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Design of municipal diatomite filters for iron removal

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DESIGN OF MUNICIPAL DIATOMITE FILTERS FOR IRON REMOVAL

by

Robert Lee LaFrenz

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Head of Major Department

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Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1961

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ABBREVIATIONS AND SYMBOLS

1. A--Filter or septum area
2. C--Constant
3. C_D--Concentration of diatomite (body feed rate) mg/l
4. CHP--Constant head permeameter
5. conc.--Concentration
6. C_s--Concentration of suspended solids (iron) mg/l
7. Cu--copper
8. d_s--weight of suspended matter per unit volume as trapped in the filter
9. Eff--Effluent
10. Exp--Experiment
11. Fe--iron, ferrous or ferric state
12. ft--feet
13. gal--gallons
14. gpm/sq ft--gallons per minute per square foot
15. h--head loss
16. H--Hydrogen
17. Inf--Influent
18. K--Coefficient of permeability or permeability of porous media
19. Ki--a given constant
20. L--Thickness of porous media
21. lb--pound
22. lb/cu ft--pounds per cubic foot

ABBREVIATIONS AND SYMBOLS (Continued)

23. mg/1--milligrams per liter, often referred to as ppm (parts per million)

24. min--minutes

25. ml--milliliters

26. no.--Number

27. O--Oxygen

28. P--The ratio of void space to the volume occupied by the filter cake

29. PP--Pilot plant

30. Q--Rate of filtration, volume per area per time

31. S_{CHP}--Slope of straight line from a CHP run (ln rate/gal)

32. S_{VHP}--Slope of straight line from a VHP run (Δ head loss/gal)

33. T--time

34. THL--Terminal head loss

35. u--micron = 1/1000 millimeter

36. V--volume

37. VHP--Variable head permeameter

I. INTRODUCTION

A. Background

"Necessity is the mother of invention" is an adage often quoted, but in the case of diatomite filtration of potable water is is quite appropriate. As American troops were moved into the Pacific Theater during World War II, a pressing need arose for a filter which would remove Entamoeba histolytica cysts from water. The filter also had to be lightweight, portable, and have a high filtration capacity. Research conducted at the U. S. Army Engineer Research and Development Laboratories (ERDL) at Fort Belvoir, Virginia, on various types of filters led to the development and use of portable diatomite filters. These filters functioned satisfactorily during the remainder of World War II in the Pacific and are now used as standard equipment for all portable installations by the Army.

Although diatomite had been widely used as a filter media in industry prior to 1943, it had not been used for filtration of potable waters. After World War II, due to the success enjoyed by the Army, many commercial filter companies began producing diatomite filters for swimming pool and municipal use. Little basic research was attempted and the filters were patterned quite closely after the original Army filters. This led to disastrous results, as the Army filter had been developed for a specific purpose with little regard for economy. In an attempt to decrease the cost per gallon for filtration with diatomite, body feeds were often reduced below a practical limit and even eliminated. This resulted in cracks in the filter cake and resultant periods of poor filtration. The reduction in body feed also caused high head losses to develop rapidly, necessitating frequent stoppages for backwashing. These stoppages in turn reduced the economy even further since the added precoat and labor required were an appreciable percentage of the operating cost for short runs. Diatomite filter operations were further aggravated by the lack of qualified operators in most plants. All of these difficulties combined gave diatomite filtration a severe setback. This is emphasized in Baumann's survey made in 1957 (4). It revealed that at that time 20 states would not approve diatomite filters as a satisfactory filter for potable water supplies. The remaining states either had no fixed policy or approved only with certain reservations. This is basically the situation which exists today. Diatomite filters are widely used on swimming pools and their use for municipal installations is increasing, however, considerable work must still be done to establish reliable design, operating, and maintenance procedures before they reach their full potential.

B. Purpose of This Thesis

Nearly all of the failures and problems which developed in municipal diatomite filters can be traced to a lack of understanding of the basic factors affecting filtration with diatomite. If sound basic research had proceeded filter production by commercial firms, the science of diatomite filtration would be considerably more advanced today. The purpose of this thesis is to provide a better understanding of the basic factors affecting diatomite filtration. By the proper application of the basic principles, a more dependable filtration system can be developed. No one investigator can hope to cover thoroughly all of the different types of water which may be encountered and to study all of the factors involved. With this in mind, one type of iron-bearing water was used in this study. It was felt that this would be one of the most useful waters which could be used. Iron-bearing waters are encountered not only in many well supplies, but also when a surface supply is coagulated with an iron base coagulant.

It was felt that the design and understanding of a system which could be applied to a water supply, already bacteriologically safe such as an iron-bearing well supply, would be of the greatest immediate value. It is for this type of water supply that a Public Health Department would most readily approve a diatomite filtration system. It is important that satisfactorily operating plants be built so that operating experience can be obtained.

The specific objectives of this thesis are:

1. To study two of the basic factors affecting diatomite filtration: rate of filtration and rate of body feed.

2. To determine the optimum rate of filtration and rate of body feed for iron-bearing waters and to show how these optimums vary.

3. To indicate how filtration rate, body feed rate, and other pertinent factors must be taken into account in the design of a municipal diatomite plant.

4. To demonstrate a simplified method of making tests on a given water to determine its filtering characteristics or filtrability.

5. To develop from the factors affecting diatomite filtration a theory of filtration supported by experimental evidence which may be used to design municipal diatomite filters for the filtration of potable iron-bearing water.

C. Definition of Terms

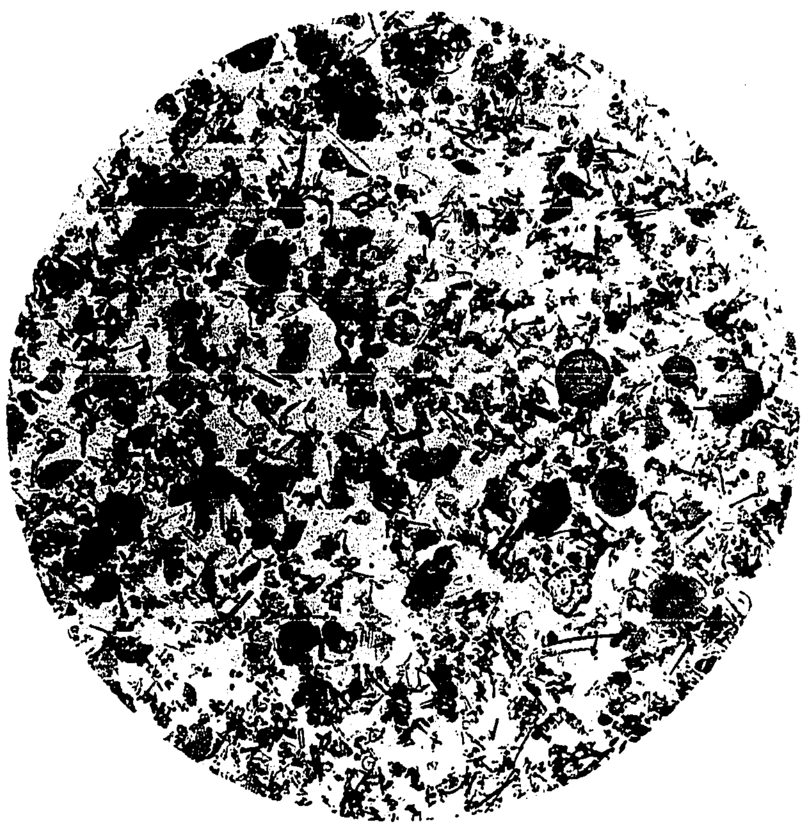
Diatomite filtration is a relatively new field and one which employs several principles which vary from those applied in conventional water filtration. Some of the terms normally used may be defined as follows:

1. Diatomite

Diatomite is the term applied to filter media. It is also often referred to as diatomaceous earth, diatomaceous silica, moler or kieselguhr. When diatoms, which are microscopic, flowerless water plants related to algae, die and decay, a siliceous shell remains (Figure 1). Beds of countless numbers of these relatively pure microscopic siliceous skeletons are found in the western United States and Canada in large diatomite deposits. Quarrying of the crude product is followed by drying, grinding, screening, and calcining. Some examples of diatoms found in Celite 535 are shown in Figure 1.

A cubic inch of diatomite consists of skeletons of 40 to 70 million diatoms. Approximately 10,000 distinct species of diatoms have been reported with sizes ranging from 5 to 1000 microns (2). Diatomite weighs approximately 7 lb/cu ft dry and loose, approximately 16 lb/cu ft when packed by wetting and up to 20 lb/cu ft in a filter cake. It has a specific gravity of approximately 2.35 and a filter cake porosity of 88 to 90 per cent (5). The diatomite used in this research was Celite 535 produced by Johns-Manville Corporation. This is a rather coarse grade, but one which provides satisfactory removal of iron, (15). Diatomite can be obtained in several grades of varying particle size. The grade chosen

Figure 1. Photomicrograph of C-535 diatomite filter aid



for a particular application will depend upon the character of the suspended solids in the water to be filtered.

2. Precoat

Precoat is the layer of diatomite which is placed on the septum prior to the filtration of water. A normal precoat will require from 0.1 to 0.2 lb of diatomite per sq ft of filter septum and will produce a precoat cake about 1/8 in. thick.

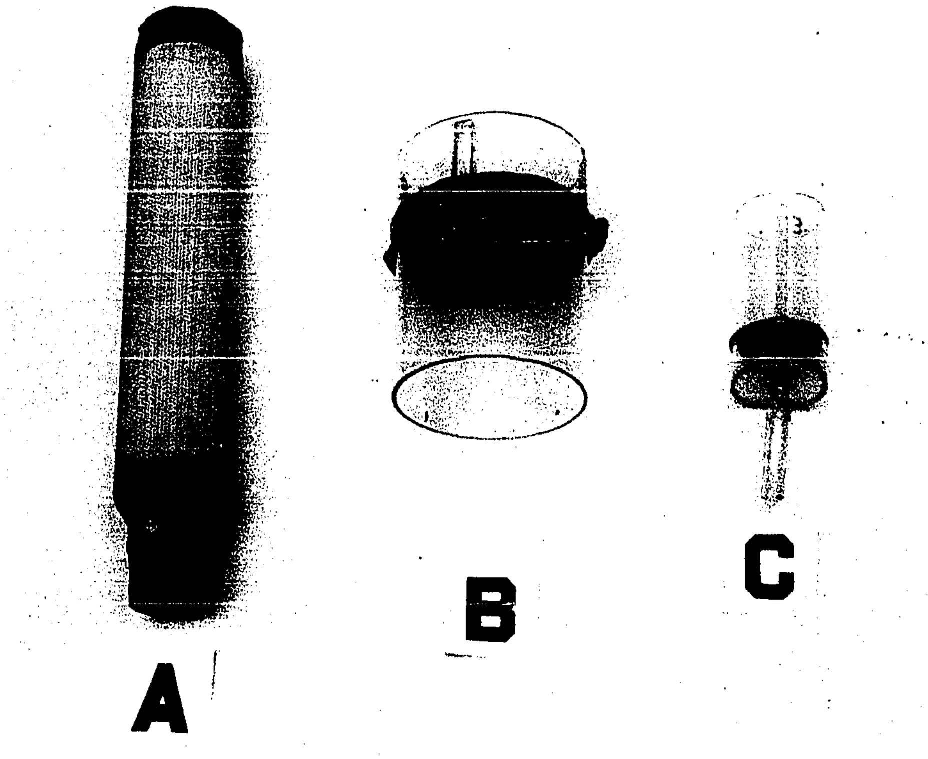
3. Body feed

Body feed is the diatomite which is added to the raw water continuously during the filtration cycle. During filtration, the body feed is filtered out with the impurities in the water and forms a porous cake on the raw water side of the precoat. Body feeds will normally be used at rates of 10 to 100 mg/l.

4. Septums

Septums in diatomite filtration serve as a supporting medium for the diatomite precoat. The septums used in the three filters in this study are shown in Figure 2. Septum A is a typical cylindrical-type septum with synthetic cloth sock cover and is used in the pilot plant filter. Septum B consists only of a disc of stainless steel wire mesh, effective diameter of 5.7 inches, and is used in the variable head

Figure 2. Diatomite filter septums, A-PP, B-VHP, C-CHP



permeameter. Septum C is made of the same type wire mesh, effective diameter of 2.7 inches, and is used in the constant head permeameter.

5. Pilot plant

The pilot plant used in this study is shown in Figures 3, 4, and 5. It is in reality a small diatomite filtration plant built to obtain actual plant operating data. The plant has a filter septum surface area of approximately 6 sq ft and can be operated to a 100 ft head loss.

6. Variable head permeameter

The variable head permeameter might be described as a miniature or model pressure filter. It is used in this study for constant rate, variable head tests and for permeability determinations. It is shown physically in Figure 6 and schematically in Figure 7. The variable head permeameter will be abbreviated to VHP throughout this study.

7. Constant head permeameter

The constant head permeameter might also be described as a constant head, variable rate filter, but since it was developed for permeability studies, the term permeameter has been retained (14). It is shown physically in Figure 8 and schematically in Figure 9. It will be also referred to as

CHP throughout this study.

8. Iron

The term iron, as used througnout tnis study, refers to tne ferric or ferrous ions in solution or in suspension in water regardless of their combined state.

II. REVIEW OF PREVIOUS WORK

A. Diatomite Filtration

The process of filtration has been known and used for thousands of years. Until the 19th century, however, no appreciable effort was made to understand the process of filtration. The process was not applied to municipal water supplies until approximately 1850. Since this time, and specifically in the past 40 years, tremendous advances have been made in the art of filtration; however, there are still many factors affecting the process of filtration which are unknown or incompletely understood. Basically, filtration is the process of separating suspended solids from a fluid-solid mixture. In diatomite filtration the suspended solids consist of two classes of material, the foreign particles in the water which we desire to remove and the body feed, added continuously to the raw water prior to filtration. The diatomite added as body feed performs two functions. It maintains the cake in a non-compressible form and provides a porous medium for the flow of the water through the filter. The suspended solids in the water are deposited on a thin precoat layer of diatomite. This is in turn supported by a septum. A number of different phenomena combine to produce the process of filtration. The most important of these phenomena are mechanical straining, sedimentation, biological metabolism and electrolytic action. Of these factors, mechanical straining and electrolytic action are probably the only two of importance in diatomite filtration.

Principal credit must be given to the Engineer Research and Development Laboratories of the U. S. Army (ERDL) for the practical application of diatomite filters to the production of potable water in the United States. The results of developmental studies conducted at Fort Belvoir were reported by Black and Spaulding in 1944 (8). One of the first really comprehensive studies of diatomite filtration as applied to water supplies was made by Baumann in 1954 (5). This report was a compilation of six years of investigations conducted at the University of Illinois in cooperation with the Water Supply Branch of ERDL. The research conducted by Baumann was centered on the following topics: an evaluation of the factors affecting the precoat, backwash and hydraulic characteristics of the filter septum; a study of the factors affecting the permeability of filter aids; a study of the theoretical and practical effects of body feed; and the operation of water pretreatment units. Each of these topics was presented in an individual report by Babbitt and Baumann to ERDL, but these were not published. Two reports, concerning the effects of body feed on the filtration of water through diatomite and the removal of Entamoeba histolytica cysts from water, have been published as University of Illinois Engineering Experiment Station Bulletins (2, 3). A practical method of designing diatomite filters for municipal water supplies was proposed in 1953 (6). This work has provided a valuable understanding of some of the basic factors affecting diatomite filtration and has done much to advance the art of diatomite filtration.

Numerous reports have been published concerning the operations and experiences encountered with municipal diatomite filters. One of the first actual applications of diatomite filtration to a municipal water supply in the United States was at Gasport, New York. Frazer reported on this in 1949, and in 1953 he presented a paper discussing four diatomite filtration plants in New York State (10).

Perhaps the most extensive early investigation of the applicability of diatomite filtration to municipal water supplies was made by Sanchis and Merrell at Los Angeles, in 1951 (16). Their work was done using impounded water in which green and blue-green algae were a problem. They concluded that the diatomite process is capable of producing filter effluents comparable in quality to those obtained with conventional procedures, and that for average water quality conditions, the total cost per unit volume of water treated will be very nearly equal for diatomite and conventional filtration. In addition, they concluded that if space is limited and pumping is necessary to regain head losses, diatomite had decided advantages over conventional sand filtration.

George R. Bell presented a relatively comprehensive comparison of diatomite and sand filtration based on actual plant data from the Johns-Manville Research Center at Manville, New Jersey (7). He concluded, from data acquired over a one year operating period on each type of plant, that the cost of diatomite filtration of raw water is approximately equal to the cost of sand filtration plus pretreatment. If the water was pretreated prior to the diatomite filtration process, the costs were found to be somewhat higher.

Other investigators have reported on diatomite filter installations, but their reports are similar to those previously mentioned. An installation of interest was reported by Kendall in 1960, which may be a future trend in diatomite filtration (13). It was a completely automatic 5 mgd diatomite filtration plant installed at Saratoga, California.

Although municipal diatomite filters are increasing in popularity, little basic research, other than by several of the investigators previously mentioned, has been conducted.

A comparison of pressure and vacuum filters was made by Miley and Wiggers at Iowa State University (15, 17). Diatomite filtration has found a large field of application in the area of swimming pool clarification, but there is a considerable difference between the filtration of swimming pool water and an iron-bearing or surface water.

B. Theory of Filtration

Many investigators have attempted to develop a theory of filtration over the past 50 years. One of the earliest carefully evaluated discussions on the theory of filtration was published by Hatscheck in 1908 (11). He introduced the ideas of flow resistance and the effects of porosity, particle size, and particle shape on cake structure. He recognized the existence of throttling-layer resistance which results when the initial layer of particles comes into contact with the septum. This is one of the reasons for using a layer of porous diatomite as a precoat and for the addition of body feed to the raw water. The diatomite itself develops a certain resistance at the septum interface, but since diatomite is highly permeable, this resistance is negligible compared to that which would be developed by raw water turbidity. Other investigators, such as Sperry, Alloit, Carmen, Hinchley, Underwood, Waterman, Ruth, and Kozeny have developed theoretical expressions which they have related to experimental results for cake filtration (14). The majority of these hold only in specific instances and are often complicated and include constants difficult or impossible to evaluate. Since most of these theoretical relationships were developed from industrial applications of the filtration process, they have been found to be of little value for the filtration of potable water.

Most research which has been conducted on water filtration has been done using sand as a filter media. Consequently, any theories which have been advanced have been based on and compared with results obtained from sand filters. Hudson attempted in 1948 to develop a relationship between the quality of the water applied to a rapid sand filter and its design and function (12). In his development, he assumed penetration of turbidity to some depth in the filter. In practice, this depth is difficult to determine and the amount of turbidity deposited from top to bottom of this depth will not be uniform. Another term which is used, weight of suspended matter per unit volume as trapped in the filter, is difficult to evaluate and these two factors have limited the application of his theory. Previous work was well summarized and an excellent study of rapid sand filtration was made by Cleasby at Iowa State University in 1960 (9).

III. THEORY OF DIATOMITE FILTRATION

Diatomite usage for filtration of potable water supplies is increasing. It would, therefore, be extremely advantageous if a relationship could be found relating the filtering characteristics of the suspended solids, body feed, and filtration rate with the head loss which could be expected after filtering a given amount of water. No efforts to develop a theory of diatomite filtration for potable water supplies have been reported previously.

If we first accept Darcy's law, which states that for laminar flow the velocity through a porous medium is proportional to some constant times the hydraulic gradient, we can write:

$$h = K\,Q\,L \qquad (1)$$

where:

h = head loss (ft)
K = constant, reciprocal of the coefficient of permeability (min. sq ft/gal)
Q = filtration rate (gal/min. sq ft)
L = filter cake thickness (ft)

The head loss developed across a typical diatomite filter can be considered to consist of two parts; the head loss through the precoat, which will be essentially constant, and the head loss through the filter cake which will vary, increasing with time for a constant flow rate, water quality, and body feed.

Throughout this discussion the subscript "1" will refer to the precoat terms and the subscript "2" will refer to the body feed terms. At the beginning of a filter cycle after the precoat is in place, the head loss will be given by:

$$h = K_1 Q_1 L_1 \qquad 2$$

where:

L_1 = thickness of precoat

$$L_1 = \frac{w}{d_D} \qquad 3$$

where:

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

d_D = wet (packed by filtration) density of diatomite (lb/cu ft)

The volume of a filter cake composed of body feed and suspended solids which will be available for retention of the suspended solids per unit area will be:

$$V_v = L_2 P \qquad 4$$

where:

L_2 = thickness of body feed cake

$$L_2 = \frac{Q\ T\ C_D}{d_D} \qquad 5$$

where:

C_D = concentration of body feed (mg/l)

P = the ratio of void space to the volume occupied by the filter cake

T = time (min)

V_v = volume of voids in the filter cake

An assumption is made that the suspended solids do not increase the thickness of the cake appreciably. This will be approximately correct, at least for body feed to suspended solids ratios of 5 to 1 or greater. The head loss equation as finally developed will depend upon the weight of body feed rather than the cake thickness so this assumption will not be a significant factor. The volume of the suspended solids included in a given cake per sq ft will be:

$$V_s = \frac{Q_1 \; T \; C_s}{d_s} \qquad 6$$

where:

V_s = volume of suspended solids in the filter cake (per sq ft)

C_s = concentration of suspended solids in the water (Mg/1)

d_s = weight of the suspended solids per unit volume as trapped in the filter (lb/cu ft)

It is assumed that all of the suspended solids will be retained in the filter cake. The portion of the voids which will be filled by suspended solids can be obtained by dividing equation 6 by equation 4.

$$\frac{V_s}{V_v} = \frac{Q_1 \; T \; C_s}{d_s \; P \; L_2} \qquad 7$$

$$\frac{V_s}{V_v} = \frac{d_D \;\; C_s}{ds \; P \; C_D} \qquad 8$$

The void volume which is available for flow will be reduced by this ratio. For an infinitesimal depth, the area available for flow is proportional to the void volume. If the area originally available for flow passage is assumed to be unity, the reduced flow area will be given by

$$A = 1 - \frac{d_D \;\; C_s}{d_s \; C_D \; P} \qquad 9$$

where:

A = relative area available for flow passage

This area will remain constant throughout a filter run as long as the concentrations of body feed and suspended solids remain constant. To maintain the original rate of filtration, Q_1, the velocity through the remaining area will have to be increased with consequent increase in head loss. The increased velocity will be inversely proportional to the reduced flow area as shown in equation 10. The permeability of the body feed layer and the flow rate through the remaining voids of the body feed layer are both affected by the reduction in void volume caused by the suspended matter. This is shown in equation 10:

$$K_2 \; Q_2 = \frac{K_1 \; Q_1}{1 - \frac{d_D \; C_s}{d_s \; P \; C_D}} \qquad 10$$

where:

K_2 = reciprocal of the coefficient of permeability of the filter cake

The solution of equation 10 can only be determined experimentally. K_1, Q_1, C_s and C_D can be determined for a given filter run. The term $\frac{d_D}{d_s \; P}$ can be determined from experimental observations of head loss during the filter run. While the actual change in K_1 and Q_1 during a filter run can not be evaluated, the net affect is included in the experimental evaluation of the term $d_D/ds \; P$.

The head loss through the filter cake will be the sum of the head loss in the precoat layer and the body layer:

$$h_T = K_1Q_1L_1 + K_2Q_2L_2$$

$$h_T = \frac{K_1Q_1w}{d_D} + \frac{\dfrac{K_1Q_1^2\ T\ C_D \cdot 8.345 \cdot 10^{-6}}{d_D}}{1 - \dfrac{C_s}{C_D}\dfrac{d_D}{d_s\ P}} \qquad 11$$

In the above equation, all the terms are known except K_1/d_D and d_D/d_sP. The term K_1/d_D will be a constant for a given filter and grade of diatomite and can be determined by filtering clean water at different rates through a diatomite cake of known weight. The term (d_D/d_sP) takes into account the density of the iron floc, the density of the wet diatomite and the porosity of the filter cake. It should be a constant for a given suspended solids <u>versus</u> body feed ratio. In its final form the equation would be:

$$h_t = K_3Q_1W + \frac{K_3Q_1^2T\ C_D \cdot 8.345 \cdot 10^{-6}}{1 - \dfrac{C_s}{C_D\ K_4}} \qquad 12$$

where:

$$K_3 = \frac{K_1}{d_D}$$

$$K_4 = \frac{d_s\ P}{d_D}$$

Equation 12 as developed is for a homogeneous distribution of turbidity throughout the filter cake, which is the case for diatomite filtration. The equation does not have a depth of penetration term which defies determination, as is the case for a sand filter. It assumes a straight line relation between head loss and gallons of filtrate which passes through the origin. This study will concern itself with equation 12 in an attempt to determine if this equation applies to actual diatomite filtration practice and to determine the constants.

IV. LABORATORY APPARATUS AND PROCEDURES

A. Water

Several studies have been made at Iowa State in an attempt to duplicate a given natural water for filtration purposes in a laboratory (14, 17). These studies were based on adding ferric iron to a water. As a result of tests conducted on Ames city water, it was decided to add iron in the form of ferrous sulfate to the University tap water (9). Iowa State University water is treated by aeration and rapid sand filtration. This treatment removes approximately 7-8 mg/l of iron. By adding ferrous iron to the tap water and then aerating, it was hoped that the basic University water could be reproduced since the chemicals originally in the well water would still be present. Ferrous sulfate was mixed with distilled water to form a concentrated solution of about 25,000 mg/l ferrous iron. The concentrated solution was fed through a capillary tube into a mix tank along with 6.7 gpm of tap water. The tap water and ferrous sulfate were mixed by compressed air in the mix tank, which had a theoretical detention time of 10 minutes. The air also served as the means of aeration for the oxidation of the ferrous form of iron to the ferric state. The water was either filtered or allowed to flow to waste after leaving the chemical mix tank.

Tests for iron content and pH indicated that the synthetic water was of the same character as the original water in these respects. Microscopic examinations of the synthetic water revealed average iron floc particles of approximately 4 to 5 microns; there were variations from 1 to 10 microns and a few were as large as 20 microns. The flocs were approximately the same size as the floc in the original water. Several trial filter runs were conducted which revealed that the synthetic water developed head losses which compared favorably with similar tests made on the raw University well water. The water obtained from mixing ferrous sulfate with the University tap water was adopted therefore, as the test water to be used throughout this study. It carried an average pH of 7.30 and a positive Zeta potential which averaged about 14. A sample of raw university water had a Zeta potential of +16.8, which compares favorably with the values obtained from the water containing ferrous sulfate. A Zeta potential of +11.1 was measured with the 8 mg/l iron water when 1 mg/l of copper was added while a value of +9.9 was found with the 4 mg/l iron water with $\frac{1}{2}$ mg/l of copper. Potential units are in millivolts.

A thermostatic control valve was placed on the tap water line to preclude any variation of results due to temperature changes. This valve automatically mixed hot and cold water to maintain a 60°F temperature for all of the tests conducted. Tests were conducted on the heated water to ascertain if any changes took place in hardness or alkalinity during the heating process. No changes were observed.

B. Control Methods

Since it was estimated that nearly 2000 iron concentration determinations would have to be made in the course of the research, a simplified method was needed. The Spectronic-20, a Bausch and Lomb photoelectric instrument designed for colorimetric tests, was used. Two iron tests were evaluated, the 1, 10-phenanthroline colorimetric method and the 2,2-bipyridine method, both described in Standard Methods (18). Both colorimetric tests have been simplified by the Hach Chemical Company, Ames, Iowa, by the use of patented powder reagents, Ferrover and Biver. These reagents combine the reduction, heating, and chemical addition steps in the basic test. The bipyridine test was believed to be more accurate than the phenanthroline method, at least in low iron concentrations. The bipyridine test was used throughout the study.

The principle of the colorimetric test is to measure the percentage of light of a specified wave length transmitted through a sample. The wave length used in this iron test was 512.5 millimicrons. The setting of the specified wave length selects the color of light used in the test. The instrument was standardized using Biver powder and distilled water.

When a test is to be conducted, a given quantity of the Biver powder is added to 25 milliliters of sample water. If iron is present, a pink or red solution of variable color intensity is produced. The solution is then placed in a clean test tube and inserted into the Spectronic-20. A reading of percentage of transmittance is obtained on the scale and with the aid of a calibration chart, this reading is converted into total iron content in mg/1. All samples were diluted as needed with distilled water until a reading of 1.5 mg/1 or less was obtained from the Spectronic-20. Tests were made for total iron at intervals of 10 to 20 minutes on both the influent and the effluent of the filter being used. Another reagent, bipyridine solution B, was used for soluble iron determinations using the same procedure outlined above.

A Beckman pH meter which had been standardized against a pH 7.0 buffer solution was used to determine the pH of all samples. These tests were conducted when desired on the influent and effluent water of the filter.

Zeta potential measurements were made using a cataphoresis cell of the Arthur Thomas Company. No specific use was made of the zeta potential measurements. They were made and included in the hope that at some later date, when more is known about the effects of electrokinetics, the data might be useful in fully explaining the results obtained.

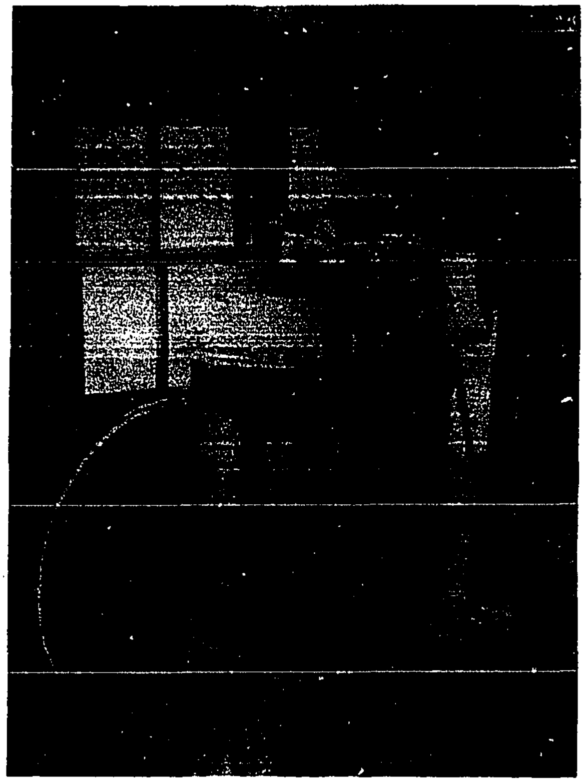
During the study, it was noted that in water of 7-8 mg/1 of total iron, approximately 0.7 mg/1 of this would be soluble iron. At low rates of filtration, the majority of this would be removed during the filtration process, but at higher rates, as much as 0.3 to 0.5 mg/1 of the soluble iron would pass through the filter. It had been reported previously that the addition of a small amount of copper would result in the complete precipitation of soluble iron (9). Copper in the form of copper sulfate was used in several series of this study. Copper determinations were also made with the aid of the Spectronic-20. The cuprethal test from Standard Methods was used, employing cupretnal solution A and solution B, reagents of Hach Chemical Company (1).

C. Pilot Plant

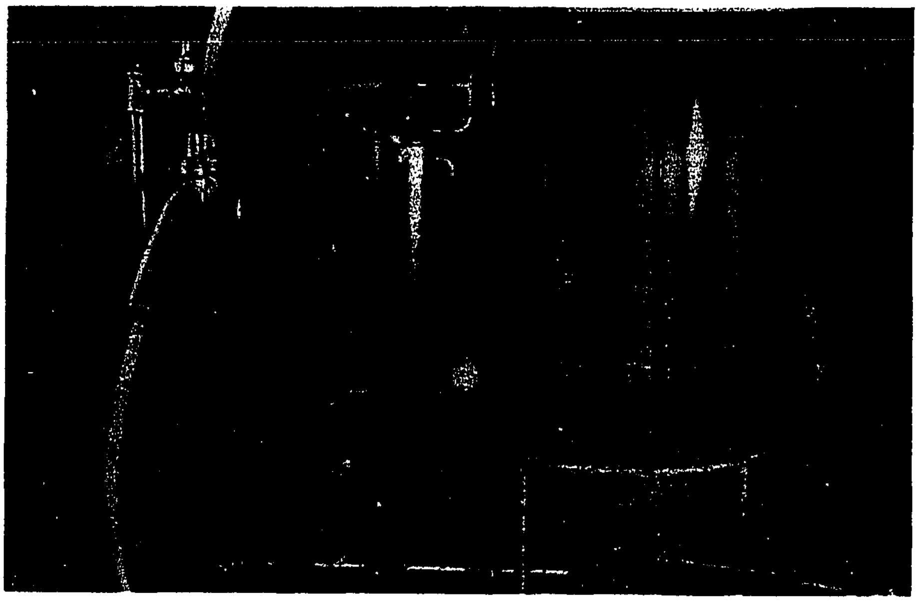
The preliminary series of tests in this study were conducted with the pilot plant, PP, shown in photographs in Figures 3 and 4, and schematically in Figure 5. The objective of the preliminary tests was principally to determine the relation between the head loss vs. time curves for various body feeds, when filtering to a head loss of 50 feet or greater. Originally it was planned to utilize this filter for tests at different filtration rates. The capacity of the makeup water system was not sufficient however, to supply water to the filter at rates greater than 1 gpm/sq ft. When some of the

Figure 3. Pressure filter, PP

Figure 4. Pressure filter showing service pump, precoat pot, flow regulator, rotameter, and precoated septums

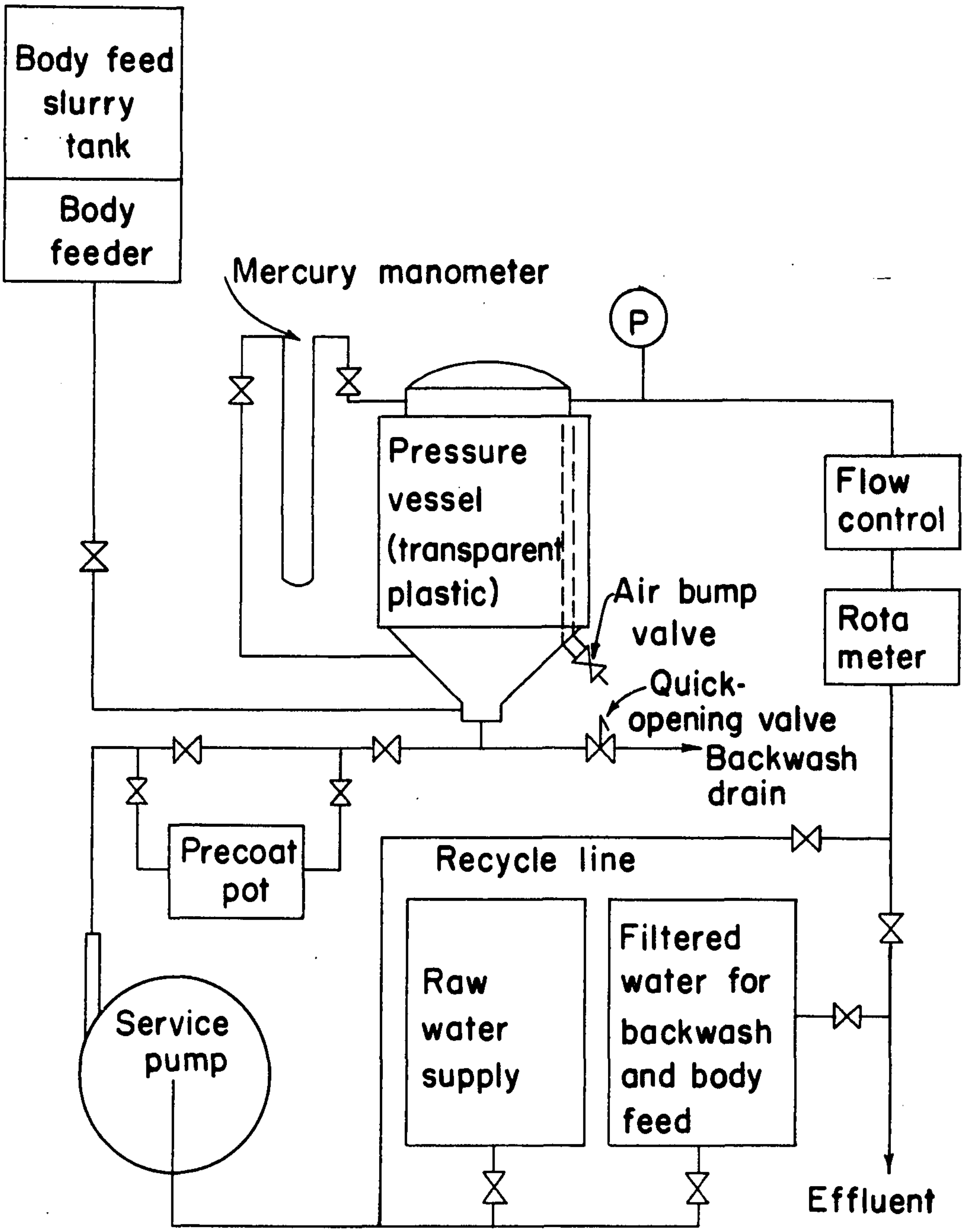


Pressure filter.



Pressure filter showing service pump, precoat pot, flow regulator, rotameter, and precoated septums.

Figure 5. Schematic drawing of pilot plant, PP


Body feed slurry tank
Body feeder
Mercury manometer
P
Pressure vessel (transparent plastic)
Flow control
Rota meter
Air bump valve
Quick-opening valve
Backwash drain
Precoat pot
Recycle line
Service pump
Raw water supply
Filtered water for backwash and body feed
Effluent

septums were removed to reduce the filter area, the ratio of volume of septum housing to septum area was such that a poor distribution of precoat and body feed was obtained.

The pilot plant construction and operation has been described in detail by Miley and will be only briefly summarized here (15). The filter septums are 3 1/2 inches in diameter, cylindrically shaped, and consist of a sock of synthetic fabric stretched over a fluted plastic frame. One of these septums is shown in Figure 6. Difficulties had been encountered previously with these septums due to cracking of the cake between the ridges of the fluted plastic sock support. Cracks also developed on the ends. The filter cake cracking problem was solved by wrapping the plastic fluted septum with a thin perforated plastic sheet. The sock fit tightly over this with no wrinkles and the ends of the sock were dipped in a rubberized paint to make them impervious. With these innovations no cake cracking and subsequent passage of iron was noted, even at high head losses. The septums are contained in a plastic housing which enables the operator to view the cake development.

The remainder of the plant consists of the normal pieces of equipment necessary to operate a pressure diatomite filtration plant. A mercury manometer and two pressure gages indicate head loss across the filter cake. A precoat pot or tank is included in the influent line which may be bypassed after the precoating operation is complete. A high pressure centrifugal pump takes water from the mixing tank and provides the pressure head to the filter. Rates of filtration are measured by a rotameter and are maintained constant by a flow regulator in the effluent line. The body feeder used with the pilot plant in this study was a Wallace and Tiernan positive feed, A-710 diatomite slurry feeder.

Prior to starting a filter cycle, a slurry of the appropriate concentration of diatomite, based upon the feed rate, filtration rate and desired body feed, was mixed in the body feed slurry tank. An appropriate amount of diatomite was also placed in the precoat pot to give the desired precoat in lb/sq ft of filter area. The cycle was then started by pumping previously filtered water through the precoat pot and into the septum housing. This clean water was recycled until all of the precoat had been deposited on the septums. When the precoat was in place, the body feed unit was turned on; the influent line from the raw water was opened; the recycle circuit was closed; and the effluent valve was opened. The proper rate of filtration was set on the rate of flow controller; the precoat pot bypass line was opened, and the filtration process proceeded. Data were recorded with respect to head loss development as a function of time and influent and effluent iron determinations were made. At the completion of a run, the filter was backwashed by air bumping and washing the cake to waste.

D. Variable Head Permeameter

The variable head permeameter, VHP, was developed principally to determine the relationship between head loss and filtration rate when filtering a specific water with varying amounts of body feed. It is shown in the photograph in Figure 6 and schematically in Figure 7. It is, in effect, a small pressure filter. It was patterned after the constant head permeameter used previously (14). To obtain sufficient flow through the septum to be measurable at 1 gpm/sq ft, a 6 inch diameter plastic tube was used. The septum is shown in Figure 2.

The apparatus contains the same basic components as the pilot plant. These components are shown by numerals in Figure 6. The filter itself consists of a 5.7 inch inside diameter plastic tube (A). The bottom portion is detachable and contains a horizontal wire mesh screen with a cross sectional area of 0.177 sq ft. The filter discharges through a float valve, as shown in Figure 6, into a tank which in turn maintains a constant head on the rotameter (E) used to gage the filtration rate. This type of arrangement is necessary to overcome fluctuations in flow due to the action of the pulsating body feeder. The body feeder (D) is a Proportioneers heavy duty Chem-O-Feeder and feeds from an air and mechani-

Figure 6. Variable head permeameter, VHP

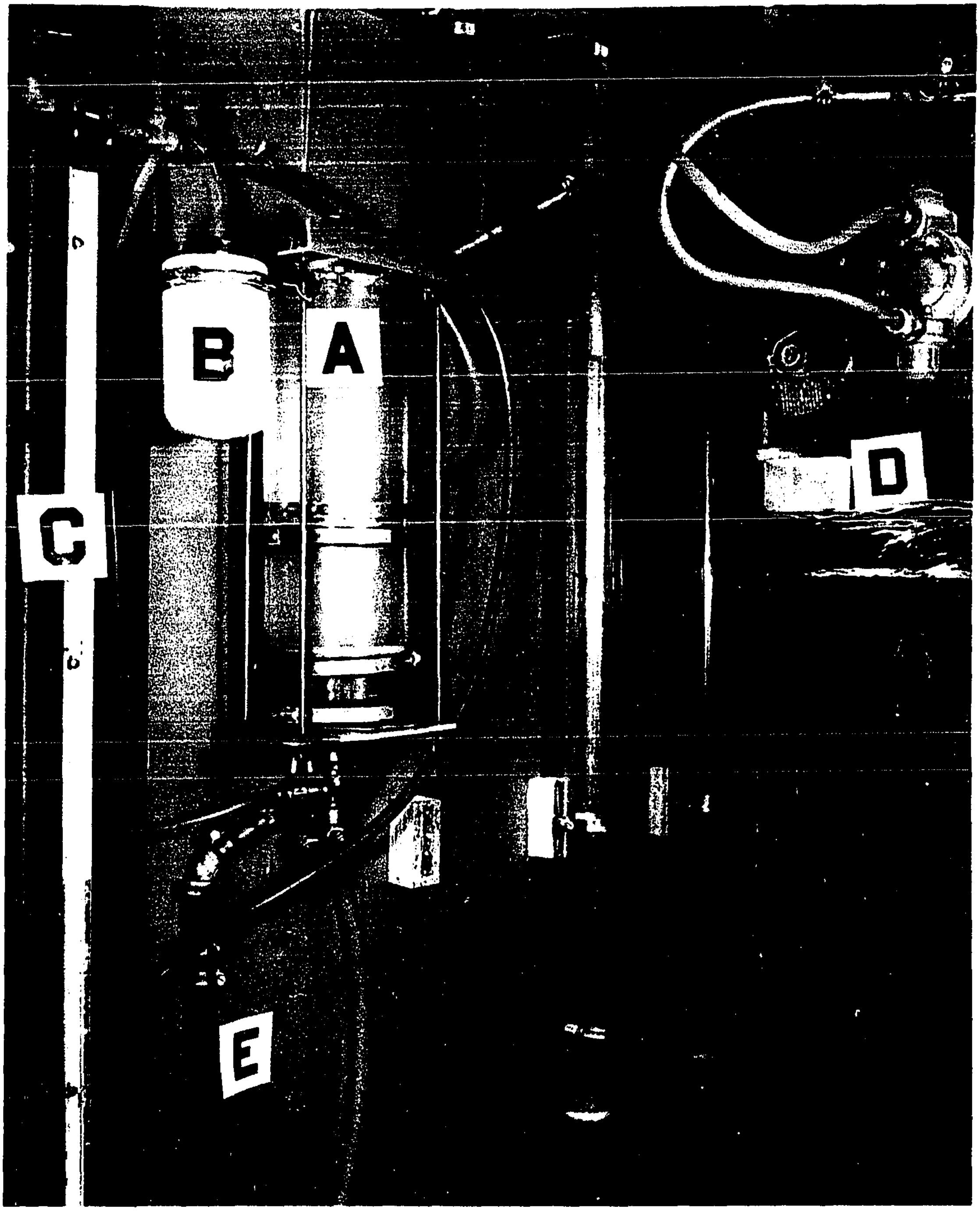
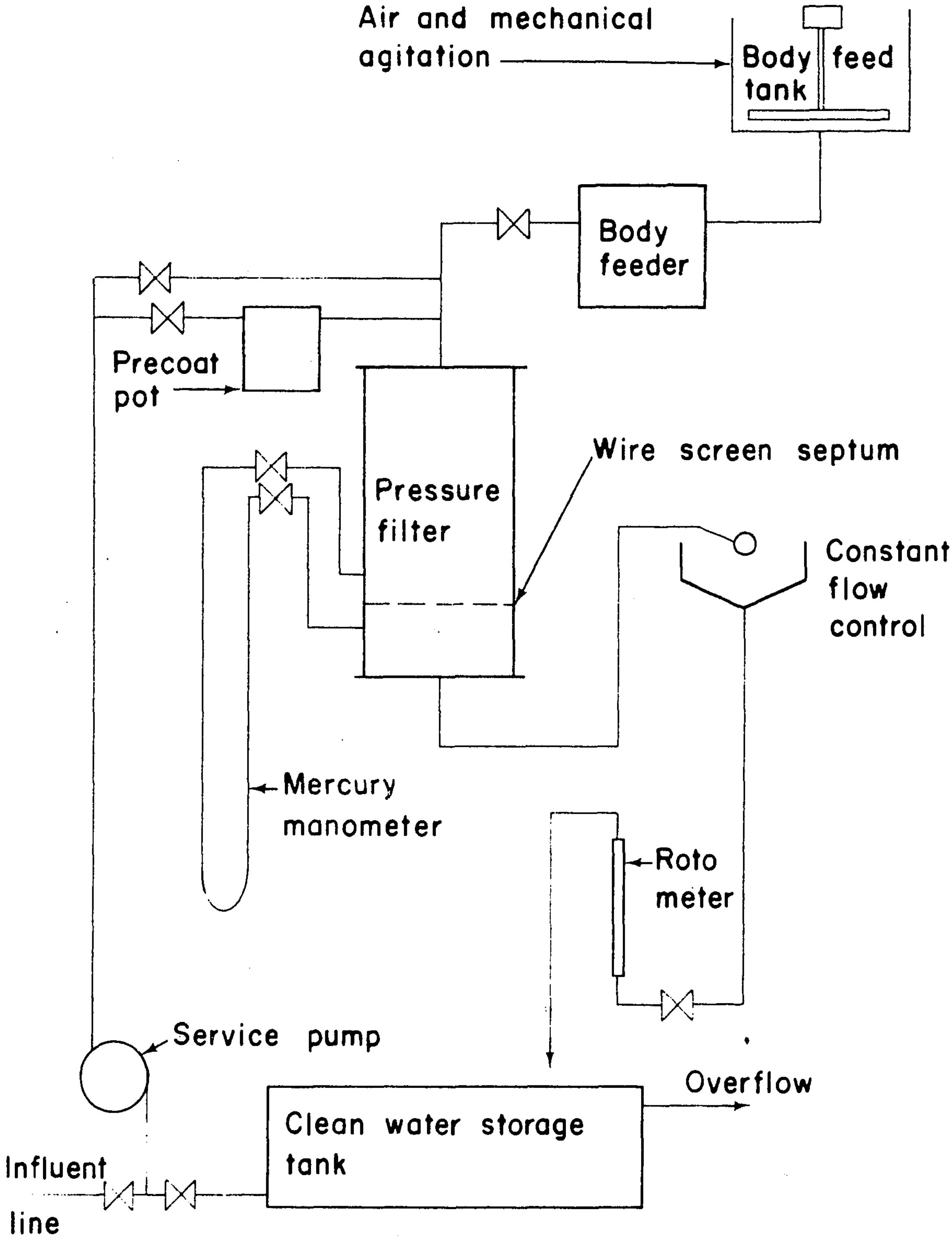

B
A
C
D
E

Figure 7. Schematic drawing of variable head permeameter, VHP



Schematic of variable head permeameter

cally agitated body feed slurry tank. The remainder of the equipment consists of a mercury manometer (C), precoat pot (B), centrifugal pump, and filtered water storage tank.

The filtration cycle was approximately the same as that described for the pilot plant. It consists of a precoating period and a filtration period. Backwashing as such was not done. The filtration cycle was stopped and the filter was prepared for the next test by removing the septum and physically washing away the cake. The range of operation is limited by the minimum and maximum amounts of water which the rotameter will record. This corresponds to filtration rates between 1 gpm/sq ft and 3 gpm/sq ft.

E. Constant Head Permeameter

The constant head permeameter, CHP, is shown in the photograph in Figure 8 and schematically in Figure 9. Although it was designed for permeability studies, it can be considered and was used as a constant head, variable rate filter in this study (14). Physically, it consists of an overflow tank which feeds a long plastic 3 inch diameter tube, at the bottom of which there is a wire screen septum. The septum discharges into a 1000 ml beaker which has an overflow spout used for sampling. The constant head is the distance from the water level in the overflow tank to the beaker. There are three CHP tubes so that three simultaneous tests could be conducted. The

Figure 8. Constant head permeameter, CHP

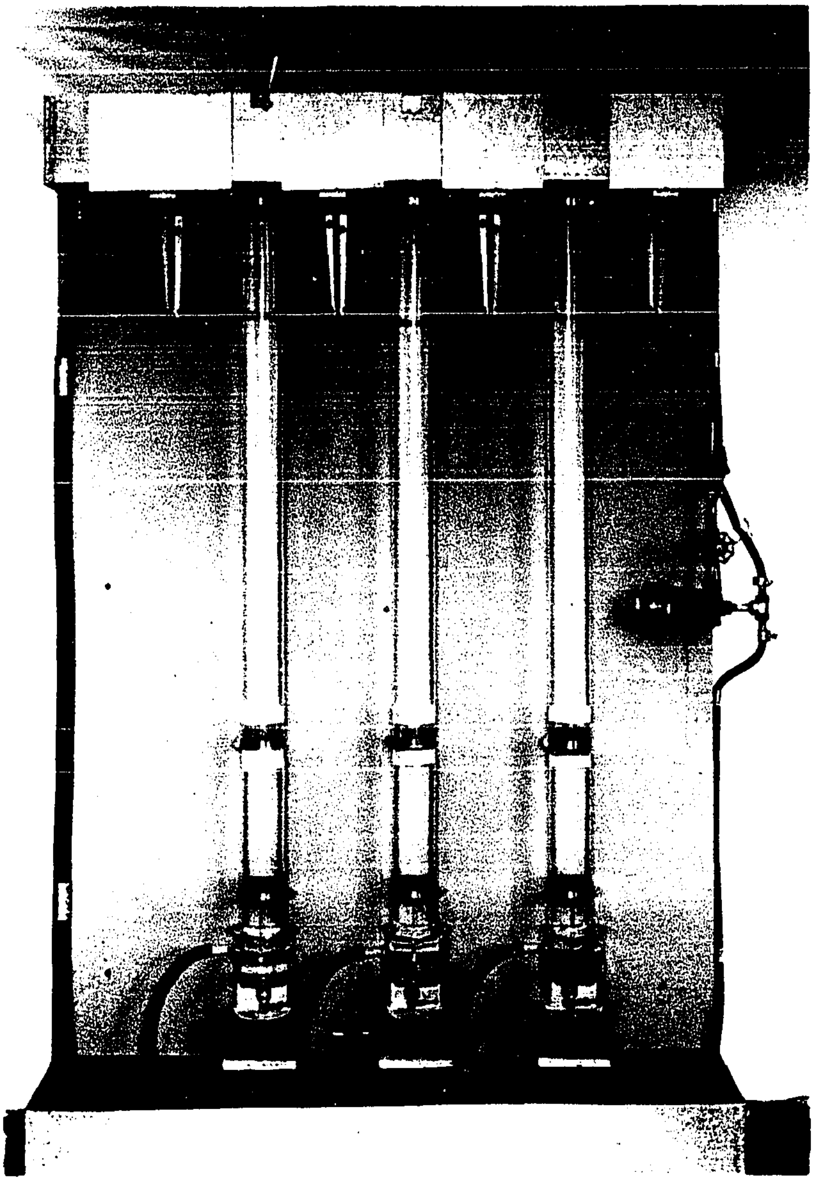
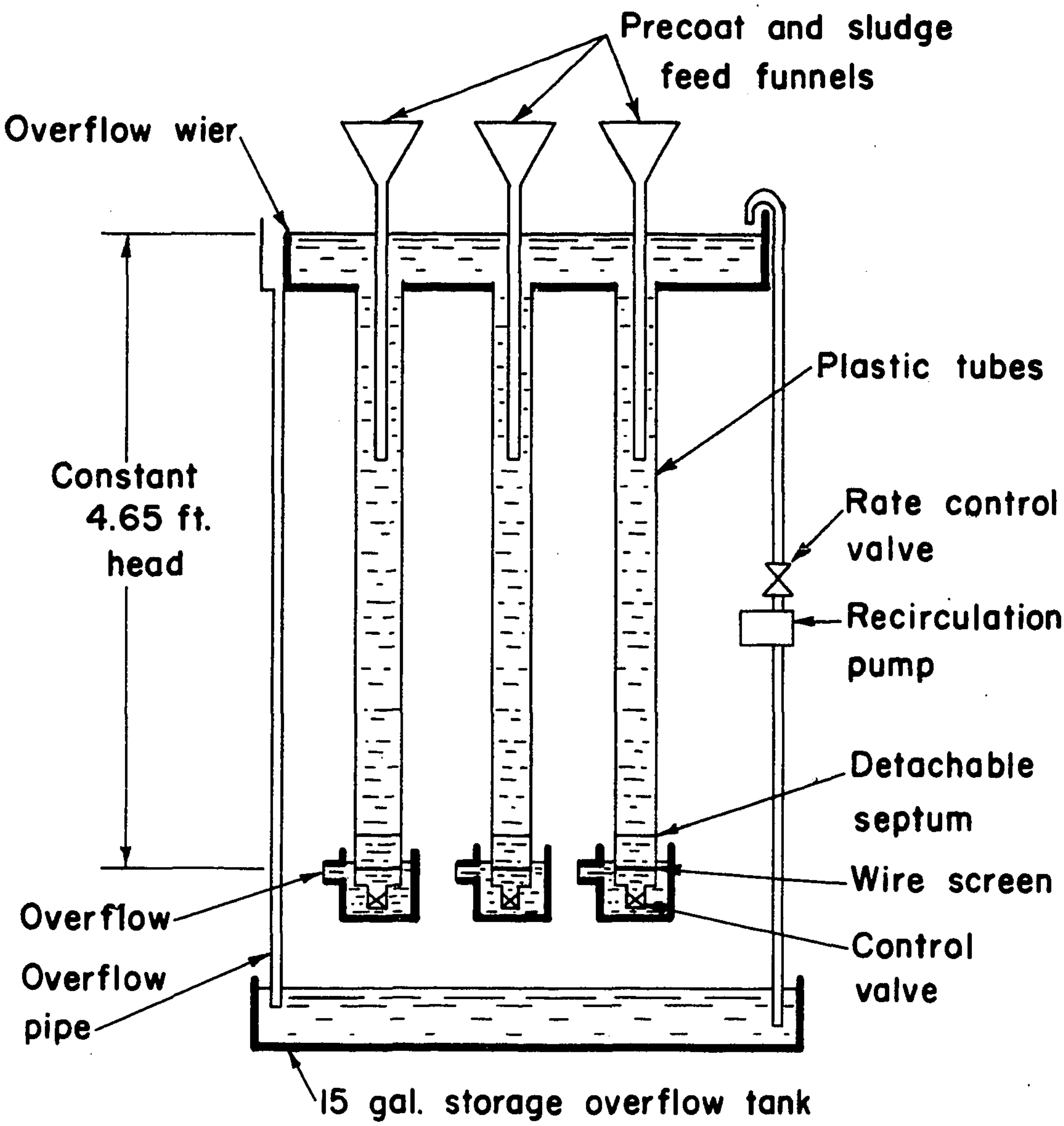


Figure 9. Schematic drawing of constant head permeameter, CHP



Schematic of constant head permeameter

water, either distilled or previously filtered, was circulated from the bottom storage tank to the top tank by a small centrifugal pump. A funnel extends from the top downward into each tube making it possible to dose each tube with the material to be filtered without affecting the recirculation water or the other filters.

The operation of the system was started by filling the bottom storage tank with clean water. The valves below the septums were closed and the pump started. This filled the tubes and upper tank with water. A given amount of diatomite as precoat, was next introduced into a tube through its funnel. The valve at the base of the septum being precoated was opened slightly to allow a slow rate of flow through the wire screen to form a precoat. An initial high rate of flow would carry a large amount of the precoat through the screen. When the precoat was formed, the valve was opened fully and the flow allowed to reach equilibrium. The rate of filtration was then measured by noting the time to collect a 2000-ml sample. A quantity of the raw water 2-5 gallons, depending on the filtrability, was mixed with an appropriate amount of diatomite as body feed. A small amount, approximately 500-1000 ml, of this mixture was then introduced into the filter by means of its funnel. When this material had been filtered out by the precoat and the system was again in equilibrium, the rate of filtration was determined as before. This procedure was repeated until the flow rate was reduced below a level at which the diatomite settled by gravity faster than the material was filtered. At the completion of the test, the pump was turned off and the water allowed to return to the bottom tank. The septum housing was then disconnected from the bottom of the tube and the cake washed to waste.

In this study only two tubes were used, one as a continuous filter for the recirculation water and the other to conduct tests. A more portable unit could be constructed using only one tube and this could be made in sections.

F. Computer

To determine the optimum body feed, optimum filtration rate, and optimum terminal head loss for a filter plant for a specific sized city with a specific water, four factors must be considered. These factors are cost of diatomite, power, labor and equipment. The first three represent operating costs and the last factor represents a fixed cost. The calculation of these factors for tests conducted at several flow rates and a number of body feeds is a time consuming process. For the purposes of this study three cities of different size were considered. Three waters each containing a different amount of iron were tested for each city using three rates for each water and approximately eight rates of body feed with each filtration rate. Calculations for optimums for all of these conditions would have required an inordinate amount of time. Therefore, the problem was programed for solution on the Iowa State University Cyclone Computer. The Cyclone digital computer is a 1024 word binary computer with each word 40 bits long. It is capable of storing data, adding, multiplying, and doing numerous other operations. The use of this computer reduced all of the calculations listed above to usable data in a relatively short time.

V. TEST RESULTS

A. General

The factors which vary between runs and series in this study are: type of filter, iron concentration, copper addition to the iron-bearing water, rate of filtration, and body feed. The term "run" is used to designate a test in which all of these factors are constant. The results of a typical run are shown in Figure 11. Run lengths normally varied from $1\frac{1}{2}$ hours to 15 hours depending upon the filtration rate, body feed, and iron content in the raw water. The term "series" designates a number of runs with different body feeds, but all other factors constant. The number of runs per series varied from 3 to 14. Table 1 summarizes all of the series conducted in this study. The individual runs within each series are shown as curves on the graphs of head loss *versus* total quantity of filtrate per sq ft for each series.

B. Trial Runs

Several trial runs were conducted using the pilot plant to determine the advisability of using ferrous sulfate as an artificial source of iron in the water. The results compared favorably with tests conducted with the raw water previously with the same filter apparatus. Based on these trial tests, ferrous sulfate was used throughout the remainder of the

Table 1. Summary of all tests conducted

Series designation	Run no.	Rate of filtration gpm/sq ft	Body feed mg/1	Inf. iron mg/1	Ave. eff.iron mg/1	Approx. copper conc. mg/1
PP-1	Trial	1		7-8		0
PP-2	1	1	10	7-8	0.48	
	2		20		0.30	
	3		30		0.18	
	4		40		0.19	
	5		50		0.25	
	6		60		0.20	
	7		80		0.18	
	8		100		0.18	
	9		120		0.22	
VHP-1	Trial	1		7-8		0
VHP-2	1	1	20		0.25	0
	2		40		0.17	
	3		60		0.17	
	4		80		0.15	
	5		100		0.2	
	6		120		0.3	
	7		160		0.3	
	8		200		0.15	
	9		400		0.2	
	10		600		0.2	
	11		800		0.2	
	12		1000		0.2	
VHP-3	1	2	20	7-8	0.9	0
	2		40		0.5	
	3		60		0.7	
	4		80		0.6	
	5		100		0.5	
	6		120		0.6	
	7		140		0.6	
	8		160		0.65	
	9		200		0.8	
	10		300		0.6	
VHP-4	1	3	0	7-8	3.0	0
	2		20		1.1	
	3		40		0.6	
	4		60		0.7	
	5		80		0.6	

Table 1. (Continued)

Series designation	Run no.	Rate of filtration gpm/sq ft	Body feed mg/1	Inf. iron mg/1	Ave. eff.iron mg/1	Approx.copper conc. mg/1
VHP-4 (Continued)						
	6		100		0.6	
	7		120		0.7	
	8		140		0.8	
	9		160		0.8	
	10		200		0.45	
VHP-12	1	3	20	7-8	0.5	1
	2		40		0.15	1
	3		60		0.1	1
	4		80		0.05	1
	5		80		0.05	½
	6		100		0.05	½
	7		120		0.10	¼
	8		160		0.05	0.1
VHP-8	6	1	0	4	0.8	0
	1		10		0.14	
	2		20		0.10	
	3		60		0.05	
	4		100		0.10	
	5		160		0.08	
VHP-5	1	2	10	4	0.35	0
	2		20		0.35	
	3		40		0.30	
	4		60		0.25	
	6		100		0.25	
	7		160		0.25	
VHP-10	1	3	20	4	0.10	½
	2		60		0.05	½
	3		100		0.20	½
	4		120		0.10	½
VHP-9	1	1	0	2	0.30	0
	2		20		0.05	
	3		60		0.05	
	4		100		0.05	
	5		160		0.05	
VHP-6	1	2	10	2	0.08	0
	2		20		0.10	
	3		40		0.08	
	4		60		0.15	
	5		60		0.10	
	6		100		0.10	
	7		160		0.15	

Table 1. (Continued)

Series designation	Run no.	Rate of filtration gpm/sq ft	Body feed mg/l	Inf. iron mg/l	Ave. eff.iron mg/l	Approx. copper conc. mg/l
VHP-11	1	3	20	2	0.25	0
	2		60		0.20	
	3		100		0.15	
	4		120		0.20	
	5		160		0.10	
VHP-7	1	variable	20	7-8	0.8	0
	2		80		0.7	
	3		160		0.7	
CHP-1	1	variable	20	7-8	0	0
	2		40		0	
	3		60		0	
	4		80		0	
	5		100		0	

study. The trial runs were also used to determine the effectiveness of the septum modifications. The modifications included the addition of a thin perforated plastic sheet beneath the cloth sock, and the dipping of the septum ends in an impervious paint. These modifications completely eliminated the cracking of the cake which had previously been experienced with low body feed rates due to the fluted septums.

A number of runs were conducted during the trial period in an effort to obtain correlation between head loss *versus* total quantity of filtrate for different runs when all conditions were the same except the septum surface area. The surface area in the pilot plant was changed by reducing the number of septums. It was not possible to correlate results with this pilot plant apparatus for several reasons. The run starts with the septum housing full of clean water. A larger septum surface area in this volume will give a more rapid displacement of the clean water than a smaller area, for the same filtration rate. Since there is a dilution effect which takes place during the first part of the run, due to this volume of clean water, there will be a difference in the head loss development as a function of time for two different areas. Perhaps of greater importance is the body feed distribution within the filter housing. When the septum area is reduced, the upward velocity of the water being filtered is less. When this upward velocity is less than approximately 12 gal/min/sq ft, the diatomite is no longer kept in a uniform suspension and some begins to settle out. This was visible in the filter operation, since a larger amount of cake formed at the bottom of the septum. Dimensionless parameters were used in an attempt to relate the results of the two sized filters. The use of these parameters was unsuccessful since it would seem that the actual conditions were different rather than the method of relating them. It was also found impossible to correlate results from the variable head permeameter with results from the pilot plant. In this case not only the volume to area ratios and dilution problems were present, but there was also a difference in the material and configuration of the septum.

The problem of the inability to predict from model to prototype has been reported previously. George Bell has reported, however, from studies conducted at the Johns-Manville research center, that it is possible to predict prototype results from a model, provided the same type of septum is used and that the volume to area ratio and configuration are the same.[1] The inability to predict results from a small to a large filter was of no consequence in this study since the results were used for comparison purposes only, but it is a factor which must be considered in design work. Studies are continuing in this area.

Numerous methods of operating the VHP were also evaluated during the trial series. The first method tried was a batch process. Twenty-five gallons of iron water were mixed with the appropriate amount of diatomite as body feed. The diatomite and iron were kept in suspension by air and mechanical agitation. This mixture was then filtered through the VHP. Operation in this manner eliminated the need for a body feeder since the body feed was fed with the iron water through the service pump. It was found, however, that the filtering characteristics and pH of the water changed with time and with the degree of agitation. To eliminate any variation due to these effects, it was decided to use a water which was prepared continuously and a slurry type body feeder. When the operational problems had been solved and proper operating

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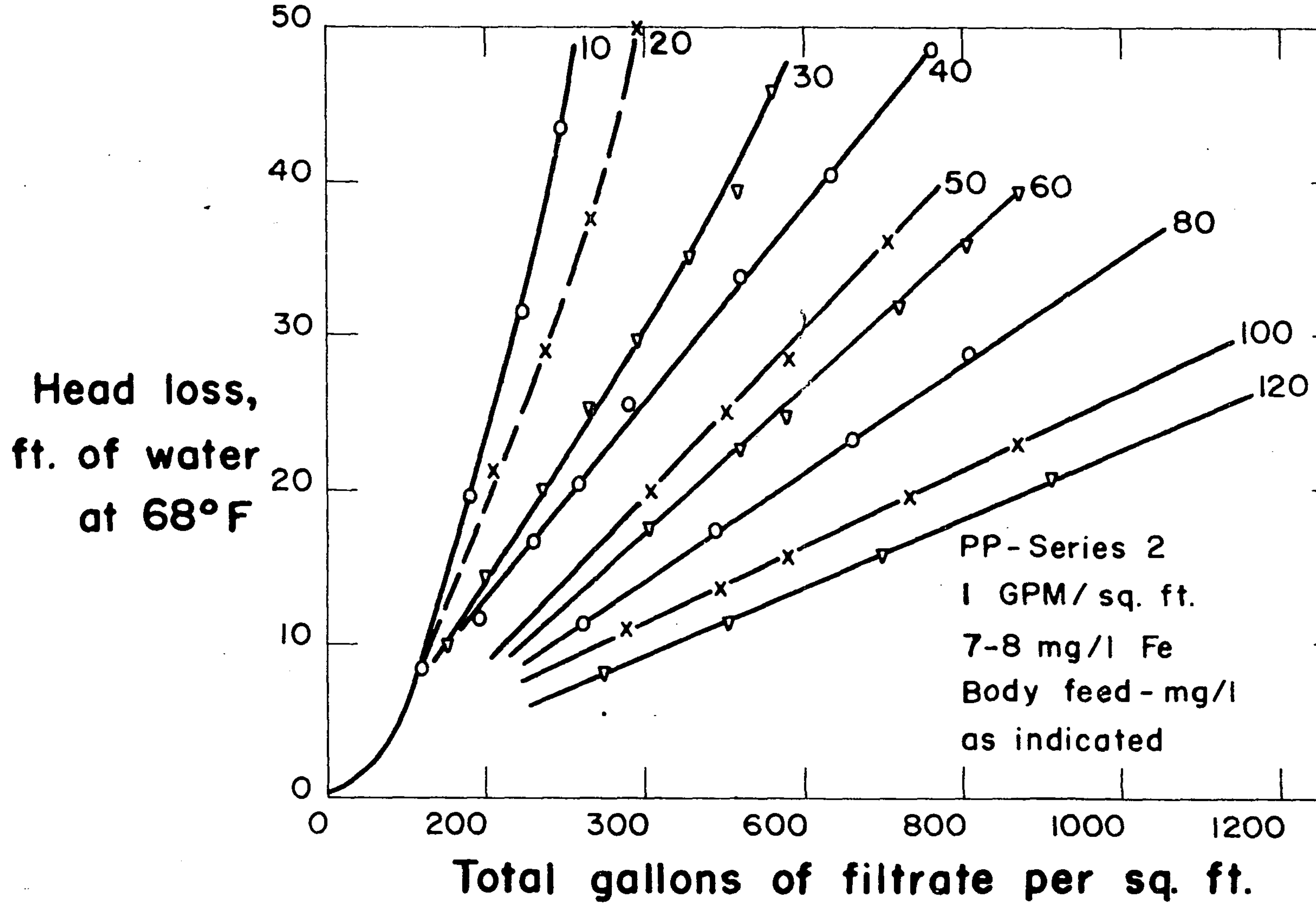
[1]Bell, George R., Ames, Iowa. Private communication, 1961

techniques had been developed, the actual test series were started with the two filters.

C. PP Results

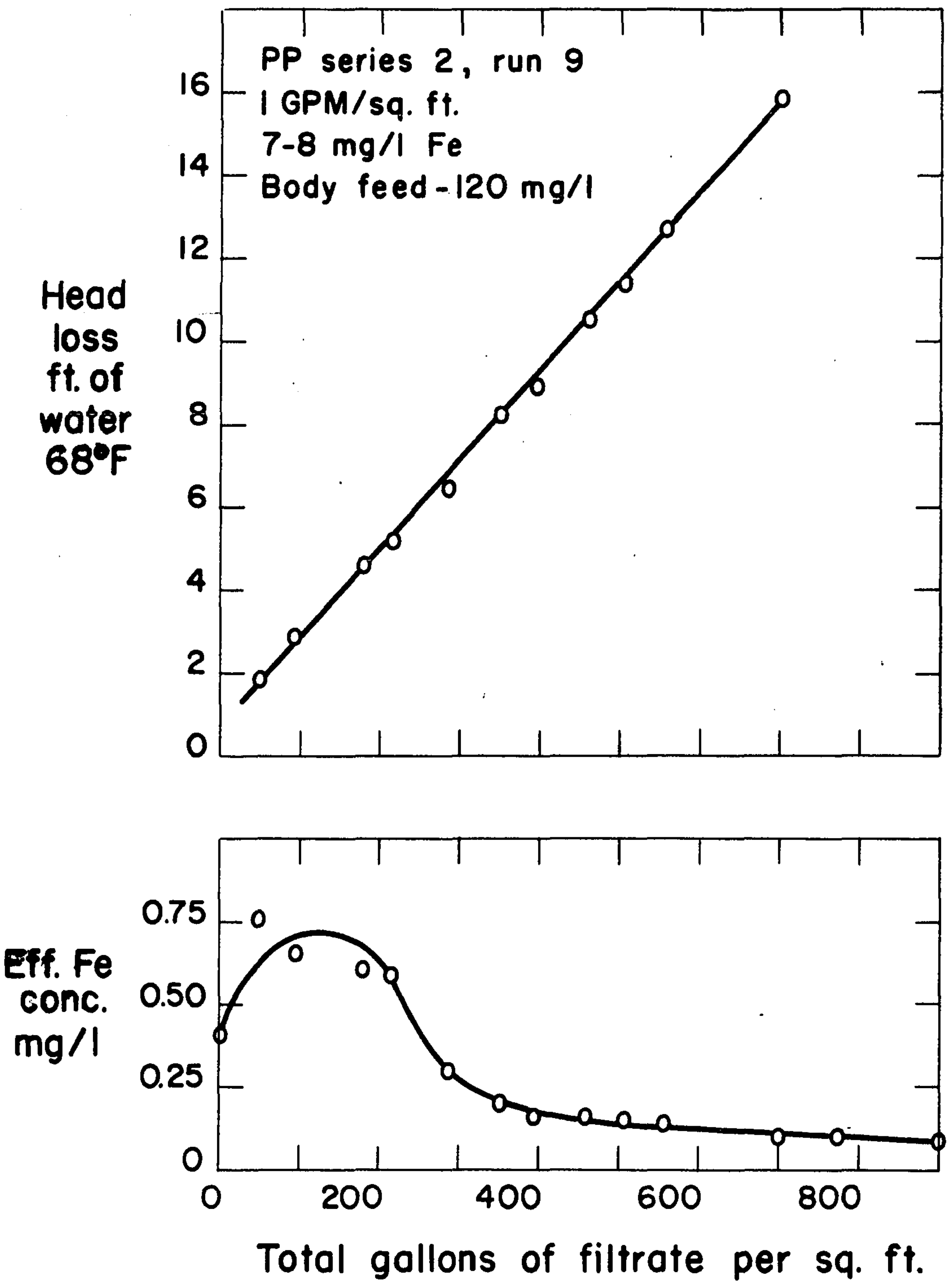
The series, PP-2, was conducted primarily to determine the relation between the head loss _versus_ total filtrate curves for different body feeds when the tests were conducted to relatively high head losses. The results of this series are shown in Figure 10. The plot of the test results curves upward slightly for body feeds of 10, 20, and 30 mg/1, but become straight lines for higher body feeds. The dilution effect of the clean water in the pressure vessel at the beginning of the run distorts the early portion of the curves. This can be observed in Figure 10. The curves obtained from plotting head loss and iron concentration in the effluent _versus_ total gal of filtrate per sq ft in Figure 11 shows the typical results of one run conducted with a pressure filter. The effluent iron concentration varies with time as the run progresses. The first effluent iron concentration determined shortly after the run is started, is normally low due to dilution. The subsequent readings are normally higher, decreasing as the run progresses. As reported previously, the pilot plant has the ability to remove more and more of the soluble iron as the run progresses and more of a sludge cake is formed (12). Readings of head loss and iron

Figure 10. Results of PP-2 runs conducted at 1 gpm/sq ft with 7-8 mg/1 iron water and body feeds as indicated



50
40
30
20
10
0
Head loss, ft. of water at 68°F
0
200
300
600
800
1000
1200
Total gallons of filtrate per sq. ft.
10
20
30
40
50
60
80
100
120
PP-Series 2
1 GPM/ sq. ft.
7-8 mg/l Fe
Body feed-mg/l
as indicated

Figure 11. Results of a typical pressure diatomite filter run


PP series 2, run 9
I GPM/sq. ft.
7-8 mg/l Fe
Body feed - 120 mg/l
Head loss ft. of water 68°F
0
2
4
6
8
10
12
14
16
Eff. Fe conc. mg/l
0
0.25
0.50
0.75
0
200
400
600
800
Total gallons of filtrate per sq. ft.

concentrations were taken every 30 minutes. The head loss readings were in inches of mercury. These readings were converted to feet of water and corrected to a standard reference temperature of 68°F even though all runs were made at a temperature of 60°F.

D. VHP Results at 7-8 mg/l of Iron

The results of the VHP-2 (1 gpm/sq ft), VHP-3 (2 gpm/sq ft), and VHP-4 (2 gpm/sq ft) runs are shown in Figures 12, 13, and 14 respectively. Influent iron concentrations varied from 7 to 8 mg/l with an average value of 7.5 mg/l. As noted in Table 1, the effluent iron concentrations increased with increasing rates. The majority of the iron passing the filter appeared to be in the soluble or ferrous form. Since the effluent iron concentration was excessive, particularly in the 3 gpm/sq ft series, it was decided to repeat series 4 using copper to obtain complete precipitation of the influent iron. The 3 gpm/sq ft series was repeated, VHP-12, and is shown in Figure 15. The addition of the copper completely reduced the soluble ferrous iron to the insoluble form and consequently almost complete removal was obtained on the filter. The head losses observed in the VHP-12 runs were higher than the corresponding head losses in VHP-4 runs, however, nearly 1 mg/l additional iron was removed.

Figure 12. Results of VHP-2 runs conducted at 1 gpm/sq ft with 7-8 mg/l iron water and body feeds as indicated

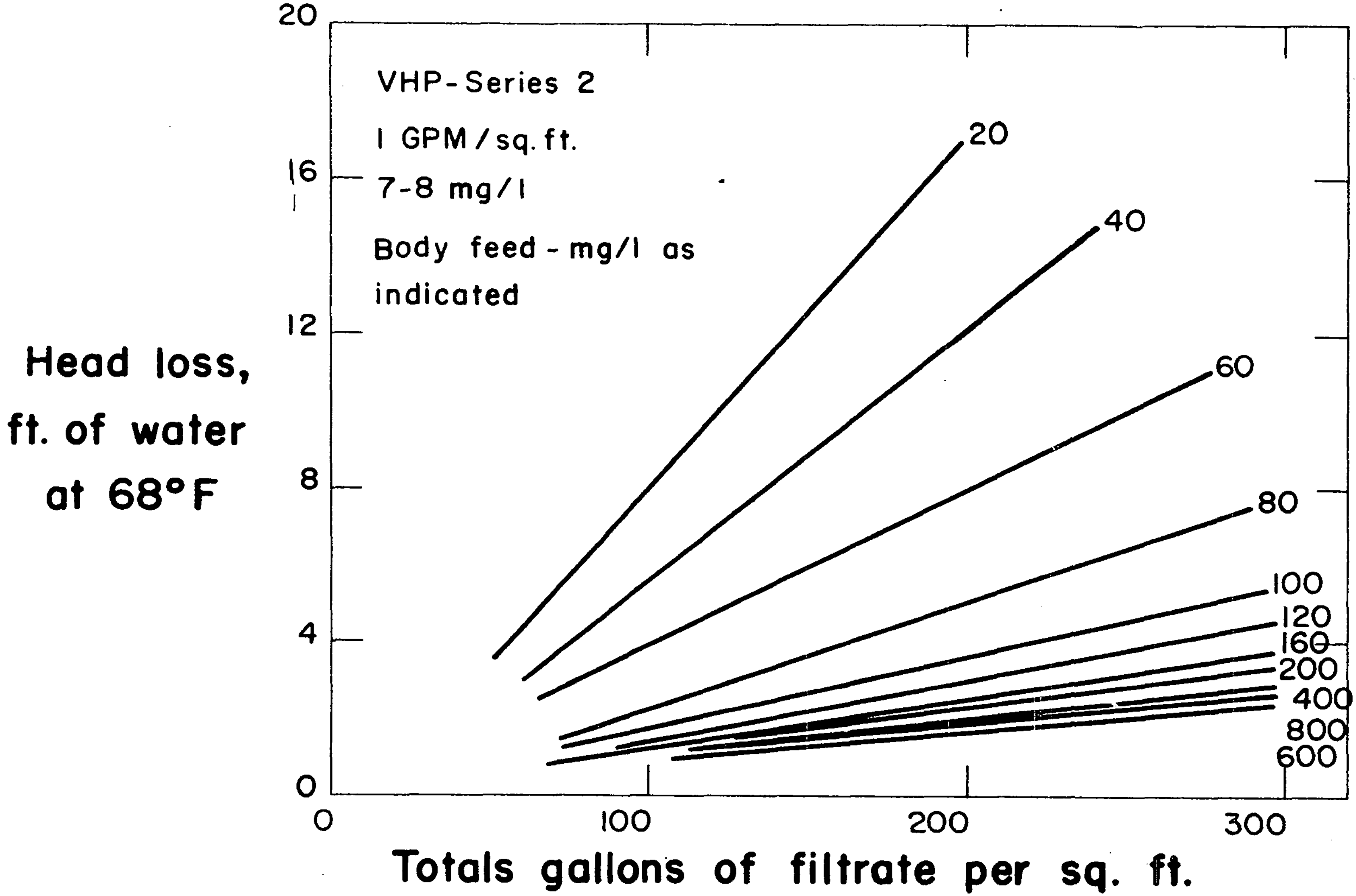

VHP-Series 2
1 GPM/sq. ft.
7-8 mg/l
Body feed - mg/l as indicated
Head loss, ft. of water at 68°F
Totals gallons of filtrate per sq. ft.
20
16
12
8
4
0
0
100
200
300
20
40
60
80
100
120
160
200
400
800
600

Figure 13. Results of VHP-3 runs conducted at 2 gpm/sq ft with 7-8 mg/1 iron water and body feeds as indicated

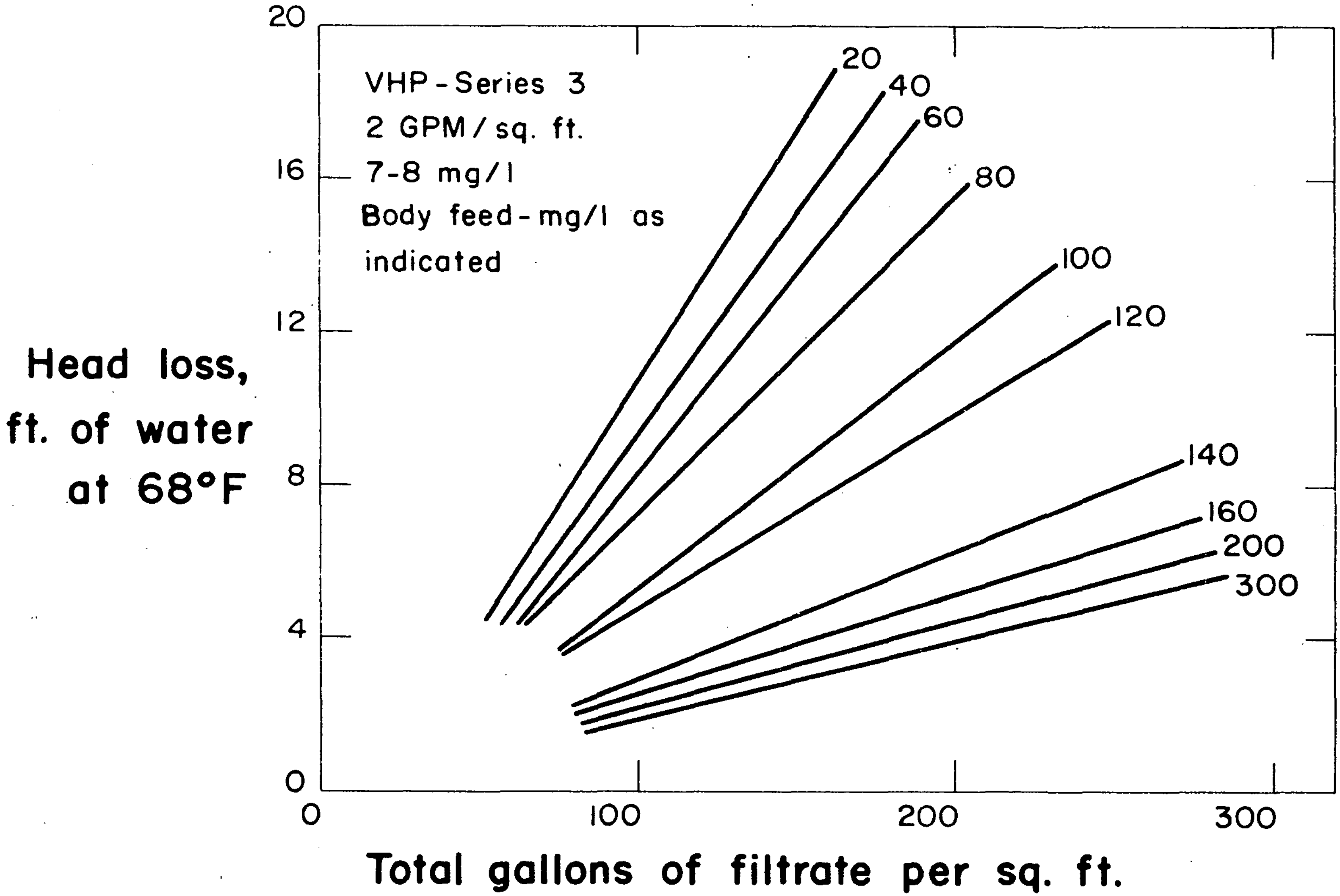

VHP - Series 3
2 GPM / sq. ft.
7-8 mg/l
Body feed - mg/l as indicated
Head loss, ft. of water at 68°F
Total gallons of filtrate per sq. ft.
20
40
60
80
100
120
140
160
200
300
0
4
8
12
16
20
0
100
200
300

Figure 14. Results of VHP-4 runs, conducted at 3 gpm/sq ft with 7-8 mg/1 iron water and body feeds as indicated

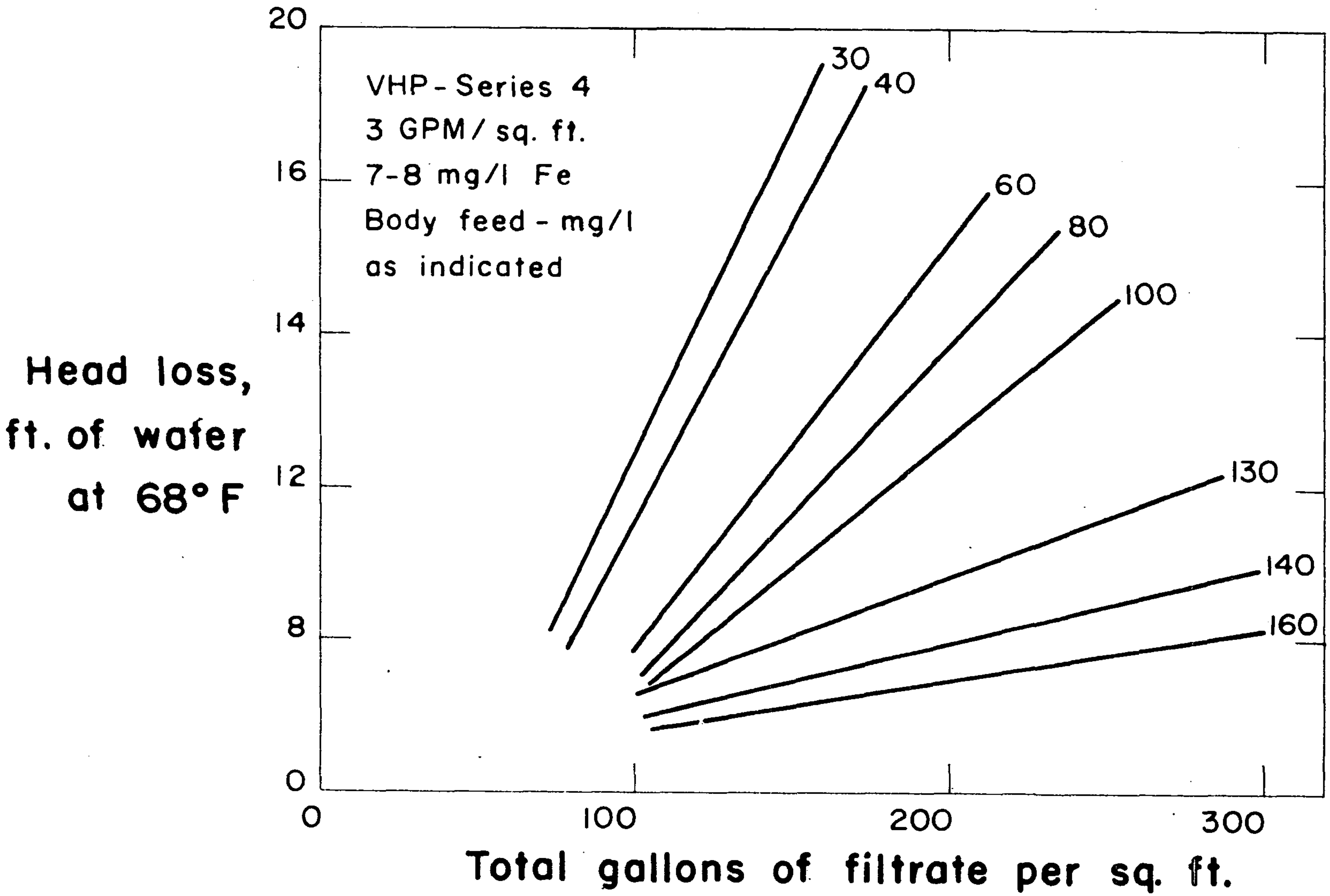
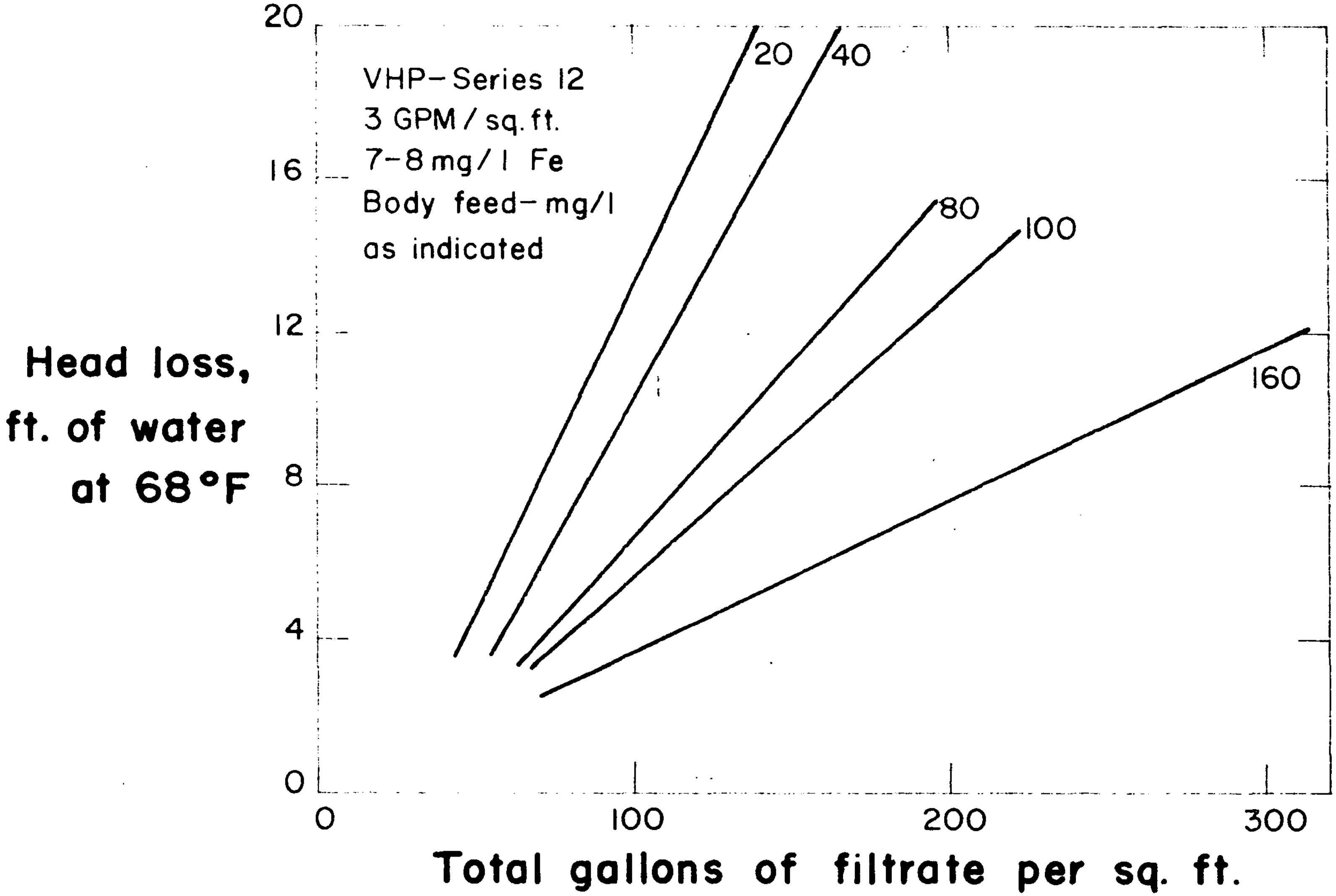

VHP - Series 4
3 GPM / sq. ft.
7-8 mg/l Fe
Body feed - mg/l
as indicated
Head loss,
ft. of water
at 68° F
Total gallons of filtrate per sq. ft.
0
8
12
14
16
20
0
100
200
300
30
40
60
80
100
130
140
160

Figure 15. Results of VHP-12 runs conducted at 3 gpm/sq ft with 7-8 mg/1 iron water, 1 mg/1 of copper and body feeds as indicated

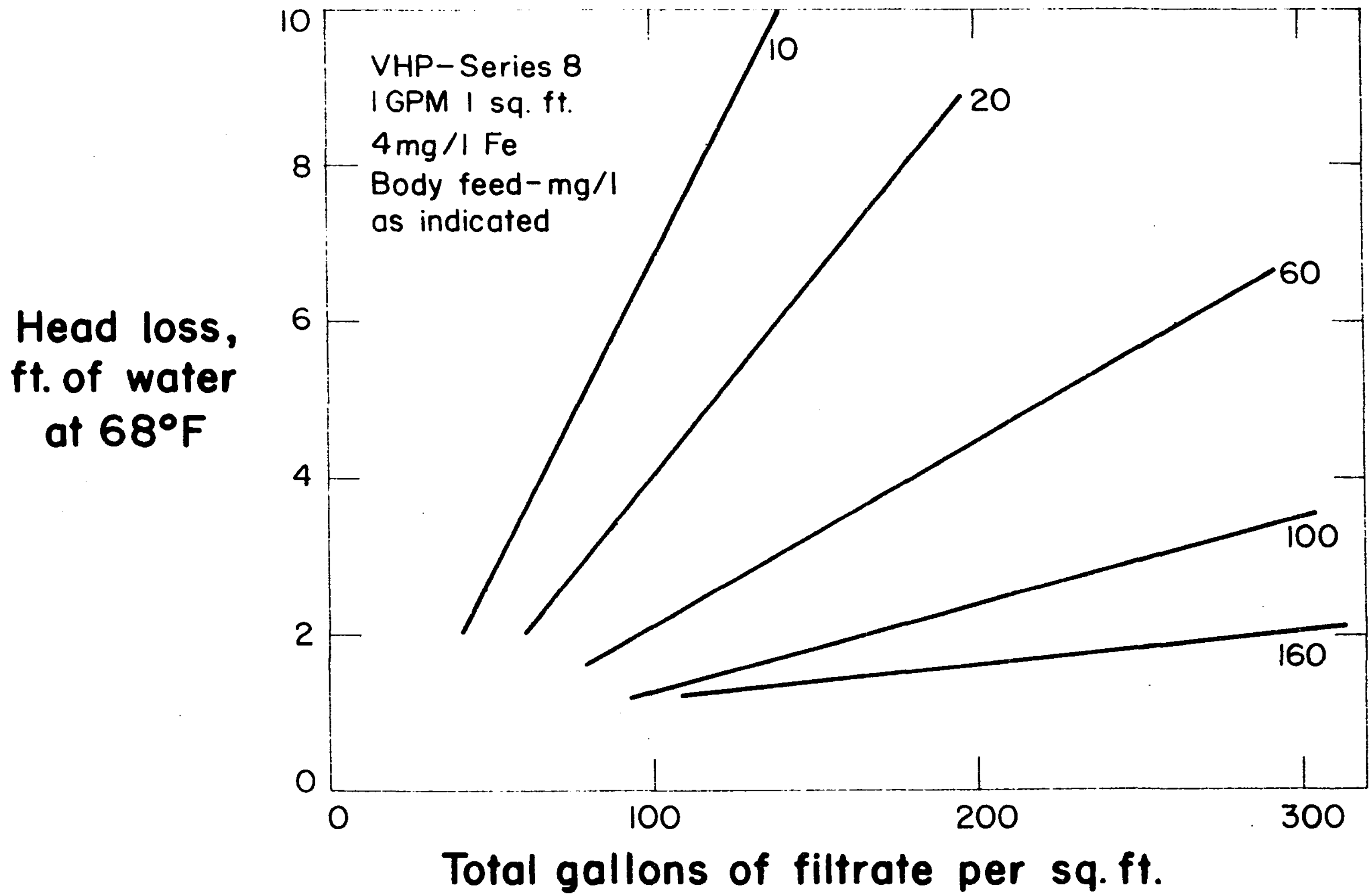

VHP-Series 12
3 GPM / sq. ft.
7-8 mg / l Fe
Body feed-mg/l
as indicated
20
40
80
100
160
Head loss,
ft. of water
at 68°F
0
4
8
12
16
20
0
100
200
300
Total gallons of filtrate per sq. ft.

Very large body feed additions were used in some VHP-2 runs. This was done to find the head loss optimum body feed. The head loss optimum body feed is that body feed rate at which the increased permeability obtained due to body feed is just balanced by the negative effect due to the increased thickness of cake through which the water must pass. The head loss optimum body feed will produce the maximum number of gallons per foot of head loss. It can be seen from Figure 12, that for this 7-8 mg/l iron water filtered at 1 gpm/sq ft, the optimum occurs somewhere between 400 and 800 mg/l of body feed.

E. VHP Results at 4 mg/l of Iron

The results of the VHP-8 (1 gpm/sq ft), VHP-5 (2 gpm/sq ft) and VHP-10 (3 gpm/sq ft) runs are shown in Figures 16, 17, and 18 respectively. The runs were conducted with an iron content as near 4 mg/l as it was possible to obtain. Influent iron contents normally varied from 3.8 mg/l to 4.2 mg/l. It was found that a significant amount of iron was passing the filter at the 3 gpm/sq ft filtration rate, consequently, 1/2 mg/l of copper was added to all runs in series VHP-5. With this addition, almost complete removal of the iron was obtained. Fewer runs were conducted in each of the 4 mg/l iron series than had been conducted in the 8 mg/l series. The relation between the results obtained at different body feeds was known well enough from the tests with 7-8

Figure 16. Results of VHP-8 runs conducted at 1 gpm-sq ft with 4 mg/1 iron water and body feeds as indicated



VHP-Series 8
1 GPM 1 sq. ft.
4 mg/l Fe
Body feed-mg/l
as indicated
10
20
60
100
160
Head loss, ft. of water at 68°F
Total gallons of filtrate per sq. ft.
0
2
4
6
8
10
0
100
200
300

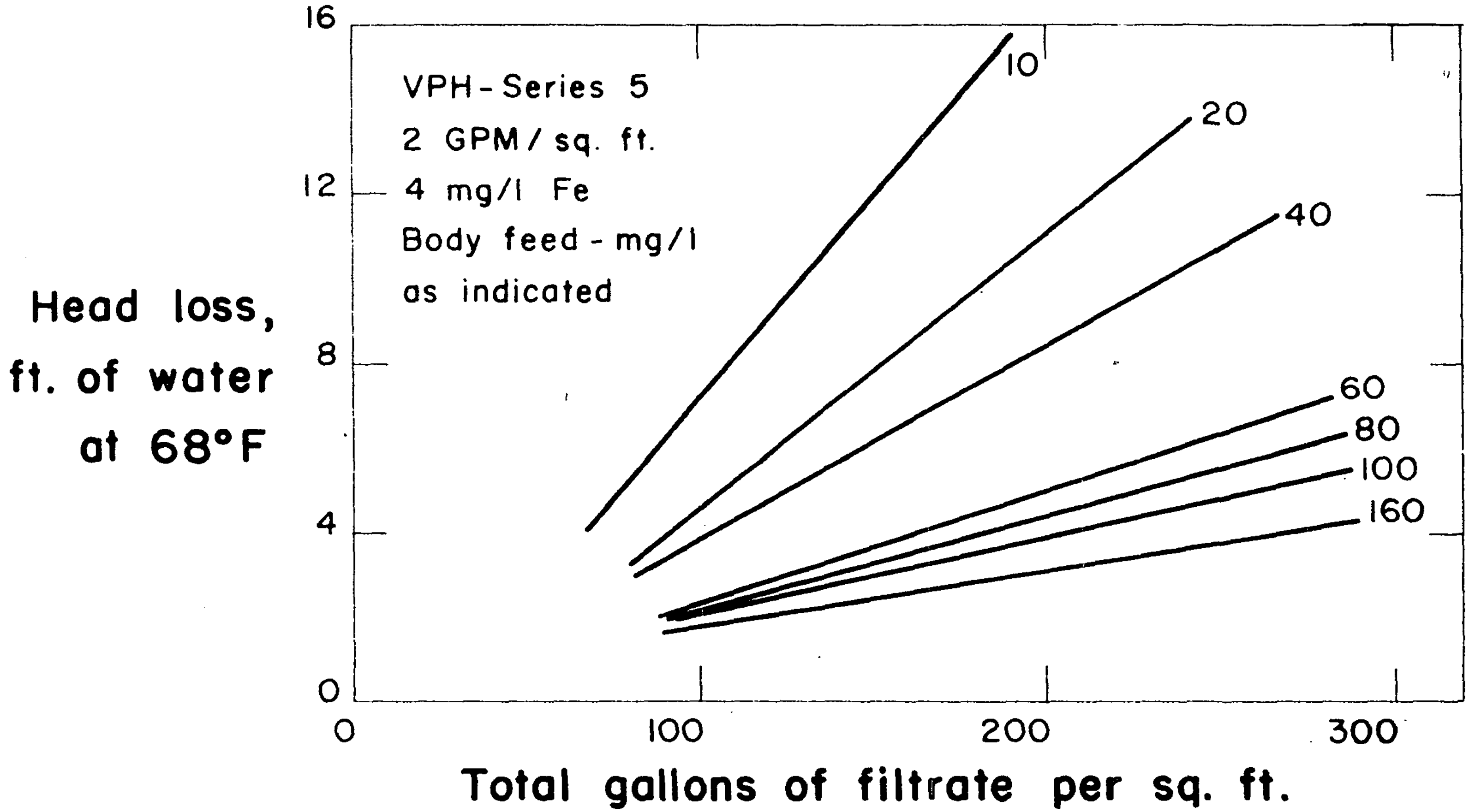
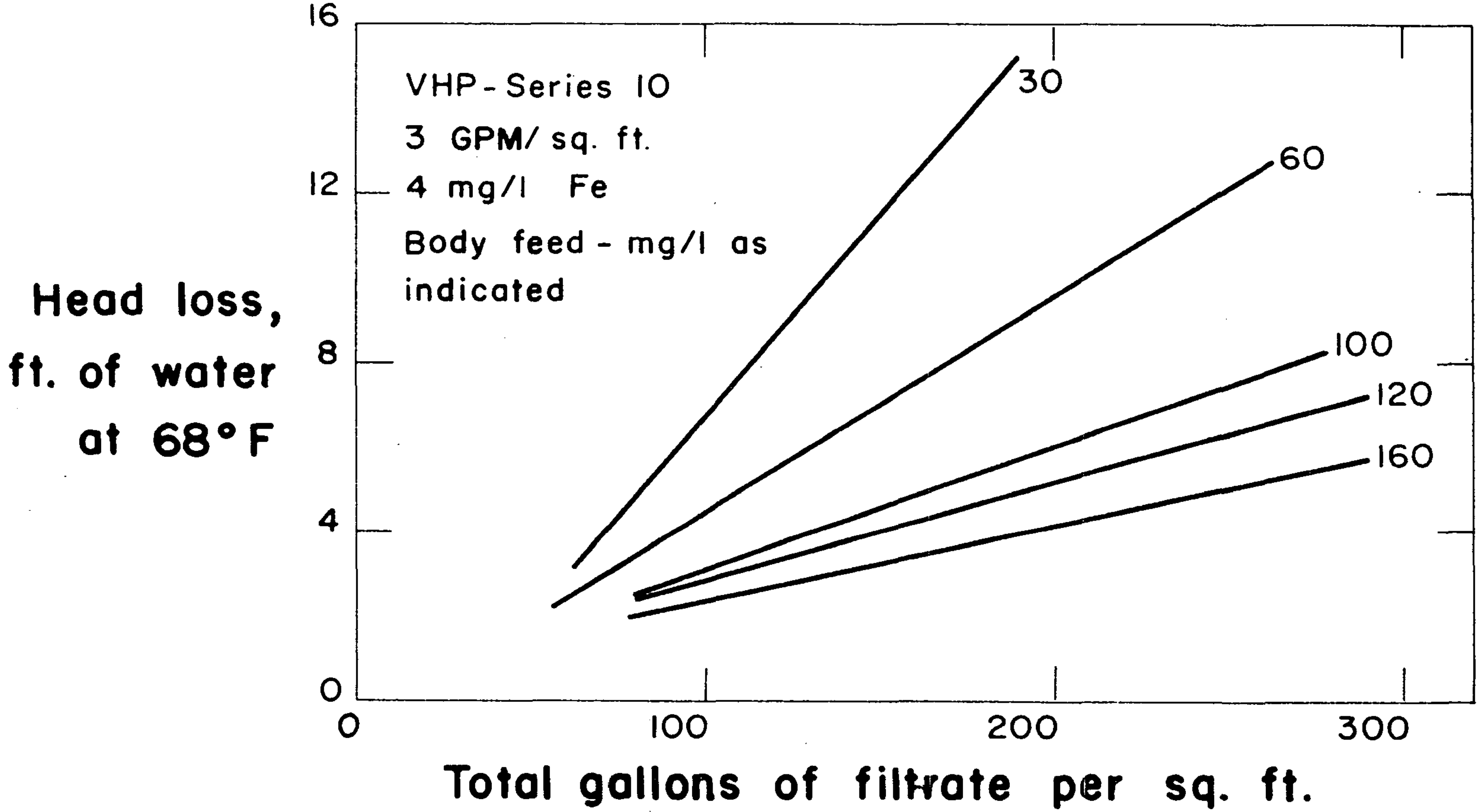

VPH-Series 5
2 GPM / sq. ft.
4 mg/l Fe
Body feed - mg/l
as indicated
Head loss, ft. of water at 68°F
Total gallons of filtrate per sq. ft.
0
4
8
12
16
0
100
200
300
10
20
40
60
80
100
160

Figure 18. Results of VHP-10 runs conducted at 3 gpm/sq ft with 4 mg/1 iron water, ½ mg/1 copper and body feeds as indicated


VHP - Series 10
3 GPM/ sq. ft.
4 mg/l Fe
Body feed - mg/l as indicated
30
60
100
120
160
Head loss, ft. of water at 68°F
16
12
8
4
0
100
200
300
Total gallons of filtrate per sq. ft.

mg/l iron that results from intermediate body feeds could be interpolated if desired.

F. VHP Results at 2 mg/l of Iron

Since it was desired to find how diatomite filtration results compared not only for different rates, but over a wide range of iron concentrations, a relatively low influent iron concentration of 2 mg/l was used in some tests. The results of VHP-9 (1 gpm/sq ft), VHP-6 (2 gpm/sq ft), and VHP-11 (3 gpm/sq ft) runs conducted with a 2 mg/l iron water are shown in Figures 19, 20, and 21 respectively. No copper was used in the runs of these series since the maximum iron passing, even at 3 gpm/sq ft, was well within the tolerance level.[1] Some difficulty was encountered, particularly for the high body feeds in VHP-9 runs at 1 gpm/sq ft, due to the fact that the head loss developed too slowly. It was difficult therefore, to obtain accurate head loss data in a reasonable length of time, 5 hours of operation per run, since the manometer continuously fluctuated due to the pulsating body feeder over a greater range than the actual head loss.

G. Results of VHP-7 Runs

The results of VHP-7 runs are shown graphically in Figure 22. The series consists of three runs conducted at body feeds of 20, 80 and 160 mg/l with influent iron concentrations

[1]U.S.P.H.S.

Figure 19. Results of VHP-9 runs conducted at 1 gpm/sq ft with 2 mg/l iron water and body feeds as indicated

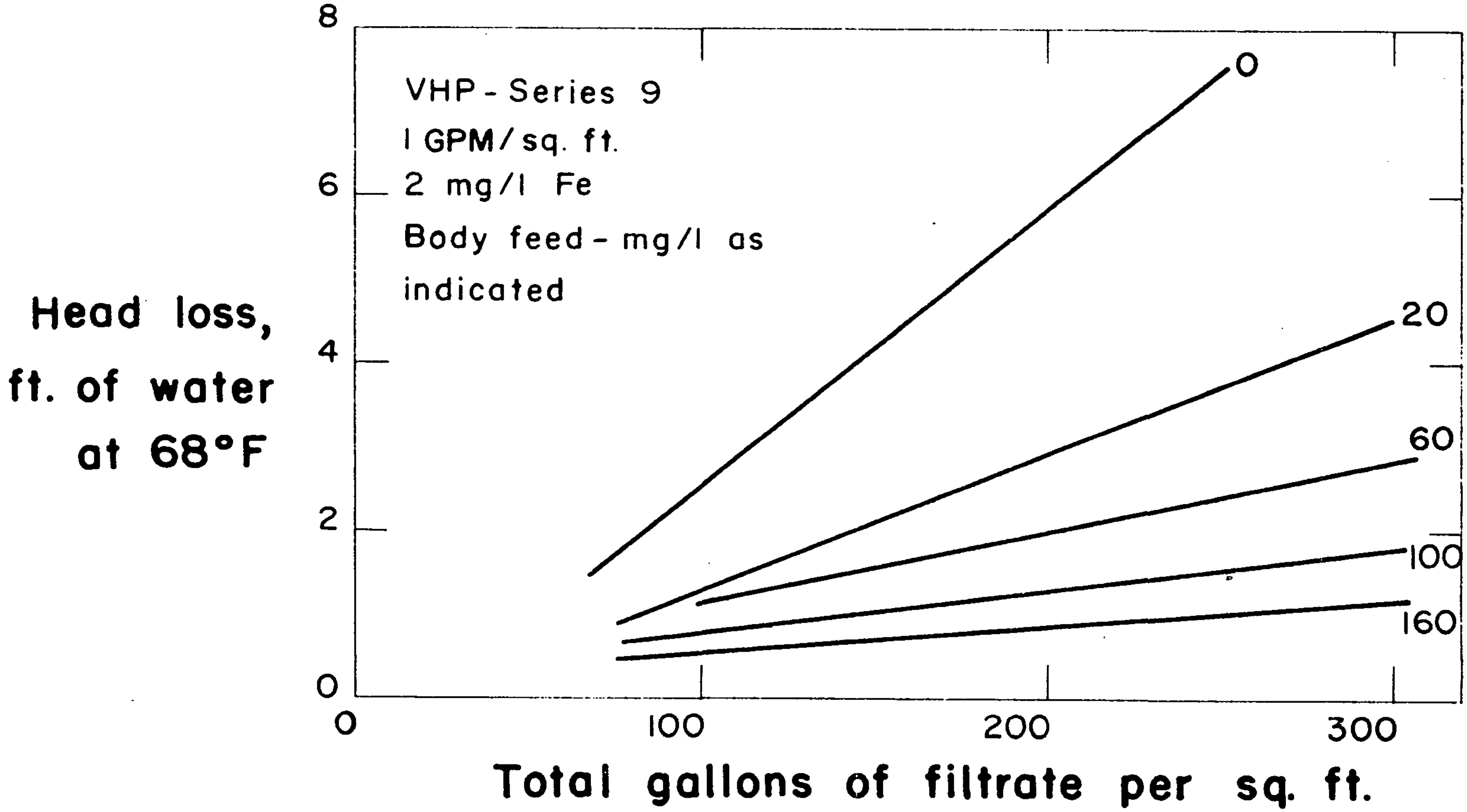

VHP - Series 9
1 GPM/sq. ft.
2 mg/l Fe
Body feed - mg/l as indicated
Head loss, ft. of water at 68°F
Total gallons of filtrate per sq. ft.
0
20
60
100
160
0
2
4
6
8
100
200
300

Figure 20. Results of VHP-6 runs conducted at 2 gpm/sq ft with 2 mg/l iron water and body feeds as indicated

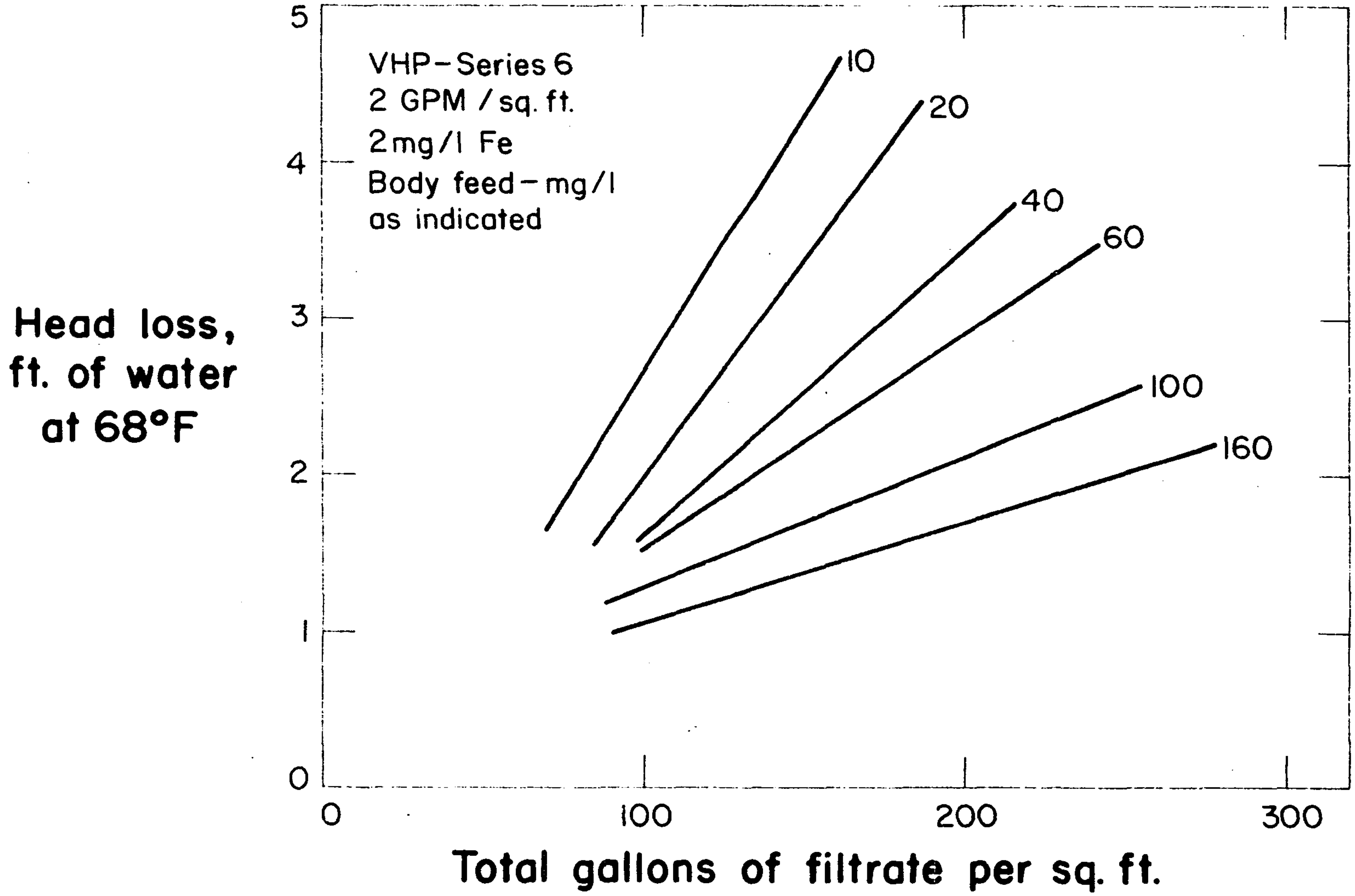
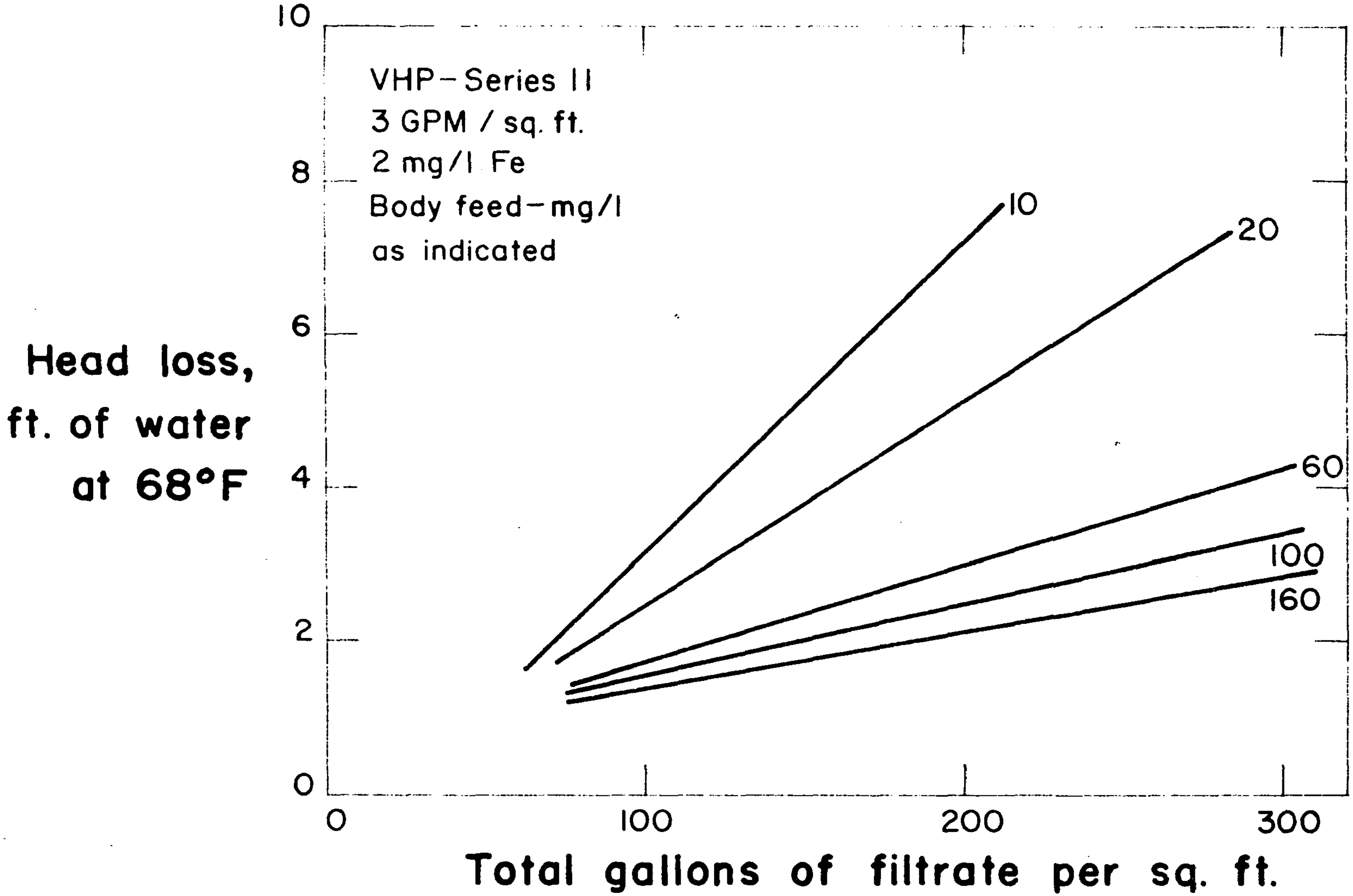

VHP-Series 6
2 GPM / sq. ft.
2mg/l Fe
Body feed - mg/l
as indicated
10
20
40
60
100
160
Head loss, ft. of water at 68°F
0
1
2
3
4
5
0
100
200
300
Total gallons of filtrate per sq. ft.

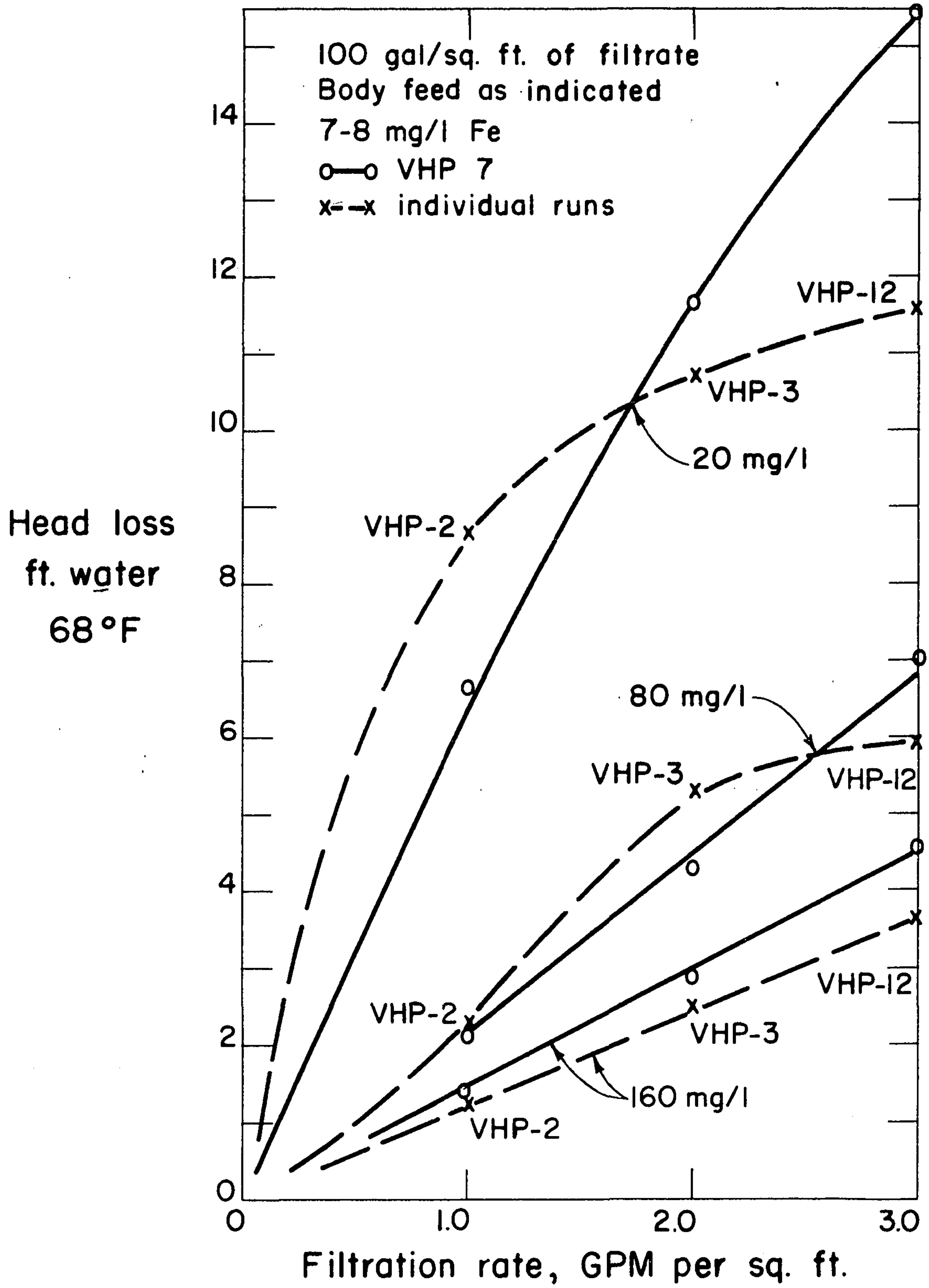
Figure 21. Results of VHP-11 runs conducted at 3 gpm/sq ft with 2 mg/l iron water and body feeds as indicated


VHP – Series II
3 GPM / sq. ft.
2 mg/l Fe
Body feed – mg/l
as indicated
10
20
60
100
160
Head loss,
ft. of water
at 68°F
0
2
4
6
8
10
0
100
200
300
Total gallons of filtrate per sq. ft.

of 7-8 mg/l. The objective of the series was to determine the effect of filtering at a given rate, and then observing the head loss through a prescribed amount of this cake when the rate was changed. It was desired to see if the rate of deposition was a factor in determining head loss. In this case the water was filtered at 2 gpm/sq ft until a quantity equal to 100 gal/sq ft had been filtered. At this time, the head loss was recorded and the rate adjusted to 1 gpm/sq ft. After waiting approximately a minute until the filter was again in equilibrium, the head loss was recorded at this rate. The rate was then increased to 3 gpm/sq ft and the head loss at this rate was recorded. Filtration was then continued at 2 gpm/sq ft until 200 gal/sq ft had been filtered and the head losses at the different rates were again determined. The results of this test are compared in Figure 22 with the head losses obtained after filtering the same amount of water at each specific rate of filtration. Since the same relationships were found at botn 100 gal of total filtrate and 200 gal of total filtrate, only the results found at 100 gal total filtrate are shown in Figure 22.

The results of this series indicate that regardless of the body feed to iron ratio, when the cake is formed at one specific filtration rate, the head loss increases nearly linearly with the rate of filtration. This is not true, how-

Figure 22. Results of VHP-7 runs conducted with a 7-8 mg/l water, variable rates and body feeds as indicated


100 gal/sq. ft. of filtrate
Body feed as indicated
7-8 mg/l Fe
o—o VHP 7
x--x individual runs
Head loss ft. water 68 °F
Filtration rate, GPM per sq. ft.
0
1.0
2.0
3.0
2
4
6
8
10
12
14
VHP-2
VHP-3
VHP-12
20 mg/l
80 mg/l
160 mg/l

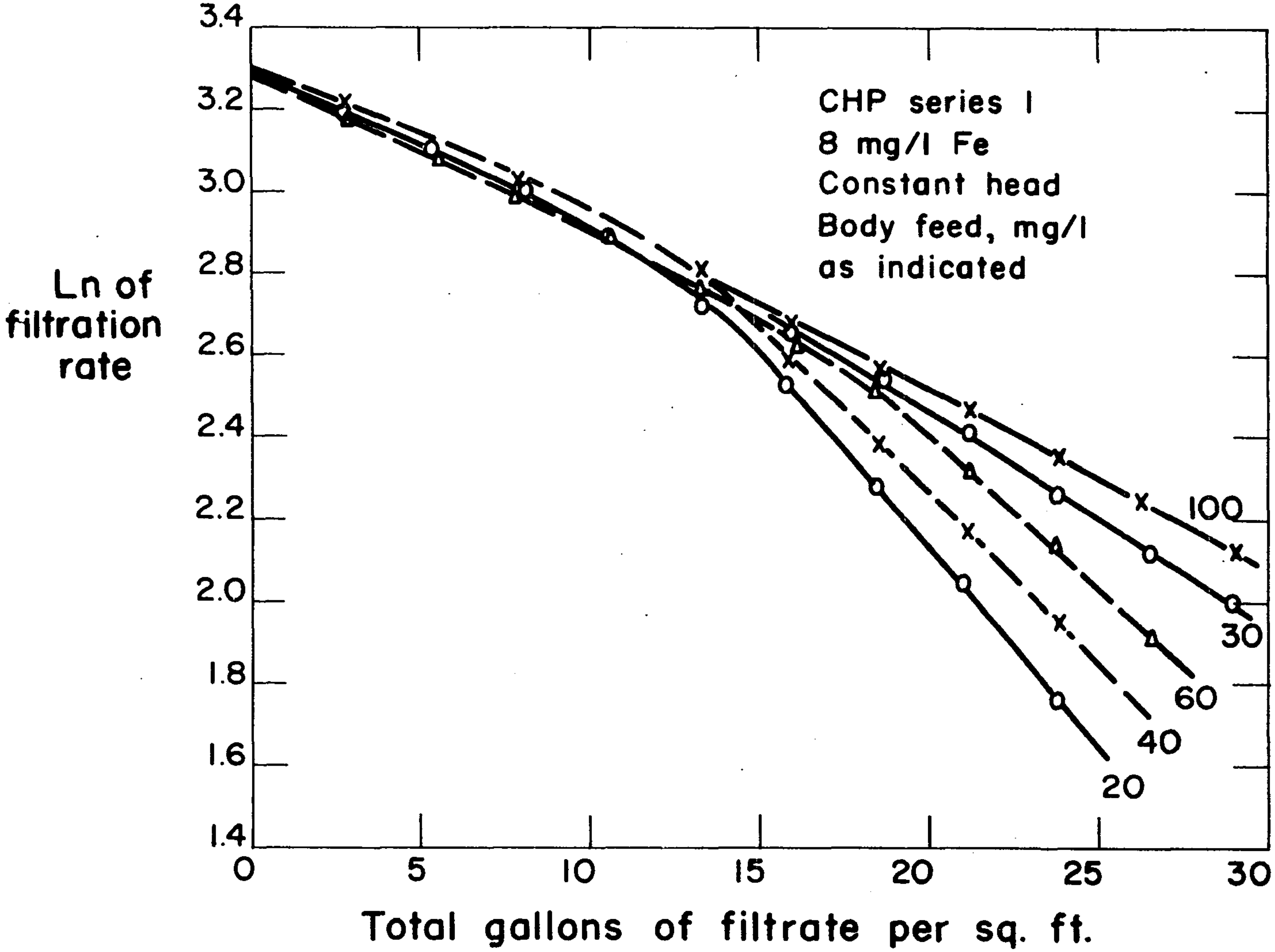
ever, when the cake contains a low ratio of body feed to iron and is formed at the specific rate at which the head loss is measured. It can be seen in Figure 22, that when a low body feed to iron ratio is used at a high rate, the head loss is less than that which would be predicted by forming the cake at one rate and varying the rate through this cake. This could be due to a greater penetration of the iron floc into the precoat at high rates and also to the fact that as the cake is deposited at high rates, the iron floc is removed in the cake in a different manner, keeping certain channels open for flow.

H. Constant Head Permeameter Results

The full potentialities of this filter were not developed in this thesis. The general procedures, some developmental possibilities, and some of the problems involved in the use of the apparatus will be included, however, as a guide for future investigations. The advantages of using a constant head permeameter or filter of the type used in this study are discussed in detail in section VI, discussion of test results.

The results of CHP-1 runs are shown in Figure 23. Trial runs indicated that unless runs were started at the same rate of flow through the precoat, considerable variations in results would be obtained. Constant rates of flow through the precoat were obtained for the runs in this series by starting with a

Figure 23. Results of CHP-1 run conducted with a 7-8 mg/l water, a constant head of 4.65 feet of water, and body feeds as indicated



CHP series I
8 mg/l Fe
Constant head
Body feed, mg/l
as indicated
Ln of filtration rate
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
0
5
10
15
20
25
30
Total gallons of filtrate per sq. ft.
100
30
60
40
20

small amount of precoat and then adding enough additional precoat to bring the flow to some constant value for all runs.

It can be seen from Figure 23 that for filtration or flow rates of 25 gpm/sq ft to 15 gpm/sq ft, ln values of 3.2 and 2.7, respectively, the curves are nearly superimposed on each other regardless of the body feed. Below approximately 15 gpm/sq ft, they separate and assume their own individual slopes. The superimposed portions are believed to be due principally to the construction of the apparatus. It can be seen in Figure 2, that the bottom of the septum housing is reduced to a tube which can be closed for precoating purposes. It is believed that this restricted cross section probably acted as a rate controller at high flow rates and that the major portion of the head was dissipated in this section at the high rates. As the head loss in the cake increased, the head loss in the restriction becomes less of a factor and at flows of approximately 15 gpm/sq ft, it becomes negligible. At this point the curves of rate <u>versus</u> total gallons of filtrate assumed the shape associated with the cake composition. For future studies the septum housing should be modified so that the restricted cross section could be removed after the precoat is in place.

VI. DISCUSSION OF TEST RESULTS

A. Optimums

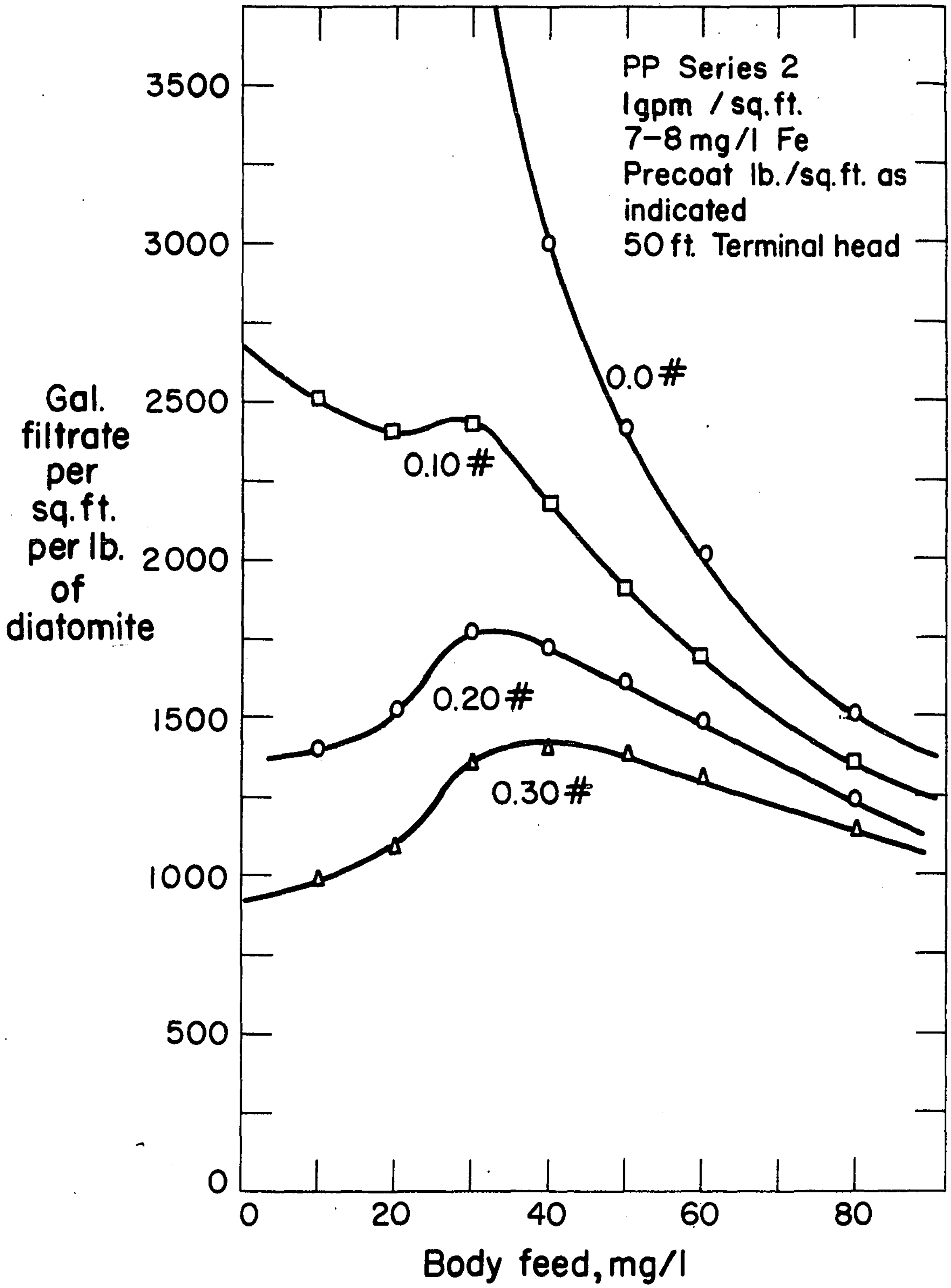
A thorough understanding of the term "optimum" as applied to filtration theory and practice is necessary before the results of this study can be discussed. The term is used differently by research personnel, who often optimize one factor, and by practicing engineers who desire to optimize all factors. In this study several optimums are discussed. The body feed which produces the maximum number of gallons of filtrate, when filtering to some specific head loss, is referred to as the "head loss optimum body feed." The body feed which produces the maximum number of gallons of filtrate per lb of diatomite at some specific head loss is referred to as the "diatomite economy optimum body feed". The body feed, the terminal head loss, and the rate of filtration which combine to produce potable water for a specific city for the minimum cost per gallong, considering all cost factors, are referred to as "optimum body feed", "optimum terminal head loss", and "optimum rate", respectively.

Since all filtration rates, weights of diatomite, and volumes of filtrate obtained were on a per sq ft basis in this study, the term per sq ft will be omitted from further discussions.

B. Diatomite Economy and Head Loss Optimum Body Feeds

The amount of precoat used per run is a factor which can play a significant part in the cost of filtration in a diatomite filtration plant. This precoat effect is demonstrated graphically in Figure 24. The curves in this figure are based upon the results of PP-2 which was conducted to a terminal head loss of 50 feet. The amount of precoat used has little effect on the head loss, consequently, the runs were conducted with a precoat of 0.15 lb/sq ft. Previous studies indicated that a precoat of at least 0.15 lb/sq ft is necessary to prevent fouling of the septum and this amount was used throughout this study. The calculations were based on the total number of gallons of filtrate obtained at the 50 ft terminal head, the amount of body feed used in filtering this amount of water at each body feed, and the amount of diatomite which would have been consumed if the varying precoats shown on the graph were used. The curve designated 0.0 lb represents the maximum number of gallons of filtrate per pound of diatomite which could be obtained at a given body feed if no precoat were used or if only the body feed is considered. Decreasing the amount of precoat brings the resulting curve closer to this maximum or envelope curve. Decreasing the precoat also causes the peak of the curve, the diatomite economy optimum body feed, to shift to lower body feeds. It shifted from 40 mg/l with 0.30 lb/sq ft to 25 mg/l with 0.10 lb/sq ft of precoat. This effect results

Figure 24. Effect of precoat on the gallons of filtrate obtained per pound of diatomite



PP Series 2
1gpm / sq.ft.
7–8 mg/l Fe
Precoat lb./sq.ft. as indicated
50 ft. Terminal head
Gal. filtrate per sq.ft. per lb. of diatomite
3500
3000
2500
2000
1500
1000
500
0
0.0#
0.10#
0.20#
0.30#
0
20
40
60
80
Body feed, mg/l

from the fact that the precoat is most significant in optimum calculations when added to lower body feeds and the smaller the precoat the smaller the body feed which is materially affected.

Figure 25 clearly demonstrates the effect of terminal head loss on the total gallons of filtrate obtained per lb of diatomite. These curves were calculated from the results of PP-2 for a constant amount of precoat. The curves of figure 10, PP-2, were extrapolated to obtain the values for the 100 ft curve. The same envelope or maximum number of gallons of filtrate per lb of diatomite which was noted in Figure 24 is applicable in this situation. This envelope represents the maximum number of gallons of filtrate which could be obtained per lb of diatomite, based on both precoat and body feed, if the run were conducted to an infinite head loss. The diatomite economy optimum body feed decreases with increasing head. It shifts from 50 mg/l at 10 feet of head loss to 25 mg/l at 50 feet of head loss and disappears at head losses of 100 feet or greater. A mechanical limitation controls the actual head loss which can be obtained in practice. In some cases little or no body feed appears to produce more water than the body feed at which the curve peaks. These low body feeds are usually not feasible since cake cracking develops and acceptable water is not produced.

The curves in Figure 26 show vividly the difference between diatomite economy optimum body feed and head loss optimum body feed. These graphs were prepared from the results of

Figure 25. Effect of terminal head loss on the gallons of filtrate obtained per lb of diatomite

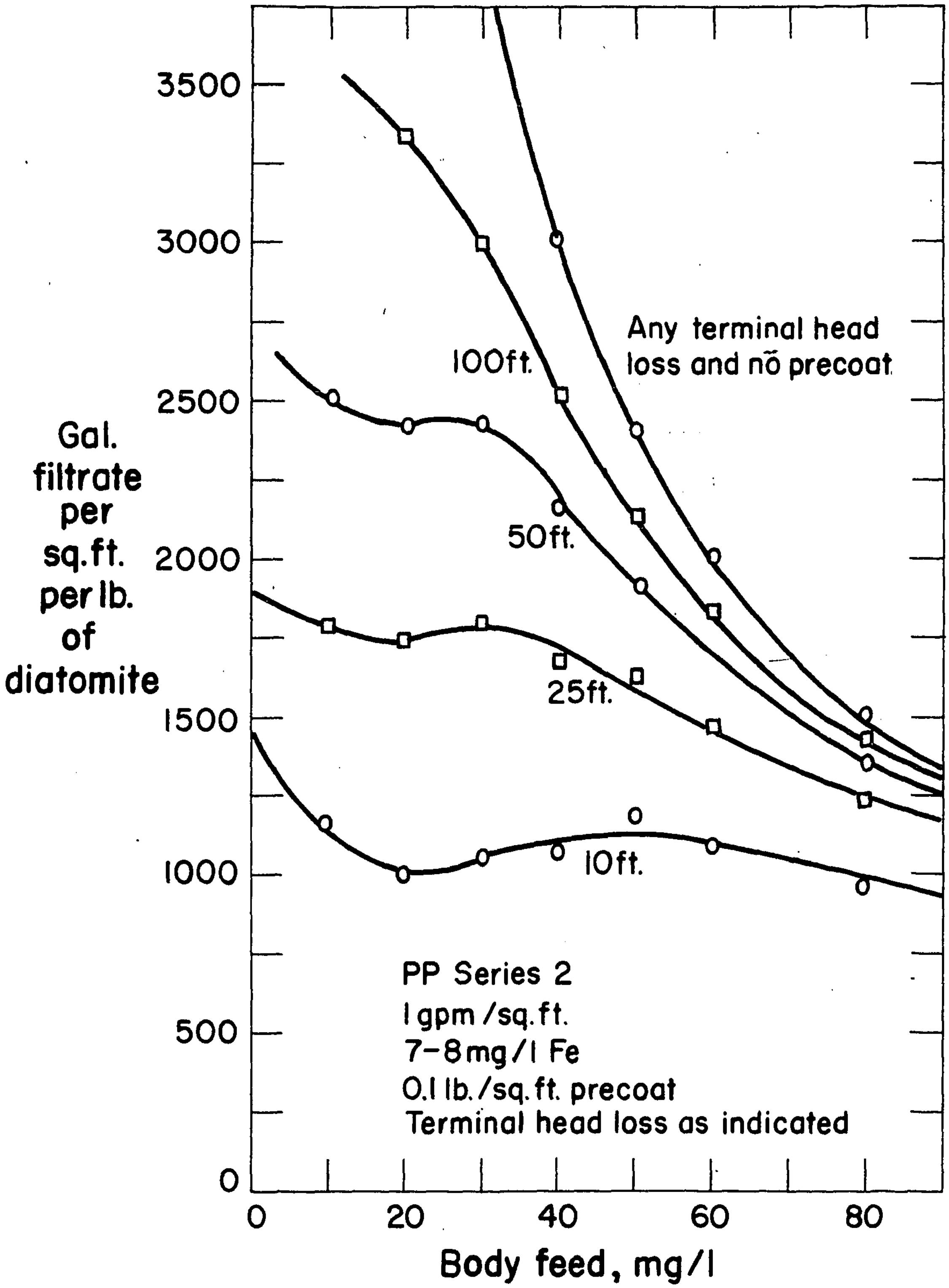
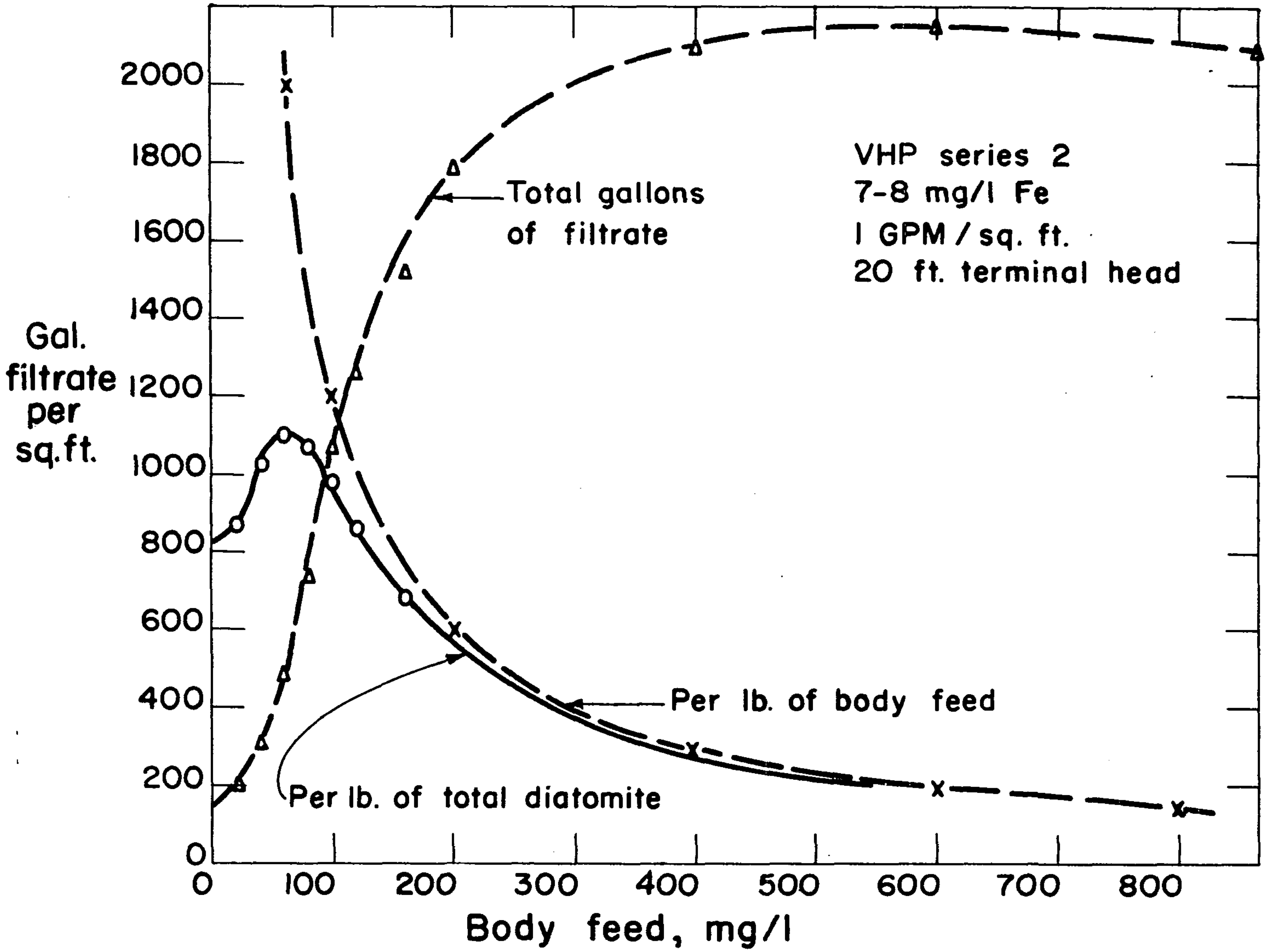

3500
3000
2500
2000
1500
1000
500
0
Gal. filtrate per sq.ft. per lb. of diatomite
0
20
40
60
80
Body feed, mg/l
Any terminal head loss and no precoat
100ft.
50ft.
25ft.
10ft.
PP Series 2
1 gpm /sq.ft.
7-8 mg/l Fe
0.1 lb./sq.ft. precoat
Terminal head loss as indicated

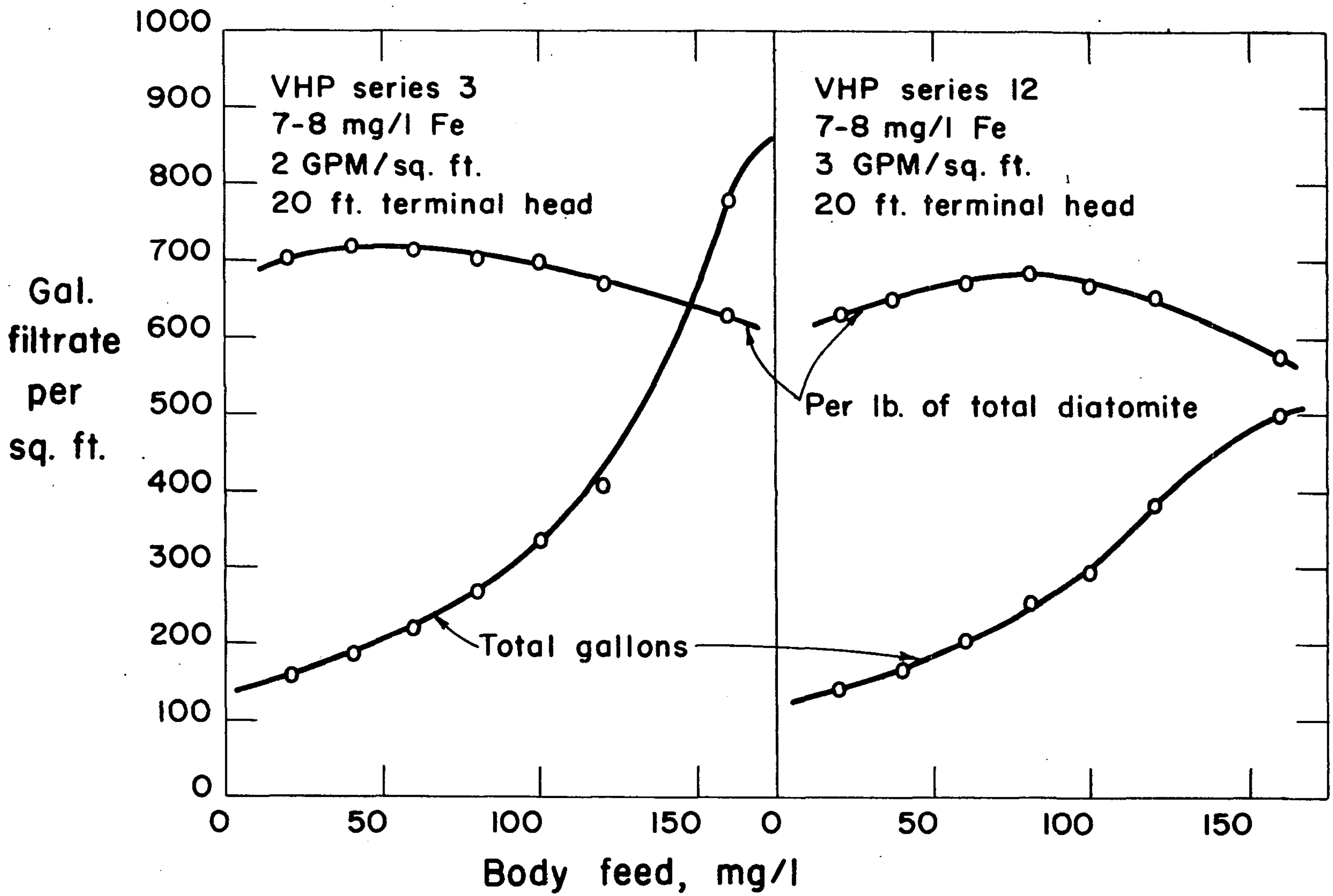
Figure 26. A comparison of diatomite economy optimum body feed and head loss optimum body feed for VHP-2



VHP series 2
7-8 mg/l Fe
1 GPM / sq. ft.
20 ft. terminal head
Total gallons of filtrate
Per lb. of body feed
Per lb. of total diatomite
Gal. filtrate per sq.ft.
Body feed, mg/l
0
200
400
600
800
1000
1200
1400
1600
1800
2000
100
300
500
700

VHP-2 conducted at 1 gpm/sq ft with water containing 7-8 mg/l iron. The curve marked "gal of filtrate per lb of total diatomite" has a peak value at approximately 50 mg/l of body feed. This is the body feed which should be used for a filter run with this water and filter operated to a head loss of 20 feet with 0.20 lb of precoat to obtain the maximum number of gallons per lb of diatomite. This body feed is called, therefore, the diatomite economy optimum body feed. The curve labeled "total gal of filtrate" has a peak point at approximately 600 mg/l. This is the body feed for this water and filter system which will produce the maximum number of gallons of filtrate per run to any terminal head loss. It is also the body feed which will produce the lowest head loss for the production of a specific amount of filtrate. For this reason, it is called the head loss optimum body feed. As the ratio of body feed diatomite to suspended solids in the cake increases, the cake becomes more porous. At the head loss optimum body feed, the beneficial effect of the increased porosity is balanced by the increased thickness of the cake through which the water must pass. At higher body feeds, the increased cake thickness effect outweighs the increased porosity. Figure 27 shows the relation between gallons of filtrate per lb of diatomite and total gallons of filtrate per run, for body feeds up to 150 mg/l, from VHP-3 at 2 gpm/sq ft and VHP-12 at 3 gpm/sq ft. Similar relations were found for the remainder of the series but these have not been shown graphically.

Figure 27. Gallons of filtrate per lb of diatomite and total gallons of filtrate per run relations for VHP-3 and VHP-12


VHP series 3
7-8 mg/l Fe
2 GPM/sq. ft.
20 ft. terminal head
VHP series 12
7-8 mg/l Fe
3 GPM/sq. ft.
20 ft. terminal head
Gal. filtrate per sq. ft.
Per lb. of total diatomite
Total gallons
Body feed, mg/l
0
100
200
300
400
500
600
700
800
900
1000
50
150

C. Rate and Water Comparisons

The effect of rate of filtration on the diatomite economy optimum body feed is shown in Figure 28. There was a large variation in the number of gallons of filtrate per lb of diatomite obtained, particularly between 1 gpm and 3 gpm. There does not appear, however, to be much variation between the body feeds at which the maximum number of gallons were obtained for each rate. The diatomite economy optimum body feed appears to be between 50 and 70 mg/l. This would tend to indicate that although less filtrate was obtained per lb of diatomite at high filtration rates, the cake development followed the same pattern for different body feed rates when the filtration rate was constant.

Figure 29 is a plot of total gallons of filtrate to a terminal head of 25 feet versus the rate of filtration for the 7-8 mg/l iron water. The curves indicate that for all body feed rates, more filtrate per run was obtained as the filtration rate was decreased. This increase in volume of filtrate was small at low body feed rates but became very pronounced at high body feeds. The largest difference in the amount of filtrate obtained was between 1 and 2 gpm rates. Less difference was noted between the 2 and 3 gpm filtration rates. Figure 30 and Figure 31 reflect the same relationships for the 4 mg/l and 2 mg/l waters respectively. Although both follow the same pattern as the 7-8 mg/l water, the difference

Figure 28. Effect of filtration rate on the diatomite economy optimum body feed

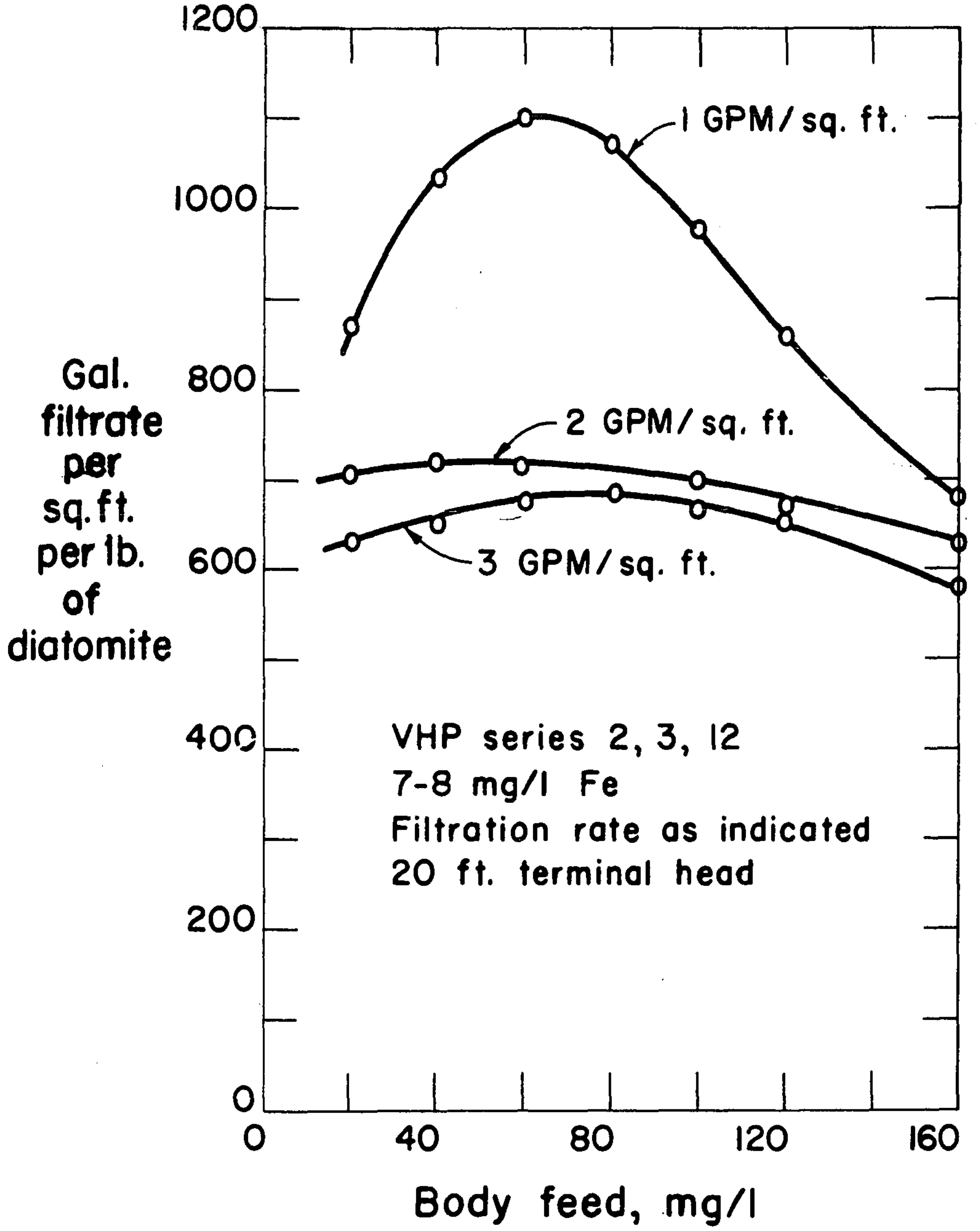

1200
1000
800
600
400
200
0
Gal. filtrate per sq. ft. per lb. of diatomite
1 GPM/sq. ft.
2 GPM/sq. ft.
3 GPM/sq. ft.
VHP series 2, 3, 12
7-8 mg/l Fe
Filtration rate as indicated
20 ft. terminal head
0
40
80
120
160
Body feed, mg/l

Figure 29. Total filtrate per run *versus* filtration rate for 7-8 mg/l iron water and various body feeds

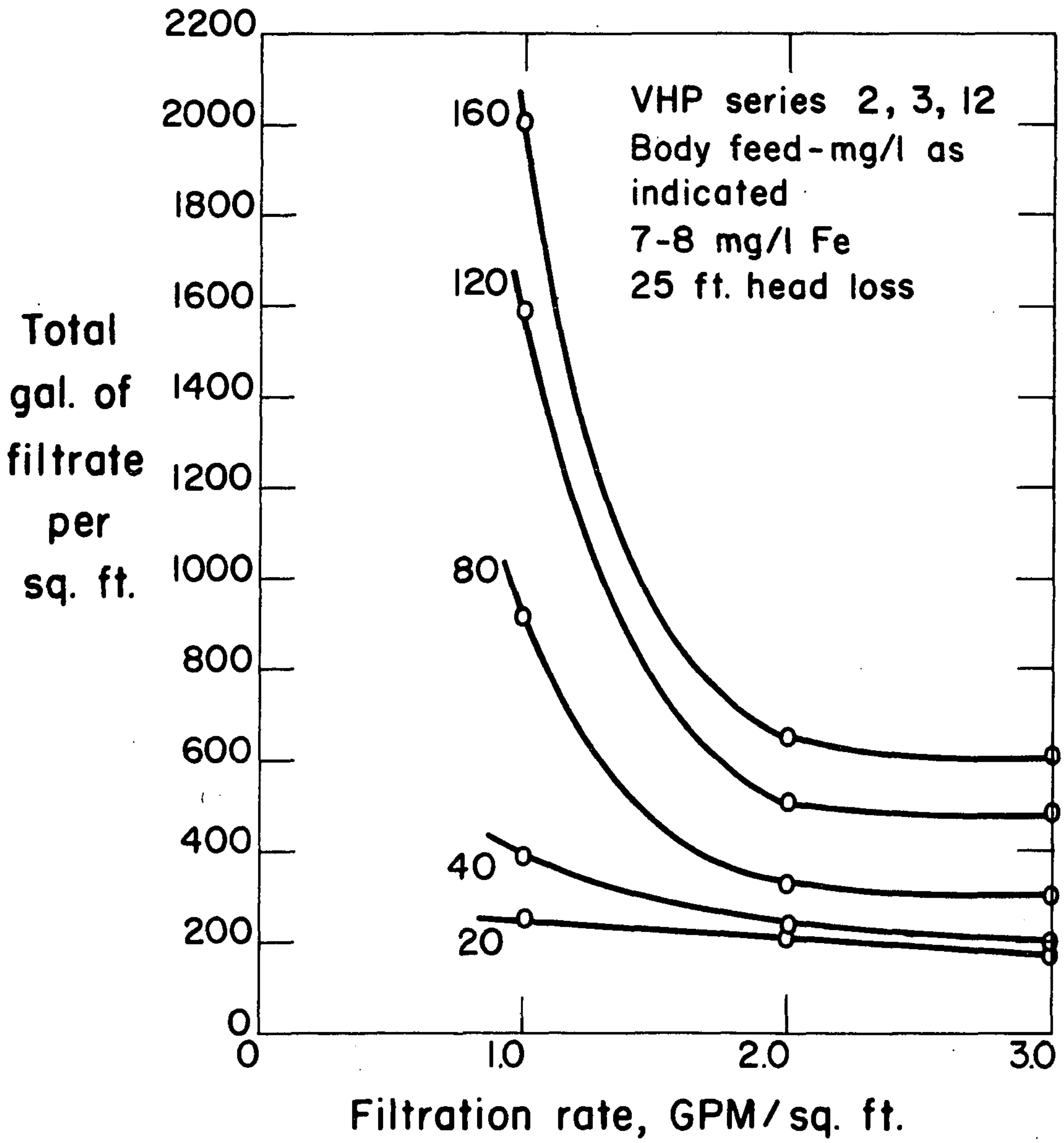

VHP series 2, 3, 12
Body feed-mg/l as indicated
7-8 mg/l Fe
25 ft. head loss
Total gal. of filtrate per sq. ft.
Filtration rate, GPM/sq. ft.
160
120
80
40
20
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
0
1.0
2.0
3.0

Figure 30. Total filtrate per run *versus* filtration rate for 4 mg/1 iron water and various body feeds

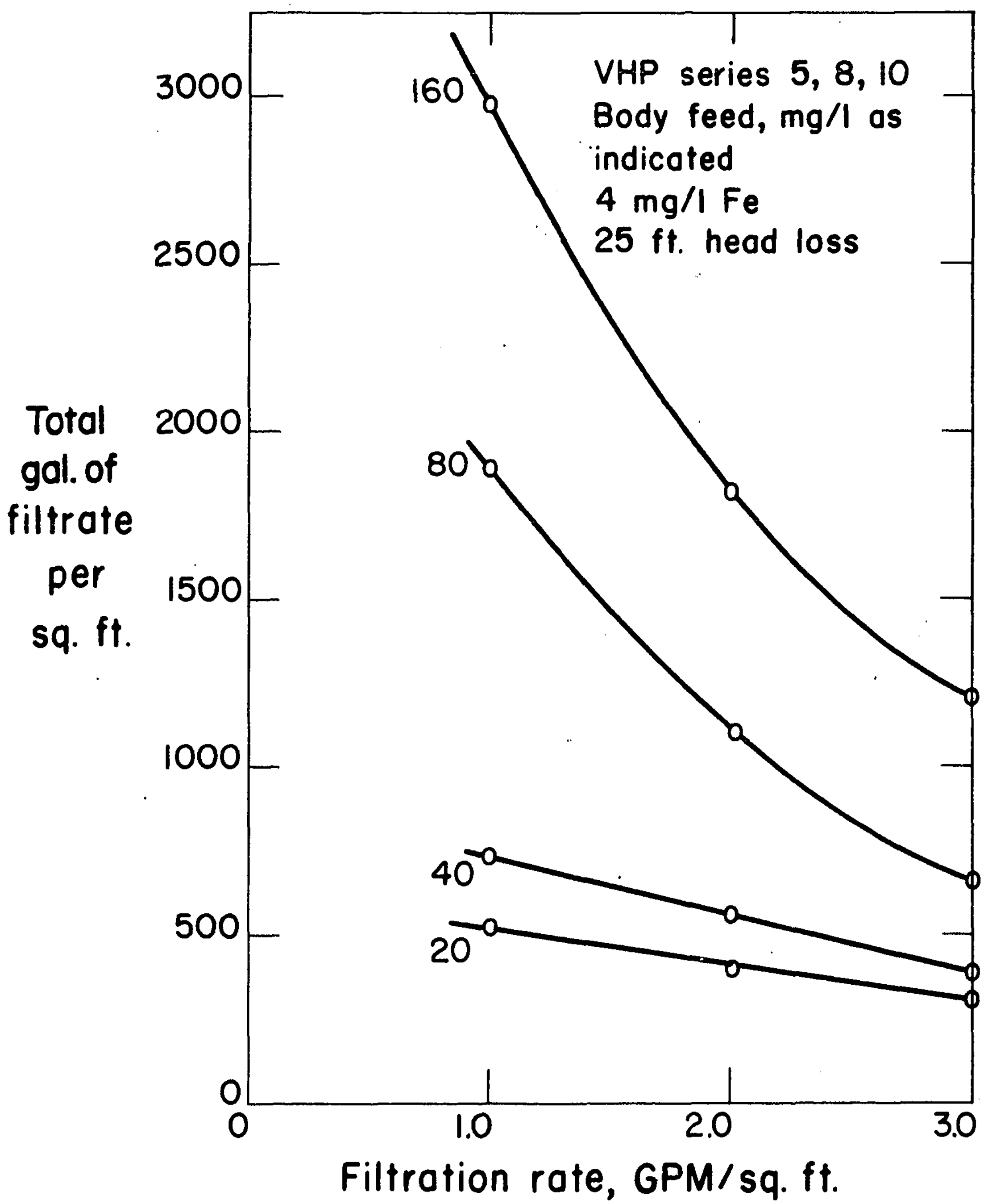
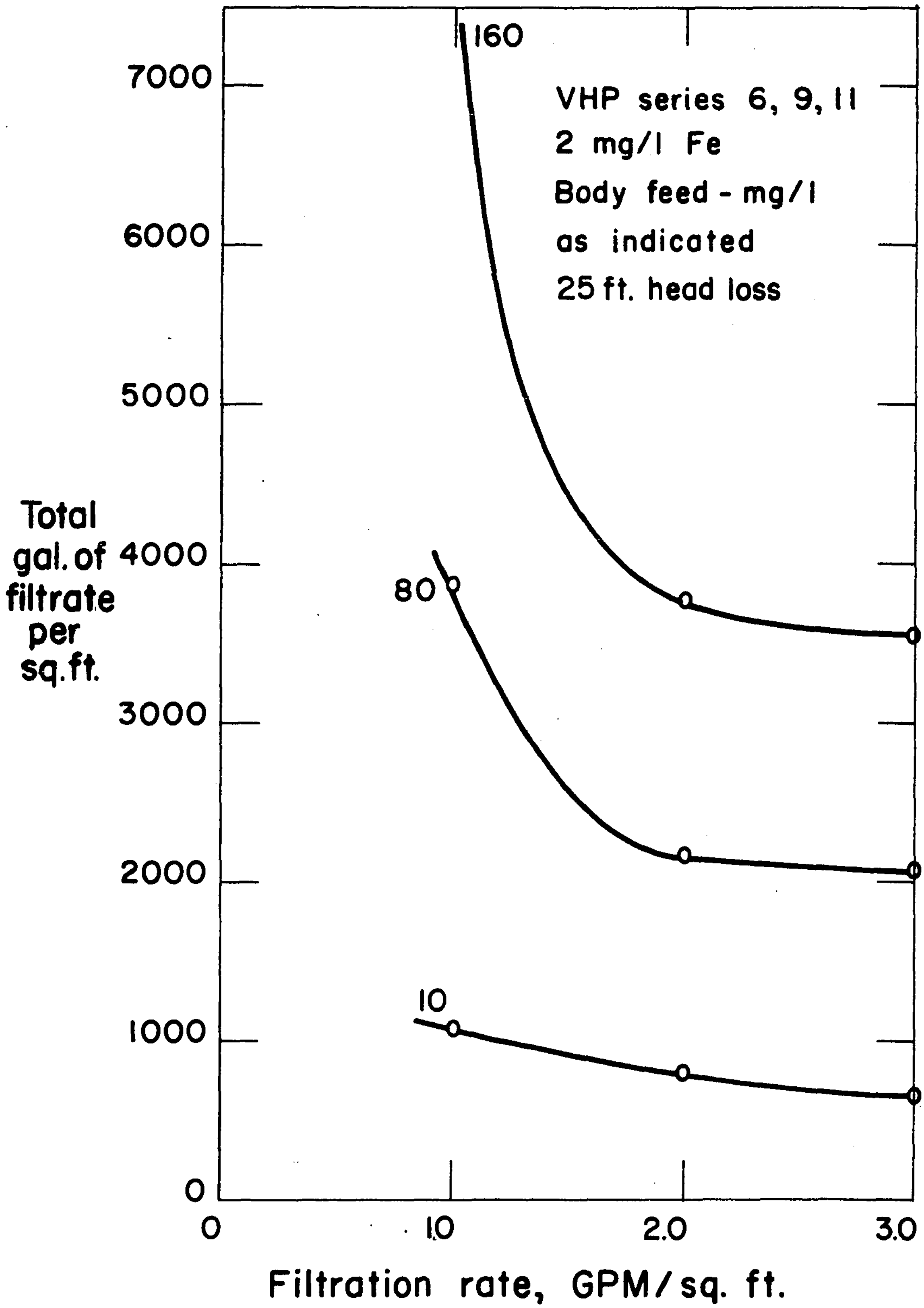

VHP series 5, 8, 10
Body feed, mg/l as indicated
4 mg/l Fe
25 ft. head loss
160
80
40
20
Total gal. of filtrate per sq. ft.
3000
2500
2000
1500
1000
500
0
0
1.0
2.0
3.0
Filtration rate, GPM/sq. ft.

Figure 31. Total filtrate per run *versus* filtration rate for 2 mg/l iron water and various body feeds


160
VHP series 6, 9, 11
2 mg/l Fe
Body feed - mg/l
as indicated
25 ft. head loss
7000
6000
5000
4000
3000
2000
1000
0
Total gal. of filtrate per sq. ft.
80
10
0
1.0
2.0
3.0
Filtration rate, GPM/sq. ft.

between rates are not as pronounced.

Figure 32 shows the relation between gallons of filtrate per lb of diatomite and rate of filtration for the 7-8 mg/l iron water. The diatomite economy optimum body feed would be represented by the body feed which gives the maximum number of gallons per lb of diatomite at the filtration rate under consideration. For this water this optimum is at approximately 50-60 mg/l of body feed.

A comparison of gallons of filtrate per lb of diatomite versus body feed at 1 gpm/sq ft is shown in Figure 33 for the three iron waters used in this study. As would be expected, more gallons of filtrate per lb of diatomite are obtained with lower iron concentrations. Since a lower iron concentration will permit a longer run to a given head loss at a specific body feed, the diatomite economy optimum body feed decreases with decreasing iron content. This optimum body feed varies from approximately 60 to 70 mg/l for the 7-8 mg/l iron water to approximately 12 to 18 mg/l for the 2 mg/l iron water.

Figure 34 portrays graphically a typical relation between head loss development and total gallons of filtrate for one body feed when first the iron concentration is constant and the filtration rate changes and secondly when different iron concentrations are filtered at the same filtration rate. This data was abstracted from a number of different series.

Figure 32. Gallons of filtrate per lb of diatomite *versus* rate of filtration for 7-8 mg/l iron water using various body feeds

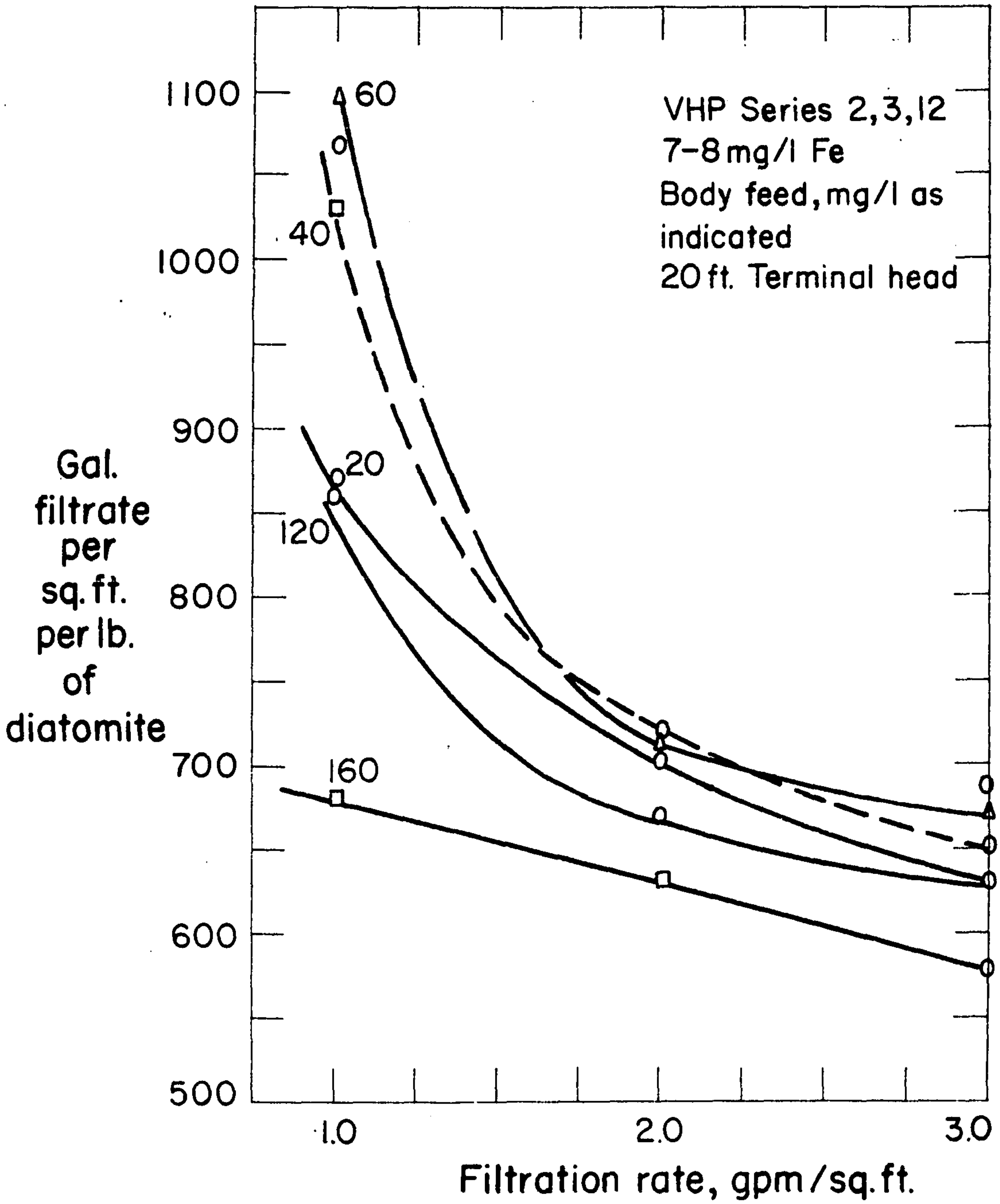

VHP Series 2,3,12
7-8 mg/l Fe
Body feed, mg/l as indicated
20 ft. Terminal head
Gal. filtrate per sq. ft. per lb. of diatomite
Filtration rate, gpm/sq. ft.
1100
1000
900
800
700
600
500
1.0
2.0
3.0
60
40
20
120
160

Figure 33. Gallons of filtrate per lb of diatomite *versus* body feed for 3 iron concentrations filtered at 1 gpm/sq ft

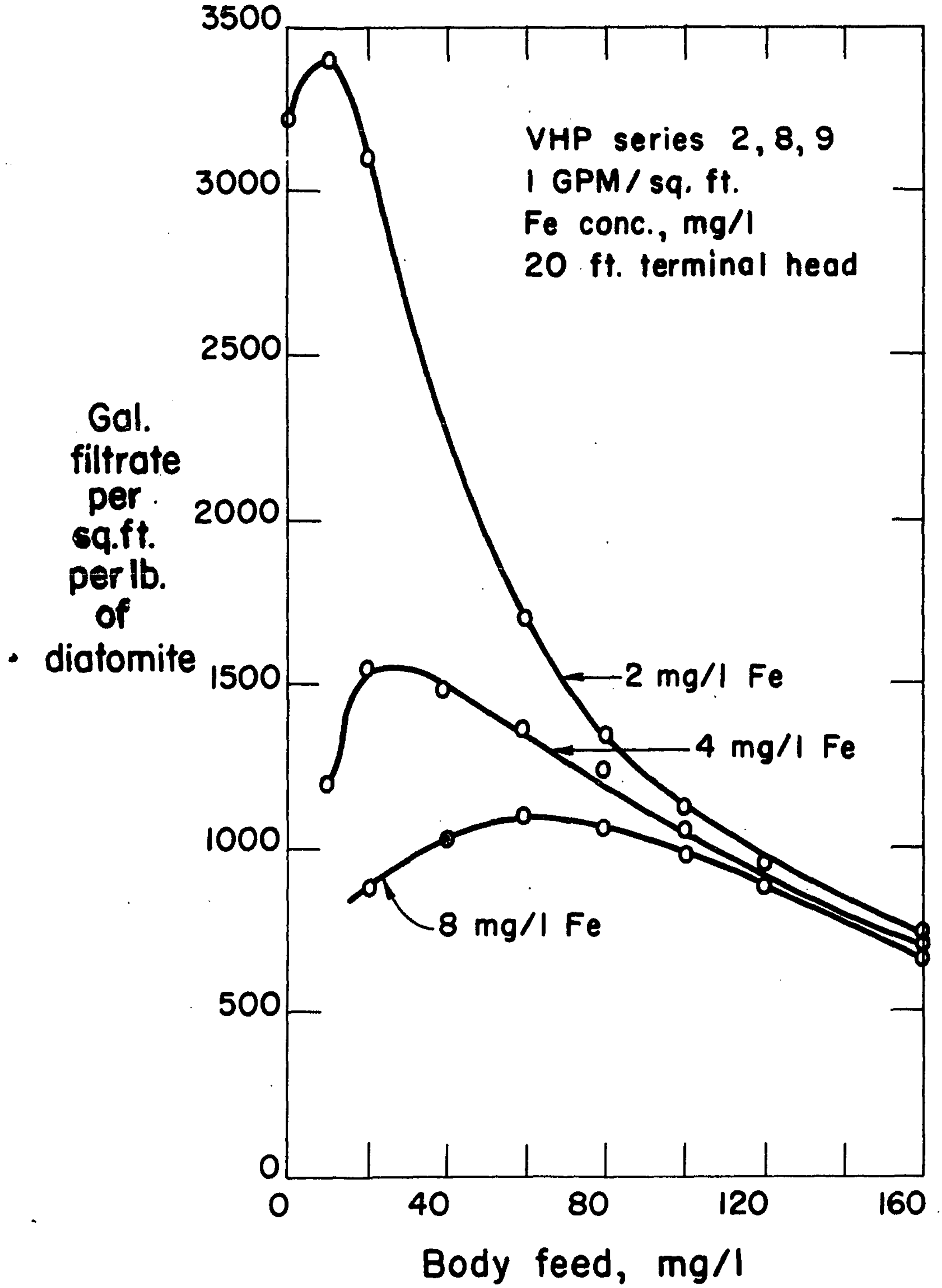
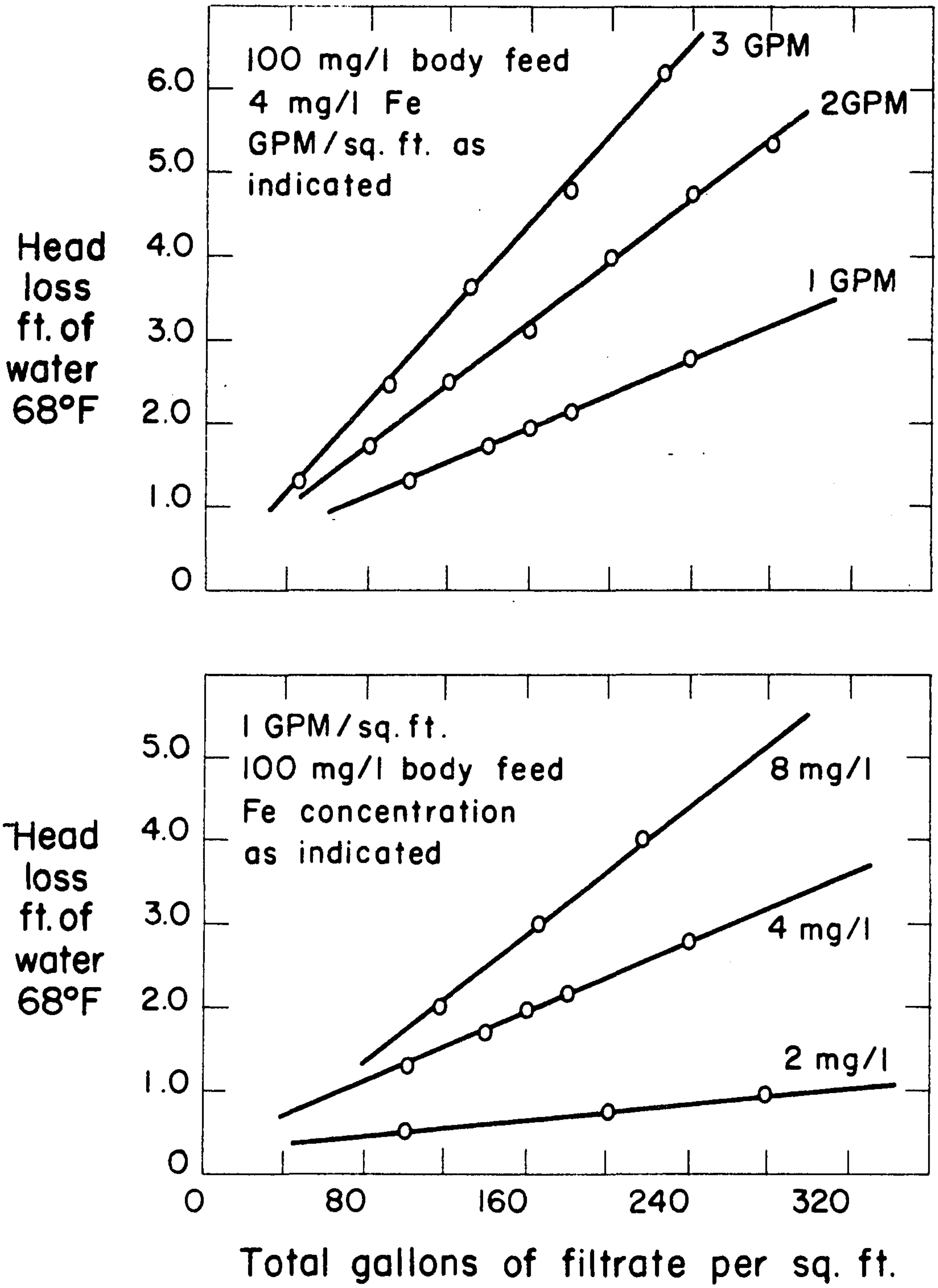

VHP series 2, 8, 9
1 GPM / sq. ft.
Fe conc., mg/l
20 ft. terminal head
Gal. filtrate per sq.ft. per lb. of diatomite
Body feed, mg/l
2 mg/l Fe
4 mg/l Fe
8 mg/l Fe
3500
3000
2500
2000
1500
1000
500
0
0
40
80
120
160

Figure 34. Head loss development with time for different filtration rates with a constant iron content water and for different iron waters at a constant filtration rate


100 mg/l body feed
4 mg/l Fe
GPM/sq. ft. as indicated
3 GPM
2GPM
1 GPM
Head loss ft. of water 68°F
6.0
5.0
4.0
3.0
2.0
1.0
0
1 GPM/sq. ft.
100 mg/l body feed
Fe concentration as indicated
8 mg/l
4 mg/l
2 mg/l
Head loss ft. of water 68°F
5.0
4.0
3.0
2.0
1.0
0
0
80
160
240
320
Total gallons of filtrate per sq. ft.

D. Copper Additions

The complete oxidation of ferrous iron to the ferric state:

$$H_2O + 2\ Fe^{++} + \tfrac{1}{2}\ O_2 \longrightarrow 2\ Fe^{+++} + 2OH^- \qquad 13$$

by aeration is a relatively slow process. It was found that the 15 minute aeration and detention time in the mixing tank and the short detention time in the filter was not sufficient to convert all of the iron to the ferric form. This was evidenced by ferrous iron which passed through the filter cake, particularly at high filtration rates. When water from the mixing tank was allowed to stand for several hours, it was noted that the pH increased from 7.3 to approximately 7.8. This can be explained from equation (13). As the reaction proceeds, additional (OH^-) ions are produced which would tend to make the solution more basic.

It has been reported previously that the addition of copper to the water speeds up the reaction in equation 13. No studies have been made, however, on amounts of copper necessary, reaction rates, or the mechanisms involved. The general reaction can be explained by the variable oxidation states which copper can assume. As the copper is added to the water, it will be acted upon by the ferrous iron to form:

$$Fe^{++} + Cu^{++} \longrightarrow Fe^{+++} + Cu^{+} \qquad 14$$

In this form, the copper readily assimilates an oxygen molecule:

$$Cu^{+} + O_2 \rightarrow (Cu\ O_2)^{+} \qquad 15$$

The copper in effect operates as a carrier, for in the $(Cu\ O_2)^{+}$ ion form the oxygen readily oxidizes additional ferrous iron to the ferric state:

$$H^{+} + (Cu\ O_2)^{+} + Fe^{++} \rightarrow Cu^{++} + (HO_2)^{-} + Fe^{+++} \qquad 16$$

This oxidation releases the copper ion which in turn picks up another oxygen molecule and repeats the process. Still additional conversion of ferrous iron to the ferric state is accomplished by the $(HO_2)^{-}$ ion:

$$3\ H^{+} + (HO_2)^{-} + 2\ Fe^{++} \rightarrow 2\ Fe^{+++} + 2\ H_2O \qquad 17$$

More complicated intermediary steps no doubt exist, however, this is the general concept of the reaction which takes place.

Oxidation by copper addition proceeds rapidly and amounts of copper as low as 0.1 mg/l accomplished the reaction as well as did 1.0 mg/l. Both copper influent and copper effluent tests were made in VHP-12. These results are shown in Table 2, and indicate an average retention of copper in the filter of approximately 80 percent. Run 8 of VHP-12, which had an influent concentration of 0.12 mg/l of copper, had an effluent concentration of 0.01 mg/l. However, this concentration was completely effective in converting the ferrous iron to the ferric state. Two duplicate runs, 4 and 5 of VHP-12, were conducted to determine if different influent copper concentrations had an effect on head loss development.

Table 2. Copper influent and effluent concentrations, VHP-12

Run no.	Influent	Effluent	% Cu retained in filter, %
4	1.32	0.30	77
5	0.66	0.12	82
7	0.33	0.08	76
8	0.12	0.01	91

Run 4, containing 1.32 mg/l of Cu and 80 mg/l of body feed demonstrated almost exactly the same head loss development as run 5 with 0.66 mg/l of Cu and 80 mg/l of body feed.

E. Diatomite Theory Application

To utilize the theory developed in section II-B, the two constants K_3 and K_4 of equation 12 must be known. The constant K_3 is a function of the type of diatomite and the filter while K_4 is a function of the wet density of the diatomite, the porosity, and the in-place density of the iron. Since the porosity and densities individually are difficult to determine and combine to produce one effect, they have been grouped as a constant, K_4, and may be handled in this manner. The total head loss is a function of the two constants, the filtration rate, the weight of precoat, the iron concentration, the body feed rate, and the length of the filter run. These factors are combined in equation 12:

$$h_T = K_3 Q_1 w + \frac{K_3 Q_1^2 T\, C_D \cdot 8.345 \cdot 10^{-6}}{1 - \frac{C_s}{C_D K_4}} \qquad 12$$

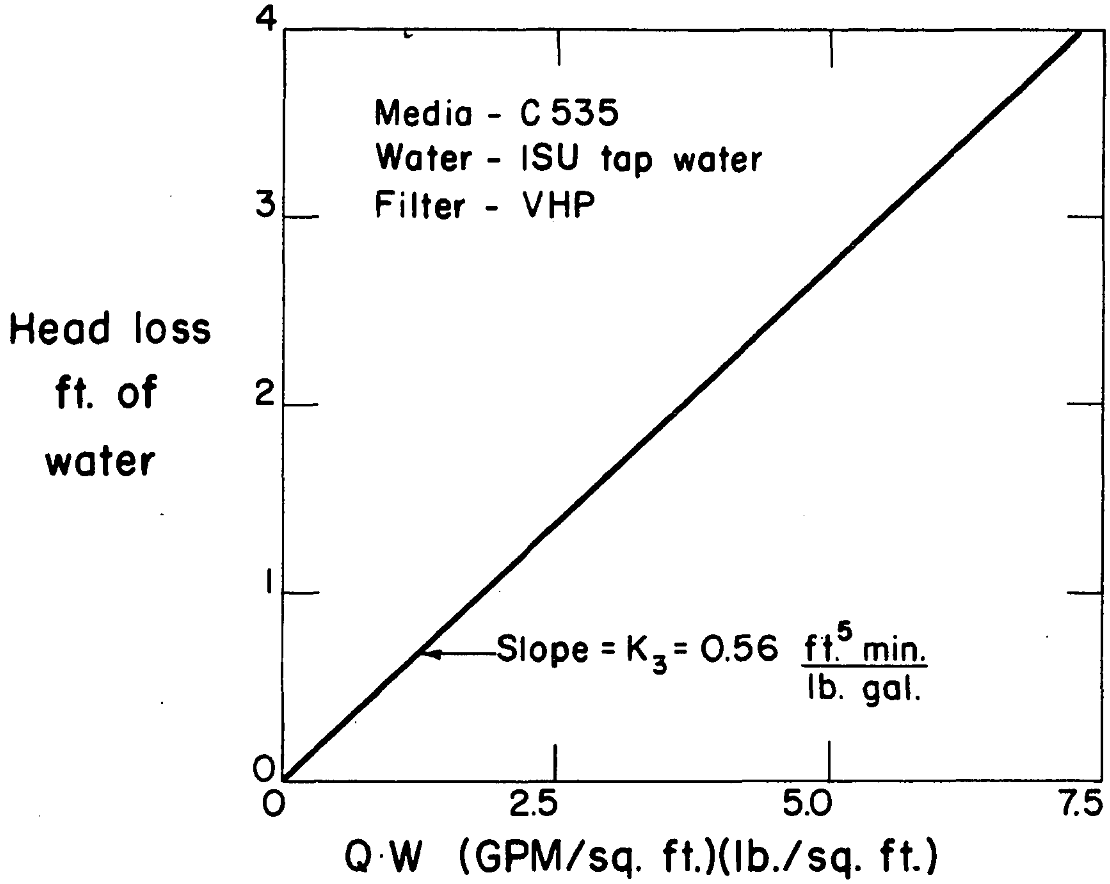
The constant K_3, for C-535 diatomite and the VHP, was obtained by filtering clean water through a layer of precoat diatomite at different rates. Since it is known that:

$$h_1 = K_1\, Q_1\, L_1 = \frac{K_1\, Q_1\, w}{d_D} \qquad 18$$

by plotting h_1 <u>versus</u> $Q_1 \cdot w$, the slope of the straight line obtained is $K_3 = K_1/d_D$. This value of K_3 for C-535 and the VHP was found from figure 35 to be 0.56 ft^5 min/gal lb. This was verified by measuring the thickness of the cake, calculating the value of d_D, finding K_1, and using these values to check the results found using K_3.

The results of over 70 runs were available from the VHP series and were used to solve for K_4. All factors in equation 12 were known for these runs except the constant K_4. Runs were picked at random using different filtration rates, different iron concentrations, and various body feeds to solve for the constant K_4. The value was not found to be a constant. However, when the value K_4 from each run was plotted <u>versus</u>

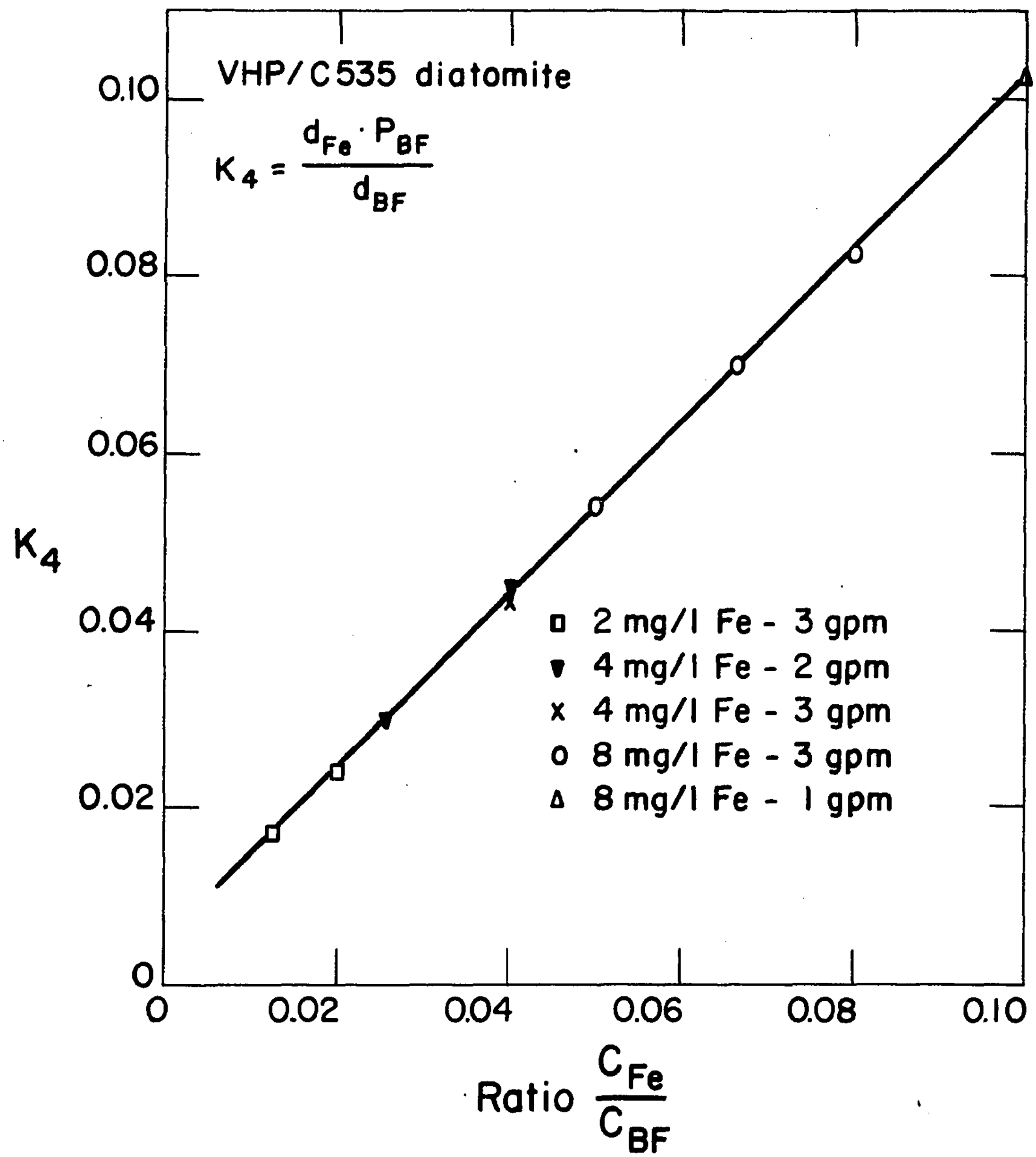
Figure 35. Head loss *versus* filtration rate times weight of pure diatomite/sq ft for determining the constant K_3 of C-535 diatomite and the VHP


Media - C 535
Water - ISU tap water
Filter - VHP
Head loss ft. of water
Slope = K_3 = 0.56 $\frac{ft.^5 min.}{lb.\ gal.}$
0
1
2
3
4
0
2.5
5.0
7.5
Q·W (GPM/sq. ft.)(lb./sq. ft.)

the iron to body feed ratio for that run, the points formed a straight line over the entire range of data, Figure 36. The straight line relation between these two factors for all three waters used and for all three filtration rates is a very significant fact and offers tremendous possibilities for the development of diatomite filtration.

To obtain sufficient information on which to design a municipal diatomite filter for optimum conditions would require 25 to 50 filter runs and possibly more if the suspended solids load varied considerably. The number of these runs could be reduced to 4 or 5 to determine K_3 and the relationship between K_4 and the ratio C_S/C_D. The results of all other typical runs could then be predicted by application of equation 12. A run would have to be made on the filter with the grade of diatomite to be used. This run would give the value of K_3. Several runs would then have to be made at different ratios of C_S/C_D to determine accurately the straight line relation between K_4 and C_S/C_D. An accurate determination of this line is important as a small change in K_4 can result in a large change in the head loss predicted. With values of K_4, equation 12 could be used to develop the families of curves of head loss <u>versus</u> body feed concentration for various rates of filtration and suspended solids concentrations. From these families of curves, a complete analysis could be made for an optimum filter plant design.

Figure 36. K_4 *versus* the ratio of iron concentration to body feed concentration in the cake for the VHP and C-535 diatomite



VHP/C535 diatomite
$K_4 = \frac{d_{Fe} \cdot P_{BF}}{d_{BF}}$
0.10
0.08
0.06
0.04
0.02
0
K_4
2 mg/l Fe - 3 gpm
4 mg/l Fe - 2 gpm
4 mg/l Fe - 3 gpm
8 mg/l Fe - 3 gpm
8 mg/l Fe - 1 gpm
0
0.02
0.04
0.06
0.08
0.10
Ratio $\frac{C_{Fe}}{C_{BF}}$

F. CHP Application

After conducting a considerable number of filter runs with the three filters used in this study, the author is fully aware that reproducability with diatomite filters at least within narrow confidence limits is difficult, that no two waters are the same, that an individual water may vary from day to day, and that for accurate filtrability determinations, the water should be degasified. Regardless of these factors, we must have some method of predicting the filtering characteristics of a given water. We must determine what type of filter aid is best suited to the water, what body feed rate gives optimum conditions, what effects various filter aid coatings have, and what amounts and types of precoat are best.

One method of determining these variables is to move or build a large pilot plant on the site of the proposed plant. This approach presents moving and plant location problems. A pilot plant requires large quantities of water, some previously filtered water, power, and long runs to obtain satisfactory results. Another solution is the use of a model or miniature constant rate pressure filter. This type of apparatus solves some of the problems but in order to reproduce pilot plant or full scale plant results, the model must have the same type of septum and the same volume to area ratio as the large plant. The runs are long, a body feeder is required, the tests must still be conducted at the raw water site, and many of the other problems are still present.

A different approach is offered by the use of a constant head permeameter or constant head filter. It has many advantages but presents the problem of predicting constant rate-variable head results from constant pressure-variable rate tests. As long as the flow in both cases is in the laminar range, this relation should be possible. A CHP of the type described in this study, has the advantage of needing only a small amount of water, 2-5 gal, to conduct a test run. The water to be tested could be brought to a laboratory for test purposes or the filter could be easily transported to the site. The CHP does not require a body feeder since the small amount of water to be tested can be mixed with the appropriate amount of diatomite as body feed and filtered. The test runs are short and 10-15 gal of filtered water is sufficient for operation of the filter. The equipment needed is limited and the operation is simple.

The CHP could be correlated with the pilot plant or full scale filter of the type proposed for the new filter plant. Runs on the water in question conducted with the CHP could then be transposed into the type of curves of head loss *versus* gal of filtrate normally obtained from a constant rate filter. From these results, the optimum design for the new plant could be obtained. The objective of this portion of this study was to demonstrate how these tests could be conducted and how the results of the CHP and a constant rate filter could be correlated.

The operation of the filter and the results of CHP-1 have been discussed previously. For the purpose of demonstrating a method of correlation, the results of CHP-1 will be related to those obtained by constant rate filtration of the same water in VHP-2. Since the results of CHP runs of filtration rate <u>versus</u> total gallons of filtrate plotted as a straight line on semi logarithmic graph paper and the results of the VHP runs plotted as straight lines on normal arithmetic scales, the first relation tried for each body feed was of the form:

$$S_{CHP} = C \cdot S_{VHP} \qquad 19$$

where:

S_{CHP} = slope of a CHP run. (ln rate/gal)

C = a constant

S_{VHP} = slope of the corresponding VHP run (Δ head loss/gal)

This method produced a different value of the constant for each body feed. This would have been an acceptable method of relating the two systems but an equation which related the curves for all body feeds would be more desirable. A relation of the type:

$$S_{CHP} = C\ (S_{VHP})^{x} \qquad 20$$

was tried next. The equations relating the slopes for two body feeds were solved simultaneously and the resulting equation was:

$$S_{CHP} = 0.3 \cdot (S_{VHP})^{\frac{1}{2}} \qquad 21$$

This equation was then applied to the other body feeds and it was found that the values predicted from equation 21 checked the experimental values within 3 percent as shown in Table 3. The results of CHP-1 were also related to PP-2 and although the constant and exponent were slightly different, the same type of equation related all slopes. Other methods of relating the equations of the two lines were tried but they could all be reduced to the system used. Equation 20 might be considered a coupling equation for the results of the CHP and VHP.

Table 3. Comparison of CHP-1 and VHP-2 results

Body feed (mg/l)	S_{VHP}-exp. (head/gal)	S_{CHP}-exp. (ln rate/gal)	C_{CHP}-calculated (ln rate/gal)
20	0.111	0.1	0.10
40	0.0715	0.081	0.080
60	0.0416	0.0625	0.610
80	0.0278	0.0515	0.050
100	0.0191	0.041	0.0415

The results indicated that test data from a constant head filter can be transposed to obtain variable head filter results. A complete development of the constant head system to include the modification of the septum housing previously mentioned and the verification of the relations described, using different waters, would simplify considerably the preliminary tests necessary to obtain the data on which to design a municipal filter plant.

VII. EVALUATION OF DATA FOR DESIGN PURPOSES

A. Factors to Be Considered

Two factors are of ultimate importance in the design of a diatomite filter plant; acceptable water quality and the minimum total cost per gallon for the water. This study has not been concerned with the quality of water as produced by different grades of filter aid but studies have been made on this subject. In general, the coarsest grade of filter aid which produces acceptable water should normally be used since it will give the lowest head loss. The second factor, the minimum cost per gallon, is the most complicated factor and consequently the one most often neglected.

To design a plant which will produce acceptable water at a minimum cost per gallon requires a consideration of the four basic factors which influence this cost: diatomite, labor, power and equipment. Some combination of these four factors will give a minimum cost per gallon and this point will determine the optimum filtration rate, body feed, and head loss. The calculation of the minimum cost requires several items. A series of curves of head loss *versus* time for different body feeds and at different filtration rates must be available. These may be obtained by use of equation 12 when constants K_3 and K_4 have been determined. The cost of diatomite per lb must be known as well as the cost of power *versus* terminal head loss. A curve of labor cost *versus* length of run must also be calculated. With these tools, an optimum plant design is possible.

One point should be emphasized at this time. Cost factors vary considerably from one location to another as well as with time. Therefore, although local Iowa costs were predicted as accurately as possible in this study, they were used for comparison purposes only to find the optimum plant design and should be considered only in this light.

B. Comparisons Made in This Study

This study produced a series of curves of head loss *versus* gallons of filtrate for different body feeds conducted at three different rates on three different waters. For comparison purposes, these data were used to design both automatic and manually operated diatomite filtration plants for three different sized cities. The rates and water types have been discussed previously. The three cities were designated A, B, and C. City A had a population of 2,000, city B, 10,000 and city C, 50,000. A per capita usage of 100 gal/person/day was assumed as the basis for the amount of water produced. All costs were prorated over the total amount of water produced in the unit of time being considered. Calculations were made at 6 terminal head losses: 25, 50, 75, 100, 150, and 200 ft.

Labor costs were calculated on the basis that a precoating and backwashing operation would require one hour of labor and a periodic 12-hour check of an operating filter would require 1/2 hour. Using these facts and a labor cost of $2.00/hr, the curves in Figure 37 were developed for each city. It was assumed that runs of less than 4 hours would require a 24 hour per day labor force.

Power costs were based on the prevailing rates in Iowa. Since rates decline with an increasing number of kilowatt-hours used, the price decreased with the size of the city. The data used in this study for power cost is shown in Figure 38.

Since a high rate of filtration will require less filter area, equipment cost is a factor which must be considered in a determination of optimum rate. The equipment costs were based on all equipment which would be needed for the plant. This equipment included the filters, rate controllers, recirculation storage tank and pump, body feeder to include hoppers, mixing tank and booster pump, service pumps, and a filter building. Equipment costs were prorated over the water produced in a 15-year period. The costs are shown in Table 4.

Table 4. Costs for a manually controlled diatomite filter plant (equipment)

Rate	cents/1000gal		
gpm/sq ft	Plant A	Plant B	Plant C
1	0.115	0.073	0.056
2	0.089	0.047	0.033
3	0.072	0.019	0.025

Figure 37. Labor cost *versus* length of filtration run for optimum design calculations

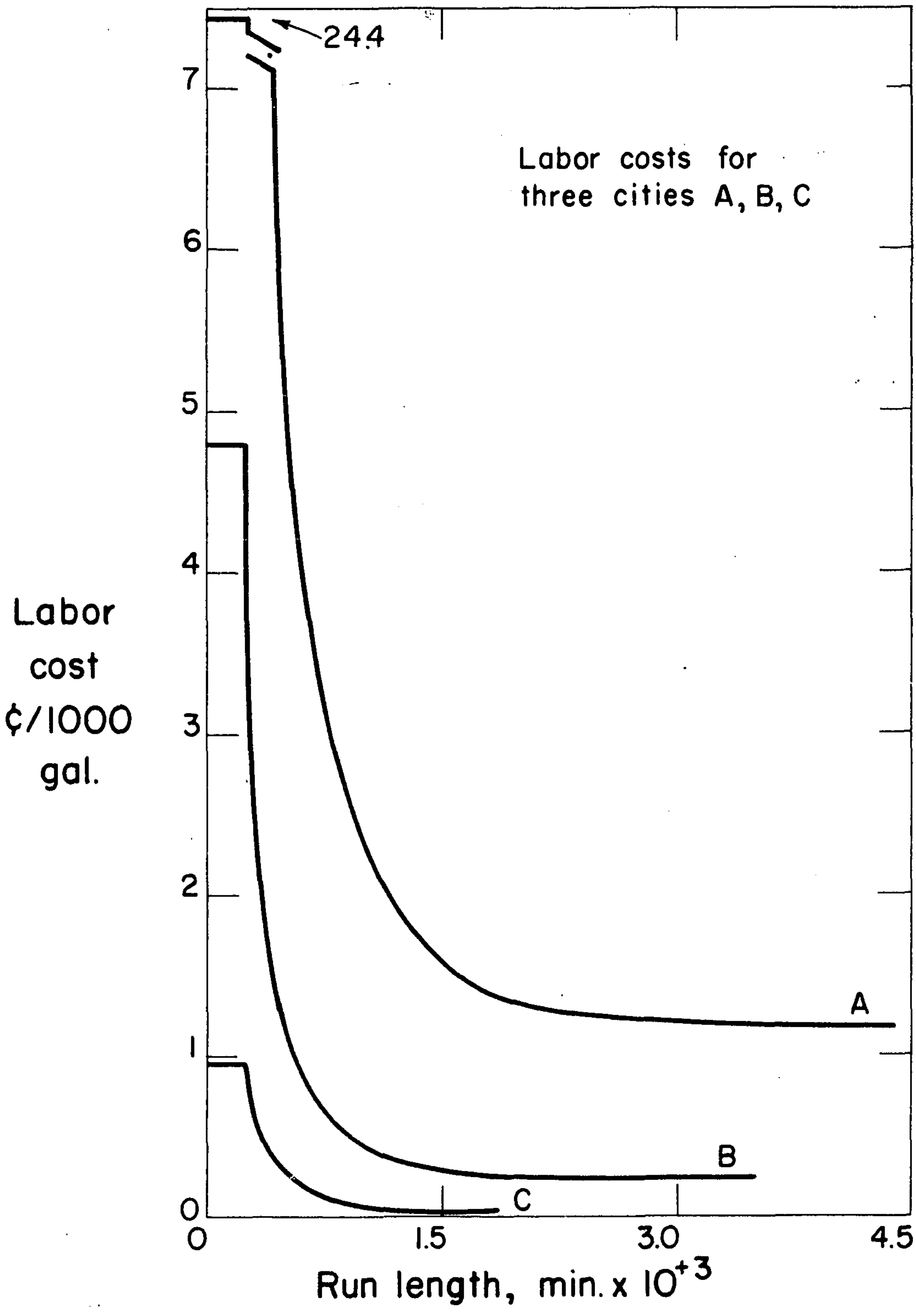
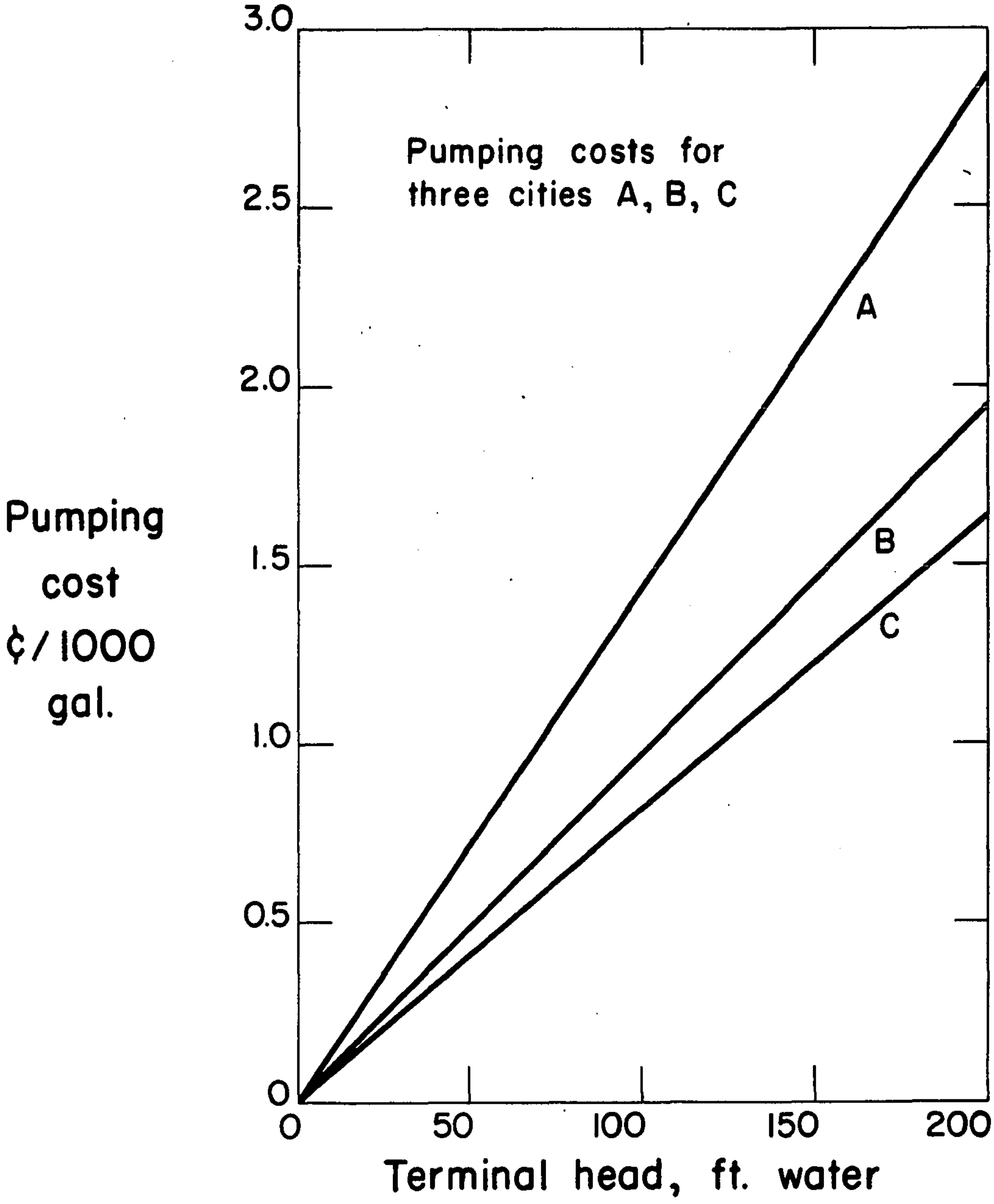

244
Labor costs for three cities A, B, C
Labor cost ¢/1000 gal.
7
6
5
4
3
2
1
0
A
B
C
0
1.5
3.0
4.5
Run length, min. x 10+3

Figure 38. Pumping cost versus terminal head loss for optimum design calculations


Pumping costs for three cities A, B, C
A
B
C
Pumping cost ¢/1000 gal.
3.0
2.5
2.0
1.5
1.0
0.5
0
0
50
100
150
200
Terminal head, ft. water

The costs for automation of the plant included the master control and the wiring of each filter. This cost was added to the equipment cost and the labor cost was deleted from the calculations for the optimum. A small amount of labor would still be required but it would be approximately constant, not being dependent on filtration rate, head loss, or body feed. The total equipment costs including automation are shown in Table 5.

Table 5. Cost for an automatically controlled diatomite filter plant (equipment)

Rate	Cents/1000 gal		
gpm/sq ft	Plant A	Plant B	Plant C
1	0.135	0.080	0.059
2	0.108	0.054	0.036
3	0.082	0.046	0.027

It was found in PP-2 that the plot of head loss _versus_ total gallons of filtrate curved upward slightly for body feed rates of 10 mg/l and 20 mg/l. The terminal head loss possible in the VHP was not high enough for these curves to develop. Therefore, the gallons of filtrate obtained from straight line interpolation at each head loss with these two body feeds on VHP-2, 3, and 12 runs were reduced by the same percentage that the values from PP-2 would have been in error if straight line interpolation had been used. Corrections were made only on the 10 mg/l body feed rate for the water containing 4 mg/l of iron and no corrections were made on the 2 mg/l iron water since the straight line relation should begin at the same iron to body feed ratio in all runs.

Diatomite cost data would depend on the transportation required and quantities purchased. The costs used for this study differed only by the quantity used and were: for plant A, 7.0 cents/lb, for plant B, 6.0 cents/lb, and for plant C, 5.0 cents/lb. The first step in determining the cost for diatomite results in curves similar to those in Figure 25. The cost of diatomite per pound is derived by dividing the cost per lb of diatomite by the ordinates of this curve, gal per lb, and multiplying the result by 1000 to give the cost per 1000 gallon.

C. Results of Comparisons

A detailed description of the calculations made for one city and one water are shown in the Appendix. Basically it consisted of finding the minimum combination of labor, power, diatomite, and equipment cost at each filtration rate, and the body feed and head loss at which the minimum occurred. Cost per 1000 gallons was plotted *versus* body feed rate for each filtration rate and the point which represented the lowest cost on the entire graph determined the optimum body feed and rate of filtration. The head loss at which this point was determined becomes the optimum head loss.

The results of plotting costs in cents/1000 gal for power, labor, and diatomite *versus* terminal head loss for several body feeds are shown in Figure 39. These are results for a 1 gpm/sq ft filtration rate on the 7-8 mg/l iron water with calculations based on data from city A. It can be noted that the minimum cost occurred at increasingly higher head losses as the body feed rate was decreased. This occurred since low body feed rates produced relatively short runs and with short runs, the labor cost was high. Therefore, the combination of costs which give a total minimum cost at low body feeds resulted at the higher head losses. As the body feed was increased, the run length increased and labor costs were reduced so that a minimum was achieved at a lower head loss. At body feed rates above 80 mg/l, the variation between the cost at 25 ft and 50 ft of terminal head was negligible.

The results from plotting cents/1000 gal for power and diatomite used in an automatically operated plant *versus* terminal head loss for several body feeds are shown in Figure 40. These calculations are for the same data as shown in Figure 39. However, in this case it was assumed that the plant was automatically controlled. It can be noted that the minimum costs at each body feed occurred at lower head losses for this automatic operation. High head losses were not necessary for automatic operation since labor costs, which depend on run length, were not included.

Figure 41 shows the final results of the calculations

Figure 39. Cost of labor, power and diatomite per 1000 gallons of filtered water, from VHP-2 for city A, manually controlled, as a function of terminal head loss for various body feeds

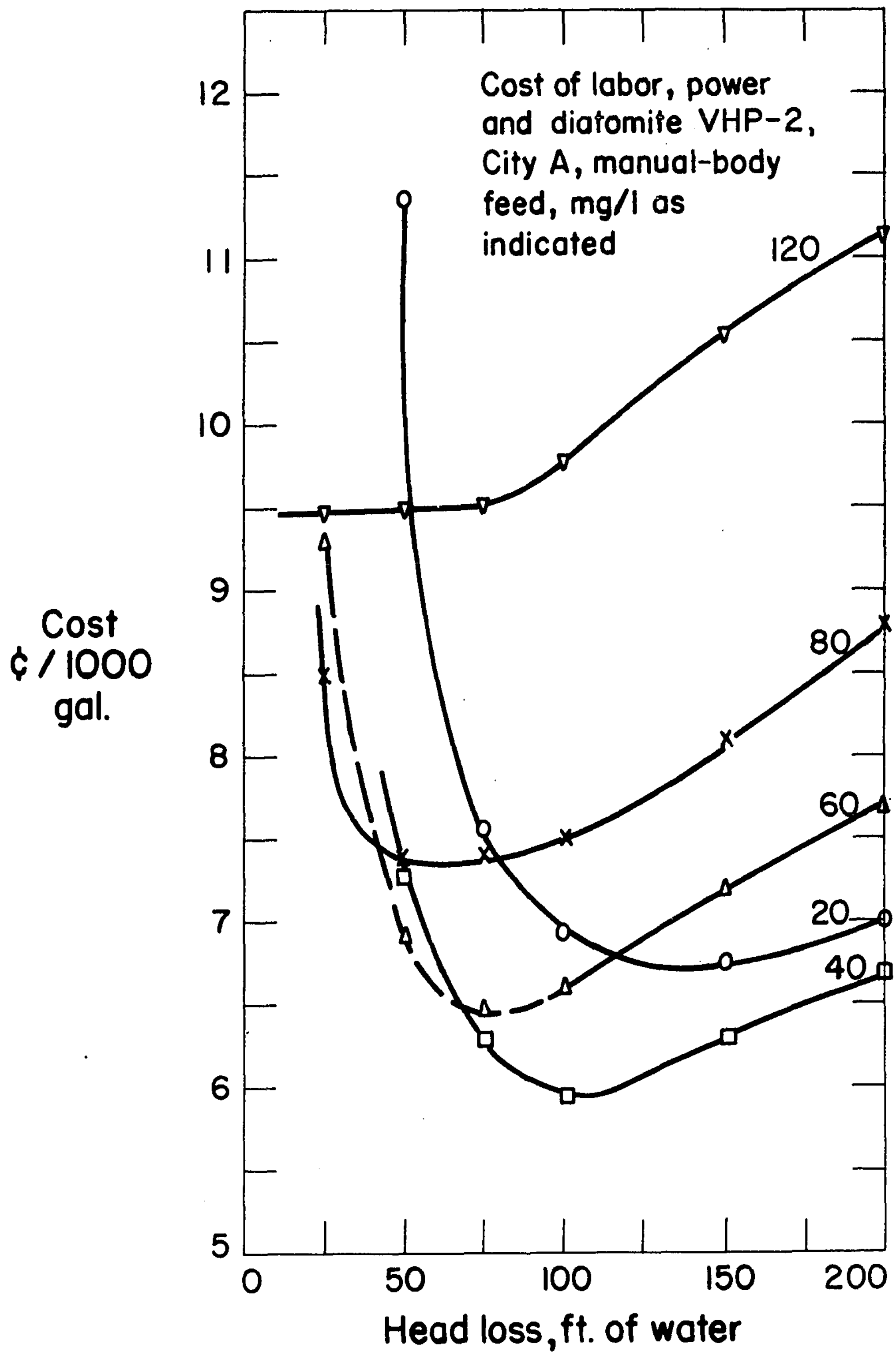
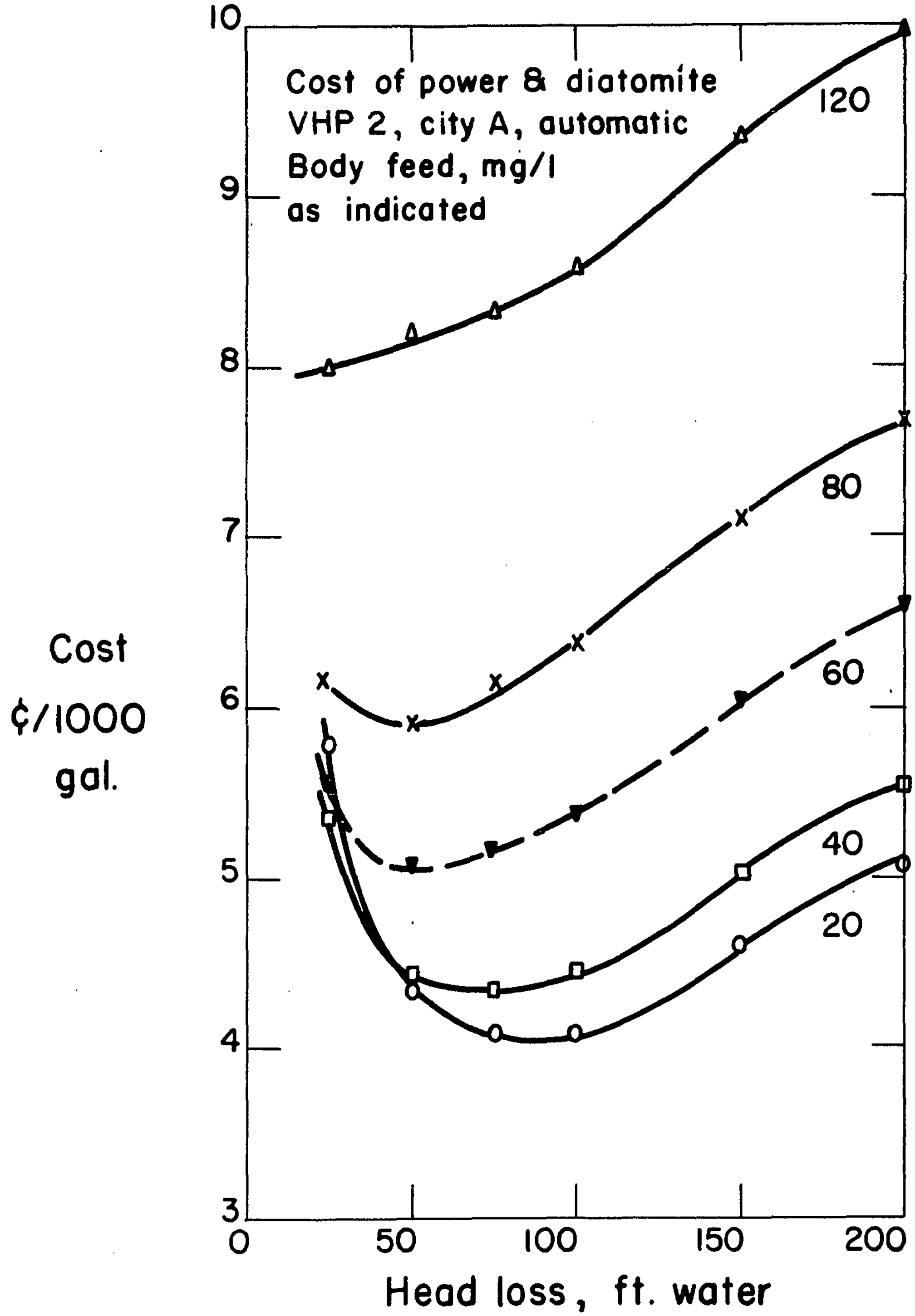
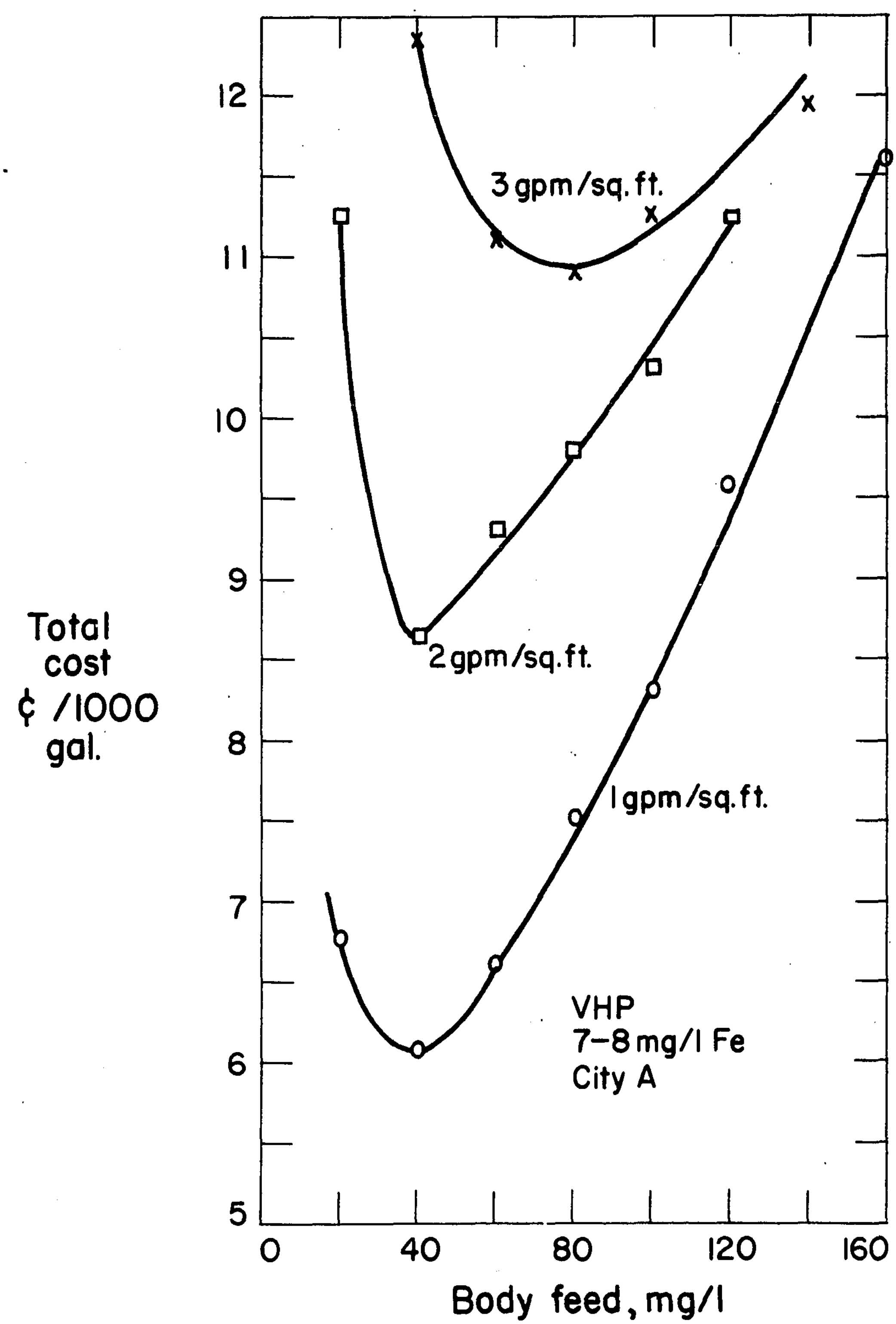

Cost of labor, power and diatomite VHP-2, City A, manual-body feed, mg/l as indicated
120
80
60
20
40
Cost ¢ / 1000 gal.
12
11
10
9
8
7
6
5
0
50
100
150
200
Head loss, ft. of water

Figure 40. Cost of power and diatomite per 1000 gallons of filtered water, from VHP-2 for city A, automatically controlled, as a function of terminal head loss for various body feeds



Cost of power & diatomite
VHP 2, city A, automatic
Body feed, mg/l
as indicated
120
80
60
40
20
Cost
¢/1000
gal.
10
9
8
7
6
5
4
3
0
50
100
150
200
Head loss, ft. water

Figure 41. Total cost per 1000 gallons of filtered water as a function of body feed for different rates



12
11
10
9
8
7
6
5
0
40
80
120
160
Total cost ¢ /1000 gal.
Body feed, mg/l
3 gpm/sq. ft.
2 gpm/sq. ft.
1 gpm/sq. ft.
VHP
7–8 mg/l Fe
City A

necessary to determine optimum design conditions for a city. The results shown are for city A with a population of 2000, a 7-8 mg/l iron bearing water, C-535 filter aid, manually operated, a VHP type filter and three rates of filtration. The minimum water production cost for this city, determined from Figure 41, was obtained with a 1 gpm/sq ft filtration rate and 40 mg/l of body feed. From Figure 39 the optimum head loss is observed to be 100 ft. The most significant observation in this determination is the fact that this optimum condition occurs at approximately the lowest body feed which developed a straight line relation between head loss and total gallons of filtrate for this water, see Figure 10.

Similar graphs were developed for each city and each water, but, for simplicity, the data have been consolidated in Table 6. The same trend is obvious. In all cases, a combination of the 1 gpm/sq ft filtration rate, a low body feed, and a relatively high head loss produce the optimum design. The cost decreases slightly for the 4 mg/l water and again for the 2 mg/l water, however, the optimums do not change appreciably. Additional runs to higher head losses and with lower body feed would have to be conducted on low iron concentration waters to determine the optimums exactly. However, it was not possible to obtain acceptable quality water with C-535 filter aid and the VHP at body feed rates much below those

Table 6. Cost comparisons for optimum determinations

	Cents/1000 gal City A 7-8 mg/1 water					
	Manual					
	Rate 1		Rate 2		Rate 3	
Body feed	Min. cost	THL	Min. cost	THL	Min. cost	THL
20	6.765	150	10.239	200	28.662	100
40	6.064	100	8.644	200	12.43	150
60	6.600	75	9.315	200	11.11	200
80	7.475	50	9.820	200	10.92	200
100	8.315	50	10.330	150	11.47	200
120	9.584	25	11.25	150	11.94	150
160	11.61	50	12.43	100	13.96	150
200	13.92	25	14.65	75	-	-
	Automatic					
20	4.075	100	4.318	100	4.672	100
40	4.491	75	5.052	100	5.341	100
60	5.218	50	6.104	100	6.189	100
80	6.095	50	6.987	75	7.026	75
100	7.085	50	7.849	75	8.009	75
120	8.154	25	8.876	50	8.889	50
160	10.360	25	10.71	50	10.990	50
200	12.64	25	12.98	50	--	--

Table 6. (Continued)

	Cents/1000 gal	City A	4 mg/l water			
	Manual					
	Rate 1		Rate 2		Rate 3	
Body feed	Min. cost	THL	Min. cost	THL	Min. cost	THL
10	5.265	100	7.290	200	-	-
20	4.533	100	6.035	150	7.024	200
40	5.339	75	6.376	150	7.891	200
60	6.097	50	6.655	100	8.426	150
80	6.973	50	7.632	75	9.032	150
100	8.003	25	8.611	75	9.530	100
120	9.117	25	-	-	10.290	100
160	11.390	25	11.970	75	12.470	100
200	13.650	25	-	-	14.40	75
	Automatic					
10	3.045	75	3.138	75	-	-
20	3.042	50	3.309	75	3.600	75
40	3.908	50	4.129	50	4.449	75
60	4.837	50	4.886	50	5.336	50
80	5.713	25	5.970	50	6.255	50
100	6.773	25	7.050	50	7.226	50
120	7.887	25	-	-	8.258	50
160	10.810	25	10.380	25	10.560	50
200	12.47	25	-	-	12.720	25

Table 6. (Continued)

Body feed	Cents/1000 gal City A 2 mg/l water					
	Manual					
	Rate 1		Rate 2		Rate 3	
	Min. cost	THL	Min. cost	THL	Min. cost	THL
10	3.202	50	3.928	100	4.985	150
20	3.546	50	4.342	100	4.673	100
40	-	-	5.083	75	5.367	100
60	5.566	25	5.984	50	6.173	75
80	6.599	25	7.244	75	7.311	75
100	7.699	25	8.032	50	8.221	50
120	8.835	25	9.153	25	9.301	50
160	11.130	25	11.410	25	11.520	50
200	-	-	-	-	-	-
	Automatic					
10	1.921	50	2.068	50	2.216	50
20	2.313	25	2.582	50	2.484	50
40	-	-	3.540	50	3.505	50
60	4.356	25	4.552	25	4.475	25
80	5.428	25	5.613	25	5.607	25
100	6.539	25	6.645	25	6.673	25
120	7.675	25	7.771	25	7.804	25
160	9.966	25	10.080	25	10.070	25
200	-	-	-	-	-	-

Table 6. (Continued)

	Cents/1000 gal		City B Manual		7-8 mg/1 water	
	Rate 1		Rate 2		Rate 3	
Body feed	Min. cost	THL	Min. cost	THL	Min. cost	THL
10	----	--	---	--	---	--
20	3.750	100	5.087	150	8.500	100
40	3.919	100	4.935	150	5.704	150
60	4.544	75	5.718	150	6.438	200
80	5.323	50	6.431	150	6.881	150
100	6.172	50	7.017	100	7.642	150
120	7.196	25	7.855	100	8.191	100
160	9.034	25	9.391	75	9.898	100
200	10.990	25	11.310	75	---	--
			Automatic			
10	---	---	---	--	---	--
20	3.156	100	3.394	100	3.706	100
40	3.591	75	4.025	100	4.286	100
60	4.301	75	4.927	100	5.014	100
80	5.080	50	5.723	100	5.757	100
100	5.929	50	6.466	75	6.618	75
120	6.903	25	7.382	75	7.393	75
160	8.791	25	9.035	50	9.267	75
200	10.750	25	10.980	50	---	--

Table 6. (Continued)

	Cents/1000 gal		City B		4 mg/1 water	
	Manual					
	Rate 1		Rate 2		Rate 3	
Body feed	Min. cost	THL	Min. cost	THL	Min. cost	THL
10	2.773	100	3.517	150	---	--
20	2.686	75	3.308	100	3.816	200
40	3.473	75	3.820	100	4.473	150
60	4.245	50	4.394	75	5.161	100
80	5.054	50	5.307	75	5.813	100
100	5.973	25	6.257	75	6.542	75
120	6.928	25	--	--	7.398	75
180	8.896	25	9.064	50	9.342	75
200	10.850	25	--	--	11.130	50
	Automatic					
10	2.360	75	2.434	75	---	--
20	2.393	75	2.575	75	2.810	100
40	3.206	50	3.337	75	3.567	75
60	4.002	50	4.041	50	4.367	75
80	4.811	25	4.970	50	5.223	100
100	5.720	25	5.896	50	6.061	50
120	6.675	25	---	--	6.945	50
180	8.643	25	8.810	25	8.922	50
200	10.600	25	---	--	10.81	50

Table 6. (Continued)

	Cents/1000 gal	City B	2 mg/1 water			
	Manual					
	Rate 1		Rate 2		Rate 3	
Body feed	Min. cost	THL	Min. cost	THL	Min. cost	THL
10	1.756	50	2.000	75	2.327	100
20	2.116	50	2.407	75	2.421	75
40	---	--	3.181	50	3.257	75
60	3.901	25	3.908	50	4.061	50
80	4.801	25	5.116	25	5.039	50
100	5.753	25	5.901	25	5.990	50
120	6.726	25	6.826	25	6.941	50
180	8.690	25	8.806	25	8.883	25
200	--	--	--	--	--	--
			Automatic			
10	1.503	50	1.626	50	1.741	75
20	1.866	50	2.066	75	1.997	50
40	---	--	2.887	50	2.871	50
60	3.648	25	3.813	50	3.761	25
80	4.567	25	4.723	25	4.732	25
100	5.549	25	5.607	25	5.645	25
120	6.493	25	6.573	25	6.615	25
180	8.456	25	8.553	25	8.560	25
200	---	--	---	--	---	--

Table 6. (Continued)

	Cents/1000 gal	City C		7-8 mg/1 water		
	Manual					
	Rate 1		Rate 2		Rate 3	
Body feed	Min. cost	THL	Min. cost	THL	Min. cost	THL
10	--	--	--	--	--	--
20	2.755	100	3.413	100	4.075	100
40	3.010	75	3.680	100	3.981	150
60	3.644	75	4.382	100	4.698	150
80	4.266	50	4.945	100	5.205	150
100	4.973	50	5.526	100	5.827	100
120	5.784	25	6.259	75	6.398	100
180	7.357	25	7.611	50	7.969	75
200	8.986	25	9.202	50	--	--
	Automatic					
10	--	--	--	--	--	--
20	2.657	100	2.866	100	3.117	100
40	3.005	75	3.383	100	3.599	100
60	3.592	50	4.135	100	4.205	100
80	4.219	50	4.784	100	4.821	75
100	4.926	50	5.399	75	5.524	75
120	5.737	25	6.162	75	6.170	75
180	7.310	25	7.514	50	7.724	50
200	8.939	25	9.134	50	--	--

Table 6. (Continued)

Body feed	Rate 1 Min. cost	Rate 1 THL	Rate 2 Min. cost	Rate 2 THL	Rate 3 Min. cost	Rate 3 THL
	Cents/1000 gal City C 4 mg/1 water					
	Manual					
10	2.076	75	2.303	100	--	--
20	2.054	75	2.306	100	2.765	150
40	2.704	50	2.888	75	3.274	100
60	3.367	50	3.449	50	3.882	100
80	4.040	25	4.183	50	4.510	100
100	4.797	25	4.995	50	5.190	75
120	5.593	25	--	--	5.868	50
180	7.234	25	7.374	50	7.515	50
200	8.864	25	--	--	9.160	25
	Automatic					
10	1.980	75	2.036	75	--	--
20	2.007	75	2.157	75	2.369	100
40	2.657	50	2.791	75	2.981	75
60	3.320	50	3.352	50	3.648	50
80	3.993	25	4.126	50	4.339	50
100	4.750	25	4.898	50	5.033	50
120	5.546	25	--	--	5.770	50
180	7.187	25	7.325	25	7.417	50
200	8.820	25	--	--	8.989	50

Table 6. (Continued)

	Cents/1000 gal	City C	2 mg/l water			
	Manual					
	Rate 1		Rate 2		Rate 3	
Body feed	Min. cost	THL	Min. cost	THL	Min. cost	THL
10	1.262	50	1.437	50	1.658	75
20	1.565	50	1.803	50	1.810	75
40	--	--	2.488	50	2.473	50
60	3.048	25	3.211	50	3.188	50
80	3.814	25	3.986	25	4.011	50
100	4.608	25	4.703	25	4.783	25
120	5.419	25	5.507	25	5.591	25
160	7.055	25	7.158	25	7.172	25
200	--	--	--	--	--	--
	Automatic					
10	1.238	50	1.339	50	1.454	50
20	1.541	50	1.706	50	1.646	50
40	--	--	2.390	50	2.375	50
60	3.024	25	3.160	25	3.115	25
80	3.790	25	3.918	25	3.924	25
100	4.583	25	4.655	25	4.685	25
120	5.395	25	5.460	25	5.493	25
160	7.031	25	7.110	25	7.114	25
200	--	--	--	--	--	--

used in this study. If the optimum body feed as calculated on a minimum cost basis does not produce potable water, then a body feed must be used which is high enough to produce potable water and this body feed becomes the optimum.

Automatic operation appears to result in a significant savings for a small plant since operating costs are not prorated over as much water as they are in larger plants. The difference is most noticeable between plants A and B. Maintenance of automatic equipment is a factor which must be considered in a small plant, however, since a small town may not have qualified personnel available to maintain the equipment.

Another significant factor which is obvious from Table 6 is the tremendous increase in water production costs which could be introduced in a diatomite filter plant if it were designed and operated at <u>other</u> than the optimum conditions. The cost per gallon for city A with 7-8 mg/l water would be increased over 100 percent by filtering at a rate of 3 gpm/sq ft rather than 1 gpm/sq ft with the same body feed. Approximately a 100 percent increase would also develop if 160 mg/l of body feed rather than 40 mg/l were used at a flow rate of 1 gpm/sq ft. Even greater increases in cost could develop if other than the optimum head losses were used. In some cases, which would result if present design practices were followed, the costs could be as high as 400-500 percent greater than the cost of producing water under optimum conditions.

VIII. SUMMARY AND CONCLUSIONS

A. Summary

Since its inception during World War II, diatomite filtration for municipal potable water supplies has not developed as rapidly as expected, principally due to setbacks in its early municipal application. The early failures can be traced to a lack of understanding of the basic principles affecting diatomite filtration. A better understanding of some of these factors, principally precoat and body feed, was presented by Baumann in 1954. Several other investigators have conducted some research on the subject, but, in general, considerable work still remains before the process is completely understood and can be applied under all conditions.

The objective of this study was basically twofold: to develop a better understanding of the fundamentals and theory of diatomite filtration, and to apply these fundamentals to the design of a municipal diatomite filter so that optimum conditions are obtained. For these purposes, three filters were utilized, a pressure filter in the form of a pilot plant, a variable head permeameter or miniature pressure filter, and a constant head permeameter or constant head pressure filter. Water to be filtered was obtained by adding ferrous sulfate to Iowa State University tap water and aerating this mixture to convert the iron to the ferric state. Three concentrations of iron were used in the study; 7-8 mg/1, 4 mg/1, and 2 mg/1. To aid in conversion of the ferrous iron small amounts of copper in the form of copper sulfate were added in some runs.

One test series was conducted on the pilot plant to determine the shape of the curves of head loss versus total gallons of filtrate for runs conducted to a high head loss. The series conducted with the constant head filter was used to demonstrate a method of relating results from constant head filtration to results obtained from constant rate filtration. A series of runs was conducted at each of three different rates and with three different waters to determine the effect of filtration rate and iron concentration on the optimum conditions for filtration, using the VHP.

The data analysis included the development of a theory for diatomite filtration and a discussion of the effect of filtration rate and body feeds on filtration costs. It also included a comparison of the series at different rates to obtain an optimum rate of filtration, an optimum head loss, and an optimum body feed rate. The final cost analysis was conducted for the three waters at three different sized cities with plants both manually and automatically controlled.

B. Conclusions

The following conclusions have been reached as a result of this study:

1. Filtration of an iron bearing water under normal conditions of body feed, iron concentration and filtration rate, can be expressed by the equation:

$$h_T = K_3\ Q_1 w + \frac{K_3\ Q_1^2\ T\ C_D\ .\ 8.345\ .\ 10^{-6}}{1 - \dfrac{C_S}{C_D\ K_4}}$$

This equation involves the determination of only two unknowns, K_3 and K_4. K_3 is a constant which depends only on the type of filter and grade of diatomite. K_4 is a function of the in-place density of the iron, the cake porosity, and the wet density of the diatomite. The unknowns, K_3 and K_4, may be determined by approximately four test runs. When these two terms are known, the head loss <u>versus</u> time relation for any combination of iron concentration, body feed rate and filtration rate may be calculated. This relation was verified for 2, 4, and 8 mg/1 iron waters with body feed rates from 20 to 160 mg/1 and for filtration rates of 1, 2, and 3 gpm/sq ft.

2. For the purposes of conducting the series of tests to verify the above equation, or for design purposes, certain characteristics of the water and filter must be considered.

a. A water with reproducible filtering characteristics may be produced by the addition of ferrous sulfate to tap water. The mixture must then be aerated to convert the ferrous iron to the ferric state. The iron bearing water produced in this way with Iowa State University tap water exhibited essentially the same filtering characteristics as raw Iowa State University well water with an equal iron concentration.

b. A miniature diatomite filter used to predict results from a large filter or pilot plant should be constructed with the same features as the large filter. It should contain a septum of the same configuration and material as the large filter and should have an equal ratio of pressure vessel volume to septum surface area. The miniature filter should be designed to be capable of reaching the same total head loss as the large filter so that the exact shape of curves of low body feeds may be determined at high head losses.

c. Curves of head loss _versus_ total gallons of filtrate for the 7-8 mg/l water were concave upward for body feeds below 30 mg/l and became straight lines for body feeds higher than these values. This would indicate that at an iron to body feed ratio of approximately 0.25 there is sufficient diatomite present in the cake to change the structure from a compressible cake to a porous cake. A compressible cake produces head loss <u>versus</u> time curves which are concave upward while porous filter cakes produce straight line relationships.

d. The effluent iron concentration increases for the first few minutes of a run. The concentration reaches a peak and then decreases as the body feed and turbidity plug up any holes or imperfections in the precoat. As the sludge cake develops, the ability of the filter to remove dissolved iron increases. At low body feeds, increasing amounts of iron are forced through the filter cake as the head loss increases.

e. The addition of a small amount of copper to the iron water greatly increased the speed and efficiency of the conversion of ferrous iron to the ferric state.

(1) Only small amounts of copper were needed, 0.1 mg/l was sufficient for precipitating 7-8 mg/l of Fe.

(2) Most of the copper, particularly if small amounts were used, was removed in the filtration process.

(3) Doubling the amount of copper added had no effect on the head loss development with time.

3. In diatomite filtration, three different body feeds rates may be considered the "optimum body feed", depending upon the condition to be optimized. If the largest number of gallons of filtrate per run to some terminal head loss are de-

sired, then the "head loss optimum body feed" should be used. For the maximum number of gallons per pound of diatomite, the "diatomite economy optimum body feed" should be used. It is not dependent upon any physical cake condition but is a function of the slopes of the curves obtained at different head losses, the terminal head, and the precoat. To obtain filtered water at the minimum cost, the "optimum body feed" is used. It represents the body feed rate which minimizes labor, diatomite, power, and equipment costs.

a. The diatomite economy optimum body feed, for the same water, decreases with an increasing terminal head loss and decreases with a lower amount of precoat.

b. Filtration rate had little effect on the diatomite economy optimum body feed.

c. The head loss optimum body feed occurs at high body feeds. For the water containing 7-8 mg/l of iron it occurred at 600 mg/l while the diatomite economy optimum occurred at 50 mg/l.

d. A filtration rate of 1 gpm/sq ft produced the most gal/sq ft per run to a given terminal head loss. The 1 gpm/sq ft rate also produced the most gallons per pound of diatomite. The difference between the results of the 2 gpm and 3 gpm filtration rate series was small.

e. Decreasing the iron concentration in the water lowered the body feed at which the optimum occurred for diatomite economy purposes.

4. The design of a diatomite filtration plant should be based on an optimum combination of filtration rate, head loss, and body feed which will produce potable water at a minimum cost. The cost is a function of labor, power, diatomite, and equipment. A method of finding this optimum combination is demonstrated for three different sized cities with waters of three iron concentrations.

a. With manual operation, short runs are not economically practical due to high labor costs. Precoat cost raises the cost per gallon for short runs with either type of operation.

b. A filtration rate of 1 gpm/sq ft was the optimum rate for all three sized cities and all three waters.

c. The optimum body feed in this study was low. For city A and water containing 7-8 mg/l of iron, the optimum occurred at 40 mg/l of diatomite. This corresponded to the first body feed rate which produced a straight line head loss *versus* time relationship. This represents an optimum body feed of 20 mg/l with the 4 mg/l iron water and an optimum body feed of 10 mg/l with the 2 mg/l iron water if the straight line curves for head loss appear at the same iron to body feed ratio.

d. High terminal head losses were optimum at low body feed rates since a long run was necessary for labor economy.

e. At high body feed rates, power becomes the dominating cost factor and consequently a lower terminal head loss produced the minimum cost.

f. Automation reduced the terminal head loss at which minimum cost conditions occurred. This resulted since labor was no longer a factor and long runs were not necessary to achieve the minimum production cost per 1000 gallons.

g. Automatic operation resulted in the largest production cost saving for the smallest city, however, it proved more economical for all cities and all waters. Maintenance of an automated plant could prove to be a problem in a small town if qualified personnel were not readily available.

h. Lower iron concentrations were cheaper to filter due to the occurrence of longer runs at low body feeds. Minimum costs also occurred at lower head losses.

i. Production costs were less for a large city in comparison with a small city since the total production costs do not increase in direct proportion to the water production.

j. Water production costs could be 400-500 per cent higher than necessary if other than optimum conditions were used.

5. The constant head permeameter or constant pressure filter offers definite possibilities for saving time, labor,

and money in the investigation of the filtering characteristics of a water supply. By use of the CHP and a coupling equation, the curves of head loss *versus* total gallons of filtrate normally found from a pressure filter can be developed.

IX. RECOMMENDATIONS

The 80 runs conducted in this study with the VHP to determine optimum conditions for design purposes could have been reduced to 4 or 5 by the use of the theory which was developed. In order that the theory may be of value to an engineer for design purposes, additional values of K_3 and K_4 should be available for different grades of diatomite. It is recommended, therefore, that additional test series be conducted with various grades of diatomite using the same filter and water used in this study. Additional tests should then be conducted to determine if the theory applies to other types of suspended solids. Types of waters which could be filtered include a water coagulated with alum and containing alum carryover and effluent from a lime soda-ash softening plant.

A study should be conducted on the effect of copper additions to iron bearing waters. Details to be studied would be: the rate of oxygen uptake with different concentrations of copper, the amount of copper needed for different iron concentrations, the amount of copper needed as a function of time after aeration begins, whether aeration is even needed with copper additions, and the detailed interactions which take place.

The CHP should be modified so that the flow restriction in the bottom of the tube can be removed after the precoat is in place. With this modification, CHP series should be conducted on different waters and compared with VHP series on the same waters to determine if the same relationships hold between the two filters for different waters.

The CHP could also be used to determine the effect of different ion concentrations in the recirculating water. This would determine if any clean water could be used as the recirculation water in the permeameter or if the water would have to be filtered water from the source being tested.

A study should be conducted to determine the mechanisms of removal in diatomite filtration. Specifically, the effect of copper additions should be investigated and the additional removal of soluble iron as a run progresses.

The VHP should be modified so that higher head losses can be obtained.

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XII. APPENDIX

A. Calculations for Optimums

The general pattern will be developed in an outline form. Each sub-step is dependent upon the preceding major heading. Sample calculations are based upon data from VHP-2, which was conducted at 1 gpm/sq ft using 7-8 mg/l iron water, and city A.

I. Choose a rate
(1 gpm/sq ft)

A. Choose a body feed rate
(40 mg/l)

1. Choose a head loss
(50 feet)

a. Determine length of run from data
(767 min)

AA. Multiply run length x filtration rate
(767 min x 1 gpm/sq ft = 767 gal/sq ft)

BB. Multiply (AA) x body feed **rate** x 8.345 x 10^{-6}
(767 gal/sq ft x 40 x 8.345 x 10^{-6} = 0.256 lb diatomite/sq ft.)

b. Add precoat and body feed
(0.15 lb + 0.256 lb = 0.406 lb/sq ft)

c. Divide (AA), total gallons, by (b), total diatomite
(767 gal/sq ft ÷ 0.406 lb/sq ft = 1889 gal/lb)

d. Divide diatomite cost x 1000 by (c), gal/lb
(7¢/lb x 1000 gal ÷ 1889 gal/lb = 3.706¢ /1000 gal)

e. Using length of run (a) find labor cost from graph (2.9¢/1000 gal)

f. Find power cost from graph using head loss (1.)
(0.71¢/1000 gal)

g. Add diatomite, labor, and power cost, (d) + (e) + (f)
(3.706 + 2.9 + 0.71 = 7.316¢/1000 gal)

2. Repeat I-A-1 calculations for other 5 head losses

3. Select minimum cost/1000 gal from I-A-1
(5.949¢/1000 gal at 100 ft terminal head)

4. Add equipment cost for rate and city to minimum found in I-A-3
(5.949 + 0.115 = 6.064¢/1000 gal)

5. Plot total cost I-A-4 *versus* mg/l of body feed I-A

B. Repeat I-A and all included steps for remaining body feeds

II. Repeat I and all included steps for remaining rates.

The resulting graph of cost/1000 gal *versus* body feed is shown in Figure 41.