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Prediction of filter life by measurement of cake resistance

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PREDICTION OF FILTER LIFE BY MEASUREMENT OF CAKE RESISTANCE

by

Abdul Amir A. R. Al-Khafaji

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DOCTOR OF PHILOSOPHY

Major Subject: Civil Engineering

Approved:

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In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

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Dean of Graduate College

Iowa State University
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Ames, Iowa

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ABBREVIATIONS

cu ft	cubic feet
Eff.	Effluent
ft	feet
gal	gallons
gpm	gallons per minute
gpm/sq ft	gallons per minute per square foot
hr	hour
Inf.	Influent
JCU or JTU	Jackson Candle Units (measure of turbidity)
lb	pounds
lb/cu ft	pounds per cubic foot
log	base 10 logarithm
mg/l	milligrams per liter, often referred to as ppm (parts per million)
min.	minutes
ml	milliliters
No.	number
psi	pounds per square inch
sec	seconds
sq ft	square feet

NOTATION

A = cross-sectional area of cake perpendicular to direction to direction of flow, sq ft

A_c = area of contact between filter cake particles, sq ft

B = constant defined in Equation 38 and equal the slope of the curves of Figure (11), dimensionless

c = mass of solid particles in filter cake resulting from a unit volume of filtrate, lb/cu ft

Fs = solids compressive force, lb force

g = constant of gravity; conversion factor in Newton's law of motion 32.17 ft/(sec)^2

K = coefficient of permeability, ft^4/lb-sec

K' = modified coefficient of permeability that is independent of viscosity, ft^2

K_1 = factor of filter medium resistance defined in Equation 26, sec/ft

K_2 = factor of filter cake resistance defined in Equation 27, sec/ft^6 or min/ml^2

L = cake thickness in direction of flow, ft

n = compressibility coefficient of filter cake, dimensionless

p = applied filtration pressure, lb force/sq ft

Pi = low pressure below which is constant, lb force/sq ft

Po = hydraulic pressure on discharge side of filter medium, lb force/sq ft

Px = hydraulic pressure at distance x from medium, lb force/sq ft

Ps = solids compressive pressure at distance x from medium, lb force/sq ft

P_1 = pressure at interface of medium and cake, lb force/sq ft

ΔP = total hydraulic pressure drop across cake and filter medium, lb force/sq ft

ΔPc = hydraulic pressure drop across filter cake, lb force/sq ft

ΔPm = hydraulic pressure drop across filter medium lb force/sq ft

Q = instaneous rate of flow of filtrate through cake, cu ft/sec

q = Q/A, cu ft/sec/sq ft

Rc = filter cake resistance 1/ft

Rm = filter medium resistance 1/ft

s = emperical constant related to the slope of the graphs of Figure (11)

t = time of filtration, sec

V = volume of filtrate collected at time t, cu ft

W = total mass of dry solids in filter cake per unit area, lb/sq ft

Wx = mass of solids per unit area in distance x from medium, lb/sq ft

α = average specific cake resistance, ft/lb

α_x = value of specific resistance at distance x from medium, ft/lb

α_o = empirical constant in Equation 33

ϵ_i = filter cake porosity in infinitesimal surface layer, dimensionless

ϵ_x = filter cake porosity at distance x from medium, dimensionless

ρ = density of solid particles in filter cake, lb/cu ft

μ* = filtrate viscosity, lb/ft-sec

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*It is a common practice in Sanitary Engineering to express water viscosity in units of $lb.sec/ft^2$ - conversion of such units to lb/ft-sec is obtained by multiplication with the constant of gravity g. Values of water viscosity expressed as centipose or lb/ft-sec are reported in Appendix D.

INTRODUCTION

Background

The separation of solids from liquids by filtration is a natural phenomena similar to the clarification of water by drainage through a granular soil. This method of clarification has been copied by man since he became aware of the need for cleaning water to make it drinkable. Since filtration is accepted as applying to a great variety of separations, it seems desirable to define as closely as possible the type of filtration that is discussed here, namely the separation of undissolved suspended solids from water. The separation is caused by forcing the water through a porous medium which retains the solids, the force being the difference in hydraulic pressure between the two sides of the filter medium.

The porous material which removes the suspended solids from the water and upon whose surface the filter cake forms is commonly referred to as the filter medium. In the filtration of water supplies, sand, carbon and diatomaceous earth are the three mostly used filter media, sand being the most common for filtration of municipal supplies (9). When the filter medium is of a relatively small particle size, a surface filter cake is formed soon after filtration begins because practically all the solids are retained at the surface of the filter media. With a relatively large particle size medium, such as sand, the solids penetrate further into the bed and consequently more time is needed to clog the pores at the surface and to form a surface filter cake.

The use of carbon in water treatment is not new. Its history has been traced back to the pre-Christian era at which time the Ousruta Sanghita instructed: "It is good to keep water in copper vessels, to expose it to sunlight and filter through charcoal" (13). Though there is a great difference between the aforementioned charcoal and the activated carbons of today, the reasons for using either are the same.

The use of small precoat carbon filters in households or camps to produce clear water for drinking from potentially contaminated supplies became popular earlier in this century. These household filters were required to remove objectionable odor, as well as suspended matter, from the water. Charcoal, whether of animal or vegetable origin, was found highly suitable because of its absorptive capacity, inertness, and free-filtering nature as a filter medium and a good many "Patented" filters were constructed. The use of activated carbon as one component of the filter media in household precoat filters was pioneered by Everpure, Inc.* in Chicago. Their precoat carbon filter was designed originally for use in individual residences in Chicago for the filtration for drinking purposes of Lake Michigan water which at that time was pumped

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*Everpure, Inc., 2100 Clearwater Drive, Oak Brook, Illinois.

into the distribution system chlorinated but without prior treatment for either suspended solids or taste and odor removal (1).

During the 1950's, the use of precoat carbon filtration was combined with the use of a simple but effective chlorinator to provide a system of super-chlorination-dechlorination of small water supplies (1). This water disinfection procedure has found widespread adoption for treatment of water in small water supply installations. The precoat carbon filter in such a system is necessary to perform the following services:

(1) Dechlorination of residual chlorine in the water,

(2) Removal of turbidity, iron or other suspended solids from the water,

(3) Removal of iron in solution after it has been oxidized to an insoluble state by chlorination, and

(4) Removal of tastes and odors from the water.

As the use of precoat activated carbon filters began to spread, a need was recognized for more information concerning the factors that influenced the effectiveness of these filters. Much research has been done at Iowa State University in the area of superchlorination-dechlorination of small water supplies. Extensive laboratory tests were conducted to determine the ability of an activated carbon filter to remove chlorine from water under various conditions of chlorine loading and flow rate. The results of these studies, published in a number of papers (1, 13, 19, 21, 33) were used to predict the service life of such filters for residual chlorine removal in a superchlorination-dechlorination small water supply system.

The Current Study

The ability of a precoat carbon filter to remove turbidity or iron from water has been demonstrated in the current study. The filter unit used is a precoat, activated carbon filter produced by Everpure, Inc., and commercially known as an "Everpure" filter. A precoat filter is a filter device in which the filter medium, or precoat, used to remove the suspended solids is supported on a septum. The precoat of an "Everpure" is composed of a mixture of activated carbon, various filtering aids and a binder to help hold the carbon in filtering position during interruptions in the filtering operation. These filters are usually designed to perform a dual service:

(1) To remove suspended solids from water and

(2) To remove tastes, odors, and color producing substances from water.

In all the tests conducted in this study, the effluent turbidity was negligible and the iron concentration was always less than 0.10 mg/l. The need to replace the filter at the end of a filtering cycle was indicated by the drop of the flow rate to a pre-determined minimum level rather than by the passage of iron or turbidity in the effluent. Here, we deal with the continuous accumulation of solids in sufficient quantity so that a filter cake is formed on the surface of the medium. The filtering cycle usually continues until the accumulated resistance of the filter cake causes the pressure drop to reach that allowed for the filter (constant rate filtration), or the flow rate falls below an acceptable level (constant pressure filtration).

In practically all cases of water filtration, the filter medium is much more permeable than the solids cake which it is called upon to retain. The finest particles in suspension in water generally penetrate farther, at first, into the body of the filter medium -- they may in some cases pass right through -- than do the coarser ones. A steady-state case in which all advancing particles are stopped at a sharply defined boundary is not reached until some time after filtration has started and the surface filter cake is formed.

Filtration of turbid waters through a precoat activated carbon filter is not an exception. As a matter of fact, it is a manifestation of the aforementioned phenomena. However, the filter medium in this case is of very small particle size. The filter cake is formed soon after filtration begins because practically all the solids are removed at the surface. Furthermore, the activation process of the carbon creates many cracks and fissures in the carbon mass. The formation of these additional capillary spaces or channels increases the porosity of the filter medium. Thus, more water is produced in the early stages of filtration and the filter cake is formed soon after filtration has started. Successive filtration is done through the increasing thickness of the filter cake and the case becomes essentially a cake-filtration problem in which the suspended solids are removed on suspended solids of the same characteristics previously removed on the surface of the filter media.

Filter cakes formed during filtration on the surface of a precoat carbon filter can be either compressible or incompressible depending on the type of suspended impurities present in the water. A cake is called incompressible if its porosity remains essentially constant during filtration (7). Compressible cakes are more dense adjacent to the filter medium because of the greater pressure gradient in the initial stages of cake formation. Compressible cakes are generally very resistant to flow (low porosity).

The work reported in this thesis has as one of its major objectives the determination of the flow resistance of filter cakes formed during filtration of turbid waters. The types of water filtered include iron-bearing water and clay-bearing water.

Objectives

The primary objective of this study was to determine the ability of a precoat, activated carbon filter to remove suspended solids from water under various conditions of solids loading and flow rate. It was hoped that the results would lead to the development of laboratory test procedures for the prediction of the productive life of such filters when used to remove suspended impurities from raw waters in small water supply installations. As was indicated in the previous section, filtration through a precoat carbon filter is essentially a cake filtration problem. Thus, the productive life of the filter is greatly determined by the flow resistance of the filter cakes formed during filtration on the surface of the filter medium.

Prediction of the filtration resistance of a particular material from non-filtration data is generally not possible. Most suspended impurities encountered in water filtration are compressible and do not form a simple structure of a bed of individual rigid particles. The usual suspension is a mixture of flocs consisting of loose assemblies of very small particles, and the resistance characteristics of the cake depend upon the properties of the flocs rather than on the geometry of the individual particles (20). When the flocs are deposited on the upstream face of the filter medium, they form a filter cake whose compressibility is best determined by experimental measurement of the flow resistance. In view of this and to achieve the overall objectives of this thesis, it became necessary to establish a research program designed to:

(1) Collect actual filtration data during the filtration of clay bearing waters through an activated carbon filter under various conditions of solids loading and flow rate.

(2) Design and build a laboratory, constant-pressure filtration apparatus that could be used to predict flat vertical surfaces.

(3) Develop empirical prediction equations for predicting changes in flow resistance of filter cakes for corresponding changes in suspended solid concentration and applied pressure.

(4) Develop equations for predicting the productive life of a precoat carbon filter used to remove a particular suspended impurity from water from a knowledge of its laboratory determined cake resistance characteristics.

(5) Correlate the predicted productive life of the filter with that obtained from the actual filtration data in removing the same suspended impurity.

THEORY OF FILTRATION

History

Historically, filtration theory of real import started with the work of Poiseuille who developed equations for viscous flow in capillaries. In 1842, he published the relation:

$$Q = P\, r^4 g / 8\, l\, \mu \text{ - - - - - - - - } (1)$$

where Q = rate of flow of filtrate, cu ft/sec

P = pressure drop across capillary, lb/sq ft

r = radius of capillary, ft

μ = coefficient of viscosity, lb/ft-sec (see footnote on page vii)

l = length of capillary, ft

g = constant of gravity ft/sec^2

Attempts have been made to use this equation for correlating filtration data using the assumption that the capillary length and cake thickness could be considered equal. Needless to say, such attempts failed. However, the real importance of the Poiseuille equation is the fact that it predicted the powerful effect that decreasing capillary (pore) size would have on filtration resistance.

The work of d'Arcy's which describes flow of ground waters through underground strata is another important contribution to the theory of filtration. The equation stating d'Arcy's law is commonly presented as:

$$u = KP/L \text{ - - - - - - - - - } (2)$$

where u = superficial flow velocity, ft/sec

K = coefficient of permeability of the bed, ft^4/lb-se

L = thickness of bed, ft

It has long been realized that the velocity of flow is inversely proportional to viscosity. Consequently, d'Arcy's equation is usually modified to:

$$u = \frac{1}{A}\,\frac{dV}{dt} = \frac{K'gP}{\mu L} \text{ - - - - - - - - - } (3)$$

where $\frac{dV}{dt}$ = flow rate, cu ft/sec

t = time of filtration, sec

A = area of filter cake, sq ft

K' = permeability coefficient independent of fluid viscosity, ft^2

μ = fluid viscosity, lb/ft-sec

Since cake permeability is defined as the ease with which liquid is passed through the cake, cake resistance is conversely defined as the difficulty with which liquid is passed through the filter cake. Thus, K' = 1/Rc where Rc is the cake resistance per unit thickness. This concept of filtration resistance is of utmost importance because of its physical significance. The modified d'Arcy's equation is usually written for filtration operations as:

$$\frac{dV}{dt} = K'\,\frac{A\,g\,P}{\mu\,L} = \frac{1}{Rc}\,\frac{A\,g\,\Delta Pc}{\mu\,L} \text{ - - - - - - - - - } (4)$$

where ΔPc is the pressure drop across the cake.

The filtration of water through a filter cake is analogous to the flow of water through porous media. However, in cake filtration we feal with the passage of water through a solids bed of continually increasing thickness and not a bed of fixed dimensions and characteristics. Thus, the cake thickness (L) in Equation 4 is usually expressed in terms of the volume of filtrate.

$$L = \frac{c\ V}{A\rho} \text{ - - - - - - - - - } (5)$$

where c = weight of cake solids per unit volume of filtrate, lb/cu ft

ρ = in-place cake density, lb/cu ft

Equation 4 may now be written

$$\frac{dV}{dt} = \frac{A^2 \rho\ g\ \Delta Pc}{c\ Rc\ V} \text{ - - - - - - - - - } (6)$$

The filter cake density, ρ, varies from a maximum value at the precoat-cake interface to a minimum value at the cake surface. Since there is no simple method to evaluate the magnitude of ρ throughout the cake thickness, it is a common practice to use a coefficient α, specific cake resistance, to replace Rc/ρ.

Equation 6 expresses the time-volume filter discharge relationship, but does not take into account any changes which occur in the resistance of the filter cake during the filtration cycle. Sperry (27) first pointed this out. By assuming that filtration resistance consists of the resistance of the cake and the medium in series, both of which follow the d'Arcy equation, the following modified filtration equation can be derived:

$$\frac{dV}{dt} = \frac{A^2 g \Delta P}{\mu(\alpha c V + RmA)} \text{ - - - - - - - - - } (7)$$

in which Rm is the resistance of the filter medium while is the average specific resistance of the cake. Here ΔP is the total pressure drop across both cake and medium.

This equation, generally referred to as the filtration-rate equation, is the most useful and proven tool for dealing with cake filtration problems. Its validity has been demonstrated by many workers, notably Ruth (24), Grace (12), Fair and Hatch (11), Bonila (5), and Dillingham (9). Furthermore, Equation 7 can be applied to actual filter cakes under conditions of both constant pressure and constant rate filtration.

Cake Filtration

The solids removed during filtration often form a cake on the surface of the original filter media through which the filtrate must flow. Filtration through the collected solids is commonly referred to as cake filtration. In filtration of water through slow sand filters and through precoat carbon filters, cake filtration is the primary mode of solids removal. It is also a primary mode of removal in diatomite filtration. The significant difference between diatomite filtration and precoat carbon filtration is that in the former diatomite filter aid is added to the influent water in order to form a porous cake that is essentially incompressible. Suspended impurities in raw waters used in municipal and in individual small water supplies, however, almost invariably form compressible filter cakes (9).

In a filtration cycle, the filtrate passes through three kinds of resistance in series. These include: (1) the resistance of the channels conducting the suspension to the upstream face of the cake, (2) the resistance of the cake, and (3) the resistance associated with the filter medium and the septum which supports the filter cake. In a well-designed filter, the resistances of the inlet and outlet connections are small and can be neglected in comparison with those of the cake and filter medium. In actual filtrations, the resistance associated with the filter medium is greater than that offered by a clean filter medium to the flow of a clear filtrate. During the first moments of filtration before a cake is formed, solid particles become embedded in the pores of the filter medium and so develop an increased resistance to subsequent flow. The entire resistance built up in the filter medium, including that from the embedded particles, is called the filter medium resistance (Rm). The resistance offered by all solids not associated with the filter-medium is called (8) the cake resistance (Rc). The cake resistance is zero at the beginning of the filtration. The continuous deposition of solids on the medium serves to increase cake thickness so that the cake resistance will increase steadily with time of filtration.

When suspended solids are deposited on the fixed filter media during cake filtration, water flows through the openings of the compressible bed in the direction of decreasing hydraulic pressure gradient. The solids forming the cake are compact and dense at the surface of the filter medium whereas the cake surface layer is more open and porous. The cake porosity ϵ_x will be a minimum at the point of contact between the cake and medium, where x = o, Figure (1), and a maximum at the surface (x = L) where the water enters. The frictional drag of the filtrate passing through the voids is responsible for the decreasing porosity.

In Figure (1), the particles forming the filter bed are illustrated to show that the porosity decreases as the filtrate passes through the solids and approaches the septum. Some of the smaller suspended particles are shown having already pentrated the precoat.

The hydraulic pressure is Px at any distance x from the precoat-filter cake interface: p at x = L; Po at the interface between the septum and the precoat; and p_1 at the interface between the precoat and the filter cake.

In Figure (2), the variation of the porosity ϵ_x is shown as a function of the distance from the filter medium-filter cake interface x at different time intervals. The first infinitesimal layer at the cake surface has a constant porosity ϵ_i corresponding to zero compressive pressure. At each instant of time, the porosity drops throughout the cake to its minimum at the medium. As time passes, the cake thickness increases, and at a given x, the porosity decreases. As cake pressure drop increases, the porosity at the medium-filter cake interface decreases and eventually reaches a minimum value determined by the maximum applied pressure (31).

Figure (3) shows the effect of total pressure drop across the filter cake on the average porosity of a number of substances (29, 30, 32). As can be seen from the graphs, filtration pressure has its greatest effect on porosity in the low pressure range. For the latex, porosity tends to remain constant with increasing pressure above about 10 psi.

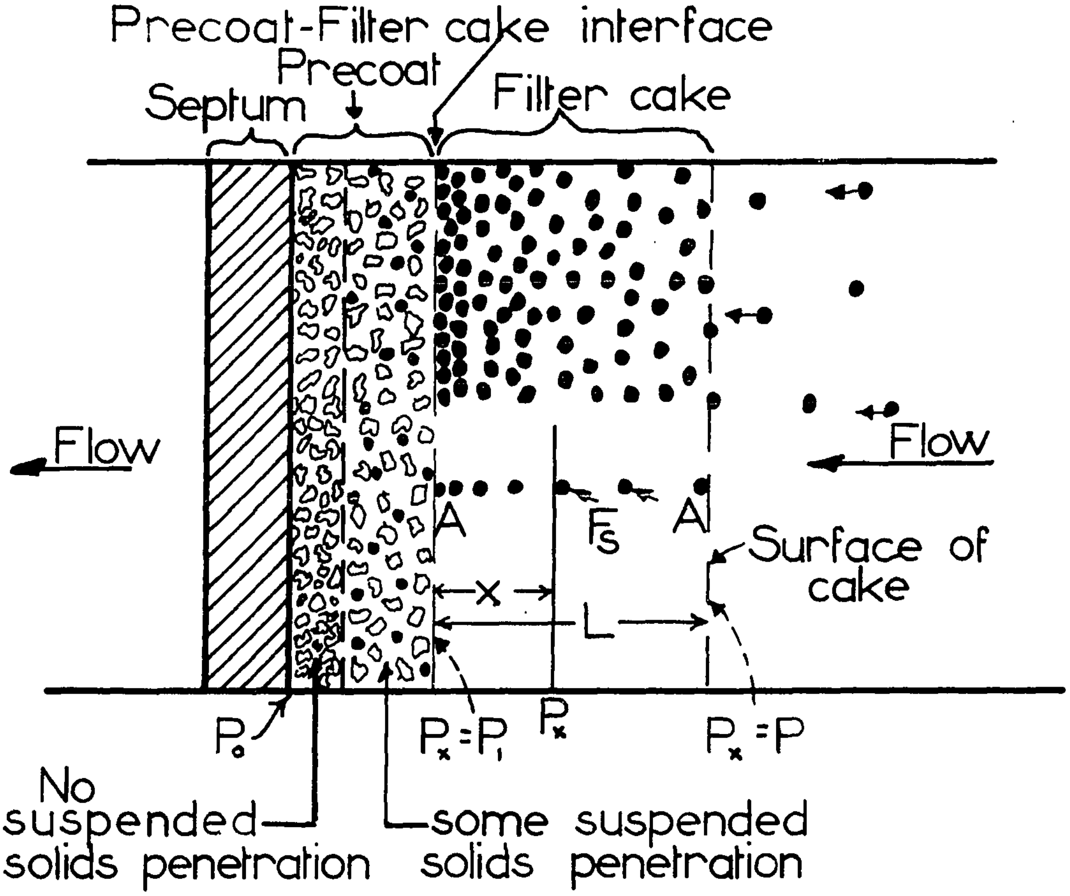
The Compressive Force

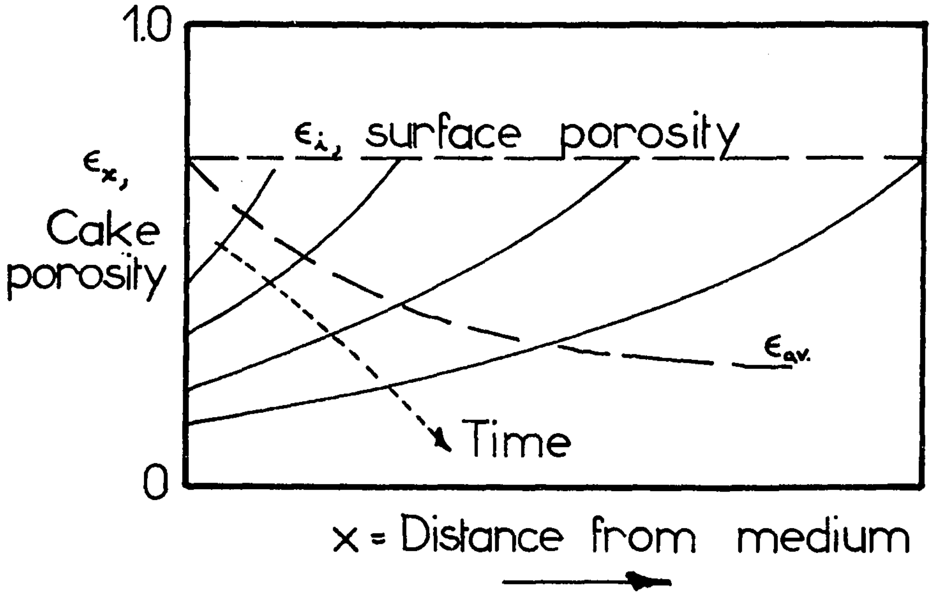
The viscous drag on successive particles in a filter cake is illustrated along A-A in Figure (1). The drag on each particle is communicated to the next particle and, consequently, the net solid compressive pressure increases as the medium is approached. Accumulative drag is zero in an infinitesimal surface layer, and the porosity at the surface thus remains at its maximum regardless of applied pressure (34). Pressure drop, or the compressive force due to differences in pressure across the filter cake, not total pressure, is responsible for porosity decreases.

In developing theoretical drag relations, the particles are assumed to be in point contact, as in Figure (4). The water completely bathes each particle and communicates its

Figure (1) Section through filter cake and medium, showing porosity gradient because of filtrate frictional drag.

Figure (2) Filter cake porosity is shown as a function of distance from medium at different filtration times.


Precoat-Filter cake interface
Precoat
Septum
Filter cake
Flow
Flow
A
F_s
A
Surface of cake
x
L
P_o
$P_x = P_1$
P_x
$P_x = P$
No suspended solids penetration
some suspended solids penetration


1.0
ϵ_i, surface porosity
ϵ_x, Cake porosity
$\epsilon_{av.}$
Time
0
x = Distance from medium

pressure uniformly along a plane perpendicular to the flow. The hydraulic pressure Px is effective over the entire cross-section of the cake because the contact area is negligible. The net force on the total mass in the differential distance, dx, is given by:

$$\text{Force} = Fs + dFs + A(Px + dPx) - Fs - A\,Px \text{ - - } (8)$$

$$= dFs + A\,dPx = o \text{ - - - - - - - - - - - - } (9)$$

This net force equals the product of the mass within dx (includes both the liquid and the solid) and the acceleration. Although the solid actually moves in the cake toward the medium, the accelaration is negligible. Thus, equating the net force in Equation 9 to zero is justified.

In actual cakes, there is a small area of contact Ac between particles. For area rather than point contact, Equation 9 would have to be written:

$$dFs + (A-Ac)\,dPx = o \text{ - - - - - - - - - } (10)$$

which reduces to Equation 9 when Ac = o. At the present stage of filtration theory, it appears that the assumption of Ac = o is justified. Integration of Equation 9 yields:

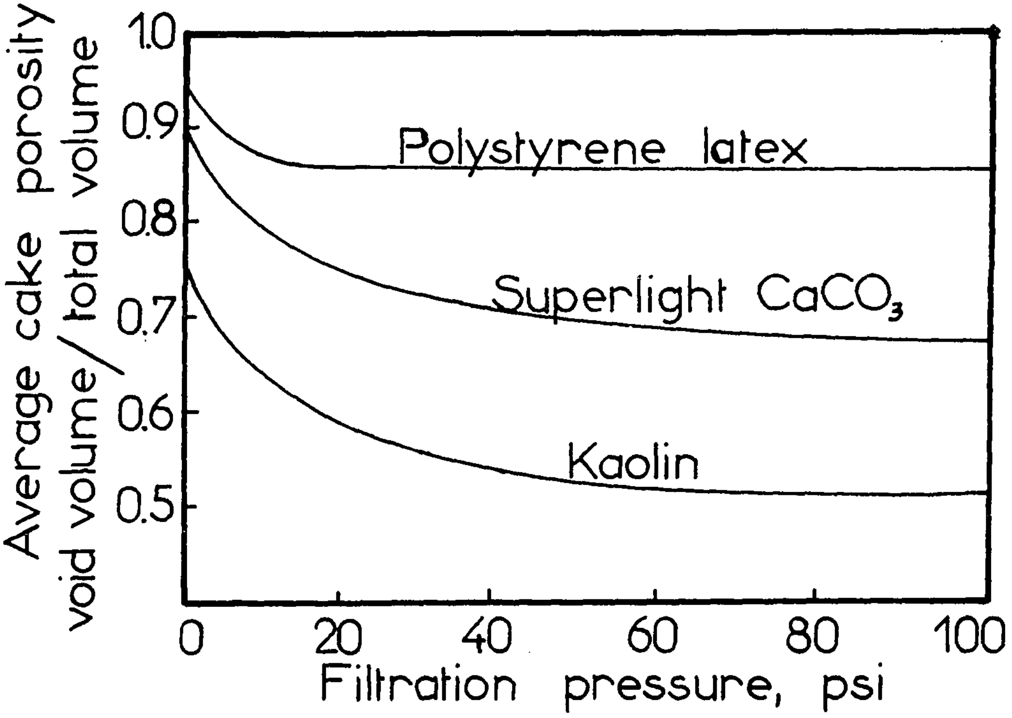
$$\frac{Fs}{A} + Px = P \text{ - - - - - - - - - } (11)$$

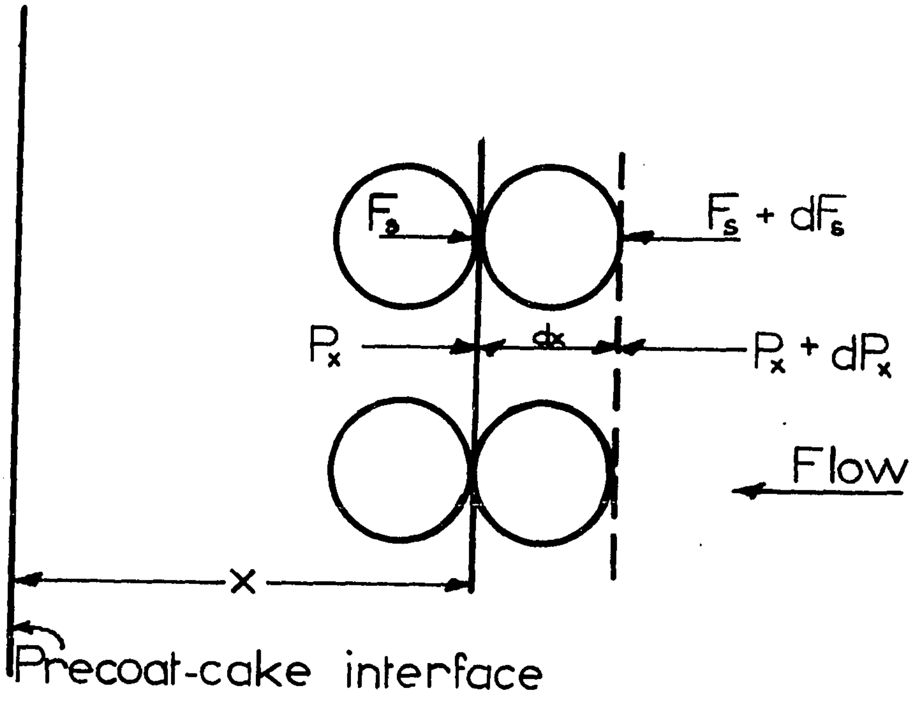
where Fs is the compressive force and P is the applied filtration pressure at the surface of the cake.

During the formation of filter cakes, filtrate moves through the filter medium and the filter cake as a result of the applied pressure. The fluid pressure in a filter cake

Figure (3) Effect of total pressure drop across the filter cake on the average cake porosity of a number of different materials (29, 30, 32).

Figure (4) Compressive force due to frictional drag (after Tiller 1961).


Average cake porosity,
void volume/total volume
1.0
0.9
0.8
0.7
0.6
0.5
Polystyrene latex
Superlight $CaCO_3$
Kaolin
0
20
40
60
80
100
Filtration pressure, psi


F_s
$F_s + dF_s$
P_x
dx
$P_x + dP_x$
Flow
x
Precoat-cake interface

varies from a maximum at the upstream face to a minimum at the filter medium. The entire thrust given up by the water is absorbed by the solids in the cake such that at any point in the cake the two are complementary, i.e. the point sum of the fluid pressure (Px) and the compressive pressure on the solids (Fs/A) always equals the total pressure (P) at the face of the cake.

Filtration Resistance

In filtration through compressible cakes, the varying compressive pressure (Ps) throughout the depth of the deposited cake produces a variation in cake porosity and specific resistance. The average filtration resistance, as originally defined by Ruth (24), is shown by the following:

$$\alpha = \frac{P-P_1}{\int_0^{P-P_1} dPs/\alpha x} \text{ - - - - - - - - - } (12)$$

where P is the pressure drop across the filter (septum, medium, and cake), P_1 is the pressure required to overcome the septum and medium resistance and αx is the point specific cake resistance. Both Ruth (24) and Carman (7) have shown that, although the point specific filtration resistance of compressible particles varies throughout the bed, it may be assigned an average value for the whole bed. This mean specific resistance is the filtration resistance (α) defined by conventional filtration rate equations.

However, the findings of Ruth (24) were derived from constant-pressure filtration data. As will be seen later, the postulation of an average cake resistance value for the whole bed is justified for constant pressure operations but not for other processes. It is the belief of the author that frequent lack of good (± 20%) agreement (and occasional wide variation) in calculated and experimental values of α are partially accounted for by the unconditional acceptance of Ruth's basic assumption as well as by experimental difficulties.

In order to develop a general filtration rate equation, let us, begin with the basic flow equation in the form

$$q = \frac{1}{A}\frac{dV}{dt} = \frac{g}{\mu \alpha_x}\frac{dPs}{dWx} \text{ - - - - - - - - - } (13)$$

where Wx is weight of solids per unit area in distance x from medium. Equation 13 simply states that for a differential cake thickness the instant flow rate is equal to a driving force (dPs) divided by a differential cake resistance (α_x).

To derive an expression for the total cake thickness per unit area, Equation 13 is placed in the form:

$$\int_0^{P-P_1} dPs/\alpha_x = \frac{\mu}{g}\int_0^{W} q \enspace dWx \text{ - - - - - - - - - } (14)$$

For the instant considered, V and A are the same for all layers, making q, the instant flow rate, constant[a]. The right-

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[a] Tiller and Shirato (32) suggest that, for concentrated suspensions (30 to 40% solids) q varies throughout the cake and the filtration rate equation should include the velocity of liquid relative to the solids. In the most general water filtrations, however, suspensions are dilute and it is safe to assume that the flow rate is constant throughout the cake.

hand side of Equation 14 can be integrated and the equation reduces to

$$\int_0^{P-P_1} dPs/\alpha_x = \frac{\mu q}{g} W \text{ - - - - - - - - - } (15)$$

$$= \frac{\mu q c}{g A} V \text{ - - - - - - - - - } (16)$$

where V is the volume of filtrate, and c is the weight of cake solids per unit volume of filtrate.

Assume now that the differential cake resistance αx is known as a function of Ps (or P-Px) through an equation or an experimental curve. The left hand side of Equation 16 may then be integrated either analytically or graphically. Figure (5) shows a characteristic graphical integration of the left hand integral of Equation 16. The reciprocal of α_x, $1/\alpha_x$, is plotted against (P-Px), and the area under the curve is measured between the ordinate axis and the ordinate $(P-P_1)$. For any functional relationship between αx and (P-Px) the integral depends only on $(P-P_1)$, the pressure drop through the cake.

Now, may be defined by the equation

$$\int_0^{P-P_1} \frac{dPs}{\alpha_x} = \int_0^{P-P_1} \frac{d(P-Px)}{\alpha_x} = \frac{P-P_1}{\alpha}, \text{ - - - - - - } (17)$$

in which α is the reciprocal of the average ordinate under the curve of Figure (5). Equation 17 can be rearranged to show that

$$\alpha = \frac{P-P_1}{\int_0^{P-P_1} dPs/\alpha_x} \text{ - - - - - - - - - } (18)$$

which is the average filtration resistance as originally defined by Ruth (24) and as was shown in Equation 12.

For cases where the assumption of constant average filtration resistance is justified, Equation 16 may be written as

$$\frac{P-P_1}{\alpha} = \frac{\mu qc}{gA} V \text{ - - - - - - - - - } (19)$$

The pressure P_1 required to overcome the filter medium resistance, can be related to that resistance, by analogy with Equation 19, by the equation

$$\frac{P_1 - Po}{Rm} = \frac{\mu q}{g} \text{ - - - - - - - - - } (20)$$

or

$$P_1 = \frac{\mu q}{g} Rm + Po \text{ - - - - - - - - - } (21)$$

Substituting Equation 21 into Equation 19 yields

$$P - \frac{\mu q}{g} Rm - Po = \frac{\mu qc}{gA} V \text{ - - - - - - - - - } (22)$$

or

$$(P-Po) = \frac{\mu q}{g} \left(\frac{c\alpha}{A} V + Rm\right) \text{ - - - - - - - - - } (23)$$

where (P-Po) is the total pressure drop across the filter medium and filter cake and is usually denoted as ΔP.

Rearranging Equation 23 yields

$$q = \frac{g \ \Delta P}{\mu \left(\frac{c\alpha}{A} V + Rm\right)} \text{ - - - - - - - - - } (24)$$

which is the customary form for presenting the filtration rate equation.

Equation 24 can be placed into the form

$$\frac{g \ \Delta P}{\mu \ q} = \frac{c\alpha}{A} V + Rm \text{ - - - - - - - - - } (25)$$

Equation 25 will be used later as a basis for the analysis of constant pressure filtration data.

FILTRATION PROCESSES

Filtration processes may be classified according to the relation of the applied filtration pressure and flow rate to time. Generally, the pumping mechanism determines the filter flow characteristics and serves as a basis for division of filtration processes into the following categories:

(1) Constant pressure filtration,
(2) Constant rate filtration,
(3) Variable rate - variable pressure filtration
    (a) centrifugal pump
    (b) constant rate pump with bypass control,
(4) Stepped pressure by manual methods.

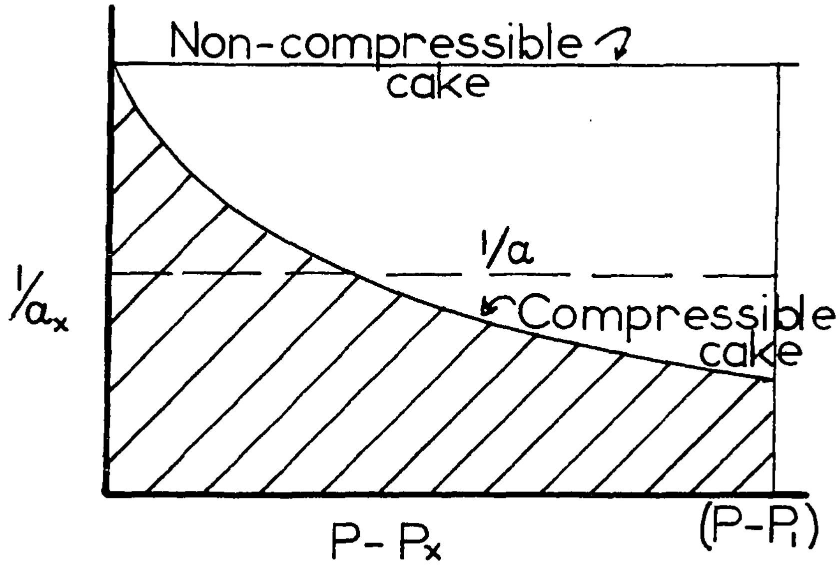
Flow rates vs. pressure characteristics for the four types of filtration are illustrated in Figure (6). Arrows on the curves point in the direction of increasing time. The constant pressure and constant rate processes are represented by vertical and horizontal lines, respectively.

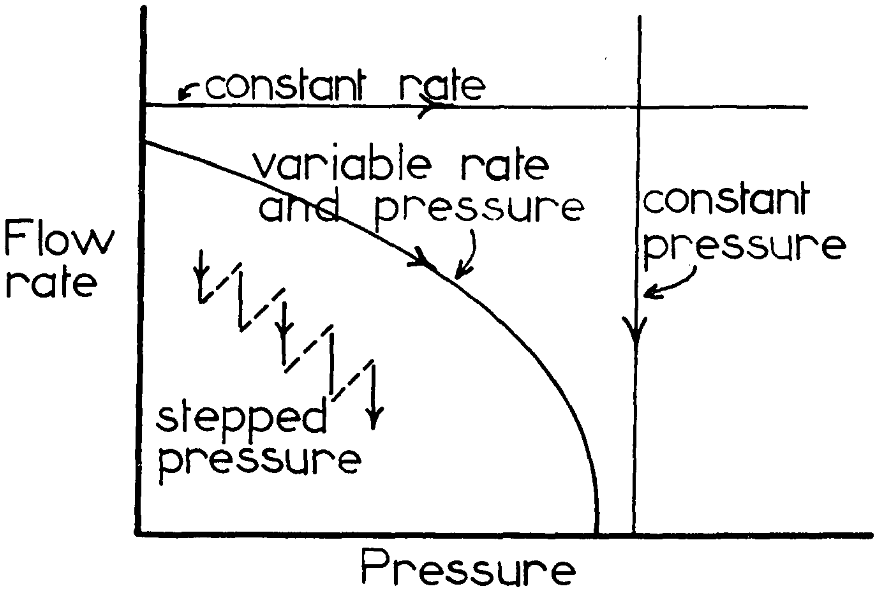
Constant Pressure Filtration

The simplest method of operating a filter is to apply the full pressure at the start of the filtration and maintain the pressure constant throughout the run. The flow rate of filtrate will be a maximum at the start of the filtration and will decrease continuously as the cake thickness builds up. This method of operation is referred to as constant pressure filtration.

Figure (5) Integration of Equation (16).

Figure (6) Filtration processes.


Non-compressible cake
1/a
$^1/_{a_x}$
Compressible cake
P - Px
(P-P1)


constant rate
variable rate and pressure
constant pressure
Flow rate
stepped pressure
Pressure

Equation 16 can be used for the general solution of a constant pressure filtration cycle. However, the pressure P as it appears in the limit of integration is set equal to a constant. The pressure P_1, required to overcome the medium resistance, approaches a constant value shortly after filtration is started. Therefore, the upper limit of the integral of Equation 16 is constant. For any functional relationship between α_x and Ps, the result of the integration will be independent of cake thickness. For the case of constant pressure filtration on a flat vertical septum, the average specific cake resistance α, as was defined in Equation 12, also becomes independent of cake thickness. Thus, the assumption of constant α is justified and Equation 25 can be used in the analysis of constant pressure filtration data.

$$\frac{g \quad \Delta P}{\mu (Q/A)} = \frac{c\,\alpha}{A} V + Rm \text{ - - - - - - - - - } (25)$$

A plot of 1/Q (or dt/dv) vs. V will yield a straight line whose intercept is K_1 and whose slope is K_2

where $K_1 = \frac{\mu\, Rm}{gA\Delta P}$ - - - - - - - - - (26)

$$K_2 = \frac{\mu\, c\,\alpha}{g\, A^2 \Delta P} \text{ - - - - - - - - } (27)$$

This plot is most easily prepared from data of V vs. t by taking the differences of both V and t, dividing the t difference by the V difference, and plotting the quotient as the height of a rectangle, using the ΔV value as the base. A straight line is drawn, as illustrated in Figure (7), through the tops of these rectangles, as nearly as possible through their mid-points, in such a way that the areas of the triangles above the line equal the areas of those below the line.

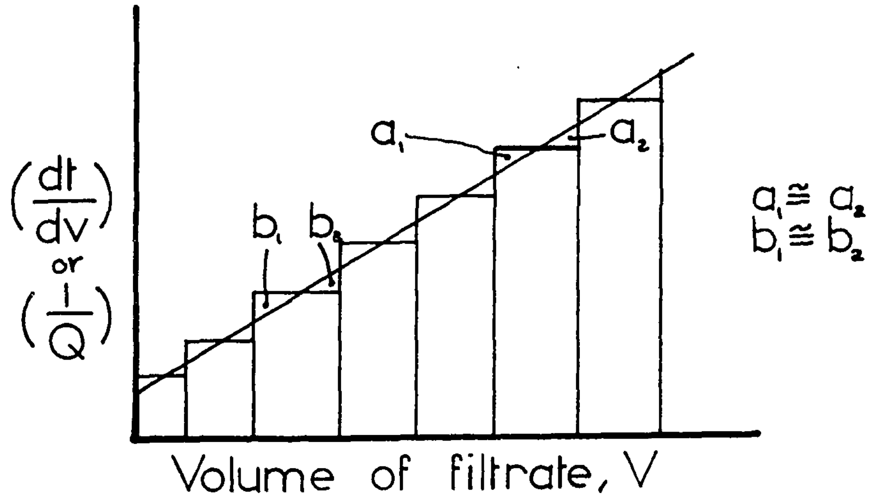
Values of α and Rm for any pressure drop can be obtained from Equations 26 and 27. To obtain the variation of α with filtration pressure, ΔP, a series of constant pressure filtrations is necessary. If α is independent of ΔP, the filter cake is non-compressible. Ordinarily, α increases with ΔP, as most filter cakes are at least to some extent compressible.

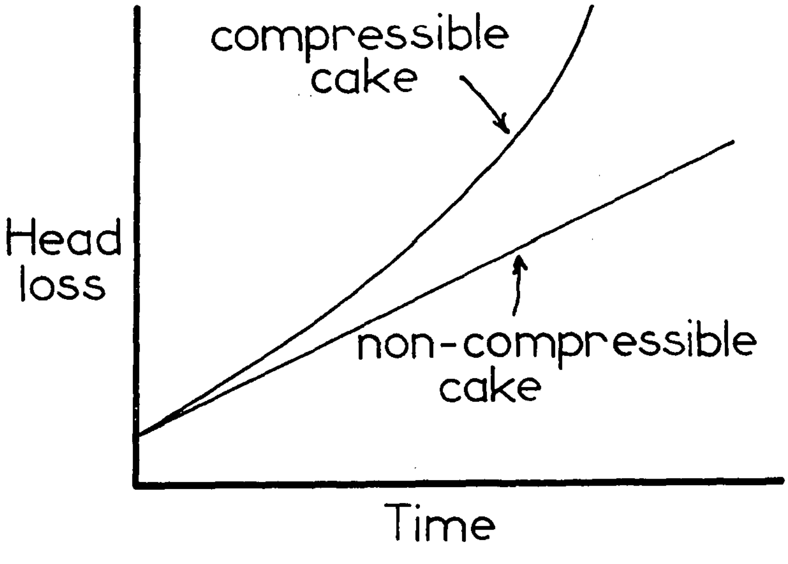
Constant Rate Filtration

When a slurry is delivered to a filter at a constant volumetric flow rate, the process is referred to as a constant rate filtration. Since the filtration resistance increases as the cake increases in thickness, the pressure drop across the filter must be increased continuously to maintain the rate of flow constant. In general, the filter inlet pressure remains constant during a constant rate filtration cycle. At the beginning of a filter run, most of the available pressure is used in providing flow through the flow rate controller. The head loss through the flow rate controller plus the head loss through the filter septum, medium, and filter cake will equal the applied inlet pressure. As the head loss through the cake increases with time, the flow rate controller will automatically adjust to decrease the head loss through the controller to keep the flow rate through the system constant.

Figure (7) Plot for constant pressure filtration data.

Figure (8) Head loss versus time curves for compressible and non-compressible filter cakes on flat septa in constant rate filtration.


$\left(\frac{dt}{dv}\right)$ or $\left(\frac{1}{Q}\right)$
Volume of filtrate, V
a_1
a_2
b_1
b_2
$a_1 \cong a_2$
$b_1 \cong b_2$


compressible cake
non-compressible cake
Head loss
Time

This is in contrast to the mode of operation in which the filter inlet pressure is held constant and equal to the pressure drop across the filter while the flow rate diminishes with time as the cake resistance increases.

In a constant rate filter operation, the filtration resistance increases not only because the cake increases in thickness but also due to the greater compaction of the cake solids as a result of the continuous increase in pressure drop across the cake. The specific cake resistance, αx, at any point within the cake increases in response to the increasing pressure drop across the cake.

Constant rate filtration is used either alone or in combination with constant pressure filtration. In some filtration practices, the early stages of filtration are conducted at constant rate as the controlling factor is the capacity of the pump to deliver. As the cake becomes thicker and offers more resistance to the flow of water, the limiting factor becomes the pressure developed by the pump and the filtration proceeds at nearly constant pressure.

Figure (8) shows the theoretical head loss versus time of filtration curves for compressible and non-compressible cakes that would result from filtration on flat septa. The head loss across the cake during filtration is a linear function of time for non-compressible cakes and a logarithmic function of time for compressible filter cakes. The function is nonlinear for compressible cakes because the cake resistance to flow increases as the cake grows thicker and the pressure drop across the cake consequently increases faster than cake thickness.

In order to solve Equation 16 for the general case of constant rate filtration, it is necessary to obtain the integral of dPs/α_x either by numerical methods or by integration. The assumption of a constant average filtration resistance is not valid in this case and Equation 25 cannot be used for the analysis of constant rate filtration data.

For most moderately compressible materials (16), the value of α_x is assumed to be a function only of Ps and the following approximation can be made for α_x:

$$\alpha_x = \alpha_o \, Ps^s \text{ - - - - - - - - - } (28)$$

where α_o and s are empirical constants. The integral of Equation 16 can be placed in the form

$$\int_o^{P-P_1} \frac{dPs}{\alpha_x} = \int_o^{P-P_1} \frac{dPs}{\alpha_o Ps^s} = \frac{(P-P_1)^{1-s}}{\alpha_o(1-s)} \text{ - - - } (29)$$

Substituting Equation 29 into 16 yields

$$\frac{(P-P_1)^{1-s}}{\alpha_o(1-s)} = \frac{\mu\, q\, c}{g\, A} V \text{ - - - - - - - - - } (30).$$

Since $V = q.t.A$ - - - - - - - - - - (31),

Equation 30 can be put in the form

$$\frac{(P-P_1)^{1-s}}{\alpha_o(1-s)} = \frac{\mu\, c\, q^2}{g} t \text{ - - - - - - - - - } (32)$$

For a given filtration run, the factors α_o, s, μ, c, g, and q (or Q/A) are constant. It is convenient to lump all of these factors as they appear in Equation 32 into a single quantity K_3 defined by the following equation

$$K_3 = \frac{\alpha_o \mu (1-s)\ c\ Q^2}{g\ \ A^2} \text{ - - - - - - - - - } (33)$$

Substituting Equation 33 into Equation 32 and taking the logarithms of both sides yields

$$(1-s) \log (P-P_1) = \log K_3 + \log t \text{ - - - - } (34).$$

If $\log (P-P_1)$ is plotted as the abscissa against $\log t$ as the ordinate, a straight line should be obtained whose slope is equal to $(1-s)$. The value of K_3 is calculated by means of Equation 34, from the coordinates of any convenient point on the line. The value of α_o can then be evaluated by means of Equation 33. The use of the method will be illustrated in Example 3 on page (91).

Although Equation 28 is generally accepted for relating α_x to Ps, it is obviously subject to considerable error at low pressure drops, as it indicates a zero resistance at zero Ps. The results of this study have indicated that Equation 28 is valid only for values of Ps greater than Pi, where Pi is a low compressive pressure below which the cake porosity and resistance are constant. The value of α_x is given as

$$\alpha_x = \alpha_o\ Ps^s \qquad \text{for } Ps > Pi \text{ - - - - - - - - - } (35)$$

and

$$\alpha_x = \alpha_o\ Pi^s \qquad \text{for } Ps < Pi \text{ - - - - - - - - - } (36)$$

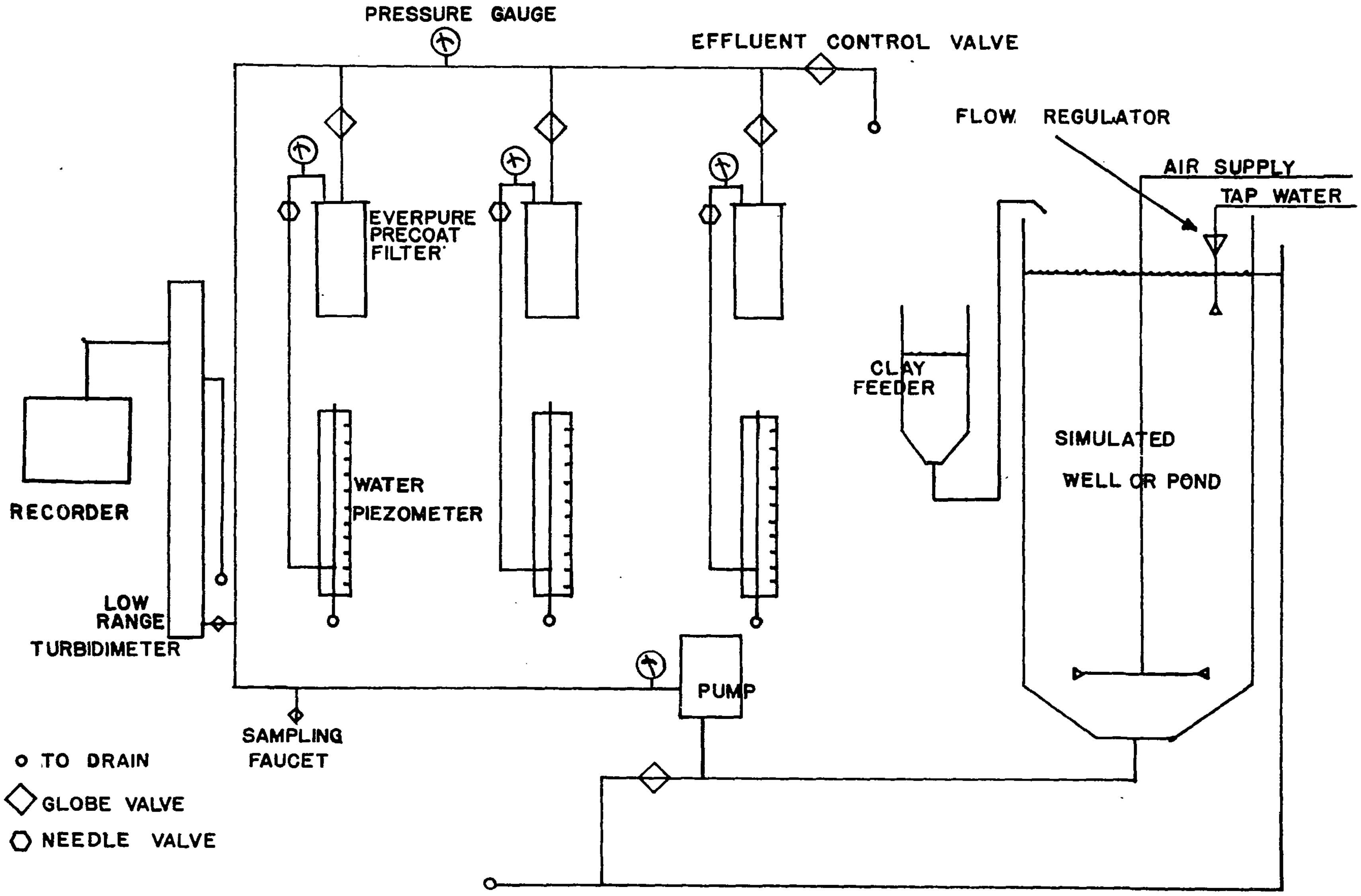
The use of Equation 34 for the analysis of constant rate filtrations has to be modified and will be discussed later.

LABORATORY APPARATUS AND PROCEDURES

Simulated Small Water Supply System

The simulated, small water supply system shown schematically in Figure (9) was set up in the laboratory to represent a typical field installation used for iron and turbidity removal. A 150-gallon mixing tank containing synthetic turbid water was used to simulate a well or pond water supply. The water level in the tank was maintained constant by using an overflow outlet near the top of the tank. Water was withdrawn from the simulated well or pond by means of a Fairbanks-Morse, three stage, vertical pump and delivered into the system. The effluent control valve was set to maintain a pressure of 82 psi at the pump discharge so that the pump always worked against a constant head and therefore pumped at a constant rate. The discharge line from the pump fed three C-3 Everpure filters installed in parallel. The discharge to each filter could be adjusted by means of a globe valve at each filter inlet to provide a maximum rate of flow through the filter. The discharge from each filter was controlled by means of a needle valve. The rate of flow of filtrate from each filter was measured by a pre-calibrated water flowmeter connected to the discharge line of the filter. A constant rate of filtration was obtained by periodically adjusting the needle valves on the discharge side of each filter to maintain a given reading on the flow meter scale.

Figure (9) Schematic diagram for simulated water supply system.


PRESSURE GAUGE
EFFLUENT CONTROL VALVE
FLOW REGULATOR
AIR SUPPLY
TAP WATER
EVERPURE PRECOAT FILTER
CLAY FEEDER
SIMULATED WELL OR POND
RECORDER
WATER PIEZOMETER
LOW RANGE TURBIDIMETER
PUMP
SAMPLING FAUCET
TO DRAIN
GLOBE VALVE
NEEDLE VALVE

The system was constructed of 3/4 in. galvanized steel pipe for the main supply line and ½ in. pipe for the laterals to each filter. A by-pass to waste and a sample faucet were also provided in the set up.

To measure the turbidity of the influent water, a photoelectric low-range turbidimeter[a], Figure (10), and an automatic recorder[b], Figure (11), were connected to the system. The turbidimeter was calibrated against the Jackson Candle Turbidimeter for each clay used. Calibration curves are presented in Appendix C. A description of the turbidimeter and the method used for calibration of the low-range turbidimeter and the multipoint recorder are well presented in the manufacturer's manual and in a M.S. thesis by Regunathan (23).

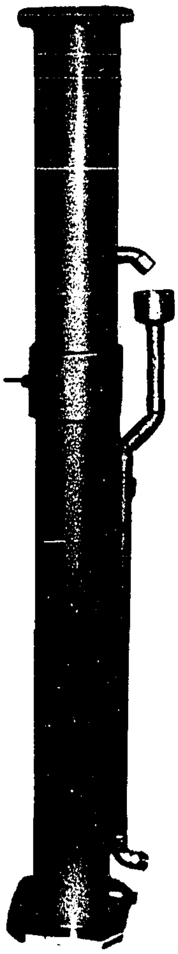
The turbidimeter was periodically disconnected from the raw water system and used to measure the turbidity of the filter effluent. The filtrate from each filter was collected in a bucket and a small centrifugal pump was used to circulate the effluent through the turbidimeter and the turbidity level was recorded. When the effluent turbidity was less than that of distilled water, it was reported as 0.00 unit.

---

[a] C.R. Low-range turbidimeter, Hach Chemical Co., Ames, Iowa.

[b] Type 153 Universal Electronic Multipoint Recorder, Minneapolis-Honeywell Regulator Co., Philadelphia, Pennsylvania.

Figure (10) Low-range turbidimeter.



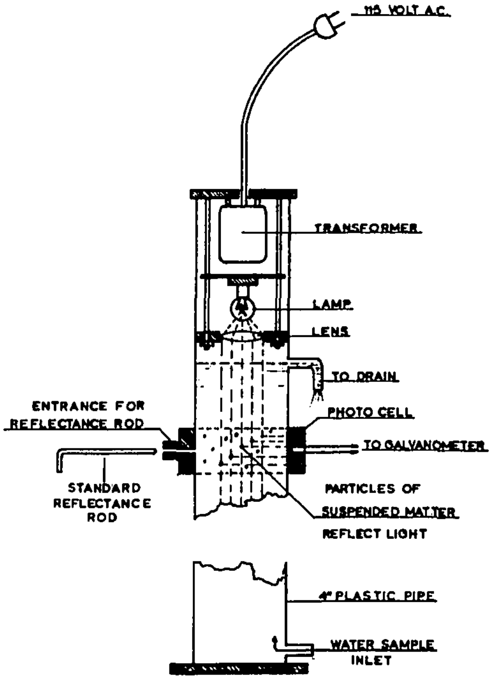
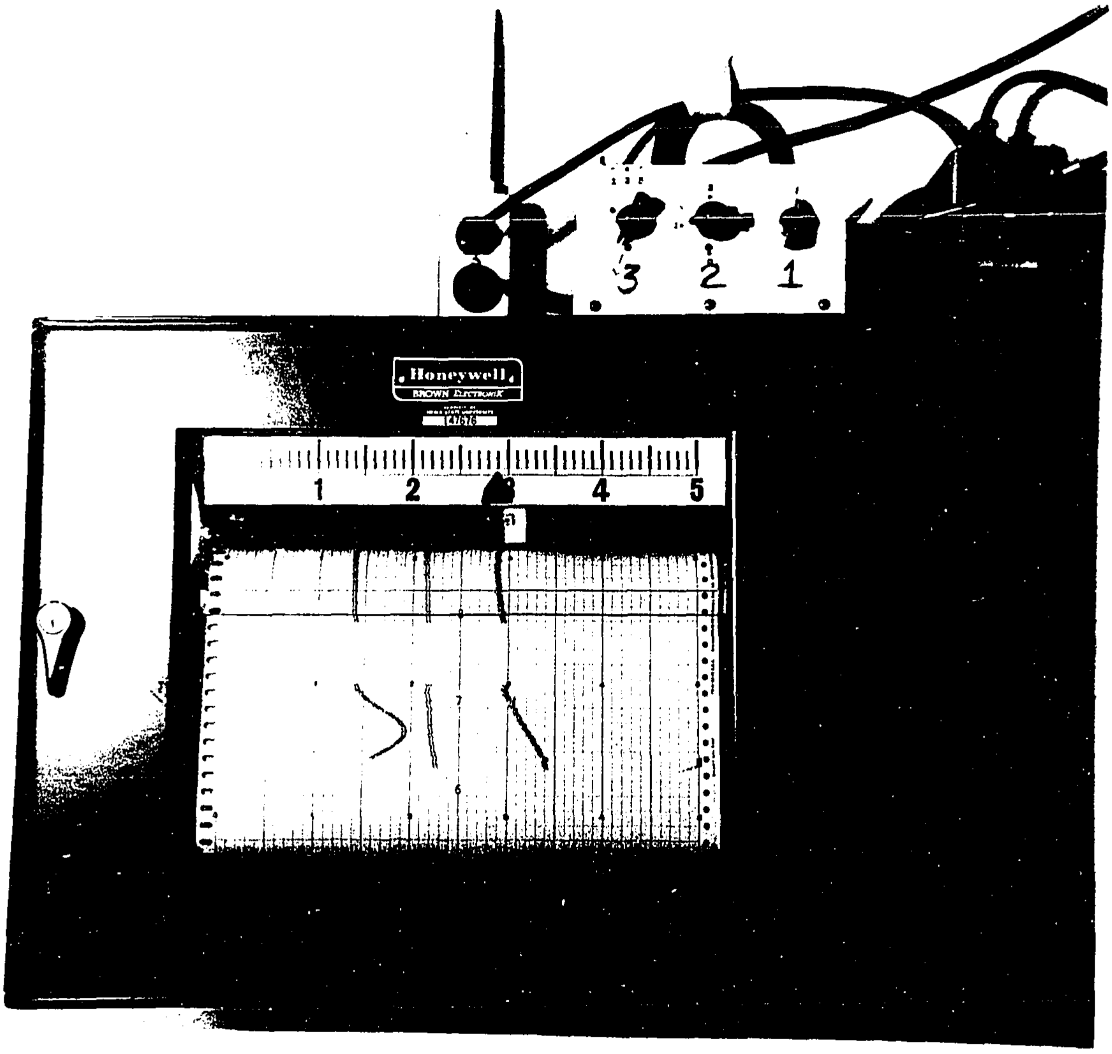

115 VOLT A.C.
TRANSFORMER
LAMP
LENS
TO DRAIN
ENTRANCE FOR REFLECTANCE ROD
PHOTO CELL
TO GALVANOMETER
STANDARD REFLECTANCE ROD
PARTICLES OF SUSPENDED MATTER REFLECT LIGHT
4" PLASTIC PIPE
WATER SAMPLE INLET

Figure (11) Photograph of the multipoint recorder used to record raw and filtered water turbidity.


Honeywell
BROWN ELECTRONIK
1
2
3
4
5
1
2
3

The Filter Unit

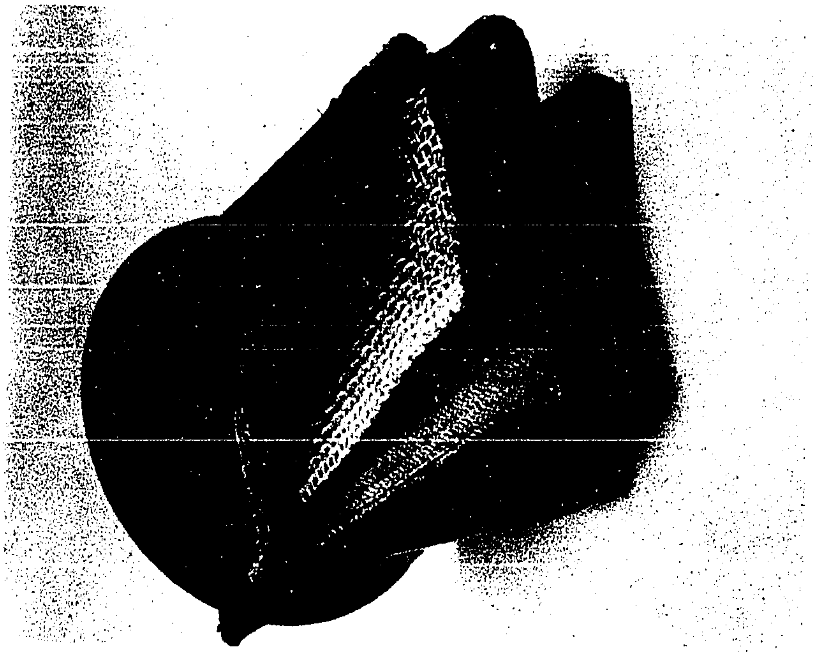
The filter unit used in this study was the standard Everpure, precoat activated carbon filter. The filter, produced by Everpure, Inc., is available in various sizes and capacities as shown in Table 1.

Table 1. "Everpure" Filters

Model	Approximate size	Approximate filter area, sq ft	Recommended service flow, gpm
C-1	5"Dia. x 8"	1.0	$\frac{1}{2}$
C-3	5"Dia. x 15"	2.6	1
T-9	9"Dia. x 17"	9.0	2
T-20	9"Dia. x 31"	20.0	3

In this study, only C-3 model filters were used with the intention of obtaining information which could also be applied in the evaluation of the performance of other units. The C-3 filter, shown in Figure (12), is composed of an outer shell within which a replaceable U-Fil cartridge is housed. The U-Fil cartridge contains a filter media charge consisting of activated carbon and other materials and a filter septum to hold the carbon in a filtering position. The septum is a fabric envelope, folded to provide a large surface area in a small container. The two layers of the septum were separated by the inert spacer shown also in Figure (12). The spacer

Figure (12) Components of Everpure C-3 replaceable cartridge.



maintained a minimum clearance between the two layers of the septum fabric and permitted the filtered water to flow through the channel thus created to the effluent tube. The effluent tube was threaded so that it could be screwed into the top of the filter housing. The inlet tube opening was located near the periphery of the top of the container. As water left the inlet tube it came into contact with the Everpure charge which had concentrated at the bottom of the container. The water mixed with the carbon and the resultant suspension of carbon in water was deposited on the septum.

Synthetic Turbid Water

Two clay minerals, ball clay[a] and Wyoming bentonite[b] clay, were used to produce synthetic turbid waters in this work. The ball clay and bentonite clays were kaolinite and sodium montmorillonite clays, respectively. The turbid water was prepared by adding tap water and a concentrated clay slurry continuously to the mixing tank representing a simulated pond. University tap water was added to the tank continuously at a constant rate of 7.5 gpm through a flow control regulator. The clay slurry was fed into the mixing tank by means of a

---

[a] Old Hickory No. 5 ball clay, Old Hickory Co., Paducah, Kentucky. (kaolinite mineral).

[b] Black Hills Bentonite, International Mineral and Chemical Corporation, Skokie, Illinois. (sodium montmorillonite mineral).

slurry feeder[a]. The slurry was prepared in the feeder by mixing a known amount of clay in distilled water and leaving it overnight with air agitation for 18 hours. A pump attached to the feeder flushed out the slurry in small equal quantities into the mixing tank. The turbidity of the resulting water could be varied by either adjusting the length of stroke of the metering diaphragm in the feeder or by changing the concentration of slurry. The turbidity of water used in this work varied between 5 and 20 Jackson Candle Turbidity units (calibrated with the clay suspension used).

The university tap water used in the study is a filtered well water containing a total hardness of 440 mg/l as $CaCO_3$, a bicarbonate alkalinity of 320 mg/l as $CaCO_3$, and a total iron content of less than 0.05 mg/l (19). In all the tests conducted, the tap water pH was between 7.3 and 7.6.

Test Procedure

To prepare the system for conducting a constant rate filtration test, it was necessary to operate the system equipment for a period of time long enough to allow the water turbidity and temperature to come to equilibrium. Generally, a period of 2-3 hours was required.

---

[a] Series A-710 Slurry Feeder, Wallace and Tiernan, Inc., Belleville, New Jersey.

When the desired water turbidity was attained in the system, a fresh filter unit was installed in each filter housing. Water was admitted to the filter unit at a slow rate until the filter housing and cartridge were filled and water flowed from the outlet pipe. The time was noted and the flow was increased to 1.5 gpm for 5.0 minutes. This break-in flow rate is recommended by the manufacturer to resuspend the carbon filter medium from the bottom of the cartridge and to precoat it on the septum. The filter medium was precoated on the septum during the break-in procedure, After 5 minutes, the flow was reduced to the desired rate (0.50, 0.75, or 1.0 gpm) and the constant rate filtration test was begun. The head loss across the filter was recorded at regular intervals, and the flow rate was adjusted manually to the desired rate as the increased pressure drop caused a decrease in flow rate.

During the course of the filter run, the raw water turbidity was maintained as close to the required level as possible. Turbidity measurements were recorded continuously on the multipoint recorder. The effluent turbidity was measured periodically both by means of grab samples and using the recorder. The temperature and pH of the water were also measured and recorded. Measurement of pH was made using Beckman pH meter. The pH of the water with all levels of turbidity remained between 7.3 and 7.6.

A plot of head loss, in psi, versus time in minutes was prepared while a run was proceeding. When the head loss across the filter unit approached the total applied pressure in the system, the run was terminated.

Test Results

The experimental runs conducted using the Everpure filters were performed under constant rate operation. Two clay minerals and three flow rates were used. Table 2 shows a summary of the test runs made and the conditions of each test. Complete filter operation data, however, are reported in Appendix A.

Several trial runs were made to become familiar with the equipment and the procedures to be used during a run. During these runs, few adjustments were made in the system.

Most of the runs reported herein were conducted with continuous flow of filtrate and no interruptions in the filtration cycle. Adjustment of the needle valves to maintain a constant rate of flow from each filter was accomplished manually whenever needed. Each filter was observed 24 hours a day until the run was terminated.

A few runs were conducted on an intermittent or interrupted flow basis. Most such runs were terminated for an overnight rest period and continued the next day. These runs are grouped in Series A of Table 2. Since no definite intermittent flow pattern was used and the rest periods were not specified, the results from these runs are reported only as trial runs.

Table 2. Summary of Constant Rate Filtration Test Conditions

Series	Run No.	Clay Mineral	Raw Water Turbidity, JCU	Flow Rate, gpm	Number of filters tested
A	1	Ball clay	19	0.75	3
	2	"	19	0.50	3
	3	"	10	1.00	3
B	1	Ball clay	19	1.00	3
	2	"	19	0.75	3
	3	"	19	0.50	2
C	1	Ball clay	10	1.00	3
	2	"	10	0.75	3
	3	"	10	0.50	3
D	1	Ball clay	5	1.00	3
	2	"	5	0.75	2
	3	"	5	0.50	3
E	1	Wyoming Bentonite	10	1.00	2
	2	"	10	0.75	2
	3	"	10	0.50	1
F	1	Wyoming Bentonite	15	1.00	3
	2	"	5	1.00	2

The typical head loss versus time of filtration curves obtained by plotting the raw data are shown in Figures 23-27, Appendix A. A plot of the log of flow time, t, in minutes, versus log ($\Delta P - \Delta Pi$), the pressure drop across the cake in psi, was made for each test. The resulting curves are presented in Figure (13).

The straight lines of Figure (13) indicate that the flow time, t, may be expressed as an exponential function of the pressure drop ($\Delta P - \Delta Pi$). An empirical relationship can be derived as follows: From Figure (13) we obtain

$$\log t = \log \frac{1}{K_3} + B \log (\Delta P - \Delta Pi) \text{ - - - - - - - - - } (37)$$

or

$$t = \frac{1}{K_3} (\Delta P - \Delta Pi)^B \text{ - - - - - - - - - - - - } (38)$$

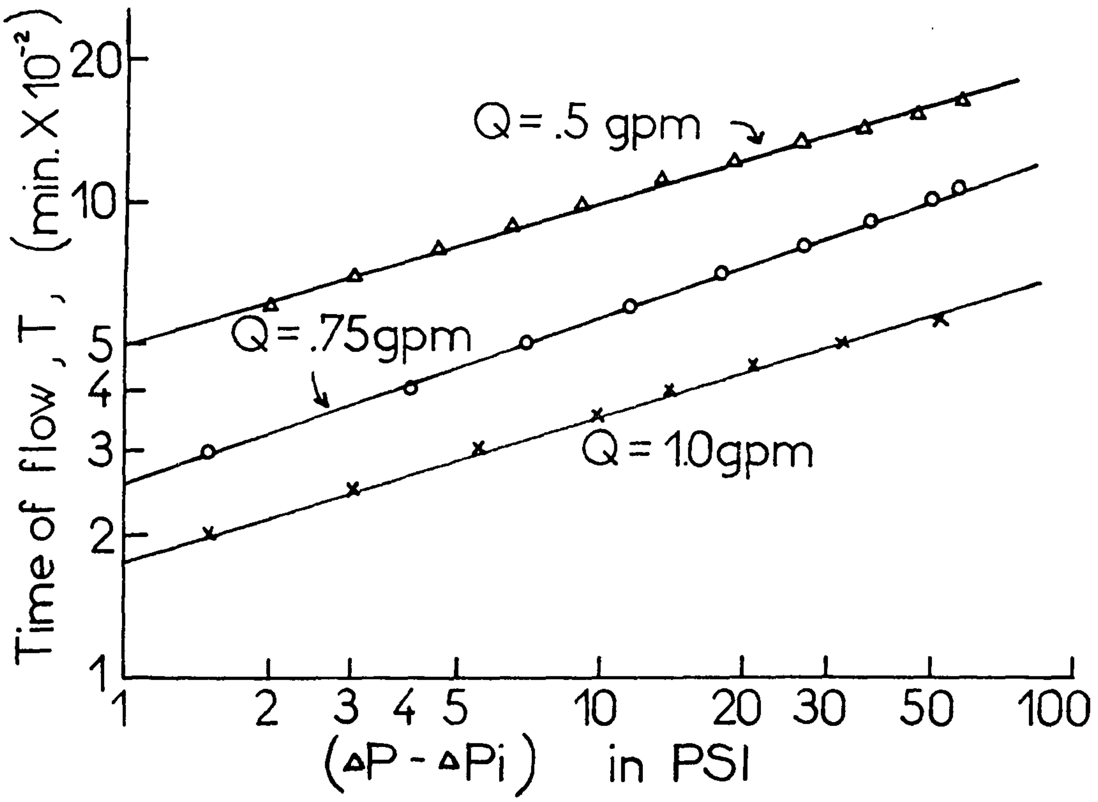
where B is the slope of the straight line on the plot of log ($\Delta P - \Delta Pi$) vs. log t and K_3 is calculated, by means of Equation 38, from the coordinates of any convenient point on the line.

Since the actual data obtained from a constant rate filter operation are the over-all pressure drop, ΔP, and time t, the pressure drop ΔPi is not recorded directly and must be estimated. A tentative magnitude for ΔPi can be found by plotting t vs. ΔP on rectangular coordinates, passing a smooth curve through the points (see Appendix A), and extrapolating the curve to the pressure axis, where t = o. The resulting value of pressure drop when t = o is the pressure drop across the filter medium ΔPm. A tangent line to the lower portion of the curve drawn through ΔPm predicts the

Figure (13) Plots of log t vs. log (ΔP-Pi) for suspensions of ball clay and Wyoming bentonite

Figure (13-a) Series B, Runs 1, 2, 3

Figure (13-b) Series C, Runs 1, 2, 3


Time of flow, T, (min. X 10^{-2})
20
10
5
4
3
2
1
Q = .5 gpm
Q = .75gpm
Q = 1.0gpm
1
2
3
4
5
10
20
30
50
100
(ΔP - ΔPi) in PSI

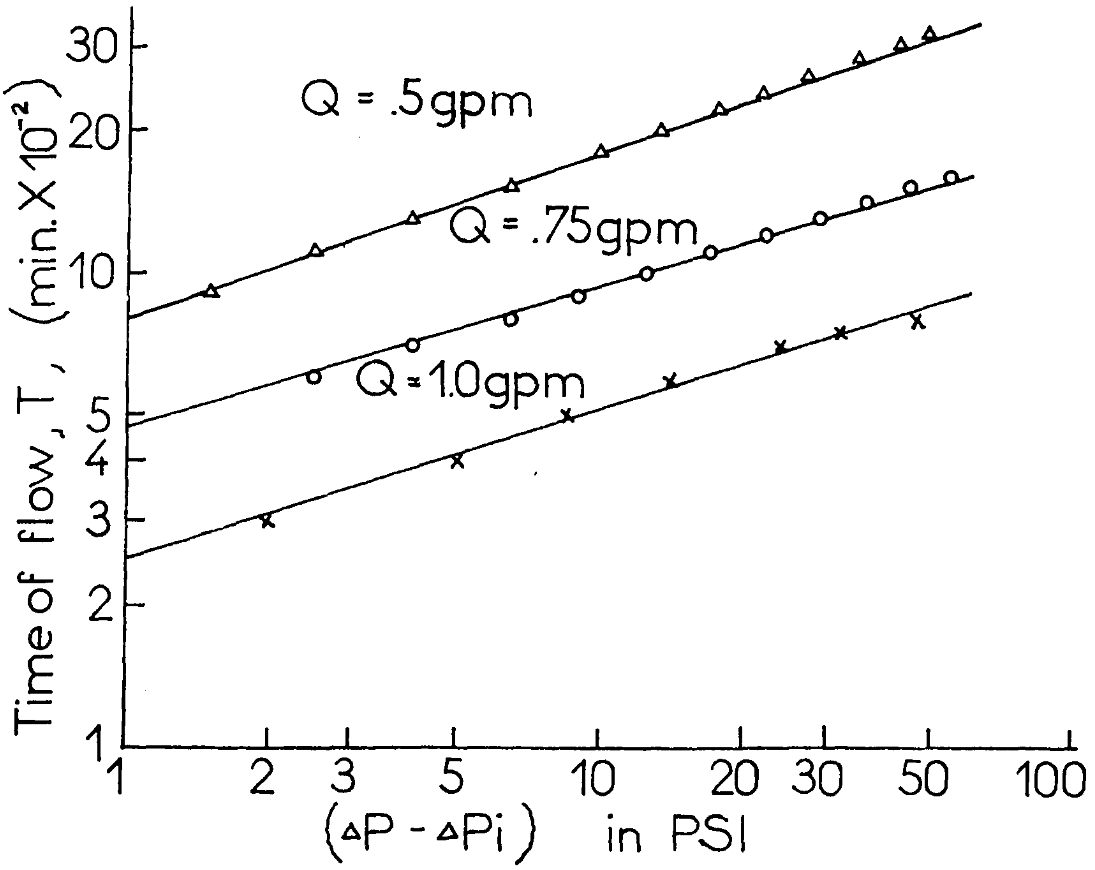

Time of flow, T, (min. X 10^{-2})
30
20
10
5
4
3
2
1
Q = .5gpm
Q = .75gpm
Q = 1.0gpm
1
2
3
5
10
20
30
50
100
(ΔP - ΔPi) in PSI

Figure (13-c) Series D, Runs 1, 2, 3

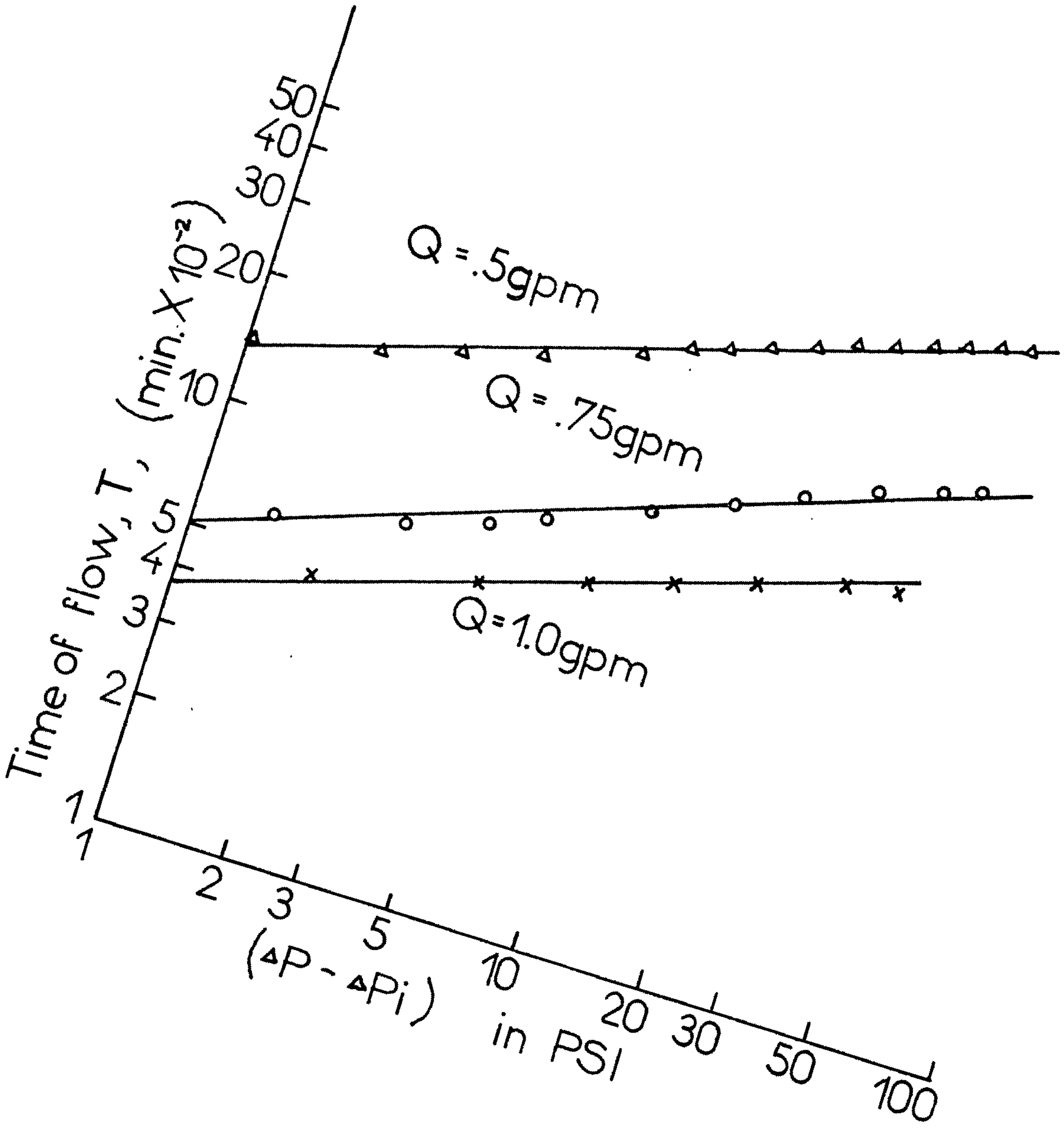
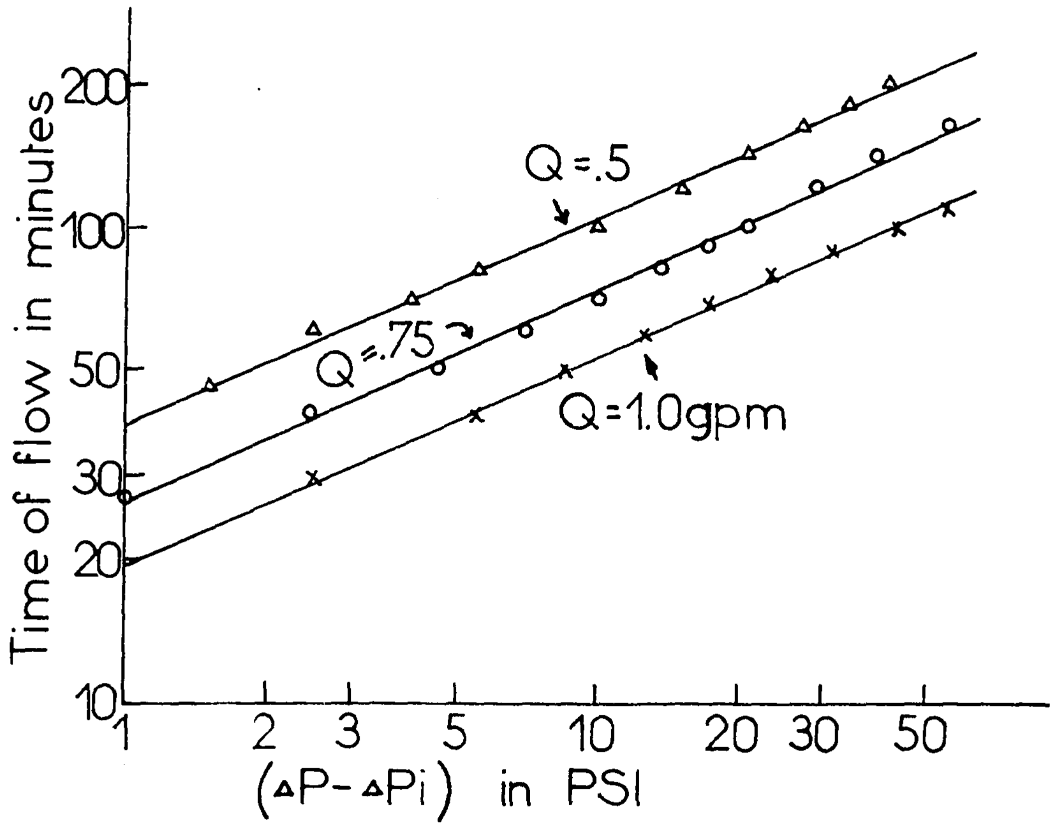
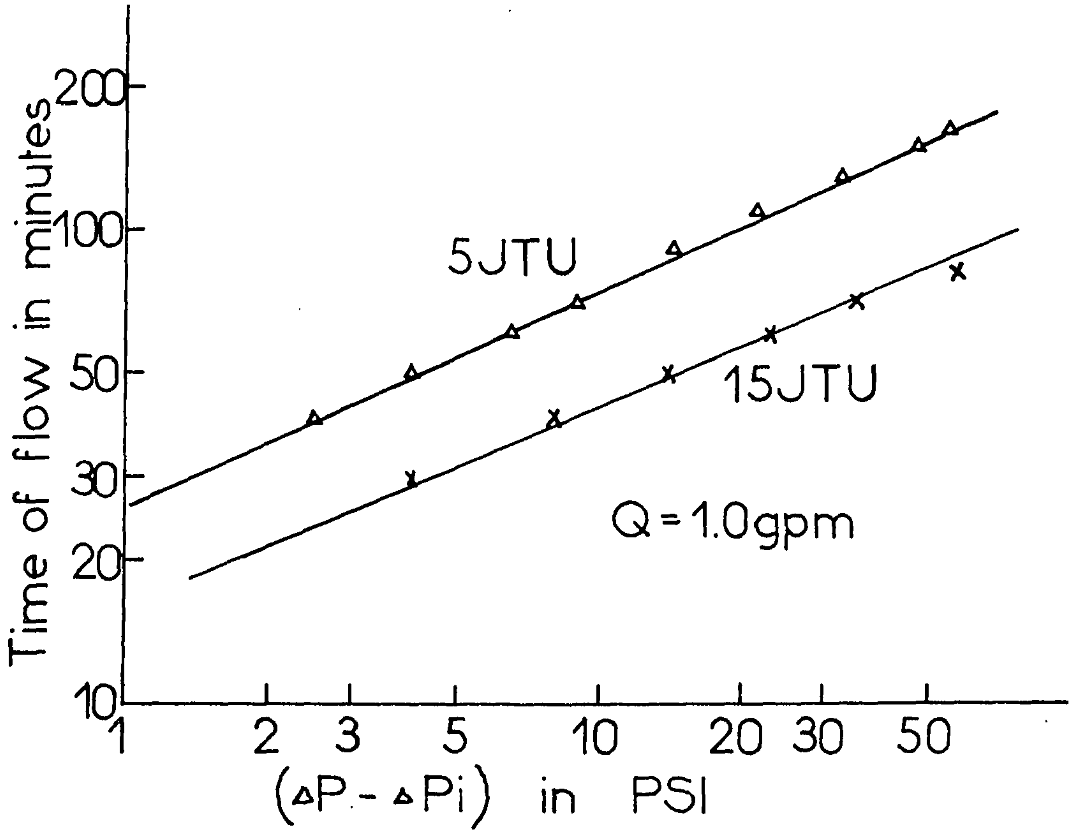

Time of flow, T, (min. X 10^{-2})
50
40
30
20
10
5
4
3
2
1
1
2
3
5
10
20
30
50
100
($\Delta P - \Delta P_i$) in PSI
Q = .5gpm
Q = .75gpm
Q = 1.0gpm

Figure (13-d) Series E, Runs 1, 2, 3

Figure (13-e) Series F, Runs 1, 2


Time of flow in minutes
10
20
30
50
100
200
1
2
3
5
10
20
30
50
(ΔP - ΔPi) in PSI
Q = .5
Q = .75
Q = 1.0gpm


Time of flow in minutes
10
20
30
50
100
200
1
2
3
5
10
20
30
50
(ΔP - ΔPi) in PSI
5JTU
15JTU
Q = 1.0gpm

relationship between ΔP and t if the cake was non-compressible. The point of departure of the curve from the tangent line corresponds to the value of ΔPi. A tentative result for ΔPi is thus found, which can be used for preparing a plot of $(\Delta P-\Delta Pi)$ vs. t on logarithmic cordinates. If the line so obtained is straight, the tentative value of ΔPi can be taken as final. If the line so obtained is curved, additional approximations for ΔPi can be made until a straight line is achieved.

When a straight line has been obtained on the plot of log $(\Delta P-\Delta Pi)$ vs. log t, the constant "B" is obtained from the slope of the line. The factor K_3 is calculated from the coordinates of any convenient point on the line. An explanation of the data analysis and calculation of K_3 is included in example 3 on page 91.

Interpretation of Results

Analysis of the curves of Appendix A shows that the (ΔP) vs. t curve can be divided into a straight line portion at low pressure drop and an exponential portion following it. The filter cake resistance was constant, as indicated by the straight line, until the pressure drop across the cake exceeded ΔPi. The additional pressure needed at this stage to maintain a constant rate of flow, was needed due to the increasing cake thickness. For pressure drops greater than ΔPi the rate of increase of cake resistance is not constant. The cake filtration resistance increases exponentially with the cake thickness or volume of filtrate.

If Equation 34 is to be used in this analysis, it should be applied for pressure drops greater than ΔP_i as follows,

$$(1-s) \log (\Delta P-\Delta Pi) = \log K_3 + \log t \text{ - - - - } (39)$$

Combining Equation 39 and 37 gives

$$B = (1-s) \text{ - - - - - - - - - - } (40)$$

i.e. the slope of the straight lines of Figure (13) is a quantitative measure of the constant s. Values of ΔPm, K_3, αo, and s for the data of Figure (13) are given in Table 3. A detailed explanation of how the data in Table 3 were obtained is given in Example 3 on page 91.

Values of the cake compressibility factor, s, were not affected by either the flow rate or the suspended solids concentration. The constant s is a quantitative measure of the cake compressibility and is not expected to change appreciably for a given material. According to Table 3, the ball clay (kaolinite) had an average s value of 0.67 and Wyoming bentonite (montmorillonite) had an average s value of 0.55.

The value of αo was significantly affected by both flow rate and solids concentration. Figures (14-a and 14-b) show the variation of αo with Q for the filtration of ball clay and Wyoming bentonite suspensions. As can be seen from the figures, the magnitude of αo decreases with increasing solids concentration, possibly owing to flocculation or changing cake structure.

The filter-medium resistance, denoted by Rm, was

Table 3. Summary of constant rate filtration results

Series and run	Q gpm*	Clay in suspension		ΔP_m psi	B	s	K'_3 lb/ft^2/sec	α_0 ft/lb	Rm 1/ft
		JCU	mg/l†						
A-1									
A-2									
A-3									
B-1	1.00	19	20.5	8.5	0.33	0.67	5.1×10^{-5}	6.88×10^{10}	6.07×10^{10}
B-2	0.75	19	20.5	6.5	0.34	0.66	3.4×10^{-5}	8.00×10^{10}	6.18×10^{10}
B-3	0.50	19	20.5	4.5	0.30	0.70	1.64×10^{-5}	9.13×10^{10}	6.42×10^{10}
C-1	1.00	10	11.0	8.5	0.32	0.68	3.3×10^{-5}	8.56×10^{10}	6.07×10^{10}
C-2	0.75	10	11.0	6.5	0.31	0.69	1.83×10^{-5}	8.70×10^{10}	6.18×10^{10}
C-3	0.50	10	11.0	5.0	0.35	0.65	1.18×10^{-5}	11.20×10^{10}	7.10×10^{10}
D-1	1.00	5	5.5	8.5	0.31	0.69	2.14×10^{-5}	11.45×10^{10}	6.07×10^{10}
D-2	0.75	5	5.5	6.5	0.34	0.66	1.77×10^{-5}	15.40×10^{10}	6.18×10^{10}
D-3	0.50	5	5.5	4.5	0.33	0.67	$.84\times10^{-5}$	17.40×10^{10}	6.42×10^{10}
E-1	1.00	10	16.0	8.5	0.45	0.55	8.2×10^{-3}	10.40×10^{11}	6.07×10^{10}
E-2	0.75	10	16.0	6.5	0.45	0.55	5.9×10^{-3}	13.30×10^{11}	6.18×10^{10}
E-3	0.50	10	16.0	4.75	0.45	0.55	4.2×10^{-3}	21.40×10^{11}	6.78×10^{10}
F-1	1.00	15	24.0	9.5	0.45	0.55	6.0×10^{-3}	5.07×10^{11}	6.78×10^{10}
F-2	1.00	5	8.0	8.0	0.43	0.57	9.1×10^{-3}	13.9×10^{11}	5.72×10^{10}

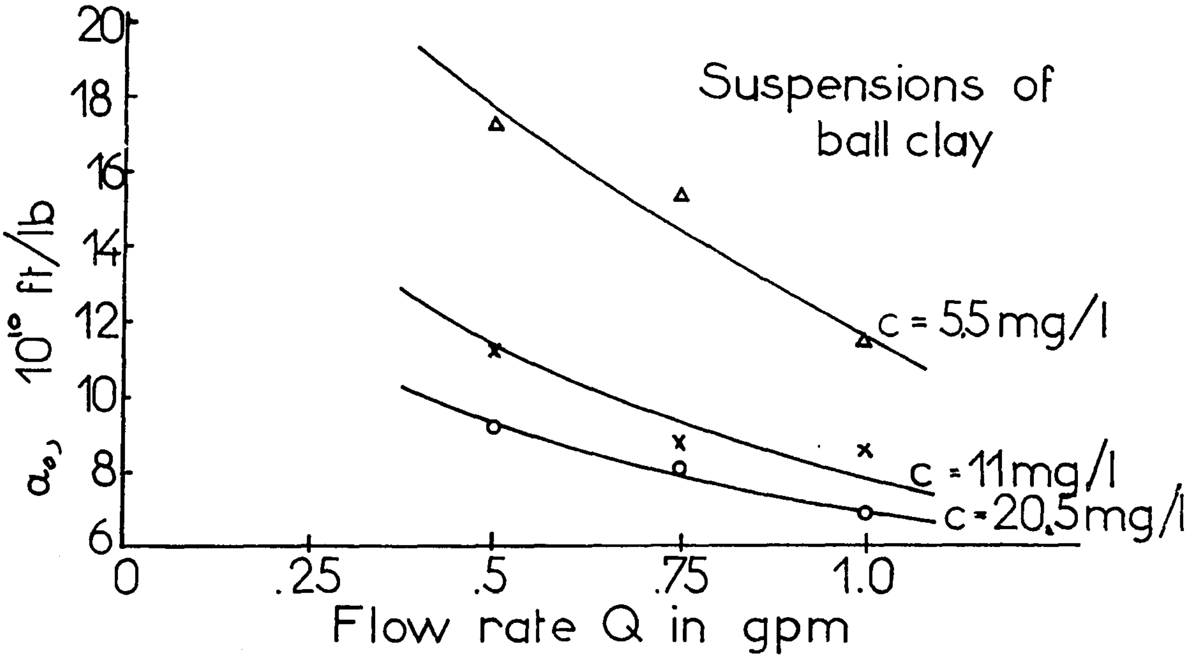
*To convert to ft^3/sec multiply by 2.24×10^{-3}

†To convert to lb/ft^3 multiply by 6.24×10^{-5}

previously defined by Equation 20. The factors controlling the magnitude of Rm, according to Equation 20, are the pressure drop across the medium ΔPm and the rate of flow of filtrate Q. Figures (15-a and 15-b) show the variation of ΔPm and Rm with Q respectively. Neither the solids concentration nor its compressibility had a measurable effect on the ΔPm values. The Rm values listed in Table 3 also include any resistance to flow that may exist in the leads to and from the filter.

Figure (14-a) Plots of α_o vs. Q for ball clay suspensions.

Figure (14-b) Plots of α_o vs. Q for bentonite clay suspension.


Suspensions of ball clay
a_∞, 10^{10} ft/lb
20
18
16
14
12
10
8
6
0
.25
.5
.75
1.0
Flow rate Q in gpm
c = 5.5 mg/l
c = 11 mg/l
c = 20.5 mg/l

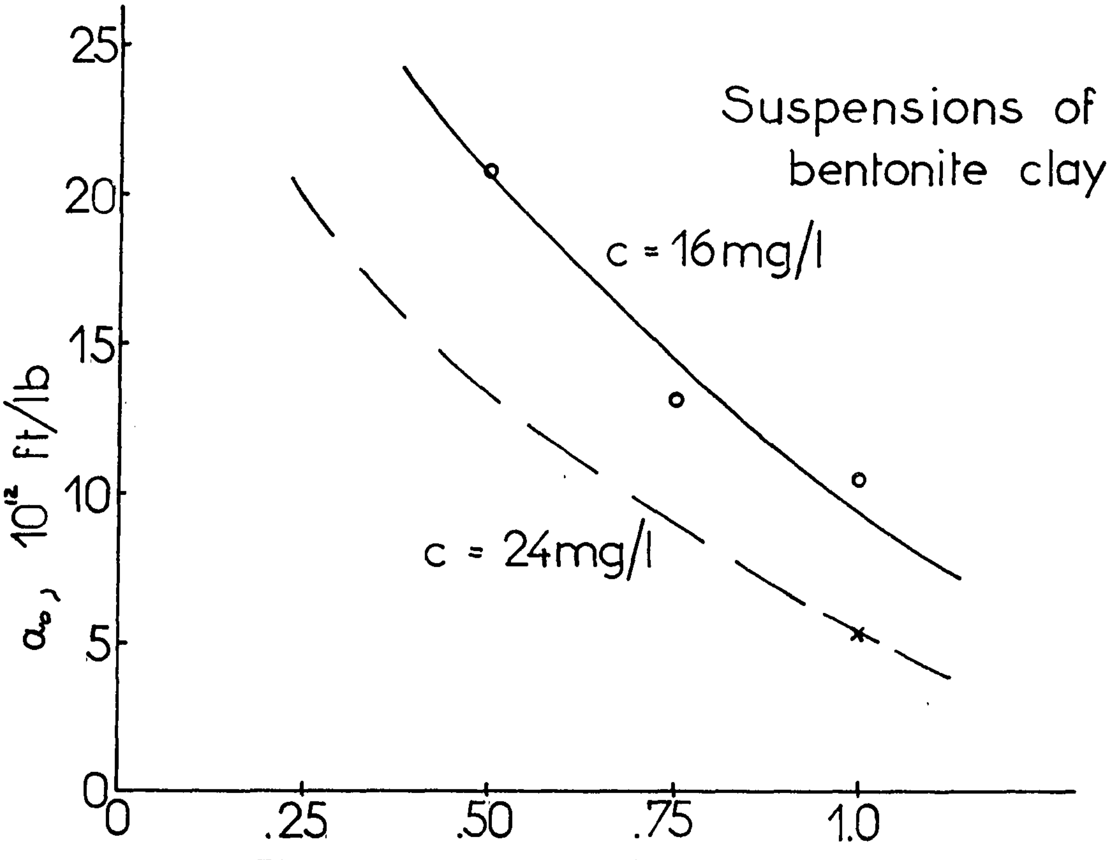
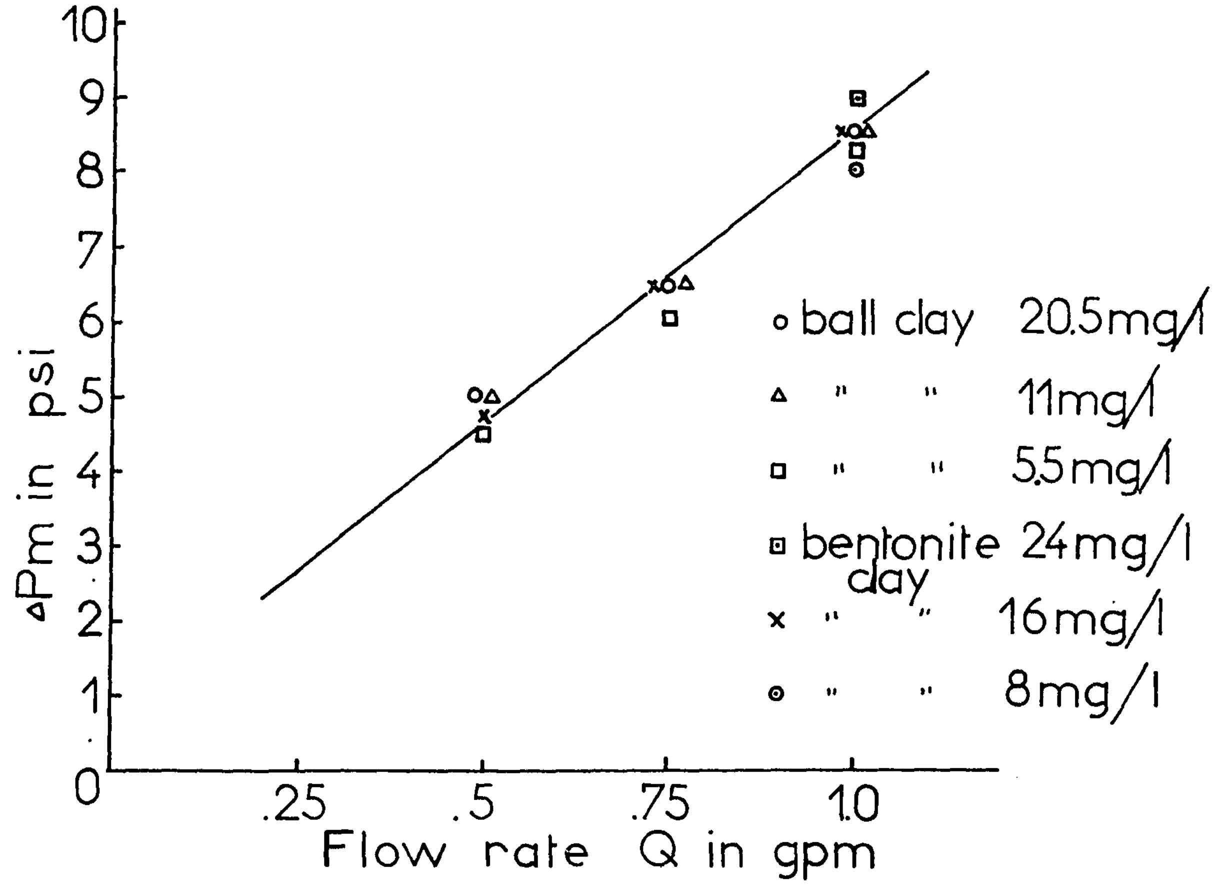
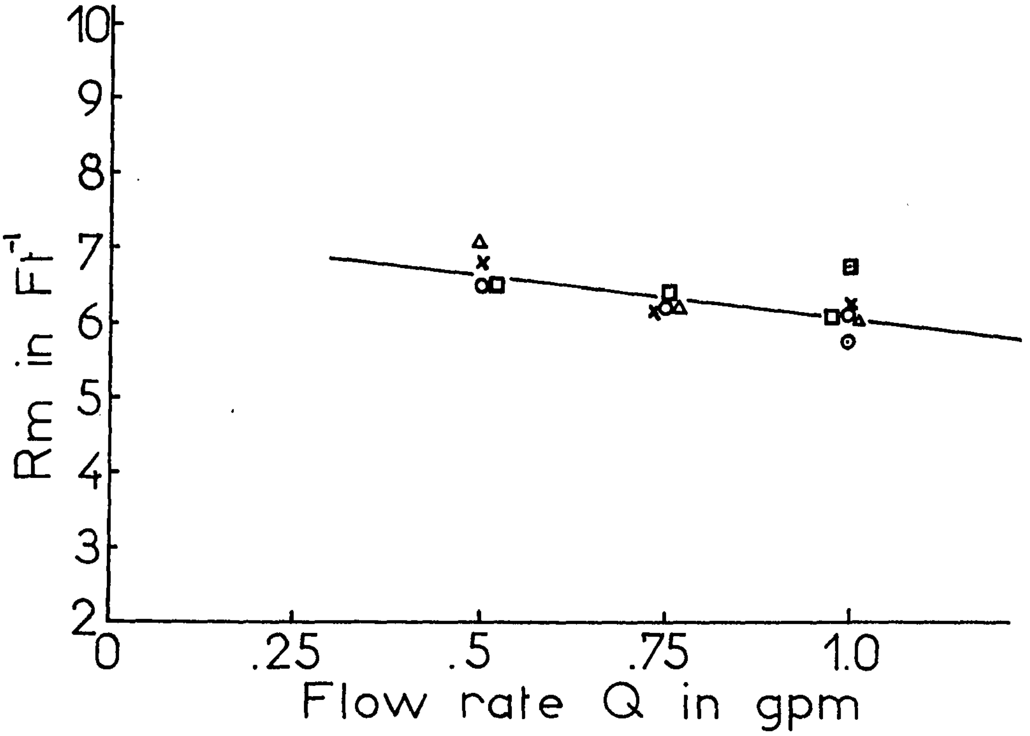

Suspensions of bentonite clay
a_∞, 10^{12} ft/lb
25
20
15
10
5
0
0
.25
.50
.75
1.0
Flow rate Q in gpm
c = 16 mg/l
c = 24 mg/l

Figure (15-a) Head lose across filter-medium vs. flow rate for both ball clay and Wyoming bentonite suspensions.

Figure (15-b) Plot of Rm vs. Q of the activated carbon filter-medium obtained from filtering ball clay and bentonite clay suspensions.


ΔPm in psi
0
1
2
3
4
5
6
7
8
9
10
.25
.5
.75
1.0
Flow rate Q in gpm
○ ball clay 20.5mg/l
△ " " 11mg/l
□ " " 5.5mg/l
⊡ bentonite clay 24mg/l
× " " 16mg/l
⊙ " " 8mg/l


Rm in Ft^{-1}
2
3
4
5
6
7
8
9
10
0
.25
.5
.75
1.0
Flow rate Q in gpm

PILOT FILTER UNIT FOR MEASURING CAKE RESISTANCE

Values of the cake resistance of a particular material are subject to wide variation even when filtering the same suspension. The understanding of factors controlling such cake resistance variations is limited and the prediction of α values from the physical properties of the solids, independent of any filtration experience, is generally not possible (6). An even more serious limitation is the difficulty in predicting the changes in the cake resistance which accompany changes in degree of suspension flocculation. Such changes in flocculation may result in tenfold discrepancies between laboratory test results and actual filtration data. The only established fact about the cake resistance is that it varies with the pressure drop with most filter cakes (11, 12, 17, 25, 27).

The experimental work reported in this portion of this study presents a flexible filtration technique which can be used to measure the filter cake resistance of a suspension and to predict the variation in the cake resistance that would result from changes in flow or pressure conditions. Simply stated, this method involves the measurement of the average specific cake resistance of a filter cake under conditions of constant pressure filtration. Thus, the average specific cake resistance, α, can be established as a function of pressure. The cake resistance under conditions of actual pressure filtration can then be calculated simply for any filtration pressure by utilizing the filtration-rate equation.

The use of a small-scale pilot pressure filtration unit to predict the filtration resistance of a given suspension can be applied to a number of filtration operations. Sizing household filters prior to installation and evaluating subsequent performance can be accomplished easily from filtration data obtained with the pilot unit.

For large filters and plant operations, it is advisable to perform filtration on the pilot unit before and after the suspension has passed through the pump. Many pumps produce sufficient shearing force to break up flocs and change particle size.

Evaluating and monitoring filter operation is almost nonexistent in present-day filtration practice. There is seldom a careful correlation of how filtration and medium resistance vary with changes in process variables. For satisfactory control, it should be possible, through the use of the pilot unit, to determine the pressure and filtrate volume (or rate) as a function of average cake resistance. If the solids content varies, then it is essential to know not only the variation of the filtration resistance but also how mixing and flocculation affect the cake resistance.

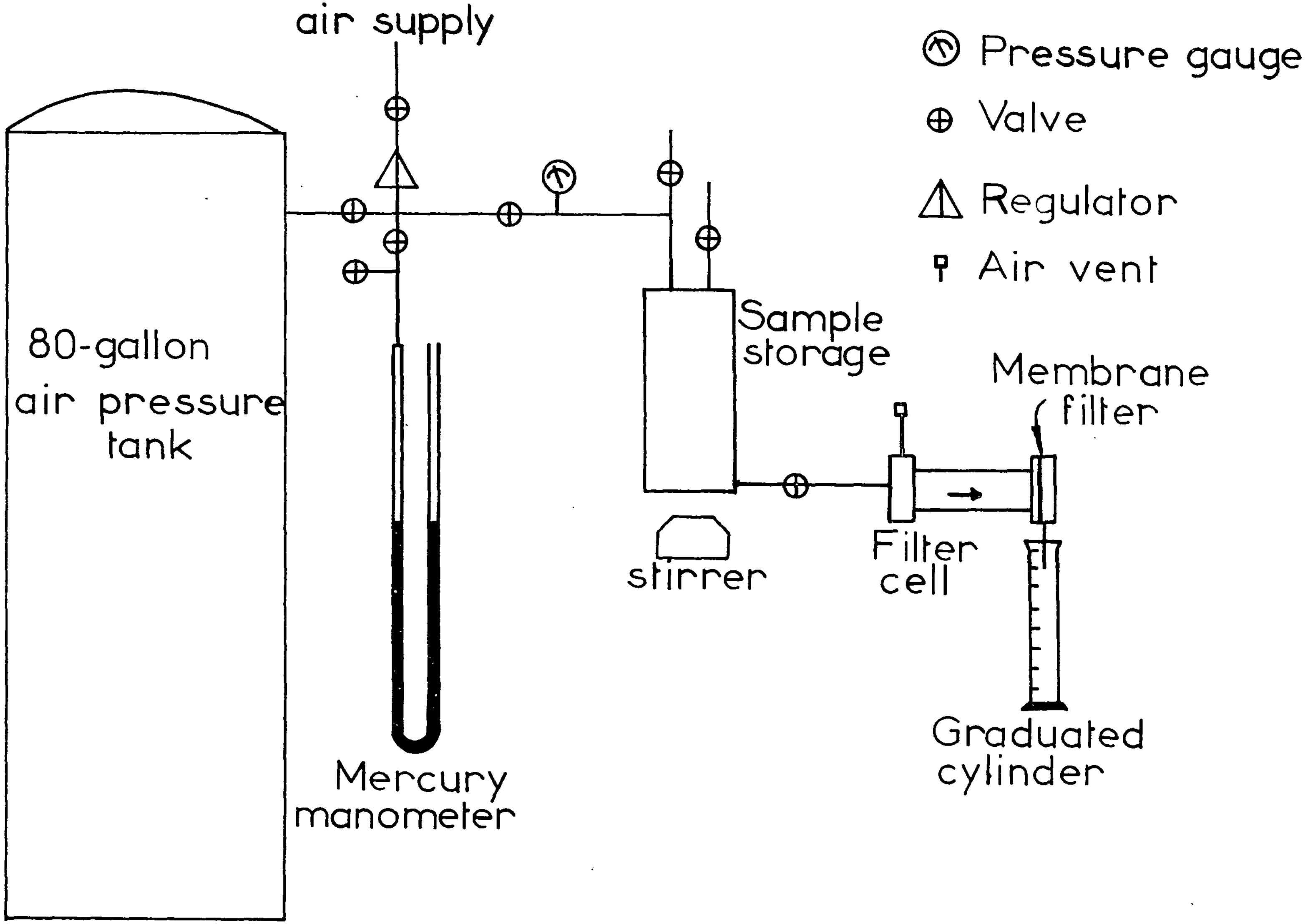
As cake resistance increases, use of filter aids and body feed in pressure filters becomes common. Filter aid addition can be controlled by laboratory tests performed on the pilot unit. The laboratory data could yield sufficient information to determine optimum desirable concentrations of filter aid.

The Pilot Constant Pressure Filtration Apparatus

Figure (16) shows a schematic diagram of the laboratory, pilot, filtration apparatus used in this study. It was designed and built for making laboratory constant pressure filtration runs on a flat, vertical filtering surface. It consists essentially of an 80-gallon air-pressure tank to maintain a constant inlet pressure during the run, a cylindrical container to house the water sample to be filtered, a lucite filter cell containing a millipore filter paper and support, and a graduated cylinder to measure the volume of filtrate at any instant. The system was connected to the air supply through 3/8 inch galvanized steel pipings and the air pressure was controlled by means of a pressure regulator. Pressure measurements were made using a mercury manometer for low pressure operations (up to 20 psi) and by a pre-calibrated pressure gage for high pressure operations.

The principal part of the apparatus is the filter cell shown disassembled in Figure (18). The cell is composed of three plastic units joined together by four bolts and wing-nuts. The inlet unit contains a $\frac{1}{4}$ inch brass pipe and a small air vent to bleed the air out of the cell. The outlet unit, housing the millipore filter paper and its 100-mesh support.

Figure (16) Laboratory pilot filtration apparatus for constant pressure operation.


air supply
Pressure gauge
Valve
Regulator
Air vent
80-gallon air pressure tank
Sample storage
Membrane filter
Filter cell
stirrer
Mercury manometer
Graduated cylinder

discharges freely to the atmosphere through a $\frac{1}{4}$ inch brass tube. The two units are connected by a transparent, plastic cylindrical body with an inside diameter of one inch.

White grid Millipore filter papers of 37mm diameter and 0.45μ pore size were used in this study as the filter medium. The actual filtering surface area, however, was the cylinder cross-sectional area which was 0.785 sq in.

Preparation of Clay Slurry

A clay slurry was prepared by mixing 10 grams of the desired clay mineral in 5 liters of distilled water and air-agitating it for 14 hours. The suspension was then allowed to settle for 6 hours and the supernate was drawn out to be used as the slurry. The water sample to be filtered was obtained by adding zero-turbidity tap water to a given volume of the slurry and shaking the mixture for a few minutes. Tap water of zero turbidity was obtained by filtering university tap water through a 0.45μ Millipore filter paper under an inlet pressure of 40 psi. The resulting filtrate had a turbidity equal to or less than that of distilled water and was considered to be zero.

Turbidities of the water samples were measured using a Hach turbidimeter[a] and the amount of clay in suspension was determined from the turbidimeter calibration curves in

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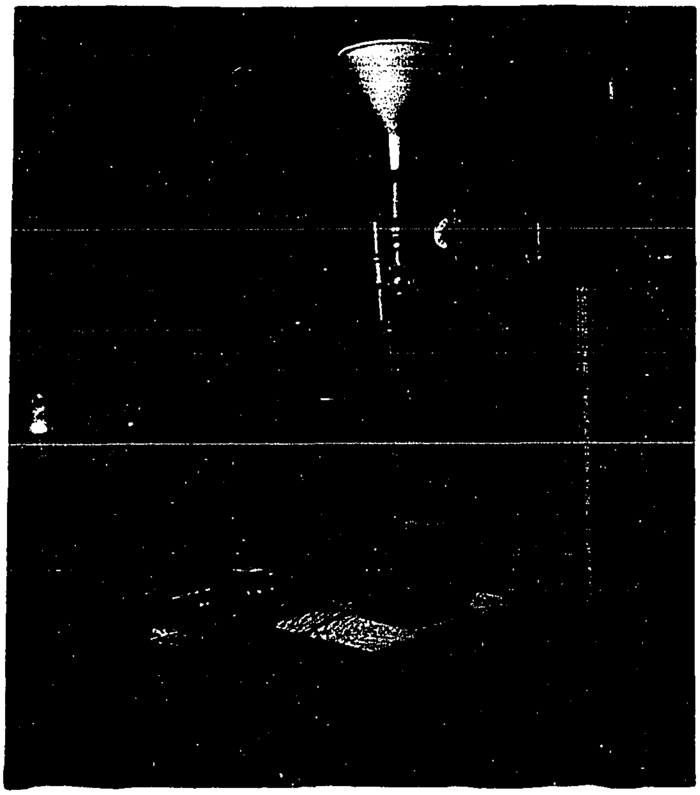
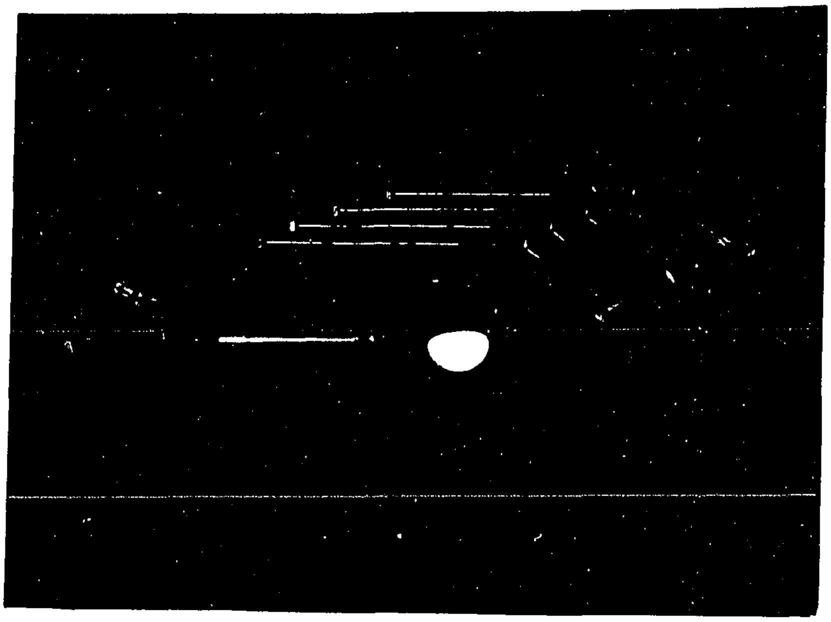
[a] Hach Laboratory Turbidimeter Model 1860, Hach Chemical Co., Ames, Iowa.

Figure (17) Photograph of the pilot filtration apparatus.

Figure (18) The principal parts of the lucite filter cell.





Appendix C. The sample pH and temperature were recorded in each test and were approximately the same as those of the tap water. In all tests conducted, the university tap water had a pH between 7.5 and 8.0 and a water temperature between 22 to 24° C.

The Filtration Operation

At the beginning of any filtration experiment, air was introduced to the pressure tank and the pressure regulator set to the desired level of pressure. The water sample to be filtered was introduced to the sample container, where it was mixed continuously using a magnetic stirrer under atmospheric pressure. The lucite filter cell containing a new Millipore filter was connected to the system. The suspension was allowed to flow to the cylinder body of the filter cell until all the air was out, then the air vent was turned off.

The filtration process was started by pressurizing the system to the level needed and permitting the suspension to flow through the filter paper. The resulting filtrate was collected in the graduated cylinder and when a predetermined volume of filtrate was obtained, the stop watch was started. The time needed to filter successive known volumes of filtrate was recorded until the run was terminated.

In all tests with ball clay (kalonite) suspensions, the zero time was started when a volume of 100 milliliters of filtrate had been collected. Time increments corresponding to successive 100's milliliters of filtrate were recorded. Runs were terminated when a volume of 1000 milliliters of filtrate had been collected in the graduated cylinder. This total volume of filtrate was found convenient because it produced a cake of appreciable thickness under the various test conditions, and gave enough statistical data to establish the straight line of Figure (30). In the case of Wyoming Bentonite (montmorillonite) clay, usually known to produce a more resistant cake, runs were terminated at a total filtrate volume of 250 milliliters and volume increments of 20 milliliters were used as shown in Figure (32).

A new slurry was prepared for each series of tests made in the study in the manner previously described. This method of operation was adopted to produce a suspension with the same degree of flocculation in all tests. The filtrate pH and temperature were read and recorded at the termination of each run. No appreciable change in pH or temperature was observed between the water sample and its filtrate.

A full experimental filtration series (Table 4) consists of five to eight runs conducted at pressure drops between 5 and 60 psi. The raw data from the laboratory, pilot filter runs made to evaluate the effect of pressure drop on cake resistance are reported in Appendix B.

Analysis and Interpretation of Results

The laboratory filtrations conducted with constant pressure drop through suspensions of clay with various loading

Table 4. Summary of constant pressure filtration test conditions

Series	Run number	Clay	Turbidity, JCU	ΔP, psi
I	1	Ball clay	13	10
	2	Ball clay	13	15
	3	Ball clay	13	20
	4	Ball clay	13	30
	5	Ball clay	13	40
	6	Ball clay	13	50
II	1	Ball clay	17	10
	2	Ball clay	17	15
	3	Ball clay	17	20
	4	Ball clay	17	30
	5	Ball clay	17	40
III	1	Ball clay	31	5
	2	Ball clay	31	10
	3	Ball clay	31	15
	4	Ball clay	31	20
	5	Ball clay	31	30
	6	Ball clay	31	40
	7	Ball clay	31	50
	8	Ball clay	31	60
IV	1	Ball clay	40	10
	2	Ball clay	40	15
	3	Ball clay	40	20
	4	Ball clay	40	30
	5	Ball clay	40	40
V	1	Bentonite clay	8	5
	2	Bentonite clay	8	10
	3	Bentonite clay	8	15
	4	Bentonite clay	8	20
	5	Bentonite clay	8	30
	6	Bentonite clay	8	40
	7	Bentonite clay	8	50
	8	Bentonite clay	8	60
VI	1	Bentonite clay	24.5	5
	2	Bentonite clay	24.5	10
	3	Bentonite clay	24.5	20
	4	Bentonite clay	24.5	30
	5	Bentonite clay	24.5	40
	6	Bentonite clay	24.5	50

conditions gave the data included in Appendix B. Two clay minerals, ball clay and bentonite clay, were used to produce the turbid waters used in this study. The filtering surface area was the same for all tests and equal to 0.785 sq in. Other test conditions are reported with the data from each test in Appendix B.

The first step in the analysis of the raw data was to prepare plots for each of the constant-pressure experiments showing $\frac{\Delta T}{\Delta V}$ vs. $\frac{V_1+V_2}{2}$ for each increment of filtrate volume. The resulting curves are shown in Appendix B in Figures (28-32). The slope of each line in these plots represent the value of K_2 in minutes per milliliter per milliliter. The slopes, in the observed and in converted units, along with the test conditions of each test are given in Table 5. Values of the average specific cake resistance, α, were calculated using Equation 27 and are listed in Table 5. The procedure used to make the calculations will be illustrated in Example 1 on page 85.

Figure (19) shows a logarithmic plot of α vs. ΔP for the Montmorillonite and Kalonite clay suspensions. As can be seen from this graph, the experimental points form a straight line which indicate that α is an exponential function of ΔP and can be expressed mathematically as

$$\alpha = \alpha' (\Delta P)^n \text{ - - - - - - - - - } (41)$$

where α' is an empirical constant and n, the slope of the line, is the cake compressibility factor. The value of n is a

Table 5. Values of K_2 and in constant-pressure filtration tests

Run number	Clay suspension	Pressure drop ΔP		Solids concentration c		Slope K_2		α
		lb/sq in	lb/sq ft	mg/l	lb/cu ft	min/ml^2	sec/ft^6	ft/lb
I-1	Ball clay	10	1440	13	$8.11x10^{-4}$	$3.78x10^{-5}$	$1.82x10^{6}$	$4.76x10^{12}$
I-2	Ball clay	15	2160	13	$8.11x10^{-4}$	$2.96x10^{-5}$	$1.42x10^{6}$	$5.60x10^{12}$
I-3	Ball clay	20	2880	13	$8.11x10^{-4}$	$2.74x10^{-5}$	$1.32x10^{6}$	$6.90x10^{12}$
I-4	Ball clay	30	4320	13	$8.11x10^{-4}$	$2.42x10^{-5}$	$1.16x10^{6}$	$9.17x10^{12}$
I-5	Ball clay	40	5760	13	$8.11x10^{-4}$	$2.14x10^{-5}$	$1.03x10^{6}$	$10.8x10^{12}$
I-6	Ball clay	50	7200	13	$8.11x10^{-4}$	$1.86x10^{-5}$	$0.89x10^{6}$	$11.7x10^{12}$
II-1	Ball clay	10	1440	17	$10.61x10^{-4}$	$4.45x10^{-5}$	$2.14x10^{6}$	$4.28x10^{12}$
II-2	Ball clay	15	2160	17	$10.61x10^{-4}$	$3.82x10^{-5}$	$1.84x10^{6}$	$5.53x10^{12}$
II-3	Ball clay	20	2880	17	$10.61x10^{-4}$	$3.47x10^{-5}$	$1.67x10^{6}$	$6.69x10^{12}$
II-4	Ball clay	30	4320	17	$10.61x10^{-4}$	$3.01x10^{-5}$	$1.45x10^{6}$	$8.72x10^{12}$
II-5	Ball clay	40	5760	17	$10.61x10^{-4}$	$2.77x10^{-5}$	$1.33x10^{6}$	$10.70x10^{12}$
III-1	Ball clay	5	720	31	$19.34x10^{-4}$	$11.6x10^{-5}$	$5.58x10^{6}$	$3.07x10^{12}$
III-2	Ball clay	10	1440	31	$19.34x10^{-4}$	$9.0x10^{-5}$	$4.33x10^{6}$	$4.76x10^{12}$
III-3	Ball clay	15	2160	31	$19.34x10^{-4}$	$7.74x10^{-5}$	$3.73x10^{6}$	$6.14x10^{12}$
III-4	Ball clay	20	2880	31	$19.34x10^{-4}$	$6.86x10^{-5}$	$3.30x10^{6}$	$7.27x10^{12}$
III-5	Ball clay	30	4320	31	$19.34x10^{-4}$	$5.99x10^{-5}$	$2.84x10^{6}$	$9.36x10^{12}$
III-6	Ball clay	40	5760	31	$19.34x10^{-4}$	$5.40x10^{-5}$	$2.62x10^{6}$	$11.50x10^{12}$
III-7	Ball clay	50	7200	31	$19.34x10^{-4}$	$5.08x10^{-5}$	$2.44x10^{6}$	$13.45x10^{12}$
III-8	Ball clay	60	8640	31	$19.34x10^{-4}$	$4.70x10^{-5}$	$2.26x10^{6}$	$14.92x10^{12}$
IV-1	Ball clay	10	1440	40	$25.0x10^{-4}$	$12.30x10^{-5}$	$5.92x10^{6}$	$5.02x10^{12}$
IV-2	Ball clay	15	2160	40	$25.0x10^{-4}$	$10.08x10^{-5}$	$4.85x10^{6}$	$6.20x10^{12}$
IV-3	Ball clay	20	2880	40	$25.0x10^{-4}$	$8.60x10^{-5}$	$4.14x10^{6}$	$7.05x10^{12}$
IV-4	Ball clay	30	4320	40	$25.0x10^{-4}$	$7.50x10^{-5}$	$3.61x10^{6}$	$9.23x10^{12}$
IV-5	Ball clay	40	5760	40	$25.0x10^{-4}$	$6.56x10^{-5}$	$3.16x10^{6}$	$10.75x10^{12}$

Table 5. (continued)

Run number	Clay suspension	Pressure drop ΔP		Solids concentration $\bar{c}$		Slope K_2		α
		lb/sq in	lb/sq ft	mg/l	lb/cu ft	min/ml^2	sec/ft^6	ft/lb
V-1	Bentonite clay	5	720	8.0	5.0×10^{-4}	2.0×10^{-3}	9.62×10^{7}	2.05×10^{14}
V-2	Bentonite clay	10	1440	8.0	5.0×10^{-4}	1.6×10^{-3}	7.70×10^{7}	3.28×10^{14}
V-3	Bentonite clay	15	2160	8.0	5.0×10^{-4}	1.6×10^{-3}	7.70×10^{7}	4.93×10^{14}
V-4	Bentonite clay	20	2880	8.0	5.0×10^{-4}	1.58×10^{-3}	7.60×10^{7}	6.48×10^{14}
V-5	Bentonite clay	30	4320	8.0	5.0×10^{-4}	1.38×10^{-3}	6.64×10^{7}	8.50×10^{14}
V-6	Bentonite clay	40	5760	8.0	5.0×10^{-4}	1.30×10^{-3}	6.25×10^{7}	10.65×10^{14}
V-7	Bentonite clay	50	7200	8.0	5.0×10^{-4}	1.35×10^{-3}	6.50×10^{7}	13.85×10^{14}
V-8	Bentonite clay	60	8640	8.0	5.0×10^{-4}	1.33×10^{-3}	6.40×10^{7}	16.40×10^{14}
VI-1	Bentonite clay	5	720	24.5	15.3×10^{-4}	5.70×10^{-3}	2.74×10^{8}	1.91×10^{14}
VI-2	Bentonite clay	10	1440	24.5	15.3×10^{-4}	4.85×10^{-3}	2.33×10^{8}	3.24×10^{14}
VI-3	Bentonite clay	20	2880	24.5	15.3×10^{-4}	4.85×10^{-3}	2.33×10^{8}	6.48×10^{14}
VI-4	Bentonite clay	30	4320	24.5	15.3×10^{-4}	3.90×10^{-3}	1.88×10^{8}	7.82×10^{14}
VI-5	Bentonite clay	40	5760	24.5	15.3×10^{-4}	3.40×10^{-3}	1.64×10^{8}	9.10×10^{14}
VI-6	Bentonite clay	50	7200	24.5	15.3×10^{-4}	3.35×10^{-3}	1.61×10^{8}	11.90×10^{14}

quantitative measure of the cake compressibility. It is zero for non-compressible cakes and is positive for compressible ones; higher values applying to the more compressible cakes.

The value of the constant, α', can be calculated by reading the coordinates of any convenient point on the line in Figure (19) and calculating α' by Equation 41. For example, when $\Delta P = 10$ psi, $n = 0.58$, and $\alpha = 4.6 \times 10^{12}$ ft/lb, then α' for ball clay is

$$\alpha' = \frac{\alpha}{(\Delta P)^n} = \frac{4.6 \times 10^{12}}{(10 \times 144)^{0.58}}$$

$$= 6.80 \times 10^{10} \text{ ft}^{-1}$$

and α' for Wyoming bentonite is

$$\alpha' = \frac{\alpha}{(\Delta P)^n} = \frac{360 \times 10^{2}}{(10 \times 144)^{0.83}}$$

$$= 8.48 \times 10^{11} \text{ ft}^{-1}.$$

Example 1. Laboratory filtrations conducted with constant pressure drop on a suspension of ball clay gave the data shown in Table 6. The filter area was 0.785 sq in, the mass of solid per unit volume of filtrate was 13 mg/l, and the temperature was 22° C. Evaluate in foot and pound units the value of α as a function of pressure drop, ΔP.

Solution The first step is to prepare plots, for each of the six experiments, of $\frac{\Delta T}{\Delta V}$ vs. $\frac{V_1 + V_2}{2}$ for each increment of filtrate volume. The data and calculations for the first experiment are given in Table 7, and the plots for all experiments are shown in Figure (20).

Figure (19) Plot of log a vs. log ΔP for the Montmorillonite and Kaolinite clay suspensions.

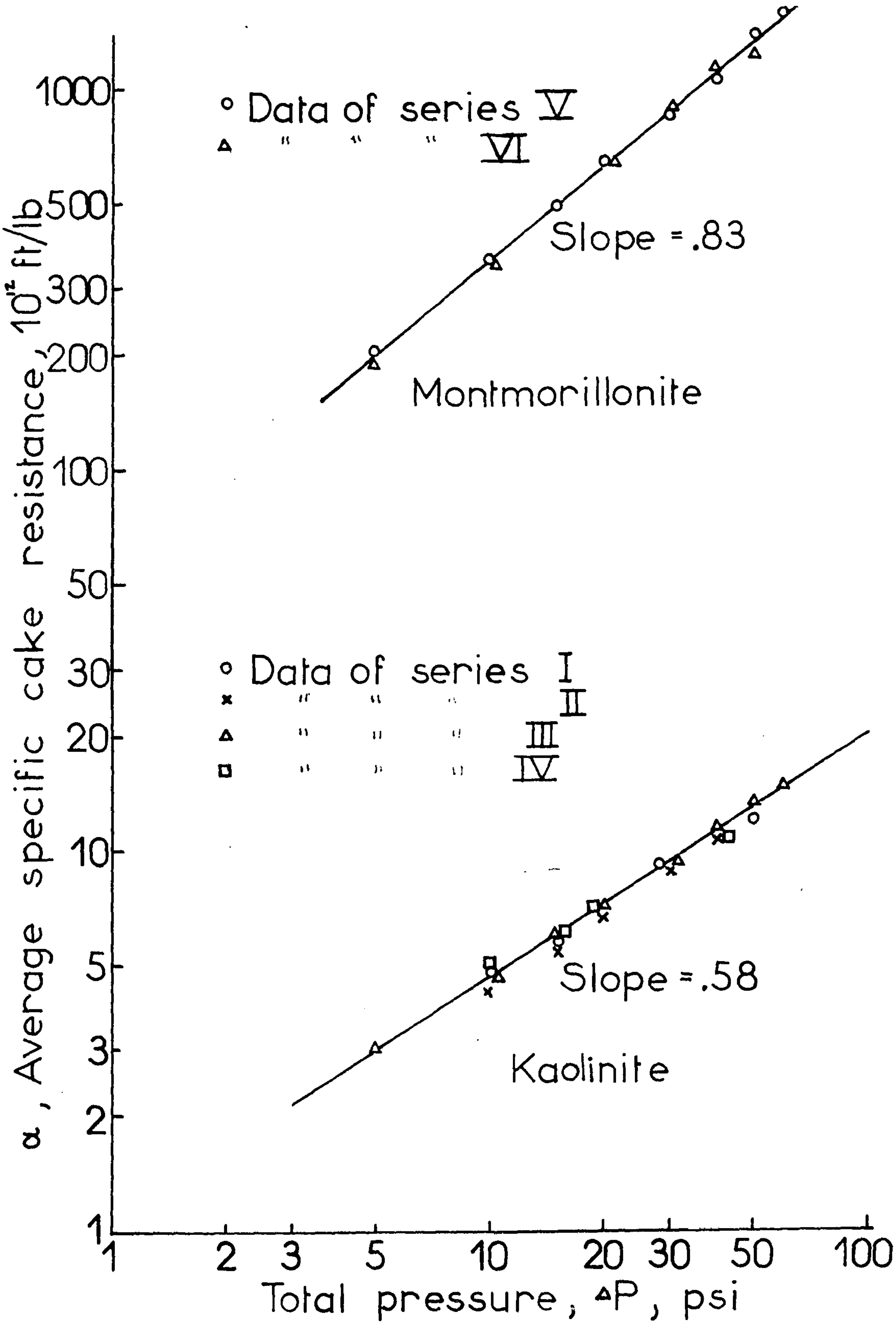

α , Average specific cake resistance, 10^{12} ft/lb
1000
500
300
200
100
50
30
20
10
5
3
2
1
1
2
3
5
10
20
30
50
100
Total pressure, ΔP, psi
○ Data of series V
△ " " " VI
Slope = .83
Montmorillonite
○ Data of series I
× " " " II
△ " " " III
□ " " " IV
Slope = .58
Kaolinite

Table 6. Data from a constant pressure filtration run (Series I, Appendix B)

Experiment number	I-1	I-2	I-3	I-4	I-5	I-6
Pressure drop, ΔP, psi	10	15	20	30	40	50
Filtrate Volume, V, ml	Time, minutes					
100	0.0	0.0	0.0			
200	0.64	0.49	0.41	0.0	0.0	0.0
300	1.60	1.24	1.08	0.53	0.45	0.39
400	2.94	2.30	2.00	1.28	1.10	0.96
500	4.68	3.70	3.22	2.29	1.97	1.72
600	6.81	5.41	4.71	3.53	3.04	2.67
700	9.33	7.45	6.50	5.04	4.34	3.81
800	12.28	9.83	8.55	6.78	5.85	5.14
900	15.57	12.52	10.90	8.76	7.57	6.66
1000	19.15	15.46	13.48	10.98	9.49	8.36

Table 7. $\Delta T/\Delta V$ vs. $(V_1 + V_2)/2$ in Experiment I-1 (from Series I, Appendix B)

ΔP psi	V ml	T min.	ΔV ml	ΔT min.	$\Delta T/\Delta V$ min./ml	K_2 min./ml^2
10	100	0.0	100	0	0	
	200	0.64	100	0.64	0.0064	
	300	1.60	100	0.96	0.0096	
	400	2.94	100	1.34	0.0134	
	500	4.68	100	1.74	0.0174	3.78×10^{-5}
	600	6.81	100	2.13	0.0213	
	700	9.33	100	2.52	0.0252	Slope of
	800	12.28	100	2.95	0.0295	ΔP = 10 psi
	900	15.57	100	3.29	0.0329	curve in
	1000	19.15	100	3.58	0.0358	Figure (20)

The slope of each line of Figure (20) is K_2, in minutes per milliliter per milliliter. To convert to seconds per cubic foot per cubic foot the conversion factor is:

$$(60)\ (28.31 \times 1000)^2 = 4.81 \times 10^{10}$$

The viscosity of water at 22°C is 0.95 centipoise, or, converted to units of lb/ft-sec:

$$0.95 \times 6.72 \times 10^{-4} = 6.48 \times 10^{-4} \text{ lb/ft-sec.}$$

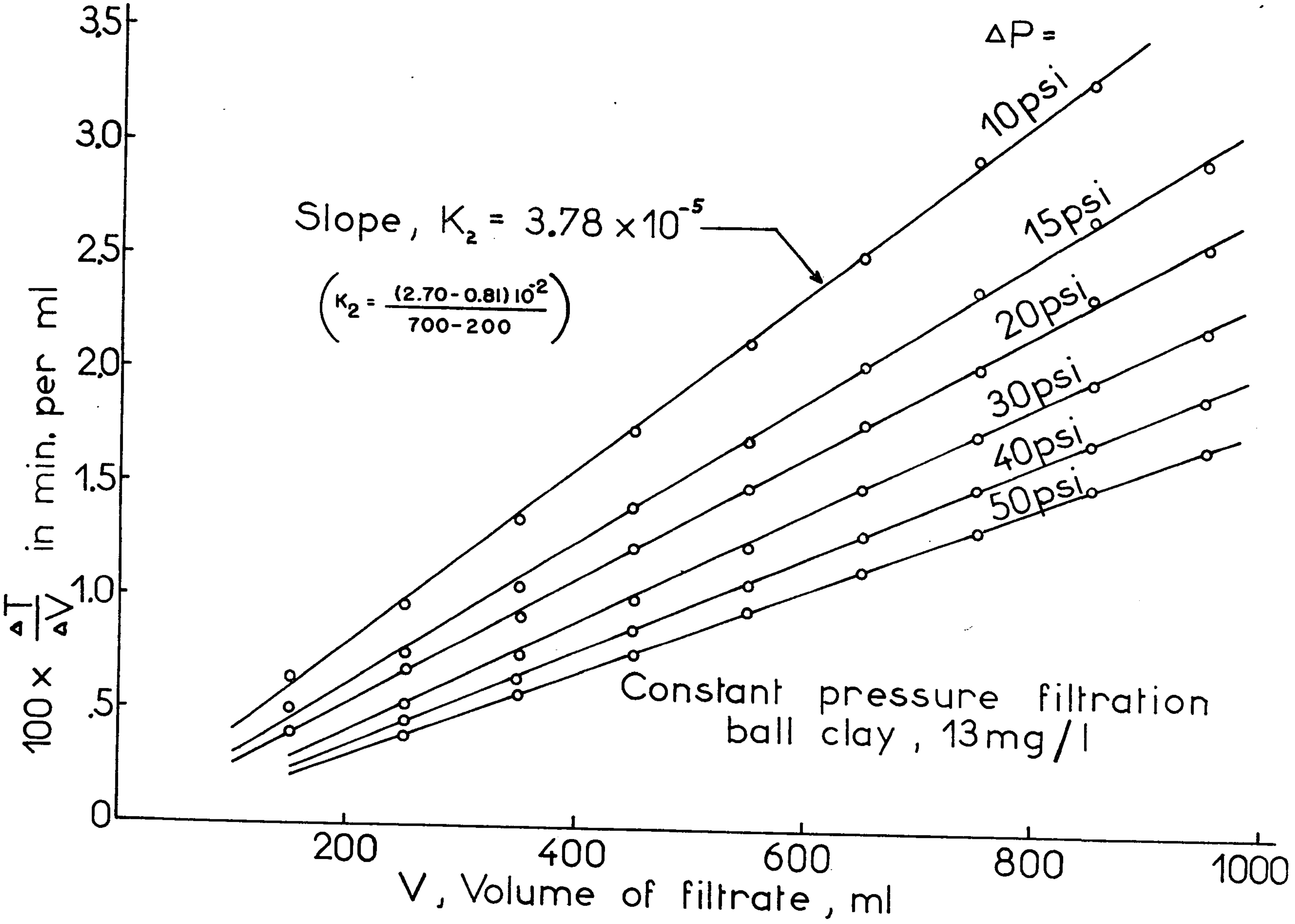
The filter area is

$$0.785/144 = 5.45 \times 10^{-3} \text{ sq ft}$$

The conversion factor for changing the suspended solids concentration, c, from mg/l to lb/cu ft is

$$\frac{c \times 28.31}{1000 \times 454} = 6.24 \times 10^{-5} \text{ lb/cu ft}$$

Figure (20) Plots of $\frac{\Delta T}{\Delta V}$ vs. $\frac{V_1 + V_2}{2}$ for Example 1.


ΔP =
10psi
15psi
20psi
30psi
40psi
50psi
Slope, $K_2 = 3.78 \times 10^{-5}$
$\left(K_2 = \frac{(2.70-0.81)10^{-2}}{700-200}\right)$
Constant pressure filtration
ball clay, 13mg/l
$100 \times \frac{\Delta T}{\Delta V}$ in min. per ml
V, Volume of filtrate, ml
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
200
400
600
800
1000

Now, the value of, a, in ft/lb can be obtained from Equation 27 as follows

$$a = \frac{A^2}{c}\frac{g}{\mu} K_2 (\Delta P) \text{ - - - - - - - - - } (27)$$

$$= \frac{(5.45 \times 10^{-3})^2 \times 32.17}{6.24 \times 10^{-5} \times 6.48 \times 10^{-4}} (4.81 \times 10^{10}) (144) \frac{K_2 \Delta P}{c}$$

$$= 1.64 \times 10^{17} \frac{K_2 \Delta P}{c}$$, with values of K_2, ΔP, and c as collected.

For the value of K_2 in Table 5, the corresponding a value is

$$= 1.64 \times 10^{17} \left(\frac{3.78 \times 10^{-5} \times 10}{13}\right)$$

$$= 4.76 \times 10^{12} \text{ ft/lb}$$

Values of K_2 and a for each of the experiments of Example 1 are shown in the first part of Table 5.

FILTER PRODUCTIVE LIFE

The productive life of a filter is defined as the volume of filtrate, V, produced during the filtering operation. In constant rate filtration, the filter cycle usually continues until the accumulated resistance of the filter cake causes the pressure drop to reach that allowed for the filter. Filtration under constant pressure, however, is terminated when the flow rate of filtrate falls below an acceptable minimum level.

Prediction of the filter production in a constant pressure operation can be made from Equation 25.

$$\frac{g \quad \Delta P}{\mu (Q/A)} = \frac{c\alpha}{A} V + Rm \text{ - - - - - - - - - } (25)$$

By conducting a series of constant pressure filtrations on the pilot unit using a sample of the raw water to be filtered, a logarithmic plot of α vs. ΔP similar to that of Figure (19) can be constructed. If Rm is known, the filter production can be predicted corresponding to any given filtration pressure and any predetermined minimum flow rate. The use of the method will be illustrated in the following example:

<u>Example 2</u> Based on the laboratory experiments, the results of which are shown in Figure (19), estimate the productive life of a precoat carbon filter with a filtering surface area of 2.6 sq ft used to filter a suspension of ball clay at a concentration of 10 mg/l under a constant pressure

drop, ΔP, of 40 psi at a temperature of 15°C. The run will be terminated when the rate of flow of filtrate has dropped to 0.10 gpm.

Solution From Figure (19), the average ball clay cake resistance, α, corresponding to a pressure drop, ΔP, of 40 psi is 11.2×10^{12} ft/lb. The filter medium resistance, Rm, as it appears in Table 3 is 6.5×10^{10} 1/ft. The water viscosity at 15°C is 7.53×10^{-4} lb/ft-sec.

From Equation 25

$$\frac{c\alpha}{A} V = \frac{g\ \Delta P}{\left(\frac{Q}{A}\right)\mu} - Rm \text{ - - - - - - - - - } (42)$$

or

$$\frac{10 \times 6.24 \times 10^{-5} \times 11.2 \times 10^{12}}{2.6} V$$

$$= \frac{32.17 \times 40 \times 144}{7.53 \times 10^{-4} \times \frac{0.10 \times 2.24 \times 10^{-3}}{2.6}} - 6.5 \times 10^{10}$$

$$2.69 \times 10^{9}\ V = (2.85 - 0.065) \times 10^{12}$$

hence V = 1,040 cu ft

Table 8 shows the estimated production of the Everpure filters when used to filter suspensions of ball clay and bentonite clay under constant pressure conditions. Though Everpure filters cannot be truly operated under constant pressure conditions due to an inlet restriction, values in Table 8 are approximate and serve here as an illustrative example.

Table 8. Estimated productive life of Everpure C-3 units operated under constant pressure

Model	Area sq ft	Suspension	C mg/l	μ lb/ft sec	Q gpm	Rm 1/ft	ΔP psi	α ft/lb	V cu ft
C-3	2.6	Ball clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	10	4.6×10^{12}	590
C-3	2.6	Ball clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	20	7.2×10^{12}	790
C-3	2.6	Ball clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	30	9.4×10^{12}	920
C-3	2.6	Ball clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	40	11.2×10^{12}	1040
C-3	2.6	Ball clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	50	12.8×10^{12}	1140
C-3	2.6	Ball clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	60	14.5×10^{12}	1210
C-3	2.6	Ball clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	100	20.0×10^{12}	1470
C-3	2.6	Bentonite clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	10	3.50×10^{14}	7.7
C-3	2.6	Bentonite clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	20	6.20×10^{14}	9.2
C-3	2.6	Bentonite clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	30	8.60×10^{14}	10.1
C-3	2.6	Bentonite clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	40	11.0×10^{14}	10.6
C-3	2.6	Bentonite clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	50	13.2×10^{14}	11.0
C-3	2.6	Bentonite clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	60	15.5×10^{14}	11.3
C-3	2.6	Bentonite clay	10	7.53×10^{-4}	0.10	6.50×10^{10}	100	23.4×10^{14}	12.6

The productive life of a filter in constant rate operation can be made from Equation 30:

$$\frac{(P-P_1)^{1-s}}{\alpha_o\ (1-s)} = \frac{\mu\ q\ c}{g\ A}\ V \text{ - - - - - - - - - } (30)$$

Substituting ΔPc for $(P-P_1)$, Equation 30 can be written as

$$\frac{(\Delta Pc)^{1-s}}{\alpha_o\ (1-s)} = \frac{\mu\ q\ c}{g\ A}\ V \text{ - - - - - - - - - } (43)$$

where ΔPc is the pressure drop across the cake.

A series of constant rate filtrations conducted on either a pilot unit or an actual filter could produce sufficient data to construct the curves of Figure (13) and estimate the factors α_o and s. The filter capacity corresponding to a given maximum pressure drop, ΔPc, can be predicted from Equation 43 as illustrated in following Example 3.

Example 3 The data of Table 9 were obtained from a constant rate filtration of a suspension of bentonite clay using a C-3 Everpure carbon unit. The flow rate was 1.0 gpm, the viscosity of water was 7.53×10^{-4} lb/ft-sec, and the turbidity level was 5 JCU (8 mg/l = c). Evaluate, in foot and pound units the Rm, s, and α_o for this suspension. Also evaluate the filter production at a maximum limiting pressure drop of 50 psi.

Solution To obtain a preliminary result for ΔPm and ΔPi, ΔP is plotted against t on rectangular coordinates, as shown in Figure (21). From the tangent line we obtain ΔPm = 8 psi and $\Delta Pi \cong$ 10 psi.

Table 9. Head loss-time data in constant-rate filtration for Example 3 (Appendix A, Figure 27)

Run number	Q gpm	Time min	Pressure drop, ΔP, psi Filter #1	Filter #2
F-2	1.0	1	8	8
		30	11	11
		60	16	16
		75	20	20
		90	25	25
		105	31	29
		120	38	34
		135	48	41
		150	63	52
		165	82	68
		175	-	82

Figure (22) is a logarithmic plot of (ΔP-10) vs. T. A satisfactory straight line is established by the points in Figure (22) and the preliminary evaluation of ΔPi can be accepted as final. From Equation 20

$$Rm = \frac{\Delta Pm\ g}{\mu(Q/A)} = \frac{8 \times 144 \times 32.17 \times 2.6}{7.54 \times 10^{-4} \times 1.0 \times 2.24 \times 10^{-3}}$$

$$= 5.72 \times 10^{10}\ 1/ft$$

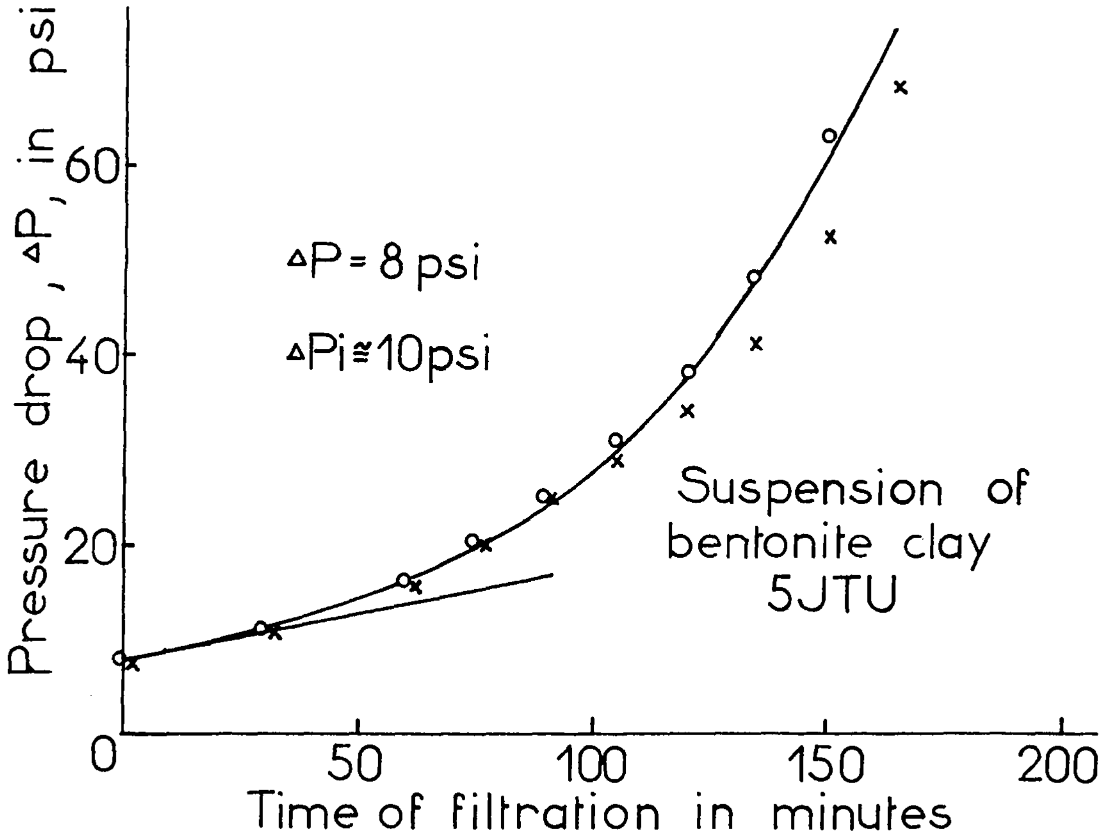
The slope of the line of Figure (22), equal to (1-s), is 0.43, and s $\doteq$ 0.57.

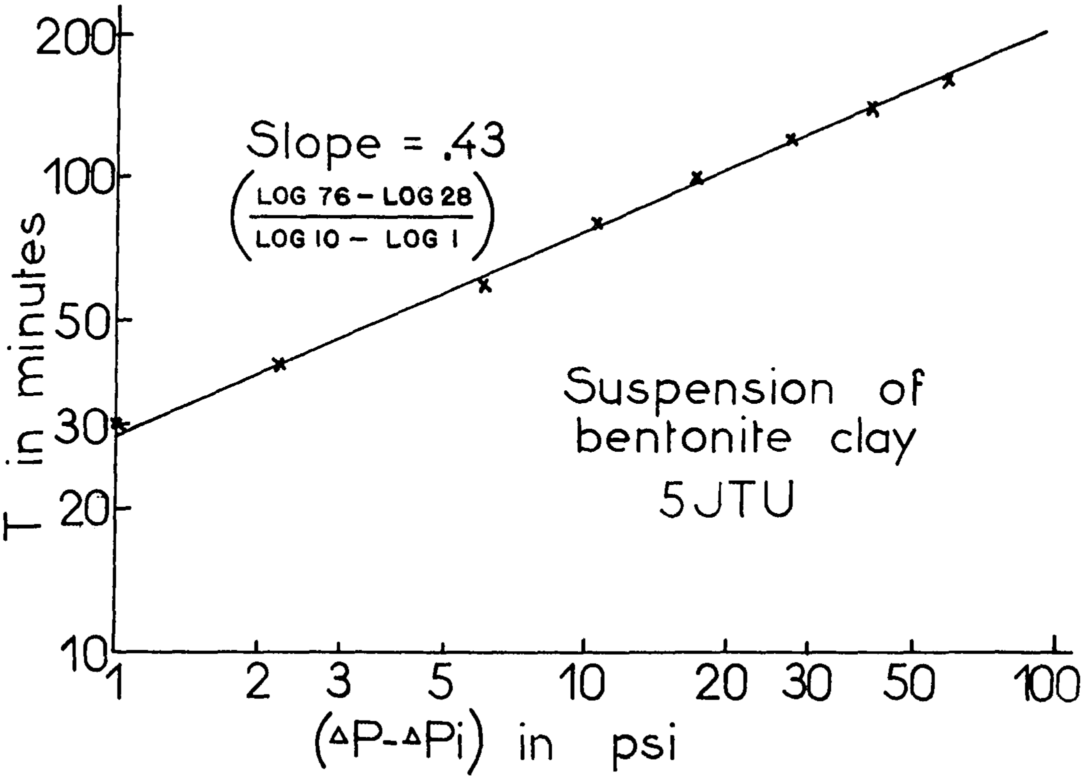
From Figure (22), when (ΔP-ΔPi) $\doteq$ 10 psi, t $\doteq$ 76 min. Substituting these values into Equation 34 we obtain

$$K_3 = \frac{(10 \times 144)^{0.43}}{76 \times 60} = 5.03 \times 10^{-3}\ lb/ft^2/sec$$

Figure (21) Plot of ΔP vs. t for the data in Example 3.

Figure (22) Plot of log (ΔP-ΔPi) vs. log t for the data in Example 3.


Pressure drop, ΔP, in psi
60
40
20
0
ΔP = 8 psi
ΔPi ≅ 10psi
Suspension of
bentonite clay
5JTU
50
100
150
200
Time of filtration in minutes


T in minutes
200
100
50
30
20
10
Slope = .43
(LOG 76 − LOG 28 / LOG 10 − LOG 1)
Suspension of
bentonite clay
5JTU
1
2
3
5
10
20
30
50
100
(ΔP-ΔPi) in psi

From Equation 33

$$\alpha_o = \frac{K_3 \, g \, A^2}{\mu Q^2 \, c \, (1-s)}$$

$$= \frac{5.03 \times 10^{-3} \times 32.17 \times 2.6 \times 2.6}{7.54 \times 10^{-4} \times (1.0 \times 2\text{-}24 \times 10^{-3})^2 \times 8 \times 6.24 \times 10^{-5} \times 0.43}$$

$$= 13.9 \times 10^{11} \text{ ft/lb}$$

The filter production, V, can now be obtained from Equation 43

$$\frac{(50 \times 144)^{0.43}}{13.9 \times 10^{11} \times 0.43} =$$

$$\frac{7.54 \times 10^{-4} \times 1.0 \times 2.24 \times 10^{-3} \times 8.0 \times 6.24 \times 10^{-5}}{32.17 \times 2.6 \times 2.6} V$$

or $V = 19.8$ cu ft

Table (10) shows the capacities of a C-3 Everpure unit when filtering suspensions of ball clay and Wyoming bentonite clay under a constant rate operation. The predicted filter productions as they appear in the table are within ± 12% of the actual values obtained from the curves of Appendix A.

Table 10. Filter capacity of Everpure C-3 units in constant rate operation

Area sq ft	Suspension	$\bar{c}$ mg/l	ΔP, psi	μ lb/ft sec	Q gpm	α_o [a] ft/lb	s [a]	V, cu ft Predicted	Actual[b]	% Variation
2.60	Ball clay	5.5	50	7.53×10^{-4}	0.50	17.2×10^{10}	0.67	250	280	12
2.60	Ball clay	5.5	50	7.53×10^{-4}	0.75	15.4×10^{10}	0.67	197	195	-1
2.60	Ball clay	5.5	50	7.53×10^{-4}	1.00	11.45×10^{10}	0.69	169	148	-12
2.60	Ball clay	11.0	50	7.53×10^{-4}	0.50	11.2×10^{10}	0.65	217	210	-3
2.60	Ball clay	11.0	50	7.53×10^{-4}	0.75	8.7×10^{10}	0.69	146	149	2
2.60	Ball clay	11.0	50	7.53×10^{-4}	1.00	8.56×10^{10}	0.68	118	106	-10
2.60	Ball clay	20.5	50	7.53×10^{-4}	0.50	9.13×10^{10}	0.70	106	103	-3
2.60	Ball clay	20.5	50	7.53×10^{-4}	0.75	8.0×10^{10}	0.66	102	100	-2
2.60	Ball clay	20.5	50	7.53×10^{-4}	1.00	6.88×10^{10}	0.67	84	76	-9
2.60	Bentonite clay	16.0	50	7.53×10^{-4}	0.50	21.4×10^{11}	0.55	15.3	15	-2
2.60	Bentonite clay	16.0	50	7.53×10^{-4}	0.75	13.3×10^{11}	0.55	16.4	15	-9
2.60	Bentonite clay	16.0	50	7.53×10^{-4}	1.00	10.4×10^{11}	0.55	15.7	14	-11
2.60	Bentonite clay	8.0	50	7.53×10^{-4}	1.00	13.9×10^{11}	0.57	19.8	20	1

[a] Values of α_o and S were taken from Table 3.

[b] Actual values of V were obtained from the curves of Appendix A.

SUMMARY AND CONCLUSIONS

Filtration can be divided into two broad fields, depending upon whether or not a cake is formed on the surface of the filter media. In depth filtration, suspended particles are retained in the interstices of a porous medium, or a permanent bed (like sand) of loose particles. Cake filtration is normally preceded by depth filtration, i.e. some suspended particles pass directly into the filter medium before a surface cake begins to form. This depth filtration stage, however, is terminated quickly and a strictly cake filtration operation continues thereafter.

Filtration of raw waters through a precoat carbon filter is a cake filtration process. Suspended solids are deposited on a fine activated carbon precoat and the filtrate flows through the openings of the compressible bed being formed. The resistance offered by all solids not associated with the filter medium is called the cake resistance. The cake resistance is zero at the beginning of filtration, and because of continuous deposition of solids on the medium, this resistance increases steadily with time of filtration.

The variation in resistance of a compressible cake from layer to layer is caused by a cumulative drag of filtrate flowing through the cake pores. Since the over-all frictional thrust increases in the direction of filtrate flow, the specific cake resistance, α_x, increases in the same direction.

The average specific cake resistance, α, under such conditions can be obtained by writing the expression for α_x for a differential weight of cake solids and integrating between limits of compressive pressure at the faces of the cake. Mathematical expressions for α in cases of pressure filtration on a flat vertical septum have been developed in this thesis.

The primary objective of this thesis was the development of mathematical expressions and test procedures that could be used to predict the productive life of a precoat carbon filter in both constant-pressure and constant-rate filtrations. In order to accomplish this, it was necessary to be able to predict the variation of filter cake resistance with pressure drop, since cake resistance is one of the primary factors influencing filter production.

A pressure filtration pilot unit was designed to measure cake resistance at various conditions of flow rate and solids loading. Filtration equations were theoretically developed from the generally accepted filtration-rate equation for conditions of constant-pressure and constant-rate operations. The method of predicting cake resistance in actual filtrations involves the use of empirical equations whose constants are determined from laboratory filtration data.

The laboratory filter runs summarized in Appendix B were used to develop the empirical relationship between α and ΔP. The actual filtrations of Appendix A were used to verify the theoretical filtration equations developed to predict the productive life of a precoat carbon filter.

A graphical method for the analysis of actual constant-rate filtration data was presented. The validity of the approach was verified using the filter runs of Appendix A. The graphical analysis produced enough information that could be used to predict the filter production at various conditions of rate and loading.

The following conclusions have been reached from this study.

1. Filtration of clay-bearing waters through a precoat carbon filter produced a compressible filter cake whose resistance is a logarithmic function of the pressure drop.

2. Filter cake resistance of montmorillonite clay as the suspended solid is about 100 times greater than the values obtained with Kalonite as the suspended solid, for comparable levels of turbidity.

3. The assumption of constant average specific cake resistance independent of cake thickness can only be justified for constant-pressure filtrations. The specific cake resistance of filter cakes in constant-rate filtrations, however, is affected by both solid concentration and rate of flow of filtrate (i.e. cake thickness)

4. Graphical analysis of constant-rate filtration data is possible and could be used to reduce the head loss-time relationship to a simple logarithmic function.

5. The productive life of a precoat carbon filter used

to filter clay suspensions can be predicted from laboratory filtration data obtained from the pilot filter unit.

RECOMMENDATIONS

1. Additional studies using the pressure pilot unit should be conducted for measuring cake resistance of suspensions of iron flocs and other types of suspended solids encountered in water.

2. The graphical approach for analyzing constant rate filtration data should be used in similar filtration investigations and the validity of the emperically developed equations verified.

3. That Everpure, Inc., using the pressure pilot unit, develop α vs. ΔP relations for various waters. The productive life of any Everpure filter unit used to filter a particular raw water can then be predicted following the outlined procedure of Appendix E.

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APPENDIX A

Filter Production Tests

Series A

Suspension of ball clay
Turbidity level = 19 Jackson Turbidity Units (JTU)
Filtrate temperature 14 C, filtrate pH 7.6
Filtration through C-3 Everpure Filters

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in.		
			Filters		
			#1	#2	#3
A-1	0.75	1	4	6	6
		60	4	6	6
		120	4	6	6
		240	5	7	7
		330	5	7	7
		390	6	7	8
		450	6	8	8
		750	8	9	10
		990	9	11	12
		1050	11	13	14
		1200	12	16	17
		1330	14	19	21
		1450	18	22	24
		1570	26	31	35
		1690	32	38	44
		1750	39	46	58
		1790	49	58	82
		1850	70	82	82
		1870	82	--	--
A-2	0.50	1	3	4	4
		60	3	4	4
		120	3	4	5
		180	3	4	5
		240	3	4	5
		300	3	5	5
		420	4	6	6
		600	4	6	6

Series A (continued)

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in. Filters #1	#2	#3
A-2	0.50	780	6	7	7
		1200	8	8	9
		1380	9	9	10
		1440	10	10	11
		1550	14	13	14
		1790	17	18	19
		1850	22	22	25
		1980	28	27	32
		2060	34	32	39
		2110	36	35	41
		2170	43	40	48
		2210	47	45	54
		2270	57	53	70
		2300	63	60	77
		2320	66	63	82
		2350	75	74	--
		2380	82	82	--

Filter Production Tests

Series B

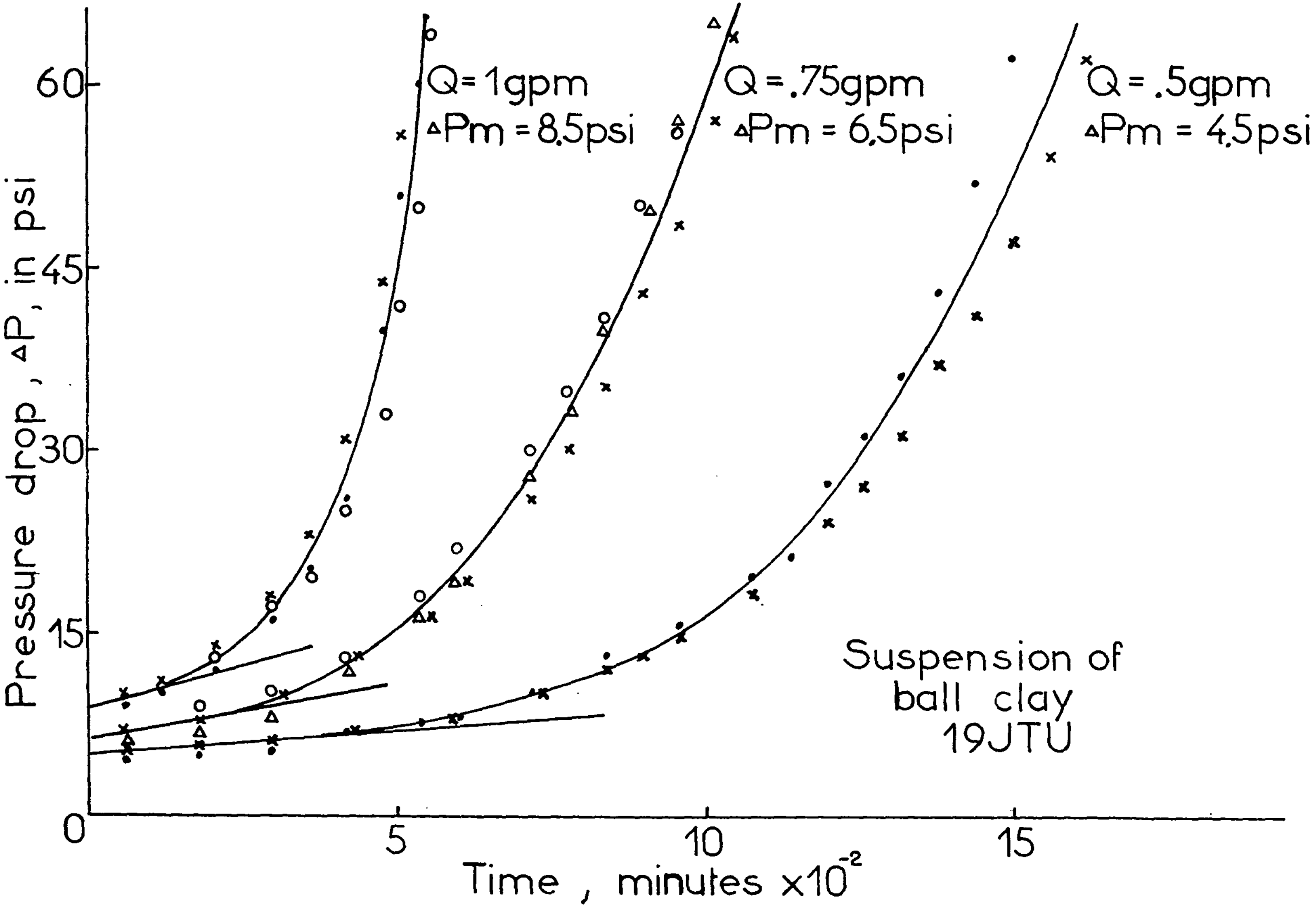
Suspension of ball clay
Turbidity level = 19 Jackson Turbidity Units (JTU)
Filtrate temperature 16 C, filtrate pH 7.6
Filtration through C-3 Everpure filters

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in. Filters		
			#1	#2	#3
B-1	1.00	1	8	9	9
		60	9	10	10
		120	10	11	11
		210	12	14	13
		300	16	18	17
		360	20	23	20
		420	26	31	25
		480	40	44	33
		510	51	56	42
		540	60	68	50
		560	70	82	64
		580	82	--	76
B-2	0.75	1	6	8	7
		60	6	8	7
		120	6	8	8
		180	6	9	8
		240	7	9	9
		300	8	10	10
		360	10	12	11
		420	12	13	13
		480	13	16	14
		540	16	18	16
		600	19	22	19
		660	23	26	21
		720	28	30	26
		780	33	35	30
		840	40	41	35
		900	50	50	43

Series B (continued)

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in. Filters #1	#2	#3
B-2	0.75	960	57	56	48
		1020	65	67	57
		1050	79	82	64
B-3	0.50	1	4	5	
		120	5	6	
		240	5	6	
		360	6	7	
		480	7	7	
		600	8	8	
		720	10	10	
		780	11	10.5	
		840	13	12	
		900	14	13	
		960	15.5	14	
		1020	17.5	15.5	
		1080	19.5	18	
		1140	21	19	
		1200	27	24	
		1260	31	27	
		1320	36	31	
		1380	43	37	
		1440	52	41	
		1500	62	47	
		1560	--	54	
		1620	--	62	

Figure (23) Plots for constant rate filtrations of a suspension of ball clay at 19 JTU.


Pressure drop , ΔP, in psi
0
15
30
45
60
0
5
10
15
Time , minutes x10⁻²
Q= 1gpm
ΔPm = 8.5psi
Q = .75gpm
ΔPm = 6.5psi
Q = .5gpm
ΔPm = 4.5psi
Suspension of
ball clay
19JTU

Series C

Suspension of ball clay
Turbidity level = 10 JTU
Filtrate temperature 15 C, filtrate pH 7.6
Filtration through C-3 Everpure filters

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in. Filters		
			#1	#2	#3
C-1	1.00	1	8	8	8
		60	9	9	9
		120	9	9	9
		180	10	10	10
		240	11	12	10
		300	13	13	11
		360	14	15	12
		420	17	17	14
		480	20	20	16
		540	23	24	19
		600	28	32	22
		660	34	40	31
		720	43	45	40
		750	51	50	45
		780	58	58	50
		810	69	70	57
		850	82	82	67
		880	--	--	78
C-2	0.75	1	7	7	7
		120	8	8	8
		240	8	8	8
		360	8	9	9
		480	8	10	11
		600	10	12	13
		720	12	14	16
		840	14	18	20
		960	17	23	25
		1080	20	28	32
		1140	24	32	37
		1200	26	35	42
		1260	29	39	47
		1320	31	43	54
		1380	36	50	66

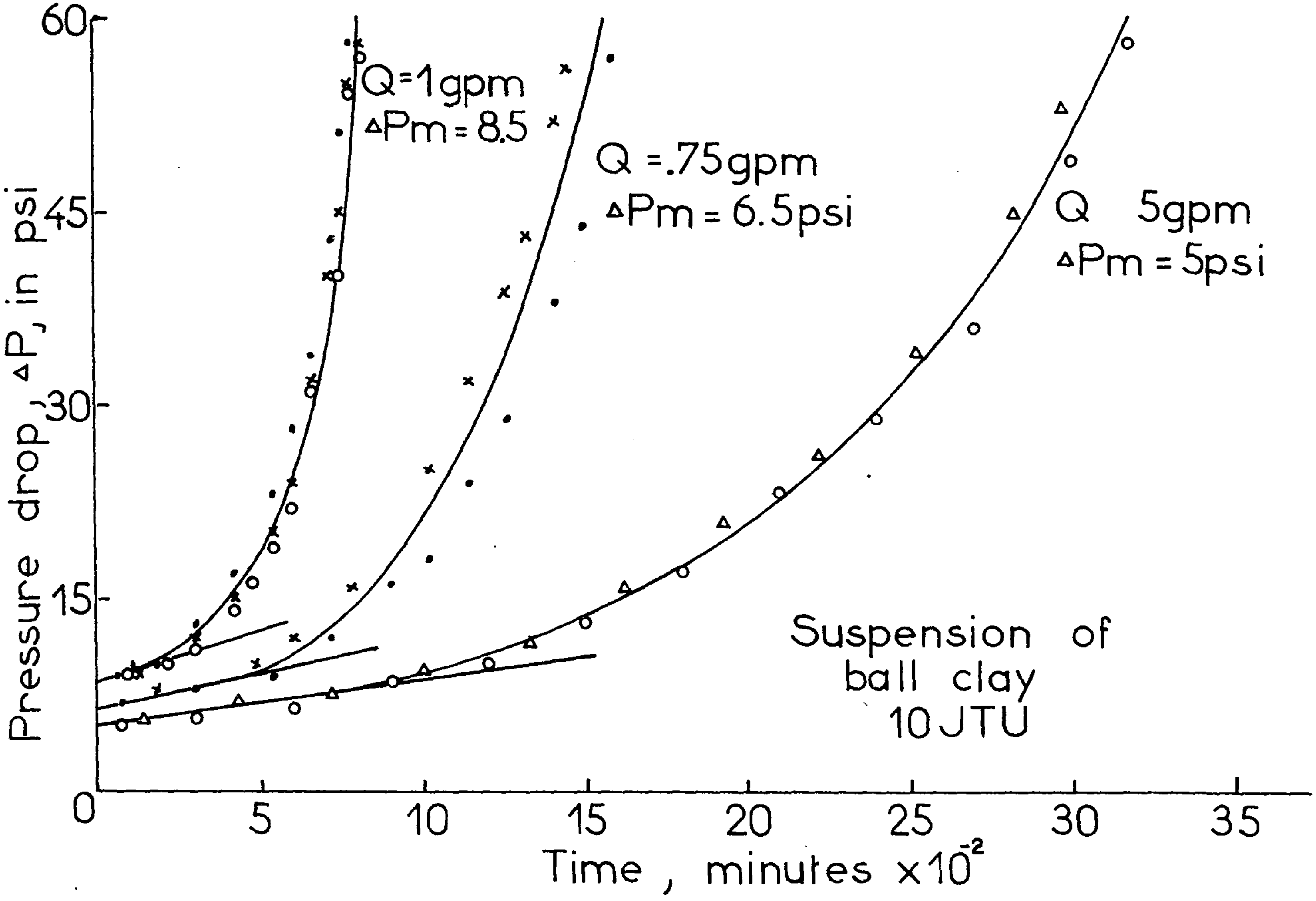
Series C (continued)

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in. Filters		
			#1	#2	#3
C-2	0.75	1410	38	52	71
		1440	40	56	79
		1470	42	61	--
		1500	44	64	--
		1590	57	82	--
		1620	64	--	--
		1650	69	--	--
		1680	76	--	--
C-3	0.50	1	5	6	5
		240	5.5	6.5	5.5
		480	6	7	6
		720	7	8	7.5
		840	8	9	8
		960	8.5	9.5	9
		1080	9.5	10	10
		1200	10	10.5	10.5
		1320	11	11.5	11.5
		1440	12	13	12
		1560	14	15	12.5
		1680	15	17	13.5
		1800	17	19	15
		1920	19	21	17
		2040	21.5	24.5	21
		2160	24	30	24
		2280	27	33	28
		2400	29	36	31
		2460	30	37.5	32
		2520	31	39	33
		2580	32.5	41	35
		2640	34	43.5	37
		2700	36	45	39
		2760	39	47.5	41
		2820	42	50	43
		2880	44	53	45
		2940	47	56	48
		3000	49	59	51
		3060	52	62	53

Series C (continued)

Run number	Flow rate Q gpm	Time T min.	Pressure drop, , lb/sq in. Filters #1	#2	#3
C-3	0.50	3120	55	--	56
		3180	58	--	60
		3240	62	--	62

Figure (24) Plots for constant rate filtrations of a suspension of ball clay at 10 JTU.


Pressure drop, ΔP, in psi
60
45
30
15
0
5
10
15
20
25
30
35
Time, minutes ×10⁻²
Q=1gpm
ΔPm=8.5
Q =.75gpm
ΔPm = 6.5psi
Q 5gpm
ΔPm = 5psi
Suspension of
ball clay
10JTU

Filter Production Tests

Series D

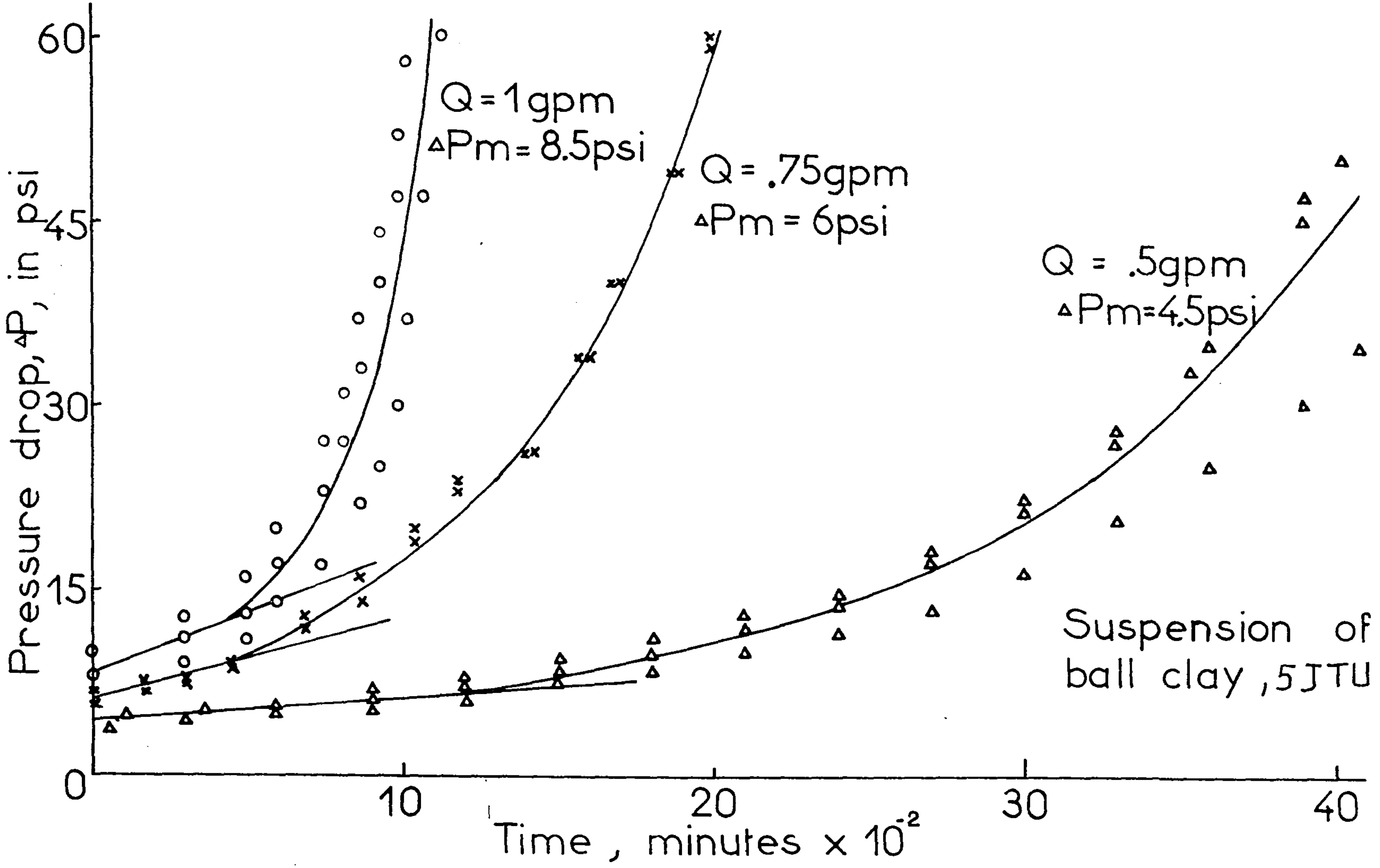
Suspension of ball clay
Turbidity level = 5 JTU
Filtrate temperature 14°C, filtrate pH 7.6
Filtration through Everpure C-3 filters

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in. Filters #1	#2	#3
D-1	1.00	1	8	8	10
		300	11	9	13
		500	13	11	16
		600	17	14	20
		750	23	17	27
		810	27	19	31
		870	33	22	37
		930	40	25	44
		990	47	30	52
		1020	58	37	62
		1050	73	--	76
		1080	82	47	82
		1140	--	60	--
		1170	--	72	--
D-2	0.75	1	6	7	
		150	7	8	
		300	8	9	
		450	9	10	
		680	12	13	
		860	14	16	
		1040	19	20	
		1180	23	24	
		1420	26	26	
		1600	34	34	
		1700	40	40	
		1900	49	50	
		2000	64	65	
		2050	82	82	

Series D (continued)

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in. Filters		
			#1	#2	#3
D-3	0.50	1	4	5	5
		300	4.5	5.5	5.5
		600	5	6	6.5
		900	5.5	6.5	7
		1200	6	7.5	8
		1500	7.5	8.5	9.5
		1800	8.5	10	11
		2100	10	12	13
		2400	11.5	14	14.5
		2700	13.5	17.5	18
		2820	15	19	20.5
		2940	16	20.5	21.5
		3060	17.5	23	24
		3180	18.5	24	25
		3300	20.5	27	28
		3420	21.5	29	31
		3540	23.5	33	33
		3660	25.5	36.5	37
		3780	27.5	42	42.5
		3900	30	47	45
		4020	33	53	50
		4140	36.5	58	54
		4260	40	--	62
		4380	43	--	--
		4440	46	--	--
		4500	48	--	--
		4560	50	--	--
		4620	53	--	--
		4680	57	--	--
		4740	61	--	--

Figure (25) Plots for constant rate filtrations of a suspension of ball clay at 5 JTU.


Pressure drop, ΔP, in psi
0
15
30
45
60
Time, minutes x 10⁻²
10
20
30
40
Q = 1gpm
ΔPm = 8.5psi
Q = .75gpm
ΔPm = 6psi
Q = .5gpm
ΔPm = 4.5psi
Suspension of ball clay, 5JTU

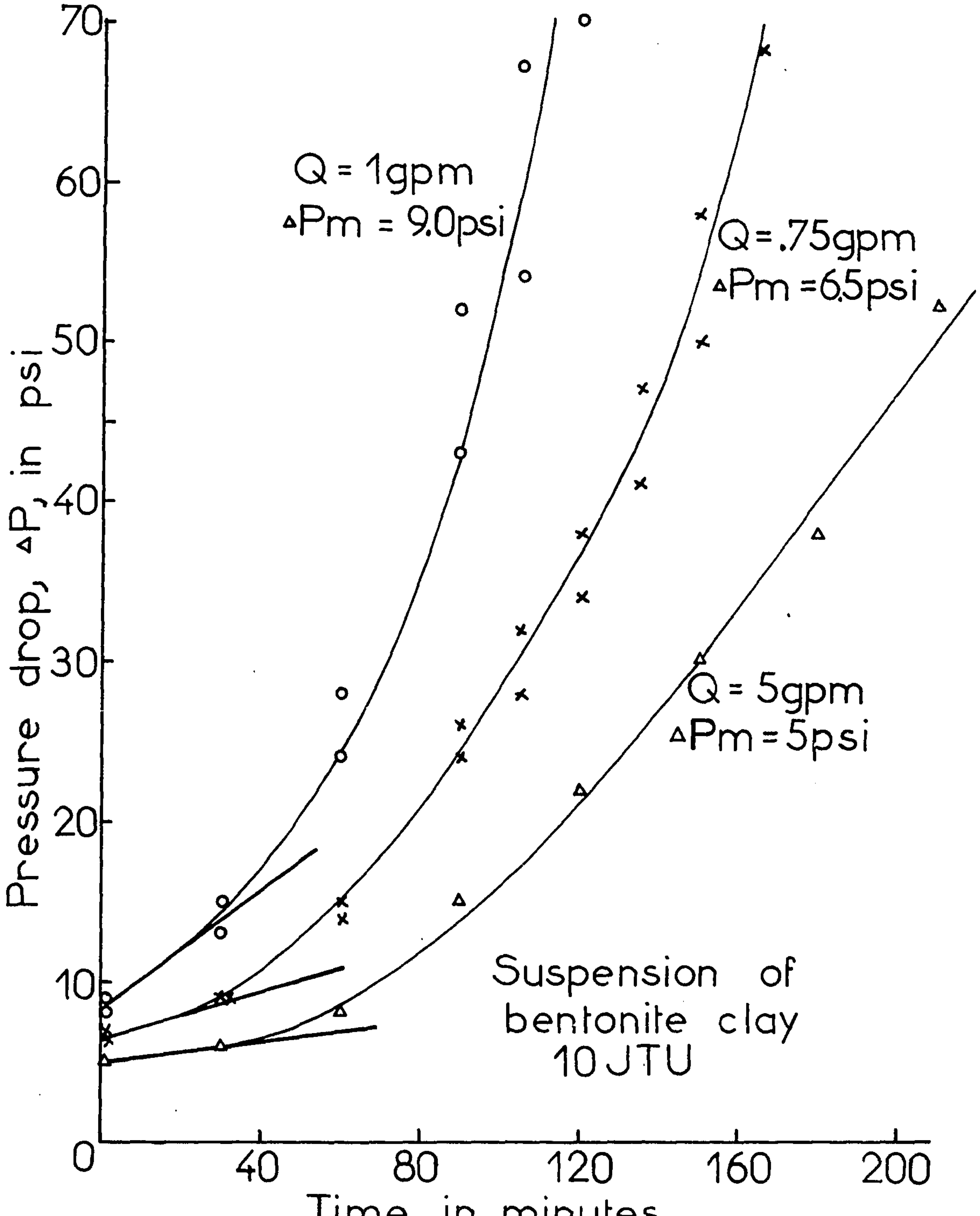
Filter Production Tests

Series E

Suspension of bentonite clay
Turbidity level = 10 JTU
Filtrate temperature 15°C, filtrate pH 7.6
Filtration through Everpure C-3 filters

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ΔP, lb/sq in. Filters		
			#1	#2	#3
E-1	1.00	1	8	9	
		30	13	15	
		60	24	28	
		90	43	52	
		105	54	67	
		120	70	82	
		130	82	--	
E-2	0.75	1	7	6	
		30	9	9	
		60	14	15	
		90	24	26	
		105	28	32	
		120	34	38	
		135	41	47	
		150	50	58	
		165	68	72	
		175	82	82	
E-3	0.50	1	5		
		30	6		
		60	8		
		90	15		
		120	22		
		150	30		
		180	38		
		210	52		
		225	59		
		240	71		
		250	82		

Figure (26) Plots for constant rate filtrations of a suspension of bentonite clay @ 15 JTU.


Pressure drop, ΔP, in psi
0
10
20
30
40
50
60
70
40
80
120
160
200
Time, in minutes
Q = 1gpm
ΔPm = 9.0psi
Q = .75gpm
ΔPm = 6.5psi
Q = 5gpm
ΔPm = 5psi
Suspension of
bentonite clay
10 JTU

Filter Production Tests

Series F

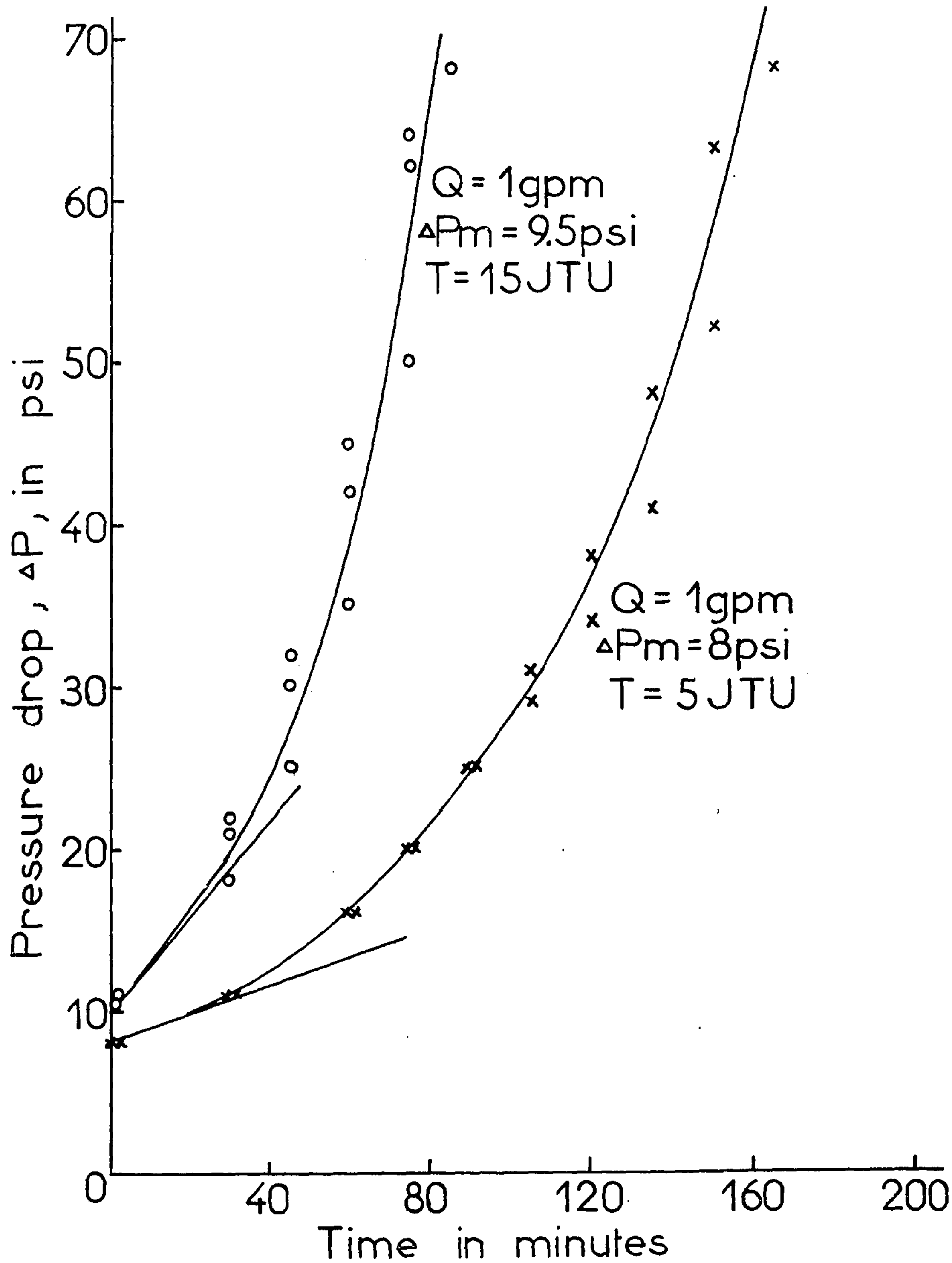
Suspension of bentonite clay
Turbidity level = 15 JTU
Filtrate temperature 15°C, filtrate pH 7.6
Filtration through Everpure C-3 filters

R number	Flow rate Q gpm	Time T min.	Pressure drop, ∆P, lb/sq in. Filters #1	#2	#3
F-1	1.00	1	11	11	10
		30	22	21	18
		45	32	30	25
		60	45	42	35
		75	64	62	50
		85	82	82	68
		90	--	--	82

Suspension of bentonite clay
Turbidity level = 5 JTU
Filtrate temperature 16°C, filtrate pH 7.6
Filtration through Everpure C-3 filters

Run number	Flow rate Q gpm	Time T min.	Pressure drop, ∆P, lb/sq in. Filters #1	#2	#3
F-2	1.00	1	8	8	
		30	11	11	
		60	16	16	
		75	20	20	
		90	25	25	
		105	31	29	
		120	38	34	
		135	48	41	
		150	63	52	
		165	82	68	
		175	--	82	

Figure (27) Plots for constant rate filtrations of a suspension of bentonite clay at 15 and 5 JTU.


Pressure drop , ΔP , in psi
0
10
20
30
40
50
60
70
0
40
80
120
160
200
Time in minutes
Q = 1gpm
ΔPm = 9.5psi
T = 15JTU
Q = 1gpm
ΔPm = 8psi
T = 5JTU

APPENDIX B

Laboratory Pilot Filter Data

Results and Analysis

Constant Pressure Operation Series I

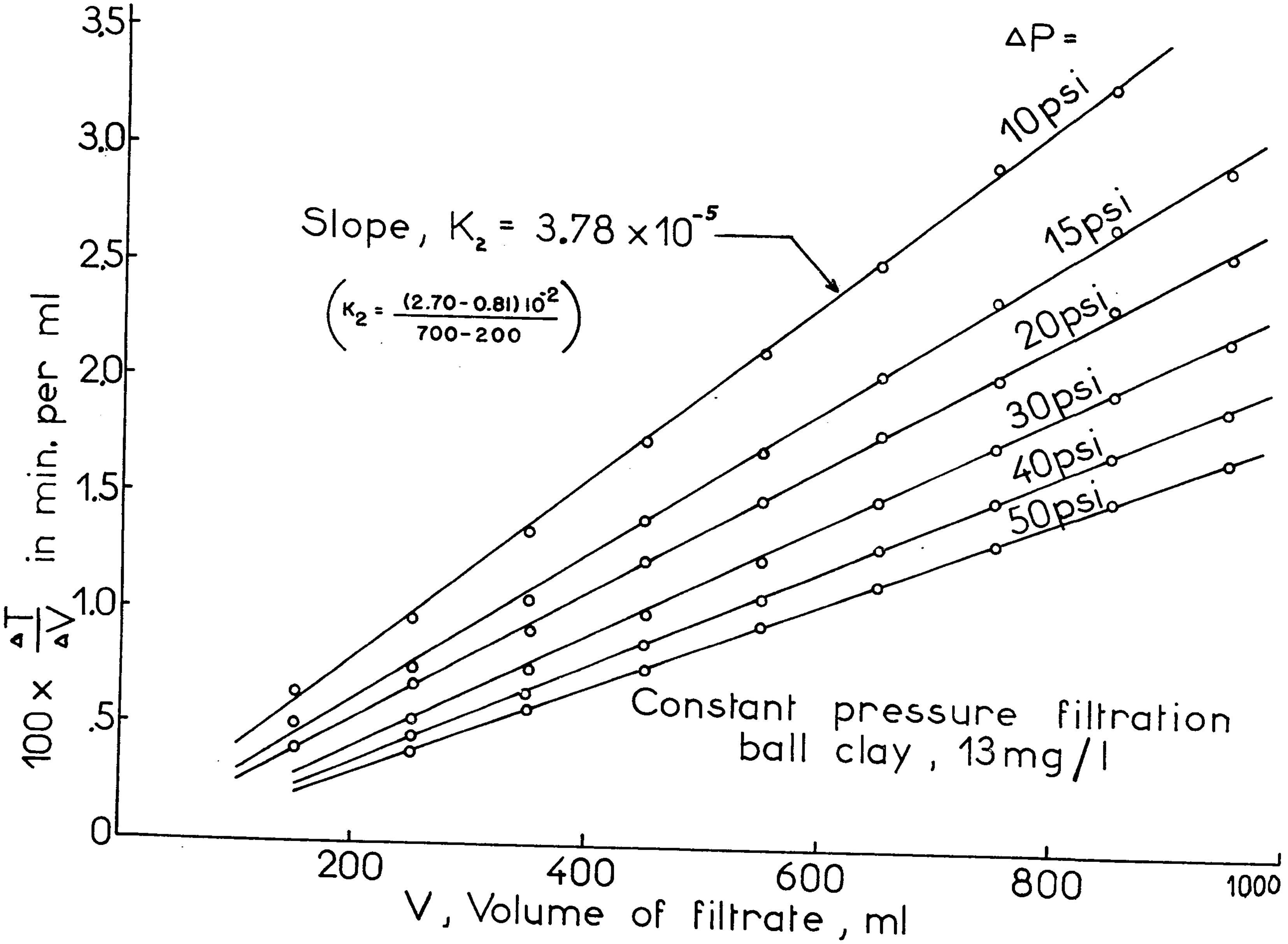
Suspension of ball clay at concentration of 13 mg/l
Filter area 0.785 sq/in.
Filtrate temperature 22° C, filtrate pH 7.7
Filtration through a millipore filter having a pore size of 0.45μ, millipore no. HAWG - 037

Run number	ΔP psi	V ml	T min.	ΔV ml	ΔT min.	$\Delta T/\Delta V$ min/ml
I-1	10	100	0.0	100	0	0
		200	0.64	100	0.64	0.0064
		300	1.60	100	0.96	0.0096
		400	2.94	100	1.34	0.0134
		500	4.68	100	1.74	0.0174
		600	6.81	100	2.13	0.0213
		700	9.33	100	2.52	0.0252
		800	12.28	100	2.95	0.0295
		900	15.57	100	3.29	0.0329
		1000	19.15	100	3.58	0.0358
I-2	15	100	0.0	100	0	0
		200	0.49	100	0.49	0.0049
		300	1.24	100	0.75	0.0075
		400	2.30	100	1.06	0.0106
		500	3.70	100	1.40	0.0140
		600	5.41	100	1.71	0.0171
		700	7.45	100	2.04	0.0204
		800	9.83	100	2.38	0.0238
		900	12.52	100	2.69	0.0269
		1000	15.46	100	2.94	0.0294
I-3	20	100	0.0	100	0	0
		200	0.41	100	0.41	0.0041

Series I (continued)

Run number	ΔP psi	V ml	T min.	ΔV ml	ΔT min.	$\Delta T/\Delta V$ min/ml
I-3	20	300	1.08	100	0.67	0.0067
		400	2.00	100	0.92	0.0092
		500	3.22	100	1.22	0.0122
		600	4.71	100	1.49	0.0149
		700	6.50	100	1.79	0.0179
		800	8.55	100	2.05	0.0205
		900	10.90	100	2.35	0.0235
		1000	13.48	100	2.58	0.0258
I-4	30	100	0.0	100	0.0	0
		200	0.0	100	0.0	0
		300	0.53	100	0.53	0.0053
		400	1.28	100	0.75	0.0075
		500	2.29	100	1.01	0.0101
		600	3.53	100	1.24	0.0124
		700	5.04	100	1.51	0.0151
		800	6.78	100	1.74	0.0174
		900	8.76	100	1.98	0.0198
		1000	10.98	100	2.22	0.0222
I-5	40	200	0.0	200	0.0	0
		300	0.45	100	0.45	0.0045
		400	1.10	100	0.65	0.0065
		500	1.97	100	0.87	0.0087
		600	3.04	100	1.07	0.0107
		700	4.34	100	1.30	0.0130
		800	5.85	100	1.51	0.0151
		900	7.57	100	1.72	0.0172
		1000	9.49	100	1.92	0.0192
I-6	50	200	0.0	200	0.0	0
		300	0.39	100	0.39	0.0039
		400	0.96	100	0.57	0.0057
		500	1.72	100	0.76	0.0076
		600	2.67	100	0.95	0.0095
		700	3.81	100	1.14	0.0114
		800	5.14	100	1.33	0.0133
		900	6.66	100	1.52	0.0152
		1000	8.36	100	1.70	0.0170

Figure (28) Plots for constant pressure filtrations of a suspension of ball clay at a concentration of 13 mg/l.


ΔP =
10psi
15psi
20psi
30psi
40psi
50psi
Slope, $K_2 = 3.78 \times 10^{-5}$
$\left(K_2 = \frac{(2.70 - 0.81)10^{-2}}{700-200}\right)$
Constant pressure filtration
ball clay, 13mg/l
$100 \times \frac{\Delta T}{\Delta V}$ in min. per ml
V, Volume of filtrate, ml
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
200
400
600
800
1000

Laboratory Pilot Filter Data

Results and Analysis

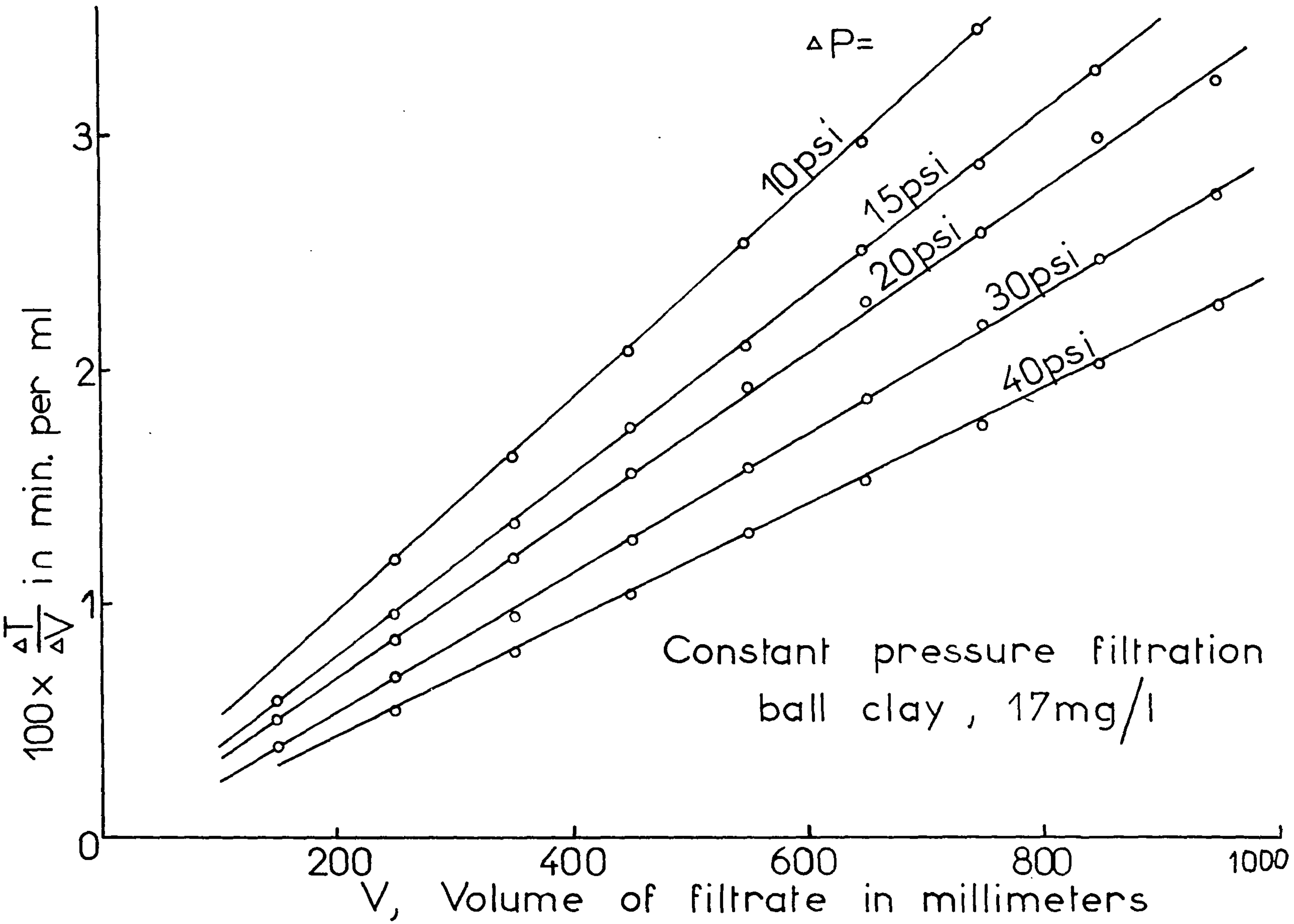
Constant Pressure Operation   Series II
Suspension of ball clay at a concentration of 17 mg/l
Filtrate temperature 23° C, filtrate pH 7.6
Filtration through a millipore filter having a pore size of 0.45μ,
millipore no. HAWG-037

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	$\Delta T/\Delta V$ min/ml
II-1	10	200	0.0	200	0.0	0
		300	1.19	100	1.19	0.0119
		400	2.82	100	1.63	0.0163
		500	4.90	100	2.08	0.0208
		600	7.44	100	2.54	0.0254
		700	10.41	100	2.97	0.0297
		800	13.85	100	3.44	0.0344
		900	17.71	100	3.86	0.0386
II-2	15	100	0.0	100	0.0	0
		200	0.59	100	0.59	0.0059
		300	1.55	100	0.96	0.0096
		400	2.88	100	1.33	0.0133
		500	4.64	100	1.76	0.0176
		600	6.74	100	2.10	0.0210
		700	9.25	100	2.51	0.0251
		800	12.12	100	2.87	0.0287
		900	15.39	100	3.27	0.0327
II-3	20	100	0.0	100	0.0	0
		200	0.50	100	0.50	0.0050
		300	1.34	100	0.84	0.0084
		400	2.53	100	1.19	0.0119
		500	4.08	100	1.55	0.0155
		600	6.00	100	1.92	0.0192
		700	8.28	100	2.28	0.0228
		800	10.86	100	2.58	0.0258
		900	13.86	100	3.00	0.0300
		1000	17.09	100	3.23	0.0323

Series II (continued)

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	ΔT/ΔV min/ml
II-4	30	100	0.0	100	0.0	0
		200	0.39	100	0.39	0.0039
		300	1.07	100	0.68	0.0068
		400	2.03	100	0.96	0.0096
		500	3.31	100	1.28	0.0128
		600	4.88	100	1.57	0.0157
		700	6.76	100	1.88	0.0188
		800	8.95	100	2.19	0.0219
		900	11.42	100	2.47	0.0247
		1000	14.17	100	2.75	0.0275
II-5	40	200	0.0	200	0.0	0
		300	0.55	100	0.55	0.0055
		400	1.34	100	0.79	0.0079
		500	2.38	100	1.04	0.0104
		600	3.68	100	1.30	0.0130
		700	5.21	100	1.53	0.0153
		800	6.79	100	1.76	0.0176
		900	9.00	100	2.03	0.0203
		1000	11.28	100	2.28	0.0228

Figure (29) Plots for constant pressure filtrations of a suspension of ball clay at a concentration of 17 mg/l.


ΔP=
10psi
15psi
20psi
30psi
40psi
Constant pressure filtration
ball clay , 17mg/l
$100 \times \frac{\Delta T}{\Delta V}$ in min. per ml
0
1
2
3
200
400
600
800
1000
V, Volume of filtrate in millimeters

Laboratory Pilot Filter Data

Results and Analysis

Constant Pressure Operation   Series III

Suspension of ball clay at a concentration of 31 mg/l
Filter area 0.785 sq in.
Filtrate temperature 22° C, filtrate pH 7.8
Filtration through a millipore filter having a pore size of 0.45μ,
millipore no. HAWG - 037

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	$\Delta T/\Delta V$ min/ml
III-1	5	100	0.0	100	0.0	0
		150	0.94	50	0.94	0.0188
		200	2.15	50	1.21	0.0242
		250	3.65	50	1.50	0.0300
		300	5.47	50	1.82	0.0364
		350	7.56	50	2.09	0.0418
		400	9.98	50	2.42	0.0484
		450	12.65	50	2.67	0.0534
		500	15.63	50	2.98	0.0596
III-2	10	100	0.0	100	0.0	0
		200	1.40	100	1.40	0.0140
		300	3.73	100	2.33	0.0233
		400	6.98	100	3.25	0.0325
		500	11.20	100	4.22	0.0422
		600	16.36	100	5.16	0.0516
		700	22.36	100	6.00	0.0600
		800	29.35	100	6.99	0.0699
		900	37.04	100	7.69	0.0769
		1000	45.64	100	8.60	0.0860
III-3	15	100	0.0	100	0.0	0
		200	1.11	100	1.11	0.0111
		300	3.03	100	1.92	0.0192
		400	5.72	100	2.69	0.0269
		500	9.23	100	3.51	0.0351
		600	13.54	100	4.31	0.0431
		700	18.62	100	5.08	0.0508
		800	24.36	100	5.74	0.0574

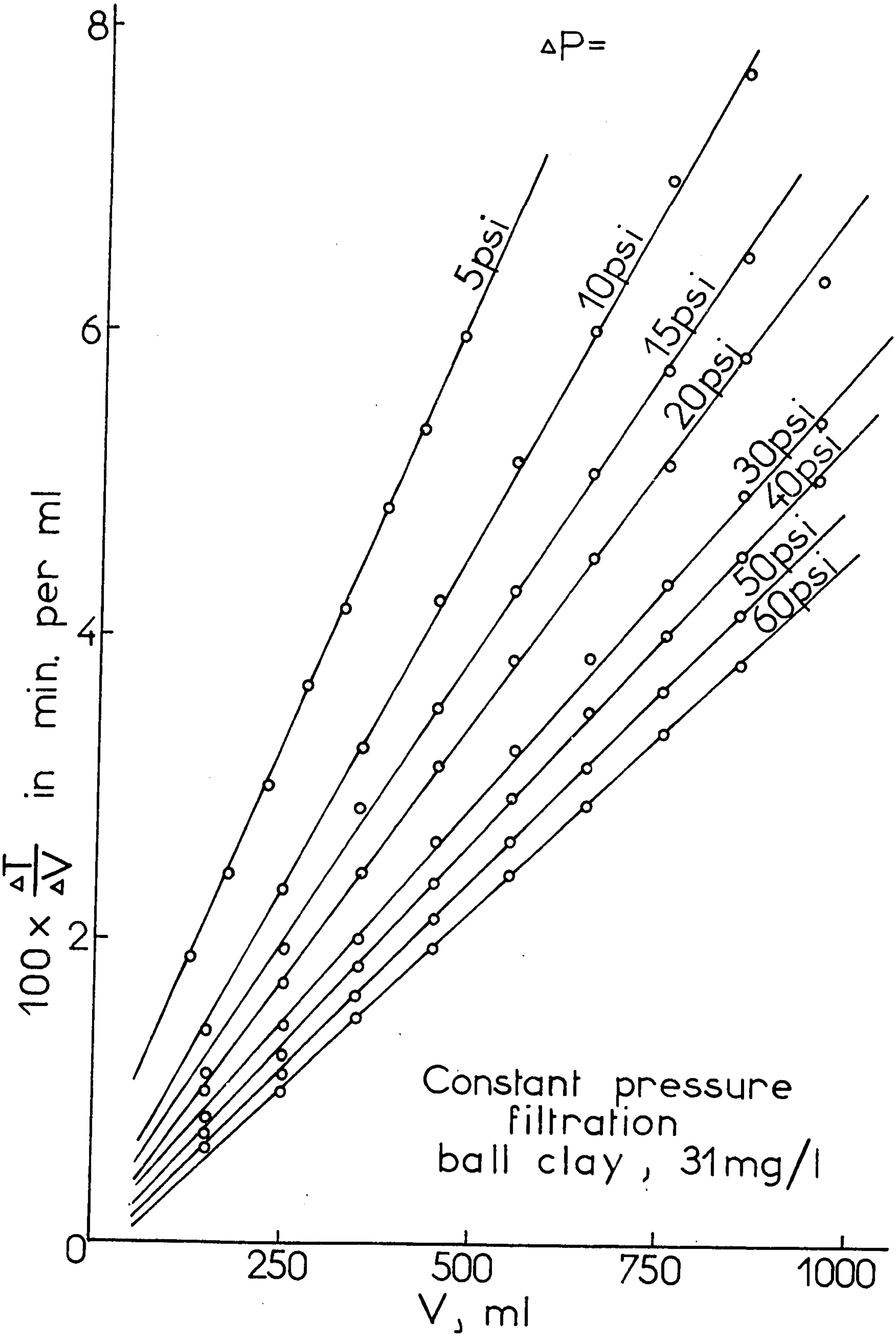
Series III (continued)

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	ΔT/ΔV min/ml
III-3	15	900	30.87	100	6.51	0.0651
III-4	20	100	0.0	100	0.0	0
		200	1.00	100	1.00	0.0100
		300	2.71	100	1.71	0.0171
		400	5.13	100	2.42	0.0242
		500	8.62	100	3.13	0.0313
		600	12.10	100	3.84	0.0384
		700	16.62	100	4.52	0.0452
		800	21.74	100	5.12	0.0512
		900	27.59	100	5.85	0.0585
		1000	33.92	100	6.33	0.0633
III-5	30	100	0.0	100	0.0	0
		200	0.82	100	0.82	0.0082
		300	2.25	100	1.43	0.0143
		400	4.25	100	2.00	0.0200
		500	6.90	100	2.65	0.0265
		600	10.14	100	3.24	0.0324
		700	14.00	100	3.86	0.0386
		800	18.36	100	4.36	0.0436
		900	23.31	100	4.95	0.0495
		1000	28.70	100	5.39	0.0539
III-6	40	100	0.0	100	0.0	0
		200	0.69	100	0.69	0.0069
		300	1.93	100	1.24	0.0124
		400	3.73	100	1.80	0.0180
		500	6.10	100	2.37	0.0237
		600	9.05	100	2.95	0.0295
		700	12.55	100	3.50	0.0350
		800	16.58	100	4.03	0.0403
		900	21.14	100	4.56	0.0456
		1000	26.20	100	6.06	0.0606
III-7	50	100	0.0	100	0.0	0
		200	0.63	100	0.63	0.0063
		300	1.74	100	1.11	0.0111
		400	3.37	100	1.63	0.0163
		500	5.50	100	0.13	0.0213
		600	8.14	100	2.64	0.0264

Series III (continued)

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	ΔT/ΔV min/ml
III-7	50	700	11.28	100	3.14	0.0314
		800	14.92	100	3.64	0.0364
		900	19.07	100	4.15	0.0415
III-8	60	200	0.0	100	0.0	0
		300	1.01	100	1.01	0.0101
		400	2.48	100	1.47	0.0147
		500	4.43	100	1.95	0.0195
		600	6.85	100	2.42	0.0242
		700	9.74	100	2.89	0.0289
		800	13.11	100	3.37	0.0337
		900	16.93	100	3.82	0.0382

Figure (30) Plots for constant pressure filtrations of a suspension of ball clay at a concentration of 31 mg/l.


8
6
4
2
0
$100 \times \frac{\Delta T}{\Delta V}$ in min. per ml
250
500
750
1000
V, ml
ΔP=
5psi
10psi
15psi
20psi
30psi
40psi
50psi
60psi
Constant pressure
filtration
ball clay, 31mg/l

Laboratory Pilot Filter Data

Results and Analysis

Constant Pressure Operation   Series IV

Suspension of bentonite clay at a concentration of 8 mg/l
Filter area 0.785 sq in.
Filtrate temperature 24^{o} C, filtrate pH 8.0
Filtration through a millipore filter having a pore size of 0.45μ,
millipore no. HAWG - 037

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	ΔT/ΔV min/ml
IV-1	5	30	0.0	30	0.0	0
		50	1.50	20	1.50	0.0750
		70	3.79	20	2.29	0.1145
		90	6.89	20	3.10	0.1550
		110	10.80	20	3.91	0.1955
		130	15.45	20	4.65	0.2325
		150	20.91	20	5.46	0.2730
		170	27.13	20	6.22	0.3110
		190	34.15	20	7.02	0.3510
		210	41.86	20	7.71	0.3855
IV-2	10	30	0.0	30	0.0	0
		50	0.93	20	0.93	0.0465
		70	2.53	20	1.60	0.0800
		90	4.82	20	2.29	0.1145
		110	7.73	20	2.91	0.1455
		130	11.32	20	3.59	0.1795
		150	15.52	20	4.20	0.2100
		170	20.36	20	4.84	0.2420
		190	25.71	20	5.35	0.2675
		210	31.70	20	5.99	0.2995
		230	38.29	20	6.59	0.3245
		250	45.48	20	7.19	0.3595
IV-3	15	50	0.0	50	0.0	0
		70	1.28	20	1.28	0.0640
		90	3.21	20	1.93	0.0965
		110	5.79	20	2.58	0.1290
		130	9.08	20	3.29	0.1645
		150	13.00	20	3.92	0.1960

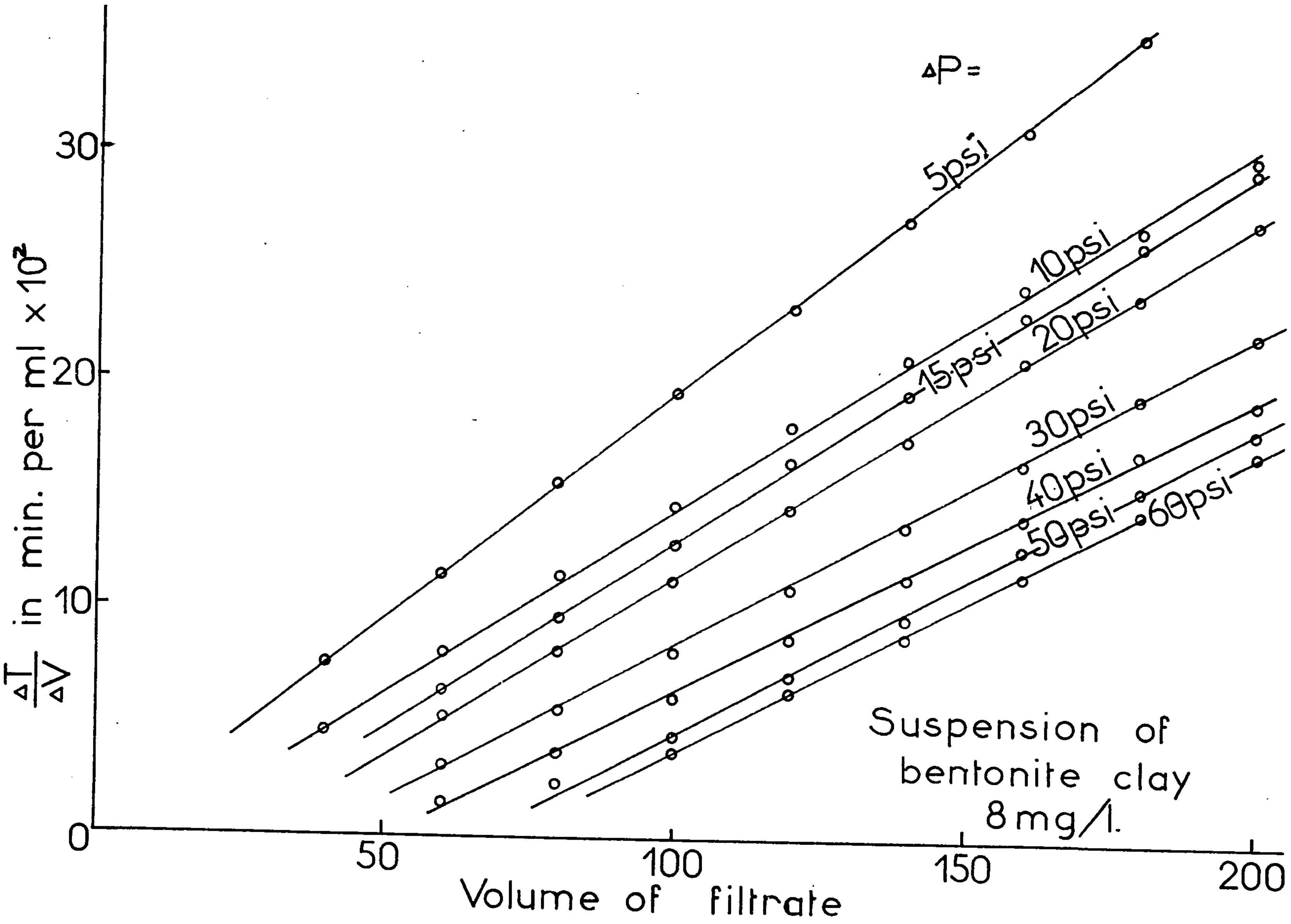
Series IV (continued)

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	$\Delta T/\Delta V$ min/ml
IV-3	15	170	17.65	20	4.65	0.2325
		190	22.93	20	5.28	0.2640
		210	28.81	20	5.88	0.2940
		230	35.27	20	6.46	0.3230
		250	42.44	20	7.17	0.3585
IV-4	20	50	0.0	50	0.0	0
		70	1.04	20	1.04	0.0520
		90	2.67	20	1.63	0.0815
		110	4.93	20	2.26	0.1130
		130	7.82	20	2.89	0.1445
		150	11.33	20	3.51	0.1755
		170	15.52	20	4.19	0.2095
		190	20.34	20	4.82	0.2410
		210	25.81	20	5.47	0.2735
		230	31.81	20	6.00	0.3000
IV-5	30	50	0.0	50	0.0	0
		70	0.63	20	0.63	0.0315
		90	1.76	20	1.13	0.0565
		110	3.41	20	1.65	0.0825
		130	5.60	20	2.19	0.1095
		150	8.35	20	2.75	0.1375
		170	11.63	20	3.28	0.1640
		190	15.51	20	3.88	0.1940
		210	19.95	20	4.45	0.2225
		230	24.93	20	4.97	0.2485
IV-6	40	50	0.0	50	0.0	0
		70	0.32	20	0.32	0.0160
		90	1.06	20	0.74	0.0370
		110	2.28	20	1.22	0.0610
		130	4.03	20	1.75	0.0875
		150	6.33	20	2.30	0.1150
		170	9.16	20	2.83	0.1415
		190	12.55	20	3.39	0.1695
		210	16.40	20	3.85	0.1925

Series IV (continued)

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	ΔT/ΔV min/ml
IV-7	50	70	0.0	70	0.0	0
		90	0.48	20	0.48	0.0240
		110	1.39	20	0.91	0.0455
		130	2.82	20	1.43	0.0715
		150	4.76	20	1.94	0.0970
		170	7.30	20	2.54	0.1270
		190	10.40	20	3.10	0.1550
		210	14.00	20	3.60	0.1800
		230	18.18	20	4.18	0.2090
		250	22.98	20	4.80	0.2400
IV-8	60	90	0.0	90	0.0	0
		110	0.78	20	0.78	0.0390
		130	2.07	20	1.29	0.0645
		150	3.83	20	1.76	0.0880
		170	6.15	20	2.32	0.1160
		190	9.04	20	2.89	0.1445
		210	12.47	20	3.43	0.1715

Figure (31) Plots for constant pressure filtration of a suspension of bentonite clay at a concentration of 8 mg/l.


ΔP =
5psi
10psi
15psi
20psi
30psi
40psi
50psi
60psi
$\frac{\Delta T}{\Delta V}$ in min. per ml × 10^2
0
10
20
30
50
100
150
200
Volume of filtrate
Suspension of bentonite clay 8 mg/l.

Laboratory Pilot Filter Data

Results and Analysis

Constant Pressure Operation Series V

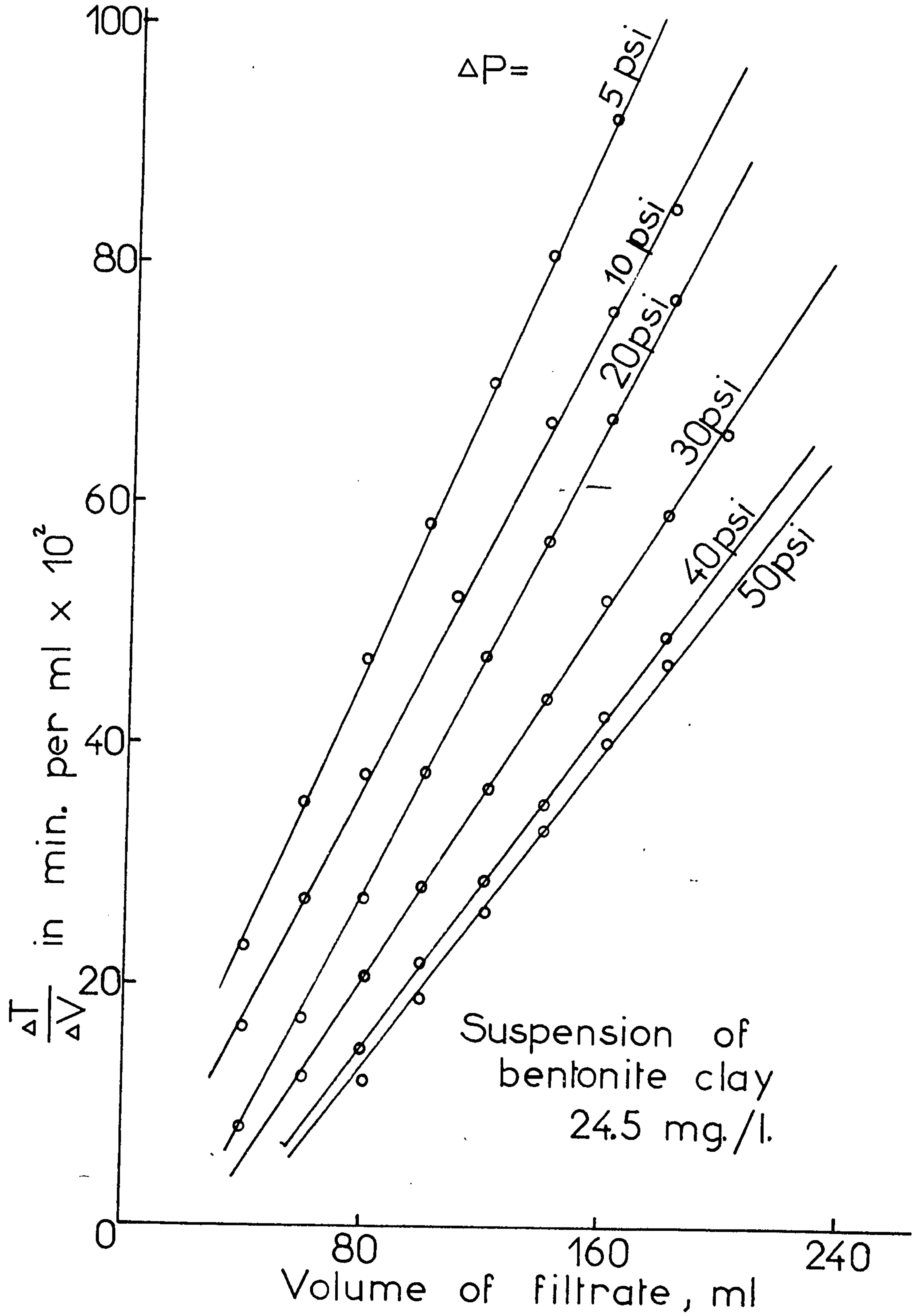
Suspension of bentonite clay at a concentration of 24.5 mg/l
Filter area 0.785 sq in.
Filtrate temperature 24° C, filtrate pH 7.9
Filtration through a millipore filter having a pore size of 0.45μ,
millipore no. HAWG -037

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	$\Delta T/\Delta V$ min/ml
V-1	5	30	0.0	30	0.0	0
		50	4.60	20	4.60	0.2300
		70	11.58	20	6.98	0.3490
		90	21.00	20	9.42	0.4710
		110	32.6	20	11.66	0.5830
		130	46.72	20	14.06	0.7030
		150	62.87	20	16.15	0.8075
		170	81.30	20	18.43	0.9215
		190	101.58	20	20.28	1.0140
V-2	10	30	0.0	30	0.0	0
		50	3.30	20	3.30	0.1650
		70	8.68	20	5.38	0.2690
		90	16.16	20	7.48	0.3740
		110	--	--	--	--
		130	37.02	40	20.86	0.5215
		150	50.37	20	13.35	0.6675
		170	65.57	20	15.20	0.7600
		190	82.50	20	16.93	0.8465
V-3	20	30	0.0	30	0.0	0
		50	1.60	20	1.60	0.0800
		70	5.07	20	3.47	0.1735
		90	10.47	20	5.40	0.2700
		110	17.95	20	7.48	0.3740
		130	27.35	20	9.40	0.4700
		150	38.75	20	11.40	0.5700
		170	52.13	20	13.38	0.6690
		190	67.57	20	15.44	0.7720

Series V (continued)

Run number	ΔP lb/sq in.	V ml	T min.	ΔV ml	ΔT min.	ΔT/ΔV min/ml
V-4	30	50	0.0	50	0.0	0
		70	2.47	20	2.47	0.1235
		90	6.55	20	4.08	0.2040
		110	12.18	20	5.63	0.2815
		130	19.43	20	7.25	0.3625
		150	28.16	20	8.73	0.4365
		170	38.57	20	10.41	0.5205
		190	50.40	20	11.83	0.5915
		210	63.64	20	13.24	0.6620
V-5	40	70	0.0	70	0.0	0
		90	2.91	20	2.91	0.1455
		110	7.21	20	4.30	0.2150
		130	12.92	20	5.71	0.2855
		150	19.92	20	7.00	0.3500
		170	28.40	20	8.48	0.4240
		190	38.18	20	9.78	0.4890
V-6	50	70	0.0	70	0.0	0
		90	2.38	20	2.38	0.1190
		110	6.15	20	3.77	0.1885
		130	11.35	20	5.20	0.2600
		150	18.00	20	6.65	0.3325
		170	26.06	20	8.06	0.4030
		190	35.48	20	9.42	0.4710

Figure (32) Plots for constant pressure filtrations of a suspension of bentonite clay at a concentration of 24.5 mg/l.


$\frac{\Delta T}{\Delta V}$ in min. per ml × 10^2
0
20
40
60
80
100
80
160
240
Volume of filtrate, ml
ΔP=
5 psi
10 psi
20psi
30psi
40psi
50psi
Suspension of
bentonite clay
24.5 mg./l.

APPENDIX C

Calibration Curves

The amount of suspended matter in a water suspension is normally measured as either turbidity or weight of solids per unit volume. Turbidity measurements are generally easier and can be made continuously using one of the many commercial turbidimeters available on the market. Conversion of turbidity to weight per unit volume can be obtained from curves similar to those in Figures (33) and (34).

The Jackson Candle Turbidimeter is commonly accepted as a standard device for measuring suspended turbidity. Accordingly, other instruments for turbidity measurements are calibrated against the Jackson Candle Turbidimeter.

Turbidities of clay suspensions used in constant-rate filtrations of Appendix A were measured with a low-range turbidimeter and reported as Jackson Candle Units or JCU. Turbidities of clay suspensions used in the constant-pressure filtrations, however, were measured with a Hach Turbidimeter and reported as Hach Turbidity Units or HTU.

Standard solutions of the clay minerals containing known amounts of suspended solids were prepared and the turbidity of each suspension was measured on both the Jackson Candle Turbidimeter and the Hach Turbidimeter. The resulting information were plotted in Figures (33) and (34) and used to convert turbidity measurements to units of weight per unit volume or mg/l.

In preparing Figure (33) a clay slurry was obtained from the clay feeder and the amount of clay in suspension was determined gravitmerically. Samples for calibration were obtained by adding zero-turbidity water to known volumes of the slurry and shaking the mixture for a few minutes. Turbidities of the resulting suspensions were measured on a Jackson Candle Turbidimeter and used to prepare Figure (33).

Clay suspensions used in developing Figure (34) were prepared by mixing 10 grams of the desired clay mineral in 5 liters of distilled and air agitating it for 14 hours. The suspension was then allowed to settle for 6 hours and the supernate was drawn out to be used as the clay slurry. The amount of clay in the slurry was determined gravitmerically. Samples of the clay suspension used for calibration were obtained by adding zero-turbidity tap water to given volumes of the slurry and shaking the mixtures for few minutes. Turbidities of the resulting samples were measured on the Hach Turbidimeter and used to prepare Figure (34).

Calibration curves for other equipment used in this study are found in data book No. 1 of this investigation.

Figure (33) Curves for clay concentration, c, in mg/l vs. turbidity in JTU

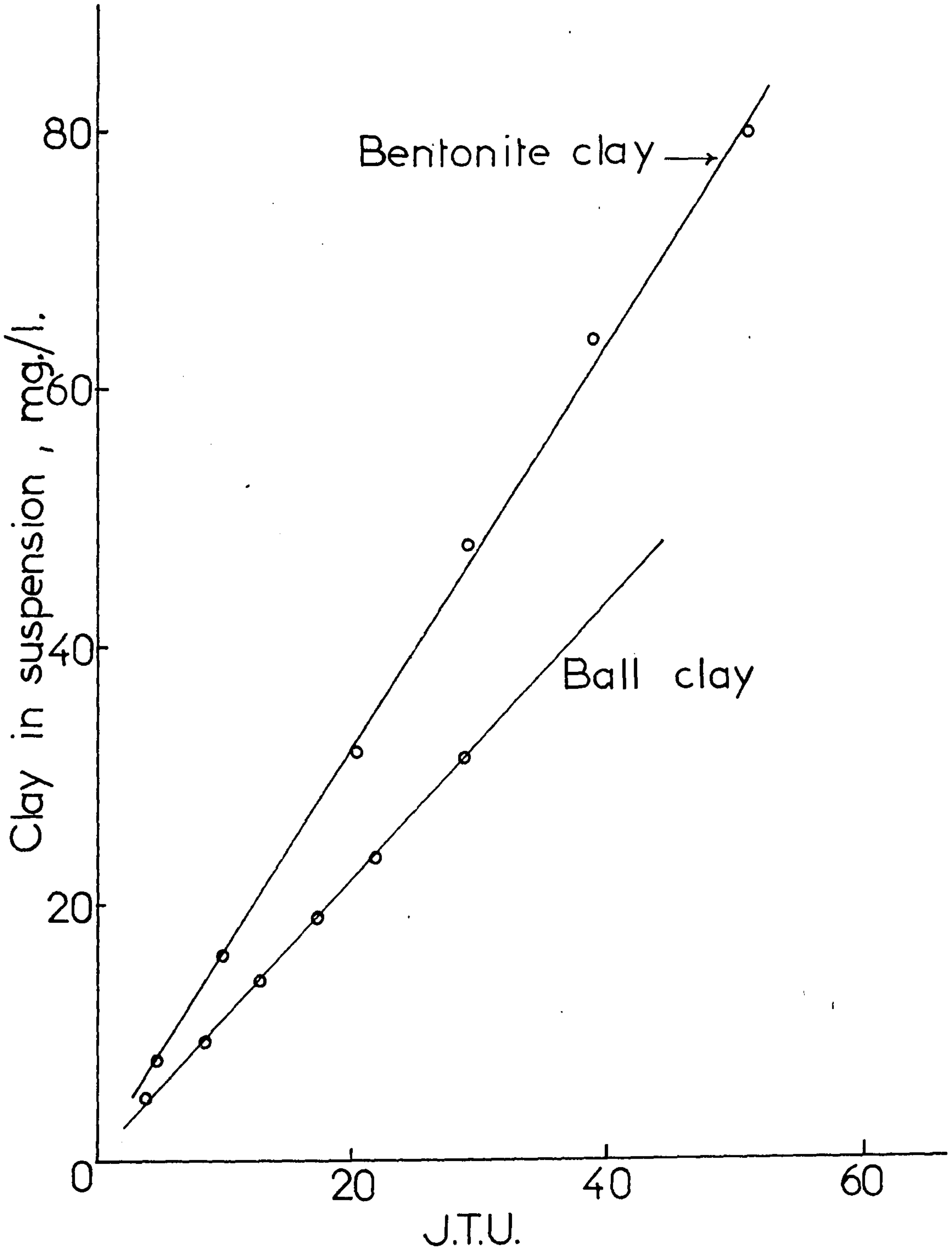
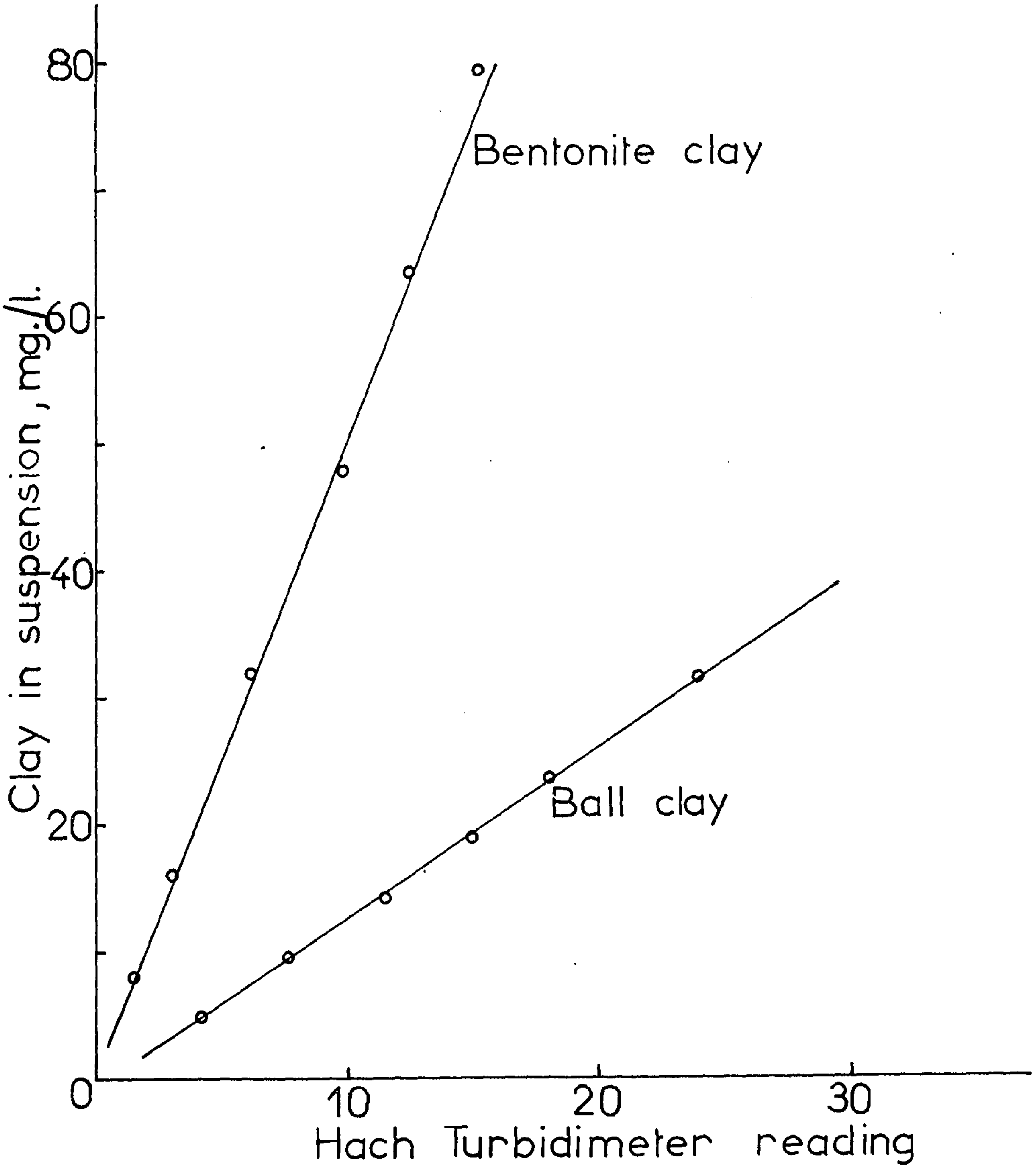

Clay in suspension , mg./l.
80
60
40
20
0
20
40
60
J.T.U.
Bentonite clay
Ball clay

Figure (34) Curves for clay concentration, c, in mg/l vs. Hach turbidity readings.


Clay in suspension, mg./l.
80
60
40
20
0
10
20
30
Hach Turbidimeter reading
Bentonite clay
Ball clay

APPENDIX D

Unit Conversion Factors

Item	Units normal in laboratory	Conversion factor	Units in Equations
Area , A	sq ft	1.0	sq ft
Solids Concentration, C	mg/l	6.24×10^{-5}	lb/cu ft
K_2	min./ml^4	4.81×10^{10}	sec/ft^6
pressure drop, ΔP	psi	144	psf
flow rate, Q	gpm	2.24×10^{-3}	cu ft/sec
water viscosity,	centipoises	6.72×10^{-4}	lb/ft-sec

Viscosity of Water

Temperature	Water Viscosity	
T° c	centipoise	lb/ft-sec
10	1.308	8.79×10^{-4}
15	1.140	7.66×10^{-4}
17	1.083	7.27×10^{-4}
19	1.030	6.92×10^{-4}
21	0.981	6.52×10^{-4}
23	0.936	6.29×10^{-4}
25	0.894	6.01×10^{-4}

APPENDIX E

Procedure to be Followed in Predicting Productive Life of Everpure Filters with Various Waters

(1) Develop a vs. ΔP relations for various waters using the pilot filter unit and the filtration technique presented in this investigation.

(2) Calculate productive life of Everpure filter units in constant pressure operation to observe effect of suspended solids concentration, pressure drop, water temperature, water pH, etc. on filter production.

(3) Observe field productive life of Everpure units in constant rate operation using the same source of water.

(4) Correlate laboratory results and predicted filter production with observed field data.