1965

Use of digital computer in design of diatomite filtration plants

James Hugh Dillingham
Iowa State University

Recommended Citation

Dillingham, James Hugh, "Use of digital computer in design of diatomite filtration plants " (1965). *Retrospective Theses and Dissertations*. 3342.
https://lib.dr.iastate.edu/rtd/3342

DILLINGHAM, James Hugh, 1938-
USE OF DIGITAL COMPUTER IN DESIGN OF
DIATOMITE FILTRATION PLANTS.

Iowa State University of Science and Technology
Ph.D., 1965
Engineering, sanitary and municipal

University Microfilms, Inc., Ann Arbor, Michigan

USE OF DIGITAL COMPUTER IN DESIGN OF DIATOMITE FILTRATION PLANTS

by

James Hugh Dillingham

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Sanitary Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1965

TABLE OF CONTENTS

INTRODUCTION

General

The removal of solids from a solid-liquid mixture by passing the liquid through a porous medium that retains the solids is called filtration. Three filter media used in the filtration of water supplies are sand, carbon, and diatomaceous earth or diatomite, sand being the most common for municipal supplies. This thesis will be concerned primarily with diatomite filtration of municipal water supplies.

The solids removed during filtration often form a cake on the surface of the original filter media that the liquid must pass through. This occurs when the solids clog the pores of the media. Filtration through the collected solids is commonly referred to as cake filtration.

The time needed to form a filter cake depends on the size of the filter media (relative to the size of the solids being removed). When the media is of relatively small particle size, a filter cake is formed soon after filtration begins because practically all the solids are removed at the surface. With relatively large media such as sand, however, the solids penetrate further into the bed, and consequently, more time is needed to clog the pores at the surface and form a filter cake.

Suspended impurities in raw waters used for municipal water supplies almost invariably form compressible filter cakes. Compressible cakes are typically very resistant to flow (low permeability). Because of this high resistance, rapid sand filter runs are usually terminated and the removed impurities washed from the sand bed at about the time a filter cake is beginning to form. In slow sand filtration and filtration through carbon, however, filtration through a filter cake is a primary mode of removal.

Cake filtration is also a primary mode of removal in diatomite filtration. The significant difference is that diatomite filter aid is added to the influent water in order to form a porous cake that is essentially incompressible. The action of the filter aid particles is to form a rigid mat with sufficient pore volume to accomodate the suspended impurities (10, 11). The filter aid added to the influent is commonly referred to as body feed. The amount of body feed that should be added is a very important consideration in the design of diatomite filtration plants.

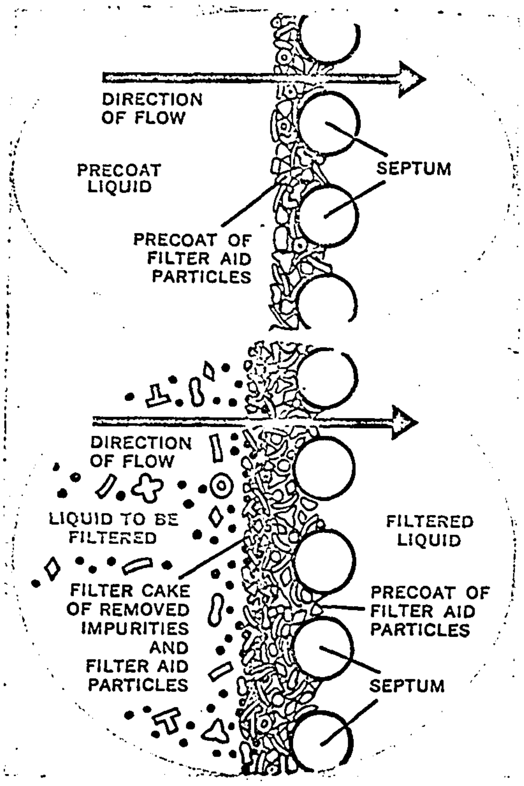
In diatomite filtration, a filtering cycle consists of three operations:

1. Precoating - - A thin diatomite precoat is formed on a porous support called a septum by cycling water that contains a predetermined amount of diatomite through the septum (Fig. 1). The purpose of the precoat is to prevent impurities from passing through the septum at the beginning of a filter run.

2. Filtering - - The operation of removing the suspended impurities and filter aid particles by forming a homogeneous porous filter cake of increasing thickness (Fig. 1).

3. Backwashing - - The filter cake and precoat is discarded and the filtering cycle repeated when the terminal pressure drop (or head loss) across the cake is reached.

Throughout this thesis: the term body feed will refer to the



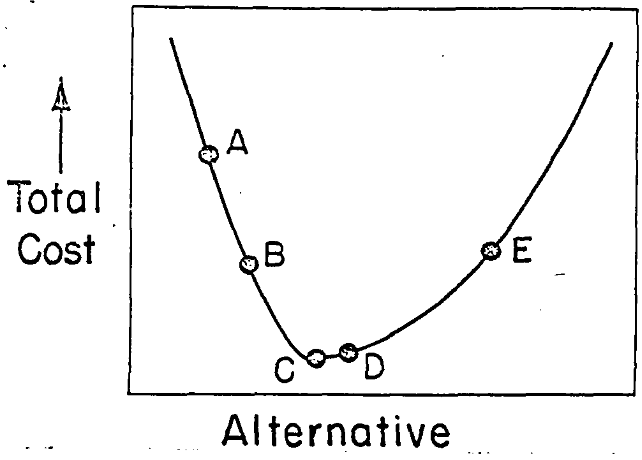


Fig. 2. Schematic diagram of total cost of water production for different alternatives

Fig. 1. Top - precoating operation
Bottom - filtering operation (23)

diatomite filter aid added to the influent; suspended solids (or just solids) will not include the body feed; filter cake will include only the body feed-suspended solids cake (does not include the precoat).

Alternative Costs

Traditionally, cost comparisons for various designs are made by comparing various alternatives. Fig. 2 represents a schematic diagram of five alternatives of design. Bear in mind that it is rarely possible to draw a two-dimensional plot such as Fig. 2 that will show the variation in cost with one parameter that represents a particular combination of all variables that influence cost. However, the diagram is useful for illustrative purposes. Variables that influence cost include quantity of water needed, characteristics of the raw water, characteristics of the filter aid, characteristics of the equipment (type of installation), flow rate, body feed concentration, terminal head loss, etc.

Point C in Fig. 2 represents the least cost design. However, in some cases, it may be more practical to design at some point near the least cost point, such as point D. A filtration plant can rarely be operated at a particular choice of operating conditions because of variations in the influent quality, body feeding equipment, etc. Since the hypothetical curve in Fig. 2 is steeper on the left of point C, small changes in operating conditions could shift the point of operation to the left resulting in significant increase in costs. But, if the plant were designed to operate at point D, cost of production would not be so sensitive with respect to small changes in operating conditions.

Traditionally, filtration plants are not designed to operate at optimum economy. According to the recent Task Group Report on Diatomite Filtration (37): "As far as the committee has discovered, no diatomite or rapid sand plant has yet been designed to operate in its most economical range, although several installations may approach this condition." One of the main reasons for this lack of optimum economical design is that accurate cost predictions for varying operating conditions are very difficult. Total cost of production is a very complex function of the several variables involved, and accurate cost predictions have not generally been possible.

The desireable approach is to compare several alternatives to get a more accurate picture of cost variation. The greater the number of combinations of the variables considered, the more accurately the cost picture will be known. It is impractical to make more than a few comparisons because of the large number of calculations necessary. However, with the use of a digital computer, as many comparisons as desired can be made in a relatively short time.

Objectives

The primary objective of this thesis is to develop a digital computer program that can be used to design a diatomite filtration plant to produce filtered water of requisite quality at least cost. In order to achieve this objective, it is necessary to be able to predict operating costs for different combinations of filter aid grade, flow rate, type and concentration of suspended solids, terminal head loss, body feed concentration, and different types of equipment (pressure or vacuum filters, degree of automation, etc.). Preludes to the development of this program are:

1. A critical look at the present theory of diatomite filtration.
2. Development of theoretical diatomite filtration equations that can be used to describe the head loss-time relationship of diatomite filter cakes formed on flat and cylindrical septa.
3. Development of empirical prediction equations for predicting changes in flow resistance of filter cakes for corresponding changes in suspended solids concentration, body feed concentration, and possibly filter aid grade.

These prediction equations will be empirical relationships whose coefficients will be determined by least squares techniques using a high speed digital computer. Although the use of a digital computer is not necessary for least squares analysis, its use in the preparation of this thesis made practical a more extensive analysis of the available data.

Most of the data analyzed in this thesis were summarized in past theses and publications (3, 4, 5, 15, 16, 19, 20, 25, 27, 35). The data analyzed in this thesis include data collected using water containing iron, turbidity in the form of clay particles, and carry-over from the lime-soda ash softening process. None of the data for filter runs filtering effluent from the lime-soda ash softening process have been published.

REVIEW OF LITERATURE

Diatomite Filtration of Potable Water

The use of diatomite for filtration of potable water was initiated by the U. S. Army in World War II. A portable purification unit was needed that could supply potable water to field troops in the Pacific Theater. The units available at that time were not capable of removing the causitive agent of amoebic dysentery. Since that time, diatomite filters have been used more and more for municipal water supplies (37). Many difficulties were encountered with the early plants because of faulty design and poor operating techniques. Baumann's rather comprehensive study completed in 1954 (2) did much to alleviate these difficulties.

Phillips (34) analyzed and summarized most of the important research on diatomite filtration of potable water up to 1957. His thesis presents a good summary of the work done prior to 1957. Since that time, the bulk of the research on diatomite filtration of water supplies has been carried out at Iowa State University. This work has been reported in the form of graduate theses, progress reports, and publications in technical journals - - e.g.: effect of chemical coagulation on resistance (reciprocal of permeability) of filter cakes (26); theory of diatomite filtration, optimums in diatomite filtration, and optimum economical design (3, 4, 5, 25, 27); effect of streaming potential, chemicals, and polyelectrolyte coatings (1, 31, 32, 33); hydraulic and particle size characteristics of filter aids (15, 16); resistance of filter cakes containing various grades of filter aid and flocculent iron oxide (19), containing various flocculent solids (20), and containing various clay minerals (35). Some of the data collected during these studies will be discussed and analyzed in other sections of this thesis.

Bell discussed the application of coagulant coatings for filter aids in 1961 (7). In 1962, he suggested several design criteria for municipal diatomite filters (8). A recent Task Group Report on Diatomite Filtration was published in 1965 (37). This publication includes a bibliography on diatomite filtration containing 178 references.

In addition to the literature cited above, several reports have been published on operating experiences encountered with municipal diatomite filter installations.

Theory of Diatomite Filtration

In the following review of the theory of diatomite filtration, the nomenclature of some of the investigators has been changed to conform to that of the author's for the sake of continuity. Each term used is defined where it first appears and also listed in Appendix A. Since different units were used by different investigators, equations presented in this thesis will be in dimensionally homogeneous form using the basic dimensions of force, length, and time. A dimensionally homogeneous equation is one that can be used with any consistent set of basic units such as foot-pound-second, centimeter-gram-second, etc. Dimensions of terms will be indicated within brackets using the letters F (force), L (length), and T (time).

Consider the relatively simple flux equation:

$$\frac{dU}{Adt} = K \frac{dP}{dL} \qquad (1)$$

where A = area

L = length

P = potential

U = flux or flow

t = time

K = proportionality constant.

This equation stated in words: the time rate of flux per unit area is equal to a constant times the potential gradient. This very useful flux equation finds many applications in applied physics. Three analogous physical applications of Equation 1 are Ohm's law of electricity, Fick's law of diffusion, and D'Arcy's law of flow through porous media. These three laws have been demonstrated by numerous investigators and hardly need further justification.

For Ohm's law dU/dt is the electrical current, A is the cross-sectional area of the conductor, dP/dL is the electrical potential gradient, and K is the inverse of the resistivity. Ohm's law is more readily recognized in its integrated form (I = E/R where I = current, E = potential difference, and R = resistance = L/KA).

For Fick's law, dU/dt is the time rate of diffusion, A is the cross-sectional area perpendicular to the direction of diffusion, dP/dL is the concentration gradient, and K is the coefficient of diffusion or specific diffusion rate.

For D'Arcy's law, the flux is the flow of water, the potential gradient is the hydraulic gradient, and the proportionality constant is the coefficient of permeability. D'Arcy's law is commonly presented in the form:

$$v = K i \tag{2}$$

where $v = Q/A$ = approach or face velocity $[LT^{-1}]$

Q = flow rate $[L^3T^{-1}]$

A = gross cross-sectional area of porous media perpendicular to direction of flow $[L^2]$

$i = dH/dL$ = hydraulic gradient [dimensionless]

H = head loss or pressure difference in terms of length of water column $[L]$

L = thickness of porous media in direction of flow $[L]$

K = coefficient of permeability $[LT^{-1}]$.

The filtration of water, especially diatomite filtration, is analogous to the flow of water through porous media. Thus, what is essentially D'Arcy's law has been applied to filtration in the form of the generally accepted filtration rate equation. Although presented in many forms, probably the simplest is Equation 3:

$$\frac{dV}{Adt} = \frac{dP}{\mu a dL} \tag{3}$$

where V = volume of filtrate filtered in time t $[L^3]$

dP/dL = pressure gradient $[FL^{-3}]$

μ = dynamic or absolute viscosity $[FTL^{-2}]$

a = specific resistance $[L^{-2}]$.

This equation is probably the most useful tool available for dealing with cake-filtration problems. Its validity has been demonstrated by several workers including Carman (10, 11), Fair and Hatch (17), Ruth (36), Hoffing and Lockhart (21), Grace (18), and Kottwitz (24). Equation 3 can be changed to:

$$v = gi/\nu a \qquad (4)$$

since $v = (1/A)dV/dt$

$i = dH/dL = dP/dL\ \gamma_w$

$\nu = \mu g/\gamma_w$ = kinematic viscosity $[L^2T^{-1}]$

where γ_w = density of water $[FL^{-3}]$

g = gravity constant $[LT^{-2}]$.

Comparison of Equations 2 and 4 clearly illustrates that the filtration rate equation and D'Arcy's equation are essentially the same, and the specific resistance is inversely proportional to the coefficient of permeability ($a = g/K\nu$). It has long been realized that the velocity of flow is inversely proportional to the viscosity, and consequently, D'Arcy's equation is usually modified to include viscosity as follows (10, 11, 21):

$$v = K_1 gi/\nu \qquad (5)$$

where K_1 is a modified permeability coefficient independent of viscosity and has the dimensions $[L^2]$. The modified permeability coefficient (K_1) and the specific resistance (a) are reciprocals of each other ($K_1 = 1/a$).

The specific resistance a in Equation 4 is typical of the filter medium. Comparison of Equation 4 with the following pipe flow equation derived by dimensional analysis (17) illustrates that the specific resistance concept can be applied to pipe flow:

$$i = \frac{v\nu k}{g\ d^2} \qquad (6)$$

where d = pipe diameter $[L]$

k = a constant of pipe flow [dimensionless] .

Thus, a pipe would have a specific resistance of k/d^2. If k = 32, Equation 6 is identical to Poiseuille's equation for flow through capillary tubes. It is understandable then that some workers have derived the filtration rate equation intuitively from Poiseuille's equation (18) by replacing the factor $32/d^2$ with a specific resistance parameter typical of the filter medium.

There have been attempts to relate specific resistance of porous media to Reynold's number and friction factor in analogy with pipe flow concepts. However, this approach has not been very fruitful for cake-filtration problems (21).

Several theoretical and empirical studies have attempted to develop an expression relating specific resistance to physical properties of the filter medium. The most successful such expression is the Kozeny-Carman-Fair and Hatch equation (10, 11, 17, 21) that expresses the specific resistance as follows:

$$a = kS_s^2 (1 - n)^2/n^3$$

where k = Kozeny constant, nominally 5 ± 0.5

S_s = specific surface of particles defined as surface area per unit volume $\left[L^2L^{-3} = L^{-1}\right]$

n = porosity, [dimensionless L^3L^{-3}] .

However, its practical application has been limited to ideal conditions, such as the flow of clean water through clean uniform sand; it has been found to be of little value in the filtration of water supplies under real conditions. The presence of suspended solids in the water greatly complicates the problem. There has been no good correlation between specific resistance and physical properties of the filter cake in filtration of water supplies, except under very limited conditions.

Most research on filtration of water supplies has been done using sand as the filter media. Accordingly, most theories are based on sand (clean uniform sand at that) and have found little application in diatomite filtration. Earlier work on sand filtration was well summarized in the excellent study on sand filtration rates made by Cleasby in 1960 (12, 13). Another excellent paper on sand filtration by Camp was published in 1964 (9).

There has been relatively little work done on the theory of diatomite filtration of water supplies. Fortunately, however, the theory of cake filtration is applicable; in fact, the theory is somewhat simplified by the action of filter aids (10, 11). Carman demonstrated that a filter aid is efficient only if the proper proportion (with respect to the suspended solids) is used and that it is most efficient when mixed with suspended solids that form compressible cakes (10, 11). Small proportions of filter aid only add bulk to the cake with no increase in permeability. Large proportions add excessive thickness to the cake that overshadows the increase in permeability. Essentially the same thing was later demonstrated by Baumann and LaFrenz (2, 25, 27).

Equation 4 can be written for the precoat and filter cake, respectively:

$$H_p = \frac{v\gamma}{g}\left(\frac{a_pV_p}{A}\right) \qquad H_c = \frac{v\gamma}{g}\left(\frac{a_cV_c}{A}\right) \qquad (7)$$

since $i_p = H_pA/V_p$ and $i_c = H_cA/V_c$ where V_p and V_c are volumes of precoat and filter cake and the subscripts p and c refer to the precoat and filter cake, respectively. The factors in parentheses represent what is usually called resistance. Since the specific resistance a represents the resistance of a unit volume of filter cake per unit area, a is usually referred to as the specific resistance based on volume of filter cake. Since the thickness of the filter cake is difficult to measure accurately, several workers have suggested that the specific resistance be referred to the weight of the filter cake by replacing the volume of the cake (V_c) in the above equation with the dry weight of the cake (W_c). Carman (10, 11) suggested that the specific resistance be referred to the weight of the solids (excluding body feed) in the filter cake (W_S) rather than the total weight of the filter cake (W_c).

In diatomite filtration of water supplies, sufficient body feed is added to the influent to form an essentially incompressible filter cake. Also, the concentrations of suspended solids and body feed are usually constant during a filter run. Therefore, the relative values of V_c, W_c, W_S, and even W_D (the weight of diatomite in the filter cake) remain the same, and the in place bulk density of the filter cake (γ_c) is constant. Thus, the relative values of specific resistances based on volume of filter cake, weight of filter cake, weight of solids in the filter cake, or weight of diatomite in the filter cake would remain the same. If specific resistance based on one of these four factors remains constant, then specific resistances based on the other three factors also remain constant but differ in numerical value.

LaFrenz included the filtration rate equation in the literature review section of his M.S. thesis (26), but he evidently failed to recognize its applicability to diatomite filtration of water supplies. In his Ph.D. thesis (25), he derived a diatomite filtration equation starting from the unmodified form of D'Arcy's equation (Equation 2). As will be shown, subsequent work with his equation has led back to the filtration rate equation.

LaFrenz' expressions for the head loss through the precoat (H_p) and the filter cake (H_c) can be respectively written:

$$H_p = K_3vw \qquad H_c = \frac{K_3}{1 - \frac{C_S}{C_D K_4}} v^2 t C_D \gamma_w (10)^{-6} \tag{8}$$

where w = precoat weight per unit area $[FL^{-2}]$

C_D = body feed concentration in ppm $[(10)^{-6}FF^{-1} = 10^{-6}]$

C_S = concentration of suspended solids in ppm $[10^{-6}FF^{-1} = 10^{-6}]$

$K_3 = 1/K_p\gamma_p$ $[F^{-1}L^2T]$

K_p = permeability of precoat $[LT^{-1}]$

γ_p = in place bulk density of the precoat $[FL^{-3}]$

$K_4 = \gamma_S n/\gamma_p$ [dimensionless]

γ_S = in place bulk density of solids in the filter cake $[FL^{-3}]$

Since the quantity $vtC_D\gamma_w(10)^{-6}$ is equivalent to the weight of diatomite in the filter cake per unit area (W_D/A) (assuming that none of the body feed passes through the filter cake), the expression for H_c can be written as follows:

$$H_c = BvW_D/A \tag{9}$$

where $B = K_3/(1-C_S/C_DK_4)$ $[F^{-1}L^2T]$. LaFrenz' coefficient $K_3/(1-C_S/C_DK_4)$ will be referred to as B by the author.

If Equation 7 is rewritten referring the specific resistance to the weight of diatomite, then:

$$H_p = \frac{v\nu}{g} z_p w \qquad H_c = \frac{v\nu}{g} \frac{z_c W_D}{A} \tag{10}$$

where z = specific resistance based on weight of diatomite $[F^{-1}L]$.

Comparison of Equation 10 with LaFrenz' expressions illustrates that K_3 is proportional to the specific resistance of the precoat ($K_3 = z_p\nu/g$) and is temperature dependent. (If LaFrenz had started his derivation with the modified D'Arcy equation (Equation 5), K_3 would have been independent of viscosity.) Similarly, B is proportional to the specific resistance of the filter cake ($B = z_c\nu/g$).

LaFrenz was essentially trying to predict the specific resistance of filter cakes for different values of C_S/C_D after determining K_3 and K_4 for a few runs. As it turns out, the expression for B is incorrect. In the derivation of the expression, LaFrenz expected that K_4 would be a constant typical of the type of solids being removed and the filter aid. He found that K_4 did not remain constant but varied with C_S and C_D, and when plotted against the ratio C_S/C_D gave a straight line. This straight line plot actually invalidated his coefficient $K_3/(1-C_S/C_DK_4)$. The expression for B in Equation 9 can be written as $C_S/C_DK_4 = 1-K_3/B$. For practically all of LaFrenz' data, the factor K_3/B was so small that it was insignificant, and therefore, the factor C_S/C_DK_4 was approximately unity. Accordingly, any plot of K_4 versus C_S/C_D should be expected to be a straight line with slope of unity and approximately zero intercept. This was the case with LaFrenz' data as shown by the straight line plot taken from his thesis (Fig. 3).

The error of LaFrenz' original expression was soon discovered because in 1962 Baumann, Cleasby, and LaFrenz expressed the head losses through the precoat and filter cake as follows (3):

$$H_p = K_3 v w$$

$$H_c = K_4 v W_D / A \qquad (11)$$

where $K_4 = 1/K_c \gamma_p$ $[F^{-1}L^2T]$

K_c = permeability of filter cake $[LT^{-1}]$.

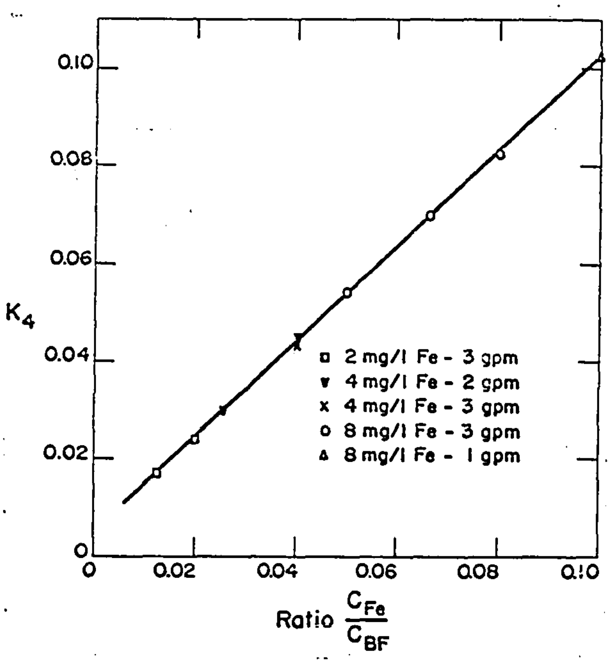


Fig. 3. K_4 versus C_S/C_D from LaFrenz' thesis (25)

The expression for H_p is the same as it was in LaFrenz' thesis, but K_4 has been redefined. Comparison with the filtration rate equation in the form of Equation 10 illustrates that K_4 is now proportional to the specific resistance of the filter cake based on weight of diatomite in the filter cake ($K_4 = z_c \nu / g$). But still, the effect of viscosity is not included in the above expressions, and therefore, K_3 and K_4 are temperature dependent. For this reason, experimental K_3 and K_4 values were either referred to a standard temperature of 20°C by multiplying by the ratio of the viscosity at the test temperature to viscosity at 20°C (15), or experiments were conducted at a standard constant temperature.

In 1964, Baumann and Oulman published a modified form of the diatomite filtration equation (6) that accounted for viscosity. In dimensionally homogeneous form the expressions for H_p and H_c in the modified equation can be written:

$$H_p = v\nu\alpha_1 w/g^2 \qquad H_c = v\nu\alpha_2 W_D/g^2 A \tag{12}$$

where α_1 = factor of precoat resistance $[F^{-1}L^2T^{-2}]$

α_2 = factor of filter cake resistance $[F^{-1}L^2T^{-2}]$.

It is clear after comparison with Equation 10 that the modified diatomite filtration equation is equivalent to the filtration rate equation and that $\alpha_1 = z_p g$ and $\alpha_2 = z_c g$.

DIATOMITE FILTRATION EQUATIONS

At the beginning of a filter run, the filter housing is full of clean water from the precoating operation. The mixing of influent (unfiltered water) with the clean water in the housing results in a transition period that lasts until the quality of the water in the housing is the same as that of the influent. This transition period is the effect of initial dilution.

When filtering through cylindrical septa, the gross outer surface area of the filter cake perpendicular to the direction of flow (A) increases as the thickness of the cake increases. This increasing area has a significant effect on the head loss-time relationship for a filter run, especially when using small diameter septa. Since there are several diatomite filtration plants in existence that filter municipal water supplies using small diameter septa, a diatomite filtration equation that accounts for increasing area effects is needed. Several filter manufacturers use cylindrical septa in their filters and at least two manufacturers use septa as small as 1 inch in diameter (14, 29).

In reviewing the literature, the author found no filtration equation that accounted for either initial dilution effect or the effect of increasing area associated with cylindrical septa.

All previous diatomite filtration equations have been developed on the assumption that the surface area of the filter cake (A) remains constant. Throughout the remainder of this thesis, septa that do not produce increasing area effects will be referred to as flat septa.

The effect of increasing area has negligible effect on the head loss through the precoat (H_p) because the precoat is so thin that its area is approximately equal to the area of the septum. Therefore, the expression for H_p in Equation 10 is valid for cylindrical septa and can be written in the following form:

$$H_p = q\nu\xi w/g \tag{13}$$

where $q = Q/A_s$ = flow rate per unit septum area $[LT^{-1}]$

A_s = septum area $[L^2]$

ξ = filter aid resistance index or ξ index = z_p by definition $[LF^{-1}]$.

Equation 13 is valid for any type of septum as long as the precoat is thin since A_s is approximately equal to the outer surface area of the precoat. The filter aid resistance index is equivalent to the specific resistance of the precoat based on weight of diatomite and can be determined experimentally from Equation 13.

In Equation 4, v depends on the thickness of the cake for cylindrical filter cakes. Since v is directly proportional to i, the hydraulic gradient across a cylindrical filter cake is not constant throughout the cake and therefore not equal to H_c/L_c. Thus, it must be expressed in differential form ($i_c = dH_c/dL_c$). Accordingly, Equation 4 for the filter cake can be written:

$$dH_c = \frac{v\nu}{g} a_c dL_c \tag{14}$$

Consider a cylindrical septum with radius R_s. The small volume of filter cake formed during the interval of time dt is:

$$dV_c = Q\gamma_w S_f dt/\gamma_c \tag{15}$$

where dV_c = volume of filter cake formed in the time interval dt $[L^3]$

S_f = weight fraction of solids-body feed (both solids and body feed) in the water in the filter housing [dimensionless].

S_f is less than S_i (weight fraction of solids-body feed in the influent) at the beginning of the run because of initial dilution. But S_f can be written in terms of S_i if we assume the filter to be a completely mixed system. In a small increment of time Δt, the weight of solids-body feed that enters the filter and the weight of solids-body feed removed from the water in the filter are respectively $Q\gamma_w S_i \Delta t$ and $Q\gamma_w S_f \Delta t$. The change in weight of solids-body feed in suspension in the filter is therefore $\Delta W = Q\gamma_w(S_i - S_f)\Delta t$. Dividing through by the weight of water in the filter yields:

$$\frac{\Delta W}{V_f \gamma_w} = \frac{Q\gamma_w(S_i-S_f)\Delta t}{V_f\gamma_w} \implies \Delta S_f = \delta(S_i-S_f)\Delta t$$

where $\Delta S_f = \Delta W / V_f \gamma_w$

δ = Q/V_f = theoretical dilution rate $[T^{-1}]$

V_f = volume of filter housing $[L^3]$.

Passing to the limit leads to a differential equation that can be integrated:

$$\frac{dS_f}{S_i-S_f} = \delta dt \implies \ln(S_i-S_f) = -\delta t + c \implies$$

$$S_i - S_f = e^{-\delta t} e^c$$

where c = integration constant. For the initial condition $S_f = 0$ at $t = 0$, $e^c = S_i$, and:

$$S_f = S_i(1-e^{-\delta t}) = (C_S+C_D)\ (10)^{-6}(1-e^{-\delta t}) \tag{16}$$

since $S_i = (C_S+C_D)\ (10)^{-6}$. Substitution for S_f in Equation 15 yields:

$$dV_c = \frac{Q\gamma_w}{\gamma_c}(C_S + C_D)\ (10)^{-6}(1-e^{-\delta t})dt \qquad (17)$$

Assume that the solids removed in the filter cake do not increase the cake thickness appreciably over the thickness that would result if the cake contained only body feed; this is equivalent to the expression:

$$\frac{C_D}{\gamma_p} \approx \frac{C_S+C_D}{\gamma_c} \qquad (18)$$

The symbol ≈ means "approximately equal to". Substitution for $(C_S+C_D)/\gamma_c$ in Equation 17 leads to:

$$dV_c = \frac{Q\gamma_w}{\gamma_p}\ C_D(10)^{-6}(1-e^{-\delta t})dt \qquad (19)$$

Since $dL_c = dV_c/A$, substitution for dL_c in Equation 14 yields the differential equation for diatomite filtration:

$$dH_c = \frac{v\nu}{g}\ a_c\left[\frac{Q\gamma_w}{A\gamma_p}\ C_D(10)^{-6}(1-e^{-\delta t})dt\right]$$

$$dH_c = \frac{v^2\nu}{g}\left[\frac{a_c\gamma_w}{\gamma_p}\ (10)^{-6}\right]\ C_D(1-e^{-\delta t})dt$$

$$dH_c = \frac{v^2\nu}{g}\ \beta\ C_D(1-e^{-\delta t})dt \qquad (20)$$

where $\beta = a_c\gamma_w(10)^{-6}/\gamma_p$ by definition and will be denoted as the cake resistance index or β index $[L^{-2}]$. The cake resistance index remains constant during a filter run and can be determined experimentally as will be demonstrated later. β is essentially equal to a constant $(\gamma_w(10)^{-6})$ times the specific resistance of the filter cake based on weight of diatomite (z_c) since $z_c = a_c/\gamma_p$ if Equation 18 is valid.

The surface area of a cylindrical septum is $A_S = 2\pi R_S L_S$, and the gross outer filter area of a cylindrical filter cake of radius R is $A = 2\pi RL_s$. Thus $A = A_s(R/R_s)$ and $v = Q/A = Q/A_s(R/R_s) = qR_s/R$. Substitution for v in Equation 20 gives:

$$dH_c = \left[\frac{q^2 R_s^2}{R^2} \right] \frac{\nu}{g} \beta C_D (1-e^{-\delta t})dt \implies$$

$$dH_c = \frac{R_s^2 \sigma (1-e^{-\delta t})dt}{R^2} \qquad (21)$$

where $\sigma = q^2 \nu \beta C_D/g$ = constant $[LT^{-1}]$. The parameter σ is defined as $q^2\nu\beta C_D/g$ for convenience.

The total volume enclosed within the outer surface area of a filter cake (V_T) of radius R is:

$$V_T = V_s + V_p + V_c = \pi R^2 L_s$$

where V_s = volume of septum $[L^3]$

L_s = length of septum $[L]$.

Differentiating:

$$dV_T = dV_c = 2\pi L_s R dR \qquad (22)$$

since $dV_s = dV_p = 0$. Equating the right hand sides of Equations 19 and 22 leads to:

$$2\pi L_s R dR = \frac{Q\gamma_w C_D (10)^{-6}}{\gamma_p} (1-e^{-\delta t})dt \implies$$

$$2RdR = \left[\frac{2R_s}{2R_s} \right] \frac{Q\gamma_w C_D (10)^{-6}}{\pi L_s \gamma_p} (1-e^{-\delta t})dt$$

Remember that $q = Q/A_s = Q/2\pi R_s L_s$, and therefore:

$$2RdR = R_s \left[\frac{2q\gamma_w C_D (10)^{-6}}{\gamma_p} \right] (1-e^{-\delta t})dt$$

$$= R_s\phi\,(1-e^{-\delta t})dt \qquad (23)$$

where ϕ is defined as $2q\gamma_w C_D(10)^{-6}/\gamma_p$ for convenience; ϕ remains constant during a filter run and has the dimensions $[LT^{-1}]$. This differential equation can be integrated as follows:

$$\int_{R_o}^{R} 2RdR = R_s\phi \int_{o}^{t} (1-e^{-\delta t})dt \implies$$

$$R^2\Big]_{R_o}^{R} = R_s\phi\left[t + \frac{e^{-\delta t}}{\delta}\right]_o^t = R_s\phi\left[t + \frac{e^{-\delta t}}{\delta} - \frac{1}{\delta}\right] \implies$$

$$R^2 = R_o^{\,2} + R_s\phi\left[t - \frac{1-e^{-\delta t}}{\delta}\right] = R_o^{\,2} + R_s\phi x \qquad (24)$$

where $x = t - (1-e^{-\delta t})/\delta \quad [T]$

$R_o = R_s + L_p = R_s + w/\gamma_p = R$ at $t = 0$.

Notice that x is equal to t decreased by the factor $(1-e^{-\delta t})/\delta$. Thus, the action of initial dilution is, in effect, a time delay equal to $(1-e^{-\delta t})/\delta$. This time delay factor decreases with increasing δ, and for very large δ, x is approximately equal to t. Also, dx is approximately equal to dt for large t since:

$$dx = dt - \frac{\delta e^{-\delta t}dt}{\delta} = (1-e^{-\delta t})dt\ .$$

Substitution of the expression for R^2 (Equation 24) in Equation 21 and integration leads to an expression for H_c, as follows:

$$dH_c = \frac{R_s^{\,2}\sigma(1-e^{-\delta t})dt}{R_o^{\,2}+R_s\phi x} = \frac{R_s^{\,2}\sigma dx}{R_o^{\,2}+R_s\phi x} \implies$$

$$\int_0^{H_c} dH_c = \frac{R_s{}^2\sigma}{R_s\phi} \int_0^x \frac{R_s\phi\, dx}{R_o{}^2+R_s\phi x} = \frac{R_s\sigma}{\phi}\Big[\ln(R_o{}^2+R_s\phi x)\Big]_0^x \Longrightarrow$$

$$H_c = \frac{R_s\sigma}{\phi}\Big[\ln(R_o{}^2+R_s\phi x) - \ln R_o{}^2\Big] = \frac{R_s\sigma}{\phi}\ln\Big(1+\frac{R_s\phi x}{R_o{}^2}\Big) \tag{25}$$

In deriving Equation 25, the following hypotheses were assumed to be true during a filter run:

1. Q remains constant (constant rate filtration).

2. The body feed rate is sufficient to form an essentially incompressible filter cake.

3. The filtration rate equation in differential form (Equation 14) is valid for cylindrical filter cakes.

4. γ_p and γ_c remain constant.

5. C_S and C_D remain constant, and no solids pass through the cake.

6. There are no concentration gradients in the filter housing (completely mixed system).

7. Equation 18 is valid - - i.e., the solids retained in the filter cake do not increase the cake thickness appreciably.

If these hypotheses are true, then the flow resistive indexes (ξ and β) remain constant for a particular run and can be determined experimentally.

Equation 25 is a significant improvement over previously published diatomite filtration equations:

1. It includes the effect of initial dilution at the beginning

of a filter run.

2. It includes the effect of increasing area for cylindrical septa.

3. It is derived from an equation that includes the effect of viscosity.

4. It is dimensionally homogeneous and therefore can be used with any consistent set of units without modification (ft-lb-hr are convenient English units).

For very large diameter septa (a flat septum would have an infinite diameter) Equation 25 can be simplified since ln(1 + x) ≈ x for small x, and $R_s \approx R_o$ for large R_s:

$$H_c = \frac{R_s\sigma}{\phi}\left[\frac{R_s\phi x}{R_o^2}\right] \Longrightarrow$$

$$H_c = \sigma x \tag{26}$$

The use of t in place of x in Equation 26 conforms to previous equations that do not include dilution or increasing area effects.

The total thickness of precoat and filter cake ($L = L_p + L_c$) at time t for cylindrical septa can be determined from Equation 24, and is equal to:

$$L = R - R_s = \sqrt{R_o^2 + R_s\phi x} - R_s \tag{27}$$

For flat septa, $dV_c = A_s dL_c$. Equating this expression for dV_c to the right hand side of Equation 19 leads to:

$$A_s dL_c = \frac{Q\gamma_w}{\gamma_p} C_D (10)^{-6}(1-e^{-\delta t})dt = A_s \frac{\phi}{2}\, dx$$

since $A_s\phi = 2Q\gamma_w C_D(10)^{-6}/\gamma_p$. Integration leads to:

$$\int_o^{L_c} dL_c = \frac{\phi}{2}\int_o^x dx \implies L_c = \frac{\phi x}{2}$$

$$L = L_p + \frac{\phi x}{2} \tag{28}$$

The basic equation for the total filtration head loss is:

$$H = (H_e + H_p) + H_c = H_o + H_c \tag{29}$$

which in words states that the total head loss is equal to the sum of the head losses through the equipment (piping, septum, etc.), the precoat, and the filter cake. H_o is the head loss at $t = 0$. Since $H_c = 0$ at $t = 0$, $H_o = H_e + H_p$. The expressions developed in this thesis for head loss through the precoat (H_p), head loss through the filter cake (H_c), and the combined thickness of the precoat and filter cake (L) for both flat and cylindrical septa are:

(for any septum)

$$H_p = q\nu\xi w/g \tag{13}$$

(cylindrical septum)

$$H_c = \frac{R_s\sigma}{\phi}\ln\left(1 + \frac{R_s\phi x}{R_o^2}\right) \tag{25}$$

$$L = \sqrt{R_o^2 + R_s\phi x} - R_s \tag{27}$$

(flat septum)

$$H_c = \sigma x \tag{26}$$

$$L = L_p + \frac{\phi x}{2} \tag{28}$$

where $\sigma = q^2\nu\beta C_D/g \quad [LT^{-1}]$

$\phi = 2q\gamma_w C_D(10)^{-6}/\gamma_p \quad [LT^{-1}]$

$x = t - (1-e^{-\delta t})/\delta \quad [T]$

$\delta = Q/V_f \quad [T^{-1}]$

$$R_o = R_s + L_p \quad [L]$$

$$L_p = w/\gamma_p \quad [L] \, .$$

The above expressions are repeated here for the reader's convenience. The expressions for the combined thickness of the precoat and filter cake are included because, in some cases, this thickness limits the length of filter run before the terminal head loss is reached. This possibility was not included in LaFrenz' procedure for determining the optimum combination of flow rate, body feed concentration, and terminal head loss (25).

Determination of β Index

Fig. 4 illustrates the theoretical head loss-time relationships for the hypothetical conditions indicated in the figure for a flat septum and two cylindrical septa, one of 3.50 inch and one of 1.00 inch diameter. The curves in Fig. 4 were determined by computing the head loss ($H_o + H_c$) for one hour increments from 0 to 50 hours. H_c was computed from Equation 26 for curve A and from Equation 25 for curves B and C. The resulting head loss-time relationships for the first 25 hours are shown in Fig. 4.

Previous diatomite filtration equations that account for neither initial dilution nor increasing area describe a head loss-time curve having constant slope for all values of time (equivalent to substituting t for x in Equation 26). Fig. 4 illustrates that the old equations can be used to determine cake resistance only when flat septa are used since only curve A becomes linear with increasing time. The old equations were used to determine K_4 and α_2 values by plotting head loss

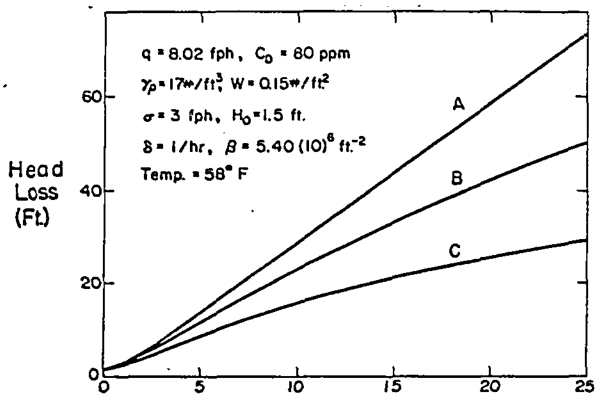


Fig. 4. Theoretical head loss versus time curves for conditions indicated

Curve A - flat septum
Curve B - 3.50 inch diameter
Curve C - 1.00 inch diameter

versus time and measuring the slope of the straight line of best fit, neglecting points in the transition zone (initial dilution effect). Using the old equations to determine cake resistance when using cylindrical septa is essentially the same as saying that curves A, B, and C in Fig. 4 are all the same curve. This is obviously not the case. It should be recognized, therefore, that there would be poor correlation of results between flat and cylindrical septa when using the old equations. LaFrenz found this to be true (25).

In light of the foregoing, we see that the effect of increasing area cannot be ignored. Further, even though the expression for H_c for cylindrical septa (Equation 25) is more complicated than for flat septa (Equation 26), cylindrical septa (especially those of small diameter) offer definite advantages over flat septa with respect to head loss increase with time.

The β index can be determined from a plot of head loss versus time when using flat septa. The resulting curve should become linear with slope σ as illustrated by curve A of Fig. 4. β can then be computed from the definition of σ. The value of δ is not needed to determine β when using flat septa. The β index can also be determined from a plot of H

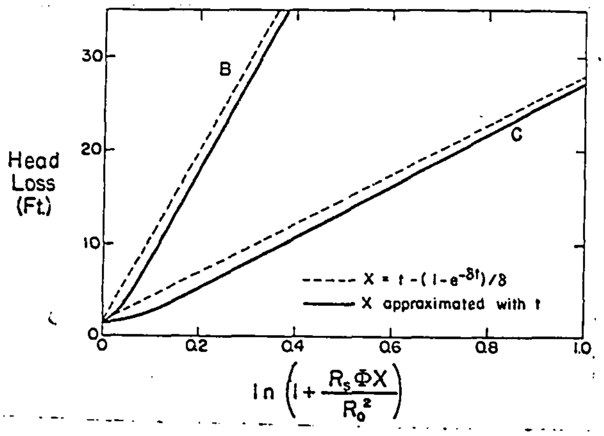


Fig. 5. Theoretical plots of head loss versus natural log portion of Equation 25 for curves B and C of Fig. 4 (for solid curves, t was used in place of x)

versus x. The resulting curve should be linear with slope σ for all values of x in accordance with Equation 26. Even if the wrong value of δ is used, the plot of H versus x should become linear with slope σ.

When using cylindrical septa, the determination of β index is more difficult. Its value cannot be determined from a plot of H versus t because the curve will not become linear. However, a plot of H versus the ln term of Equation 25 should be linear with slope $R_s\sigma/\phi$ as illustrated by the dashed curves in Fig. 5. β can then be computed using the definitions of σ and ϕ. An approximate value of β can be determined by using t in place of x in the above plot as illustrated by the solid curves in Fig. 5 (i.e., plot of H versus $\ln(1 + R_s\phi t/R_o^2)$). This approximation is more accurate for large values of δ. The resulting curve should become linear with slope of approximately $R_s\sigma/\phi$.

When using cylindrical septa, the value of ϕ and therefore the value of γ_p must be known to determine β accurately. This value was not needed for the old equations, and consequently, few efforts were made in the past to measure it. However, when γ_p is not known, an approximate value of β can still be determined by trying different values of γ_p and choosing the γ_p (and its corresponding β index) that best fits the data.

This procedure is somewhat indirect and involves more work than would be necessary if γ_p were known; but at least it is a procedure that can be used when a value of γ_p is not available.

Further difficulty is encountered in determining β index for cylindrical filter cakes because of initial dilution. The theoretical dilution rate (Q/V_f) is the dilution rate for a filter having no concentration gradients within its housing - - a condition seldom realized. The author has found that the actual dilution rate often varies, probably because of unsteady conditions during the first few minutes of a filter run such as changes in flow rate, body feed concentration, etc. When the dilution rate is large, good results can be obtained by approximating x with t and measuring the slope of the H versus $\ln(1 + R_s\phi x/R_o^2)$ curve (solid curves in Fig. 5). But when the dilution rate is small, this approximation may not be good enough. In these cases, a value of δ should be estimated from the data. This can be done by a trial and error procedure such as the one described for determining β index when γ_p is not known.

A method of estimating δ from a plot of H versus t used by the author has been found to be very useful. In this method, the assumption is made that the inflection point of the H versus t curve occurs when δt is approximately 3. When $\delta t = 3$, the factor $(1 - e^{-\delta t}) = 0.950$. Assuming complete mixing, the concentrations of body feed and suspended solids in the filter housing should be 95% of the concentrations in the influent (Equation 16), and initial mixing is essentially complete. (Notice also that initial mixing is complete at the inflection point because the H versus t curve is concave upward during initial dilution and concave downward after the transition.) An approximate δ can then be computed from an estimate of the time of inflection (t_i) as follows:

$$\delta \approx 3/t_i \tag{30}$$

The value of t_i is estimated from the plot of H versus t.

The difficulties in determining β index for cylindrical filter cakes are caused by the fact that the rate of head loss increase (dH/dt) is dependent on the thickness of the cake (Equation 21). These difficulties are not encountered with flat filter cakes because dH/dt is independent of cake thickness when using flat septa.

For accurate evaluation of the β index, filter runs should extend well past the transition period caused by initial dilution. Also, when using cylindrical septa, special effort should be made to keep C_S, C_D, and Q constant during the run, including the transition period. It is suggested that Equation 30 be used to estimate δ when determining cake resistance for cylindrical cakes. Then the data points beyond the transition period can be used to determine β index by plotting H versus $\ln(1 + R_s\phi x/R_o^2)$.

Even though γ_p must be known to determine β accurately for cylindrical cakes, a good approximation of the head loss-time curve can be obtained when using an estimated value of γ_p. This is demonstrated in Table 1. Values of H for one hour increments from 0 to 50 were computed for the hypothetical data shown in Fig. 4 for a 1.00 inch and for a 3.50 inch diameter septum (curves B and C). Values of H were found by adding a precoat loss of 1.5 ft to the values of H_c computed from Equation 25. The corresponding values of H and t were then treated as data, and values of β corresponding to values of γ_p from 14 to 20 #/ft^3 were determined by regression analysis (regression of H on $\ln(1 + R_s\phi x/R_o^2)$)

Table 1. Least squares approximation of curves B and C of Fig. 4 using various values of γ_p (R is the correlation coefficient)

γ_p, #/ft^3	β, $(10)^6$ft^{-2}	R, %
	Curve B, 3.50 inch septum	
14	5.89	99.991
15	5.70	99.996
16	5.54	99.999
17	5.40	100.000
18	5.27	99.999
19	5.16	99.997
20	5.00	99.994
	Curve C, 1.00 inch septum	
14	6.21	99.993
15	5.90	99.997
16	5.63	99.999
17	5.40	100.000
18	5.19	99.999
19	5.00	99.997
20	4.83	99.994

using a digital computer. The results are shown in Table 1. The values of H were computed using $\gamma_p = 17$ #/ft^3, so naturally, the correct β index of 5.40 $(10)^6$ft^{-2} with a correlation coefficient of 100.000% was determined when using this value of γ_p. The lowest correlation coefficient in Table 1 is 99.991% for the 3.50 inch diameter septum (curve B) using $\gamma_p = 14$ #/ft^3. The range of the two approximate regression curves for curve C using γ_p of 14 and 20 #/ft^3 are shown in Fig. 6.

Table 1 and Fig. 6 illustrate that the accuracy of prediction of head loss-time relationships, for cakes formed on cylindrical septa of the same diameter used for determining β, is relatively insensitive to errors in γ_p. The accuracy of prediction for cakes formed on septa of different size or shape is much more sensitive, however, because an error in γ_p results in corresponding errors in evaluation of β indexes. Therefore, the diameter of the septum used and the value of γ_p used to determine β indexes for cylindrical cakes should be stated.

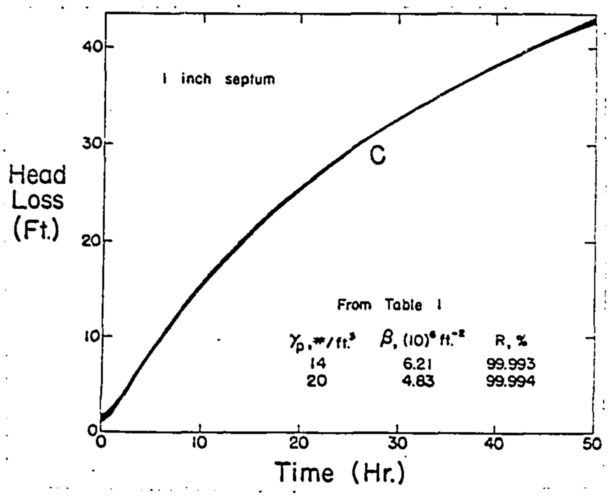


Fig. 6. Range of two least squares approximations of Curve C in Fig. 4 using γ_p = 14 and 20 #/cu ft

DESIGN APPROACH

A computer program has been developed as a part of this study for use in determining the optimum operating conditions for a specific type of plant filtering a particular water using a specified grade of filter aid. This program has been named POPO (Program for Optimization of Plant Operation). POPO determines the optimum combination of filtration rate, body feed concentration, and terminal head loss by simply computing costs of filtration for many different combinations and choosing the ten most economical. Different types of equipment and different grades of filter aid can be compared by making appropriate changes in the input data, repeating the optimization process for each, and comparing the results. A reference manual for POPO is included in this thesis (Appendix D).

A combination of flow rate (q), body feed concentration (C_D), and terminal head loss (H) will be abbreviated as an ordered set of three numbers enclosed in double parentheses ((q, C_D, H)) - - e.g., the combination q = 1 gsfm, C_D = 30 ppm, and H = 130 ft of water would be ((1, 30, 130)).

Filtration costs are made up of the first cost of the plant and the operating costs. Plant first cost includes the filters, body feeding equipment, pumps and piping, filter building, and all other necessary equipment. Operating costs include costs of power, labor, maintenance, diatomite, and backwashing. There are other incidental costs included in the total cost of filtration, such as administration, insurance, etc., but these are minor and do not ordinarily vary with the choice of operating conditions.

The cost of filtration depends on the filterability of the water. Filterability in this thesis is defined as the capability or relative ease of being filtered, based on resistance of filter cakes formed when filtering the water. A water that typically results in filter cakes of high resistance or requires relatively large amounts of body feed to form incompressible cakes has a low filterability. On the other hand, a water that typically results in filter cakes of low resistance or requires relatively small amounts of body feed to form incompressible cakes has a high filterability. Effluent quality or the amount of solids passing through the cake is not a factor in this definition. Throughout this thesis, it is assumed that the effluent quality is acceptable for each combination ((q, C_D, H)) being considered.

The β index depends on the concentration of solids (C_S) and the concentration of body feed (C_D) in the water being filtered and also on the particular filter aid used. Thus, a method of describing the variation of β index with C_S and C_D for a particular grade of filter aid would be a method of representing the filterability.

The best available means of describing the variation of β index is empirical prediction equations based upon data collected for the water using a pilot plant. Prediction equations have been determined by least squares techniques for the data analyzed in this thesis, and will be discussed in the next chapter.

The use of POPO in the design of a diatomite filtration plant involves:

1. The accumulation of cost estimates needed for computation of

filtration costs.

2. The determination of the filterability of the water to be filtered by running pilot plant tests at the source. Sufficient pilot plant filter runs should be made to determine β index prediction equations for each type of filter aid to be considered.

3. The use of POPO to determine the optimum operating conditions ((q, C_D, H)) for each type of plant and each type of filter aid being considered. The use of POPO is explained in Appendix D.

POPO is designed to determine the optimum combination ((q, C_D, H)) for a particular type of plant filtering a water of known filterability using a particular filter aid. The filterability is represented by the β index prediction equation for the particular filter aid. For each combination ((q, C_D, H)), POPO follows the procedure indicated below:

1. Computes the filter area needed by dividing the total plant flow by the unit flow rate ($A = Q/q$).

2. Predicts β index by using an appropriate β index prediction equation.

3. Computes the length of filter run and the terminal filter cake thickness, including precoat thickness, from the diatomite filtration equations developed in Chapter 3. The length of filter run is the time during the filter cycle that the filter is in the filtering operation, i.e., does not include time of precoating and time of backwashing.

4. Computes the first cost, operating costs, and total cost of filtration.

5. Compares the resulting total filtration cost with total costs previously computed for other combinations. If it is one of the ten

cheapest combinations for which costs have been computed, the results are stored for subsequent output.

Then, after costs have been computed and compared for all the specified combinations, the results for the ten cheapest combinations are printed out.

PREDICTION EQUATIONS FOR β INDEX

Filtration Data

Many filter runs made by different investigators were analyzed in this study. These filter runs were made for the purpose of determining filter cake resistance. Each of these filter runs was assigned a symbolic code number (ID) for reference. Also, each of the six different types of suspensions was assigned a suspended solids code number from 1 to 6. These code numbers and the types of suspensions are explained in the summary of filter runs (Appendix B).

The data include filter runs made using flat septa and 3.5 inch diameter cylindrical septa.

Filters

The different types of filters have been described by the various investigators, and only brief descriptions will be presented here.

The first digit of the filter run identification code number identifies the particular group of filter runs. Filter runs made by Regunathan in the preparation of his thesis (35) begin with the digit 1. He filtered Iowa State University tap water with either one of two types of clay added. The types of clay used were Kentucky ball clay consisting mostly of Kaolinite and Wyoming bentonite consisting mostly of Montmorillonite. These waters will be referred to by the type of clay they contain in subsequent discussion. These filter runs were made using a pressure filter containing 3.5 inch diameter septa. This pressure filter has been referred to as the pilot plant and has been used in several investigations at Iowa State University (3, 19, 20, 25, 27, 35). For all of Regunathan's filter runs listed in Appendix B, turbidity units were used in place of C_S.

Filter runs with ID numbers beginning with 4 and 5 were also made using the pilot plant. University tap water containing hydrous ferric oxide floc was filtered in these filter runs. This water was prepared by adding iron salts, followed by aeration and mixing of the water. This water will be referred to as iron bearing water. Filter runs with ID numbers beginning with 4, made primarily by Iowa State University students who were hired as hourly employees, are denoted as extra runs. Filter runs with ID numbers beginning with 5 were made by Hall and Hawley in the preparation of their theses (19, 20).

Filter runs with ID numbers beginning with 7 were conducted using a U. S. Army mobile purification unit filtering effluent from the lime-soda ash softening process at the Ames, Iowa, municipal water treatment plant. This water contained small amounts of suspended $CaCO_3$ not previously removed. This water will be referred to as softened water. This mobile purification unit is referred to as Miss Purity. It is on loan from the U. S. Army Research and Development Laboratories, Fort Belvoir, Virginia. The filter in Miss Purity contains 3.5 inch diameter septa and is very similar to the pilot plant. Miss Purity is also equipped with a pretreatment unit - - a solids contact type upflow clarifier. Turbidity units were used in place of C_S in all filter runs made with Miss Purity.

Filter runs with ID numbers beginning with 2 and 3 were respectively made by Foyster and LaFrenz using a small variable head permeameter (VHP) with a 6 inch diameter flat septum. Iron bearing water was filtered in these runs. The VHP has been described in detail by LaFrenz (25).

Filter runs with ID numbers beginning with 6 were made at the water treatment plant at Lompoc, California. These filter runs represent the only full scale plant data included in Appendix B. They were actual filter runs made in the production of potable water for the City of Lompoc. The diatomite filters at the Lompoc plant are vacuum filters manufactured by BIF, Division of the New York Air Brake Company, Providence, Rhode Island. The septa used are flat. Softened water is filtered at Lompoc. The Lompoc plant is a conventional lime-soda ash softening plant except for the use of diatomite filters rather than rapid sand filters. It has been described by Lawrence (28), Chief Sanitary Engineer for Koebig & Koebig, Inc., the engineering firm that designed the plant. Turbidity units were used in place of C_S in the Lompoc filter runs.

β Indexes

Appendix B presents a summary of β indexes for approximately 200 filter runs. Also included are unit flow rate (q, Q in the Appendix), solids concentration (C_S, CS in the Appendix), body feed concentration (C_D, CD in the Appendix), ξ index (ξ, XI in the Appendix), β index (β, BETA in the Appendix), correlation coefficient of the least squares head loss-time curve in percent (R), and the type of suspended solids (SS). The letter R was defined as the outer radius of cylindrical filter cakes in the development of Equation 25 in Chapter 3. The correlation coefficient is also denoted by R in this thesis. However, no confusion should result from this dual use of R because the proper meaning of R in each case is evident from its context. Also, R is only used to denote the filter cake radius in Chapter 3.

There is no correlation coefficient included in the Appendix for the flat filter cakes (ID numbers beginning with 2, 3, or 6). For these runs, β was computed from the K_4 value determined by the original investigator. The equation $\beta = (10)^{-6} g \gamma_w K_4/\nu$ was used to convert K_4 to β. This equation is valid for flat filter cakes, but not for cylindrical ones.

For the cylindrical filter cakes (ID numbers beginning with 1, 4, 5, or 7) β was determined by regression of H on $\ln(1 + R_s \phi x/R_o^2)$ as explained in Chapter 3. Values of δ were estimated from an estimate of the inflection point of the H versus t curve (Equation 30) as explained in Chapter 3. Cylindrical septa of 3.5 inch diameter were used in all of these filter runs. In determining β index, a value of 15 #/cf was used for γ_p. The IBM 7074-1401 computer system at Iowa State University was used for the regression analyses. The correlation coefficient for the β index of each of the cylindrical cakes is included in Appendix B, and they are generally well above 99%.

Fig. 7 illustrates the regression head loss-time curves for six of the cylindrical filter cakes (Runs 1203, 4007, 5055, 5060, 5155, 7020). Each curve in Fig. 7 is the curve of best fit determined by regression of H on $\ln(1 + R_s \phi x/R_o^2)$.

The old diatomite filtration equations assumed that the head loss-time curve (H-t curve) became linear after initial dilution. This is true for flat septa, but not for cylindrical septa. However, when using 3.5 inch diameter septa, the H-t curve may appear linear for a relatively long time, especially for filter runs with a low body feed concentration. When C_D is low, the thickness of the cake increases slowly, and the effect

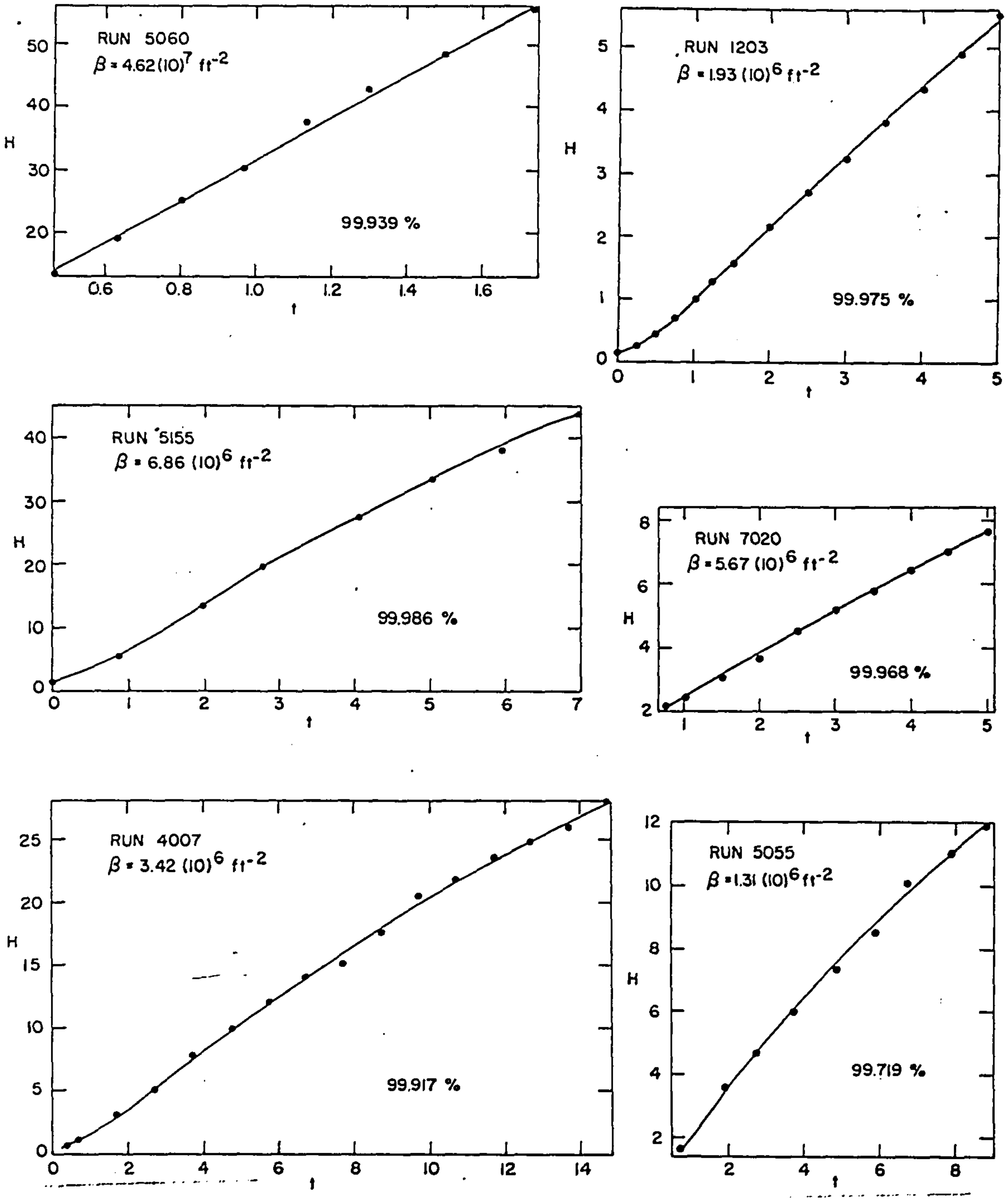


Fig. 7. Regression head loss-time curves for six cylindrical filter cakes (head loss (H) is in ft and time (t) is in hr; corresponding run numbers, β indexes, and correlation coefficients in percent are indicated)

of increasing area is less noticeable.

The increasing area effect is more noticeable for 1.0 inch septa (Curve C, Fig. 4), when C_D is high, and in long filter runs after an appreciable cake thickness has formed.

The H-t curves for Runs 7020, 1203, and especially 5060 (Fig. 7) are practically linear after the transition period. Many of the other filter runs analyzed also appeared linear either because the body feed concentration was low or the filter run was relatively short. It is not difficult to understand, then, that the old equations were thought to be valid for cylindrical septa, at least for 3.5 diameter cylindrical septa.

However, some of the longer runs and runs with high C_D illustrate the effect of increasing area and the inadequacy of the old equations for cylindrical septa (Runs 5055, 4007, and 5155 in Fig. 7).

The filter runs summarized in Appendix B verify the filtration head loss equations for flat (Equation 26) and cylindrical septa (Equation 25). They demonstrate that β remains constant during a filter run as long as q, C_S, and C_D remain constant.

It is worthy of note that practically all of the cake resistances for cylindrical cakes determined using the old equations were lower than corresponding resistances determined using Equation 25. This was expected because curves B and C of Fig. 4 have smaller slopes than curve A immediately following the transition period. Thus, it would be expected that a β index determined for a cylindrical cake using the equation for flat septa (Equation 26) would be too low.

Prediction Equations

The prediction equations for β index used in this thesis are of the general form:

$$\beta \;=\; 10^{b_1} (C_S/C_D)^{b_2} \, C_D^{\;b_3} \, \xi^{b_4} \tag{31}$$

where b_1, b_2, b_3, and b_4 are exponents determined empirically. The general prediction equation can be made linear with a log transformation leading to:

$$\log \beta = b_1 + b_2 \log (C_S/C_D) + b_3 \log C_D + b_4 \log \xi \tag{32}$$

The coefficients b_1, b_2, b_3, and b_4 can be determined by linear regression taking log β as the dependent variable and log (C_S/C_D), log C_D, and log ξ as the dependent variables.

In some cases, b_3 or b_4 or both may be zero. For example, if the prediction equation were for a group of filter runs for which the same filter aid was used, then ξ would be the same for all the filter runs, and log ξ would not be a variable. In such a case, log ξ should be dropped ($b_4 = 0$).

Also, if C_S is constant or nearly constant for a group of filter runs then C_S/C_D and C_D would not be independent variables. In such a case, log C_D should be dropped ($b_3 = 0$). If C_S is nearly constant and the same filter aid was used for a group of filter runs, then log C_D and log ξ should both be dropped and both b_3 and b_4 would be zero.

When b_3 and b_4 are both zero in Equation 31 ($b_3 = b_4 = 0$), the prediction is similar to the previously used method of predicting cake resistance by means of a log-log plot of K_4 versus C_S/C_D (3, 4, 5, 19, 20, 35). In this case the prediction equation is of the form:

$$\beta = 10^{b_1} (C_S/C_D)^{b_2} C_D^{0} \xi^{0} = 10^{b_1} (C_S/C_D)^{b_2} \qquad (33)$$

A summary of prediction equations for the filter runs summarized in Appendix B is presented in Appendix C. Several of the prediction equations are of the form shown in Equation 33 ($b_3 = b_4 = 0$).

The prediction equations for filter runs filtering iron bearing water at the same concentration using the same filter aid gave some of the highest R values (prediction equations for Runs 2010-2013; 302020-302800; 305020-305160; 309020-309160; 310030-310160; 312020-312100; 5038-5043; 5053-5056; 5057-5063; 5091-5096). These prediction equations have the form of Equation 33. In practice, this type of prediction equation would probably find more application for iron removal from ground water supplies because the iron concentration of the raw water would probably remain constant over long periods of time.

Plots of computed log β versus observed log β for some of the prediction equations in Appendix C are shown in Fig. 8. These plots are shown mainly to illustrate the relative scatter of points associated with the various R values. Computed versus observed plots are commonly used to illustrate scatter for least squares fitted equations, especially those containing more than one independent variable.

One of the lowest values of R is the one for the prediction equation for Runs 6209-6219 shown in Fig. 8. R for this equation is 86.2%. As demonstrated by Fig. 8, R should be above 90% and preferably above 95% for good β prediction. However, as demonstrated by Appendix C, most of the R's are above 95%.

It is reasonable to assume that β is some function of C_S/C_D, and

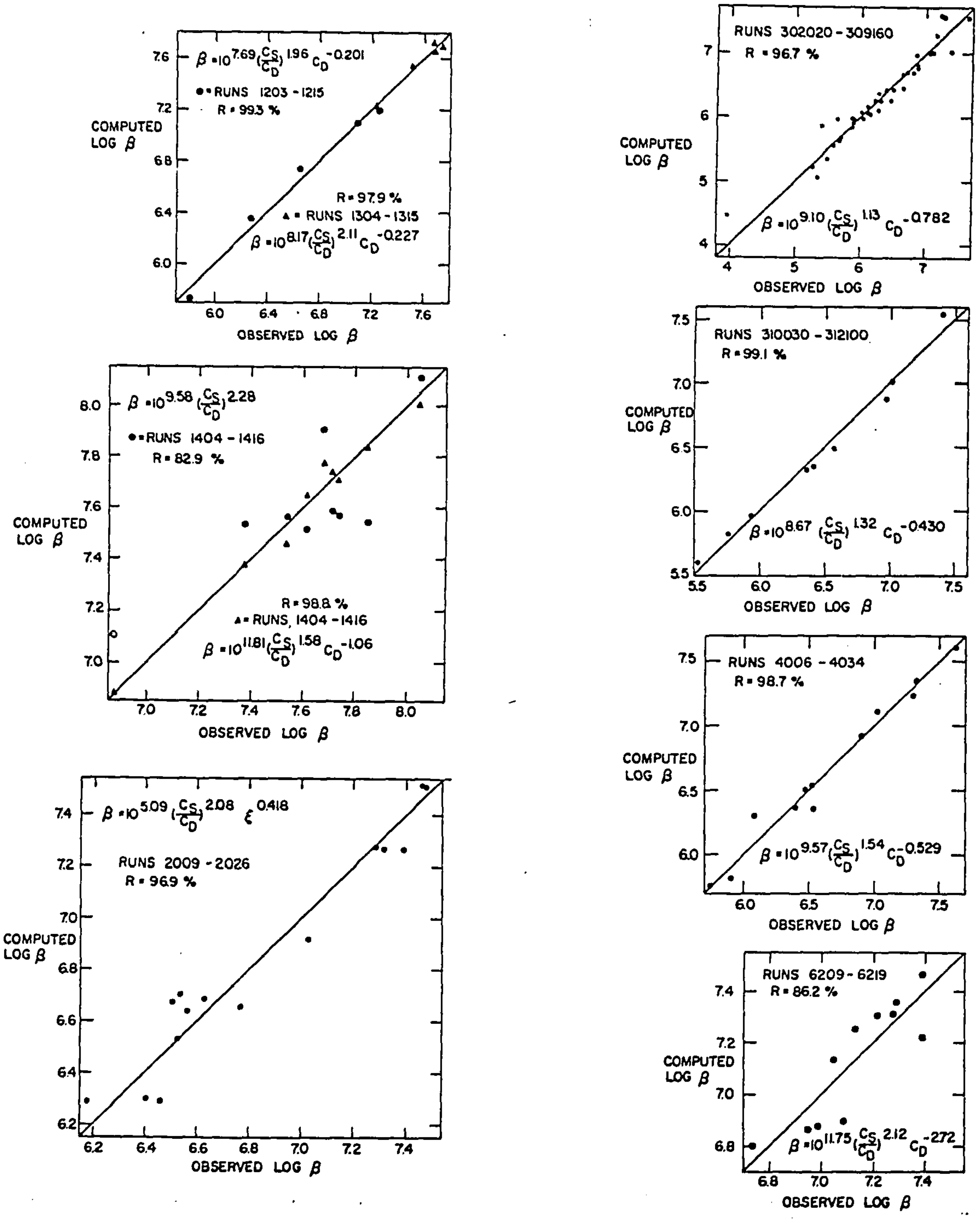


Fig. 8. Plots of computed log β versus observed log β for some of the prediction equations in Appendix C (inclusive filter run numbers, prediction equation, and correlation coefficient in percent are indicated for each plot)

therefore, that the use of Equation 33 would result in fairly high R values. If this ratio were constant for a group of filter runs, it would seem that the resulting filter cakes would have the same characteristics, and thus, the same β index. For example, if a filter run were repeated under the same conditions except that C_S and C_D were doubled, the ratio C_S/C_D would be the same. It would be reasonable to assume that the resulting filter cake would be the same as the first, but formed twice as fast.

However, the use of a prediction equation like Equation 33 did not result in relatively high R's for some of the waters filtered. Relatively high R's were obtained for water containing Kaolinite (Runs 1203-1215; 1304-1315) and iron bearing water (Runs 302020-309160; 310030-312100; 4006-4034) when C_S was not the same for each group of filter runs, but relatively low R's resulted for water containing Montmorillonite (Runs 1404-1416) and softened water (Runs 6111-6121; 6209-6219; 6322-6332; 7003-7023). Regunathan (35) also found that relatively low correlation was obtained with water containing Montmorillonite when trying to predict the variation of cake resistance (as represented by K_4 determined using Equation 11) with C_S/C_D by use of a log-log plot of K_4 versus C_S/C_D.

The following form of the prediction equation ($b_4 = 0$ in Equation 31) was used in an attempt to improve β prediction, especially for water containing Montmorillonite:

$$\beta = 10^{b_1} (C_S/C_D)^{b_2} C_D^{b_3} \qquad (34)$$

As illustrated by Appendix C, the use of Equation 34 made substantial improvements in β prediction for softened water and for water containing Montmorillonite. R increased from 82.9% for Equation 33 to 98.8% for Equation 34 for Runs 1404-1416. This is also illustrated by the plot of computed log β versus observed log β for the two prediction equations for these runs (Fig. 8).

The use of Equation 34 also improved β prediction, but not as significantly, for iron bearing water (Runs 302020-309160; 310030-312100; 4006-4034) and water containing Kaolinite (Runs 1203-1215; 1304-1315).

An explanation of the different degrees of β prediction improvement for different waters, resulting from the use of Equation 34 rather than Equation 33, is not readily apparent. The author suspects that the use of β index, rather than the specific cake resistance based on weight of diatomite (z_c), is a major contributing factor. However, a true value of z_c is very difficult to determine, especially when using cylindrical septa.

If accurate values of C_S, C_D, and γ_p were known, and all the hypotheses assumed in the derivation of Equation 25 were true for a particular run used for the determination of β index, an accurate value of z_c could be determined from the β index. This is rarely the case, and therefore, β is not ordinarily a true measure of cake resistance. It is therefore referred to as an index of cake resistance.

However, it is a very good index of cake resistance as demonstrated be the very high R values in Appendix B. The fact that a value of β index can be determined that accurately describes the head loss-time curve for a filter run even when using estimated values of γ_p, using turbidity units in place of C_S (turbidity units are used in place of C_S for filter runs with ID numbers beginning with 1, 6, and 7), and possibly when the solids do increase cake thickness appreciably makes practical the use of β index. The important thing is that the use of Equation 34, rather than Equation 33, tremendously increases the accuracy of β index prediction in some cases.

If the use of β index rather than z_c is the primary reason for the differences, then the C_D term in the prediction equation serves primarily as a factor that compensates for inaccuracies in β relative to z_c.

The swelling property exhibited by Montmorillonite when placed in water may be a factor contributing to inaccuracies in β determination. The swelling of this clay, if it occurs in a filter cake, would increase the thickness of the filter cake and result in an error in the determination of β. Regunathan (35) thought that this swelling property might be a significant factor in the explanation of the poor correlation of log K_4 with $\log(C_S/C_D)$ for Wyoming bentonite.

The poor correlation, when using Equation 33, for water containing Montmorillonite and for softened water may be a result of using turbidity in place of C_S in the correlation. Turbidity is a measure of the scatter of light beams passed through the water, and is not normally considered a good measure of suspended solids concentration (C_S). Also, turbidities of the unfiltered water were normally less than 10 for the softened water, and the accuracy of such low turbidities is questionable.

The C_S/C_D exponent in the second prediction equation for Runs 7003-7023 is only 0.0361. This is an indication that the variation in β for these runs was largely due to the variation in C_D and practically independent of C_S. This is a strong indication that the turbidity values were probably in error.

Low R values for the Lompoc filter runs (Runs 6111-6332) were undoubtedly the combined result of several factors, primarily, the fact that the Lompoc plant was designed and built for the production of potable water for the city of Lompoc and not for research purposes. Measurement of the actual flow rate, turbidity, and body feed concentration for each of the filters, although adequate for plant operation, was not possible to the accuracy desired by the author. Turbidity and body feed concentration could not be determined for each filter, and therefore, values for the total flow had to be used. It was noticed, in some instances, that the rate of increase of cake thickness was not the same for all three filters, and therefore, that the flow rate, turbidity, and body feed concentration were not all the same for all three filters.

Notice that the exponent of C_D is negative for all prediction equations that contain the C_D term. This is an indication that the variation of β index is more affected by changes in C_D than in C_S.

Some of the prediction equations in Appendix C contain ξ (Equation 31). The use of this form of the prediction equation is not recommended because the ξ index, although a good index of hydraulic characteristics, is not an adequate index of the filtering characteristics of filter aids (15, 16). It is more desirable to determine separate prediction equations for each grade of filter aid. However, good results can be obtained if the correlation coefficient was high and no attempt is made to predict β index for a filter aid grade that was not included in the pilot filter runs from which the prediction equation exponents were determined.

The prediction equations that include ξ were determined because they give an indication of the variation of β index with ξ index (i.e., variation of cake resistance with precoat resistance or filter aid resistance). The exponent of ξ for every one of these equations is less than 1. This indicates that changes in filter aid resistance result in relatively smaller changes in filter cake resistance. Hall demonstrated this result for iron bearing water with Runs 5150-5156 (19). The prediction equations demonstrate the same result for water containing Kaolinite (Runs 1203-1315) and for softened water (Runs 6111-7023).

COST ASSUMPTIONS AND METHODS OF COMPUTATION

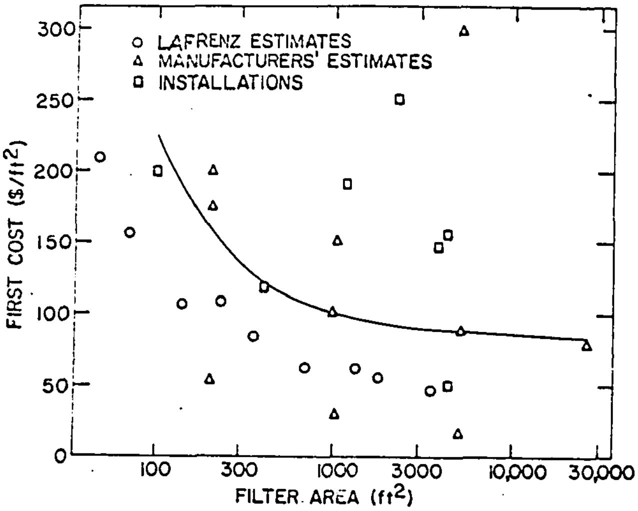
First Cost

It is assumed that the first cost of the plant is primarily dependent on filter area needed and the flow capacity required. Since the filter area needed is equal to the total flow divided by the unit flow rate (Q/q), plant first cost is dependent on q. A plant of a given filter area, say 1000 sf would cost more if it treated a larger flow because pumps and piping, body feeding equipment, and other equipment would have to be larger to handle the larger flow.

A plot of plant first cost in dollars per square foot versus filter area (log scale) is shown in Fig. 9. The cost information plotted includes cost information obtained from filter manufacturers and some existing filtration installations, and cost estimates made by LaFrenz in the preparation of his thesis (25).

This cost information was accumulated only for the purpose of demonstrating the use of POPO, and should not be used in the design of an actual filtration plant. Costs can vary tremendously, depending on the type of plant, location, etc., as demonstrated by Fig. 9. Costs can also vary with time. The more accurate and current the data used by the consultant to prepare a first cost-area curve similar to the curve in Fig. 9, the better will be the resulting cost optimization.

After the first cost-area curve has been prepared for a particular installation, the first cost of plants of various areas can be determined from this curve. (See discussion of rate factor in POPO user manual, Appendix D.)



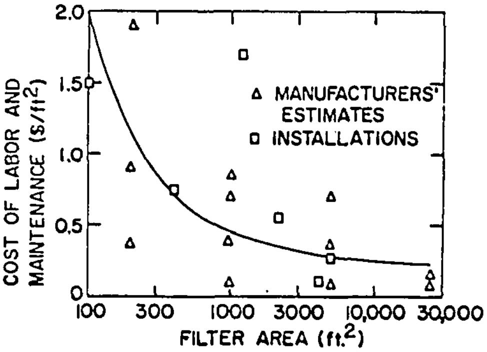


Fig. 9, left. Semilog plot of plant first cost per unit filter area versus filter area (log scale) for cost estimates made by LaFrenz (25) and filter manufacturers' representatives and for cost information on some existing installations

Fig. 10, right. Semilog plot of monthly labor and maintenance cost per unit filter area versus filter area (log scale) for cost estimates supplied by manufacturers and for cost information on some existing installations

Labor and Maintenance Cost

It is assumed that both labor and maintenance depend primarily on the size of the plant (similar to plant first cost assumption), i.e., filter area and capacity. For this reason, labor and maintenance costs are combined and computed the same way as plant first costs.

Fig. 10 illustrates the plot of combined monthly labor and maintenance costs per unit filter area versus area (log scale) for some cost data for various installations and estimates made by manufacturers' representatives. Most of the points shown in Fig. 10 are representative of automatic backwashing filter plants. There seems to be a definite trend towards automatic backwash plants for diatomite filter installations, for which less operational attendance is needed.

Fig. 10, like Fig. 9, was prepared only for the demonstration of the use of POPO, and should not be used when designing an actual installation. Actual estimates of monthly labor and maintenance costs should be made and a cost-area curve similar to the one shown in Fig. 10 prepared for each installation to be designed.

Diatomite Cost

The cost of diatomite is computed as simply the total weight of diatomite times the cost per unit weight. The total weight of diatomite needed includes diatomite used for precoating and body feed. The weight of body feed is found by multiplying the weight of water produced by the weight fraction of body feed used. The weight of precoat per filter cycle is equal to the filter area times the precoat weight per unit area. Diatomite cost per unit volume of water produced is a function of body feed concentration and length of filter run.

Power Cost

The cost of power is computed on the basis of a unit cost per kilowatt-hour (kwh). It is realized that power costs usually consist of a demand charge and an energy charge. Methods of computing these charges vary from one location to the next. The energy charge is usually computed on the basis of decreasing unit cost per kwh for successive increments of energy - - i.e., 4 cents per kwh for the first 400 kwh, 3.5 cents per kwh for the next 500 kwh, etc.

It is assumed that the energy needed to pump the water through the filter is a small portion of the total energy needs of the installation.

Energy may also be needed for heating, pumping the water into the distribution system and storage reservoirs (possibly including elevated storage), booster pumps, well pumps, etc. These other energy needs, for the most part, are independent of the terminal head loss through the filters, and therefore, are excluded from energy cost computations made for the purpose of plant optimization.

It is further assumed that the total energy needs are great enough that the lowest unit cost per kwh can be used to compute the cost of energy needed for filtering. The demand charge is not included in the power cost calculation because of the many different ways it is computed, and because it is usually a fairly small portion of the total power bill.

The validity of these assumptions will depend on the particular installation. However, it is felt that this method of power cost computation will be generally applicable to different types and sizes of filtration plants in different locations.

The energy needed per month for filtering is computed on the basis of pumping the quantity of water produced per month against the terminal head loss - - i.e., the weight of water produced per month times the terminal head loss divided by an assumed overall efficiency of energy conversion. This quantity is converted to kwh and multiplied by the unit cost per kwh to obtain monthly power cost.

There is a potential power cost savings in the use of variable-speed pumping because the average head loss through the filter cake for a filter run is considerably less than the terminal head loss. This potential economy was not considered in this thesis and is an area of future application of POPO. Some of the more recently constructed diatomite filtration plants utilize variable-speed pumping - - including the one at Massena, New York (30).

Backwashing Cost

The length of a filtering cycle is equal to the sum of the length of the filter run, and the time needed for backwashing and precoating the filter for the next filter run. Water is not produced by the filter during the time needed for backwashing and precoating (down time). The filter would have to operate at a slightly higher rate to filter the same quantity of water during a filter cycle that would have been filtered if it were in operation for the entire filter cycle. In addition, filtered water must be used for backwashing, and it too will have to be replaced by a slight increase in the flow rate.

It is assumed that the increase in costs resulting from providing filtered backwash water increases the operating costs proportionately - - i.e., monthly cost of backwash water is equal to the total monthly operating cost times the ratio of the quantity of backwash water needed per month divided by the quantity of finished water produced per month. The need to provide backwash water would not increase the first cost of the plant unless it was so large a percentage of total production that additional filter area had to be provided.

The cost of producing the water that would have been produced during the down time is computed as the operating costs (excluding power costs) times the ratio of down time to length of filter run. Power costs are excluded from this computation because the total design flow is used to compute power costs.

The method proposed above for calculating backwash costs is only approximate, but it eliminates the need for an iterative calculation process. The increase in the filtration rate that would be needed to overcome production loss during down time and to provide backwash water will decrease the filter run length, and thus, increase the amount of down time per day above that which is calculated based on the design filtration rate. The resulting increase in down time is greater than the proportional increase in filtration rate (Equation 25 or 26). Thus, the filtration rate would have to be increased again to compensate for the more than proportional increase in down time. Therefore, it is apparent that an iterative process would have to be used to find the actual combination of filtration rate and filter area that would result in the desired quantity of finished water being produced.

However, the proposed method should give good results because the backwashing cost is ordinarily a small portion of the total operating cost. Backwashing cost cannot be neglected altogether because it can be a significant cost factor for short filter runs. The method proposed would not be adequate for extremely short filter runs (less than four hours), but this inadequacy will not affect the use of the program since extremely short runs do not provide optimum economy.

OPTIMUM DESIGN

The output for a POPO run in which 13 jobs were processed is included in Appendix D. The input data card images for each job appear first in the output for each job. The input data, by its format design, give a good description of the type of installation being designed for each job. The POPO results then follow the input data.

Jobs 1-8, and 13 are for hypothetical installations. Jobs 9-12 are based on the conditions at Lompoc, California.

For all jobs processed, the cost-area curves shown in Figs. 9 and 10 were used to compute first cost and combined labor and maintenance costs. It should be kept in mind that actual costs for a particular installation could vary considerably from these two curves. Still, some very interesting observations can be made from the output for these 13 jobs.

An appropriate β index prediction equation was selected from Appendix C for each job in the POPO run.

A summary of the 13 jobs processed by POPO and included in Appendix D is shown in Fig. 11. Included for each job number are the design flow for the plant (Q), the type and concentration (C_S) of solids, the grade of filter aid being considered, the water temperature, type of septum, the length of filter run (t_r), the predicted β index, the two most economical combinations ((q, C_D, H)) for 100% of predicted β values, and the total, first, and operating costs ($/MG).

The optimum combination ((q, C_D, H)) varies for each type of installation, depending primarily on the filterability of the water as represented by the β index prediction equation. As the filterability decreases,

SUMMARY OF 13 JOBS IN POPO RUN INCLUDED IN APPENDIX D

Job	Q	Solids		Filter	Temp	Septum	t_r	β	$((\bar{q}, C_D, H))$	$ /MG		
	MGD	ppm	type	aid	°F	inch	hr	10^4 ft^{-2}	For 100% β	Total	First	Oper
1	1	7.5	iron	C-503	55	Flat	17.5	8172	((0.6,40,150))	77.2	17.4	59.8
							9.9	8172	((0.8,40,150))	77.3	14.2	63.2
2	1	7.5	iron	C-503	55	1	18.1	8172	((0.8,40,140))	67.1	14.2	52.9
							19.7	8172	((0.8,40,150))	67.1	14.2	52.9
3	7	7.5	iron	C-503	55	3.5	14.4	6961	((0.8,40,150))	59.8	12.4	47.4
							10.8	11920	((0.8,30,150))	59.9	12.4	47.5
4	7	7.5	iron	HSC	55	3.5	9.9	9852	((0.8,40,150))	59.1	12.4	46.7
							12.4	6491	((0.8,50,150))	59.3	12.4	46.9
5	7	4	iron	HSC	55	3.5	13.7	7323	((1,25,150))	44.2	10.4	33.8
							12.7	7323	((1,25,140))	44.2	10.4	33.8
6	3	50*	KBC	HSC	48	1	11.2	5819	((1,50,150))	58.0	14.7	43.2
							9.8	5819	((1,50,135))	58.2	14.7	43.4
7	3	50*	KBC	HSC	72	1	11.6	9537	((1,40,150))	54.1	14.7	39.4
							10.2	9537	((1,40,135))	54.2	14.7	39.5
8	3	30*	WB	HSC	72	1	8.8	11725	((0.5,200,150))	140.6	25.8	114.8
							10.0	10308	((0.5,210,150))	140.7	25.8	114.9
9	4.5	8.5*	LSA	C-503	65	Flat	31.8	973	((0.73,24,25))	32.3	12.4	19.9
							26.0	1295	((0.73,22,25))	32.3	12.4	19.9
10	4.5	8.5*	LSA	HSC	65	Flat	16.5	1866	((0.73,24,25))	31.7	12.4	19.3
							14.9	2252	((0.73,22,25))	31.8	12.4	19.4
11	7	8.5*	LSA	HSC	65	Flat	6.0	824	((1.50,35,25))	27.6	7.1	20.5
							7.2	1151	((1.25,30,25))	27.7	8.1	19.6
12	7	8.5*	LSA	HSC	65	1	8.7	1708	((2.50,25,85))	21.3	5.2	16.2
							9.5	1708	((2.25,25,75))	21.4	5.5	15.9
13	25	8.5*	LSA	HSC	65	1	8.7	1708	((2.50,25,85))	19.9	4.9	15.0
							9.5	1708	((2.25,25,75))	19.9	5.2	14.7

HSC = Hyflo Super-Cel

KBC = Kentucky ball clay (Kaolinite)

WB = Wyoming bentonite (Montmorillonite)

LSA = Carry-over from lime-soda ash process

---

* Turbidity units rather than ppm by weight

Fig. 11. Summary of POPO run

the optimum flow rate decreases and the body feed concentration and terminal head loss increase. In general, when total operating cost is high (low filterability) compared with the first cost, the lower flow rates are more economical because first cost is a relatively small portion of the total cost and decreasing the flow rate decreases total operating cost.

Fig. 11 and the POPO output in Appendix D illustrate that the optimum design or optimum $((q, C_D, H))$ depends on the particular situation, and can vary considerably. The optimum flow rates ranged from less than 0.5 to more than 2.0 gsfm (Appendix D). Therefore, the use of a fixed filtration rate of 1 gsfm should be avoided. Most of the present application of diatomite filters in the water supply field is in the filtration of water of relatively high filterability and thus relatively higher optimum filtration rates. The water filtered at Massena, New York (30) is a water of very high filterability. According to information sent to the author by the Department of Public Works in Massena, the plant is presently filtering at about 0.5 gsfm and filter runs are 4 and 5 days long. In light of the results indicated in Fig. 11, the Massena plant probably should have been designed to operate at 2 or 3 gsfm for optimum economy.

Increasing β index from 50 to 175% of predicted values (Appendix D) for all 13 jobs resulted in smaller flow rates and larger body feed concentrations and terminal head losses for maximum economy. Relatively large β indexes are typical of waters of low filterability.

Changing from flat septa to 1 inch cylindrical septa as shown in Jobs 1 and 2 decreased the cost of water production by about 13%. This assumes, of course, that the same first cost and labor and maintenance costs are applicable to both jobs. Also, in changing from a vacuum filtration plant with flat septa (Job 11) to a pressure filtration plant with 1 inch septa (Job 12), the total cost dropped from $27.6 to $21.3 per MG. However, in practice, there may be practical advantages for using flat septa or vacuum filters, and in some cases, it may be felt that these advantages justify the extra cost.

Hyflo Super-Cel is considerably finer than C-503 filter aid. The ξ index for Hyflo Super-Cel is about $5(10)^9$ ft/# and for C-503 is about $2(10)^9$ ft/#. However, differences in β index are less than corresponding ξ indexes, and Hyflo Super-Cel costs less than C-503. The question then arises as to whether difference in prices of the two filter aids is great enough to make the use of Hyflo Super-Cel economical since the resulting higher cake resistances will decrease the length of filter run and increase backwashing cost and the amount of precoat diatomite. If the costs are comparable between the two filter aids, it would probably be more desirable to use Hyflo Super-Cel because the finer filter aid can remove smaller particles.

Hyflo Super-Cel costs about $20/ton less than C-503. Comparison of Jobs 3 and 4 and Jobs 9 and 10 illustrate, at least for these two particular cases, that the use of Hyflo Super-Cel resulted in slightly lower costs than C-503.

Jobs 9 and 10 illustrate the use of POPO in optimizing operating costs at an existing plant. Information collected at the Lompoc plant was used in Jobs 9 through 12. The variables used in Job 9 approximate the conditions at the plant in the latter part of June, 1964. The cost-area curve shown in Fig. 9 was used for computing first cost and may not be entirely representative of the Lompoc plant. Since the filter area and terminal head loss are fixed for the plant, only C_D is optimized by POPO.

The actual first cost of the filtration portion of the Lompoc plant is somewhat less than the first cost determined from the curve shown in Fig. 9.

The turbidity load to the filters during June ranged from about 3 to 11 units and was usually about 6 to 10 units. The optimum body feed for both C-503 and Hyflo Super-Cel under the specified conditions (Jobs 9 and 10) is 24 ppm for the first cheapest operating cost and 22 ppm for the second cheapest. The plant was being operated at 20 ppm most of the time that the author was there, and therefore, was being operated very near the optimum body feed rate. In both Jobs 9 and 10, for β indexes less than 100% of the predicted values and for $C_S = 8.5$ units, the optimum body feed concentrations were nearer to 20 ppm. Smaller β indexes would be expected if the turbidity load to the filters were less than 8.5 units. This illustrates that the Lompoc plant was being operated at approximately the optimum body feed concentration.

Assume that the Lompoc plant were not yet constructed and POPO were to be used to design similar filter units for the plant (Job 11). POPO will optimize filtration rate and body feed concentration for 25 ft terminal head loss since terminal head loss is limited to approximately 25 ft because the filters are vacuum filters.

The results for Job 11 indicate that water could have been filtered more cheaply if the Lompoc plant had been designed to operate at a higher filtration rate and using higher body feed concentrations. Of course, POPO was not available when the Lompoc plant was designed.

Provision was made in the design of the Lompoc plant for the addition of new filter units to double the filter area for future expansion (28). According to the results of Job 11, it should be found that the present filter area is adequate for much larger plant flows and additional filter units may not be necessary. However, it may be necessary to increase the capacity of some of the pumps, pipes and other equipment to handle the larger flows.

It was specified for the Lompoc plant that the length of filter run shall not be less than 14 hr for a plant flow of 7 MGD (28). The length of filter run for many of the optimum combinations of Job 10 is less than 14 hr, and the length of filter run for all of the optimum combinations in Job 11 is less than 14 hr. Thus, the specification is poor unless there are reasons other than economy that the length of filter run should be at least 14 hr.

A further advantage of shorter filter runs at Lompoc is in backwashing. The filters are more easily washed when the filter cakes are thinner. One of the difficulties observed in the operation of the Lompoc plant was that thick filter cakes were difficult to wash from the filter housings. In some cases, a filter had to be washed manually in order to remove the filter cake completely.

Job 12 illustrates that if pressure filters containing 1 inch septa were to be designed for Lompoc that the optimum filtration rate would be even higher, and overall economy would be greater. The greater economy, of course, is based on the assumption that the first cost and labor and maintenance cost are comparable for vacuum filters with flat septa and pressure filters with 1 inch septa since the same cost-area curves (Figs. 9 and 10) were used in Jobs 11 and 12.

Comparison of Jobs 12 and 13 illustrates that the total cost per MG is less for plants of greater capacity. The reason for this is that first cost and labor and maintenance costs per MG are not constant but decrease with increasing capacity.

The tremendous potential of POPO in both the design of new filtration plants and the optimization of existing plants is demonstrated in the above discussion of the POPO output. POPO should be used to optimize the operation of existing plants because total plant flow generally increases with time, and optimum operating conditions will change over the life of the plant.

SUMMARY AND CONCLUSIONS

The total cost of filtering potable water is a very complex function of several variables. Because of the complexity, reasonably accurate calculation of costs for varying conditions of operation has not been generally possible. As a result, filtration plants have traditionally been designed to be adequate, rather than to produce potable water at minimum cost. However, in the case of diatomite filtration, the desirable goal of practical least cost design is nearer reality. The problem is more difficult in the case of sand filtration because a generally acceptable mathematical expression for the head loss-time relationship of sand filters is not available.

The primary objective of this thesis was the development of a digital computer program that could be used in the design of diatomite filtration plants for optimum economy. In order to accomplish this, it was necessary to be able to predict the variation of filter cake resistance for various conditions since cake resistance is one of the primary factors influencing costs.

In the course of this study, diatomite filtration equations were theoretically developed from the generally accepted filtration rate equation. The hypotheses assumed in the derivation of these equations are presented.

The method that had been used to predict the variation of cake resistance with suspended solids concentration and body feed concentration (plot of K_4 versus C_S/C_D) has been expanded. The method of predicting cake resistance involves the use of empirically developed prediction equations whose coefficients are determined by least squares techniques.

The filter runs summarized in Appendix B were used to verify the diatomite filtration equations developed and the form of prediction equation used.

The computer program developed for this thesis, called POPO (Program for Optimization of Plant Operation), is explained in the POPO reference manual (Appendix D). Included in the reference manual are a user manual explaining the use of POPO, a FORTRAN list of the actual program, and actual POPO output for some hypothetical installations and for the Lompoc, California, installation. Each of the elements of filtration cost are computed in separate subprograms of POPO to simplify any future modifications of the program for special type installations.

The following conclusions were drawn from the results of this investigation:

1. The diatomite filtration head loss equations developed in this thesis for flat septa (Equation 26) and cylindrical septa (Equation 25) can be used to describe the head loss-time relationships, including the brief transitional period at the beginning of a filter run, for filter cakes containing several different types of filtered solids. These equations have been verified for filter cakes containing iron, clay, and carry-over from the lime-soda ash softening process.

2. Head loss through the filter cake is a linear function of time for flat septa and a logarithmic function of time for cylindrical septa except for the initial transitional period.

3. The time rate of head loss increase is less when using cylindrical septa than it is when using flat septa, other things being equal. The smaller the septum diameter, within practical limits, the lower is the time rate of head loss increase.

4. Relatively accurate description of the head loss-time curves for filter cakes can be obtained even when approximate values of precoat bulk density (γ_p) are used in the determination of the filter cake resistance index (β index). However, the use of approximate values of γ_p result in approximate values of the β index. Thus, the value of γ_p and the type of septum used in the determination of β index should be stated with the value of β index.

5. The form of the β index prediction equation used in this thesis can be used to describe the variation of cake resistance with the concentration of solids and concentration of body feed, and in some cases, the precoat resistance index (ξ index).

6. The use of a β index prediction equation of the form $\beta = 10^{b_1} (C_S/C_D)^{b_2} C_D^{b_3}$ rather than one of the form $\beta = 10^{b_1} (C_S/C_D)^{b_2}$, significantly increases the accuracy of prediction in some cases. This was especially true for water containing Montmorillonite clay and lime-soda ash softened water.

7. Variation of ξ index results in correspondingly less variation in β index.

8. POPO has tremendous potential application in both the design of new filtration plants and in the optimization of the operation of existing plants.

9. The combination of flow rate, body feed concentration, and terminal head loss, ((q, C_D, H)), that result in least cost depends entirely on the particular situation and can vary considerably. Therefore, the use of a rule of thumb flow rate such as 1 gsfm for all types of installations should be avoided, and the optimum flow rate should be determined for each particular case.

10. The optimum combination ((q, C_D, H)) and the cost of filtration depend primarily on the filterability of the water. Filterability, as defined in this thesis, refers to head loss considerations only as defined by the prediction equations. Effluent quality is assumed acceptable in all cases.

11. Results of the POPO output included in Appendix D, which are based on the type of solids filtered, the cost assumptions made, and the methods of cost computation used in POPO, indicate that:

a. Cylindrical septa are more economical than flat septa; and the smaller the diameter of cylindrical septa, within practical limits, the greater the economy.

b. Hyflo Super-Cel is probably more economical than C-503, even though its ξ index is considerably larger, because it costs less, and variations in ξ index result in relatively smaller variations in β index. However, the relative economy of different grades should be checked in each case.

RECOMMENDATIONS

In consideration of the results of this investigation, it is recommended that:

1. The diatomite filtration equations developed in this thesis be used to determine filter cake resistance.

2. The β index prediction equation in the form of Equation 34 be used except when the values of C_S for the group of pilot filter runs being considered are practically the same - - then Equation 33 should be used.

3. The validity of the assumption that the solids in the filter cake do not increase cake thickness be investigated for various types of suspended solids. This will involve some method of determining cake thickness reasonably accurately.

4. POPO, either in its present form or in a form modified to allow different methods of cost computation, be used in the design of diatomite filtration plants and also in the optimization of existing plants.

5. The basic principles of cost optimization used in POPO be used to develop computer programs to optimize other sanitary engineering unit operations.

6. The potential economy of variable-speed pumping be investigated by modifying the subroutine in POPO where power costs are computed (subroutine CPOWR).

7. More filter runs be made with Miss Purity to determine β indexes and β index prediction equations for various surface waters at the source - - both with and without pretreatment.

LITERATURE CITED

1. Abdulrahman, M. S. Effect of ions in solution on the permeability of diatomite filter aids. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1964.

2. Baumann, E. R. The design and operation of diatomite precoat filters for water. Unpublished Ph.D. thesis. Urbana, Illinois, Library, University of Illinois. 1954.

3. Baumann, E. R., J. L. Cleasby, and R. L. LaFrenz. A theory of diatomite filtration. American Water Works Association Journal 54: 1109-1119. 1962.

4. Baumann, E. R., J. L. Cleasby, and P. E. Morgan. Theoretical aspects of diatomite filtration. Water and Sewage Works (Reference Number issue) 111: R113-R134. 1964.

5. Baumann, E. R. and R. L. LaFrenz. Optimum economical design for municipal diatomite filter plants. American Water Works Association Journal 55: 48-58. 1963.

6. Baumann, E. R. and C. S. Oulman. Modified form of diatomite filtration equation. American Water Works Association Journal 56: 330-332. 1964.

7. Bell, G. R. Coagulant coatings open new applications to filter aids. Engineering Society of Western Pennsylvania, International Water Conference Proceedings 22: 129-133. 1961.

8. Bell, G. R. Design criteria for diatomite filters. American Water Works Association Journal 54: 1241-1256. 1962.

9. Camp, T. R. Theory of water filtration. American Society of Civil Engineers, Sanitary Engineering Division Journal 90, No. SA4: 1-30. 1964.

10. Carman, P. C. The action of filter aids. Industrial and Engineering Chemistry 30: 1163-1167. 1938.

11. Carman, P. C. The action of filter aids. Industrial and Engineering Chemistry 31: 1047-1050. 1939.

12. Cleasby, J. L. Selection of optimum filtration rates for sand filters. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1960.

13. Cleasby, J. L. and E. R. Baumann. Selection of sand filtration rates. American Water Works Association Journal 54: 579-602. 1962.

14. De Laval Turbine, Inc. Filtration Systems Division. Sparkling clear water. De Laval Turbine, Inc. Bulletin 4801. 1964.

15. Dillingham, J. H. Hydraulic characteristics of some diatomite filter aids. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1963.

16. Dillingham, J. H. and E. R. Baumann. Hydraulic and particle size characteristics of some diatomite filter aids. American Water Works Association Journal 56: 793-808. 1964.

17. Fair, G. M. and L. P. Hatch. Fundamentals factors governing the stream-line flow of water through sand. American Water Works Association Journal 25: 1551-1563. 1933.

18. Grace, H. P. Resistance and compressibility of filter cakes. Chemical Engineering Progress 49: 303-318. 1953.

19. Hall, B. B. Permeability of various grades of diatomite filter cakes containing flocculent iron oxide. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1964.

20. Hawley, J. F. Permeability of diatomite filter cakes containing various flocculent solids. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1964.

21. Hoffing, E. H. and F. J. Lockhart. Resistance to filtration. Chemical Engineering Progress 47: 3-10. 1951.

22. International Business Machines Corporation. IBM 7070 series programing systems: FORTRAN. IBM Reference Manual C28-6170. 1962.

23. Johns-Manville Corporation. Celite Division. The filtration of water. Johns-Manville Corporation Brochure FA-74A. 1964.

24. Kottwitz, F. A. Prediction of filtration resistance by compression-permeability techniques. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1955.

25. LaFrenz, R. L. Design of municipal diatomite filters for iron removal. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1961.

26. LaFrenz, R. L. Effect of chemical coagulation on permeability of diatomite water filters. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1960.

27. LaFrenz, R. L. and E. R. Baumann. Optimums in diatomite filtration. American Water Works Association Journal 54: 847-851. 1962.

28. Lawrance, C. H. Design aspects of Lompoc water treatment plant. American Society of Civil Engineers, Sanitary Engineering Division Journal 90, No. SA6: 81-113. 1964.

29. Metafiltration Company Limited. The modern pre-coat metafilter. Metafiltration Company Limited Brochure M1. ca. 1964.

30. Neubauer, W. K. Largest diatomaceous-earth filters. The American City 79, No. 11: 76-78. 1964.

31. Oulman, C. S. Streaming potentials in diatomite filtration of water. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1963.

32. Oulman, C. S. and E. R. Baumann. Streaming potentials in diatomite filtration of water. American Water Works Association Journal 56: 915-930. 1964.

33. Oulman, C. S., D. E. Burns, and E. R. Baumann. Effect on filtration of polyelectrolyte coatings of diatomite filter media. American Water Works Association Journal 56: 1233-1238. 1964.

34. Phillips, E., Jr. Recommended practices for the design and operation of diatomite water filters. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1957.

35. Regunathan, P. Permeability of diatomite filter cakes containing various clay minerals. Unpublished M.S. thesis. Ames, Iowa, Library Iowa State University of Science and Technology. 1965.

36. Ruth, B. F. Correlating filtration theory with industrial practice. Industrial and Engineering Chemistry 38: 564-571. 1946.

37. Task Group 2710P - - Diatomite Filtration (E. R. Baumann, Chairman). Diatomite filters for municipal use. American Water Works Association Journal 57: 157-180. 1965.

ACKNOWLEDGMENTS

The author wishes to extend his sincere appreciation:

1. To Professors J. L. Cleasby and E. R. Baumann for their assistance and guidance during the course of this study.

2. To Dale Batchelor and C. A. Thompson, City of Lompoc, Lompoc, California, for their courteous hospitality while the author was there collecting field data.

3. For cost information supplied by:

   a. C. H. Becker and J. S. Brown, De Laval Turbine, Inc., Millbrae, California.

   b. D. F. Anspoch, R. P. Adams Co., Inc. Buffalo, New York.

   c. T. H. Bivens, Sparkler Manufacturing Company, Conroe, Texas.

   d. C. N. Tozer, Julian Mutual Water Company, Julian, California.

   e. Department of Public Works, Village of Massena, Massena, New York.

   f. Village of Palmyra, Palmyra, New York.

   g. D. P. Johnston, Goleta County Water District, Goleta, California.

   h. City of Vacaville, Vacaville, California.

4. To his wife, who helped in many ways.

This investigation was supported (in part) by a research fellowship (5-F1-WP-20,084) from the Division of Water Supply and Pollution Control, Public Health Service, and by the Iowa Engineering Experiment Station, through funds made available by a research grant (WP-00196) from the Division of Water Supply and Pollution Control, Public Health Service.

APPENDIX A. NOMENCLATURE

Definition of Terms

Term	Meaning
Body feed	Filter aid added to influent or unfiltered water for purpose of forming a porous, incompressible cake.
Filterability	Capability of being filtered. Used to describe head loss characteristics as defined by β index prediction equations. Effluent quality assumed acceptable in all cases.
Filter cake	The body feed - suspended solids layer that forms on the precoat during filtration.
Filter run	A filter test made for purpose of determining cake resistance. Operation of the filter from the beginning to the end of the filtering operation.
Filter run length	The elapsed time from beginning to end of filtering operation.
Suspended solids	All solids suspended in water except body feed.

Abbreviations

Abbrev.	Dimensions	Meaning
cf	L^3	cubic feet, ft^3
fph	LT^{-1}	feet per hour, ft/hr
ft	L	feet
gpm	L^3T^{-1}	gallons per minute
gsfm	LT^{-1}	gallons per square foot per minute, gpm/ft^2
hr	T	hour
kw	FLT^{-1}	kilowatt
kwh	FL	kilowatt-hour
ln		natural logarithm
log		base 10 logarithm

Abbrev.	Dimensions	Meaning
MG	L^3	million gallons
MGD	L^3T^{-1}	million gallons per day
min	T	minute
mo	T	month
ppm		parts per million
sec	T	second
sf	L^2	square feet, ft^2
#	F	pound, lb
$((q, C_D, H))$		short form of indicating a combination of unit flow rate or filtration rate (q), body feed concentration (C_D), and terminal head loss (H)

Notation

The subscripts p and c refer to the precoat and filter cake, respectively, and will not be indicated below.

Symbol	Dimensions	Meaning
A	L^2	Gross outer cross sectional area of porous media (filter cake) perpendicular to direction of flow
A_s	L^2	Septum area
a	L^{-2}	Specific resistance based on volume of filter media
α_1	$F^{-1}L^2T^{-2}$	Precoat resistance factor
α_2	$F^{-1}L^2T^{-2}$	Filter cake resistance factor
β	L^{-2}	Filter cake resistance index or β index
C_D		Body feed concentration, ppm by weight
C_S		Suspended solids concentration, ppm by weight

Symbol	Dimensions	Meaning
d	L	pipe diameter
δ	T^{-1}	Dilution rate, theoretically Q/V_f
g	LT^{-2}	Gravity constant
γ	FL^{-3}	Bulk density
γ_S	FL^{-3}	In place bulk density of solids in filter cake
γ_W	FL^{-3}	Density of water
H	L	Head loss or pressure difference in terms of length of water column
H_e	L	Head loss through filter equipment (piping, septum, etc.)
H_o	L	$H_e + H_p$
i		Hydraulic gradient, dH/dL
K	LT^{-1}	Coefficient of permeability
K_1	L^2	Modified coefficient of permeability that is independent of viscosity
K_3	$F^{-1}L^2T$	Factor of precoat resistance, $1/K_p\gamma_p$
K_4		In Equation 8, $\gamma_S n/\gamma_p$
K_4	$F^{-1}L^2T$	In Equation 11, $1/K_c\gamma_p$
L	L	Thickness of porous media in direction of flow
L_s	L	Length of septum
μ	FTL^{-2}	Dynamic or absolute viscosity
n		Porosity, volume voids / total volume

Symbol	Dimensions	Meaning
ν	L^2T^{-1}	Kinematic viscosity
P	FL^{-2}	Pressure
ϕ	LT^{-1}	$2q\gamma_w C_D(10)^{-6}/\gamma_p$
Q	L^3T^{-1}	Flow rate, dV/dt
q	LT^{-1}	Flow rate per unit septum area (filtration rate, Q/A_s)
R	L	Outer radius of cylindrical filter cake. Also, correlation coefficient
R_o	L	$R_s + L_p$, R at t = 0
R_s	L	Radius (outer) of septum
S_i		Weight fraction of solids-body feed in influent
S_f		Weight fraction of solids-body feed in the water in the filter housing
σ	LT^{-1}	$q^2\nu\beta C_D/g$
t_i	T	Time of inflection point of head loss-time curve for cylindrical filter cakes
t_r	T	Length of filter run
V	L^3	Volume of filtrate filtered in time t
V_f	L^3	Volume of filter housing
v	FT^{-1}	Approach or face velocity, Q/A
W_c	F	Dry weight of filter cake
W_D	F	Dry weight of diatomite in filter cake
W_S	F	Dry weight of solids in filter cake

Symbol	Dimensions	Meaning
w	FL^{-2}	Precoat weight per unit area
x	T	$t - (1-e^{-\delta t}) /\delta$
ξ	LF^{-1}	Filter aid resistance index or ξ index
z	$F^{-1}L$	Specific resistance based on weight of diatomite in filter cake

APPENDIX B. SUMMARY OF FILTER RUNS

```
                    SUMMARY OF FILTER RUNS
                    ======================

ID = FILTER RUN IDENTIFICATION CODE NUMBER, AS FOLLOWS

    REGUNATHAN RUNS.  FIRST DIGIT = 1
       SECOND DIGIT = 2 FOR SERIES B
                    = 3 FOR SERIES C
                    = 4 FOR SERIES D
          LAST THREE DIGITS = RUN NUMBER
    FOYSTER RUNS.  FIRST DIGIT = 2
       LAST THREE DIGITS = RUN NUMBER
    LAFRENZ RUNS.  FIRST DIGIT = 3
       NEXT TWO DIGITS = VHP SERIES NUMBER
          LAST THREE DIGITS = BODY FEED CONCENTRATION (CO)
      (LAFRENZ CODE NUMBER SIX DIGITS LONG, ALL OTHERS FOUR)
    EXTRA RUNS.  FIRST DIGIT = 4
       LAST THREE DIGITS = RUN NUMBER
    HALL AND HAWLEY RUNS.  FIRST DIGIT = 5
       LAST THREE DIGITS = RUN NUMBER
    LOMPOC DATA (DILLINGHAM).  FIRST DIGIT = 6
       SECOND DIGIT = FILTER NUMBER
          LAST TWO DIGITS = RUN NUMBER
    MISS PURITY AT AMES PLANT.  FIRST DIGIT = 7
       LAST THREE DIGITS = RUN NUMBER

                           EXAMPLES
                           --------

      1206      REGUNATHAN, SERIES B, RUN 6
      2009      FOYSTER, RUN 9
      312100    LAFRENZ, SERIES VHP-12, 100 PPM BODY FEED
      4024      EXTRA RUN NUMBER 24
      5155      HALL AND HAWLEY, RUN 155
      6320      LOMPOC, FILTER 3, RUN 20
      7015      MISS PURITY, RUN 15

R  = CORRELATION COEFFICIENT IN PERCENT

SS = SUSPENDED SOLIDS CODE NUMBER

     1 = FERROUS SULFATE ADDED TO UNIVERSITY TAP WATER
     2 = FERRIC CHLORIDE ADDED TO UNIVERSITY TAP WATER
     3 = FERROUS CHLORIDE ADDED TO UNIVERSITY TAP WATER
     4 = KENTUCKY BALL CLAY ADDED TO UNIVERSITY TAP WATER
     5 = WYOMING BENTONITE ADDED TO UNIVERSITY TAP WATER
     6 = EFFLUENT FROM LIME SODA ASH PROCESS
   (FOR FILTER RUNS FILTERING SS 4, 5, OR 6, CS = TURBIDITY)
```

ID	Q	CS	CD	XI	BETA	R	SS
	GSFM	PPM	PPM	10^9 FT/LB	10^4 FT^{-2}	0/0	
1203	1	37	110	0.822	193	99.975	4
1204	1	37	211	0.822	63	99.975	4
1208	1	108	133	0.822	1230	99.992	4
1209	1	115	126	0.822	1850	99.976	4
1215	1	119	213	0.822	444	99.963	4
1304	1	68	74	5.50	4740	99.993	4
1305	1	90	90	5.50	4720	99.965	4
1311	1	92	94	5.50	5692	99.977	4
1314	1	88	105	5.50	3244	99.979	4
1315	1	92	149	5.50	1714	99.981	4
1404	1	78	599	5.50	3446	99.972	5
1406	1	91	495	5.50	4800	99.969	5
1407	1	93	410	5.50	11250	99.983	5
1409	1	85	1033	5.50	740	99.990	5
1410	1	45	336	5.50	5150	99.986	5
1412	1	46	347	5.50	5420	99.996	5
1414	1	46	365	5.50	4140	99.988	5
1415	1	85	670	5.50	2400	99.996	5
1416	1	32	254	5.50	7070	99.948	5
2009	1	7.4	120	0.78	256		1
2010	1	7.4	40	2.76	2931		1
2011	1	7.3	40	2.76	2974		1
2012	1	7.6	80	2.76	1063		1
2013	1	7.4	120	2.76	334		1
2014	1	7.3	40	0.73	2069		1
2016	1	7.4	80	0.73	586		1
2018	1	7.4	120	0.73	283		1
2019	1	7.2	40	0.78	2478		1
2020	1	7.3	40	0.78	1939		1
2021	2	7.7	80	0.78	340		1
2022	2	7.3	120	0.78	150		1
2024	2	7.6	80	0.78	424		1
2025	2	7.5	80	0.78	318		1
2026	2	7.2	80	0.78	366		1
302020	1	7.0	20	0.75	4686		1
302040	1	7.5	40	0.75	1544		1
302060	1	7.4	60	0.75	615		1
302080	1	7.3	80	0.75	319		1
302100	1	7.5	100	0.75	169		1
302160	1	7.1	160	0.75	73		1

ID	Q	CS	CD	XI	BETA	R	SS
	GSFM	PPM	PPM	10^9 FT/LB	10^4 FT^{-2}	0/0	
302400	1	6.7	400	0.75	22.0		1
302800	1	6.9	800	0.75	0.90		1
303020	2	7.4	20	0.75	1867		1
303040	2	7.4	40	0.75	1237		1
303060	2	7.4	60	0.75	727		1
303080	2	7.4	80	0.75	450		1
303100	2	7.4	100	0.75	288		1
303120	2	7.4	120	0.75	187		1
303140	2	7.4	140	0.75	107		1
303160	2	7.4	160	0.75	75		1
303200	2	7.4	200	0.75	51.2		1
303300	2	7.4	300	0.75	30.0		1
304020	3	7.4	20	0.75	1717		1
304040	3	7.4	40	0.75	1248		1
304060	3	7.4	60	0.75	520		1
304100	3	7.4	100	0.75	197		1
304130	3	7.4	130	0.75	142		1
304140	3	7.4	140	0.75	42.7		1
304160	3	7.4	160	0.75	24.7		1
305020	2	4.0	20	0.75	1440		1
305040	2	4.0	40	0.75	514		1
305060	2	4.0	60	0.75	193		1
305080	2	4.0	80	0.75	128		1
305100	2	4.0	100	0.75	78		1
305160	2	4.0	160	0.75	39		1
309020	1	2.0	20	0.75	750		1
309060	1	2.0	60	0.75	124		1
309100	1	2.0	100	0.75	48		1
309160	1	2.0	160	0.75	18.7		1
310030	3	4.0	30	0.75	937		1
310060	3	4.0	60	0.75	258		1
310100	3	4.0	100	0.75	85.5		1
310120	3	4.0	120	0.75	57.0		1
310160	3	4.0	160	0.75	33.4		1
312020	3	7.4	20	0.75	2504		1
312040	3	7.4	40	0.75	1035		1
312080	3	7.4	80	0.75	371		1
312100	3	7.4	100	0.75	226		1

ID	Q GSFM	CS PPM	CD PPM	XI 10^{9} FT/LB	BETA 10^{4} FT^{-2}	R 0/0	SS
4006	0.94	7.6	39.9	0.78	4252	99.971	1
4007	0.94	7.5	160	0.78	342	99.917	1
4012	0.94	3.8	82	0.78	294	99.969	1
4013	0.94	1.9	19.6	0.78	2238	99.992	1
4015	2.18	7.6	60	0.78	1994	99.896	1
4017	2.18	7.6	160	0.78	247	99.925	1
4018	2.18	8.1	172	0.78	210	99.985	1
4019	2.18	7.8	319	0.78	55	99.793	1
4023	2.18	6.2	60	0.78	1036	99.981	1
4030	3.28	7.8	177	0.78	120	99.899	1
4032	3.28	7.9	308	0.78	78	98.965	1
4034	3.28	7.8	88	0.78	802	99.916	1
5005	0.97	8.1	294	0.984	669	99.558	1
5006	0.94	8.1	308	0.984	816	99.458	1
5007	0.94	8.4	308	0.984	673	99.805	1
5009	0.94	8.1	308	0.984	692	99.195	1
5010	0.94	8.0	308	0.984	658	99.456	1
5020	2	7.9	77	0.984	1253	99.834	1
5021	2	8.0	77	0.984	1049	99.915	1
5022	2	8.0	77	0.984	1357	99.793	1
5024	2	7.8	58	0.984	2517	99.913	1
5025	3	7.8	61	0.984	1981	99.756	1
5026	3	7.8	61	0.984	1597	99.600	1
5027	3	8.0	61	0.984	1793	99.780	1
5028	3	8.2	61	0.984	1529	99.840	1
5029	3	8.2	61	0.984	1487	99.894	1
5030	1	8.2	54	0.984	3261	99.916	1
5031	2	7.8	57	0.984	2269	99.627	1
5032	1	8.2	82	1.95	1966	99.928	1
5033	0.98	7.8	139	1.95	575	99.947	1
5034	0.98	8.0	284	1.95	232	99.784	1
5035	0.94	7.8	48	1.95	5894	99.330	1
5036	0.94	8.0	82	1.95	2447	99.630	1
5037	0.94	8.1	82	1.95	3467	99.905	1
5038	1	8.0	87	1.01	1669	99.380	1
5039	1	8.0	87	1.01	1607	99.870	1
5040	1	8.1	87	1.01	1633	99.937	1
5041	1	8.1	146	1.01	590	99.939	1
5042	1	8.7	206	1.01	373	99.997	1
5043	1	7.9	304	1.01	130	99.917	1

ID	Q GSFM	CS PPM	CD PPM	XI 10^{9} FT/LB	BETA 10^{4} FT^{-2}	R 0/0	SS
5048	1	7.7	124	5.47	1030	99.906	1
5049	1	7.7	205	5.47	526	99.353	1
5053	0.96	8.0	170	0.984	324	99.936	1
5054	0.96	8.0	73	0.984	1766	99.948	1
5055	0.94	8.1	305	0.984	131	99.719	1
5056	0.96	7.8	48	0.984	3901	99.936	1
5057	0.96	7.8	73	0.984	20700	99.994	2
5058	0.96	8.0	73	0.984	25300	99.955	2
5059	0.96	7.9	73	0.984	29520	99.976	2
5060	0.96	8.0	154	0.984	4620	99.939	2
5061	0.96	8.0	328	0.984	1090	99.938	2
5062	0.96	8.2	52	0.984	52000	99.975	2
5063	0.96	8.2	77	0.984	20140	99.825	2
5091	1	8.1	292	0.984	128	99.974	3
5092	0.98	7.4	211	0.984	213	99.864	3
5093	1	7.9	153	0.984	338	99.861	3
5094	1	7.3	79	0.984	1053	99.977	3
5095	1	8.0	83	0.984	1300	99.955	3
5096	1	7.4	88	0.984	1390	99.916	3
5150	1	8.2	173	5.47	575	99.886	1
5151	1	7.9	147	1.95	644	99.923	1
5152	1	7.9	224	1.95	382	99.956	1
5153	1	7.9	124	1.95	879	99.901	1
5154	1	8.1	79	1.37	2179	99.962	1
5155	1	8.4	209	5.47	686	99.986	1
5156	0.98	8.2	207	5.47	527	99.884	1
6111	0.43	11	19.5	1.95	2927		6
6112	0.43	8.7	21.4	1.95	1244		6
6113	0.43	9.6	20.6	1.95	1939		6
6114	0.47	7.5	13.7	1.95	4468		6
6115	0.48	6	17.3	1.95	2149		6
6116	0.34	6	17.5	1.95	1622		6
6117	0.60	6	17.4	1.95	1789		6
6118	0.77	9	22.7	1.95	960		6
6119	0.77	8	21.5	1.95	771		6
6121	0.58	6	24.3	1.95	327		6
6209	1.11	5.4	20.2	1.95	751		6
6210	1.18	7	23	1.95	734		6
6211	0.96	6.1	20.3	1.95	781		6

ID	Q GSFM	CS PPM	CD PPM	XI 10^9 FT/LB	BETA 10^4 FT^{-2}	R 0/0	SS
6212	0.62	7.5	21.8	1.95	1851		6
6213	0.62	10	21.8	1.95	2889		6
6214	0.58	10	21.8	1.95	1624		6
6215	0.70	8.4	22	1.95	2035		6
6216	0.68	9	22	1.95	2033		6
6217	0.31	5.5	17.6	1.95	2273		6
6218	0.60	6	20.5	1.95	1363		6
6219	0.60	5	22	1.95	635		6
6322	0.77	9.5	21.8	1.95	1430		6
6323	1.04	9	26.4	1.95	818		6
6324	0.97	3	32.4	1.95	102		6
6326	0.77	6.5	20	1.95	619		6
6327	0.74	7.5	22	1.95	1131		6
6328	0.77	8	22	1.95	1243		6
6329	0.77	9.5	29	1.95	570		6
6330	0.86	6.3	21.7	1.95	710		6
6331	0.96	7	25.5	1.95	617		6
6332	0.72	6	21	1.95	1245		6
7003	1	4.4	12.6	5.40	1619	99.975	6
7004	1	4.3	11.5	5.40	2033	100.000	6
7005	1	4.3	22.8	5.40	592	99.999	6
7006	1	9.5	26.2	5.40	1477	99.982	6
7007	1	9.6	43	5.40	599	99.994	6
7008	1	9.3	49	5.40	353	99.997	6
7015	1	2.9	15.4	5.40	3613	99.980	6
7016	1	2.2	13.2	5.40	3780	99.953	6
7017	1	3.3	12.2	5.40	7450	99.953	6
7019	1	5.6	22.8	5.40	1848	99.980	6
7020	1	4.6	38.3	5.40	567	99.968	6
7022	1	4.9	10.2	5.40	7272	100.000	6
7023	1	4.0	67.3	5.40	209	99.998	6

APPENDIX C. SUMMARY OF PREDICTION EQUATIONS

In the following summary:

1. The group of runs used to determine each prediction equation are indicated. For example, the prediction equation for Runs 2009, 2019-2026 was determined from the data of Run 2009 and the Runs inclusively listed from Run 2019 to Run 2026 in Appendix B.

2. The correlation coefficient (R, %) for each prediction equation is indicated.

3. Filter runs were separated into groups for the determination of prediction equations on the basis of filter used, suspensions filtered, and filter aid grade used. The same filter aid grade was used in the filter runs of each group except for the five groups that have a prediction equation that contains ξ. The same suspension (same SS number, Appendix B) was filtered and the same filter used in each group of filter runs except for the group made up of Runs 6111-7023, which includes Lompoc filter runs and Miss Purity filter runs. Softened water was filtered in this group. The filterability of the water filtered in Runs 310030-312100 was not the same as the filterability of the water filtered in Runs 302020-309160. In the former group a small quantity of Cu^{++}, was added to aid in the oxidation of Fe^{++} to Fe^{+++}, and resulted in significantly different filterability.

```
                    SUMMARY OF PREDICTION EQUATIONS
                    ===============================

   RUNS     *                 PREDICTION EQUATION                 * R,0/0
------------*-----------------------------------------------------*-------
            *         7.26       2.00                             *
1203-1215   * BETA = 10     (CS/CD)                               *  99.2
            *                                                     *
            *         7.69       1.96  -0.201                     *
            * BETA = 10     (CS/CD)     CD                        *  99.3
------------*-----------------------------------------------------*-------
            *         7.73       2.38                             *
1304-1315   * BETA = 10     (CS/CD)                               *  97.8
            *                                                     *
            *         8.17       2.11  -0.227                     *
            * BETA = 10     (CS/CD)     CD                        *  97.9
------------*-----------------------------------------------------*-------
            *         3.43      1.96   -0.254   0.491             *
1203-1315   * BETA = 10     (CS/CD)    CD       XI                *  99.6
------------*-----------------------------------------------------*-------
            *         9.58       2.28                             *
1404-1416   * BETA = 10     (CS/CD)                               *  82.9
            *                                                     *
            *         11.81       1.58  -1.06                     *
            * BETA = 10      (CS/CD)    CD                        *  98.8
------------*-----------------------------------------------------*-------
            *         8.90       1.92                             *
2010-2013   * BETA = 10     (CS/CD)                               *  99.0
------------*-----------------------------------------------------*-------
2009,       *         8.98       2.29                             *
2019-2026   * BETA = 10     (CS/CD)                               *  96.6
------------*-----------------------------------------------------*-------
            *         5.09       2.08  0.418                      *
2009-2026   * BETA = 10     (CS/CD)    XI                         *  96.9
------------*-----------------------------------------------------*-------
302020-     *         8.72       2.14                             *
   302800   * BETA = 10     (CS/CD)                               *  98.3
------------*-----------------------------------------------------*-------
303020-     *         8.24       1.67                             *
   303300   * BETA = 10     (CS/CD)                               *  97.4
------------*-----------------------------------------------------*-------
304020-     *         8.34       1.96                             *
   304160   * BETA = 10     (CS/CD)                               *  93.5
------------*-----------------------------------------------------*-------
305020-     *         8.43       1.79                             *
   305160   * BETA = 10     (CS/CD)                               *  99.7
------------*-----------------------------------------------------*-------
```

```
   RUNS    *            PREDICTION EQUATION                 * R,0/0
-----------*------------------------------------------------*-------
309020-    *          8.66        1.76                      *
   309160  * BETA = 10    (CS/CD)                           *  99.9
-----------*------------------------------------------------*-------
310030-    *          8.75        2.02                      *
   310160  * BETA = 10    (CS/CD)                           *  99.9
-----------*------------------------------------------------*-------
312020-    *          8.05        1.47                      *
   312100  * BETA = 10    (CS/CD)                           *  99.7
-----------*------------------------------------------------*-------
302020-    *          8.36        1.79                      *
   309160  * BETA = 10    (CS/CD)                           *  94.8
           *                                                *
           *           9.10        1.13  -0.782             *
           *  BETA = 10    (CS/CD)     CD                   *  96.7
-----------*------------------------------------------------*-------
310030-    *           8.24        1.65                     *
   312100  *  BETA = 10    (CS/CD)                          *  98.9
           *                                                *
           *           8.67        1.32  -0.430             *
           *  BETA = 10    (CS/CD)     CD                   *  99.1
-----------*------------------------------------------------*-------
           *           9.23        2.14                     *
4006-4034  *  BETA = 10    (CS/CD)                          *  97.4
           *                                                *
           *           9.57        1.54  -0.529             *
           *  BETA = 10    (CS/CD)     CD                   *  98.7
-----------*------------------------------------------------*-------
           *           7.80        0.618                    *
5005-5031  *  BETA = 10    (CS/CD)                          *  89.9
-----------*------------------------------------------------*-------
           *           9.33        1.95                     *
5032-5037  *  BETA = 10    (CS/CD)                          *  97.7
-----------*------------------------------------------------*-------
           *           9.26        1.98                     *
5038-5043  *  BETA = 10    (CS/CD)                          *  99.9
-----------*------------------------------------------------*-------
           *           9.05        1.88                     *
5053-5056  *  BETA = 10    (CS/CD)                          *  99.9
-----------*------------------------------------------------*-------
           *           10.41        2.10                    *
5057-5063  *  BETA = 10     (CS/CD)                         *  99.6
-----------*------------------------------------------------*-------
           *           9.05        1.89                     *
5091-5096  *  BETA = 10    (CS/CD)                          *  98.5
-----------*------------------------------------------------*-------
```

```
   RUNS     *              PREDICTION EQUATION                     * R,0/0
------------*------------------------------------------------------*------
            *          8.70          1.431                         *
5150-5156   * BETA = 10     (CS/CD)                                *  95.1
            *                                                      *
            *          7.30          1.61  0.173                   *
            * BETA = 10     (CS/CD)      XI                        *  96.2
------------*------------------------------------------------------*------
5032-5056   *          6.09          1.87  0.335                   *
5150-5156   * BETA = 10     (CS/CD)      XI                        *  98.9
------------*------------------------------------------------------*------
            *          8.14          2.41                          *
6111-6121   * BETA = 10     (CS/CD)                                *  80.3
            *                                                      *
            *          11.15           1.61  -2.59                 *
            * BETA = 10       (CS/CD)      CD                      *  96.2
------------*------------------------------------------------------*------
            *          8.04          1.89                          *
6209-6219   * BETA = 10     (CS/CD)                                *  78.5
            *                                                      *
            *          11.75           2.12  -2.72                 *
            * BETA = 10       (CS/CD)      CD                      *  86.2
------------*------------------------------------------------------*------
            *          7.75          1.67                          *
6322-6332   * BETA = 10     (CS/CD)                                *  92.8
            *                                                      *
            *          9.32          1.36  -1.26                   *
            * BETA = 10     (CS/CD)     CD                         *  94.8
------------*------------------------------------------------------*------
            *          10.20           1.43  -1.86                 *
6111-6332   * BETA = 10       (CS/CD)      CD                      *  91.2
------------*------------------------------------------------------*------
            *          8.04          1.35                          *
7003-7023   * BETA = 10     (CS/CD)                                *  65.4
            *                                                      *
            *          9.33          0.0361  -1.608                *
            * BETA = 10     (CS/CD)        CD                      *  90.4
------------*------------------------------------------------------*------
            *          3.23          0.914  -1.25  0.637           *
6111-7023   * BETA = 10     (CS/CD)       CD      XI               *  85.3
------------*------------------------------------------------------*------
```

APPENDIX D. POPO REFERENCE MANUAL

User Manual

POPO (Program for Optimization of Plant Operation) has been developed for use with the IBM 7074 computer system at Iowa State University. It has been coded in FORTRAN (22), and a FORTRAN list of the entire program is included in this manual. The FORTRAN list includes a generous supply of comment statements (statements that begin with C in column 1) for the purpose of explaining the program and its logic. It is suggested that the FORTRAN list be examined even by those who are not familiar with the FORTRAN computer language.

POPO has been designed to optimize diatomite filtration plant operation by determining the optimum combination of flow rate (q), body feed concentration (C_D), and terminal head loss (H) that will result in potable water at minimum cost. A combination of q, C_D, and H will be indicated in double parentheses, ((q, C_D, H)). POPO will optimize the operation of a particular type of installation filtering a water of known quality (or filterability) using a particular grade of filter aid. Comparison of different types of installations and different types of filter aids requires repeated use of POPO. POPO has been developed for repeated use. Any number of POPO jobs can be processed in one computer run.

POPO can be used to optimize operation of existing plants. When used for this purpose, the body feed concentration will be the main variable to optimize. For existing plants, the unit flow rate (q) is fixed by the total flow through the plant and the available filter area.

The terminal head loss may also be fixed depending on the pumping head available and the type of equipment used to control flow rate through the filters. If the terminal head loss is not fixed, then POPO can be used to determine the optimum combination of flow rate and terminal head loss.

POPO has been designed to be easily modified for special applications. The computation of each of the factors of cost (first cost, filter aid, labor, maintenance, power, and backwashing) and the necessary data input for their computation has been separated into separate subroutines (see FORTRAN list). If it becomes desirable to change the method of computation of any of the factors of cost, this can be accomplished by simply changing the subroutine where the particular cost is computed - - even if the new method of computation requires a different type of data and a different method of data input. The methods of cost computation included in the present program were chosen because they were thought to be more applicable to many different types of installations.

POPO input has been designed to be largely self-explanatory. POPO data sheets have been prepared for the user's convenience (Fig. 12). The POPO data sheet simplifies data card preparation because it is only necessary to write in the values of the specified variables for each job. Each data card image read by POPO is reproduced on the first page of output and serves as a convenient description of the particular job. POPO output for 13 jobs is included in this reference manual for demonstration purposes. The first page of output for each job illustrates the input data cards used and serve as examples of data input.

POPO DATA JOB NO. BY

```
    1 DESIGN FLOW                       MGD
    2 SALVAGE VALUE                     PERCENT FIRST COST
    3 ENERGY CONVERSION                 PERCENT
    4 INTEREST RATE                     PERCENT
    5 PLANT LIFE                        YEARS
    6 SOLIDS (CS)                       PPM
    7 XI INDEX                          FT/LB
    8 TEMPERATURE                       DEGREES F
    9 PRECOAT WEIGHT                    LB/SF
   10 PRECOAT DENSITY                   LB/CF
   11 SEPTUM DIAMETER                   INCHES
   12 BETA PREDICTION
   13 UNIT FLOW RATE                              GSFM
   14 BODY FEED                                   PPM
   15 TERMINAL HEAD                               FT
   16 DIATOMITE COST                    $/TON
   17 FIRST COST              AREA      $/SF






   18 POWER COST                        CENTS/KWH
   19 LABOR COST              AREA      $/SF PER MONTH






   20 BACKWASH COST                     GAL/SF, MIN
     BEGIN
```

Fig. 12. POPO data sheet

Each type of input data card has its own typical card number punched in columns 4 and 5 (Fig. 12) and a brief description of the type of information contained on the card. The card number is referred to as the card index number or card index. This number is used by POPO to determine the type of information contained on the card. There are 21 different card indexes for POPO. The first 20 are indicated on the POPO data sheet. Card index 21 is reserved for input of maintenance cost information. It is not included on the POPO data sheet because maintenance cost is included with labor cost. When POPO is used to process more than one job in one computer run, it may not be necessary to read in all of the input information for each job. Only that information that changes from one job to the next has to be read in.

Comment cards may be included in the input data deck as desired for purposes of explanation or further description. These comment cards will be included in the output with the input data cards, but are ignored by POPO. Any input card that has no index number or has an index number that is not between 1 and 21, inclusively, is treated as a comment card. An example of a comment card can be seen on the first page of output for Job 3. The card that reads

(PREDICTION EQ FOR RUNS 5032-5056, 5150-5156)

is a comment card. Also, the card that reads

JOB 3. SAME AS JOB 2 EXCEPT FOR FOLLOWING

and the blank card that follows it are comment cards. The blank card is included only to improve readability.

CAUTION - - A comment card should not begin with a number or have the letters B or S punched in column 6.

The BEGIN card instructs POPO that all necessary data have been read in and the optimization can begin. The B of BEGIN must be punched in column 6.

A STOP card (with the S of STOP punched in column 6) is optional. It instructs POPO that all jobs have been completed.

Each data card and the information it contains is best explained by considering an example. The input data for Job 1 is listed on the output for Job 1 (see POPO output for Job 1). This data will be used to explain the individual input cards by index number.

1. The design flow for Job 1 is 1 MGD.

2. The salvage value of the plant after 25 years (plant life) is assumed to be 15% of the first cost of the plant.

3. Overall efficiency of converting electrical energy to actual work is assumed to be 70%.

4. The annual interest rate is taken as 4%.

5. A plant life of 25 years is used.

6. The water to be filtered contains 7.5 ppm iron.

7. The filter aid being considered has a ξ index of $1.95\ (10)^9$ ft/# (exponents of 10 are entered by preceeding the exponent with the letter E, $1.95E9 = 1.95\ (10)^9$).

8. The water temperature is 55^oF.

9. The weight of precoat used will be 0.15 #/sf.

10. The in place bulk density of the precoat (γ_p) is taken as 15 #/cf. The value of γ_p used to determine β indexes and the resulting prediction equation should be used. A value of γ_p must be specified on this card even when using flat septa because it is used to determine filter cake

thickness for both flat and cylindrical septa as well as the length of filter run for cylindrical septa.

11. Flat septa are used in Job 1. If cylindrical septa were used, the septum diameter in inches would be punched in the card (see Job 2).

12. This card contains the exponents of the β prediction equation. In this case, the prediction equation is

$$\beta = 10^{9.33}(C_S/C_D)^{1.95}C_D{}^0\xi^0 = 10^{9.33}(C_S/C_D)^{1.95} .$$

13. This card contains respectively the beginning, increment, and final values of unit flow rate to use in making cost comparisons. In this case, the card instructs POPO that costs are to be computed and compared for $q = 0.4, 0.6, 0.8, \ldots, 1.8$ gsfm. If only one value of q is to be considered, only that value is entered (Job 9).

14. Compute and compare costs for body feed concentrations (C_D) of 30, 40, 50, ..., 100 ppm.

15. Compute and compare costs for terminal head losses of 50, 60, 70, ..., 150 ft.

16. Cost of diatomite filter aid delivered to plant is $100 per ton. (Cost at Massena, N. Y. plant is $102 per ton).

17. The first cost card is followed by cards that contain points taken from the first cost ($/sf) - Area (log scale) curve (Fig. 13) for the particular plant. Each point requires a separate card. The cards must be in the order of increasing area, and the last point card must have an asterisk (or some character other than a blank) punched in column 6. For all jobs included in the Output section of this reference manual, the First Cost-Area curve shown in Fig. 13 was used. From this curve (and the input cards of Job 1) first costs are $225/sf for a 100 sf

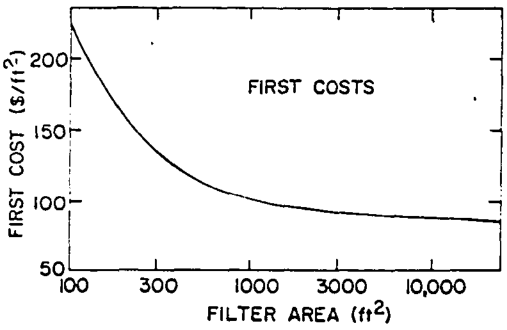


Fig. 13. Cost-Area curve for first cost

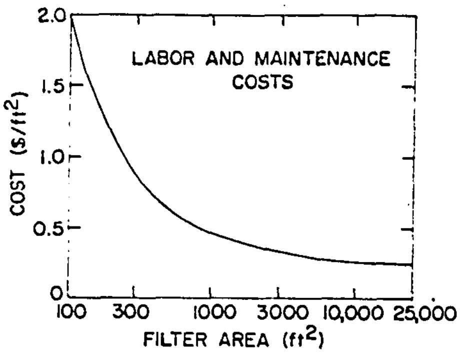


Fig. 14. Cost-Area curve for combined labor and maintenance costs

plant, $160/sf for a 200 sf plant, etc.

18. Power costs for Job 1 are computed on the basis of a unit cost of 2¢/kwh.

19. Same form as first cost input (card index = 17). In the present form of POPO, the-combined cost of labor and maintenance are entered with card index 19. The labor cost card is followed by cards that contain points taken from an appropriate Labor and maintenance cost-Area curve (Fig. 14). For the 13 Jobs included in the Output section of this reference manual, the Labor and maintenance cost-Area curve shown in Fig. 14 was used. From this curve (and the input cards of Job 1), labor and maintenance costs are: for a 100 sf plant, $2.00/sf per month or $200 per month; for a 200 sf plant, $1.15/sf per month or $230 per month; etc.

20. The values contained on this card indicate that 10 gal of backwash water are needed for each sf of filter area each time the filter is washed and the filter is out of operation for 30 minutes each time it

is washed.

Use of POPO requires the preparation of two cost curves (Figs. 13 and 14). Preferably, these curves should be prepared for each particular installation with a known design flow. For example, consider a plant with a design flow of 2 MGD (1 MGD is approximately 700 gpm). To prepare the cost curves, estimates of first cost and monthly labor and maintenance costs could be made for a plant of 1400 sf filtering at 1 gsfm, 2800 sf filtering at 0.5 gsfm, 700 sf filtering at 2 gsfm. The estimated costs are then divided by the filter area and plotted against the filter area (log scale). Smooth curves are then drawn through the points and these curves used to determine first cost and combined labor and maintenance cost for various filter areas (Figs. 13 and 14).

Points from the resulting curves are then used as input data for first cost (card index 17) and monthly labor and maintenance cost (card index 19). The points should be chosen from the curves in such a way that linear interpolation will not result in appreciable error.

If desirable, a log-log plot of cost per unit area versus area can be used for both first cost and labor and maintenance cost. A log-log plot would have less curvature and would probably be better when designing plants of 3 or 4 MGD or less.

When the cost curves are prepared in this way, the cost estimates are based on the total design flow or design capacity of the plant.

An alternative method of preparing the Cost-Area curves (Figs. 13 and 14) is to base the cost estimates on filtration rate rather than plant capacity. In this case, cost estimates for each filter area are made for the same filtration rate, say 1 gsfm.

The Cost-Area curves shown in Figs. 13 and 14 are the same curves respectively shown in Figs. 9 and 10. These curves were determined from cost information that is representative, for the most part, of automated filtration plants filtering at 1 gsfm, and are therefore based on filtration rate rather than plant capacity. These curves were used for all 13 jobs of the POPO computer run included in this manual.

For cases where cost estimates are based on filtration rate, a rate factor has been introduced to compensate for different flow rates. The cost determined from the Cost-Area curves are multiplied by this rate factor. The rate factor is computed on the assumption that costs are 20% greater for each gsfm that the flow rate exceeds 1 gsfm - - e.g., rate factor = 1 at 1 gsfm, rate factor = 1.2 at 2 gsfm, rate factor = 1.4 at 3 gsfm, rate factor = 0.9 at 0.5 gsfm.

It is preferable for accuracy that cost estimates be based on plant capacity rather than filtration rate when designing diatomite filtration plants. This eliminates the need of the rate factor. However, it is more practical to base cost estimates on filtration rate because Cost-Area curves based on filtration rate can be more easily adjusted for use in the subsequent design of other filtration plants.

Two copies of POPO are available. The only difference in the two programs is in the two subroutines where first cost (CFUST, see FORTRAN list) and labor and maintenance cost (CLABR) are computed. In one copy these two subroutines do not include a rate factor (costs based on plant capacity), and in the other, the rate factor is included in these two subroutines (costs based on filtration rate).

The copy of POPO with the rate factor included was used for all 13 jobs included in the Output section.

Annotated POPO output is mostly self-explanatory. On the first page of output for each job (see Output section) are the card images for input data cards for the particular job. The POPO results then follow. The printed results include the ten most economical combinations $((q, C_D, H))$ for β indexes equal to 50, 75, 100, 125, 150, and 175% of those predicted by the prediction equation. Results for different percentages of β index are included because actual β indexes may vary considerably from predicted values depending on the accuracy of the prediction equation.

Final choice of optimum $((q, C_D, H))$ is left up to the designer. Values printed for each of the ten least cost combinations include the flow rate (gsfm), terminal head loss (ft), body feed concentration (ppm), β index ($10^4 ft^{-2}$), length of filter run (hr), terminal cake thickness including precoat thickness (inch), and individual operating costs, total operating cost, first cost, and total cost in dollars per million gallons ($/MG) as well as the total monthly cost ($/mo).

FORTRAN List

```
C                         FORTRAN LIST
C
C  P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION
C
       DIMENSION IN(40),B(4),ANS(13,10)
       COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
      1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
      2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
      3 QMGMO,EFF,CS,BETA,ANS
C
C                           NOMENCLATURE
C    IN=INPUT ARRAY                      UQ=UNIT FLOW, FPH
C    FACTR=BETA MULTIPLICATION           QI,QS,QF=INITIAL,STEP,FINAL
C       FACTOR                              VALUES OF UQ, FPH
C    CD=BODY FEED CON, PPM               TH=TERMINAL HEAD LOSS, FT
C    CDI,CDS,CDF=INITIAL,STEP,           THI,THS,THF=INITIAL,STEP,
C       FINAL VALUES OF CD                  FINAL VALUES OF TH
C    XI=XI INDEX, FT/LB                  B=ARRAY CONTAINING BETA
C    HP=PRECOAT HEAD LOSS, FT               PREDICTION COEFFICIENTS
C    HC=FILTER CAKE HEAD LOSS            VIS=KINEMATIC VISCOSITY,
C    W=PRECOAT WEIGHT, LB/SF                SF/HR
C    XLP=PRECOAT THICKNESS, FT           GP=PRECOAT DENSITY, LB/CF
C    G=GRAVITY, FT/HR/HR                 PHI=PHI
C    RS=SEPTUM RADIUS, FT                RO=R SUB ZERO
C    TR=TIME OF RUN, HR                  THICK=THICKNESS OF FILTER
C    AREA=SEPTUM FILTER AREA, SF            CAKE + XLP, FT
C    RF=RATE FACTOR                      SIGMA=SIGMA
C    CDE=DIATOMITE COST, $/MO            CPO=POWER COST, $/MO
C    CF=FIRST COST, $/MO                 CL=LABOR COST, $/MO
C    CM=MAINTENANCE COST, $/MO           CB=BACKWASH COST, $/MO
C    QGPM=DESIGN FLOW, GPM               COPER=OPERATING COSTS, $/MO
C    CTOTL=TOTAL COST, $/MO              GW= DENSITY OF WATER, LB/CF
C    AMORT=AMORTIZATION FACTOR           QMGMO=DESIGN FLOW, MG/MO
C    EFF=ENERGY CONVERSION               CS=SOLIDS CONCENTRATION,PPM
C       EFFICIENCY                       ANS=ARRAY WHERE RESULTS ARE
C    BETA=BETA INDEX                        STORED UNTIL PRINTED
C
C   COSTS ARE COMPUTED FOR EVERY COMBINATION OF UQ, CD, AND TH.
C   CHEAPEST 10 COMBINATIONS ARE STORED FOR SUBSEQUENT OUTPUT.
C
C   *  SUBROUTINE READR READS IN ALL INPUT DATA
    1 CALL READR
            DO 10 MM=50,175,25
            FACTR=FLOATF(MM)/100.0
C   * * *  COSTS ARE COMPUTED FOR FACTR TIMES PREDICTED BETA
C   * * *  INDEX, WHERE FACTR = 0.50,0.75,1.00,1.25,1.50,1.75
                        UQ=QI-QS
    5                   UQ=UQ+QS
C   * * * * * * * *     STMTS BETWEEN HERE AND STMT 9 REPEATED FOR
C   * * * * * * * *     UQ=QI,QI+QS,QI+QS+QS, ..., QF
```

```
                    IF(UQ-QF)2,2,7
  2                          CD=CDI-CDS
  6                          CD=CD+CDS
C  *  *  *  *  *  *  *  *  * STMTS HERE TO STMNT 9 REPEATED
C  *  *  *  *  *  *  *  *  * FOR CD=CDI,CDI+CDS, ..., CDF
                             IF(CD-CDF)3,3,5
  3                                   TH=THI-THS
  8                                   TH=TH+THS
C  *   *   *   *   *   *   *   *   *  STMNTS FROM HERE TO 9
C  *   *   *   *   *   *   *   *   *  REPEATED FOR TH=THI,
C  *   *   *   *   *   *   *   *   *  THI+THS, ..., THF
                                      IF(TH-THF)4,4,6
  4                                   CALL DIEQS
                                      CALL COSTS
                                      CALL STRES
  9                                   GO TO 8
C  * * *  RESULTS ARE PRINTED FOR EACH VALUE OF FACTR
  7       CALL OUTPT
 10       CONTINUE
      GO TO 1
      END



      SUBROUTINE READR
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C                  READR NOMENCLATURE
C   INDEX=CARD NUMBER, NUMBER        QMGD=DESIGN FLOW, MGD
C      IN COLUMNS 1 TO 4             PCT=SALVAGE VALUE PERCENT
C   RATEI=RATE OF INTEREST           YRS=PLANT LIFE
C
C                    DATA CARD FORMATS
C   1 DESIGN FLOW                         MGD
C   2 SALVAGE VALUE                       PERCENT FIRST COST
C   3 ENERGY CONVERSION                   PERCENT
C   4 INTEREST RATE                       PERCENT
C   5 PLANT LIFE                          YEARS
C   6 SOLIDS  (CS)                        PPM
C   7 XI INDEX                            FT/LB
C   8 TEMPERATURE                         DEGREES F
C   9 PRECOAT WEIGHT                      LB/SF
C  10 PRECOAT DENSITY                     LB/CF
C  11 SEPTUM DIAMETER                     INCHES
C  12 BETA PREDICTION
C  13 UNIT FLOW RATE                                GSFM
```

```
C  14 BODY FEED                                            PPM
C  15 TERMINAL HEAD                                        FT
C  16 DIATOMITE COST          BRANCH TO CDIAT
C  17 FIRST COST              BRANCH TO CFUST
C  18 POWER COST              BRANCH TO CPOWR
C  19 LABOR COST              BRANCH TO CLABR
C  20 BACKWASH COST           BRANCH TO CBAKW
C  21 MAINTENANCE COST        BRANCH TO CMAIN
C    BEGIN
C
      WRITE(2,31)
   31 FORMAT(46H1P C P O -- PROGRAM FOR OPTIMIZATION OF PLANT
     1  9HOPERATION/1H0)
      BIG=1000000.**8.0
C  7TH ROW OF ANS IS INITIALIZED WITH LARGE NUMBER
      DO 100 L=1,10
  100 ANS(7,L)=BIG
      G=32.2*3600.0*3600.0
      GW=62.4
C  CARDS ARE READ WITH ALPHAMERIC FORMAT AND STORED IN IN
C  ARRAY.  5TH ELEMENT OF IN CORRESPONDS TO 6TH COLUMN OF CARD
C  10TH THROUGH 34TH ELEMENTS OF IN CORRESPOND TO 26TH THROUGH
C  50TH COLUMNS OF CARD.  INDEX OR CARD NUMBER IS STORED IN
C  ELEMENTS 1 TO 4 OF IN.  OTHER INPUT NUMBERS (COLUMNS 26-50
C  OF CARD) ARE STORED IN ELEMENTS 10-34 OF IN.  CAUTION.  IF
C  INPUT CARD CONTAINS MORE THAN 1 NUMBER IN COLUMNS 26-50
C  (E.G., CARDS WITH INDEX=12,13,14, OR 15), NUMBERS MUST BE
C  SEPARATED BY BLANK CHARACTERS EXCEPT FOR 1ST CHARACTER
C  FOLLOWING NUMBER -- IT CAN BE ANY CHARACTER OTHER THAN  +
C  -  .  E   OR A DIGIT.
   45 READ(1,40)(IN(I),I=1,40)
      WRITE(2,40)(IN(I),I=1,40)
   40 FORMAT(1X5A1,A4,3A5,25A1,6A5)
C  IF COLUMN 6 CONTAINS B, BRANCH TO 41, OTHERWISE TO 43
      IF(IN(5)-620000000)43,41,43
   41 F1=(1.+RATEI)**YRS
C  AMORT IS AN AMORTIZATION FACTOR THAT CONVERTS PLANT FIRST
C  COST TO A UNIFORM MONTHLY SERIES -- EQUAL MONTHLY PAYMENTS
      AMORT=(RATEI/(F1-1.))*(F1-PCT/100.)/12.
      WRITE(2,30)
   30 FORMAT(1H1, 41HFLOW  TERM   CD  B E T A  TIME  THICK * -
     1 50H---- COSTS, $ PER MILLION GALLONS ------ *   TOTAL/
     2 7X4HHEAD,9X5H4  -2,14X1H*,20X4HLAB+,19X1H*,4X4HCOST /
     3 52H GSFM   FT   PPM  10 FT     HR      IN  * TOTAL   1ST
     4 40H  OPER  MAIN  POWR  DIAT  BAKW *    $/MO/1H
     5 38(1H-),1H*,43(1H-),1H*,8(1H-))
      RETURN
C  IF COLUMN 6 CONTAINS S, STOP, OTHERWISE BRANCH TO 44
   43 IF(IN(5)-820000000)44,42,44
C  VALUE IS A SUBROUTINE THAT DETERMINS VALUE OF NUMBER STORED
```

```
C  IN IN ARRAY IN ALPHAMERIC NOTATION.  THE ARGUMENT SPECIFIES
C  WHICH ELEMENT OF IN ARRAY TO BEGIN WITH.  VALUE(1.0) IS THE
C  CARD INDEX NUMBER.  VALUE(10.0) IS THE FIRST NUMBER IN
C  COLUMNS 26-50 OF CARD.  VALUE(FACTR) IS THE FIRST NUMBER
C  FOLLOWING THE NUMBER JUST DETERMINED BY VALUE SUBROUTINE.
C  FACTR IN THIS USEAGE IS NOT THE BETA MULTIPLICATION FACTOR.
   44 INDEX=VALUE(1.0)
C  IF INDEX IS 1 TO 21, BRANCH TO STMT NUMBER = INDEX,
C  OTHERWISE IGNORE CARD AND READ THE NEXT CARD.  AFTER
C  NUMBERS ON CARD ARE DETERMINED, GO TO 45 AND READ NEXT CARD
      IF(INDEX)45,45,46
   46 IF(INDEX-21)47,47,45
   47 GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,
     1 19,20,21),INDEX
    1 QMGD=VALUE(10.0)
      QMGMO=QMGD*30.4
      QGPM=QMGD*1000000.0/1440.0
      GO TO 45
    2 PCT=VALUE(10.0)
      GO TO 45
    3 EFF=VALUE(10.0)/100.
      GO TO 45
    4 RATEI=VALUE(10.0)/100.
      GO TO 45
    5 YRS=VALUE(10.0)
      GO TO 45
    6 CS=VALUE(10.0)
      GO TO 45
    7 XI=VALUE(10.0)
      GO TO 45
    8 FTEMP=VALUE(10.0)
C  VISCO IS SUBROUTINE THAT CONVERTS TEMP TO VIS
      VIS=VISCO(FTEMP)*3600.0
      GO TO 45
    9 W=VALUE(10.0)
      GO TO 45
   10 GP=VALUE(10.0)
      GO TO 45
   11 RS=VALUE(10.0)/24.0
C  RS=0 FOR FLAT SEPTUM
      GO TO 45
C  ELEMENTS 1 TO 4 OF B ARRAY CONTAIN COEFFICIENTS OF BETA
C  PREDICTION EQUATION
   12 B(1)=VALUE(10.0)
      B(2)=VALUE(FACTR)
      B(3)=VALUE(FACTR)
      B(4)=VALUE(FACTR)
      GO TO 45
C  FACTOR 8.02 CONVERTS GSFM TO FPH
   13 QI=VALUE(10.0)  *8.02
```

```
      QS=VALUE(FACTR) *8.02
C   IF QS=0, ONLY ONE VALUE OF UQ WILL BE USED IN CALCULATIONS.
C   THEREFORE, QS+QI MUST BE GREATER THAN QF.
      IF(QS)50,50,51
   51 QF=VALUE(FACTR) *8.02
      GO TO 45
   50 QS=1.
      QF=QI
      GO TO 45
   14 CDI=VALUE(10.0)
      CDS=VALUE(FACTR)
      IF(CDS)52,52,53
   53 CDF=VALUE(FACTR)
      GO TO 45
   52 CDS=1.
      CDF=CDI
      GO TO 45
   15 THI=VALUE(10.0)
      THS=VALUE(FACTR)
      IF(THS)54,54,55
   55 THF=VALUE(FACTR)
      GO TO 45
   54 THS=1.
      THF=THI
      GO TO 45
   16 CALL CDIAT(1)
      GO TO 45
   17 CALL CFUST(1)
      GO TO 45
   18 CALL CPOWR(1)
      GO TO 45
   19 CALL CLABR(1)
      GO TO 45
   20 CALL CBAKW(1)
      GO TO 45
   21 CALL CMAIN(1)
      GO TO 45
   42 STOP
      END


      FUNCTION VALUE(WHERE)
      DIMENSION IN(40)
      COMMON IN,FACTR
C
C   THIS SUBROUTINE DETERMINES VALUE OF NUMBER STARTING WITH
C   ELEMENT =WHERE= OF IN ARRAY BY USE OF VALU SUBROUTINE.
C   IF TERMINATION CHARACTER (CHARACTER FACTR-1 OF IN ARRAY
C   AFTER RETURNING FROM VALU) IS AN E, MEANS NUMBER JUST AFTER
```

```
C   E IS AN EXPONENT OF 10 FOR NUMBER JUST DETERMINED BY VALU.
C   E.G., NUMBER  1.3E8 ON CARD IS EQUAL TO 130000000.
C
      TEMP=VALU(WHERE)
      M=FACTR
      IF(IN(M-1)-6500000000)1,2,1
    1 VALUE=TEMP
      RETURN
    2 VALUE=TEMP*10.0**VALU(FACTR)
      RETURN
      END



      FUNCTION VALU (WHERE)
      DIMENSION IN(40)
      COMMON IN,FACTR
C
C   THIS SUBROUTINE CONVERTS NUMBER STORED IN IN ARRAY IN
C   ALPHAMERIC FORM TO NUMERIC FORM STARTING WITH ELEMENT WHERE
C   OF IN AND ENDING WITH TERMINATION CHARACTER.  TERMINATION
C   CHARACTERS FOR VALU ARE ANY CHARACTER OTHER THAN  +  -  .
C   OR A DIGIT.  IF NO DIGITS APPEAR BEFORE TERMINATION CHARAC-
C   TER, NUMBER IS TAKEN AS ZERO.
C
      M=WHERE
      VALU =0.0
      DO 40 K=M,34
      IF(IN(K)) 41,40,41
   40 CONTINUE
  122 RETURN
   41 SIGN=1.0
      NUMBR=0
      L=0
    1 M=K
      DO 22 K=M,34
      INK=IN(K)/100000000
A                MSP  INK
   23 IF (INK-20) 24,22,24
   24 IF (INK-30) 27,25,27
   25 SIGN =-1.0
      GO TO 22
   27 IF (INK-15) 29,28,29
   28 L=1
      GO TO 22
   29 IF(INK/10-9)2,38,2
   38 NUMBR=NUMBR*10+INK-90
      IF(L)3,22,3
    3 L=L*10
   22 CONTINUE
```

```
    2 FACTR=K+1
      IF(L)17,17,18
   17 VALU =SIGN*FLOATF(NUMBR)
      GO TO 5
   18 VALU =SIGN*FLOATF(NUMBR)/FLOATF(L)
    5 RETURN
      END



      FUNCTION VISCO(C)
C
C  THIS SUBROUTINE CONVERTS FARENHEIT TEMPERATURE (ARGUMENT C)
C  TO KINEMATIC VISCOSITY IN  SQUARE FEET PER SECOND.
C
      VISCO=(286.405-SQRTF(53671.0-3.1027*(C-152.45)**2))*.0000001
      RETURN
      END



      SUBROUTINE DIEQS
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C  THIS SUBROUTINE BY USE OF BETA PREDICTION EQUATION AND THE
C  DIATOMITE FILTRATION EQUATIONS FINDS AREA, BETA, LENGTH OF
C  FILTER RUN (TR), AND FILTER CAKE THICKNESS (THICK).
C  DILUTION EFFECT IS NEGLECTED IN THE CALCULATIONS.
C
C              DIATOMITE FILTRATION EQUATIONS
C  (ANY SEPTUM)   HP=UQ*XNU*XI*W/G
C  (CYLINDRICAL)  HC=RS*SIGMA*LOGF(1+RS*PHI*TR/RO**2)/PHI
C                 THICK=SQRTF(RO*RO+RS*PHI*TR)-RS
C  (FLAT)         HC=SIGMA*TR
C                 THICK=XLP+PHI*TR/2
C     WHERE  SIGMA=UQ*UQ*XNU*BETA*CD/G
C            PHI=2*UQ*GW*CD*(10)**(-6)/GP
C            RO=RS+XLP
C            XLP=W/GP
C            HC=TH-HP  (EQUIPMENT LOSSES IGNORED)
C
C  PRED IS SUBROUTINE FOR BETA PREDICTION
      BETA=PRED(FACTR)
      PHI=2.0*UQ* GW *CD*.000001/GP
      SIGMA=UQ*UQ*VIS*BETA*CD/G
      AREA=QGPM/(UQ/8.02)
```

```
      XLP=W/GP
      HP=UQ*VIS*XI*W/G
      HC=TH-HP
C   BRANCH TO 1 FOR FLAT SEPTUM, 2 FOR CYLINDRICAL.  (RS IS
C   STORED AS ZERO FOR FLAT SEPTUM)
      IF(RS)2,1,2
    1 TR=HC/SIGMA
      THICK=XLP+PHI*TR/2.0
      GO TO 3
    2 RO=RS+XLP
      TR=RO*RO*(EXPF(HC*PHI/(RS*SIGMA))-1.0)/(RS*PHI)
      THICK=SQRTF(RO*RO+RS*PHI*TR)-RS
    3 RETURN
      END



      FUNCTION PRED(DUMMY)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   THIS SUBROUTINE COMPUTES BETA FROM THE PREDICTION EQUATION.
C   THE ARGUMENT DUMMY IS EQUAL TO FACTR WHEN PRED IS CALLED.
C
      PRED=DUMMY*10.0**B(1)*(CS/CD)**B(2)
      IF(B(3))1,2,1
    1 PRED=PRED*CD**B(3)
    2 IF(B(4))3,4,3
    3 PRED=PRED*XI**B(4)
    4 RETURN
      END



      SUBROUTINE COSTS
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   THIS SUBROUTINE CALLS THE INDIVIDUAL COST SUBROUTINES. ALL
C   THE COSTS ARE COMPUTED AS THE TOTAL FOR ONE MONTH.
C
C   ALL OF THE INPUT AND COST COMPUTATIONS FOR THE INDIVIDUAL
C   COSTS (FIRST, LABOR, MAINTENANCE, DIATOMITE, POWER, AND
C   BACKWASHING) ARE INCLUDED IN SEPARATE SUBROUTINES.  THESE
```

```
C  COST SUBROUTINES HAVE ONE ARGUMENT THAT IS EITHER 1 FOR
C  NECESSARY INPUT FOR THE COMPUTATION OF THE PARTICULAR COST
C  OR 2 FOR THE ACTUAL COMPUTATION.  THESE ARGUMENTS ARE ALL
C  1 WHEN THE COST SUBROUTINES ARE CALLED IN SUBROUTINE READR
C  AND ARE ALL 2 WHEN CALLED FROM SUBROUTINE COSTS.  ALL COSTS
C  ARE COMPUTED ON A MONTHLY BASIS IN THE INDIVIDUAL ROUTINES.
C  THIS WAS DONE SO THAT CHANGES IN THE METHOD OF COMPUTING
C  ANY OF THE COSTS CAN BE MADE WITH THE LEAST DIFFICULTY --
C  I.E., BY CHANGING ONLY THE PARTICULAR SUBROUTINE.
C
      CALL CFUST(2)
      CALL CLABR(2)
      CALL CDIAT(2)
      CALL CMAIN(2)
      CALL CPOWR(2)
      CALL CBAKW(2)
      COPER=CDE+CM+CPO+CL+CB
      CTOTL=CF+COPER
      RETURN
      END



      SUBROUTINE STRES
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C  THIS SUBROUTINE COMPARES CTOTL WITH THE TEN CHEAPEST VALUES
C  OF CTOTL COMPUTED THUS FAR (CTOTL IS STORED IN THE 7TH ROW
C  OF THE ANS ARRAY).  IF CTOTL IS LESS THAN ANY OF THE TEN
C  VALUES STORED, IT IS STORED IN ITS PROPER PLACE IN ANS.
C
      LIMIT=10
C  *  STORE IF ONE OF CHEAPEST 10
      DO 51 K=1,LIMIT
      IF(CTOTL-ANS(7,K))52,51,51
   51 CONTINUE
      RETURN
   52 J=LIMIT
   56 IF(J-K)54,54,53
   53 L=J-1
      DO 55 I=1,13
   55 ANS(I,J)=ANS(I,L)
      J=L
      GO TO 56
C  THE STMTS BELOW ILLUSTRATE WHAT IS STORED IN EACH OF THE 13
C  ROWS OF ANS FOR SUBSEQUENT OUTPUT.
```

```
   54 ANS(1,K)=UQ
      ANS(2,K)=TH
      ANS(3,K)=CD
      ANS(4,K)=BETA
      ANS(5,K)=TR
      ANS(6,K)=THICK
      ANS(7,K)=CTOTL
      ANS(8,K)=CF
      ANS(9,K)=COPER
      ANS(10,K)=CL+CM
      ANS(11,K)=CPO
      ANS(12,K)=CDE
      ANS(13,K)=CB
      RETURN
      END



      SUBROUTINE OUTPT
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C  THIS SUBROUTINE PRINTS THE RESULTS FOR EACH OF THE 6 VALUES
C  OF FACTR.
C
C  *  I=FACTR CONVERTED TO PERCENT
      I=FACTR*100.0
      WRITE(2,1)I
    1 FORMAT(1H028X14HBETA INDEXES =I4,
     1 28H PERCENT OF PREDICTED VALUES)
      DO 2 I=1,10
C  *  UNIT FLOW RATE IS CONVERTED TO GSFM FOR OUTPUT
      ANS(1,I)=ANS(1,I)/8.02
C  *  J=TH, K=CD, L=BETA/10000
      J=ANS(2,I)
      K=ANS(3,I)
      L=ANS(4,I)/10000.0
C  *  CAKE THICKNESS IS CONVERTED TO INCHES FOR OUTPUT
      ANS(6,I)=ANS(6,I)*12.
C  *  M=TOTAL COST PER MONTH
      M=ANS(7,I)
C  *  MONTHLY COSTS ARE CONVERTED TO $/MG BY DIVIDING THE
C  *  MONTHLY COSTS BY THE QUANTITY OF WATER PRODUCED IN
C  *  ONE MONTH IN MG.
      DO 4 KK=7,13
    4 ANS(KK,I)=ANS(KK,I)/QMGMO
    2 WRITE(2,3)ANS(1,I),J,K,L,(ANS(N,I),N=5,13),M
```

```
    3 FORMAT(F5.2,I6,I5,I8,F7.1,F7.2,2H *,7F6.1,2H *,I8)
C   *  THE 7TH ROW OF ANS IS REINITIALIZED FOR THE NEXT VALUE
C   *  OF FACTR.
       BIG=1000000.**8.0
       DO 100 L=1,10
  100  ANS(7,L)=BIG
       RETURN
       END
```

```
      FUNCTION YINT(LIMIT,X,AX,AY)
      DIMENSION AX(50),AY(50)
C
C  THIS SUBROUTINE IS A LINEAR INTERPOLATION ROUTINE.  AY IS
C  THE DEPENDENT VARIABLE ARRAY, AX IS THE INDEPENDENT
C  VARIABLE ARRAY, LIMIT IS THE NUMBER OF ELEMENTS IN ARRAYS
C  AX AND AY, X IS THE VALUE OF X FOR WHICH A CORRESPONDING
C  VALUE OF Y IS DESIRED.  YINT IS THE INTERPOLATED VALUE OF Y
C
      IF(X-AX(1))6,6,5
    6 YINT=AY(1)
      RETURN
    5 DO 1 I=2,LIMIT
      IF(X-AX(I))2,3,1
    1 CONTINUE
    3 YINT=AY(LIMIT)
      GO TO 4
    2 J=I-1
      YINT=AY(J)+(X-AX(J))*(AY(I)-AY(J))/(AX(I)-AX(J))
    4 RETURN
      END
```

```
      SUBROUTINE CFUST(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
      DIMENSION A(50),Z(50)
C  A=LOG(AREA), Z=LOG(FIRST COST PER UNIT AREA,$/SF)
C
C  CFUST IS THE SUBROUTINE WHERE FIRST COST IS COMPUTED.
C  BRANCH TO STMNT 1 FOR INPUT, STMNT 2 FOR COMPUTATION
C  POINTS FROM THE CURVE OF FIRST COST ($/SF) VERSUS AREA (LOG
C  SCALE) ARE READ IN BY THIS SUBROUTINE.  THE POINTS CHOSEN
C  FOR INPUT SHOULD BE SUCH THAT LINEAR INTERPOLATION DOES NOT
C  LEAD TO APPRECIABLE ERROR.  DATA CARD FORMATS FOR INPUT OF
```

```
C  FIRST COST INFORMATION SHOULD BE AS FOLLOWS
C
C  17 FIRST COST                    AREA      $/SF
C                                    100       225
C                                    200       160
C                                    ---       ---
C                                    ---       ---
C    *                             25000        85
C
C  THE NUMBERS WRITTEN IN ABOVE ARE ONLY FOR ILLUSTRATION.
C  ACTUAL NUMBERS ENTERED WILL DEPEND ON THE PARTICULAR FIRST
C  COST-AREA CURVE.  AS MANY AS 50 POINTS FROM THE CURVE MAY
C  BE READ IN.  THE POINTS MUST BE ENTERED SO THAT THE VALUES
C  OF AREA ARE IN ASCENDING ORDER.  CAUTION -- THE LAST DATA
C  POINT CARD MUST HAVE SOME CHARACTER PUNCHED IN COLUMN 6,
C  PREFERRABLY AN ASTERISK * .  COLUMN 6 OF ALL OTHER DATA
C  POINT CARDS MUST BE BLANK.
C
C  FOR EACH DATA POINT READ IN, LOG(AREA) IS STORED IN ITS
C  PROPER POSITION IN ARRAY A, LOG(FIRST COST PER UNIT AREA)
C  IS STORED IN THE CORRSPONDING POSITION IN ARRAY Z.
C  FOR A GIVEN AREA, LOG(AREA) IS COMPUTED AND ITS CORRES-
C  PONDING FIRST COST PER UNIT AREA IS FOUND BY TAKING THE
C  ANILOG OF THE INTERPOLATED VALUE OF LOG(FIRST COST PER UNIT
C  AREA.  THE AMORTIZED FIRST COST IS THEN COMPUTED AS THE
C  FIRST COST PER UNIT AREA TIMES THE AREA TIMES AMORT TIMES A
C  RATE FACTOR (RF).
C
C  FOR PROPER USE OF POPO, THE FIRST COST-AREA CURVE SHOULD BE
C  DETERMINED FOR A PATICULAR TYPE OF INSTALLATION AND A KNOWN
C  DESIGN FLOW.  IN THIS CASE, THE PLANT FIRST COSTS ESTIMATED
C  FOR THE PURPOSE OF DETERMINING THE FIRST COST-AREA CURVE
C  WOULD ALL BE ON THE BASIS OF THE DESIGN FLOW.  IN SUCH A
C  CASE, THE RATE FACTOR SHOULD BE UNITY BECAUSE THE EFFECT OF
C  FLOW RATE IS INCLUDED IN THE ORIGINAL COST ESTIMATES.
C  HOWEVER, IF THE PLANT FIRST COSTS ARE ALL ESTIMATED ON THE
C  BASIS OF A UNIT FLOW RATE OF 1 GSFM, THEN PLANT FIRST COSTS
C  DETERMINED FROM THE RESULTING FIRST COST-AREA CURVE WOULD
C  BE TOO LOW FOR A PLANT FILTERING AT A UNIT FLOW RATE
C  GREATER THAN 1 GSFM BECAUSE PUMPS AND PIPING, BODY FEEDERS,
C  ETC. WOULD HAVE TO BE LARGER TO HANDLE THE LARGER FLOW.  IN
C  THIS CASE, AN ARBITRARY RATE FACTR IS INTRODUCED TO COMPEN-
C  SATE.  IN DETERMINING THIS RATE FACTOR, IT IS ASSUMED THAT
C  THE FIRST COST OF THE PLANT IS INCREASED BY 20 PERCENT FOR
C  EACH GSFM THAT THE UNIT FLOW RATE EXCEEDS 1 GSFM.  THIS
C  RATE FACTOR IS COMPUTED AS    RF=1.+(UQ-8.)/40.
C
      IF(L-1)1,1,2
    1 DO 3 I=1,50
      READ(1,40)(IN(J),J=1,40)
```

```
      WRITE(2,40)(IN(J),J=1,40)
   40 FORMAT(1X5A1,A4,3A5,25A1,6A5)
      TEMP=VALUE(10.0)
      A(I)=LOGF(TEMP)
      TEMP=VALUE(FACTR)
      Z(I)=LOGF(TEMP)
      IF(IN(5))4,3,4
    3 CONTINUE
    4 LIMIT=I
      RETURN
    2 TEMP=LOGF(AREA)
      RF=1.+(UQ-8.)/40.
      TEMP=YINT(LIMIT,TEMP,A(1),Z(1))
      CF=EXPF(TEMP)*AREA*AMORT*RF
      RETURN
      END


      SUBROUTINE CLABR(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
      DIMENSION A(50),Z(50)
C  A=LOG(AREA), Z=LOG(COST OF MAIN+LABOR IN $/MO.SF)
C
C  CLABR IS THE SUBROUTINE WHERE LABOR COST IS COMPUTED.
C  HOWEVER, FOR THE PRESENT TIME, BOTH LABOR AND MAINTENANCE
C  COST ARE COMPUTED TOGETHER IN THIS SUBROUTINE.  INPUT AND
C  COMPUTATION ARE DONE BY THIS SUBROUTINE EXACTLY THE SAME AS
C  IN SUBROUTINE CFUST.  THE ONLY DIFFERENCE IS THE ABSENCE OF
C  THE AMORTIZATION FACTOR (AMORT) IN THIS SUBROUTINE.
C  DATA CARD FORMATS FOR LABOR AND MAINTENANCE COSTS INFOR-
C  MATION INPUT SHOULD BE AS FOLLOWS
C
C  19 LABOR COST              AREA      $/SF PER MONTH
C                              100       2.00
C                              200       1.15
C                              ---        ---
C                              ---        ---
C    *                        4500       0.30
C
C     CAUTION -- ASTERISK (OR SOME CHARACTER) MUST BE PUNCHED
C                IN COLUMN 6 OF LAST DATA POINT CARD.
C
      IF(L-1)1,1,2
    1 DO 3 I=1,50
      READ(1,40)(IN(J),J=1,40)
```

```
      WRITE(2,40)(IN(J),J=1,40)
   40 FORMAT(1X5A1,A4,3A5,25A1,6A5)
      TEMP=VALUE(10.0)
      A(I)=LOGF(TEMP)
      TEMP=VALUE(FACTR)
      Z(I)=LOGF(TEMP)
      IF(IN(5))4,3,4
    3 CONTINUE
    4 LIMIT=I
      RETURN
    2 TEMP=LOGF(AREA)
      TEMP=YINT(LIMIT,TEMP,A(1),Z(1))
      CL=EXPF(TEMP)*AREA*RF
      RETURN
      END


      SUBROUTINE CDIAT(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C     CDIAT IS WHERE DIATOMITE COST IS COMPUTED.  IT IS COMPUTED
C     BY MULTIPLYING THE UNIT COST PER TON TIMES THE NUMBER OF
C     TONS USED PER MONTH FOR PRECOAT AND BODY FEED.  THE NUMBER
C     OF TONS OF PRECOAT AND BODY FEED NEEDED PER MONTH ARE
C             PREDE=W*AREA*24*30.4/(TR*2000)
C             BFDE=CD*QMGMO*8.33/2000
C
C     FOR INPUT, L=1 AND THE UNIT COST OF DIATOMITE IS DETERMINED
C     FROM THE DIATOMITE COST CARD (INDEX=16).  THE FORMAT FOR
C     THIS CARD SHOULD BE AS FOLLOWS
C
C     16 DIATOMITE COST                  100   $/TON
C
C     THE VALUE OF 100 IS SHOWN FOR ILLUSTRATION.  ACTUAL VALUE
C     DEPENDS ON PARTICULAR CASE.
C
      IF(L-1)1,1,2
    1 UCDE=VALUE(10.0)
      F1=  24.*30.4/2000.
      F2=8.33/2000.
      RETURN
    2 PREDE=F1*W*AREA/TR
      BFDE=F2*CD*QMGMO
       CDE=UCDE*(PREDE+BFDE)
      RETURN
```

```
      END


      SUBROUTINE CPOWR(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C  POWER COST IS COMPUTED IN THIS SUBROUTINE.  IT IS COMPUTED
C  ON THE BASIS OF THE DESIGN FLOW RATE BEING PUMPED CON-
C  TINUOUSLY AT THE TERMINAL HEAD LOSS.  A SINGLE VALUE OF
C  CENTS PER KWH IS USED.  AN OVERALL EFFICIENCY OF ENERGY
C  CONVERSION (EFF) IS ASSUMED.  THE MONTHLY ENERGY USE IS
C  COMPUTED AS
C     QGPM*GW*TH*.746*24*30.4/(449*550*EFF)
C  THE MONTHLY COST IS FOUND BY MULTIPLYING THE COST PER KWH
C  (EQUIVALENT TO VALUE(10.)/100. DETERMINED FROM THE POWER
C  COST CARD) TIMES THE KWH OF ENERGY USED IN ONE MONTH.  THE
C  FORMAT FOR THE POWER COST CARD (INDEX=18) SHOULD BE
C
C  18 POWER COST                      1.5  CENTS/KWH
C
C  A VALUE OF 1.5 CENTS PER KWH HAS BEEN INDICATED FOR
C  DEMONSTRATION.  ACTUAL VALUE WOULD DEPEND ON THE PARTICULAR
C  CASE.
C
      IF(L-1)1,1,2
    1 CONST=(VALUE(10.)/100.)*GW*.746*24.*30.4/(449.*550.)
      RETURN
    2 CPO=CONST*TH*QGPM/EFF
      RETURN
      END


      SUBROUTINE CMAIN(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C  CMAIN IS THE SUBROUTINE WHERE MAINTENANCE COST WOULD
C  ORDINARILY BE COMPUTED.  HOWEVER, IN THE PRESENT FORM OF
C  THE PROGRAM, MAINTENANCE COST IS INCLUDED WITH LABOR COST,
C  AND THEREFORE, COMPUTED IN CLABR.  THE PRESENT CMAIN
C  SUBROUTINE PERFORMS NO MAINTENANCE COST COMPUTATIONS. IT IS
```

```
C  INCLUDED JUST IN CASE IT BECOMES DESIREABLE TO SEPARATE
C  LABOR AND MAINTENANCE COSTS COMPUTATION IN THE FUTURE.  A
C  MAINTENANCE COST CARD (CARD INDEX 21) IS NOT NEEDED FOR THE
C  PROGRAM IN ITS PRESENT FORM.
C
C  *  L=1 FOR INPUT AND 2 FOR COMPUTATION
C  *  NO INPUT FOR PRESENT FORM OF SUBROUTINE
C  *  CM SET = TO 0 BECAUSE IT IS ADDED TO THE OTHER COSTS IN
C  *  SUBROUTINE COSTS.  CM IS INCLUDED IN CL AND THEREFORE CM
C  *  MUST BE ZEROED.
      IF(L-1)1,1,2
    1 RETURN
    2 CM=0.0
      RETURN
      END



      SUBROUTINE CBAKW(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C  BACKWASHING COSTS ARE COMPUTED IN THIS SUBROUTINE.  DURING
C  FILTERING OPERATION, THE QUANTITY OF WATER USED FOR WASHING
C  THE FILTERS AND THE QUANTITY OF WATER THAT WOULD HAVE BEEN
C  FILTERED DURING FILTER DOWN TIME (FOR WASHING) MUST ALSO BE
C  FILTERED IF COST COMPARISONS ARE TO BE BASED ON THE SAME
C  QUANTITY OF FINISHED WATER LEAVING THE PLANT.  THUS, THE
C  UNIT FLOW RATE WOULD HAVE TO BE INCREASED SLIGHTLY.  IT IS
C  ASSUMED THAT FILTERING BAKWASH WATER INCREASES CDE, CL, CM,
C  CB PROPORTIONATELY, AND THAT FILTERING WATER NOT FILTERED
C  WHEN WASHING INCREASES CL, CM, CDE, CB PROPORTIONATELY. THE
C  RESPECTIVE FRACTIONAL INCREASES ARE TAKEN AS THE RATIO OF
C  THE BACKWASH WATER USED PER MONTH TO THE FINISHED WATER
C  PRODUCED PER MONTH (BWMGM/QMGMO) AND THE RATIO OF BACKWASH
C  DOWN TIME TO LENGTH OF FILTER RUN (BWT/TR).  THE FORMAT FOR
C  THE BACKWASH COST CARD (INDEX=20) SHOULD BE
C
C  20 BACKWASH COST           10, 30     GAL/SF, MIN
C
C  VALUES OF 10 GAL/SF AND 30 MIN HAVE BEEN INDICATED FOR
C  DEMONSTRATION.
C
C                    CBAKW NOMENCLATURE
C   BWGSF=BACKWASH WATER NEEDED     BWMGM=BACKWASH WATER NEEDED
C      IN GAL/SF                       IN MG/MO
C   CB1=COST OF BACKWASH WATER      CB2=COST PER MONTH FOR
```

```
C       PER MONTH                                   FILTERING WATER NOT
C    BWT=BACKWASH DOWN TIME, HR                     FILTERED DURING DOWN
C                                                   TIME FOR WASHING
      IF(L-1)1,1,2
    1 BWGSF=VALUE(10.0)
      F1=   BWGSF*24.*30.4*.000001
      BWT=VALUE(FACTR)/60.
      RETURN
    2 BWMGM=F1*AREA/TR
      F3=BWMGM/QMGMO
      F4=BWT/TR
      CB1=F3*(CDE+CL+CM+CPO)
      CB2=F4*(CL+CM+CDE+CB1)
      CB=F3*(CDE+CL+CM+CPO+CB1+CB2)+F4*(CL+CM+CDE+CB1+CB2)
      RETURN
      END
```

Output (Examples)

```
P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

        JOB 1.  IRON REMOVAL

  1 DESIGN FLOW                  1      MGD
  2 SALVAGE VALUE               15      PERCENT FIRST COST
  3 ENERGY CONVERSION           70      PERCENT
  4 INTEREST RATE                4      PERCENT
  5 PLANT LIFE                  25      YEARS
  6 SOLIDS  (CS)               7.5      PPM
  7 XI INDEX                1.95E9      FT/LB
  8 TEMPERATURE                 55      DEGREES F
  9 PRECOAT WEIGHT            0.15      LB/SF
 10 PRECOAT DENSITY             15      LB/CF
 11 SEPTUM DIAMETER           FLAT      INCHES
 12 BETA PREDICTION         9.33/1.95/0/0
 13 UNIT FLOW RATE          0.4/0.2/1.8          GSFM
 14 BODY FEED               30/10/100            PPM
 15 TERMINAL HEAD           50/10/150            FT
 16 DIATOMITE COST             100      $/TON
 17 FIRST COST              AREA        $/SF
                             100         225
                             200         160
                             350         128
                             600         110
                            1000         100
                            2000          94
  *                        25000          85
 18 POWER COST                   2      CENTS/KWH
 19 LABOR COST              AREA        $/SF PER MONTH
                             100         2.00
                             200         1.15
                             300         0.83
                             500         0.63
                             800         0.50
                            2000         0.37
                            4500         0.30
                           13000         0.25
  *                        25000         0.24
 20 BACKWASH COST           10, 30      GAL/SF, MIN
   BEGIN
```

```
                                      JOB 1


FLOW  TERM   CD  B E T A  TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD         4  -2                *                     LAB+                 *    COST
GSFM   FT   PPM  10 FT     HR      IN   * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
------------------------------------------*-----------------------------------------*--------

                          BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.80   150   30    7160   15.0   0.26 *  65.9  14.2  51.7  13.3  13.5  22.9   2.0 *    2002
0.80   140   30    7160   14.0   0.25 *  65.9  14.2  51.7  13.3  12.6  23.7   2.2 *    2003
0.80   130   30    7160   13.0   0.24 *  66.1  14.2  51.9  13.3  11.7  24.5   2.4 *    2008
0.80   120   30    7160   12.0   0.24 *  66.4  14.2  52.3  13.3  10.8  25.5   2.6 *    2019
1.00   150   30    7160    9.6   0.24 *  66.6  12.3  54.3  12.3  13.5  25.5   3.1 *    2024
0.80   130   40    4086   17.1   0.34 *  66.8  14.2  52.7  13.3  11.7  25.8   1.8 *    2031
0.80   120   40    4086   15.8   0.32 *  66.9  14.2  52.7  13.3  10.8  26.6   2.0 *    2033
0.80   140   40    4086   18.4   0.36 *  66.9  14.2  52.7  13.3  12.6  25.1   1.7 *    2034
1.00   140   30    7160    9.0   0.23 *  66.9  12.3  54.6  12.3  12.6  26.4   3.3 *    2034
1.00   150   40    4086   12.6   0.32 *  66.9  12.3  54.6  12.3  13.5  26.6   2.3 *    2035

                          BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80   150   40    6129   13.2   0.29 *  72.1  14.2  58.0  13.3  13.5  28.5   2.6 *    2192
0.80   140   40    6129   12.3   0.28 *  72.3  14.2  58.1  13.3  12.6  29.4   2.8 *    2198
0.80   150   30   10740   10.0   0.22 *  72.5  14.2  58.4  13.3  13.5  28.1   3.4 *    2205
0.60   150   30   10740   17.8   0.25 *  72.6  17.4  55.2  15.5  13.5  24.2   2.0 *    2207
0.80   130   40    6129   11.4   0.27 *  72.7  14.2  58.5  13.3  11.7  30.4   3.1 *    2209
0.60   140   30   10740   16.6   0.24 *  72.7  17.4  55.3  15.5  12.6  25.0   2.2 *    2211
0.60   130   30   10740   15.4   0.23 *  73.0  17.4  55.6  15.5  11.7  26.0   2.4 *    2219
0.80   140   30   10740    9.3   0.21 *  73.1  14.2  58.9  13.3  12.6  29.2   3.8 *    2222
0.80   120   40    6129   10.5   0.25 *  73.3  14.2  59.1  13.3  10.8  31.5   3.5 *    2227
0.60   130   40    6129   20.3   0.31 *  73.4  17.4  56.0  15.5  11.7  26.9   1.9 *    2231

                          BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.60   150   40    8172   17.5   0.29 *  77.2  17.4  59.8  15.5  13.5  28.5   2.3 *    2346
0.80   150   40    8172    9.9   0.25 *  77.3  14.2  63.2  13.3  13.5  32.5   3.8 *    2350
0.60   140   40    8172   16.4   0.28 *  77.3  17.4  59.9  15.5  12.6  29.4   2.5 *    2351
0.60   150   30   14321   13.3   0.22 *  77.5  17.4  60.1  15.5  13.5  28.1   3.0 *    2355
0.60   130   40    8172   15.2   0.27 *  77.7  17.4  60.2  15.5  11.7  30.4   2.7 *    2360
0.80   150   50    5289   12.2   0.32 *  77.8  14.2  63.6  13.3  13.5  33.6   3.1 *    2364
0.80   140   40    8172    9.2   0.24 *  77.9  14.2  63.8  13.3  12.6  33.6   4.2 *    2369
0.60   140   30   14321   12.5   0.21 *  78.0  17.4  60.6  15.5  12.6  29.2   3.3 *    2370
0.80   140   50    5289   11.4   0.30 *  78.1  14.2  63.9  13.3  12.6  34.6   3.4 *    2373
0.60   120   40    8172   14.0   0.25 *  78.2  17.4  60.8  15.5  10.8  31.5   3.0 *    2376

                          BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.60   150   40   10215   14.0   0.25 *  80.9  17.4  63.5  15.5  13.5  31.5   3.0 *    2460
0.60   140   40   10215   13.1   0.25 *  81.4  17.4  64.0  15.5  12.6  32.6   3.3 *    2473
0.60   150   50    6611   17.3   0.33 *  81.7  17.4  64.3  15.5  13.5  32.8   2.5 *    2484
0.60   140   50    6611   16.2   0.31 *  81.9  17.4  64.5  15.5  12.6  33.7   2.7 *    2489
0.60   130   40   10215   12.2   0.24 *  82.0  17.4  64.6  15.5  11.7  33.8   3.6 *    2493
0.80   150   50    6611    9.8   0.28 *  82.1  14.2  67.9  13.3  13.5  36.8   4.2 *    2494
0.60   130   50    6611   15.0   0.30 *  82.2  17.4  64.8  15.5  11.7  34.7   3.0 *    2500
0.60   150   30   17901   10.7   0.20 *  82.5  17.4  65.1  15.5  13.5  32.0   4.1 *    2507
0.80   140   50    6611    9.1   0.27 *  82.7  14.2  68.5  13.3  12.6  38.0   4.6 *    2514
0.80   150   40   10215    7.9   0.22 *  82.7  14.2  68.5  13.3  13.5  36.5   5.3 *    2514

                          BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.60   150   40   12258   11.7   0.23 *  84.8  17.4  67.3  15.5  13.5  34.5   3.9 *    2576
0.60   150   50    7933   14.5   0.29 *  84.8  17.4  67.4  15.5  13.5  35.2   3.2 *    2577
0.60   140   50    7933   13.5   0.28 *  85.2  17.4  67.8  15.5  12.6  36.3   3.4 *    2589
0.60   140   40   12258   10.9   0.22 *  85.5  17.4  68.1  15.5  12.6  35.7   4.3 *    2599
0.60   130   50    7933   12.5   0.27 *  85.8  17.4  68.4  15.5  11.7  37.5   3.8 *    2609
0.60   150   60    5559   17.2   0.37 *  86.2  17.4  68.8  15.5  13.5  37.1   2.7 *    2621
0.60   140   60    5559   16.0   0.35 *  86.4  17.4  69.0  15.5  12.6  38.0   2.9 *    2627
0.80   150   50    7933    8.1   0.25 *  86.5  14.2  72.3  13.3  13.5  40.0   5.4 *    2628
0.60   130   40   12258   10.1   0.22 *  86.5  17.4  69.1  15.5  11.7  37.2   4.7 *    2630
0.60   120   50    7933   11.6   0.26 *  86.7  17.4  69.3  15.5  10.8  38.8   4.2 *    2636

                          BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.60   150   50    9255   12.4   0.27 *  87.9  17.4  70.5  15.5  13.5  37.6   3.9 *    2672
0.60   140   50    9255   11.6   0.26 *  88.6  17.4  71.2  15.5  12.6  38.8   4.2 *    2692
0.60   150   40   14301   10.0   0.22 *  88.7  17.4  71.3  15.5  13.5  37.4   4.8 *    2695
0.60   150   60    6486   14.7   0.33 *  88.8  17.4  71.4  15.5  13.5  39.1   3.3 *    2700
0.60   140   60    6486   13.7   0.32 *  89.2  17.4  71.8  15.5  12.6  40.1   3.6 *    2712
0.60   130   50    9255   10.7   0.25 *  89.5  17.4  72.1  15.5  11.7  40.2   4.7 *    2720
0.60   140   40   14301    9.4   0.21 *  89.7  17.4  72.3  15.5  12.6  38.9   5.3 *    2728
0.60   130   60    6486   12.8   0.30 *  89.9  17.4  72.4  15.5  11.7  41.3   3.9 *    2731
0.40   150   40   14301   22.6   0.26 *  89.9  24.1  65.8  19.5  13.5  30.5   2.4 *    2733
0.40   140   40   14301   21.1   0.25 *  90.2  24.1  66.1  19.5  12.6  31.5   2.6 *    2742
```

```
                    JOB 2.  SAME AS JOB 1 EXCEPT FOR USE OF 1 INCH
                            DIAMETER SEPTA  (CYLINDRICAL)

                 11 SEPTUM DIAMETER               1  INCH
                   BEGIN
               ____________________________________________________

FLOW  TERM    CO.  B E T A  TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD          4  -2                *                      LAB+                  *    COST
GSFM   FT    PPM  10 FT       HR      IN  * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
-----------------------------------------*-----------------------------------------*--------

                              BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.00   130   30    7160    15.7    0.26 *  58.3  12.3  45.9  12.3  11.7  20.4    1.6 *     1770
1.00   140   30    7160    17.2    0.27 *  58.3  12.3  46.0  12.3  12.6  19.8    1.4 *     1772
1.00   120   30    7160    14.3    0.25 *  58.4  12.3  46.0  12.3  10.8  21.2    1.8 *     1774
1.00   150   30    7160    18.8    0.28 *  58.5  12.3  46.2  12.3  13.5  19.2    1.3 *     1777
0.80   120   30    7160    23.5    0.28 *  58.6  14.2  44.4  13.3  10.8  19.2    1.1 *     1780
0.80   110   30    7160    21.1    0.27 *  58.6  14.2  44.4  13.3   9.9  19.9    1.3 *     1780
1.00   110   30    7160    12.9    0.23 *  58.7  12.3  46.3  12.3   9.9  22.2    2.0 *     1783
0.80   130   30    7160    25.9    0.30 *  58.7  14.2  44.5  13.3  11.7  18.5    1.0 *     1784
0.80   100   30    7160    18.7    0.25 *  58.8  14.2  44.6  13.3   9.0  20.8    1.4 *     1786
1.00   110   40    4086    19.4    0.33 *  58.9  12.3  46.6  12.3   9.9  23.1    1.3 *     1790

                              BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80   140   30   10740    17.3    0.24 *  63.3  14.2  49.1  13.3  12.6  21.5    1.6 *     1923
0.80   150   30   10740    18.8    0.25 *  63.3  14.2  49.1  13.3  13.5  20.8    1.5 *     1924
0.80   130   30   10740    15.8    0.23 *  63.4  14.2  49.2  13.3  11.7  22.4    1.8 *     1927
1.00   140   40    6129    15.7    0.30 *  63.5  12.3  51.2  12.3  12.6  24.6    1.8 *     1931
1.00   150   40    6129    17.1    0.31 *  63.6  12.3  51.3  12.3  13.5  24.0    1.6 *     1932
1.00   130   40    6129    14.3    0.28 *  63.6  12.3  51.3  12.3  11.7  25.4    2.0 *     1934
0.80   120   40    6129    21.4    0.31 *  63.6  14.2  49.5  13.3  10.8  24.0    1.4 *     1934
0.80   130   40    6129    23.8    0.33 *  63.6  14.2  49.5  13.3  11.7  23.2    1.2 *     1934
0.80   120   30   10740    14.4    0.22 *  63.7  14.2  49.5  13.3  10.8  23.3    2.1 *     1936
1.00   150   30   10740    11.5    0.22 *  63.8  12.3  51.4  12.3  13.5  23.3    2.4 *     1938

                              BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.80   140   40    8172    18.1    0.28 *  67.1  14.2  52.9  13.3  12.6  25.3    1.7 *     2040
0.80   150   40    8172    19.7    0.30 *  67.1  14.2  52.9  13.3  13.5  24.6    1.6 *     2040
0.80   130   40    8172    16.5    0.27 *  67.3  14.2  53.1  13.3  11.7  26.1    1.9 *     2044
0.80   150   30   14321    13.4    0.22 *  67.5  14.2  53.3  13.3  13.5  24.2    2.3 *     2051
0.80   120   40    8172    14.9    0.26 *  67.6  14.2  53.4  13.3  10.8  27.1    2.2 *     2054
1.00   150   40    8172    12.0    0.26 *  67.7  12.3  55.3  12.3  13.5  27.1    2.5 *     2056
0.80   140   30   14321    12.4    0.21 *  67.8  14.2  53.6  13.3  12.6  25.1    2.6 *     2060
1.00   140   40    8172    11.0    0.25 *  68.0  12.3  55.6  12.3  12.6  28.0    2.8 *     2065
0.80   110   40    8172    13.5    0.25 *  68.1  14.2  54.0  13.3   9.9  28.3    2.5 *     2071
0.80   130   50    5289    23.2    0.37 *  68.1  14.2  54.0  13.3  11.7  27.6    1.4 *     2071

                              BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.80   150   40   10215    15.0    0.26 *  70.3  14.2  56.1  13.3  13.5  27.1    2.2 *     2137
0.80   140   40   10215    13.8    0.25 *  70.6  14.2  56.4  13.3  12.6  28.0    2.4 *     2144
0.80   150   50    6611    20.8    0.35 *  70.9  14.2  56.7  13.3  13.5  28.3    1.6 *     2155
0.80   140   50    6611    19.0    0.33 *  70.9  14.2  56.7  13.3  12.6  29.0    1.8 *     2156
0.80   130   40   10215    12.6    0.24 *  71.0  14.2  56.8  13.3  11.7  29.1    2.7 *     2158
0.80   130   50    6611    17.2    0.31 *  71.1  14.2  56.9  13.3  11.7  29.9    2.0 *     2160
0.80   120   50    6611    15.6    0.30 *  71.4  14.2  57.2  13.3  10.8  30.9    2.3 *     2171
0.60   140   40   10215    26.2    0.30 *  71.5  17.4  54.1  15.5  12.6  24.6    1.4 *     2172
0.60   130   40   10215    23.8    0.28 *  71.5  17.4  54.1  15.5  11.7  25.4    1.5 *     2174
1.00   150   50    6611    12.4    0.30 *  71.5  12.3  59.2  12.3  13.5  30.9    2.6 *     2174

                              BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.80   150   50    7933    16.4    0.30 *  73.5  14.2  59.3  13.3  13.5  30.4    2.1 *     2234
0.80   150   40   12258    12.0    0.23 *  73.6  14.2  59.4  13.3  13.5  29.7    2.9 *     2236
0.80   140   50    7933    15.0    0.29 *  73.7  14.2  59.5  13.3  12.6  31.2    2.4 *     2240
0.60   150   40   12258    22.7    0.28 *  73.9  17.4  56.5  15.5  13.5  25.8    1.6 *     2245
0.60   140   40   12258    20.8    0.26 *  74.0  17.4  56.5  15.5  12.6  26.7    1.8 *     2248
0.80   140   40   12258    11.1    0.23 *  74.1  14.2  59.9  13.3  12.6  30.8    3.3 *     2252
0.80   130   50    7933    13.7    0.28 *  74.1  14.2  59.9  13.3  11.7  32.2    2.7 *     2252
0.60   130   40   12258    19.0    0.25 *  74.2  17.4  56.8  15.5  11.7  27.6    2.0 *     2255
0.60   120   40   12258    17.3    0.24 *  74.7  17.4  57.2  15.5  10.8  28.7    2.3 *     2269
0.60   150   30   21481    15.6    0.20 *  74.7  17.4  57.3  15.5  13.5  25.9    2.4 *     2269

                              BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.80   150   50    9255    13.5    0.27 *  76.1  14.2  62.0  13.3  13.5  32.4    2.7 *     2314
0.60   150   40   14301    18.8    0.25 *  76.2  17.4  58.8  15.5  13.5  27.7    2.1 *     2316
0.60   140   40   14301    17.3    0.24 *  76.5  17.4  59.1  15.5  12.6  28.7    2.3 *     2324
0.80   140   50    9255    12.4    0.26 *  76.6  14.2  62.4  13.3  12.6  33.4    3.0 *     2327
0.60   150   50    9255    26.0    0.33 *  76.7  17.4  59.3  15.5  13.5  28.8    1.5 *     2332
0.60   140   50    9255    23.8    0.32 *  76.8  17.4  59.3  15.5  12.6  29.6    1.7 *     2333
0.80   150   60    6486    17.8    0.35 *  76.9  14.2  62.7  13.3  13.5  33.8    2.1 *     2336
0.60   130   50    9255    21.6    0.30 *  76.9  17.4  59.5  15.5  11.7  30.5    1.9 *     2338
0.80   150   40   14301    10.0    0.22 *  76.9  14.2  62.8  13.3  13.5  32.2    3.7 *     2339
0.60   130   40   14301    15.9    0.23 *  76.9  17.4  59.5  15.5  11.7  29.8    2.5 *     2339
```

```
                    JOB 3.  SAME AS JOB 2 EXCEPT FOR FOLLOWING

                     1 DESIGN FLOW                 7      MGD
                     7 XI INDEX                1.95E9     FT/LB  (CELITE 503)
                    11 SEPTUM DIAMETER           3.5      INCHES
                    12 BETA PREDICTION       6.09/1.87/0/0.335
                           (PREDICTION EQ FOR RUNS 5032-5056, 5150-5156)
                    18 POWER COST                1.5      CENTS/KWH
                      BEGIN
                   ___________________________________________________________

FLOW  TERM   CD  B E T A  TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *    TOTAL
      HEAD         4  -2                 *                      LAB+                    *     COST
GSFM   FT   PPM  10 FT     HR       IN   * TOTAL   1ST  OPER   MAIN  POWR  DIAT   BAKW *     $/MO
-----------------------------------------*----------------------------------------------*--------

                                BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.00   150   30    5960   14.3   0.27 *  50.1  10.4  39.6    6.8  10.1  21.3    1.5 *    10650
1.00   140   30    5960   13.2   0.26 *  50.2  10.4  39.8    6.8   9.4  21.9    1.6 *    10683
1.00   130   30    5960   12.2   0.25 *  50.5  10.4  40.1    6.8   8.8  22.7    1.8 *    10744
0.80   140   30    5960   21.1   0.30 *  50.6  12.4  38.2    7.8   9.4  19.9    1.1 *    10769
0.80   150   30    5960   22.8   0.31 *  50.7  12.4  38.2    7.8  10.1  19.4    1.0 *    10778
1.20   150   30    5960    9.8   0.25 *  50.7   9.1  41.5    6.1  10.1  23.2    2.2 *    10781
0.80   130   30    5960   19.5   0.29 *  50.7  12.4  38.3    7.8   8.8  20.5    1.2 *    10782
0.80   120   30    5960   17.8   0.27 *  50.9  12.4  38.4    7.8   8.1  21.3    1.3 *    10822
1.00   120   30    5960   11.2   0.24 *  51.0  10.4  40.5    6.8   8.1  23.6    2.0 *    10842
1.20   140   30    5960    9.1   0.24 *  51.0   9.1  41.9    6.1   9.4  24.0    2.4 *    10859

                                BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80   150   30    8940   14.7   0.25 *  55.2  12.4  42.8    7.8  10.1  23.1    1.7 *    11744
0.80   140   30    8940   13.6   0.24 *  55.5  12.4  43.1    7.8   9.4  24.0    1.9 *    11810
0.80   130   30    8940   12.6   0.23 *  56.0  12.4  43.6    7.8   8.8  24.9    2.1 *    11910
1.00   150   30    8940    9.3   0.22 *  56.0  10.4  45.6    6.8  10.1  26.0    2.7 *    11921
1.00   150   40    5220   12.4   0.30 *  56.1  10.4  45.7    6.8  10.1  26.8    2.1 *    11943
0.80   150   40    5220   19.8   0.34 *  56.2  12.4  43.8    7.8  10.1  24.6    1.3 *    11958
0.80   140   40    5220   18.3   0.33 *  56.3  12.4  43.9    7.8   9.4  25.2    1.4 *    11976
1.00   140   40    5220   11.5   0.28 *  56.5  10.4  46.0    6.8   9.4  27.6    2.3 *    12012
0.80   130   40    5220   16.9   0.31 *  56.5  12.4  44.1    7.8   8.8  25.9    1.6 *    12020
0.60   150   30    8940   26.7   0.29 *  56.6  15.7  40.9    9.5  10.1  20.3    1.0 *    12040

                                BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.80   150   40    6961   14.4   0.29 *  59.8  12.4  47.4    7.8  10.1  27.5    2.0 *    12726
0.80   150   30   11920   10.8   0.21 *  59.9  12.4  47.5    7.8  10.1  26.9    2.6 *    12745
0.60   150   30   11920   19.6   0.25 *  59.9  15.7  44.2    9.5  10.1  23.1    1.5 *    12750
0.80   140   40    6961   13.4   0.27 *  60.2  12.4  47.8    7.8   9.4  28.3    2.2 *    12805
0.60   140   30   11920   18.2   0.24 *  60.2  15.7  44.5    9.5   9.4  24.0    1.6 *    12811
0.80   140   30   11920   10.1   0.21 *  60.6  12.4  48.2    7.8   9.4  28.0    2.9 *    12892
0.60   130   30   11920   16.8   0.23 *  60.6  15.7  45.0    9.5   8.8  24.9    1.8 *    12904
0.80   130   40    6961   12.3   0.26 *  60.7  12.4  48.3    7.8   8.8  29.3    2.4 *    12919
1.00   150   40    6961    9.1   0.25 *  60.9  10.4  50.5    6.8  10.1  30.5    3.1 *    12960
0.60   150   40    6961   26.4   0.34 *  61.0  15.7  45.3    9.5  10.1  24.6    1.1 *    12976

                                BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.60   150   30   14901   15.4   0.22 *  63.3  15.7  47.6    9.5  10.1  26.0    2.1 *    13476
0.80   150   40    8701   11.3   0.25 *  63.5  12.4  51.1    7.8  10.1  30.5    2.7 *    13517
0.60   150   40    8701   20.6   0.30 *  63.6  15.7  47.9    9.5  10.1  26.8    1.6 *    13535
0.60   140   40    8701   19.1   0.28 *  63.9  15.7  48.2    9.5   9.4  27.6    1.7 *    13592
0.60   140   30   14901   14.4   0.21 *  63.9  15.7  48.2    9.5   9.4  27.0    2.3 *    13594
0.80   140   40    8701   10.5   0.24 *  64.2  12.4  51.8    7.8   9.4  31.5    3.0 *    13659
0.60   130   40    8701   17.6   0.27 *  64.3  15.7  48.6    9.5   8.8  28.5    1.9 *    13681
0.80   150   50    5732   14.3   0.32 *  64.3  12.4  51.9    7.8  10.1  31.8    2.2 *    13688
0.60   130   30   14901   13.3   0.21 *  64.6  15.7  49.0    9.5   8.8  28.2    2.5 *    13754
0.80   140   50    5732   13.2   0.31 *  64.7  12.4  52.3    7.8   9.4  32.6    2.4 *    13777

                                BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.60   150   40   10441   16.9   0.27 *  66.3  15.7  50.6    9.5  10.1  29.0    2.0 *    14104
0.60   140   40   10441   15.7   0.26 *  66.8  15.7  51.1    9.5   9.4  29.9    2.2 *    14205
0.60   150   30   17881   12.8   0.20 *  66.8  15.7  51.1    9.5  10.1  28.8    2.7 *    14219
0.80   150   40   10441    9.3   0.23 *  67.3  12.4  54.9    7.8  10.1  33.4    3.6 *    14330
0.60   130   40   10441   14.5   0.25 *  67.4  15.7  51.7    9.5   8.8  31.0    2.5 *    14346
0.80   150   50    6879   11.7   0.29 *  67.4  12.4  55.0    7.8  10.1  34.2    2.9 *    14349
0.60   150   50    6879   21.4   0.35 *  67.5  15.7  51.8    9.5  10.1  30.6    1.6 *    14362
0.60   140   30   17881   11.9   0.20 *  67.7  15.7  52.0    9.5   9.4  30.0    3.0 *    14395
0.60   140   50    6879   19.8   0.33 *  67.8  15.7  52.1    9.5   9.4  31.3    1.8 *    14418
0.80   140   50    6879   10.8   0.28 *  68.1  12.4  55.7    7.8   9.4  35.2    3.2 *    14491

                                BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.60   150   40   12181   14.3   0.24 *  69.0  15.7  53.3    9.5  10.1  31.2    2.5 *    14683
0.60   140   40   12181   13.3   0.24 *  69.7  15.7  54.0    9.5   9.4  32.3    2.8 *    14830
0.60   150   50    8025   18.0   0.31 *  69.7  15.7  54.0    9.5  10.1  32.4    2.0 *    14834
0.60   140   50    8025   16.7   0.30 *  70.2  15.7  54.5    9.5   9.4  33.3    2.2 *    14928
0.60   150   30   20861   10.9   0.19 *  70.4  15.7  54.7    9.5  10.1  31.7    3.4 *    14978
0.80   150   50    8025    9.9   0.26 *  70.6  12.4  58.2    7.8  10.1  36.6    3.6 *    15025
0.60   130   40   12181   12.3   0.23 *  70.6  15.7  54.9    9.5   8.8  33.6    3.1 *    15025
0.60   130   50    8025   15.4   0.29 *  70.8  15.7  55.1    9.5   8.8  34.3    2.5 *    15059
0.80   150   40   12181    7.9   0.21 *  71.3  12.4  58.9    7.8  10.1  36.4    4.6 *    15167
0.80   150   60    5707   11.9   0.32 *  71.5  12.4  59.1    7.8  10.1  38.1    3.1 *    15208
```

```
                         JOB 4.  SAME AS JOB 3 BUT USE HYFLO SUPER-CEL AT
                                 COST OF  $80/TON

                      7 XI INDEX                   5.5E9     FT/LB
                     16 DIATOMITE COST              80       $/TON
                       BEGIN
                    ____________________________________________________

FLOW   TERM    CD   B E T A   TIME   THICK • ----- COSTS, $ PER MILLION GALLONS ------ •   TOTAL
       HEAD          4  -2                 •                     LAB+                  •    COST
GSFM    FT    PPM   10 FT      HR      IN  • TOTAL    1ST   OPER  MAIN   POWR  DIAT  BAKW •   $/MO
-------------------------------------------•------------------------------------------•--------

                              BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.00    150    30     8436     9.8    0.23 •  49.6   10.4   39.2   6.8   10.1  20.2   2.1 •   10561
0.80    150    30     8436    15.6    0.26 •  49.7   12.4   37.3   7.8   10.1  18.0   1.4 •   10580
0.80    140    30     8436    14.5    0.25 •  49.8   12.4   37.4   7.8    9.4  18.6   1.5 •   10596
1.00    150    40     4926    13.1    0.31 •  49.9   10.4   39.4   6.8   10.1  20.9   1.6 •   10610
1.00    140    40     4926    12.2    0.29 •  49.9   10.4   39.5   6.8    9.4  21.5   1.8 •   10629
1.00    140    30     8436     9.1    0.22 •  50.0   10.4   39.5   6.8    9.4  21.0   2.4 •   10629
0.80    130    30     8436    13.4    0.24 •  50.0   12.4   37.6   7.8    8.8  19.4   1.7 •   10639
1.00    130    40     4926    11.2    0.28 •  50.2   10.4   39.7   6.8    8.8  22.2   2.0 •   10674
1.20    150    40     4926     9.0    0.27 •  50.3    9.1   41.2   6.1   10.1  22.6   2.4 •   10706
0.80    120    30     8436    12.3    0.23 •  50.3   12.4   37.9   7.8    8.1  20.2   1.9 •   10714

                              BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80    150    40     7389    13.5    0.28 •  54.8   12.4   42.4   7.8   10.1  22.6   1.8 •   11658
0.80    140    40     7389    12.5    0.26 •  55.0   12.4   42.6   7.8    9.4  23.3   2.0 •   11707
0.80    150    30    12654    10.1    0.21 •  55.1   12.4   42.7   7.8   10.1  22.3   2.5 •   11731
1.00    150    40     7389     8.5    0.24 •  55.4   10.4   44.9   6.8   10.1  25.1   2.9 •   11781
0.80    130    40     7389    11.5    0.25 •  55.4   12.4   43.0   7.8    8.8  24.2   2.3 •   11787
0.80    140    30    12654     9.4    0.20 •  55.6   12.4   43.2   7.8    9.4  23.3   2.7 •   11840
1.00    150    50     4868    10.6    0.31 •  55.7   10.4   45.3   6.8   10.1  26.1   2.4 •   11856
0.60    150    30    12654    18.3    0.24 •  55.8   15.7   40.1   9.5   10.1  19.1   1.4 •   11873
0.80    150    50     4868    17.1    0.36 •  55.8   12.4   43.4   7.8   10.1  24.0   1.5 •   11877
0.80    140    50     4868    15.8    0.34 •  55.9   12.4   43.5   7.8    9.4  24.6   1.6 •   11890

                              BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.80    150    40     9852     9.9    0.24 •  59.1   12.4   46.7   7.8   10.1  26.0   2.8 •   12577
0.80    150    50     6491    12.4    0.30 •  59.3   12.4   46.9   7.8   10.1  26.7   2.3 •   12625
0.60    150    40     9852    18.0    0.28 •  59.5   15.7   43.8   9.5   10.1  22.6   1.6 •   12659
0.80    140    50     6491    11.5    0.29 •  59.7   12.4   47.3   7.8    9.4  27.5   2.5 •   12698
0.80    140    40     9852     9.2    0.23 •  59.7   12.4   47.3   7.8    9.4  26.9   3.1 •   12701
0.60    140    40     9852    16.7    0.26 •  59.7   15.7   44.0   9.5    9.4  23.3   1.8 •   12702
0.60    150    30    16872    13.5    0.21 •  59.7   15.7   44.1   9.5   10.1  22.3   2.2 •   12714
0.60    130    40     9852    15.4    0.25 •  60.0   15.7   44.4   9.5    8.8  24.1   2.0 •   12775
0.80    130    50     6491    10.6    0.27 •  60.2   12.4   47.8   7.8    8.8  28.4   2.8 •   12807
0.60    140    30    16872    12.6    0.20 •  60.2   15.7   44.5   9.5    9.4  23.2   2.4 •   12814

                              BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.60    150    40    12315    14.1    0.24 •  62.6   15.7   46.9   9.5   10.1  25.1   2.2 •   13322
0.80    150    50     8113     9.7    0.26 •  63.0   12.4   50.5   7.8   10.1  29.5   3.1 •   13398
0.60    140    40    12315    13.1    0.23 •  63.1   15.7   47.4   9.5    9.4  26.0   2.4 •   13417
0.60    150    50     8113    17.8    0.31 •  63.1   15.7   47.4   9.5   10.1  26.0   1.8 •   13429
0.60    140    50     8113    16.5    0.30 •  63.3   15.7   47.7   9.5    9.4  26.8   2.0 •   13479
0.80    150    60     5769    11.8    0.32 •  63.6   12.4   51.2   7.8   10.1  30.6   2.6 •   13531
0.80    150    40    12315     7.8    0.21 •  63.6   12.4   51.2   7.8   10.1  29.3   4.0 •   13534
0.80    140    50     8113     9.0    0.25 •  63.6   12.4   51.2   7.8    9.4  30.5   3.5 •   13535
0.60    130    40    12315    12.2    0.23 •  63.7   15.7   48.0   9.5    8.8  27.0   2.7 •   13551
0.60    130    50     8113    15.2    0.28 •  63.7   15.7   48.1   9.5    8.8  27.6   2.2 •   13562

                              BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.60    150    50     9736    14.6    0.28 •  65.7   15.7   50.0   9.5   10.1  28.1   2.3 •   13981
0.60    150    40    14778    11.7    0.22 •  65.8   15.7   50.1   9.5   10.1  27.6   2.9 •   14001
0.60    140    50     9736    13.5    0.27 •  66.1   15.7   50.5   9.5    9.4  29.0   2.5 •   14075
0.60    140    40    14778    10.8    0.22 •  66.5   15.7   50.8   9.5    9.4  28.7   3.2 •   14151
0.60    150    60     6923    17.7    0.34 •  66.7   15.7   51.0   9.5   10.1  29.4   2.0 •   14187
0.80    150    50     9736     8.0    0.24 •  66.7   12.4   54.3   7.8   10.1  32.3   4.1 •   14198
0.80    150    60     6923     9.6    0.29 •  66.7   12.4   54.3   7.8   10.1  33.0   3.5 •   14204
0.60    130    50     9736    12.5    0.26 •  66.8   15.7   51.1   9.5    8.8  30.0   2.8 •   14209
0.60    140    60     6923    16.3    0.33 •  66.9   15.7   51.3   9.5    9.4  30.2   2.1 •   14245
0.60    130    60     6923    15.1    0.31 •  67.4   15.7   51.7   9.5    8.8  31.1   2.4 •   14336

                              BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.60    150    50    11359    12.3    0.25 •  68.4   15.7   52.7   9.5   10.1  30.2   2.9 •   14545
0.60    150    60     8077    14.9    0.31 •  68.9   15.7   53.2   9.5   10.1  31.2   2.4 •   14663
0.60    140    50    11359    11.5    0.24 •  69.0   15.7   53.3   9.5    9.4  31.2   3.2 •   14685
0.60    150    40    17241     9.9    0.21 •  69.1   15.7   53.4   9.5   10.1  30.1   3.7 •   14698
0.60    140    60     8077    13.8    0.30 •  69.4   15.7   53.7   9.5    9.4  32.1   2.7 •   14759
0.60    130    50    11359    10.6    0.24 •  69.9   15.7   54.2   9.5    8.8  32.4   3.6 •   14872
0.60    130    60     8077    12.7    0.28 •  70.0   15.7   54.3   9.5    8.8  33.1   3.0 •   14895
0.80    150    60     8077     8.2    0.26 •  70.0   12.4   57.6   7.8   10.1  35.3   4.4 •   14896
0.60    140    40    17241     9.2    0.20 •  70.0   15.7   54.4   9.5    9.4  31.4   4.1 •   14905
0.60    150    70     6054    17.6    0.38 •  70.2   15.7   54.5   9.5   10.1  32.8   2.1 •   14936
```

```
                         JOB 5.  SAME AS JOB 4 EXCEPT FOR IRON CONCENTRATION

                      6 SOLIDS (CS)                   4     PPM IRON
                     14 BODY FEED                 20/5/70            PPM
                       BEGIN
                    ________________________________________________________

FLOW  TERM    CD   B E T A   TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD           4  -2                *                    LAB+                   *    COST
GSFM   FT    PPM   10 FT      HR      IN  * TOTAL    1ST   OPER   MAIN   POWR   DIAT   BAKW *    $/MO
--------------------------------------------*-------------------------------------------*--------

                             BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.20   120    20     5557    12.4    0.23 *  37.8    9.1   28.7    6.1    8.1   13.4    1.2 *     8052
1.20   130    20     5557    13.5    0.24 *  37.8    9.1   28.7    6.1    8.8   12.8    1.0 *     8053
1.40   120    25     3661    11.2    0.26 *  37.9    8.2   29.7    5.7    8.1   14.7    1.3 *     8057
1.40   130    25     3661    12.3    0.27 *  37.9    8.2   29.7    5.7    8.8   14.2    1.1 *     8059
1.20   110    25     3661    14.1    0.27 *  37.9    9.1   28.8    6.1    7.4   14.2    1.0 *     8067
1.40   140    20     5557    10.6    0.23 *  37.9    8.2   29.8    5.7    9.4   13.4    1.3 *     8070
1.20   120    25     3661    15.5    0.29 *  37.9    9.1   28.8    6.1    8.1   13.7    0.9 *     8071
1.40   130    20     5557     9.8    0.22 *  37.9    8.2   29.8    5.7    8.8   13.9    1.4 *     8074
1.20   140    20     5557    14.6    0.25 *  38.0    9.1   28.8    6.1    9.4   12.4    0.9 *     8075
1.20   110    20     5557    11.3    0.22 *  38.0    9.1   28.9    6.1    7.4   14.0    1.3 *     8079

                             BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
1.20   140    25     5492    11.8    0.25 *  41.4    9.1   32.2    6.1    9.4   15.4    1.3 *     8800
1.20   150    25     5492    12.7    0.26 *  41.4    9.1   32.3    6.1   10.1   14.9    1.2 *     8811
1.20   130    25     5492    10.9    0.24 *  41.4    9.1   32.3    6.1    8.8   16.0    1.5 *     8811
1.20   130    30     3905    13.1    0.29 *  41.5    9.1   32.4    6.1    8.8   16.3    1.2 *     8841
1.00   130    25     5492    16.0    0.26 *  41.6   10.4   31.1    6.8    8.8   14.6    1.0 *     8847
1.00   120    25     5492    14.6    0.25 *  41.6   10.4   31.1    6.8    8.1   15.2    1.1 *     8849
1.20   120    25     5492    10.0    0.23 *  41.6    9.1   32.5    6.1    8.1   16.6    1.7 *     8851
1.20   120    30     3905    12.0    0.28 *  41.6    9.1   32.5    6.1    8.1   16.9    1.4 *     8852
1.20   140    30     3905    14.3    0.30 *  41.6    9.1   32.5    6.1    9.4   15.8    1.1 *     8854
1.40   150    25     5492     9.3    0.24 *  41.7    8.2   33.5    5.7   10.1   16.0    1.7 *     8863

                             BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
1.00   150    25     7323    13.7    0.24 *  44.2   10.4   33.8    6.8   10.1   15.6    1.3 *     9409
1.00   140    25     7323    12.7    0.24 *  44.2   10.4   33.8    6.8    9.4   16.2    1.4 *     9411
1.20   150    30     5207    11.2    0.27 *  44.3    9.1   35.2    6.1   10.1   17.4    1.5 *     9419
1.20   140    30     5207    10.4    0.26 *  44.3    9.1   35.2    6.1    9.4   18.0    1.7 *     9431
1.00   130    30     5207    14.1    0.27 *  44.3   10.4   33.9    6.8    8.8   17.1    1.3 *     9436
1.00   140    30     5207    15.3    0.28 *  44.3   10.4   33.9    6.8    9.4   16.5    1.2 *     9436
1.00   130    25     7323    11.7    0.23 *  44.3   10.4   33.9    6.8    8.8   16.8    1.5 *     9437
1.20   150    25     7323     9.4    0.22 *  44.4    9.1   35.3    6.1   10.1   17.2    1.9 *     9444
1.00   150    30     5207    16.5    0.30 *  44.4   10.4   34.0    6.8   10.1   16.1    1.1 *     9456
1.00   120    30     5207    12.9    0.26 *  44.5   10.4   34.0    6.8    8.1   17.7    1.4 *     9461

                             BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
1.00   150    30     6509    12.9    0.26 *  46.5   10.4   36.1    6.8   10.1   17.7    1.5 *     9894
1.00   140    30     6509    12.0    0.25 *  46.6   10.4   36.1    6.8    9.4   18.3    1.6 *     9908
1.00   150    25     9154    10.8    0.22 *  46.7   10.4   36.2    6.8   10.1   17.6    1.8 *     9927
1.00   130    30     6509    11.1    0.24 *  46.8   10.4   36.3    6.8    8.8   19.0    1.8 *     9949
1.00   140    35     4879    14.1    0.30 *  46.8   10.4   36.4    6.8    9.4   18.8    1.4 *     9958
1.00   150    35     4879    15.2    0.31 *  46.8   10.4   36.4    6.8   10.1   18.3    1.3 *     9964
1.00   140    25     9154    10.0    0.21 *  46.9   10.4   36.4    6.8    9.4   18.3    1.9 *     9971
1.20   150    30     6509     8.9    0.24 *  46.9    9.1   37.7    6.1   10.1   19.4    2.1 *     9971
1.00   130    35     4879    13.0    0.28 *  46.9   10.4   36.4    6.8    8.8   19.4    1.5 *     9974
1.20   150    35     4879    10.3    0.28 *  46.9    9.1   37.8    6.1   10.1   19.7    1.8 *     9974

                             BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
1.00   150    30     7811    10.6    0.24 *  48.6   10.4   38.2    6.8   10.1   19.4    1.9 *    10342
1.00   150    35     5855    12.4    0.28 *  48.7   10.4   38.2    6.8   10.1   19.7    1.6 *    10353
1.00   140    35     5855    11.5    0.27 *  48.8   10.4   38.3    6.8    9.4   20.3    1.8 *    10377
1.00   140    30     7811     9.9    0.23 *  48.8   10.4   38.4    6.8    9.4   20.1    2.1 *    10393
0.80   150    30     7811    16.9    0.27 *  48.9   12.4   36.5    7.8   10.1   17.4    1.2 *    10415
0.80   140    30     7811    15.7    0.26 *  49.0   12.4   36.5    7.8    9.4   18.0    1.3 *    10418
0.80   150    25    10985    14.1    0.22 *  49.0   12.4   36.6    7.8   10.1   17.2    1.5 *    10424
1.00   130    35     5855    10.6    0.25 *  49.0   10.4   38.6    6.8    8.8   21.1    2.0 *    10429
1.00   150    40     4561    14.3    0.32 *  49.1   10.4   38.6    6.8   10.1   20.3    1.4 *    10443
0.80   130    30     7811    14.5    0.25 *  49.1   12.4   36.7    7.8    8.8   18.6    1.5 *    10445

                             BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
1.00   150    35     6831    10.5    0.25 *  50.5   10.4   40.1    6.8   10.1   21.2    2.1 *    10749
0.80   150    30     9113    14.3    0.24 *  50.6   12.4   38.2    7.8   10.1   18.7    1.5 *    10761
0.80   140    30     9113    13.3    0.24 *  50.7   12.4   38.3    7.8    9.4   19.4    1.7 *    10792
1.00   150    40     5321    12.1    0.29 *  50.7   10.4   40.3    6.8   10.1   21.6    1.8 *    10794
1.00   150    30     9113     9.0    0.22 *  50.8   10.4   40.3    6.8   10.1   21.1    2.4 *    10801
0.80   150    35     6831    16.8    0.29 *  50.8   12.4   38.3    7.8   10.1   19.1    1.3 *    10802
1.00   140    35     6831     9.8    0.24 *  50.8   10.4   40.3    6.8    9.4   21.9    2.3 *    10806
0.80   140    35     6831    15.5    0.28 *  50.8   12.4   38.4    7.8    9.4   19.7    1.4 *    10810
1.00   140    40     5321    11.2    0.28 *  50.9   10.4   40.4    6.8    9.4   22.3    2.0 *    10827
0.80   150    25    12816    12.0    0.21 *  50.9   12.4   38.5    7.8   10.1   18.7    1.8 *    10835
```

```
P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

         JOB 6.  KENTUCKY BALL CLAY

   1 DESIGN FLOW                 3     MGD
   2 SALVAGE VALUE              15     PERCENT FIRST COST
   3 ENERGY CONVERSION          70     PERCENT
   4 INTEREST RATE               4     PERCENT
   5 PLANT LIFE                 15     YEARS
   6 SOLIDS  (CS)               50     PPM CLAY (TURBIDITY)
   7 XI INDEX                5.1E9     FT/LB
   8 TEMPERATURE                48     DEGREES F
   9 PRECCAT WEIGHT            0.1     LB/SF
  10 PRECOAT DENSITY            15     LB/CF
  11 SEPTUM DIAMETER             1     INCHES
  12 BETA PREDICTION     3.43/1.96/-0.254/0.491
  13 UNIT FLOW RATE       0.5/0.5/2             GSFM
  14 BODY FEED             40/10/100            PPM
  15 TERMINAL HEAD         75/15/150            FT
  16 DIATOMITE COST             80    $/TON
  17 FIRST COST              AREA     $/SF
                              100      225
                              200      160
                              350      128
                              600      110
                             1000      100
                             2000       94
    •                       25000       85
  18 POWER COST                 1.5   CENTS/KWH
  19 LABOR COST              AREA     $/SF PER MONTH
                              100      2.00
                              200 1.15
                              300      0.83
                              500      0.63
                              800      0.50
                             2000      0.37
    •                        4500      0.30
  20 BACKWASH COST            10, 30  GAL/SF, MIN
   BEGIN
```

```
                                        JOB 6

FLOW  TERM   CD  B E T A  TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD        4  -2                *                     LAB+                  *    COST
GSFM   FT   PPM  10 FT     HR       IN * TOTAL   1ST  OPER   MAIN  POWR  DIAT  BAKW *    $/MO
---------------------------------------*-------------------------------------------*--------

                                BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.50   150   40    4768    7.2    0.21 *  50.4  11.2  39.2    7.0  10.1  19.5   2.6 *    4598
1.50   135   40    4768    6.3    0.20 *  50.7  11.2  39.5    7.0   9.1  20.4   3.1 *    4626
1.50   135   50    2909    9.4    0.29 *  50.7  11.2  39.5    7.0   9.1  21.4   2.1 *    4626
1.50   150   50    2909   10.9    0.31 *  50.8  11.2  39.6    7.0  10.1  20.8   1.8 *    4631
1.00   120   40    4768   13.5    0.24 *  50.9  14.7  36.2    8.4   8.1  18.3   1.5 *    4644
1.50   120   50    2909    8.0    0.26 *  50.9  11.2  39.8    7.0   8.1  22.2   2.5 *    4645
1.00   135   40    4768   15.7    0.27 *  51.0  14.7  36.3    8.4   9.1  17.6   1.2 *    4651
1.00   105   40    4768   11.4    0.22 *  51.1  14.7  36.4    8.4   7.1  19.2   1.8 *    4664
1.00   150   40    4768   18.1    0.29 *  51.3  14.7  36.5    8.4  10.1  17.0   1.1 *    4676
1.50   120   40    4768    5.5    0.18 *  51.4  11.2  40.2    7.0   8.1  21.4   3.7 *    4687

                                BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
1.00   150   40    7153   10.8    0.21 *  54.7  14.7  40.0    8.4  10.1  19.5   2.0 *    4989
1.00   135   40    7153    9.5    0.20 *  54.9  14.7  40.1    8.4   9.1  20.4   2.3 *    5005
1.00   135   50    4364   14.1    0.29 *  55.1  14.7  40.4    8.4   9.1  21.4   1.6 *    5029
1.00   120   50    4364   12.1    0.26 *  55.2  14.7  40.5    8.4   8.1  22.2   1.9 *    5038
1.50   150   50    4364    6.4    0.23 *  55.3  11.2  44.1    7.0  10.1  23.6   3.4 *    5041
1.00   150   50    4364   16.3    0.31 *  55.3  14.7  40.6    8.4  10.1  20.7   1.3 *    5042
1.00   120   40    7153    8.2    0.18 *  55.4  14.7  40.6    8.4   8.1  21.4   2.8 *    5050
1.50   150   60    2914    9.0    0.31 *  55.6  11.2  44.4    7.0  10.1  24.9   2.4 *    5073
1.00   105   50    4364   10.2    0.24 *  55.7  14.7  41.0    8.4   7.1  23.2   2.3 *    5078
1.50   135   60    2914    7.8    0.29 *  55.8  11.2  44.7    7.0   9.1  25.7   2.9 *    5092

                                BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
1.00   150   50    5819   11.2    0.25 *  58.0  14.7  43.2    8.4  10.1  22.6   2.1 *    5286
1.00   135   50    5819    9.8    0.23 *  58.2  14.7  43.4    8.4   9.1  23.5   2.5 *    5305
1.00   150   40    9537    7.7    0.18 *  58.4  14.7  43.6    8.4  10.1  22.0   3.1 *    5322
1.00   120   50    5819    8.4    0.21 *  58.7  14.7  44.0    8.4   8.1  24.6   3.0 *    5355
1.00   135   60    3886   13.8    0.32 *  58.8  14.7  44.1    8.4   9.1  24.8   1.8 *    5363
1.00   150   60    3886   16.0    0.35 *  58.9  14.7  44.1    8.4  10.1  24.2   1.5 *    5369
1.00   120   60    3886   11.8    0.29 *  59.0  14.7  44.3    8.4   8.1  25.7   2.2 *    5381
1.00   135   40    9537    6.8    0.17 *  59.0  14.7  44.3    8.4   9.1  23.2   3.7 *    5383
1.50   150   60    3886    6.2    0.25 *  59.4  11.2  48.2    7.0  10.1  27.2   3.9 *    5417
1.00   105   60    3886    9.9    0.26 *  59.6  14.7  44.9    8.4   7.1  26.8   2.7 *    5435

                                BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
1.00   150   50    7274    8.4    0.21 *  60.8  14.7  46.0    8.4  10.1  24.6   3.0 *    5542
1.00   150   60    4858   11.8    0.29 *  61.1  14.7  46.3    8.4  10.1  25.7   2.2 *    5567
1.00   135   60    4858   10.2    0.26 *  61.3  14.7  46.5    8.4   9.1  26.5   2.6 *    5588
1.00   135   50    7274    7.4    0.20 *  61.4  14.7  46.6    8.4   9.1  25.6   3.5 *    5596
1.00   120   60    4858    8.8    0.24 *  61.9  14.7  47.1    8.4   8.1  27.6   3.1 *    5640
1.00   135   70    3453   14.0    0.35 *  62.2  14.7  47.5    8.4   9.1  28.1   1.9 *    5675
1.00   150   40   11921    5.9    0.16 *  62.2  14.7  47.5    8.4  10.1  24.6   4.5 *    5675
1.00   150   70    3453   16.3    0.39 *  62.2  14.7  47.5    8.4  10.1  27.4   1.6 *    5676
1.00   120   50    7274    6.5    0.18 *  62.4  14.7  47.7    8.4   8.1  27.0   4.3 *    5691
1.00   120   70    3453   11.8    0.32 *  62.5  14.7  47.8    8.4   8.1  29.0   2.3 *    5698

                                BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
1.00   150   60    5829    9.3    0.25 *  63.3  14.7  48.6    8.4  10.1  27.2   2.9 *    5774
1.00   150   50    8729    6.8    0.19 *  63.7  14.7  49.0    8.4  10.1  26.5   4.0 *    5810
1.00   135   60    5829    8.1    0.23 *  63.9  14.7  49.1    8.4   9.1  28.2   3.5 *    5823
1.00   150   70    4144   12.5    0.33 *  64.1  14.7  49.3    8.4  10.1  28.6   2.2 *    5842
1.00   135   70    4144   10.8    0.30 *  64.3  14.7  49.6    8.4   9.1  29.5   2.6 *    5863
1.00   135   50    8729    6.0    0.18 *  64.7  14.7  50.0    8.4   9.1  27.8   4.8 *    5901
1.00   120   60    5829    7.0    0.21 *  64.8  14.7  50.1    8.4   8.1  29.5   4.2 *    5912
1.00   120   70    4144    9.3    0.27 *  64.9  14.7  50.1    8.4   8.1  30.5   3.2 *    5916
1.00   150   80    3083   17.0    0.44 *  65.5  14.7  50.8    8.4  10.1  30.6   1.7 *    5972
1.00   135   80    3083   14.4    0.39 *  65.5  14.7  50.8    8.4   9.1  31.3   2.0 *    5973

                                BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
1.00   150   60    6801    7.6    0.22 *  65.7  14.7  50.9    8.4  10.1  28.7   3.8 *    5989
1.00   150   70    4834   10.2    0.29 *  66.0  14.7  51.2    8.4  10.1  29.9   2.9 *    6014
1.00   135   70    4834    8.8    0.26 *  66.4  14.7  51.7    8.4   9.1  30.9   3.4 *    6059
1.00   135   60    6801    6.7    0.21 *  66.5  14.7  51.8    8.4   9.1  29.9   4.4 *    6068
1.00   150   50   10183    5.7    0.17 *  66.8  14.7  52.0    8.4  10.1  28.4   5.2 *    6090
1.00   150   80    3597   13.4    0.38 *  67.0  14.7  52.3    8.4  10.1  31.6   2.2 *    6113
1.00   135   80    3597   11.5    0.34 *  67.3  14.7  52.5    8.4   9.1  32.4   2.6 *    6134
1.00   120   70    4834    7.6    0.24 *  67.4  14.7  52.6    8.4   8.1  32.1   4.1 *    6143
1.00   120   80    3597    9.8    0.31 *  67.8  14.7  53.1    8.4   8.1  33.5   3.2 *    6187
1.00   120   60    6801    5.8    0.19 *  67.9  14.7  53.2    8.4   8.1  31.4   5.3 *    6196
```

```
                          JOB 7.  SAME AS JOB 6 EXCEPT FOR TEMPERATURE

                     8 TEMPERATURE                   72     DEGREES F
                      BEGIN

                    _____________________________________________________

FLOW   TERM    CD   B E T A   TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
       HEAD          4  -2                 *                     LAB+                  *    COST
GSFM    FT    PPM   10 FT      HR       IN * TOTAL   1ST   OPER  MAIN   POWR  DIAT  BAKW *    $/MO
-----------------------------------------*------------------------------------------------*--------

                              BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.50    135    40     4768     9.7    0.25 *  47.0  11.2  35.8    7.0    9.1  17.9   1.8 *    4282
1.50    120    40     4768     8.3    0.23 *  47.0  11.2  35.9    7.0    8.1  18.7   2.1 *    4290
1.50    150    40     4768    11.1    0.28 *  47.1  11.2  35.9    7.0   10.1  17.3   1.5 *    4296
1.50    105    40     4768     7.1    0.21 *  47.5  11.2  36.3    7.0    7.1  19.6   2.6 *    4330
1.50    120    50     2909    12.9    0.35 *  47.8  11.2  36.6    7.0    8.1  20.1   1.4 *    4357
1.50    105    50     2909    10.7    0.31 *  47.8  11.2  36.6    7.0    7.1  20.8   1.8 *    4361
2.00    150    40     4768     5.8    0.22 *  47.9   9.4  38.5    6.3   10.1  19.1   3.0 *    4365
1.50    135    50     2909    15.3    0.39 *  48.0  11.2  36.8    7.0    9.1  19.6   1.2 *    4377
2.00    135    50     2909     7.6    0.30 *  48.2   9.4  38.8    6.3    9.1  21.0   2.4 *    4392
2.00    135    40     4768     5.1    0.21 *  48.2   9.4  38.8    6.3    9.1  19.9   3.5 *    4395

                              BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
1.50    150    40     7153     6.7    0.20 *  51.1  11.2  40.0    7.0   10.1  20.0   2.9 *    4664
1.50    150    50     4364    10.0    0.30 *  51.3  11.2  40.1    7.0   10.1  21.1   1.9 *    4679
1.50    135    50     4364     8.7    0.27 *  51.3  11.2  40.1    7.0    9.1  21.8   2.3 *    4680
1.00    120    40     7153    12.5    0.23 *  51.5  14.7  36.7    8.4    8.1  18.6   1.6 *    4692
1.00    135    40     7153    14.6    0.25 *  51.5  14.7  36.7    8.4    9.1  17.9   1.4 *    4693
1.50    135    40     7153     5.9    0.19 *  51.5  11.2  40.4    7.0    9.1  20.9   3.4 *    4700
1.50    120    50     4364     7.5    0.25 *  51.6  11.2  40.4    7.0    8.1  22.6   2.8 *    4708
1.00    150    40     7153    16.7    0.28 *  51.7  14.7  37.0    8.4   10.1  17.3   1.2 *    4714
1.00    105    40     7153    10.6    0.21 *  51.8  14.7  37.0    8.4    7.1  19.6   2.0 *    4720
1.00    105    50     4364    16.1    0.31 *  52.3  14.7  37.6    8.4    7.1  20.8   1.3 *    4771

                              BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
1.00    150    40     9537    11.6    0.22 *  54.1  14.7  39.4    8.4   10.1  19.1   1.8 *    4935
1.00    135    40     9537    10.2    0.21 *  54.2  14.7  39.5    8.4    9.1  19.9   2.1 *    4943
1.50    150    50     5819     6.9    0.24 *  54.5  11.2  43.3    7.0   10.1  23.1   3.1 *    4968
1.00    120    40     9537     8.8    0.19 *  54.6  14.7  39.9    8.4    8.1  20.9   2.5 *    4979
1.00    135    50     5819    15.3    0.30 *  54.6  14.7  39.9    8.4    9.1  21.0   1.4 *    4983
1.00    120    50     5819    13.1    0.27 *  54.7  14.7  39.9    8.4    8.1  21.8   1.7 *    4985
1.00    150    50     5819    17.7    0.33 *  54.9  14.7  40.1    8.4   10.1  20.4   1.2 *    5002
1.50    135    50     5819     6.0    0.22 *  54.9  11.2  43.7    7.0    9.1  24.0   3.6 *    5010
1.00    105    50     5819    11.0    0.25 *  55.0  14.7  40.3    8.4    7.1  22.7   2.1 *    5017
1.50    150    60     3886     9.8    0.33 *  55.0  11.2  43.8    7.0   10.1  24.5   2.2 *    5017

                              BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
1.00    150    40    11921     8.8    0.19 *  56.7  14.7  41.9    8.4   10.1  20.9   2.6 *    5166
1.00    150    50     7274    13.1    0.27 *  56.7  14.7  42.0    8.4   10.1  21.8   1.7 *    5171
1.00    135    50     7274    11.4    0.25 *  56.8  14.7  42.0    8.4    9.1  22.5   2.1 *    5175
1.00    135    40    11921     7.8    0.18 *  57.1  14.7  42.3    8.4    9.1  21.9   3.0 *    5205
1.00    120    50     7274     9.8    0.23 *  57.1  14.7  42.3    8.4    8.1  23.4   2.5 *    5206
1.50    150    60     4858     7.2    0.27 *  57.6  11.2  46.4    7.0   10.1  26.1   3.2 *    5254
1.00    135    60     4858    16.4    0.35 *  57.7  14.7  43.0    8.4    9.1  24.1   1.5 *    5263
1.00    120    60     4858    13.9    0.32 *  57.7  14.7  43.0    8.4    8.1  24.8   1.8 *    5266
1.00    105    50     7274     8.3    0.21 *  57.8  14.7  43.1    8.4    7.1  24.7   3.0 *    5275
1.50    150    50     7274     5.2    0.20 *  57.9  11.2  46.7    7.0   10.1  25.2   4.4 *    5277

                              BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
1.00    150    50     8729    10.3    0.24 *  58.6  14.7  43.9    8.4   10.1  23.1   2.3 *    5348
1.00    135    50     8729     9.1    0.22 *  58.9  14.7  44.2    8.4    9.1  24.0   2.7 *    5375
1.00    150    40    14306     7.1    0.17 *  59.3  14.7  44.6    8.4   10.1  22.7   3.4 *    5407
1.00    150    60     5829    14.7    0.33 *  59.4  14.7  44.7    8.4   10.1  24.5   1.7 *    5417
1.00    135    60     5829    12.7    0.30 *  59.4  14.7  44.7    8.4    9.1  25.2   2.0 *    5417
1.00    120    50     8729     7.9    0.20 *  59.6  14.7  44.9    8.4    8.1  25.1   3.3 *    5435
1.00    120    60     5829    10.9    0.27 *  59.7  14.7  45.0    8.4    8.1  26.1   2.4 *    5443
1.00    135    40    14306     6.3    0.16 *  60.1  14.7  45.3    8.4    9.1  23.9   4.0 *    5479
1.50    150    60     5829     5.7    0.24 *  60.4  11.2  49.2    7.0   10.1  27.8   4.3 *    5504
1.00    105    60     5829     9.1    0.25 *  60.4  14.7  45.7    8.4    7.1  27.3   2.9 *    5507

                              BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
1.00    150    50    10183     8.5    0.21 *  60.6  14.7  45.9    8.4   10.1  24.5   3.0 *    5530
1.00    150    60     6801    11.9    0.29 *  60.9  14.7  46.2    8.4   10.1  25.6   2.2 *    5558
1.00    135    60     6801    10.4    0.27 *  61.2  14.7  46.4    8.4    9.1  26.4   2.5 *    5577
1.00    135    50    10183     7.5    0.20 *  61.2  14.7  46.5    8.4    9.1  25.5   3.5 *    5582
1.00    120    60     6801     8.9    0.24 *  61.7  14.7  47.0    8.4    8.1  27.5   3.0 *    5627
1.00    150    40    16690     6.0    0.16 *  62.0  14.7  47.3    8.4   10.1  24.5   4.4 *    5658
1.00    135    70     4834    14.2    0.36 *  62.1  14.7  47.4    8.4    9.1  28.0   1.9 *    5666
1.00    150    70     4834    16.5    0.39 *  62.2  14.7  47.4    8.4   10.1  27.4   1.6 *    5669
1.00    120    50    10183     6.5    0.18 *  62.2  14.7  47.5    8.4    8.1  26.9   4.2 *    5674
1.00    120    70     4834    12.0    0.32 *  62.4  14.7  47.6    8.4    8.1  28.9   2.3 *    5688
```

```
                    JOB 8.  JOB 7 EXCEPT WYOMING BENTONITE AND FOLLOWING

                     6 SOLIDS                       30    PPM CLAY (TURBIDITY)
                    12 BETA PREDICTION      11.81/1.58/-1.06/0
                    13 UNIT FLOW RATE        0.3/0.2/1.1          GSFM
                    14 BODY FEED            200/10/300            PPM
                      BEGIN
                    ________________________________________________________

FLOW  TERM   CD  B E T A  TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *  TOTAL
      HEAD         4  -2                *                    LAB+                  *   COST
GSFM   FT   PPM  10 FT     HR      IN   * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *   $/MO
----------------------------------------*------------------------------------------*--------

                              BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.70   150  200     5862  10.7   0.47 * 122.0  19.5 102.5  10.2  10.1  75.6   6.6 *   11128
0.50   150  200     5862  26.7   0.69 * 123.0  25.8  97.2  12.6  10.1  71.6   2.8 *   11213
0.70   150  210     5154  12.5   0.54 * 123.1  19.5 103.6  10.2  10.1  77.6   5.7 *   11226
0.50   135  200     5862  22.0   0.60 * 123.7  25.8  97.9  12.6   9.1  72.7   3.5 *   11277
0.70   135  200     5862   9.0   0.42 * 124.0  19.5 104.5  10.2   9.1  77.2   8.0 *   11309
0.70   150  220     4558  14.8   0.62 * 124.4  19.5 104.9  10.2  10.1  79.7   4.9 *   11349
0.70   135  210     5154  10.5   0.48 * 124.8  19.5 105.3  10.2   9.1  79.0   6.9 *   11378
0.50   120  200     5862  18.0   0.53 * 124.9  25.8  99.1  12.6   8.1  74.1   4.4 *   11389
0.50   150  210     5154  32.7   0.81 * 124.9  25.8  99.1  12.6  10.1  74.0   2.4 *   11390
0.50   135  210     5154  26.6   0.71 * 125.4  25.8  99.6  12.6   9.1  75.0   2.9 *   11437

                              BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.50   150  200     8794  13.4   0.43 * 131.2  25.8 105.4  12.6  10.1  76.6   6.2 *   11968
0.50   150  210     7731  15.7   0.50 * 132.3  25.8 106.5  12.6  10.1  78.5   5.3 *   12065
0.50   135  200     8794  11.4   0.39 * 133.2  25.8 107.4  12.6   9.1  78.3   7.4 *   12148
0.50   150  220     6837  18.4   0.57 * 133.6  25.8 107.8  12.6  10.1  80.6   4.6 *   12187
0.50   135  210     7731  13.2   0.44 * 134.0  25.8 108.2  12.6   9.1  80.0   6.4 *   12218
0.50   135  220     6837  15.4   0.51 * 135.0  25.8 109.3  12.6   9.1  82.0   5.6 *   12316
0.50   150  230     6080  21.7   0.66 * 135.2  25.8 109.4  12.6  10.1  82.8   4.0 *   12332
0.50   120  200     8794   9.6   0.35 * 136.1  25.8 110.3  12.6   8.1  80.5   9.1 *   12409
0.70   150  210     7731   6.7   0.35 * 136.1  19.5 116.6  10.2  10.1  84.2  12.0 *   12411
0.70   150  220     6837   7.6   0.40 * 136.2  19.5 116.7  10.2  10.1  85.8  10.5 *   12417

                              BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.50   150  200    11725   8.8   0.33 * 140.6  25.8 114.8  12.6  10.1  81.8  10.3 *   12820
0.50   150  210    10308  10.0   0.37 * 140.7  25.8 114.9  12.6  10.1  83.2   9.0 *   12832
0.50   150  220     9117  11.5   0.42 * 141.2  25.8 115.4  12.6  10.1  84.9   7.9 *   12880
0.50   150  230     8107  13.2   0.47 * 142.1  25.8 116.3  12.6  10.1  86.7   6.9 *   12959
0.50   150  240     7245  15.3   0.53 * 143.2  25.8 117.4  12.6  10.1  88.7   6.1 *   13064
0.50   135  210    10308   8.6   0.34 * 143.7  25.8 117.9  12.6   9.1  85.4  10.8 *   13101
0.50   135  220     9117   9.8   0.38 * 143.8  25.8 118.0  12.6   9.1  86.9   9.5 *   13116
0.50   135  200    11725   7.6   0.30 * 144.0  25.8 118.2  12.6   9.1  84.2  12.3 *   13128
0.50   135  230     8107  11.2   0.42 * 144.4  25.8 118.6  12.6   9.1  88.5   8.4 *   13164
0.50   150  250     6505  17.7   0.60 * 144.6  25.8 118.8  12.6  10.1  90.8   5.3 *   13191

                              BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.50   150  220    11396   8.3   0.34 * 149.6  25.8 123.8  12.6  10.1  89.4  11.7 *   13641
0.50   150  230    10134   9.4   0.38 * 149.7  25.8 123.9  12.6  10.1  90.8  10.4 *   13650
0.50   150  210    12885   7.3   0.30 * 149.9  25.8 124.1  12.6  10.1  88.1  13.3 *   13672
0.50   150  240     9057  10.7   0.42 * 150.1  25.8 124.3  12.6  10.1  92.5   9.2 *   13693
0.50   150  200    14656   6.5   0.27 * 150.8  25.8 125.0  12.6  10.1  87.2  15.1 *   13751
0.50   150  250     8132  12.1   0.47 * 150.9  25.8 125.1  12.6  10.1  94.3   8.2 *   13764
0.30   150  200    14656  22.4   0.43 * 151.6  40.3 111.4  19.6  10.1  76.6   5.0 *   13826
0.50   150  260     7332  13.8   0.53 * 152.0  25.8 126.2  12.6  10.1  96.3   7.2 *   13861
0.30   150  210    12885  26.1   0.50 * 152.8  40.3 112.6  19.6  10.1  78.5   4.3 *   13937
0.50   135  230    10134   8.1   0.34 * 153.1  25.8 127.3  12.6   9.1  93.1  12.5 *   13962

                              BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.30   150  200    17588  17.0   0.36 * 156.6  40.3 116.4  19.6  10.1  79.7   6.9 *   14283
0.30   150  210    15462  19.6   0.41 * 157.3  40.3 117.1  19.6  10.1  81.3   6.0 *   14349
0.50   150  240    10868   8.1   0.35 * 157.6  25.8 131.8  12.6  10.1  96.3  12.8 *   14372
0.50   150  250     9758   9.2   0.39 * 157.7  25.8 132.0  12.6  10.1  97.9  11.4 *   14386
0.50   150  230    12161   7.3   0.32 * 157.8  25.8 132.0  12.6  10.1  95.0  14.3 *   14395
0.50   150  260     8798  10.3   0.43 * 158.2  25.8 132.4  12.6  10.1  99.6  10.2 *   14431
0.30   150  220    13675  22.7   0.47 * 158.4  40.3 118.1  19.6  10.1  83.1   5.3 *   14444
0.50   150  220    13675   6.5   0.29 * 158.6  25.8 132.8  12.6  10.1  93.9  16.1 *   14460
0.50   150  270     7964  11.6   0.48 * 159.0  25.8 133.2  12.6  10.1 101.4   9.1 *   14502
0.30   135  200    17588  14.6   0.33 * 159.0  40.3 118.8  19.6   9.1  81.8   8.2 *   14504

                              BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.30   150  200    20519  13.7   0.32 * 161.9  40.3 121.6  19.6  10.1  82.9   9.0 *   14762
0.30   150  210    18039  15.6   0.35 * 162.1  40.3 121.8  19.6  10.1  84.2   7.9 *   14782
0.30   150  220    15954  17.9   0.40 * 162.7  40.3 122.4  19.6  10.1  85.8   6.9 *   14837
0.30   150  230    14188  20.4   0.45 * 163.6  40.3 123.4  19.6  10.1  87.5   6.1 *   14921
0.30   150  240    12680  23.5   0.51 * 164.8  40.3 124.6  19.6  10.1  89.4   5.4 *   15030
0.30   135  210    18039  13.5   0.32 * 164.9  40.3 124.6  19.6   9.1  86.5   9.4 *   15036
0.50   150  260    10265   8.2   0.37 * 164.9  25.8 139.1  12.6  10.1 103.0  13.5 *   15040
0.50   150  250    11384   7.3   0.34 * 165.0  25.8 139.2  12.6  10.1 101.5  15.0 *   15050
0.30   135  200    20519  11.9   0.29 * 165.1  40.3 124.8  19.6   9.1  85.4  10.7 *   15052
0.30   135  220    15954  15.3   0.36 * 165.1  40.3 124.9  19.6   9.1  87.8   8.3 *   15060
```

```
P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

         JOB 9.  SOFTENING, LOMPOC PLANT (OPERATING COSTS)

   1 DESIGN FLOW                    4.5   MGD
   2 SALVAGE VALUE                  15    PERCENT FIRST COST
   3 ENERGY CONVERSION              70    PERCENT
   4 INTEREST RATE                   4    PERCENT
   5 PLANT LIFE                     30    YEARS
   6 SOLIDS  (CS)                   8.5   PPM
   7 XI INDEX                     1.95E9  FT/LB
   8 TEMPERATURE                    65    DEGREES F
   9 PRECOAT WEIGHT                 0.1   LB/SF
  10 PRECOAT DENSITY                15    LB/CF
  11 SEPTUM DIAMETER               FLAT   INCHES
  12 BETA PREDICTION          10.2/1.43/-1.86/0
  13 UNIT FLOW RATE                0.73             GSFM
  14 BODY FEED                  10/2/30             PPM
  15 TERMINAL HEAD                 25               FT
  16 DIATOMITE COST                 69    $/TON
  17 FIRST COST                 AREA      $/SF
                                 100       225
                                 200       160
                                 300       128
                                 600       110
                                1000       100
                                2000        94
    *                          25000        85
  18 POWER COST                     1    CENTS/KWH
  19 LABOR COST                 AREA      $/SF PER MONTH
                                 100       2.00
                                 200       1.15
                                 300       0.83
                                 500       0.63
                                 800       0.50
                                2000       0.37
                                4500       0.30
                               13000       0.25
    *                          25000       0.24
  20 BACKWASH COST               6, 30   GAL/SF, MIN
   BEGIN
```

```
                                        JOB 9

FLOW   TERM    CD  B E T A  TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
       HEAD          4  -2                 *                          LAB+                  *    COST
GSFM    FT    PPM  10 FT     HR       IN   * TOTAL    1ST   OPER   MAIN   POWR   DIAT   BAKW *    $/MO
-----------------------------------------*-------------------------------------------------*--------

                                   BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.73     25    20     886    41.9   0.32 *  30.4   12.4   18.0    9.0    1.1    7.6    0.3 *     4161
0.73     25    18    1253    32.9   0.25 *  30.4   12.4   18.0    9.0    1.1    7.6    0.3 *     4163
0.73     25    22     647    52.1   0.41 *  30.6   12.4   18.2    9.0    1.1    7.8    0.2 *     4183
0.73     25    16    1847    25.1   0.20 *  30.7   12.4   18.3    9.0    1.1    7.7    0.4 *     4201
0.73     25    24     486    63.6   0.53 *  30.8   12.4   18.4    9.0    1.1    8.1    0.2 *     4219
0.73     25    26     373    76.4   0.66 *  31.2   12.4   18.8    9.0    1.1    8.5    0.1 *     4266
0.73     25    14    2866    18.5   0.16 *  31.4   12.4   19.0    9.0    1.1    8.3    0.6 *     4300
0.73     25    28     293    90.5   0.82 *  31.6   12.4   19.2    9.0    1.1    8.9    0.1 *     4320
0.73     25    30     233   106.0   1.01 *  32.0   12.4   19.6    9.0    1.1    9.4    0.1 *     4379
0.73     25    12    4759    13.0   0.13 *  33.0   12.4   20.6    9.0    1.1    9.5    1.0 *     4515

                                   BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.73     25    22     971    34.7   0.30 *  31.5   12.4   19.0    9.0    1.1    8.6    0.3 *     4303
0.73     25    20    1329    27.9   0.24 *  31.5   12.4   19.1    9.0    1.1    8.6    0.4 *     4311
0.73     25    24     729    42.4   0.38 *  31.6   12.4   19.2    9.0    1.1    8.8    0.3 *     4318
0.73     25    26     560    50.9   0.47 *  31.8   12.4   19.4    9.0    1.1    9.0    0.2 *     4348
0.73     25    18    1880    21.9   0.20 *  31.8   12.4   19.4    9.0    1.1    8.8    0.5 *     4355
0.73     25    28     439    60.3   0.57 *  32.1   12.4   19.7    9.0    1.1    9.4    0.2 *     4389
0.73     25    30     350    70.7   0.70 *  32.4   12.4   20.0    9.0    1.1    9.7    0.2 *     4438
0.73     25    16    2770    16.7   0.16 *  32.6   12.4   20.2    9.0    1.1    9.3    0.7 *     4455
0.73     25    14    4299    12.3   0.13 *  34.0   12.4   21.6    9.0    1.1   10.4    1.1 *     4652
0.73     25    12    7138     8.7   0.11 *  36.8   12.4   24.4    9.0    1.1   12.5    1.7 *     5032

                                   BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.73     25    24     973    31.8   0.30 *  32.3   12.4   19.9    9.0    1.1    9.4    0.4 *     4417
0.73     25    22    1295    26.0   0.25 *  32.3   12.4   19.9    9.0    1.1    9.3    0.5 *     4425
0.73     25    26     747    38.2   0.37 *  32.4   12.4   20.0    9.0    1.1    9.5    0.3 *     4430
0.73     25    28     586    45.2   0.45 *  32.6   12.4   20.2    9.0    1.1    9.8    0.3 *     4458
0.73     25    20    1772    20.9   0.20 *  32.6   12.4   20.2    9.0    1.1    9.5    0.6 *     4463
0.73     25    30     467    53.0   0.54 *  32.9   12.4   20.5    9.0    1.1   10.1    0.2 *     4497
0.73     25    18    2507    16.5   0.17 *  33.3   12.4   20.9    9.0    1.1   10.0    0.8 *     4551
0.73     25    16    3694    12.6   0.14 *  34.5   12.4   22.1    9.0    1.1   10.9    1.1 *     4716
0.73     25    14    5732     9.3   0.12 *  36.7   12.4   24.3    9.0    1.1   12.5    1.6 *     5017
0.73     25    12    9518     6.5   0.10 *  40.8   12.4   28.4    9.0    1.1   15.6    2.7 *     5577

                                   BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.73     25    26     934    30.5   0.31 *  33.0   12.4   20.6    9.0    1.1   10.1    0.4 *     4513
0.73     25    24    1216    25.4   0.26 *  33.0   12.4   20.6    9.0    1.1   10.0    0.5 *     4517
0.73     25    28     732    36.2   0.38 *  33.1   12.4   20.7    9.0    1.1   10.2    0.3 *     4528
0.73     25    22    1619    20.8   0.21 *  33.2   12.4   20.8    9.0    1.1   10.1    0.6 *     4548
0.73     25    30     583    42.4   0.45 *  33.3   12.4   20.9    9.0    1.1   10.5    0.3 *     4557
0.73     25    20    2216    16.8   0.18 *  33.8   12.4   21.3    9.0    1.1   10.4    0.8 *     4618
0.73     25    18    3134    13.2   0.15 *  34.7   12.4   22.3    9.0    1.1   11.2    1.0 *     4750
0.73     25    16    4617    10.0   0.13 *  36.4   12.4   24.0    9.0    1.1   12.4    1.5 *     4983
0.73     25    14    7165     7.4   0.11 *  39.4   12.4   27.0    9.0    1.1   14.7    2.2 *     5394
0.73     25    12   11897     5.2   0.10 *  45.0   12.4   32.6    9.0    1.1   18.6    3.8 *     6151

                                   BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.73     25    26    1121    25.5   0.27 *  33.6   12.4   21.2    9.0    1.1   10.6    0.5 *     4597
0.73     25    28     879    30.2   0.33 *  33.6   12.4   21.2    9.0    1.1   10.7    0.4 *     4599
0.73     25    30     700    35.3   0.39 *  33.8   12.4   21.3    9.0    1.1   10.9    0.4 *     4617
0.73     25    24    1459    21.2   0.23 *  33.8   12.4   21.4    9.0    1.1   10.6    0.6 *     4618
0.73     25    22    1943    17.4   0.19 *  34.2   12.4   21.7    9.0    1.1   10.9    0.8 *     4672
0.73     25    20    2659    14.0   0.16 *  34.9   12.4   22.5    9.0    1.1   11.4    1.0 *     4775
0.73     25    18    3761    11.0   0.14 *  36.2   12.4   23.8    9.0    1.1   12.4    1.3 *     4954
0.73     25    16    5541     8.4   0.12 *  38.4   12.4   26.0    9.0    1.1   14.0    1.9 *     5258
0.73     25    14    8598     6.2   0.11 *  42.3   12.4   29.9    9.0    1.1   16.8    3.0 *     5786
0.73     25    12   14277     4.3   0.10 *  49.4   12.4   37.0    9.0    1.1   21.6    5.2 *     6755

                                   BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.73     25    28    1025    25.9   0.29 *  34.1   12.4   21.7    9.0    1.1   11.1    0.5 *     4670
0.73     25    30     817    30.3   0.35 *  34.2   12.4   21.8    9.0    1.1   11.2    0.4 *     4678
0.73     25    26    1308    21.8   0.25 *  34.2   12.4   21.8    9.0    1.1   11.1    0.6 *     4682
0.73     25    24    1702    18.2   0.21 *  34.5   12.4   22.1    9.0    1.1   11.2    0.7 *     4721
0.73     25    22    2267    14.9   0.18 *  35.1   12.4   22.7    9.0    1.1   11.6    0.9 *     4798
0.73     25    20    3102    12.0   0.15 *  36.1   12.4   23.7    9.0    1.1   12.3    1.2 *     4935
0.73     25    18    4387     9.4   0.13 *  37.7   12.4   25.3    9.0    1.1   13.6    1.7 *     5162
0.73     25    16    6464     7.2   0.11 *  40.5   12.4   28.1    9.0    1.1   15.6    2.4 *     5541
0.73     25    14   10031     5.3   0.10 *  45.3   12.4   32.9    9.0    1.1   18.9    3.8 *     6192
0.73     25    12   16657     3.7   0.09 *  54.0   12.4   41.6    9.0    1.1   24.7    6.8 *     7390
```

```
                     JOB 10.  SAME AS JOB 9 WITH CHANGES BELOW

                  7 XI INDEX                  5E9     FT/LB
                 12 BETA PREDICTION       3.23/0.914/-1.25/0.637
                 16 DIATOMITE COST             50     $/TON
                 20 BACKWASH COST            7, 30    GAL/SF, MIN
                   BEGIN
                 ______________________________________________

FLOW   TERM    CD   B E T A   TIME   THICK • ----- COSTS, $ PER MILLION GALLONS ------ •   TOTAL
       HEAD          4  -2                 •                      LAB+                 •    COST
GSFM    FT    PPM   10 FT      HR      IN  • TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW •    $/MO
-------------------------------------------•-------------------------------------------•--------

                         BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.73    25    18    1738    23.6    0.20 •  29.2  12.4  16.7   9.0   1.1   6.2   0.4 •    3987
0.73    25    16    2243    20.5    0.18 •  29.2  12.4  16.7   9.0   1.1   6.1   0.5 •    3988
0.73    25    20    1384    26.6    0.24 •  29.2  12.4  16.8   9.0   1.1   6.3   0.4 •    3999
0.73    25    14    2995    17.6    0.15 •  29.3  12.4  16.9   9.0   1.1   6.2   0.6 •    4007
0.73    25    22    1126    29.8    0.27 •  29.4  12.4  17.0   9.0   1.1   6.5   0.4 •    4020
0.73    25    24     933    32.9    0.31 •  29.6  12.4  17.2   9.0   1.1   6.7   0.3 •    4048
0.73    25    12    4181    14.7    0.13 •  29.7  12.4  17.2   9.0   1.1   6.4   0.7 •    4056
0.73    25    26     784    36.1    0.35 •  29.8  12.4  17.4   9.0   1.1   7.0   0.3 •    4080
0.73    25    28     668    39.4    0.40 •  30.1  12.4  17.7   9.0   1.1   7.3   0.3 •    4117
0.73    25    10    6204    11.9    0.11 •  30.4  12.4  18.0   9.0   1.1   6.9   0.9 •    4154

                         BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.73    25    20    2076    17.8    0.18 •  30.6  12.4  18.1   9.0   1.1   7.4   0.6 •    4180
0.73    25    22    1689    19.8    0.21 •  30.6  12.4  18.2   9.0   1.1   7.5   0.6 •    4181
0.73    25    18    2608    15.7    0.16 •  30.6  12.4  18.2   9.0   1.1   7.4   0.7 •    4192
0.73    25    24    1399    21.9    0.23 •  30.7  12.4  18.2   9.0   1.1   7.6   0.5 •    4193
0.73    25    26    1177    24.1    0.26 •  30.8  12.4  18.4   9.0   1.1   7.8   0.5 •    4213
0.73    25    16    3365    13.7    0.14 •  30.9  12.4  18.5   9.0   1.1   7.5   0.8 •    4224
0.73    25    28    1002    26.3    0.29 •  31.0  12.4  18.6   9.0   1.1   8.0   0.4 •    4238
0.73    25    30     863    28.5    0.33 •  31.2  12.4  18.8   9.0   1.1   8.3   0.4 •    4268
0.73    25    14    4493    11.7    0.13 •  31.3  12.4  18.9   9.0   1.1   7.8   1.0 •    4286
0.73    25    12    6272     9.8    0.11 •  32.1  12.4  19.7   9.0   1.1   8.3   1.3 •    4394

                         BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.73    25    24    1866    16.5    0.20 •  31.7  12.4  19.3   9.0   1.1   8.5   0.7 •    4341
0.73    25    22    2252    14.9    0.18 •  31.8  12.4  19.4   9.0   1.1   8.4   0.8 •    4346
0.73    25    26    1569    18.1    0.22 •  31.8  12.4  19.4   9.0   1.1   8.6   0.7 •    4347
0.73    25    28    1336    19.7    0.24 •  31.9  12.4  19.5   9.0   1.1   8.7   0.6 •    4362
0.73    25    20    2768    13.3    0.16 •  31.9  12.4  19.5   9.0   1.1   8.5   0.9 •    4365
0.73    25    30    1151    21.3    0.27 •  32.0  12.4  19.6   9.0   1.1   8.9   0.6 •    4382
0.73    25    18    3477    11.8    0.14 •  32.2  12.4  19.8   9.0   1.1   8.6   1.1 •    4403
0.73    25    16    4487    10.3    0.13 •  32.7  12.4  20.3   9.0   1.1   8.9   1.2 •    4469
0.73    25    14    5991     8.8    0.12 •  33.5  12.4  21.0   9.0   1.1   9.4   1.5 •    4576
0.73    25    12    8363     7.3    0.11 •  34.7  12.4  22.3   9.0   1.1  10.3   1.9 •    4749

                         BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.73    25    26    1961    14.5    0.19 •  32.8  12.4  20.4   9.0   1.1   9.4   0.9 •    4485
0.73    25    28    1671    15.8    0.21 •  32.8  12.4  20.4   9.0   1.1   9.5   0.8 •    4487
0.73    25    24    2332    13.2    0.17 •  32.8  12.4  20.4   9.0   1.1   9.3   1.0 •    4493
0.73    25    30    1439    17.1    0.23 •  32.9  12.4  20.5   9.0   1.1   9.6   0.8 •    4498
0.73    25    22    2816    11.9    0.16 •  33.0  12.4  20.6   9.0   1.1   9.4   1.1 •    4514
0.73    25    20    3461    10.7    0.14 •  33.3  12.4  20.9   9.0   1.1   9.5   1.2 •    4554
0.73    25    18    4347     9.4    0.13 •  33.8  12.4  21.4   9.0   1.1   9.8   1.4 •    4620
0.73    25    16    5609     8.2    0.12 •  34.5  12.4  22.1   9.0   1.1  10.3   1.7 •    4721
0.73    25    14    7488     7.0    0.11 •  35.7  12.4  23.2   9.0   1.1  11.0   2.1 •    4877
0.73    25    12   10454     5.9    0.10 •  37.4  12.4  25.0   9.0   1.1  12.2   2.7 •    5120

                         BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.73    25    28    2005    13.1    0.19 •  33.7  12.4  21.3   9.0   1.1  10.2   1.0 •    4615
0.73    25    30    1727    14.2    0.20 •  33.7  12.4  21.3   9.0   1.1  10.3   0.9 •    4615
0.73    25    26    2354    12.0    0.17 •  33.8  12.4  21.4   9.0   1.1  10.2   1.1 •    4625
0.73    25    24    2799    11.0    0.16 •  34.0  12.4  21.6   9.0   1.1  10.2   1.2 •    4647
0.73    25    22    3379     9.9    0.14 •  34.3  12.4  21.9   9.0   1.1  10.3   1.4 •    4687
0.73    25    20    4153     8.9    0.13 •  34.7  12.4  22.3   9.0   1.1  10.6   1.6 •    4749
0.73    25    18    5216     7.9    0.12 •  35.4  12.4  23.0   9.0   1.1  11.0   1.9 •    4843
0.73    25    16    6731     6.8    0.11 •  36.4  12.4  24.0   9.0   1.1  11.7   2.2 •    4982
0.73    25    14    8986     5.9    0.10 •  37.9  12.4  25.5   9.0   1.1  12.7   2.8 •    5190
0.73    25    12   12545     4.9    0.10 •  40.3  12.4  27.9   9.0   1.1  14.2   3.6 •    5510

                         BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.73    25    30    2015    12.2    0.19 •  34.6  12.4  22.2   9.0   1.1  10.9   1.2 •    4735
0.73    25    28    2339    11.3    0.17 •  34.7  12.4  22.3   9.0   1.1  10.9   1.3 •    4745
0.73    25    26    2746    10.3    0.16 •  34.9  12.4  22.4   9.0   1.1  10.9   1.4 •    4767
0.73    25    24    3265     9.4    0.15 •  35.1  12.4  22.7   9.0   1.1  11.1   1.5 •    4805
0.73    25    22    3942     8.5    0.13 •  35.6  12.4  23.1   9.0   1.1  11.3   1.7 •    4863
0.73    25    20    4845     7.6    0.12 •  36.2  12.4  23.8   9.0   1.1  11.7   2.0 •    4949
0.73    25    18    6086     6.7    0.12 •  37.1  12.4  24.7   9.0   1.1  12.2   2.3 •    5072
0.73    25    16    7853     5.9    0.11 •  38.4  12.4  26.0   9.0   1.1  13.1   2.8 •    5252
0.73    25    14   10484     5.0    0.10 •  40.3  12.4  27.9   9.0   1.1  14.3   3.5 •    5516
0.73    25    12   14635     4.2    0.09 •  43.3  12.4  30.9   9.0   1.1  16.1   4.6 •    5918
```

```
                 JOB 11.  SAME AS JOB 10 WITH FOLLOWING CHANGES

                  1 DESIGN FLOW                 7     MGD
                 13 UNIT FLOW RATE          0.5/0.25/3.5          GSFM
                 14 BODY FEED               10/5/50               PPM
                 20 BACKWASH COST              10, 30   GAL/SF, MIN
                   BEGIN

FLOW  TERM    CD  B E T A   TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *    TOTAL
      HEAD         4  -2                .*                   LAB+                  *     COST
GSFM   FT    PPM  10 FT      HR      IN * TOTAL    1ST  OPER   MAIN   POWR   DIAT  BAKW *     $/MO
-----------------------------------------*-------------------------------------------*---------

                            BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.75    25    30     575    7.3   0.23 *  23.4    6.4  17.0    5.1    1.1    9.5   1.3 *     4988
1.75    25    25     854    5.9   0.18 *  23.5    6.4  17.1    5.1    1.1    9.2   1.6 *     4996
1.50    25    25     854    8.1   0.20 *  23.5    7.1  16.4    5.5    1.1    8.6   1.2 *     5003
2.00    25    30     575    5.6   0.21 *  23.5    5.9  17.7    4.8    1.1   10.0   1.7 *     5011
1.50    25    30     575   10.0   0.26 *  23.7    7.1  16.6    5.5    1.1    9.0   1.0 *     5040
2.00    25    35     412    6.7   0.27 *  23.7    5.9  17.8    4.8    1.1   10.4   1.5 *     5045
1.75    25    35     412    8.7   0.29 *  23.8    6.4  17.4    5.1    1.1   10.0   1.1 *     5055
2.00    25    25     854    4.5   0.17 *  23.8    5.9  17.9    4.8    1.1    9.8   2.2 *     5070
1.50    25    20    1384    6.2   0.15 *  23.9    7.1  16.8    5.5    1.1    8.6   1.5 *     5079
2.25    25    35     412    5.2   0.25 *  23.9    5.5  18.4    4.6    1.1   10.8   1.9 *     5088

                            BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
1.50    25    30     863    6.7   0.20 *  25.7    7.1  18.6    5.5    1.1   10.4   1.6 *     5476
1.50    25    35     618    8.0   0.25 *  25.8    7.1  18.7    5.5    1.1   10.8   1.4 *     5498
1.75    25    35     618    5.8   0.22 *  25.9    6.4  19.5    5.1    1.1   11.4   1.9 *     5508
1.25    25    30     863    9.6   0.22 *  26.0    8.1  17.9    6.0    1.1    9.7   1.1 *     5535
1.75    25    30     863    4.9   0.18 *  26.0    6.4  19.6    5.1    1.1   11.1   2.3 *     5537
1.25    25    25    1281    7.8   0.18 *  26.1    8.1  18.0    6.0    1.1    9.5   1.4 *     5544
1.75    25    40     463    6.8   0.27 *  26.1    6.4  19.7    5.1    1.1   11.8   1.6 *     5551
1.50    25    25    1281    5.4   0.16 *  26.1    7.1  19.0    5.5    1.1   10.4   2.0 *     5553
1.50    25    40     463    9.3   0.30 *  26.2    7.1  19.1    5.5    1.1   11.3   1.2 *     5576
1.25    25    35     618   11.5   0.28 *  26.3    8.1  18.2    6.0    1.1   10.2   1.0 *     5600

                            BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
1.50    25    35     824    6.0   0.21 *  27.6    7.1  20.5    5.5    1.1   11.9   2.0 *     5879
1.25    25    30    1151    7.2   0.19 *  27.7    8.1  19.6    6.0    1.1   10.9   1.6 *     5890
1.25    25    35     824    8.6   0.23 *  27.7    8.1  19.6    6.0    1.1   11.1   1.4 *     5894
1.50    25    40     617    7.0   0.25 *  27.7    7.1  20.6    5.5    1.1   12.3   1.7 *     5900
1.50    25    30    1151    5.0   0.17 *  27.9    7.1  20.8    5.5    1.1   11.8   2.4 *     5941
1.25    25    40     617   10.1   0.28 *  28.0    8.1  19.9    6.0    1.1   11.6   1.2 *     5959
1.75    25    40     617    5.1   0.22 *  28.0    6.4  21.6    5.1    1.1   13.0   2.4 *     5960
1.50    25    45     478    8.0   0.30 *  28.1    7.1  21.0    5.5    1.1   12.8   1.5 *     5972
1.25    25    25    1708    5.8   0.15 *  28.2    8.1  20.1    6.0    1.1   10.9   2.1 *     5992
1.75    25    35     824    4.4   0.19 *  28.2    6.4  21.8    5.1    1.1   12.7   2.8 *     5993

                            BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
1.25    25    35    1031    6.9   0.20 *  29.1    8.1  21.1    6.0    1.1   12.1   1.8 *     6199
1.25    25    40     772    8.1   0.24 *  29.2    8.1  21.1    6.0    1.1   12.5   1.6 *     6218
1.50    25    40     772    5.6   0.21 *  29.3    7.1  22.2    5.5    1.1   13.3   2.3 *     6238
1.25    25    30    1439    5.8   0.17 *  29.4    8.1  21.3    6.0    1.1   12.0   2.2 *     6261
1.50    25    45     598    6.4   0.25 *  29.4    7.1  22.3    5.5    1.1   13.7   2.0 *     6264
1.50    25    35    1031    4.8   0.18 *  29.5    7.1  22.4    5.5    1.1   13.1   2.7 *     6280
1.25    25    45     598    9.3   0.29 *  29.6    8.1  21.5    6.0    1.1   13.0   1.4 *     6289
1.00    25    30    1439    9.1   0.19 *  29.7    9.5  20.1    6.8    1.1   10.8   1.4 *     6316
1.00    25    35    1031   10.8   0.23 *  29.7    9.5  20.2    6.8    1.1   11.1   1.2 *     6328
1.50    25    50     476    7.2   0.30 *  29.8    7.1  22.7    5.5    1.1   14.2   1.8 *     6336

                            BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
1.25    25    40     926    6.7   0.21 *  30.5    8.1  22.4    6.0    1.1   13.3   2.0 *     6485
1.25    25    35    1237    5.8   0.18 *  30.6    8.1  22.5    6.0    1.1   13.1   2.4 *     6515
1.25    25    45     718    7.7   0.25 *  30.6    8.1  22.6    6.0    1.1   13.7   1.8 *     6521
1.00    25    35    1237    9.0   0.21 *  30.8    9.5  21.3    6.8    1.1   11.9   1.5 *     6559
1.50    25    45     718    5.3   0.22 *  30.9    7.1  23.8    5.5    1.1   14.6   2.6 *     6568
1.50    25    40     926    4.7   0.19 *  31.0    7.1  23.9    5.5    1.1   14.3   3.0 *     6591
1.00    25    30    1727    7.6   0.17 *  31.0    9.5  21.5    6.8    1.1   11.8   1.8 *     6595
1.00    25    40     926   10.6   0.25 *  31.0    9.5  21.5    6.8    1.1   12.3   1.3 *     6596
1.25    25    50     571    8.7   0.30 *  31.0    8.1  22.9    6.0    1.1   14.2   1.6 *     6599
1.50    25    50     571    6.0   0.26 *  31.0    7.1  23.9    5.5    1.1   15.0   2.3 *     6603

                            BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
1.25    25    45     837    6.6   0.23 *  31.8    8.1  23.7    6.0    1.1   14.4   2.2 *     6758
1.25    25    40    1081    5.8   0.20 *  31.8    8.1  23.7    6.0    1.1   14.1   2.5 *     6761
1.00    25    35    1443    7.7   0.19 *  31.9    9.5  22.4    6.8    1.1   12.7   1.8 *     6795
1.00    25    40    1081    9.0   0.22 *  31.9    9.5  22.4    6.8    1.1   12.9   1.6 *     6796
1.25    25    50     667    7.5   0.27 *  32.0    8.1  23.9    6.0    1.1   14.9   1.9 *     6808
1.25    25    35    1443    4.9   0.17 *  32.2    8.1  24.1    6.0    1.1   14.0   2.9 *     6844
1.00    25    45     837   10.4   0.27 *  32.2    9.5  22.7    6.8    1.1   13.4   1.4 *     6853
1.50    25    50     667    5.2   0.24 *  32.3    7.1  25.2    5.5    1.1   15.8   2.8 *     6879
1.00    25    30    2015    6.5   0.16 *  32.4    9.5  22.8    6.8    1.1   12.7   2.2 *     6884
1.50    25    45     837    4.6   0.20 *  32.4    7.1  25.2    5.5    1.1   15.4   3.2 *     6884
```

```
                    JOB 12.  SAME AS JOB 11 WITH FOLLOWING CHANGES

               11 SEPTUM DIAMETER               1     INCHES
               15 TERMINAL HEAD              25/10/150         FT
                 BEGIN

            ____________________________________________________________

FLOW   TERM    CD   B E T A   TIME   THICK • ----- COSTS, $ PER MILLION GALLONS ------ •    TOTAL
       HEAD          4  -2                 •                    LAB+                  •     COST
GSFM    FT    PPM   10 FT      HR       IN • TOTAL    1ST  OPER  MAIN  POWR  DIAT  BAKW •     $/MO
-------------------------------------------•------------------------------------------•--------

                                BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
2.75     75    20     1384     9.8    0.24 •  18.9    4.9  14.0   4.3   3.4   5.7   0.6 •     4031
2.50     65    20     1384    10.1    0.23 •  18.9    5.2  13.8   4.4   2.9   5.8   0.6 •     4032
2.75     65    20     1384     8.1    0.22 •  19.0    4.9  14.1   4.3   2.9   6.0   0.8 •     4033
3.00     75    20     1384     8.0    0.23 •  19.0    4.7  14.3   4.2   3.4   5.9   0.8 •     4036
2.50     75    20     1384    12.2    0.26 •  19.0    5.2  13.8   4.4   3.4   5.5   0.5 •     4042
3.00     85    20     1384     9.4    0.25 •  19.0    4.7  14.3   4.2   3.8   5.6   0.6 •     4049
3.00     65    20     1384     6.7    0.21 •  19.0    4.7  14.4   4.2   2.9   6.2   1.0 •     4053
2.75     85    20     1384    11.5    0.27 •  19.0    4.9  14.1   4.3   3.8   5.5   0.5 •     4053
2.50     55    20     1384     8.2    0.21 •  19.1    5.2  13.9   4.4   2.5   6.2   0.8 •     4056
3.25     75    20     1384     6.7    0.21 •  19.1    4.5  14.5   4.2   3.4   6.1   0.9 •     4057

                                BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
2.50     85    20     2076     8.6    0.21 •  20.3    5.2  15.1   4.4   3.8   6.1   0.8 •     4318
2.50     75    20     2076     7.4    0.20 •  20.3    5.2  15.2   4.4   3.4   6.4   0.9 •     4324
2.25     75    20     2076     9.3    0.21 •  20.3    5.5  14.9   4.6   3.4   6.2   0.7 •     4327
2.50     75    25     1281    10.8    0.28 •  20.4    5.2  15.2   4.4   3.4   6.8   0.6 •     4331
2.75     75    25     1281     8.6    0.26 •  20.4    4.9  15.5   4.3   3.4   7.0   0.8 •     4333
2.75     85    20     2076     6.9    0.20 •  20.4    4.9  15.5   4.3   3.8   6.4   1.0 •     4333
2.50     95    20     2076     9.8    0.23 •  20.4    5.2  15.2   4.4   4.3   5.9   0.7 •     4334
2.25     85    20     2076    10.9    0.23 •  20.4    5.5  14.9   4.6   3.8   5.9   0.6 •     4335
2.50     65    25     1281     8.9    0.25 •  20.4    5.2  15.2   4.4   2.9   7.1   0.8 •     4337
2.75     95    20     2076     7.9    0.22 •  20.4    4.9  15.5   4.3   4.3   6.1   0.8 •     4338

                                BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
2.50     85    25     1708     8.7    0.25 •  21.3    5.2  16.2   4.4   3.8   7.1   0.8 •     4542
2.25     75    25     1708     9.5    0.24 •  21.4    5.5  15.9   4.6   3.4   7.2   0.8 •     4552
2.50     75    25     1708     7.5    0.22 •  21.4    5.2  16.3   4.4   3.4   7.4   1.0 •     4554
2.50     95    25     1708    10.1    0.27 •  21.4    5.2  16.3   4.4   4.3   6.9   0.7 •     4555
2.25     85    25     1708    11.1    0.27 •  21.4    5.5  15.9   4.6   3.8   6.9   0.6 •     4556
2.25     85    20     2768     7.7    0.19 •  21.4    5.5  15.9   4.6   3.8   6.6   0.9 •     4557
2.25     95    20     2768     8.8    0.20 •  21.4    5.5  15.9   4.6   4.3   6.3   0.8 •     4558
2.50     95    20     2768     6.9    0.19 •  21.4    5.2  16.3   4.4   4.3   6.6   1.0 •     4561
2.75     95    25     1708     8.1    0.25 •  21.4    4.9  16.5   4.3   4.3   7.1   0.9 •     4563
2.75     85    25     1708     7.0    0.23 •  21.4    4.9  16.5   4.3   3.8   7.4   1.0 •     4563

                                BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
2.25     85    25     2135     8.4    0.22 •  22.2    5.5  16.8   4.6   3.8   7.4   0.9 •     4728
2.25     95    25     2135     9.7    0.24 •  22.2    5.5  16.8   4.6   4.3   7.1   0.8 •     4732
2.50     95    25     2135     7.6    0.23 •  22.2    5.2  17.1   4.4   4.3   7.4   1.0 •     4732
2.50    105    25     2135     8.6    0.24 •  22.3    5.2  17.1   4.4   4.7   7.1   0.8 •     4742
2.50     85    25     2135     6.6    0.21 •  22.3    5.2  17.1   4.4   3.8   7.7   1.2 •     4745
2.00     85    25     2135    11.0    0.25 •  22.3    5.9  16.4   4.8   3.8   7.1   0.7 •     4751
2.25     75    25     2135     7.2    0.21 •  22.3    5.5  16.9   4.6   3.4   7.8   1.1 •     4752
2.50     85    30     1439     9.1    0.28 •  22.3    5.2  17.2   4.4   3.8   8.1   0.9 •     4754
2.25    105    25     2135    11.0    0.26 •  22.3    5.5  16.9   4.6   4.7   6.9   0.7 •     4755
2.00     75    25     2135     9.4    0.22 •  22.4    5.9  16.5   4.8   3.4   7.4   0.8 •     4756

                                BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
2.25     95    25     2562     7.7    0.21 •  23.0    5.5  17.5   4.6   4.3   7.6   1.0 •     4889
2.25    105    25     2562     8.7    0.23 •  23.0    5.5  17.5   4.6   4.7   7.3   0.9 •     4894
2.00     95    25     2562    10.0    0.23 •  23.0    5.9  17.2   4.8   4.3   7.3   0.8 •     4902
2.00     85    25     2562     8.7    0.21 •  23.0    5.9  17.2   4.8   3.8   7.6   0.9 •     4902
2.25     85    30     1727     9.2    0.26 •  23.1    5.5  17.6   4.6   3.8   8.3   0.9 •     4906
2.50    105    25     2562     6.9    0.21 •  23.1    5.2  17.9   4.4   4.7   7.6   1.1 •     4906
2.25     85    25     2562     6.7    0.20 •  23.1    5.5  17.6   4.6   3.8   8.0   1.2 •     4908
2.50     95    30     1727     8.3    0.27 •  23.1    5.2  17.9   4.4   4.3   8.3   1.0 •     4909
2.25     95    30     1727    10.6    0.29 •  23.1    5.5  17.6   4.6   4.3   8.0   0.8 •     4912
2.50    115    25     2562     7.7    0.23 •  23.1    5.2  18.0   4.4   5.2   7.4   1.0 •     4916

                                BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
2.00     95    25     2989     8.3    0.21 •  23.7    5.9  17.8   4.8   4.3   7.7   1.0 •     5038
2.25    105    25     2989     7.2    0.21 •  23.7    5.5  18.2   4.6   4.7   7.8   1.1 •     5039
2.25     95    30     2015     8.7    0.26 •  23.7    5.5  18.2   4.6   4.3   8.4   1.0 •     5039
2.00    105    25     2989     9.4    0.22 •  23.7    5.9  17.8   4.8   4.7   7.4   0.9 •     5043
2.25    115    25     2989     8.1    0.22 •  23.7    5.5  18.2   4.6   5.2   7.5   1.0 •     5046
2.25    105    30     2015     9.9    0.28 •  23.7    5.5  18.3   4.6   4.7   8.1   0.8 •     5049
2.25     85    30     2015     7.5    0.23 •  23.7    5.5  18.3   4.6   3.8   8.7   1.1 •     5052
2.25     95    25     2989     6.4    0.19 •  23.7    5.5  18.3   4.6   4.3   8.1   1.3 •     5052
2.00     85    30     2015     9.8    0.26 •  23.8    5.9  17.9   4.8   3.8   8.4   0.9 •     5054
2.50    105    30     2015     7.7    0.25 •  23.8    5.2  18.6   4.4   4.7   8.4   1.1 •     5054
```

```
                    JOB 13.  SAME AS JOB 12 EXCEPT 25 MGD

                 1 DESIGN FLOW                  25     MGD
                  BEGIN

              ---------------------------------------------------

FLOW   TERM    CD   B E T A   TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
       HEAD          4  -2                 *                     LAB+                 *    COST
GSFM    FT    PPM   10 FT      HR      IN  * TOTAL   1ST  OPER   MAIN   POWR  DIAT  BAKW *    $/MO
-------------------------------------------*------------------------------------------*--------

                             BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
3.00     75    20    1384     8.0    0.23 *  17.4    4.4  13.0   3.1    3.4   5.9   0.7 *   13254
2.75     65    20    1384     8.1    0.22 *  17.5    4.6  12.8   3.2    2.9   6.0   0.7 *   13263
2.75     75    20    1384     9.8    0.24 *  17.5    4.6  12.8   3.2    3.4   5.7   0.6 *   13265
2.50     65    20    1384    10.1    0.23 *  17.5    4.9  12.6   3.3    2.9   5.8   0.6 *   13293
3.25     75    20    1384     6.7    0.21 *  17.5    4.2  13.3   3.0    3.4   6.1   0.8 *   13295
3.00     65    20    1384     6.7    0.21 *  17.5    4.4  13.1   3.1    2.9   6.2   0.9 *   13300
3.00     85    20    1384     9.4    0.25 *  17.5    4.4  13.1   3.1    3.8   5.6   0.6 *   13308
3.25     85    20    1384     7.8    0.24 *  17.5    4.2  13.3   3.0    3.8   5.8   0.7 *   13311
2.50     75    20    1384    12.2    0.26 *  17.6    4.9  12.7   3.3    3.4   5.5   0.5 *   13339
2.75     85    20    1384    11.5    0.27 *  17.6    4.6  12.9   3.2    3.8   5.5   0.5 *   13354

                             BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
2.50     85    20    2076     8.6    0.21 *  18.8    4.9  13.9   3.3    3.8   6.1   0.7 *   14303
2.50     75    20    2076     7.4    0.20 *  18.8    4.9  14.0   3.3    3.4   6.4   0.8 *   14317
2.75     85    20    2076     6.9    0.20 *  18.8    4.6  14.2   3.2    3.8   6.4   0.9 *   14322
2.25     75    20    2076     9.3    0.21 *  18.9    5.2  13.7   3.5    3.4   6.2   0.7 *   14332
2.75     75    25    1281     8.6    0.26 *  18.9    4.6  14.2   3.2    3.4   7.0   0.7 *   14338
2.75     95    20    2076     7.9    0.22 *  18.9    4.6  14.2   3.2    4.3   6.1   0.7 *   14348
2.50     75    25    1281    10.8    0.28 *  18.9    4.9  14.0   3.3    3.4   6.8   0.6 *   14363
2.25     85    20    2076    10.9    0.23 *  18.9    5.2  13.7   3.5    3.8   5.9   0.5 *   14369
2.50     95    20    2076     9.8    0.23 *  18.9    4.9  14.0   3.3    4.3   5.9   0.6 *   14371
3.00     85    25    1281     8.3    0.27 *  18.9    4.4  14.5   3.1    3.8   6.9   0.7 *   14374

                             BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
2.50     85    25    1708     8.7    0.25 *  19.9    4.9  15.0   3.3    3.8   7.1   0.8 *   15107
2.25     75    25    1708     9.5    0.24 *  19.9    5.2  14.7   3.5    3.4   7.2   0.7 *   15135
2.50     75    25    1708     7.5    0.22 *  19.9    4.9  15.0   3.3    3.4   7.4   0.9 *   15138
2.25     85    20    2768     7.7    0.19 *  19.9    5.2  14.7   3.5    3.8   6.6   0.9 *   15140
2.75     85    25    1708     7.0    0.23 *  19.9    4.6  15.3   3.2    3.8   7.4   0.9 *   15144
2.25     95    20    2768     8.8    0.20 *  19.9    5.2  14.7   3.5    4.3   6.3   0.7 *   15152
2.75     95    25    1708     8.1    0.25 *  19.9    4.6  15.3   3.2    4.3   7.1   0.8 *   15154
2.25     85    25    1708    11.1    0.27 *  19.9    5.2  14.7   3.5    3.8   6.9   0.6 *   15158
2.50     95    20    2768     6.9    0.19 *  19.9    4.9  15.1   3.3    4.3   6.6   0.9 *   15158
2.50     95    25    1708    10.1    0.27 *  20.0    4.9  15.1   3.3    4.3   6.9   0.6 *   15162

                             BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
2.25     85    25    2135     8.4    0.22 *  20.7    5.2  15.5   3.5    3.8   7.4   0.8 *   15758
2.50     95    25    2135     7.6    0.23 *  20.8    4.9  15.9   3.3    4.3   7.4   0.9 *   15776
2.25     95    25    2135     9.7    0.24 *  20.8    5.2  15.6   3.5    4.3   7.1   0.7 *   15780
2.50     85    25    2135     6.6    0.21 *  20.8    4.9  15.9   3.3    3.8   7.7   1.1 *   15810
2.50    105    25    2135     8.6    0.24 *  20.8    4.9  15.9   3.3    4.7   7.1   0.8 *   15821
2.00     85    25    2135    11.0    0.25 *  20.8    5.6  15.2   3.7    3.8   7.1   0.6 *   15826
2.25     75    25    2135     7.2    0.21 *  20.8    5.2  15.6   3.5    3.4   7.8   1.0 *   15833
2.00     75    25    2135     9.4    0.22 *  20.8    5.6  15.2   3.7    3.4   7.4   0.8 *   15834
2.00     95    20    3461     8.7    0.19 *  20.9    5.6  15.3   3.7    4.3   6.6   0.8 *   15858
2.25     95    20    3461     6.7    0.18 *  20.9    5.2  15.7   3.5    4.3   6.9   1.0 *   15861

                             BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
2.25     95    25    2562     7.7    0.21 *  21.5    5.2  16.3   3.5    4.3   7.6   0.9 *   16327
2.00     85    25    2562     8.7    0.21 *  21.5    5.6  15.9   3.7    3.8   7.6   0.8 *   16352
2.25    105    25    2562     8.7    0.23 *  21.5    5.2  16.3   3.5    4.7   7.3   0.8 *   16353
2.00     95    25    2562    10.0    0.23 *  21.5    5.6  15.9   3.7    4.3   7.3   0.7 *   16359
2.25     85    25    2562     6.7    0.20 *  21.6    5.2  16.4   3.5    3.8   8.0   1.1 *   16384
2.50    105    25    2562     6.9    0.21 *  21.6    4.9  16.7   3.3    4.7   7.6   1.0 *   16389
2.25     85    30    1727     9.2    0.26 *  21.6    5.2  16.4   3.5    3.8   8.3   0.8 *   16398
2.50     95    30    1727     8.3    0.27 *  21.6    4.9  16.7   3.3    4.3   8.3   0.9 *   16415
2.50     95    25    2562     6.1    0.20 *  21.6    4.9  16.7   3.3    4.3   7.9   1.2 *   16418
2.25     95    30    1727    10.6    0.29 *  21.6    5.2  16.4   3.5    4.3   8.0   0.7 *   16427

                             BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
2.00     95    25    2989     8.3    0.21 *  22.2    5.6  16.6   3.7    4.3   7.7   0.9 *   16835
2.25    105    25    2989     7.2    0.21 *  22.2    5.2  17.0   3.5    4.7   7.8   1.0 *   16855
2.00    105    25    2989     9.4    0.22 *  22.2    5.6  16.6   3.7    4.7   7.4   0.8 *   16858
2.25     95    30    2015     8.7    0.26 *  22.2    5.2  17.0   3.5    4.3   8.4   0.9 *   16870
2.25    115    25    2989     8.1    0.22 *  22.2    5.2  17.0   3.5    5.2   7.5   0.9 *   16890
2.25     95    25    2989     6.4    0.19 *  22.2    5.2  17.0   3.5    4.3   8.1   1.2 *   16894
2.00     85    25    2989     7.2    0.19 *  22.2    5.6  16.6   3.7    3.8   8.1   1.1 *   16896
2.00     85    30    2015     9.8    0.26 *  22.2    5.6  16.6   3.7    3.8   8.4   0.8 *   16900
2.25     85    30    2015     7.5    0.23 *  22.2    5.2  17.0   3.5    3.8   8.7   1.0 *   16905
2.25    105    30    2015     9.9    0.28 *  22.3    5.2  17.1   3.5    4.7   8.1   0.7 *   16915
```