

FORMULATION AND COMPARISON OF TRICKLING
FILTER EQUATIONS--
based on actual plant data

by

CHIN DEE LEE

B. S., Chung Yen College of Science & Engineering,
Taiwan, 1962

5878

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

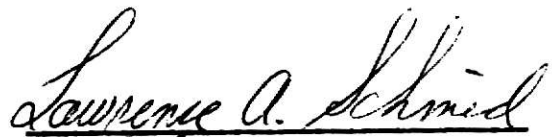
MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1972

Approved by:


Major Professor

LD
2668
R4
1972
L43
C. 2

TABLE OF CONTENTS

INTRODUCTION	1
LITERATURE REVIEW	3
Description of the Trickling Filter	
Trickling Filter Kinetics	
PLANT OPERATION	24
General Description of the Plant	
Flow Control and Measurement	
Sampling Procedures	
RESULTS	27
Characteristics of Wastewater	
The Development of Prediction Equation	
DISCUSSION	37
CONCLUSIONS	42
BIBLIOGRAPHY	44
APPENDIX I	47
APPENDIX II	48
APPENDIX III	49

ACKNOWLEDGMENTS

I wish to sincerely thank Dr. Lawrence A. Schmid, my major professor, for his help and support during my study. I am grateful to Dr. Douglas A. Wallace for his help in directing this study and in developing the computer programs required. I am also grateful to Dr. Jack B. Blackburn, Head of the Department of Civil Engineering, Dr. Larry Erickson, Dr. Louis R. Fina, and Professor Ralph I. Lipper for serving on the review committee.

INTRODUCTION

The trickling filter process is one of the most commonly applied methods of biological treatment of municipal wastewater. This and the activated sludge process account for practically all of the currently used biological treatment methods. The primary reason for the popularity of the rock trickling filter is the low operation cost and the simplicity of operation. A trickling filter with field stone as filter media was introduced to Taiwan when the capital of the provincial government was relocated in 1957. A community named Chunghsin Village was developed. A waste treatment plant to serve it was completed in 1959. The laboratory was set up not only for controlling the operation but for collecting the data in order to provide a reliable and practical reference for future design. Since then, daily sampling and daily experiments have been done in the plant. The records have been calculated on the basis of monthly average in terms of BOD (Biochemical Oxygen Demand), SS(Suspended Solids), pH, temperature, flow rate, etc., at the influent and effluent of the facilities, such as the primary clarifier, trickling filter, and final clarifier. The plant treats the domestic wastewater from the administration building and residential area of the community with a total population of 12,000.

Because of the favorable conditions of subtropical climate and the ready availability of rock filter media, trickling filters play an important role in the field of wastewater treatment process design in Taiwan. It therefore seems to be a suitable time for studying the performance formulation of the trickling filter and, subsequently, the characteristics of domestic waste-

water along with the operation data in order to provide a contribution to future work in Taiwan.

In regards to the performance formulation of the trickling filter as recently as 1962, R. E. McKinney (1) stated that

Thus far, the theoretical aspects of trickling filters have not progressed to the point where the engineer can design a filter for a given waste and predict in advance the results to be expected. The number of variables and their interrelationships in trickling filter design have complicated the development of a complete fundamental theory. The development of a sound fundamental theory for trickling filters is one of the great uncharted areas of research.

Since then, many attempts have been made to predict trickling filter formulas, but all formulations are based on laboratory and pilot plant investigations which usually proceed under controlled conditions and are frequently not directly analogous to conditions in existing plants.

The objectives of this study are: (1) to determine the characteristics of the raw wastewater; (2) to evaluate the performance of operation of the plant; (3) to predict the performance formulation of the trickling filter based on a study of the various formulas which have been proposed.

LITERATURE REVIEW

Description of the Trickling Filter

From the first trickling filter constructed in England in the 1890's, many different types have developed. In general, the trickling filter can be separated into three elements: (1) the media bed, (2) the method of distribution of the wastewater over the surface of the bed, and (3) the underdrain, which collects the treated water from the bottom of the media and carries it away from the filter (see Fig. 1).

Historically, the media of the filter bed has been crushed stone or gravel. More recently, new plastics and related materials have been used. On occasion, hard coal, coke, cinders, clay, wood, and ceramic materials have been used. However, the majority of trickling filters in existence have crushed rock media.

Early trickling filters were rectangular in shape. Wastewater was applied to the filter through nozzles fixed to the surface of the filter. Flow was regulated by dosing siphons, 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 micro-organisms rest and an aeration period 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 nozzles attached horizontally to the distributor arms which spread the wastewater over the surface. Intermittent

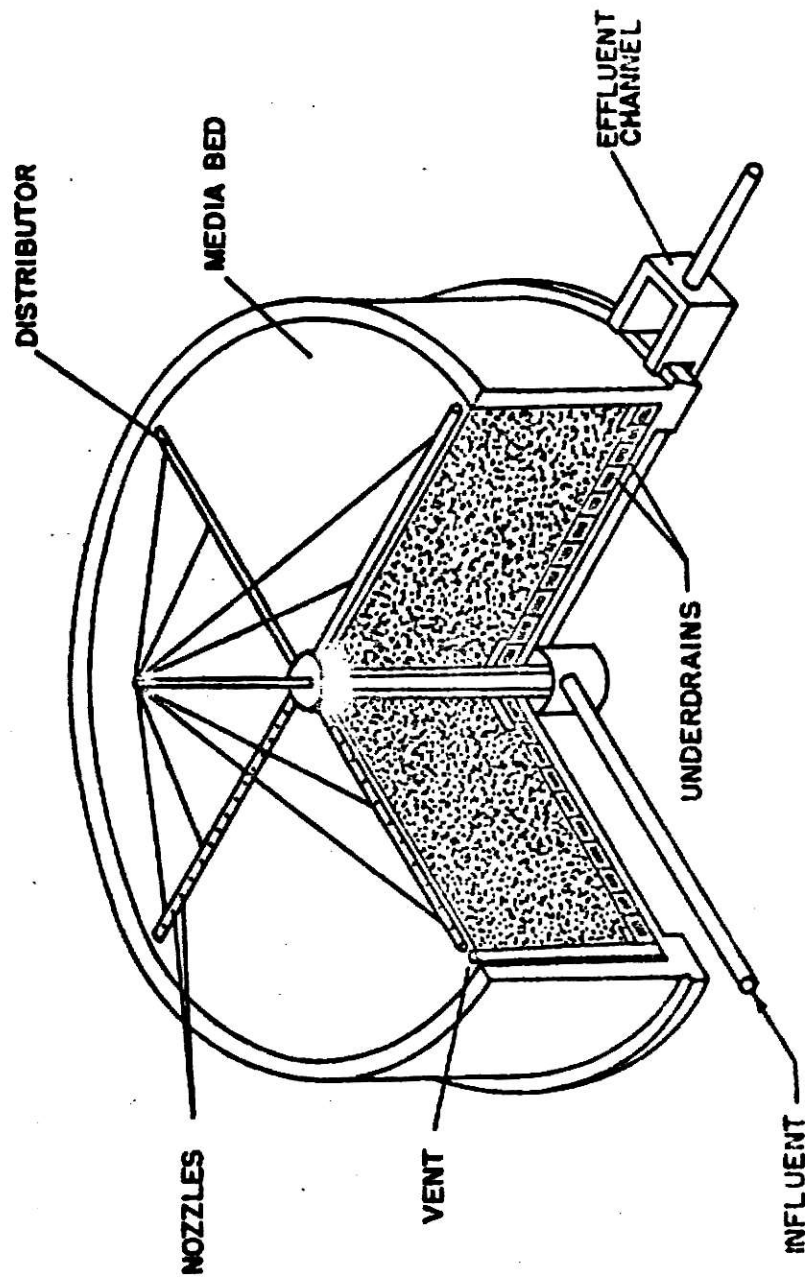


FIG.1 A TYPICAL TRICKLING FILTER

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 supplemented by the circular type with rotary distribution.

The underdrain collects the treated wastewater and conveys it to the filter effluent channel. Today, underdrains are usually specially made filter blocks of vitrified clay or concrete. 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 treatment which includes screening, 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 basin flows through the secondary treatment section. This includes the trickling filter 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 by the ability of the unit to remove waste from the wastewater. The established method of determining the strength of a wastewater is the 5-day biochemical oxygen demand (BOD) determination. 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 reduction of BOD concentration through the unit.

The applied BOD and the amount removed by trickling filters 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

$$W = 8.34 L_1 Q$$

where

W = the organic load, lb/day.

Q = the hydraulic flow rate, million gallons/day.

L_1 = the 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.

Mechanism of the Trickling Filter Treatment Process

The trickling filter waste treatment system comprises a fixed bed (film

flow) reactor and a clarifier. The clarifier is used for settling the filter humus that sloughs off the trickling filter. The mechanism of waste removal by the microorganisms in the fixed bed reactor has been described conventionally as "under favorable environmental conditions the zoogaea absorb and utilize suspended, colloidal and dissolved organic matter from the wastewater which passes in a relatively thin film over its surface (3)." The phenomenon was stated by W. W. Eckenfelder (4) as biosorption and coagulation.

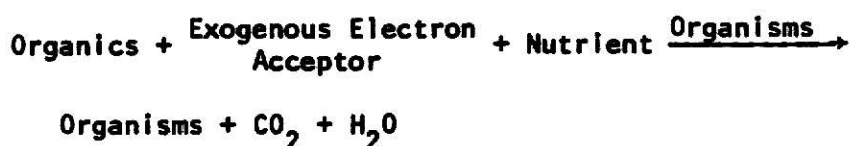
The mechanism of a fluid bed reactor is very complicated. Some interpretations have been proposed for two possible mechanisms. The first, as stated by G. M. Fair and J. C. Geyer (5):

The most important element of biological flocculation and precipitation would appear to be the transfer of the pollutorial load to the film. There it undergoes decomposition commensurate with the duration of its storage and releases its end products to the atmosphere or to the wastewater that washes it.

The second, as suggested by C. F. Gurnham (6) is that the process of removal is essentially due to high rates of oxidation at the surface of the film on the filter media. The concepts of removal and storage have been originally described by E. B. Phelps (7) and commented on by C. E. Renn, and advanced by R. E. McKinney.

Until 1963, the fundamental interpretation was proposed that atmospheric oxygen is transferred to the microbial mass through a liquid film. Hydrodynamically, the system may be represented as a gravity liquid flow over a surface as shown in Figure 2.

Swilley (8) proposed the trickling filter as a film flow reactor and for different controlling mechanisms and kinetics to be generalized as:



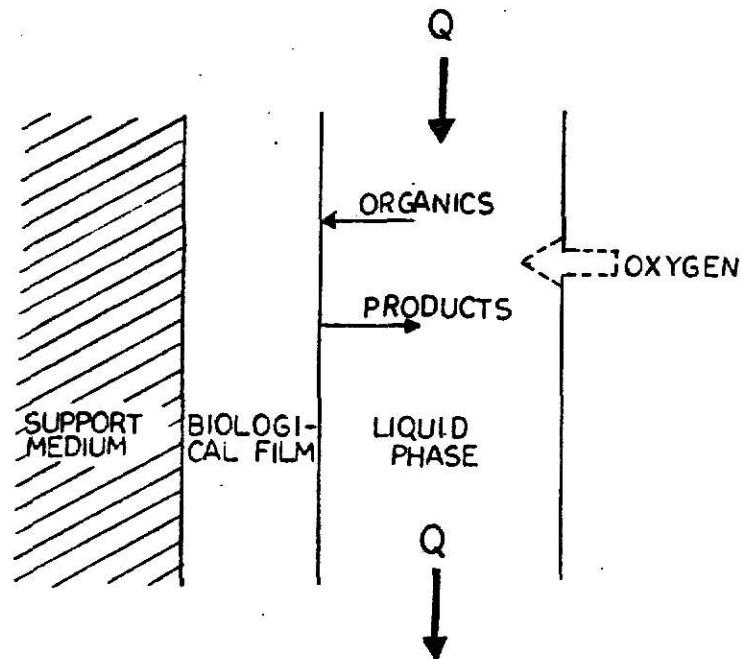


FIG.2 SCHEMATIC OF REACTION

Essentially the reaction occurring in the film can be described by a first order reaction and represented by an irreversible reaction as:



A is the incoming organic substrate to the reactor, B is the exogenous hydrogen acceptor, and C is the desired product.

The amount of film substance retained in trickling filters and the length of time during which transferred substances undergo decomposition is a function of (1) temperature, BOD, and rate of activity; (2) area dimensions of the supporting surface and their exposure to moving liquid films or masses; (3) such scour as may be engendered by the moving fluids; and (4) the rate of diffusion of oxygen into the accumulating film (9).

Trickling Filter Kinetics

Early experiments and observations regarding the high rate trickling filter were made by Mahlman (10), Halvorson (11), and Herrick (12). Their results were summarized by Stanley (13) as showing that the high rate filters produced an inferior BOD removal and, consequently, inferior effluent quality as compared to standard rate filters. It was noted that a possible combination of a high-rate filter and additional treatment might improve the economics of treatment.

In Baltimore in 1938-1939, Keefer and Kratz (14) made experiments on a portion of a large old standard-rate trickling filter with fixed nozzles, which was converted to rotary distributors. The results indicated that the 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 wastewater 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 layer of the filter. These results did not include the effect of final sedimentation following the filter. They concluded that as rate of flow increases, an increase in effluent BOD will result, accompanied by a decrease in nitrates of the effluent.

In 1942 Horton, Porges, and Baily (15) reported 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 mainly dependent upon time of contact between the wastewater and the microorganism in the filter bed. With recirculation of unsettled filter effluent, efficiency increased until the recirculation ratio reached 5. High ratios gave a decrease in efficiency.

It was postulated that the effect of recirculation of unsettled filter effluent was to seed the influent sewage and provide solids contact somewhat similar to the activated sludge process. In the studies, time of contact was shown to depend upon the hydraulic flow rate through the filter.

In 1946 the Committee on Sanitary Engineering of the National Research Council (16) presented the results from a study of sewage treatment plants at military installations all over the United States. The data was collected from 34 plants. A statistical study was made for the expression of efficiency in trickling filter performance. The efficiency of biological sewage treatment was pointed out to be dependent upon (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 the growth and sewage, and (6) provision for settling of agglomerated materials and detached excessive growths. On the basis of results shown, both organic loading (lb BOD/acre-foot) and hydraulic loading [million gallons per acre per day (mgad)] are significant, and the former has greater influence upon efficiency in trickling filters. The equation for per cent efficiency which fits the curve of results is:

$$E = \frac{1}{1 + C\sqrt{\frac{W}{VF}}}$$

where

E = the fraction of BOD removed

C = the constant, equal to 0.0085 in acre ft, or 0.0561 for value in thousands of cu ft

W = organic loading, lbs/day

V = the volume of media

F = the recirculation ratio and the number of passes through filter,
as follows:

$$F = \frac{1 + \frac{R}{I}}{[1 + (1 - p) \frac{R}{I}]^2}$$

R = the volume of recirculated effluent in mgd

I = the influent of settled sewage in mgd

p = a weighting factor which reflects the amount and availability
of organic matter remaining after each passage relative to the
individual amount; this value ranges from 0.81 to 0.95, with
an average value of 0.90.

An examination of data used for developing the foregoing formulations and the theoretical curve, which shows a wide scattering of points about the curve, leads one to believe that there is a need for improvement in empirical methods to determine BOD reduction in trickling filters.

In 1948, C. J. Velz (17) recognized that the explanation of the performance of biological beds is similar to the biological oxidation law developed by Phelps, and may be expressed in differential form as:

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

Velz postulated that "the rate of extraction of organic matter per interval of depth of a biological bed is proportional to the remaining concentration of organic matter, measured in terms of its removability." Then, the

Phelps equation can be integrated to

$$\frac{L_D}{L} = e^{-KD}$$

whence

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

where

L = the total removable fraction of BOD

D = the depth

L_D = the corresponding quantity of removable BOD at depth D

k = the rate of extraction, base 10.

In application of the foregoing formula, the removable fraction of BOD, L, and the rate of extraction, k, must be determined empirically. Velz stated that the removable load is a function of the rate of biological oxidation and the storage capacity for accumulation of organic matter within the bed. Since biological oxidation is a function of temperature, L is lower in cold weather and higher in hot weather, with the exception of equilibrium loadings. The values for k for a 460 gal/day/ft² plant at New Jersey were determined to be 0.1505 for the high rate filter and 0.175 for the low rate filter with an L of 0.784.

In 1953, R. S. Rankin (18) compared the actual performance of several plants to the results 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 a formula based on these standards. For a single-stage trickling

filter including final settling, the efficiency of BOD removal is given by

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

where

L_e = BOD of settled filter effluent

L_i = BOD of primary settling effluent

R = recirculation ratio

Rankin demonstrated that the Velz formula gave results closest to the actual performance, the Standards, the next closest, and the National Research Council, the least close. 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 had no significant effect on efficiency in his study.

In 1956, J. M. Fairall (19) proposed empirical formulas on the basis of a statistical correlation from 44 trickling filter loading and performance data in the area of the Upper Mississippi Valley. The formulas are shown as:

For filters without recirculation

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

where

n = the fraction of BOD in settled raw sewage remaining in the following clarifier effluent

V = the volume of filter media (1,000 cu ft)

Q = the plant hydraulic flow rate (mgd).

For filters with recirculation

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

where

R = the recirculation ratio.

In 1957, V. T. Stack, Jr., (20) developed a theoretical formula for the performance of the trickling filter process. The theoretical derivations were 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 the unit depth, (3) removable BOD is the fraction of the observed BOD which can be removed by biosorption, (4) the quantity of BOD that can be absorbed by one unit volume of a filter has a maximum limit. Stack derived an equation for the performance of a trickling filter operated with no recirculation and expressed it as:

$$L_r = XfS + f(L - XfS) \left[1 + (1-f) + (1-f)^2 + (1-f)^3 + \dots + (1-f)^{D-X-1} \right]$$

where

L_r = the removal of removable BOD

X = the number of unit volumes saturated by a given load of BOD

f = the coefficient of biosorption; it is related to Velz's theory
as $f = 1 - 10^{-k}$

S = load of removable BOD which must be applied to saturate one
unit depth with BOD

L = the applied load of removable BOD

D = the filter depth.

The theoretical expression for a trickling filter operated with recirculation and at a loading less than the applied load which will saturate one unit depth is equal to

$$\frac{(R + 1) c f L}{1 + R c f}$$

where

R = the recirculation ratio. The values of removable BOD, f , and s must be determined empirically.

When Stack modified the Velz's law to incorporate recirculation, the total organic removal could be expressed as:

$$L_r = \frac{r L_i (1 + \frac{R}{I})}{(1 + r \frac{R}{I})}$$

where

L_r = the total organic removal

$r L_i$ = the organic removed first passage

R = the recirculation flow

I = the settled sewage flow.

In 1958, W. E. Howland (21) derived a mathematical expression for the time of fluid flow over a sphere, which resembles the flow of wastewater through the porous media in a trickling filter. In application, he concluded that the time of travel through a trickling filter might vary inversely with the two-thirds power of the liquid rate of application, and directly with the depth, D , of the filter and with a correction factor for the effect of temperature of 1.035^{T-20} . The expression is shown as:

$$X = 1.035^{T-20} \cdot \frac{D}{Q_a}^{\frac{2}{3}}$$

where

X = the time of travel

T = temperature in degrees centigrade

D = depth

Q_a = rate of flow of sewage in a filter per horizontal area of filter (mgad).

The effect of an intermittent period of discharge between passes of the distributor arm, according to Howland's analysis, has the same effect in improving the quality of the effluent as would an increase in the depth of the filter. It tends to equalize the rate of flow and has an important effect in pulling down air into the filter. However, he indicated that intermittent discharge is beneficial to the aeration of a filter.

The effect of recirculation is described as affecting the thickness of the "flowing film" which will vary with recirculation as $(1 + p)^{1/3}$ (p = recirculation ratio). The expression for the time of flow which included the recirculation is as shown:

$$X = (1.035^{T-20} \cdot \frac{D}{Q_a}^{\frac{2}{3}}) (1 + p)^{\frac{1}{3}}$$

Furthermore, Howland explained there is another way to set up the effect of recirculation as a function of time of flow. It is assumed that the total liquid rate of flow applied to the trickling filter is a homogeneous matter which can be described by an average concentration, L_i , while the effluent concentration is L_e . Thus, the concentration of the applied flow is

$$L_o = \frac{L_i + PL_e}{1 + P}$$

where

P = the recirculation ratio as stated previously.

In 1959, W. T. Ingram (22) reported the results of filtration experiments which were made with deep filters of 12 inches diameter and 18 feet in depth. The filters were built as single columns and were separated into six sections, each 3 feet deep. Air was supplied from the bottom of each section. Ingram concluded that the non-removable BOD can be removed with increased depth and that the temperature undoubtedly has some effect on the performance. His studies also indicated that the organic loading of a filter is much more important than the hydraulic loading.

In 1960, K. L. Schulze (23, 24, 25) conducted studies with a series of one-half inch mesh vertical screens which served as media. His analysis of the fraction of influent BOD remaining in the filter effluent was as shown:

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

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

Schulze derived values of the constants c and K as 0.67 and 0.079, respectively. It is noted that the value of c is the same as that of Howland in his expression for contact time, that is, $t = \frac{D^{2/3}}{Q}$. The value was also confirmed by studies of Bloodgood, Teletzke, and Pohland (26).

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

$$\frac{L_e}{L_i} = e^{-Kt}$$

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

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

Converting to base 10 logarithms:

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

Schulze determined that the value of k ranged between 0.22 and 0.33, and suggested that $K_{20} = 0.30$ be used. In consideration of the temperature effect, the equation became

$$\frac{L_e}{L_i} = 10^{-bK_{20}D/(Q/A)^{2/3}}$$

where

$$b = 1.035^{T-20}$$

Schulze also stated that the trickling filter process appears as an adsorption process where hydraulic load determines contact time and this in

turn determines the level of efficiency.

In 1961, W. W. Eckenfelder, Jr. (4) presented a formulation on the basis of Velz's law, an extension of the Howland and Schulze equation. This included a consideration of the type of filter media and the hydraulic characteristics of the filter yield as was shown

$$\frac{L_e}{L_i} = e^{(-K) (1/D^m) (D/Q^n)} = e^{(-KD^{1-m})/Q^n}$$

where the exponent $1-m$ is the coefficient which relates the type of filter media and the hydraulic characteristics of the filter. This exponent becomes 1.0 when the biological film is approximately uniformly distributed throughout the filter depth. Usually the exponent is less than 1.0.

In order to determine a formulation applicable to the design, the formula expressed as overall removal is:

$$\frac{L_e}{L_i} = \frac{100}{1 + \frac{CD^{1-m}}{Q^n}}$$

where

L_e = the BOD remaining in effluent, (mg/l)

L_i = BOD of influent, (mg/l)

D = depth, (ft)

Q = flow, (mgad)

C = constant

$1-m$ = constant

n = constant.

The constant C and the exponents $(1-m)$ and n were determined by multiple re-

gression analysis as 2.5, 0.67 and 0.50, respectively.

Eckenfelder assumed that the effect of recirculation is to dilute the Influent BOD, as given by Howland; that is

$$L_o = \frac{L_a + RL_e}{1 + R}$$

and the equation became:

$$\frac{L_e}{L_a} = \frac{1}{1 + R(1 + \frac{CD^{1-m}}{Q^n}) - R}$$

In 1964, Galler and Gotaas (27) developed a mathematical model using 322 sets of data from the literature that described the reduction of BOD in the waste liquid as it passed through a trickling filter in terms of five physical parameters. These parameters were depth, hydraulic rate, temperature, recirculation volume, and organic loading. Letting the BOD remaining in the effluent of the trickling filter be the dependent variable and using multiple regression analysis, an equation was derived as follows:

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

where

L_e = BOD remaining in the effluent, (mg/l)

L_o = BOD in the Influent, (mg/l)

R = recirculation ratio

Q = flow rate, (mgad)

D = depth, (ft)

T = temperature, (°C)

Galler stated that the depth contributed significantly to the BOD reduction. An exponent of 0.67 was obtained which agreed with Eckenfelder's. Temperature was included as a parameter as in Velz's and Howland's conclusion. Galler and Gotaas also postulated that the recirculation of effluent can improve the quality of the plant discharge, but a practical limit of about 4 to 1 exists. Although the hydraulic loading was included in the equation, the results of his work show that it is not an important factor in determining the fraction of BOD remaining in the trickling filter effluent. This contradicts those who proposed the hydraulic loading as the controlling factor.

In 1966, Galler and Gotaas (28) proposed a method for the optimum design of trickling filters which was used to minimize the cost of the wall, floor, media, distribution system, power for recirculation pumping, pumps, and annual costs. The results of their studies showed that deep filters with forced air ventilation were more economical than shallow filters for reduction of BOD when there was no need to pump the influent to the top of the filter.

In 1966, J. E. Germain (29) reported that BOD removal by plastic media trickling filters would follow the equations 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.

In 1968, J. M. Baker and Q. B. Graves (30) in their study of the design formulas of the National Research Council, the Eckenfelder formula, and the Galler-Gotaas formula noted that the dimension of these formulas is time. It

has been shown that the NRC and Eckenfelder formulas have the same dimensional form, that is

$$E = \frac{t}{1 + t}$$

where

E = the efficiency of the trickling filter

t = time of contact.

The dimensional form of the Galler-Gotaas formula has been shown as

$$E = 1 - \frac{1}{t}.$$

Instead of the efficiency term as in the formula of the NRC, Eckenfelder and Galler-Gotaas used the term of required trickling filter volume for optimum practical design. They noted: (1) In the NRC formula, volume varies directly with flow rate, influent BOD, and recirculation; the volume will decrease with a greater recirculation ratio to a maximum ratio of 8; (2) in the Eckenfelder formula, volume varies directly with flow rate, recirculation and depth; recirculation reaches a practical limit at a ratio of 4 to 5; (3) in Galler-Gotaas formula, volume is a function of flow rate, influent BOD, filter depth, recirculation and temperature. The recirculation and efficiency are independent. A decrease in volume with increased recirculation is shown only with higher efficiency.

In 1969, S. B. Balakrishman and W. W. Eckenfelder (31, 32, 33) modified the original Eckenfelder equation for BOD removal and nitrification. The modified equation is:

$$\frac{L_e}{L_o} = e^{-K_s A v^m D/Q^n}$$

or

$$\frac{L_e}{L_o} = e^{-Ks' D/Q^n}$$

in which $Ks' = Ks Av^n$

where

L_e = the BOD remaining in the effluent

L_o = the applied BOD concentration

Av = the specific surface, (ft²/ft³)

Ks' = a constant, for domestic sewage at 20° C is given by

$$Ks' = 0.0362 Av^{0.664} L_o^{0.54}$$

They also modified the temperature effect for BOD removal. The modified formula became:

$$E_T = 1 - e^{-Ks' 20^\circ C (1.035)^{T-20} D/Q^n}$$

Due to the increased sensitivity of nitrifying bacteria to temperature, the resulting efficiency for the nitrification relationship is

$$E_T = 1 - e^{-Ks' 20^\circ C (1.070)^{T-20} D/Q^n}$$

PLANT OPERATION

General Description of the Plant

The treatment plant was completed in 1959 to treat 0.6 MGD of domestic wastewater from a population of 12,000. For the purpose of design, the 5-day BOD and suspended solids of the raw wastewater were estimated at 400 mg/l and 450 mg/l, respectively and, thus, the daily BOD₅ load and suspended solids at 2,000 lb and 2,250 lb, respectively. An overall removal of 90% BOD₅ and 80% S.S. was assumed. The expected BOD₅ and S.S. of the plant effluent were then calculated to be 40 mg/l and 54 mg/l.

The primary treatment facilities consisted of the following units: bar-screens with 1 inch spacing, inclined downstream at an angle of 30° from the horizontal; two grit chambers in parallel with a proportional weir, and with 1 ft per second of flow velocity and 20 seconds of detention time; two rectangular hopper-bottomed automatic belt scraper primary settling basins in parallel with 600 gal/ft²/day overflow rate and 2 hours of detention time. It was assumed that the percentage removal of BOD₅ and S.S. in primary treatment would be 35% and 50%, respectively. The sludge from the primary settling basins is pumped to one circular anaerobic digester with 56 days of detention time. The sewage from the basins is pumped to the trickling filter process for further treatment.

The trickling filter process is one trickling filter followed by one final settling basin. The high rate trickling filter is circular, 51 ft in diameter and 3 ft in depth. It is provided with a four-arm rotary distributor that distributes the flow over the filter media. It was assumed that the

filter would treat 200 lb of BOD_5 /1,000 cu ft/day with a flow rate of 40 mgd/acre. The recirculation ratio was 2:1. Recirculation flow was before the final settling basin. It was assumed that the reduction percentage of BOD_5 in the filter and the final settling tank was 64%. The final settling basin is circular with an automatic sludge scraper. The overflow rate and the detention time of the basin is 860 gal/sq ft/day and 1.5 hours, respectively.

Flow Control and Measurement

Wastewater flow was regulated at a control manhole at the entrance to the plant, where a 16-inch main sewer was intercepted. The flow was measured by an automatic flow meter with parshall flume.

Recirculation, measured by the drop in water level in the recirculation compartment, was adjusted to a constant 2:1 ratio by means of a gate valve in the recirculation line.

Sampling Procedures

Wastewater samples were collected regularly by catching a sample at the following points: (1) raw sewage inlet, (2) effluent channel of the primary settling basins, (3) effluent channel of the trickling filter, and (4) effluent channel of the final settling basin. The times of sampling were determined by the result of dispersion tests. Fractional samples were collected twice a day, and composited according to flow. At the end of sampling, the samples were brought to the laboratory for analysis. The samples were measured for temperature; total, volatile, soluble, and suspended solids; chloride and chlorine requirement; free ammonia nitrogen and protein nitrogen; pH and BOD_5 . The analytical methods were conducted according to the Tenth Edition of Standard Method for the Examination of Water and Wastewater.

The samples have been collected since a laboratory was built in 1959.
The experimental data has been computed into monthly averages since 1965.

RESULTS

Characteristics of Wastewater

The design and the operation of the trickling filter process depends upon the characteristics of the raw and settled wastewater and, thus, on the living characteristics of the community. For Taiwan communities, sufficient information on such characteristics is not available. The analytical data of the plant from 1965 to 1970 provides some valuable information regarding the operation of the existing plant and the design of future trickling filter processes in Taiwan.

The composite samples were collected over six years. The figures given in TABLE 1 represent the maximum, minimum, arithmetic average, and mean values of major constituents of raw wastewater on the basis of monthly values in the given years.

The variation of BOD_5 and suspended solids concentration of the raw wastewater with months are shown in Figures 3 and 4.

Performance of the Plant

The performance data are indispensable information for evaluating the operation of the plant and for development of a prediction equation in the following section. TABLE 2 gives the performance data of S S and BOD_5 for the primary settling, trickling filter and trickling filter including final settling basin of the plant on the basis of arithmetic average from 1965 to 1970. Figure 5 gives the variation of the free ammonia nitrogen and organic nitrogen throughout the process.

TABLE I
THE CHARACTERISTICS OF RAW WASTEWATER
OF CHUNGHSIN PLANT, 1965-1970

Constituent	No. of data	Maximum	Minimum	Average	Mean	Standard Deviation
Temperature	72	28	19	24	23.66- 24.34	2.23
pH	72	8.10	7.00	7.41	7.37- 7.45	0.21
Total solid	72	810	474	564	551.20-576.80	65.06
Volatile solid	72	518	209	305	293.54-316.46	58.27
Dissolved solid	72	409	319	384	377.02-390.98	35.51
Suspended solid	72	320	103	184	175.31-192.69	44.17
Chloride	72	40	23	30	29.14- 30.86	4.38
Chlorine Requirement	72	23	9	14	13.16- 14.84	4.27
Ammonia--N	72	48	20	32	31.14- 32.86	4.39
Organic--N	72	12	4	6	5.51- 6.49	2.53
BOD ₅	72	188	62	127	122.48-131.52	22.97

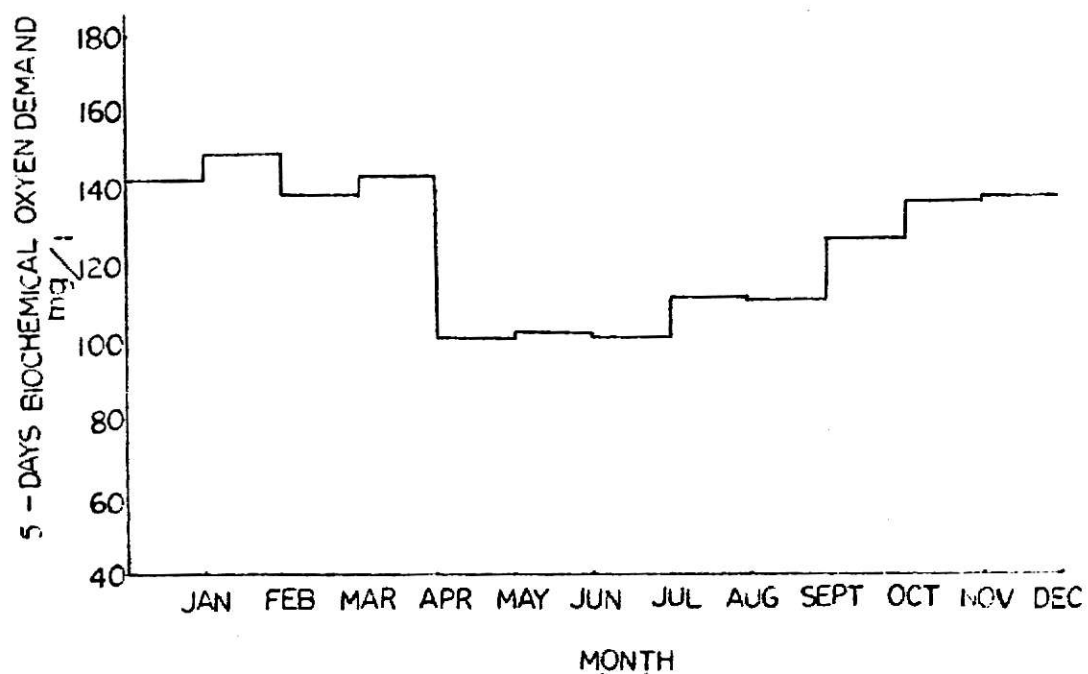


FIG.3 THE VARIATIONS OF BOD₅ WITH MONTH
FROM 1965 TO 1970

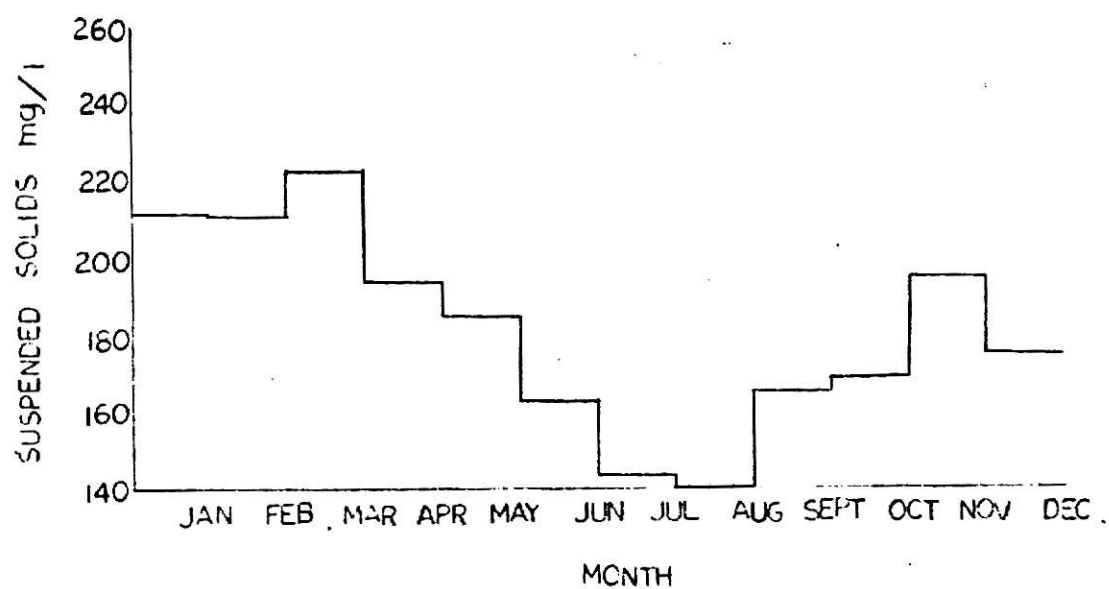


FIG.4 THE VARIATION OF S.S. WITH MONTH
FROM 1965 TO 1970

TABLE 2

THE PERFORMANCE DATA OF CHUNGHSIN PLANT
1965-1970

Year	Suspended Solid				5-day Biochemical Oxygen Demand										
	Raw waste water	Primary settling	Trickling filter only	T. F. including F. S.	Raw waste water	Primary settling	Trickling filter only	T. F. including F. S.	Over- all Eff. %						
	mg/l	Eff. %	mg/l	Eff. %	mg/l	Eff. %	mg/l	Eff. %							
1965	197	60	69.54	53	11.69	37	38.33	143	84	41.25	40	52.40	31	63.09	79.00
1966	185	73	60.54	65	10.95	58	20.54	133	79	40.60	39	50.60	30	70.00	77.50
1967	152	42	72.36	39	7.15	28	33.33	125	75	40.00	36	52.00	28	62.66	84.60
1968	164	50	69.51	44	13.62	35	30.00	112	64	42.85	32	50.00	21	67.18	81.40
1969	207	61	70.53	47	24.00	40	34.42	137	66	51.82	36	45.50	26	60.60	81.00
1970	180	66	63.33	42	36.40	35	46.96	115	80	30.43	46	42.50	37	53.75	67.80
Avg.	180	58	67.77	48	17.24	38	34.48	127	74	41.73	38	48.60	28	62.16	78.00

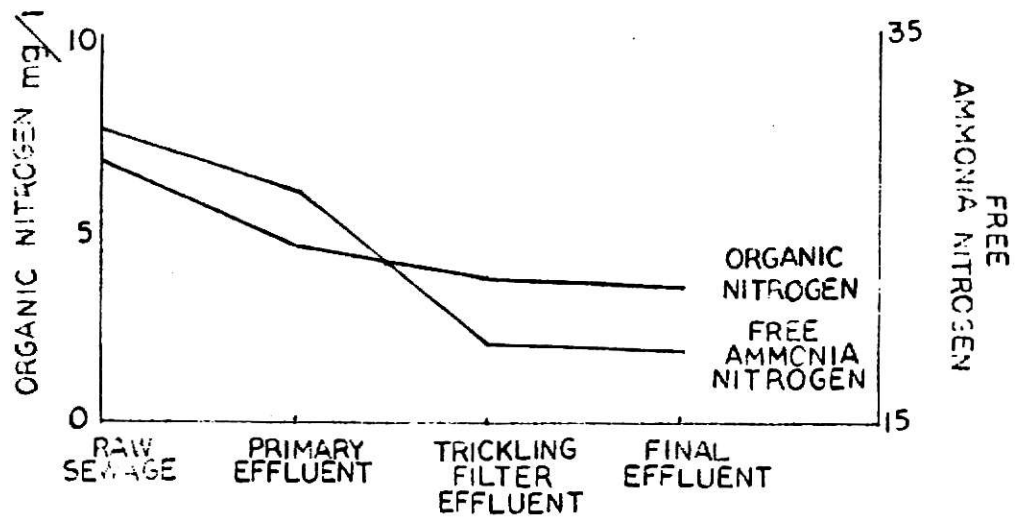


FIG.5 NITROGEN CHANGES IN PROCESS

The Development of Prediction Equation

As stated previously, there have been many attempts at formulating the performance equation for the trickling filter process. There are many factors which complicate attempts to develop generalized formulations. None of them can evaluate the performance of the existing plants completely. The National Research Council equation is the first formulation which was developed and, thus, it is widely applied in the field. Eckenfelder's formulation is the first attempt to include the known factors up to 1960 on the basis of the concept of biological oxidation. The Galler and Gotaas formulation is the most recent one and includes many more factors than any of the previous ones. These three formulations were adopted for evaluating the performance of the plant operation in terms of BOD_5 remaining in the effluent. The three equations that were employed are:

National Research Council Formula

$$L_e = L_o - \frac{L_o}{1 + 0.0561 \left(\frac{W}{VF} \right)^{0.5}}$$

$$F = \frac{1 + R}{[1 + (1 - p) R]^2}$$

where

L_e = the BOD₅ remaining in the effluent, (mg/l)

L_o = the BOD₅ in the Influent, (mg/l)

W = organic loading, lbs/day

V = volume of media, 1,000 cu ft

F = recirculation factor

R = recirculation ratio

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

W. W. Eckenfelder, Jr., Formula

$$L_e = \frac{L_o}{(1 + R) \left(1 + 2.5 \frac{D^{0.67}}{Q^{0.50}}\right) - R}$$

where

L_o = the BOD₅ remaining in the effluent, (mg/l)

L_e = the BOD₅ in the Influent, (mg/l)

R = recirculation ratio

Q = flow rate, (mgd)

D = depth, (ft)

Galler and Gotaas Formula

$$L_e = \frac{0.464 L_o^{1.19} (1 + R)^{0.28} Q^{0.13}}{(1 + D)^{0.67} T^{0.15}}$$

where

L_e = the BOD₅ remaining in the effluent, (mg/l)

L_o = the BOD_5 in the influent, (mg/l)

R = recirculation ratio

Q = flow rate, (mgad)

D = depth, (ft)

T = temperature, ($^{\circ}C$)

The results obtained from the three equations were computed with the IBM 360/50 computer. (The program is given in Appendix I.) Figure 6 shows the comparative graphs with the actual values of BOD_5 remaining in the effluent.

Figure 6 reveals the various trends in comparison to the actual values. The results of the Galler and Gotaas equation is the closest one of the three. The National Research Council's is the next, and Eckenfelder's is the last. The parameters included in the Galler and Gotaas equation are organic concentration in the influent, the recirculation ratio, the flow rate, the depth and the temperature. It was derived from 322 observations. A regression analysis was conducted on the observations as stated previously. Thus, it is believed that development of prediction equation from the operational data of the plant on the basis of the Galler-Gotaas formulation is preferable.

Some variables which were included in the Galler and Gotaas equation are constant in this existing plant, such as the depth and the recirculation ratio. The variables that can be counted are organic concentration, the flow rate, and the temperature. Thus a multiple regression equation for the fraction of BOD_5 remaining in the effluent was formed as:

$$\log L_e = \log C + A_1 \log L_o + A_2 \log Q + A_3 \log T$$

in which A_1 , A_2 , and A_3 are the partial regression coefficients, $\log C$ is the intercept value, the variables of L_o , Q and T are organic concentration (mg/l),

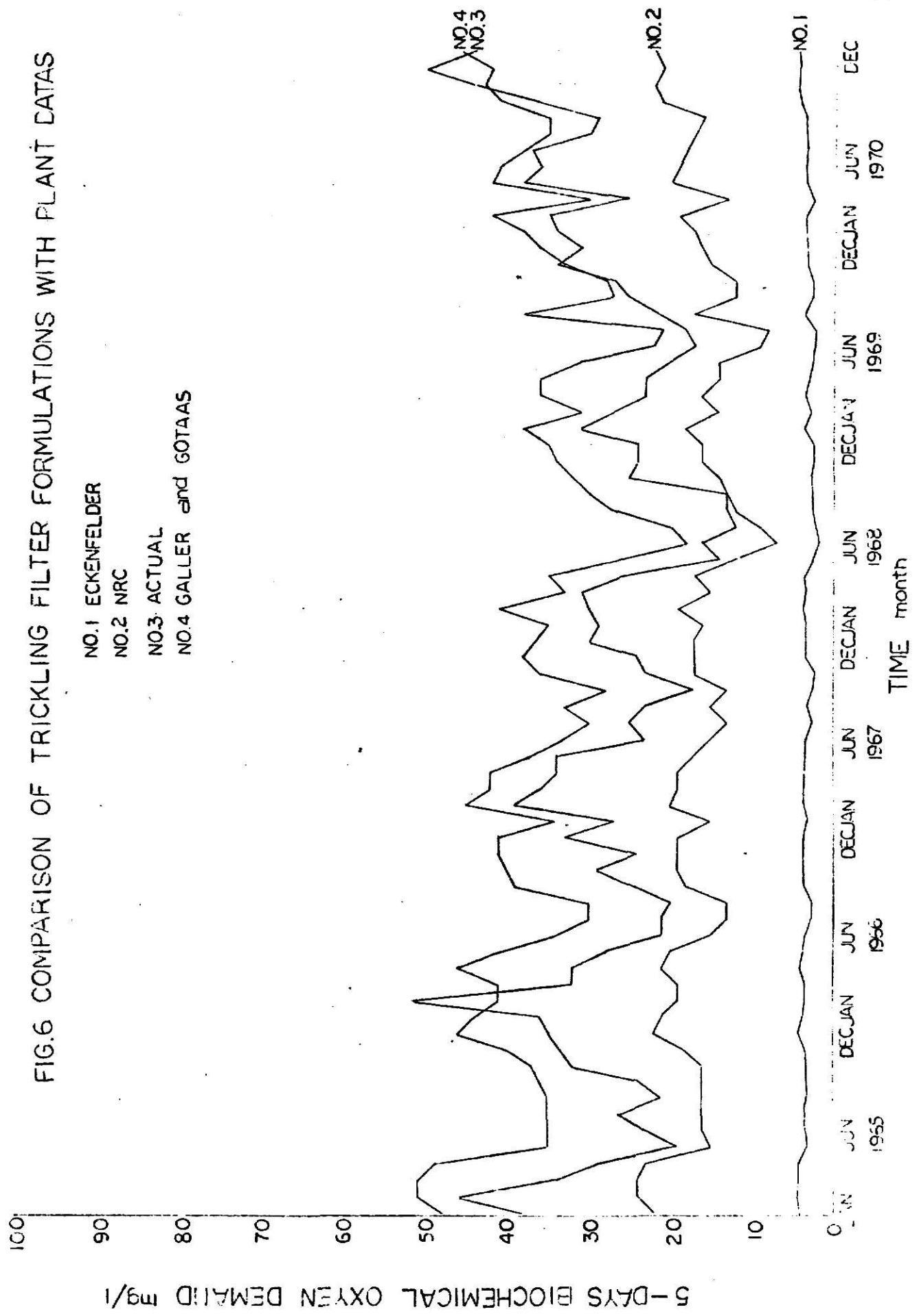


FIG.6 COMPARISON OF TRICKLING FILTER FORMULATIONS WITH PLANT DATAS

flow rate (MGAD), and temperature ($^{\circ}\text{C}$), respectively.

A regression analysis was conducted on the operation data. This was done on the IBM 360/50 computer using a general purpose multiple regression program. The equation determined by the analysis considering BOD_5 in terms of mg/l is:

$$L_e = \frac{0.0758 L_o^{1.41} Q^{0.40}}{T^{0.37}}$$

which has a multiple correlation coefficient for this data of 0.80.

Comparing this with the actual operation values of BOD_5 remaining in the effluent, the results obtained from this equation were computed. This was done on the IBM 360/50 computer. (The program is given in Appendix III.) Figure 7 gives the comparative graphs and the effect of the variables organic concentration, temperature and flow rate. The difference in the figures will be discussed in the subsequent section.

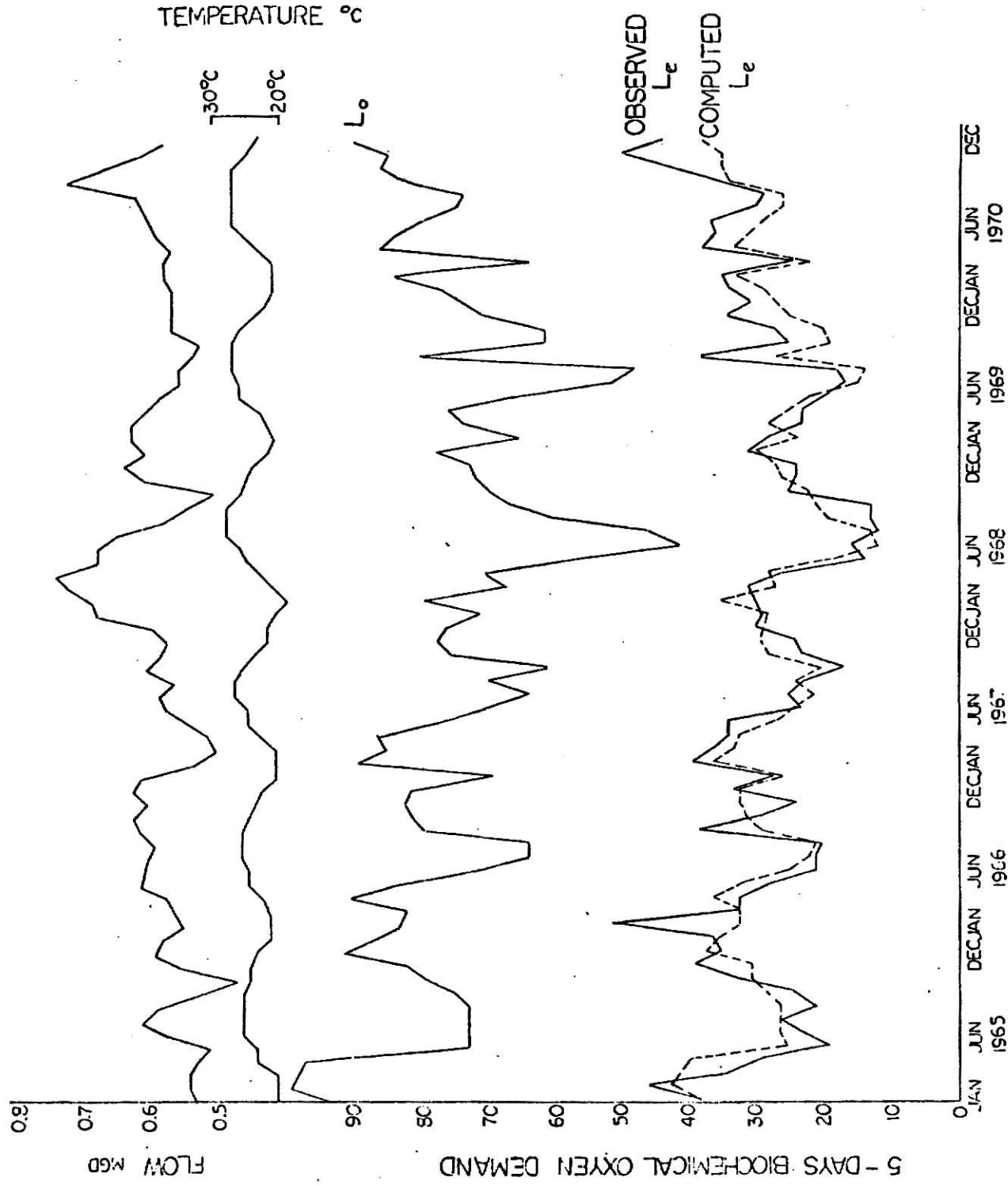


FIG.7 COMPARISON OF THE DEVELOPED EQUATION WITH PLANT DATAS

DISCUSSION

As pointed out earlier, determination of the characteristics of wastewater is essential to the proper design of a treatment plant. This point becomes much more obvious in trickling filter processes. As is well known, the process depends on transport of oxygen and substrate to the organisms. There is a maximum quantity of BOD which can be assimilated by the biological life of the bed. In the previous kinetic study, as Rankin (34) pointed out, the NRC formula was developed on filters with BOD loading of about 8,000 lb per acre-ft. W. W. Eckenfelder (4) noted that at the low BOD concentration applied one could assume first order kinetics, but for complex industrial waste the modification by a retardant function was required. Many of the problems caused by industrial wastes are due to organic loadings beyond the reactive capacity of the bed and, thus, the data obtained from the final effluent cannot be considered representative. In this study, the actual average BOD_5 loading applied to the filter is 2920 lb per acre-ft, which is lower than the expected value, since the maximum BOD_5 of raw wastewater was 188 mg/l, the minimum 62 mg/l, and the arithmetic average 127 mg/l. Using the Student's test the 95 per cent confidence interval of the mean was 122.5-131.5 mg/l. The standard deviation is 22.97. The characteristics of constituents listed in TABLE I are in the range of medium to weak strength in comparison with those listed by Babbitt (35). The value of BOD_5 of the raw wastewater was predicted to be 400 mg/l in the original design of the plant. Obviously, the assimilative capacity of the plant has not reached its maximum.

It should be pointed out here that the effect of the infiltration from rainfall to the sewer greatly lessens the organic concentration of raw wastewater during the raining season. This occurs from April to September, as shown in the bar graph in Figure 3. The effect on suspended solids is shown in Figure 4.

Another evaluation of the reliability of the existing plant may be conveniently considered under the heading of the performance of the filter. From TABLE 2, regarding the trickling filter performance including the final settling basin, removals are from 60% to 70% or more from 1965 to 1969. The overall efficiency of the plant is more or less around 80%. Thus, the operation of the plant can be considered to be normal.

There are some points which can be brought out from the comparative study of TABLE 2. First of all, in 1969 and 1970, regarding the performance of the filter only, the percentage reduction of BOD_5 dropped down to 45% and 42% in comparison to that of the previous years, but the percentage reduction of suspended solids was up to 24% and 36%, which was greater than that of around 10% from 1965 to 1968. It represented the clogging phenomenon, which is caused by the accumulation of filter film not sloughing off as it should through the ten years operation. Evidently the assimilative capacity of the bed was decreased and, thus, the function of biological flocculation and precipitation became greater than the biosorption and coagulation mechanism in the filter. Secondly, the effect of the settling basin following the trickling filter is clearly shown in TABLE 2. The percentage reduction of BOD_5 remained constantly around 10% even in the years during which the removal percentage of the trickling filter was obviously decreased. It is an important point in the study of performance formulations because of the fact that the

effect of settling basins following trickling filtration has never been evaluated.

Aside from the point of BOD_5 reduction, the effect of nitrification in the process is shown in Figure 5. It reveals that the free ammonia and organic nitrogen were lessened appreciably through the treatment process.

In the study of development of the prediction equation, there were variations in the effluent BOD as computed from the NRC, Eckenfelder, and Galler and Gotaas formulas, in comparison to that of actual values as shown in Figure 6. Before the interpretation of various trends, the difference in some physical variables between the existing plant and the theoretical performance should be recognized. In the existing plant, the physical variables of the depth, the recirculation ratio, and the characteristics of filter media were constant. Under these circumstances, the parameters of the filter media characteristics, depth and the recirculation ratio which were emphasized in the Eckenfelder formula were not significant because they are constant. Besides, there are two things that must be explained. First, the explanation of mechanisms of BOD_5 in trickling filter by Eckenfelder (4), as earlier detailed, are from biosorption and coagulation of that portion of the flow that passes rapidly through the filter. The mechanism of biological flocculation and precipitation were neglected, as pointed out by V. C. Behn, et al. (36). Up to this point, the percentage reduction of suspended solids as shown in TABLE 2 showed that the mechanisms of precipitation undoubtedly existed. The attribution of BOD_5 reduction by storage became greater when the operation of the plant became longer. Second, it is recognized that the BOD_5 reduction in trickling filters is based on the degree of assimilation by microorganism in the biological oxidation. The the biological oxidation, the amount of

biological growth is controlled primarily by the food available and the growth will increase as the organic load increases until a maximum effect is reached. Thus, the organic loading is a basic parameter in the parameter in the performance formula. However, influent BOD is not a parameter in the Eckenfelder formula. Consequently, the result of BOD_5 in the effluent obtained from the Eckenfelder formula shows the least comparison to the actual data.

The National Research Council and Galler and Gotaas formula were based on actual data. They were not based on Eckenfelder's explanation of the mechanism of a filter, but rather on pure mathematical and static fitness. Commonly, the organic loading was emphasized in their formulas. But at the time of formulation of the National Research Council formula, the temperature factor was not considered. As is well known, the removal of BOD is a function of the activity of the microorganisms comprising the slime coating of the filter media, but the activity of microorganisms associated with wastewater temperature normally decreases with decreasing temperature. Thus, temperature should be included in the empirical formulation. This was accounted for in the Galler and Gotaas formula. The foregoing difference between the NRC and the Galler and Gotaas formulas reflects the difference of trends in Figure 6. The Galler and Gotaas was the closest one of the three results.

The result in terms of BOD_5 remaining in the effluent obtained from the predicted performance formula based on the method of the Galler and Gotaas formula and the operating data of the existing plant has been compared and is shown in Figure 7. The difference which appeared on the graph is in the range from 0.644 to 1.659 (the figure based on the ratio of the computed value to actual value detailed in Appendix III). This shows that other factors affecting BOD_5 reduction in the process, such as the interruption of operation, the

sloughing off of biological film from the filter, and the increment of accumulation with increasing years of operation need further study in order to be counted as physical variables in the performance formula. There are two points which must be noted here. First, the data used by Galler and Gotaas included settled and unsettled effluent, but this study used settled effluent only. Second, there are three physical variables which could be involved in the predicted formula, but because of the restriction of the existing plant, the formula is suggested to be employed as an evaluation tool for the performance of the existing plant rather than future design.

CONCLUSIONS

1. For evaluating the reliability of operation data, the characteristics of raw wastewater are summarized. The values for BOD_5 are maximum 188, minimum 62, average 127, and using the Student's test the 95 per cent confidence interval of the mean was 122.5-131.5 mg/l. The standard deviation was 22.97. The values for suspended solids are maximum 320, minimum 103, average 184, and using the Student's test the 95 per cent confidence interval of the mean was 175.31-192.69 mg/l. The standard deviation was 44.17. The overall strength of domestic wastewater is in the range of medium to weak in comparison to that of the United States'.
2. For the same foregoing reason, the operation efficiency is summarized also. The results reflect that the operating efficiency was not as high as that expected by the designers. Though the quality of the effluent generally met the requirement, it was probably because of the low BOD_5 in the raw wastewater.
3. The mechanism of BOD removal not only occurs by biosorption and coagulation in the trickling filter process, but also by biological flocculation and precipitation. The results of suspended solids reduction of the plant are cited. On the other hand, the reduction of suspended solids can be used for evaluation of the clogging phenomenon in the process.
4. The effect of the final settling basin regarding BOD_5 reduction in this plant was cited around 10%. It indicated that the effect of the final set-

tlng basin played some role in the BOD reduction when the process included the basin.

5. The performance formula for evaluating the operation of the plant was developed. The result computed from the predicted formula and the actual value of BOD_5 remaining in the effluent was compared.

6. The phenomena which occur in the operation, such as biological film sloughing off from the filter and the evidence of accumulation and subsequent oxidation of organic material, need further study in order to be included as physical parameters in the performance formulation.

BIBLIOGRAPHY

1. McKinney, R. E. Microbiology for Sanitary Engineers. p. 211. McGraw-Hill, New York. (1962).
2. Sewage Treatment Plant Design. Water Pollution Control Federation Manual of Practice No. 8. Washington, D. C. (1959).
3. Sewage Treatment Plant Design. Water Pollution Control Federation Manual of Practice No. 8. Washington, D. C. (1959) p. 152.
4. Eckenfelder, W. W., Jr. "Trickling Filtration Design and Performance." Proc. Amer. Soc. Civil Engrs., Jour. San. Engr. Div., Vol. 87, No. SA4 (July, 1961) p. 33-44.
5. Fair, G. M., and Geyer, J. C. Elements of Water Supply and Wastewater Disposal. p. 411. John Wiley & Sons, Inc., New York. (1958).
6. Gurnham, C. F. Principles of Industrial Waste Treatment. p. 267. John Wiley & Sons, Inc., New York. (1955).
7. Phelps, E. B. Stream Sanitation. p. 88. John Wiley & Sons., Inc., New York. (1944).
8. Swilley, E. L., and B. Atkinson. "A Mathematical Model for the Trickling Filter." Proceedings, 18th Annual Industrial Waste Conference, Purdue University. (1963).
9. Fair, G. M., J. C. Geyer, and D. A. Okun. Elements of Water Supply and Wastewater Disposal. p. 529. 2nd ed., John Wiley & Sons., Inc. (1971).
10. Mohlman, F. W. "One Year's Operation of an Experimental High-Rate Trickling Filter." Sewage Works Journal. Vol. 8, 904-914. (1936).
11. Halvorson, H. O., G. M. Savage, and E. L. Piret. "Fundamental Factors Concerned in the Operation of Trickling Filters." Sewage Works Journal. Vol. 8, 888-903. (1936).
12. Herrick, T. L. "Experimental Work in Progress at Chicago." Sewage Works Journal. Vol. 10, 276-292. (1938).
13. Stanley, W. E. "The Trickling Filter in Sewage Treatment." Modern Sewage Disposal. Federation of Sewage Works Associations, New York. p. 51-67. (1938).

14. Keefer, C. E., and H. Kratz, Jr. "Experiments with High-Rate Trickling Filters at Baltimore." Sewage Works Journal. Vol. 12, 477-484. (1940).
15. 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, 818-833. (1942).
16. "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, 787-1028. (1946).
17. Velz, C. J. "A Basic Law for the Performance of Biological Filters." Sewage Works Journal. Vol. 20, 607-617. (1948).
18. Rankin, E. B. "Evaluation of the Performance of Biofiltration Plants." Trans. Amer. Soc. Civ. Engr. Vol. 120, 823-842. (1955).
19. Fairall, J. M. "Correlation of Trickling Filter Data." Sewage and Ind. Wastes. Vol. 28, 1069-1074.
20. Stack, V. T., Jr. "Theoretical Performance of the Trickling Filtration Process." Sewage and Ind. Wastes. Vol. 29, 987-1001. (1957).
21. Howland, W. E. "Flow Over Porous Media as in a Trickling Filter." Proceedings. 12th Ind. Wastes Conf. at Purdue University, Purdue Univ. Engineering Extension Series, No. 94, 435-465. (1958).
22. Ingram, W. T. "An Investigation of the Mechanisms of Controlled Filtration." Sewage and Ind. Wastes. Vol. 31, 1147-1158. (1959).
23. Schulze, K. L. "Experimental Vertical Screen Trickling Filter." Sewage and Ind. Wastes. Vol. 29, 458-467. (1957).
24. Schulze, K. L. "Load and Efficiency of Trickling Filters." Journal Water Pollution Control Federation. Vol. 32, 245-261. (1960).
25. Schulze, K. L. Discussion of "Analysis of Biological Filter Variables." by W. S. Galler and H. B. Gotaas (28). Proceedings Amer. Soc. Civil Engrs., Jour. San. Engr. Div. Vol. 91, No. SA3, 129-131. (June, 1965).
26. Bloodgood, D. E., G. H. Teletzke, and F. G. Pohland. "Fundamental Hydraulic Principles of Trickling Filters." Sewage and Ind. Wastes. Vol. 31, 243-253. (1959).
27. Galler, W. S., and H. B. Gotaas. "Analysis of Biological Filter Variables." Proc. Amer. Soc. Civil Engrs., Journal San. Engr. Div. Vol. 90, No. SA6, 59-79. (December, 1964).

28. 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, 163-182. (February, 1966).
29. Germain, J. E. "Economical Treatment of Domestic Waste by Plastic-Medium Trickling Filters." Jour. Water Pollution Control Federation. Vol. 38, 192-203. (1966).
30. Baker, J. M., and Q. B. Graves. "Recent Approaches for Trickling Filter Design." Proc. Amer. Soc. of Civil Engrs., Jour. San. Engr. Div. Vol. 94, No. SA1, 65-83. (February, 1968).
31. Balakrishnan, S., W. W. Eckenfelder, and C. Brown. "Organic Removal by Selected Trickling Filter Media." Jour. Water and Wastes Engineering. Vol. 6, No. 1, A-22--A-25. (January, 1969).
32. Balakrishnan, S., and W. W. Eckenfelder. "Nitrogen Relationships in Biological Treatment Process. II. Nitrification in Trickling Filters." Journal Inter. Asso. of Water Pollution Research. Vol. 3, No. 2, 167-174. (February, 1969).
33. Balakrishnan, S., and W. W. Eckenfelder. Discussion of "Recent Approaches for Trickling Filter Design," by Baker, J. M., and Q. B. Graves. Proc. Amer. Soc. Civil Engrs. Jour. San. Engr. Div. Vol. 95, No. SA1, 185-187. (February, 1969).
34. Rankin, R. S. "Evaluation of the Performance of Biofiltration Plants." Trans. Amer. Soc. Civil Engrs. Vol. 120, 823. (1955).
35. Babbitt, H. E. Sewerage and Sewage Treatment. 7th ed. John Wiley and Sons, Inc., New York. p. 312. (1953).
36. Behn, V. C., W. F. Ames, and K. Keshavan. Discussion of "Trickling Filter Design and Performance," by Eckenfelder, W. W., Jr. (4). Proc. Amer. Civil Engrs. Jour. San. Engr. Div. Vol. 88, No. SA1, 31-38. (January, 1962).

APPENDIX I

```

REAL LO,LE1,LE2,LE3
DIMENSION W(80),LO(80),T(80),Q(80),LE1(80),LE2(80),LE3(80)
READ(5,110) N, A, D, V, R, (W(I),I=1,N), (LO(I),I=1,N), (Q(I),I=1,N),
C(T(I),I=1,N)
110 FORMAT(110,4F10.5/(8F10.5/8F10.5/8F10.5/8F10.5/8F10.5/8F10.5/8F10.5/8F10.5/5F10.5))
WRITE(6,120)
120 FORMAT(/5X,'THE INPUT DATA ARE')
WRITE(6,130) N,A,D,V,R
130 FORMAT(15,4F10.3)
DO 10 I=1,N
10 WRITE(6,140) W(I),LO(I),Q(I),T(I)
140 FORMAT(4F10.2)
C=0.0561
P=0.9
F=(1.+R)/((1.+(1.-P)*R)**2.)
U=V*F
DO 20 I=1,N
LE1(I)=LO(I)/(1.+C*((W(I)/U)**0.5))
20 LE1(I)=LO(I)-LE1(I)
DO 30 I=1,N
DEN=(1.+R)*(1.+2.5*D**0.67/Q(I)**0.5)-R
30 LE2(I)=LO(I)/DEN
X=(1.+R)**0.28
Z=(1.+D)**0.67
DO 40 I=1,N
Y=(Q(I)/A)**0.13
40 LE3(I)=(0.464*(LO(I)**1.19)*X*Y)/(Z*(T(I)**0.15))
WRITE(6,150)
150 FORMAT(/5X,'COMPUTED EFFLUENT BOD VALUES ARE')
WRITE(6,160)
160 FORMAT(/5X,' LE1      LE2      LE3 ')
DO 50 I=1,N
50 WRITE(6,170) LE1(I),LE2(I),LE3(I)
170 FORMAT(/1X,3F10.2)
RETURN
END

```

ILLEGIBLE DOCUMENT

**THE FOLLOWING
DOCUMENT(S) IS OF
POOR LEGIBILITY IN
THE ORIGINAL**

**THIS IS THE BEST
COPY AVAILABLE**

TRICKLING FILTER ANALYSIS

MULTIPLE REGRESSION.....

SELECTION..... 1

VARIABLE NO.	MEAN	STANDARD DEVIATION	CO-RELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.	ERROR COEFF.	COMPUTED T VALUE
6	4.29875	74	0.17147	0.78411	0.14121510	01	0.15689
7	2.52253	12.4	0.10049	0.01471	0.37712350	00	0.24051
8	3.18312	24	0.09670	-0.43732	-0.36754820	00	0.27566
DEPENDENT							
5	3.31778	27.5	0.32166				

$$\text{INTERCEPT} = -0.25845140 \text{ 01} = \log C \quad C = -2.58 \quad \frac{1}{C} = 13.2 = 0.0758$$

MULTIPLE CORRELATION 0.80026

STD. ERROR CF ESTIMATE 0.19728

MULTIPLE CORRELATION SORD 0.64042

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	3	0.450563189970	01	0.150187729990
DEVIATION FROM REGRESSION	65	0.252582442160	01	0.389203757160-01
TOTAL	68	0.703545632130	01	

$$L = C L_0^{A_1} \left(\frac{Q}{A} \right)^{A_2} T^{A_3}$$

$$L_c = \frac{0.0753 L_0}{1.41 \left(\frac{Q}{A} \right)} \quad 0.40$$

$$L_c = \frac{0.0753 L_0}{(T^{0.27})}$$

$$\log L_c = \log C + A_1 \log L_0 + A_2 \log \left(\frac{Q}{A} \right) + A_3 \log T$$

APPENDIX III

```

$JOB
1      REAL LC,LEA,LEC
2      DIMENSION LO(80),LEA(80),LEC(80),QA(80),T(80),X(80)
3      N=69
4      DO 10 I=1,N
5          10 READ(5,100) LEA(I),LO(I),QA(I),T(I)
6          100 FORMAT(4F10.5)
7          DO 20 I=1,N
8              20 WRITE(6,110) LEA(I),LO(I),QA(I),T(I)
9              110 FORMAT(4F10.5)
10         DO 30 I=1,N
11             LEC(I)=0.0758*(LO(I)**1.41)*(QA(I)**0.40)/(T(I)**0.37)
12         30 X(I)=LEC(I)/LEA(I)
13         DO 40 I=1,N
14             40 WRITE(6,120) LEA(I),LEC(I),X(I)
15         120 FORMAT(1/3X,3F10.3)
16         RETURN
17         END

```

L_e ACTUAL	L_e COMPUTED	L_c/L_a
38.000	38.631	1.017
46.000	42.488	0.924
34.000	41.884	1.232
29.000	39.018	1.345
19.000	25.730	1.354
23.000	26.110	1.135
26.000	26.828	1.032
21.000	26.477	1.261
32.000	27.421	0.857
39.000	30.774	0.789
35.000	37.213	1.063
36.000	35.828	0.995
51.000	32.821	0.644
32.000	32.495	1.015
32.000	36.704	1.147

28.000	32.622	1.165
21.000	25.048	1.193
21.000	22.140	1.054
20.000	21.994	1.100
38.000	22.989	0.789
29.000	31.732	1.094
24.000	32.345	1.348
33.000	32.726	0.992
27.000	26.816	0.993
39.000	36.309	0.931
36.000	33.231	0.923
34.000	32.934	0.969
34.000	27.949	0.822
23.000	24.970	1.086
25.000	21.543	0.862
23.000	24.100	1.048
17.000	20.691	1.217
23.000	28.142	1.224
24.000	29.945	1.248
29.000	28.990	1.000
30.000	35.176	1.173
31.000	27.340	0.882
26.000	28.437	1.094
14.000	19.449	1.389
16.000	12.350	0.772
12.000	13.876	1.156
13.000	19.267	1.482
13.000	21.565	1.659
25.000	22.583	0.915
24.000	26.004	1.084

24.000	27.458	1.144
31.000	30.569	0.986
27.000	24.651	0.913
23.000	28.539	1.241
20.000	22.815	1.141
17.000	15.527	0.913
18.000	14.057	0.781
38.000	27.967	0.736
25.000	19.270	0.771
27.000	20.128	0.745
34.000	25.173	0.740
31.000	27.582	0.890
34.000	29.700	0.874
35.000	33.865	0.968
25.000	22.957	0.918
38.000	33.626	0.885
36.000	31.973	0.888
37.000	29.186	0.789
30.000	26.793	0.893
29.000	26.456	0.912
36.000	34.320	0.953
44.000	35.812	0.814
50.000	35.061	0.701
44.000	38.547	0.875

**FORMULATION AND COMPARISON OF TRICKLING
FILTER EQUATIONS--
based on actual plant data**

by

CHIN DEE LEE

**B. S., Chung Yen College of Science & Engineering,
Taiwan, 1962**

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

**KANSAS STATE UNIVERSITY
Manhattan, Kansas**

1972

This study predicted the performance formula for the operation of an existing trickling filter plant. The formula was formed with the variables of organic loading, hydraulic loading and temperature. The parameters of depth, recirculation ratio and the characteristics of filter media were counted as constant.

The results of the National Research Council formula, the Eckenfelder formula and the Galler and Gotaas formula for trickling filter performance were compared. The Galler and Gotaas formula was determined to be the one of best fit for this plant data. The development of the performance formula was conducted by multiple regression analysis on data collected from 1965 to 1970 from one of the existing plants in Taiwan.