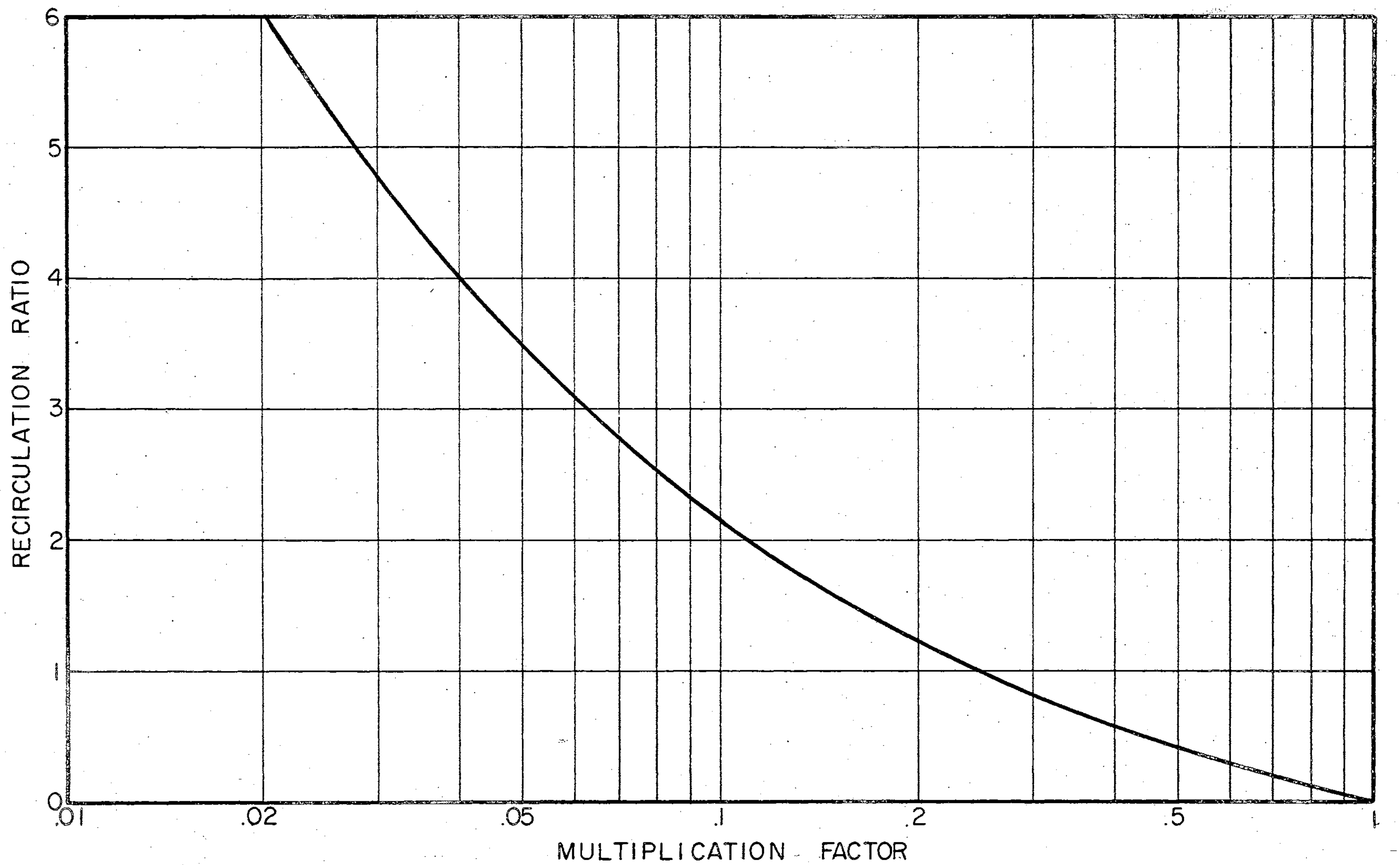


Figure 33 - Chart II for Two-Stage Trickling Filter Design by the Eckenfelder Formula. Multiply Volume Determined from Chart I by Appropriate Factor for Filters with Recirculation.

of $1/(1-E_1)^{0.5}$ appeared to produce a retardation similar to that observed with the NRC formula and the modification of the Eckenfelder formula. The modified Galler-Gotaas formula for second-stage filters then becomes

$$E = 1 - \left(\frac{1}{V}\,\frac{\pi D}{1000}\right)^{.125} \cdot \frac{CQ^{.13}L_i^{.19}(1+R(1-E_2))^{1.19}}{T^{.15}(1+D)^{.67}(1+R)^{.78}(1-E_1)^{.5}} \quad (84)$$

The effect of this modified formula is illustrated in Figure 34. As in the NRC formula and the modified Eckenfelder formula, a greater volume is required for a second-stage filter required to produce the same efficiency as a first-stage filter.

Figure 34 may be used for design of two-stage filters. For an influent BOD = 100 mg/l, Q = 1.0 mgd, and no recirculation, with an efficiency of 60 per cent, the volume required for 6 feet of depth is 1,100 cu.ft. To meet an effluent requirement of 16 mg/l, the efficiency of the second stage must also be 60 per cent. The required volume is determined from the 60 per cent first-stage efficiency curve at 60 per cent second-stage efficiency. The required second-stage volume is 11,000 cu.ft., which is ten times that of the first-stage filter. However, the total volume requirement is 12,100 cu.ft., which is 61 per cent of that required by the NRC formula and only about 20 per cent of that calculated by the Eckenfelder formula.

Recirculation will reduce the volume requirement calculated by Figure 34. Appropriate multiplication factors for recirculation ratios to be maintained may be

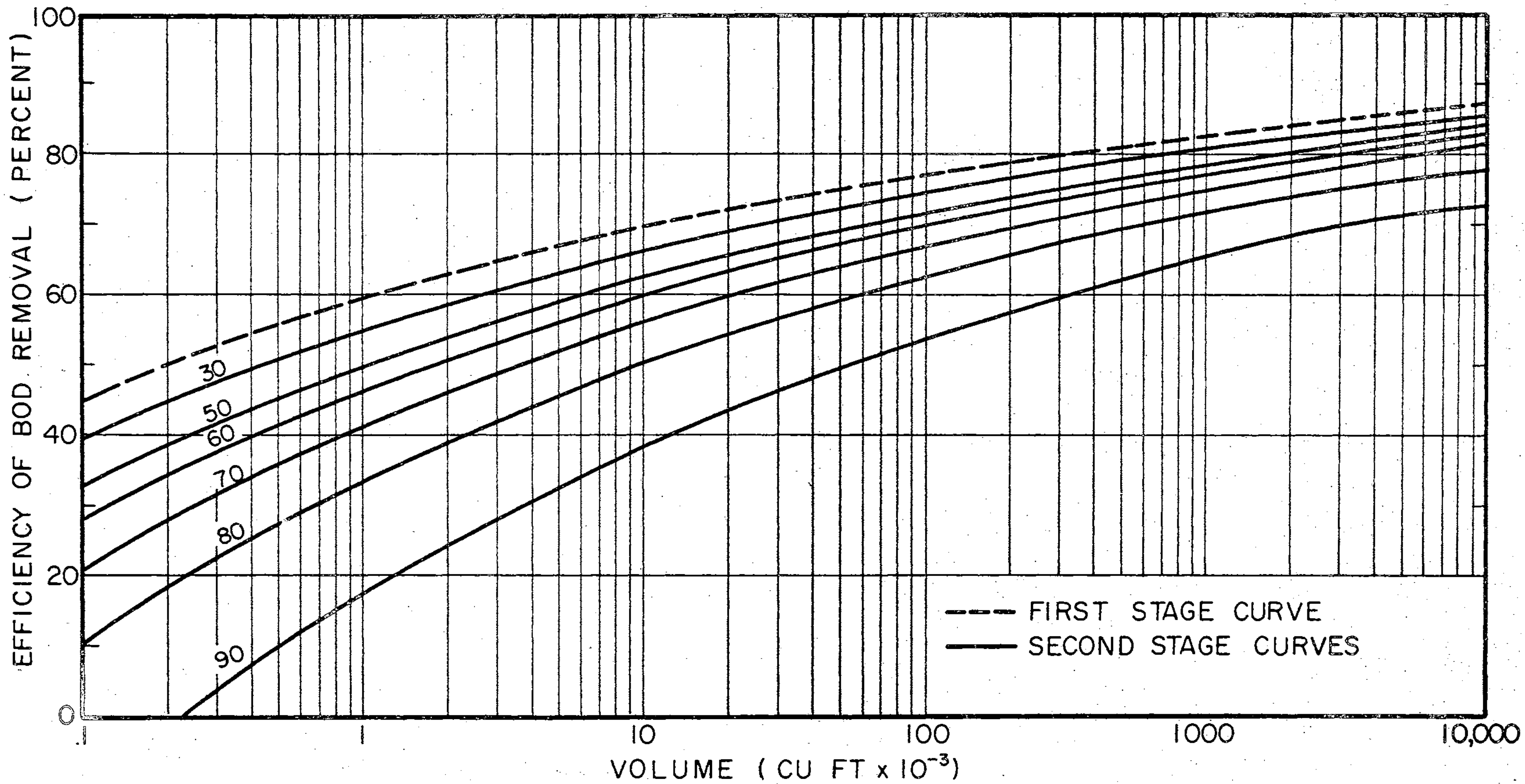


Figure 34 - Chart I for Two-Stage Trickling Filter Design by the Galler-Gotaas Formula. Constructed on the Base of L_i = 100 mg/l, Q = 1.0 mgd, R = 0.0, D = 6.0 ft., and T = 20°C.

determined from Figure 35. Factors for depth increases, influent BOD, and rate of flow differences may be determined from Figures 20, 21, and 22, respectively.

5. Optimum Design of Two-Stage Trickling Filters

The NRC formula and the modified Eckenfelder and Galler-Gotaas formulas for two-stage trickling filters have been presented. Charts for calculating the volume by each of the three design formulas have been presented also. A computer program for the IBM 7040 for calculating the volume by the three formulas for two-stage filters is presented in Appendix III.

The design engineer is primarily interested in the most economical, or optimum, design. The factors affecting the optimum solution for single-stage filters which have been presented previously are also applicable to two-stage filters. However, in most cases, all of the formulas will give a lesser total volume with a two-stage design than with a single-stage design to meet the same requirements and with the same depth and recirculation ratio.

The problem posed to the designing engineer is the means of making an optimum design solution. The design methods for two-stage filters presented in preceding subchapters may be used to make an adequate two-stage design, but the design of minimum volume must be determined by a laborious trial-and-error process. However, a digital computer can be programmed to make this determination. In this study, programs were developed for the IBM 7040 to

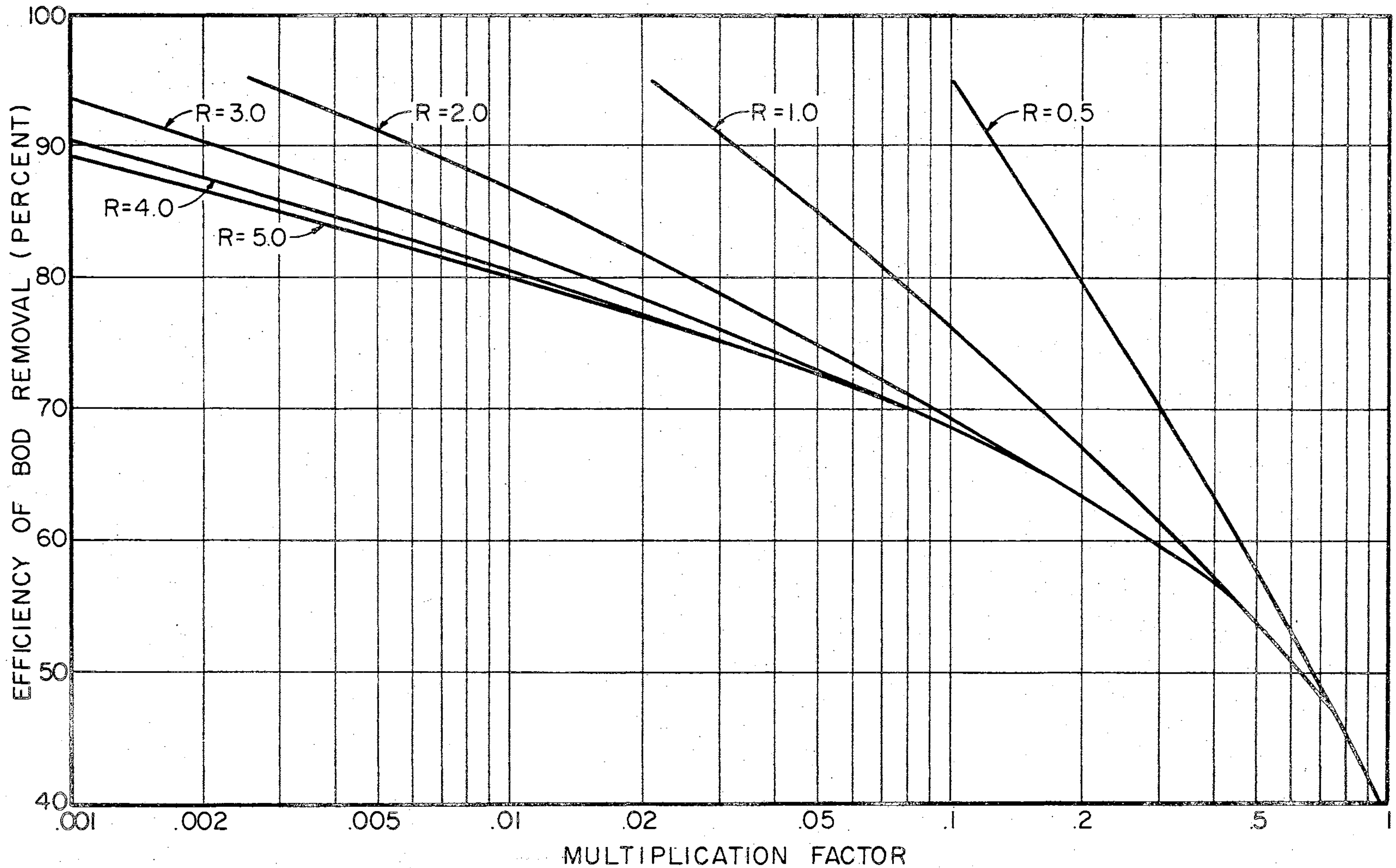


Figure 35 - Chart II for Two-Stage Trickling Filter Design by Galler-Gotaas Formula. Multiply Volume from Chart I by Appropriate Factor for Filters with Recirculation.

determine the minimum volume combination of two-stage filters by the NRC, Eckenfelder, and Galler-Gotaas formulas. These programs are given in Appendix III[1]. The programs require as input information the plant influent BOD and effluent BOD, the flow rate, the efficiency of BOD removal of the primary settling unit, the recirculation ratios, and the depths of the first-stage and second-stage filters. The program calculates the first-stage filter volume required for an initial first-stage efficiency, calculates the required second-stage filter efficiency to meet the effluent BOD requirement, then adds an increment to the first-stage efficiency, and repeats the process. As the iterative procedure continues, the total volume decreases because the first-stage efficiency is increasing, and less volume is required to obtain a certain efficiency with a first-stage filter than to obtain an equal efficiency with a second-stage filter. With further increases in efficiency of the first-stage, however, a point is reached where the removal by the first stage is so great that the removal by the second stage decreases in significance, and the total volume increases with further incremental increases in first-stage efficiency. This point is the breakpoint where the minimum total volume occurs. For each set of input conditions, the computer proceeds with the iterative calcu-

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[1]The programs for optimum volume are based on work originated by Quintin B. Graves.

lations of first-stage and second-stage volume for increases in first-stage efficiency until the minimum total volume is reached. At this point the computer prints the volume of first and second stages, the total volume, and the corresponding efficiencies.

The minimum volume for various sets of conditions was calculated by the computer in the studies reported herein. General trends were apparent in the relative proportions of first-stage volume and second-stage volume at the point of minimum total volume. Figure 36 illustrates these proportions. The curves for this figure were generated for each of the three formulas by modifying the computer program for minimum volume so that the volumes calculated for each value of first-stage efficiency in the iterative procedure of addition of an increment to the first-stage efficiency were printed out by the computer. The ratio of first-stage volume to second-stage volume was then computed for each set of answers, and the volume ratio was plotted against the total volume in Figure 36. The conditions at which these volumes were calculated are Q = 1.0 mgd, plant influent BOD = 200 mg/l, plant effluent BOD = 15 mg/l, efficiency of primary settling = 0.30, recirculation ratio of both filters = 1.0, and depth of both filters = 6.0 feet. The minimum volume occurs at the vertex of the parabolic curves generated. For the NRC formula, a ratio of first-stage volume to second-stage volume at the point of minimum total volume is 0.852; for the Eckenfelder formula, the

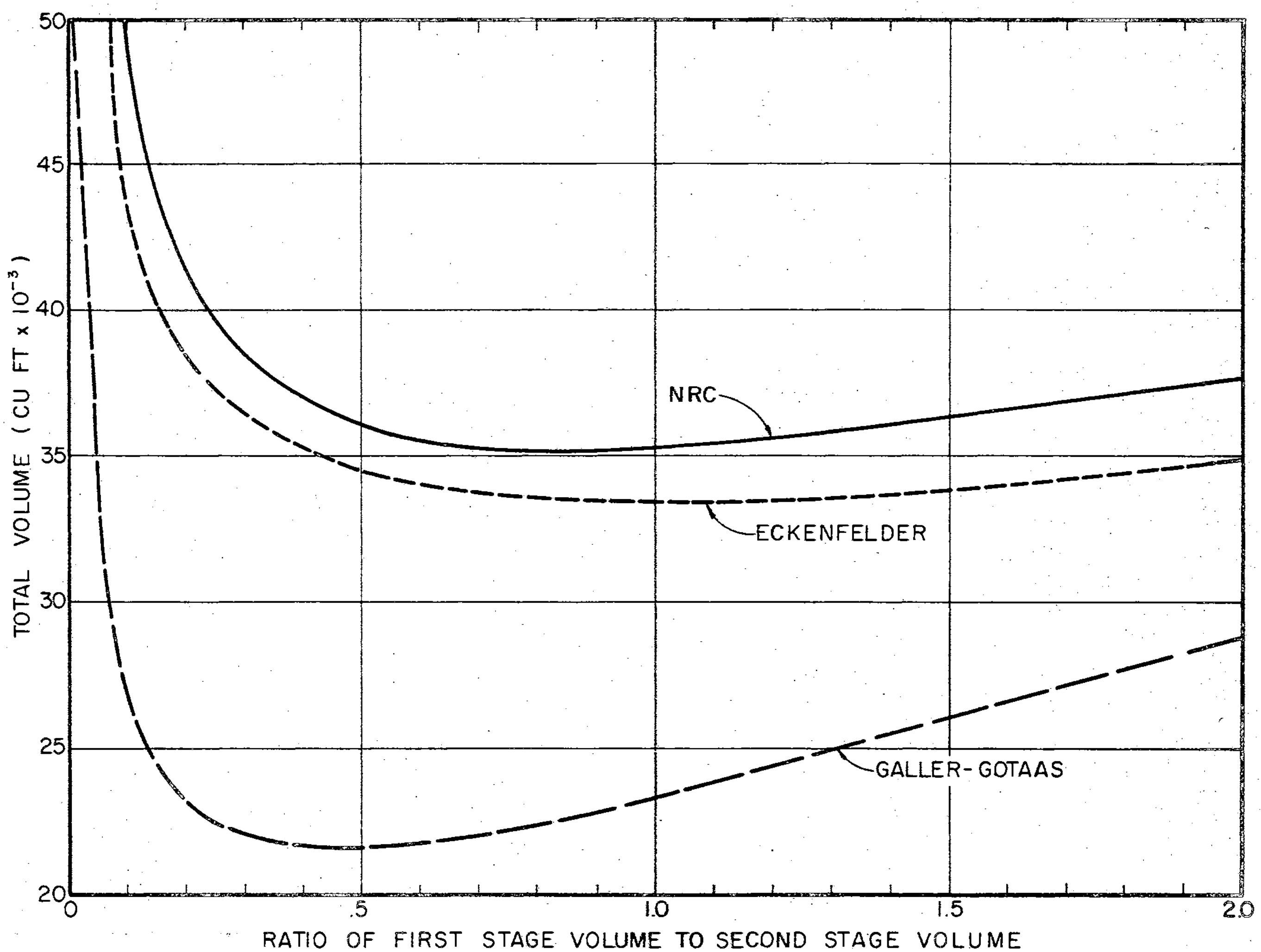

Figure 36 - Optimum Volume of Two-Stage Filters with NRC, Eckenfelder, and Galler-Gotaas Formulas. Plant Influent BOD = 200 mg/l, L_e = 15 mg/l, Q = 1.0 mgd. Primary Settling Efficiency = 0.30, R = 1.0 (Both Filters) and D = 6.0 ft (Both Filters).

ratio is 1.1; for the Galler-Gotaas formula, the ratio is 0.477. The minimum total volumes calculated are NRC, 35,273 cu.ft.; Eckenfelder, 38,312 cu.ft.; and Galler-Gotaas, 21,611 cu.ft. In comparison, the volumes required for a single-stage filter to meet the same influent and effluent requirements and at the same depth and recirculation ratio are NRC, 154,377 cu.ft.; Eckenfelder, 66,992 cu. ft.; and Galler-Gotaas, 2,448,494 cu.ft. (See Table I). Calculations of the minimum volume combination at conditions of efficiency other than those illustrated in Figure 36 indicate that the ratio of first-stage to second-stage volume does not vary more than plus or minus 10-15 per cent of the volume ratios for the conditions of Figure 36. In general, it appears that the design engineer could closely approximate the minimum volume combination by designing equal first-stage and second-stage volumes with the NRC and Eckenfelder formulas and at a ratio of 1:2 with the Galler-Gotaas formula.

The results of the optimization analysis using the NRC formula made in this study are in concurrence with the results of the National Research Council (14).

Archer and Robinson (31) made a study of the optimum volume combinations of two-stage filters using the NRC formula. Their results indicated that a maximum total efficiency of about 92.5 per cent would be reached at a first-stage volume of 3,050 cu.ft., and a second-stage volume of 3,920 cu.ft. The total volume is then 6,970 cu.

TABLE I

OPTIMUM TWO-STAGE TRICKLING FILTER VOLUME

Conditions

Flow Rate	1.0 mgd
Plant Influent BOD	200 mg/l
Plant Effluent BOD	15 mg/l
Efficiency of Primary Settling	0.30
Recirculation Ratio (Both Filters)	1.0
Depth (Both Filters)	6.0 ft.

NRC Formula	Volume cu.ft.	Efficiency	Organic Loading lbs/1000 cu.ft./day	Hydraulic Loading gal/day/sq.ft.
First Stage	16,250	.73	71.8	369
Second Stage	19,023	.60	16.5	316
Total	35,273	.89	33.1	-

$\frac{\text{First-Stage Volume}}{\text{Second-Stage Volume}} = .852$

Eckenfelder Formula				
First Stage	20,043	.81	58.0	298
Second Stage	18,269	.44	12.2	329
Total	38,312	.89	30.5	-

$\frac{\text{First-Stage Volume}}{\text{Second-Stage Volume}} = 1.1$

Galler-Gotaas Formula				
First Stage	6,975	.74	167.4	860
Second Stage	14,636	.59	20.7	410
Total	21,611	.89	54.0	-

$\frac{\text{First-Stage Volume}}{\text{Second Stage Volume}} = .477$

ft. The writers state that this calculation was made for a flow of 100 gpm and an influent BOD of 100 mg/l.

A check was made of this calculation, using the optimization of volume program for the NRC formula developed in this study. It was assumed that the primary settling unit removed 35 per cent of the influent BOD of 100 mg/l, and that there was no recirculation, and that the effluent BOD was 5 mg/l, giving an efficiency of trickling filtration of 92.3 per cent. The volumes calculated by the computer are first-stage, 3,088 cu.ft., second stage, 3,863 cu.ft., and total volume, 6,951 cu.ft. These answers are very close to those of Archer and Robinson.

It can be concluded that two-stage trickling filtration plants can be designed and constructed with a great saving in filter volume in most cases over that which would be required for a single-stage filter to achieve the same efficiency with the same depth and recirculation ratio. In some cases, particularly for smaller treatment plants, single-stage plants may be more economical, due to the relatively smaller volume requirement with either a single-stage or two-stage design. In some locations the topography may limit the available gravity head and cause excessively costly pumping to be required with a two-stage plant. A chief disadvantage of the trickling filter is that the hydraulic head loss through the filter is high compared to some alternate treatment processes. However, in general, it has been shown that a two-stage design is much more economical for most trickling filter plants other than the very smallest ones.

Regardless of the optimum volume solution which may be designed for the requirements and conditions at hand, the design engineer frequently must design within "state standards," which are usually expressed in terms of maximum and minimum hydraulic and organic loading rates which are frequently "rules of thumb" based on experience with existing plants that are known to give good performance. For example, the Oklahoma State Department of Health Standards (8) define high rate filters as those having a hydraulic loading from 230 to 690 gal/day/sq.ft. and an organic loading of 30 to 110 lbs/day/1000 cu.ft. A casual examination of the loading rates for the optimum volume solutions given in Table I shows that some of the loadings of these solutions do not come within these ranges. This is another problem which must be considered by the design engineer.

6. Comparison of Proposed Two-Stage Design Methods with an Existing Trickling Filter Plant

In this study the National Research Council formulas for the design of two-stage trickling filters have been presented, and a factor to include the decrease in treatability of wastewater reaching the second-stage filter has been applied to the Eckenfelder and Galler-Gotaas formulas in a manner analogous to the NRC formula. In order to make a test on the validity of these modifications of the Eckenfelder and Galler-Gotaas formulas, plant performance data was obtained from an existing two-stage trickling filter treatment plant[1].

The Southside Water Pollution Control Plant at Oklahoma City, Oklahoma, was placed in operation in 1950. The plant is a large trickling filter plant and includes intermediate sedimentation between the two stages of filters. The plant was designed for an average flow of 25 mgd and plant influent BOD of 375 mg/l, which is relatively high, due to waste contributed from meat-packing industries. The first-stage filters were designed as "high rate" filters, with a volume of 519,155 cu.ft., receiving an organic loading of about 100 lbs/day/1000 cu.ft., and a hydraulic loading of about 288 gal/day/sq.ft. The second-stage filters were designed as "standard rate" with a volume of 1,303,577 cu.ft., receiving an organic loading of 9.5 lbs/day/1000 cu.ft. and a hydraulic loading of 115 gal/day/sq.ft. The NRC formula predicts the performance of the trickling filters at the design loading to be about 70 per cent in the first stage and about 68 per cent in the second stage, which together with primary sedimentation would produce a plant effluent BOD of about 23 mg/l. These efficiencies would be achieved with a recirculation ratio of 1.0 maintained around the first-stage filters and primary clarifiers, and also around the second-stage filters.

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[1]Data obtained through the courtesy of Mr. Frank S. Taylor, Director, Water and Sewer Department, Oklahoma City.

After sixteen years of operation, data for the operating period July 1965-June 1966 indicates that the average plant influent BOD is 302 mg/l and the average removal by primary settling is 42.3 per cent, which gives an average BOD influent to the trickling filters of 174 mg/l. The actual BOD reduction in the first stage is about 41 per cent, and about 73 per cent in the second stage, producing an average effluent BOD of 28 mg/l. Average recirculation ratios maintained are 0.48 in the first stage, and 0.29 in the second stage. The average plant flow rate is close to the design flow rate, 25 mgd. It appears that the overall treatment efficiency of the plant is somewhat less than that predicted, although the organic loading to the plant is less than that predicted for design purposes. The BOD removal efficiency of trickling filtration is 84 per cent compared with a predicted value of 90 per cent at the design loading, even though the plant is receiving only about 80 per cent of the influent BOD concentration for which the plant was designed.

The volume required according to the efficiencies achieved, influent BOD, flow rate, and recirculation ratio at which the plant was operating according to the 1965-1966 data was computed by the NRC, Eckenfelder, and Galler-Gotaas formulas. The results are given in Table II. The computed volumes for the first stage are much lower than the actual volume with all formulas. The second-stage volumes computed by the NRC and Eckenfelder formulas are within 12 per cent

TABLE II

COMPUTED VOLUME REQUIREMENT FOR THE OKLAHOMA CITY SOUTHSIDE WATER POLLUTION CONTROL PLANT

1965-66 Data

Plant Influent BOD	302 mg/l	Influent BOD to Filters	174 mg/l
Plant Flow Rate	25.6 mgd	Plant Effluent BOD	28 mg/l

	First Stage	Second Stage	Total
Actual Volume (cu.ft.)	519,155	1,303,577	1,822,732
Depth (feet)	6.0	6.0	-
Recirculation Ratio	0.48	0.29	-
Efficiency (percent)	40.8	72.8	83.8
Organic Loading lbs/day/1000 cu.ft.	71.5	16.8	20.3
Hydraulic Loading gal/day/sq.ft.	289	115	-
Computed Volumes			
Volume Requirement According to NRC	40,843	1,155,292	1,196,135
% of Actual Volume	7.8	88.8	65.5
Organic Loading	910.2	19.1	31.1
Hydraulic Loading	3,763	133	-
Volume Requirement According to Eckenfelder	20,473	1,172,979	1,193,452
% of Actual Volume	2.5	90.0	65.5
Organic Loading	1,815.8	18.8	31.2
Hydraulic Loading	7,508	131	-
Volume Requirement According to Galler-Gotaas	3,085	2,488,971	2,492,056
% of Actual Volume	0.5	191.0	136.5
Organic Loading	12,051.0	8.8	14.9
Hydraulic Loading	49,826	62	-

of the actual volume. The second-stage volume calculated by the Galler-Gotaas formula is nearly twice that of the actual volume, however.

It appears on the basis of these calculations that either the first-stage filters are greatly over-sized or the formulas are not accurate in this situation. With the values calculated, however, the normally acceptable ranges of organic and hydraulic loading are greatly exceeded. The ratio of the actual first-stage volume to second-stage volume at the Southside Plant is 1:2.5. It may be that all of the formulas for two-stage filters are inadequate for a plant having filters with this proportion.

The volume of the first stage computed by the Eckenfelder formula is lower than the NRC formula, because the Eckenfelder formula will not give an increase in volume with a relatively higher influent BOD such as 174 mg/l. It can be seen that the ratio of the first-stage volume to the second-stage volume calculated by the Galler-Gotaas formula is very small, which indicates that the modified Galler-Gotaas formula for two-stage filters is probably not applicable to this case.

The optimum trickling filter volume was computed for the conditions of 1965-66 by each of the three formulas, using the computer programs for the IBM 7040, and is tabulated in Table III. The total volume calculated by the NRC formula was 689,900 cu.ft., and by the Eckenfelder formula, 707,900 cu.ft. Both of these volumes are about

TABLE III

OPTIMUM TWO-STAGE VOLUME FOR THE OKLAHOMA CITY SOUTHSIDE WATER POLLUTION CONTROL PLANT
1965-66 Data

	First Stage	Second Stage	Total
Actual Volume (cu.ft.)	519,155	1,303,577	1,822,732
Depth (feet)	6.0	6.0	-
Organic Loading (lbs/day/1000 cu.ft.)	71.5	16.8	20.3
Hydraulic Loading (gal/day/sq.ft.)	289	115	-
Efficiency (percent)	40.8	72.8	83.8
	Calculated Optimum Volume		
Optimum Volume, NRC	329,100	360,100	689,900
Organic Loading	113.0	35.1	54.0
Hydraulic Loading	467	416	-
Efficiency	66.0	53.0	84.0
Volume Required for a Single-Stage Filter			2,412,470
Optimum Volume, Eckenfelder	405,900	302,000	707,900
Organic Loading	91.7	30.7	52.5
Hydraulic Loading	379	508	-
Efficiency	75.0	36.1	84.0
Volume Required for a Single-Stage Filter			1,245,727
Optimum Volume, Galler-Gotaas	124,800	183,900	308,600
Organic Loading	243.8	74.4	121.2
Hydraulic Loading	1,000	955	-
Efficiency	67.0	51.6	84.0
Volume Required for a Single-Stage Filter			20,517,655

Optimum volumes computed for 1965-66 data. The depth of all filters is 6 feet.
The recirculation ratio in the first and second stages is 1.0 for the optimum volume calculations.

40 per cent of the actual volume of the plant. Neither the volumes calculated by the NRC formula nor the Eckenfelder formula have hydraulic or organic loadings outside the guidelines of the Oklahoma Standards (8). The ratio of first-stage volume to second-stage volume is 0.9 for the NRC formula and 1.3 for the Eckenfelder formula. Ratios in these ranges have been shown previously to be the conditions for optimum volume in these formulas. The Galler-Gotaas formula computed a volume of 308,600 cu.ft., which is only 17 per cent of the critical volume. The loadings applied to the first stage-filter computed by this formula are considerably above the guidelines of the Oklahoma Standards.

While far from optimum, the actual volume of the Southside Plant is still less than that required for a single-stage filter by the NRC and Galler-Gotaas formula. However, a single-stage filter designed by the Eckenfelder formula would have only 68 per cent of the actual volume. This is probably due to the fact that the Eckenfelder formula does not provide for increases in volume with increased influent BOD, and the filter influent BOD of 174 mg/l of the Southside Plant is relatively high.

The optimum volume was computed for the case under study with filter depths of 6 feet and equal recirculation ratios of 1.0. Greater recirculation would cover the total volume requirement, as would greater depth. However, the desirability of altering these variables would depend on limits of loading rates to be met, economics of increased pumping, topography, and other factors.

It appears from these studies that the trickling filter volume at the Southside Plant is probably in excess of what is needed. However, it must be remembered that the plant was designed for a higher concentration of influent BOD than the plant received in 1965-66. The design engineer frequently designs "conservatively" to include a "factor of safety" in the design to ensure that the plant will function properly to meet the required effluent quality under unforeseen conditions and to reduce the risk due to the many factors which cannot be accurately evaluated.

CHAPTER V

SUMMARY AND CONCLUSIONS

1. Summary of Design Formula Evaluation

This study has investigated three formulas for the design of trickling filters: the National Research Council formula, the Eckenfelder formula, and the Galler-Gotaas formula.

The NRC formula is

$$E = \frac{1}{1+.0561\left[\frac{L_i xQx8.34}{VF}\right]^{0.5}} \quad (2)$$

This formula includes as parameters of trickling filter efficiency influent BOD, L_i, flow rate, Q, volume, V, and recirculation as factor F.

The Eckenfelder formula is

$$E = 1 - \frac{1}{1+.379\,\frac{D^{.67}A^{0.5}(1+R)}{Q^{0.5}}} \quad (38)$$

The parameters of trickling filter efficiency are: flow rate, Q; recirculation, R; and volume, V. However, volume is divided into area, A, and depth, D, with different effects attributed to each. The influent BOD, L_i, is not a parameter as in the NRC formula. The constant of the formula (.379) may be modified for variations in filter media characteristics.

The dimension of the NRC and Eckenfelder formulas is time. It has been shown that both formulas have the same dimensional form: $E = \frac{t}{1+t}$ (59)

The Galler-Gotaas formula for trickling filter efficiency is

$$E = 1 - \left(\frac{1}{V} \cdot \frac{\pi D}{1000}\right)^{.125} \cdot \frac{CQ^{.13} L_i^{.19} (1+R(1-E))^{1.19}}{T^{.15} (1+D)^{.67} (1+R)^{.78}} \qquad (68)$$

The dimensional form of this equation is

$$E = 1 - \frac{1}{t} \qquad (70)$$

According to this equation, efficiency is a parameter of volume (separated into depth and area effects), influent BOD, L_i, flow rate, Q, recirculation ratio, R, and temperature of the wastewater, T. Besides the difference in form, the effect of recirculation in the Galler-Gotaas formula is considerably different than in the NRC and Eckenfelder formulas. Temperature is directly included only in the Galler-Gotaas formula, although Howland's formula for the effect of temperature on efficiency (formula 50) may be applied to the Eckenfelder formula and to the NRC formula.

The volume required for a trickling filter is dependent upon the efficiency which must be achieved in a trickling filter according to all three formulas. The design engineer is usually interested in the required volume for a plant which must be designed for a certain influent BOD, flow rate, and BOD removal efficiency. According to all three formulas, required volume will increase almost directly with increases in flow, and will increase with increases in influent BOD with the NRC and Galler-Gotaas formulas, but not with the Eckenfelder formula.

The Eckenfelder and Galler-Gotaas formulas indicate that a greater advantage may be gained by increased depth rather than increased area; according to this formula, a deep filter will require less total volume than a shallow filter to produce the same efficiency. However, the NRC formula does not indicate any difference between increases in area and depth to increase volume to produce a greater efficiency.

Increases in recirculation will decrease volume requirements according to the NRC formula and the Eckenfelder formula, reaching a practical limiting recirculation ratio of 4 or 5. The same effect is shown with the Galler-Gotaas formula, except in ranges of efficiency below a certain level which must be determined for each set of conditions.

The effect of temperature, according to both the Galler-Gotaas formula and the Howland formula, is to require a greater volume to produce the same efficiency with wastewater of cooler temperatures than with warmer temperatures.

2. Summary of Two-Stage Filtration Evaluation

The wastewater which reaches a second-stage filter is less treatable than the wastewater influent to a first-stage filter. Therefore, a factor must be introduced into formulas for single-stage filters to account for this retardation, so that the formulas may be applied to second-stage filters. The decrease in treatability is dependent upon the fraction of the applied BOD removed in the first stage. The National Research Council incorporates a factor to take this into consideration in predicting second-stage filter efficiency and required volume. In this study it has been proposed that this factor or a similar factor may be applied to the Eckenfelder and Galler-Gotaas formulas in order that they may be applied to second-stage filters. Proposed modified Eckenfelder and Galler-Gotaas formulas for second-stage filters have been presented. The effect of the modification according to the NRC formula and the proposed Eckenfelder and Galler-Gotaas modified formulas is to make a larger volume required for a second-stage filter to produce the same efficiency as a single-stage or first-stage filter operating under the same conditions.

3. Optimum Design of Trickling Filters

The optimum design of a trickling filter is usually the design of minimum volume, since construction costs usually increase with volume. It has been shown that decreases in volume can be achieved by increasing depth and recirculation in some cases. However, the cost savings from this decrease in volume may be offset by increases in pumping cost.

Computer programs have been developed to compute the minimum two-stage volume combination with the NRC formula and with proposed modifications of the Eckenfelder and Galler-Gotaas formulas for a given set of conditions. Approximate ratios of first-stage volume to second-stage volume at which the minimum total volume occurs are 0.8 for the NRC formula, 1.1 for the Eckenfelder formula, and 0.5 for the Galler-Gotaas formula. It is indicated that the design engineer could approximate the optimum or minimum volume solution by constructing first-stage and second-stage filter units of equal size when design is based on the NRC or Eckenfelder formulas. An optimum two-stage trickling filter design will require in most cases less total volume than a single-stage design for the same conditions.

4. Conclusions as to the Applicability of the Formulas to Trickling Filter Design

It has been shown that there are conditions where the three formulas under study will yield required volume values fairly close together and under other conditions the values may be very widespread. It is apparent that there is lack of agreement between the work of various investigators concerning trickling filter efficiency.

It can be concluded that the NRC, Eckenfelder, and Galler-Gotaas formulas are probably valid for certain conditions, and invalid for others. The problem is, then, to determine the regions of validity. It is beyond the scope of this study to make fixed statements about these regions of validity, but some conclusions may be made. It appears that the Eckenfelder formula is probably valid where the influent BOD to the filters is below 150 mg/l, and is invalid for higher BOD values. It is quite possible that the constant in this formula could be adjusted for high BOD values, since the Eckenfelder formula is essentially of the same form as the NRC formula. The Eckenfelder and Galler-Gotaas formulas show a volume reduction with increased depth. There is probably a limit which should be placed on depth and volume, even when forced air is used, since according to these formulas, a filter of infinite depth will require almost no surface area and very little volume. The recirculation factor of the Galler-Gotaas formula can be applied only to ranges of efficiency where increases in recirculation decrease the required volume.

It is apparent that the NRC, Eckenfelder, and Galler-Gotaas formulas are worthy attempts to describe trickling filter efficiency, but have limitations. The NRC and Galler-Gotaas formulas were developed from analysis of plant operating data, while the Eckenfelder formula was developed from theory proposed by Howland and Schulze and applied to operating data by Eckenfelder.

Laboratory and pilot plant investigations usually proceed under controlled conditions which are frequently not directly analogous to conditions in existing plants where frequently large daily fluctuations in flow and influent BOD are present. One noticeable effect of recirculation is to help even the hydraulic load on the filter and keep the distributor rotating at all times. Frequently, operating data obtainable is of questionable accuracy and is confused by factors such as whether samples and measurements include settling following filtration, or whether or not they include the recirculated flow. All of these factors are hindrances to the development of reliable formulas to predict trickling filter efficiency and volume requirements.

It can be seen that there is a great need to set limitations for the design formulas under study, since each of them is probably valid in some region. The scope of this work has not produced definite limits for all situations, but the following guidelines are suggested for the design of trickling filters:

1. The NRC or the Eckenfelder formula may be applied to cases where the BOD influent to the filters is below 150 mg/l.
2. The NRC formula may be applied to cases where the influent BOD to the filters is above or below 150 mg/l.
3. A two-stage design with either the NRC or the Eckenfelder formula will give a savings in volume over a single-stage design at optimum design conditions which may be approximated by designing first-stage and second-stage filters equal in volume.

4. The Galler-Gotaas formula should be used with caution until further studies have been made to indicate its applicability.

5. In all design cases, standards of state agencies should be used as guidelines due to the indefinite nature of the applicability of any of the design formulas to a particular situation.

CHAPTER VI

SUGGESTIONS FOR FUTURE STUDY

In light of the lack of agreement among the NRC, Galler-Gotaas, and Eckenfelder formulas which has been demonstrated in this work, a great deal of further research of the parameters of trickling filter efficiency is clearly indicated. Due to the fact that there is a great lack of reliable operating data available, an effort to accumulate data is definitely needed. A distinction should be made between data and calculated values which include recirculation and settling, and those which do not. This will aid in the evaluation of these operations on trickling filter performance. Investigators should consider separately the effects of influent BOD, flow rate, recirculation, depth, area, and temperature. The effect of flow fluctuation on plant efficiency is in great need of further study.

Since the formulas predict a considerable volume savings at optimum design conditions with two-stage filters, more research attention should be devoted to two-stage trickling filters. There are very few sources of plant operating data for two-stage plants available. An accumulation of data from existing two-stage plants would be of great benefit to the analysis and design of two-stage trickling filters. In this study, modifications of the Eckenfelder and Galler-Gotaas formulas to make them applicable to two-stage filters have been proposed. The validity of these modifications could be verified with further comparison to operating data.

A SELECTED BIBLIOGRAPHY

1. Fair, G. M., and J. C. Geyer, Water Supply and Waste-Water Disposal. John Wiley and Sons, New York, N. Y. (1954).

2. Sewage Treatment Plant Design. Water Pollution Control Federation Manual of Practice No. 8. Washington, D. C. (1959).

3. Standard Methods for the Examination of Water and Wastewater. American Public Health Ass'n., New York, N. Y. (1965).

4. Eckenfelder, W. W., Industrial Water Pollution Control. McGraw-Hill, New York, N. Y. (1966).

5. Schulze, K. L., "Trickling Filter Theory." Water and Sewage Works, Vol. 107 (1960) 100-103.

6. Clark, J. W., and W. Viessman, Jr., Water Supply and Pollution Control. International Textbook Co., Scranton, Pa. (1965).

7. Stanley, W. E., "The Trickling Filter in Sewage Treatment." Modern Sewage Disposal. Federation of Sewage Works Associations, New York (1938) 51-67.

8. Standards for Water Pollution Control Facilities. Oklahoma State Department of Health, Oklahoma City, Oklahoma (1963).

9. Mohlman, F. W., "One Year's Operation of an Experimental High-Rate Trickling Filter." Sewage Works Journal, Vol. 8 (1936) 904-914.

10. Halvorson, H. O., G. M. Savage, E. L. Piret, "Fundamental Factors Concerned in the Operation of Trickling Filters." Sewage Works Journal, Vol. 8 (1936) 888-903.

11. Herrick, T. L., "Experimental Work in Progress at Chicago." Sewage Works Journal, Vol. 10 (1938) 276-292.

12. Keefer, C. E., and H. Kratz, Jr., "Experiments with High-Rate Trickling Filters at Baltimore." Sewage Works Journal, Vol. 12 (1940) 477-484.

13. Horton, R. K., R. Porges, and H. G. Baity, "Studies on the Treatment of Sewage and Textile Wastes by Recirculating Filtration. II. Domestic Sewage on a Continuous Basis." Sewage Works Journal, Vol. 14 (1942) 818-833.

14. "Sewage Treatment at Military Installations." Report of the Subcommittee on Sewage Treatment in Military Installations of the Committee on Sanitary Engineering, National Research Council. Sewage Works Journal, Vol. 18 (1946) 787-1028.

15. Velz, C. J. "A Basic Law for the Performance of Biological Filters." Sewage Works Journal, Vol. 20 (1948) 607-617.

16. Phelps, E. B., Stream Sanitation. John Wiley and Sons, New York, N. Y. (1944).

17. Rankin, R. S., "Evaluation of the Performance of Biofiltration Plants." Trans. Amer. Soc. Civ. Engr., Vol. 120 (1955) 823-842.

18. Fairall, J. M., "Correlation of Trickling Filter Data." Sewage and Ind. Wastes, Vol. 28 (1956) 1069-1074.

19. Stack, V. T., Jr., "Theoretical Performance of the Trickling Filtration Process." Sewage and Ind. Wastes, Vol. 29 (1957) 987-1001.

20. Howland, W. E., "Flow over Porous Media as in a Trickling Filter." Proc. 12th Ind. Wastes Conf. at Purdue Univ., Purdue Univ. Engineering Extension Series No. 94 (1958) 435-465.

21. Ingram, W. T., "An Investigation of the Mechanisms of Controlled Filtration." Sewage and Ind. Wastes, Vol. 31 (1959) 1147-1158.

22. Schulze, K. L., "Experimental Vertical Screen Trickling Filter." Sewage and Ind. Wastes, Vol. 29 (1957) 458-467.

23. Schulze, K. L., "Load and Efficiency of Trickling Filters." Jour. Water Pollution Control Federation, Vol. 32 (1960) 245-261.

24. Bloodgood, D. E., Teletzke, G. H., and Pohland, F. G., "Fundamental Hydraulic Principles of Trickling Filters." Sewage and Ind. Wastes, Vol. 31 (1959) 243-253.

25. Eckenfelder, W. W., Jr., "Trickling Filtration Design and Performance." Trans. Amer. Soc. of Civil Engrs. Vol. 128 (1963) Part III, 371-398.

26. Eckenfelder, W. W., Jr., and D. J. O'Connor, Biological Waste Treatment. Pergamon Press, New York, N. Y. (1961)

27. Galler, W. S., and H. B. Gotaas, "Analysis of Biological Filter Variables." Proc. Amer. Soc. Civil Engrs., Jour. San. Engr. Div., Vol. 90, No. SA6 (December, 1964) 59-79.

28. Moore, W. A., R. S. Smith, and C. C. Ruchhoft, "Efficiency Study of a Recirculating Sewage Filter at Centralia, Mo." Sewage and Ind. Wastes, Vol. 22 (1950) 184-189.

29. Galler, W. S., and H. B. Gotaas, "Optimization Analysis for Biological Filter Design." Proc. Amer. Soc. of Civil Engrs., Jour. San. Engr. Div., Vol. 92, No. SA1 (Feb., 1966) 163-182.

30. Germain, J. E., "Economical Treatment of Domestic Waste by Plastic-Medium Trickling Filters." Jour. Water Poll. Control Fed., Vol. 38 (1966) 192-203.

31. Archer, E. C., and L. R. Robinson, Jr., "Design Considerations for Biological Filters." Public Works, Vol. 98, No. 2 (Feb., 1967) 98-102.

32. Howland, W. E., "Effect of Temperature on Sewage Treatment Processes." Sewage and Ind. Wastes, Vol. 25 (1953) 161-169.

33. Schulze, K. L., Discussion of "Analysis of Biological Filter Variables," by W. S. Galler and H. B. Gotaas (27). Proc. Amer. Soc. Civil Engrs., Jour. San. Engr. Div., Vol. 91, No. SA3 (June, 1965) 129-131.

34. Blain, W. A., and A. J. McDonnell, Discussion of "Analysis of Biological Filter Variables," by W. S. Galler and H. B. Gotaas (27). Proc. Amer. Soc. Civil Engrs., Jour. San. Engr. Div., Vol. 91, No. SA4 (Aug., 1965) 57-61.

35. Culp, G. L., "Direct Recirculation of High-Rate Trickling Filter Effluent." Jour. Water Poll. Con. Fed., Vol. 35 (1963) 742-747.

36. Sorrels, J. H., and P. J. A. Zeller, "Two-Stage Trickling Filter Performance." Sewage and Industrial Wastes, Vol. 28 (1956) 943-954.

37. Grantham, G. R., "Trickling Filter Performance at Intermediate Loading Rates." Sewage and Industrial Wastes, Vol. 23 (1951) 1227-1234.

38. Abdul-Rahim, S. A., E. Hindin, and G. H. Dunstan, "Research on High-Rate Trickling Filter Efficiency." Public Works, Vol. 91, No. 1 (Jan., 1960) 87-89, 168-169.

39. Rigbi, M., A. Amramy, and H. Shuval, "Efficiency of a Small High-Rate Trickling Filter Plant at Jerusalem, Israel." Sewage and Ind. Wastes, Vol. 28 (1956) 852-865.

APPENDIX I

LIST OF SYMBOLS

A = surface area of filter, sq.ft.

a = filter radius, ft. (Galler-Gotaas formula)

b = coefficient of biosorption (Stack)

D = depth of filter media bed, ft.

E = efficiency of BOD removal, expressed as a fraction = $\frac{L_i - L_e}{L_i}$

E_1 = efficiency of first-stage filter

E_2 = efficiency of second-stage filter

E_t = total efficiency of two-stage filtration

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

f = $1/(1-E_1)^2$

h = fraction of time surface receives wastewater (Howland)

L = fraction of removable BOD (Velz, Stack)

L_D = BOD remaining at depth D (Velz)

L_t = BOD remaining at time to (Phelps)

L_R = fraction of removable BOD removed (Stack)

L_e = BOD of settled filter effluent, mg/l

L_{e_1} = BOD of first-stage filter effluent, mg/l

L_{e_2} = BOD of second-stage filter effluent, mg/l

L_i = BOD influent to trickling filters, mg/l

L_{i_1} = BOD influent to first-stage filter, mg/l

L_{i_2} = BOD influent to second-stage filters, mg/l = L_{e_1}

M = 0.67

n = 0.5

p = weighting factor for recirculation (NRC formula)

Q = plant influent flow rate, mgd

r = rate of recirculation, mgd

R = recirculation ratio = r/Q

S = load of removable BOD which will saturate one unit of depth (Stack)

t = time

T = temperature of wastewater, ^{o}C.

V = volume of filter media, thousand cu.ft.

w = organic load, lbs/day = $Q \cdot L_i \cdot 8.34$

w_e = organic load in filter effluent, including recirculation

w_i = organic load influent to trickling filters

w_o = organic load actually applied to filter, including recirculation

w_r = organic load in recirculation

w_1 = organic load influent to first stage

w_2 = organic load influent to second stage

X = number of unit volumes saturated (Stack)

x = time of flow (Howland)

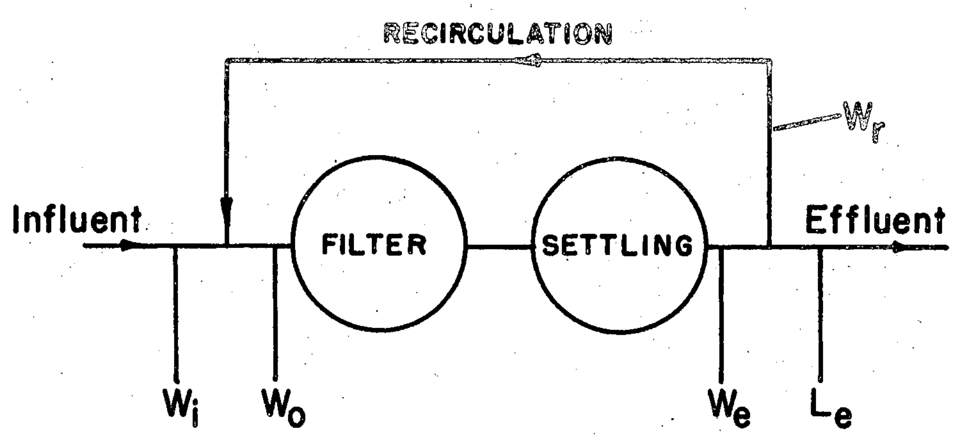

Figure 37 - Definition of Organic Loadings:

$$w_i = L_i \cdot Q \cdot 8.34$$

$$w_o = w_i + w_r = L_i \cdot Q \cdot 8.34 + L_e \cdot Q \cdot R \cdot 8.34$$

$$= L_o \cdot Q \cdot 8.34 \cdot (1+R)$$

$$w_e = L_e \cdot Q \cdot 8.34 \cdot (1+R)$$

$$w_r = L_e \cdot Q \cdot R \cdot 8.34$$

APPENDIX II

A. <u>NRC Formula Derivation</u>

From (14)

$$E = \frac{1}{1+.0085\left(\frac{w}{VF}\right)^{0.5}} \qquad (2)$$

To change volume from acre ft. to cu.ft. x 10^{-3}

$$V(\text{cu.ft. x } 10^{-3}) = 43.56 \text{ x } V \text{ (acre ft.)}$$

$$V(\text{acre ft.}) = \frac{V(\text{cu.ft. x } 10^{-3})}{43.56}$$

$$\therefore \quad E = \frac{1}{1+.0085\left(\frac{w}{V(\text{cu.ft. x } 10^{-3})}\right)^{0.5}}$$

$$E = \frac{1}{1+.0085\cdot 6.6\left(\frac{w}{VF}\right)^{0.5}} = \frac{1}{1+.0561\left(\frac{w}{VF}\right)^{0.5}} \qquad (2)$$

For second stage filters

$$E_2 = \frac{1}{1+\frac{.0561}{1-E}\left(\frac{w}{VF}\right)^{0.5}} \qquad (10)$$

Solving for volume, V

$$\frac{.0561}{1-E_1}\left(\frac{w}{VF}\right)^{0.5} = \frac{1}{E_2} - 1$$

$$\frac{w}{VF} = \left[\frac{\frac{1}{E_2} - 1}{\frac{.0561}{1-E_1}}\right]^2$$

$$V = \frac{W}{F}\left[\frac{\frac{.0561}{1-E_1}}{\frac{1}{E_2}-1}\right]^2 = \frac{W}{F}\left[\frac{.0561\ E_2}{(1-E_1)(1-E_2)}\right]^2 \qquad (85)$$

In the case of first-stage or single-stage filters, $E_1 = 0$, and the formula becomes

$$V = \frac{W}{F}\left[\frac{.0561\ E_1}{1-E_1}\right]^2 \qquad (45)$$

B. Eckenfelder Formula Derivation

From (25)

$$\frac{L_e}{L_o} = \frac{1}{1+2.5\,\frac{D^{.67}}{\sqrt{Q/A}}} \qquad (38)$$

To introduce the effect of recirculation

$$L_o = \frac{L_i+RL_e}{R+1} \qquad (29)$$

$$\frac{L_e(1+R)}{L_i+RL_e} = \frac{1}{1+\frac{2.5D^{.67}}{\sqrt{Q/A}}}$$

$$\frac{L_e}{L_i+RL_e} = \frac{1}{(1+R)\cdot\left(1+\frac{2.5D^{.67}}{\sqrt{Q/A}}\right)}$$

$$\frac{L_i RL_e}{L_e} = (1+R)\cdot\left(1+\frac{2.5D^{.67}}{\sqrt{Q/A}}\right)$$

$$\frac{L_i}{L_e} + R = (1+R)\cdot\left(1+\frac{2.5D^{.67}}{\sqrt{Q/A}}\right)$$

$$\frac{L_i}{L_e} = (1+R)\cdot\left(1+\frac{2.5D^{.67}}{\sqrt{Q/A}}\right) - R$$

$$\frac{L_e}{L_i} = \frac{1}{(1+R)\cdot\left(1+\frac{2.5D^{.67}}{\sqrt{Q/A}}\right) - R}$$

$$E = 1 - \frac{1}{1+R+\left(\frac{2.5D^{.67}}{\sqrt{Q/A}}\right)(1+R) - R}$$

$$E = 1 - \frac{1}{1+\left(\frac{2.5^{.67}}{\sqrt{Q/A}}\right)\cdot(1+R)} \qquad (53)$$

To solve for A:

$$1-E = \frac{1}{1+ \frac{2.5D^{.67}}{\sqrt{Q/A}} \; (1+R)}$$

$$1+ \frac{2.5D^{.67}}{\sqrt{Q/A}} \cdot (1+R) = \frac{1}{1-E}$$

$$\frac{2.5D^{.67}(1+R)}{\sqrt{Q/A}} = \frac{1}{1-E} - 1$$

$$\sqrt{Q/A} = \frac{2.5D^{.67}(1+R)}{\frac{1}{1-E} - 1}$$

$$\frac{\sqrt{Q}\left(\frac{1}{1-E} - 1\right)}{2.5D^{.67} \; (1+R)} = \sqrt{A}$$

$$A = Q \; \frac{\left(\frac{1}{1-E} - 1\right)^2}{D^{1.33}(1+R)^2 6.25}$$

Then

$$V = AD = \frac{Q\left(\frac{1}{1-E} - 1\right)^2}{D^{.33}(1+R)^{.2} \; 6.25}$$

$$V(\text{cu.ft. x } 10^{-3}) = 43.56 \text{ x } V(\text{acres})$$

$$V(\text{acres}) = \frac{V\ (\text{cu.ft. x } 10^{-3})}{43.56}$$

$$\frac{V(\text{cu.ft. x } 10^{-3})}{43.56} = \frac{Q\left(\frac{1}{1-E} - 1\right)^2}{D^{.33}(1+R)^2 6.25}$$

$$V(\text{cu.ft. x } 10^{-3}) = \frac{Q(\frac{1}{1-E} - 1)^2}{D^{.33}(1+R)^2 .143}$$

$$= \frac{Q}{D^{.33}} \left[\frac{\frac{E}{1-E}}{(1+R)\,(.379)} \right]^2 \qquad (46)$$

C. Galler and Gotaas Formula Derivation

From Reference 27,

$$L_e = \frac{K\left(QL_i + QRL_e\right)^{1.19}}{(Q+QR)^{.78}(1+D)^{.67}a^{.25}} \tag{40}$$

$$K = \frac{.464\left(\frac{43,560}{\pi}\right)^{.13}}{Q^{.28}T^{.15}} \tag{41}$$

$$C = .464\left(\frac{43,560}{\pi}\right)^{.13} = 1.60$$

$$L_e = \frac{C}{T^{.15}} \cdot \frac{Q^{1.19}}{Q^{.28}Q^{.78}} \cdot \frac{\left(L_i + RL_e\right)^{1.19}}{(1+R)^{.78}} \cdot \frac{1}{(1+D)^{.67}a^{.25}}$$

$$L_e = \frac{C}{T^{.15}} \cdot Q^{.13} \cdot \frac{\left(L_i + RL_e\right)^{1.19}}{(1+R)^{.78}(1+D)^{.67}} \cdot \frac{1}{a^{.25}}$$

Solving for fraction of BOD remaining in effluent, L_e/L_i

$$\frac{L_e}{L_i} = \frac{1}{L_i} \cdot \frac{CQ^{.13}}{T^{.15}} \cdot \frac{\left(L_i + RL_e\right)^{1.19}}{(1+R)^{.78}(1+D)^{.67}a^{.25}}$$

Solving for efficiency of BOD removal, E

$$E = 1 - \frac{L_e}{L_i} = 1 - \frac{CQ^{.13}}{L_iT^{.15}} \cdot \frac{\left(L_i + RL_e\right)^{1.19}}{(1+R)^{.78}(1+D)^{.67}a^{.25}}$$

$$a^{.25} = \frac{CQ^{.13}\left(L_i + RL_e\right)^{1.19}}{L_iT^{.15}(1+R)^{.78}(1+D)^{.67}(1-E)}$$

$$\frac{L_e}{L_i} = 1-E$$

$$L_e = L_i(1-E)$$

$$a^{.25} = \frac{CQ^{.13}}{T^{.15}} \cdot \frac{L_i^{1.19}(1+R(1-E))^{1.19}}{L_i(1+R)^{.78}(1+D)^{.67}(1-E)}$$

$$a^{.25} = \frac{CQ^{.13}}{T^{.15}} \cdot \frac{L_i^{.19}}{(1+D)^{.67}} \cdot \frac{(1+R(1-E))^{1.19}}{(1-E)(1+R)^{.78}}$$

$$a = \left[\frac{CQ^{.13}}{T^{.15}} \cdot \frac{L_i^{.19}}{(1+D)^{.67}} \cdot \frac{(1+R(1-E))^{1.19}}{(1-E)(1+R)^{.78}}\right]^4$$

$$V(\text{cu.ft.x } 10^{-3}) = \frac{AD}{1000} = \frac{\pi a^2 D}{1000}$$

$$= \frac{\pi D}{1000}\left[\frac{CQ^{.13}L_i^{.19}(1+R(1-E))^{1.19}}{T^{.15}(1+D)^{.67}(1-E)(1+R)^{.78}}\right]^8$$

Now, solving this form for efficiency

$$(1-E)^8 = \frac{1}{V} \cdot \frac{\pi D}{1000} \cdot \left[\frac{CQ^{.13}L_i^{.19}(1+R(1-E))^{1.19}}{T^{.15}(1+D)^{.67}(1+R)^{.78}}\right]^8$$

$$E = 1-\left(\frac{1}{V} \cdot \frac{\pi D}{1000}\right)^{.125} \cdot \frac{CQ^{.13}L_i^{.19}(1+R(1-E))^{1.19}}{T^{.15}(1+D)^{.67}(1+R)^{.78}}$$

APPENDIX III

COMPUTER PROGRAMS

The computer programs herein are written in FORTRAN IV, and were executed by an IBM 7040 computer.

Program I. Design of a Single-Stage Trickling Filter by the National Research Council, Galler-Gotaas, or Eckenfelder Formula

DEFINITION OF VARIABLES

AECK	Filter area by Eckenfelder formula, 1000 sq.ft.
AECKSF	Filter area by Eckenfelder formula, sq.ft.
AG	Filter area by Galler-Gotaas formula, 1000 sq.ft.
AGSF	Filter area by Galler-Gotaas formula, sq.ft.
ANRC	Filter area by NRC formula, 1000 sq.ft.
ANRCSF	Filter area by NRC formula, sq.ft.
BOD	BOD influent to trickling filter
BODE	Plant effluent BOD, mg/l
BODR	Plant influent BOD, mg/l
D	Depth of filter media, ft.
DTNRC	Diameter of filter by NRC formula, ft.
DTRECK	Diameter of filter by Eckenfelder formula, ft.
DTRG	Diameter of filter by Galler-Gotaas formula, ft.

F	Recirculation factor, NRC formula
PTF	Efficiency of trickling filter, fraction
PTP	Efficiency of treatment plant, fraction
P1F	Efficiency of primary sedimentation, fraction
Q	Plant influent flow rate, mgd
QAECK	Hydraulic loading, Eckenfelder formula, gal/day/sq.ft.
QAG	Hydraulic loading, Galler-Gotaas formula, gal/day/sq.ft.
QANRC	Hydraulic loading, NRC formula, gal/day/sq.ft.
R	Recirculation ratio
T	Temperature of wastewater, ^oC.
VECK	Volume of filter, Eckenfelder formula, 1000 cu.ft.
VG	Volume of filter, Galler-Gotaas formula, 1000 cu.ft.
VNRC	Volume of filter, NRC formula, 1000 cu.ft.
WI	Organic loading to filter, lbs/day
WVECK	Organic loading, Eckenfelder formula, lbs/day/1000 cu.ft.
WVNRC	Organic loading, NRC formula, lbs/day/1000 cu.ft.
WVG	Organic loading, Galler-Gotaas formula, lbs/day/1000 cu.ft.

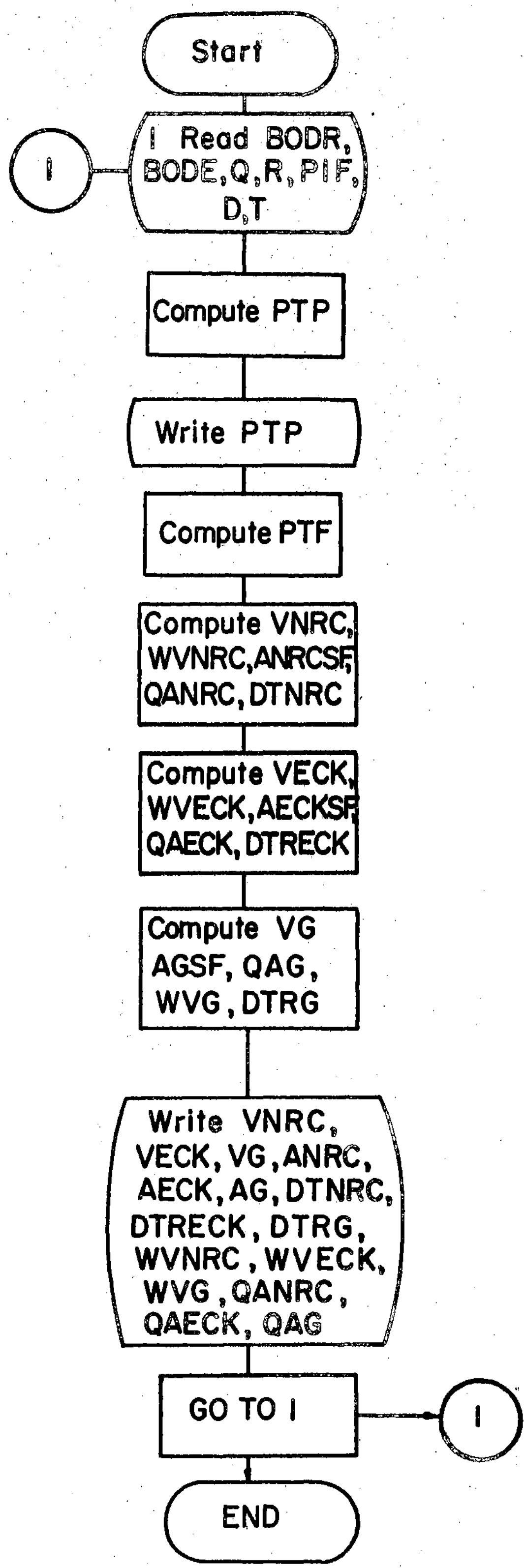

Figure 38 - Flowchart for Program I.

PROGRAM I

```
C     DESIGN OF SINGLE STAGE TRICKLING FILTERS BY NRC, GALLER-GOTAAS, OR
C     ECKENFELDER FORMULAS.
1     READ (5,200) BODR,BODE,Q,R,P1F,D,T
      WRITE (6,270)
      WRITE (6,370)
      WRITE (6,210)
      WRITE (6,200) BODR,BODE,Q,R,P1F,D,T
      PTP=(BODR-BODE)/BODR
      WRITE (6,250) BODE
      PTF=1.-((1.-PTP)/(1.-P1F))
      WI=BODR*Q*8.34*(1.-P1F)
      BOD=BODR*(1.-P1F)
C     CALCULATION OF VOLUME BY NRC FORMULA
      F=(1.+R)/((1.+(.1*R))**2)
      CN=.003147*WI
      VNRC=CN*PTF*PTF/((1.-PTF)*(1.-PTF)*F)
      WVNRC=WI/VNRC
      QG=Q*1000000.
      ANRC=VNRC/D
      ANRCSF=ANRC*1000.
      QANRC=QG/ANRCSF
      DTNRC=2.*SQRT(ANRCSF/3.1416)
C     CALCULATION OF VOLUME BY ECKENFELDER FORMULA
      CE=Q*6.97/((D**.33)*((1.+R)**2))
      VECK=(((1./(1.-PTF))-1.)**2)*CE
      WVECK=WI/VECK
      AECK=VECK/D
      AECKSF=AECK*1000.
      QAECK=QG/AECKSF
      DTRECK=2.*SQRT(AECKSF/3.14159)
C     CALCULATION OF VOLUME BY GALLER-GOTAAS FORMULA
      CG=(.464*((43560.*Q/3.1416)**.13))/(T**.15)
      AS=((1.+((1.-PTF)*R))**1.19)/((1.+R)**.78)
      AG=.0031416*((((BOD**.19)*CG*AS)/((1.-PTF)*((1.+D)**.67)))**8)
      AGSF=AG*1000.
      VG=AG*D
      QAG=QG/AGSF
      WVG=WI/VG
      DTRG=2.*SQRT(AG)
      WRITE (6,260)
      WRITE (6,280) VNRC,VECK,VG
      WRITE (6,290) ANRC,AECK,AG
      WRITE (6,300) DTNRC,DTRECK,DTRG
      WRITE (6,310) WVNRC,WVECK,WVG
      WRITE (6,320) QANRC,QAECK,QAG
      GO TO 1
200   FORMAT (2F6.1,F10.3,2F6.2,2F6.1)
210   FORMAT (45H  BODR  BODE   Q (MGD)   R    P1   D (FT)   T)
270   FORMAT (1H1)
370   FORMAT (43H  VOLUME FOR SINGLE STAGE TRICKLING FILTERS)
250   FORMAT (20H  PLANT EFFLUENT BOD,F6.2,6H   PPM)
260   FORMAT (66H                              NRC      ECKENFELDER    GA
     1LLER-GOTAAS,/)
280   FORMAT (25H VOLUME,THOUSAND CU.FT.   ,F10.3,5X,F10.3,5X,F10.3/)
290   FORMAT (25H AREA,THOUSAND SQ.FT.     ,F10.3,5X,F10.3,5X,F10.3/)
300   FORMAT (25H DIAMETER, FT.            ,F10.1,5X,F10.1,5X,F10.1/)
310   FORMAT (25H BOD LOADING,LBS/1000CUFT,F10.2,5X,F10.2,5X,F10.2/)
320   FORMAT (25H HYD. LOADING,GAL/SQ.FT. ,F10.2,5X,F10.2,5X,F10.2)
      END
```

Program II. Design of Two-Stage Trickling Filters

DEFINITION OF VARIABLES

AG1	Area of first stage, Galler-Gotaas formula, 1000 sq.ft.
AG2	Area of second stage, Galler-Gotaas, 1000 sq.ft.
D1	Depth of first stage, ft.
D2	Depth of second stage, ft.
DP2	Increment of first-stage efficiency
DP3	Increment of second-stage efficiency
F1	NRC formula recirculation factor for first stage
F2	NRC formula recirculation factor for second stage
N1	Number of incrementations of P2(I)
N2	Number of incrementations of P3(J)
P2F	Efficiency of first stage, fraction
P3F	Efficiency of second stage, fraction
P2(I)	Efficiency of first stage, percent
P3(J)	Efficiency of second stage, percent
Q	Plant influent flow rate, mgd
QAE1	Hydraulic loading of first stage, Eckenfelder formula, mgd/1000 sq.ft.
QAE2	Hydraulic loading of second stage, Eckenfelder formula, mgd/1000 sq.ft.
QAG1	Hydraulic loading of first stage, Galler-Gotaas formula, mgd/1000 sq.ft.
QAG2	Hydraulic loading of second stage, Galler-Gotaas formula, mgd/1000 sq.ft.

QANRC1	Hydraulic loading of first stage, NRC formula, mgd/1000 sq.ft.
QANRC2	Hydraulic loading of second stage, NRC formula, mgd/1000 sq.ft.
R1	Recirculation ratio, first stage
R2	Recirculation ratio, second stage
T	Temperature of wastewater, ^{o}C. (Galler-Gotaas formula only)
VETL	Total volume, Eckenfelder formula, 1000 cu.ft.
VE1	First-stage volume, Eckenfelder formula, 1000 cu.ft.
VE2	Second-stage volume, Eckenfelder formula, 1000 cu.ft.
VGTL	Total volume, Galler-Gotaas formula, 1000 cu.ft.
VG1	First-stage volume, Galler-Gotaas formula, 1000 cu.ft.
VG2	Second-stage volume, Galler-Gotaas formula, 1000 cu.ft.
VNRCT	Total volume, NRC formula, 1000 cu.ft.
VNRC1	Total volume, NRC formula, 1000 cu.ft.
VNRC2	Total volume, NRC formula, 1000 cu.ft.
WG1	Organic load to first stage, lbs/day
WG2	Organic load to second stage, lbs/day
WVETL	Organic loading to total volume, Eckenfelder formula, lbs/day/1000 cu.ft.
WVE1	Organic loading to first stage, Eckenfelder formula, lbs/day/1000 cu.ft.
WVE2	Organic loading to second stage, Eckenfelder formula, lbs/day/1000 cu.ft.
WVGTL	Organic loading to total volume, Galler-Gotaas

formula, lbs/day/1000 cu.ft.

WVG1 Organic loading to first stage, Galler-Gotaas formula, lbs/day/1000 cu.ft.

WVG2 Organic loading to second stage, Galler-Gotaas formula, lbs/day/1000 cu.ft.

WVNTL Organic loading to total volume, NRC formula, lbs/day/1000 cu.ft.

WVNRC1 Organic loading to first stage, NRC formula, lbs/day/1000 cu.ft.

WVNRC2 Organic loading to second stage, NRC formula, lbs/day/1000 cu.ft.

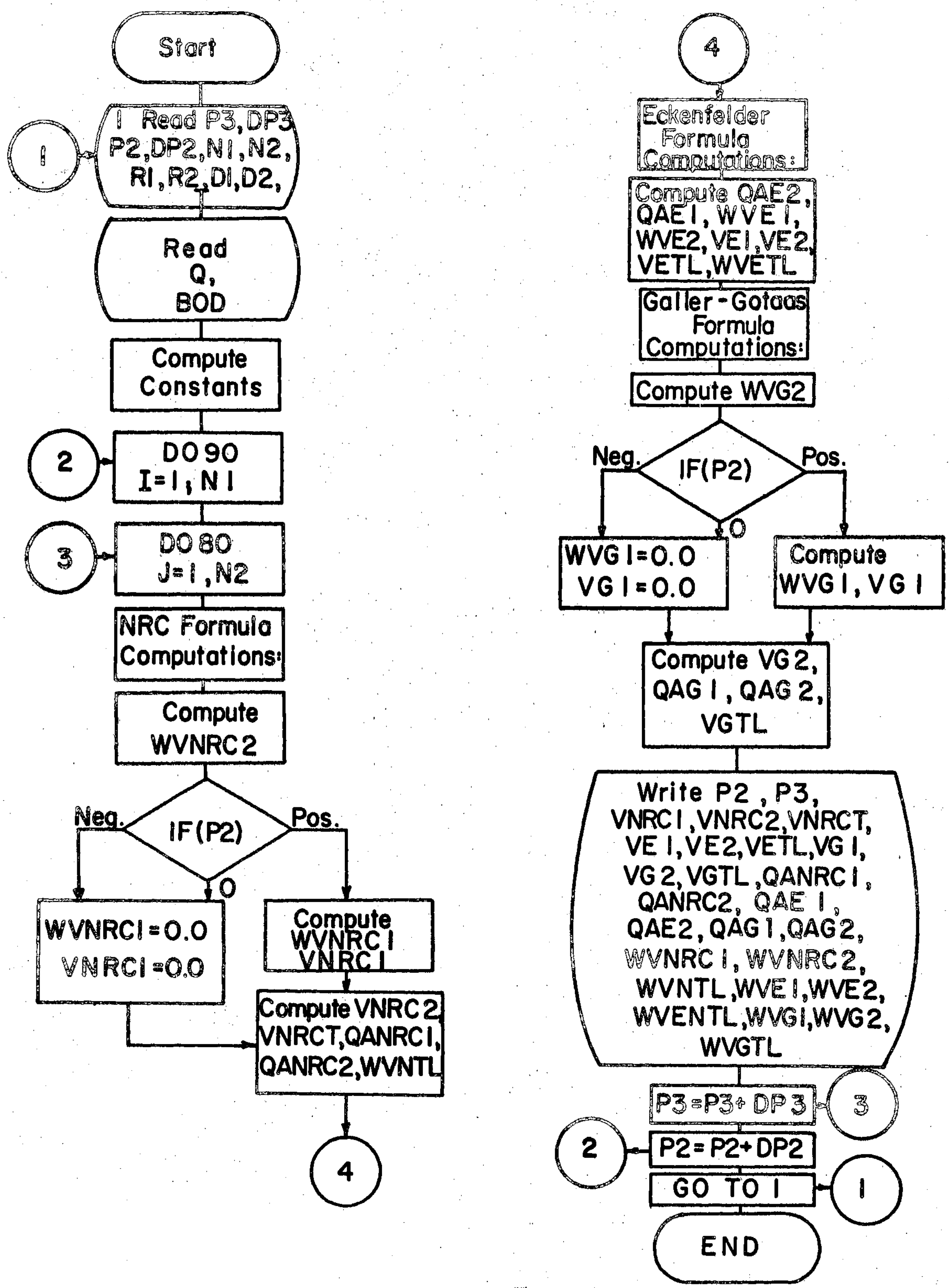

Figure 39 - Flowchart for Program II.

PROGRAM II

```
C     DESIGN OF TWO-STAGE TRICKLING FILTERS
      DIMENSION P3(50),P2(50)
1     READ (5,200) P3(1),DP3,P2(1),DP2,N1,N2,R1,R2,D1,D2,T
      WRITE (6,300)
      WRITE (6,210)
      WRITE (6,200) P3(1),DP3,P2(1),DP2,N1,N2,R1,R2,D1,D2,T
      READ (5,220) Q,BOD
      WRITE (6,230)
      WRITE (6,220) Q,BOD
      F1=(1.+R1)/((1.+.1*R1)**2)
      F2=(1.+R2)/((1.+.1*R2)**2)
      C=(.464*((43560.*Q/3.1416)**.13))/(T**.15)
      WRITE (6,290)
      WRITE (6,240)
      WRITE (6,250)
      DO 90 I=1,N1
      P2F=P2(I)/100.
      DO 80 J=1,N2
      P3F=P3(J)/100.
C     NRC FORMULA SEQUENCE
      WVNRC2=F2*((((1./P3F)-1.)*(1.-P2F))**2)/.003147
      IF (P2(I)) 20,20,10
10    WVNRC1=F1*(((1./P2F)-1.)**2)/.003147
      VNRC1=(BOD*Q*8.34)/WVNRC1
      GO TO 25
20    WVNRC1=0.0
      VNRC1=0.0
25    VNRC2=(BOD*(1.-P2F)*Q*8.34)/WVNRC2
      VNRCT=VNRC1+VNRC2
      QANRC1=WVNRC1*D1/(BOD*8.34)
      QANRC2=WVNRC2*D1/(BOD*8.34*(1.-P2F))
      WVNTL=(BOD*Q*8.34)/VNRCT
C     ECKENFELDER FORMULA SEQUENCE
      QAE2=((.379*(D2**.67)*(1.-P2F)*(1.+R2))/((1.0/(1.-P3F))-1.))**2
      QAE1=((.379*(D1**.67)*(1.+R1))/((1./(1.-P2F))-1.))**2
      WVE1=(BOD*QAE1*8.34)/D1
      WVE2=(BOD*(1.-P2F)*QAE2*8.34)/D2
      VE1=Q*D1/QAE1
      VE2=Q*D2/QAE2
      VETL=VE1+VE2
      WVETL=(BOD*Q*8.34)/VETL
C     GALLER-GOTAAS FORMULA SEQUENCE
      GF1=((1.+((1.-P2F)*R1))**1.19)/((1.+R1)**.78)
      GF2=((1.+((1.-P3F)*R2))**1.19)/((1.+R2)**.78)
      WG2=BOD*(1.-P2F)*8.34*Q
      BD2=BOD*(1.-P2F)
      A2=(((BD2**.19)*GF2*C)/((1.-P3F)*((1.-P2F)**.125)*((1.+D2)**.67)))
     1**8
      AG2=.0031416*A2
      WVG2=WG2/(AG2*D2)
      IF (P2(I)) 40,40,30
30    WG1=BOD*8.34*Q
      A1=(((BOD**.19)*GF1*C)/((1.-P2F)*((1.+D1)**.67)))**8
      AG1=.0031416*A1
      WVG1=WG1/(AG1*D1)
      VG1=AG1*D1
      GO TO 45
40    WVG1=0.0
      VG1=0.0
45    VG2=AG2*D2
      QAG1=WVG1*D1/(BOD*8.34)
      QAG2=WVG2*D2/(BOD*8.34*(1.-P2F))
```

PROGRAM II (continued)

```
      VGTL=VG1+VG2
      WVGTL=(BOD*Q*8.34)/VGTL
      WRITE (6,260) P2(I),P3(J),VNRC1,VNRC2,VNRCT,VE1,VE2,VETL,VG1,VG2,V
     1GTL
      WRITE (6,270) QANRC1,QANRC2,QAE1,QAE2,QAG1,QAG2
      WRITE (6,280) WVNRC1,WVNRC2,WVNTL,WVE1,WVE2,WVETL,WVG1,WVG2,WVGTL
      JJ=J+1
      P3(JJ)=P3(J)+DP3
80    CONTINUE
      II=I+1
      P2(II)=P2(I)+DP2
90    CONTINUE
      GO TO 1
200   FORMAT (4F6.1,2I5,5F6.1)
210   FORMAT (65H  P3(1)  DP3  P2(1)  DP2   N1   N2    R1    R2 D1(FT) D
     12(FT) TEMP)
220   FORMAT (2F10.1)
230   FORMAT (24H  FLOW(MGD) BOD IN (PPM))
240   FORMAT (106H            NATIONAL RESEARCH COUNCIL
     1    ECKENFELDER                     GALLER AND GOTAAS)
250   FORMAT (119H  P2    P3        V1          V2    TOTAL VOL
     1V1          V2     TOTAL VOL          V1          V2       TOTAL VOL )
260   FORMAT (2F5.0,9F12.3)
270   FORMAT (1H ,10H  Q/A      ,2F12.3,12X,2F12.3,12X,2F12.3)
280   FORMAT (1H ,10H  W/V      ,9F12.3/)
290   FORMAT (75H  VOLUME IN 1000 CU.FT.  Q/A IN MGD/1000 SQ.FT.  W/V IN
     1 LBS/1000 CU.FT./DAY)
300   FORMAT (1H1)
      END
```

Programs III, IV, and V. Optimum Volume of Two-Stage Trickling Filters

DEFINITION OF VARIABLES
(All Programs)

AP2	Efficiency of first stage at minimum volume conditions
BODE	Plant effluent BOD, mg/l
BODR	Plant influent BOD, mg/l
DBODE	Increment to be added to BODE
DP2F	Increment to be added to P2F
D1	Depth of first stage, ft.
D2	Depth of second stage, ft.
NBODE	Number of incrementations of BODE
NP2F	Number of incrementations of P2F
PTF	Efficiency of trickling filtration
PTP	Efficiency of treatment plant
P1F	Efficiency of primary sedimentation
P2F	Efficiency of first-stage trickling filtration
P3F	Efficiency of second-stage trickling filtration
Q	Plant influent flow rate, mgd
R1	Recirculation ratio of first stage
R2	Recirculation ratio of second stage
TV	Initial temporary total volume
TVT	Temporary total volume
TP2	Temporary efficiency of first stage
TP3	Temporary efficiency of second stage
TV1	Temporary volume of first stage

TV2	Temporary volume of second stage
VSS	Volume of a single-stage filter required to meet the input conditions with R = R1 and D = D1
VT	Total volume at minimum volume conditions
V1	First-stage volume at minimum volume conditions
V2	Second-stage volume at minimum volume conditions

GALLER-GOTAAS
(Program V)

BD2	BOD influent to second stage, mg/l
BOD	BOD influent to trickling filters, mg/l
QAG1	Hydraulic loading to first stage, mgd/1000 sq.ft.
QAG2	Hydraulic loading to second stage, mgd/1000 sq.ft.
WG1	Organic load to first stage, lbs/day
WG2	Organic load to second stage, lbs/day
WVGTL	Organic loading to total volume, lbs/day/1000 cu.ft.
WVG1	Organic loading to first stage, lbs/day/1000 cu.ft.
WVG2	Organic loading to second stage, lbs/day/1000 cu.ft.

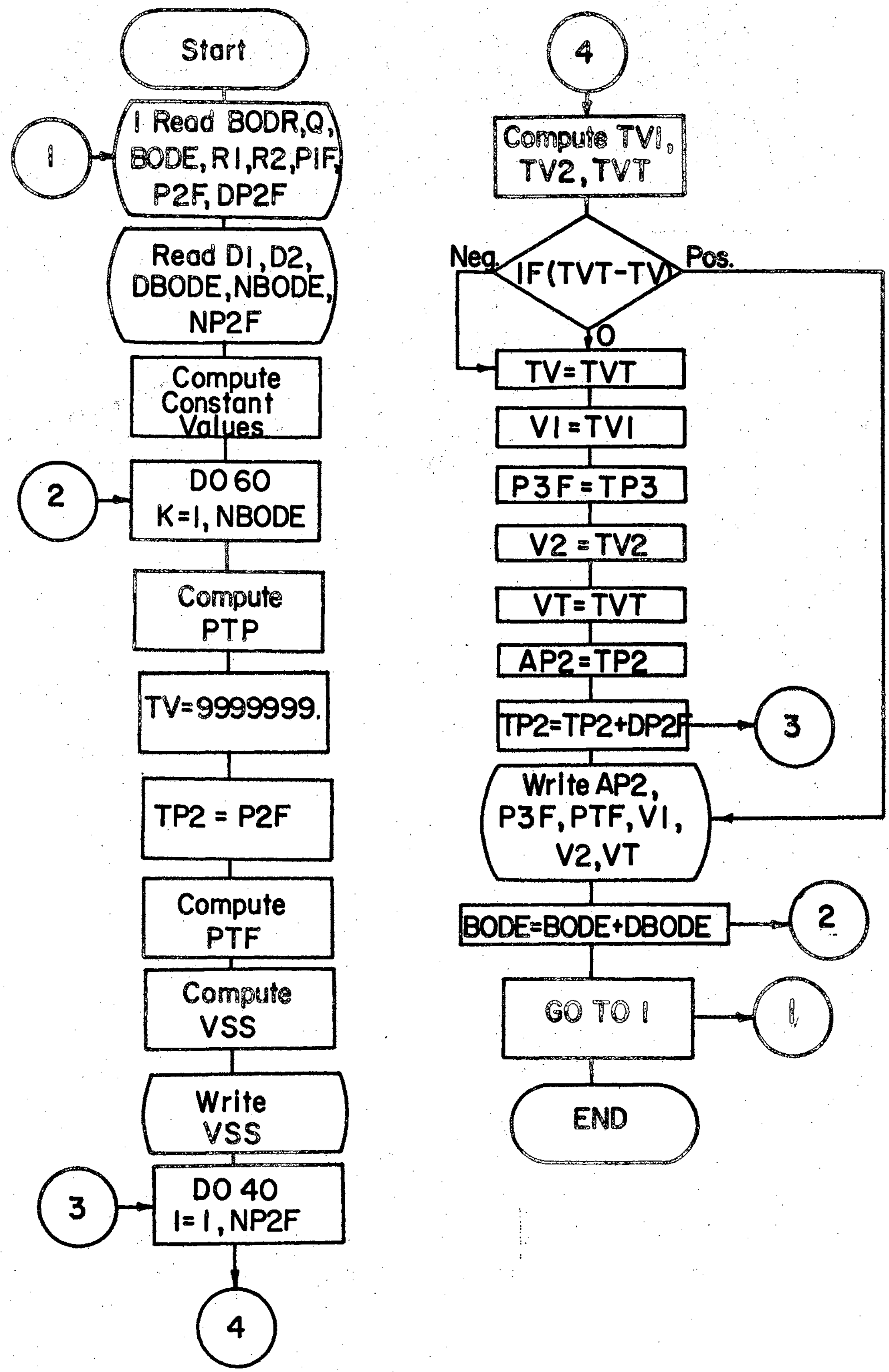

Figure 40 - Flowchart for Programs III, IV, and V.

PROGRAM III

```
C      OPTIMUM VOLUME FOR TRICKLING FILTERS BY ECKENFELDER'S FORMULA
1      READ (5,200) BODR,Q,BODE,R1,R2,P1F,P2F,DP2F
       WRITE (6,270)
       WRITE (6,370)
       WRITE (6,210)
       WRITE (6,200) BODR,Q,BODE,R1,R2,P1F,P2F,DP2F
2      READ (5,220) D1,D2,DBODE,NBODE,NP2F
       WRITE (6,230)
       WRITE (6,220) D1,D2,DBODE,NBODE,NP2F
       C1=Q*6.97/((D1**.33)*((1.+R1)**2))
       C2=Q*6.97/((D2**.33)*((1.+R2)**2))
       DO 60 K=1,NBODE
       PTP=(BODR-BODE)/BODR
       WRITE (6,250) BODE
       TV=9999999.
       TP2=P2F
       PTF=1.-((1.-PTP)/(1.-P1F))
       VSS=(((1./(1.-PTF))-1.)**2)*C1
       WRITE (6,360) VSS
       WRITE (6,260)
       DO 40 I=1,NP2F
       TV1=(((1./(1.-TP2))-1.)**2)*C1
       TP3=1.-((1.-PTP)/((1.-P1F)*(1.-TP2)))
       TV2=C2*(((1./(1.-TP3))-1.)/(1.-TP2))**2
       TVT=TV1+TV2
       IF (TVT-TV) 39,39,38
39     TV=TVT
       V1=TV1
       P3F=TP3
       V2=TV2
       VT=TVT
       AP2=TP2
40     TP2=TP2+DP2F
38     CONTINUE
       WRITE (6,280) AP2,P3F,PTF
       WRITE (6,300) V1,V2,VT
       WRITE (6,350)
60     BODE=BODE+DBODE
       GO TO 1
200    FORMAT (3F6.1,5F6.2)
210    FORMAT (54H    BODR Q(MGD) BODE   R1    R2    P1     P2   DP2     )
220    FORMAT (3F6.1,2I5)
230    FORMAT (30H D1(FT) D2(FT) DBODE NBODE NP2)
250    FORMAT (20H  PLANT EFFLUENT BOD,F6.2,6H   PPM)
260    FORMAT (50H                    FILTER 1 FILTER 2 BOTH FILTERS)
270    FORMAT (1H1)
280    FORMAT (20H EFFICIENCY (FRACT.),2F8.4,F12.4)
300    FORMAT (20H FILTER VOLUME TCUFT,2F8.3,F12.3)
350    FORMAT (1H0)
360    FORMAT (106H VOLUME REQUIRED FOR A SINGLE STAGE FILTER TO GIVE SAM
      1E REMOVAL AS THESE COMBINATIONS OF TWO-STAGE FILTERS,F12.3)
370    FORMAT (70H  ECKENFELDER FORMULA-OPTIMUM VOLUME COMBINATION FOR TW
      1O STAGE FILTERS)
       END
```

PROGRAM IV

```
C      OPTIMUM VOLUME OF TRICKLING FILTERS BY NRC FORMULA  4/20/67
1      READ (5,200) BODR,Q,BODE,R1,R2,P1F,P2F,DP2F
       WRITE (6,270)
       WRITE (6,370)
       WRITE (6,2 0)
       WRITE (6,200) BODR,Q,BODE,R1,R2,P1F,P2F,DP2F
2      READ (5,220) D1,D2,DBODE,NBODE,NP2F
       WRITE (6,230)
       WRITE (6,220) D1,D2,DBODE,NBODE,NP2F
       F1=(1.+R1)/((1.+(.1*R1))**2)
       F2=(1.+R2)/((1.+(.1*R2))**2)
       WR=BODR*Q*8.34
       CK=.003147*WR*(1.-P1F)
       DO 60 K=1,NBODE
       PTP=(BODR-BODE)/BODR
       WRITE (6,250) BODE
       TV=9999999.
       TP2=P2F
       PTF=1.-((1.-PTP)/(1.-P1F))
       VSS=CK*PTF*PTF/((1.-PTF)*(1.-PTF)*F1)
       WRITE (6,360) VSS
       WRITE (6,260)
       DO 40 I=1,NP2F
       TV1=CK*TP2*TP2/((1.-TP2)*(1.-TP2)*F1)
       TP3=1.-((1.-PTP)/((1.-P1F)*(1.-TP2)))
       TV2=CK*TP3*TP3/((1.-TP3)*(1.-TP3)*(1.-TP2)*F2)
       TVT=TV1+TV2
       IF (TVT-TV) 39,39,38
39     TV=TVT
       V1=TV1
       P3F=TP3
       V2=TV2
       VT=TVT
       AP2=TP2
40     TP2=TP2+DP2F
38     CONTINUE
       WRITE (6,280) AP2,P3F,PTF
       WRITE (6,300) V1,V2,VT
       WRITE (6,350)
60     BODE=BODE+DBODE
       GO TO 1
200    FORMAT (F6.1,F6.3,F6.1,5F6.2)
210    FORMAT (54H    BODR Q(MGD) BODE    R1    R2     P1      P2    DP2     )
220    FORMAT (3F6.1,2I5)
230    FORMAT (30H D1(FT) D2(FT) DBODE NBODE NP2)
250    FORMAT (20H  PLANT EFFLUENT BOD,F6.2,6H   PPM)
260    FORMAT (50H                         FILTER 1 FILTER 2 BOTH FILTERS)
270    FORMAT (1H1)
280    FORMAT (20H EFFICIENCY (FRACT.),2F8.4,F12.4)
300    FORMAT (20H FILTER VOLUME TCUFT,2F8.3,F12.3)
350    FORMAT (1H0)
360    FORMAT (106H VOLUME REQUIRED FOR A SINGLE STAGE FILTER TO GIVE SAM
      1E REMOVAL AS THESE COMBINATIONS OF TWO-STAGE FILTERS,F12.3)
370    FORMAT (84H  NATIONAL RESEARCH COUNCIL FORMULA-OPTIMUM VOLUME COMB
      1INATION FOR TWO STAGE FILTERS)
       END
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PROGRAM V

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C     OPTIMUM VOLUME OF TRICKLING FILTERS BY GOTAAS FORMULA
1     READ (5,200) BODR,Q,BODE,R1,R2,P1F,P2F,DP2F
      WRITE (6,270)
      WRITE (6,370)
      WRITE (6,210)
      WRITE (6,200) BODR,Q,BODE,R1,R2,P1F,P2F,DP2F
2     READ (5,220) D1,D2,DBODE,NBODE,NP2F
      WRITE (6,230)
      WRITE (6,220) D1,D2,DBODE,NBODE,NP2F
      T=20.0
      C=(.464*((43560.*Q/3.1416)**.13))/(T**.15)
      DO 60 K=1,NBODE
      PTP=(BODR-BODE)/BODR
      WRITE (6,250) BODE
      TV=9999999.
      TP2=P2F
      PTF=1.-((1.-PTP)/(1.-P1F))
      BOD=BODR*(1.-P1F)
      GFS=((1.+((1.-PTF)*R1))**1.19)/((1.+R1)**.78)
      AS=(((BOD**.19)*GFS*C)/((1.-PTF)*((1.+D1)**.67)))**8
      ASS=.0031416*AS
      VSS=ASS*D1
      WRITE (6,360) VSS
      WRITE (6,260)
      DO 40 I=1,NP2F
      GF1=((1.+((1.-TP2)*R1))**1.19)/((1.+R1)**.78)
      A1=(((BOD**.19)*GF1*C)/((1.-TP2)*((1.+D1)**.67)))**8
      AG1=.0031416*A1
      TV1=AG1*D1
      TP3=1.-((1.-PTP)/((1.-P1F)*(1.-TP2)))
      GF2=((1.+((1.-TP3)*R2))**1.19)/((1.+R2)**.78)
      BD2=BOD*(1.-TP2)
      A2=(((BD2**.19)*GF2*C)/((1.-TP3)*((1.-TP2)**0.50)*((1.+D2)**.67)))
     1**8
      AG2=.0031416*A2
      TV2=AG2*D2
      WG2=BD2*8.34*Q
      WVG2=WG2/(AG2*D2)
      QAG2=WVG2*D2/(BD2*8.34)
30    WG1=BOD*8.34*Q
      WVG1=WG1/(AG1*D1)
      QAG1=WVG1*D1/(BOD*8.34)
      TVT=TV1+TV2
      IF (TVT-TV) 39,39,38
39    TV=TVT
      V1=TV1
      P3F=TP3
      V2=TV2
      VT=TVT
      WVGTL=(BOD*Q*8.34)/VT
      AP2=TP2
40    TP2=TP2+DP2F
38    CONTINUE
      WRITE (6,280) AP2,P3F,PTF
      WRITE (6,300) V1,V2,VT,QAG1,QAG2,WVG1,WVG2,WVGTL
      WRITE (6,350)
60    BODE=BODE+DBODE
      GO TO 1
200   FORMAT (3F6.1,5F6.2)
210   FORMAT (54H    BODR Q(MGD) BODE   R1     R2     P1      P2    DP2     )
220   FORMAT (3F6.1,2I5)
230   FORMAT (30H D1(FT) D2(FT) DBODE NBODE NP2)


250   FORMAT (20H  PLANT EFFLUENT BOD,F6.2,6H   PPM)
260   FORMAT (50H                         FILTER 1 FILTER 2 BOTH FILTERS)
270   FORMAT (1H1)
280   FORMAT (20H EFFICIENCY (FRACT.),2F8.4,F12.4,72H  Q/A-FILTER 1  Q/A
     1-FILTER 2  W/V-FILTER 1  W/V-FILTER 2  W/V-TOTAL VOL.)
300   FORMAT (20H FILTER VOLUME TCUFT,2F8.3,F12.3,2X,F12.3,2X,F12.3,2X,F
     112.3,2X,F12.3,2X,F12.3)
350   FORMAT (1H0)
360   FORMAT (106H VOLUME REQUIRED FOR A SINGLE STAGE FILTER TO GIVE SAM
     1E REMOVAL AS THESE COMBINATIONS OF TWO-STAGE FILTERS,F12.3)
370   FORMAT (65H GOTAAS FORMULA  OPTIMUM VOLUME COMBINATION FOR TWO STA
     1GE FILTERS)
      END
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VITA

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Candidate for the Degree of

Master of Science

Thesis: AN EVALUATION OF RECENT APPROACHES FOR THE DESIGN OF TRICKLING FILTERS

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Professional Experience: Laboratory Assistant, Oklahoma State Department of Health; Junior Assistant Health Service Officer, U. S. Public Health Service; Assistant Engineer, Oklahoma State Department of Health; Graduate Assistant, Oklahoma State University.

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