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Design requirements of precoat filters for water filtration

Harold Ray Bridges
Iowa State University

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DESIGN REQUIREMENTS OF PRECOAT FILTERS FOR WATER FILTRATION

by

Harold Ray Bridges

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Dean of Graduate College

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INTRODUCTION

History of Filtration

Filtration may be defined as the process of separating a mixture of solid particles and a fluid by passing the mixture through a porous medium which allows the fluid to pass through but retains the solid particles. The fluid may be liquid or gas and the solid particles may be of infinite variety. The desired product from this process may be either the removed solids or the filtered fluid. In the context of this thesis the desired product is water suitable for domestic use.

The word "filter" (fylter, filtre) is probably derived from the Latin *filtrum*, closely related to *feltrum*, meaning felt or compressed wool, and both are related to the Greek word, ιπσλ, signifying hair (24). The term "filtration" did not come into general use until the 16th century. Before that time, the words "sifting" and "straining" were used.

Actually, the "art of filtration" was probably practiced by ancient man long before the invention of the wheel since wherever man existed, at certain periods his drinking water must have become turbid, making some method of clarification necessary. Although there is no record of how man learned the simple principle, undoubtedly it was from repeated observation of some form of clarification as by the purification of water by trickling through sandy soil or by the accidental passage of rainwater through an outstretched skin, garment, or tent cover. In any case man has apparently known the process since the dawn of history, far beyond the earliest records, wherein it was accepted as an established practice. References have been found to the manufacture of wine by the Chinese in about 2000 B.C. and it can be assumed that some kind of filtration was employed (24). At about this same period, persons in India were known to treat water by filtering it through charcoal, keeping it in copper containers, and exposing it to sunlight (24).

The earliest (about 1250 B.C.) written record of filtration is that cut on the walls of the tomb of Rameses II, at Thebes, Egypt (24). There, illustrations depicted a kitchen scene with the drawing off of liquids of various kinds by means of threads. The earliest book which makes reference to filtration is Plato's "Symposium" (360 A.D.) in which capillary siphoning is also referred to. Additional references were made by Aristotle to the passage of water through earthen vessels and by Hippocrates, the "Father of Medicine", who advocated the boiling and filtering of polluted water before drinking (24).

After the fall of the Roman empire and throughout the Middle Ages, the art of filtration practiced by the ancient Egyptians and advanced by the Greeks and Romans was forgotten.

Some filtration was carried on by alchemists who generally employed capillary siphoning. Sand filters similar to the type used in modern practice weren't developed until the 18th century. What is generally thought to be the first filter patent ever issued was that granted to Joseph Amy by the French Government in 1789 (24). This called for downward filtration through sand or sponge in a vessel having a false bottom. The first British filter patent was granted to Peacock in 1791. Peacock described his invention as a new method of filtration by ascent through coarse gravel followed by graded sand which today is called upflow filtration. This method of filtration is even today receiving considerable research interest. Several other current research topics were mentioned in early patents. For example, in 1884 Isaiah Smith Hyatt took out a process patent on simultaneous coagulation and filtration. The basic principle of this patent involved doing away with the necessity of pre-sedimentation and pre-coagulation of water prior to its filtration.

Modern public water filtration dates from 1829, when James Simpson built the first slow sand filters for the Chelsea Water Company of London. The use of slow sand filters was at first slowly and then rapidly adopted. Two incidents led to the rapid adoption of sand filters. First, John Snow gave epidemiological proof that the London cholera epidemic of 1854 was traceable to contaminated and unfiltered water drawn from the Broad Street well. Second, in 1892 Dr. Robert Koch traced the cholera epidemic in Hamburg, Germany, to its unfiltered raw water supply. He did this by observing that the city of Altona on the opposite bank of the Elbe, which used the same water, but filtered it, had significantly less disease.

The first slow sand filters in the United States were built in 1872 at Poughkeepsie, New York by James Kirkwood who had previously traveled to Europe to study water filtration practices there. Shortly thereafter Patrick Clark, superintendent of the Rahway, New Jersey, water works installed a small rapid sand filter. Rapid sand filtration experiments at Louisville by George W. Fuller in 1895-97 showed that rapid sand filtration was successful if preceded by proper coagulation and sedimentation. Since Fuller's historic work, rapid sand filters have become firmly established in their use and major design features. Sand filter design into the early 1960's was based principally on past experience and only in recent years have efforts been made to put the design of filters on a scientific basis. The ultimate goal of these efforts is to develop methods which can be used to optimize the filtration process.

In order to optimize successfully the design of a particular filtration process to give the maximum amount of acceptable filtrate per unit cost, it is necessary to develop a mathematical theory which fully describes the process. This theory is needed to relate such filtration variables as head loss, filter run length, filtration rate, influent water temperature, and the characteristics of the suspended solids in the raw water. Today, there is considerable research interest in developing such a theory or theories for rapid sand filtration which is used extensively for the filtration of public water supplies. To date there is no theory which is generally applicable for rapid sand filtration, therefore optimum design of rapid sand filters has not been achieved.

During the past fifteen years considerable research has been conducted at Iowa State University on both rapid sand filtration and diatomite or precoat filtration. This research has led to the development of a theory of precoat filtration and an appropriate design method by which the design and operation of precoat filters may be optimized. The primary purpose of this thesis is to present this design method in a form which is readily usable to a design engineer and to define clearly the limitations and applicability of the theory of precoat filtration.

Precoat Filtration

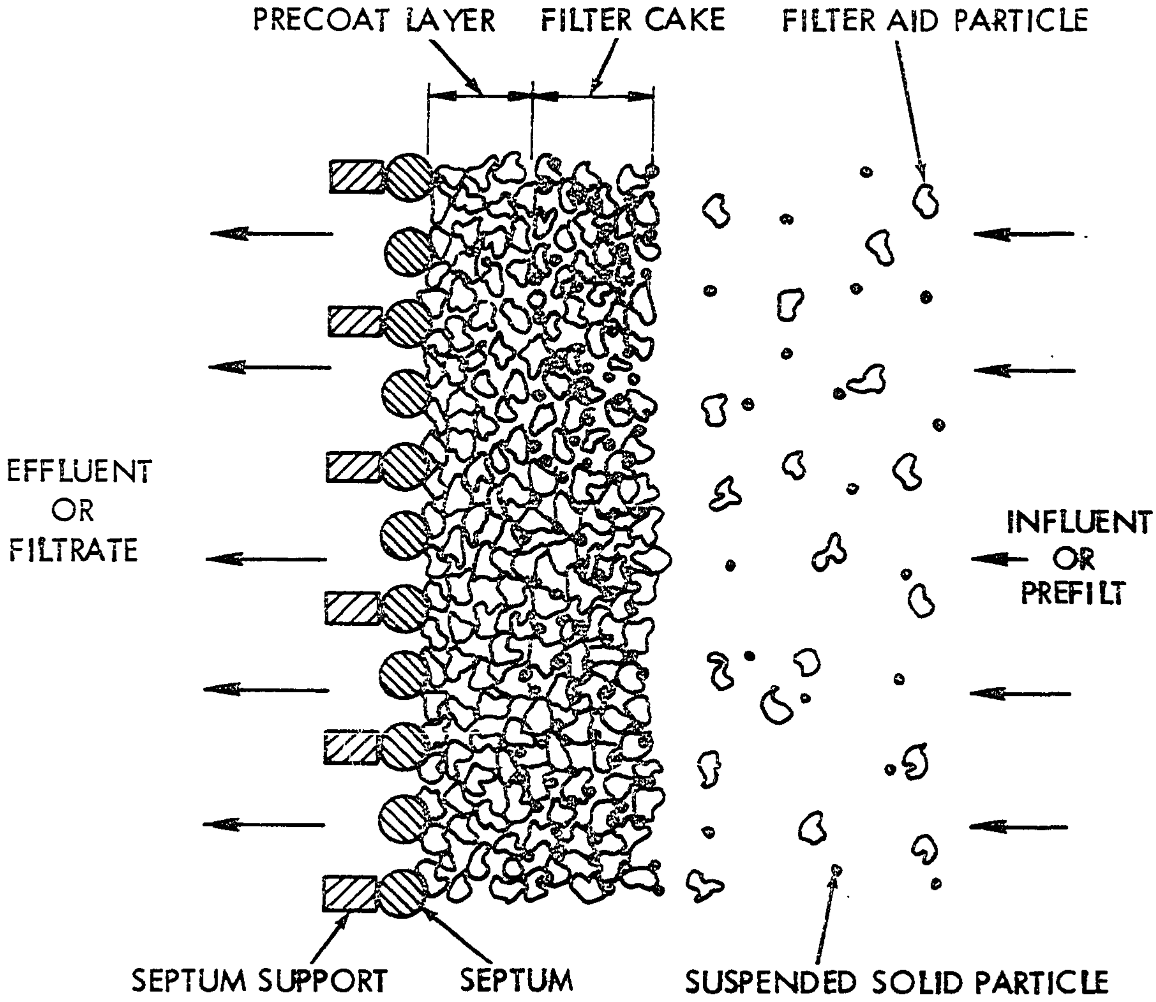
General

Precoat filtration is a term applied to the process of filtration employing a thin (approximately 1/8-inch) layer of filter medium or filter aid. This process is a three-step operation. First, a thin protective layer of filter aid called the precoat (hence the term precoat filtration) is built up on the filter septum by recirculating a slurry of the filter aid (see Figure 1). After precoating, the filtering step is started. A small amount of filter aid called body feed is added to the incoming water. As the body feed is deposited at the filter surface a new filtering surface is formed. This prevents the formation of an impervious mat on the surface of the filter medium by the impurities removed from the water. After a predetermined head loss through the filter is reached, the filter is backwashed. The precoat is removed along with the body feed and impurities from the filtered water.

Filter equipment

Various types of precoat water filters are available. They usually fall into two general classifications depending on how the driving force is applied across the filter: pressure filters and vacuum filters.

Figure 1. Cross section of a precoat filter


PRECOAT LAYER
FILTER CAKE
FILTER AID PARTICLE
EFFLUENT OR FILTRATE
INFLUENT OR PREFILT
SEPTUM SUPPORT
SEPTUM
SUSPENDED SOLID PARTICLE

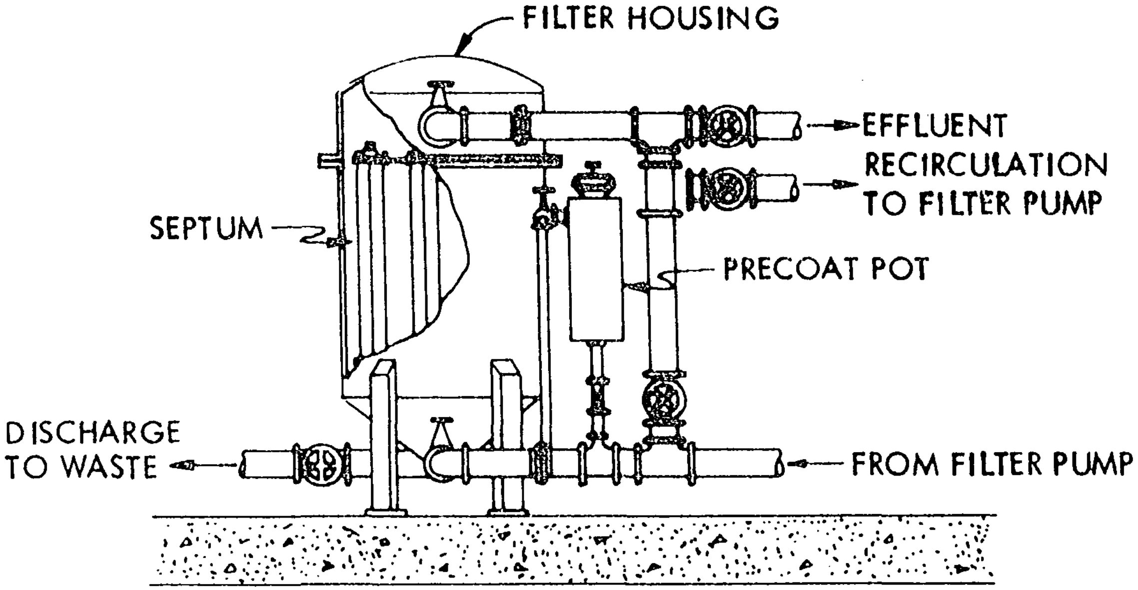
Pressure filters As the name implies, the prefilt is forced through the filter by either a pump in the influent line or by an available hydrostatic head. The pressure in the filter cake is designed to be greater than atmospheric pressure and the pressure differential across the cake is unlimited.

The most common types of pressure filters used in water filtration are cylindrical element filters and vertical leaf filters (Figure 2). These differ according to the shape of the filter septa (cylindrical or flat) and the manner by which the filter is backwashed.

The cylindrical element filters consist of vertical cylinders (about 1 to 3 in. diameter is typical) fastened to a tube sheet or header at the top (Figure 2(a)). They may be backwashed by reversing the flow of water or by "air bump" backwash. In this case, air is trapped on the filtered water side of the filter septa. At the end of the filtration cycle, the effluent valve is closed and the air is compressed to the maximum operating pressure of the filter pump. When the filter drain valve is opened, the air expands rapidly, forcing the water back through the septa with explosive force, thereby effectively loosening the cake from the septa. A variation of this is "multiple air bump" which was used by the U.S. Army Engineer Research and Development Laboratories (ERDL), Fort Belvoir, Virginia, in their

Figure 2. Precoat filters

a) Pressure filter - cylindrical elements


FILTER HOUSING
EFFLUENT
RECIRCULATION TO FILTER PUMP
SEPTUM
PRECOAT POT
DISCHARGE TO WASTE
FROM FILTER PUMP

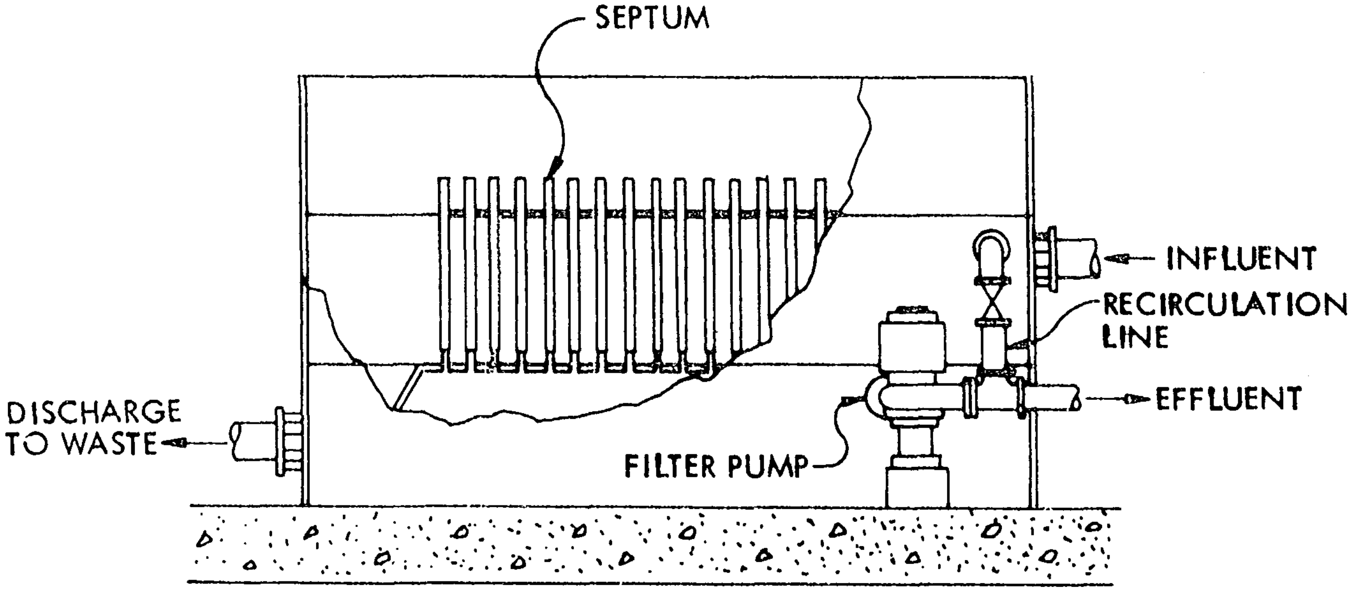


Figure 2 (Continued)

(b) Vacuum filter - vertical leaf elements mobile treatment units during World War II. In this system, air is also trapped on the raw water side of the filter septa. Immediately after opening the filter drain valve, the air on the raw water side is suddenly released, forming a pocket into which the backwash water can surge before draining out.

Vertical leaf filters provide a flat filtering surface as opposed to cylindrical element filters. All vertical leaf filters are basically the same as far as precoating and filtering procedures are concerned, but they differ in the method of cake removal. These filters may therefore be further classified by the method of cake discharge as dry discharge filters and wet discharge filters. With dry discharge filters the filter leaves are either pulled out of the shell, or the shell is pulled away from the leaves. The cake can be removed as a wet mud by mechanical scraping or as a slurry by manual sluicing. Wet discharge filters are equipped with an internal cake sluicing device, thus eliminating the need for opening the filter for cake removal. A system of water jets is generally used in a manner which peels off the cake from the leaves, breaks it up, and flushes it out of the drain. Another type of vertical leaf filter is the reversible flow - wet discharge filter. These filters are designed so that by reversing the direction of flow, the spent cake can be removed from one side of the filter element while the opposite side is being precoated. During this operation, the filter discharge is directed to waste.

Vacuum filters In the vacuum filter, the filter is located on the suction side of the pump so that the pressure on the influent side of the filter is at atmospheric pressure. This allows filtration to be performed in an open tank where the filter elements can be seen at all times. The principle disadvantage of vacuum filters is that the driving force (pressure differential) across the filter is limited to the vacuum that can be pulled by a normal pump (about 18 to 22 ft of water). Therefore, the vacuum filter is limited to use with raw waters of relatively good quality where little driving force is required for long filter runs. The pressure filter is indicated where a heavy suspended solids load must be removed and a larger driving force is required to provide a reasonable length of filter run.

As with the pressure filter, the septa of a vacuum filter can be either of the cylindrical or the vertical leaf type. The vacuum filter can also be cleaned by either manual or automatic sluicing.

A recent development in precoat filtration is the rotary vacuum filter. This filter is similar in construction to the vacuum filters used to dewater sewage sludges. For precoat filtration, a thick precoat is laid on the filter and during the filtration cycle the filter cake and a small amount of the precoat layer are continuously removed by a rotary knife. This allows long filter runs to be made with a low driving force across the filter. In one installation, Hutto (39) reports the use of a 7-cm thick precoat and a knife advance rate of one cm per day so that a filter run would last for a full week.

Filter operation

Precoat filters can be operated under three conditions depending on how the pressure is applied across the filter and/or how the flow rate through the filter is regulated. These conditions are referred to as constant-rate filtration, constant-pressure filtration, and declining-rate filtration.

Constant-rate filtration   Constant-rate filtration is most commonly used in current water works practice. In this method of operation, a constant pressure is usually supplied to the filter system and the flow rate through the filter is held constant by a manually operated or automatic flow control valve on the effluent line. Thus, as the filter resistance increases during a filter run, the pressure loss or driving force across the filter increases in order to maintain a constant rate of flow according to Equation 1:

$$\text{Rate of flow} = \frac{\text{driving force}}{\text{filter resistance}} \tag{1}$$

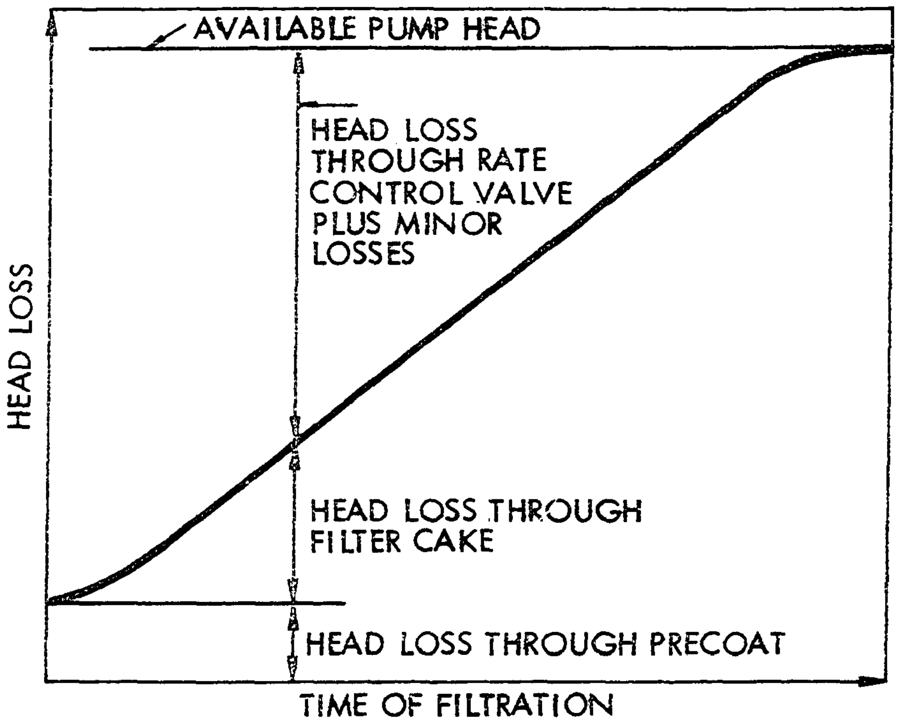
This is shown diagrammatically in Figure 3.

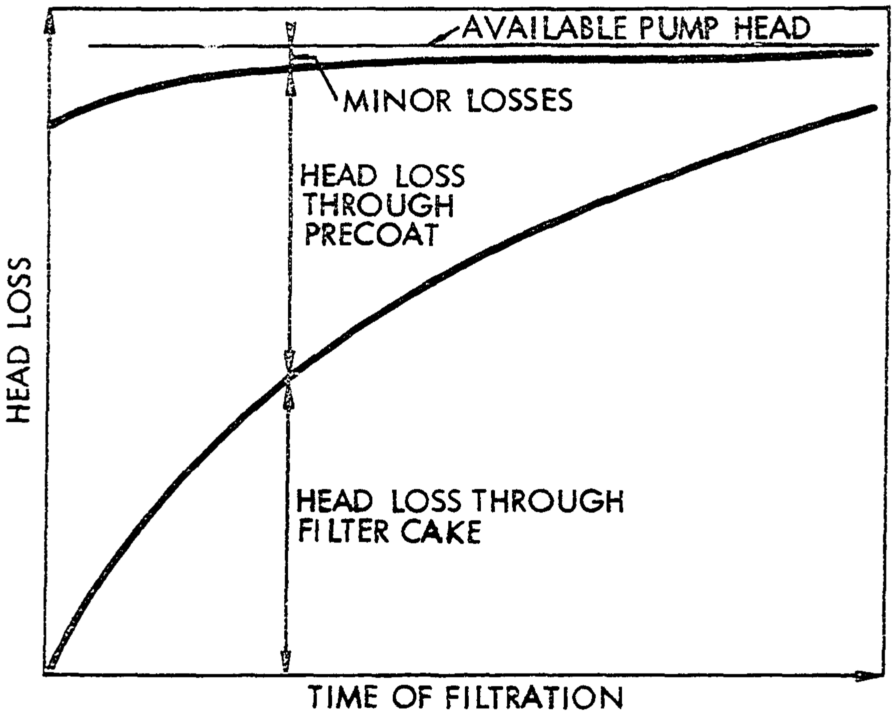
When the head loss through the precoat and filter cake reaches a value equal to the available pump head minus minor losses and the loss through the control valve when completely open, the constant rate run must be terminated. Since any further increase in filter resistance cannot be compensated for by the control valve, the ratio of driving force/filter resistance (Equation 1) will decrease and the flow rate must also decrease.

Constant-pressure filtration In constant-pressure filtration, the total available driving force is applied across the filter throughout the filter run and no provision is made to regulate the flow rate through the filter. Thus, the initial flow rate is equal to the total available driving force divided by the resistance of the precoat layer. As the filter run continues, the filter becomes clogged with solids and the filter resistance will increase. Therefore, since the available driving force remains constant, the flow rate will decrease. Actually, as the flow rate decreases, the minor head losses through the pipes, etc., will decrease and thus make a greater head loss through the filter available. These minor losses can generally be neglected

Figure 3. Head loss versus time for constant-rate filtration

Figure 4. Head loss versus time for constant-pressure filtration


AVAILABLE PUMP HEAD
HEAD LOSS THROUGH RATE CONTROL VALVE PLUS MINOR LOSSES
HEAD LOSS
HEAD LOSS THROUGH FILTER CAKE
HEAD LOSS THROUGH PRECOAT
TIME OF FILTRATION


AVAILABLE PUMP HEAD
MINOR LOSSES
HEAD LOSS THROUGH PRECOAT
HEAD LOSS
HEAD LOSS THROUGH FILTER CAKE
TIME OF FILTRATION

for filter systems designed to operate at constant pressure. Also there may be an increase in the available pump head since most centrifugal pumps show an increase in head as the flow rate through the pump decreases (7). This type of operation is shown in Figure 4.

The constant-pressure method of filtration is seldom used in water filtration practice. Piping and all other appurtenances must be designed to carry the large volume of flow during the initial stages of a constant-pressure filter run. In addition, provision is required for relatively large volumes of water storage on both the upstream and downstream sides of the filter. These considerations have made constant-pressure filtration on a large scale uneconomical. This method of operation also makes difficult the addition of a constant proportion of body feed to the filter influent.

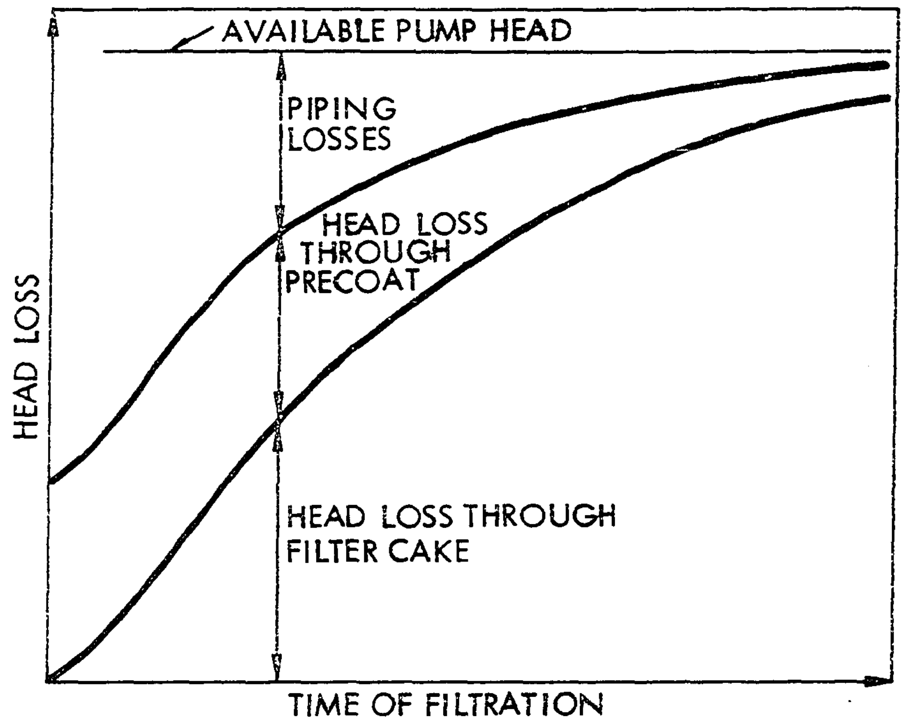
Declining-rate filtration   Declining-rate filtration is a special case of constant-pressure filtration in that the total available driving force is applied across the entire filter system. It differs from constant-pressure filtration due to the fact that the filter influent and effluent piping is designed so that the associated head losses are not negligible compared to the loss through the filter itself. Therefore, at the beginning of a filter run, the piping will provide most of the head loss in the system since the clean filter will have little head loss (Figure 5). Thus, the piping losses will control the flow rate early in the run. As the filter becomes clogged, the pressure loss through the filter will increase to a point where it overshadows the losses in the piping and the filter losses will gain control of the flow rate (Figure 5). The decrease in flow rate will be more gradual than in constant-pressure filtration because as the loss through the piping decreases, more head is made available across the filter. As with constant-pressure filtration, the filter run would be terminated when the flow rate becomes too low to satisfy requirements.

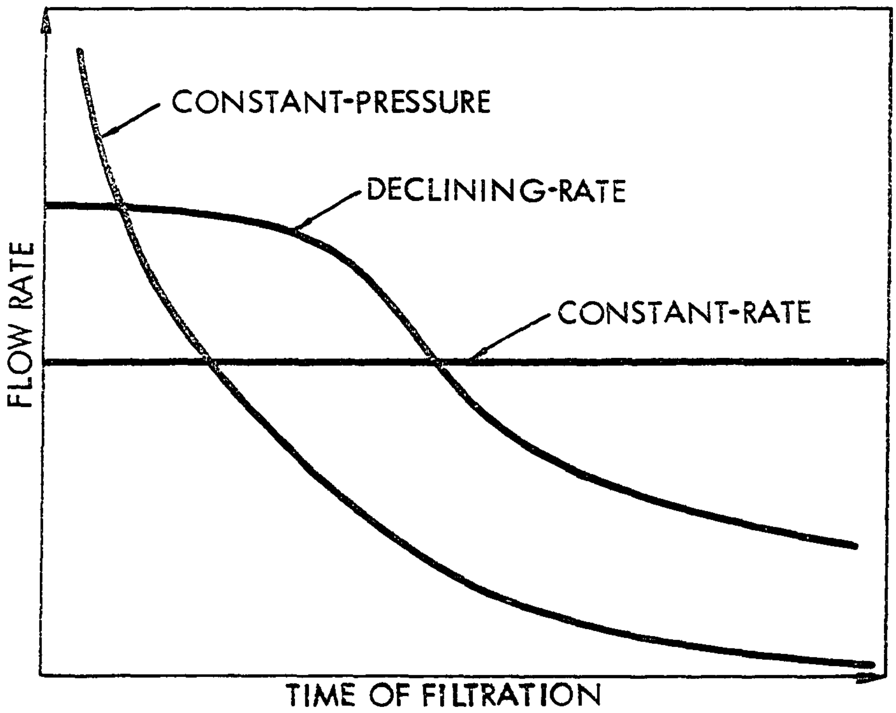
Declining-rate filtration is usually limited to small, non-municipal water filtration systems (small swimming pools) where no provision is made for automatic flow control needed for constant-rate operation and it is not desirable to handle the wide range of flow rates obtained with constant-pressure filtration.

The preceding methods of filter operation produce the flow rate patterns shown in Figure 6. Constant-rate filtration is almost solely used for precoat filtration of water due to its inherent advantages of providing economy in the design of filter influent and effluent piping and the ease of adding body feed in constant proportion to the filter influent.

Figure 5. Head loss versus time for declining-rate filtration

Figure 6. Rate of flow curves for the three methods of filter operation


AVAILABLE PUMP HEAD
PIPING LOSSES
HEAD LOSS THROUGH PRECOAT
HEAD LOSS THROUGH FILTER CAKE
HEAD LOSS
TIME OF FILTRATION


CONSTANT-PRESSURE
DECLINING-RATE
CONSTANT-RATE
FLOW RATE
TIME OF FILTRATION

Filter aids

The first material used as a filter aid for precoat filtration of water was diatomaceous earth or diatomite. Prior to the introduction of other filter aid materials, the terms diatomite and D-E filtration were used rather than precoat filtration. Diatomite filtration is still a most common term although precoat filtration is more generally applicable.

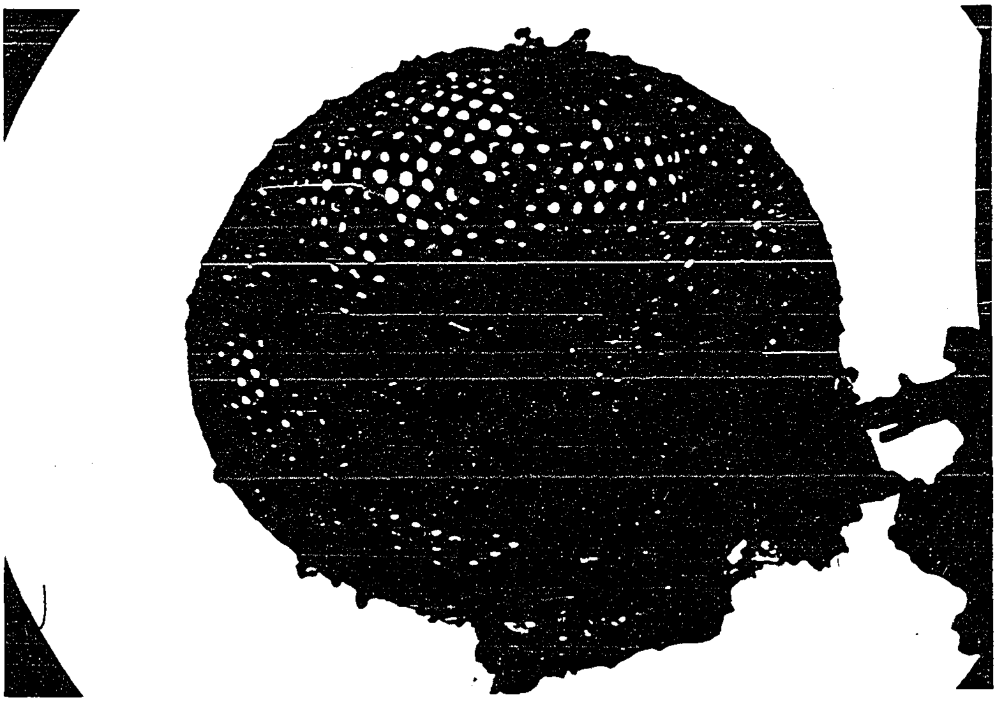
Diatomite is composed of fossil-like skeletons of microscopic water plants called diatoms, members of the Bacillariophyceae class of algae. In the geological past of 15 or more million years ago, over 10,000 species of diatoms flourished in the waters covering certain of today's coastal areas. When these diatoms died and their skeletons sank to the ocean floor, large deposits of almost pure silica were formed. Later the land rose from the ocean floor and the deposits are now mined in open quarries. The largest and purest deposit of diatomaceous earth is located near Lompoc, California. Other deposits are mined along the western coast of the United States and Canada and throughout the world. The United States is the world's largest producer and user of diatomite. U.S. production during 1960-62 averaged more than 482,000 short tons per year, valued at about 24 million dollars (57).

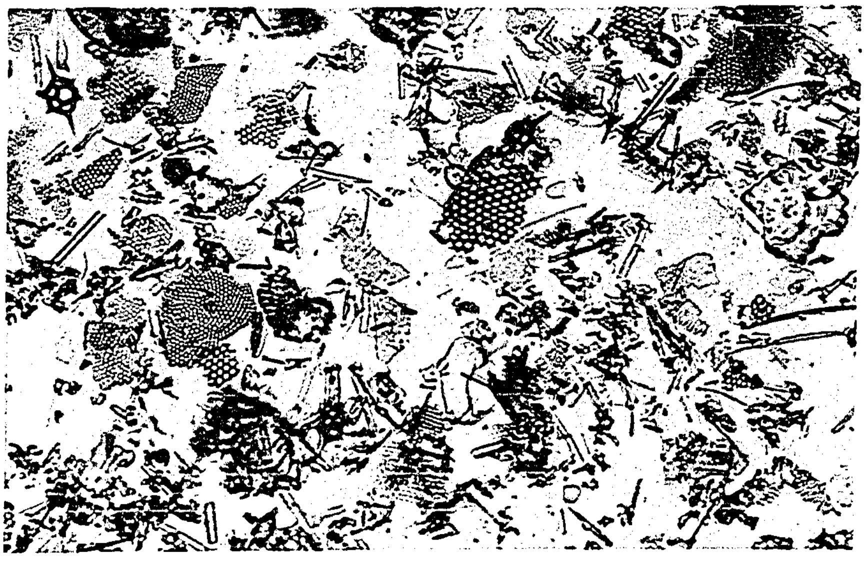
Diatomaceous earth has many applications: as a filter aid in the filtration of sugar syrups, beverages, and various chemicals as well as water; as a mineral filler in lacquers and paints, polishes, plastics, paper, insecticides, etc.; as high-temperature insulation; as an admixture for concrete; as an absorbent; and for countless other industrial applications (42). Processing the crude diatomaceous earth for use as a filter aid includes grinding, drying, and flux calcining. When flux calcining takes place, 3 to 10 percent by weight of either soda ash, sodium chloride, or caustic soda is added to the crude ore. Calcination affects the filtering properties of diatomite by changing the surface texture, agglomerating fines, and converting clay minerals to aluminum silicate slag (57). The slag particles are then largely eliminated in later processing steps. During the processing, the diatomite is separated into different particle size fractions by air classification. Particle sizes of individual diatoms vary from under 5 to over 100 microns. Grades of diatomite separated by air classification have mean particle sizes ranging from about 14 to 25 microns (55).

The performance of diatomite as a filter aid depends on the unique physical structure of the diatom particle (Figures 7 and 8). The almost infinite variety of shapes and sizes and the extremely porous framework of the skeletons provide numerous microscopic waterways and microscopic sieves which, when used as filter aids, serve to trap impurities.

Figure 7. An electron micrograph of an individual diatom from a typical diatomite, giving an indication of the straining potential of the media (4200X)

Figure 8. A micrograph of a typical diatomite showing irregular diatom fragments (250X)





Since the particles are rigid and strong, contact is limited to their outer points with the result that packing does not occur and the filter cake formed remains extremely porous. The porosity of a clean filter cake varies from 80 to about 90 percent for various grades of diatomite. Other typical properties of diatomite filter aids are found in Table 1 (42).

Table 1. Typical Celite[a] properties

Physical properties		Chemical properties	
Specific gravity	2.0-2.3	Average analysis in %, dry basis	
Refractive index	1.42-1.48		
Specific heat, cal/g°C	0.24	Silica (SiO_2)	89.7
Particle charge	negative	Alumina (Al_2O_3)	3.7
Retained on 325 mesh, maximum	0.5-3.0 %	Iron oxide (Fe_2O_3)	1.5
		Titanium oxide (TiO_2)	0.1
Average absorption, % Gardner-Coleman method		Lime (CaO)	0.4
Water	150-220	Magnesia (MgO)	0.7
Linseed oil	120-205	Alkalies (as Na_2O)	0.8
Bulk density, lb/cu ft		Ignition loss (combined H_2O, CO_2 and organics)	
Dry, loose	8-10		3.7
In filter cake	15-28		

[a] Registered trademark, diatomite filter aids, Johns-Manville Products Corporation, Manville, New Jersey.

Several other materials have been used as filter aids. Most successful of these is perlite, a material obtained by processing perlitic rock. Perlitic rock is composed essentially of aluminum silicate and contains 3 to 5 percent water (48). When crushed and heated, the rock expands and fractures to produce a light porous material similar to diatomite in both appearance and hydraulic characteristics. Perlite is used in many of the same ways as diatomite. As a filter aid, perlite is available in different grades which vary in both particle size and specific gravity. An average analysis of 10 perlites currently produced in 6 different states is given in Table 2 (48). A noticeable characteristic of perlite is that its bulk density in a filter cake is about one-half that of diatomite filter aids.

Like diatomite, perlite filter aids are produced in several grades of different particle size distributions. It has been found that there may also be differences in the characteristics of filter aid from various production lots of a particular grade and even from various bags of a particular lot (8). These differences arise from variations between deposits of diatomaceous earth or perlitic rock and the methods of processing the filter aids. Physical properties of several commercial filter aids are given in Table 3 (55). The values shown in Table 3 are averages of values obtained from tests with filter aids from several different production lots.

Table 2. Typical perlite properties

Physical properties[a]		Chemical properties	
Specific gravity	1.70-2.10	Moisture loss at 105°C	0.20
Particle charge	negative	Total moisture loss after ignition at 800°C	3.83
Bulk density in a filter cake, lb/cu ft	9.5-13.5	Aluminum oxide (Al_2O_3), including any phosphorous pentoxide or manganese oxide	13.08
		Lime (CaO)	0.72
		Iron oxide (Fe_2O_3)	0.89
		Magnesia (MgO)	0.18
		Potassium monoxide (K_2O)	4.44
		Silicon dioxide (SiO_2)	73.20
		Sodium monoxide (Na_2O)	3.31
		Sulphur trioxide (SO_3)	0.04
		Titanium dioxide (TiO_2)	0.09

[a] From laboratory tests conducted at Iowa State University.

Filter aids S2, S3, and S4 are perlite filter aids; all other filter aids listed in Table 3 are diatomite filter aids. The filter aid designations are explained in Appendix A.

Table 3. Physical properties of several commercial filter aids (55)

Filter aid designation	Effective specific gravity	In-place bulk density (lb/cu ft)	ξ index[a] (10^9 ft/lb)
S2	1.57	9.9	6.8
S3	1.73	12.6	9.1
S4	1.98	13.0	10.4
J4	2.30	19.7	1.8
J3	2.32	19.9	1.9
J0	2.30	19.9	3.1
HFC	2.30	20.7	5.2
E6	2.22	19.3	1.1
E5	2.30	23.2	1.8
E2	2.28	20.7	2.5
G4	2.27	23.5	1.8
G1	2.28	22.3	3.7

[a] Defined on page 46.

BACKGROUND AND LITERATURE REVIEW

Precoat Filtration of Water

The first extensive use of diatomite was for filtration of raw cane sugar liquor as early as 1876 (57). Today the primary industrial application of diatomite is as an industrial filtration medium for liquids ranging from municipal water supplies to alcoholic beverages. In contrast, substantial commercial production of perlite did not begin until 1946. In 1963 only 15 percent of the perlite produced in the United States was used as filter media (48). The major use was as an aggregate in building plaster.

The use of precoat filtration as a method of water treatment was not developed until World War II. During the Guadalcanal campaign, the U.S. Army found that military rapid sand filters were ineffective in removing cysts of *Entamoeba hystolytica* at the high filtration rates employed in the field (6-12 gpm/sq ft). These cysts are the causative agent of amoebic dysentery and are resistant to chlorination. Extensive research by the U.S. Army ERDL showed that diatomite filtration was effective in the removal of these cysts (14).

The successful use of diatomite filtration during the war stimulated its application to civilian use, principally for the filtration of swimming pool water. However, due to inadequate knowledge of the design and operation of these filters, many failed to provide an acceptable effluent at a cost comparable to sand filtration.

As a result of research concerning the basic principles of diatomite filtration and the development of better design and operating criteria, the use of diatomite filters steadily increased. In 1957, Phillips (58) effectively summarized what was then known about the design and operation of diatomite filters. His thesis contained an extensive literature review of diatomite filtration prior to 1957. Also in 1957, the American Water Works Association established a Task Group to determine more adequate design criteria for diatomite filters. In 1965, this group presented its report (67) which included a more current bibliography of the literature than Phillips' thesis.

In the thirteen years since 1957, much research in the precoat filtration of water has been conducted at Iowa State University under contract with the U.S. Public Health Service and, later, the Federal Water Pollution Control Administration. Eight Ph.D. theses and 15 master degree theses were completed during this time that are directly related to precoat filtration. Most of this research has been directed toward the development and evaluation of a theory of precoat filtration by which the design and operation of filters may be optimized (27, 43). Other research has been concerned with the characteristics of different filter aids and grades (2, 26, 35, 49), the evaluation of the filtering properties of various suspended solids (3, 15, 37, 44, 61), and the use of polyelectrolytes and aluminum sulfate to improve the filtering characteristics of filter aids (16, 17, 20, 52, 56, 60). Extensive laboratory studies have been made to determine the applicability of precoat filters for the removal of iron (2, 35, 43, 50, 70), various flocculant solids (37, 44), clays (3, 20, 60, 61), and suspended solids from coagulated and settled surface waters (15), raw surface waters, softened waters (15, 27), and trickling filter effluent (36). A summary of almost all of the precoat filter runs made by these researchers is included in Appendix A.

Theory of Precoat Filtration

General

Since its conception by ancient man, the practice of filtration has developed as an art. Improvements in the "art of filtration" have been made by trial and error and from a series of successes and failures the present design of filters has evolved. The art of filtration is slowly becoming the science of filtration. Water pretreatment practices have been improved to the point where filtration is now considered as only a polishing step. Content with the knowledge that they can design filters that will work, engineers are now trying to determine how filters work and how filters can be designed and operated at least cost.

In effort to determine how filters work, several authors have proposed various mechanisms by which suspended particles are removed within a filter. Burns (17) has presented an excellent discussion of the possible removal mechanisms involved in water filtration. Included are straining, gravitational forces, inertial forces, Brownian movement and particle diffusion, Van der Waals forces, electrical forces between surfaces, and chemical forces. In rapid sand filtration a considerable amount of the suspended solids are removed within the sand bed (i.e., depth removal) although in certain instances removal at the surface of the sand bed (i.e., surface removal) may predominate. Within a filter bed, all of the aforementioned removal mechanisms may occur, including interstitial straining near the point of contact(s) between filter grains. This has made the development of a single unified theory of rapid sand filtration a very complicated, if not impossible, task.

Precoat filtration is a form of cake filtration which is a fundamentally different process than fixed-bed granular filtration. In cake filtration the suspended solids are removed by straining at the surface of the filter to form a mat or cake of solids. Subsequent suspended solids are removed by straining at the surface of the previously formed filter cake. In precoat filtration the filter consists of the supporting septum and the precoat layer. A grade of filter aid is chosen which is fine enough to strain the suspended solids to be removed mechanically. This is a special form of cake filtration in that filter aid is added to the influent as body feed. In effect, the addition of body feed may be considered as a method of pretreatment to reduce the flow resistance of the resulting filter cake.

The action of filter aid

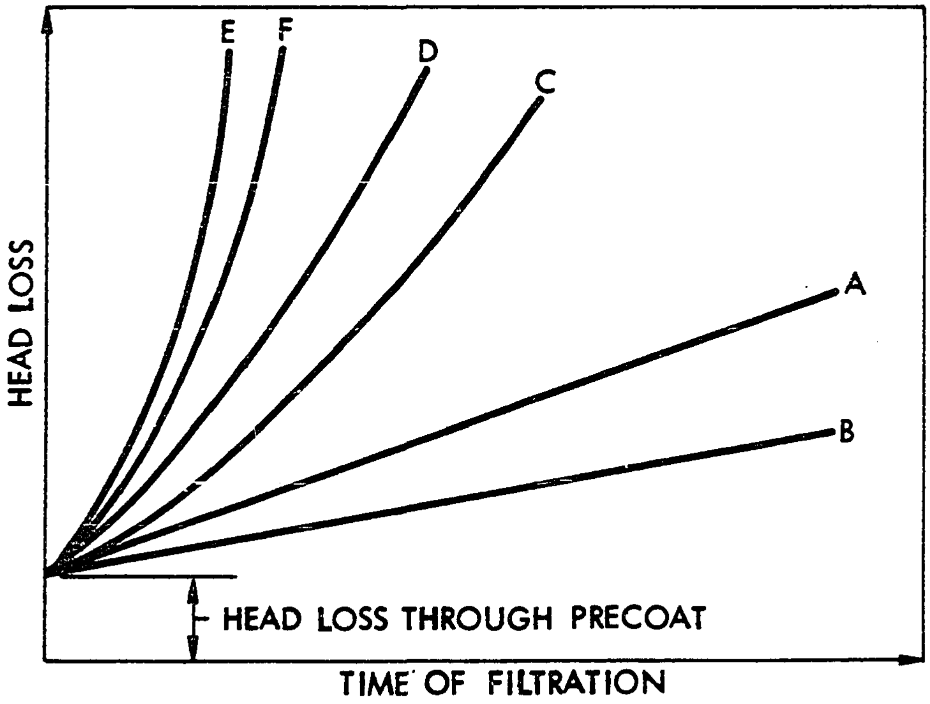
Since filter aid particles are rigid and strong, they form a filter cake which is incompressible within the range of pressures encountered in water filtration (47). If enough filter aid is added as body feed so that point-to-point contact between particles of filter aid is maintained in the filter cake, the cake will be essentially incompressible. The specific resistance of an incompressible filter cake remains constant as the pressure on the cake changes. Therefore, for constant-rate filtration, the head loss through any previously formed portion of the filter cake remains constant throughout the filter run and, the only increase in head loss through the filter is due to the solids being removed at the surface of the filter cake. Now, the amount of solids (impurities plus body feed) removed per unit time remains constant during constant-rate filtration. Thus, the increase in head loss through the filter per unit time will remain constant. This results in a linear head loss versus time curve as shown by Curve A in Figure 9.

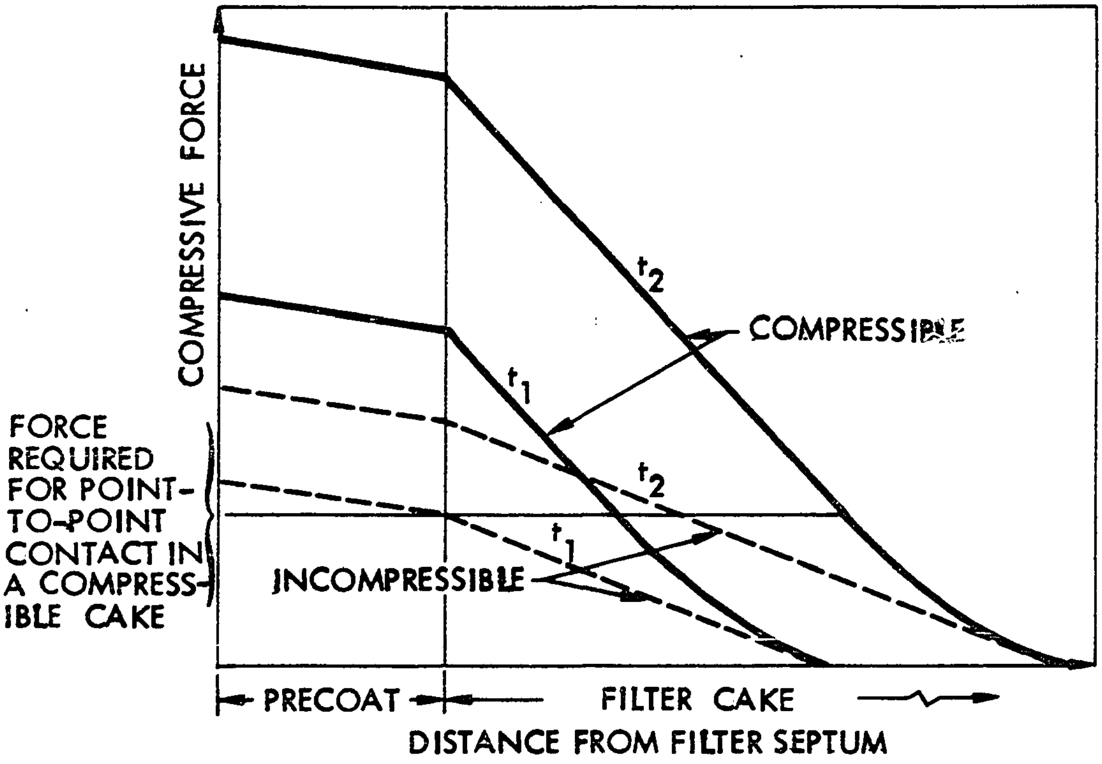
Adding a greater proportion of body feed to the filter influent results in the formation of a filter cake which is more porous and therefore contains a greater volume of void spaces available for flow but also results in a thicker cake. Thus, the specific resistance of the filter cake may be less and the increase in head loss per unit time may be lower (Curve B, Figure 9).

If the proportion of body feed is lowered, eventually the point is reached where the filter aid particles do not make point-to-point contact when they are initially deposited on the filter cake. Essentially all of the impurities encountered in water filtration are compressible. Therefore, as the pressure on a layer of filter cake increases, the layer compresses until contact is made between particles of the filter aid. Compression reduces the volume of voids in the cake, increases the apparent specific resistance of the cake, and increases the head loss through the cake. The compressive pressure on any layer within a filter cake is equal to the pressure loss through the cake lying above that layer. Shown in Figure 10 is the distribution of compressive force within a filter cake at different times, t_1 and t_2, during a filter run. As the filter cake

Figure 9. Head loss development curves for filter cakes with various amounts of body feed, flat septa

Figure 10. Distribution of compressive force within a filter cake at times t_1 and t_2


E
F
D
C
A
B
HEAD LOSS
HEAD LOSS THROUGH PRECOAT
TIME OF FILTRATION


COMPRESSIVE FORCE
t_2
t_1
COMPRESSIBLE
t_2
t_1
FORCE REQUIRED FOR POINT-TO-POINT CONTACT IN A COMPRESSIBLE CAKE
INCOMPRESSIBLE
PRECOAT
FILTER CAKE
DISTANCE FROM FILTER SEPTUM

thickens, the compressive force on the layer of filter cake next to the precoat increases to the value where point-to-point contact is made between filter aid particles. After this time, the thickness of filter cake which is compressible remains constant and the thickness of the incompressible layer next to the precoat increases constantly throughout the filter run (Figure 10).

Compression of the filter cake results in an exponential rate of head loss increase (Curve C, Figure 9). Any further decrease in the amount of body feed increases the compressive pressure required to make point-to-point contact between filter aid particles. This increases the thickness of the compressible layer of filter cake and the exponential rate of increase in head loss (Curve D, Figure 9).

Finally, if no body feed is added, a head loss curve such as shown by Curve F in Figure 9 may result. Addition of a very small amount of body feed only adds to the thickness of the filter cake and increases the rate at which head loss increases (Curve E, Figure 9). One might expect that the maximum rate of head loss increase would occur when just enough body feed is added so that point-to-point contact within the filter cake is not made until the very end of the filter run.

Several authors have developed theories applicable to compressive cakes (19, 64, 68). However, the application of these theories to precoat filtration of water would require the determination of compressibility factors of filter cakes with various amounts of body feed added, resulting in an extreme amount of difficult experimental work. Baumann and LaFrenz (10) have found that the optimum amount of body feed for least cost filtration produces a linear head loss curve and, therefore, an incompressible filter cake. For these reasons, the theory of precoat filtration has been developed for incompressible cakes only.

Precoat filtration equations

Darcy stated the basic concept for laminar flow through an incompressible porous bed in 1856 (23). Darcy's law states that the velocity of flow through a porous bed is directly proportional to the pressure gradient across the bed or:

$$\frac{dV}{Adt} = K \frac{dP}{dL} \tag{2}$$

where:

V = volume of filtrate passing through the bed in time t $[L^3]$

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

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

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

P = pressure loss across the porous media in the direction of flow $[FL^{-2}]$

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

The letters within brackets indicate the basic dimensions, force (F), length (L), and time (T), of the above terms.

In later years considerable data have shown the rate of flow through porous beds to be inversely proportional to the viscosity of the fluid so that Darcy's equation is usually modified as follows:

$$\frac{dV}{Adt} = \frac{K_1}{\mu}\frac{dP}{dL} \qquad (3)$$

where

K_1 = modified permeability coefficient independent of viscosity $[L^2]$

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

If the specific resistance to permeability on a volume basis, a, is defined as the reciprocal of the modified permeability coefficient, it is seen that the above modification of Darcy's law is the equivalent of Poiseuille's law for laminar flow through capillaries as presented in 1846 (59). Darcy's and Poiseuille's laws are both expressions of the basic flow relation given by Equation 1. The coefficient of viscosity is included as a correction factor to account for the effects of temperature.

LaFrenz (43) recognized that Darcy's law was applicable to flow through a precoat filter. He developed an equation for head loss development during a constant-rate filter run by applying the unmodified Darcy equation (Equation 2) to both the precoat layer and the filter cake. His equation was improved and published in the following form (5):

$$H = H_p + H_c$$

$$= K_3qw + K_4C_Fq^2t\ (8.33 \times 10^{-6}) \qquad (4)$$

where:

H = total head loss through the filter (ft of water)

H_p = head loss through the precoat layer (ft of water)

H_c = head loss through the filter cake (ft of water)

K_3, K_4 = constants including the coefficient of permeability of the filter cake and the bulk density of the filter aid in the precoat layer and filter cake respectively (min ft^5/lb gal)

q = filtration rate (gpm/sq ft)

w = weight of precoat layer (lb/sq ft)

C_F = concentration of body feed (mg/l or ppm)

t = elapsed time of filtration (min)

The head loss through the precoat layer is equal to the initial head loss at the beginning of a filter run and was assumed to remain constant throughout the run (i.e., no suspended solids are removed within the precoat layer). The term for the head loss through the filter cake was developed under the assumption that the thickness of the filter cake is determined by the amount of body feed and not increased by the suspended solids removed from the filter influent. This assumption is probably valid under the conditions for which Darcy's law may be applied (i.e., incompressible filter cake).

Because LaFrenz used the Darcy equation in its unmodified form, the coefficient of viscosity is not included in his equation. Therefore, the resistance coefficients K_3 and K_4 are not true constants but vary with the temperature of the water. Baumann and Oulman (12) modified LaFrenz's equation to correct for changes in viscosity.

Dillingham (27) reviewed the theory of precoat filtration in 1965 and found that two factors had not been considered. First, at the end of the precoating operation the filter housing is full of clean water. Therefore, at the beginning of the filtering cycle the filter influent is diluted before it passes through the filter. This results in a transition period which lasts until the quality of the water in the housing is the same as that of the influent. During this period of "initial dilution", the rate of head loss development is lower than it is during the remainder of the filter run.

Second, when cylindrical septa are used, the outer surface area of the filter cake increases as the thickness of the filter cake increases. This causes the flow rate per unit area of filtering surface to decrease throughout a filter run which has a marked effect on the head loss development during the run, especially when using small diameter septa.

Dillingham applied the modified Darcy equation (Equation 3) to develop a theory of precoat filtration which accounts for both the "initial dilution" and "increasing area" effects. The resulting equations are summarized in Table 4 (29). These equations may be used with any consistent set of units for the basic dimensions of force, length, and time. Units commonly used are pounds, feet, and hours.

Table 4. Summary of precoat filtration equations

	Equation	Equation number
Any septum	$H_p = q\nu\xi w/g$	(5)
Cylindrical septum	$H_c = \frac{R_s\sigma}{\phi}\ln(1 + \frac{R_s\phi X}{R_o^2})$	(6)
	$L = \sqrt{R_o^2 + R_s\phi X} - R_s$	(7)
Flat septum[a]	$H_c = \sigma X$	(8)
	$L = L_p + \frac{\phi X}{2}$	(9)

[a] Septum that does not exhibit increasing area effect.

Table 4 (Continued)

Equation

where:

$$\sigma = q^2 \nu \beta C_F / g$$

$$\phi = 2q\gamma_w C_F (10)^{-6} / \gamma_p$$

$$X = t - (1 - e^{-\delta t})/\delta$$

$$R_o = R_s + L_p$$

$$L_p = w/\gamma_p$$

$$\delta = Q/V_f$$

$$\beta = \frac{a_c \gamma_w (10)^{-6}}{\gamma_p}$$

$$\xi = \frac{a_p}{\gamma_p}$$

Symbol	Meaning	Dimension
A_s	Septum area	$[L^2]$
a_c	Specific resistance of filter cake based on volume of filter media	$[L^{-2}]$
a_p	Specific resistance of precoat layer based on volume of filter media	$[L^{-2}]$
C_F	Body feed concentration, ppm by weight	[--][b]

---

[b] Dimensionless.

Table 4 (Continued)

Symbol	Meaning	Dimension
C_S	Suspended solids concentration, ppm by weight	[--]
g	Gravity constant	$[LT^{-2}]$
H_c	Head loss through filter cake	[L]
H_p	Head loss through precoat layer	[L]
L_c	Thickness of filter cake	[L]
L_p	Thickness of precoat layer	[L]
L	$L_p + L_c$	[L]
Q	Flow rate	$[L^3T^{-1}]$
q	Flow rate per unit septum area or filtration rate, Q/A_s	$[LT^{-1}]$
R_o	Outer radius of precoated septum, $R_s + L_p$	[l]
R_s	Outer radius of septum	[L]
t	Elapsed time of filtration	[T]
V_f	Volume of filter housing	$[L^3]$
w	Precoat weight per unit septum area	$[FL^{-2}]$
X	Elapsed time corrected for initial dilution	[T]
β	Filter cake resistance index or β index	$[L^{-2}]$
γ_c	Bulk density of filter cake	$[FL^{-3}]$
γ_p	Bulk density of precoat layer	$[FL^{-3}]$
γ_w	Density of water	$[FL^{-3}]$

Table 4 (Continued)

Symbol	Meaning	Dimension
δ	Dilution rate, theoretically Q/V_f	$[T^{-1}]$
ν	Kinematic viscosity of influent	$[L^2T^{-1}]$
ξ	Filter aid resistance index or ξ index	$[F^{-1}L]$
σ	Arbitrary group of terms	$[LT^{-1}]$
ϕ	Arbitrary group of terms	$[LT^{-1}]$

A complete derivation of these equations is included in Appendix B. Their derivation is quite straightforward and includes the following assumptions:

1. Enough body feed is added to form an essentially incompressible filter cake.

2. Darcy's law applies (i.e., the flow is laminar).

3. Constant-rate filtration.

4. The outer surface area of the precoat layer is approximately equal to the outer surface area of the septa (i.e., thin precoat layer).

5. There are no concentration gradients in the filter housing (i.e., completely mixed system).

6. All solids, body feed and suspended solids, are removed at the surface of the filter cake (i.e., no solids pass through the filter and none are removed in the precoat layer).

7. The suspended solids retained in the filter cake do not increase the cake thickness appreciably.

8. The bulk densities of the precoat layer and filter cake (γ_p and γ_c) remain constant throughout a filter run.

9. The concentrations of suspended solids and body feed (C_S and C_F) remain constant throughout a filter run.

A filter cake is incompressible if enough body feed is added to provide point-to-point contact between filter aid particles in the cake. Point-to-point contact of filter aid particles would require that the suspended solids in the cake be deposited in the voids where they would not cause separation of the filter aid particles. Therefore, if the body feed rate is sufficient such that Assumption 1 is valid then Assumption 7 will also be met.

Since the channels in a precoat filter cake are very small, flow through them is considered laminar in accordance with Assumption 2. For flow in pipes and other large sections, the Reynolds number, which expresses the dimensionless ratios of inertial to viscous (or resistive) forces, serves as a criterion to distinguish between laminar and turbulent flow. Hence, by analogy, the Reynolds number has been employed to establish the limit of flows described by Darcy's law.

Reynolds number is expressed as:

$$N_R = \frac{\rho v D}{\mu} \qquad (10)$$

where:

ρ = fluid density (γ_w/g) $[FT^2L^{-4}]$

v = velocity of flow $[LT^{-1}]$

D = diameter of pipe $[L]$

μ = viscosity of fluid $[FTL^{-2}]$

To adapt this criterion to flow in a filter cake, the apparent velocity or filtration rate, q, is used for v and an average grain diameter, d, is substituted for D. Rose (63) found that laminar flow in porous media exists at $N_R<1$ and that turbulent flow exists when $N_R>10$. Thus, the maximum filtration rate at which the flow in a precoat filter cake is laminar can be calculated as:

$$q = \frac{N_R \mu}{\rho d} \qquad (11)$$

If $N_R = 1$

$\mu = 2.359 \times 10^{-5}$ lb sec/ft^2 at 60° F

$\rho = 1.938$ slug/ft^3

and

$d = 30$ microns $= 98.4 \times 10^{-6}$ ft

then

$q = 0.124$ ft/sec $= 55.5$ gpm/sq ft.

Obviously the flow is laminar at the filtration rates used in precoat filtration (1-3 gpm/sq ft).

Assumptions 3, 4, 8, and 9 impose conditions during a filter run which are generally met in practice. In certain cases such as filtration of a river water, however, the concentration of suspended solids may not remain constant during a filter run.

In order to describe the effect of initial dilution, it was necessary to assume completely mixed conditions within the filter housing (Assumption 5). It is very doubtful, however, if a filter has ever been built, or could be built, which achieved complete mixing. Just how well an actual filter housing approximates complete mixing has not been investigated.

It has been said that, "All filters pass some suspended solids all of the time." This is certainly the case in normal water filtration. Assumption 6, which states that no solids pass through the filter, was necessary in order to describe the effects of initial dilution. In this respect, the assumption is probably valid. However, it is assumed throughout the derivation that the specific resistance per unit volume of the precoat layer and filter cake both remain constant during a filter run. This implies that the precoat layer and filter cake are incompressible and that no solids are dislodged or deposited within the precoat layer or previously formed filter cake (i.e., no depth removal).

Since some solids are known to pass through a filter, it is likely that there are solids removed within the filter cake and precoat layer by interstitial straining or some other depth removal mechanisms. This is another possible source of error in the theory of precoat filtration that deserves investigation.

Prediction of filter cake resistance

In the precoat filtration equations, the filter cake resistance is indicated by the β index. The precoat layer resistance is indicated by the filter aid resistance index or ξ index.

Baumann et al. (5) reasoned that filter cakes containing equal ratios of suspended solids to body feed (C_S/C_F) should have equal specific resistance per unit volume (or weight) of cake. Therefore, specific resistance should vary only with changes in the type of suspended solids, grade of filter aid, or C_S/C_F ratio. Values of K_4 were determined for several filter runs using University tap water to which ferrous sulfate had been added. It was found that a log log plot of K_4 versus C_S/C_F formed a straight line corresponding to the equation:

$$K_4 = a(C_S/C_F)^b \qquad (12)$$

where:

a,b = empirical constants

The ability of Equation 12 to predict the value of K_4

was verified for several waters used in subsequent investigations by Hawley (37), Hall (35), and Regunathan (61). Regunathan, however, found that this relationship did not fit results from the filtration of University tap water containing sodium montmorillonite clay mineral (Wyoming bentonite). Instead, the specific resistance was lower for higher values of C_S and C_F, even though C_S/C_F remained constant. This "solids concentration effect" was thought to be caused by the swelling properties of sodium montmorillonite.

From these studies it was evident that for a certain suspended solid, the specific resistance of the filter cake depended on the ratio C_S/C_F, the concentration C_F or C_S, and the grade of filter aid. Therefore, Dillingham _et al_. (30) presented a prediction equation for β index of the general form:

$$\beta = 10^{b_1} (C_S/C_F)^{b_2} C_F^{b_3} \xi^{b_4} \qquad (13)$$

where b_1, b_2, b_3, and b_4 are exponents determined empirically.

The ξ index was included in the β prediction equation to account for differences in the β index when different filter aids are used. The use of the equation in this form, however, was not recommended. The ξ index is an index of the hydraulic characteristics of clean filter aid, not filtering characteristics. For example, Dillingham and Baumann (28) found that a filter aid with a higher ξ index (K_3) may possibly form a filter cake with a lower β index (K_4), even though C_S and C_F remain the same. This was substantiated by data reported by Baumann et al. (8) and Oulman et al. (55). Dillingham felt it was best to determine separate β prediction equations of the form:

$$\beta = 10^{b_1} (C_S/C_F)^{b_2} C_F^{b_3} \qquad (14)$$

for each grade of filter aid used.

If the exponent b_3 is 0, the above equation becomes:

$$\beta = 10^{b_1} (C_S/C_F)^{b_2} \qquad (15)$$

which is identical to Equation 12. Dillingham included C_F (Equation 14) as a variable separate from C_S/C_F in an attempt to improve β prediction for waters containing suspended solids such as sodium montmorillonite. This improved the β predictions for all waters, especially for water containing sodium montmorillonite and softened water (30), which both showed significant solids concentration effects.

Turbidity has been used as a relative measure of suspended solids concentration in studies by Regunathan (61) and Bridges (15). Regunathan used turbidity as a measure of the concentration of clay added to University tap water and Bridges measured turbidity in the field while filtering coagulated and settled surface waters. In both cases, the use of turbidity in place of suspended solids concentration, C_S, did not reduce the effectiveness of Equations 14 and 15 as β prediction equations. This is as expected since turbidity and suspended solids concentration are directly related and a plot of turbidity versus suspended solids concentration is usually a straight line passing through the origin (1, 61). Thus:

$$T = mC_S \tag{16}$$

where:

T = turbidity, usually JTU

m = slope of T versus C_S plot

The exponents in Equation 15, for example, are determined by taking the logarithms of both sides of the equation to give:

$$\log \beta = b_1 + b_2 \log(C_S/C_F) \tag{17}$$

and then performing a simple linear regression between $\log \beta$ and $\log(C_S/C_F)$. If turbidity is substituted for the suspended solids concentration in Equation 15, then:

$$\beta = 10^{b_1} (T/C_F)^{b_2}$$

or:

$$\beta = 10^{b_1} (mC_S/C_F)^{b_2}$$

and taking logarithms of both sides of the equation:

$$\log \beta = b_1 + b_2 \log(mC_S/C_F)$$

$$= (b_1+b_2 \log m) + b_2 \log(C_S/C_F) \qquad (18)$$

Thus, replacing the suspended solids concentration by turbidity does not change the form of the prediction equations. It acts only to change the value of the exponent b_1. All other exponents and the regression coefficient remain the same.

Baumann _et_ _al_. (5) expected that filter cakes with the same weight of suspended solids per unit weight of filter aid in the cake (C_S/C_F) would have the same resistance to flow and the same β index. It was evident, however, that filter cakes with equal C_S/C_F ratios would not have the same β index when different types or grades of filter aids were employed. This required that separate β prediction equations be determined for each filter aid that was used. Recently, Oulman and Baumann (54) suggested that the resistance to flow through a filter cake is really a function of the volume of void spaces in the cake that are available for flow and deposition of suspended solids. Thus, it was expected that a prediction equation of the form:

$$\beta = 10^{b_1} (C_S/V_V)^{b_2} \qquad (19)$$

where:

V_V = volume of voids $[L^3]$

would have the same exponents, b_1 and b_2, for different grades of filter aid. The volume of voids was calculated as the total volume of filter cake, assuming that the suspended solids do not increase the volume of the cake, minus the volume of the filter aid in the cake or:

$$V_V = \text{volume of cake} - \text{volume of filter aid}$$

$$= \frac{C_F}{\gamma_p} - \frac{C_F}{\gamma_w \rho_F} \tag{20}$$

where:

ρ_F = effective specific gravity of filter aid [--]

Since C_F is expressed in mg/l or ppm by weight, the volume of voids calculated by Equation 20 will be the volume of voids in a cake formed by filtering a million pounds of influent. C_S is also expressed in mg/l therefore the ratio C_S/V_V expresses the weight of suspended solids per unit of void volume in the filter cake.

Oulman and Baumann also observed from Equation 8 for the head loss through a flat filter cake that the product βC_F must be the same for all filter aids in order to give the same head loss under identical operating conditions. Thus, they thought it would be more reasonable to use a prediction equation of the form:

$$\beta C_F = 10^{b_1} C_S^{b_2} V_V^{b_3} \qquad (21)$$

This equation was applied to data obtained from the filtration of University tap water containing iron floc produced by adding ferric chloride. For all filter aids used, the value of b_2 was 2 and b_3 was -1 within the precision of the data, but the value of b_1 varied for different grades of filter aid. Also, when C_S is equal to zero, βC_F must be equal to $\beta_0 C_F$ where β_0 is the filter cake resistance index for a clean filter cake. Equation 21 was modified to give:

$$\beta C_F = \beta_0 C_F + k\, C_S^2 / V_V \qquad (22)$$

where:

β_0 = resistance index of a clean filter cake

$= \xi \gamma_w 10^{-6} \quad [L^{-2}]$

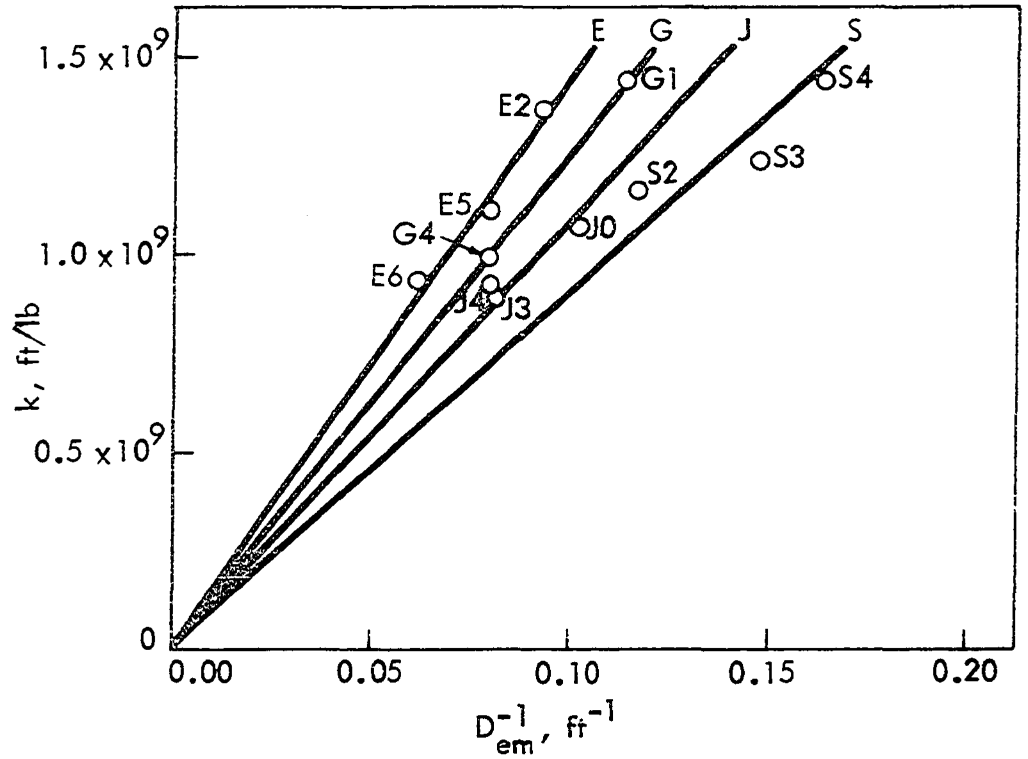
k = empirical constant

Further investigation revealed that k was directly related to the effective particle size of the filter aids and that a different k value-particle size relationship existed for the filter aids produced by different manufacturers. The data from which this conclusion was based are shown in Figure 11. The effective particle size, D_{em}, was determined from

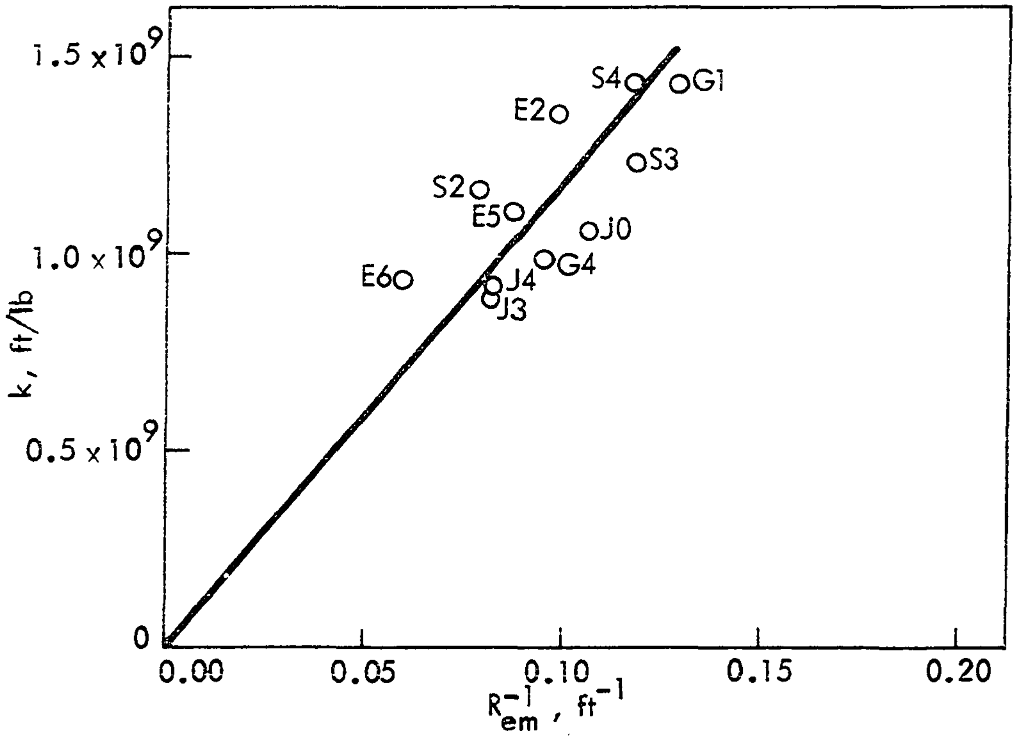
Figure 11. Relation of k value to effective particle size

E = Eagle-Picher Industries, Inc.
G = Great Lakes Carbon Corp.
J = Johns-Manville Products Corp.
S = Sil-Flo Corp.

Figure 12. Relation of k value to hydraulic radius



E
G
J
S
E2
G1
S4
S3
S2
E5
J0
G4
E6
J4
J3
1.5 x 10^9
1.0 x 10^9
0.5 x 10^9
0
k, ft/lb
0.00
0.05
0.10
0.15
0.20
D_{em}^{-1}, ft^{-1}



S4
G1
E2
S3
S2
E5
J0
E6
G4
J4
J3
1.5 x 10^9
1.0 x 10^9
0.5 x 10^9
0
k, ft/lb
0.00
0.05
0.10
0.15
0.20
R_{em}^{-1}, ft^{-1}

permeability data and theoretical relationships derived from the Rose equation (22, pp. 302-304) which relates the resistance of flow through a porous bed to the physical properties of the material in the bed. The Rose equation was given as

$$H_c - \left(\frac{1.067}{S}\right) \left(\frac{C_d}{g}\right) (L) \left(\frac{q^2}{\varepsilon^4}\right) \Sigma \frac{X}{d} \tag{23}$$

where:

S = particle shape factor = $6V_p/DA_p$ [--]

V_p = particle volume [L^3]

A_p = particle surface area [L^2]

C_d = drag coefficient = $24/N_R$ for $N_R < 10^4$ [--]

L = thickness of porous bed [L]

ε = porosity [--]

X = weight fraction of particle in a given size range [--]

d = particle diameter [L]

By combining Equations 8 and 23 and assuming a straight line particle size distribution and a mean uniformity coefficient, the following equation was developed for the effective filter aid particle size in microns:

$$D_{em} = \frac{1794(\gamma_w/\beta_0 \gamma_F)^{\frac{1}{2}}}{\varepsilon^2} \tag{24}$$

where γ_w and γ_F have units of lb/cu ft and β_0 has units of ft^{-2}.

This equation was then used to determine an expression for the hydraulic radius of a filter cake. From the data shown in Figure 12, Oulman and Baumann (54) found that the functional relationship between k and hydraulic radius was:

$$k = \frac{12.0 \times 10^9}{R_{em}} \qquad (25)$$

where:

R_{em} = effective hydraulic radius, in microns

Equations 8, 22, and 25 were combined to give a single relationship between the physical and filtration characteristics of all filter aids:

$$V_F = 3.95 \times 10^{-3}\ I \qquad (26)$$

where:

V_F = volume of body feed in cu ft/MG required for the specified filtration conditions:

q = 1 gpm/sq ft
t = 6 hrs
H_c = 100 ft of water
C_S = 4 ppm iron
Water temperature = 20° C
Flat septa

$$I = \text{filter aid index} = \frac{\gamma_F^{3/2} \beta_0^{1/2}}{\rho_F}$$

It was proposed that filter aid for the removal of iron floc could then be specified as having an effective size within a particular range and a filter aid index equal to or below a stated value. It was assumed that filter aids meeting the specification produce acceptable effluent quality.

Optimum Design of Precoat Filters

The first investigations which dealt with the cost of precoat filtration were primarily concerned with the comparison of diatomite filtration to sand filtration. One of the most extensive studies was made in 1951 by Sanchis and Merrell (66) of the Los Angeles Department of Water and Power. Their purpose was to determine the applicability of diatomite filtration for the removal of taste and odor caused by plankton growths in open reservoirs. They discovered that diatomite filtration was effective in producing water of a quality comparable to that produced by conventional methods of pretreatment followed by rapid sand filtration. In addition, they found that diatomite filters had lower space requirements and lower first cost. It was concluded that for average water quality conditions, the total cost per unit volume of water was about the same for diatomite without pretreatment as for rapid sand filtration with pretreatment.

A plant scale comparison of diatomite and rapid sand filtration of Raritan River water in New Jersey was made by

Bell in 1956 (13). Three methods of filtration were used; diatomite filtration of raw water, diatomite filtration of pretreated water, and rapid sand filtration of pretreated water. The results of the investigation showed that the installation costs for diatomite filtration, with or without pretreatment, were considerably lower than for sand filtration and the operating costs for diatomite filtration were slightly higher than for sand filtration. Bell concluded that the cost of diatomite filtration of the raw water was approximately equal to the cost of sand filtration plus pretreatment.

These and similar studies helped to dispel some of the hesitancy which engineers and state health departments had to the use of precoat filters. In 1965, the American Water Works Association Task Group on Diatomite Filtration concluded that, "...diatomite filter systems, if properly designed, constructed, and operated, can be successfully used in the production of potable water for municipal use" (67). This task group also stated, "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."

The filtration research conducted at Iowa State University has had as its ultimate goal the development of straightforward techniques which can be used to determine the optimum design characteristics of both precoat and sand filters. The "theory of precoat filtration" was developed by LaFrenz, Dillingham, and others for use in optimizing the design and/or operation of precoat filters.

Before developing his theory of precoat filtration, LaFrenz (43) made a total of more than 120 filter runs in order to assess some of the "optimums" in precoat filtration. He made tests with three precoat filters; (1) a constant-rate pilot plant, (2) a constant-rate, bench scale filter, and (3) a constant-pressure, bench scale filter. All tests were made with University tap water to which ferrous sulfate was added. The results and conclusions drawn from these tests have been published in several articles (9, 10, 45).

Previous efforts had been made to determine the optimum amount of body feed, however LaFrenz pointed out that the optimum body feed rate depends upon which factors are used to define the optimum. He considered three optimum body feeds:

1. Filter aid economy optimum body feed - That body feed which produces the maximum number of gallons of potable filtrate per pound of filter aid for a given water, filter, and type and grade of filter aid.

2. Head loss optimum body feed - That body feed which produces the maximum number of gallons of filtrate per filter

run, when filtering to some specific head loss. It is also the body feed which will produce the lowest head loss for the production of a specific amount of filtrate.

3. Overall optimum body feed - That body feed which produces potable water at the minimum cost per gallon.

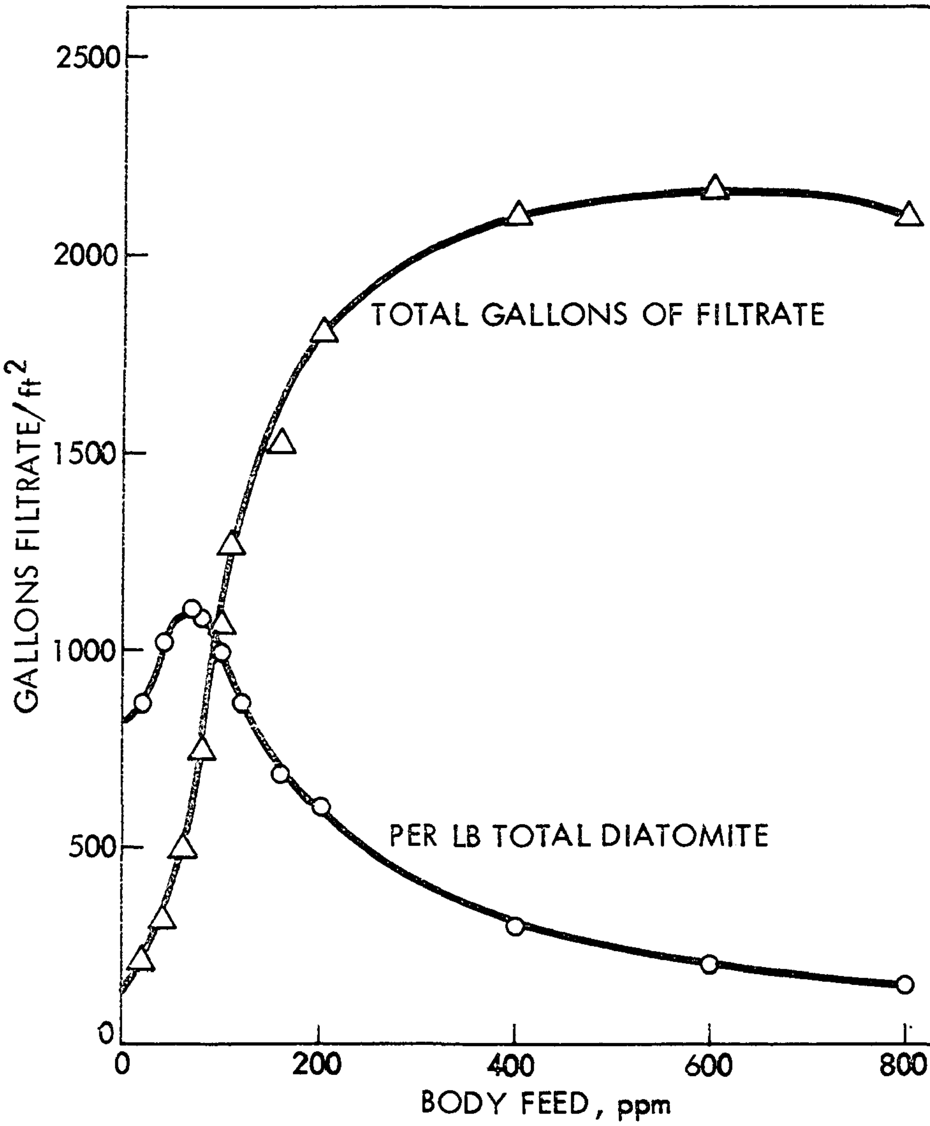
These three optimum body feeds are not the same even under identical filtering conditions. This fact was clearly shown by LaFrenz's data in Figure 13. For this data, the head loss optimum body feed is approximately 600 ppm whereas the filter aid economy optimum body feed is only 60 ppm.

At first glance, one might expect that the head loss optimum body feed would be infinite since as more body feed is added, the more porous the filter cake becomes, and therefore the run length increases. Eventually, however, the point is reached where the beneficial effects of increased porosity are balanced by the detrimental effects of the increased thickness of the filter cake. At higher body feed rates, this detrimental effect outweighs the beneficial effect, shortens the run length and decreases the total volume of filtrate during the run. The body feed rate at which these effects are balanced is the head loss optimum body feed. It varies only with factors which determine the composition of the filter cake such as type and grade of filter aid and type and amount of suspended solids.

Figure 13. A comparison of diatomite economy and head loss optimum body feed

LaFrenz's (43) data with constant-rate, bench scale filter with:

C_S = 7-8 ppm iron
q = 1 gpm/sq ft
H_t = 20 ft
w = 0.20 lb/sq ft


GALLONS FILTRATE/ft^2
2500
2000
1500
1000
500
0
0
200
400
600
800
BODY FEED, ppm
TOTAL GALLONS OF FILTRATE
PER LB TOTAL DIATOMITE

The filter aid economy optimum body feed was found to depend on both the amount of precoat and the terminal head loss. LaFrenz found that, in general, the filter aid economy optimum body feed decreased when the amount of precoat was decreased and the terminal head loss increased.

In designing a filtration plant, the engineer's principal concern should be to design a plant which can be operated to produce the desired amount of potable water at the least possible cost per gallon. Therefore, the optimum body feed which he should evaluate is the overall optimum body feed. Baumann and Babbitt (4) found that the most important factors affecting the cost of precoat filtration are: raw water quality, flow rate, terminal head loss, and the type, grade, and amount of filter aid. Thus, for a particular source of raw water and filter aid, there is a set combination of body feed rate, filtration rate, and terminal head loss which together result in the production of water at the least cost per gallon. This combination is the optimum body feed, optimum filtration rate, and optimum head loss. The optimum body feed is by definition the overall optimum body feed.

LaFrenz and Baumann (45) noted that the above three optimums are influenced by four basic cost factors: filter aid, labor, power, and equipment. They then presented a procedure for manually calculating the optimum combination of body feed, filtration rate, and terminal head loss. Before this procedure can be used, the type of filter and the type and grade of filter aid must be chosen. LaFrenz (43) stated that both cylindrical and flat septums are acceptable and that the most economical filter aid is the coarsest grade which will produce an acceptable quality of water. Basically, his procedure consists of choosing a filtration rate and body feed rate and then calculating the total cost per 1000 gal at various terminal head losses. From these calculations, the minimum total cost at the chosen filtration rate and body feed rate can be obtained (Figure 14). Similar calculations are made at several body feed rates for each filtration rate that is considered. The minimum total costs obtained from all of these calculations are then plotted against the rate of body feed as is done in Figure 15. From this figure, the minimum total cost and optimum design conditions can be obtained.

To use LaFrenz's procedure for calculating optimum precoat filter design, several filter runs must be made. The data from these filter runs are needed in order to define the length of run for each combination of body feed, filtration rate, and terminal head loss. In addition, this procedure requires many time consuming calculations. Therefore, Dillingham (25, 27) developed a digital computer program named POPO (Program for Optimization of Plant Operation) which can be used to design a precoat filtration plant which will operate at least cost. Minimum, maximum,

Figure 14. Effect of terminal head loss on filtration costs

LaFrenz's (43) data with constant-rate, bench scale filter with:

C_S = 7-8 ppm iron

q = 1 gpm/sq ft

w = 0.15 lb/sq ft

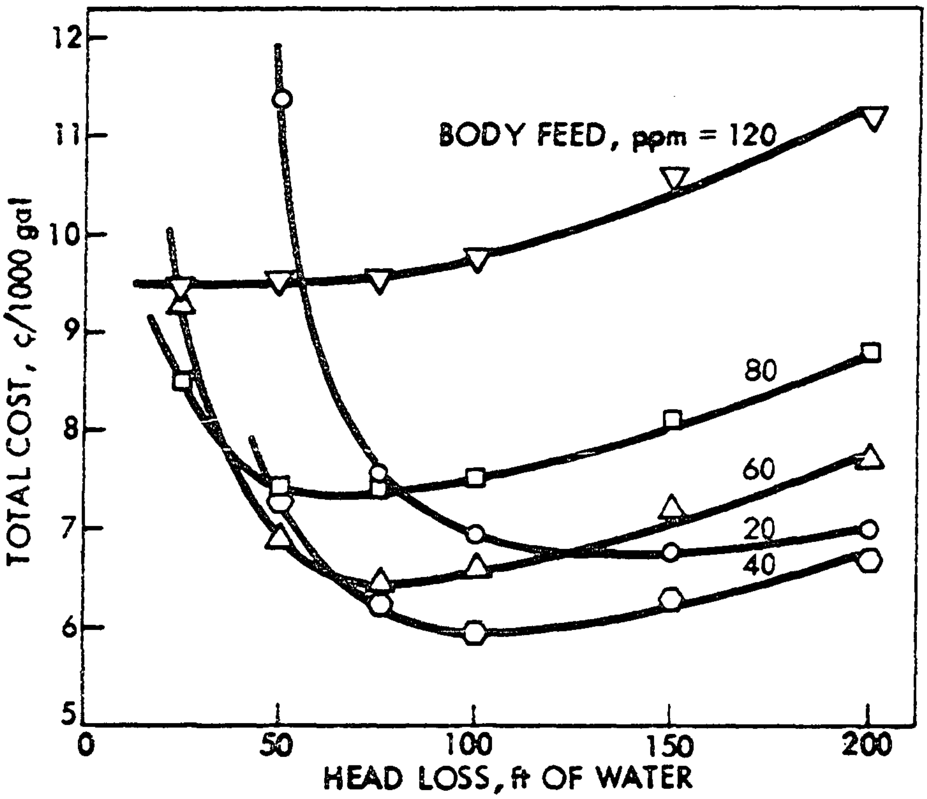
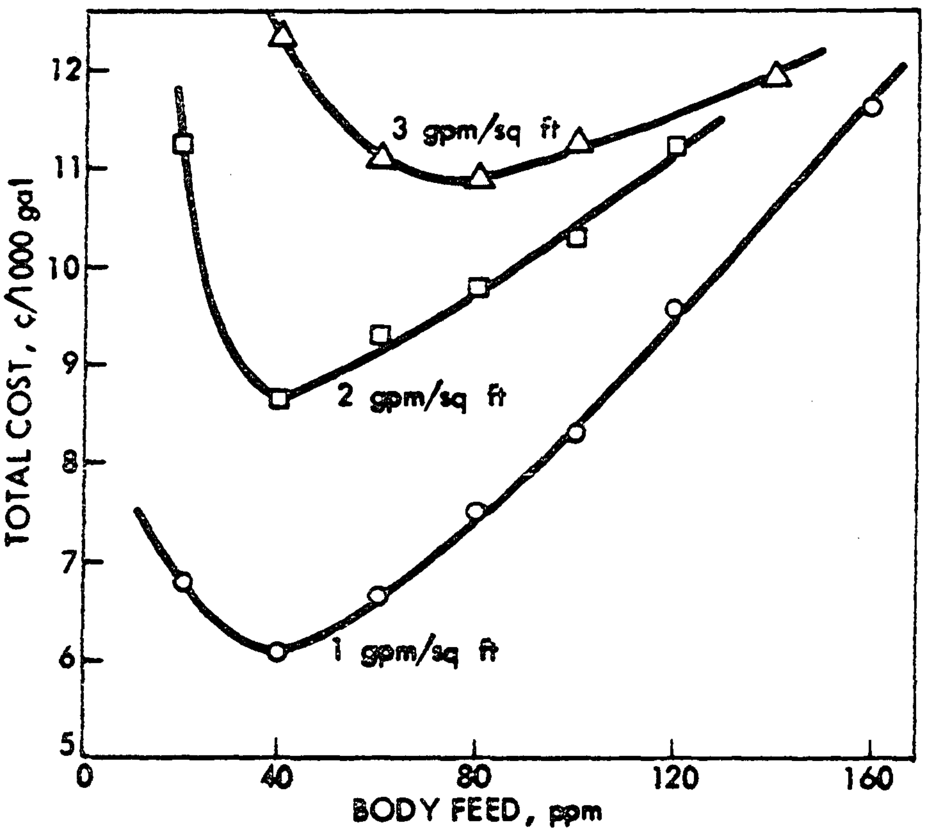

BODY FEED, ppm = 120
80
60
20
40
TOTAL COST, ¢/1000 gal
HEAD LOSS, ft OF WATER
5
6
7
8
9
10
11
12
0
50
100
150
200

Figure 15. Total minimum cost as a function of body feed for different rates

LaFrenz's (43) data with constant-rate, bench scale filter with:

C_S = 7-8 ppm iron

w = 0.15 lb/sq ft


TOTAL COST, ¢/1000 gal
5
6
7
8
9
10
11
12
BODY FEED, ppm
0
40
80
120
160
3 gpm/sq ft
2 gpm/sq ft
1 gpm/sq ft

and incremental values of body feed rate, filtration rate, and terminal head loss are read into the computer. POPO then determines and prints out the ten most economical combinations of these three factors and the respective filtration costs. The program employs a β prediction equation (Equation 13) to calculate β for each body feed rate and uses Dillingham's precoat filtration equations to determine the length of run for each combination of body feed rate, filtration rate, and terminal head loss. Thus, the only filter run data needed are those necessary to define adequately the β prediction equation.

Dillingham used POPO and data from previous research at Iowa State University to optimize the design of several hypothetical installations. He also collected data at a lime-soda ash softening plant at Lompoc, California, and used POPO to optimize the operation of that precoat filtration plant. His conclusions from this work were:

1. Cylindrical septa are more economical than flat septa. The smaller the diameter of cylindrical septa, within practical limits, the greater the economy.

2. A smaller grained filter aid may prove to be more economical than a coarser grained filter aid, even though the smaller grained filter aid results in greater head loss at the same body feed rate. This is because smaller grained filter aids generally cost less per unit weight.

These conclusions invalidated LaFrenz's suggestions that either cylindrical or flat septa are acceptable and that the most economical filter aid is the coarsest grade which will produce acceptable water.

PURPOSE AND SCOPE

The development of the theory of precoat filtration and the techniques for optimizing the design of precoat filters have been reported in numerous theses, reports, and published papers over the past fifteen years. As previously stated, the primary purpose of this thesis is to present the method for optimum design of precoat filters in a form which is readily usable to the design engineer. An additional objective is to review the present theory of precoat filtration in order to determine its shortcomings and to point out its limitations. In essence, this thesis represents an up-to-date design manual for precoat filters. The scope of this thesis is limited to the theory and procedures for determining the conditions that an engineer must specify for the optimum design and operation of precoat filtration plants. Specific details concerning the construction of various filter components and general considerations in the design of any water treatment facility will not be included.

The problems that an engineer encounters in the design of a precoat filtration plant may be classified in three broad categories. These are data collection, data reduction, and determination of optimum design conditions. The specific objectives of this thesis were established to answer the questions that an engineer might have in each of these areas. The specific objectives and the categories in which they are contained are:

Data Collection

1. To explain what data are needed, what important variables are involved, and over what range of these variables the data should be collected. This includes both cost data and raw filtration data obtained by pilot plant studies at the proposed plant site.
2. To show how data can be collected without elaborate pilot plant equipment to determine the filtering characteristics of the raw water.

Data Reduction

3. To explain how to calculate the filter cake resistance index or β index from the filtration data and to demonstrate the effects of certain factors on the value of the β index.
4. To show how to develop β index prediction equations and to provide possible insight into the form of the resulting equations.

Determination of Optimum Design Conditions

5. To demonstrate how the optimum design conditions may be obtained.
6. To show how several of the filtration variables

and cost factors influence the optimum design conditions.

In past research projects concerned with precoat filtration, considerable reliance has been placed in the use of the digital computer. Manuals for computer programs which have been developed for use in determining β indices, β predictions equations, and optimum design conditions will be presented in this thesis. It is not intended however that the computer and a knowledge of computer programming be a necessity for the design of precoat filters. Therefore, an additional objective of this thesis is to present and demonstrate procedures for manually calculating β indices, β prediction equations, and optimum design conditions.

The development of a sound, rational theory is probably the most important prerequisite to the optimum design of any process. Therefore, a review was made of the present theory of precoat filtration in order to determine in what respects it might be improved. In past research, two factors concerning the theory of precoat filtration have caused the most problems. First, the β index prediction equations have been developed empirically and no attempt has been made to derive prediction equations on a rational basis. Thus, the β prediction equations that have been developed for various waters are useful only within the range of data on which the equations are based and do not account for changes in variables that remained constant during the collection of the original data. The second factor which has caused problems is initial dilution. In many instances it has been found that the theoretical dilution rate does not adequately account for effects attributed to initial dilution. It has been assumed that this is due to inadequate mixing or short-circuiting within the filter housing. Therefore, to determine the β index from filtration data, the effects of initial dilution are generally either neglected or else the initial dilution rate is selected to fit the raw data. In the determination of optimum design conditions, initial dilution effects have been completely ignored. What effect this may have has never been examined. Therefore, a further objective of this thesis is to study the period of initial dilution and to suggest how its effects may be included in the determination of optimum design conditions.

DATA COLLECTION

Filtration Data

General

In the design of a precoat filter plant for a municipal water supply, the first consideration should be the determination of the characteristics of the raw water which will fix the plant design. The characteristics which must be determined are:

1. Temperature of the raw water.
2. Suspended solids concentration in the raw water.
3. Variation of the β index with changes in the body feed concentration and suspended solids concentration.

These characteristics are of primary importance because they determine the combination of filtration rate, body feed concentration, and terminal head loss required for optimum design. In addition, it is necessary to determine the most economical grade of filter aid to be used to obtain the desired filtered water quality.

Design water quality

The temperature of and concentration of suspended solids in some waters, in particular those from ground water sources, may remain relatively constant. Other waters, such as a river water, may have large variations in both temperature and quality. If this is the case, it is necessary to analyze variations in water quality which have occurred over a long period of time in order to determine the temperature and suspended solids concentration (and their filtration characteristics) to be used in design. This temperature and suspended solids concentration would be used to determine the optimum combination of filtration rate, terminal head loss, and body feed rate. Once the filtration rate and terminal head loss are set, the optimum body feed rate can be calculated for the temperature and turbidity variations which are to be expected as a guide for the operation of the filter.

River waters in northern climates have an annual variation in both temperature and turbidity. For example, graphs showing the variation in temperature and turbidity of weekly samples collected during 1968 and 1969 from the Des Moines River near Boone, Iowa, are shown in Figures 16 and 18 respectively. Frequency distribution diagrams for these 104 weeks of data are presented in Figures 17 and 19. During 1968 the mean temperature of the water was 12.9 °C and during 1969 it was 11.5 °C. The mean turbidity was 30.5 JTU during 1968 and 29.6 JTU during 1969. If a precoat filter were to be used to filter this water, the design temperature and turbidity must be chosen to achieve the minimum annual cost of filtration. This will involve a study of how the annual cost of filtration is affected by the design conditions of the filter. An example showing how the design water quality affects the annual cost of filtration will be

Figure 16. Variation of water temperature observed in the Des Moines River at Boone, Iowa

Figure 17. Frequency[1] distribution diagram of temperatures observed in the Des Moines River at Boone, Iowa

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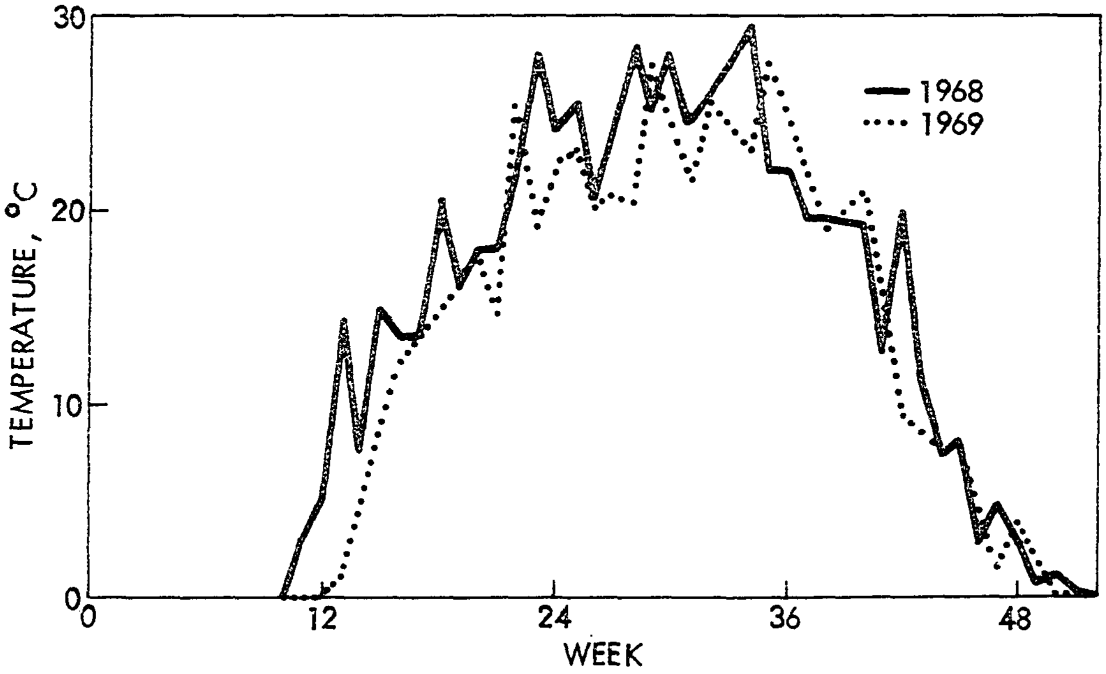
[1] Number of occurrences in 104 (weekly) samples.


30
20
10
0
TEMPERATURE, °C
0
12
24
36
48
WEEK
1968
1969

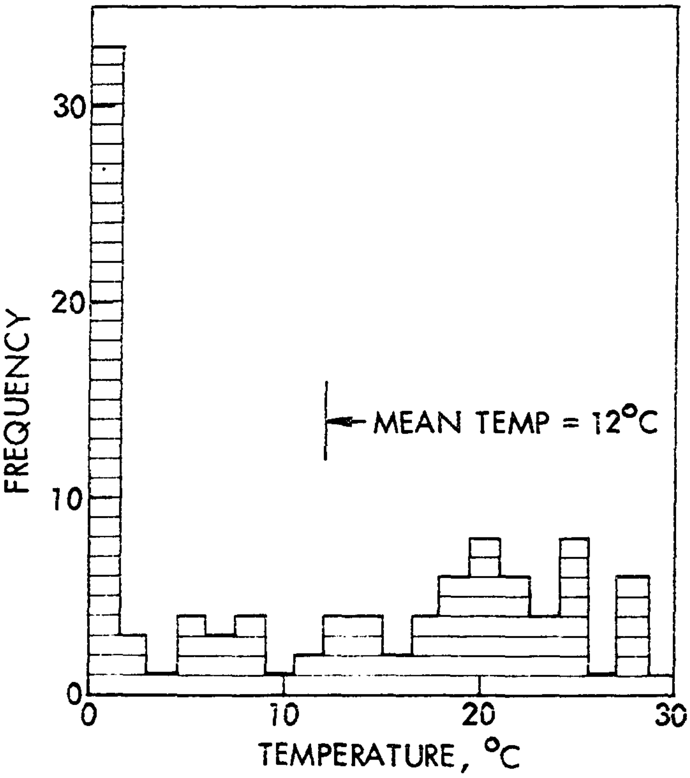
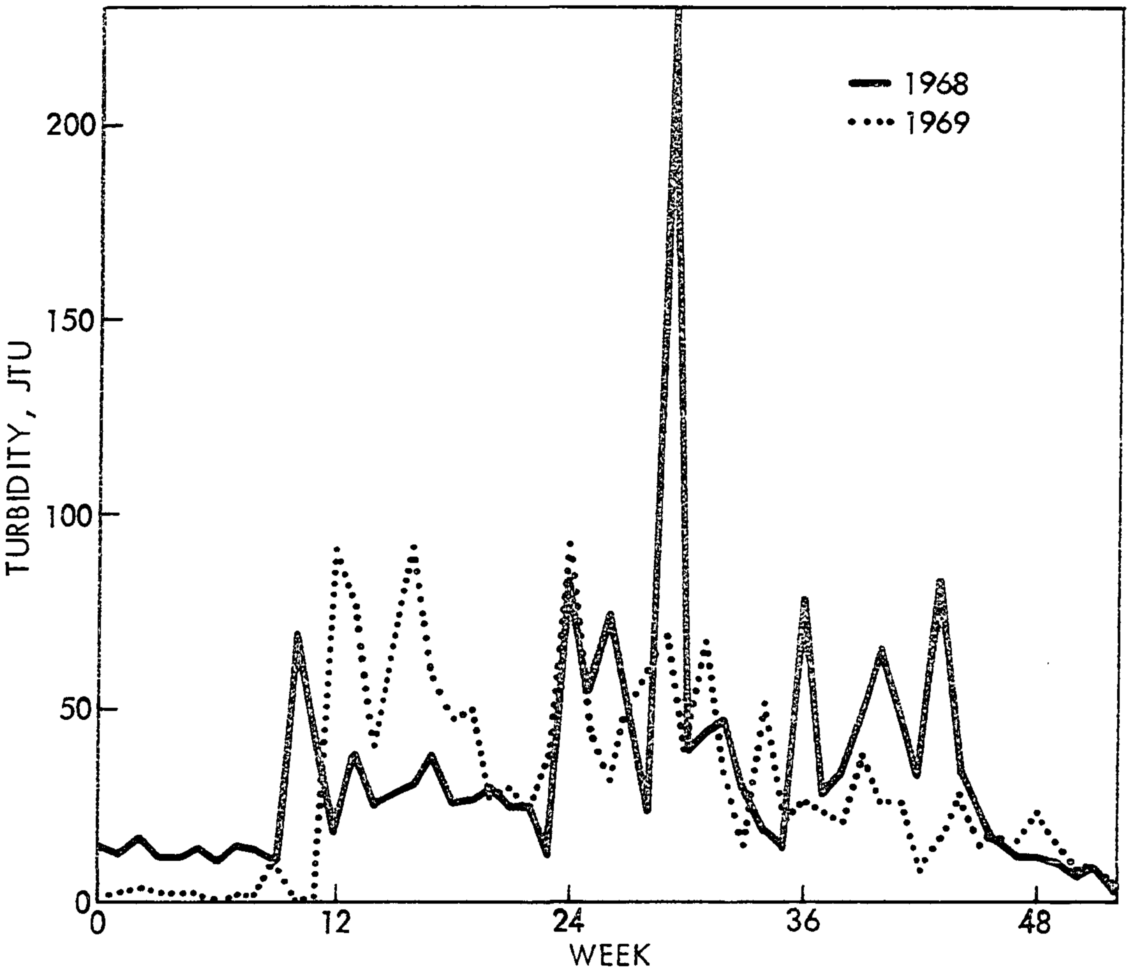

30
20
10
0
FREQUENCY
0
10
20
30
TEMPERATURE, °C
MEAN TEMP = 12°C

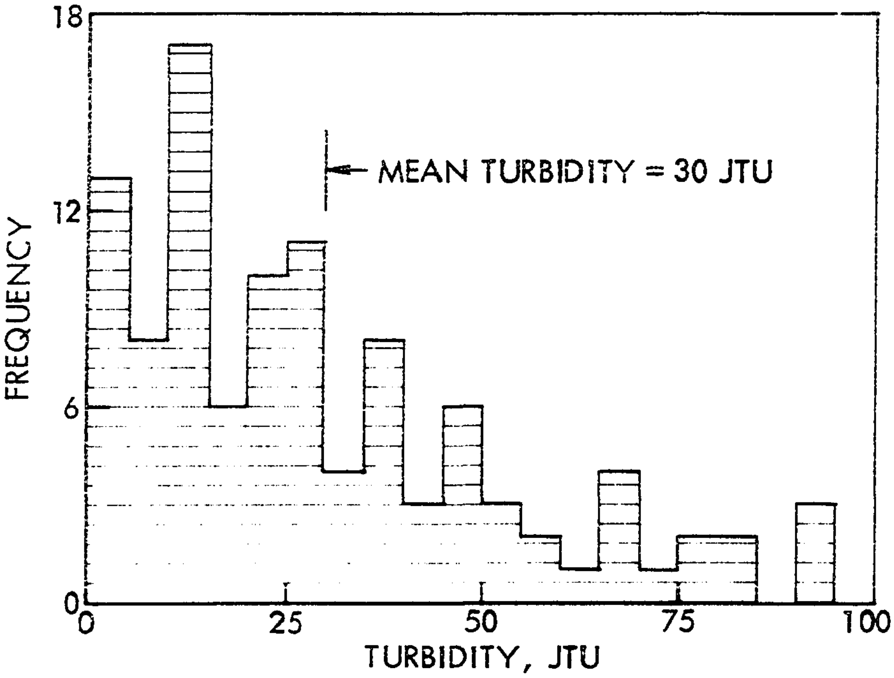
Figure 18. Variation of water turbidity observed in the Des Moines River at Boone, Iowa

Figure 19. Frequency[1] distribution diagram of turbidities observed in the Des Moines River at Boone, Iowa

---

[1] Number of occurrences in 104 (weekly) samples.


1968
1969
TURBIDITY, JTU
200
150
100
50
0
0
12
24
36
48
WEEK


MEAN TURBIDITY = 30 JTU
FREQUENCY
18
12
6
0
0
25
50
75
100
TURBIDITY, JTU

presented in a later chapter (p. 188).

β prediction data

<u>General</u> The relative value of the β index and its variation with changes in the concentrations of body feed and suspended solids are characteristic of the water filtered. Past research indicates that the value of the β index is greatly influenced by the type of suspended solid. Hawley (37) filtered University tap water to which ferric chloride and ferrous chloride were added. Celite 535[1] was used as the filter media in both cases. His data showed that for the same iron concentration and body feed rate, the β index for water containing ferric iron floc is almost 25 times that for water containing ferrous iron floc. Laboratory data gathered by Regunathan (61) also indicated large differences in the characteristics of waters containing Kentucky Ball clay[2] and Wyoming bentonite clay[3] when both waters were filtered using Hyflo Super-Cel[4] as the filter media. At equal ratios of influent turbidity to body feed rate, the β index for water

---

[1] Diatomaceous earth filter aid, Johns-Manville Corporation, New York, N.Y.

[2] Old Hickory No. 5 Ball Clay, Old Hickory Clay Co., Paducah, Kentucky.

[3] Black Hills Bentonite, International Mineral and Chemical Corporation, Skokie, Illinois.

[4] Diatomaceous earth filter aid, Johns-Manville Corporation, New York, N.Y.

containing Wyoming Bentonite clay was over 70 times that observed for water to which Kentucky Ball clay had been added.

The large range of values of the β index indicated by these results demonstrates that the only way to determine the value of the β index and to describe its variation with body feed and suspended solids concentrations is by collecting filtration data with the water to be filtered at the proposed plant site. Even data collected at a nearby plant which filters water from a similar source may be of little value. For example, Creston, Iowa, and Albia, Iowa, are both located in the central part of southern Iowa and obtain their water supplies from impounding reservoirs. A pilot filter was used to gather data on these waters after they had been treated by coagulation using alum and lime followed by settling (15). It was found that at the same ratio of turbidity to body feed rate, the β index for the water at Albia was approximately 30 times that for the Creston water.

The data necessary for the prediction of the β index at various suspended solids concentrations and body feed rates can be collected by making a few filter runs with a pilot filter. A bench-scale filter which was designed for this purpose will be described later in this section. The minimum data collected during a filter run should include:

1. Filter aid grade.

2. Amount of precoat.
3. Filtration rate.
4. Water temperature.
5. Body feed rate.
6. Influent suspended solids concentration.
7. Effluent suspended solids concentration.
8. Head loss across the filter at regular intervals of elapsed filtration time.

Filter aid grade The main requirement of the filter aid is that an effluent of acceptable quality be produced. A few filter runs using different filter aid grades can be made to determine the coarsest grade that will still produce an acceptable effluent quality. The recommended procedure is to start with the coarser grade of filter aid and to use progressively finer grades in successive test runs until a filter aid is found which will produce consistently the desired water quality. The selection of the most economical grade of filter aid from those which produce acceptable effluent is complicated by the fact that the coarser grades of filter aid cost more per unit weight. Thus, switching to a coarser grade of filter aid may reduce the costs of labor, precoat filter aid, and backwashing due to an increase in run length but still result in higher overall operating costs. As example, data presented by Baumann *et al*. (8) were used to prepare Table 5. The filter aids in Table 5 are arranged from coarse to fine according to the body feed rate required to give equivalent performance under identical filtration conditions. The filtration conditions are the filtration of water containing 4 mg/l of iron at a temperature of 68 °F. Equivalent performance is defined such that filtering with flat septa at a filtration rate of 1 gpm/sq ft for 6 hours results in a head loss through the filter cake of 100 feet of water. It is seen that the cost of body feed per million gallons of filtrate increases with finer filter aids under

Table 5. Filtration costs using different filter aids

Filter aid designation	Unit cost of filter aid, ¢/lb	Equivalence performance		Optimum performance
		C_F, ppm	Filter aid cost, \$/MG	Total cost, \$/MG
S2	4.365	76	27.63	78.5
S3	3.815	104	33.37	78.8
S4	3.715	112	34.66	79.9
J4	5.000	114	47.48	88.0
J3	4.900	118	48.16	88.2
E6	5.000	125	52.06	93.4
J0	4.650	141	54.62	92.6
G4	4.900	162	66.12	94.9
E5	4.900	178	72.65	97.3
E2	4.750	189	74.78	99.1
G1	4.750	227	89.82	98.1

these circumstances. All other costs, except precoating, will be equal for different filter aids since the run lengths and terminal head losses are identical.

The overall optimum filtration costs (Table 5, last column) were determined for the same filtration conditions (C_S= 4 mg/l iron and a temperature of 68 °F) using the computer program POPO. Cost data gathered by Dillingham (25, 27) and the following design conditions were used in this analysis:

1. Design flow = 1 MGD
2. Salvage value = 15 percent of first cost
3. Energy conversion = 70 percent
4. Interest rate = 4 percent
5. Plant life = 25 years
6. Precoat weight = 0.15 lb/sq ft
7. Power cost = 2 cents/kwh
8. Flat septa
9. Backwashing requires 10 gal of water per sq ft of filter area
10. 30 min are required for precoating and backwashing during each filter run

From the results of these analyses it appears that there is little difference in the total cost per million gallons when different filter aids are used. In general, the coarser filter aids are cheaper to use. However, if there is a large difference in price between two filter aids, it may be necessary to determine β prediction equations and optimum costs for both filter aids. In this example, only two filter aids finer than those higher on the list in Table 5, J0 and G1, are cheaper to use than a coarser grade for filtering iron floc.

Precoat weight and filtration rate The weight of precoat filter aid per unit septum area and the filtration rate used in collecting filtration data should be within the range of values used in practice (approximately 0.05 to 0.15 lb/sq ft and 0.5 to 2.0 gpm/sq ft, respectively). A precoat weight of 0.15 lb/sq ft and a filtration rate of 1.0 gpm/sq ft have been most commonly used for data collection in past research projects.

Water temperature The temperature measured should be that of the water as it passes through the filter cake. A temperature increase as high as 6 °C has been observed for water as it passed through a bench scale filter. If possible, the temperature of the water within the filter housing should be measured, if not the effluent temperature should be recorded. In any event, the water temperature should remain constant during a filter run and precautions should be taken to prevent heating of the raw water when it passes through the filter pump.

Body feed (C_F) and suspended solids (C_S) For a particular filter aid and suspended solid, the body feed rate and suspended solids concentration determine the composition and characteristics of the filter cake. Therefore, C_F and C_S are the only variables necessary to predict the β index under these conditions. The data necessary to develop a β prediction equation can be obtained from a few filter runs at different values of C_S and C_F. The precoat weight, filtration rate, and temperature may be the same for each filter run.

Two important considerations must be kept in mind when collecting data for different combinations of C_F and C_S in order to develop a β prediction equation. First, the theory of precoat filtration was derived under the restriction that the body feed rate must be high enough to form an essentially incompressible filter cake. Any attempt to predict the β index for values of C_F and C_S which do not result in the formation of an incompressible filter cake is meaningless. Therefore, during the process of collecting data for β index prediction, it is imperative that the point where the filter cake becomes compressible be determined. This can be done by finding what the highest ratio of C_S to C_F is before a plot of head loss versus time becomes exponential.

The second important point to remember is that in order to determine valid regression coefficients, data must be gathered over a significant range of values for each variable included in the β prediction equation. Much of the laboratory data for the filtration of iron floc have been collected with C_S held essentially constant and only C_F varied. These data were then used to develop β prediction equations of the form:

$$\beta = 10^{b_1} (C_S/C_F)^{b_2} C_F^{b_3} \tag{14}$$

and

$$\beta = 10^{b_1} (C_S/C_F)^{b_2} \tag{15}$$

Since C_S was held constant, a β prediction equation such as:

$$\beta = 10^{b_1} C_F^{b_2} \tag{27}$$

would be equally valid, however it could only be used to predict β for an influent with a suspended solids concentration equal to that used to collect the data from which the equation was developed. A prediction equation with the form of Equation 15 developed from such data can be used to predict β for an influent with a different suspended solids concentration only if the assumption is made that the β index is the same for equal ratios of C_S/C_F.

If C_S is held constant, then Equation 14 can be written as:

$$\beta = (10^{b_1} C_S^{b_2}) (1/C_F)^{b_2} C_F^{b_3}$$

$$= 10^{b_1} C_S^{b_2} (1/C_F)^{b_2 - b_3}$$

$$= (10^{b_1} C_S^{b_3}) (C_S/C_F)^{b_2 - b_3}$$

$$= 10^{a_1} (C_S/C_F)^{a_2} \qquad (28)$$

where:

$$10^{a_1} = 10^{b_1} C_S^{b_3} = \text{a constant}$$

$$a_2 = b_2 - b_3$$

Thus, when only C_F is varied, b_2 and b_3 are not coefficients of independent variables and even with filtration data gathered under identical conditions, their individual values may vary widely as long as the value of b_2-b_3 remains the same. A good example of this is demonstrated by the β prediction equations presented by Baumann <u>et al</u>. (8) in Table 6. Note that these prediction equations were developed from data collected with C_S held constant at about 8.0 mg/l (7.5 to 8.5 range) of iron. The coefficients b_2 and b_3 vary considerably, even for the same grade of filter aid. A few calculations can be made to show that b_2-b_3 of Equation 14 is approximately equal to b_2 of Equation 15 and that $10^{b_1} C_S^{b_3}$ (where C_S = 8 mg/l) of Equation 14 is approximately equal to 10^{b_1} of Equation 15 as suggested by consideration of Equation 28. The prediction equations developed in the

Table 6. β prediction equations presented by Baumann *et al.* (8)

Constants: Source of iron: $FeCl_3$ solution in tap water plus 0.5 mg/ℓ of copper sulfate, as copper.
Effluent Iron Concentration: 0.to 0.06 mg/ℓ
Temperature: 60°F
C_S: about 8.0 mg/ℓ (7.5-8.5 range)
q: 1 gpm/sq ft
C_F: variable between runs
C_S/C_F: ranges from about 0.02 to 0.2 between runs
Filter area: 3.20 sq ft

		β-prediction equations and values of R (From laboratory test results)						
			$\beta = 10^{b_1} \cdot (C_S/C_F)^{b_2} \cdot (C_F)^{b_3}$				$\beta = 10^{b_1} (C_S/C_D)^{b_2}$	
Filter aid identification	Runs	R	$b_1=$	$b_2=$	$b_3=$	R	$b_1=$	$b_2=$
S2-4	39-45	99.909	12.98741436	-0.85497481	-3.02242184	99.827	10.3851089	2.18793297
S2-3	46-52	99.786	11.13402271	1.27628231	-0.88177395	99.608	10.45026302	2.24277973
S2-1	53-60	99.844	10.77726841	1.63628960	-0.51455784	99.754	10.33092785	2.15612984
S2-20	61-66	99.288	5.42328548	7.53267097	5.40589237	99.152	10.24094296	2.09768581
S2-5	122-126	99.783	13.02931213	-0.94849741	-3.06680107	99.530	10.27379322	2.13686562
S2-9	127-131	99.794	10.50879574	1.84311581	-0.26402664	99.748	10.26930141	2.10673809
S2-6	132-136	99.756	7.98150253	4.53664684	2.45759678	99.558	10.12129307	2.03666687
S2-21	169-173	99.822	15.85924244	-5.20033073	-6.86884212	99.345	10.13061142	2.00464249
S3-4	29-38	99.575	10.52720261	1.73644829	-0.28884602	99.566	10.30090046	2.04407120
S3-2	73-78	99.475	10.29731274	1.81636715	-0.13136101	99.492	10.16197256	1.93898773
S3-1	79-86	99.285	11.24680042	0.98341548	-1.05665302	99.115	10.34136105	2.06498718
S3-3	87-92	99.868	11.12258816	0.74192983	-1.14020252	99.721	10.20643139	1.94099712
S4-3	111-115	99.954	11.75993252	0.73294222	-1.43278217	99.966	10.50884056	2.20301819
S4-2	116-121	99.522	15.31389523	-4.12016678	-5.88876820	99.169	10.29753590	1.97551537
S4-1	179-183	99.761	2.62629986	10.35785007	8.38543415	99.301	10.23429012	1.93304539
J4-6	107-110	99.973	9.16131401	3.05229187	1.10412025	99.964	10.21306419	1.97430611
J4-4	152-156	99.856	11.59778118	0.80631971	-1.28725147	99.591	10.39118481	2.06353569
J4-7	260-264	99.929	13.37145615	-1.83411789	-3.67333317	99.894	10.04663086	1.80446148
J3-5	93-97	99.975	10.57284260	1.40189075	-0.49469757	99.955	10.14858437	1.90635872
J3-6	98-102	99.443	10.07520294	2.36152458	0.32397366	99.408	10.29101086	1.98994541
J3-7	164-168	100.000	13.72517300	-1.62155533	-3.67566967	99.704	10.30087757	1.97055626
J0-4	103-106	100.000	11.09186363	1.73551178	-0.46211338	99.986	10.68011379	2.20969772
J0-1	159-163	100.000	12.46984577	-0.62650388	-2.48561573	99.933	10.23762989	1.88322449
J0-6	265-269	99.872	13.97296619	-1.75044441	-3.85347652	99.715	10.59562193	2.12386036
E6-4	188-191	99.968	10.71950626	1.87823772	-0.24578762	99.975	10.50224018	2.12663460
E6-2	201-204	99.906	12.82551670	-0.91011024	-2.86617184	99.827	10.47600460	2.09503746
E6-3	256-259	99.705	16.08139038	-4.01337624	-6.11972234	99.348	10.59508705	2.15499687
E5-1	137-141	100.000	10.31914234	2.26166344	0.26898193	100.000	10.51323986	1.96711254
E5-17	184-187	99.957	12.63197327	-1.04734612	-2.83272552	99.841	10.31385231	1.92853832
E5-3	197-200	99.890	12.48021412	-0.30677181	-2.28769398	99.863	10.45404720	1.98954678
E2-4	192-196	100.000	11.24984550	1.19025707	-0.80966377	99.952	10.56048584	2.02056885
E2-1	205-208	99.894	13.62593174	-1.49916363	-3.52555656	99.759	10.51301670	2.00597382
E2-3	220-224	99.984	12.18756104	0.12043186	-1.86335564	99.968	10.49256706	1.97578430
E2-2	270-275	99.947	12.29683590	-0.02055234	-2.00966655	99.895	10.57424831	2.03129101
G4-1	142-146	99.840	10.43643379	1.83071041	-0.08190536	99.840	10.36339092	1.91228580
G4-2	209-213	99.901	10.03252029	2.46023083	0.46097279	99.908	10.48875809	2.02904510
G4-5	226-229	99.990	10.58006477	1.64126110	-0.28952312	99.980	10.32860470	1.93623259
G4-4	231-235	99.956	10.73429871	1.34741688	-0.53086472	99.934	10.28011227	1.89345551
G4-3	236-240	99.810	8.65023391	3.84545612	1.88726139	99.814	10.40164185	1.99196053
G1-1	147-151	99.611	11.29054165	0.50536501	-1.25476742	99.430	10.19460106	1.77184582
G1-2	214-219	99.825	9.95458506	2.26117706	0.43965054	99.825	10.35547256	1.83100605
G1-3	251-255	99.801	11.97352219	0.09870034	-1.78785324	99.536	10.48374462	1.97423553

form of Equation 14 are valid only when the value of C_S is the same as that from which the equations were developed. If this is not realized, considerable error will result. For example, consider the Equation 14 prediction equations developed for filter aids S4-1 and S4-2. These are two bags of the same grade of filter aid, thus one would not expect a very great difference between the values of β calculated with the same values of C_S and C_F. If $C_S = 8$ mg/l (which is the value of C_S at which the filtration data were gathered) and $C_F = 160$ mg/l so that $C_S/C_F = 0.05$, then:

$$\beta \text{ for S4-1} = 42.95 \times 10^6 \text{ ft}^{-2}$$

and

$$\beta \text{ for S4-2} = 49.52 \times 10^6 \text{ ft}^{-2}$$

which differ by only 14 percent. However, if $C_S = 4$ mg/l and $C_F = 80$ mg/l so that C_S/C_F is still 0.05, the calculated β indices are:

$$\beta \text{ for S4-1} = 12.84 \times 10^4 \text{ ft}^{-2}$$

and

$$\beta \text{ for S4-2} = 29.34 \times 10^8 \text{ ft}^{-2}$$

which differ over 20,000 fold!

Any measurement which is directly proportional to the concentration of suspended solid in the filter influent may be used in place of C_S for predicting β indices. In laboratory projects, iron concentration has been used as a measure of iron floc concentration and, in field and laboratory studies, turbidity has been found to be an acceptable measure of C_S.

Effluent suspended solids   The concentration of suspended solids (or turbidity, etc.) in the filter effluent should be measured occasionally during each filter run to assure that the filter is working properly. An imperfection in the filter septum or an improperly formed precoat may be detected in this way. These measurements are also useful for predicting the quality of water which would be obtained by large scale precoat filtration.

Head loss   The head loss across the filter cake should be measured at uniform time intervals during the filter run and it is recommended that a plot of head loss versus elapsed time of filtration be made as the filter run progresses. Any unusual changes in the body feed rate, suspended solids concentration, filtration rate, etc., can be detected by a change in the slope of this curve. The filter run should be continued until a well-defined curve is obtained. In past studies, filter runs have usually been extended one to two hours past the period of initial dilution and head loss measurements made every 10 to 30 minutes.

Bench scale apparatus

Background   The need for a small, inexpensive, easy-to-operate apparatus for collecting filtration data with the water at the proposed plant site was recognized as early as 1961. LaFrenz (43) built and operated a bench scale, constant rate filter with which he gathered the data used to evaluate the optimums in precoat filtration. LaFrenz concluded, however, that it was impossible to correlate the results from the bench-scale filter to those from a large-scale pilot plant. This conclusion was based on comparison of the head loss curves obtained with these filters. The differences in the results observed for the two filters were thought to be due to differences in the ratio of septum area to volume of filter housing (initial dilution effects) and the shape of septums (increasing area effects).

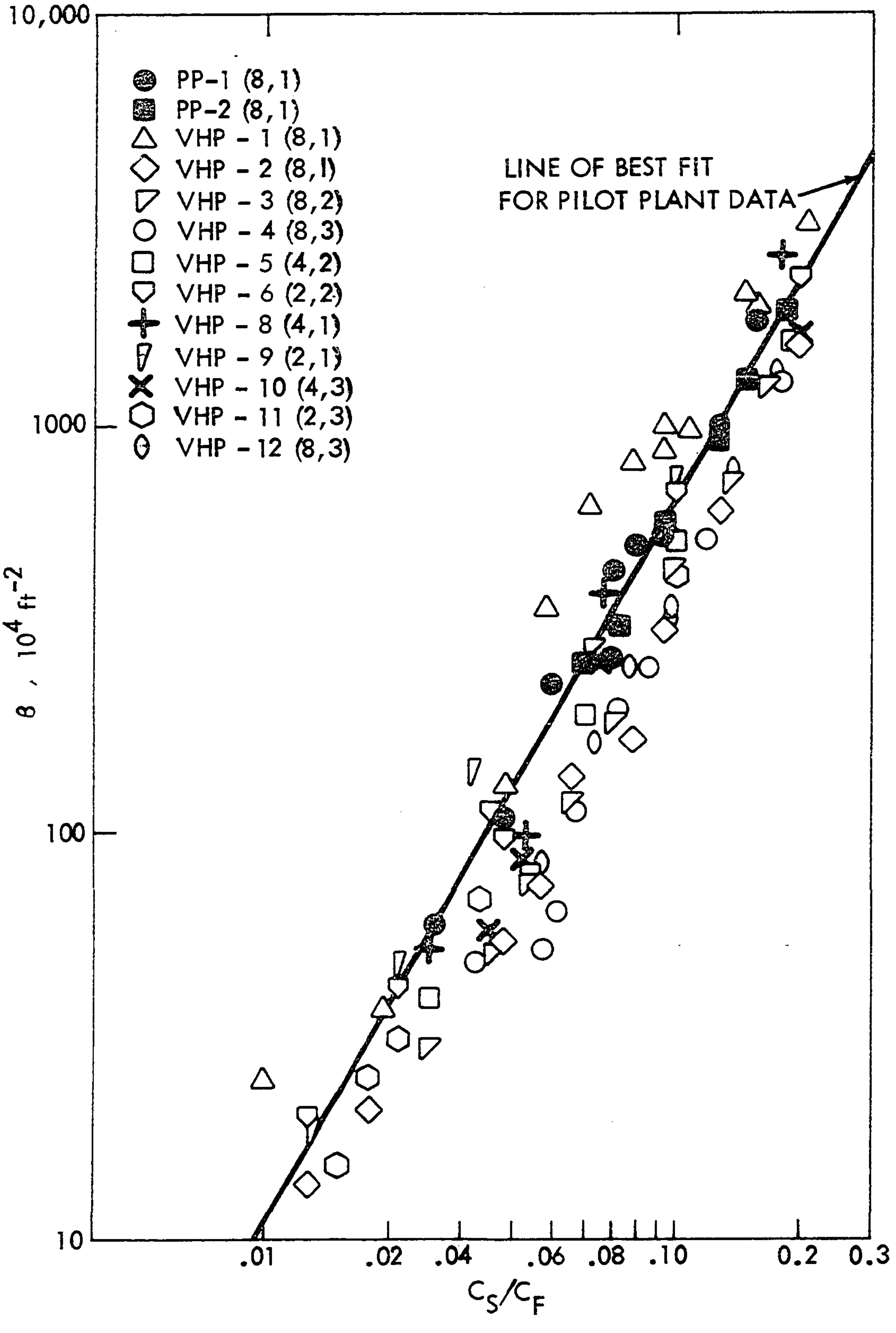
In the time since LaFrenz's work was completed, the effects to which he attributed the difference in head loss between model and prototype filters have been accounted for in the equations for precoat filtration derived by Dillingham (27). A true comparison of the model and prototype results would be to compare values of the β index for filter runs which should have formed identical filter cakes; i.e. equal body feed rates and suspended solids concentrations. β indices for all of LaFrenz's filter runs with both the pilot plant and bench-scale filter were calculated and are included with the summary of filter runs in Appendix A (Tables 22 and 23). In Figure 20, a comparison of β indices at equal values of C_S/C_F is made for all of LaFrenz's filter runs. There is

Figure 20. Comparison of LaFrenz's (43) data for pilot plant and bench-scale filters

PP-x (C_S,q) = pilot plant data

VHP-x (C_S,q) = bench-scale filter (Variable Head Permeameter) data

x = series number


10,000
1000
100
10
● PP-1 (8,1)
■ PP-2 (8,1)
△ VHP - 1 (8,1)
◇ VHP - 2 (8,1)
▽ VHP - 3 (8,2)
○ VHP - 4 (8,3)
□ VHP - 5 (4,2)
▽ VHP - 6 (2,2)
+ VHP - 8 (4,1)
▽ VHP - 9 (2,1)
× VHP - 10 (4,3)
⬡ VHP - 11 (2,3)
○ VHP - 12 (8,3)
LINE OF BEST FIT
FOR PILOT PLANT DATA
β , 10^4 ft^{-2}
.01
.02
.04
.06
.08
.10
0.2
0.3
C_S/C_F

considerable scatter in the results obtained with the bench-scale filter. However, these results do cluster around the results of the filter runs made with the pilot plant. Some of the scatter in the results for the bench-scale filter may possibly be due to differences in iron concentration or filtration rate. If only the bench-scale filter results for runs with the same iron concentration and filtration rate as used during the pilot plant runs (8 mg/l iron and 1.0 gpm/sq ft) are used in the comparison (see Figure 21), the result is still the same. The bench-scale filter results shown in Figure 21 vary from the pilot plant results (at equal C_S and C_F) by as much as -50 percent to as little as +10 percent. It appears then, that contrary to LaFrenz's conclusion, a bench-scale, constant-rate filter may be used to predict the results of a full-scale filter.

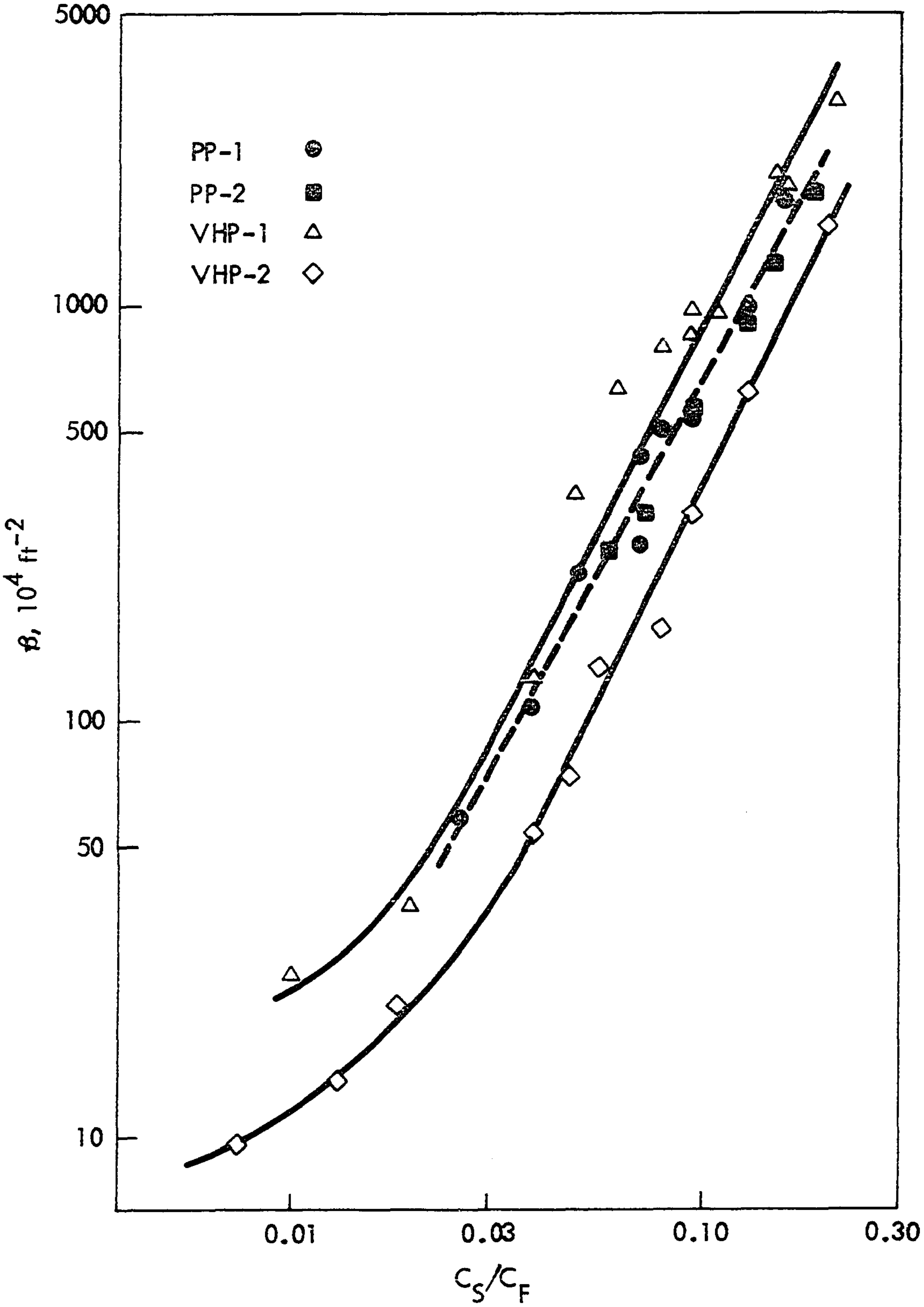
During 1967 and 1968, research was conducted at Iowa State University in order to develop specifications for filter aids used by the U.S. Army (11). During the initial stages of this project, two bench-scale filters were built for determining the ξ index and in-place bulk density of filter aids, a constant-pressure filter similar to that used by Al-Khafaji (1a) and a constant-rate filter. Because of its simplicity of operation and the short time required to make a filter run, the constant-pressure filter was used exclusively throughout the study.

Figure 21. Comparison of LaFrenz's (43) data gathered under identical filtration conditions (C_S = 8 mg/l iron, q = 1 gpm/sq ft)

PP-x = pilot plant data

VHP-x = bench-scale filter (Variable Head Permeameter) data

x = series number


5000
1000
500
100
50
10
β, 10⁴ ft⁻²
PP-1 ●
PP-2 ■
VHP-1 △
VHP-2 ◇
0.01
0.03
0.10
0.30
CS/CF

An investigation of the possibility of the use of the constant-pressure filter to predict results for constant-rate filtration was recently completed by Arora (3). He concluded that constant-pressure results could not be used to predict constant-rate results, the primary reason being the inherent differences in the porosity distribution of the cakes laid in the two processes. The constant-rate filter built during the early stages of the filter aid specification study (11) was then evaluated for use in predicting the results of large-scale, constant-rate filtration. Arora found that this apparatus was successful in predicting the filter cake resistance obtained in filter runs made using the pilot plant and iron-bearing waters (8). The apparatus and its operation are described in the following sections.

Description The apparatus is called the small-scale, constant-rate filter or SSCR filter. A photograph of it is shown in Figure 22. The unique feature of this apparatus is the system of three gears and three 3-way plug valves which facilitates switching from precoating to filtering and filtering to backwashing cycles by turning a single lever. A photograph of this valve system is shown in Figure 23 and working drawings are contained in Appendix C. Other components of the apparatus include:

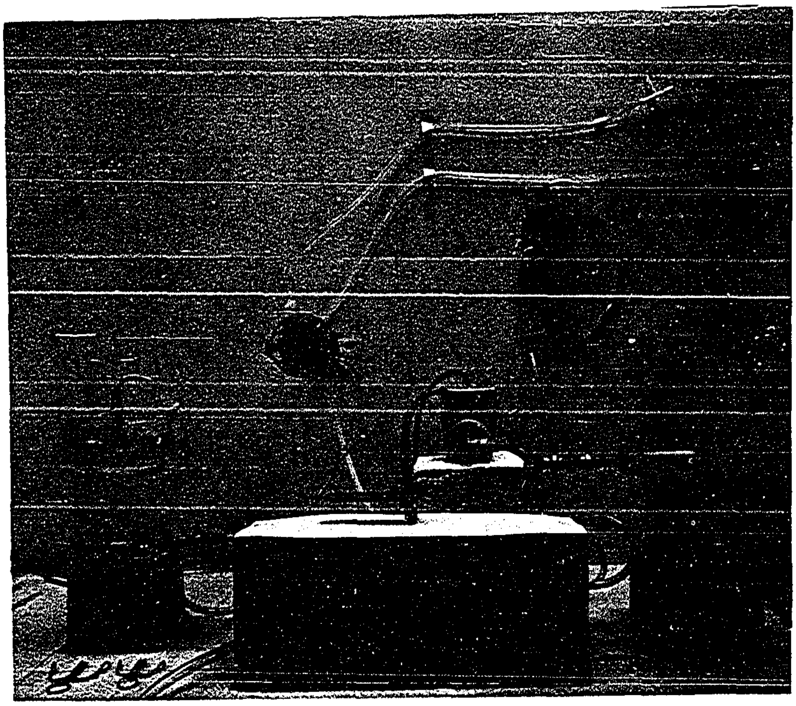
1. A precoat pot of about one liter capacity and made out of plexiglas. Working drawings are given in

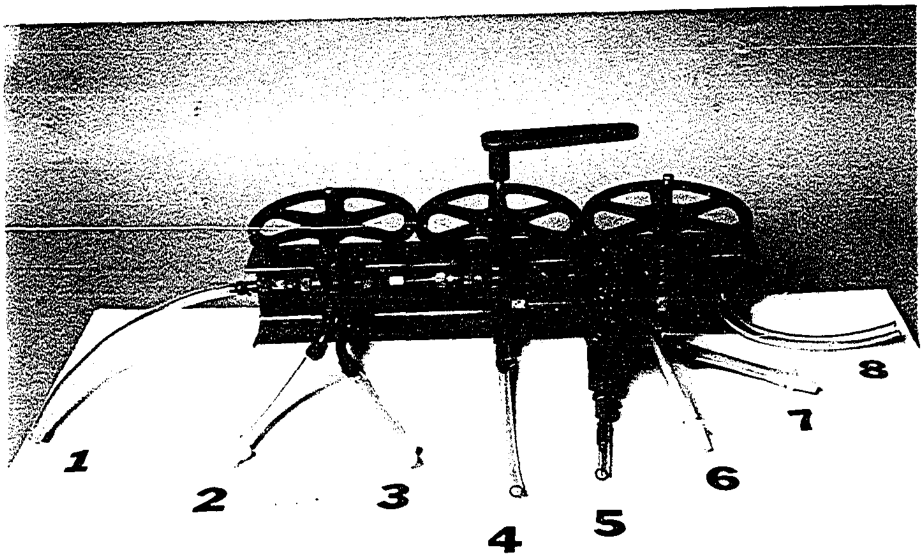
Figure 22. The SSCR filter apparatus

1 = Precoat pot
2 = Filter cell
3 = Pump
4 = Rotameter
5 = Raw water and backwash water holder
6 = Manometer
B = Backwash position
F = Filter position
P = Precoat position

Figure 23. View from behind control valves (top plate removed)

1 = Pump inlet
2 = Rotameter inlet
3 = Filter outlet
4 = Pump outlet
5 = Precoat inlet with precoat control valve
6 = Precoat outlet
7 = Filter inlet
8 = Backwash waste




1
2
3
4
5
6
7
8

Appendix C.

2. A raw water and backwash water holder with a capacity of two liters, made of plexiglas. Working drawings are given in Appendix C.
3. Pump Model No. 2, E-38N, Patent No. 194,570. Little Giant Pump Co., Oklahoma City, Oklahoma.
4. A filter assembly built of plexiglas to permit viewing of the precoat and filter cake. The flat filter septum is two inches in diameter (3.142 sq in.). Working drawings are contained in Appendix C.
5. Mercury manometer Model BUB-24, 64 cm. King Engineering Corp., Ann Arbor, Michigan.
6. Rotameter Model No. 2-1355-V, SHO-RATE. Brooks Instrument Co., Inc. Hatfield, Pa. A tube of size R-2-15-C is used with a 1/8-inch diameter stainless steel float. Maximum flow capacity with this arrangement is about 320 ml/min which corresponds to a filtration rate of 3.9 gpm/sq ft through a two inch diameter filter.
7. Magnetic stirrers (Magnestir, Catalog No. 52617, Chicago Apparatus Company. Chicago, Illinois) with two inch stirring bars are used to prevent settling or segregation of the contents of the precoat pot and raw water holder.

A schematic diagram of the SSCR filter is shown in

Figure 24. All connections between filter components are made with 1/4-inch ID tygon tubing. A needle valve at the inlet of the rotameter tube is used to regulate the filtration rate and a gate valve on the inlet line to the precoat pot is provided to control the flow rate during precoating. To facilitate removing air from the filter system and to prevent air binding of the pump, the apparatus components should be arranged so that the pump is at the lowest level followed by the control valves, filter cell, raw water holder, and then the manometer inlets and air bleeds at the highest level.

Operation Prior to the start of a filter run, the following materials should be available:

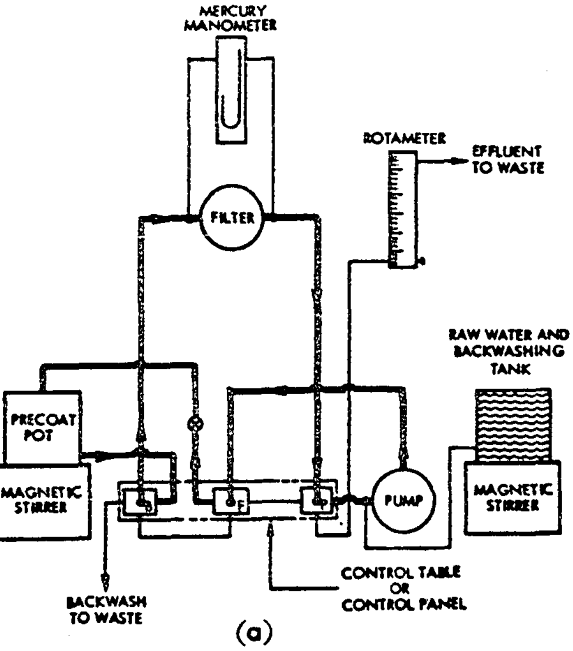
1. At least 10 liters (approximately 4 gallons) of raw water.
2. Approximately 5 gallons of clean water (preferably distilled) for precoating and backwashing.
3. A weighed amount of precoat. For a precoat of 0.15 lb/sq ft on the 2 inch diameter filter, 1.5 grams of filter aid are required.
4. 8-10 weighed amounts (±0.0002 gram) of the filter aid required per liter of raw water.

Instructions for making a complete filter run with the SSCR filter are outlined below:

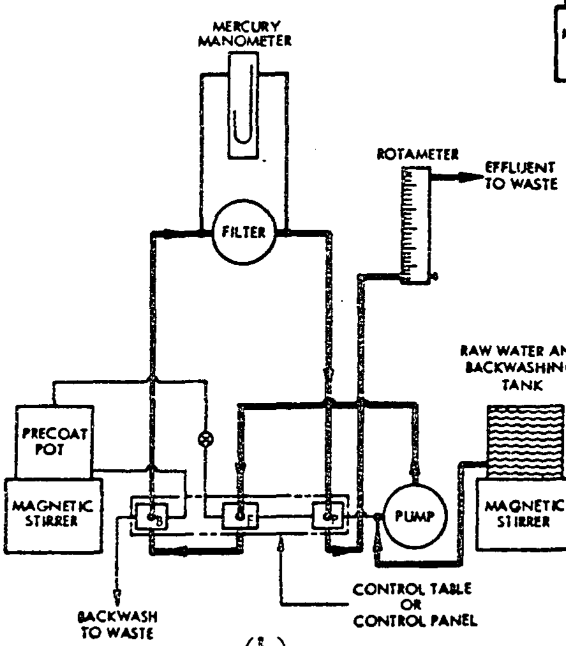
Figure 24. Schematic diagram of the SSCR filter apparatus

a. indicates flow path during precoating
b. indicates flow path during filtering
c. indicates flow path during backwashing

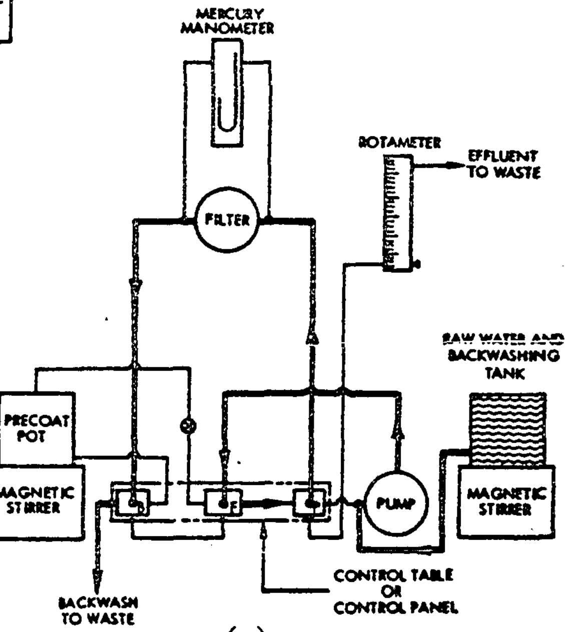
shown by thick lines


MERCURY MANOMETER
ROTAMETER
EFFLUENT TO WASTE
FILTER
RAW WATER AND BACKWASHING TANK
PRECOAT POT
MAGNETIC STIRRER
B
F
P
PUMP
MAGNETIC STIRRER
BACKWASH TO WASTE
CONTROL TABLE OR CONTROL PANEL

(a)


MERCURY MANOMETER
ROTAMETER
EFFLUENT TO WASTE
FILTER
RAW WATER AND BACKWASHING TANK
PRECOAT POT
MAGNETIC STIRRER
B
F
P
PUMP
MAGNETIC STIRRER
BACKWASH TO WASTE
CONTROL TABLE OR CONTROL PANEL

(b)


MERCURY MANOMETER
ROTAMETER
EFFLUENT TO WASTE
FILTER
RAW WATER AND BACKWASHING TANK
PRECOAT POT
MAGNETIC STIRRER
B
F
P
PUMP
MAGNETIC STIRRER
BACKWASH TO WASTE
CONTROL TABLE OR CONTROL PANEL

(c)

1. Fill both the precoat pot and raw water holder with clean water.
2. With the control lever in filter position, start the pump.
3. Open the air bleed lines to remove air trapped on both sides of the filter septum. If air bubbles become bound in the pump impeller, stop the pump and let the trapped air move into the pump effluent line.
4. After all of the air has been removed from the pump, filter cell, rotameter, and manometer lines, turn the control lever to precoat position and open the precoat control valve wide open. Most of the air trapped in the precoat lines will be removed to the precoat pot, however some may become trapped in the pump or filter cell.
5. Turn the control lever to backwash position. Any air now trapped in the pump or filter cell can be removed by turning the control lever to filter position and opening the air bleed lines.
6. Repeat steps 3, 4, and 5 if necessary.
7. Set the precoat control valve to provide the proper flow rate for precoating. Too low a flow rate allows settling of filter aid in the filter cell and too high a flow rate causes an uneven precoat layer to

form. The proper rate was found to be with the precoat control valve open 2-1/2 turns and a 4 cm Hg head loss at the end of the precoating step (using 0.15 lb/sq ft precoat).

8. With the control lever in filter position, add the precoat filter aid to the precoat pot and turn on the magnetic stirrer under the precoat pot.
9. Turn the control lever to precoat position.
10. While the filter is being precoated, remove any clean water that remains in the raw water holder. After the water in the precoat pot has become clear and a uniform precoat layer has formed, fill the raw water holder with one liter of the water to be filtered and a weighed amount of body feed filter aid. Turn on the magnetic stirrer under the raw water holder and turn off the one under the precoat pot.
11. Simultaneously turn the control lever to filter position and start the stopwatch or note the clock time.
12. Immediately adjust the rotameter needle valve to give the desired filtration rate. The flow rate needed to give a filtration rate of 1.0 gpm/sq ft through a 2-inch diameter filter is 82.6 ml/min. This corresponded to a reading of 26 with the

rotameter arrangement described previously.

13. Observe and record the head loss and elapsed filtration time at appropriate intervals. Plot the head loss versus time curve as the run progresses. Also record the effluent temperature and effluent quality at various times during the filter run. At least once during the run, check the flow rate by collecting the effluent over a period of 10 minutes in a graduated cylinder. The rotameter should be watched carefully to be sure that a constant flow rate is maintained.
14. Add an additional liter of raw water and body feed when needed. This is necessary approximately every 10 minutes for a 2 inch diameter filter and 1.0 gpm/sq ft filtration rate.
15. At the end of the filtering cycle, allow the raw water holder to empty. Then fill the holder with clean water.
16. Open the rotameter needle valve so that any filter aid particles that may have lodged in the valves are removed on the filter cake. Keep the raw water holder full of clean water.
17. Turn the control lever to backwash position. It may be necessary to alternately turn the control lever from backwash to filter positions in order to

break up large pieces of filter cake.

18. Another filter run can now be made starting with Step 8. To assure that there is no air in the system, begin with Step 3.

Cost Data

General

The collection of accurate cost data is as important for the optimum design and operation of a precoat filtration plant as the collection of accurate filtration data. Costs vary greatly from one location to another and over a period of time. Therefore, it is important that the costs used in design be appropriate for the location of the proposed plant and the time it is to be built. If any of the cost factors used in the design of a plant change greatly after the plant is in operation, the operating conditions can be changed to achieve minimum operating cost under the new conditions.

The total cost of filtration is composed of the first cost of the plant and its operating costs. First cost represents the costs of the building, land, filters, pumps, body feeding equipment, piping, etc. Operating costs include the costs for filter aid, power, labor and maintenance. Other costs connected with the administration of a water supply system generally do not vary with the choice of design conditions and therefore are not included in the determination of optimum design conditions.

The cost data needed are discussed in the following sections. The used of these data in determining the optimum design conditions will be discussed in a later chapter.

First cost

Once the type of building construction and plant location are chosen, the first cost of a plant is a function of the filter area to be provided and the filtration rate. The filtration rate is a factor because, for a specific filter area, the filtration rate determines the size of pumps, piping, body feeders, and other equipment which vary in size and cost according to the total quantity of flow. Therefore, the first cost data needed is that to define a curve of first cost in $/sq ft versus filter area for a particular filtration rate and a filtration rate factor. The filtration rate factor is defined as the percent increase in first cost per 1.0 gpm/sq ft increase in the filtration rate. Enough first cost-area data must be available to allow linear interpolation between points with little error.

Additional information required for amortizing the first cost are the salvage value in percent of the first cost, the plant life, and the annual interest rate.

Operating costs

The only cost data necessary for calculating the cost of filter aid is the price per ton of filter aid delivered to the plant site.

Power costs are determined by the volume of water filtered and the total head pumped against according to the equation:

$$CP = \frac{QH_t}{E}\left(\frac{8.34\ \text{lb/gal}}{2.655 \times 10^6\ \text{ft-lb/kwh}}\right) C \qquad (29)$$

where:

CP = cost of power in \$/unit time or \$/1000 gal

Q = volume of water filtered in gal/unit time or equals 1000 gal depending on desired cost basis

H_t = terminal head loss in ft

E = overall efficiency of energy conversion

C = energy cost in \$/kw

Thus, the cost data necessary for computing the power cost for pumping are the unit cost per kilowatt-hour and the overall efficiency of energy conversion.

It is assumed that the cost of labor and maintenance depend on the size of the plant just as first cost. Therefore, the necessary data are the cost of labor and maintenance in \$/sq ft versus filter area for a particular filtration rate and the filtration rate factor.

The need to backwash and reprecoat a filter at the end of a filter run affects filtration costs in two ways:

1. Since no filtered water can be produced during the backwashing cycle, the filter area must be increased so that the water produced during the filtering cycle will be enough to provide the required plant output each day in spite of the filter down time for backwashing.

2. Since filtered water is used in backwashing and wasted, the filter area must also be increased slightly to provide daily the water needed for backwashing during the normal filtering cycle.

The data necessary to calculate the increased filter area required are the volume of clean water in gal/sq ft required for backwashing and the length of time per filter run needed to backwash and precoat the filter.

DATA REDUCTION

β Index Determination

Flat septum

The head loss through a flat filter cake is determined by the formula:

$$H_c = \sigma X \tag{8}$$

where:

$$\sigma = q^2 \nu \beta C_F / g$$

and

$$X = t - (1 - e^{-\delta t})/\delta$$

If the head loss, H_c, is plotted versus X, the resulting curve should be linear with slope σ. Thus, by determining the value of the slope, the value of β contained in σ can be calculated since all other components of σ are known for a particular filter run.

It has been found that it is difficult to determine an exact value of the theoretical dilution rate, δ, primarily due to a lack of complete mixing within the filter housing. However, since:

$$\lim_{t \to \infty} (1 - e^{-\delta t})/\delta = 1/\delta$$

then for large values of t:

$$\begin{aligned} X &= t - 1/\delta \\ &= t - t_d \end{aligned} \qquad (30)$$

where:

t_d = theoretical detention time, V_f/Q

This shows that the effect of initial dilution is to offset the head loss versus time curve by a length of time equal to t_d (Figure 25). Thus, to determine the value of β from data gathered using a flat filter septum, simply measure the slope of the linear portion of the head loss versus time curve and calculate β as:

$$\beta = \frac{g}{q^2 \nu} \frac{\text{Slope}}{C_F} \qquad (31)$$

Cylindrical septum

The head loss through a cylindrical filter cake is determined by the formula:

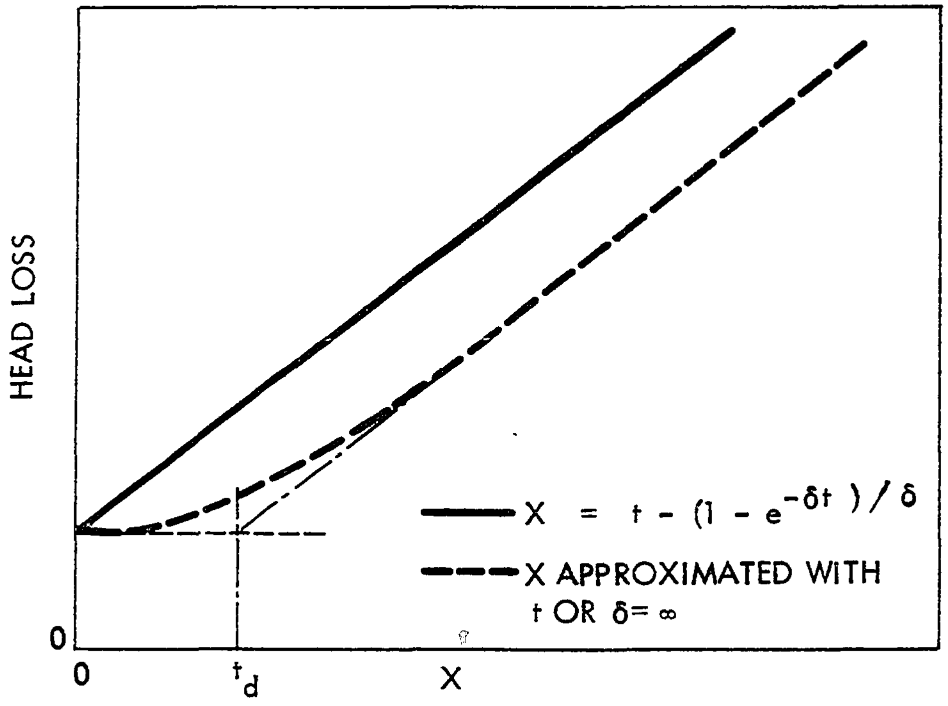
$$H_c = \frac{R_s \sigma}{\phi} \ln\left(1 + \frac{R_s \phi X}{R_o^2}\right) \qquad (6)$$

where:

$\phi = 2q\gamma_w C_F (10^{-6})/\gamma_p$

If the head loss, H_c, is plotted versus $\ln(1 + R_s\phi X/R_o^2)$, the resulting curve should be linear with slope $R_s\sigma/\phi$. By determining the value of the slope, the value of β contained in σ can be determined since all other components of the term $R_s\sigma/\phi$ are known for a particular filter run.

Figure 25. Theoretical plot of head loss versus X for flat septa


HEAD LOSS
0
0
t_d
X
X = t - (1 - $e^{-\delta t}$)/δ
X APPROXIMATED WITH
t OR δ= ∞

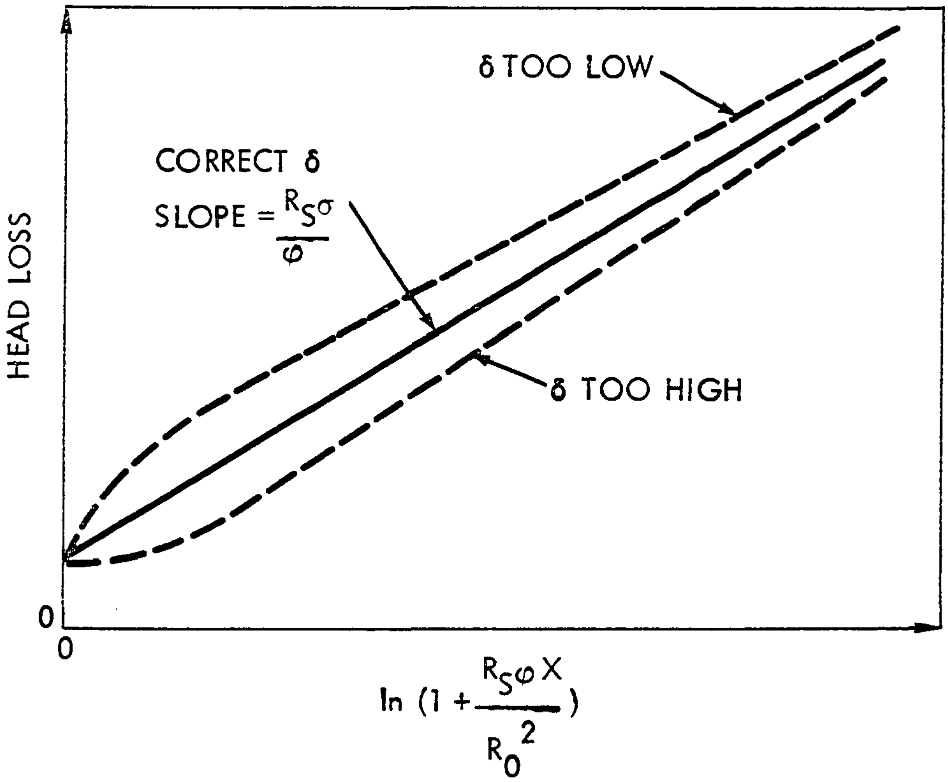
With cylindrical septa the initial dilution rate and also the in-place bulk density, γ_p, of the filter aid must be known before the true value of β can be calculated.

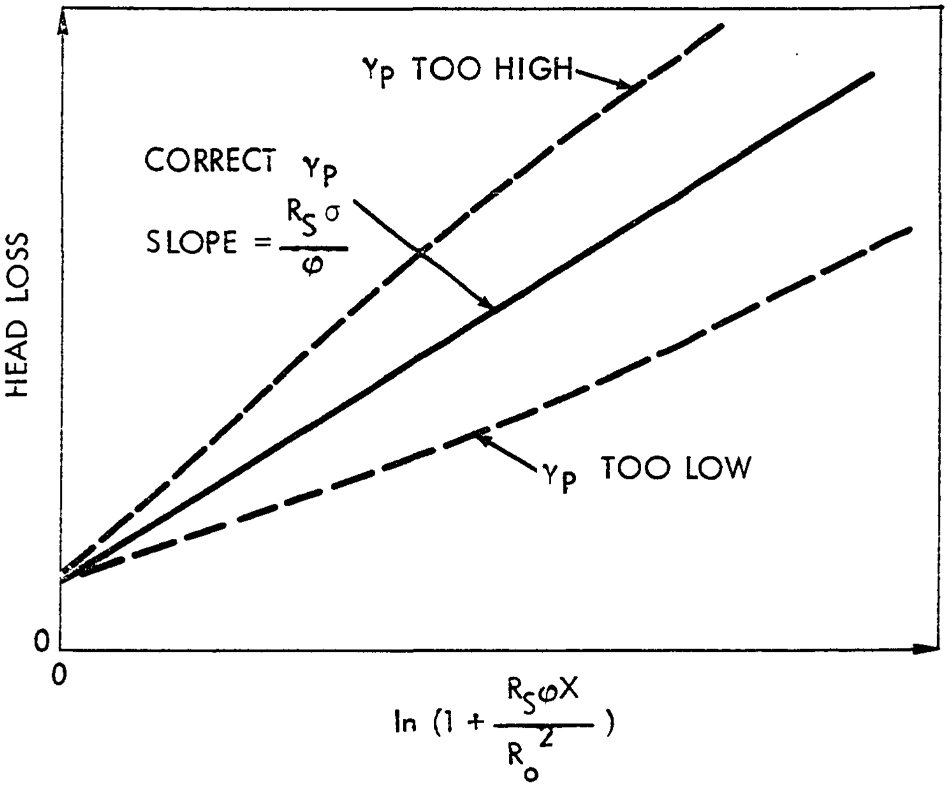
The effects of using the wrong value of δ when calculating β from the results of a filter run with cylindrical septa are shown in Figure 26. If too high a value of δ is used, the effects of initial dilution are not sufficiently accounted for as shown by the initial part of the curve in Figure 26. Also, the decrease caused by initial dilution in the amount of filter cake formed and increase in surface area is not accounted for which results in an increased slope of the later part of the curve in Figure 26. Using too low a value of δ causes opposite effects.

The value of β is calculated from the slope of the linear regression line for a plot of H versus $\ln(1+R_s\phi X/R_o^2)$. If the data collected during the early part of a filter run are neglected or the data from a very long filter run are used, the calculated value of β will always be higher than the true β when too high a value of δ is used and lower than the true value of β when too low a value of δ is used. However, including the data from the early part of the filter run decreases the slope of the regression line and the value of the calculated β for the case where δ is too high and increases them when δ is too low. Thus, the calculated value of β may be higher or lower than the true value depending on

Figure 26. Theoretical plot of head loss versus natural log term for cylindrical septa showing the effects of using wrong values of δ

Figure 27. Theoretical plot of head loss versus natural log term for cylindrical septa showing the effects of using wrong values of γ_p


δ TOO LOW
CORRECT δ
SLOPE = $\frac{R_S \sigma}{\varphi}$
δ TOO HIGH
HEAD LOSS
0
0
$\ln\left(1 + \frac{R_S \varphi X}{R_0^2}\right)$


γ_P TOO HIGH
CORRECT γ_P
SLOPE = $\frac{R_S \sigma}{\varphi}$
γ_P TOO LOW
HEAD LOSS
0
0
$\ln\left(1 + \frac{R_S \varphi X}{R_o^2}\right)$

such factors as the length of the run, the actual dilution rate, the actual β, the body feed rate, and the size of the septa. This is demonstrated in Table 7. Values of head loss for elapsed times of filtration of 5, 30, 60, 90, ..., 300 minutes were computed for both a 1.0 inch and a 3.5 inch

Table 7. Effect of using wrong δ on values of β found by regression analysis

δ/hr	$\beta, 10^6$ ft^{-2}	s_E, ft H_2O	R, %	% error
		1.0 inch diameter septum		
2	10.289	0.435	99.807	+2.89
4	10.056	0.169	99.971	+0.56
6	10.017	0.074	99.994	+0.17
8	10.006	0.027	99.999	+0.06
10	10.000	0.000	100.000	0.00
12	10.003	0.017	100.000	+0.03
14	10.003	0.029	99.999	+0.03
16	10.005	0.036	99.999	+0.05
18	10.006	0.042	99.998	+0.06
∞[a]	10.041	0.057	99.997	+0.41
		3.5 inch diameter septum		
2	10.427	0.558	99.838	+4.27
4	10.111	0.215	99.976	+1.11
6	10.042	0.094	99.995	+0.42
8	10.016	0.034	99.999	+0.16
10	10.000	0.000	100.000	0.00
12	9.996	0.021	100.000	-0.04
14	9.992	0.036	99.999	-0.08
16	9.989	0.045	99.999	-0.11
18	9.988	0.052	99.999	-0.12
∞[a]	9.995	0.073	99.997	-0.05

[a] t used in place of X.

diameter septum with the following hypothetical conditions:

$\delta = 10/\text{hr}$

γ_p = 16 lb/cu ft

β = 10 x 10^6 ft^{-2}

C_F = 100 mg/l

q = 1.00 gpm/sq ft

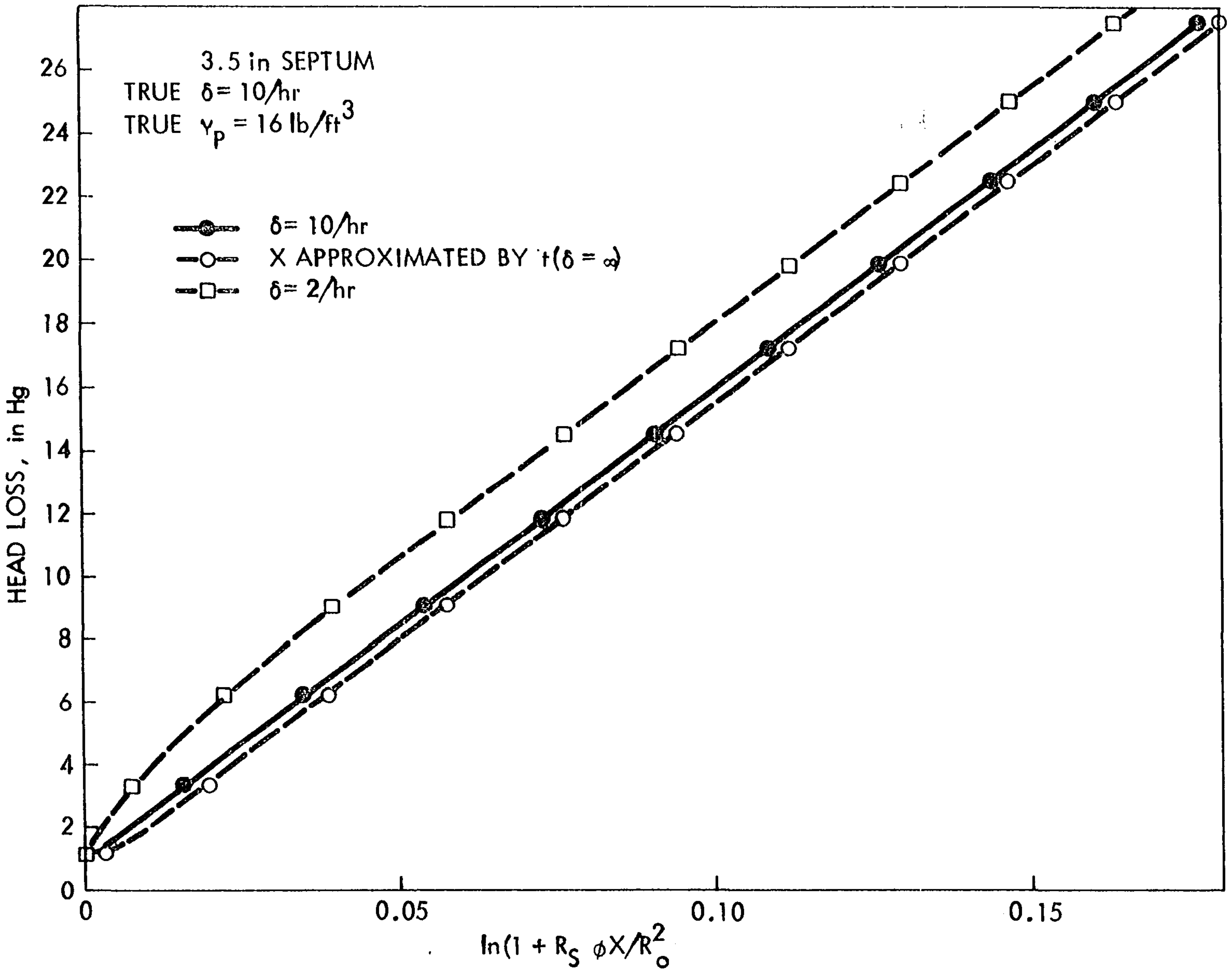
w = 0.10 lb/sq ft

and

temperature = 60 °F

Values of β using different values for δ were then calculated from the slopes of linear regression lines (Figure 28) of H versus $\ln(1 + R_s\phi X/R_o^2)$. The results of these calculations show that using the wrong value of δ, or even neglecting initial dilution by using time in place of X, does not cause serious errors in calculating β. For very short filter runs, especially if data are not collected beyond the period of initial dilution, the errors are greater. In such cases, a good estimate of δ is needed. For a completely mixed system, the initial dilution rate is theoretically equal to the flow rate divided by the volume of the filter housing. Since it has been found that the theoretical dilution rate does not always account for observed effects attributed to initial dilution, it is recommended that a method for estimating δ to fit observed data be used (27). In this method, the assumption is made that the inflection point of the head loss versus time curve occurs when $\delta t = 3$. When $\delta t = 3$, the term $(1 - e^{-\delta t}) = 0.95$ and the

Figure 28. Plot of head loss versus natural log term for the hypothetical data used to prepare Table 7


3.5 in SEPTUM
TRUE δ= 10/hr
TRUE γ_p = 16 lb/ft^3
δ= 10/hr
X APPROXIMATED BY t(δ = ∞)
δ= 2/hr
HEAD LOSS, in Hg
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0
0.05
0.10
0.15
$\ln(1 + R_S \phi X/R_o^2$

concentrations of body feed and suspended solids in the filter housing should be 95 percent of the concentrations in the influent if the contents of the housing are completely mixed (See Equation 54, Appendix B). It is assumed that at this point, the increase in the rate of head loss development caused by the increasing concentrations of body feed and suspended solids in the filter housing is balanced by the decrease in the rate of head loss development caused by the increasing surface area of the filter septums. By estimating the time of inflection, t_i, from a plot of head loss versus time, δ may be estimated as:

$$\delta \simeq 3/t_i \qquad (32)$$

The effects of using the wrong value of γ_p when calculating β from the results of a filter run with a cylindrical septum filter are shown in Figure 27. If the value of δ_p used is too high, the actual increase in septum area that occurred during the filter run is not completely accounted for. Therefore, at any particular time, the observed head loss is lower than the theoretical head loss required for the calculated β to be equal to the actual β. Thus, the calculated value of β will be lower than the actual value of β. If the value of γ_p used is too low, the calculated value of β will be higher than the actual value. This is demonstrated by the results presented in Table 8. The same hypothetical data used in preparing Table 7 were used to prepare Table 8. The results show that using the wrong value of γ_p may cause serious error in the value of β calculated, especially when small diameter septa are used. Therefore, an accurate value of γ_p should be obtained before β is calculated. A standard procedure for measuring γ_p has been proposed by Baumann and Oulman (6). Values of γ_p for several grades of perlite and diatomite filter aids have been given in Table 3 (p. 29).

BID program

A user manual for a computer program for Beta Index Determination or the BID program is given in Appendix D. The program allows calculation of the β index from the results of filtration with flat or cylindrical septa.

The main use of the BID program has been to analyze the results from hundreds of filter runs made during research studies. If only a few filter runs are made, it is just as easy to calculate values of β manually; especially if the filter runs are made using flat septa such as used in the SSCR filter. Even with cylindrical septa it is not difficult to calculate β indices manually for several filter runs if many of the variables (q, R_s, w, etc.) are the same and head loss is measured at the same times for every filter run. In fact, it is recommended that manual calculations be made so that any errors in the analysis will be immediately noticed.

Table 8. Effect of using wrong γ_p on values of β found by regression analysis

γ_p, lb/ft^3	β,10^6 ft^{-2}	s_E, ft H_2O	R, %	% error
		1.0 inch diameter septum		
8	14.158	0.176	99.968	+41.58
10	12.470	0.121	99.985	+24.70
12	11.365	0.074	99.994	+13.65
14	10.584	0.034	99.999	+5.84
16	10.000	0.000	100.000	0.00
18	9.554	0.029	99.999	-4.46
20	9.195	0.055	99.997	-8.05
22	8.903	0.078	99.994	-10.97
24	8.660	0.098	99.990	-13.40
		3.5 inch diameter septum		
8	11.595	0.173	99.984	+15.95
10	10.958	0.110	99.994	+9.58
12	10.534	0.064	99.998	+5.34
14	10.231	0.028	100.000	+2.31
16	10.000	0.000	100.000	0.00
18	9.826	0.023	100.000	-1.74
20	9.685	0.041	99.999	-3.15
22	9.569	0.057	99.998	-4.31
24	9.473	0.071	99.997	-5.27

Examples of the manual calculation of β from results using both flat and cylindrical septa are given in the BID Program User Manual in Appendix D.

β Index Prediction

Empirical prediction equations

β prediction equations have been presented most often in the form of Equation 15:

$$\beta = 10^{b_1} (C_S/C_F)^{b_2} \tag{15}$$

As discussed previously, this equation was developed by reasoning that filter cakes containing equal ratios of suspended solids to body feed should have equal resistances per unit weight of cake (5). It was then discovered that when β was plotted versus C_S/C_F on log log graph paper, a straight line was formed which corresponds to Equation 15. The values of b_1 and b_2 can be determined from such a plot since the slope is equal to b_2 and when C_S/C_F is 1.0, 10^{b_1} equals β. Also, Equation 15 can be transformed to a linear equation by a logarithmic transformation; i.e., $\log \beta = b_1 + b_2 \log(C_S/C_F)$. Therefore, b_1 and b_2 can be determined by linear regression of log β and $\log(C_S/C_F)$.

The Equation 15 form of the β prediction equation has been found to be acceptable by several investigators because either C_S was held constant or because the suspended solid did not show a sufficient concentration effect. If C_S is not varied, Equation 15 can be used to predict β for waters containing different amounts of the suspended solid than the water used for collecting data <u>only if it is assumed that</u>

concentration effects are negligible (i.e., the same C_S/C_F always results in the same β). If this assumption is not valid, Equation 15 can only be used when C_S is equal to that used for collecting the data. In such a case Equation 27 is equally valid:

$$\beta = 10^{b_1} C_F^{b_2} \tag{27}$$

For example, data presented by Baumann et al. (8) for the filtration of water containing 8.0 ± 0.5 mg/l of iron were used to develop β prediction equations of the form of Equation 27. Equations were developed for each of the 11 filter aids used and the values of b_2 were found to vary from 1.81 to 2.15. In fact, if b_2 is set equal to 2.00, a plot of β versus $1/C_F^2$ yields a straight line which passes through the origin and has a slope equal to 10^{b_1}. Typical results are shown in Figures 29 and 30.

Waters which have been shown to exhibit negligible concentration effects are: University tap water containing unsettled Ball clay (61), University tap water containing settled Ball clay (3), distilled water containing unsettled Ball caly (3), distilled water containing settled Ball clay (3), and several coagulated and settled surface waters (15). For such waters, the prediction equation represented by Equation 15 can be used.

The only waters definitely shown to exhibit pronounced

Figure 29. Typical result of plotting β versus $1/C_F^2$ with data from Baumann *et al*. (8) C_S constant at 8.0 mg/l iron

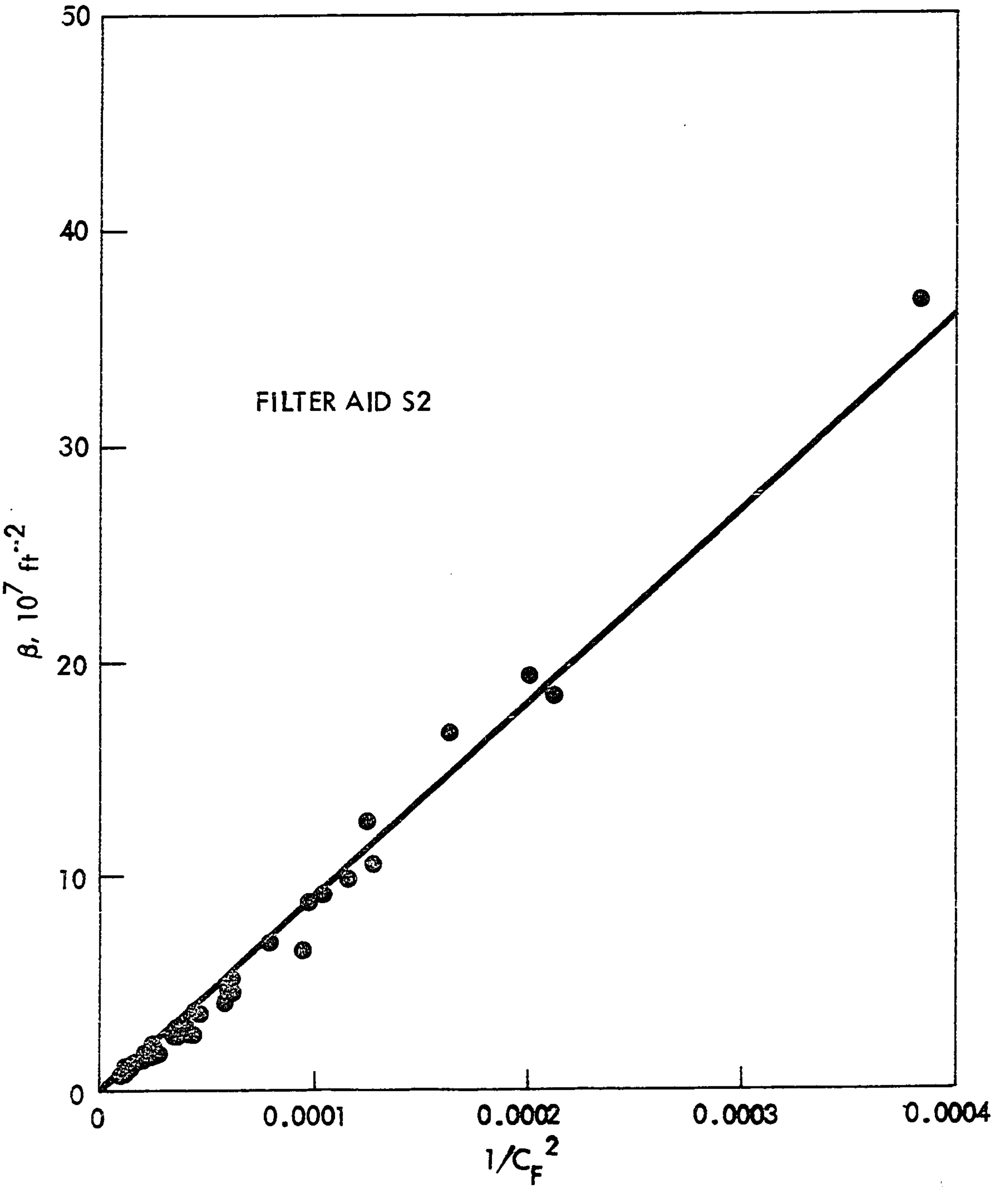
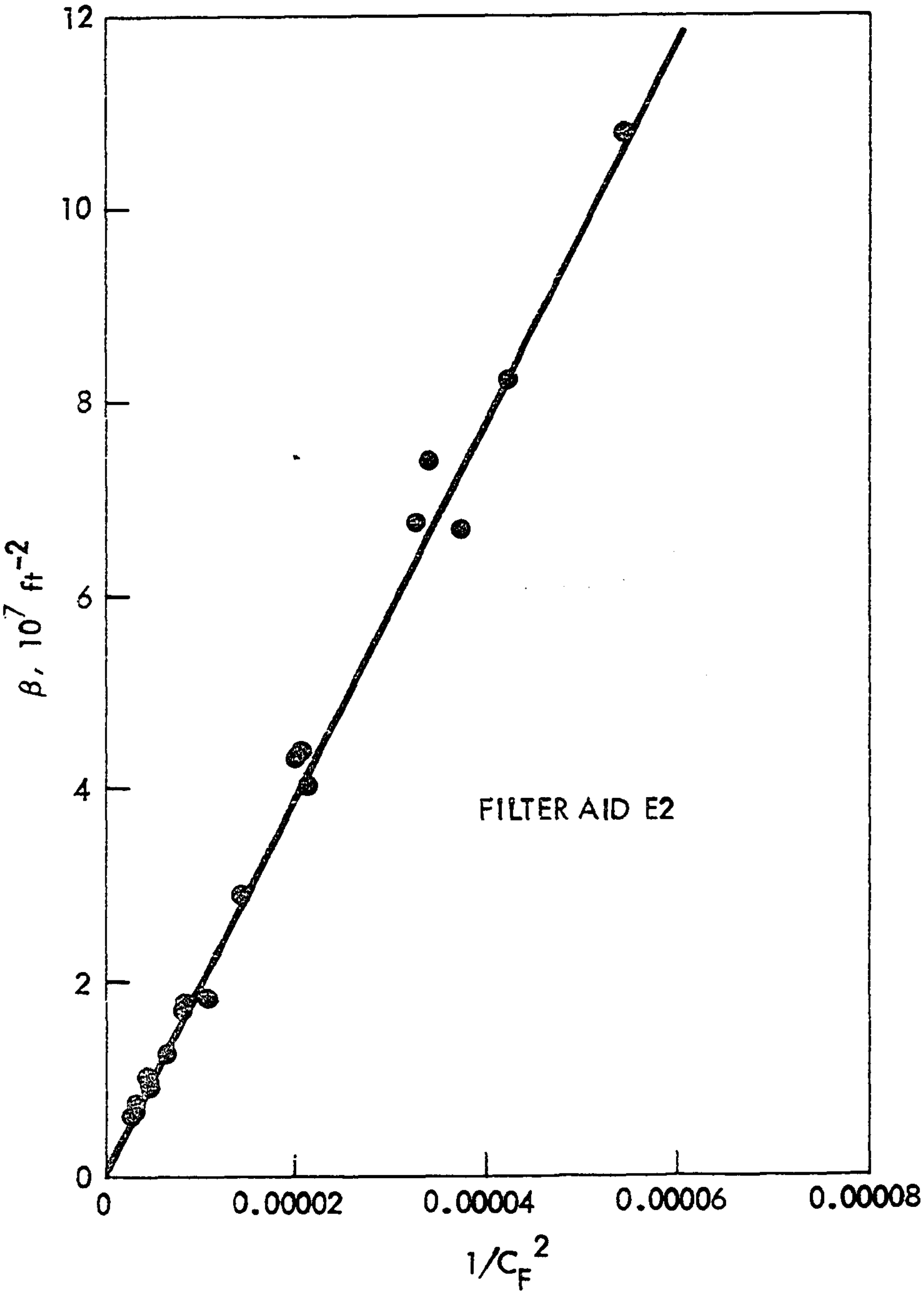

50
40
30
20
10
0
FILTER AID S2
β, 10^7 ft^{-2}
0
0.0001
0.0002
0.0003
0.0004
$1/C_F^2$

Figure 30. Typical result of plotting β versus $1/C_F^2$ with data from Baumann *et al*. (8) C_S constant at 8.0 mg/l iron


12
10
8
6
4
2
0
β, 10^7 ft^-2
0
0.00002
0.00004
0.00006
0.00008
1/C_F^2
FILTER AID E2

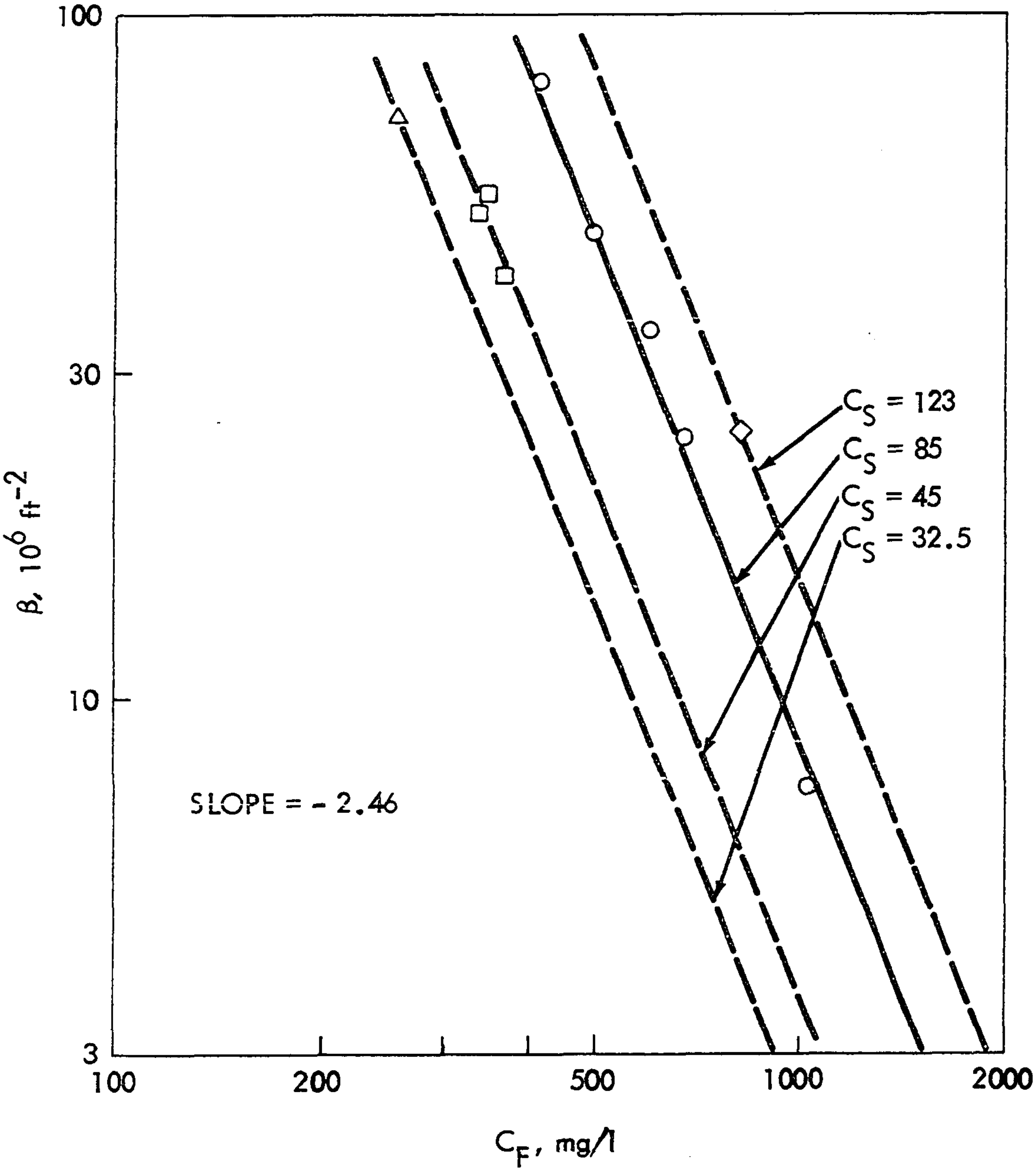
concentration effects are University tap water containing Wyoming bentonite clay (3, 61) and University tap water containing iron floc (3). There are indications that effluent from the lime-soda ash softening process also exhibit concentration effects (15, 27), however the data available for these effluents are field data collected without substantial variations in C_S.

The most complete data for developing a β prediction equation for University tap water containing Wyoming bentonite clay were collected by Regunathan (61). For a water such as this, which exhibits a definite concentration effect, it is recommended that a β prediction equation of the following form be used:

$$\beta = 10^{b_1} C_S^{b_2} C_F^{b_3} \tag{33}$$

Regunathan's data for tap water plus Wyoming bentonite clay (Series D runs) are contained in Appendix A (Table 25). If a log log plot of β versus C_F is made (Figure 31), the value of b_3 can be determined as the slope of the straight line drawn through points for which C_S values are the same. The value of b_3 for Regunathan's data was found to be -2.46 which is the slope of the straight line drawn through the 5 points for which C_S was approximately 85 JTU. If it is then assumed that the value of b_3 is the same for all values of C_S, parallel lines can be drawn through points collected at

Figure 31. Log β versus log C_F for University tap water containing Wyoming bentonite clay. Data from Regunathan (61)


100
30
10
3
100
200
500
1000
2000
β, 10^6 ft^{-2}
C_F, mg/l
C_S = 123
C_S = 85
C_S = 45
C_S = 32.5
SLOPE = - 2.46

the other values of C_S (dashed lines in Figure 31). From these lines, values of β at the same value of C_F can be determined for each value of C_S at which data were gathered. In the example, the following values of β were determined at $C_F = 600$ mg/l:

C_S, mg/l	β, 10^6 ft^{-2}
32.5	8.6
45	12.7
85	29.9
123	52.0

These values were then used to make the log log plot of β versus C_S shown in Figure 32. The slope of the straight line in Figure 32 is b_2 which was found to have a value of +1.31. Now, $\beta = 29.9 \times 10^6 \ ft^{-2}$ when $C_S = 85$ JTU and $C_F = 600$ mg/l. Therefore:

$$29.9 \times 10^6 = 10^{b_1} (85)^{1.31} (600)^{-2.46}$$

and taking the log of both sides of the equation:

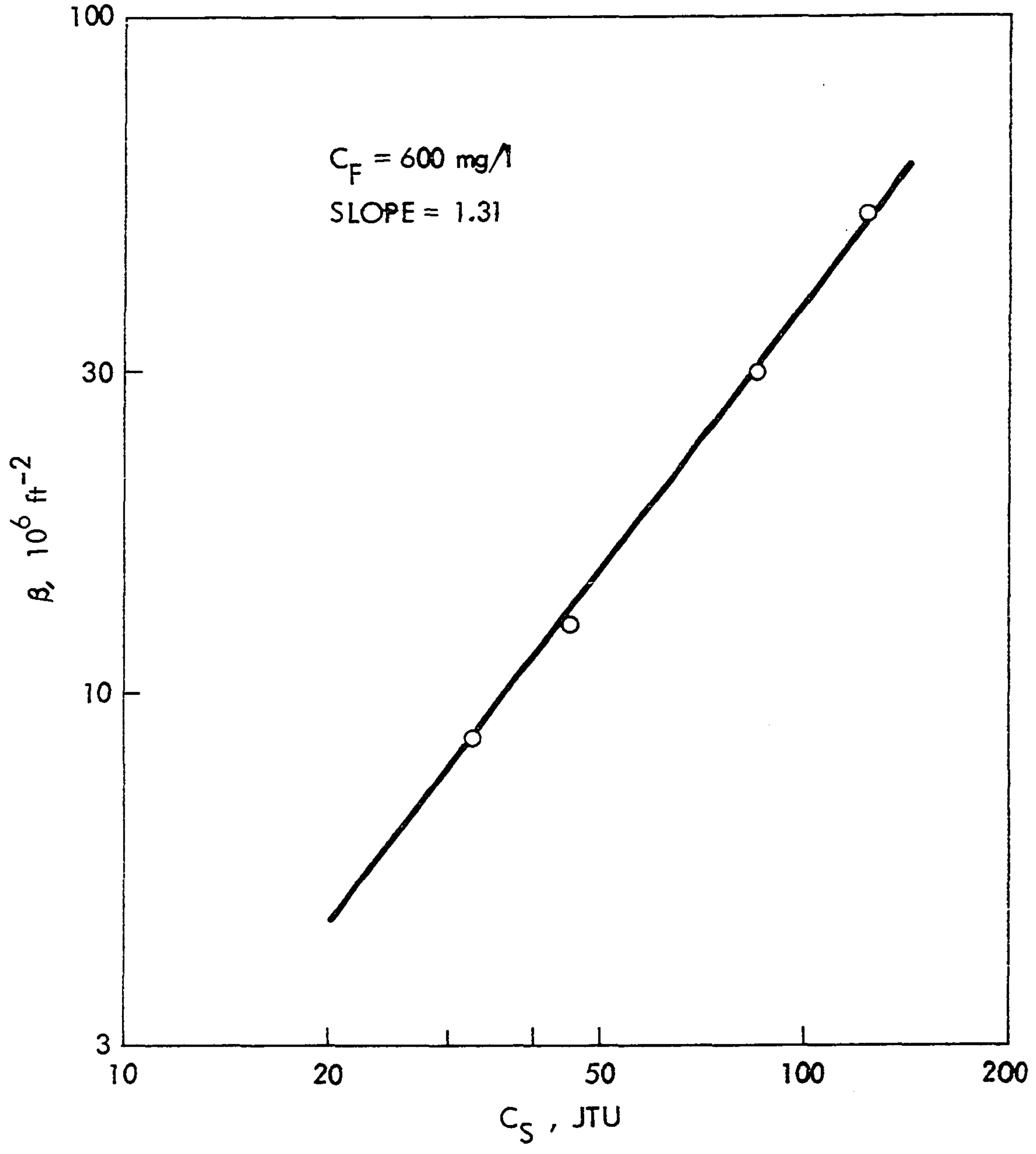
$$7.476 = b_1 + (1.31 \times 1.929) + (-2.46 \times 2.778)$$

and

$$b_1 = 7.474 - 2.527 + 6.834$$
$$= 11.783$$

Therefore, for University tap water containing Wyoming bentonie clay:

Figure 32. Log β versus log C_S for University tap water containing Wyoming bentonite clay. Data from Regunathan (61)


C_F = 600 mg/l
SLOPE = 1.31
β, 10^6 ft^{-2}
100
30
10
3
10
20
50
100
200
C_S , JTU

$$\beta = 10^{11.783}\, C_S^{\,1.31}\, C_F^{\,-2.46}$$

Equation 33 can also be transformed to a linear equation by a logarithmic transformation; i.e., $\log \beta = b_1 + b_2 \log(C_S) + b_3 \log(C_F)$, and b_1, b_2, and b_3 can thus be determined by linear regression of $\log \beta$, $\log(C_S)$, and $\log(C_F)$. This was done using Regunathan's data with the following result:

$$\beta = 10^{11.6685}\, C_S^{\,1.2940}\, C_F^{\,-2.4054}$$

which agrees with the prediction equation calculated manually. Similar calculations are made in Appendix E for the results from filtering iron floc.

If Equation 33 is used for predicting β for waters which do not exhibit concentration effects, then b_2 should equal $-b_3$ so that the equation can be written as Equation 15.

Several theories have been proposed to explain why concentration effects occur. Some of the theories presented in chemical engineering literature pertaining to constant pressure filtration of concentrated slurries have recently been discussed by Arora (3). The only one of these theories which might possibly explain the decrease in β with increases in C_S and C_F observed for constant rate filtration of water is the theory that at higher concentrations, there is interference or crowding between particles as they are laid on the surface of the filter cake (38). Because of this interference, the particles do not form as dense a cake as they would if they had more freedom of movement. This theory gives a qualitative explanation of the concentration effects that have been observed; however, it does not explain why concentration effects have been observed with some suspended solids but not with others, even though the same types and approximate amounts of filter aids were used.

Regunathan (61) thought that the concentration effects observed with tap water containing Wyoming bentonite clay were due to swelling of the montmorillonite clay mineral within the filter cake. Regunathan agitated the clay slurry for 15 to 21 hours before a filter run was made so it is doubtful if the clay would swell within the cake. This theory also does not explain the concentration effects observed with iron-bearing waters or lime-soda ash process effluents.

Dillingham (27) proposed that concentration effects may be due to the use of the β index rather than specific resistance based on the weight of filter aid or due to errors in the assumption that the suspended solids do not increase the cake thickness. Neither of these explanations indicate why concentration effects are not observed for all suspended solids or why they are observed with flat septa as well as cylindrical septa. Also, there are several articles in the literature which report concentration effects when specific resistance is calculated (38, 65, 69). Dillingham also thought that the concentration effects that Regunathan observed could have been the result of using turbidity in place of suspended solids concentration for C_S. It has since been shown that the effects are still observed when suspended solids concentrations are used.

No one has yet shown proof as to whether concentration effects are due to the concentration of solids (suspended solids plus body feed) *per se* or if they are due to changes in the physical properties of the suspended solid particles caused by changes in concentration. This may explain why some solids exhibit concentration effects while others do not.

Rational prediction equation

A relation between the β index and the physical properties of the filter cake can be derived by equating the precoat filtration equations to the Kozeny-Carman equation for the head loss for laminar flow through a uniform bed of solids. The Kozeny-Carman equation was derived from Darcy's law by assuming that a granular bed is equivalent to a group of identical, parallel channels such that the total internal surface area and volume are equal to the particle surface area and volume of voids, respectively (18). This derivation is presented in most textbooks on unit operations (46, 62).

The equation may be written as:

$$\frac{H_c}{L_c} = 36k \frac{q\nu}{g} \frac{(1-\varepsilon)^2}{\varepsilon^3} \left(\frac{1}{\psi d}\right)^2 \qquad (34)$$

where:

d = mean spherical diameter of particles

ψ = sphericity, defined as the ratio of the surface area of the equivalent-volume sphere to the actual or true surface area (33). For spherical particles, $\psi = 1.0$, and for all other shapes, ψ is less than unity.

k = constant

Carman (19) found that the value of k was about 5.0 so that 36k = 180. More recently, Ergun (32) reviewed data in the literature and found that 36k = 150.

Now consider Equation 8 for the head loss through a flat filter cake:

$$H_c = \sigma X \qquad (8)$$

Since:

$\sigma = q^2 \nu \beta C_F / g$ by definition

$\beta = a_c \frac{\gamma_w}{\gamma_p} (10^{-6})$ by definition

and:

$q = \frac{Q}{A}$

then Equation 8 can be written as:

$$H_c = a_c \frac{q\nu}{g} \left[\frac{Q}{A} C_F \frac{\gamma_w}{\gamma_p} (10^{-6}) X\right]$$

Note that the term in brackets is equivalent to the thickness, L_c, of the filter cake since:

QX = cu ft of water filtered

$QX\gamma_w$ = lbs of water filtered

and:

C_F = lb filter aid/10^6 lb water

$C_F(10^{-6})$ = lb filter aid/lb water

so that:

$QX\gamma_w C_F(10^{-6})$ = lb filter aid deposited

and:

$$\frac{QX\gamma_w C_F(10^{-6})}{A\gamma_p} = \frac{\text{cu ft deposited}}{\text{unit area}} = L_c$$

Therefore:

$$\frac{H_c}{L_c} = a_c \frac{q\nu}{g} \qquad (35)$$

The right hand side of this equation may now be equated to the right hand side of the Kozeny-Carman equation (Equation 34) which leads to:

$$a_c = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \left(\frac{1}{\psi d}\right)^2 \qquad (36)$$

and from the definition of the β index:

$$\beta = 150 \ (10^{-6}) \ \frac{\gamma_w}{\gamma_p} \frac{(1-\varepsilon)^2}{\varepsilon^3} \left(\frac{1}{\psi d}\right)^2 \qquad (37)$$

For the filtration of a dilute suspension of a non-homogeneous mixture of suspended solids and filter aid, Equation 37 appears to have little practical merit. Arora (3) presented Table 9 which shows the large variation of the factor $\varepsilon^3/(1-\varepsilon)^2$ with only slight variations in ε. The difficulties in determining ε, ψ, and d of a dirty filter cake make this method of predicting β too impractical.

Table 9. Variation of permeability factor, $\varepsilon^3/(1-\varepsilon)^2$ with porosity ε (3)

	ε	$\varepsilon^3/(1-\varepsilon)^2$
Clean filter aid porosity	0.90	72.9
	0.85	27.3
	0.80	12.8
	0.78	10.0
	0.75	6.7
	0.70	3.8
	0.65	2.2
	0.57	1.0
	0.50	0.5

Equation 37 does, however, have some theoretical merit. It has been theorized that an empirical prediction equation such as:

$$\beta = 10^{b_1} (C_S/V_V)^{b_2} \qquad (19)$$

would have the same exponents for all filter aids when the same suspended solid was filtered (54). Consideration of Equation 37 reveals that even if the permeability factor is accounted for, there are still considerable differences in the bulk densities, sphericities, and mean particle sizes of the filter cakes formed using different filter aids.

MAIDS program

A user manual for a computer program for determination of β prediction equations by MAnipulation and Interpretation of Data Systems or the MAIDS program is given in Appendix E. The program was written as a general program to perform linear regressions and to transform and print out data. The main use of the MAIDS program has been for determining β prediction equations. The coefficients of any prediction equation that is, or can be transformed to, a linear equation with from 2 to 8 variables, can be determined using MAIDS. Any desired transformation, such as a logarithmic transformation, is possible with MAIDS.

Examples of the determination of β prediction equations are presented in the user manual. Examples of estimation of the regression coefficients by graphical methods are also given.

CALCULATION OF OPTIMUM DESIGN CONDITIONS

General

The general procedure for computer calculation of the optimum design conditions is to calculate the total filtration cost for each combination of q, C_F, and H_t with q, C_F, and H_t varied by desired increments over specified ranges and then picking out that combination which results in the least total cost. For example, if q is varied by 0.1 gpm/sq ft from 0.2 to 2.5 gpm/sq ft, C_F is varied by 10 mg/l from 20 to 100 mg/l, and H_t is varied by 10 ft from 50 to 150 ft there are 21 x 9 x 11 or 2079 combinations for which the total cost is calculated. That combination which results in the least total cost is the optimum.

With a high-speed, digital computer these calculations can be made in a matter of seconds. For manual calculation, the total number of combinations for which the total cost is calculated can be greatly reduced by using the graphical techniques presented by LaFrenz (see p. 68). If manual calculations are made, the ranges of values of q, C_F, and H_t and therefore the number of calculations required, can be reduced if a good approximation of the optimum q, C_F, and H_t combination is made beforehand. To aid in making this approximation, the effects of several of the filtration variables and cost factors on the optimum design conditions are discussed later in this chapter.

Initial Dilution

The filter run length must be calculated so that the number of filter runs that can be made in a certain length of time can be determined. The number of filter runs must be known in order to calculate the cost of precoat filter aid and the increase in filter area required to provide filtered water for backwashing.

The filter run length can be calculated using Equation 8 for flat septa or Equation 6 for cylindrical septa. Dillingham (25, 27) neglected initial dilution when calculating t by approximating X by t since when X is used there are not explicit solutions for t of either Equation 8 or Equation 6. Arora (3) has stated that this can result in serious error. Initial dilution can be considered and explicit solutions of Equations 8 and 6 obtained by replacing X with $t - t_d$ since $X = t - t_d$ when t is large (Equation 30). The errors in doing this to calculate the filter run length are negligible since X approaches $t - t_d$ very rapidly. For example, if δ is only 1.0/hr or $t_d = 1.0$ hr, X is equal to $t - 0.950$ hr when t is only 3 hr. A more practical example occurs when $\delta = 10$/hr or $t_d = 0.1$ hr. In this case, $X = t - 0.099$ hr when t is only 0.5 hr and $X = t - 0.099995$ hr when t is only 1.0 hr. In most cases, the length of filter runs for optimum design will be greater than 6 hr.

Several filter runs were made by the author and Madan L. Arora using the SSCR filter. The primary purpose of this study was to evaluate the ability of the SSCR filter to predict the results of large-scale filters. These results have been reported by Arora (3) and are presented in Appendix A (Table 32). Several different suspensions were filtered. With each suspension, filter runs were made with the same value of C_S/C_F but various values of C_S and C_F. This was done to study the effects of the solids concentration on the β index and a discussion of the results was made by Arora (3).

During the course of these studies it became apparent that the suspended solids concentration, and/or the body feed concentration since C_S/C_F was held constant, had a marked effect on the observed initial dilution rate and apparent detention time. The head loss versus time curves for one series of filter runs (Runs 55-60) with unsettled ball clay in distilled water and Hyflo Super-Cel filter aid are shown in Figure 33. Notice that the apparent detention time varies from about 3 min to 46 min. Theoretically, the detention time should be a constant of about 1.2 min based on the filter volume and filtration rate. Furthermore, it was found that a log log plot of C_S, (or C_F since C_S/C_F was held constant) versus the apparent detention time was a straight line (Figure 34) corresponding to the equation:

$$t_a = b_1 C_S^{\,b_2} \tag{38}$$

where:

b_1 and b_2 are constants.

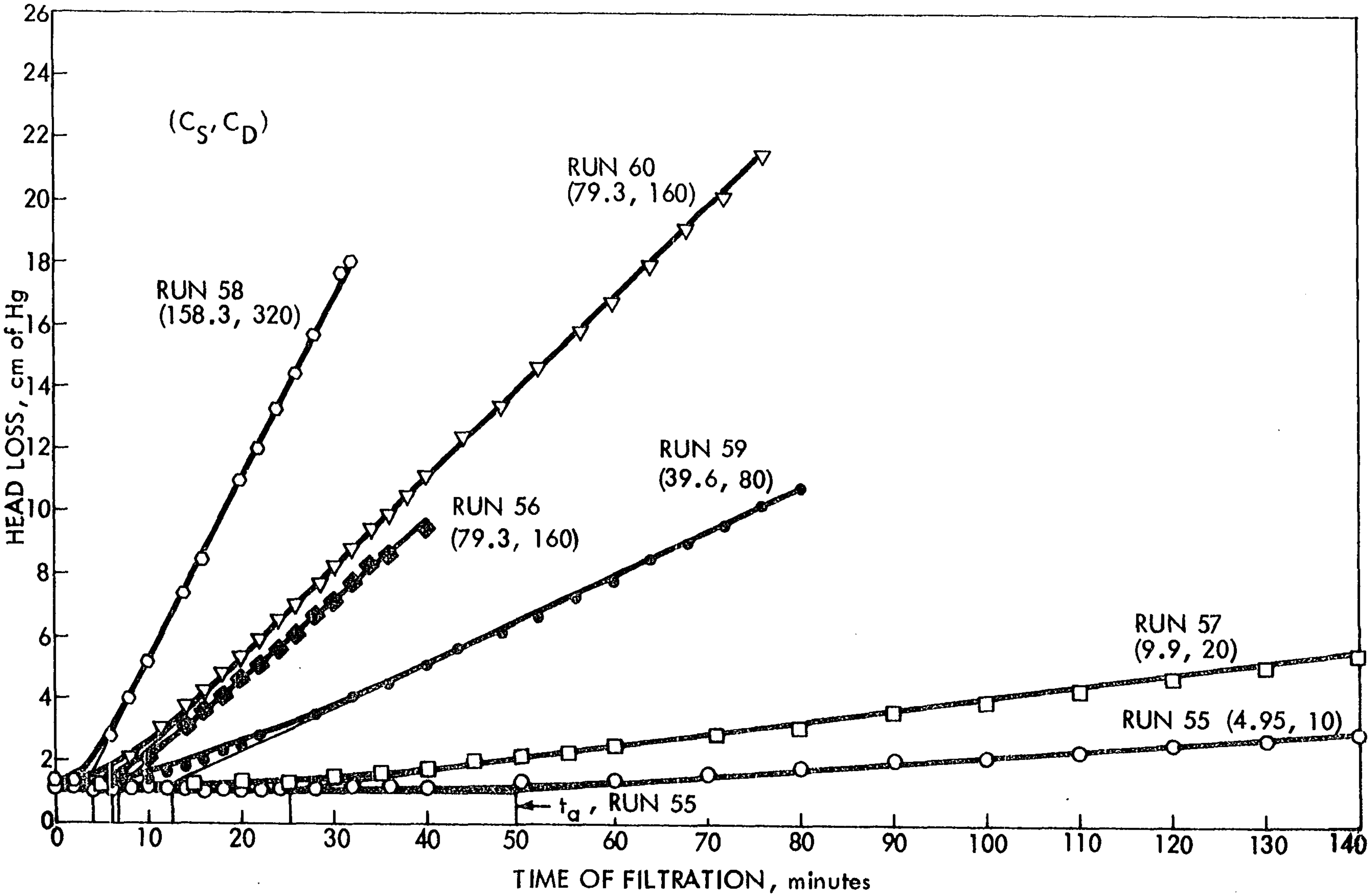
t_a = apparent detention time observed during a filter run.

It is theorized that the apparent detention time varies with the solids concentration because at the beginning of a filter run a definite amount of time is required for a filter cake to form. Before the cake is formed, the majority of the suspended solids removal is at the surface of the precoat layer. As the surface of the precoat layer becomes "plugged", a greater percentage of the suspended solids are removed resulting in the observed increase in the rate of head loss increase. After a filter cake is formed, the rate of head loss increase is constant for flat septa.

According to this theory, the quality of the filter effluent should continually improve during the early part of a filter run until the filter cake is formed. This was observed in this study. For example, during Filter Run 59 which is included in Figure 33, the effluent turbidity was 2.7 JTU after 14 min of filtration, 0.06 JTU after 32 min, and 0.03 JTU after 44 min. From Figure 33 it appears that

Figure 33. Plots of head loss versus time of filtration for filter runs with unsettled Ball Clay in distilled water using Hyflo Super-Cel as a filter aid at $C_S/C_F = 0.495$

Filter runs 55-60 in Appendix A, Table 32

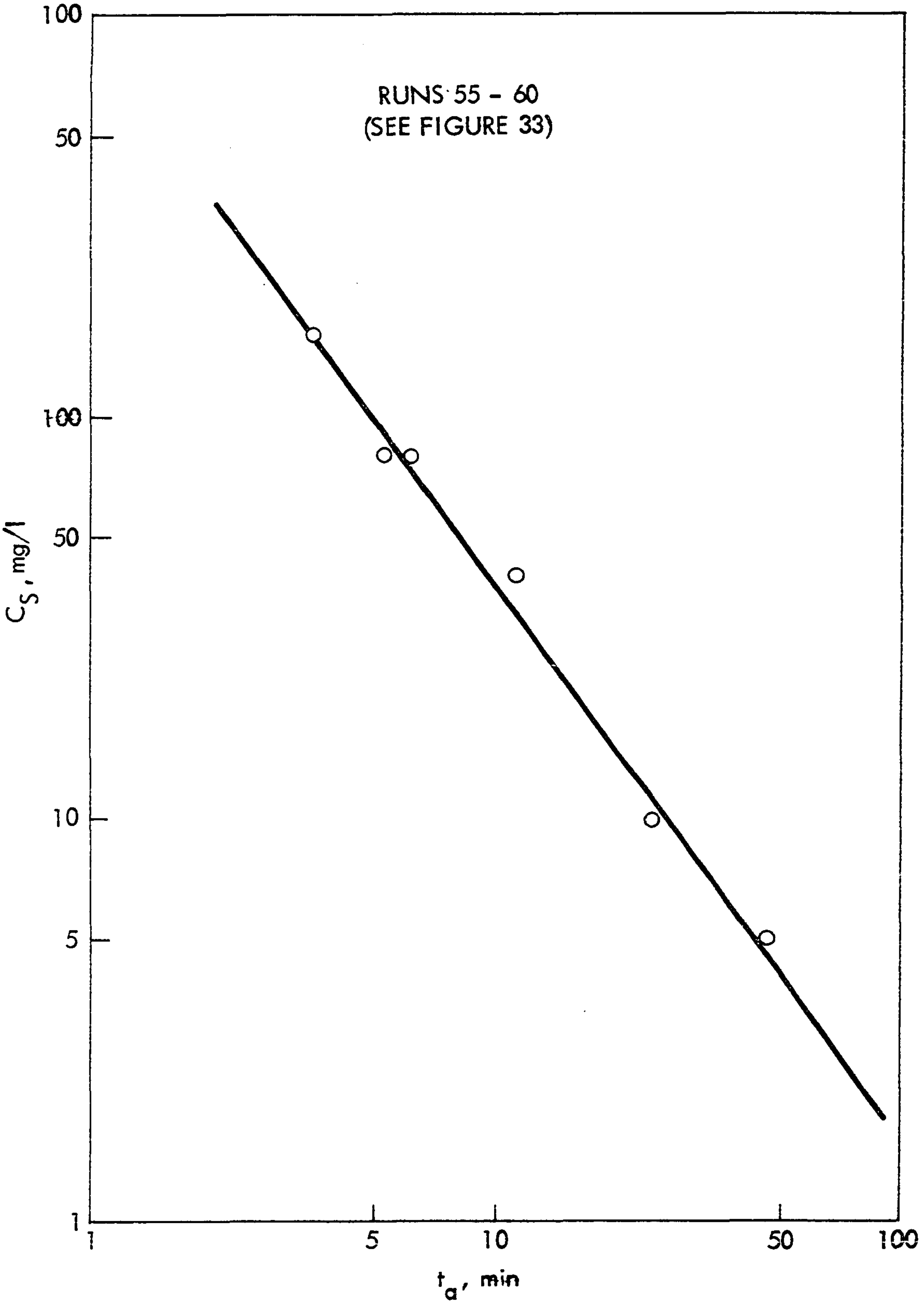


HEAD LOSS, cm of Hg
0
2
4
6
8
10
12
14
16
18
20
22
24
26
TIME OF FILTRATION, minutes
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
(C_S, C_D)
RUN 58
(158.3, 320)
RUN 60
(79.3, 160)
RUN 56
(79.3, 160)
RUN 59
(39.6, 80)
RUN 57
(9.9, 20)
RUN 55 (4.95, 10)
← t_a, RUN 55

Figure 34. Log C_S versus log t_a for data from the series of filter runs shown in Figure 33

Suspension = unsettled Ball clay in distilled water

Filter aid: Hyflo Super-Cel

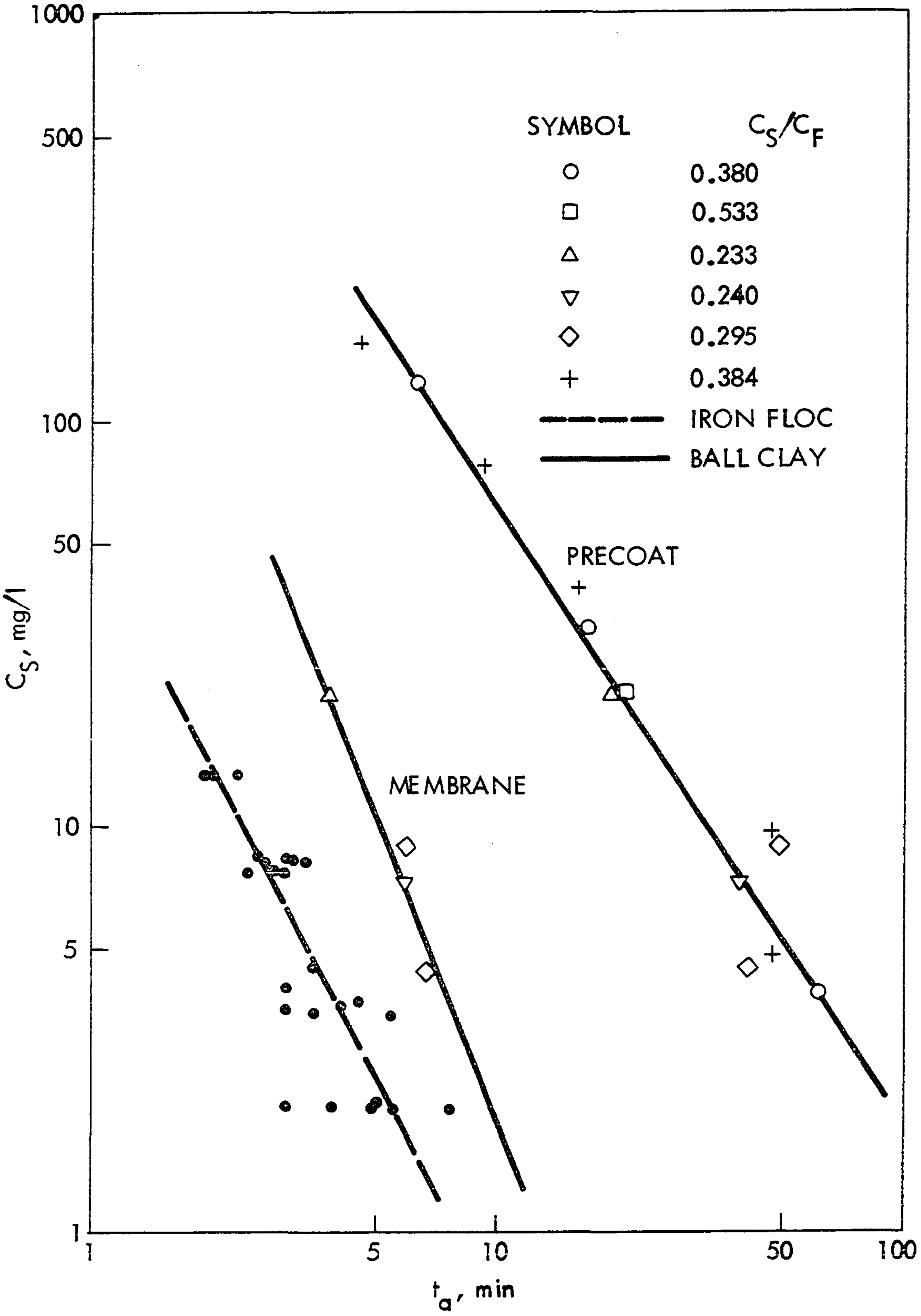

RUNS 55 - 60
(SEE FIGURE 33)
100
50
100
50
10
5
1
C_S, mg/l
1
5
10
50
100
t_a, min

the cake was completely formed at about 30 min. Influent turbidity during this filter run was about 45-48 JTU.

The proposed theory would lead one to predict that if the same concentrations of suspended solids are filtered, a suspended solid such as clay (1-2 μ diameter) which is less readily removed by straining at the surface of the precoat layer will result in a longer apparent detention time than a suspended solid such as iron floc (20-30 μ diameter) which is more readily removed by straining. Similarly, for the same suspended solid, the use of a coarse filter aid should produce longer apparent detention times than a fine grained filter aid. These predictions are borne out by the results shown in Figure 35. The apparent detention times when filtering settled Ball clay were approximately 15 times the apparent detention times observed when filtering iron floc. Filter runs were not made using different filter aids with the same suspended solid; therefore, there is no direct evidence to show the effects of different filter aids. However, a few filter runs were made using a Millipore filter (0.45 μ pore size) in place of a precoat layer. The apparent detention time for these filter runs were 5-10 times less than those observed when the same suspension was filtered using a precoat of Hyflo Super-Cel.

If it is assumed that the same amount of a particular suspended solid is always required to plug precoats of the

Figure 35. Log C_s versus log t_a for data from the filtration of settled Ball clay in distilled water and iron floc in University tap water


1000
500
100
50
10
5
1
C_S, mg/l
1
5
10
50
100
t_a, min
SYMBOL
C_S/C_F
○ 0.380
□ 0.533
△ 0.233
▽ 0.240
◇ 0.295
+ 0.384
IRON FLOC
BALL CLAY
PRECOAT
MEMBRANE

same filter aid, then one can write:

$$C_S\ t_a\ q - C_P = a_1$$

where:

C_P = amount of suspended solid that passes through the filter

a_1 = constant

If it is further assumed that the same amount of suspended solid always passes through the filter (i.e. C_p is independent of C_S) then:

$$C_S\ t_a\ q = a_2 \qquad (39)$$

where:

a_2 = constant.

The filter runs made by the author and Arora were all made using q equal to 1.05 gpm/sq ft. For the results of this study, the following equation should apply:

$$t_a = b_1\ C_S^{-1}$$

which is identical to Equation 38 with $b_2 = -1$. The values of b_1 and b_2 for the results of this study are given in Table 10. Obviously b_2 is not equal to -1 as theorized. The assumptions that were made are very broad, however the theory is presented here to indicate that t_a is inversely related to C_S and q and since the data were collected with q

Table 10. Prediction of apparent detention times, $t_a = b_1 C_S^{b_2}$

Solid	Water	Precoat	b_1	b_2
Iron floc	Tap	J3	8	-0.53
Settled ball clay	Distilled	HFC	150	-0.66
Settled ball clay	Tap	HFC	100	-0.68
Unsettled Wyo. bentonite	Tap	HFC	52	-0.82
Unsettled ball clay	Distilled	HFC	138	-0.73
Settled ball clay	Distilled	Membrane	13	-0.41

held constant, one must not assume that t_a does not also vary with q. Arora (3) expressed the opinion that t_a may also be a function of C_F. It is the opinion of this author that t_a varies very little with C_F. The data shown in Figure 35 for the filtration of a suspension of settled Ball clay in distilled water using Hyflo Super-Cel filter aid were collected at five different values of C_S/C_F. No apparent effect of C_F on t_a was observed. Filter run 12 was made with $C_S/C_F = 21.3/40 = 0.53$ and Filter run 14 was made with $C_S/C_F = 21.0/90 = 0.233$. The apparent detention times observed for these two filter runs were 20.5 min and 19.0 min. respectively. The two points which fall the furthest from the straight line are both for filter runs with $C_S/C_F = 0.295$.

For the filter runs shown in Figure 33, $t_a = 138\ C_S^{-0.73}$. This equation was used to predict t_a for each of these filter runs. The predicted values of t_a and the observed values of β were used to calculate the head loss versus time curves for each of these filter runs. The results are shown in Figure 36. The empirical equation for predicting t_a gives excellent results.

Total Cost Calculations

The necessary steps for calculating the total cost of filtration for a particular combination of q, C_F, and H_t are outlined below. These steps are the same for both computer and manual calculation although for manual calculation some simplifying assumptions can be made. The costs are expressed in \$/month and units of pounds, feet, and hours are used. Sample calculations are included in Appendix F.

β index

The β index is calculated using Equation 33:

$$\beta = 10^{b_1}\ C_S^{b_2}\ C_F^{b_3} \qquad (33)$$

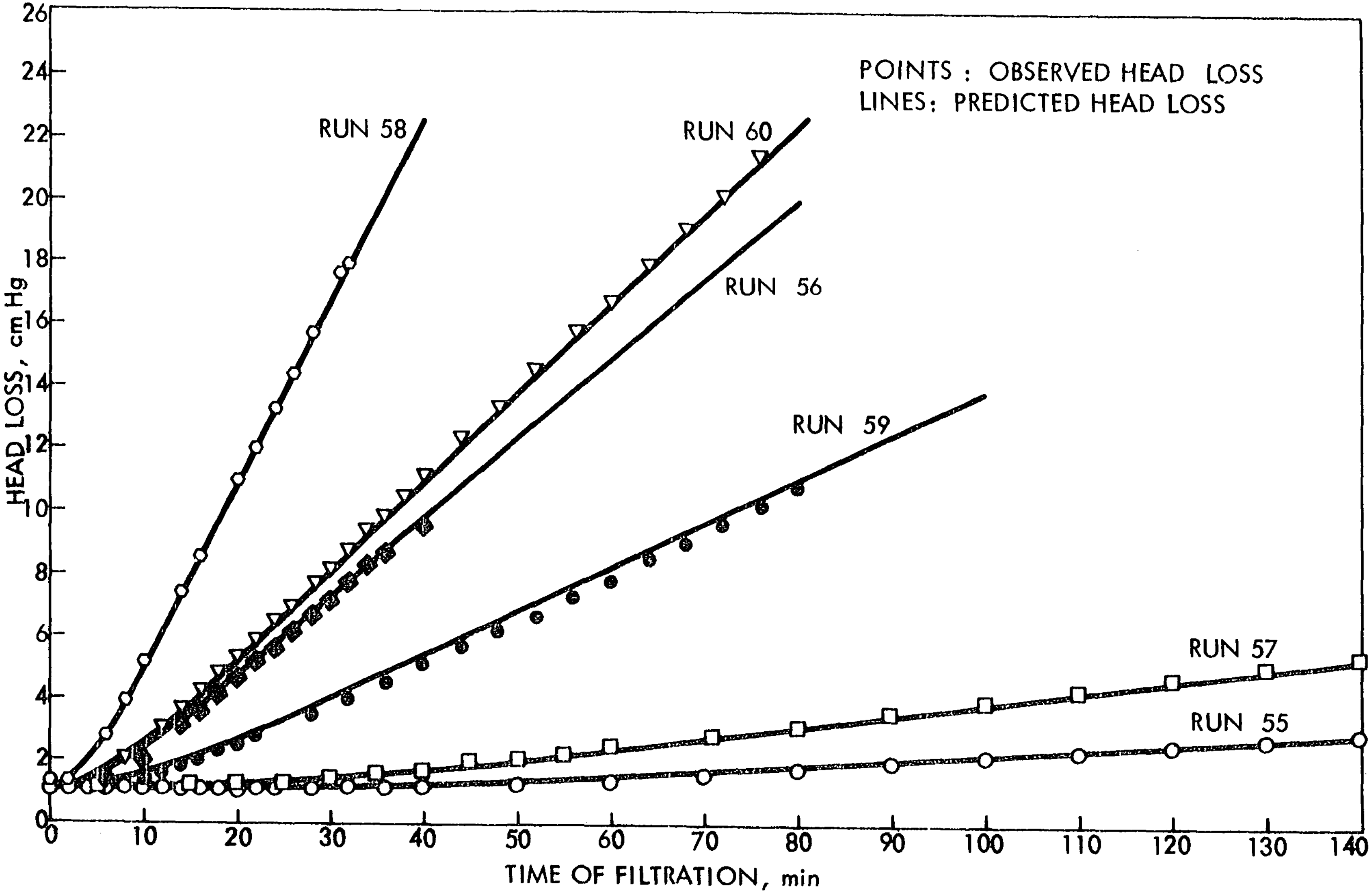
This equation is equivalent to Equation 15 by letting

Figure 36. Plots showing predicted head loss versus time curves and observed data for filtration runs with unsettled Ball Clay in distilled water using Hyflo Super-Cel as a filter aid at $C_S/C_F = 0.495$

Filter runs 55-60 in Appendix A, Table 32

Apparent detention time was predicted by the equation:

$$t_a = 138\ C_S^{-0.728}$$


POINTS : OBSERVED HEAD LOSS
LINES: PREDICTED HEAD LOSS
RUN 58
RUN 60
RUN 56
RUN 59
RUN 57
RUN 55
HEAD LOSS, cm Hg
TIME OF FILTRATION, min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

$b_2 = -b_3$ and to Equation 27 if b_2 is set equal to 0.

Filter run length - detention time considered

The head loss through the precoat layer is calculated from Equation 5:

$$H_p = q\nu\xi w/g \tag{5}$$

and the head loss through the filter cake is calculated as:

$$H_c = H_t - H_p \tag{40}$$

The head loss through the precoat is very small compared to the head loss through the filter cake. Therefore, for manual calculations, H_c can be considered equal to H_t.

By replacing X by $t - t_a$ in Equations 8 and 6, the length of the filtering cycle, t_f, can now be calculated as:

$$t_f = \frac{H_c}{\sigma} + t_a \tag{41}$$

for flat septa, and:

$$t_f = \frac{(e^{H_c\phi/R_s\sigma} - 1)\ R_o^2}{R_s\phi} + t_a \tag{42}$$

for cylindrical septa. The total length of the filter run is then equal to the length of the filtering cycle plus the estimated time required to backwash and precoat the filter.

Filter run length - detention time ignored

In order to include detention time in the filter run length, it is necessary to know the detention time for every value of filtration rate that is considered. The apparent detention time is thought to be due to 1) the detention time attributed to initial dilution in the filter housing, and 2) the detention time attributed to the time required for precoat plugging and cake formation. The detention time due to initial dilution is theoretically equal to V_f/Q. The flow rate, Q, is constant. However, the volume of the filter housing, V_f, will probably vary with the area of the filter septa and therefore, the filtration rate, q. According to the theory presented for developing Equation 39, the detention time due to precoat plugging and cake formation is inversely related to the filtration rate. No data are available to substantiate this.

It is doubtful that the apparent detention time is simply equal to the detention time due to initial dilution plus that due to precoat plugging and cake formation. The detention time due to precoat plugging and cake formation is probably a function of the initial dilution rate. Obviously, more research is needed before initial dilution and detention time will be fully understood.

Under optimum design condititions, filter run lengths are quite long. If the concentration of suspended solids is reduced the apparent detention time will be longer, but the optimum run length will also be increased. Also, the filter run length is only used to determine the number of filter runs per month which is needed for calculating the cost of precoat filter aid and the increase in filter area required to produce water used for backwashing. The cost of precoat filter aid and the cost ascribed to backwashing are usually a minor part of the total cost. They are only significant for very short filter runs which do not provide optimum conditions. Therefore, it is the opinion of this author that detention time can be ignored without seriously affecting the calculation of optimum design conditions. For example, the data collected by the author for a suspension of settled Ball clay in distilled water were used to develop the β prediction equation:

$$\beta = 10^{8.31} C_S^{2.12} C_F^{-2.17}$$

This equation was then used in the determination of the optimum design conditions for a 1 MGD plant and suspended solids concentrations of 3 mg/l (t_a=72.0 min), 20 mg/l (t_a=20.5 min), and 100 mg/l (t_a=7.2 min). The apparent detention times were taken from Figure 35 and identical calculations were also made with apparent detention times ignored (t_a=0). It was assumed that t_a varied inversely with q (Equation 39). The cost data presented by Dillingham (27) were used for these analyses and the results are presented in Table 11.

Table 11. Effect of apparent detention time on optimum design conditions

C_S mg/l	t_a min	Optimum conditions q	H_t	C_F	t_f hr	Total cost $/MG
3	72.0	1.60	30	14	17.9	34.2
	0.0	1.60	30	14	17.1	34.5
20	20.5	0.80	140	30	14.7	65.3
	0.0	0.80	140	30	14.3	65.7
100	7.2	0.40	150	110	9.7	145.8
	0.0	0.40	150	110	9.4	147.3

Neglecting the apparent detention time did not have any effect on the optimum design conditions that could be observed with the incremental values of q, H_t and C_F used (0.2 gpm/sq ft, 5 ft and 5 mg/ℓ, respectively). Therefore, the length of the filtering cycle can be calculated by assuming $t_a = 0$ and using Equation 41 for flat septa and Equation 42 for cylindrical septa. The total run length is again equal to the length of the filtering cycle plus the estimated time for backwashing and precoating.

Filter area

The filter area required can be calculated as:

$$\text{Area} = \frac{\text{QGPM}'}{q} \qquad (43)$$

where:

QGPM' = flow rate in gpm required to meet both demand and backwashing requirements

$$= \frac{\text{QMGD}' \times 10^6}{1440 - n(\text{BWT})}$$

where:

n = number of filter runs per day

$$= \frac{24 \text{ hr/day}}{\text{filter run length}}$$

BWT = time required per filter run for backwashing and precoating, hr

and:

QMGD' = flow rate in MGD required to meet both demand and backwashing requirements

$$= \text{QMGD} + \left(\frac{n\ (\text{Area})\ (\text{BWGSF})}{10^6}\right)$$

where:

QMGD = design flow rate in MGD required to meet demand requirements

BWGSF = amount of water required to backwash the filter in gal/sq ft of filter area

Since the filter area is dependent on QGPM' and QGPM' is dependent on the filter area, an iterative calculation process is called for. This can be done as follows:

1. Assume QMGD' = QMGD
2. Calculate QGPM'
3. Calculate Area
4. Calculate QMGD' and repeat steps 2 and 3

The above process is continued until the areas calculated in successive iterations do not differ by more than one percent. In most cases only two or three iterations will be required. More iterations are required when the filter run length is very short.

First cost

The total first cost can be calculated by multiplying the area by the first cost in \$/sq ft obtained from the plot of first cost versus filter area. The total cost should be multiplied by the rate factor if the filtration rate is different than that for which the first cost data were obtained. The first cost is amortized over the design life of the plant by the equation:

$$\text{CF per year} = \text{TFC}\left\{\frac{i[(1+i)^n - \text{SV}/100]}{(1+i)^n-1}\right\} \qquad (44)$$

and

$$\text{CF per month} = \frac{\text{CF per year}}{12}$$

where:

CF = amortized first cost, \$

TFC = total first cost, \$

i = interest rate

n = design life, yr

SV = salvage value, % first cost

Labor and maintenance cost

Both labor and maintenance costs are assumed to vary primarily with the filter area and are therefore combined. This cost can be calculated by multiplying the filter area by the cost of labor and maintenance in \$/sq ft per month obtained from the plot of labor and maintenance cost versus filter area. The cost should be multiplied by the rate factor if the filtration rate is different than that for which the labor and maintenance cost data were obtained.

Filter aid cost

The amount of precoat filter aid used in lb/month is equal to:

$$PFA = w(\text{Area})N \qquad (45)$$

where N is the number of filter runs per month and is equal to 24 hr/day x 30.4 days/month divided by the filter run length.

The amount of body feed filter aid used in lb/month is equal to:

$$BFA = C_F\ (QMGMO')\ 8.33 \qquad (46)$$

where QMGMO' is the flow rate in MG per month required to meet demand and backwashing requirements and is equal to QMGD' x 30.4 days/month.

The total cost of filter aid per month is then equal to:

$$CFA = \frac{PFA + BFA}{2000} \times \$/\text{ton} \qquad (47)$$

Power cost

The amount of power used per month can be calculated using Equation 29. If QMGMO' is used, the equation becomes:

$$P = \frac{QMGMO' \times H_t}{E} \left(\frac{8.33}{2.655}\right) \qquad (48)$$

The power cost per month then equals P multiplied by the unit cost in $/kwh.

Total and operating cost

The operating cost is calculated as:

$$COPER = CL + CM + CFA + CP \qquad (49)$$

and the total cost is:

$$CTOTL = CF + COPER \qquad (50)$$

POPO Program

A user manual for a computer program called Program for Optimization of Plant Operation or the POPO program is given in Appendix F. This program reads in all of the necessary filtration data and cost information and computes the total filtration cost for all desired combinations of q, H_t, and C_F. The 10 combinations which result in the lowest total costs are printed out along with other filtration and cost information. These results are computed and printed out for β indices equal to 50, 75, 100, 125, 150, and 175 percent of those predicted by the β prediction equation. Results for different percentages of the β index are included because the actual β may vary from the predicted value depending on the accuracy of the prediction equation and to indicate how the optimum design conditions may vary with changes that might occur in the characteristics of the filter influent.

An example of the manual calculation of the total filtration cost is also included in Appendix F.

Effects of Filtration and Cost Factors on Optimum Design Conditions

Several optimum design calculations were made using the POPO program to show how the optimum design conditions and total cost vary with certain filtration and cost factors. Those factors considered were:

1. Filter cake resistance
2. Filter aid cost
3. Suspended solids concentration

4. First cost
5. Power cost
6. Labor and maintenance cost

The design data shown in Table 12 were used for these analyses. The cost data used were obtained by Dillingham (27) from filter manufacturers and some existing filtration installations. These data were collected prior to 1965 and are presented here only for demonstration purposes.

Effect of filter cake resistance on optimum design conditions

From a review of the β prediction equations developed by Dillingham *et al*. (29) from data obtained by various investigators and those developed from recent data, it appears that the equation:

$$\beta = 10^{b_1} (C_S/C_F)^2$$

or

$$\beta = 10^{b_1} C_S^{\,2}\, C_F^{\,-2}$$

is appropriate for suspensions which do not exhibit concentration effects. Therefore, the relative cake resistance of these suspensions is indicated by the value of b_1. The range of values of b_1 that have been observed is from approximately 7.0 to 11.0 (i.e., the cake resistance exhibited by the most resistant suspension is about 10^4 times that exhibited by the least resistant suspension for the same

Table 12. Basic data used to study the effects of various factors on optimum design conditions

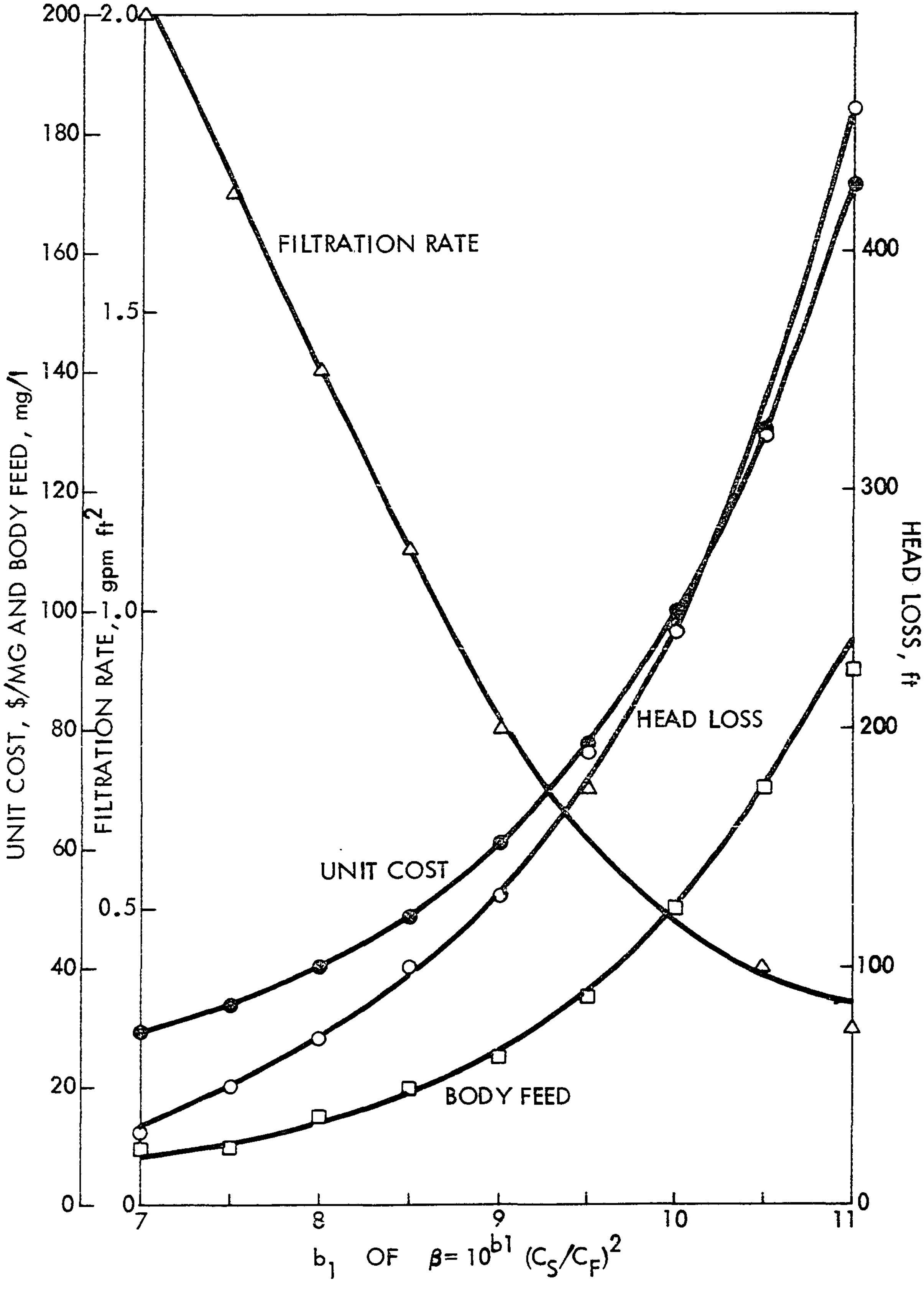
Design flow	1	MGD
Salvage value	15	percent first cost
Energy conversion	70	percent
Interest rate	4	percent
Plant life	25	years
Solids (C_S)	8	mg/l
ξ index	1.90×10^9	ft/lb
Temperature	60	°F
Precoat weight	0.10	lb/sq ft
Precoat density	20	lb/cu ft
Septum diameter	Flat	
Filter aid cost	100	$/ton
Power cost	2	cents/kwh
First cost	Area	$/sq ft
	100	225
	200	160
	350	128
	600	110
	1000	100
	2000	94
	25000	85
Labor & maint. cost	Area	$/sq ft/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
Backwashing cost	10 gal/sq ft	30 min

C_S/C_F ratio).

To show the effect of filter cake resistance, the optimum design conditions were computed for values of b_1 ranging from 7.0 to 11.0. The results are shown in Figure 37. It is observed that as the filter cake resistance increases, there is an exponential increase in the optimum body feed rate, terminal head loss, and total cost whereas the optimum filtration rate decreases. No limit was placed on the terminal head loss when making these calculations. In practice, the head loss is limited to about 150 ft. If head loss was limited to 150 ft in this example, the optimum design conditions for values of b_1 greater than 9.0 would be affected.

An estimate of the effect of an error in predicting β on the optimum design conditions can be obtained from Figure 37. For example, 15 filter runs were made using the SSCR filter (Appendix A, Table 32, filter runs 21-35) to determine the ability of the bench-scale filter to predict the results obtained with a large-scale pilot plant for the filtration of University tap water to which ferric chloride was added. The average difference between the values of β obtained with the SSCR filter and the pilot plant was 15 percent. This corresponds to a difference in the values of b_1 of only 0.06. From Figure 37, it is obvious that a 15 percent error in predicting the β index does not have any

Figure 37. Plots showing the effects of the relative cake resistance on optimum design conditions and total cost


UNIT COST, $/MG AND BODY FEED, mg/l
0
20
40
60
80
100
120
140
160
180
200
FILTRATION RATE, gpm ft^2
0
0.5
1.0
1.5
2.0
HEAD LOSS, ft
0
100
200
300
400
FILTRATION RATE
HEAD LOSS
UNIT COST
BODY FEED
7
8
9
10
11
b_1 OF $\beta = 10^{b1} (C_S/C_F)^2$

significant effect on the optimum design conditions.

Another observation that can be made from Figure 37 is the effect of the type and grade of filter aid on the optimum design conditions. Results presented by Baumann, et al. (8) for the filtration of University tap water plus ferric chloride (C_S approximately 8.0 mg/l) with 11 different types and grades of filter aids produced by 4 manufacturers were fitted to the equation $\beta = 10^{b_1} (C_S/C_F)^2$. The calculated values of b_1 are shown in Table 13. The values of b_1 for different grades of filter aid produced by any one manufacturer do not vary by more than 0.21. This small a change in b_1 does not cause very large changes in the optimum design conditions shown in Figure 37. Thus, the main factor which influences the filter cake resistance and the total cost is the filtering characteristics of the raw water. The total costs of filtering the various waters that have been studied at Iowa State University differ by as much as 500 percent whereas the largest difference in the total cost of filtering iron bearing water with different filter aids is about 30 percent. For a particular water, the type and grade of filter aid used is a significant factor. However, in future research, it may be more beneficial to study methods of reducing filter cake resistance by improving the filtering characteristics of the raw water rather than by improving the characteristics of filter aids.

Table 13. Values of b_1 of $\beta = 10^{b_1} (C_S/C_F)^2$ for the filtration of University tap water plus ferric chloride

Filter aid designation	b_1
S2	10.120
S3	10.259
S4	10.335
J4	10.290
J3	10.320
J0	10.399
E6	10.328
E5	10.496
E2	10.524
G4	10.452
G1	10.585

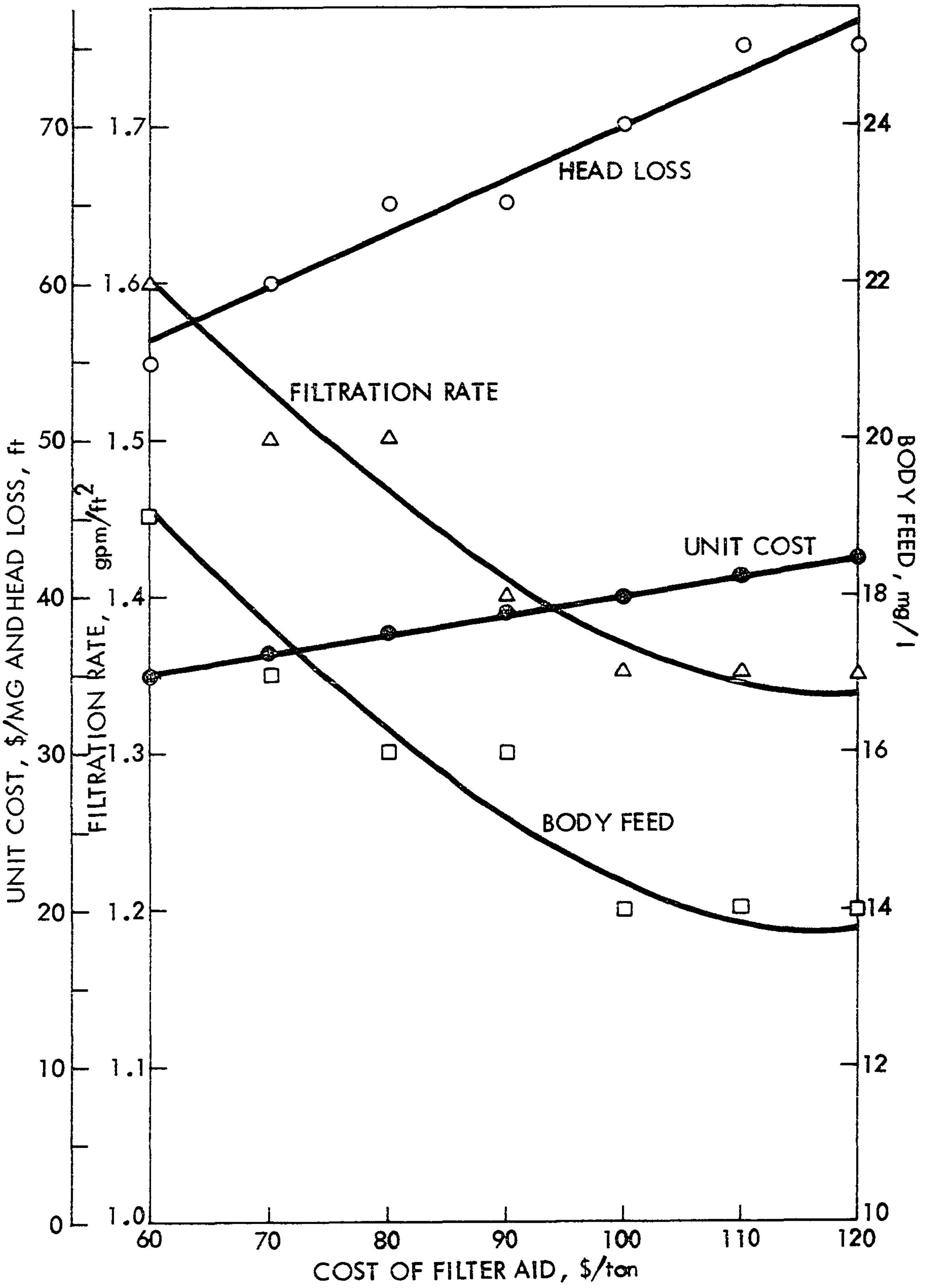
Effect of filter aid cost on optimum design conditions

The cost of filter aid is a significant portion of the total cost of precoat filtration and due to shipping costs, the unit price of filter aid may vary widely depending on the location of the proposed plant. To study the effect of filter aid cost, the optimum design conditions were determined for filter aid prices varying from \$60 to \$120 per ton. The data contained in Table 12 were used along with the β prediction equation:

$$\beta = 10^8 C_S^2 C_F^{-2}$$

As shown in Figure 38, the optimum head loss and total cost increase linearly with the unit cost of filter aid while the optimum filtration rate and body feed rate both

Figure 38. Plots showing the effects of filter aid cost on optimum design conditions and total cost


HEAD LOSS
FILTRATION RATE
UNIT COST
BODY FEED
UNIT COST, $/MG AND HEAD LOSS, ft
FILTRATION RATE, gpm/ft²
BODY FEED, mg/l
COST OF FILTER AID, $/ton
0
10
20
30
40
50
60
70
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
10
12
14
16
18
20
22
24
60
70
80
90
100
110
120

decrease. The effect of filter aid cost is much less than was expected. The optimum body feed rate decreased from 19 mg/l to about 14 mg/l and the total cost only increased from \$35/mg to about \$42/mg when the cost of filter aid was increased from \$60/ton to \$120/ton.

Effect of suspended solids concentration on optimum design conditions

For certain waters, the concentration of suspended solids in the filter influent will vary from season to season, day to day, or even from one hour to another. To study the effect of suspended solids concentration, the optimum design conditions for filtering an influent containing from 5 to 50 mg/l of suspended solids were determined. The data contained in Table 12 were used along with the β predicted equation:

$$\beta = 10^8 \, C_S^{\,2} \, C_F^{\,-2}$$

The optimum filtration rate decreased with increasing concentrations of suspended solids as shown in Figure 39. All other factors increased when suspended solids were increased. The proportional increase in the optimum body feed rate was less than the proportional increase in the concentration of suspended solids. In this example, C_S/C_F increased from 0.42 at C_S = 5 mg/l to 1.25 at C_S = 50 mg/l.

It has been stated as a rule-of-thumb that for a particular water there is a certain ratio of C_S/C_F that should be maintained for optimum operation. The results shown here indicate that this is not true.

Effect of cost factors on optimum design conditions

The effect of the price of filter aid on optimum design conditions has previously been discussed. Other cost factors which will vary with time and location are first cost and power, labor and maintenance costs. To study the effect of these cost factors two cases were considered:

Case 1. The filtration of effluent from the lime-soda ash softening process. The β prediction equation for this water:

$$\beta = 10^{10.20}\ C_S^{1.43}\ C_F^{-3.29}$$

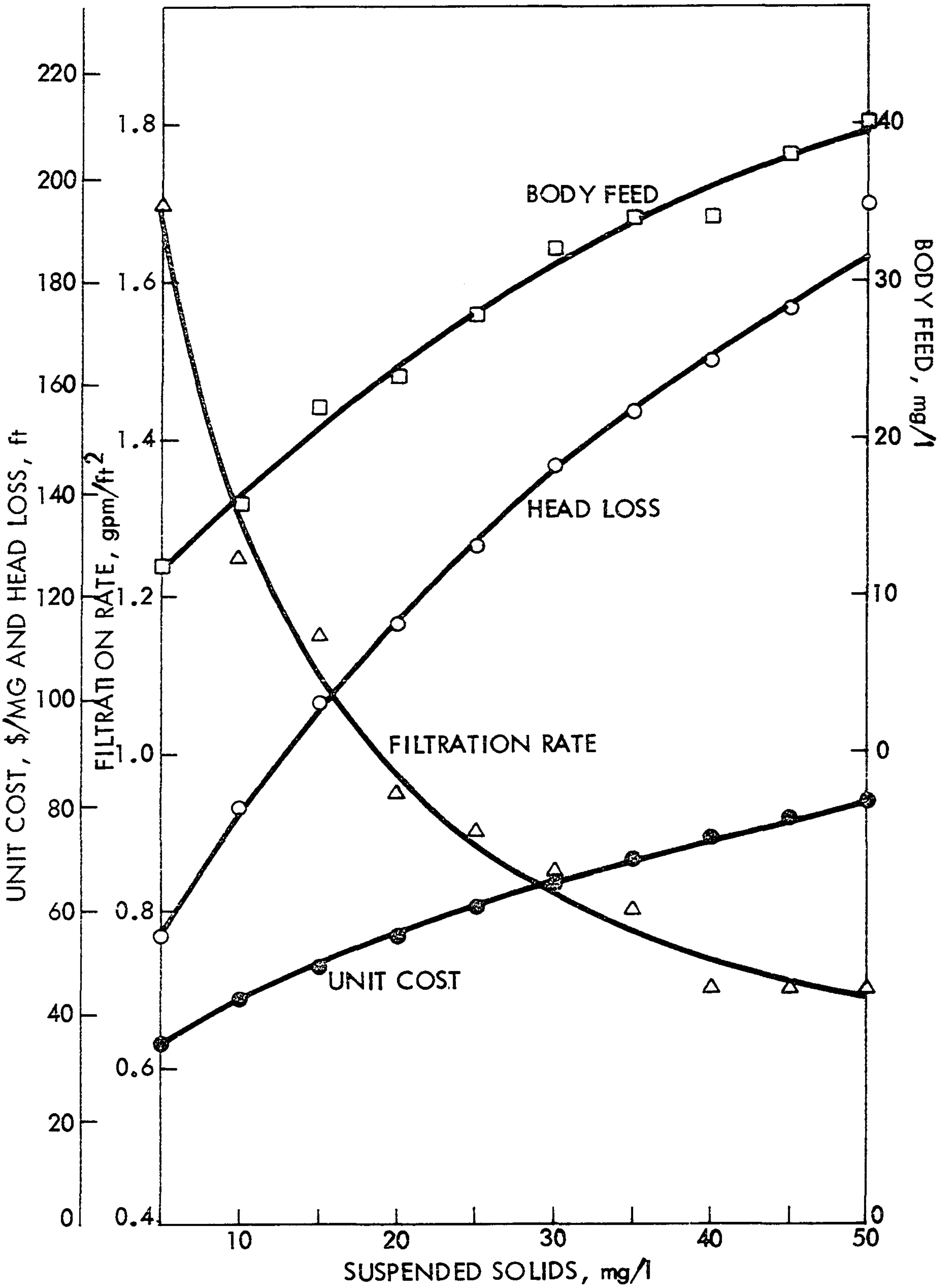
was developed by Dillingham (27) from data collected at Lompoc, California. Celite 503 filter aid was used at a price of \$69/ton.

Case 2. The filtration of iron-bearing water. The β prediction equation for this water:

$$\beta = 10^{9.33}\ C_S^{1.95}\ C_F^{-1.95}$$

was developed from data collected by Hall (35) for the filtration of University tap water with ferrous sulfate added. Celite 503 was used at a price of \$100/ton.

Figure 39. Plots showing the effects of suspended solids concentration on optimum design conditions and total cost


UNIT COST, $/MG AND HEAD LOSS, ft
0
20
40
60
80
100
120
140
160
180
200
220
FILTRATION RATE, gpm/ft²
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
BODY FEED, mg/l
0
10
20
30
40
BODY FEED
HEAD LOSS
FILTRATION RATE
UNIT COST
SUSPENDED SOLIDS, mg/l
10
20
30
40
50

These cases were considered because for Case 1 the optimum head loss is well below the practical limit of 150 ft. For Case 2 the optimum head loss is limited by the 150 ft practical limit. Optimum design calculations were made with the first cost and labor and maintenance cost the same as and twice the values given in Table 12 and with power costs of 1.5 ¢/kwh and 3.0 ¢/kwh. These calculations were made at all possible combinations of first, power, and labor and maintenance costs so that 8 optimum design conditions were determined for each case. The incremental values of q, H_t, and C_F were 0.1 gpm/sq ft, 5 ft, and 5 mg/l, respectively.

The results of these calculations are presented in Table 14 for Case 1 and in Table 15 for Case 2. In general doubling the first, power, and labor and maintenance costs does not cause a very large change in the optimum design conditions. Unless a very small incremental value for q, H_t, or C_S were used, no change in the respective optimum would be observed. However, it can be concluded from these results that:

A. Increasing the power cost

   1. Decreases the optimum q
   2. Decreases the optimum H_t
   3. Increases the optimum C_F
   4. Increases the total cost

Table 14. Effect of first, power, and labor and maintenance costs on the optimum design conditions for the filtration of lime-soda ash process effluent

First cost	LM -- Labor and maintenance cost	2LM
	Power cost --------- 1.5 ¢/kwh	
F	(2.5, 55, 30; 26.1)[a]	(2.8, 60, 30; 31.5)
2F	(3.1, 60, 30; 31.2)	(3.2, 65, 30; 36.4)
	Power cost -------- 3.0 ¢/kwh	
F	(2.0, 35, 30; 28.9)	(2.5, 35, 35; 34.5)
2F	(2.8, 35, 35; 34.3)	(3.1, 40, 35; 39.7)

[a] (Filtration rate, Head loss, Body feed; Unit Cost)
gpm/sq ft ft mg/l $/MG .

Table 15. Effect of first, power, and labor and maintenance costs on the optimum design conditions for the filtration of iron bearing water

First cost	LM -- Labor and maintenance cost	2LM
	Power cost ---------- 1.5 ¢/kwh	
F	(0.7, 150, 40; 73.3)[a]	(0.8, 150, 45; 88.2)
2F	(0.9, 150, 45; 88.0)	(0.9, 150, 45; 101.7)
	Power cost --------- 3.0 ¢/kwh	
F	(0.7, 140, 40; 83.5)	(0.8, 150, 45; 98.5)
2F	(0.9, 150, 45; 98.3)	(0.9, 150, 45; 112.1)

[a] (Filtration rate, head loss, body feed; unit cost)
gpm/sq ft ft mg/l $/MG .

B. Increasing the first cost

  1. Increases the optimum q
  2. Increases the optimum H_t
  3. Increases the optimum C_F
  4. Increases the total cost

C. Increasing labor and maintenance costs

  1. Increases the optimum q
  2. Increases the optimum H_t
  3. Increases the optimum C_F
  4. Increases the total cost

APPLICATIONS

Variable Water Quality Situation

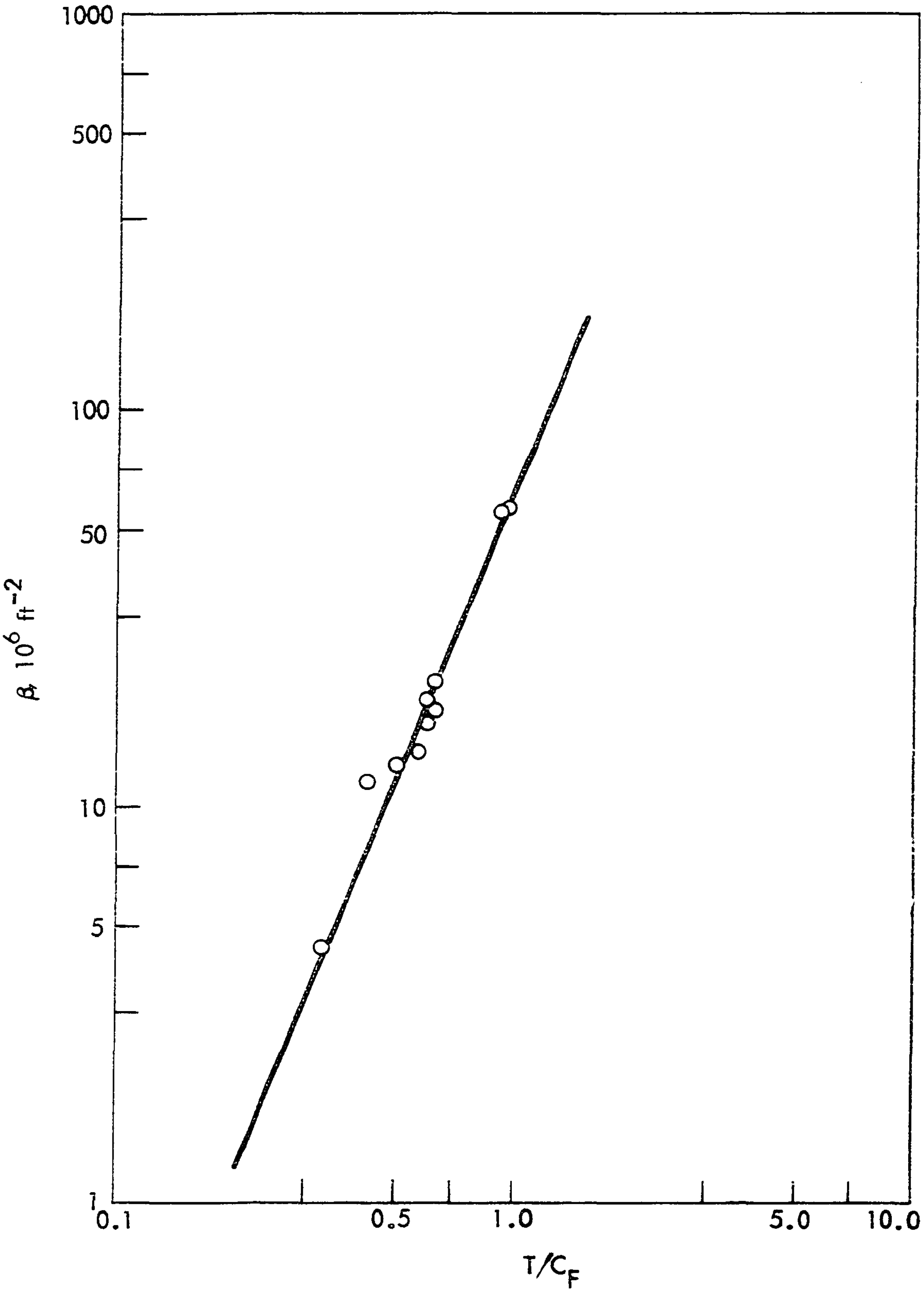
Figures 16-19 (pp. 80-82) show how the temperature and turbidity of the water in the Des Moines River near Boone, Iowa, vary during the year. If a precoat filter was to be used to filter this water, the temperature and turbidity used for making the optimum design calculations should be chosen so that the annual cost of filtration will be minimized. To study how the annual cost of filtering water from the Des Moines River is affected by the design temperature and design turbidity, it was assumed that the filter cake resistance prediction equation:

$$\beta = 10^{7.80} \; (T/C_F)^{2.43}$$

would be applicable. This β prediction equation was developed with data gathered from filter runs made with raw water from the Missouri River at Council Bluffs, Iowa, using Hyflo Super-Cel as filter aid (Appendix A, Table 28). The plot of log β versus log T/C_F for these filter runs is shown in Figure 40. The head loss versus time curve became exponential, indicating that a compressible cake was formed, when the T/C_F ratio was greater than 1.5. Therefore, the minimum value of C_F used in all design calculations was chosen so that the maximum value of T/C_F considered would be less than or equal to 1.5. All optimum design and optimum operation calculations

Figure 40. Log β versus log T/C_F for raw water from the Missouri River at Council Bluffs, Iowa

Hyflo Super-Cel filter aid


1000
500
100
50
10
5
1
β, 10⁶ ft⁻²
0.1
0.5
1.0
5.0
10.0
T/C_F

were made with the ξ index, in-place bulk density and cost of Hyflo Super-Cel equal to 5.2×10^9 ft/lb, 20.7 lb/cu ft and $90/ton, respectively. Other cost data are shown in Table 12.

First of all, optimum design calculations were made with the design turbidity equal to the mean turbidity of 30 JTU and with the design temperature varied from 0 to 30° C. The results of these calculations are shown in Table 16. From these results it was concluded that the design temperature does not have a very large effect on the optimum design conditions. Therefore, the main factor affecting the annual cost of filtering this water will be the design turbidity.

Table 16. Effect of design temperature on optimum design conditions (Influent turbidity = 30 JTU)

Temperature (°C)	(°F)	Optimum Filtration rate (gpm/sq ft)	Optimum Terminal head loss (ft)	Optimum Body feed rate (mg/l)
0	32	0.9	120	40
5	41	0.9	120	35
10	50	0.9	110	35
15	59	1.0	110	35
20	68	1.0	105	35
25	77	1.0	105	30
30	86	1.0	100	30

Next, calculations were made to determine the optimum design conditions at various design turbidities ranging from 5 to 100 JTU. The mean water temperature of 12° C was used as the design temperature in all of these calculations. The results shown in Table 17 indicate the large effect the design turbidity has on the optimum design conditions.

Table 17. Effect of design turbidity on optimum design conditions (Water temperature = 12°C)

Design Turbidity (JTU)	Optimum Filtration rate (gpm/sq ft)	Optimum Terminal head loss (ft)	Optimum Body feed rate (mg/l)
5	1.9	45	10
10	1.6	60	20
20	1.2	90	30
30	1.0	115	35
40	0.9	140	40
50	0.8	150 (maximum	50
60	0.7	150 permissible	55
70	0.6	150 head loss)	60
80	0.6	150	65
90	0.5	150	70
100	0.5	150	80

Table 17 lists the optimum design conditions for a precoat filtration plant designed for continuous operation at each of several turbidities. An actual plant must be designed using only one set of these optimum conditions. In general, the plant will operate at turbidity levels different than that used in optimizing the plant design. In such a plant, the flow rate and head loss would be fixed in the design and only the body feed rate can then be reoptimized when the turbidity level changes.

Optimum operation calculations for various design turbidities were then made with several sets of design data from Table 17 to determine the optimum body feed rate and minimum filtration cost for influent turbidities varying from 5 to 100 JTU. For example, if the design turbidity is 30 JTU, the filter would be designed to operate at a filtration rate of 1.0 gpm/sq ft and with a terminal head loss equal to 115 ft (Table 17). Optimum operation calculations for several other levels of turbidity were made, therefore, with the filtration rate equal to 1.0 gpm/sq ft and the terminal head loss equal to 115 ft. The results for this example are shown in Table 18.

Table 18. Optimum operating conditions at various influent turbidities (Design turbidity = 30 JTU and design temperature = 12° C)

Influent turbdiity (JTU)	Optimum Operating Body feed rate (mg/l)	Unit cost ($/MG)
5	5	38.5
10	10	42.3
20	25	50.0
30	35	58.0
40	50	66.5
50	60	75.2
60	75	84.4
70	90	93.9
80	105	103.8
90	120	114.1
100	135	124.7

The effect of the design turbidity on the filtration cost at various influent turbidities is shown in Figure 41. As the difference between the influent turbidity and the design turbidity increases, the difference between the filtration costs for optimum operation and optimum design also increases. If the design turbidity is very low, the difference between the filtration costs for optimum operation and optimum design are very large at high turbidities. This is due to the extremely short filter run lengths which result when a filter is designed for a low turbidity but operated at a high turbidity.

The annual cost of filtration was calculated for each design turbidity. An example of how annual cost calculations were made is shown in Table 19. The number of weeks shown in column 2 of Table 19 were determined from the frequency distribution diagram shown in Figure 19. For example, the turbidity was between 0 and 5 JTU in 13 of the weekly samples, between 5 and 10 JTU in 8 of the weekly samples, etc. It was assumed that the turbidity was 5 JTU for 13 weeks, 10 JTU for 8 weeks, etc. This assumption causes the calculated annual costs to be larger than the actual cost would be if optimum operating conditions were maintained at all times. However, in an actual situation it is doubtful that optimum operating conditions would be maintained at <u>all</u> times.

Figure 41. Plots showing the effects of design turbidity on the unit cost of filtration at various influent turbidities

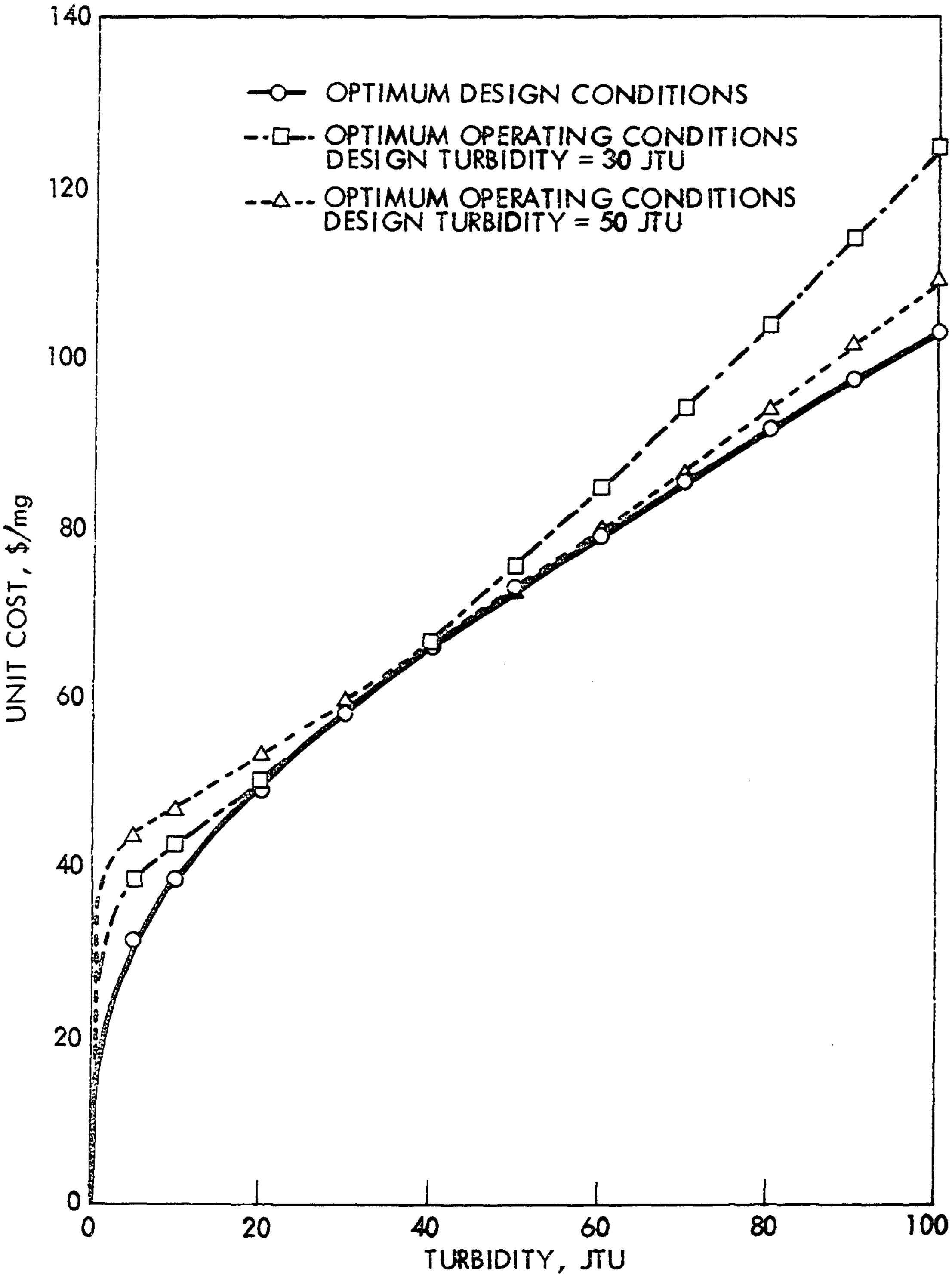

OPTIMUM DESIGN CONDITIONS
OPTIMUM OPERATING CONDITIONS DESIGN TURBIDITY = 30 JTU
OPTIMUM OPERATING CONDITIONS DESIGN TURBIDITY = 50 JTU
UNIT COST, $/mg
0
20
40
60
80
100
120
140
TURBIDITY, JTU
0
20
40
60
80
100

Table 19. Example calculation of the annual cost of filtration (Design turbidity = 30 JTU)

(1) Influent turbidity (JTU)	(2) Number of weeks	(3) Optimum operating cost ($/MG)	(4) (2) x (3) (weeks x $/MG)
5	13	38.5	500.5
10	8	42.3	338.4
15	17	46.3	787.1
20	6	50.0	300.0
25	10	54.1	541.0
30	11	58.0	638.0
35	4	62.4	249.6
40	8	66.5	532.0
45	3	71.0	213.0
50	6	75.2	451.2
55	3	80.1	240.3
60	2	84.4	168.8
65	1	89.2	89.2
70	4	93.9	375.6
75	1	99.1	99.1
80	2	103.8	207.6
85	2	109.0	218.0
90	0	114.1	0.0
95	3	119.2	357.6
100	0	124.7	0.0
	Σ = 104 weeks = 2 years		Σ = 6307.0

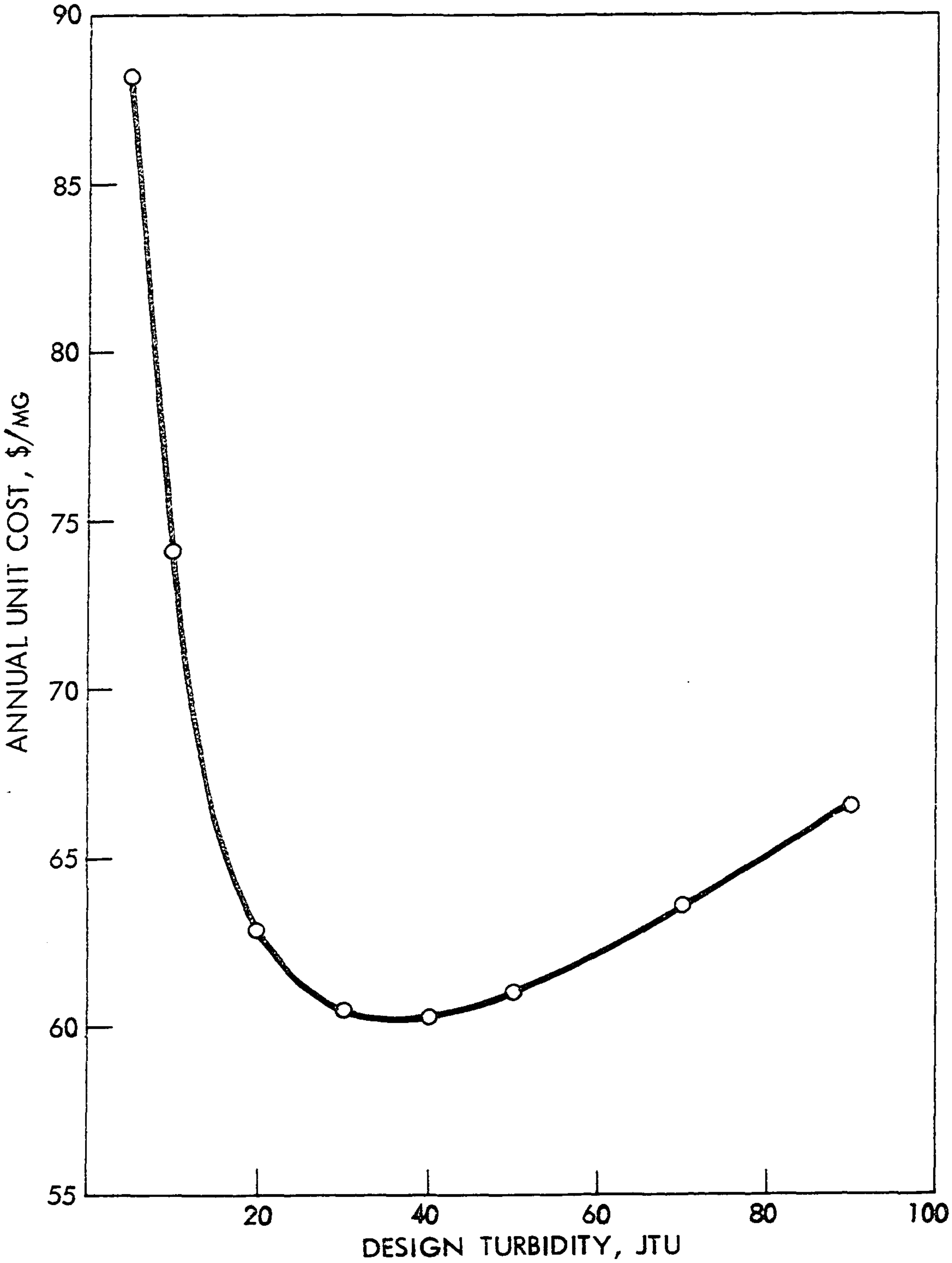
6307.0 weeks ($/MG) x 7 MG/week ÷ 2 yr = $22,075/yr

$22,075/yr ÷ 365 MG/year = <u>$60.5 per MG</u>

Figure 42 is a plot of the annual unit cost of filtration versus the design turbidity. The shape of the frequency distribution diagram for turbidity (Figure 19) might lead one to predict that the optimum design turbidity

Figure 42. Annual unit cost of filtration versus the design turbidity

Raw water from the Des Moines River near Boone, Iowa


90
85
80
75
70
65
60
55
20
40
60
80
100
ANNUAL UNIT COST, $/MG
DESIGN TURBIDITY, JTU

would be less than the mean turbidity of 30 JTU. However, from Figure 42 the optimum design turbidity is about 40 JTU. The optimum design turbidity is higher than might be expected because of the short filter runs and high costs that result when a filter designed for a low turbidity is operated at a high turbidity. Another observation from Figure 42 is that using a design turbidity that is too low has a more adverse effect than using a design turbidity that is larger than the optimum.

Pretreatment of Raw Water

It would be economical to pretreat a water prior to filtering if the cost of filtering the pretreated water plus the cost of pretreatment is less than the cost of filtering the raw water. Precoat filtration data have been collected using Celite 535 filter aid with both raw and pretreated water from an impounding reservoir at Albia, Iowa. All of the filter runs were made using a U.S. Army mobile water treatment unit. The pressure filter in this unit contains 3.5 - inch diameter septa which comprise a total surface area of 10 sq ft. The filter is described in detail by Bridges (15).

The data obtained with pretreated water have been reported previously (15) and are summarized in Appendix A (Table 27). The water was pretreated in the city treatment plant. Pretreatment consisted of coagulation and settling in a solids contact type upflow clarifier with coagulant dosages of 26 mg/l of alum and 26 mg/l of lime when the raw water turbidity was approximately 10 JTU. Due to carryover of floc from the clarifier, the turbidity of the pretreated water averaged approximately 6 JTU. Data obtained with the raw water were collected when the average turbidity was 10 JTU (Appendix A, Table 28, filter runs 1-10).

β prediction equations were determined to be:

$$\beta = 10^{9.27} (T/C_F)^{1.74}$$

for the pretreated water, and:

$$\beta = 10^{8.75} (T/C_F)^{1.88}$$

for the raw water. At the same ratio of turbidity to body feed rate, the filter cake resistance for the pretreated water was 4 to 6 times the filter cake resistance for the raw water. Thus, for this water, the value of pretreatment is to reduce the turbidity of the filter influent.

The optimum design conditions and filtration cost were computed for both the raw and pretreated water at various influent turbidities. These results are listed in Table 20. All calculations were made with the ξ index, in-place bulk density and cost of Celite 535 equal to 1.9×10^9 ft/lb, 19.9 lb/cu ft and \$98 per ton, respectively. Other design data are shown in Table 12. The total cost of pretreatment was determined to be \$15.4 per MG. This figure was calculated using the following cost data:

lime . . . . \$22 per ton

alum . . . . \$80 per ton

clarifier . . . . . .\$26,500 first cost

From the unit cost figures listed in Table 20, it is evident that if the raw water turbidity was 10 JTU, it would not be economical to pretreat the water unless the turbidity

Table 20. Optimum design conditions for the filtration of raw and pretreated water at Albia, Iowa

Influent turbidity (JTU)	Optimum filtration rate (gpm/sq ft)	Optimum head loss (ft)	Optimum body feed rate (mg/l)	Unit cost[a] (\$/MG)
		Raw Water		
10	1.0	105	50	63.1
30	0.7	150	150	119.5
		Pretreated Water		
1	1.5	60	10	51.1
2	1.2	85	14	59.1
3	1.0	110	16	65.4
4	0.9	120	20	70.4
5	0.9	145	22	75.4
6	0.8	150	24	79.7
7	0.7	150	26	83.7

[a] Includes the cost of pretreatment.

of the pretreated water was 2 JTU or less. It is assumed that an acceptable filter effluent is obtained with either raw or pretreated water. The turbidity of the pretreated water from the city treatment plant was high (6 JTU) because of floc carryover caused by intermittent operation of the clarifier. Jar tests with the raw water showed that if the clarifier was operated properly, the turbidity could be reduced to less than 1.5 JTU using 20 to 30 mg/l of alum.

If the turbidity of the raw water was 30 JTU, it would be economical to pretreat the water even if the turbidity of the pretreated water was greater than 6 JTU (Table 20).

Backwash Waste Disposal

The method chosen for disposal of the backwash waste from a precoat filtration plant will depend upon local conditions such as availability and cost of land for dewatering and land fill facilities, the sewage treatment system and method of sludge disposal, the loading that the backwash waste would present on the sewage collection and treatment facilities, etc. The spent filter aid from swimming pool filters is often discharged directly to the sewer. Since this represents only a small proportion of the total sewage flow, no significant problems in the sewage collection or treatment systems have been observed (lb, p. 6). If the backwash waste represents a sizable loading on the sewage collection and treatment systems, problems may result from clogging of the sewers and abrasion of pumps and other mechanical equipment. If sewage sludge is treated by anaeroerobic digestion, the spent filter aid will occupy digestion tank space needed for organic materials, thus reducing digestion efficiency. However, if the sewage sludge is dewatered by vacuum filtration, the spent filter aid may be beneficial for increasing the porosity of the sludge cake.

In general, it is recommended that backwash wastes be dewatered in a settling lagoon or tank and then disposed of by land fill. This method is used by most of the existing precoat filtration plants. Since waste filter aid has a tendency to shrink under loading, no land fill site should be contemplated for building purposes unless the deposits are compacted in a controlled manner (lb, p. 10).

SUMMARY AND CONCLUSIONS

The long-term goal of the research in precoat filtration at Iowa State University has been to provide a scientific basis for the optimum design of precoat filters for municipal applications. To realize this goal it was necessary to develop:

1. A theory to predict filter performance in terms of filter run constants (filtration rate, water temperature, etc.) and the filtrability characteristics of the filter influent.

2. The means of predicting the filtrability characteristics of the filter influent.

3. A method of employing the theory to optimize filter design.

The theory of precoat filtration and the methods for predicting filter cake resistance and optimizing filter design were developed in studies made by LaFrenz (43) and Dillingham (27). Further studies have been made to determine the applicability of the theory for the filtration of water containing various types of suspended solids, to determine the characteristics of different types and grades of filter aids, and to determine the applicability of the method of predicting filter cake resistance for these waters and filter aids.

The objectives of this study were basically two-fold. The first and primary objective was to outline the procedures for determining the optimum design conditions of a proposed precoat filtration plant. These procedures include collection of filtration and cost data, reduction of the data and development of equations for predicting filter cake resistance, and calculation of the optimum design conditions.

The second objective was to review and summarize the research on which the method of optimizing the design of precoat filters is based. The goals of this review were to define the limitations of the present theory of precoat filtration and to determine what improvements could be made in the theory and method of predicting filter cake resistance.

Based on the review of previous research and the results presented in this study, the following significant conclusions can be made.

1. The filtration data necessary for optimizing the design and/or operation of a precoat filtration plant can be collected using a small-scale, constant-rate filter (SSCR filter). Results from this study indicate that the SSCR filter may be used to determine both the filtrability characteristics of the filter influent and the quality of the filter effluent.

2. The filter cake resistance indicated by the β index can best be predicted by the equation:

$$\beta = 10^{b_1} C_S^{b_2} C_F^{b_3} \qquad (33)$$

To develop such an equation to predict β for filtering a particular water, it is necessary to collect filtration data with significant variation in both the suspended solids concentration and the rate of body feed. If the suspended solids concentration of the filter influent is expected to remain constant at the value for which the filtration data is collected, the equation:

$$\beta = 10^{b_1} C_F^{b_2} \qquad (27)$$

is applicable. The β prediction equation:

$$\beta = 10^{b_1} (C_S/C_F)^{b_2} \qquad (15)$$

is valid only under the assumption (which is frequently invalid) that the value of β is the same for equal ratios of suspended solids concentration to body feed concentration (i.e. no concentration effects).

3. The apparent detention time observed during the initial stages of a precoat filter run is due to both initial dilution of the filter influent in the filter housing and the time required for a filter cake to form. From the results gathered in this study, the apparent detention time is inversely proportional to the concentration of suspended solids in the filter influent and has little, if any, dependence on

the amount of body feed. Theoretically, the apparent detention time is also inversely related to the filtration rate.

4. The apparent detention times observed in this study have no significant effect on the calculated optimum design conditions and can therefore be ignored when optimum design calculations are made.

5. The theory of precoat filtration is limited to filtration through incompressible filter cakes. Therefore, optimum design calculations are limited by the lowest body feed rate which results in the formation of an incompressible filter cake.

6. The main factors which determine the optimum design conditions of a precoat filter are the concentration and filtrability characteristics of the suspended solids in the filter influent. Therefore, the determining factor of the optimum design conditions is the design water quality and the main criteria for selecting the type and grade of filter aid is the quality of filter effluent that is produced.

7. The digital computer is a valuable tool for reducing filtration data and calculating the optimum design conditions for precoat filtration plants. However, all of the computations necessary for design a precoat filtration plant can be done manually in a reasonable time period.

8. Pretreating a water by coagulating and settling may

increase the specific resistance of the filter cake formed during precoat filtration. However, it may still be economical to pretreat the water if the suspended solids concentration of the pretreated water is significantly less than the suspended solids concentration of the raw water.

RECOMMENDATIONS

Based on the results of this and previous studies it is recommended that the procedures outlined in this dissertation be used to optimize the design of proposed precoat filtration plants and to optimize the operation of precoat filtration plants now in operation. It is further recommended that:

1. An investigation be undertaken to determine the ability of the SSCR filter to predict filter cake resistance and effluent quality at several precoat filter installations now in operation. The collection of accurate filtration data at the proposed plant site is an important prerequisite for the design of a precoat filtration plant and an investigation of this type would definitely prove the value of the SSCR filter for collecting the required filtration data.

2. The effects of suspended solids concentration, body feed rate, filtration rate, and filter aid grade on apparent detention time should be studied in more detail. It is suggested that filter runs be made using the SSCR filter and a suspension known to exhibit a wide range of apparent detention times with different suspended solids concentrations. Several series of filter runs could be made with C_S, C_F, q, or the grade of filter aid as the only variable to determine the effect of each individual variable on the apparent

detention time.

3. A study be made to determine if the filtrability characteristics, as indicated by the β prediction equation, of surface waters show annual variations.

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APPENDIX A

Summary of Precoat Filtration Data

A summary of the data from almost all of the precoat filter runs made by researchers at Iowa State University are contained in this appendix. The data are identified by:

1) Name of the researcher
2) Filter used
3) Water filtered
4) Dates, inclusive, during which the filter runs were made

The filter aid identification system used is listed in Table 21. Different bags of the same filter aid are indicated

Table 21. Filter aid identification system

Manufacturer	Grade of filter aid	Identification system designation
Sil-Flo Corp.	272[a]	S2
	332[a]	S3
	443[a]	S4
Johns-Manville Products Corp.	Hyflo Super-Cel	HFC
	Celite 503	J0
	Celite 535	J3
	Celite 545	J4
Eagle-Picher Industries, Inc.	FW-60	E6
	FW-50	E5
	FW-20	E2
Great Lakes Carbon Corp. (Dicalite)	4200	G4
	Speedex	G1

[a] Perlite filter aids. All other filter aids are diatomite.

by a bag identification number attached to the filter aid designation. For example, a filter aid identified with designation J3-12 would be a filter aid taken from bag 12 of a Celite 535 shipment.

Table 22. LaFrenz's pilot plant data (43)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
LAFRENZ	LABORATORY PILOT PLANT - SERIES 1			UNIVERSITY TAP WATER PLUS FERROUS SULFATE					8/4/60 - 11/22/60
1A	J3	1	58.0	7.0	0.24	76	850.3	99.304	TRIAL RUN
1	J3	1	58.3	7.4	0.37	80	534.1	99.965	
2	J3	1	57.7	7.3	0.74	0	---	---	EXPONENTIAL HEAD LOSS CURVE
3	J3	1	58.6	7.0	0.23	100	438.5	99.824	
4	J3	1	59.2	7.8	0.30	50	1793.5	99.969	
5	J3	1	58.5	7.4	0.28	93.5	500.8	99.800	
6	J3	1	59.0	7.4	0.24	150	229.7	99.594	
7	J3	1	58.0	7.2	0.29	57.2	997.6	99.766	
8	J3	1	58.8	7.4	0.37	106	267.8	99.940	
9	J3	1	59.2	7.8	0.54	125	---	---	VOID ** INFLUENT STOPPED DURING RUN
10	J3	1	58.4	7.6	0.26	200	106.5	99.666	
11	J3	1	58.6	7.7	0.39	300	59.16	99.705	
12	J3	1	58.4	7.8	0.08	35	---	---	EXPONENTIAL HEAD LOSS CURVE
13	J3	1	58.0	7.6	0.75	35	---	---	EXPONENTIAL HEAD LOSS CURVE
14	J3	1	59.5	7.2	0.55	35	---	---	EXPONENTIAL HEAD LOSS CURVE
15	J3	1	60.2	7.4	0.41	70	803.5	99.864	PRECOATED WITH DIRTY WATER
LAFRENZ	LABORATORY PILOT PLANT - SERIES 2			UNIVERSITY TAP WATER PLUS FERROUS SULFATE					12/1/60 - 12/14/60
1	J3	1	59.0	7.4	0.48	10	---	---	EXPONENTIAL HEAD LOSS CURVE
2	J3	1	59.6	7.8	0.30	20	---	---	EXPONENTIAL HEAD LOSS CURVE
3	J3	1	60.0	7.5	0.18	30	---	---	EXPONENTIAL HEAD LOSS CURVE
4	J3	1	60.0	7.3	0.19	40	1885.7	99.905	
5	J3	1	60.0	7.4	0.25	50	1281.1	99.666	
6	J3	1	60.0	7.5	0.20	60	910.3	99.650	
7	J3	1	60.0	7.5	0.18	80	562.9	99.852	
8	J3	1	60.0	7.2	0.18	100	319.9	99.765	
9	J3	1	60.0	7.1	0.22	120	259.5	99.602	

Table 23. LaFrenz's variable head permeameter data (43)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
LAFRENZ	VARIABLE HEAD PERMEAMETER - SERIES 1				UNIVERSITY TAP WATER PLUS FERROUS SULFATE				8/12/60 - 11/18/60
1	J3	1	---	---	---	80	---	---	TRIAL RUN ** NO DATA
2	J3	1	---	---	---	0	---	---	TRIAL RUN ** NO DATA
3	J3	1	---	---	---	0	---	---	TRIAL RUN ** NO DATA
4	J3	1	64.0	7.7	0.14	100	803.7	99.993	
5	J3	1	63.5	7.9	0.05	50	1925.2	99.848	
6	J3	1	68.0	7.5	0.53	0	---	---	EXPONENTIAL HEAD LOSS CURVE
7	J3	1	64.0	7.3	0.07	120	635.7	99.878	
8	J3	1	61.0	7.2	0.07	150	354.9	99.823	
9	J3	1	60.0	7.5	0.05	80	997.4	99.947	
10	J3	1	61.0	7.4	0.04	80	862.2	99.917	
11	J3	1	66.4	7.6	0.07	20	---	---	EXPONENTIAL HEAD LOSS CURVE
12	J3	1	67.9	7.7	0.07	200	129.9	99.781	
13	J3	1	65.2	7.7	0.04	400	36.41	99.859	
14	J3	1	62.6	7.9	0.04	800	24.73	99.850	
15	J3	1	65.3	7.2	0.27	10	---	---	EXPONENTIAL HEAD LOSS CURVE
16	J3	1	64.8	7.4	0.03	50	2074.7	99.955	
17	J3	1	63.0	7.4	0.07	35	---	---	EXPONENTIAL HEAD LOSS CURVE
18	J3	1	64.3	7.4	0.05	35	---	---	EXPONENTIAL HEAD LOSS CURVE
19	J3	1	62.2	7.4	0.05	35	---	---	EXPONENTIAL ** CONTINUOUS BODY FEED
20	J3	1	67.4	7.4	0.05	35	---	---	EXPONENTIAL ** CONTINUOUS BODY FEED
21	J3	1	60.4	7.2	0.09	35	3076.5	99.840	CONTINUOUS BODY FEED
22	J3	1	60.2	7.5	0.05	70	965.0	99.846	CONTINUOUS BODY FEED
LAFRENZ	VARIABLE HEAD PERMEAMETER - SERIES 2				UNIVERSITY TAP WATER PLUS FERROUS SULFATE				3/4/61 - 3/18/61
1	J3	1	60	7.5	0.25	20	---	---	EXPONENTIAL HEAD LOSS CURVE
2	J3	1	60	7.9	0.17	40	1544.	---	
3	J3	1	60	7.7	0.17	60	615.	---	
4	J3	1	60	7.5	0.15	80	319.	---	
5	J3	1	60	7.8	0.2	100	169.	---	
6	J3	1	60	6.7	0.3	120	134.9	99.650	
7	J3	1	60	7.4	0.3	160	73.	---	
8	J3	1	60	7.6	0.15	200	54.39	99.739	
9	J3	1	60	7.1	0.2	400	22.0	---	
10	J3	1	60	7.5	0.2	600	13.66	99.709	
11	J3	1	60	7.2	0.2	800	10.55	---	
12	J3	1	60	7.3	0.2	1000	9.90	99.751	
LAFRENZ	VARIABLE HEAD PERMEAMETER - SERIES 3				UNIVERSITY TAP WATER PLUS FERROUS SULFATE				3/1/61 - 3/2/61
1	J3	2	60	7.5	0.9	20	---	---	VOID ** ERRATIC HEAD LOSS INCREASE
2	J3	2	60	6.6	0.5	60	1237.	---	

Table 23 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
3	J3	2	60	8.0	0.7	60	727.	---	
4	J3	2	60	7.8	0.6	80	450.	---	
5	J3	2	60	6.2	0.5	100	288.	---	
6	J3	2	60	8.4	0.6	120	187.	---	
7	J3	2	60	7.6	0.6	140	120.3	99.810	
8	J3	2	60	7.0	0.65	160	75.	---	
9	J3	2	60	7.2	0.8	200	51.2	---	
10	J3	2	60	7.4	0.6	300	30.0	---	
LAFRENZ VARIABLE HEAD PERMEAMETER - SERIES 4 UNIVERSITY TAP WATER PLUS FERROUS SULFATE 12/8/60									
1	J3	3	60	7.1	3.0	0	---	---	VOID ** ERRATIC HEAD LOSS INCREASE
2	J3	3	60	7.2	1.1	20	---	---	VOID ** ERRATIC HEAD LOSS INCREASE
3	J3	3	60	7.2	0.6	40	1248.	---	
4	J3	3	60	7.0	0.7	60	520.	---	
5	J3	3	60	6.8	0.6	80	251.6	99.588	
6	J3	3	60	7.1	0.6	100	197.	---	
7	J3	3	60	6.8	0.7	120	111.9	99.909	
8	J3	3	60	7.2	0.8	140	42.7	---	
9	J3	3	60	6.9	0.8	160	24.7	---	
10	J3	3	60	6.5	0.45	200	47.79	99.698	
LAFRENZ VARIABLE HEAD PERMEAMETER - SERIES 5 UNIVERSITY TAP WATER PLUS FERROUS SULFATE 3/23/61 - 4/13/61									
1	J3	2	60	4.0	0.35	10	---	---	VOID ** ERRATIC HEAD LOSS INCREASE
2	J3	2	60	3.8	0.35	20	1562.7	99.870	
3	J3	2	60	4.0	0.30	40	514.	---	
4	J3	2	60	3.6	0.25	60	193.	---	
6	J3	2	60	4.4	0.25	100	78.	---	
7	J3	2	60	4.0	0.25	160	39.	---	
LAFRENZ VARIABLE HEAD PERMEAMETER - SERIES 6 UNIVERSITY TAP WATER PLUS FERROUS SULFATE 3/24/61 - 4/5/61									
1	J3	2	60	2.0	0.08	10	2273.6	99.696	
2	J3	2	60	2.0	0.10	20	669.4	99.803	
3	J3	2	60	2.0	0.08	40	223.8	99.888	
4	J3	2	60	2.1	0.15	60	111.2	99.000	
5	J3	2	60	2.3	0.10	60	95.89	99.739	
6	J3	2	60	2.1	0.10	100	40.86	99.854	
7	J3	2	60	2.0	0.15	160	20.33	98.995	

Table 23 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
LAFRENZ VARIABLE HEAD PERMEAMETER - SERIES 7 UNIVERSITY TAP WATER PLUS FERROUS SULFATE 3/22/61 - 3/25/61									
1	J3	1,2,3	60	7.4	0.8	20	---	---	VARIABLE FILTRATION RATE
2	J3	1,2,3	60	7.5	0.7	80	---	---	VARIABLE FILTRATION RATE
3	J3	1,2,3	60	7.4	0.7	160	---	---	VARIABLE FILTRATION RATE
LAFRENZ VARIABLE HEAD PERMEAMETER - SERIES 8 UNIVERSITY TAP WATER PLUS FERROUS SULFATE 3/23/61 - 4/15/61									
1	J3	1	60	4.1	0.14	10	---	---	VOID ** ERRATIC HEAD LOSS INCREASE
2	J3	1	60	3.6	0.10	20	2597.9	99.813	
3	J3	1	60	4.0	0.05	60	386.5	99.967	
4	J3	1	60	4.3	0.10	100	96.95	99.772	
5	J3	1	60	4.0	0.08	160	51.63	99.797	
6	J3	1	60	4.0	0.8	0	---	---	VOID ** ERRATIC HEAD LOSS INCREASE
LAFRENZ VARIABLE HEAD PERMEAMETER - SERIES 9 UNIVERSITY TAP WATER PLUS FERROUS SULFATE 3/28/61 - 4/3/61									
1	J3	1	60	2.1	0.30	0	---	---	
2	J3	1	60	2.0	0.05	20	750.	---	
3	J3	1	60	1.9	0.05	60	143.2	99.501	
4	J3	1	60	2.1	0.05	100	48.	---	
5	J3	1	60	2.1	0.05	160	18.7	---	
LAFRENZ VARIABLE HEAD PERMEAMETER - SERIES 10 UNIVERSITY TAP WATER PLUS FERROUS SULFATE 3/22/61 - 4/10/61									
1	J3	3	60	4.0	0.10	20	1648.8	99.516	1/4 MG/L COPPER ADDED
2	J3	3	60	3.9	0.05	60	258.	---	1/4 MG/L COPPER ADDED
3	J3	3	60	4.2	0.20	100	85.5	---	1/4 MG/L COPPER ADDED
4	J3	3	60	4.2	0.10	120	57.0	---	1/4 MG/L COPPER ADDED
LAFRENZ VARIABLE HEAD PERMEAMETER - SERIES 11 UNIVERSITY TAP WATER PLUS FERROUS SULFATE 4/4/61 - 4/14/61									
1	J3	3	60	2.0	0.25	20	425.3	99.822	
2	J3	3	60	2.0	0.20	60	68.29	99.944	
3	J3	3	60	2.2	0.15	100	31.12	100.000	
4	J3	3	60	2.1	0.20	120	24.90	99.942	
5	J3	3	60	2.4	0.10	160	15.16	99.731	

Table 23 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
LAERENZ	VARIABLE HEAD PERMEAMETER - SERIES 12				UNIVERSITY TAP WATER PLUS FERROUS SULFATE			3/28/61 - 4/17/61	
1	J3	3	60	7.6	0.5	20	---	---	1 MG/L COPPER ADDED VOID ** ERRATIC HEAD LOSS INCREASE
2	J3	3	60	7.0	0.15	40	1325.6	99.581	1 MG/L COPPER ADDED
3	J3	3	60	8.2	0.1	60	773.6	99.846	1 MG/L COPPER ADDED
4	J3	3	60	7.8	0.05	80	336.8	99.931	1/2 MG/L COPPER ADDED
5	J3	3	60	7.7	0.05	80	355.9	99.979	1 MG/L COPPER ADDED
6	J3	3	60	7.6	0.05	100	253.8	99.962	1/4 MG/L COPPER ADDED
7	J3	3	60	7.7	0.10	120	166.1	99.751	1/4 MG/L COPPER ADDED
8	J3	3	60	7.6	0.05	160	83.64	99.372	0.1 MG/L COPPER ADDED

Table 24. Hall and Hawley's pilot plant data (35, 37)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
HALL AND HAWLEY		LABORATORY PILOT PLANT		UNIVERSITY TAP WATER PLUS FERROUS SULFATE					3/12/63 - 8/20/63
1	J3	1.97	60.	6.62	0.27	163.	536.	99.638	PRELIMINARY RUN
2-1	J3	1.26	60.	7.23	0.09	254.	150.	99.764	PRELIMINARY RUN
2-2	J3	1.26	60.	7.10	0.05	254.	219.	98.091	PRELIMINARY RUN ** AFTER POWER INTERRUPTION
3-1	J3	1.87	60.	8.42	0.30	138.	484.	99.992	PRELIMINARY RUN
3-2	J3	1.87	60.	8.41	0.14	138.	573.	99.619	PRELIMINARY RUN ** AFTER MOMENTARY LOSS OF PRIME IN INFLUENT PUMP
4	J3	1.87	60.4	7.85	0.13	138.	479.	99.600	PRELIMINARY RUN
5	J3	0.97	60.6	8.07	0.11	80.	1932.	99.927	PRELIMINARY RUN
6	J3	0.94	61.0	8.08	0.11	80.	2285.	99.626	DUPLICATION OF RUN 5
7	J3	0.94	60.	8.44	0.13	80.	1807.	99.876	DUPLICATION OF RUN 5
8	J3	0.94	61.0	8.20	0.14	---	---	---	BODY FEED ADDED TO MIX TANK CONCENTRATION UNKNOWN
9	J3	0.94	61.3	8.12	0.08	80.	1896.	99.630	DUPLICATION OF RUN 5
10	J3	0.94	61.	8.00	0.16	80.	1929.	99.731	BODY FEED ADDED TO MIX TANK DUPLICATION OF RUN 5
11	J3	0.94	60.7	7.98	0.10	80.	1762.	97.745	BODY FEED ADDED TO MIX TANK DUPLICATION OF RUN 5
12	J3	0.94	60.3	7.75	0.13	80.	1894.	99.849	BODY FEED ADDED TO MIX TANK DUPLICATION OF RUN 5
13	J3	0.94	60.	8.64	0.15	80.7	2966.	99.868	NO PRECOAT
14	J3	0.94	60.	7.94	0.16	80.7	2139.	99.720	NO PRECOAT ** DUPLICATION OF RUN 13
15	J3	0.94	60.	7.78	0.12	84.5	2165.	98.959	NO PRECOAT ** DUPLICATION OF RUN 13
16	J3	0.94	60.	8.02	0.10	84.5	2449.	98.012	NO PRECOAT ** DUPLICATION OF RUN 13
17	J3	0.94	60.	8.05	0.07	80.	3284.	99.627	DIRTY PRECOAT USED
18	J3	0.94	60.	8.35	0.10	80.	3097.	98.560	DIRTY PRECOAT USED ** DUPLICATION OF RUN 17
19	J3	0.94	60.	7.98	0.19	80.	3554.	98.717	DIRTY PRECOAT USED ** DUPLICATION OF RUN 17
NOTE ** THE BODY FEED CONCENTRATIONS GIVEN FOR RUNS 1-19 MAY BE IN ERROR									
20	J3	2.0	60.	7.90	0.21	77.	1253.	99.834	
21	J3	2.0	60.	7.95	0.22	77.	1049.	99.915	DUPLICATION OF RUN 20
22	J3	2.0	60.5	7.98	0.16	77.	1357.	99.793	DUPLICATION OF RUN 20
23	J3	2.0	60.	7.75	0.18	41.	4336.	99.795	SLIGHTLY EXPONENTIAL HEAD LOSS CURVE
24	J3	2.0	60.7	7.75	0.20	59.	2517.	99.913	
25	J3	3.0	60.	7.75	0.31	61.	1956.	99.968	
26	J3	3.0	60.	7.75	0.51	61.	1638.	99.833	DUPLICATION OF RUN 25
27	J3	3.0	60.	8.00	0.38	61.	1756.	99.986	DUPLICATION OF RUN 25
28	J3	3.0	60.	8.20	0.36	61.	1516.	99.994	DUPLICATION OF RUN 25
29	J3	3.0	60.	8.20	0.40	61.	1436.	99.951	DUPLICATION OF RUN 25
30	J3	1.0	60.	8.20	0.09	54.	3066.	99.886	
31	J3	2.0	60.	7.90	0.19	57.	2105.	99.849	DUPLICATION OF RUN 24

Table 24 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
32	J0-1	1.0	59.	8.20	0.09	82.	1855.	99.815	
33	J0-1	0.98	59.5	7.95	0.18	139.	575.	99.947	
34	J0-1	0.98	59.	8.03	0.11	284.	232.	99.784	
35	J0-1	0.94	61.	7.80	0.10	48.	5894.	99.330	
36	J0-1	0.94	60.	8.02	0.11	82.	2447.	99.630	DUPLICATION OF RUN 32
37	J0-1	0.94	60.	8.07	0.05	82.	3467.	99.905	DUPLICATION OF RUN 32
38	J4-1	1.0	60.	8.05	0.09	87.	1669.	99.380	
39	J4-1	1.0	59.5	8.00	0.13	87.	1607.	99.870	DUPLICATION OF RUN 38
40	J4-1	1.0	59.5	8.07	0.13	87.	1633.	99.937	DUPLICATION OF RUN 38
41	J4-1	1.0	59.	8.07	0.13	146.	590.	99.939	
42	J4-1	1.0	60.3	8.66	0.14	206.	373.	99.997	
43	J4-1	1.0	60.	7.94	0.15	304.	130.	99.917	
44	HFC-1	1.0	59.	8.05	0.21	84.	2047.	99.880	
45	HFC-1	1.0	60.	7.93	0.20	84.	1730.	99.588	DUPLICATION OF RUN 44
46	HFC-1	1.0	59.	7.90	0.15	84.	2710.	99.876	DUPLICATION OF RUN 44
47	HFC-1	1.0	59.3	8.35	0.11	84.	1778.	97.059	DUPLICATION OF RUN 44
48	HFC-1	1.0	59.	7.66	0.06	124.	1030.	99.906	
49	HFC-1	1.0	60.	7.67	0.09	205.	526.	99.353	
50	J3	0.94	60.	7.94	0.15	160.	702.	99.857	VOID ** BODY FEED CONCENTRATION IN ERROR
51-1	J3	0.94	60.	7.90	0.13	400.	206.	99.870	VOID ** BODY FEED CONCENTRATION IN ERROR
51-2	J3	0.94	60.	7.90	0.09	400.	210.	99.948	AFTER INFLUENT PUMP STOPPED 5 SEC. VOID ,** BODY FEED CONCENTRATION IN ERROR
52	J3	0.94	60.	7.92	0.24	50.	5307.	98.746	VOID ** BODY FEED CONCENTRATION IN ERROR
53	J3	0.96	60.	7.95	0.11	170.	324.	99.936	
54	J3	0.96	60.	8.04	0.11	72.9	1766.	99.948	
55	J3	0.94	60.	8.13	0.06	305.	131.	99.719	
56	J3	0.96	60.	7.84	0.09	47.7	3901.	99.936	
150	HFC-1	1.0	60.5	8.15	0.12	173.	575.	99.886	
151	J0-1	1.0	60.	7.93	0.08	147.	644.	99.923	DUPLICATION OF RUN 33
152	J0-1	1.0	60.	7.87	0.14	224.	382.	99.956	
153	J0-1	1.0	60.	7.90	0.10	124.	879.	99.901	
154	J3-2	1.0	60.	8.09	0.08	79.	2179.	99.962	
155	HFC-1	1.0	60.	8.37	0.09	209.	686.	99.986	
156	HFC-1	0.98	61.5	8.18	0.04	207.	527.	99.884	DUPLICATION OF RUN 155

Table 24 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
HALL AND HAWLEY		LABORATORY PILOT PLANT		UNIVERSITY TAP WATER PLUS FERRIC CHLORIDE					6/5/63 - 7/1/63
57	J3	0.96	59.	7.75	0.00	73.4	20700.	99.994	
58	J3	0.96	62.	7.98	0.00	73.4	25300.	99.955	DUPLICATION OF RUN 57
59	J3	0.96	60.	7.87	0.00	73.4	29520.	99.976	DUPLICATION OF RUN 57
60	J3	0.96	61.7	8.05	0.14	154.5	4620.	99.939	
61	J3	0.96	61.3	8.05	0.09	328.	1090.	99.938	
62	J3	0.96	66.	8.20	0.06	51.5	52000.	99.975	
63	J3	0.96	62.7	8.20	0.02	77.0	20140.	99.825	BODY FEED ADDED TO MIX TANK
62A	J3	0.96	68.	8.71	0.30	45.0	61864.	99.569	
63A	J3	0.94	60.3	8.20	0.16	72.8	23474.	99.921	
HALL AND HAWLEY		LABORATORY PILOT PLANT		UNIVERSITY TAP WATER PLUS FERRIC SULFATE					6/10/63 - 7/2/63
64	J3	0.96	60.	8.27	0.13	77.4	19705.	99.884	
65	J3	0.96	60.	8.20	0.00	77.4	22342.	99.724	DUPLICATION OF RUN 64
66	J3	0.96	60.	8.20	0.03	77.4	15026.	99.826	DUPLICATION OF RUN 65
67	J3	0.94	61.	8.13	0.03	309.	979.	99.653	
68	J3	0.94	60.	7.98	0.05	153.1	3209.	99.125	
69	J3	0.94	60.	8.20	0.00	54.8	34257.	99.972	
70	J3	0.94	60.	8.42	0.07	79.7	16130.	99.773	BODY FEED ADDED TO MIX TANK
70A	J3	0.94	59.	7.87	0.07	75.2	21847.	99.900	BODY FEED ADDED TO MIX TANK
HALL AND HAWLEY		LABORATORY PILOT PLANT		UNIVERSITY TAP WATER PLUS ALUMINUM SULFATE					6/25/63 - 8/26/63
71	J3	0.96	60.	8.7	---	160.	---	---	TRIAL RUN ** NO DATA
72	J3	0.96	60.	7.50	0.25	135.	11615.	99.127	
73	J3	0.96	60.	7.50	0.06	135.	9942.	99.971	DUPLICATION OF RUN 72
74	J3	0.96	60.	7.20	0.06	135.	9636.	99.659	DUPLICATION OF RUN 72
75	J3	0.94	60.	7.20	0.06	293.	3164.	99.685	
76	J3	0.94	60.	8.10	0.00	44.5	65046.	99.973	
77	J3	0.94	60.	8.20	0.06	66.8	50808.	99.971	EXPONENTIAL HEAD LOSS CURVE
78	J3	0.94	60.	7.40	0.06	80.4	30204.	99.429	
79	J3	0.94	60.	7.40	0.03	85.5	31700.	98.823	
80	J3	0.94	60.	7.60	0.03	75.5	15802.	99.821	BODY FEED ADDED TO MIX TANK
81	J3	0.94	60.	8.00	0.01	47.7	54682.	99.679	
82	J3	0.94	60.	7.55	0.02	147.	8034.	99.944	
83	J3	0.94	60.	8.15	0.05	85.5	29850.	99.728	
83A	J3	1.0	60.	3.45	---	294.	1335.	99.924	
83B	J3	1.0	60.	3.60	0.06	152.	4893.	99.906	

Table 24 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
HALL AND HAWLEY		LABORATORY PILOT PLANT		UNIVERSITY TAP WATER PLUS FERROUS SULFATE					7/29/63 - 8/16/63
84	J3-2	1.0	59.	7.72	0.16	74.8	2040.	99.878	SULFURIC ACID ADDED TO MAKE SULFATE CONCENTRATION EQUAL TO FERRIC SULFATE WATER
85	J3-2	1.0	60.	7.01	---	79.	---	---	POTASSIUM DICHROMATE ADDED TO OXIDIZE FERROUS ION ** RUN DISCONTINUED
86	J3-2	1.0	60.	7.01	0.05	79.	17243.	99.739	POTASSIUM DICHROMATE ADDED TO OXIDIZE FERROUS ION
87	J3-2	1.0	60.	7.01	0.06	79.	16320.	99.825	POTASSIUM DICHROMATE ADDED TO OXIDIZE FERROUS ION
88	J3-2	1.0	60.	8.20	0.06	290.	1468.	99.953	POTASSIUM DICHROMATE ADDED TO OXIDIZE FERROUS ION
89	J3-2	1.0	60.	7.91	0.11	148.	5912.	99.865	POTASSIUM DICHROMATE ADDED TO OXIDIZE FERROUS ION
90	J3-2	1.0	60.	7.75	0.03	201.	2908.	99.934	POTASSIUM DICHROMATE ADDED TO OXIDIZE FERROUS ION
HALL AND HAWLEY		LABORATORY PILOT PLANT		UNIVERSITY TAP WATER PLUS FERROUS CHLORIDE					8/26/63 - 8/27/63
91	J3-2	1.0	60.	8.14	0.11	292.	128.	99.974	
92	J3-2	0.98	60.	7.43	0.10	211.	213.	99.864	
93	J3-2	1.0	60.	7.93	0.23	153.	338.	99.861	
94	J3-2	1.0	60.	7.31	0.13	78.9	1053.	99.977	
95	J3-2	1.0	60.	8.00	0.13	82.8	1300.	99.955	
96	J3-2	1.0	56.	7.40	0.20	87.7	1390.	99.916	

Table 25. Regunathan's pilot plant data (61)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
REGUNATHAN LABORATORY PILOT PLANT - SERIES A UNIVERSITY TAP WATER PLUS KENTUCKY BALL CLAY (KAOLINITE) 1/2/64 - 1/26/64									
1	J4-1	1.27	---	29	---	87.8	---	---	TRIAL RUN
2	J4-1	3.0	60	35	---	21.4	---	---	TRIAL RUN ** TURBIDITY INCREASED DURING RUN
3	J4-1	1.0	60	32	0.2	102.	---	---	TRIAL RUN
4	J4-1	1.5	60	21	0.2	62.7	---	---	TRIAL RUN
5	HFC-1	1.5	60	21	TRACE	28.1	---	---	TRIAL RUN
REGUNATHAN LABORATORY PILOT PLANT - SERIES UNIVERSITY TAP WATER PLUS KENTUCKY BALL CLAY (KAOLINITE) 6/18/64 - 7/30/64									
1	J4-1	1.0	60	34.5	3.0	0	---	---	EXPONENTIAL HEAD LOSS CURVE
2	J4-1	1.0	60	42.0	0.03	53.8	1229.8	99.832	
3	J4-1	1.0	60	37.0	0.08	110.0	182.3	99.985	
4	J4-1	1.0	60	37.0	0.00	211.9	63.	99.975	
5	J4-1	1.0	60	62.0	0.03	68.8	---	---	POSSIBLE BODY FEED DEGRADATION
6	J4-1	1.0	60	81.0	0.17	66.6	---	---	POSSIBLE BODY FEED DEGRADATION
7	J4-1	1.0	60	136.0	1.0	85.0	---	---	EXPONENTIAL HEAD LOSS CURVE
8	J4-1	1.0	60	108.0	0.05	132.7	1230.	99.992	
9	J4-1	1.0	60	115.0	0.15	125.5	1850.	99.976	
10	J4-1	1.0	60	115.0	0.20	92.0	---	---	EXPONENTIAL HEAD LOSS CURVE
11	J4-1	1.0	60	105.5	0.10	101.0	---	---	EXPONENTIAL HEAD LOSS CURVE
12	J4-1	1.0	60	108.5	0.18	131.4	997.1	99.870	DUPLICATION OF RUN 8
13	J4-1	1.0	60	106.0	0.10	131.5	1033.4	99.826	DUPLICATION OF RUN 8
14	J4-1	1.0	60	108.0	0.05	131.8	1162.0	99.854	DUPLICATION OF RUN 8
15	J4-1	1.0	60	119.0	0.08	213.0	444.	99.963	
16	J4-2	1.0	63.5	128.0	1.30	155.5	1103.5	99.897	
17	J4-2	1.0	60	64.0	0.90	76.3	1083.4	99.926	
18	J4-2	1.0	60	100.0	1.75	125.5	872.6	99.937	
REGUNATHAN LABORATORY PILOT PLANT - SERIES C UNIVERSITY TAP WATER PLUS KENTUCKY BALL CLAY (KAOLINITE) 6/17/64 - 7/9/64									
1	HFC-1	1.0	60	80.5	0.08	0	---	---	EXPONENTIAL HEAD LOSS CURVE
2	HFC-1	1.0	60	127.0	0.00	73.5	---	---	EXPONENTIAL HEAD LOSS CURVE
3	HFC-1	1.0	60	121.5	0.00	106.6	8691.8	99.916	
4	HFC-1	1.0	60	68.0	0.02	73.7	4540.2	99.991	
5	HFC-1	1.0	60	90.0	0.00	90.1	4720.	99.965	
6	HFC-1	1.0	60	88.0	0.01	74.8	11010.	99.957	
7	HFC-1	1.0	60	70.0	0.00	50.1	13550.	99.969	
8	HFC-1	1.0	60	---	0.00	51.3	---	---	INFLUENT TURBIDITY DECREASED DURING RUN
9	HFC-1	1.0	60	101.5	0.00	62.3	---	---	EXPONENTIAL HEAD LOSS CURVE
10	HFC-1	1.0	60	104.0	0.00	85.8	---	---	EXPONENTIAL HEAD LOSS CURVE
11	HFC-1	1.0	60	92.0	0.00	94.4	5692.	99.977	

Table 25 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
12	HFC-1	1.0	60	86.0	0.00	58.7	---	---	EXPONENTIAL HEAD LOSS CURVE
13	HFC-1	1.0	60	87.0	0.00	49.8	---	---	EXPONENTIAL HEAD LOSS CURVE
14	HFC-1	1.0	60	87.5	0.00	105.0	3244.	99.979	
15	HFC-1	1.0	60	92.0	0.00	149.3	1714.	99.981	
REGUNATHAN	LABORATORY PILOT PLANT - SERIES D				UNIVERSITY TAP WATER PLUS WYOMING BENTONITE CLAY				7/17/64 - 8/6/64
1	HFC-1	1.0	62.5	88.0	0.00	120.5	---	---	EXPONENTIAL HEAD LOSS CURVE
2	HFC-1	1.0	61.0	89.0	0.00	150.0	---	---	EXPONENTIAL HEAD LOSS CURVE
3	HFC-1	1.0	61	96.5	0.00	191.0	---	---	EXPONENTIAL HEAD LOSS CURVE
4	HFC-1	1.0	62	78.5	0.00	599	3446.	99.972	
5	HFC-1	1.0	60	86.0	0.00	767	---	---	VOID ** RAN OUT OF BODY FEED
6	HFC-1	1.0	61	91.0	0.00	495	4800.	99.969	
7	HFC-1	1.0	62.5	91.0	0.00	410	7963.7	99.975	
8	HFC-1	1.0	63	93.0	0.00	220	---	---	EXPONENTIAL HEAD LOSS CURVE
9	HFC-1	1.0	63	85.0	0.00	1033	740.	99.980	
10	HFC-2	1.0	60	45.0	0.00	335.5	5150.	99.986	
11	HFC-2	1.0	60	123.	0.00	806	2457.3	99.326	
12	HFC-2	1.0	60	45.5	0.00	347	5420.	99.996	
13	HFC-2	1.0	60	45.5	0.00	---	---	---	VOID ** BODY FEEDER DIFFICULTIES
14	HFC-2	1.0	60	45.5	0.00	365	4140.	99.988	
15	HFC-2	1.0	60	85.0	0.00	670	2400.	99.996	
16	HFC-2	1.0	61	32.5	0.00	253.5	7070.	99.948	
REGUNATHAN	LABORATORY PILOT PLANT - SERIES E				UNIVERSITY TAP WATER PLUS WYOMING BENTONITE CLAY				7/18/64
1	J4-2	1.0	63.5	94.0	26.	177	---	---	EXPONENTIAL HEAD LOSS CURVE
2	J4-2	1.0	60	92.5	25.	303.5	---	---	EXPONENTIAL HEAD LOSS CURVE

Table 26. Dillingham's Lompoc, California, data (27)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
DILLINGHAM	LOMPOC FILTER NO. 1			EFFLUENT FROM LIME - SODA ASH PROCESS AT LOMPOC, CALIFORNIA					5/31/64 - 6/25/64
1	JO	0.56	63	7.6	0.45	22.9	231.	---	
2	JO	0.56	63	7.0	0.41	22.9	505.	---	
3	JO	0.51	63	5.5	0.33	21	434.	---	
4	JO	1.16	63	6.5	0.41	23	625.	---	
5	JO	0.94	63	6.1	0.48	20	840.	---	
5.5	JO	0.94	63	6.2	0.43	20.3	887.	---	
6	JO	0.94	63	6.2	0.38	20.5	964.	---	
7	JO	0.48	64	8.5	0.44	21.8	4240.	---	
7.5	JO	0.48	64	9.5	0.54	21.8	4640.	---	
8	JO	0.48	64	10	0.67	21.8	5760.	---	
9	JO	0.43	64	9	0.55	20.4	3860.	---	
10	JO	0.4	64	9	0.77	21.0	4990.	---	
11	JO	0.43	64	11	0.22	19.5	2930.	---	
12	JO	0.43	64	8.7	0.31	21.4	1240.	---	
13	JO	0.43	64	9.5	0.36	20.6	1940.	---	
14	JO	0.48	66	7.5	0.52	13.7	4470.	---	
15	JO	0.48	66	6	0.49	17.3	2150.	---	
16	JO	0.34	66	6	0.53	17.5	1620.	---	
17	JO	0.60	66	6	0.37	17.4	1790.	---	
18	JO	0.77	65	9	0.40	22.7	960.	---	
19	JO	0.77	65	8	0.35	21.9	641.	---	
19.5	JO	0.77	65	8	0.44	21.5	771.	---	
20	JO	0.77	65	8	0.60	21.4	875.	---	
21	JO	0.57	65	6	0.35	24.6	298.	---	
21.5	JO	0.58	65	6	0.35	24.3	327.	---	
22	JO	0.58	65	6	0.38	24	356.	---	
23	JO	0.56	66	9	0.27	21.8	778.	---	
24	JO	0.94	66	9	0.20	21.7	4300.	---	
25	JO	0.94	66	7	0.20	22.8	1510.	---	
26	JO	0.53	65	10	0.30	22	636.	---	
27	JO	0.56	65	8	0.46	21.7	1010.	---	
28	JO	0.5	65	10	0.43	20	808.	---	
29	JO	0.67	65	8.4	0.41	19.6	1810.	---	
30	JO	0.9	66	6.4	0.33	22	1510.	---	
31	JO	0.67	66	6	0.20	21.4	2760.	---	
32	JO	0.72	66	7	0.50	25	578.	---	
33	JO	0.63	66	6.5	0.20	26.5	463.	---	
DILLINGHAM	LOMPOC FILTER NO. 2			EFFLUENT FROM LIME - SODA ASH PROCESS AT LOMPOC, CALIFORNIA					5/27/64 - 6/29/64
1	JO	0.7	64	7.5	0.42	22	1050.	---	
2	JO	0.68	63	7.4	0.31	22.3	791.	---	
3	JO	0.67	63	5.2	0.27	20.6	712.	---	

Table 26 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
4	JO	0.74	63	8	0.54	23	777.	---	
5	JO	0.63	63	5.1	0.46	21.6	1190.	---	
6	JO	0.63	63	5.4	0.28	20	2290.	---	
7	JO	1.1	62	4.4	0.30	20.4	1980.	---	
8	JO	1.1	62	4.4	0.26	20	3650.	---	
9	JO	1.11	63	5.4	0.53	20.2	751.	---	
10	JO	1.18	64	7	0.33	23	734.	---	
11	JO	0.96	64	6.1	0.43	20.3	781.	---	
12	JO	0.62	64	7.5	0.56	21.8	1850.	---	
13	JO	0.62	64	10	0.66	21.8	2890.	---	
14	JO	0.58	64	10	0.67	21.8	1620.	---	
15	JO	0.7	64	8.4	0.90	22	2040.	---	
16	JO	0.68	64	9	0.65	22	2030.	---	
17	JO	0.31	67	5.5	0.40	17.6	2270.	---	
18	JO	0.60	67	6	0.40	20.5	1360.	---	
19	JO	0.60	67	5	0.37	22	635.	---	
20	JO	0.77	65	8	0.35	22.6	651.	---	
21	JO	0.55	65	6.5	0.90	42.5	152.	---	
22	JO	0.77	65	7	0.20	15.9	2360.	---	
23	JO	0.86	64	6.5	0.35	22.8	665.	---	
24	JO	0.55	64	7	0.50	22	7820.	---	
25	JO	0.46	64	7	0.38	23	812.	---	
26	JO	0.90	66	8.3	0.20	23.6	3150.	---	
27	JO	0.55	66	6.5	0.35	21.5	4090.	---	
28	JO	0.92	64	6	0.40	25.8	1120.	---	
29	JO	0.51	65	7.5	0.30	20.5	2060.	---	
30	JO	0.51	65	7	0.30	22.5	1550.	---	
31	JO	0.6	65	11	0.20	21	2920.	---	
32	JO	0.67	66	6.5	0.50	20.3	2410.	---	
33	JO	0.65	66	6	0.20	22	990.	---	
34	JO	0.77	66	5.7	0.30	20.5	1980.	---	
35	JO	0.8	66	7	0.38	25.5	576.	---	
36	JO	0.65	66	5.5	0.23	26	1030.	---	
37	JO	0.48	66	6.0	0.33	20	1740.	---	
DILLINGHAM	LOMPOC FILTER NO. 3			EFFLUENT FROM LIME - SODA ASH PROCESS AT LOMPOC, CALIFORNIA					2/21/64 - 2/29/64
1	J3	0.36	63	9.6	0.41	22.3	9890.	---	
2	JO	0.36	63	10.2	0.68	18	31200.	---	
3	JO	0.68	63	11.5	0.71	23	4420.	---	
4	JO	0.65	63	5.5	0.53	21.3	2140.	---	
5	JO	0.68	63	5.5	0.53	24.4	2140.	---	
6	JO	0.72	63	5.5	0.65	18	5090.	---	
7	JO	0.52	63	9.5	0.38	35.7	3250.	---	
8	JO	0.52	63	8.5	0.81	29	6000.	---	

Table 26 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
9	JO	0.77	63	5	0.44	12	1260.	---	
10	JO	0.77	63	5.5	0.50	20	1070.	---	
11	JO	0.77	64	5.5	0.21	19.3	1370.	---	
12	JO	0.81	64	5.5	0.20	20	1440.	---	
13	JO	1.11	65	4.8	0.44	22.4	691.	---	
14	JO	0.75	63	7.5	0.29	23.5	660.	---	
15	JO	1.18	62	5.8	0.53	20.7	1160.	---	
16	JO	0.89	65	7.5	0.40	23	1290.	---	
17	JO	0.94	65	8	0.30	21.5	544.	---	
18	JO	0.68	65	6.2	0.90	42.5	115.	---	
19	JO	0.68	65	6	0.37	15.9	2850.	---	
20	JO	1.04	65	7	0.33	22.4	328.	---	
21	JO	0.77	65	7	0.60	23.7	1280.	---	
22	JO	0.77	66	9.5	0.30	21.8	1430.	---	
23	JO	1.04	66	9	0.20	26.4	818.	---	
24	JO	0.98	66	3	0.30	32.4	71.	---	
24.5	JO	0.98	66	3	0.37	32.4	102.	---	
25	JO	0.98	66	3	0.40	32.4	162.	---	
26	JO	0.77	64.5	6.5	0.33	20	619.	---	
27	JO	0.74	65	7.5	0.30	22	1130.	---	
28	JO	0.77	65	8	0.52	22	1240.	---	
29	JO	0.77	65	9	0.42	29	570.	---	
30	JO	0.86	66	6.3	0.26	21.7	710.	---	
31	JO	0.96	66	7	0.48	25.5	617.	---	
32	JO	0.72	66	6	0.20	21	1250.	---	

Table 27. Bridges' data from filtration of pretreated surface waters (15)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
BRIDGES	MOBILE TREATMENT UNIT		COAGULATED, FLOCCULATED, AND SETTLED LAKE WATER AT CRESTON, IOWA					6/15/66 - 7/12/66	
1	J3	0.98	21.5	11.6	0.98	13.2	12660.	99.763	SEPTUMS WERE SLIGHTLY CLOGGED
2	J3	0.98	21.2	11.1	0.94	13.8	9969.	99.954	
3	J3	0.98	21.5	10.3	0.61	16.4	7951.	99.956	
4	J3	0.98	21.7	10.7	0.91	54.6	730.4	99.854	
5	J3	0.98	23.3	12.5	0.94	29.0	2684.	99.929	
6	J3	0.98	23.1	12.7	0.55	41.0	1360.	99.537	
7	J3	0.98	23.5	11.1	0.19	78.0	386.8	99.912	
8	J3	0.98	22.8	10.3	0.86	144.5	155.7	99.977	
9	J3	0.98	23.4	10.5	0.38	229.2	83.07	99.765	
10	J3	0.75	23.2	12.1	0.35	53.7	888.7	99.196	
11	J3	0.75	23.1	10.9	0.63	17.2	5720.	99.933	
12	J3	0.75	25.1	12.1	0.65	35.3	2165.	99.738	
13	J3	0.75	25.1	11.8	0.73	73.5	381.9	99.070	
14	J3	0.75	29.2	12.3	0.80	13.0	35030.	99.392	SEPTUMS WERE STILL CLOGGED
15	J3	0.98	26.0	11.9	0.78	40.9	690.9	99.927	SEPTUMS CLEANED BEFORE RUN
16	J3	0.98	27.0	11.1	0.80	27.0	1641.	99.914	
17-1	J3	0.98	25.7	9.9	0.80	54.3	421.3	99.935	
17-2	J3	0.98	26.1	10.5	0.77	60.7	241.6	99.326	
18-1	J3	0.98	27.4	9.5	0.96	131.0	90.98	99.793	
18-2	J3	0.98	27.3	10.2	0.98	144.3	64.43	98.249	
19	J3	0.98	26.7	9.6	0.88	17.3	---	---	EXPONENTIAL HEAD LOSS CURVE
20	J3	0.98	26.0	8.1	0.47	29.3	948.8	99.962	
21	J3	0.98	27.0	9.0	1.07	22.7	1643.	99.921	
22	J3	1.47	27.1	8.4	0.76	27.4	912.0	99.828	
23	J3	1.47	26.1	7.4	0.48	37.8	406.0	99.518	
24	J3	1.47	26.2	7.8	0.78	49.9	255.9	99.881	
25	J3	1.47	26.5	8.1	0.94	101.8	109.9	99.596	
26	J3	1.47	25.6	7.9	0.73	17.5	---	---	EXPONENTIAL HEAD LOSS CURVE COPPER SULFATE ADDED TO SETTLING BASIN
27	J3	1.47	26.5	8.5	0.67	39.0	1362.	99.970	
28-1	J3	1.47	27.0	8.4	0.76	43.7	756.3	99.834	
28-2	J3	1.47	26.6	9.3	0.55	48.3	717.5	99.488	TURBIDITY INCREASE DUE TO DYING ALGAE IN SETTLING BASIN
29	J3	0.98	25.2	7.9	0.61	26.6	2599.	99.978	
30	HFC	0.98	26.1	8.2	0.79	28.4	4256.	99.870	
31	J3	0.98	29.0	11.2	0.82	39.7	693.7	99.887	
32	J3	1.47	27.6	9.8	0.66	203.9	61.40	99.907	
33	J3	1.47	28.7	10.7	0.88	23.7	1439.	99.926	

Table 27 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
BRIDGES	MOBILE TREATMENT UNIT		COAGULATED, FLOCCULATED, AND SETTLED LAKE WATER AT WINTERSET, IOWA					7/14/66 - 7/26/66	
34	J3	0.98	20.6	11.3	1.50	56.5	7070.	99.496	
35	J3	0.98	21.0	13.4	3.23	126.7	1758.	99.826	
36	J3	0.98	21.0	13.0	1.60	166.4	798.6	99.947	COPPER SULFATE ADDED TO LAKE
37	J3	0.98	21.0	18.2	2.14	181.6	875.2	99.854	
38	J3	0.98	20.7	14.4	1.19	152.2	1419.	99.672	
39	J3	0.99	20.6	15.0	1.21	230.0	577.5	99.859	
40	HFC	0.98	21.7	11.5	1.24	183.1	---	---	INFLUENT TURBIDITY INCREASED THROUGHOUT THE RUN
41	HFC	0.98	21.6	13.1	3.90	241.2	793.7	99.874	
42	HFC	0.98	21.4	12.4	3.67	263.4	687.2	99.926	
43-1	J3	0.98	22.0	16.0	1.88	257.3	485.9	99.792	
43-2	J3	0.98	22.4	13.1	2.50	257.3	293.6	99.788	
44	J3	0.98	22.0	16.0	1.23	146.2	952.1	99.997	
45	J3	0.98	21.8	15.5	0.35	197.8	542.8	99.969	
46	J3	0.98	22.0	15.3	0.44	267.7	312.8	99.542	
47	HFC	0.98	22.0	17.3	0.44	171.1	1476.	99.910	
48	J3	0.75	21.9	18.4	0.69	290.0	318.8	99.982	
49	J3	0.75	22.0	14.6	0.98	225.3	417.7	99.418	
50	J3	0.75	22.0	15.0	0.60	136.2	1211.	99.897	
51	J3	0.75	21.6	18.6	0.69	107.0	2128.	99.972	
52	J3	0.75	22.0	16.6	1.13	84.7	3896.	99.663	
53	J3	0.75	22.0	17.4	1.45	73.7	4571.	99.908	
54	HFC	0.75	22.8	11.2	2.03	295.7	420.7	99.873	
55	HFC	0.75	23.0	10.3	2.29	436.5	267.0	99.946	
56	HFC	0.98	23.0	8.7	0.67	145.1	2169.	99.963	
57	J3	0.98	23.0	9.6	1.03	105.8	1168.	99.682	
BRIDGES	MOBILE TREATMENT UNIT		COAGULATED, FLOCCULATED, AND SETTLED LAKE WATER AT ALBIA, IOWA					7/28/66 - 8/11/66	
58	J3	0.98	15.0	10.0	3.8	148.3	---	---	VOID DUE TO HIGH EFFLUENT TURBIDITY
59	HFC	0.98	15.0	9.0	9.7	170.9	---	---	VOID DUE TO HIGH EFFLUENT TURBIDITY
60	HFC	0.98	15.0	9.8	11.9	259.0	---	---	VOID DUE TO HIGH EFFLUENT TURBIDITY
61	J3	0.98	14.5	8.1	5.3	215.0	---	---	VOID DUE TO HIGH EFFLUENT TURBIDITY
62	J3	0.98	14.9	7.0	4.7	105.7	---	---	VOID DUE TO HIGH EFFLUENT TURBIDITY
63	J3	1.01	15.0	5.1	0.47	159.2	577.9	99.754	SEPTUMS REPAIRED BEFORE RUN 3 NEW SEPTUMS INSTALLED
64-1	J3	1.01	15.2	6.7	0.51	128.6	1439.	99.974	SEPTUMS CLEANED BEFORE RUN
64-2	J3	1.01	15.3	6.5	0.63	136.5	644.3	99.860	
64-3	J3	1.01	15.3	7.9	0.98	149.7	938.7	99.943	
65	J3	1.01	15.0	7.0	1.19	105.8	1499.	99.906	
66	J3	1.01	14.8	5.3	0.19	178.9	514.4	99.963	
67-1	J3	1.01	15.0	5.4	0.82	242.1	354.7	99.861	
67-2	J3	1.01	15.1	6.0	0.33	275.0	206.9	99.311	

Table 27 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
68-1	J3	1.01	15.0	5.9	0.47	95.8	1180.	99.983	
68-2	J3	1.01	15.0	7.8	0.17	104.8	1949.	99.965	
69	J3	0.77	15.0	7.4	0.65	110.5	2018.	99.911	
70	J3	0.77	15.1	5.9	0.59	141.2	899.8	99.285	
71	J3	0.77	15.0	5.8	0.80	177.3	521.8	99.739	
72	J3	0.77	15.0	5.1	0.31	219.0	219.8	99.977	
73	J3	0.77	15.0	5.2	0.45	265.0	137.0	99.594	
74	HFC	1.01	15.2	4.3	0.14	166.0	498.5	99.950	
75	HFC	1.01	15.3	2.74	0.00	172.0	311.0	99.979	FILTER EFFLUENT RECIRCULATED
76	HFC	1.01	14.8	4.7	TRACE	137.0	753.3	99.916	
77-1	HFC	1.01	15.8	2.89	0.00	135.0	334.0	99.978	FILTER EFFLUENT RECIRCULATED
77-2	HFC	1.01	15.3	4.4	0.00	143.6	759.8	99.913	
78-1	HFC	1.01	16.0	2.07	0.00	86.1	437.4	99.993	FILTER EFFLUENT RECIRCULATED
78-2	HFC	1.01	15.1	4.4	0.00	92.3	1297.	99.989	
79-1	HFC	1.01	15.0	4.1	TRACE	106.4	839.8	99.995	
79-2	HFC	1.01	15.6	2.00	TRACE	111.1	452.4	99.796	FILTER EFFLUENT RECIRCULATED
80-1	HFC	1.01	16.0	2.76	TRACE	222.8	187.5	99.973	FILTER EFFLUENT RECIRCULATED
80-2	HFC	1.01	15.6	5.1	TRACE	238.0	304.2	99.925	
81-1	HFC	0.77	15.3	3.7	TRACE	215.7	284.3	99.897	
81-2	HFC	0.77	15.9	2.06	TRACE	226.7	142.9	99.997	FILTER EFFLUENT RECIRCULATED
82	---	---	---	---	---	---	---	---	GENERATOR FAILURE ** NO DATA
BRIDGES	MOBILE TREATMENT UNIT			2 STAGE LIME-SODA ASH SOFTENED DES MOINES RIVER WATER AT OTTUMWA, IOWA					8/16/66 - 8/26/66
83	J3	1.01	25.0	1.17	0.33	53.5	---	---	HEAD LOSS INCREASE TOO SMALL TO MEASURE ** SECONDARY SETTLING BASIN EFFLUENT WAS FILTERED
84	HFC	1.01	26.4	3.06	0.36	13.9	---	---	HEAD LOSS INCREASE TOO SMALL TO MEASURE
85	HFC	1.50	27.0	1.55	0.23	NONE	---	---	EXPONENTIAL HEAD LOSS CURVE
86	HFC	1.50	26.2	2.30	0.28	19.1	127.9	99.736	
87	HFC	2.03	26.0	1.04	0.20	13.6	111.7	99.691	
88	HFC	2.03	26.9	1.81	0.18	6.93	494.7	99.891	
89	HFC	2.03	27.0	2.64	0.31	3.36	2253.	99.886	
90	HFC	2.03	26.3	2.78	0.24	5.12	1231.	99.977	
91	HFC	2.03	26.8	2.30	0.19	1.67	8875.	99.947	
92	HFC	2.03	26.7	1.99	0.26	3.48	1290.	99.957	
93	HFC	2.88	26.6	2.70	0.18	14.2	176.0	99.997	
94	HFC	2.88	27.0	2.74	0.18	4.76	870.1	99.792	
95	HFC	2.88	25.1	2.82	0.19	10.1	222.6	99.904	
96	HFC	2.88	24.0	3.32	0.28	2.32	---	---	EXPONENTIAL HEAD LOSS CURVE
97	HFC	2.88	24.1	2.37	0.38	3.59	1098.	99.956	
98	J3	2.88	22.8	3.19	0.55	4.52	476.6	99.871	
99	J3	2.88	23.0	2.75	0.62	2.16	3098.	99.905	
100	J3	2.88	22.7	2.92	0.66	3.30	1144.	99.967	

Table 27 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
101	J3	2.98	22.0	2.49	0.53	8.44	279.1	99.896	
102	J3	2.03	22.5	2.11	0.48	6.19	394.4	99.934	
103	J3	2.03	22.2	3.34	0.72	3.09	1149.	99.962	
104	J3	2.03	22.0	4.14	0.67	1.65	2944.	99.962	

BRIDGES MOBILE TREATMENT UNIT COAGULATED, FLOCCULATED, AND SETTLED LAKE WATER AT BLOOMFIELD, IOWA 8/30/66 - 9/15/66

NOTE ** 3.2 MG/L CHLORINE ADDED TO BLOOMFIELD PLANT INFLUENT AND 6.4 MG/L ADDED TO SECONDARY CLARIFIER EFFLUENT

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
105	J3	1.01	24.7	5.4	0.63	96.7	557.6	99.822	SECONDARY CLARIFIER EFFLUENT FILTERED
106	J3	1.01	24.9	7.1	0.73	51.7	3428.	99.974	
107	J3	1.01	24.9	---	---	---	---	---	RUN DISCONTINUED ** NO DATA
108-1	J3	1.01	24.8	4.3	0.51	69.2	979.1	99.686	
108-2	J3	1.01	24.9	6.5	0.58	78.0	1613.	99.953	
109	J3	1.01	25.2	5.3	0.46	157.5	420.6	99.927	
110-1	HFC	1.01	24.9	5.9	0.96	103.8	549.7	99.860	
110-2	HFC	1.01	25.1	7.8	0.89	106.1	896.1	99.781	SEPTUMS HAD BECOME STAINED BY A DARK RED SUBSTANCE ** THOUGHT TO BE DUE TO MANGANESE OXIDIZED BY CHLORINE GENERATOR FAILURE ** NO DATA
111	HFC	1.01	25.2	---	---	---	---	---	
112.1	HFC	1.01	25.0	4.1	0.56	78.1	802.6	99.972	
112.2	HFC	1.01	25.0	4.8	0.57	82.8	1331.	99.775	
113	J3	2.03	25.0	4.5	0.85	73.6	1347.	99.976	
114	J3	1.50	24.0	8.1	0.64	100.9	783.8	99.986	
115	J3	1.50	23.7	7.5	0.65	132.1	375.4	99.882	
116	HFC	1.50	23.0	6.8	0.66	145.9	574.9	99.757	SEPTUMS STAINED ALMOST BLACK
117-1	J3	1.01	23.0	5.8	0.44	93.0	897.9	99.951	
117-2	J3	1.01	23.0	5.4	0.78	110.4	1142.	99.842	
118	J3	0.77	23.7	4.6	0.52	324.0	142.2	99.962	
119	J3	0.77	23.4	6.9	0.45	32.3	7907.	99.951	
120	HFC	0.77	23.4	6.3	0.45	52.3	4102.	99.962	
121	HFC	0.77	23.0	6.4	0.66	307.4	141.7	99.944	

NOTE ** BLOOMFIELD PLANT CHANGED TO COMPLETE PRECHLORINATION ** STAINING MATERIAL REMOVED IN PRIMARY CLARIFIER

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
122	J3	2.03	22.3	6.2	0.73	108.5	87.66	99.935	
123-1	J3	2.03	22.3	5.2	0.64	113.9	75.23	99.914	SEPTUMS CLEANED BEFORE RUN TO REMOVE PREVIOUS STAIN
123-2	J3	2.03	22.3	4.9	0.57	114.8	56.11	99.892	
123-3	J3	2.03	22.3	4.2	0.56	116.7	47.32	99.899	
124-1	J3	2.03	22.3	5.1	0.56	69.8	195.2	99.754	
124-2	J3	2.03	22.3	4.0	0.59	69.8	136.2	99.897	
125-1	J3	2.03	22.1	3.0	0.54	35.4	362.6	99.714	
125-2	J3	2.03	22.0	2.4	0.35	35.6	205.0	99.921	
126	J3	1.50	22.0	---	0.56	29.5	---	---	TURBIDITY DECREASED THROUGHOUT RUN
127-1	J3	2.03	21.8	3.1	0.56	22.8	965.4	99.886	
127-2	J3	2.03	21.8	2.6	0.52	23.0	464.8	99.914	

Table 28. Bridges' data from filtration of raw surface waters

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
BRIDGES	MOBILE TREATMENT UNIT			RAW LAKE WATER AT ALBIA, IOWA			6/2/67 - 6/30/67		
1	J3	0.99	17.4	10.8	0.77	182.9	156.1	99.782	GENERATOR STOPPED TWICE DURING RUN
2	J3	0.99	21.0	11.7	0.78	93.0	595.1	99.889	
3	J3	0.99	20.8	10.8	1.02	127.4	593.7	99.209	
4	J3	0.99	21.6	11.4	0.87	167.0	219.1	99.823	COPPER SULFATE ADDED TO LAKE
5	J3	0.99	21.2	7.7	0.75	63.0	1263.5	99.898	
6	J3	0.99	21.4	7.5	0.61	38.9	---	---	EXPONENTIAL HEAD LOSS CURVE
7	J3	0.99	22.4	10.0	0.95	98.8	857.0	99.887	
8	J3	0.99	21.2	7.2	0.59	181.6	183.3	99.739	
9	J3	0.99	22.9	8.4	0.85	293.4	101.1	99.738	
10	J3	0.99	24.0	10.2	0.99	248.0	127.7	99.894	
11	HFC	0.99	23.0	10.0	1.06	132.9	1060.4	99.916	LEAK IN SEPTUM REPAIRED AFTER RUN
12	HFC	0.99	22.5	52.	1.59	133.4	4436.8	99.553	HIGH TURBIDITY DUE TO HEAVY RAINS
13	HFC	0.99	22.7	76.	4.5	221.2	1922.3	99.836	
14-1	J4	0.99	22.2	82.	1.73	216.4	---	---	EXPONENTIAL HEAD LOSS CURVE
14-2	J4	0.99	22.2	57.	1.34	216.4	---	---	EFFLUENT RECIRCULATED TO REDUCE TURB. EXPONENTIAL HEAD LOSS CURVE
15-1	J4	0.99	22.6	62.	1.34	291.9	---	---	EFFLUENT RECIRCULATED ** EXPONENTIAL
15-2	J4	0.99	22.6	83.	2.0	291.9	---	---	EFFLUENT RECIRCULATED ** EXPONENTIAL
16	HFC	0.99	23.1	66.	11.0	352.9	148.7	99.719	EFFLUENT RECIRCULATED POSSIBLE LEAK IN SEPTUM
17	HFC	0.99	24.1	32.5	9.6	384.1	212.2	99.820	EFFLUENT RECIRCULATED
18	HFC	0.99	23.7	24.2	4.6	279.6	291.6	99.905	EFFLUENT RECIRCULATED
19	J3	0.99	23.6	71.	---	182.	---	---	60 MG/L ALUM MIXED WITH INFLUENT VERY RAPID HEAD LOSS INCREASE HEAVY RAIN DURING RUN
20	J3	0.99	23.0	28.5	0.4	182.	---	---	46 MG/L ALUM MIXED WITH INFLUENT EFFLUENT RECIRCULATED VERY RAPID HEAD LOSS INCREASE
21	J3	0.76	23.5	25.6	0.06	542.6	994.8	99.915	82 MG/L ALUM ** EFFLUENT RECIRCULATED
22-1	J3	0.76	24.3	20.0	6.8	522.0	105.9	99.564	EFFLUENT RECIRCULATED
22-2	J3	0.76	24.3	18.3	0.04	522.0	1174.3	99.560	84 MG/L ALUM ** EFFLUENT RECIRCULATED
23-1	J3	0.76	23.5	26.0	5.5	483.4	105.5	99.989	
23-2	J3	0.76	23.5	47.0	0.00	483.4	2349.6	100.000	160 MG/L ALUM ONLY 2 HEAD LOSS READINGS MADE
24-1	J3	0.76	23.5	31.0	11.7	498.5	90.8	99.892	
24-2	J3	0.76	23.5	34.8	0.51	498.5	3368.2	99.961	120 MG/L ALUM
25-1	J3	0.76	24.6	23.8	9.7	519.6	107.0	99.970	
25-2	J3	0.76	24.6	25.6	2.9	519.6	2919.5	99.981	80 MG/L ALUM
26-1	J3	0.76	25.1	20.8	10.0	498.1	87.1	99.670	
26-2	J3	0.76	25.1	29.5	1.6	498.1	1687.3	99.939	40 MG/L ALUM
27-1	J3	0.99	26.7	17.0	12.8	89.8	219.5	99.932	
27-2	J3	0.99	26.7	19.4	8.2	89.8	306.8	99.732	8 MG/L ALUM
28-1	J3	0.99	26.3	11.3	8.5	192.1	60.5	99.721	
28-2	J3	0.99	26.3	11.3	7.7	192.1	182.4	99.665	10 MG/L ALUM

Table 28 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
29-1	J3	0.99	26.1	12.0	10.5	40.4	453.1	99.861	
29-2	J3	0.99	26.1	16.5	7.0	40.4	2931.0	99.477	10 MG/L ALUM
30-1	HFC	0.99	25.3	16.0	10.8	94.9	357.7	99.773	
30-2	HFC	0.99	25.3	18.4	7.4	94.9	1007.7	99.624	10 MG/L ALUM
31	HFC	0.99	26.1	12.9	6.2	15.0	5979.3	99.875	SEPTUMS DID NOT BACKWASH WELL
32	HFC	0.99	25.1	15.9	10.0	7.8	21098.	99.844	SEPTUMS REMOVED AND CLEANED
33	HFC	0.99	24.7	10.2	5.6	7.9	---	---	EXPONENTIAL HEAD LOSS CURVE
34	HFC	0.99	24.9	10.1	5.8	14.7	9950.6	99.745	
35	HFC	0.99	25.2	9.8	5.3	32.9	2697.4	99.938	
36-1	HFC	0.99	26.9	8.8	6.4	99.5	574.8	99.949	
36-2	HFC	0.99	26.9	8.8	0.5	99.5	15764.	99.869	20 MG/L ALUM
37-1	HFC	0.99	26.8	8.9	7.1	134.0	382.1	99.876	
37-2	HFC	0.99	26.8	13.6	2.4	134.0	5908.5	99.879	20 MG/L ALUM
38-1	HFC	0.99	25.5	10.1	6.8	166.8	250.3	99.380	
38-2	HFC	0.99	25.5	11.3	4.4	166.8	5614.4	99.586	20 MG/L ALUM
39-1	HFC	0.99	25.7	10.2	6.4	197.7	208.0	99.962	COPPER SULFATE ADDED TO LAKE
39-2	HFC	0.99	25.7	10.7	4.4	197.7	6185.9	99.191	20 MG/L ALUM
40-1	HFC	0.99	26.8	10.4	5.5	237.8	383.7	99.891	
40-2	HFC	0.99	26.8	11.3	1.4	237.8	2886.6	99.575	20 MG/L ALUM
41-1	HFC	0.99	26.4	9.8	5.9	166.5	314.7	99.746	
41-2	HFC	0.99	26.4	11.3	0.15	166.5	9719.1	99.806	30 MG/L ALUM
42-1	HFC	0.99	26.0	10.1	6.9	200.8	268.3	99.857	
42-2	HFC	0.99	26.0	11.0	1.6	200.8	7558.6	99.953	30 MG/L ALUM
43-1	HFC	0.99	26.7	10.6	8.0	298.0	223.6	99.890	
43-2	HFC	0.99	26.7	10.6	2.5	298.0	331.3	99.183	10 MG/L ALUM
BRIDGES	MOBILE TREATMENT UNIT			MISSOURI RIVER AT COUNCIL BLUFFS, IOWA				7/7/67 - 8/1/67	
44	HFC	0.99	22.3	137.	1.4	237.0	1366.4	99.980	
45	HFC	0.76	23.1	131.	1.7	305.5	1123.8	99.916	MIXER OPERATED TO PREVENT SETTLING IN WET WELL
46	HFC	0.76	25.0	463.	2.6	470.7	5073.9	99.519	PRIMARY SETTLING IN ERDLATOR
47	HFC	0.76	25.0	400.	0.73	460.	3015.9	100.000	PRIMARY SETTLING IN ERDLATOR ONLY 2 HEAD LOSS READINGS MADE
48	J3	0.76	26.3	567.	16.3	415.3	13366.	100.000	PRIMARY SETTLING IN ERDLATOR ONLY 2 HEAD LOSS READINGS MADE
49	J3	0.76	24.8	183.	1.9	299.0	737.7	99.856	WATER TAKEN FROM PRIMARY SETTLING BASINS DURING THIS AND ALL FOLLOWING FILTER RUNS
50	J3	0.76	25.0	148.	6.1	468.6	239.6	99.930	
51	J3	0.76	25.0	115	1.12	246.1	764.4	99.970	
52	J3	0.76	24.2	103	1.23	154.5	544.5	99.747	
53	J3	0.76	23.8	345.	210.	82.1	20083.	98.718	
54	HFC	0.76	23.6	295.	2.5	308.8	5713.3	99.468	
55	HFC	0.76	23.9	273.	1.9	451.3	1627.1	99.910	

Table 28 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY		BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
				INFLUENT JTU	EFFLUENT JTU				
56	HFC	0.76	24.2	193.	1.0	319.1	1857.0	99.689	
57-1	J3	0.76	24.7	164.	5.2	439.1	174.7	99.765	SEPTUMS WERE SLIGHTLY CLOGGED
57-2	J3	0.76	24.7	164.	0.55	459.8	236.8	99.100	10 MG/L ALUM MIXED WITH INFLUENT
58-1	J3	0.76	25.3	157	1.28	296.9	468.3	99.112	SEPTUMS CLEANED BEFORE RUN
58-2	J3	0.76	25.3	157.	0.51	308.3	609.7	99.144	10 MG/L ALUM
59-1	J3	0.76	25.5	121.	1.6	177.5	746.8	99.817	
59-2	J3	0.76	25.5	121.	0.19	185.4	1266.6	99.839	10 MG/L ALUM
60-1	J3	0.76	26.0	119.	1.7	118.2	---	---	EXPONENTIAL HEAD LOSS CURVE
60-2	J3	0.76	26.0	119.	1.1	118.2	4909.3	99.995	10 MG/L ALUM
61-1	J3	0.76	26.1	111.	1.6	197.5	932.9	99.973	
61-2	J3	0.76	26.1	111.	0.64	197.5	1206.4	99.468	6 MG/L ALUM
62	HFC	0.76	25.9	95.	0.45	148.6	2088.6	99.760	
63	J3	0.76	27.2	140.	4.8	191.1	6202.8	99.720	
64-1	J3	0.76	28.0	144.	3.0	307.4	373.7	99.896	
64-2	J3	0.76	28.0	120.	0.41	307.4	625.8	99.443	20 MG/L ALUM
65-1	J3	0.76	27.1	76.	1.5	224.8	246.9	99.749	
65-2	J3	0.76	27.2	76.	0.00	224.8	291.6	99.361	4 MG/L ALUM
66-1	J3	0.76	27.6	93.	1.4	220.9	662.0	99.940	
66-2	J3	0.76	27.6	93.	0.20	220.9	1082.2	99.728	2 MG/L ALUM
67	J3	0.76	27.5	87.	0.80	112.9	972.5	99.976	
68	HFC	0.76	27.0	74.	0.09	223.2	441.2	99.966	SEPTUMS CLEANED BEFORE RUN
69	HFC	0.76	27.3	78.	0.09	122.5	1714.9	99.952	
70	HFC	0.76	27.0	74.	0.12	80.2	5549.1	99.926	
71	HFC	0.76	26.9	71.	0.12	39.7	---	---	EXPONENTIAL HEAD LOSS CURVE
72	HFC	0.76	27.0	93.	0.00	184.9	1276.6	99.924	
73	J3	0.76	27.6	119.	0.47	145.0	1408.8	99.973	
74-1	J3	0.76	27.2	107.	1.3	216.5	300.4	99.804	
74-2	J3	0.76	27.2	120.	0.09	221.3	1748.0	100.000	30 MG/L ALUM
75-1	J3	0.76	27.7	95.	0.7	230.0	331.6	99.937	
75-2	J3	0.76	27.9	108.	0.2	233.2	2861.6	99.999	50 MG/L ALUM
76-1	J3	0.76	27.0	91.	0.8	217.6	356.5	98.910	
76-2	J3	0.76	27.0	91.	0.2	217.6	3885.3	99.973	80 MG/L ALUM
BRIDGES	MOBILE TREATMENT UNIT			RAW LAKE WATER AT CLEAR LAKE, IOWA			8/3/67 - 8/31/67		
77	J3	0.76	24.8	47.1	12.2	216.7	742.4	99.623	SEPTUMS CLEANED BEFORE RUN
78	J3	0.76	25.6	55.	12.3	146.0	3668.9	99.528	
79	J3	0.99	24.6	46.5	10.9	156.0	2261.0	99.902	
80	HFC	0.76	23.8	41.2	7.3	420.2	1346.7	99.982	
81	HFC	0.76	24.9	46.2	7.3	477.7	1178.4	100.000	
82-1	HFC	0.52	24.7	47.3	6.9	680.5	1007.5	99.974	
82-2	HFC	0.52	24.7	43.9	8.6	694.3	996.5	99.974	
83	HFC	0.34	24.0	37.2	7.4	972.4	526.6	99.966	
84	HFC	0.52	27.1	42.6	8.6	689.6	842.9	99.904	
85	HFC	0.76	26.4	45.8	8.4	354.8	1968.7	99.893	

Table 28 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY		BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
				INFLUENT JTU	EFFLUENT JTU				
86	J3	0.76	24.5	42.0	10.5	440.8	462.2	99.964	
87	J3	0.52	24.7	45.0	10.4	681.3	402.3	99.801	
88	J3	0.76	23.0	40.3	10.7	288.2	992.0	99.919	
89-1	J3	0.76	23.3	43.2	11.0	454.1	492.5	99.932	
89-2	J3	0.76	23.3	43.2	9.1	454.1	605.5	99.734	10 MG/L ALUM MIXED WITH INFLUENT
90-1	HFC	0.52	22.4	38.9	6.2	641.9	843.8	99.913	
90-2	HFC	0.52	23.4	39.6	4.2	656.5	1023.6	99.944	10 MG/L ALUM
91-1	HFC	0.52	24.9	52.1	8.0	651.4	743.6	99.939	SEPTUMS CLEANED BEFORE RUN
91-2	HFC	0.52	24.7	51.7	4.8	659.0	1860.2	99.901	20 MG/L ALUM
92-1	HFC	0.34	22.4	50.2	7.2	968.1	403.3	99.891	
92-2	HFC	0.34	23.1	54.2	3.8	973.2	5382.7	99.038	30 MG/L ALUM
93-1	HFC	0.34	24.3	57.0	8.2	1021.4	473.9	99.954	
93-2	HFC	0.34	25.1	56.8	4.4	1024.7	12055.	99.983	40 MG/L ALUM
94-1	HFC	0.34	25.1	54.3	8.0	1047.9	489.0	99.870	FILTER AID MAY HAVE PASSED THROUGH SEPTUMS
94-2	HFC	0.34	24.8	53.7	13.3	1054.7	6503.6	99.724	50 MG/L ALUM ** FILTER AID MAY HAVE PASSED THROUGH SEPTUMS
95-1	HFC	0.34	23.5	43.5	8.3	982.4	463.5	99.953	
95-2	HFC	0.99	24.1	50.5	7.1	339.1	2277.4	99.998	
96-1	HFC	0.34	25.3	55.8	8.1	1028.0	436.5	99.933	FILTER AID FOUND IN EFFLUENT
96-2	HFC	0.34	25.4	55.3	10.3	1036.1	17219.	100.000	50 MG/L ALUM ** FILTER AID FOUND IN EFFLUENT ** ONLY 2 HEAD LOSS READINGS
97	J3	0.76	23.9	19.6	5.3	210.9	2504.4	99.964	EROLATOR USED WITH 50 MG/L ALUM
98	J3	0.76	24.2	20.9	7.0	439.5	606.4	99.995	EROLATOR USED WITH 50 MG/L ALUM FILTER AID FOUND IN EFFLUENT SEPTUMS REPAIRED AFTER RUN
100-1	HFC	0.34	20.0	43.8	8.2	989.5	431.7	99.969	FILTER AID STILL PASSING THROUGH SEPTUMS
100-2	HFC	0.34	20.0	42.6	10.0	999.3	5729.6	99.824	50 MG/L ALUM MIXED WITH INFLUENT FILTER AID FOUND IN EFFLUENT
101-1	J3	0.76	20.2	42.3	10.6	436.3	389.7	99.962	
101-2	J3	0.76	20.5	43.4	5.3	436.3	4165.1	100.000	50 MG/L ALUM ** ONLY 2 HEAD LOSS READINGS
102-1	HFC	0.34	20.6	44.1	6.8	966.6	525.8	99.930	
102-2	HFC	0.34	20.1	43.2	5.8	977.8	663.6	99.880	0.5 MG/L SEPARAN NP10 POLYELECTROLYTE MIXED WITH INFLUENT
103-1	HFC	0.34	19.5	44.0	6.8	980.3	457.5	99.910	
103-2	HFC	0.34	20.7	43.8	7.7	1004.4	438.1	98.725	1.0 MG/L SEPARAN MIXED WITH INFLUENT
104	J3	0.34	21.7	10.5	1.5	994.0	470.7	99.784	ERDLATOR USED WITH 70 MG/L ALUM
105-1	J3	0.34	20.7	11.7	1.5	940.2	278.2	99.880	ERDLATOR USED WITH 70 MG/L ALUM
105-2	J3	0.34	21.3	11.7	1.8	933.7	672.5	99.822	ERDLATOR USED WITH 70 MG/L ALUM PLUS 0.5 MG/L SEPARAN
106-1	J3	0.52	22.7	13.8	2.7	638.1	468.3	99.971	ERDLATOR USED WITH 70 MG/L ALUM
106-2	J3	0.52	23.7	14.2	6.4	633.8	1181.4	99.969	ERDLATOR USED WITH 70 MG/L ALUM 1.3 MG/L SEPARAN MIXED WITH INFLUENT
107	J3	0.52	22.7	12.6	3.3	720.8	409.1	99.936	ERDLATOR USED WITH 70 MG/L ALUM

Table 28 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	TURBIDITY INFLUENT JTU	TURBIDITY EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R O/O	COMMENTS
108	J3	0.52	21.5	15.2	2.0	630.0	383.2	99.908	ERDLATOR USED WITH 70 MG/L ALUM PLUS 1.0 MG/L SEPARAN
109	J3	0.76	22.0	45.5	11.7	205.9	2553.9	99.795	
110	HFC	0.76	22.2	46.8	8.9	232.4	5632.1	99.995	
111-1	J3	0.52	20.6	15.5	3.0	624.5	1075.5	99.672	ERDLATOR USED WITH 70 MG/L ALUM
111-2	J3	0.52	20.6	15.5	40.7	624.5	1632.7	99.510	ERDLATOR USED WITH 70 MG/L ALUM PLUS 1.0 MG/L SEPARAN ** LARGE AMOUNT OF FILTER AID FOUND IN EFFLUENT
112	J3	0.76	21.8	49.6	11.7	447.4	716.3	99.865	SOME FILTER AID FOUND IN EFFLUENT
113	J3	0.76	21.6	49.1	32.7	430.8	644.7	99.348	PRECOAT AND BODY FEED FILTER AID WERE COATED WITH 2 MG PURIFLOC 601 POLYE. PER GM OF FILTER AID
114	J3	0.76	21.0	44.9	11.2	444.2	808.4	99.977	BODY FEED COATED WITH 2 MG PURIFLOC 601 PER GM OF FILTER AID
115	J3	0.76	20.7	24.6	4.6	457.2	595.6	99.802	ERDLATOR USED WITH 56 MG/L FERRIC CHLORIDE AND 105 MG/L LIMESTONE
116	J3	0.52	20.7	35.1	4.9	724.0	690.0	99.841	ERDLATOR USED WITH 56 MG/L FERRIC CHLORIDE AND 105 MG/L LIMESTONE
117	J3	0.52	19.7	19.7	2.8	722.5	513.5	99.370	ERDLATOR USED WITH 79 MG/L FERRIC CHLORIDE AND 162 MG/L LIMESTONE
118	J3	0.76	20.1	43.5	10.0	458.4	418.5	99.160	PRECOAT AND BODY FEED COATED WITH 2 MG SEPARAN PER GM FILTER AID

Table 29. Cerwick's pilot plant data (20)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
CERWICK	LABORATORY PILOT PLANT			UNIVERSITY TAP WATER PLUS KENTUCKY BALL CLAY (KAOLINITE)					SUMMER, 1967
1A	HFC	1.0	25.1	17.4	0.04	42.4	972.1	99.668	
1B	HFC	1.0	25.1	17.4	0.04	42.4	123373.	99.707	72.4 MG/L ALUM FLASH MIXED WITH FILTER INFLUENT
2A	HFC	1.0	25.1	17.4	0.02	44.8	792.3	99.900	
2B	HFC	1.0	25.1	17.4	0.02	44.8	71684.	99.911	42.1 MG/L ALUM
3A	HFC	1.0	25.2	19.8	0.00	38.7	2204.8	99.928	
3B	HFC	1.0	25.2	19.8	0.00	38.7	96526.	99.992	31.6 MG/L ALUM
4A	HFC	1.0	25.3	19.8	0.01	35.1	2602.4	99.809	
4B	HFC	1.0	25.3	19.8	0.01	35.1	26870.	99.999	15.0 MG/L ALUM
5	HFC	1.0	25.2	---	---	---	---	---	VOID ** MECHANICAL DIFFICULTIES
6A	HFC	1.0	25.2	18.7	0.01	42.4	1212.8	99.880	
6B	HFC	1.0	25.2	18.7	0.01	42.4	4455.2	99.988	6.78 MG/L ALUM
7A	HFC	1.0	25.0	19.5	0.01	39.2	2270.2	99.970	
7B	HFC	1.0	25.0	19.5	0.01	39.2	38364.	99.941	23.4 MG/L ALUM
8A	HFC	1.0	24.8	18.5	0.01	42.8	1578.8	99.628	
8B	HFC	1.0	24.8	18.5	0.01	42.8	120856.	99.995	58.1 MG/L ALUM
9A	HFC	1.0	25.0	19.7	0.03	41.6	1912.8	99.836	
9B	HFC	1.0	25.0	19.7	0.03	41.6	179515.	99.740	120. MG/L ALUM
10A	HFC	1.0	25.2	19.5	0.00	38.7	2311.9	99.761	
10B	HFC	1.0	25.2	19.5	0.00	38.7	11781.	99.938	50.1 MG/L ALUM
11A	HFC	1.0	25.2	56.7	0.00	69.4	2634.3	99.940	
11B	HFC	1.0	25.2	56.7	0.00	69.4	57146.	99.896	57.3 MG/L ALUM
12A	HFC	1.0	24.6	58.6	0.02	132.0	944.8	99.835	
12B	HFC	1.0	24.6	58.6	0.02	132.0	6204.2	99.960	18.7 MG/L ALUM
13A	HFC	1.0	24.9	57.5	0.00	130.5	993.5	99.926	
13B	HFC	1.0	24.9	57.5	0.00	130.5	2321.1	99.898	5.5 MG/L ALUM
14A	HFC	1.0	24.7	54.6	0.00	141.0	790.1	99.966	
14B	HFC	1.0	24.7	54.6	0.00	141.0	3210.7	99.935	11.4 MG/L ALUM
15A	HFC	1.0	25.0	57.8	0.01	129.5	989.1	99.956	
15B	HFC	1.0	25.0	57.8	0.01	129.5	13677.	99.958	36.9 MG/L ALUM
16A	HFC	1.0	24.9	51.6	0.00	129.0	641.8	99.939	
16B	HFC	1.0	24.9	51.6	0.00	129.0	11296.	99.992	46.1 MG/L ALUM
17A	HFC	1.0	25.0	54.5	0.01	119.0	1039.7	99.955	
17B	HFC	1.0	25.0	54.5	0.01	119.0	13028.	99.968	30.3 MG/L ALUM
18A	HFC	1.0	24.7	55.1	0.00	137.0	759.5	99.956	
18B	HFC	1.0	24.7	55.1	0.00	137.0	21901.	99.901	63.6 MG/L ALUM
19A	HFC	1.0	25.0	54.9	0.00	137.0	876.0	99.813	
19B	HFC	1.0	25.0	54.9	0.00	137.0	28420.	99.382	90.4 MG/L ALUM
20A	HFC	1.0	25.0	57.0	0.00	134.5	929.3	99.935	
20B	HFC	1.0	25.0	57.0	0.00	134.5	1595.3	99.985	2.41 MG/L ALUM
21A	HFC	1.0	24.0	57.0	---	132.2	766.6	99.752	
21B	HFC	1.0	24.0	57.0	---	132.2	920.7	99.947	0.0 MG/L ALUM
22A	HFC	1.0	25.0	19.7	---	42.4	1151.1	99.865	
22B	HFC	1.0	25.0	19.7	---	42.4	987.8	99.953	0.0 MG/L ALUM

Table 30. Arora's pilot plant data (2)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R C/O	COMMENTS
ARORA	LABORATORY PILOT PLANT			UNIVERSITY TAP WATER PLUS FERROUS SULFATE				12/24/66 - 3/12/67	
1	J0	1.0	60	6.69	0.06	52.4	1920.	99.562	TRIAL RUN
2	J0	1.0	60	3.56	0.03	95.	---	---	TRIAL RUN ** BODY FEED STOPPED IN MIDDLE OF RUN
3	J0	1.0	60	8.34	0.00	86.	2931.	99.806	TRIAL RUN
4	J0	1.0	60	8.43	0.23	96.5	2259.	99.884	BODY FEED STOPPED DURING RUN
5	S3	1.0	60	8.31	0.07	84.5	1346.	99.916	
6	S3	1.0	60	8.55	0.05	91.5	1253.	99.746	
7	S3	1.0	60	8.89	0.03	91.	946.	99.975	
8	S3	1.0	60	8.51	0.03	58.5	2080.	99.662	
9	S3	1.0	60	8.52	0.07	112.	705.6	99.986	
10	S3	1.0	60	8.36	0.11	35.4	7631.	99.816	
11	S3	1.0	60	8.21	0.15	23.1	15470.	99.150	
12	S3	1.0	60	11.41	0.10	149.0	---	---	CONCENTRATION OF IRON IN INFLUENT VARIED DURING RUN
13	S3	1.0	60	8.95	0.03	227.0	280.0	99.931	
14	S3	1.0	60	8.71	0.04	352.0	163.6	99.929	
15	S3	1.0	60	---	---	---	---	---	RUN DISCONTINUED ** BYPASS VALVE LEFT OPEN
ARORA	LABORATORY PILOT PLANT			UNIVERSITY TAP WATER PLUS FERRIC CHLORIDE				3/15/67 - 3/4/68	
15A	S3	1.0	60	6.90	---	74.3	---	---	EXPONENTIAL HEAD LOSS CURVE
16	S3	1.0	60	7.48	0.06	108.0	8103.	99.778	
17	S3	1.0	60	7.43	0.06	219.5	1747.	99.820	
18	S2-22	1.0	60	6.91	0.12	150.0	2453.	99.937	
19	S2-22	1.0	60	7.51	0.05	211.2	1553.	99.946	
20	S2-22	1.0	60	7.49	0.05	248.3	1166.	99.979	
21	S2-22	1.0	60	7.52	0.06	322.6	825.1	99.965	
22	S2-22	1.0	60	7.25	0.04	139.5	3291.	99.846	
23	S2-22	1.0	60	7.15	0.06	125.6	3518.	99.861	DUPLICATION OF RUN 22
24	S2-22	1.0	60	6.20	0.03	117.2	3245.	99.872	DUPLICATION OF RUN 22
25	S2-22	1.0	60	6.51	0.03	160.8	2135.	99.881	
26	S2-22	1.0	60	6.85	0.06	242.6	1169.	99.956	
27	S2-22	1.0	60	6.98	0.04	282.2	867.4	99.979	
28	S2-22	1.0	60	6.70	0.06	73.5	10920.	99.878	
29	S3-4	1.0	60	7.50	0.09	124.0	5453.	99.784	
30	S3-4	1.0	60	7.21	0.07	125.4	5305.	99.846	DUPLICATION OF RUN 29
31	S3-4	1.0	60	7.07	0.07	118.8	5906.	99.903	DUPLICATION OF RUN 29
32	S3-4	1.0	60	7.11	0.07	96.5	10730.	99.890	
33	S3-4	1.0	60	7.21	0.06	68.9	23310.	99.481	

Table 30 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
34	S3-4	1.0	60	7.09	0.04	247.9	1429.	99.936	
35	S3-4	1.0	60	7.36	0.04	180.6	2706.	99.736	
36	S3-4	1.0	60	8.00	0.06	311.4	1134.	99.920	
37	S3-4	1.0	60	8.47	0.16	341.6	1004.	99.932	
38	S3-4	1.0	60	7.62	0.08	412.3	650.8	99.951	
39	S2-4	1.0	60	7.54	0.05	170.0	2564.	99.910	
40	S2-4	1.0	60	7.53	0.03	189.0	1750.	99.849	
41	S2-4	1.0	60	7.62	0.03	262.4	1047.	99.957	
42	S2-4	1.0	60	7.17	0.03	309.4	728.7	99.936	
43	S2-4	1.0	60	7.44	0.03	309.0	723.3	99.925	SAME AS RUN 42 EXCEPT NO COPPER SULFATE ADDED
44	S2-4	1.0	60	7.37	0.09	51.2	36670.	98.003	
45	S2-4	1.0	60	7.24	0.07	68.5	18290.	99.594	
46	S2-3	1.0	60	7.60	0.05	66.8	21600.	99.567	
47	S2-3	1.0	60	6.69	0.08	50.7	34580.	97.904	HEAD LOSS CURVE ALMOST EXPONENTIAL
48	S2-3	1.0	60	7.26	0.12	117.6	4949.	99.699	
49	S2-3	1.0	60	9.52	0.17	166.7	3827.	99.817	
50	S2-3	1.0	60	8.06	0.11	190.6	2205.	99.900	
51	S2-3	1.0	60	7.93	0.13	257.4	1263.	99.916	
52	S2-3	1.0	60	8.20	0.07	292.1	1035.	99.972	
53	S2-1	1.0	60	6.95	0.07	130.8	4064.	99.602	
54	S2-1	1.0	60	7.21	0.06	155.1	2759.	99.873	
55	S2-1	1.0	60	7.31	0.06	200.5	1822.	99.962	
56	S2-1	1.0	60	8.02	0.06	207.9	1728.	99.676	
57	S2-1	1.0	60	8.08	0.08	301.1	890.5	99.980	
58	S2-1	1.0	60	---	0.12	---	---	---	CONCENTRATION OF IRON IN INFLUENT VARIED DURING RUN
59	S2-1	1.0	60	7.86	0.15	98.2	9138.	99.647	
60	S2-1	1.0	60	7.87	0.11	101.4	8736.	99.927	DUPLICATION OF RUN 59
61	S2-20	1.0	60	7.79	0.06	92.8	9820.	99.841	
62	S2-20	1.0	60	7.94	0.07	78.4	16590.	99.642	
63	S2-20	1.0	60	7.84	0.05	102.7	6576.	99.862	
64	S2-20	1.0	60	7.99	0.07	127.1	5208.	99.936	
65	S2-20	1.0	60	7.93	0.06	148.3	3576.	99.935	
66	S2-20	1.0	60	7.91	0.05	252.0	1311.	99.966	
67	S2-23	1.0	60	8.27	0.06	86.6	14010.	99.506	
68	S2-23	1.0	60	8.00	0.07	123.8	6271.	99.796	
69	S2-23	1.0	60	7.59	0.04	125.4	5400.	99.475	
70	S2-23	1.0	60	7.63	0.07	188.6	2213.	99.851	
71	S2-23	1.0	60	8.32	0.17	242.1	1734.	99.960	
72	S2-23	1.0	60	7.58	0.04	70.1	16980.	99.762	

Table 30 (Continued)

FILTER RUN NO	FILTER AID	Q	INFLUENT TEMP	SUSPENDED SOLIDS		BODY FEED	BETA INDEX	R	COMMENTS
		GPM/SQ FT	DEG F	INFLUENT MG/L	EFFLUENT MG/L	MG/L	10^4 FT^{-2}	0/0	
73	S3-2	1.0	60	8.06	0.04	111.0	9644.	99.857	
74	S3-2	1.0	60	8.27	0.05	165.8	4252.	99.531	
75	S3-2	1.0	60	7.77	0.03	207.9	2388.	99.862	
76	S3-2	1.0	60	7.55	0.04	296.2	1391.	99.977	
77	S3-2	1.0	60	7.51	0.03	339.9	842.0	99.950	
78	S3-2	1.0	60	7.53	0.03	165.8	3496.	99.809	
79	S3-1	1.0	60	8.09	0.03	153.5	4922.	99.778	
80	S3-1	1.0	60	7.25	0.03	148.9	3849.	99.830	
81	S3-1	1.0	60	8.20	0.05	207.1	2452.	99.806	
82	S3-1	1.0	60	8.40	0.05	253.3	1722.	99.819	
83	S3-1	1.0	60	7.56	0.04	299.1	1053.	99.978	
84	S3-1	1.0	60	7.62	0.04	368.0	906.4	99.987	
85	S3-1	1.0	60	7.56	0.04	99.0	11780.	99.938	
86	S3-1	1.0	60	7.41	0.03	106.0	10200.	99.818	DUPLICATION OF RUN 73
87	S3-3	1.0	60	6.96	0.04	111.8	7876.	99.824	
88	S3-3	1.0	60	7.78	0.05	161.0	4260.	99.898	
89	S3-3	1.0	60	7.85	0.03	226.1	2361.	99.975	
90	S3-3	1.0	60	7.62	0.03	249.2	1722.	99.971	
91	S3-3	1.0	60	7.69	0.05	319.3	1132.	99.900	
92	S3-3	1.0	60	7.59	0.04	389.4	829.2	99.973	
93	J3-5	1.0	60	8.00	0.14	233.1	2250.	99.964	
94	J3-5	1.0	60	7.65	0.07	328.4	1101.	99.909	
95	J3-5	1.0	60	7.72	0.03	381.6	834.9	99.954	
96	J3-5	1.0	60	7.67	0.03	191.4	2974.	99.781	
97	J3-5	1.0	60	7.49	0.03	114.3	7953.	99.736	
98	J3-6	1.0	60	7.55	0.03	204.0	2832.	99.540	
99	J3-6	1.0	60	7.17	0.03	128.7	6561.	99.684	
100	J3-6	1.0	60	7.26	0.03	214.1	2221.	99.685	
101	J3-6	1.0	60	7.89	0.07	250.8	1808.	99.949	
102	J3-6	1.0	60	8.23	0.03	382.0	1017.	99.972	
103	J0-4	1.0	60	8.57	0.08	207.5	4143.	99.065	
104	J0-4	1.0	60	8.78	0.03	294.1	2027.	99.813	
105	J0-4	1.0	60	8.40	0.05	349.0	1278.	99.896	
106	J0-4	1.0	60	8.26	0.03	186.5	4946.	99.515	
107	J4-6	1.0	60	8.30	0.03	173.3	3983.	99.488	
108	J4-6	1.0	60	8.27	0.06	248.7	2013.	99.766	
109	J4-6	1.0	60	8.37	0.04	332.1	1159.	99.679	
110	J4-6	1.0	60	8.06	0.05	417.9	659.4	99.836	
111	S4-3	1.0	60	8.04	0.05	137.4	5924.	99.949	
112	S4-3	1.0	60	7.91	0.05	116.3	8909.	99.928	

Table 30 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BCCY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
113	S4-3	1.0	60	7.98	0.05	81.7	19430.	99.256	
114	S4-3	1.0	60	8.21	0.05	204.2	2674.	99.866	
115	S4-3	1.0	60	8.15	0.03	278.1	1386.	99.922	
116	S4-2	1.0	60	7.78	0.04	132.8	7895.	99.896	
117	S4-2	1.0	60	7.75	0.03	87.0	18230.	99.684	
118	S4-2	1.0	60	7.88	0.05	156.3	5078.	99.944	
119	S4-2	1.0	60	8.00	0.03	217.8	2406.	99.919	
120	S4-2	1.0	60	8.28	0.03	301.1	1478.	99.957	
121	S4-2	1.0	60	8.03	0.03	422.4	953.9	99.986	
122	S2-5	1.0	60	8.08	0.03	127.1	4569.	99.815	
123	S2-5	1.0	60	8.42	0.03	167.5	2816.	99.898	
124	S2-5	1.0	60	7.85	0.03	70.5	19300.	99.264	
125	S2-5	1.0	60	8.08	0.03	217.4	1780.	99.978	
126	S2-5	1.0	60	7.88	0.03	293.0	878.0	99.951	
127	S2-9	1.0	60	7.72	0.03	128.7	4717.	99.897	
128	S2-9	1.0	60	8.06	0.03	89.5	12500.	99.820	
129	S2-9	1.0	60	8.30	0.03	152.2	3772.	99.926	
130	S2-9	1.0	61	8.21	0.03	200.5	2223.	99.990	NO TEMPERATURE CONTROL
131	S2-9	1.0	60	7.91	---	265.7	1189.	99.982	
132	S2-6	1.0	61	8.11	---	258.6	1171.	99.994	NO TEMPERATURE CONTROL
133	S2-6	1.0	60	7.87	0.03	88.3	10480.	99.830	
134	S2-6	1.0	60	7.81	0.03	194.7	1734.	99.919	
135	S2-6	1.0	60	7.54	0.03	151.0	2652.	99.892	
136	S2-6	1.0	60	7.88	0.04	311.9	804.1	99.971	
137	F5-1	1.0	60	7.38	0.03	312.3	2057.	99.686	
138	E5-1	1.0	60	---	---	232.2	---	---	VOID ** IRON CONCENTRATION UNKNOWN
139	E5-1	1.0	60	7.83	0.03	422.4	1269.	99.511	
140	E5-1	1.0	60	7.73	0.04	601.8	614.1	99.625	
141	E5-1	1.0	60	8.10	0.03	535.8	871.0	99.685	
142	G4-1	1.0	60	7.32	0.03	248.3	2766.	99.843	
143	G4-1	1.0	60	7.90	0.03	187.5	5541.	99.830	
144	G4-1	1.0	60	7.74	0.03	308.1	1867.	99.607	
145	G4-1	1.0	60	7.72	0.03	423.2	1121.	99.845	
146	G4-1	1.0	60	7.73	0.03	468.6	912.5	99.850	
147	G1-1	1.0	61	7.45	0.03	229.8	3550.	99.903	NO TEMPERATURE CONTROL
148	G1-1	1.0	60	8.17	0.03	293.9	2533.	99.949	
149	G1-1	1.0	60	7.76	0.03	372.5	1535.	99.991	
150	G1-1	1.0	60	7.64	0.03	479.3	1123.	99.935	
151	G1-1	1.0	60	7.64	0.03	163.4	7358.	99.893	

Table 30 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
152	J4-4	1.0	60	8.59	0.03	214.1	3015.	99.848	
153	J4-4	1.0	60	7.63	0.03	157.6	5215.	99.630	
154	J4-4	1.0	60	7.94	0.03	264.4	1667.	99.808	
155	J4-4	1.0	60	8.04	0.03	345.7	1036.	99.853	
156	J4-4	1.0	60	7.72	0.03	424.1	666.8	99.865	
157	J0-1	1.0	60	7.87	0.03	---	---	---	VOID ** BODY FEED CONCENTRATION VARIED DURING RUN
158	J0-1	1.0	60	7.98	0.03	---	---	---	VOID ** BODY FEED CONCENTRATION VARIED DURING RUN
159	J0-1	1.0	60	8.08	0.03	296.0	2030.	99.889	
160	J0-1	1.0	60	8.11	0.03	228.9	3266.	99.763	
161	J0-1	1.0	60	8.25	0.03	378.0	1234.	99.881	
162	J0-1	1.0	60	8.27	0.03	454.2	921.9	99.936	NO TEMPERATURE CONTROL
163	J0-1	1.0	60	8.22	0.03	170.0	5652.	99.820	
164	J3-7	1.0	60	7.80	0.03	203.0	3475.	99.481	
165	J3-7	1.0	60	7.93	0.03	277.6	1756.	99.851	
166	J3-7	1.0	60	8.03	0.03	339.1	1150.	99.847	
167	J3-7	1.0	60	7.79	0.03	461.2	641.2	99.944	
168	J3-7	1.0	60	7.65	0.03	551.9	458.9	99.969	
169	S2-21	1.0	60	7.70	0.03	112.2	6879.	99.971	
170	S2-21	1.0	60	8.03	0.03	158.8	3007.	99.969	
171	S2-21	1.0	60	8.02	0.03	215.3	1827.	99.988	
172	S2-21	1.0	60	8.02	0.03	249.2	1345.	99.990	
173	S2-21	1.0	60	8.13	0.03	294.9	1081.	99.959	
174	S1-2	1.0	60	7.64	0.03	162.9	2781.	99.699	
175	S1-2	1.0	60	8.26	0.03	197.2	1772.	99.921	
176	S1-2	1.0	60	8.30	0.03	240.5	1139.	99.974	
177	S1-2	1.0	60	8.22	0.03	313.1	696.3	99.977	
178	S1-2	1.0	60	8.18	0.03	112.2	6586.	99.801	
179	S4-1	1.0	60	8.23	0.03	123.8	10160.	99.886	
180	S4-1	1.0	60	8.17	0.03	184.0	3816.	99.959	
181	S4-1	1.0	60	8.12	0.03	245.0	2129.	99.933	
182	S4-1	1.0	60	8.24	0.03	306.1	1534.	99.969	
183	S4-1	1.0	60	8.27	0.03	415.0	992.6	99.995	
184	E5-17	1.0	60	8.04	0.03	346.1	1391.	99.614	
185	E5-17	1.0	60	8.16	0.03	460.8	853.3	99.851	
186	E5-17	1.0	60	8.04	0.03	538.7	635.5	99.910	
187	E5-17	1.0	60	7.78	0.03	253.4	2566.	99.846	

Table 30 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
188	E6-4	1.0	60	7.86	0.03	232.2	2396.	99.581	
189	E6-4	1.0	60	7.94	0.03	171.6	4460.	99.531	
190	E6-4	1.0	60	7.90	0.03	136.1	7629.	99.741	
191	E6-4	1.0	60	8.01	0.03	375.3	891.5	99.880	
192	E2-4	1.0	60	7.97	0.04	340.7	1787.	99.773	
193	E2-4	1.0	60	7.94	0.03	459.5	983.0	99.838	
194	E2-4	1.0	60	7.75	0.03	548.6	682.8	99.931	
195	E2-4	1.0	60	7.83	0.03	219.5	4382.	99.918	
196	E2-4	1.0	60	7.53	0.03	153.9	8221.	99.807	
197	E5-3	1.0	60	7.87	0.03	229.8	3400.	99.611	
198	E5-3	1.0	60	7.72	0.03	165.8	6565.	99.673	
199	E5-3	1.0	60	7.78	0.03	334.5	1511.	99.711	
200	E5-3	1.0	60	7.79	0.03	463.7	876.1	99.821	
201	E6-2	1.0	60	7.86	0.03	308.1	1301.	99.769	
202	E6-2	1.0	60	8.17	0.03	436.0	686.6	99.772	
203	E6-2	1.0	60	7.98	0.03	531.3	484.5	99.914	
204	E6-2	1.0	60	7.65	0.03	167.1	4848.	99.695	
205	E2-1	1.0	60	7.56	0.03	215.8	4013.	99.710	
206	E2-1	1.0	60	7.40	0.03	163.8	6662.	99.682	
207	E2-1	1.0	60	7.60	0.03	302.0	1847.	99.834	
208	E2-1	1.0	60	7.37	0.03	444.7	914.9	99.821	
209	G4-2	1.0	60	7.52	0.05	339.1	1298.	99.662	
210	G4-2	1.0	60	7.52	0.03	455.4	773.0	99.888	
211	G4-2	1.0	60	7.31	0.03	---	---	---	VOID ** BODY FEED CONCENTRATION VARIED DURING RUN
212	G4-2	1.0	60	8.00	0.03	246.3	2896.	99.736	
213	G4-2	1.0	60	7.90	0.03	179.4	5587.	99.448	
214	G1-2	1.0	60	7.68	0.03	230.2	4745.	99.908	
215	G1-2	1.0	60	7.77	0.03	163.8	8421.	99.890	
216	G1-2	1.0	60	7.46	0.03	308.6	2323.	99.946	
217	G1-2	1.0	60	7.33	0.03	413.3	1366.	99.950	
218	G1-2	1.0	60	7.24	0.03	311.0	2385.	99.946	DUPLICATION OF RUN 216
219	G1-2	1.0	60	7.75	0.03	562.7	913.8	99.961	
220	E2-3	1.0	60	8.06	0.03	348.9	1729.	99.803	
221	E2-3	1.0	60	8.12	0.03	468.6	1025.	99.894	
222	E2-3	1.0	60	7.83	0.03	584.5	639.1	99.944	
223	E2-3	1.0	60	7.97	0.03	171.6	7378.	99.724	
224	E2-3	1.0	60	7.99	0.03	223.2	4328.	99.708	

Table 30 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS		BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
				INFLUENT MG/L	EFFLUENT MG/L				
225	G4-5	1.0	60	7.60	0.03	---	---	---	VOID ** CLEAR WATER VALVE LEFT OPEN AFTER PRECOATING
226	G4-5	1.0	60	8.05	0.03	247.5	2798.	99.685	
227	G4-5	1.0	60	7.74	0.03	184.4	4631.	99.657	
228	G4-5	1.0	60	7.89	0.03	330.0	1520.	99.473	
229	G4-5	1.0	60	7.95	0.03	453.0	859.2	99.712	
230	G4-5	1.0	60	---	0.03	---	---	---	VOID ** INFLUENT IRON CONCENTRATION DECREASED DURING RUN
231	G4-4	1.0	60	7.85	0.03	359.7	1314.	99.548	
232	G4-4	1.0	60	8.38	0.03	514.0	765.8	99.798	
233	G4-4	1.0	60	7.99	0.03	629.5	506.1	99.909	
234	G4-4	1.0	60	8.00	0.03	211.2	3889.	99.681	
235	G4-4	1.0	60	7.77	0.03	247.5	2786.	99.785	
236	G4-3	1.0	60	8.02	0.06	174.9	5376.	99.807	
237	G4-3	1.0	60	8.00	0.04	252.9	2786.	99.777	
238	G4-3	1.0	60	7.91	0.03	328.4	1381.	99.784	
239	G4-3	1.0	60	7.77	0.03	441.0	816.2	99.841	
240	G4-3	1.0	60	7.94	0.03	555.2	543.3	99.856	
241	G8-3	1.0	60	7.94	0.03	269.8	2050.	99.858	
242	G8-3	1.0	60	7.84	0.03	325.8	1264.	99.937	
243	G8-3	1.0	60	7.51	0.03	423.2	152.7	99.015	
244	G9-3	1.0	60	---	0.03	---	---	---	VOID ** INFLUENT IRON CONCENTRATION DECREASED DURING RUN
245	G8-3	1.0	60	7.50	0.03	129.5	1202.	98.556	
246	G8-3	1.0	60	8.32	0.03	171.2	871.5	99.486	
247	G8-3	1.0	--	0.00	0.00	132.8	35.85	99.493	CLEAN TAP WATER FILTERED NO TEMPERATURE CONTROL
248	G4-4	1.0	60	0.00	0.00	174.5	11.42	99.484	CLEAN TAP WATER FILTERED
249	E2-3	1.0	60	0.00	0.00	167.5	15.50	99.837	CLEAN TAP WATER FILTERED
250	G4-3	1.0	60	0.00	0.00	169.1	11.09	99.115	CLEAN TAP WATER FILTERED
251	G1-3	1.0	60	7.57	0.03	154.7	8805.	99.937	INFLUENT TEMPERATURE NOT CONSTANT
252	G1-3	1.0	60	8.27	0.03	197.2	5228.	99.929	
253	G1-3	1.0	60	8.42	0.03	323.0	2179.	99.666	
254	G1-3	1.0	60	8.02	0.03	411.7	1249.	99.806	
255	G1-3	1.0	60	8.32	0.06	482.0	1073.	99.918	
256	E6-3	1.0	60	8.23	0.04	330.0	1297.	99.768	
257	E6-3	1.0	60	8.16	0.05	436.4	675.1	99.825	
258	E6-3	1.0	60	8.10	0.03	548.2	488.8	99.968	
259	E6-3	1.0	60	8.02	0.03	234.3	2914.	99.724	

Table 30 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG F	SUSPENDED SOLIDS INFLUENT MG/L	SUSPENDED SOLIDS EFFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
260	J4-7	1.0	60	7.89	0.03	169.1	5081.	99.399	
261	J4-7	1.0	60	7.82	0.38	35.5	70197.	98.710	EXPONENTIAL HEAD LOSS CURVE
262	J4-7	1.0	60	7.83	0.03	749.1	254.3	99.891	
263	J4-7	1.0	60	7.79	0.03	1099.7	133.9	99.916	
264	J4-7	1.0	60	7.40	0.03	1955.3	54.65	99.810	
265	J0-6	1.0	60	7.91	0.03	261.9	2141.	99.825	
266	J0-6	1.0	60	7.60	0.03	395.6	957.1	99.905	
267	J0-6	1.0	60	7.63	0.03	458.7	657.1	99.917	
268	J0-6	1.0	60	7.52	0.03	110.6	14826.	99.648	
269	J0-6	1.0	60	7.67	0.03	137.8	7626.	99.454	
270	E2-2	1.0	60	7.72	0.03	136.1	10773.	99.731	
271	E2-2	1.0	60	7.73	0.03	174.9	6743.	99.786	
272	E2-2	1.0	60	7.48	0.03	263.2	2890.	99.877	
273	E2-2	1.0	60	---	---	---	---	---	VOID ** CAKE DROPPED FROM SEPTUMS
274	E2-2	1.0	60	7.90	0.03	391.1	1248.	99.809	
275	E2-2	1.0	60	7.93	0.02	526.4	768.1	99.880	
276	J4-8	1.0	60	7.94	0.10	96.1	---	---	VOID ** IRON CONCENTRATIONS IN ERROR
277	J4-8	1.0	60	7.96	0.18	73.4	---	---	VOID ** IRON CONCENTRATIONS IN ERROR
278	J4-8	1.0	60	8.78	0.35	58.2	---	---	VOID ** IRON CONCENTRATIONS IN ERROR
279	J4-8	1.0	60	8.33	0.08	119.6	---	---	VOID ** IRON CONCENTRATIONS IN ERROR
280	J4-8	1.0	60	8.05	0.03	141.5	---	---	VOID ** IRON CONCENTRATIONS IN ERROR
281	J4-8	1.0	60	7.96	0.03	280.5	---	---	VOID ** IRON CONCENTRATIONS IN ERROR

Table 31. Bridges' data from filtration of trickling filter effluent

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	HELLIGE READING INFLUENT JTU	HELLIGE READING EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2}	R 0/0	COMMENTS
BRIDGES	MOBILE TREATMENT UNIT			FINAL EFFLUENT FROM TRICKLING FILTER PLANT AT AMES, IOWA					6/10/68 - 8/28/68
1	S2-18	0.96	22.2	15.8	8.0	122.	610.3	99.780	
2-1	S2-18	0.96	20.1	16.3	7.8	61.	1039.5	99.920	
2-2	S2-18	0.96	20.7	17.7	6.3	61.	2196.0	99.925	
3	S2-18	0.96	19.1	12.4	5.6	31.	5093.8	99.233	
4-1	S2-18	0.96	20.2	11.7	5.4	57.5	570.7	99.574	
4-2	S2-18	0.96	20.3	15.3	6.0	58.0	1326.9	99.195	
4-3	S2-18	0.96	20.7	20.7	6.3	59.0	2552.2	99.753	
5	S2-18	0.96	20.1	17.0	8.8	59.	---	---	EXPONENTIAL HEAD LOSS CURVE
6	S2-19	0.96	20.2	17.7	8.1	385.0	98.4	99.629	SEPTUMS CLEANED BEFORE RUN
7	S2-19	0.96	20.1	15.5	8.5	314.0	92.1	99.819	
8-A	S2-17	0.96	18.1	18.0	8.6	232.0	130.7	99.815	
8-B	S2-17	0.96	18.3	24.5	8.4	232.0	344.6	99.511	
9-A	S2-17	0.96	19.1	14.9	7.7	200.0	183.9	99.817	
9-B	S2-17	0.96	19.7	16.0	7.2	208.0	290.1	99.706	
10-1	S2-17	0.96	19.5	19.6	7.0	60.0	1423.9	98.922	
10-2	S2-17	0.96	20.2	18.3	6.7	60.0	3486.5	99.582	
11	S2-17	0.96	19.1	16.3	7.0	79.0	745.9	98.998	
12	E5-11	0.96	20.7	37.0	9.8	400.0	354.5	99.307	
13	E5-11	0.96	20.9	19.2	7.2	369.0	94.1	99.719	
14-1	E5-12	0.96	21.1	14.7	6.7	326.7	102.4	99.672	
14-2	E5-12	0.96	21.6	32.6	10.6	341.8	273.7	99.668	
14-3	E5-12	0.96	22.2	44.3	13.7	343.7	960.1	99.899	
15-A	E5-12	0.96	21.3	11.6	6.7	362.1	59.8	99.670	
15-B	E5-12	0.96	21.8	12.5	6.5	387.1	112.0	99.657	
16-A	E5-2	0.96	21.2	13.7	6.3	339.3	63.7	99.634	
16-B	E5-2	0.96	22.1	15.0	6.7	351.6	105.5	99.960	
17-A	E5-2	0.96	22.0	13.5	7.3	300.4	71.7	99.888	
17-B	E5-2	0.96	22.7	15.9	7.4	312.1	112.6	99.926	
18	E5-10	0.96	22.2	18.8	8.5	295.2	159.3	96.549	
19-1	E5-10	0.96	22.4	14.9	7.1	257.9	73.8	99.229	
19-2	E5-10	0.96	22.5	24.6	8.2	269.2	227.4	99.315	
20-A	E5-14	0.96	22.4	14.4	7.2	376.7	53.4	99.991	
20-B	E5-14	0.96	23.3	20.9	9.1	405.3	170.9	99.286	
21-A	E5-7	0.96	22.2	11.6	6.6	341.0	55.5	99.675	
21-B	E5-7	0.96	22.6	15.0	8.5	369.8	101.8	99.938	
22	E5-7	0.96	22.0	11.2	6.5	51.6	364.1	99.498	
23	E5-7	0.96	22.4	16.4	7.8	53.5	---	---	EXPONENTIAL HEAD LOSS CURVE TURBIDITY INCREASED THROUGHOUT RUN
24	E5-7	0.96	22.9	15.0	6.7	92.3	---	---	TURBIDITY INCREASED THROUGHOUT RUN
25	E5-9	0.96	21.8	14.9	7.9	113.6	245.1	99.997	
26	E5-9	0.96	24.3	18.4	10.4	163.1	---	---	SEPTUMS CLEANED AND REPAIRED BEFORE RUN ** EXPONENTIAL HEAD LOSS CURVE

Table 31 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	HELLIGE READING INFLUENT JTU	HELLIGE READING EFFLUENT JTU	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2}	R 0/0	COMMENTS
27-A	E5-13	0.96	23.3	16.8	7.8	105.2	699.7	99.809	
27-B	E5-13	0.96	23.2	17.9	8.0	108.1	1352.8	99.851	
28	E5-13	0.96	23.2	17.7	7.4	143.6	824.9	99.778	
29-A	E5-13	0.96	22.1	15.8	8.0	189.8	253.0	99.704	
29-B	E5-13	0.96	22.7	19.2	8.5	198.9	585.7	99.763	
30-A	J0-7	0.96	22.0	11.4	6.3	218.0	160.9	99.897	
30-B	J0-7	0.96	22.6	11.2	5.8	225.5	238.4	99.942	
31	J0-7	0.96	22.4	10.3	5.5	149.1	213.9	99.912	
32	J0-7	0.96	22.6	14.5	6.7	111.4	673.8	99.650	
33-A	J0-7	0.96	23.1	15.3	6.3	136.8	456.9	99.826	
33-B	J0-7	0.96	23.5	16.5	7.0	144.2	814.6	99.687	
34-A	J0-5	0.96	23.9	12.0	6.5	221.0	148.9	99.929	
34-B	J0-5	0.96	24.2	11.5	7.5	230.6	248.8	99.752	
35	J0-5	0.96	24.7	12.5	7.2	69.6	962.2	99.365	
36	J0-5	0.96	21.6	20.0	8.7	295.1	205.5	99.250	
37-A	J0-5	0.96	21.1	12.6	7.6	174.4	202.3	99.823	
37-B	J0-5	0.96	21.4	12.8	8.0	176.5	315.8	99.842	
38-A	S2-14	0.96	21.8	21.7	8.3	159.5	690.6	99.711	
38-B	S2-14	0.96	22.2	23.0	9.5	158.1	1191.8	99.856	
39-A	S2-14	0.96	21.9	12.6	8.2	127.9	401.9	99.658	
39-B	S2-14	0.96	21.9	15.3	7.0	137.0	888.7	99.967	

Table 32. Bridges and Arora's SSCR filter data

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	SUSP. SOLIDS INFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2} MANUAL	COMPUTER	R 0/0	COMMENTS
BRIDGES AND ARORA		SSCR FILTER		UNIVERSITY TAP WATER PLUS UNSETTLED BALL CLAY (KAOLINITE)				9/18/69 - 9/19/69	
1	HFC	1.05	24.4	71	90	1160	1196	99.895	
2	HFC	1.05	24.4	71	90	1150	1154	99.901	DUPLICATION OF RUN 1
3	HFC	1.05	24.5	71	90	1200	1221	99.955	DUPLICATION OF RUN 1
4	HFC	1.05	24.6	68	150	365	358	99.966	
5	HFC	1.05	24.6	68	105	795	803	99.964	
6	HFC	1.05	24.5	68	75	1635	1634	99.953	
7	HFC	1.05	24.6	89.5	107	1410	1415	99.958	
BRIDGES AND ARORA		SSCR FILTER		DISTILLED WATER PLUS SETTLED BALL CLAY (KAOLINITE)				9/22/69 - 9/25/69	
8	HFC	1.05	24.6	121.2	320	1930	1919	99.999	
9	HFC	1.05	26.5	30.3	80	1690	1694	99.982	
10	HFC	1.05	27.2	3.82	10	2150	2162	99.863	
11	HFC	1.05	27.8	85.2	160	---	---	---	VOID ** MECHANICAL DIFFICULTIES
12	HFC	1.05	28.0	21.3	40	8300	8088	99.910	
13	HFC	1.05	25.9	21.0	90	6830	7016	99.980	HA MEMBRANE IN PLACE OF PRECOAT
14	HFC	1.05	26.9	21.0	90	1570	1354	99.492	
15	HFC	1.05	27.5	7.19	30	1025	1020	99.911	
16A	HFC	1.05	26.7	7.19	30	3830	3870	99.949	HA MEMBRANE IN PLACE OF PRECOAT
16B	HFC	1.05	27.9	7.19	30	1320	1313	99.861	HA MEMBRANE IN PLACE OF PRECOAT
17	HFC	1.05	27.6	8.86	30	2250	2358	99.769	
18	HFC	1.05	26.9	8.86	30	6600	6391	99.947	HA MEMBRANE IN PLACE OF PRECOAT
19	HFC	1.05	29.2	4.43	15	2440	2529	99.896	HA MEMBRANE IN PLACE OF PRECOAT
20	HFC	1.05	30.1	4.43	15	1500	1484	99.611	
BRIDGES AND ARORA		SSCR FILTER		UNIVERSITY TAP WATER PLUS FERRIC CHLORIDE			9/26/69 - 10/10/69		
21	J3-X	1.05	23.5	7.85	400	543	525	99.938	
22	J3-X	1.05	24.8	8.16	160	8200	7863	99.796	VERY SHORT RUN
23	J3-X	1.05	25.1	8.27	400	710	670	99.908	DUPLICATION OF RUN 21
24	J3-X	1.05	23.7	8.26	320	990	1031	99.786	
25	J3-X	1.05	24.4	8.26	266	1970	1888	99.970	
26	J3-X	1.05	24.9	8.26	230	2560	2636	99.563	
27	J3-X	1.05	23.7	8.36	400	895	879	99.927	HA MEMBRANE IN PLACE OF PRECOAT
28	S2-3	1.05	25.0	8.16	400	354	337	99.859	
29	S2-3	1.05	26.0	8.16	266	870	861	99.942	
30	S2-3	1.05	23.9	8.23	230	945	960	99.874	
31	S2-3	1.05	26.4	8.35	320	597	594	99.958	
32	S2-3	1.05	26.0	8.36	200	1850	1883	99.908	
33	S2-3	1.05	24.9	7.57	320	580	597	99.846	DUPLICATION OF RUN 31

Table 32 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	SUSP. SOLIDS INFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^4 FT^{-2} MANUAL	COMPUTER	R 0/0	COMMENTS
34	J3-X	1.05	25.5	7.57	266	1690	1790	99.737	DUPLICATION OF RUN 25
35	J3-X	1.05	25.9	7.73	400	650	639	99.776	DUPLICATION OF RUN 21
36	J3-X	1.05	25.8	3.54	200	775	788	99.966	
37	J3-X	1.05	26.0	3.36	100	4650	4730	99.921	
38	J3-X	1.05	26.6	3.59	133	3000	2976	99.935	
39	J3-X	1.05	26.5	3.56	200	765	772	99.639	DUPLICATION OF RUN 36
40	J3-X	1.05	25.8	3.65	100	3690	3867	99.942	DUPLICATION OF RUN 37
41	J3-X	1.05	25.8	4.40	145	1875	2128	99.970	
42	J3-X	1.05	25.9	4.00	185	1330	1249	99.947	
43	J3-X	1.05	25.6	13.2	500	1470	1403	99.842	
44	J3-X	1.05	25.8	13.25	750	491	504	99.880	
45	J3-X	1.05	26.3	13.4	400	2020	2553	99.821	
46	J3-X	1.05	26.5	2.10	100	1700	1665	99.991	
47	J3-X	1.05	26.1	2.00	66	2840	2972	99.975	
48	J3-X	1.05	27.0	2.00	40	7950	7687	99.968	
49	J3-X	1.05	26.6	2.00	200	393	389	99.941	
50	J3-X	1.05	25.5	2.05	135	852	844	99.984	
51	J3-X	1.05	26.4	2.03	50	5450	5454	99.991	
BRIDGES AND ARORA		SSCR FILTER		DISTILLED WATER PLUS UNSETTLED BALL CLAY (KAOLINITE)				10/13/69 - 10/15/69	
52	HFC	1.05	26.0	---	80	---	---	---	VOID ** SUSPENDED SOLIDS VARIED
53	HFC	1.05	26.1	33.9	80	338	340	99.873	MORNING RUN
54	HFC	1.05	26.3	33.6	80	298	303	99.924	EVENING RUN
55	HFC	1.05	28.7	4.95	10	840	881	99.952	
56	HFC	1.05	28.2	79.3	160	720	719	99.984	
57	HFC	1.05	28.4	9.9	20	846	855	99.965	
58	HFC	1.05	28.6	158.3	320	838	839	99.975	
59	HFC	1.05	28.8	39.6	80	805	804	99.956	
60	HFC	1.05	28.7	79.3	160	810	820	99.994	DUPLICATION OF RUN 56

Table 32 (Continued)

FILTER RUN NO	FILTER AID	Q GPM/SQ FT	INFLUENT TEMP DEG C	SUSP. SOLIDS INFLUENT MG/L	BODY FEED MG/L	BETA INDEX 10^{4} FT^{-2} MANUAL	BETA INDEX 10^{4} FT^{-2} COMPUTER	R 0/0	COMMENTS
BRIDGES AND ARORA		SSCR FILTER		DISTILLED WATER PLUS SETTLED BALL CLAY (KAOLINITE)					10/20/69 - 10/22/69
61	HFC	1.05	26.8	44.5	100	2546	2538	99.981	MORNING RUN
62	HFC	1.05	27.8	44.5	100	2436	2396	99.950	EVENING RUN
63	HFC	1.05	26.6	9.9	25	4840	4241	99.605	ERRATIC HEAD LOSS
64	HFC	1.05	26.9	38.4	100	2875	2706	99.882	
65	HFC	1.05	27.4	153.6	400	2340	2290	99.551	
66	HFC	1.05	26.8	4.8	12.5	2350	2322	99.984	
67	HFC	1.05	27.5	77.0	200	1600	1601	99.958	
68	HFC	1.05	28.0	9.6	25	2260	2297	99.978	DUPLICATION OF RUN 63
BRIDGES AND ARORA		SSCR FILTER		UNIVERSITY TAP WATER PLUS SETTLED BALL CLAY (KAOLINITE)					10/23/69
69	HFC	1.05	26.4	8.75	25	670	669	99.978	
70	HFC	1.05	26.9	35	100	660	635	99.921	
71	HFC	1.05	27.9	140	400	520	523	99.952	
72	HFC	1.05	27.2	70	200	530	535	99.984	
BRIDGES AND ARORA		SSCR FILTER		UNIVERSITY TAP WATER PLUS UNSETTLED WYOMING BENTONITE					10/27/69 - 10/28/69
73	HFC	1.05	25.7	75	365	---	---	---	VERY SHORT RUN
74	HFC	1.05	26.1	10.7	52	12050	12278	99.980	
75	HFC	1.05	25.8	5.35	26	13500	13545	99.854	
76	HFC	1.05	25.6	16.10	78	10400	10166	99.992	
77	HFC	1.05	25.8	2.68	13	16500	17647	99.946	
78	HFC	1.05	25.4	5.35	26	14100	13922	99.971	DUPLICATION OF RUN 75
79	HFC	1.05	25.7	4.12	20	15700	15978	99.956	
80	HFC	1.05	25.8	1.35	6.5	24400	24709	99.922	
81	HFC	1.05	25.7	4.13	20	17300	---	---	NO CALGON USED TO DISPERSE CLAY

APPENDIX B

Derivation of Precoat Filtration Equations

Basic equations

The precoat filtration equations are derived from the modified Darcy equation which was previously given as:

$$\frac{dV}{Adt} = \frac{K_1}{\mu} \frac{dP}{dL} \tag{3}$$

where:

V = volume of filtrate passing through the bed in time t $[L^3]$

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

K_1 = modified permeability coefficient independent of viscosity $[L^2]$

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

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

P = pressure loss across the porous media in the direction of flow $[FL^{-2}]$

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

The use of the modified Darcy equation requires that the following assumptions be made:

Assumption 1: Enough body feed is added to form an essentially incompressible filter cake.

Assumption 2: The flow through the bed is laminar. Equation 3 can be changed to:

$$v = gi/\nu a \tag{51}$$

since:

$v = (1/A)dV/dt$ = approach or face velocity $[LT^{-1}]$

$i = (dP/dL)\gamma_w = dH/dL$ = hydraulic gradient [--]

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

and

a = specific resistance based on the volume of filter media $[L^{-2}]$

where:

γ_w = density of water $[FL^{-3}]$

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

H = head loss or pressure difference in terms of height of a water column [L]

Equation 51 can be applied to filtration through precoat filters by applying it separately to the precoat and filter cake. The derivation is simplified if constant rate conditions are imposed.

Assumption 3: Constant rate filtration.

Head loss through precoat - any septa

When cylindrical septa are used, the outer surface area of the precoat is slightly larger than the outer area of the septa. However, because the precoat is very thin, the following assumption may be made:

<u>Assumption 4</u>: The outer surface area of the precoat layer is approximately equal to the outer surface area of the septa.

Therefore, Equation 51 can be written for the precoat as:

$$q = \frac{g}{\nu a_p} \frac{H_p}{L_p}$$

since:

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

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

A_s = septum area $[L^2]$

and the subscript p refers to the precoat.

Rearranging and substituting V_p/A_s for the thickness of the precoat, then

$$H_p = \frac{q\nu}{g} \left(\frac{a_p V_p}{A_s}\right)$$

where:

V_p = volume of precoat $[L^3]$

If the specific resistance is based on the weight of filter aid in the precoat rather than the volume of filter aid then

$$H_p = q\nu\xi w/g \qquad (5)$$

where:

ξ = filter aid resistance index or ξ index = specific resistance of clean filter aid based on the weight of filter aid $[LF^{-1}]$

w = weight of filter aid in the precoat per unit septum area $[FL^{-2}]$

Equation 5 is valid for any type of septum as long as the precoat is thin.

Head loss through filter cake - cylindrical septa

If cylindrical septa are used, the surface area of the filter cake increases during a filter run and therefore the face velocity, v, decreases when a constant rate of flow is maintained. Since v is directly proportional to i, the hydraulic gradient across a cylindrical filter cake is not constant throughout the cake. Therefore, to apply Equation 51 to a cylindrical filter cake, the hydraulic gradient must be expressed in differential form and Equation 51 may be written as

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

or

$$dH_c = \frac{v\nu}{g} a_c \, dL_c \qquad (52)$$

where the subscript c refers to the filter cake.

The desired equation is one which equates head loss to an easily measured variable such as time. To convert Equation 52 to terms of time, t, in place of filter cake thickness, L_c, consider a cylindrical septum with radius R_s. The small volume of filter cake formed during the interval of time dt is:

$$dV_c = Q\gamma_w S_f \, dt/\gamma_c \qquad (53)$$

where:

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

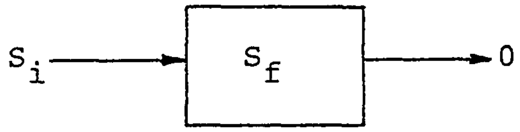
S_f = weight fraction of combined solids + body feed in the water in the filter housing [--]

At the end of the precoating operation the filter housing is full of clean water. Therefore, during the filtering operation S_f is less than S_i (weight fraction of combined solids + body feed in the filter influent) because of the effect of initial dilution. But, S_f can be written in terms of S_i if the following assumptions are made:

Assumption 5: The filter housing is a completely mixed system.

Assumption 6: No suspended solids or body feed pass through the filter cake.

Drawing a mass diagram for the filter:



Thus, in the time increment Δt

Weight of solids entering = $Q\gamma_w S_i \Delta t$

and

Weight of solids removed = $Q\gamma_w S_f \Delta t$.

The change in weight of combined 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 housing yields:

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

or

$$\Delta S_f = \delta (S_i - S_f)\Delta t$$

where:

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

$\delta = Q/V_f$ = 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:

$$\int \frac{dS_f}{S_i - S_f} = \int \delta dt$$

Therefore,

$$\ln(S_i - S_f) = -\delta t + C$$

and

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

where:

C = integration constant

For the initial condition $S_f = 0$ at $t = 0$, then $e^C = S_i$ and

$$\begin{aligned} S_f &= S_i - S_i e^{-\delta t} \\ &= S_i(1 - e^{-\delta t}) \\ &= (C_S + C_F)10^{-6}(1 - e^{-\delta t}) \qquad (54) \end{aligned}$$

since:

$$S_i = (C_S + C_F)10^6$$

where:

C_S = concentration of suspended solids in influent [--]

C_F = concentration of body feed in influent [--]

Substitution for S_f in Equation 53 yields:

$$dV_c = \frac{Q\gamma_w}{\gamma_c}(C_S + C_F)10^{-6}(1 - e^{-\delta t})dt \tag{55}$$

It is then necessary to make the following assumption:

Assumption 7: The solids removed in the filter cake do not increase the cake thickness appreciably over the thickness that would result if the cake caontained only body feed.

This is equivalent to the expression:

$$\frac{C_F}{\gamma_p} \simeq \frac{C_S+C_F}{\gamma_c}$$

The terms in the above expression are assumed to remain constant with time.

Assumption 8: γ_p and γ_c remain constant throughout a filter run.

Assumption 9: C_S and C_F remain constant throughout a filter run.

Substitution for $(C_S+C_D)/\gamma_c$ in Equation 55 leads to:

$$dV_c = \frac{Q\gamma_w}{\gamma_p} C_F \; (10^{-6}) \; (1-e^{-\delta t})dt \qquad (56)$$

and since $dL_c = dV_c/A$, substitution for dL_c in Equation 52 yields the differential equation for precoat filtration:

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

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

$$dH_c = \frac{v^2 \nu}{g} \beta \; C_F(1-e^{-\delta t})dt \tag{57}$$

where $\beta = a_c \gamma_w (10^{-6})/\gamma_p$ by definition and will be denoted as the filter cake resistance index or β index.

Note that for cylindrical septa the face velocity, v, is a function of time and must therefore be expressed in terms of time before Equation 57 can be integrated. This may be accomplished by considering that 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 $A = 2\pi R L_s$. Thus, $A = A_s\ R/R_s$ and:

$$v = \frac{Q}{A} = \frac{QR_s}{A_s R} = \frac{qR_s}{R} \tag{58}$$

However, the outer radius of the filter cake is also a function of time. To derive an expression for R in terms of t, consider that 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 $[L^3]$
V_p = volume of precoat $[L^3]$
V_c = volume of filter cake $[L^3]$

V_s and V_p are constants with respect to time, therefore:

$$dV_T = dV_c = 2\pi L_s R\ dR$$

Equating the above to the right hand side of Equation 56 leads to:

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

and

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

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

$$2R\ dR = R_s[\frac{2q\gamma_w C_F(10^{-6})}{\gamma_p}](1-e^{-\delta t})dt$$

Letting $\phi = \frac{2q\gamma_w C_F(10^{-6})}{\gamma_p}$ for convenience then:

$$2R\ dR = R_s\phi\ (1-e^{-\delta t})dt$$

This differential equation can be integrated as follows:

$$\int_{R_o}^{R} 2R\ dR = R_s\phi \int_0^t (1-e^{-\delta t})dt$$

where:

R_o = outer radius of precoated septum [L]

$= R_s + L_p$

$= R_s + w/\gamma_p$

$$[R^2]_{R_o}^{R} = R_s\phi[t + \frac{e^{-\delta t}}{\delta}]_0^t$$

$$R^2 - R_o^2 = R_s\phi[t + \frac{e^{-\delta t}}{\delta} - 0 - \frac{1}{\delta}]$$

and

$$R^2 = R_o^2 + R_s\phi[t - \frac{1-e^{-\delta t}}{\delta}]$$

Letting $X = t - \frac{(1-e^{-\delta t})}{\delta}$, then:

$$R^2 = R_o^2 + R_s\phi X \qquad (59)$$

Substituting for R in Equation 58 and likewise for v in Equation 57 leads to:

$$dH_c = \frac{R_s^2[q^2\nu\beta C_F/g] \; (1-e^{-\delta t})dt}{R_o^2 + R_s\phi X}$$

and letting

$\sigma = q^2\nu\beta C_F/g$, then:

$$dH_c = \frac{R_s^2\sigma(1-e^{-\delta t})dt}{R_o^2 + R_s\phi X} \qquad (60)$$

X is a function of time, however, if dX is substituted for dt, an equation is derived which can be integrated.

i.e.: $X = t - \frac{1}{\delta} + \frac{e^{-\delta t}}{\delta}$

therefore:

$$dX = dt - 0 - \frac{\delta e^{-\delta t}}{\delta} dt = (1-e^{-\delta t})dt$$

and substituting for $(1-e^{-\delta t})$ dt in Equation 60 gives

$$dH_c = \frac{R_s^2 \sigma dX}{R_o^2 + R_s \phi X}$$

which can be integrated as follows:

$$\int_0^{H_c} dH_c = \int_0^X \frac{R_s^2 \sigma dX}{R_o^2 + R_s \phi X}$$

$$= \frac{R_s^2 \sigma}{R_s \phi} \int_0^X \frac{R_s \phi \; dX}{R_o^2 + R_s \phi X}$$

$$[H_c]_0^{H_c} = \frac{R_s \sigma}{\phi} [\ln(R_o^2 + R_s \phi X)]_0^X$$

and

$$H_c = \frac{R_s \sigma}{\phi} [\ln(R_o^2 + R_s \phi X) - \ln(R_o^2)]$$

$$= \frac{R_s \sigma}{\phi} \ln(1 + \frac{R_s \phi X}{R_o^2}) \qquad (6)$$

The total thickness of precoat and filter cake, L, at time t for cylindrical septa can be determined from Equation 59 and is equal to:

$$L = R - R_s = \sqrt{R_o^2 + R_s \phi X} - R_s \qquad (7)$$

Head loss through filter cake - flat septa

For flat septa, the face velocity v is not a function of time and is equal to q. Therefore Equation 57 can be written as:

$$dH_c = \sigma(1-e^{-\delta t})dt$$

$$= \sigma\ dX$$

and upon integrating:

$$H_c = \sigma X \tag{8}$$

Also for flat septa, $dV_c = A_s\ dL_c$. Equating this expression to the right hand side of Equation 56 leads to:

$$A_s\ dL_c = \frac{Q\gamma_w}{\gamma_p} C_F(10^{-6})\ (1-e^{-\delta t})dt$$

$$= A_s \frac{\phi}{2} dX$$

since:

$$\phi = \frac{2q\gamma_w C_F(10^{-6})}{\gamma_p} \quad \text{and } \frac{Q}{A_s} = q.$$

Integration leads to:

$$\int_0^{L_c} dL_c = \frac{\phi}{2} \int_0^X dX$$

and

$$L_c = \frac{\phi X}{2}$$

Therefore:

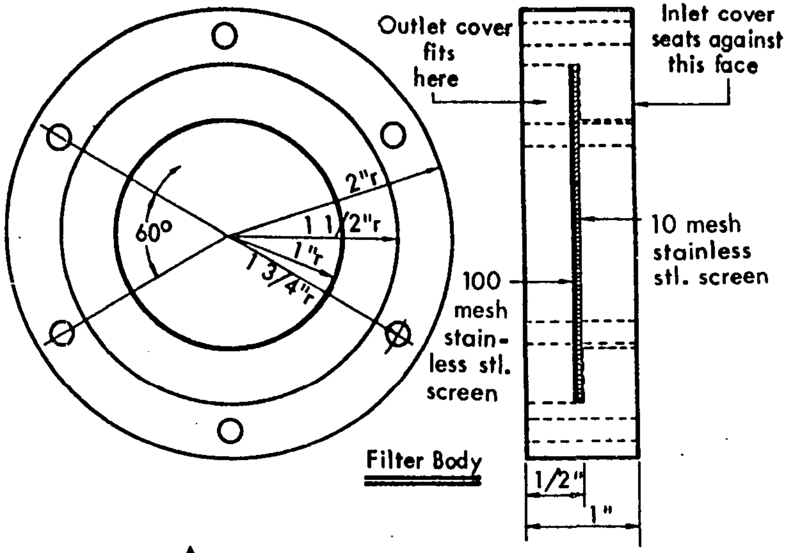
$$L = L_p + \frac{\phi X}{2} \tag{9}$$

APPENDIX C

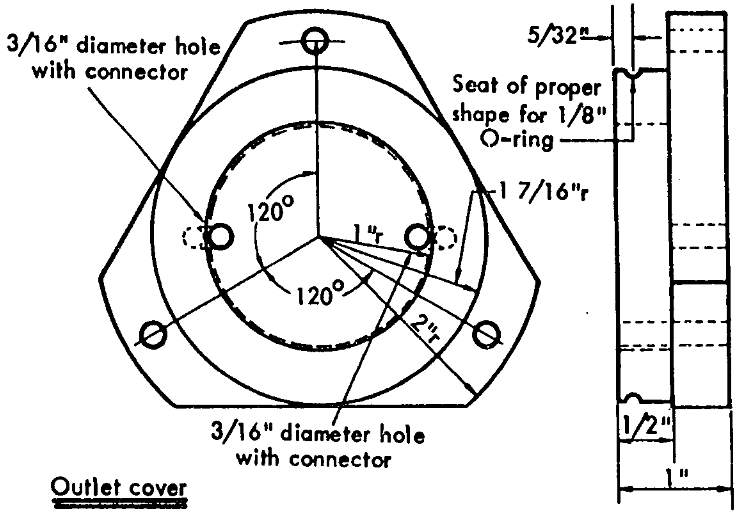
Working Drawings of the SSCR Filter Apparatus

Note: Unless otherwise noted, all dimensions shown are in inches.

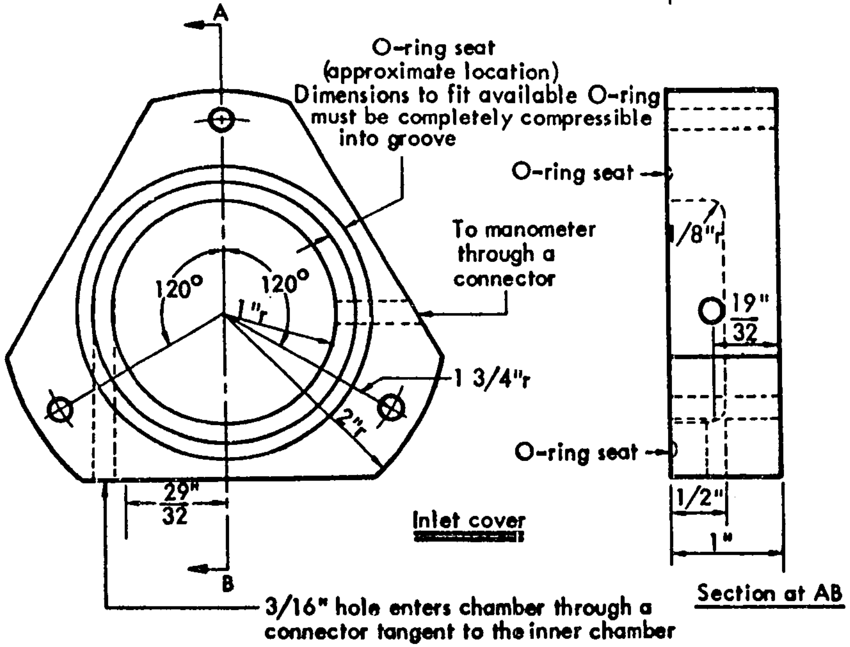
Figure 43. Working drawings of the filter assembly in SSCR apparatus



Filter Body

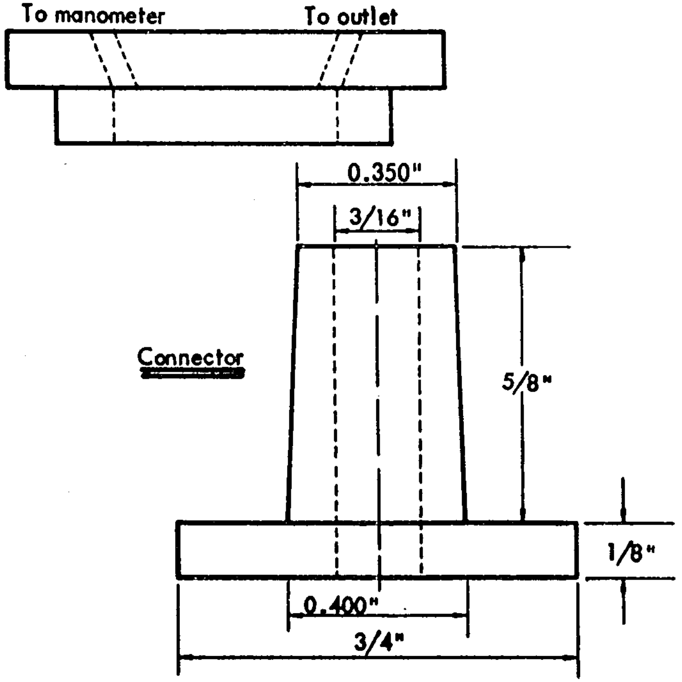


Outlet cover



Inlet cover

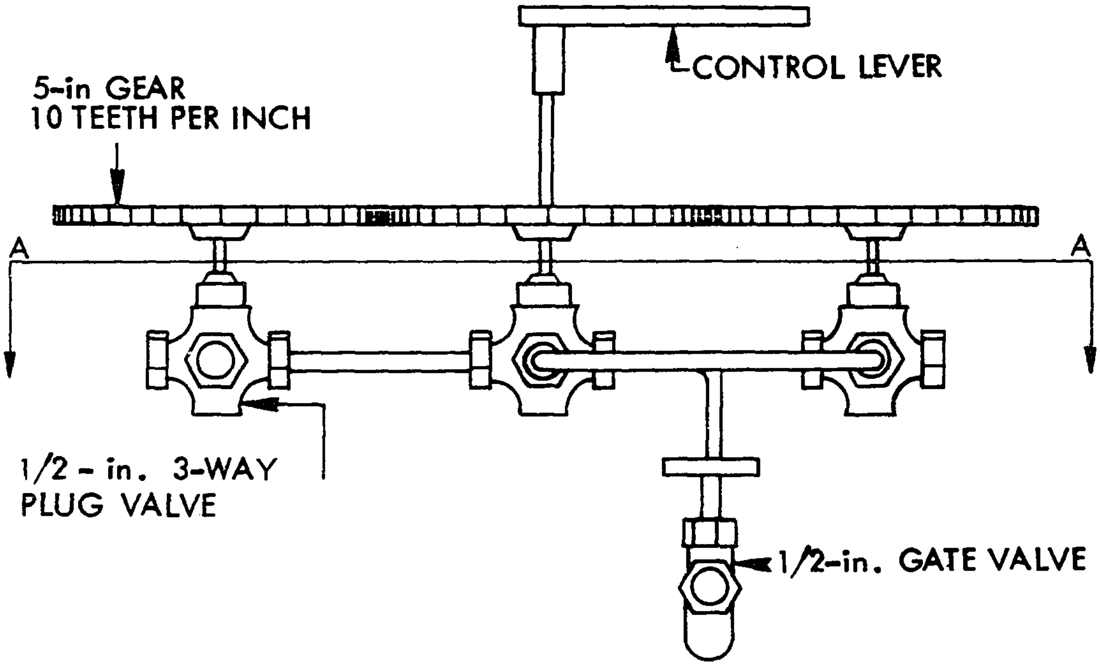
Section at AB



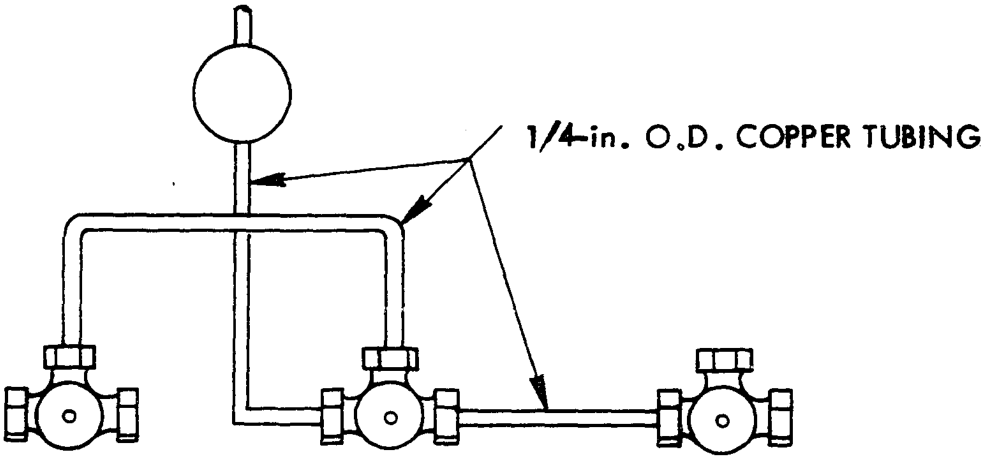
Connector

Figure 44. Working drawings of the gear and value assembly in SSCR apparatus

SCALE: 1 in. = 3 in.



FRONT VIEW



SECTION AA

Figure 45. Working drawing of the raw water and backwash water holder in SSCR apparatus

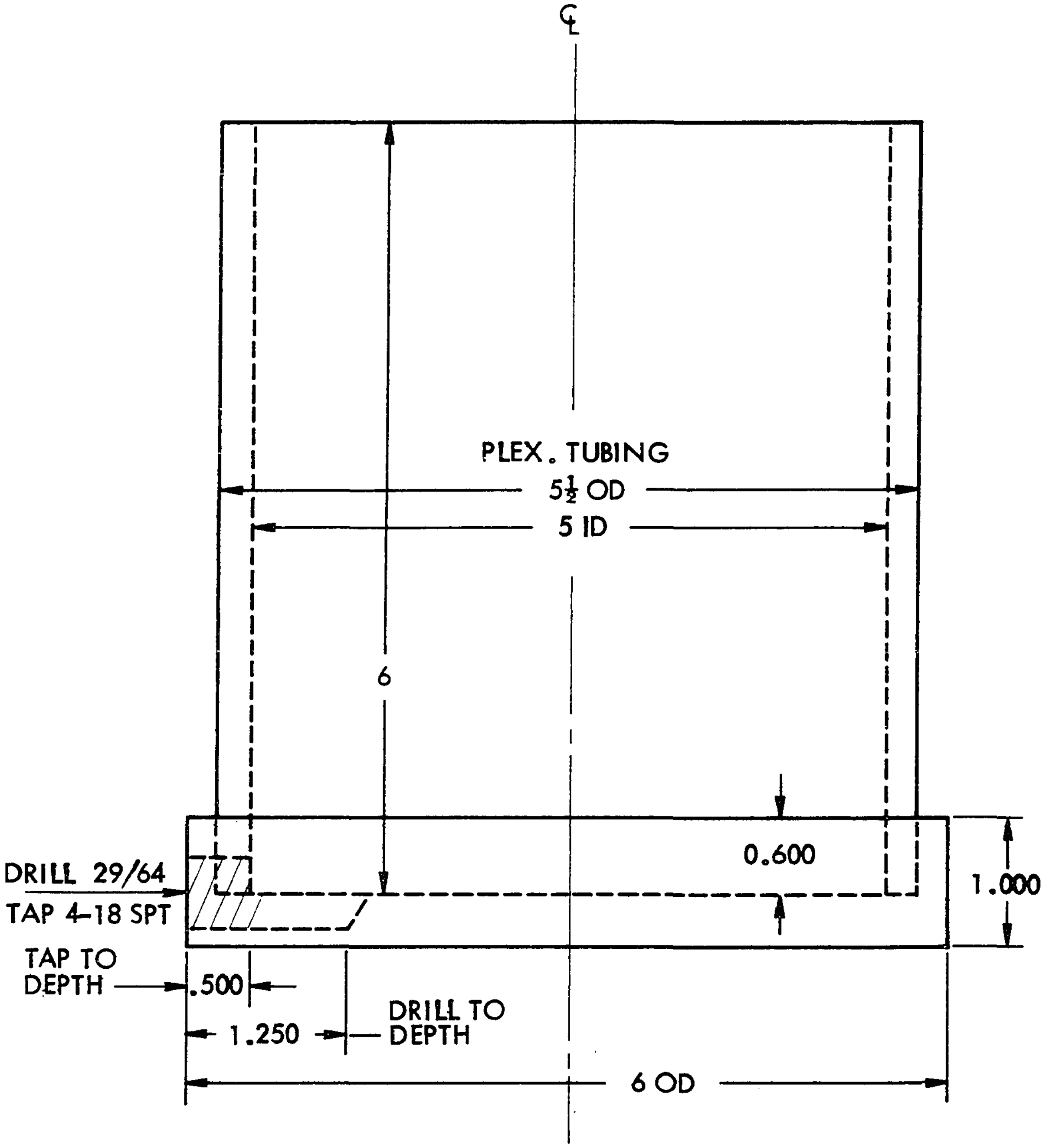
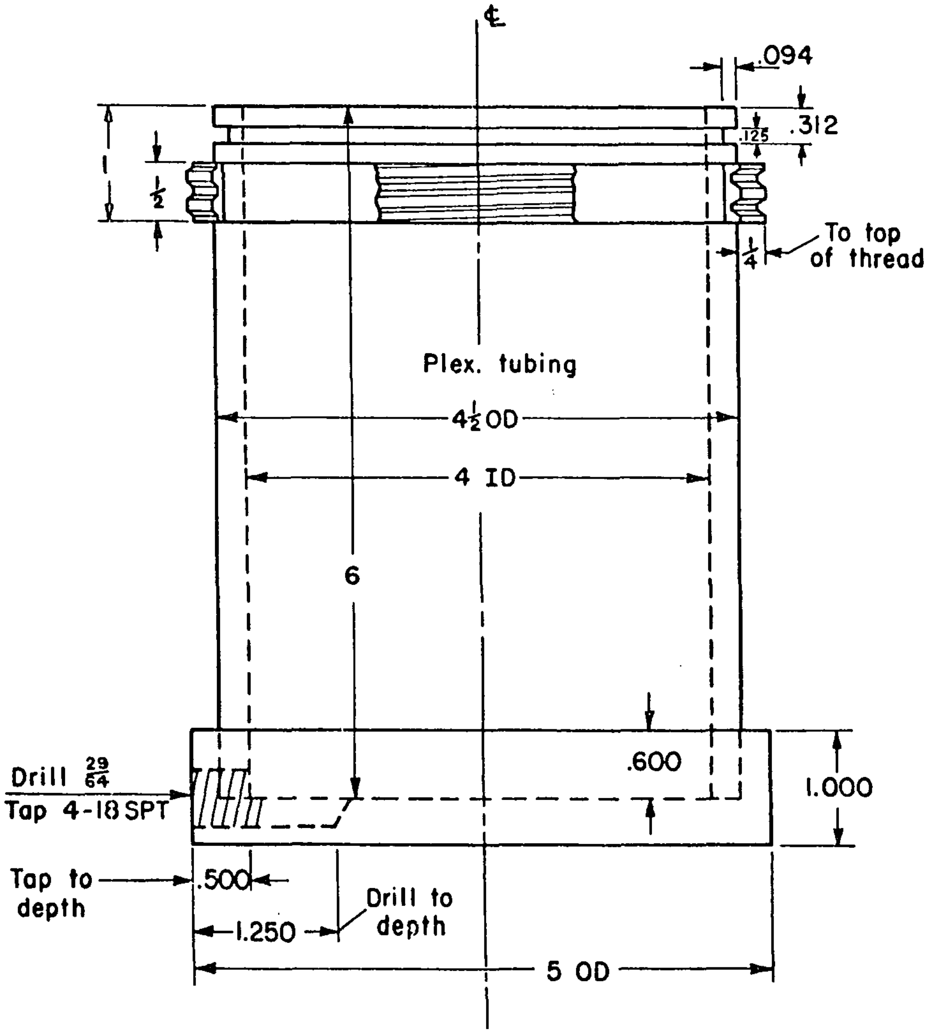

℄
PLEX. TUBING
5½ OD
5 ID
6
0.600
1.000
DRILL 29/64
TAP 4-18 SPT
TAP TO DEPTH
.500
1.250
DRILL TO DEPTH
6 OD

Figure 46. Working drawings of the precoat pot in SSCR apparatus


℄
.094
.312
.125
½
To top of thread
¼
Plex. tubing
4½ OD
4 ID
6
.600
1.000
Drill 29/64
Tap 4-18 SPT
Tap to depth
.500
Drill to depth
1.250
5 OD

TOP VIEW

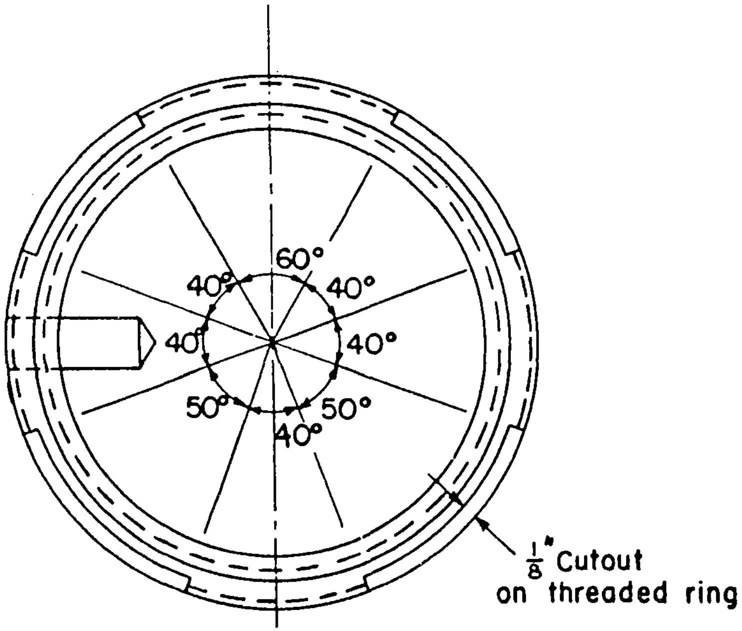
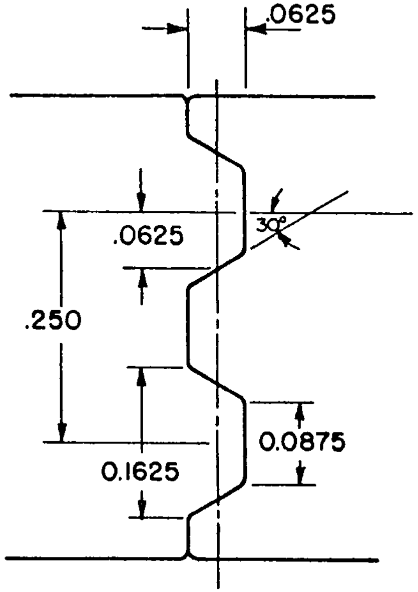

60°
40°
40°
40°
40°
50°
50°
40°
1/8" Cutout on threaded ring

Figure 47. Working drawings of the precoat pot cover in SSCR apparatus

THREAD DETAIL



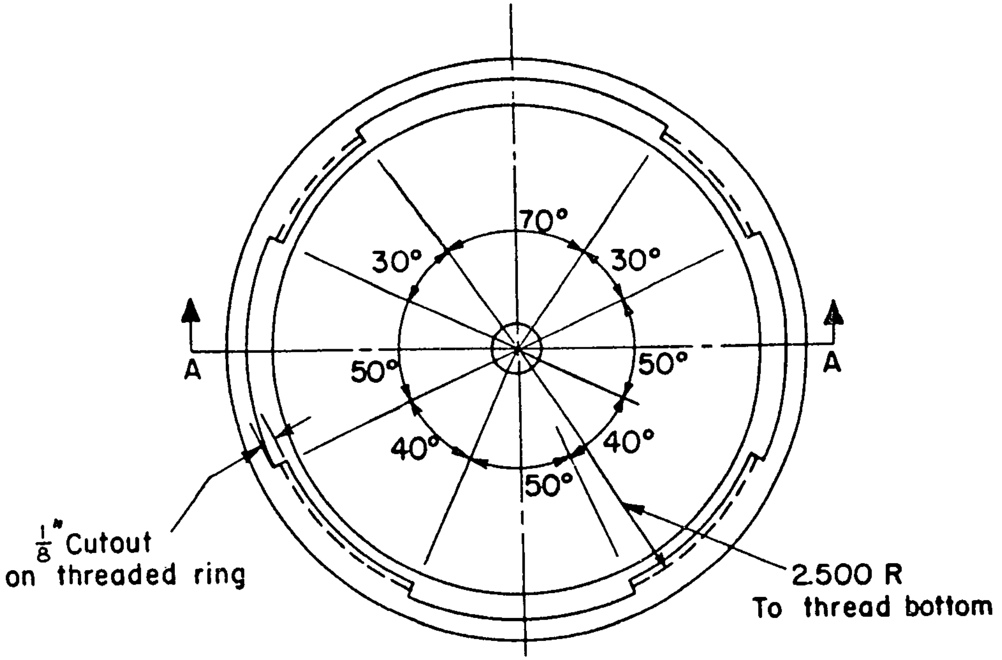
Thread cross-section cut 4 threads per inch

All dimensions $\left[\begin{smallmatrix}+.000\\ -.002\end{smallmatrix}\right.$

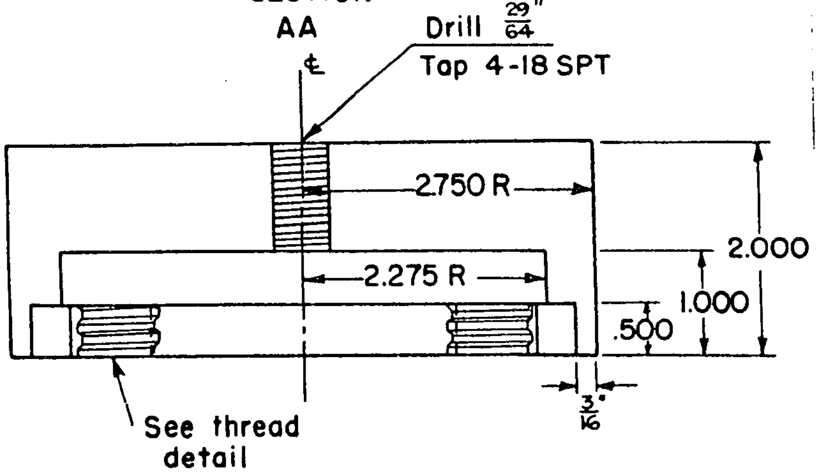
All fillets and rounds 0.010" R

Scale 8:1

BOTTOM VIEW



SECTION AA



APPENDIX D

BID Program User Manual

Introduction

The program for Beta Index Determination or the BID Program was prepared to evaluate the filter cake resistance index or β index from the results of a single or series of filter runs. A discussion of the calculation of the β index is made on pages 115-127. For flat septa, the value of β can be determined from the slope of the linear portion of a plot of head loss versus filtration time by the equation:

$$\beta = \frac{g}{q^2 \nu} \frac{\text{Slope}}{C_F} \qquad (31)$$

It is not necessary to know the values of γ_p or δ to determine the exact value of β from the results obtained using flat septa.

Using cylindrical septa, the values of β can be determined from the slope of a plot of head loss versus $\ln(1 + R_s \phi X/R_o^2)$ by the equation:

$$\beta = \frac{g}{q^2 \nu} \frac{\text{Slope}}{C_F} \frac{\phi}{R_s} \qquad (61)$$

It is necessary to know the values of γ_p and δ to determine the exact value of β from results obtained using cylindrical septa. The effects of using erroneous values of γ_p and δ on the calculated value of β are shown in Tables 7 and 8

(p. 122 and 128, respectively). By estimating the time of inflection from a plot of head loss versus filtration time, δ may be estimated as:

$$\delta \approx 3/t_i \qquad (32)$$

The computer program has been written to perform a regression of H_c versus t (or X if δ is known) for flat septa, or versus $\ln(1 + R_s\phi X/R_o^2)$ for cylindrical septa, and to determine the value of the filter cake resistance index, β. The program also determines the standard error of estimate, s_E, and the linear correlation coefficient, R, in percent, of the regression equation.

Computer input

To determine the filter cake resistance observed in a filter run, the following data must be read into the computer:

1) Data that remain constant during a filter run are read into the computer in an array named A. This array consists of:

A(1) = 1.0 if the dilution rate, δ, is known; 2.0 if the dilution rate is not known

A(2) = filtration rate, gpm/sq ft

A(3) = body feed concentration, C_F, mg/l or ppm

A(4) = influent water temperature, °C or °F

A(5) = in-place bulk density of the precoat, γ_p, lb/cu ft

A(6) = outer septum diameter, in inches, for cylindrical septum filters; leave blank for flat septum filters

A(7) = precoat weight per unit area, w, lb/sq ft

A(8) = dilution rate, δ, per hour; leave blank if unknown.

2) The number of head loss observations made during the filter run is read into the computer under the name NOOBS.

3) The observed head losses (expressed in inches of mercury or feet of water) are read into an array named H, and the corresponding times of filtration (expressed in minutes or hours) are read into an array named T. Thus, the first observed head loss and time of filtration would be identified as H(1) and T(1), respectively.

Flow chart and FORTRAN listing

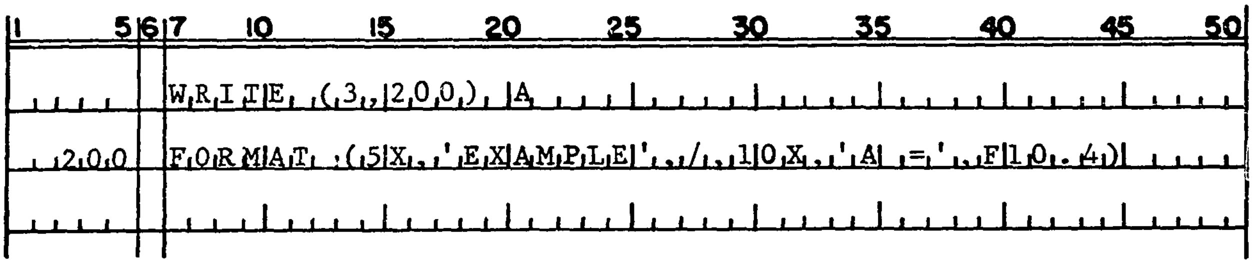
BID is written in FORTRAN IV computer language (31, 41) for use with the IBM 360/65 computer system at Iowa State University. The flow chart for the program is given in Figure 48 and is followed by the FORTRAN listing.

A detailed explanation of the input statements and output statements is not given since these vary with the computer system used. Basically, an input or output statement consists of a READ or WRITE statement and a FORMAT statement. Some of the symbols used in FORMAT statements for the Iowa State University IBM 360/65 computer system are:

'...'	All information contained within apostrophes is written on the output sheet in the same form as it is written in the FORMAT statement. The first column of each line on the output sheet is reserved for carriage control of the printer. The instruction to leave the first column blank instructs the printer to remain on that line (single space), 0 (i.e., '0') instructs the printer to skip a line (double space), and 1 (i.e., '1') instructs the printer to skip to the top of the next output sheet.
X	This instructs the printer to leave a space blank. For example, 7X instructs the printer to skip seven columns or spaces.
/	This instructs the printer to skip to the beginning of the next line. Therefore, //// tells the printer to skip four lines or leave three lines blank.
F,E,I	These are various formats for numerical data. In the FORMAT statement F10.3, F is the type of format, 10 is the size of field, in columns, reserved for the number, and 3 is the number of digits to be written to the right of the decimal point. For example, the number 23.4 would be written under a F10.3 format as 23.400 with the last digit, 0, in the right column of a ten column field. Under an E format a number is written in exponential form. The number 23.4 would be written under an E10.3 format as 0.234E 02 with the last digit, 2, in the right column of a ten column field. The I format is used for integer numbers. For example, the integer 16 would be written under an I5 format as 16 with the last digit, 6, in the right column of a five column field.
A	This is a format used for alphameric data. When an alphabetic, numeric, or special

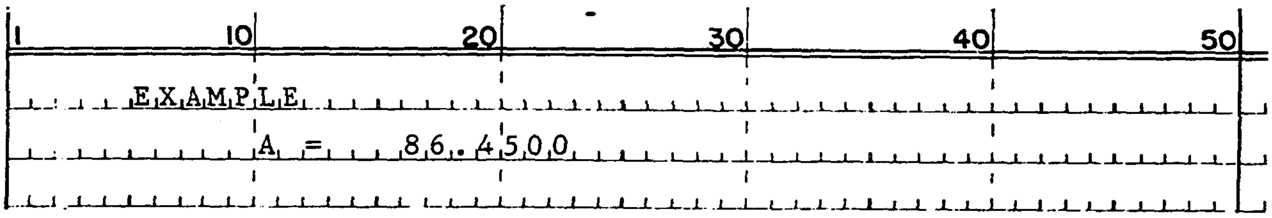
> character is read in under an A format, it is given a unique internal cose. For example, with the IBM 360/65 computer system, the letter C when read in under an A format is stored as -1019199424.

As an example, if the value of a variable named A is 86.45, the output statement:



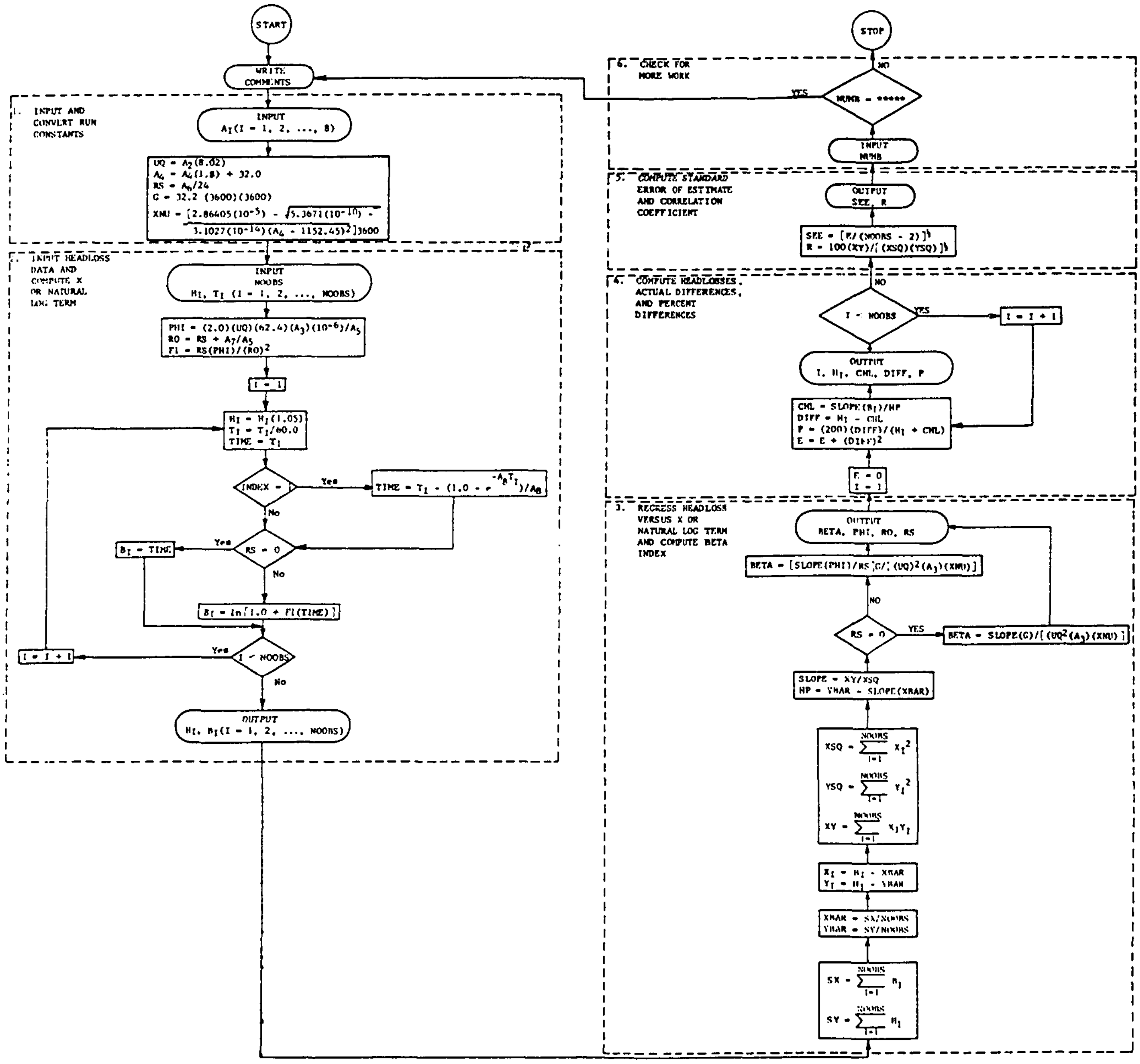
```
      WRITE (3,200) A
  200 FORMAT (5X,'EXAMPLE',/,10X,'A =',F10.4)
```

would result in the following output:



```
     EXAMPLE
          A =   86.4500
```

Figure 48. Flow chart for the BID Program


START
WRITE COMMENTS
1. INPUT AND CONVERT RUN CONSTANTS
INPUT A_I(I = 1, 2, ..., 8)
UQ = A_2(8.02)
A_4 = A_4(1.8) + 32.0
RS = A_6/24
G = 32.2 (3600)(3600)
XMU = [2.86405(10^-5) - √(5.3671(10^-10) - 3.1027(10^-14)(A_4 - 1152.45)^2)]3600
2. INPUT HEADLOSS DATA AND COMPUTE X OR NATURAL LOG TERM
INPUT NOOBS H_I, T_I (I = 1, 2, ..., NOOBS)
PHI = (2.0)(UQ)(62.4)(A_3)(10^-6)/A_5
RO = RS + A_7/A_5
FI = RS(PHI)/(RO)^2
I = 1
H_I = H_I(1.05)
T_I = T_I/60.0
TIME = T_I
INDEX = 1
Yes
TIME = T_I - (1.0 - e^(-A_8 T_I))/A_8
No
RS = 0
Yes
B_I = TIME
No
B_I = ln[1.0 + FI(TIME)]
I < NOOBS
Yes
I = I + 1
No
OUTPUT H_I, B_I(I = 1, 2, ..., NOOBS)
STOP
6. CHECK FOR MORE WORK
NO
YES
MUMB = *****
INPUT MUMB
5. COMPUTE STANDARD ERROR OF ESTIMATE AND CORRELATION COEFFICIENT
OUTPUT SEE, R
SEE = [E/(NOOBS - 2)]^½
R = 100(XY)/[(XSQ)(YSQ)]^½
4. COMPUTE HEADLOSSES, ACTUAL DIFFERENCES, AND PERCENT DIFFERENCES
NO
I < NOOBS
YES
I = I + 1
OUTPUT I, H_I, CHL, DIFF, P
CHL = SLOPE(B_I)/HP
DIFF = H_I - CHL
P = (200)(DIFF)/(H_I + CHL)
E = E + (DIFF)^2
E = 0
I = 1
3. REGRESS HEADLOSS VERSUS X OR NATURAL LOG TERM AND COMPUTE BETA INDEX
OUTPUT BETA, PHI, RO, RS
BETA = [SLOPE(PHI)/RS]G/[(UQ)^2(A_3)(XMU)]
NO
RS = 0
YES
BETA = SLOPE(G)/[(UQ^2(A_3)(XMU)]
SLOPE = XY/XSQ
HP = YBAR - SLOPE(XBAR)
XSQ = Σ_{I=1}^{NOOBS} X_I^2
YSQ = Σ_{I=1}^{NOOBS} Y_I^2
XY = Σ_{I=1}^{NOOBS} X_I Y_I
X_I = B_I - XBAR
Y_I = H_I - YBAR
XBAR = SX/NOOBS
YBAR = SY/NOOBS
SX = Σ_{I=1}^{NOOBS} B_I
SY = Σ_{I=1}^{NOOBS} H_I

```
C           BID -- BETA INDEX DETERMINATION
      DIMENSION A(50),H(100),T(100),B(100),X(100),
     1Y(100),KAN(80)
C
C     WRITE HEADINGS AND COMMENTS
C
      WRITE (3,100)
  100 FORMAT('1',//////,4X,'DETERMINATION OF ',
     1'BETA INDEX',15X,'BRIDGES - 1967',/////)
   30 READ (1,200)(KAN(K),K=1,80)
  200 FORMAT (80A1)
      IF (KAN(1)+1019199424)99,31,99
   31 WRITE (3,201)(KAN(K),K=2,80)
  201 FORMAT (1X,79A1)
      GO TO 30
   99 WRITE (3,199)
  199 FORMAT (////,10X,'INPUT DATA',///,21X,'RUN ',
     1'CONSTANTS',/,24X,'INDEX',3X,'UNIT Q',6X,'CF',
     27X,'TEMP',4X,'LB/CU FT',3X,'SEPTUM D',
     32X,'PRECOAT',2X,'DILUTION',/)
C
C     INPUT AND CONVERT FILTER RUN CONSTANTS
C
      READ (1,101)(A(I),I=1,8)
  101 FORMAT (8E10.5)
      WRITE (3,102) (A(I),I=1,8)
  102 FORMAT (20X,8F10.5,////,21X,'HEADLOSS',5X,
     1'TIME',/,25X,'FT',8X,'HR',///)
      INDEX=IFIX(A(1))
      UQ=A(2)*8.02
      A(4)=A(4)*1.8+32.0
      RS=A(6)/24.0
      G=32.2*3600.*3600.
      XNU=(.0000286405-SQRT(5.3671E-10 - 3.1027E-14
     1*(A(4)-152.45)**2))*3600.
C
C     INPUT HEAD LOSS DATA AND COMPUTE X OR LN TERM
C
      READ (1,103) NOOBS
  103 FORMAT (I5)
      READ (1,104) (H(I),T(I),I=1,NOOBS)
  104 FORMAT (2E10.5)
      PHI=2.*UQ*62.4*A(3)*.000001/A(5)
      RO=RS+A(7)/A(5)
      F1=RS*PHI/(RO*RO)
      DO 7 I=1,NOOBS
      H(I)=H(I)*1.05
      T(I)=T(I)/60.0
      TIME=T(I)
      IF (INDEX-1)4,3,4
```

```
    3 TIME=T(I)-(1.0-EXP(-A(8)*T(I)))/A(8)
    4 IF(RS)6,5,6
    5 B(I)=TIME
      GO TO 7
    6 B(I)=ALOG(1.0+F1*TIME)
    7 CONTINUE
      WRITE(3,105)(H(I),T(I),I=1,NOOBS)
  105 FORMAT (20X,2F10.5)
   40 IF(RS)43,41,43
   41 WRITE(3,42)
   42 FORMAT ('1',10X,'DATA PRIOR TO REGRESSION',
     1///,24X,'OBS',4X,'HEADLOSS',17X,'X',///)
      GO TO 44
   43 WRITE (3,106)
  106 FORMAT ('1',10X,'DATA PRIOR TO REGRESSION',
     1///,24X,'OBS',4X,'HEADLOSS',7X,'LN(1 + ',
     2'RS*PHI*X/RO**2)',///)
   44 WRITE (3,107)(I,H(I),B(I),I=1,NOOBS)
  107 FORMAT (20X,I6,4X,F10.5, 4X,E20.9,//)
C
C     REGRESS HEAD LOSS VERSUS X OR LOG TERM
C            AND COMPUTE BETA INDEX
C
      SX=0.
      SY=0.
      DO 50 I=1,NOOBS
      SX=SX+B(I)
      SY=SY+H(I)
   50 CONTINUE
      XBAR=SX/(FLOAT(NOOBS))
      YBAR=SY/(FLOAT(NOOBS))
      DO 51 I=1,NOOBS
      X(I)=B(I)-XBAR
      Y(I)=H(I)-YBAR
   51 CONTINUE
      XSQ=0.
      YSQ=0.
      XY=0.
      DO 52 I=1,NOOBS
      XSQ=XSQ+X(I)**2
      YSQ=YSQ+Y(I)**2
      XY=XY+X(I)*Y(I)
   52 CONTINUE
      SLOPE=XY/XSQ
      HP=YBAR-SLOPE*XBAR
      IF (RS)63,61,63
   61 BETA=SLOPE*G/(UQ*UQ*A(3)*XNU)
      WRITE(3,62)BETA,PHI,RS,RO
   62 FORMAT ('1',13X,'BETA, 1/SF', 6X,'PHI, FPH',
     17X,'RS, FT',9X,'LP, FT',///,10X,4E15.6)
```

```
      GO TO 64
   63 BETA=(SLOPE*PHI/RS)*G/(UQ*UQ*A(3)*XNU)
      WRITE (3,108)BETA,PHI,RS,RO
  108 FORMAT ('1',13X,'BETA, 1/SF', 6X,'PHI, FPH',
     17X,'RS, FT',9X,'RO, FT',///,10X,4E15.6)
C
C     COMPUTE HEAD LOSSES, ACTUAL DIFFERENCES,
C          AND PERCENT DIFFERENCES
C
   64 WRITE (3,109)
  109 FORMAT ('1',2X,'OBS',3X,'OBSERVED HL',3X,
     1'COMPUTED HL',10X,'DIFFERENCE',/,40X,
     2'ACTUAL',9X,'0/0',/)
      E=0.
      DO 60 I=1,NOOBS
      CHL=SLOPE*B(I)+HP
      DIFF=H(I)-CHL
      P=200.0*DIFF/(H(I)+CHL)
      E=E+DIFF*DIFF
      WRITE (3,110)I,H(I),CHL,DIFF,P
  110 FORMAT (1X,I5,2E14.5,E14.4,F11.3)
   60 CONTINUE
C
C     COMPUTE STANDARD ERROR OF ESTIMATE AND
C          CORRELATION COEFFICIENT
C
      SEE=(E/(FLOAT(NOOBS)-2.0))**0.5
      R=100.0*XY/SQRT(XSQ*YSQ)
      WRITE (3,111)SEE,R
  111 FORMAT (/////,2X,'STANDARD ERROR OF ESTIMATE',
     113X,F18.3,///,2X,'R = LINEAR CORRELATION ',
     2'COEFFICIENT       100(R) =',F8.3,/,'1')
C
C     CHECK FOR MORE WORK
C
      READ (1,112) NUMB
  112 FORMAT (A1)
      IF (NUMB-1547714624)70,30,70
   70 STOP
      END
```

In the following explanation of the program, the numbers to the left refer to the statement numbers shown in the FORTRAN listing.

0001 This statement is necessary to allocate storage for the arrays used in the program.

0002 These statements provide for writing the title heading
0003 on the output sheet.

0004 Statements 4 through 9 instruct the computer to read the first data card and determine if it is a comment card, i.e., the letter C is in the first column. If it is a comment card, the information on it is printed out and the next card is read. If it is not a comment card, the computer will continue with Statements 10 and 11 which are instructions for writing
0011 headings for the input data.

0012 The filter run constants are read into the A array
0015 and printed on the output sheet.

0016 Necessary transformations are performed on the filter run constants. The filtration rate is converted from gpm/sq ft to cu ft/hr/sq ft, the influent temperature is converted from degrees Centigrade to degrees Fahrenheit, the septum radius in feet is calculated, the acceleration of gravity is converted to ft/hr^2, and the kinematic viscostiy is calculated in sq ft/hr.

The equation used to compute the kinematic viscosity of water from the temperature (°F) was obtained by fitting a portion of an ellipse to tabulated values in a handbook (21). The values of viscosity obtained using the equation have been compared with handbook values and found to be acceptable within the range of temperature used in filtration.

If the influent temperature is input in degrees Fahrenheit, Statement 18 should be omitted, i.e., the
0021 card should be removed from the deck.

0022 The number of observations, NOOBS, is read into the computer. Then the head loss and time data are read
0025 until NOOBS number of observations have been read.

0026 Each head loss value is converted from inches of mercury to feet of water, and each value of time is converted from minutes to hours. If these conversions are unnecessary, Statements 30 and 31 should be eliminated, i.e., the cards should be removed from
0031 the deck.

0032 If the dilution rate is known, the value of X is calculated for each value of time. If the filter septa are flat, $R_s=0$, the calculated values of X are stored in an array named B. If the filter septa are cylindrical, the term $\ln(1 + R_s\phi X/R_o^2)$ is calculated for each value of X and stored in array B.

If the dilution rate is not known, values of time t,
0039 are used in place of X.

0040 The head loss values in feet and the times of observation in hours are printed out along with the values of X (or t) for flat septa or the natural log term
0049 for cylindrical septa.

0050 A simple linear regression is performed on the plot of X or $\ln(1 + R_s\phi X/R_o^2)$ versus head loss.

The regression formula for a simple linear relationship is (53):

$$\hat{Y} = b_0 + b_1 X$$

where $b_1 = \frac{\Sigma xy}{\Sigma x^2}$

and $b_0 = \bar{Y} - b_1\bar{X}$

where $x = X - \bar{X}$

and $y = Y - \bar{Y}$.

Notation: X, Y = observed values

$\bar{X}$, $\bar{Y}$ = average of observed values

$\hat{Y}$ = computed or estimated values of Y

The notation used in the program is:

B_I = X = values of X (or t) for flat septa or natural log terms for cylindrical septa

H_I = Y = head loss values

SX = ΣX

SY = ΣY

XBAR = $\bar{X}$

YBAR = $\bar{Y}$

X_I = x = X - XBAR

Y_I = y = Y - YBAR

XSQ = Σx^2

YSQ = Σy^2

XY = Σxy

SLOPE = b_1

0071 HP = b_0 = head loss through the precoat

0072 The β index is calculated, in Statement 73 for flat septa or Statement 77 for cylindrical septa from the slope of the regression line. The calculated values of β, ϕ, R_s and R_o are printed out along with the various
0081 headings

0082 Head losses are computed using the regression equation. The actual (DIFF) and percent (P) differences between the observed and computed head losses are also com-
0090 puted and printed out.

0091 The standard error of estimate (SEE) is calculated from the formula (53):

$$s_E = \sqrt{\frac{\Sigma(Y-\hat{Y})^2}{n-2}}$$

where $Y - \hat{Y}$ is the actual difference between observed and computed values of head loss. The value of $(Y - \hat{Y})^2$ was determined in Statement 87.

n = number of observations, NOOBS.

0092 The linear correlation coefficient, R, in percent, is calculated from the formula (53):

$$R = \frac{xy}{\sqrt{(\Sigma x^2)(\Sigma y^2)}} (100)$$

where x and y are as defined previously.

0093 The standard error of estimate and linear correlation
0094 coefficient are printed out.

0095 The computer reads the card following the head loss and time data cards and determines if there is an asterisk (*) in the first column. If there is, control is transferred back to Statement 4 and the next set of filter run data is processed. If there is not an asterisk in the first column, the program is stopped.

Input format and examples

Any number of comment cards, indicated by a C in the first column, may be inserted before each set of filter run data (Refer to the example input on pages 298 and 299). The information on each comment card is printed on the output sheet. After the last comment card, a card with DATA written in columns 1-4 should be inserted. If no comment cards are used, this card should still be present.

The next card contains the filter run constants (A(1), A(2), ..., A(8)) in eight 10-column fields. The decimal point must be given for each constant; however, the constant may be located anywhere within the proper field.

The following card contains the number of observations.

This number must be written in integer form with the last digit in Column 5. This card is followed by a series of cards containing the observed head losses and filtration times. On each card, the observed head loss must be located within Columns 1-10, and the filtration time must be located within Columns 11-20. The decimal point must be given for each head loss and time.

The computer will analyze the results of any number of runs in sequence. To accomplish this, a card with asterisks in Columns 1-5 must be inserted between each set of filter run data. The last set of data should be followed by a card with END written in Columns 1-3.

The following examples give the input and output for two sets of filter run data. The β indices are also calculated manually for comparison with the computer results.

80 COLUMN DATA SHEET

PROGRAM	JOB NO.	BY	DATE
BID EXAMPLE INPUT (Page 1 of 2)	U3041	Harold Bridges	5/8/70

```
C   EXAMPLE NUMBER 1
C   BRIDGES AND ARORA RUN NUMBER 53
C   DISTILLED WATER PLUS 33.9 MG/L UNSETTLED BALL CLAY
C   HYFLØ SUPER-CEL FILTER AID
C   SSCR FILTER  (FLAT SEPTUM)
DATA
    2.0       1.05      80.       26.1      20.0                0.15
   15
  0.906       24.
  1.004       28.5
  1.083       32.
  1.220       36.
  1.280       40.
  1.398       44.
  1.476       48.
  1.555       52.
  1.654       56.
  1.772       60.
  1.929       64.5
  2.028       68.
  2.087       72.
  2.185       76.
  2.264       80.
*****
```

any number of comment cards can be used

8 0 COLUMN DATA SHEET

PROGRAM BID EXAMPLE INPUT (Page 2 of 2)

JOB NO. U3041

BY Harold Bridges

DATE 5/8/70

```
1        10        20        30        40        50        60        70        80
C   EXAMPLE NUMBER 2
C   BRIDGES (1966)  FILTER RUN NUMBER 30
C   COAGULATED, FLOCCULATED, AND SETTLED LAKE WATER AT CRESTON, IOWA
C   INFLUENT TURBIDITY = 8.2 JTU
C   HYFLO SUPER-CEL FILTER AID
C   MOBILE TREATMENT UNIT  (CYLINDRICAL SEPTA)
DATA
    1.0       0.98     28.42      26.1      15.0       3.5      0.20        2.
  10
  1.80       5.0
  2.60      30.0
  4.40      60.0
  7.00      90.0
  9.50     120.0
 12.40     150.0
 14.40     180.0
 16.80     210.0
 19.20     240.0
 20.90     270.0
END
```

```
DETERMINATION OF BETA INDEX                    BRIDGES - 1967



EXAMPLE NUMBER 1
BRIDGES AND ARORA RUN NUMBER 53
DISTILLED WATER PLUS 33.9 MG/L UNSETTLED BALL CLAY
HYFLO SUPER-CEL FILTER AID
SSCR FILTER  (FLAT SEPTUM)



    INPUT DATA


           RUN CONSTANTS
              INDEX    UNIT Q      CF        TEMP

             2.00000   1.05000  80.00000  26.09999

            LB/CU FT    SEPTUM D  PRECOAT  DILUTION

             20.00000   0.0        0.15000   0.0



           HEADLOSS      TIME
              FT          HR


             0.95130    0.40000
             1.05420    0.47500
             1.13715    0.53333
             1.28100    0.60000
             1.34400    0.66667
             1.46790    0.73333
             1.54980    0.80000
             1.63275    0.86667
             1.73670    0.93333
             1.86060    1.00000
             2.02545    1.07500
             2.12940    1.13333
             2.19135    1.20000
             2.29425    1.26667
             2.37720    1.33333
```

```
DATA PRIOR TO REGRESSION

                    OBS    HEADLOSS                X


                     1      0.95130         0.399999976E 00

                     2      1.05420         0.474999964E 00

                     3      1.13715         0.533333302E 00

                     4      1.28100         0.599999964E 00

                     5      1.34400         0.666666627E 00

                     6      1.46790         0.733333290E 00

                     7      1.54980         0.799999952E 00

                     8      1.63275         0.866666615E 00

                     9      1.73670         0.933333278E 00

                    10      1.86060         0.100000000E 01

                    11      2.02545         0.107499981E 01

                    12      2.12940         0.113333321E 01

                    13      2.19135         0.119999981E 01

                    14      2.29425         0.126666641E 01

                    15      2.37720         0.133333302E 01
```

```
  BETA, 1/SF       PHI, FPH        RS, FT          LP, FT

 0.338504E 07   0.420375E-02   0.0           0.750000E-02



OBS    OBSERVED HL    COMPUTED HL           DIFFERENCE
                                        ACTUAL           0/0

  1    0.95130E 00    0.93849E 00     0.1281E-01        1.356
  2    0.10542E 01    0.10556E 01    -0.1391E-02       -0.132
  3    0.11371E 01    0.11467E 01    -0.9522E-02       -0.834
  4    0.12810E 01    0.12508E 01     0.3024E-01        2.389
  5    0.13440E 01    0.13549E 01    -0.1086E-01       -0.805
  6    0.14679E 01    0.14589E 01     0.8952E-02        0.612
  7    0.15498E 01    0.15630E 01    -0.1324E-01       -0.851
  8    0.16327E 01    0.16671E 01    -0.3438E-01       -2.084
  9    0.17367E 01    0.17712E 01    -0.3453E-01       -1.968
 10    0.18606E 01    0.18753E 01    -0.1472E-01       -0.788
 11    0.20254E 01    0.19924E 01     0.3303E-01        1.644
 12    0.21294E 01    0.20835E 01     0.4590E-01        2.179
 13    0.21913E 01    0.21876E 01     0.3757E-02        0.172
 14    0.22942E 01    0.22917E 01     0.2564E-02        0.112
 15    0.23772E 01    0.23958E 01    -0.1858E-01       -0.778



STANDARD ERROR OF ESTIMATE                               0.024

R = LINEAR CORRELATION COEFFICIENT       100(R) =   99.873
```

```
EXAMPLE NUMBER 2
BRIDGES (1966)  FILTER RUN NUMBER 30
COAGULATED, FLOCCULATED, AND SETTLED LAKE WATER AT CRESTON, IOWA
INFLUENT TURBIDITY = 8.2 JTU
HYFLO SUPER-CEL FILTER AID
MOBILE TREATMENT UNIT  (CYLINDRICAL SEPTA)



      INPUT DATA


                 RUN CONSTANTS
                    INDEX    UNIT Q       CF         TEMP

                   1.00000    0.98000   28.42000   26.09999


                 LB/CU FT    SEPTUM D  PRECOAT  DILUTION

                  15.00000    3.50000   0.20000   2.00000


                  HEADLOSS      TIME
                     FT          HR



                   1.89000    0.08333
                   2.73000    0.50000
                   4.62000    1.00000
                   7.34999    1.50000
                   9.97499    2.00000
                  13.01999    2.50000
                  15.11999    3.00000
                  17.63997    3.50000
                  20.15997    4.00000
                  21.94498    4.50000
```

```
DATA PRIOR TO REGRESSION

                    OBS     HEADLOSS        LN(1 + RS*PHI*X/RO**2)


                     1       1.89000          0.696157949E-04

                     2       2.73000          0.196549715E-02

                     3       4.62000          0.605368242E-02

                     4       7.34999          0.109037757E-01

                     5       9.97499          0.160158090E-01

                     6      13.01999          0.212045573E-01

                     7      15.11999          0.264055245E-01

                     8      17.63997          0.315934457E-01

                     9      20.15997          0.367601030E-01

                    10      21.94498          0.419020392E-01
```

```
 BETA, 1/SF      PHI, FPH        RS, FT          RO, FT

0.439596E 08   0.185843E-02   0.145833E 00   0.159167E 00




OBS    OBSERVED HL    COMPUTED HL             DIFFERENCE
                                          ACTUAL          O/O

  1    0.18900E 01    0.19822E 01    -0.9217E-01      -4.761
  2    0.27300E 01    0.29157E 01    -0.1857E 00      -6.579
  3    0.46200E 01    0.49287E 01    -0.3087E 00      -6.466
  4    0.73500E 01    0.73169E 01     0.3309E-01       0.451
  5    0.99750E 01    0.98341E 01     0.1409E 00       1.423
  6    0.13020E 02    0.12389E 02     0.6310E 00       4.967
  7    0.15120E 02    0.14950E 02     0.1700E 00       1.131
  8    0.17640E 02    0.17504E 02     0.1355E 00       0.771
  9    0.20160E 02    0.20049E 02     0.1115E 00       0.554
 10    0.21945E 02    0.22580E 02    -0.6354E 00      -2.854



STANDARD ERROR OF ESTIMATE                                0.357

R = LINEAR CORRELATION COEFFICIENT       100(R) =    99.892
```

Manual calculations

Example Number 1:

Bridges and Arora Run Number 53 (Appendix A, Table 32)

Distilled water plus 33.9 mg/l unsettled Ball clay

Hyflo Super-Cel filter aid

SSCR filter (flat septum)

Data: Filtration rate, q = 1.05 gpm/sq ft

Body feed rate, C_F = 80 mg/l

Influent temperature = 26.1 °C

Observation	Time (minutes)	Head loss (cm Hg)	Head loss (inches Hg)
1	0	1.15	0.453
2	2	1.15	0.453
3	4	1.20	0.472
4	6	1.30	0.512
5	8	1.40	0.551
6	10	1.50	0.591
7	12	1.60	0.630
8	14	1.70	0.669
9	16	1.80	0.708
10	18	1.90	0.748
11	20	2.10	0.827
12	24	2.30	0.906
13	28.5	2.55	1.004
14	32	2.75	1.083
15	36	3.10	1.220
16	40	3.25	1.280
17	44	3.55	1.398
18	48	3.75	1.476
19	52	3.95	1.555
20	56	4.20	1.654
21	60	4.50	1.772
22	64.5	4.90	1.929
23	68	5.15	2.028
24	72	5.30	2.087
25	76	5.55	2.185
26	80	5.75	2.264

Calculations:

The slope of the head loss versus time curve for this filter run (Figure 49) becomes constant at a value of 0.0625 cm Hg/min after 24 minutes of filtration. Now

$$\beta = \frac{g}{q^2 \nu} \frac{\text{Slope}}{C_F} \qquad (31)$$

where

$$q = 1.05 \text{ gpm/sq ft}$$

$$= 1.05 \frac{\text{gal}}{\text{min sq ft}} \times 60 \frac{\text{min}}{\text{hr}} \times \frac{\text{cu ft}}{7.48 \text{ gal}}$$

$$= 1.05\ (8.02)$$

$$= 8.421 \text{ ft/hr}$$

$$g = 32.2 \text{ ft/sec}^2$$

$$= 417.3 \times 10^6 \text{ ft/hr}^2$$

and

$$\nu = \frac{\text{viscosity}}{\text{density}} = \frac{\mu}{\gamma_w}$$

where

$\mu = 8.718 \times 10^{-3}$ poise From handbook (21)

$$= (8.718 \times 10^{-3})242 \text{ lb/hr ft}$$

$$= 2.110 \text{ lb/hr ft}$$

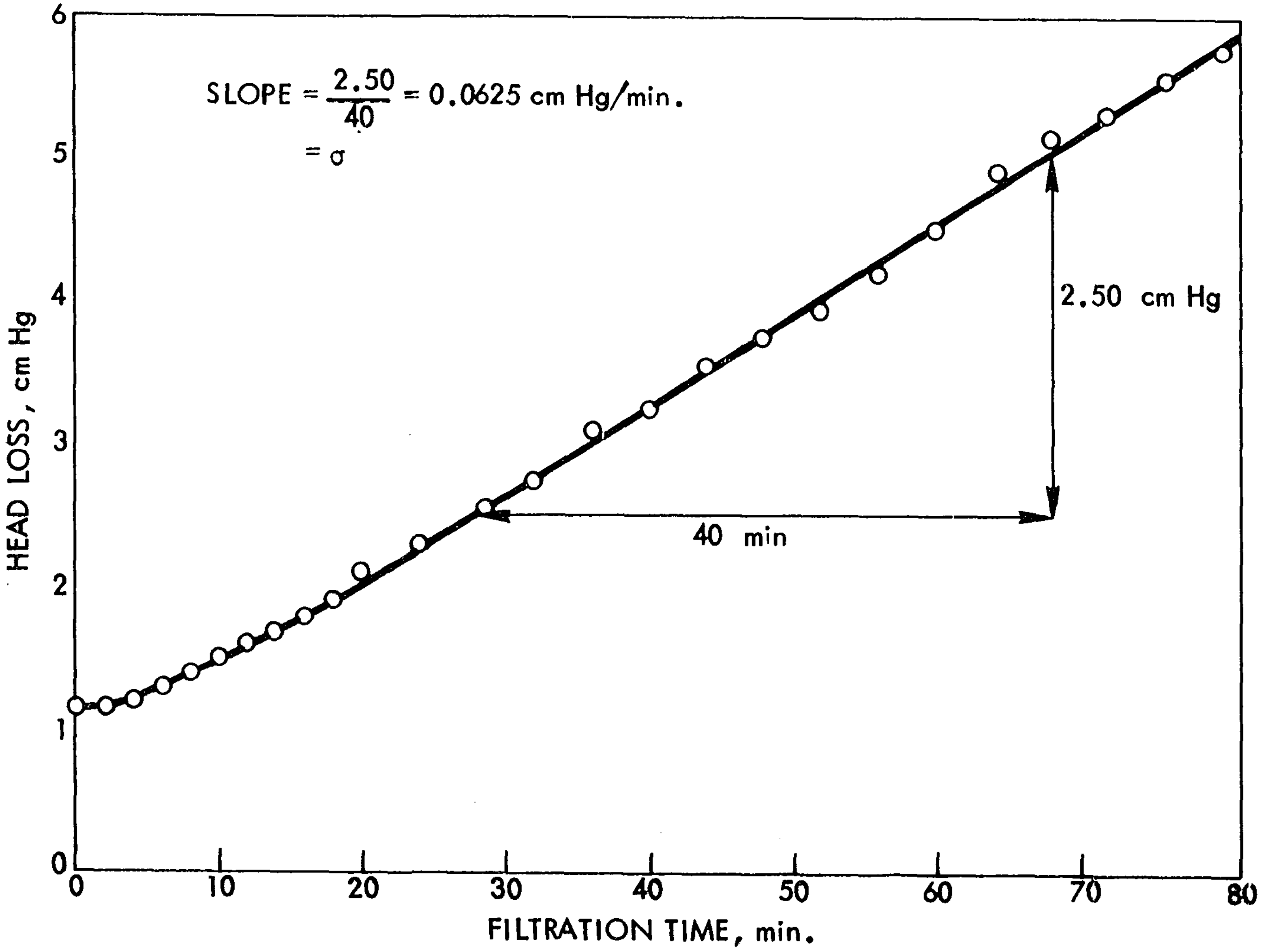
$\gamma_w = 62.23$ lb/cu ft From handbook (21)

therefore,

$$\nu = \frac{2.110}{62.23} = 3.391 \times 10^{-2} \text{ sq ft/hr}$$

Note: The value of ν calculated from the equation used

Figure 49. Head loss versus time curve for Example 1


SLOPE = $\frac{2.50}{40}$ = 0.0625 cm Hg/min.
= σ
2.50 cm Hg
40 min
HEAD LOSS, cm Hg
FILTRATION TIME, min.
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80

in the computer program is 3.393 x 10^{-2} sq ft/hr.

and

$$\text{Slope} = 0.0625\ \frac{\text{cm Hg}}{\text{min}} \times \frac{1.05\ \text{ft water/in. Hg}}{2.54\ \text{cm/in.}} \times 60\ \frac{\text{min}}{\text{hr}}$$

$$= 1.55\ \text{ft water/hr}$$

therefore

$$\beta = \frac{417.3 \times 10^{6}}{(8.421)^{2}\ (3.391 \times 10^{-2})}\ \frac{1.55}{80}$$

$$= \underline{338 \times 10^{4}\ \text{ft}^{-2}}$$

The value using the computer is 338.5 x 10^{4} ft^{-2} with a linear correlation coefficient of 0.99873 and standard error of estimate of 0.024 ft.

Example number 2:

Bridges (1966) Filter Run Number 30 (Appendix A, Table 27)

Coagulated, flocculated, and settled lake water at Creston, Iowa. Influent turbidity = 8.2 JTU.

Hyflo Super-Cel filter aid

Mobile treatment unit's filter (cylindrical septa)

Data: Septum diameter = 3.5 in
Precoat weight, w = 0.20 lb/sq ft
Precoat density, γ_p = 15 lb/cu ft
Filtration rate, q = 0.98 gpm/sq ft
Body feed rate, C_F = 28.42 mg/l
Influent temperature = 26.1 °C
Initial dilution rate, δ = 2/hr

Observation	Time (minutes)	Head loss (inches Hg)
1	5	1.80
2	30	2.60
3	60	4.40
4	90	7.00
5	120	9.50
6	150	12.40
7	180	14.40
8	210	16.80
9	240	19.20
10	270	20.90

Calculations:

The diameter of each filter septum = 3.5 in.

Therefore,

$$R_s = \frac{3.5 \text{ in.}}{2(12)\text{in./ft}} = \underline{0.146 \text{ ft}}$$

$$R_o = R_s + L_p$$

where

$$L_p = w/\gamma_p \ .$$

Therefore,

$$L_p = \frac{0.20 \text{ lb/sq ft}}{15.0 \cdot \text{lb/cu ft}}$$

$$= 0.013 \text{ ft}$$

and

$$R_o = 0.146 + 0.013$$

$$= \underline{0.159 \text{ ft}}$$

$$\phi = 2q\gamma_w C_F (10^{-6})/\gamma_p$$

where

$$q = 0.98 \text{ gpm/sq ft}$$

$$= 0.98 \ \frac{\text{gal}}{\text{min sq ft}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{\text{cu ft}}{7.48 \text{ gal}}$$

$$= 0.98 \ (8.02)$$

$$= 7.861 \text{ ft/hr}$$

$$\gamma_p = 62.4 \text{ lb/cu ft}$$

$$C_F = 28.42 \text{ mg/l or ppm}$$

$$\gamma_p = 15.0 \text{ lb/cu ft}$$

Therefore,

$$\phi = \frac{2(7.861)\ (62.4)\ (28.42)\ (10^{-6})}{15.0}$$

$$= \underline{1.858 \times 10^{-3} \text{ ft/hr}}$$

and,

$$\ln(1 + R_s \phi X/R_o{}^2) = \ln\left(1 + \frac{(0.146)(1.858 \times 10^{-3})}{(0.159)^2} X\right)$$

$$= \ln(1 + (1.0698 \times 10^{-2})\ X)$$

For manual calculations, X may be approximated by t. The value of the above quantity is shown below for each value of t.

Observation	Headloss (H_c)		Time (t)		$1+\frac{R_s\phi}{R_o^2}t$	$\ln(1+\frac{R_s\phi}{R_o^2}t)$
	Inches of mercury	Feet of water	Minutes	Hours		
1	1.80	1.890	5	0.083	1.00089	0.0009
2	2.60	2.730	30	0.500	1.00535	0.0053
3	4.40	4.620	60	1.000	1.01070	0.0106
4	7.00	7.350	90	1.500	1.01605	0.0159
5	9.50	9.975	120	2.000	1.02140	0.0212
6	12.40	13.020	150	2.500	1.02675	0.0264
7	14.40	15.120	180	3.000	1.03209	0.0316
8	16.80	17.640	210	3.500	1.03744	0.0368
9	19.20	20.160	240	4.000	1.04279	0.0419
10	20.90	21.945	270	4.500	1.04814	0.0470

H_c is then plotted versus $\ln(1 + R_s\phi t/R_o^2)$ as in Figure 50. The slope of the estimated regression line is determined to be 460 ft. The slope is equal to $R_s\sigma/\phi$. Therefore

$$\sigma = \frac{460\ \phi}{R_s}$$

$$= \frac{460\ (1.858 \times 10^{-3})}{0.146}$$

$$= \underline{5.854\ \text{ft/hr}}$$

$$\sigma = q^2\nu\beta C_F/g$$

Therefore,

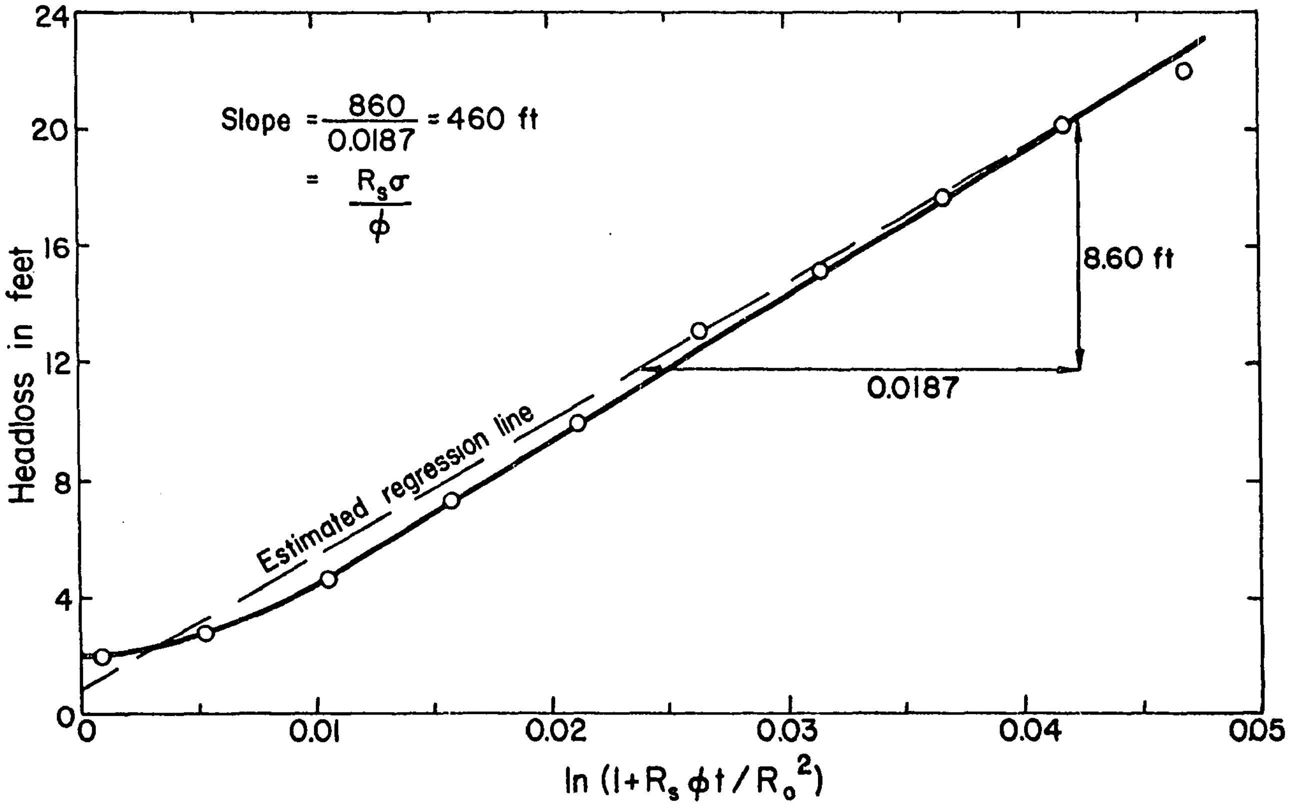
$$\beta = \frac{\sigma g}{q^2\nu C_F}$$

where

$q = 7.861$ ft/hr

$g = 32.2\ \text{ft/sec}^2 = 417.3 \times 10^6\ \text{ft/hr}^2$

Figure 50. Head loss versus the natural log term


Slope = $\frac{860}{0.0187}$ = 460 ft
= $\frac{R_s \sigma}{\phi}$
Headloss in feet
0
4
8
12
16
20
24
0
0.01
0.02
0.03
0.04
0.05
$\ln(1 + R_s \phi t / R_o^2)$
Estimated regression line
8.60 ft
0.0187

and since the temperature is the same as in Example 1,

$$\nu = 3.391 \times 10^{-2} \text{ sq ft/hr}$$

and,

$$\beta = \frac{(5.854)(417.3 \times 10^{6})}{(7.861)^{2}(3.391 \times 10^{-2})(28.42)}$$

$$= \underline{41.02 \times 10^{6} \text{ ft}^{-2}}$$

The value obtained using the computer with $\delta = 2/\text{hr}$ is 43.960 ft^{-2} with a linear correlation coefficient of 0.99892 and standard error of estimate of 0.357 ft.

APPENDIX E

MAIDS Program User Manual

Introduction

The program for Manipulation and Interpretation of Data Systems or the MAIDS Program was designed to perform a multiple regression of from two to eight variables to fit the linear model,

$$T1 = B1 + B2*T2 + B3*T3 + \ldots + Bn*Tn$$

where T1 is the dependent variable, T2 ... Tn are independent variables, B1 ... Bn are regression coefficients. n can be from two to eight.

If the model (the equation of the curve being fitted) is not linear, some transformation or combination of transformations must be performed to make the model linear. For example, the model

$$T1 = 10^{B1} * T2^{B2} * T3^{B3}$$

can be made linear by taking the logarithm (base 10) of each variable.

$$\log T1 = B1 + B2*\log T2 + B3*\log T3$$

This type of transformation is necessary for determining β prediction equations.

Any desired transformation is possible with MAIDS. Thus, the program is very useful for reducing and printing out tabular data, even though a regression analysis is not desired.

Input card forms

Data used by MAIDS is read into the computer on 80 column punched cards. The card formats used with MAIDS are listed in Table 33.

1) KAN array card:

The KAN array card is always the first input card read by the computer. Each letter, symbol, and digit on the card is stored in an array named KAN. Therefore, KAN(1) = C, KAN(2) = L, KAN(3) = D, ..., KAN(50) = U. The KAN array is then used by the computer to read the remaining input cards. This is done by comparing each letter, symbol, or digit on the input card with each element of the KAN array. For example, if the letter in the first column of an input card matches KAN(1), i.e., the letter C is punched in Column 1 of the input card, the card is a comment card. Therefore, the computer will print out the information contained on the card and then read the next input card.

2) Comment and label cards

Cards with C or L punched in Column 1 are ignored by MAIDS; however, the information on the cards is printed on the output sheet. These cards can be used to make comments or to label

Table 33. MAIDS input card formats

```
        1   10    2   20    3   30    4   40    5   50    6   60    7   70    8   80
1)  CLDTPAVRSEFOM +-.0123456789 +-*/=$LSCEADMOJ TXANIU
2)  C
    L
3)       X         X         X         X         X         X         X         X
    A    a         a         a         a         a         a         a         a
4)  T    t         t         t         t         t         t         t         t
5)  V*   i
6)  PRINT
7)  REGRESSION
8)  PACOCO
9)  *****
    *DATA
10) END
11) STOP


    NOTE: X = Value of an observed variable (number),
          a = Value of a single valued variable (number)
          t = A transformation (from Table 34)
          i = An integer from 1 to 8.
```

values in tables. Any characters can be punched in Columns 2 to 80 of a comment or label card and any number of comment cards can be used.

3) Data cards

A card with Column 1 left blank is used to input observed values of the variables (T1, T2, T3, ..., Tn) used in the regression analysis. On an 80 column data card there are eight 10-column fields available for up to eight observed variables. The first field actually contains only nine columns since the first column must be left blank. Each observed variable may be punched anywhere within a particular 10-column field. The decimal point must occupy one column. A plus sign may or may not be punched before a positive valued variable. Each data card contains one observation of each variable being read in. A particular variable must be punched in the same 10-column field on all data cards. If a 10-column field on a particular data card is blank, that field is ignored; a blank is not interpreted as zero.

A card with A punched in Column 1 may be used to read from one to eight different constants into the computer. Each constant must be punched anywhere within one of the eight 10-column fields with the decimal point occupying one column. These constants are used in transforming the observed variables.

4) Transformation card:

A card with T punched in Column 1 is a transformation card. The letter t shown in Table 33 represents the transformation symbols given in Table 35.

The observed variables input on a data card are denoted witin the program as Xk where k = 1, 2, 3, ..., 8. When a transformation is applied to Xk, the transformed variable is denoted as Tk. Tk can be transformed to a new variable which is also denoted as Tk.

The variable to be transformed by a particular transformation as specified on a transformation card is determined by in which of the eight 10-column fields the transformation symbol occurs. The symbol may be punched anywhere within the proper 10-column field. For example, in Table 34 four observations of three variables X1, X2, and X3, are read in. The

Table 34. Transformation example

1 10	20	30	40	50
10.0	50.0	90.0		
20.0	60.0	100.0		
30.0	70.0	110.0		
40.0	80.0	120.0		
T /10.0	+5.0	-60.0		
T	-T3			

Table 35. List of transformations allowed in MAIDS

Index no.[a]	Symbol	Meaning
1	LN	natural log
2	LOG	base 10 log
3	SIN	sin
4	COS	cos
5	EXP	e.g. EXP punched in columns 14-16 means e^{T2}
6	+Ti	add i-th transformed variable
7	+Xi	add i-th original (read in) variable
8	+p	add p (p = constant or Ai where Ai = i-th A value)
9	-Ti	subtract
10	-Xi	
11	-p	
12	*Ti	multiply
13	*Xi	
14	*p	
15	ABS	absolute value
16	/Ti	Divide
17	/Xi	
18	/p	
19	=Ti	set equal to
20	=Xi	
21	=p	
22	$Ti	raise to power
23	$Xi	
24	$p	
25	CUM	each element = sum of itself and all before
26	DELTA	each element = increment from previous element
27	MEAN	each element is mean of this element and preceding element
28	ORDER	e.g., if punched in Columns 22-26, rearranges transformed variables and original variables such that the new T3 would be in ascending order.
29	JANET	variable subroutines written for special transformations not included in 28 above transformations
30	LEANN	
	SUZIE	
31		

Xi = ith column of data read in
Ti = ith column of the current transformed variable.
p = either a signed constant or Ai
Ai = ith A value.

[a] See page 337.

first transformation card instructs the computer to divide X1 by 10.0, add 5.0 to X2, and subtract 60.0 from X3. This results in the transformed variables:

T1	T2	T3
1.0	55.0	30.0
2.0	65.0	40.0
3.0	75.0	50.0
4.0	85.0	60.0

The second transformation card instructs the computer to subtract T3 from T2. This gives the transformed variables:

T1	T2	T3
1.0	25.0	30.0
2.0	25.0	40.0
3.0	25.0	50.0
4.0	25.0	60.0

Transformations JANET, LEANN, and SUZIE are for special transformations. These are variable subroutines which can be written by users familiar with the FORTRAN computer language to perform a transformation which is not included in Table 35. These variable subroutines allow the user to perform any desired transformation on an original variable, Xk, or previously transformed variable, Tk. Up to three special transformations can be made, one for each of the three variable subroutines.

Most FORTRAN systems contain standard library functions, such as arc since, hyperbolic sine, etc., which have not been included in the list of MAIDS transformations. These may be used in a variable subroutine. For example, suppose it is desired to transform the variable T2 as follows:

T2 = T2 * arctan (A3/X7).

This can be done by punching JANET in the second 10-column field of a transformation card (T in Column 1) and including the following subroutine with the MAIDS program subroutines.

```
      SUBROUTINE JANET (J)
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,
     2NOVAR, LEE, KFLAG, KAN(50)
      DO 1 I = 1, NOOBS
    1 T(J,I) = T(J,I) * ATAN(A(3)/X(7,I))
      RETURN
      END
```

The SUBROUTINE and COMMON statements in the example above are similar for any variable subroutine (JANET, LEANN, SUZIE), except the name of the subroutine changes. The value of the variable J (two in this example) is the number of the 10-column field that JANET was punched in on the transformation card. Note that JANET was punched in the second 10-column field since the second variable, T2, is to be transformed. The first subscript of T (or X) is the variable number (1 to 8) and the second is the element number or observation number, i.e., T (2, 10) would be the tenth observation of T2. A(3) is the number read in from the third 10-column field of the A card. In the COMMON statement of the subroutines, B, NM, JT, IT, PT, IXT, MN, and LEE are arrays used in other parts of MAIDS and are included here as dummy variables to align COMMON sotrage. NOOBS is the number of observations of variables read in and NOVAR is the number of variables, ranging from one to eight. KFLAG is an error indicator. Its usual value is one but it is assigned a value of two if an error is encountered. Therefore, if KFLAG has a value of two when control is returned from a subroutine to the main program, an error statement is printed as follows: **UNIDENTIFIABLE CHARACTER **. KAN is the KAN array from the first input card and ATAN is the FORTRAN library function for computing arc tangent.

Whenever a variable subroutine is used, the corresponding previous variable subroutine having the same name must be removed from the program. This is necessary because there cannot be two subroutines with the same name in the same program. For some FORTRAN compilers it is required that every subroutine which is referenced in the program be included. Therefore, even if a variable subroutine is not used it should nevertheless be included in the program as a dummy subroutine that actually does nothing. For example:

```
 SUBROUTINE JANET (J)
 COMMON B(10,10), X(8,400), T(8,409), NM(80), JT(100),
1IT(100), PT(100), IXT(100), A(8), MN(75), NOOBS,
2NOVAR, LEE, KFLAG, KAN(50)
 DUMMY = 1
 RETURN
 END
```

5) V* card:

A card with V* punched in Columns 1 and 2 respectively and a number, i (i=1 to 8), punched in anywhere within Columns 3 and 10 specifies the number of variables to use when a PRINT, REGRESSION, or PACOCO statement is executed. If not specified, the number of variables is taken as eight.

6) PRINT card:

A card with PRINT punched in Columns 1 to 5 instructs the computer to print out the values of the first i transformed variables (T1, T2, T3, ..., Ti). The value of i is specified on the V* card.

7) REGRESSION card:

A card with REGRESSION punched in Columns 1 to 10 instructs the computer to determine the regression coefficients of the linear model,

T1 = B1 + B2 * T2 + B3 * T3 + ... + Bi * Ti.

The method of least squares is used to determine the regression coefficients, B1, B2, B3, ..., Bi. Included in the output are the transformed variables and the partial correlation coefficients. The computed (by the regression equation) and the observed values of the dependent variable (T1) are printed along with the standard error of estimate and multiple correlation coefficient.

8) PACOCO card:

A card with PACOCO punched in Columns 1 to 6 instructs the computer to determine and print the partial correlation coefficients for the first i (as specified on a V* card) transformed variables. As noted above, the partial correlation coefficients are printed when a REGRESSION card is executed; however, a regression is not performed when a PACOCO card is executed. Regression coefficients, B1, B2, ..., Bn, are not determined.

9) ***** card and *DATA card:

A card with ***** punched in the first five columns instructs the computer to perform the specified operations on the group of data read in prior to the ***** card. The same analysis can be performed on any number of data groups. Each data group must be followed by a ***** card. The specified operations are contained on the operation cards (T, V*, PRINT, REGRESSION, and PACOCO cards). The operation cards are included with the first group of data and need not be repeated for additional data groups on which the same operations are to be performed.

A *DATA card is used when it is desired to change only the values of constants read in via a card with A punched in the first column. An A card containing a new set of constants should follow the *DATA card. This instructs the computer to perform the specified operations on the original set of data using the new constants. An example problem using the *DATA card will be given later.

10) END card:

END punched in the first three columns of a card instructs the computer to clear its memory of operation statements. This card is used to separate the series of data groups on which different operations are to be performed. An END card is followed by another set of operation cards, (T, V*, PRINT, REGRESSION, and PACOCO) and corresponding data groups.

11) STOP card:

Whenever a card with STOP punched in the first four columns is encountered, the computer run is terminated. This should be the last card to be read by the computer.

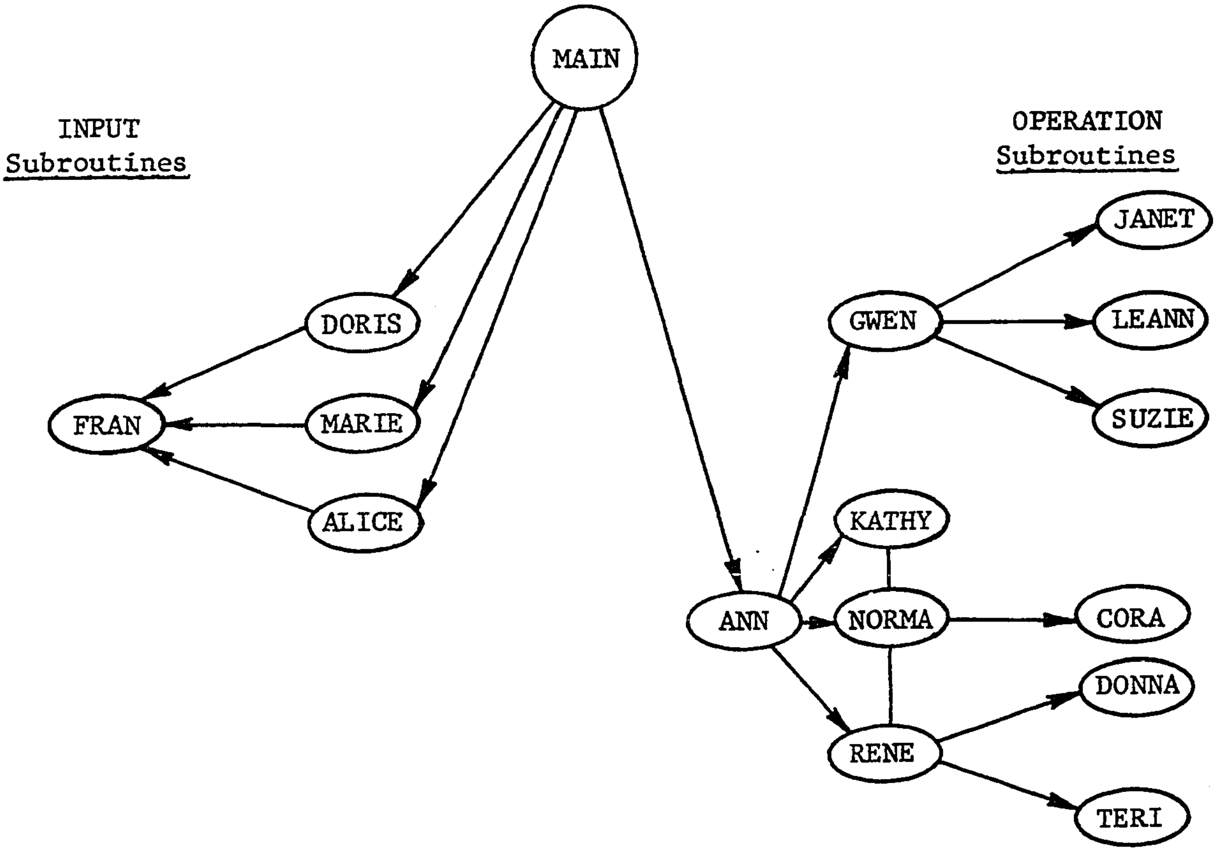
FORTRAN listing

MAIDS is written in FORTRAN IV computer language (31, 41) for use with the IBM 360/65 computer system at Iowa

State University. The FORTRAN listing of the program is given in this section. Some of the symbols used in FORMAT statements for the Iowa State University IBM 360/65 computer system have been explained in Appendix D.

A complete explanation of the FORTRAN listing for MAIDS would be very lengthy. Therefore, only a brief explanation of the basic purposes of the main program and each subroutine is given. Figure 51 is a schematic diagram showing the relationships between the various subroutines of MAIDS. The arrows in Figure 51 point to the subroutine which is called. Input subroutines are herein defined as subroutines which are used for reading and interpreting input cards. Operation subroutines are defined as subroutines used to perform the specified operations determined by the input subroutines.

Figure 51. Schematic diagram of MAIDS subroutines


MAIN
INPUT
Subroutines
DORIS
FRAN
MARIE
ALICE
OPERATION
Subroutines
JANET
GWEN
LEANN
SUZIE
KATHY
ANN
NORMA
CORA
DONNA
RENE
TERI

MAIN program

The first card in the data deck is read and the information on it is stored in the KAN array. The succeeding card is then read and the character in the first column is determined by comparison to the KAN array. Control is then transferred to an appropriate subroutine or statement number. For example, if the first character on the card is T, (TRANSFORMATION card), control is transferred to subroutine ALICE which determines what transformation is to be performed. The first character on each input card must correspond to one of the input card forms, i.e., the first character must be either C, L, blank, A, T, P, R, V, *, E, or S. If any other character is punched in the first column of a card, the error statement "UNIDENTIFIABLE CHARACTER" is printed. If an unidentifiable character is read, the computer will continue reading cards until either an END or a STOP card is read.

```
C           MAIN PROGRAM -- MAIDS
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50),LAY,FIELD(4,6),XA(4,5),YA(4,5),LA(4,5),
     3MA(4,5)
      READ(1,100) (KAN(K),K=1,50)
  100 FORMAT(80A1)
    1 LEE=0
      LAY=0
      DO 2 I=1,8
    2 A(I)=0.0
      NOVAR=8
      NOOBS=0
      KFLAG=1
```

```
      WRITE(3,200)
  200 FORMAT('1',//////,' M A I D S ',/,' DILLINGHAM 1964--',
     1'BESETT 1966--BRIDGES 1967',///)
    3 READ(1,100) (NM(I),I=1,80)
      WRITE(3,300) (NM(I),I=1,80)
  300 FORMAT('0',80A1)
      DO 4 K=1,14
      IF(NM(1)-KAN(K)) 4,5,4
    4 CONTINUE
      GO TO 22
    5 GO TO (3,3,6,7,8,6,16,17,27,1,18,20,21,6),K
    6 CALL DORIS
      GO TO (3,24),KFLAG
    7 CALL ALICE
      GO TO (3,24),KFLAG
    8 LEE=LEE+1
      IF(NM(2)-KAN(6)) 10,9,10
    9 IXT(LEE)=-6
      GO TO 3
   10 IF(NM(2)-KAN(8)) 12,11,12
   11 IXT(LEE)=-5
      GO TO 3
   12 IF(NM(2)-KAN(50)) 24,13,24
   13 IXT(LEE)=-4
   14 DO 15 KK=1,75
   15 MN(KK)=NM(KK+5)
      GO TO 3
   16 CALL MARIE
      GO TO (3,24),KFLAG
   17 LEE=LEE+1
      IXT(LEE)=0
      GO TO 3
   18 GO TO 24
   20 GO TO 24
   21 GO TO 24
   22 IF(NM(1)-KAN(31)) 24,23,24
   23 CALL ANN
      GO TO 3
   24 WRITE(3,400) (NM(I),I=1,80)
  400 FORMAT('0',5X,'**UNIDENTIFIABLE CHARACTER**',80A1)
   25 READ(1,100) K
      IF(K-KAN(10)) 26,1,26
   26 IF(K-KAN(9)) 25,27,25
   27 STOP
      END
```

Subroutine FRAN

Subroutine FRAN is used by subroutines DORIS, MARIE, and ALICE to read numerical data. When a card is read by the MAIN program, each character is stored in the array NM. For example, suppose 1.24 is punched in Columns 14 to 17 of a data card. This would not be read in as the number 1.24, but as individual characters: NM(14) = 1, NM(15) = ., NM(16) = 2, and NM(17) = 4. Subroutine FRAN is used to combine these individual characters into one numerical value. The KAN array is used for comparison to determine the numerical value of individual characters. The argument P is the number that is determined, N is the number of the column in which either a plus sign, a minus sign, or the first digit of the number if punched in, and L is the number of the last column in the 10-column field containing the number.

MAIDS could have been written to read numerical values directly. However, the method used allows each input card to be read under the same format. This increases the simplicity of the input card forms and the versatility of the program.

```
      SUBROUTINE FRAN(P,N,L)
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50)
      SN=1.0
      NUMBR=0
      KPT=-20
      IF(N-L) 1,1,3
    3 KFLAG=2
      RETURN
```

```
 1 DO 10 I=N,L
   J=NM(I)
   DO 2 K=14,27
   IF(J-KAN(K)) 2,4,2
 2 CONTINUE
   GO TO 3
 4 K=K-18
   IF(K) 5,9,9
 5 K=-K
   GO TO (6,8,10,10),K
 6 IF(KPT) 7,3,3
 7 KPT=0
   GO TO 10
 8 SN=-1.0
   GO TO 10
 9 NUMBR=NUMBR*10+K
   KPT=KPT+1
10 CONTINUE
   IF(KPT) 11,11,12
11 D=1.0
   GO TO 13
12 D=FLOAT(10**KPT)
13 P=SN*FLOAT(NUMBR)/D
   RETURN
   END
```

Subroutine DORIS

Control is transferred to subroutine DORIS whenever a data card (blank or A in first column) is read by the MAIN program. If the first column is blank, the number of observations of variables (NOOBS) is increased by one. Each successive column of the data card is checked until a column that is not blank is found. The number of this column, (K), is used to calculate the number of the 10-column field (J) and the number of the last column in the field (L) in which Column K is located. Subroutine FRAN is then used to determine the numerical value of the observed variable X(J,NOOBS), or constant, A(J). This process continues until the data in each field (J = 1, 2, 3, ..., 8) have been determined. Note that a blank field is not interpreted as zero but is left blank. Also, the values of observed variables are stored in both of the two dimensional arrays, X(J,NOOBS) and T(J,NOOBS). When a transformation is applied to an original variable, Xk (k= 1, 2, 3, ..., 8), or a transformed variable, Tk, the new transformed value is stored in the T array. Thus, the values of Xk stored in the X array remain equal to the original variables read in.

```
  SUBROUTINE DORIS
  COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
 1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
 2KFLAG,KAN(50)
  L=2
  IF(NM(1)-KAN(6)) 1,2,1
1 NOOBS=NOOBS+1
2 IF(L-80) 3,3,5
3 DO 4 K=L,80
  IF(NM(K)-KAN(14)) 6,4,6
4 CONTINUE
5 RETURN
6 J=(K+9)/10
  L=J*10
  CALL FRAN (P,K,L)
  L=L+1
  IF(NM(1)-KAN(6)) 8,7,8
7 A(J)=P
  GO TO 2
8 T(J,NOOBS)=P
  X(J,NOOBS)=P
  GO TO 2
  END
```

Subroutine MARIE

Control is transferred to subroutine MARIE from the MAIN program whenever a V* card is read. Subroutine FRAN is then called to determine the numerical value of the number of variables, NOVAR, punched between Columns 3 and 10 of the V* card. The IXT array and variable subscript, LEE, are used to keep track of the sequence of operations to be performed on the data for each job.

```
      SUBROUTINE MARIE
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50)
      CALL FRAN (P,3,10)
      NOVAR=P
      LEE=LEE+1
      IXT(LEE)=-1
      PT(LEE)=NOVAR
      IF(NOVAR-8) 2,2,1
    1 KFLAG=2
    2 RETURN
      END
```

Subroutine ALICE

Subroutine ALICE is called by the MAIN program whenever a TRANSFORMATION card is read. This subroutine uses the KAN array to determine which transformation is to be applied and sets the variable, INDEX, equal to the index number corresponding to that transformation, (see Table 35). This index number is used later by subroutine GWEN which performs the actual transformation. For transformations six through 24, subroutine FRAN is used to determine the numberical values (i or p) in the transformation.

```
      SUBROUTINE ALICE
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50)
      P=0
      M=2
    1 IF(M-80) 2,2,4
    2 DO 3 MM=M,80
      IF(NM(MM)-KAN(28)) 5,3,5
    3 CONTINUE
    4 RETURN
    5 J=(MM+9)/10
      M=J*10
      I=NM(MM)
      L=NM(MM+1)
      ISN=1
      DO 6 K=29,43
      IF(I-KAN(K)) 6,8,6
    6 CONTINUE
    7 KFLAG=2
      RETURN
    8 K=K-28
      GO TO (9,10,11,12,13,14,21,27,31,35,36,37,38,39,40),K
    9 INDEX=5
      GO TO 15
   10 INDEX=8
      GO TO 15
   11 INDEX=11
      GO TO 15
   12 INDEX=15
      GO TO 15
   13 INDEX=18
      GO TO 15
   14 INDEX=21
   15 DO 16 K=45,46
      INDEX=INDEX+1
      IF(L-KAN(K)) 16,20,16
   16 CONTINUE
      INDEX=INDEX+1
      IF(L-KAN(39)) 17,19,17
   17 L=MM+1
```

```
      ISN=0
   18 CALL FRAN (P,L,M)
      GO TO (41,7),KFLAG
   19 ISN=-1
   20 L=MM+2
      GO TO 18
   21 IF(L-KAN(42)) 22,24,22
   22 IF(L-KAN(38)) 23,25,23
   23 IF(L-KAN(48)) 7,26,7
   24 INDEX=2
      GO TO 41
   25 INDEX=30
      GO TO 41
   26 INDEX=1
      GO TO 41
   27 IF(L-KAN(49)) 28,29,28
   28 IF(L-KAN(50)) 7,30,7
   29 INDEX=3
      GO TO 41
   30 INDEX=31
      GO TO 41
   31 IF(L-KAN(42)) 32,33,32
   32 IF(L-KAN(50)) 7,34,7
   33 INDEX=4
      GO TO 41
   34 INDEX=25
      GO TO 41
   35 INDEX=5
      GO TO 41
   36 INDEX=15
      GO TO 41
   37 INDEX=26
      GO TO 41
   38 INDEX=27
      GO TO 41
   39 INDEX=28
      GO TO 41
   40 INDEX=29
   41 LEE=LEE+1
      JT(LEE)=J
      PT(LEE)=P
      IT(LEE)=ISN*IFIX(P)
      IF(IABS(IT(LEE))-8) 43,43,42
   42 IF(L-MM-1) 43,43,7
   43 IXT(LEE)=INDEX
      M=M+1
      GO TO 1
      END
```

Subroutine ANN

Subroutine ANN is called by the MAIN program whenever a ***** card or *DATA card is read. This subroutine then instructs the other operation subroutines to perform the desired sequence of operations.

```
      SUBROUTINE ANN
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50),LAY
      LAY=0
      DO 13 K=1,LEE
      IF(IXT(K)) 2,1,9
    1 CALL RENE
      GO TO 13
    2 L=-IXT(K)
      GO TO (3,4,5,6,7,8),L
    3 NOVAR=PT(K)
    4 GO TO 13
    5 NOOBS=PT(K)
    6 GO TO 13
    7 CALL KATHY
      GO TO 13
    8 CALL NORMA
      GO TO 13
    9 J=JT(K)
      I=IT(K)
      P=PT(K)
      IX=IXT(K)
      IF(I) 10,12,12
   10 I=-I
      P=A(I)
   11 I=-I
   12 CALL GWEN (J,I,P,IX)
   13 CONTINUE
      LAY=0
      IF(NM(2)-KAN(1)) 15,14,15
   14 LEE=0
      GO TO 17
   15 IF(NM(2)-KAN(3)) 16,17,16
   16 NOOBS=0
   17 WRITE(3,100)
  100 FORMAT('1',10X,'DATA')
      RETURN
      END
```

Subroutine GWEN

This subroutine performs the transformations specified on the transformation cards. Special transformations can be performed using the variable subroutines JANET, LEANN, and SUZIE.

```
      SUBROUTINE GWEN (J,I,P,IX)
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50)
      GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,
     120,21,22,23,24,25,26,27,28,29,30,31),IX
    1 DO 101 K=1,NOOBS
      IF(T(J,K)) 1000,1000,101
  101 T(J,K)=ALOG(T(J,K))
      RETURN
    2 DO 102 K=1,NOOBS
      IF(T(J,K)) 1000,1000,102
  102 T(J,K)=ALOG10(T(J,K))
      RETURN
 1000 WRITE(3,1001)
 1001 FORMAT('0',10X,'****ARGUMENT NEGATIVE OR ZERO****')
      RETURN
    3 DO 103 K=1,NOOBS
  103 T(J,K)=SIN(T(J,K))
      RETURN
    4 DO 104 K=1,NOOBS
  104 T(J,K)=COS(T(J,K))
      RETURN
    5 DO 105 K=1,NOOBS
  105 T(J,K)=EXP(T(J,K))
      RETURN
    6 DO 106 K=1,NOOBS
  106 T(J,K)=T(J,K)+T(I,K)
      RETURN
    7 DO 107 K=1,NOOBS
  107 T(J,K)=T(J,K)+X(I,K)
      RETURN
    8 DO 108 K=1,NOOBS
  108 T(J,K)=T(J,K)+P
      RETURN
    9 DO 109 K=1,NOOBS
  109 T(J,K)=T(J,K)-T(I,K)
      RETURN
```

```
   10 DO 110 K=1,NOOBS
  110 T(J,K)=T(J,K)-X(I,K)
      RETURN
   11 DO 111 K=1,NOOBS
  111 T(J,K)=T(J,K)-P
      RETURN
   12 DO 112 K=1,NOOBS
  112 T(J,K)=T(J,K)*T(I,K)
      RETURN
   13 DO 113 K=1,NOOBS
  113 T(J,K)=T(J,K)*X(I,K)
      RETURN
   14 DO 114 K=1,NOOBS
  114 T(J,K)=T(J,K)*P
      RETURN
   15 DO 115 K=1,NOOBS
  115 T(J,K)=ABS(T(J,K))
      RETURN
   16 DO 116 K=1,NOOBS
      IF(T(I,K)) 116,1000,116
  116 T(J,K)=T(J,K)/T(I,K)
      RETURN
   17 DO 117 K=1,NOOBS
      IF(X(I,K)) 117,1000,117
  117 T(J,K)=T(J,K)/X(I,K)
      RETURN
   18 IF(P) 118,1000,118
  118 DO 218 K=1,NOOBS
  218 T(J,K)=T(J,K)/P
      RETURN
   19 DO 119 K=1,NOOBS
  119 T(J,K)=T(I,K)
      RETURN
   20 DO 120 K=1,NOOBS
  120 T(J,K)=X(I,K)
      RETURN
   21 DO 121 K=1,NOOBS
  121 T(J,K)=P
      RETURN
   22 DO 122 K=1,NOOBS
      IF(T(J,K)) 1000,122,122
  122 T(J,K)=T(J,K)**T(I,K)
      RETURN
   23 DO 123 K=1,NOOBS
      IF(T(J,K)) 1000,123,123
  123 T(J,K)=T(J,K)**X(I,K)
      RETURN
   24 KP=P
      IF(P-FLOAT(KP)) 324,124,324
  124 DO 224 K=1,NOOBS
```

```
224 T(J,K)=T(J,K)**KP
    RETURN
324 DO 424 K=1,NOOBS
    IF(T(J,K)) 1000,424,424
424 T(J,K)=T(J,K)**P
    RETURN
 25 DO 125 K=2,NOOBS
125 T(J,K)=T(J,K)+T(J,K-1)
    RETURN
 26 K=NOOBS
126 T(J,K)=T(J,K)-T(J,K-1)
    K=K-1
    IF(K-1) 226,226,126
226 T(J,1)=0.0
    RETURN
 27 KP=NOOBS-1
    DO 127 K=1,KP
    I=NOOBS-K-1
127 T(J,I)=(T(J,I)+T(J,I-1))/2.0
    T(J,1)=0.0
    RETURN
 28 HUGE=10.0**48.0
    KP=NOOBS-1
    DO 328 I=1,KP
    P=HUGE
    DO 228 L=I,NOOBS
    IF(P-T(J,L)) 228,228,128
128 P=T(J,L)
    K=L
228 CONTINUE
    DO 328 L=1,8
    P=X(L,I)
    X(L,I)=X(L,K)
    X(L,K)=P
    P=T(L,I)
    T(L,I)=T(L,K)
328 T(L,K)=P
    RETURN
 29 CALL JANET (J)
    RETURN
 30 CALL LEANN (J)
    RETURN
 31 CALL SUZIE (J)
    RETURN
    END
```

Subroutines JANET, LEANN, and SUZIE

Variable subroutines JANET, LEANN, and SUZIE are included here as dummy subroutines (see page 325 of this Appendix).

```
 SUBROUTINE LEANN (J)
 COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
2KFLAG,KAN(50)
 DUMMY=1
 RETURN
 END
```

```
 SUBROUTINE JANET (J)
 COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
2KFLAG,KAN(50)
 DUMMY=1
 RETURN
 END
```

```
 SUBROUTINE SUZIE (J)
 COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
2KFLAG,KAN(50)
 DUMMY=1
 RETURN
 END
```

Subroutine KATHY

Subroutine KATHY prints out the current values of the transformed variables and the constants in the A array. This subroutine is used whenever a PRINT card is executed, and by subroutine NORMA when PACOCO or REGRESSION cards are executed.

```
      SUBROUTINE KATHY
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50)
      WRITE(3,100) (I,I=1,NOVAR)
  100 FORMAT('1',' TRANSFORMED VARIABLES',//,'0  OBS',8(13X,'T',I1))
      DO 1 I=1,NOOBS
    1 WRITE(3,200) I,(T(J,I),J=1,NOVAR)
  200 FORMAT(1X,I5,8E15.6)
      WRITE(3,300) (I,A(I),I=1,8)
  300 FORMAT('0',/,10X,'A VALUES',8(/,20X,I1,')',E15.6))
      RETURN
      END
```

Subroutine NORMA

Using the previously defined notation where T1 is the dependent variable and T2, T3, ..., Tn are independent variables, (n = number of variables, two to eight), subroutine NORMA determines the rectangular systems matrix, A/C, for subsequent use in the regression analysis. This matrix contains the normal equations used in the least squares method of estimating regression coefficients (71). The first n columns contain the matrix A and the last column contains the matrix or vector C.

$$\begin{array}{llllll}
NOOBS & \Sigma T2 & \Sigma T3 & \cdot\ \cdot & \Sigma Tn & \Sigma T1 \\
\Sigma T2 & \Sigma(T2)^2 & \Sigma T2T3 & \cdot\ \cdot & \Sigma T2Tn & \Sigma T2T1 \\
\Sigma T3 & \Sigma T2T3 & \Sigma(T3)^2 & \cdot\ \cdot & \Sigma T3Tn & \Sigma T3T1 \\
\cdot & \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot \\
\Sigma Tn & \Sigma T2Tn & \Sigma T3Tn & \cdot\ \cdot & \Sigma(Tn)^2 & \Sigma TnT1
\end{array}$$

NOOBS is the number of observations of the variables.

```
      SUBROUTINE NORMA
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50)
      DO 1 I=1,10
      DO 1 J=1,10
    1 B(I,J)=0.0
      N=NOVAR-1
      DO 5 M=1,NOOBS
      DO 5 I=1,NOVAR
      FACTR=T(I,M)
      IF(I-1) 3,2,3
    2 FACTR=1.0
    3 J=I
   31 J=J+1
      IF(J-NOVAR) 4,4,41
    4 B(I,J)=B(I,J)+FACTR*T(J,M)
      GO TO 31
   41 B(I,NOVAR+1)=FACTR*T(1,M)+B(I,NOVAR+1)
    5 B(I,I)=T(I,M)*T(I,M)+B(I,I)
      B(1,1)=NOOBS
      DO 6 I=1,N
      K=I+1
      DO 6 J=K,NOVAR
    6 B(J,I)=B(I,J)
      CALL KATHY
      CALL CORA (NOVAR)
      RETURN
      END
```

Subroutine CORA

Subroutine CORA is called by subroutine NORMA to calculate the partial correlation coefficients between all possible pairs of variables. These are calculated using the equation (51)

$$r_{ij} = \frac{N\Sigma TiTj - \Sigma Ti\Sigma Tj}{\sqrt{[N\Sigma Ti^2 - (\Sigma Ti)^2][N\Sigma Tj^2 - (\Sigma Tj)^2]}}$$

where,

r_{ij} = partial correlation coefficient between variables Ti and Tj

N = number of observations of variables or NOOBS

i,j = integer between 1 and the number of variables (maximum of 8).

More specifically, these are zero order partial correlation coefficients; the correlation between any two variables is determined neglecting all other variables. This is opposed to higher order partial correlations which determine the correlation between variables while holding all other variables constant.

```
      SUBROUTINE CORA (N)
      COMMON B(100),X(8,400),T(3272)
      WRITE(3,100)
  100 FORMAT('1',22X,'PARTIAL CORRELATION COEFFICIENTS')
      M=B(1)*8.0
      SYY=0.0
      DO 1 I=1,M,8
```

```
    1 SYY=SYY+T(I)*T(I)
      NN=N*10+1
      SYY=B(1)*SYY-B(NN)*B(NN)
      DO 4 I=2,N
      K=I-1
      M=K*10+I
      II=NN+I-1
      B(91)=(B(1)*B(II)-B(NN)*B(I))/SQRT(SYY*(B(1)*B(M)-B(I)
     1*B(I)))
      IF(I-2) 4,4,2
    2 DO 3 J=2,K
      KK=(J-1)*10+J
      L=M+J-I
    3 B(J+90)=(B(1)*B(L)-B(J)*B(I))/SQRT((B(1)*B(M)-B(I)*
     1B(I))*(B(1)*B(KK)-B(J)**2))
    4 WRITE(3,200) I,(B(J+90),J=1,K)
  200 FORMAT('0',1X,I8,F10.3,6F8.3)
      WRITE(3,300) (I,I=1,K)
  300 FORMAT('0',1X,I17,6I8)
      RETURN
      END
```

Subroutine RENE

This subroutine is called whenever a REGRESSION card is executed. Subroutine RENE first calls subroutine NORMA to determine the rectangular systems matrix and partial correlation coefficients. Subroutine DONNA is then called to calculate the coefficients (B1, B2, ..., Bn) of the regression equation,

T1 = B1 + B2*T2 + B3*T3 + ... + Bn*Tn.

The resulting regression equation is then used for each observation to calculate the estimated value, $\hat{T1}$, of the observed dependent variable, T1, and the difference, $T1 - \hat{T1}$, between observed and calculated values. This difference is also expressed as a percentage of the average of the observed and calculated values and as a percentage of the mean of all observed values of the dependent variable. The following quantities are also determined (53).

$$\text{Root mean square of percent differences} = \sqrt{\frac{\Sigma(\%\ \text{difference})^2}{N - n}}$$

$$\text{Standard error of estimate} = \sqrt{\frac{\Sigma(T1 - \hat{T1})^2}{N - n}}$$

and,

$$100R = \frac{N\Sigma T1 \cdot \hat{T1} - \Sigma T1 \Sigma \hat{T1}}{\sqrt{[N\Sigma T1^2 - (\Sigma T1)^2][N\Sigma \hat{T1}^2 - (\Sigma \hat{T1})^2]}} (100)$$

where,

N = number of observations, NOOBS

n = number of variables, NOVAR

100R = multiple correlation coefficient expressed in percent.

Finally, subroutine TERI is called to print out the matrices used in calculating the regression coefficients.

```
      SUBROUTINE RENE
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50)
      CALL NORMA
      N=NOVAR
      K=NOVAR+1
      DO 1 J=1,K
      JJ=J+400
      DO 1 I=1,N
    1 T(I,JJ)=B(I,J)
      WRITE(3,100)
  100 FORMAT(/////////,1X,'REGRESSION MODEL ----- T1 = B1 +',
     1' B2*T2 + B3*T3 + . . . . . + BN*TN',//)
      CALL DONNA (N,1)
      WRITE(3,200) (I,B(I,K),I=1,N)
  200 FORMAT('0',17X,'B',I1,'=',F20.8)
      WRITE(3,300)
  300 FORMAT('1',2X,'OBS',3X,'OBSERVED T1',3X,'COMPUTED T1',
     15X,'D  I  F  F  E  R  E  N  C  E',/,40X,'ACTUAL',9X,
     2'0/0',8X,'Z')
      Z=0.0
      DO 2 K=1,NOOBS
    2 Z=Z+T(1,K)
      YBAR=Z/(FLOAT(NOOBS))
      Z=0.0
      SY=0.0
      SYH=0.0
      SYY=0.0
      SYHYH=0.0
      SYYH=0.0
      SDIFF=0.0
      DO 4 K=1,NOOBS
      Y=T(1,K)
      YHAT=B(1,N+1)
      DO 3 I=2,NOVAR
    3 YHAT=YHAT+B(I,N+1)*T(I,K)
      T(8,K)=YHAT
      DIFF=Y-YHAT
      SDIFF=SDIFF+DIFF*DIFF
      E=100.0*DIFF/YBAR
      P=200.0*DIFF/(Y+YHAT)
      Z=Z+P*P
      SY=SY+Y
      SYH=SYH+YHAT
      SYY=SYY+Y*Y
      SYHYH=SYHYH+YHAT*YHAT
      SYYH=SYYH+Y*YHAT
    4 WRITE(3,400) K,T(1,K),YHAT,DIFF,P,E
  400 FORMAT(1X,I5,2E14.5,E14.4,F11.3,F10.3)
```

```
      P=NOOBS-N
      SEE=(SDIFF/P)**0.5
      Z=(Z/P)**0.5
      P=NOOBS
      R=(P*SYYH-SY*SYH)/SQRT((P*SYY-SY*SY)*(P*SYHYH-SYH*SYH)
     1*0.0001)
      WRITE(3,500) Z,SEE,R
  500 FORMAT('0',///,1X,'ROOT MEAN SQUARE OF PERCENT DIFFER',
     1'ENCES',F18.3,///,1X,'STANDARD ERROR OF ESTIMATE',13X,
     2F18.3,////,1X,'R = MULTIPLE CORRELATION COEFFICIENT  ',
     3'  100(R) = ',F8.3,///,6X,'Z = 100(DIFF)/(MEAN OBSERV',
     4'ED T1)')
      CALL TERI (N,1)
      RETURN
      END
```

Subroutine DONNA

Subroutine DONNA determines the regression coefficients (B1, B2, ..., Bn) along with the inverted matrix, A^{-1}, of the matrix A found in subroutine NORMA. The invert of matrix A, A^{-1}, is found by using the abbreviated Doolittle method (53, 71). The solution vector, B, containing the regression coefficients, is then equal to the product of matrix A^{-1} and vector C, (from subroutine NORMA).

```
      SUBROUTINE DONNA (N,M)
      COMMON B(10,10)
      NM=N+M
      NM1=NM+1
      N1=N+1
      N2=N+2
      DO 1 K=1,N
      B(N2,K)=K
    1 B(K,NM1)=K
      DO 10 IR=1,N
      K=N+1-IR
      BIG=0.0
      DO 4 I=1,K
      DO 4 J=1,K
```

```
      IF(ABS(B(I,J))-BIG) 4,4,3
    3 BIG=ABS(B(I,J))
      L=I
      MM=J
    4 CONTINUE
      DO 5 I=1,N2
      TEMP=B(I,1)
      B(I,1)=B(I,MM)
    5 B(I,MM)=TEMP
      DO 6 J=1,NM1
      TEMP=B(1,J)
      B(1,J)=B(L,J)
    6 B(L,J)=TEMP
      B(N1,NM)=1.0/B(1,1)
      DO 7 K=2,NM
    7 B(N1,K-1)=B(N1,NM)*B(1,K)
      TEMP=B(1,NM1)
      BIG=B(N2,1)
      DO 9 I=2,N
      IM1=I-1
      DO 8 J=2,NM
    8 B(IM1,J-1)=B(I,J)-B(I,1)*B(N1,J-1)
      B(IM1,NM)=-B(I,1)*B(N1,NM)
      B(IM1,NM1)=B(I,NM1)
    9 B(N2,IM1)=B(N2,I)
      B(N,NM1)=TEMP
      B(N2,N)=BIG
      DO 10 K=1,NM
   10 B(N,K)=B(N1,K)
      DO 11 K=1,N
      TEMP=B(K,NM1)
      B(K,NM1)=B(N2,K)
   11 B(N2,K)=TEMP
      DO 13 K=1,M
      DO 13 I=1,N
      TEMP=B(I,1)
      DO 12 J=2,NM
   12 B(I,J-1)=B(I,J)
   13 B(I,NM)=TEMP
      MM=N-1
      DO 16 I=1,MM
      XI=I
      DO 14 J=1,N
      IF(B(N2,J)-XI) 14,15,14
   14 CONTINUE
   15 DO 16 K=1,N2
      TEMP=B(K,I)
      B(K,I)=B(K,J)
   16 B(K,J)=TEMP
```

```
      DO 19 I=1,MM
      XI=I
      DO 17 J=1,N
      IF(B(J,NM1)-XI) 17,18,17
   17 CONTINUE
   18 DO 19 K=1,NM1
      TEMP=B(I,K)
      B(I,K)=B(J,K)
   19 B(J,K)=TEMP
      RETURN
      END
```

<u>Subroutine TERI</u>

This subroutine is sued to print out the matrices used in the regression analysis. First, the rectangular system's matrix, A/C, as calculated by subroutine NORMA, is printed. The identity or unit matrix, I, is then calculated as the matrix product, $A^{-1}A$. All of the elements of the identity matrix should be zero except for the elements in the principal diagonal which should be one. The identity matrix and solution vector, B, are printed out as matrix I/B. Finally, matrix A^{-1} is printed out with the solution vector.

```
      SUBROUTINE TERI (N,M)
      COMMON B(10,10),X(8,400),T(8,409),NM(80),JT(100),
     1IT(100),PT(100),IXT(100),A(8),MN(75),NOOBS,NOVAR,LEE,
     2KFLAG,KAN(50)
      WRITE(3,100)
  100 FORMAT('1',30X,'MATRIX EQUATION',5X,'A(B)=C',///,10X,
     1'RECTANGULAR SYSTEMS MATRIX',5X,'(A/C)')
      K=N+M
      L=400+K
      DO 1 I=1,N
    1 WRITE(3,200) (T(I,J),J=401,L)
```

```
200 FORMAT('0',9E13.5)
    WRITE(3,300)
300 FORMAT('0',///,' IDENTITY AUGMENTED WITH SOLUTION ',
   1'VECTOR(S)   (I/B)')
    L=N+1
    DO 4 I=1,N
    DO 3 J=1,K
    KK=400+J
    C=0.0
    DO 2 LL=1,N
  2 C=C+B(I,LL)*T(LL,KK)
  3 B(L,J)=C
  4 WRITE(3,400) (B(L,J),J=1,K)
400 FORMAT('0',9F13.6)
    WRITE(3,500)
500 FORMAT('0',///,1X,'INVERTED RSM MATRIX     (.A./B)')
    DO 5 I=1,N
  5 WRITE(3,200) (B(I,J),J=1,K)
    WRITE(3,600)
600 FORMAT('1')
    RETURN
    END
```

Example input and output

The major use of MAIDS at Iowa State University has been for the determination of prediction equations for filter cake resistance indices or β indices. The general form of the β prediction equation is:

$$\beta = 10^{b_1} C_S^{\,b_2} C_F^{\,b_3} \qquad (33)$$

which can be made linear by a logarithmic transformation; i.e., $\log \beta = b_1 + b_2 \log C_S + b_3 \log C_F$. MAIDS can therefore be used to determine the coefficients b_1, b_2, and b_3.

If data are collected with C_S constant and the assumption is made that β varies only with the ratio C_S/C_F (i.e., $b_2 = -b_3$ in Equation 33), then the following prediction equation may be used:

$$\beta = 10^{b_1} (C_S/C_F)^{b_2} \qquad (15)$$

MAIDS can again be used to determine the coefficients b_1 and b_2.

The following examples give the input and output for three MAIDS jobs. The first two examples involve the determination of β prediction equations. The β prediction equations are also calculated manually for comparison with the computer results. The third example shows the use of MAIDS for problems other than regression analysis.

80 COLUMN DATA SHEET

PROGRAM MAIDS EXAMPLE INPUT (Page 1 of 4)	JOB NO. U3041	BY Harold Bridges	DATE 5/8/70

```
CLDTPAVRSEFOM  +-..0123456789  +-*/=$LSCEADMOJ  TXANIU
C    EXAMPLE NUMBER 1
C    DETERMINATION OF BETA INDEX PREDICTION EQUATION
C         FOR THE FILTRATION OF UNIVERSITY TAP
          WATER PLUS FERRIC CHLORIDE
C    CELITE 535 FILTER AID
C    BRIDGES AND ARORA FILTER RUNS 21-27 AND 34-51
C    BETA/E04 = BETA DIVIDED BY 10000
C    DATA FOLLOW
L RUN NO.     CS        CF      BETA/E04
    21.      7.85     400.        543.
    22.      8.16     160.       8200.
    23.      8.27     400.        710.
    24.      8.26     320.        990.
    25.       8.26    266.       1970.
    26.       8.26    230.       2560.
    27.       8.36    400.        895.
    34.       7.57    266.       1690.
    35.       7.73    400.        650.
    36.     3.54       200.       775.
    37.     3.36       100.      4650.
    38.     3.59       133.      3000.
    39.     3.56       200.       765.
    40.     3.65       100.      3690.
```

Any number of comment cards can be used

Decimal points must be given for all data

The data may be written anywhere within the proper 10-column field

80 COLUMN DATA SHEET

PROGRAM MAIDS EXAMPLE INPUT (Page 2 of 4)
JOB NO. U3041
BY Harold Bridges
DATE 5/8/70

```
    41.     4.40      145.       1875.
    42.     4.00      185.       1330.
    43.      13.2      500.       1470.
    44.      13.25     750.        491.
    45.      13.4      400.       2020.
    46.     2.10      100.       1700.
    47.     2.00       66.       2840.
    48.     2.00       40.       7950.
    49.     2.00      200.        393.
    50.     2.05      135.        852.
    51.     2.03       50.       5450.
C    OPERATIONS TO BE PERFORMED FOLLOW
T                               *10000.
T  =T4
T  LOG      LOG       LOG
V*  3
REGRESSION
*****
END
C    EXAMPLE NUMBER 2
C    DETERMINATION OF BETA PREDICTION EQUATION
C         FOR THE FILTRATION OF UNIVERSITY TAP
C         WATER PLUS FERRIC CHLORIDE
C    CS HELD CONSTANT
```

Data can be read in any of the available 10-column fields and then shifted as desired

80 COLUMN DATA SHEET

PROGRAM MAIDS EXAMPLE INPUT (Page 3 of 4)	**JOB NO.** U3041	**BY** Harold Bridges	**DATE** 5/8/70

```
C    SIL-FLO 443 (BAG 2) FILTER AID
C    ARORA FILTE: RUNS 116-121
L BETA/E04    CS        CF      RUN NO.
   7895.     7.78     132.8      116.
  18230.     7.75      87.0      117.
   5078.     7.88     156.3      118.
   2406.     8.00     217.8      119.
   1478.     8.28     301.1      120.
    953.9    8.03     422.4      121.
T *10000.
T  LOG       LOG       LOG
T            -T3
V*  2
REGRESSION
*****
END
C    EXAMPLE NUMBER 3
T  ORDER     =T1       =T1
T            *A2       $2.
T            +A1       *A3
T                      +T2
V* 3
PRINT
L X VALUES
```

Operation cards do not necessarily have to follow data cards

80 COLUMN DATA SHEET

PROGRAM MAIDS EXAMPLE INPUT (Page 4 of 4)	JOB NO. U3041	**BY** Harold Bridges	**DATE** 5/8/70

```
    6.0
    4.0
    1.0
    9.0
    7.0
    3.0
    5.0
    8.0
   10.0
    2.0
A  -2.0      3.0       6.0
*DATA
A   5.0      7.0      -3.0
*****
STOP
```

```
M A I D S
DILLINGHAM 1964--BESETT 1966--BRIDGES 1967


C     EXAMPLE NUMBER 1
C     DETERMINATION OF BETA INDEX PREDICTION EQUATION
C          FOR THE FILTRATION OF UNIVERSITY TAP
C          WATER PLUS FERRIC CHLORIDE
C     CELITE 535 FILTER AID
C     BRIDGES AND ARORA FILTER RUNS 21-27 AND 34-51
C     BETA/E04 = BETA DIVIDED BY 10000
C     DATA FOLLOW
L RUN NO.       CS          CF       BETA/E04
    21.         7.85      400.           543.
    22.         8.16      160.          8200.
    23.         8.27      400.           710.
    24.         8.26      320.           990.
    25.         8.26      266.          1970.
    26.         8.26      230.          2560.
    27.         8.36      400.           895.
    34.         7.57      266.          1690.
    35.         7.73      400.           650.
    36.      3.54           200.         775.
    37.      3.36           100.        4650.
    38.      3.59           133.        3000.
    39.      3.56           200.         765.
```

```
     40.     3.65        100.       3690.

     41.     4.40        145.       1875.

     42.     4.00        185.       1330.

     43.       13.2        500.     1470.

     44.       13.25       750.      491.

     45.       13.4        400.     2020.

     46.     2.10      100.         1700.

     47.     2.00        66.        2840.

     48.     2.00        40.        7950.

     49.     2.00      200.          393.

     50.     2.05      135.          852.

     51.     2.03        50.        5450.
C    OPERATIONS TO BE PERFORMED FOLLOW
T                                     *10000.
T  =T4
T  LOG        LOG        LOG
V*  3
REGRESSION
*****
```

```
TRANSFORMED VARIABLES


 OBS                   T1                   T2                    T3                      T
   1   0.673480E 01    0.894870E 00    0.260206E 01
   2   0.791381E 01    0.911690E 00    0.220412E 01
   3   0.685126E 01    0.917505E 00    0.260206E 01
   4   0.699563E 01    0.916980E 00    0.250515E 01
   5   0.729447E 01    0.916980E 00    0.242488E 01
   6   0.740823E 01    0.916980E 00    0.236173E 01
   7   0.695182E 01    0.922206E 00    0.260206E 01
   8   0.722789E 01    0.879096E 00    0.242488E 01
   9   0.681291E 01    0.888180E 00    0.260206E 01
  10   0.688930E 01    0.549003E 00    0.230103E 01
  11   0.766745E 01    0.526339E 00    0.200000E 01
  12   0.747712E 01    0.555094E 00    0.212385E 01
  13   0.688366E 01    0.551450E 00    0.230103E 01
  14   0.756703E 01    0.562293E 00    0.200000E 01
  15   0.727300E 01    0.643453E 00    0.216137E 01
  16   0.712385E 01    0.602060E 00    0.226717E 01
  17   0.716732E 01    0.112057E 01    0.269897E 01
  18   0.669108E 01    0.112222E 01    0.287506E 01
  19   0.730535E 01    0.112710E 01    0.260206E 01
  20   0.723044E 01    0.322219E 00    0.200000E 01
  21   0.745332E 01    0.301030E 00    0.181954E 01
  22   0.790037E 01    0.301030E 00    0.160206E 01
  23   0.659439E 01    0.301030E 00    0.230103E 01
  24   0.693044E 01    0.311754E 00    0.213033E 01
  25   0.773639E 01    0.307496E 00    0.169897E 01


        A VALUES
                       1)    0.0
                       2)    0.0
                       3)    0.0
                       4)    0.0
                       5)    0.0
                       6)    0.0
                       7)    0.0
                       8)    0.0
```

(Author's note: For results in exponential form, the number following E is the power of 10.)

```
                         PARTIAL CORRELATION COEFFICIENTS

      2     -0.245

      3     -0.697    0.856

                1        2
```

(i.e. $r_{12} = -0.245$)

```
REGRESSION MODEL ----- T1 = B1 + B2*T2 + B3*T3 + . . . . . . + BN*TN


                  B1=         10.88005447

                  B2=          1.71041584

                  B3=         -2.12593842

 OBS   OBSERVED T1    COMPUTED T1       D  I  F  F  E  R  E  N  C  E
                                          ACTUAL          0/0      Z
   1   0.67348E 01    0.68788E 01    -0.1440E 00      -2.116    -2.000
   2   0.79138E 01    0.77536E 01     0.1602E 00       2.045     2.224
   3   0.68513E 01    0.69176E 01    -0.6629E-01      -0.963    -0.920
   4   0.69956E 01    0.71227E 01    -0.1270E 00      -1.800    -1.764
   5   0.72945E 01    0.72933E 01     0.1143E-02       0.016     0.016
   6   0.74082E 01    0.74276E 01    -0.1935E-01      -0.261    -0.269
   7   0.69518E 01    0.69256E 01     0.2623E-01       0.378     0.364
   8   0.72279E 01    0.72285E 01    -0.6399E-03      -0.009    -0.009
   9   0.68129E 01    0.68674E 01    -0.5448E-01      -0.796    -0.756
  10   0.68893E 01    0.69272E 01    -0.3793E-01      -0.549    -0.527
  11   0.76674E 01    0.75284E 01     0.1390E 00       1.830     1.930
  12   0.74771E 01    0.73143E 01     0.1628E 00       2.201     2.260
  13   0.68837E 01    0.69314E 01    -0.4775E-01      -0.691    -0.663
  14   0.75670E 01    0.75899E 01    -0.2291E-01      -0.302    -0.318
  15   0.72730E 01    0.73857E 01    -0.1127E 00      -1.538    -1.564
  16   0.71239E 01    0.70900E 01     0.3389E-01       0.477     0.471
  17   0.71673E 01    0.70589E 01     0.1085E 00       1.525     1.506
  18   0.66911E 01    0.66873E 01     0.3776E-02       0.056     0.052
  19   0.73053E 01    0.72761E 01     0.2929E-01       0.402     0.407
  20   0.72304E 01    0.71793E 01     0.5114E-01       0.710     0.710
  21   0.74533E 01    0.75267E 01    -0.7339E-01      -0.980    -1.019
  22   0.79004E 01    0.79891E 01    -0.8869E-01      -1.116    -1.231
  23   0.65944E 01    0.65031E 01     0.9130E-01       1.394     1.267
  24   0.69304E 01    0.68843E 01     0.4611E-01       0.668     0.640
  25   0.77364E 01    0.77941E 01    -0.5770E-01      -0.743    -0.801



ROOT MEAN SQUARE OF PERCENT DIFFERENCES                1.233


STANDARD ERROR OF ESTIMATE                             0.090


R = MULTIPLE CORRELATION COEFFICIENT    100(R) =     97.325


     Z = 100(DIFF)/(MEAN OBSERVED T1)
```

```
                                          MATRIX EQUATION     A(B)=C

                    RECTANGULAR SYSTEMS MATRIX     (A/C)

             0.25000E 02  0.17369E 02  0.57211E 02  0.18008E 03

             0.17369E 02  0.14045E 02  0.41635E 02  0.12448E 03

             0.57211E 02  0.41635E 02  0.13338E 03  0.41011E 03



          IDENTITY AUGMENTED WITH SOLUTION VECTOR(S)   (I/B)

                0.999985     -0.000015       0.000244     10.879883

                0.000015      1.000000       0.000214      1.710449

                0.0           0.0            0.999802     -2.125977



          INVERTED RSM MATRIX    (.A./B)

             0.43086E 01  0.20127E 01 -0.24763E 01  0.10880E 02

             0.20127E 01  0.18941E 01 -0.14545E 01  0.17104E 01

            -0.24763E 01 -0.14545E 01  0.15237E 01 -0.21259E 01




                     DATA

          END
```

```
M A I D S
DILLINGHAM 1964--BESETT 1966--BRIDGES 1967


C    EXAMPLE NUMBER 2

C    DETERMINATION OF BETA PREDICTION EQUATION

C            FOR THE FILTRATION OF UNIVERSITY TAP

C            WATER PLUS FERRIC CHLORIDE

C    CS HELD CONSTANT

C    SIL-FLO 443 (BAG 2) FILTER AID

C    ARORA FILTER RUNS 116-121

L BETA/E04     CS         CF       RUN NO.

    7895.      7.78     132.8       116.

   18230.      7.75      87.0       117.

    5078.      7.88     156.3       118.

    2406.      8.00     217.8       119.

    1478.      8.28     301.1       120.

     953.9     8.03     422.4       121.

T *10000.

T   LOG        LOG       LOG

T              -T3

V*   2

REGRESSION

*****
```

```
TRANSFORMED VARIABLES


 OBS              T1                T2                 T
   1    0.789735E 01  -0.123222E 01
   2    0.826079E 01  -0.105022E 01
   3    0.770569E 01  -0.129743E 01
   4    0.738129E 01  -0.143497E 01
   5    0.716967E 01  -0.156068E 01
   6    0.697950E 01  -0.172101E 01


      A VALUES
                  1)   0.0
                  2)   0.0
                  3)   0.0
                  4)   0.0
                  5)   0.0
                  6)   0.0
                  7)   0.0
                  8)   0.0



                          PARTIAL CORRELATION COEFFICIENTS

        2      0.992

                 1



REGRESSION MODEL ----- T1 = B1 + B2*T2 + B3*T3 + . . . . . . + BN*TN


                 B1=          10.29649353

                 B2=           1.97488880



OBS   OBSERVED T1    COMPUTED T1       D  I  F  F  E  R  E  N  C  E
                                          ACTUAL         0/0        Z
  1   0.78974E 01    0.78630E 01      0.3435E-01       0.436      0.454
  2   0.82608E 01    0.82224E 01      0.3835E-01       0.465      0.507
  3   0.77057E 01    0.77342E 01     -0.2852E-01      -0.369     -0.377
  4   0.73813E 01    0.74626E 01     -0.8130E-01      -1.095     -1.075
  5   0.71697E 01    0.72143E 01     -0.4466E-01      -0.621     -0.590
  6   0.69795E 01    0.68977E 01      0.8181E-01       1.179      1.081
```

```
ROOT MEAN SQUARE OF PERCENT DIFFERENCES                        0.938

STANDARD ERROR OF ESTIMATE                                     0.068


R = MULTIPLE CORRELATION COEFFICIENT    100(R) =    99.167

    Z = 100(DIFF)/(MEAN OBSERVED T1)



                                 MATRIX EQUATION     A(B)=C

          RECTANGULAR SYSTEMS MATRIX     (A/C)
  0.60000E 01 -0.82965E 01  0.45394E 02
 -0.82965E 01  0.11761E 02 -0.62198E 02


IDENTITY AUGMENTED WITH SOLUTION VECTOR(S)  (I/B)
    1.000000     -0.000031    10.296631
    0.0           0.999969     1.974915


INVERTED RSM MATRIX    (.A./B)
  0.67751E 01  0.47792E 01  0.10296E 02
  0.47792E 01  0.34563E 01  0.19749E 01



          DATA
END
```

```
M A I D S
DILLINGHAM 1964--BESETT 1966--BRIDGES 1967


C     EXAMPLE NUMBER 3

T   ORDER      =T1         =T1

T              *A2         $2.0

T              +A1         *A3

T                          +T2

V*  3

PRINT

L X VALUES

     6.0

     4.0

     1.0

     9.0

     7.0

     3.0

     5.0

     8.0

    10.0

     2.0

A  -2.0        3.0         6.0

*DATA
```

```
TRANSFORMED VARIABLES


OBS                T1                  T2                  T3                  T
  1     0.100000E 01      0.100000E 01      0.700000E 01
  2     0.200000E 01      0.400000E 01      0.280000E 02
  3     0.300000E 01      0.700000E 01      0.610000E 02
  4     0.400000E 01      0.100000E 02      0.106000E 03
  5     0.500000E 01      0.130000E 02      0.163000E 03
  6     0.600000E 01      0.160000E 02      0.232000E 03
  7     0.700000E 01      0.190000E 02      0.313000E 03
  8     0.800000E 01      0.220000E 02      0.406000E 03
  9     0.900000E 01      0.250000E 02      0.511000E 03
 10     0.100000E 02      0.280000E 02      0.628000E 03


          A VALUES
                          1)  -0.200000E 01
                          2)   0.300000E 01
                          3)   0.600000E 01
                          4)   0.0
                          5)   0.0
                          6)   0.0
                          7)   0.0
                          8)   0.0




             DATA

A    5.0        7.0         -3.0

*****
```

```
TRANSFORMED VARIABLES


OBS              T1                  T2                   T3                    T
  1   0.100000E 01    0.120000E 02    0.900000E 01
  2   0.200000E 01    0.190000E 02    0.700000E 01
  3   0.300000E 01    0.260000E 02   -0.100000E 01
  4   0.400000E 01    0.330000E 02   -0.150000E 02
  5   0.500000E 01    0.400000E 02   -0.350000E 02
  6   0.600000E 01    0.470000E 02   -0.610000E 02
  7   0.700000E 01    0.540000E 02   -C.930000E 02
  8   0.800000E 01    0.610000F 02   -0.131000E 03
  9   0.900000E 01    0.680000E 02   -0.175000E 03
 10   0.100000E 02    0.75000CE 02   -0.225000E 03


         A VALUES
                    1)    0.500CC0F 01
                    2)    0.700000F 01
                    3)   -0.300000E 01
                    4)    0.0
                    5)    0.0
                    6)    0.0
                    7)    0.0
                    8)    0.0




           DATA

STOP
```

Manual calculations

Example number 1

Bridges and Arora Filter Runs 21-27 and 34-51

Filtration of University tap water plus ferric chloride

Celite 535 filter aid

The data from these filter runs are printed out as part of the computer output (pp. 360-361). Since filter runs were made with both C_S and C_F varied, a prediction equation of the form of Equation 33 can be determined.

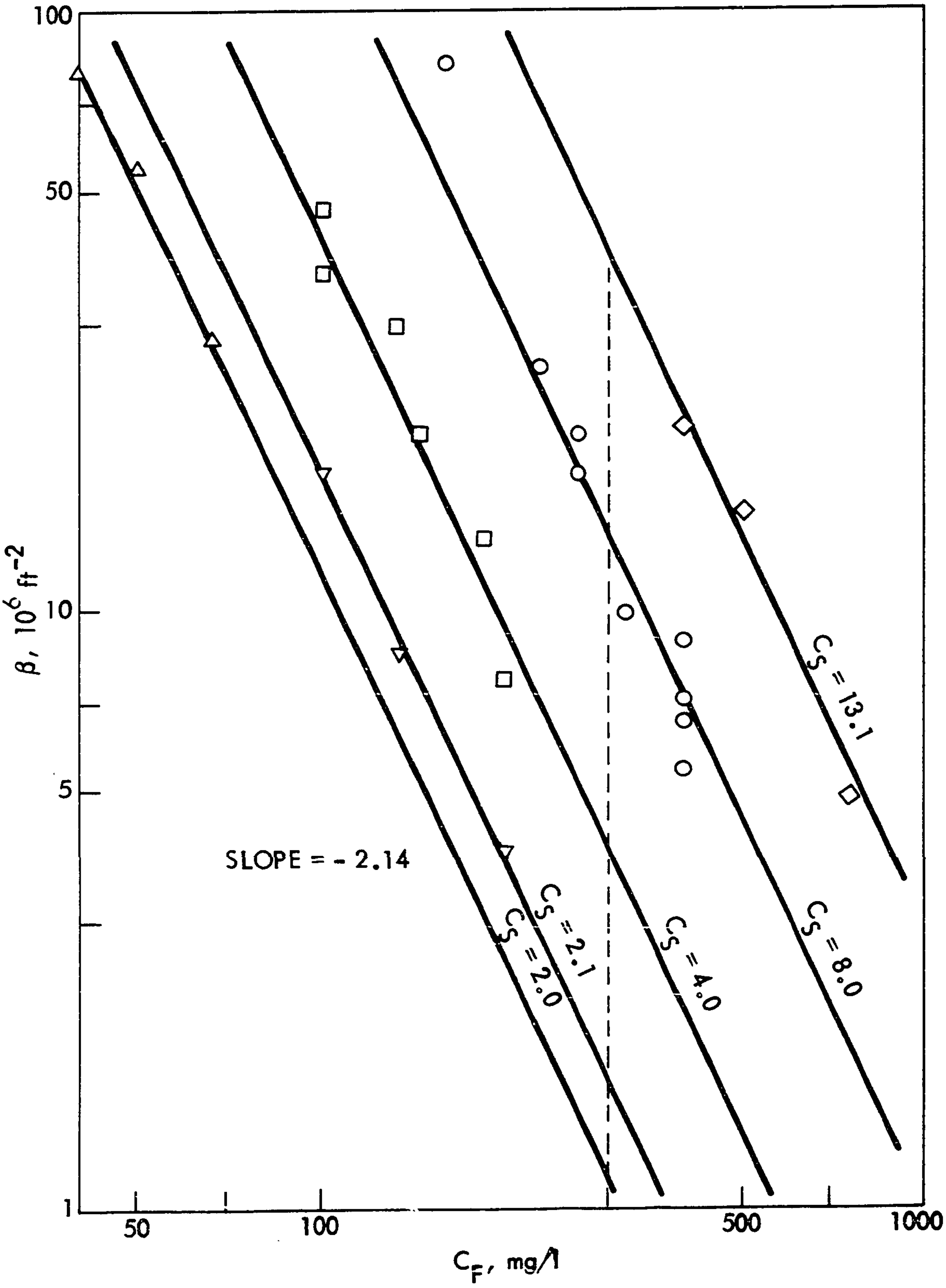
Calculations Log β versus log C_F is plotted for each value of C_S as shown in Figure 52. The slope of these plots is equal to b_3. From Figure 52:

$b_3 = -2.14$

Values of β at each value of C_S can be determined from Figure 52 at a selected value of C_F. In this case the following values were determined for C_F = 300 mg/l:

C_S, mg/l	β, 10^6 ft^{-2}
2.0	1.13
2.1	1.65
4.0	4.00
8.0	13.2
13.1	39.2

Figure 52. Log log plot of β versus C_F for the data in Example 1


100
50
10
5
1
β, 10^6 ft^{-2}
50
100
500
1000
C_F, mg/l
SLOPE = - 2.14
C_S = 2.0
C_S = 2.1
C_S = 4.0
C_S = 8.0
C_S = 13.1

A plot of log β versus log C_S at $C_F = 300$ mg/l is shown in Figure 53. The slope of this plot is equal to b_2 and from Figure 53:

$$b_2 = 1.75$$

Thus:

$$\beta = 10^{b_1} C_S^{1.75} C_F^{-2.14}$$

and from Figure 53, $\beta = 21.2 \times 10^6$ ft^{-2} when $C_S = 10$ mg/l and $C_F = 300$ mg/l. Therefore:

$$21.2 \times 10^6 = 10^{b_1} 10^{1.75} 300^{-2.14}$$

and taking the logarithm of both sides of the equation:

$$7.32634 = b_1 + 1.75(1) - 2.14(2.47712)$$

and

$$b_1 = 10.87738$$

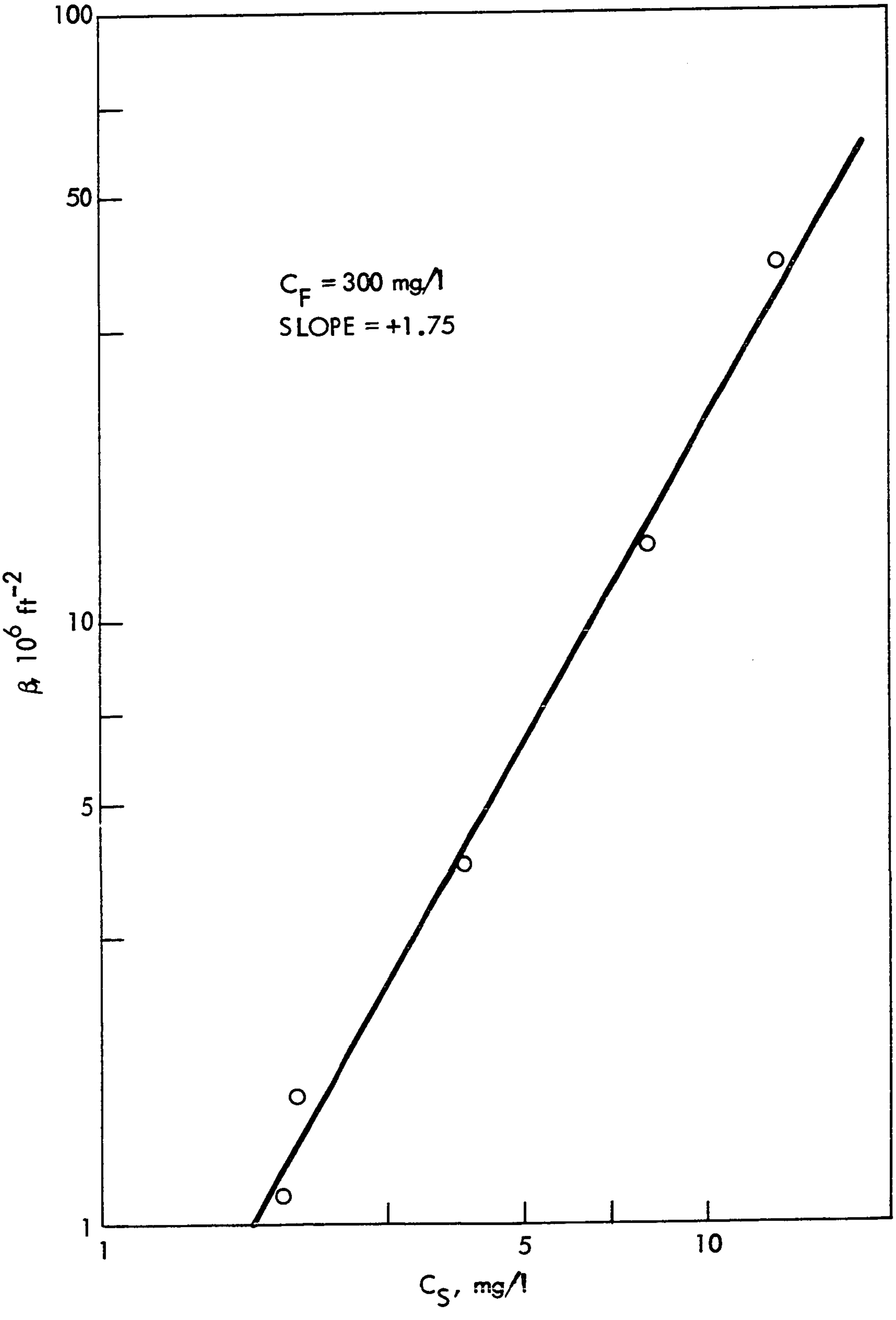
Therefore, the final result is:

$$\beta = 10^{10.88} C_S^{1.75} C_F^{-2.14}$$

The prediction equation determined by using the computer is:

$$\beta = 10^{10.88005} C_S^{1.701042} C_F^{-2.12594}$$

Figure 53. Log log plot of β versus C_S for the data in Example 1


100
50
10
5
1
1
5
10
$C_F = 300$ mg/l
SLOPE = +1.75
β, 10^6 ft^{-2}
C_S, mg/l

Example number 2

Arora Filter Runs 116-121

Filtration of University tap water plus ferric chloride

Sil-Flo 443 (Bag 2) filter aid

The data from these filter runs are printed as part of the computer output (p. 365). During these filter runs the iron concentration was held constant. It will be assumed that there are no concentration effects so that a prediction equation of the form of Equation 15 can be used.

Calculations From the plot of log β versus log C_S/C_F shown in Figure 54, the value of b_2 can be determined. In this case:

$$b_2 = 1.97$$

and from the figure, when $C_S/C_F = 0.04$, β is equal to 3.38×10^7 ft^{-2}. Therefore:

$$3.38 \times 10^7 = 10^{b_1} \ (0.04)^{1.97}$$

and by taking the logarithm of both sides of the equation:

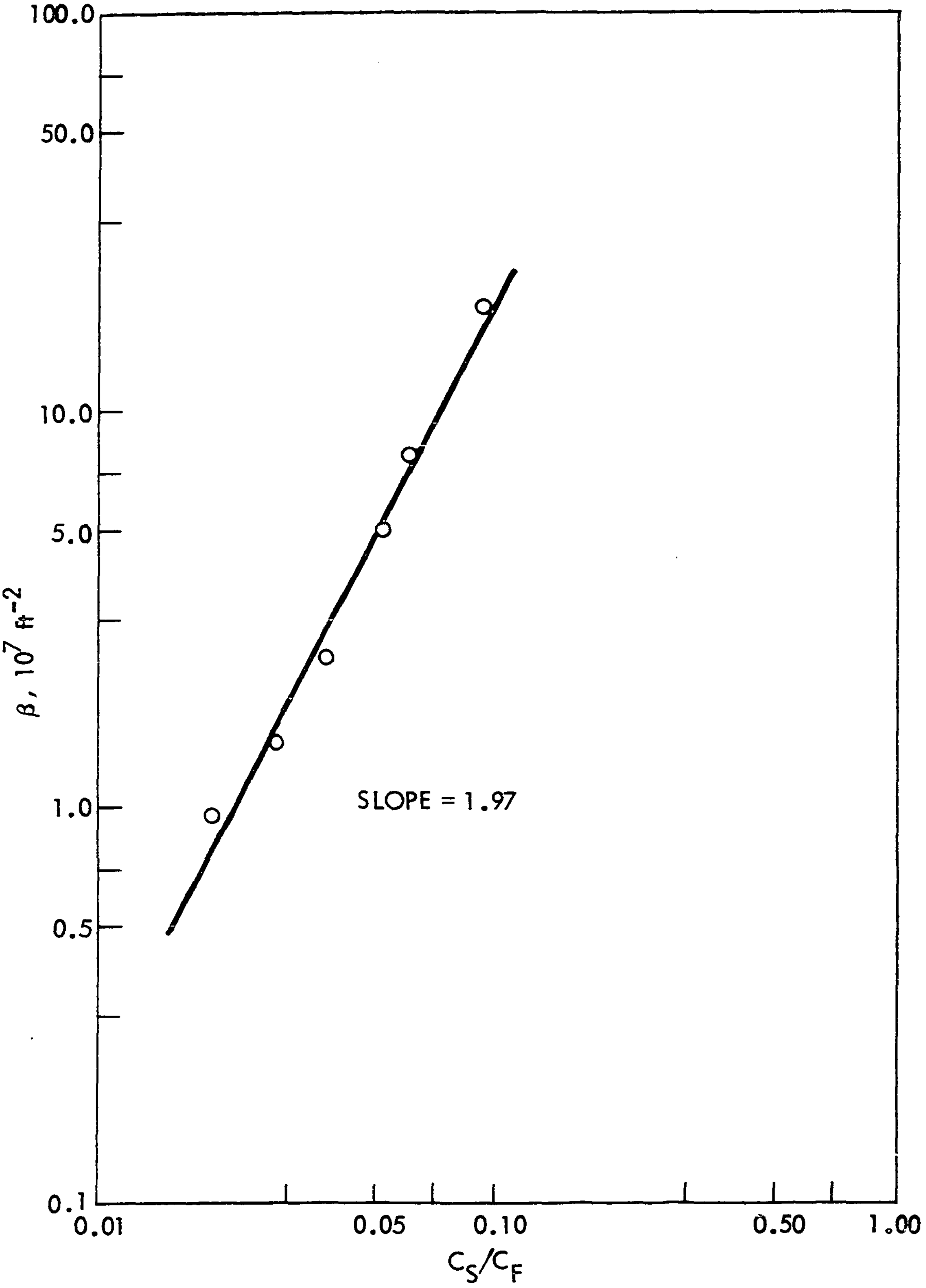
$$7.52892 = b_1 + 1.97(-1.39794)$$

Therefore:

$$b_1 = 10.28286$$

and the final result is:

Figure 54. Log log plot of β versus C_S/C_F for the data from Example 2


100.0
50.0
10.0
5.0
1.0
0.5
0.1
β, 10^7 ft^{-2}
SLOPE = 1.97
0.01
0.05
0.10
0.50
1.00
C_S/C_F

$$\beta = 10^{10.28}\ (C_S/C_F)^{1.97}$$

The prediction equation determined by using the computer is:

$$\beta = 10^{10.29649}\ (C_S/C_F)^{1.97489}$$

APPENDIX F

POPO Program User Manual

Introduction

The Program for Optimization of Plant Operation or the POPO Program was designed to read in all of the necessary filtration data and cost information and to compute the total filtration cost for all desired combinations of filtration rate, terminal head loss, and body feed rate. The 10 combinations which result in the lowest total costs are printed out for β indices equal to 50, 75, 100, 125, 150, and 175 percent of those predicted by the β prediction equation. The method of calculating total cost is identical to that outlined on pages 161-171.

POPO can be used to optimize the design of proposed filtration plants or to optimize the operation of existing plants. For an existing plant, the filter area and therefore the filtration rate are fixed. POPO can then be used to determine the combination of terminal head loss and body feed rate which can be used to give the lowest operating costs for the plant.

Any number of POPO jobs can be processed in one computer run and, in successive jobs, one or more items of the input data can be changed. Input data that are not changed remain the same as in the preceding job. This enables the comparison of different types and grades of filter aids, different types of filters, different influent water qualities, etc.

Input card formats

Data used by POPO is read into the computer on 80 column punched cards. The card formats used with POPO are shown in Table 36.

The first input card shown in Table 36 must always be the first card read by the computer. If this card is not present, the computer run is ended for the information on this card is used to determine the values of data on the other input cards. This card should not be repeated if more than one POPO job is processed in the same computer run.

All other input data cards are designated by an index number punched within columns 1 to 5. The index number determines what type of information is contained on the card. Values of data on these cards must be punched anywhere within columns 26 to 50. Columns 7 to 25 and 51 to 80 are reserved for labeling the data and are ignored by the computer. The individual data cards are explained below by index number.

0. Comment card. Any desired comments can be made within columns 7 to 80. Additional comment cards may be placed anywhere within the deck of input data cards. All comment cards must have 0 punched within columns 1 to 5.

Table 36. POPO input card forms

1 10 20 30 40 50 60 70 80

		1 2 3 4 5 6 7 8 9 0 + - . E B S 1 2 3 4 5			Required first data card
0		Comments			
1		DESIGN FLOW	x		MGD
2		SALVAGE VALUE	x		PERCENT FIRST COST
3		ENERGY CONVERSION	x		PERCENT
4		INTEREST RATE	x		PERCENT
5		PLANT LIFE	x		YEARS
6		SOLIDS (CS)	x		PPM
7		XI INDEX	x		FT/LB
8		TEMPERATURE	x		DEGREES F
9		PRECOAT WEIGHT	x		LB/SF
10		BULK DENSITY	x		LB/CF
11		SEPTUM DIAMETER	x		INCHES
12		BETA PREDICTION	b1/b2/b3/b4		
13		FILTRATION RATE	qs/qi/qf		GPM/SF
14		BODY FEED RATE	cs/ci/cf		PPM
15		TERMINAL HEAD LOSS	hs/hi/hf		FT
16		FILTER AID COST	x		$/TON
17		FIRST COST	AREA	$/SF	
			a	f	
			a	f	
			a	f	
			a	f	
	*		a	f	

Table 36 (Continued)

18		POWER COST	x		CENTS/KWH
19		LABOR & MAINT COST	AREA	$/SF/MONTH	
			a	lm	
			a	lm	
			a	lm	
			a	lm	
	*		a	lm	
20		BACKWASH COST	bw, bt		GAL/SF, MINUTES
	B	EGIN			
	S	TOP			

Note: x = Value of a filtration or cost factor

b1, b2, b3, b4 = Values of exponents of β prediction equation

qs, qi, qf = Values of starting, incremental, and final filtration rate

cs, ci, cf = Values of starting, incremental, and final body feed rate

hs, hi, hf = Values of starting, incremental, and final terminal head loss

a = Filter area in sq. ft.

f = First cost in $/sq. ft.

lm = Labor plus maintenance cost in $/sq. ft. per month

bw = Amount of backwash water required in gal/sq. ft. of filter area

bt = Time required to backwash and precoat the filter

1. The design flow in MGD.

2. The salvage value of the plant at the end of its design life in percent of the first cost.

3. The overall pumping efficiency in percent.

4. The annual interest rate in percent.

5. The expected life of the plant in years.

6. The suspended solids concentration in mg/l or ppm for use in predicting the β index.

7. The ξ index of the filter aid in ft/lb. The ξ index may be written in exponential form by placing the letter E before the exponent of 10 (i.e. 1.95E9 = 1.95×10^9).

8. The temperature of the filter influent in degrees Fahrenheit.

9. The weight of the precoat, w, in lb/sq ft.

10. The in-place bulk density of the clean filter aid, γ_p, in lb/cu ft.

11. The outer diameter of the filter septa in inches. Use 0 if flat septa are used.

12. The exponents of the β prediction equation. The general form of β prediction equation used in POPO is:

$$\beta = 10^{b_1} C_S^{b_2} C_F^{b_3} \qquad (33)$$

An additional exponent, b_4, is included on the POPO input card in case it is desired to add an additional variable, such as ξ, to the prediction equation. When Equation 33 is used, b_4 equals 0. The values of the exponents are separated by slashes (/).

13. The values of the initial, increment, and final filtration rates in gpm/sq ft. Adjacent values are separated by a slash (/).

14. The values of the initial, increment, and final body feed rates in mg/l or ppm. Adjacent values are separated by a slash (/).

15. The values of the initial, increment, and final terminal head losses in ft of water. Adjacent values are separated by a slash (/).

16. The cost of the filter aid in $/ton.

17. The card with index number 17 is followed by cards defining the first cost versus area curve for the plant. Each of these cards contains a value of filter area in sq ft and the corresponding first cost in $/sq ft. These cards must be arranged in ascending order according to the filter area. Up to 50 first cost versus area cards may be read in and the last card must have an asterisk (*) punched in Column 6.

18. The cost of electrical power in ¢/kwh.

19. The card with index number 19 is followed by cards defining the labor and maintenance cost versus area curve for the plant. Each of these cards contains a value of filter area in sq ft and the corresponding labor plus

maintenance cost in $/sq ft per month. These cards must be arranged in ascending order according to the filter area. Up to 50 labor plus maintenance cost versus area cards may be read in and the last card must have an asterisk (*) punched in column 6.

20. The amount of water required to backwash the filter in gal/sq ft and the length of time required to backwash and precoat the filter in minutes.

21. Card index number 21 is reserved for inputing maintenance cost data. In the present form of POPO, labor and maintenance costs are combined so that cards with index number 21 are not used.

The cards containing all of the necessary input data for each POPO job are followed by the BEGIN card. This card indicates to the computer that all of the input data have been read in and the optimization calculations can now be made. The B of the BEGIN card must be punched in column 6.

After the optimization calculations for a POPO job are completed and the results output, the computer will begin to read in the data for another POPO job. To end a computer run, a STOP card should be placed after the BEGIN card for the last POPO job to be processed. The S of the STOP card must be punched in column 6.

FORTRAN listing

POPO was originally written by Dillingham (27) in FORTRAN II computer language (40) for use with the IBM 7074 computer system. The program has been converted to FORTRAN IV computer language (31, 41) for use with the IBM 360/65 computer system at Iowa State University and the FORTRAN listing for the program is given in this section. The major changes in POPO necessary to convert from FORTRAN II to FORTRAN IV are as follows:

1) FUNCTION subprograms

In FORTRAN IV a FUNCTION subprogram cannot contain a SUBROUTINE statement or another FUNCTION statement. Therefore, it was necessary to convert functions VALUE, VALU, and PRED to subroutines.

2) Alphameric code

When a character is input under an A format, it is stored as an integer value. For example, the letter B was stored in FORTRAN II as 6200000000. This value was used in subroutine READR to determine if column 6 of a data card contained the letter B. Such information was also used in function VALU to read numeric data.

Different FORTRAN systems have different alphameric codes. POPO has been changed to account for these changes by inputting the following array:

```
1       10        20        30        40
          1234567890+-,E BS12345
```

Characters read under an A format are then determined by comparison with elements of the above array. This array must be read in on the first data card. If it is not, the program is stopped.

3) Library functions

FORTRAN II library functions (i.e. SQRTF (X)) have been changed to FORTRAN IV (i.e. SQRT (X)).

The only other major change from Dillingham's version of POPO is the method used to account for the costs ascribed to backwashing. Dillingham (27) assumed that the increase in monthly costs resulting from providing filtered backwash water was 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. He also assumed that the increase in monthly costs due to down time for backwashing and precoating was equal to the monthly operating cost (excluding power costs) times the ratio of the down time per filter run to the length of the filtering cycle. Apparently, these assumptions were made to avoid the iterative procedure for calculating filter area. However, since the total operating cost includes the increase in cost due to backwashing, it was still necessary for Dillingham to use an iterative procedure to calculate backwashing costs.

Dillingham's method of calculating filtration costs may be valid when the filter run length is relatively long. However, the filter run length calculated in Dillingham's version of POPO did not include the time required to backwash and precoat the filter. This error increased the calculated number of filter runs per month and therefore caused the monthly cost of precoat filter aid to be high. This in turn caused the monthly costs due to backwashing to be too high. Considerable error could result if the filter run length was short.

A complete explanation of the FORTRAN listing for POPO would be very lengthy. Therefore, only a brief explanation of the basic purposes of the main program and each subroutine is given. Some of the symbols used in FORMAT statements for the Iowa State University IBM 360/65 computer system have been explained in Appendix D. Figure 55 is a schematic diagram showing the relationships between the various subroutines of POPO. The arrows in Figure 55 point to the subroutine which is called. Input subroutines are herein defined as subroutines which are used for reading and interpreting the input cards. Operation subroutines are defined as subroutines used to perform the specified operations determined by the input subroutines. The computation of each cost factor is made in a separate subroutine so that any changes in the method of computing a particular cost factor can be easily made.

A summary of the notation used in POPO is listed in Table 37.

Figure 55. Schematic diagram of POPO subroutines

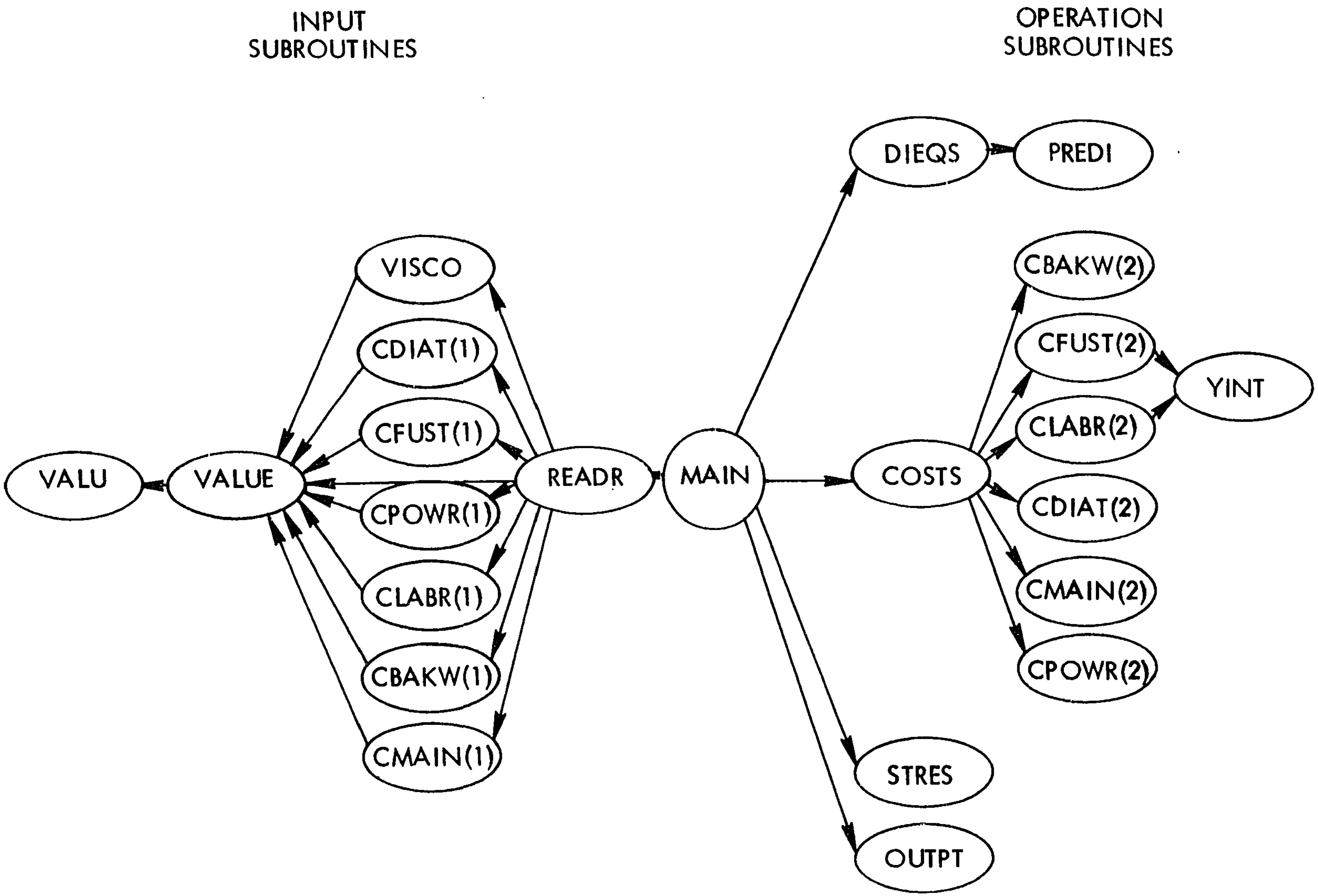

INPUT SUBROUTINES
OPERATION SUBROUTINES
VALU
VALUE
VISCO
CDIAT(1)
CFUST(1)
CPOWR(1)
CLABR(1)
CBAKW(1)
CMAIN(1)
READR
MAIN
DIEQS
PREDI
CBAKW(2)
CFUST(2)
YINT
CLABR(2)
COSTS
CDIAT(2)
CMAIN(2)
CPOWR(2)
STRES
OUTPT

Table 37. POPO notation

Name	Meaning
IN	Input array, IN(81) to IN(97) contains the array on the first data card
ANS	Answer array which stores the results for the 10 least cost design conditions
B	Array containing the coefficients of the β prediction equation
AMORT	Amortization factor
AREA	Filter area, sq ft
BETA	Filter cake resistance index, β, ft^{-2}
BWT	Time required to backwash and precoat the filter, hr
CD	Body feed rate, C_F, mg/l
CDI,CDS,CDF	Initial, increment, and final values of the body feed rate, mg/l
CDE	Unit cost of filter aid, $/month
CPO	Unit cost of electrical power, $/month
CF	First cost, $/month
CL	Labor cost, $/month
CM	Maintenance cost, $/month
CB	Backwashing cost, $/month
COPER	Operating cost, $/month
CTOTL	Total cost, $/month
CS	Influent suspended solids concentration, mg/l
EFF	Overall pumping efficiency
FACTR	β multiplication factor. Used to give results for β equal to 50,75,100, 125 150, and 175 percent of the predicted β

Table 37 (Continued)

Name	Meaning
G	Acceleration of gravity, ft/hr^2
GP	In-place bulk density of precoat, lb/cu ft
GW	Density of water, lb/cu ft
HP	Head loss through precoat, ft of water
HC	Head loss through filter cake, ft of water
KPIT	Type of input. Equals 1 for punched cards
KPOT	Type of output. Equals 3 for printed paper
PHI	ϕ term
QI,QS,QF	Initial, increment, and final values of the filtration rate, ft/hr
QGPM	Flow rate in gpm required to meet both demand and backwashing requirements
QMGD	Design flow rate in MGD for the plant
QMGDP	Flow rate in MGD required to meet both demand and backwashing requirements
RF	Filtration rate factor
RO	Outer radius of precoated septum, R_o, ft
RS	Outer radius of septum, R_s, ft
SIGMA	σ term
TH	Terminal head loss, ft of water
THI,THS,THF	Initial, increment, and final values of terminal head loss, ft of water
TR	Length of filter run, hr
THICK	Thickness of precoat layer and filter cake, ft
UQ	Filtration rate, ft/hr

Table 37 (Continued)

Name	Meaning
VIS	Kinematic viscosity, ft^2/hr
W	Weight of precoat, w, lb/sq ft
XI	ξ index, ft/lb
XLP	Thickness of precoat layer, ft

MAIN program

The array contained on the first data card is read in. If this array is missing, the program is stopped. Subroutine READR is then called to read all of the data cards for the first job. Costs are then computed for all combinations of filtration rate, body feed rate, and terminal head loss for values of β equal to 50, 75, 100, 125, 150, and 175 percent of the predicted value. After the 10 least cost combinations are printed out for each value of β, control is transferred to statement 1 and subroutine READR is called to read the data cards for the next job.

```
C           MAIN PROGRAM -- POPO
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      KPIT=1
      KPOT=3
      READ(KPIT,100)(IN(I),I=81,97),K
  100 FORMAT(10X,17A1,I5)
C
C     THE FOLLOWING MUST BE THE FIRST DATA CARD READ
C         1234567890+-.E BS12345
C
      IF(K-12345)1000,1,1000
    1 CALL READR
      DO 9 MM=50,175,25
      FACTR=FLOAT(MM)/100.0
      UQ=QI-QS
    2 UQ=UQ+QS
      IF(UQ-QF)3,3,8
    3 CD=CDI-CDS
    4 CD=CD+CDS
      IF(CD-CDF)5,5,2
    5 TH=THI-THS
    6 TH=TH+THS
      IF(TH-THF)7,7,4
    7 CALL DIEQS
      CALL COSTS
      CALL STRES
      GO TO 6
    8 CALL OUTPT
    9 CONTINUE
      GO TO 1
 1000 STOP
      END
```

Subroutine READR

After the ANS array is initialized with large numbers, a data card is read and the information on it is stored as elements 1 to 80 of the IN array and also printed out on the output sheet. If a BEGIN card is read (indicated by the letter B in column 6 so that IN(6) = B), the amortization factor is calculated, output sheet headings are written, and control is returned to the MAIN program. If a STOP card is read (indicated by the letter S in column 6), the program is stopped. If the card is not a BEGIN or STOP card, subroutine VALUE is called to determine the value of the index number in columns 1 to 5. Cards with index number 0 are ignored, otherwise control is transferred to the statement number corresponding to the index number of the card. Subroutine VALUE is called to interpret the data within columns 26 to 50 of the cards with index numbers of 1 to 15. For cards with index numbers of 16 to 21, subroutines CFUST, CPOWR, CLABR, CBAKW, and CMAIN are called to interpret first, power, labor, backwashing, and maintenance cost data, respectively.

After the data on the card has been interpreted, control is transferred to statement 51 and the next card is read.

```
      SUBROUTINE READR
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      WRITE(KPOT,100)
  100 FORMAT('1POPO -- PROGRAM FOR OPTIMIZATION OF PLANT',
     1' OPERATION',///)
      BIG=1000000.**4
      DO 50 L=1,10
   50 ANS(8,L)=BIG
      G=32.2*3600.0*3600.0
      GW=62.4
   51 READ(KPIT,200)(IN(I),I=1,80)
  200 FORMAT(80A1)
      WRITE(KPOT,300)(IN(I),I=1,80)
  300 FORMAT(1X,80A1)
      IF(IN(6)-IN(96))53,52,53
   52 F1=(1.+RATEI)**YRS
      AMORT=(RATEI/(F1-1.))*(F1-PCT/100.)/12.
      WRITE(KPOT,400)
  400 FORMAT('1','FLOW  TERM   CF  B E T A  TIME  AREA  ',
     1'THICK * --- COSTS, $ PER MILLION GALLONS -- *   ',
     2'TOTAL',/,7X,'HEAD',9X,'4  -2',20X,'*',20X,'LAB+',13X,
     3'*',4X,'COST',/,' GSFM   FT   PPM  10 FT     HR  ',
     4'SQ FT   IN   * TOTAL   1ST  OPER  MAIN  POWR  FAID',
     5' *    $/MO',//,1X,44('-'),'*',37('-'),'*',8('-'))
      RETURN
   53 IF(IN(6)-IN(97))54,63,54
   54 CALL VALUE (1,PP)
      INDEX=PP
      IF(INDEX)51,51,55
   55 IF(INDEX-21)56,56,51
   56 GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,
     119,20,21),INDEX
    1 CALL VALUE (26,QMGD)
      GO TO 51
    2 CALL VALUE (26,PCT)
      GO TO 51
    3 CALL VALUE (26,EFF)
      EFF=EFF/100.
      GO TO 51
    4 CALL VALUE (26,RATEI)
      RATEI=RATEI/100.
      GO TO 51
    5 CALL VALUE (26,YRS)
      GO TO 51
    6 CALL VALUE (26,CS)
      GO TO 51
```

```
    7 CALL VALUE (26,XI)
      GO TO 51
    8 CALL VALUE (26,FTEMP)
      VIS=VISCO(FTEMP)*3600.0
      GO TO 51
    9 CALL VALUE (26,W)
      GO TO 51
   10 CALL VALUE (26,GP)
      GO TO 51
   11 CALL VALUE (26,RS)
      RS=RS/24.
      GO TO 51
   12 CALL VALUE (26,B(1))
      CALL VALUE(0,B(2))
      CALL VALUE(0,B(3))
      CALL VALUE(0,B(4))
      GO TO 51
   13 CALL VALUE (26,QI)
      QI=QI*8.02
      CALL VALUE(0,QS)
      QS=QS*8.02
      IF(QS)58,58,57
   57 CALL VALUE(0,QF)
      QF=QF*8.02
      GO TO 51
   58 QS=1.
      QF=QI
      GO TO 51
   14 CALL VALUE (26,CDI)
      CALL VALUE(0,CDS)
      IF(CDS)60,60,59
   59 CALL VALUE(0,CDF)
      GO TO 51
   60 CDS=1.
      CDF=CDI
      GO TO 51
   15 CALL VALUE (26,THI)
      CALL VALUE(0,THS)
      IF(THS)62,62,61
   61 CALL VALUE(0,THF)
      GO TO 51
   62 THS=1.
      THF=THI
      GO TO 51
   16 CALL CDIAT(1)
      GO TO 51
   17 CALL CFUST(1)
      GO TO 51
   18 CALL CPOWR(1)
      GO TO 51
```

```
19 CALL CLABR(1)
   GO TO 51
20 CALL CBAKW(1)
   GO TO 51
21 CALL CMAIN(1)
   GO TO 51
63 STOP
   END
```

Subroutine VALUE

This subroutine interprets the data on the input card which was read in as elements 1 to 80 of the IN array by subroutine READR. Subroutine VALU is called to convert data in alphameric form in the IN array to numeric form. The argument N is the element of the IN array, or column of the input card, at which the conversion process in subroutine VALU begins, and V is the value of the data in numeric form determined by subroutine VALU. N is set equal to 1 in subroutine READR when the index number in columns 1 to 5 is to be determined and to 26 when the first data value in columns 26 to 50 is to be determined. To determine additional data values in columns 26 to 50 (i.e. cards with index numbers 12, 13, 14, 15, 17, 19, and 20), N is set equal to 0 and the conversion process in subroutine VALU then begins at column IN(100) which is the number of the column immediately following the previously determined value.

The letter E punched in the column immediately following a number indicates that the number is written in exponential form. Subroutine VALU is called to determine the exponent of 10, EX, and the number is multiplied by 10^{EX}.

```
  SUBROUTINE VALUE(N,V)
  COMMON IN(150)
  CALL VALU (N,V)
  M=IN(100)
  IF(IN(M)-IN(94))2,1,2
1 CALL VALU (M,EX)
  V=V*10.**EX
2 RETURN
  END
```

Subroutine VALU

This subroutine is used to convert data in alphameric form to numeric form. This is done by starting at the column indicated by N (see subroutine VALUE) and then checking each successive column until the number is reached. The number is then converted from alphameric to numeric form by comparing each digit of the number to the elements of the array read in on the first data card. If there is no number present, a value of 0 is returned.

```
      SUBROUTINE VALU(N,VA)
      COMMON IN(150)
      LAST=50
      IF(N)1,1,2
    1 M=IN(100)
      GO TO 3
    2 M=N
    3 KVA=0
      VA=0.
      KSN=1
      KD=0
      IF(M-LAST)4,4,8
    4 DO 7 KPOS=M,LAST
      IF(IN(KPOS)-IN(95))5,7,5
    5 DO 6 K=81,93
      IF(IN(KPOS)-IN(K))6,13,6
    6 CONTINUE
    7 CONTINUE
      IN(100)=LAST
    8 RETURN
    9 KPOS=KPOS+1
      IF(KPOS-LAST)11,11,10
   10 KPOS=LAST
      GO TO 21
   11 DO 12 K=81,93
      IF(IN(KPOS)-IN(K))12,13,12
   12 CONTINUE
      GO TO 21
   13 J=K-80
      GO TO (14,14,14,14,14,14,14,14,14,17,9,18,19),J
   14 KVA=KVA*10+J
   15 IF(KD)16,9,16
   16 KD=10*KD
      GO TO 9
   17 KVA=KVA*10
      GO TO 15
   18 KSN=-1
      GO TO 9
   19 KD=1
   20 GO TO 9
   21 VA=KVA*KSN
      IF(KD)23,23,22
   22 VA=VA/FLOAT(KD)
   23 IN(100)=KPOS
      RETURN
      END
```

Function VISCO

This subroutine calculates the value of the kinematic viscosity in ft^2/sec from the temperature in °F. The argument C is the water temperature in °F. The kinematic viscosity is converted to ft^2/hr (VIS) in subroutine READR.

```
      FUNCTION VISCO(C)
      VISCO=(286.405-SQRT(53671.0-3.1027*(C-152.45)**2))*.0000001
      RETURN
      END
```

Subroutine DIEQS

First subroutine PREDI is called to determine the value of the β index. Then, the length of the filter run (TR) and the thickness of the precoat and filter cake (THICK) at the end of the filter run are calculated. The length of the filter run is calculated as the length of the filtering cycle (TF) plus the time required to backwash and precoat the filter (BWT).

```
      SUBROUTINE DIEQS
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
```

```
      CALL PREDI(FACTR,BETA)
      PHI=2.0*UQ*GW*CD*.000001/GP
      SIGMA=UQ*UQ*VIS*BETA*CD/G
      XLP=W/GP
      HP=UQ*VIS*XI*W/G
      HC=TH-HP
      IF(RS)2,1,2
    1 TF=HC/SIGMA
      TR=TF+BWT
      THICK=XLP+PHI*TF/2.0
      GO TO 3
    2 RO=RS+XLP
      TF=RO*RO*(EXP(HC*PHI/(RS*SIGMA))-1.0)/(RS*PHI)
      TR=TF+BWT
      THICK=SQRT(RO*RO+RS*PHI*TF)-RS
    3 RETURN
      END
```

Subroutine PREDI

This subroutine calculates the value of β using the prediction equation. ξ is included as an additional variable however it is recommended that it be excluded and b_4 read in as 0. The argument DUMMY is the β multiplication factor (FACTR).

```
      SUBROUTINE PREDI(DUMMY,PRED)
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      PRED=DUMMY*10.0**B(1)
      IF(B(2))1,2,1
    1 PRED=PRED*CS**B(2)
    2 IF(B(3))3,4,3
    3 PRED=PRED*CD**B(3)
    4 IF(B(4))5,6,5
    5 PRED=PRED*XI**B(4)
    6 RETURN
      END
```

Subroutine COSTS

Subroutine CBAKW is called to calculate the required filter area. Each of the cost subroutines are then called to calculate the various costs in $/month. The operating and total cost is then calculated. Maintenance cost (CM) and backwashing cost (CB) are both equal to 0 since maintenance cost is included with labor cost (CL) and the costs ascribed to backwashing are accounted for by the increase in filter area required to produce water for backwashing (see subroutine CBAKW).

```
 SUBROUTINE COSTS
 COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
4W,XI,XLP
 CALL CBAKW(2)
 CALL CFUST(2)
 CALL CLABR(2)
 CALL CDIAT(2)
 CALL CMAIN(2)
 CALL CPOWR(2)
 COPER=CDE+CM+CPO+CL+CB
 CTOTL=CF+COPER
 RETURN
 END
```

Subroutine CBAKW

When subroutine CBAKW is called from subroutine READR, the argument L is equal to 1 and subroutine VALUE is called to determine the gallons of backwash water required per sq ft (BWGSF) and the time in minutes required to backwash and precoat the filter (TBW) punched on the data card (index number 20). When subroutine CBAKW is called from subroutine COSTS, the argument L is equal to 2 and the required filter area (AREA) and flow rate in MGD (QMGDP) required to meet both demand and backwashing requirements are calculated using the iterative procedure presented on page 169. RPD is the number of filter runs that can be made per day and TMFD is the time in minutes per day that the filter is actually filtering.

```
      SUBROUTINE CBAKW(L)
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPD,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      IF(L-1)1,1,2
    1 CALL VALUE(26,BWGSF)
      F1=BWGSF
      CALL VALUE(0,TBW)
      BWT=TBW/60.
      F2=TBW
      RETURN
    2 RPD=24./TR
      TMFD=1440.-RPD*F2
      QMGDP=QMGD
    3 QGPM=QMGDP*1000000./TMFD
      AREA=QGPM/(UQ/8.02)
```

```
      QMGDP=QMGD+RPD*AREA*F1/1000000.
      QGPM=QMGDP*1000000./TMFD
      CAREA=QGPM/(UQ/8.02)
      QMGDP=QMGD+RPD*CAREA*F1/1000000.
      F3=0.01*AREA
      F4=CAREA-AREA
      IF(F3-F4)3,3,4
    4 AREA=CAREA
      CB=0.0
      RETURN
      END
```

Subroutine CFUST

When subroutine CFUST is called from subroutine READR, the argument L is equal to 1. In this case, the input cards containing the first cost per unit area versus filter area data are read in and interpreted by calling subroutine VALUE. Logarithms of the filter area are stored in array A and the corresponding logarithms of the unit first cost are stored in array Z. LIMIT is the element of arrays A and Z which contain the last log area and log unit first cost values.

When subroutine CFUST is called from subroutine COSTS, the argument L is equal to 2. In this case, subroutine YINT is used to determine the first cost per unit area which corresponds to the required filter area (AREA) and the amortized first cost is calculated in $/month.

```
      SUBROUTINE CFUST(L)
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      DIMENSION A(50),Z(50)
      IF(L-1)1,1,4
    1 DO 2 I=1,50
      READ(KPIT,100)(IN(J),J=1,80)
  100 FORMAT(80A1)
      WRITE(KPOT,200)(IN(J),J=1,80)
  200 FORMAT(1X,80A1)
      CALL VALUE(26,TEMP)
      A(I)=ALOG(TEMP)
      CALL VALUE(0,TEMP)
      Z(I)=ALOG(TEMP)
      IF(IN(6)-IN(95))3,2,3
    2 CONTINUE
    3 LIMIT=I
      RETURN
    4 TEMP=ALOG(AREA)
      RF=1.+(UQ-8.)/40.
      TEMP=YINT(LIMIT,TEMP,A,Z)
      CF=EXP(TEMP)*AREA*AMORT*RF
      RETURN
      END
```

Subroutine CLABR

Subroutine CLABR is similar to subroutine CFUST. When it is called from subroutine READR, L equals 1 and the labor cost versus filter area data are read in and interpreted. When it is called from subroutine COSTS, L equals 2 and the cost of labor per unit filter area per month which corresponds to the required filter area is determined, and the cost of labor in $/month is calculated.

```
      SUBROUTINE CLABR(L)
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      DIMENSION A(50),Z(50)
      IF(L-1)1,1,4
    1 DO 2 I=1,50
      READ(KPIT,100)(IN(J),J=1,80)
  100 FORMAT(80A1)
      WRITE(KPOT,200)(IN(J),J=1,80)
  200 FORMAT(1X,80A1)
      CALL VALUE(26,TEMP)
      A(I)=ALOG(TEMP)
      CALL VALUE(0,TEMP)
      Z(I)=ALOG(TEMP)
      IF(IN(6)-IN(95))3,2,3
    2 CONTINUE
    3 LIMIT=I
      RETURN
    4 TEMP=ALOG(AREA)
      TEMP=YINT(LIMIT,TEMP,A,Z)
      CL=EXP(TEMP)*AREA*RF
      RETURN
      END
```

Function YINT

This subroutine is used to determine the value (YINT) of the first cost in \$/sq ft, or the cost of labor in \$/sq ft per month, which corresponds to the required filter area. This was done by linear interpolation between points read in from the first cost, or labor cost, versus area curve. X is the logarithm of the required filter area, array AX contains the logarithms of the values of filter area, and array AY contain the logarithms of the corresponding cost per unit area values. Logarithms are used to make the curve more linear.

If the required filter area is less than the lowest area for which a cost value was read in, YINT is set equal to the cost value for the lowest area read in and a caution statement is printed. If the required filter area is greater than the largest area for which a cost value is read in, YINT is set equal to the cost value for the largest area read in and a caution statement is printed. The original version of POPO (27) contained an error such that if the required filter area was exactly equal to any of the areas for which a cost value was input, YINT was set equal to the cost value for the largest area read in. The present program has been changed to correct this mistake.

```
      FUNCTION YINT(LIMIT,X,AX,AY)
      DIMENSION AX(50),AY(50)
      IF(X-AX(1))6,1,2
    1 YINT=AY(1)
      RETURN
    2 DO 3 I=2,LIMIT
      IF(X-AX(I))4,5,3
    3 CONTINUE
      YINT=AY(LIMIT)
      WRITE(KPOT,100)
  100 FORMAT(10X,'** CAUTION ** AREA ABOVE RANGE OF COST DATA')
      RETURN
    4 J=I-1
      YINT=AY(J)+(X-AX(J))*(AY(I)-AY(J))/(AX(I)-AX(J))
      RETURN
    5 YINT=AY(I)
      RETURN
    6 YINT=AY(1)
      WRITE(KPOT,200)
  200 FORMAT(10X,'** CAUTION ** AREA BELOW RANGE OF COST DATA')
      RETURN
      END
```

Subroutine CDIAT

When subroutine CDIAT is called from subroutine READR, the argument L is equal to 1 and subroutine VALUE is called to determine the price of filter aid (UCDE) punched on the input card (index number 16). When subroutine CDIAT is called from subroutine COSTS, the argument L equals 2 and the cost of filter aid (CDE) in \$/month is calculated.

```
      SUBROUTINE CDIAT(L)
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RD,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      IF(L-1)1,1,2
    1 CALL VALUE(26,UCDE)
      F1= 24.*30.4/2000.
      F2=8.33*30.4/2000.
      RETURN
    2 PREDE=F1*W*AREA/TR
      BFDE=F2*CD*QMGDP
      CDE=UCDE*(PREDE+BFDE)
      RETURN
      END
```

Subroutine CMAIN

In the present form of POPO, maintenance costs are included with the cost of labor. Therefore, the cost of maintenance (CM) is set equal to 0. The subroutine is included in case it becomes desirable to calculate maintenance cost separately from labor cost.

```
       SUBROUTINE CMAIN(L)
       COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
      1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
      2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
      3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
      4W,XI,XLP
       IF(L-1)1,1,2
     1 RETURN
     2 CM=0.0
       RETURN
       END
```

Subroutine CPOWR

When subroutine CPOWR is called from subroutine READR, the argument L is equal to 1 and subroutine VALUE is called to determine the cost of power in ¢/kwh (PP) punched on the data card (index number 18). When subroutine CPOWR is called from subroutine COSTS, the argument L is equal to 2 and the power cost in $/month (CPO) is calculated.

```
       SUBROUTINE CPOWR(L)
       COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
      1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
      2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
      3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
      4W,XI,XLP
       IF(L-1)1,1,2
     1 CALL VALUE(26,PP)
       CONST=(PP/100.)*8.33*30.4/2.655
       RETURN
     2 CPO=CONST*TH*QMGDP/EFF
       RETURN
       END
```

Subroutine STRES

Subroutine STRES is called from the MAIN program after the total cost for a particular combination of filtration rate, terminal head loss, and body feed rate has been determined. This total cost is then compared to the 10 total cost values stored in the 8th row of the ANS array. If it is less than any of these, it is stored in the proper place in ANS such that the 10 total cost values in the array are arranged in ascending order.

```
      SUBROUTINE STRES
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      LIMIT=10
      DO 1 K=1,LIMIT
      IF(CTOTL-ANS(8,K))2,1,1
    1 CONTINUE
      RETURN
    2 J=LIMIT
    3 IF(J-K)6,6,4
    4 L=J-1
      DO 5 I=1,13
    5 ANS(I,J)=ANS(I,L)
      J=L
      GO TO 3
    6 ANS(1,K)=UQ
      ANS(2,K)=TH
      ANS(3,K)=CD
      ANS(4,K)=BETA
      ANS(5,K)=TR
      ANS(6,K)=AREA
      ANS(7,K)=THICK
      ANS(8,K)=CTOTL
      ANS(9,K)=CF
      ANS(10,K)=COPER
```

```
      ANS(11,K)=CL+CM
      ANS(12,K)=CPO
      ANS(13,K)=CDE
      RETURN
      END
```

Subroutine OUTPT

This subroutine is called from the MAIN program to print the final results for each value of β. Note that the cost values presented in $/MG are based on the demand flow rate (QMGD) and not the flow rate required to meet both demand and backwashing requirements. After the results are printed out, the 8th row of the ANS array is reinitialized with large numbers.

```
      SUBROUTINE OUTPT
      COMMON IN(150),ANS(13,10),B(4),AMORT,AREA,BETA,BWT,CD,
     1CDI,CDS,CDF,CDE,CPO,CF,CL,CM,CB,COPER,CTOTL,CS,EFF,
     2FACTR,G,GP,GW,HP,HC,KPIT,KPOT,PHI,QI,QS,QF,QGPM,QMGD,
     3QMGDP,RF,RO,RS,SIGMA,TH,THI,THS,THF,TR,THICK,UQ,VIS,
     4W,XI,XLP
      I=FACTR*100.0
      WRITE(KPOT,100)I
  100 FORMAT('0',28X,'BETA INDICES =',I4,' PERCENT OF PREDICTED VALUES')
      DO 2 I=1,10
      ANS(1,I)=ANS(1,I)/8.02
      J=ANS(2,I)
      K=ANS(3,I)
      L=ANS(4,I)/10000.0
      M=ANS(6,I)
      ANS(7,I)=ANS(7,I)*12.
      NN=ANS(8,I)
      DO 1 KK=8,13
    1 ANS(KK,I)=ANS(KK,I)/(QMGD*30.4)
    2 WRITE(KPOT,200)ANS(1,I),J,K,L,ANS(5,I),M,(ANS(N,I),N=7,13),NN
  200 FORMAT(F5.2,I6,I5,I8,F7.1,I6,F7.2,' *',6F6.1,' *',I8)
      BIG=1000000.**4
      DO 3 L=1,10
    3 ANS(8,L)=BIG
      RETURN
      END
```

Example input and output

The input data and final results for two POPO jobs are presented in this section. The data is presented here for demonstration purposes only.

Job 1 illustrates the use of POPO for optimizing the design of a proposed plant. The design suspended solids concentration is 7.5 mg/l of iron and the minimum amount of body feed found to still produce an incompressible cake was about 20 mg/l. Therefore, the initial value of the body feed rate was set at 20 mg/l. The final value of the terminal head loss is limited to 150 feet. Values of the initial and final filtration rate, final body feed rate, and initial terminal head loss were chosen so that the optimum design conditions would be within the range of the conditions for which cost calculations were made.

Job 2 illustrates the use of POPO for optimizing the operation of an existing plant. In this example, both the filtration rate and the terminal head loss are fixed. Therefore, only the body feed rate was varied in the optimization calculations.

Job 1 and Job 2 were both processed during the same computer run. Job 2 illustrates that it is necessary to input only the data that is different from that of the previous job.

```
POPO -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION


  0      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              1      INCHES
 12 BETA PREDICTION          9.33/1.95/-1.95/0
 13 UNIT FLOW RATE           0.4/0.2/1.2          GSFM
 14 BODY FEED                20/10/70             PPM
 15 TERMINAL HEAD            100/10/150           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
```

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

--------------------------------------------*--------------------------------------*--------

                          BETA INDICES =  50 PERCENT OF PREDICTED VALUES
1.00   130   30    7160   16.2   724   0.26 *  57.7  12.7  45.0  12.5  11.8  20.7 *    1754
1.00   120   30    7160   14.8   727   0.25 *  57.7  12.8  44.9  12.5  10.9  21.5 *    1754
1.00   140   30    7160   17.7   721   0.27 *  57.8  12.7  45.1  12.5  12.7  19.9 *    1757
1.00   110   30    7160   13.4   730   0.23 *  57.9  12.8  45.1  12.6  10.0  22.5 *    1760
1.20   140   30    7160   12.0   611   0.24 *  58.0  11.5  46.5  11.9  12.7  21.8 *    1763
1.00   150   30    7160   19.3   719   0.28 *  58.0  12.7  45.4  12.5  13.6  19.3 *    1764
1.20   130   30    7160   11.0   614   0.23 *  58.1  11.6  46.5  12.0  11.8  22.7 *    1764
1.20   150   30    7160   13.0   608   0.25 *  58.1  11.5  46.6  11.9  13.6  21.1 *    1765
1.20   120   30    7160   10.1   617   0.22 *  58.3  11.6  46.6  12.0  10.9  23.7 *    1771
0.80   110   30    7160   21.6   897   0.27 *  58.3  14.6  43.7  13.7  10.0  20.1 *    1771

                          BETA INDICES =  75 PERCENT OF PREDICTED VALUES
1.00   130   40    6129   14.8   727   0.28 *  62.8  12.8  50.0  12.5  11.8  25.7 *    1910
1.00   140   40    6129   16.2   724   0.30 *  62.8  12.7  50.1  12.5  12.7  24.9 *    1910
1.00   150   30   10740   12.0   735   0.22 *  62.8  12.9  49.9  12.6  13.6  23.7 *    1910
0.80   140   30   10740   17.8   904   0.24 *  62.9  14.7  48.2  13.7  12.7  21.8 *    1911
0.80   130   30   10740   16.3   907   0.23 *  62.9  14.7  48.2  13.8  11.8  22.7 *    1912
0.80   150   30   10740   19.3   901   0.25 *  63.0  14.6  48.3  13.7  13.6  21.1 *    1913
1.00   150   40    6129   17.6   721   0.31 *  63.0  12.7  50.3  12.5  13.6  24.2 *    1914
1.00   140   30   10740   11.1   738   0.22 *  63.0  12.9  50.0  12.6  12.7  24.6 *    1914
1.00   120   40    6129   13.4   730   0.27 *  63.0  12.8  50.1  12.6  10.9  26.7 *    1914
0.80   120   30   10740   14.9   911   0.22 *  63.1  14.7  48.4  13.8  10.9  23.7 *    1919

                          BETA INDICES = 100 PERCENT OF PREDICTED VALUES
1.00   150   40    8172   12.5   733   0.26 *  66.6  12.9  53.7  12.6  13.6  27.5 *    2024
0.80   140   40    8172   18.6   902   0.28 *  66.6  14.6  52.0  13.7  12.7  25.6 *    2025
0.80   130   40    8172   17.0   905   0.27 *  66.7  14.7  52.0  13.7  11.8  26.5 *    2027
0.80   150   40    8172   20.2   899   0.30 *  66.7  14.6  52.1  13.7  13.6  24.8 *    2027
1.00   140   40    8172   11.5   737   0.25 *  66.8  12.9  53.8  12.6  12.7  28.5 *    2029
0.80   150   30   14321   13.9   914   0.22 *  66.8  14.8  52.0  13.8  13.7  24.6 *    2031
0.80   120   40    8172   15.4   909   0.26 *  66.9  14.7  52.2  13.8  10.9  27.5 *    2034
0.80   140   30   14321   12.9   918   0.21 *  67.0  14.8  52.2  13.9  12.8  25.6 *    2038
1.00   130   40    8172   10.6   741   0.24 *  67.1  13.0  54.1  12.7  11.8  29.6 *    2038
0.80   110   40    8172   14.0   914   0.25 *  67.3  14.8  52.6  13.8  10.0  28.7 *    2047

                          BETA INDICES = 125 PERCENT OF PREDICTED VALUES
0.80   150   40   10215   15.5   909   0.26 *  69.6  14.7  54.9  13.8  13.6  27.5 *    2116
0.80   140   40   10215   14.3   913   0.25 *  69.8  14.8  55.0  13.8  12.7  28.5 *    2121
0.80   130   40   10215   13.1   917   0.24 *  70.1  14.8  55.3  13.9  11.8  29.6 *    2130
1.00   150   40   10215    9.7   745   0.23 *  70.3  13.1  57.3  12.7  13.7  30.9 *    2137
0.80   140   50    6611   19.5   900   0.33 *  70.4  14.6  55.7  13.7  12.7  29.4 *    2138
1.00   150   50    6611   12.9   732   0.30 *  70.4  12.9  57.5  12.6  13.6  31.3 *    2138
0.80   150   50    6611   21.3   897   0.35 *  70.4  14.6  55.8  13.7  13.6  28.6 *    2140
0.80   130   50    6611   17.7   904   0.31 *  70.4  14.7  55.8  13.7  11.8  30.3 *    2140
1.00   140   50    6611   11.9   735   0.28 *  70.5  12.9  57.6  12.6  12.7  32.3 *    2143
0.80   120   40   10215   12.0   922   0.23 *  70.6  14.9  55.7  13.9  11.0  30.9 *    2146

                          BETA INDICES = 150 PERCENT OF PREDICTED VALUES
0.80   150   40   12258   12.5   920   0.23 *  72.6  14.9  57.7  13.9  13.7  30.2 *    2207
0.80   150   50    7933   16.9   906   0.30 *  72.8  14.7  58.1  13.7  13.6  30.7 *    2212
0.80   140   50    7933   15.5   909   0.29 *  72.9  14.7  58.2  13.8  12.7  31.7 *    2215
0.80   140   40   12258   11.6   924   0.23 *  73.0  14.9  58.1  13.9  12.8  31.3 *    2218
0.80   130   50    7933   14.2   913   0.28 *  73.2  14.8  58.4  13.8  11.8  32.7 *    2224
1.00   150   50    7933   10.4   741   0.26 *  73.3  13.0  60.3  12.7  13.7  34.0 *    2229
0.80   130   40   12258   10.7   929   0.22 *  73.6  15.0  58.6  14.0  11.9  32.7 *    2236
0.60   150   40   12258   23.2  1197   0.28 *  73.6  18.0  55.6  15.9  13.6  26.2 *    2237
0.80   120   50    7933   12.9   918   0.26 *  73.6  14.8  58.8  13.9  10.9  34.0 *    2238
0.60   140   40   12258   21.3  1201   0.26 *  73.6  18.0  55.6  15.9  12.7  27.0 *    2238

                          BETA INDICES = 175 PERCENT OF PREDICTED VALUES
0.80   150   50    9255   14.0   914   0.28 *  75.2  14.8  60.4  13.8  13.7  32.9 *    2285
0.80   140   50    9255   12.9   918   0.26 *  75.5  14.8  60.6  13.9  12.8  34.0 *    2294
0.80   150   40   14301   10.5   930   0.22 *  75.6  15.0  60.6  14.0  13.7  32.9 *    2298
0.60   150   40   14301   19.3  1206   0.25 *  75.8  18.1  57.8  16.0  13.6  28.2 *    2305
0.80   130   50    9255   11.8   923   0.25 *  76.0  14.9  61.0  13.9  11.9  35.3 *    2308
0.60   140   40   14301   17.8  1210   0.24 *  76.0  18.1  57.9  16.0  12.8  29.2 *    2311
0.80   150   60    6486   18.3   902   0.35 *  76.1  14.6  61.5  13.7  13.6  34.2 *    2313
0.80   140   60    6486   16.7   906   0.33 *  76.2  14.7  61.5  13.7  12.7  35.1 *    2316
0.80   140   40   14301    9.8   935   0.21 *  76.2  15.1  61.1  14.0  12.8  34.3 *    2316
1.00   150   50    9255    8.7   751   0.24 *  76.4  13.1  63.2  12.8  13.7  36.7 *    2321
```

```
POPO -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION


    0     JOB 2.   LIME-SODA ASH PROCESS EFFLUENT
    1 DESIGN FLOW                4.5     MGD
    5 PLANT LIFE                 30      YEARS
    6 SOLIDS  (CS)               8.5     PPM
    8 TEMPERATURE                 65     DEGREES F
    9 PRECOAT WEIGHT             0.1     LB/SF
   11 SEPTUM DIAMETER            FLAT    INCHES
   12 BETA PREDICTION        10.20/1.43/-3.29/0
   13 UNIT FLOW RATE            0.73              GSFM
   14 BODY FEED               10/2/30             PPM
   15 TERMINAL HEAD              25               FT
   16 DIATOMITE COST             69      $/TON
   20 BACKWASH COST             6, 30    GAL/SF, MIN
     BEGIN
```

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

---------------------------------------------*--------------------------------------*--------

                              BETA INDICES =  50 PERCENT OF PREDICTED VALUES
0.73    25    20     886   42.4  4346  0.32 *  31.6  12.6  19.0   9.1   2.2    7.7 *    4322
0.73    25    18    1253   33.4  4363  0.25 *  31.6  12.6  19.0   9.1   2.3    7.6 *    4325
0.73    25    22     647   52.6  4333  0.41 *  31.7  12.6  19.2   9.1   2.2    7.9 *    4342
0.73    25    16    1847   25.6  4389  0.20 *  31.9  12.7  19.2   9.2   2.3    7.8 *    4365
0.73    25    24     486   64.1  4323  0.53 *  32.0  12.5  19.5   9.1   2.2    8.2 *    4377
0.73    25    26     373   76.9  4316  0.66 *  32.3  12.5  19.8   9.1   2.2    8.5 *    4422
0.73    25    14    2865   19.0  4429  0.16 *  32.7  12.8  19.8   9.2   2.3    8.3 *    4467
0.73    25    28     293   91.0  4310  0.82 *  32.7  12.5  20.2   9.0   2.2    8.9 *    4475
0.73    25    30     233  106.5  4306  1.01 *  33.1  12.5  20.7   9.0   2.2    9.4 *    4534
0.73    25    12    4759   13.5  4492  0.13 *  34.2  13.0  21.2   9.3   2.3    9.6 *    4679

                              BETA INDICES =  75 PERCENT OF PREDICTED VALUES
0.73    25    22     971   35.2  4359  0.30 *  32.6  12.6  20.0   9.1   2.2    8.6 *    4463
0.73    25    20    1329   28.4  4378  0.24 *  32.7  12.7  20.0   9.2   2.3    8.6 *    4473
0.73    25    24     729   42.9  4345  0.38 *  32.7  12.6  20.1   9.1   2.2    8.8 *    4476
0.73    25    26     560   51.4  4334  0.47 *  32.9  12.6  20.4   9.1   2.2    9.0 *    4505
0.73    25    18    1880   22.4  4405  0.20 *  33.0  12.8  20.3   9.2   2.3    8.8 *    4518
0.73    25    28     439   60.8  4326  0.57 *  33.2  12.5  20.7   9.1   2.2    9.4 *    4545
0.73    25    30     350   71.2  4319  0.70 *  33.6  12.5  21.1   9.1   2.2    9.8 *    4593
0.73    25    16    2770   17.2  4444  0.16 *  33.8  12.9  20.9   9.3   2.3    9.4 *    4618
0.73    25    14    4298   12.8  4504  0.13 *  35.2  13.0  22.1   9.3   2.3   10.5 *    4811
0.73    25    12    7138    9.2  4600  0.11 *  37.8  13.3  24.5   9.5   2.3   12.7 *    5174

                              BETA INDICES = 100 PERCENT OF PREDICTED VALUES
0.73    25    24     973   32.3  4366  0.30 *  33.5  12.7  20.8   9.1   2.3    9.4 *    4576
0.73    25    22    1295   26.5  4385  0.25 *  33.5  12.7  20.8   9.2   2.3    9.4 *    4585
0.73    25    26     747   38.7  4352  0.37 *  33.5  12.6  20.9   9.1   2.2    9.6 *    4588
0.73    25    28     586   45.7  4341  0.45 *  33.7  12.6  21.2   9.1   2.2    9.8 *    4615
0.73    25    20    1772   21.4  4411  0.20 *  33.8  12.8  21.0   9.2   2.3    9.6 *    4624
0.73    25    30     467   53.5  4332  0.54 *  34.0  12.6  21.5   9.1   2.2   10.1 *    4653
0.73    25    18    2507   17.0  4447  0.17 *  34.4  12.9  21.6   9.3   2.3   10.0 *    4711
0.73    25    16    3694   13.1  4500  0.14 *  35.6  13.0  22.6   9.3   2.3   11.0 *    4872
0.73    25    14    5731    9.8  4579  0.12 *  37.7  13.2  24.5   9.5   2.3   12.7 *    5160
0.73    25    12    9518    7.0  4709  0.10 *  41.5  13.6  27.9   9.7   2.3   15.9 *    5675

                              BETA INDICES = 125 PERCENT OF PREDICTED VALUES
0.73    25    26     934   31.0  4370  0.31 *  34.1  12.7  21.5   9.1   2.3   10.1 *    4671
0.73    25    24    1216   25.9  4388  0.26 *  34.2  12.7  21.5   9.2   2.3   10.0 *    4675
0.73    25    28     732   36.7  4356  0.38 *  34.3  12.6  21.6   9.1   2.2   10.3 *    4685
0.73    25    22    1619   21.3  4412  0.21 *  34.4  12.8  21.6   9.2   2.3   10.2 *    4706
0.73    25    30     583   42.9  4345  0.45 *  34.5  12.6  21.9   9.1   2.2   10.5 *    4713
0.73    25    20    2216   17.3  4444  0.18 *  34.9  12.9  22.0   9.3   2.3   10.5 *    4776
0.73    25    18    3134   13.7  4490  0.15 *  35.9  13.0  22.9   9.3   2.3   11.3 *    4905
0.73    25    16    4617   10.5  4555  0.13 *  37.5  13.2  24.3   9.4   2.3   12.6 *    5128
0.73    25    14    7164    7.9  4656  0.11 *  40.3  13.5  26.8   9.6   2.3   14.9 *    5511
0.73    25    12   11897    5.7  4819  0.10 *  45.2  13.9  31.3   9.9   2.3   19.1 *    6182

                              BETA INDICES = 150 PERCENT OF PREDICTED VALUES
0.73    25    26    1121   26.0  4388  0.27 *  34.8  12.7  22.0   9.2   2.3   10.6 *    4754
0.73    25    28     879   30.7  4371  0.33 *  34.8  12.7  22.1   9.1   2.3   10.7 *    4755
0.73    25    30     700   35.8  4358  0.39 *  34.9  12.6  22.3   9.1   2.2   10.9 *    4773
0.73    25    24    1459   21.7  4410  0.23 *  34.9  12.8  22.1   9.2   2.3   10.7 *    4775
0.73    25    22    1943   17.9  4438  0.19 *  35.3  12.9  22.4   9.2   2.3   10.9 *    4829
0.73    25    20    2659   14.5  4477  0.16 *  36.0  13.0  23.1   9.3   2.3   11.5 *    4928
0.73    25    18    3761   11.5  4532  0.14 *  37.3  13.1  24.2   9.4   2.3   12.5 *    5101
0.73    25    16    5541    8.9  4611  0.12 *  39.4  13.3  26.0   9.5   2.3   14.2 *    5386
0.73    25    14    8597    6.7  4732  0.11 *  42.9  13.7  29.2   9.7   2.3   17.2 *    5865
0.73    25    12   14277    4.8  4930  0.10 *  48.9  14.2  34.7  10.1   2.3   22.3 *    6694

                              BETA INDICES = 175 PERCENT OF PREDICTED VALUES
0.73    25    28    1025   26.4  4386  0.29 *  35.3  12.7  22.6   9.2   2.3   11.2 *    4825
0.73    25    30     817   30.8  4371  0.35 *  35.3  12.7  22.7   9.1   2.3   11.3 *    4833
0.73    25    26    1308   22.3  4406  0.25 *  35.4  12.8  22.6   9.2   2.3   11.2 *    4837
0.73    25    24    1702   18.7  4431  0.21 *  35.6  12.8  22.8   9.2   2.3   11.3 *    4875
0.73    25    22    2267   15.4  4465  0.18 *  36.2  12.9  23.3   9.3   2.3   11.7 *    4951
0.73    25    20    3102   12.5  4511  0.15 *  37.2  13.1  24.1   9.4   2.3   12.5 *    5082
0.73    25    18    4387    9.9  4575  0.13 *  38.7  13.2  25.5   9.5   2.3   13.8 *    5297
0.73    25    16    6464    7.7  4668  0.11 *  41.3  13.5  27.8   9.6   2.3   15.9 *    5646
0.73    25    14   10030    5.8  4810  0.10 *  45.5  13.9  31.6   9.9   2.3   19.4 *    6221
0.73    25    12   16657    4.2  5043  0.09 *  52.7  14.5  38.2  10.3   2.3   25.6 *    7211
```

Manual calculations

Data

Example Number 1 - Iron removal

The filtration and cost data for this example are printed as part of the computer output (p. 416). The data from which the β prediction equation was developed was collected by Hall and Hawley (see Appendix A, Table 24, Runs 32-37) who filtered University tap water to which ferrous sulfate was added. Celite 503 filter aid was used for both precoat and body feed.

Cost calculations are made below for the case where:

$q =$ 1.00 gpm/sq ft

$H_t =$ 150 ft

$C_F =$ 40 mg/l

Calculations

1. β index

The β prediction equation is:

$$\beta = 10^{9.33} (C_S/C_F)^{1.95}$$

Therefore, since $C_S = 7.5$ mg/l and $C_F = 40$ mg/l, then:

$$\beta = 10^{9.33} (7.5/40)^{1.95}$$

$$= 10^{9.33} (0.1875)^{1.95}$$

and taking logarithms of both sides of the equation:

$$\log \beta = 9.33 + 1.95(-0.7270)$$

$= 9.33 - 1.4177$

$= 7.9123$

and:

$\underline{\beta = 8.171 \times 10^{7}\ \text{ft}^{-2}}$

2. Filter run length

$$H_p = q\nu\xi w/g \tag{5}$$

where:

$q = 1.00$ gpm/sq ft

$= 1.00(8.02)$ ft/hr

$= 8.02$ ft/hr

$\nu = \frac{\mu}{\gamma_w}$

where:

$\mu = 1.2028 \times 10^{-2}$ poise from handbook (21)

$= (1.2028 \times 10^{-2})242$ lb/hr ft

$= 2.911$ lb/hr ft

$\gamma_w = 62.39$ lb/cu ft from handbook (21)

therefore:

$\nu = \frac{2.911}{62.39} = 4.666 \times 10^{-2}$ sq ft/hr

$\xi = 1.95 \times 10^{9}$ ft/lb

$w = 0.15$ lb/sq ft

and:

$g = 32.2$ ft/sec^{2}

$$= 417.3 \times 10^{6} \text{ ft/hr}^{2}$$

Therefore:

$$H_p = \frac{(8.02)(4.666 \times 10^{-2})(1.95 \times 10^{9})(0.15)}{417.3 \times 10^{6}}$$

$$= 0.26 \text{ ft}$$

$$H_c = H_t - H_p$$

$$= 150 - 0.26$$

$$= 149.74 \text{ ft}$$

$$t_f = \frac{(e^{H_c\phi/R_s\sigma} - 1)R_o^{2}}{R_s\phi}$$

where:

$$\phi = 2q\gamma_w C_F(10^{-6})/\gamma_p$$

$$= \frac{2(8.02)(62.39)(40)10^{-6}}{15}$$

$$= 2.669 \times 10^{-3} \text{ ft/hr}$$

$$R_s = \frac{(1 \text{ inch})(1 \text{ ft/12 inches})}{2}$$

$$= 4.167 \times 10^{-2} \text{ ft}$$

$$\sigma = q^{2}\nu\beta C_F/g$$

$$= \frac{(8.02)^{2}(4.666 \times 10^{-2})(8.171 \times 10^{7})40}{417.3 \times 10^{6}}$$

$$= 23.506 \text{ ft/hr}$$

$$R_o = R_s + L_p$$

where:

$$L_p = w/\gamma_p$$

$$= \frac{0.15 \text{ lb/sq ft}}{15 \text{ lb/cu ft}}$$

$$= 0.01 \text{ ft}$$

therefore:

$$R_o = 0.04167 + 0.01$$

$$= 5.167 \times 10^{-2} \text{ ft}$$

Now:

$$\frac{H_c\phi}{R_s\sigma} = \frac{(149.74)(2.669 \times 10^{-3})}{(4.167 \times 10^{-2})(23.506)}$$

$$= 0.4080$$

and, therefore:

$$t_f = \frac{(e^{0.4080} - 1)(5.167 \times 10^{-2})^2}{(4.167 \times 10^{-2})(2.669 \times 10^{-3})}$$

$$= 12.1 \text{ hr}$$

The time required to backwash and precoat the filter is estimated to be 30 min or 0.5 hr. Therefore the total length of the filter run is <u>12.6 hr</u>.

3. Filter area

$$\text{QGPM'} = \frac{\text{QMGD'} \times 10^6}{1440 - n \text{ (BWT)}}$$

where:

$$n = \frac{24}{12.6} = 1.91 \text{ filter runs per day}$$

and:

$$BWT = 30 \text{ min per filter run}$$

so that:

$$1440 - n\ (BWT) = 1383 \text{ min}$$

If it is assumed that QMGD' = QMGD, then:

$$QGPM' = \frac{1 \times 10^6}{1383}$$

$$= 723.2 \text{ gpm}$$

and:

$$\text{Area} = \frac{QGPM'}{q}$$

$$= \frac{723.2 \text{ gpm}}{1.00 \text{ gpm/sq ft}}$$

$$= 723.2 \text{ sq ft}$$

$$QMGD' = QMGD + \frac{n\ (\text{Area})\ BWGSF}{10^6}$$

where:

$$BWGSF = 10 \text{ gal/sq ft}$$

therefore:

$$QMGD' = 1 + \frac{1.91\ (723.2)\ 10}{10^6}$$

$$= 1.0138 \text{ MGD}$$

If the preceding steps are repeated, a corrected value of Area is obtained:

$$QGPM' = \frac{1.0138 \times 10^6}{1383}$$

$$= 733.2 \text{ gpm}$$

$$\text{Area} = \frac{733.2 \text{ gpm}}{1.00 \text{ gpm/sq ft}}$$

$$= 733.2 \text{ sq ft}$$

This value of Area is more than one percent greater than the preceding value of Area. Therefore, another iteration is required.

$$QMGD' = 1 + \frac{1.91\ (733.2)\ 10}{10^6}$$

$$= 1.0140 \text{ MGD}$$

$$QGPM' = \frac{1.0140 \times 10^6}{1383}$$

$$= 733.4 \text{ gpm}$$

$$\text{Area} = \frac{733.4 \text{ gpm}}{1.00 \text{ gpm/sq ft}}$$

$$= 733.4 \text{ sq ft}$$

This value is within one percent of the preceding value of Area. Therefore, the required filter area is 733 sq ft and QMGD' is 1.0140 MGD.

4. First cost

From a plot of first cost per unit of filter area versus filter area, the first cost per unit of filter area is found to be \$107/sq ft. Therefore, the total first cost is:

$$TFC = (107\ \$/\text{sq ft})\ (733\ \text{sq ft})$$

$$= \$78{,}468$$

The first cost data were gathered for a filtration rate of 1 gpm/sq ft. Therefore, in this example, the filtration rate factor is equal to 1.0 since the filtration rate is 1.00 gpm/sq ft.

The first cost is amortized over the design life of the plant by the equation:

$$\text{CF per year} = \text{TFC}\ \{\frac{i[(1-i)^n - SV/100]}{(1-i)^n - 1}\} \qquad (44)$$

which is equivalent to:

$$\text{CF per year} = \text{TFC}\ \frac{(caf' - SV/100)}{caf}$$

where:

caf' = single payment compound amount factor (34)

caf = uniform series compound amount factor (34)

From a handbook of interest tables for i = 4% and n = 25 years:

$$caf' = 2.6658$$

and:

$$caf = 41.6459.$$

Therefore:

$$\text{CF per year} = \frac{\$78{,}468\ (2.6658 - 15/100)}{41.6459}$$

$$= \$4740 \text{ per year}$$

and:

$$\text{CF per month} = \frac{\$4740}{12} = \underline{\$395 \text{ per month}}$$

5. Labor and maintenance cost

From a plot of labor and maintenance cost in \$/sq ft per month versus filter area, the labor and maintenance cost was found to be 0.52 \$/sq ft per month. Thus;

$$\begin{aligned} CL + CM &= (0.52)(733)RF \\ &= (381 \text{ \$/month})1.0 \\ &= \underline{\$381 \text{ per month}} \end{aligned}$$

6. Filter aid cost

$$PFA = w(\text{Area})N \tag{45}$$

where:

$$N = \frac{(24 \times 30.4) \text{ hr/month}}{12.6 \text{ hr/run}}$$

$$= 58 \text{ runs/month}$$

therefore:

$$PFA = (0.15)(733)(58) = 6380 \text{ lb/month}$$

$$\begin{aligned} BFA &= C_F(QMGMO')8.33 \qquad (46) \\ &= 40(30.4 \times 1.0140)8.33 \\ &= 10{,}271 \text{ lb/month} \end{aligned}$$

The total cost of filter aid per month is:

$$CFA = \frac{(6380 + 10271)}{2000} (\$100/ton)$$

$$= \underline{\$833 \text{ per month}}$$

7. Power cost

$$P = \frac{QMGMO' \times H_t}{E} \frac{8.33}{2.655} \qquad (48)$$

$$= \frac{(30.4 \times 1.0140)(150)}{0.70} \quad \frac{8.33}{2.655}$$

$$= 20{,}725 \text{ kwh/month}$$

Therefore:

$$CP = 20725 \times 0.02 \text{ \$/kwh}$$

$$= \underline{\$415 \text{ per month}}$$

8. Total and operating costs

$$COPER = CL + CM + CFA + CP \qquad (49)$$

$$= 381 + 833 + 415$$

$$= \underline{\$1629 \text{ per month}}$$

and:

$$CTOTL = CF + COPER \qquad (50)$$

$$= 395 + 1629$$

$$= \underline{\$2024 \text{ per month}}$$

To convert these costs to $/MG of finished water, they should be divided by 30.4 MG/month.

A comparison of results of manual and computer calculations is made below.

Factor	Manual	Computer
β index, 10^4 ft^{-2}	8171	8172
Filter run length, hr	12.6	12.5
Filter area, sq ft	733	733
Total cost, $/MG	66.6	66.6
First cost, $/MG	13.0	12.9
Operating cost, $/MG	53.6	53.7
Labor and maintenance cost, $/MG	12.5	12.6
Power cost, $/MG	13.6	13.6
Filter aid cost, $/MG	27.4	27.5
Total cost, $/month	2024	2024

APPENDIX G

Abbreviations

Abbreviation	Meaning
°C	degrees centigrade
cm	centimeters
cu	cubic
°F	degrees Fahrenheit
ft	feet
gal	gallons
gpm	gallons per minute
hr	hours
in.	inches
JTU	Jackson turbidity units
kwh	kilowatt - hours
ℓ	liters
lb	pounds
log	base 10 logarithm
ln	natural logarithm
mg	milligrams
MG	million gallons
MGD	million gallons per day
min	minutes
ml	milliliters
ppm	parts per million

Abbreviation	Meaning
sec	seconds
sq	square
μ	microns

Notation

Symbol	Meaning	Dimensions
A	Gross cross sectional area of porous media perpendicular to the direction of flow	$[L^2]$
A_p	Particle surface area	$[L^2]$
A_s	Septum area	$[L^2]$
a_c	Specific resistance of filter cake based on volume of filter media	$[L^{-2}]$
a_p	Specific resistance of precoat layer based on volume of filter media	$[L^{-2}]$
BFA	Amount of body feed filter aid, lb/month	
BWGSF	Amount of backwash water required, gal/sq ft of filter area	
BWT	Time required per filter run for backwashing and precoating, hr	
C_D	Drag coefficient = $24/N_R$ for $N_R<10^4$	[--]
C_F	Body feed concentration, ppm by weight	[--]
C_S	Suspended solids concentration, ppm by weight	[--]
CF	First cost, \$/month	

Symbol	Meaning	Dimensions
CFA	Filter aid cost, \$/month	
CL	Labor cost, \$/month	
CM	Maintenance cost, \$/month	
COPER	Operating cost, \$/month	
CP	Power cost, \$/month	
CTOTL	Total cost, \$/month	
D	Pipe diameter	[L]
D_{em}	Effective particle size, μ	[L]
d	Particle diameter	[L]
E	Overall efficiency of energy conversion or pumping efficiency	[--]
g	Gravity constant	$[LT^{-2}]$
H	Head loss or pressure difference in terms of height of a water column	[L]
H_c	Head loss through filter cake	[L]
H_p	Head loss through precoat layer	[L]
H_t	Total head loss, H_c+H_p	[L]
I	Filter aid index (Equation 26)	
i	Annual interest rate (Equation 44) or hydraulic gradient, dH/dL (Equation 51)	
K	Coefficient of permeability	$[LT^{-1}]$
K_1	Modified permeability coefficient independent of viscosity	$[L^2]$
K_3,K_4	Precoat layer and filter cake resistance indices (Equation 4)	$[F^{-1}L^2T]$

Symbol	Meaning	Dimensions
L	Thickness of porous media in the direction of flow, L_p+L_c	$[L]$
L_c	Thickness of filter cake	$[L]$
L_p	Thickness of precoat layer	$[L]$
N	Number of filter runs per month	
N_R	Reynolds number	[--]
n	Number of filter runs per day or design life, yr (Equation 44)	
P	Pressure loss across porous media in the direction of flow	$[FL^{-2}]$
PFA	Amount of precoat filter aid, lb/month	
Q	Flow rate	$[L^3T^{-1}]$
QGPM'	Flow rate in gpm required to meet both demand and backwashing requirements	$[L^3T^{-1}]$
QMGD	Design flow rate, MGD	$[L^3T^{-1}]$
QMGD'	Flow rate in MGD required to meet both demand and backwashing requirements	$[L^3T^{-1}]$
QMGMO'	Flow rate in MG per month required to meet both demand and backwashing requirements	$[L^3T^{-1}]$
q	Flow rate per unit septum area or filtration rate	$[LT^{-1}]$
R	Outer radius of cylindrical filter cake. Also correlation coefficient	$[L]$
R_{em}	Effective hydraulic radius, μ	$[L]$
R_o	Outer radius of precoated septum, R_s+L_p	$[L]$

Symbol	Meaning	Dimensions
R_s	Outer radius of septum	[L]
S	Particle shape factor	[--]
S_i	Weight fraction of solids plus body feed in influent	
S_f	Weight fraction of solids plus body feed in the water in the filter housing	
SV	Salvage value, percent of first cost	
s_E	Standard error of estimate	
T	Turbidity, JTU	
TFC	Total first cost, $	
t	Elapsed time of filtration	[T]
t_a	Apparent detention time	[T]
t_d	Theoretical detention time, V_f/Q	[T]
t_f	Length of filtering cycle	[T]
t_i	Time of inflection point of head loss - time curve for cylindrical filter cakes	[T]
V	Volume of filtrate filtered in time t	$[L^3]$
V_c	Volume of filter cake	$[L^3]$
V_F	Volume of body feed (Equation 26), cu ft/MG of influent	
V_f	Volume of filter housing	$[L^3]$
V_p	Particle volume (Equation 23). Also volume of precoat layer	$[L^3]$
V_s	Volume of septum	$[L^3]$

Symbol	Meaning	Dimensions
V_T	Total volume enclosed within outer surface area of a cylindrical filter cake	$[L^3]$
V_V	Volume of voids in a clean filter cake	$[L^3]$
W	Combined weight of solids and body feed in filter housing	[F]
w	Precoat weight per unit septum area	$[FL^{-2}]$
X	Elapsed time of filtration corrected for initial dilution. Also weight fraction (Equation 23) and observed value of independent variable (Appendix D).	[T]
β	Filter cake resistance index or β index	$[L^{-2}]$
β_0	β index of clean filter aid	$[L^{-2}]$
γ_c	Bulk density of filter cake	$[FL^{-3}]$
γ_p	Bulk density of precoat layer	$[FL^{-3}]$
γ_w	Density of water	$[FL^{-3}]$
δ	Dilution rate, theoretically Q/V_f	$[T^{-1}]$
ε	Porosity	[--]
μ	Dynamic or absolute viscosity	$[FTL^{-2}]$
ν	Kinematic viscosity	$[L^2T^{-1}]$
ξ	Filter aid resistance index or ξ index	$[F^{-1}L]$
σ	Arbitrary group of terms	$[LT^{-1}]$
ϕ	Arbitrary group of terms	$[LT^{-1}]$
ρ_F	Effective specific gravity of filter aid	[--]
ψ	Sphericity (Equation 34)	[--]