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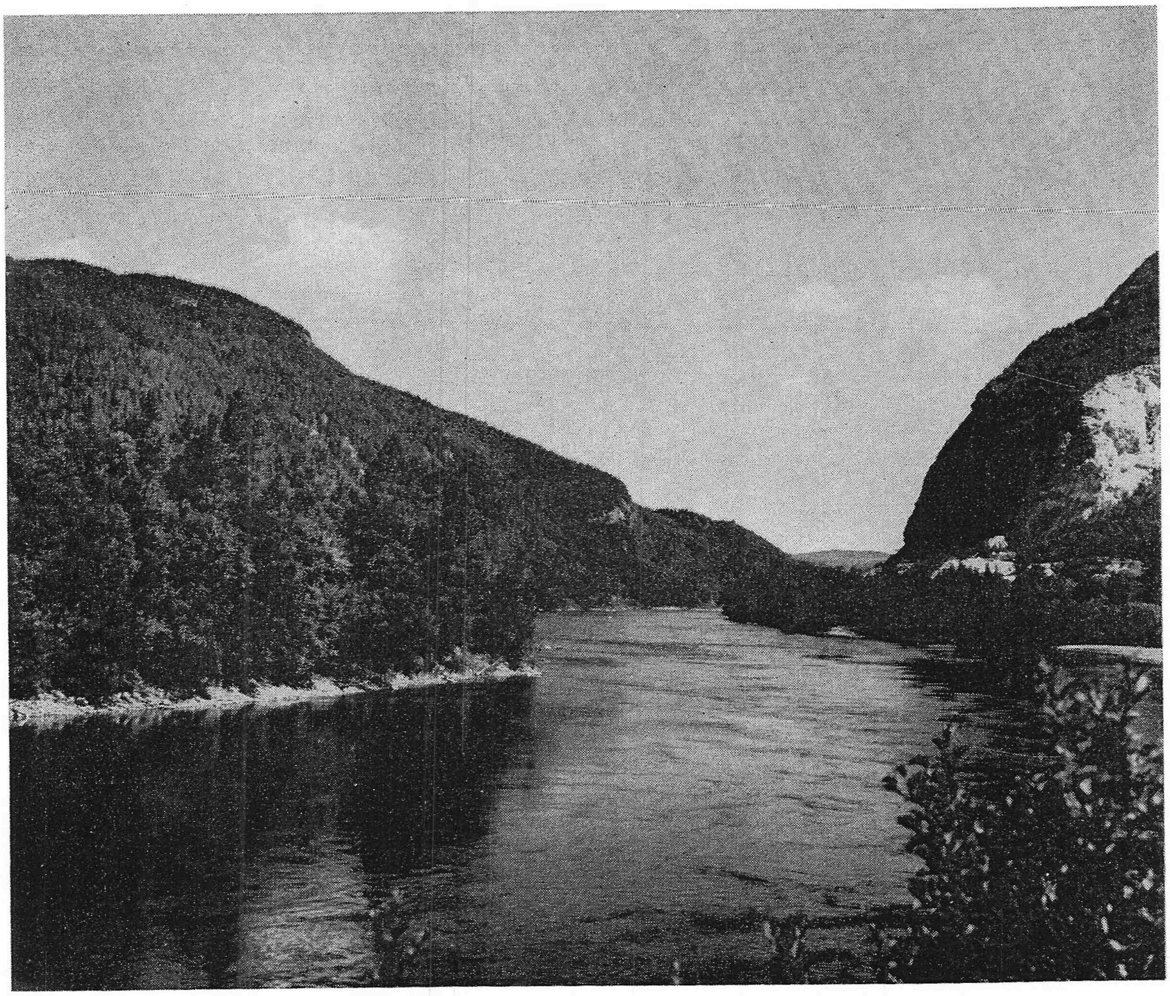

IN THIS ISSUE:

DESIGN AND APPLICATION OF MULTIMEDIA FILTERS

Walter R. Conley and Kou-ying Hsiung

In the design method proposed, say the authors, the effect of changing any of the variables pertaining to filtration efficiency can be evaluated with satisfactory precision. Data on filters of various designs, treating different kinds of raw supplies, are presented and discussed.

INTEREST in the application of high-rate multimedia filters is both intense and world-wide because of obvious economic advantages. The problems involved in high-rate filtration, although seemingly simple, become quite complex because of large numbers of variables and variety of water qualities encountered. A number of workers have developed mathematical models that attempt to describe the filtration process, but practical applications are still limited, even for single-media filters. The purpose of this paper is to present a method of designing multimedia filters and to report field experience with these filters.

Filtration Theory Status

Many possible mechanisms for particle removal by granular filters have been proposed by research workers and have been discussed more recently in detail by Mints,[9] Ives,[7] and O'Melia and Stumm.[11] It has been generally accepted that two processes contribute to the separation of suspended matter from a liquid stream. One is to transport the moving particles to the vicinity of the stationary-solids surface; the other is to attach the particles to it. The principal transport mechanisms may involve straining, sedimentation, interception, and diffusion, while the attachment mechanisms may involve the van der Waal forces, double-layer interaction, or hydrogen bonding.

Fair and Geyer suggested that the filter offers opportunity for flocculation.[5] In fact, the same colloidal forces are operating in filtration as in the coagulation-flocculation process. For example, Brownian motion becomes significant, causing the collision of colloidal particles smaller than 2 μ, and consequently periflocculation may occur within the filter pores. Under certain conditions orthoflocculation, effected by velocity gradients, may also take place. Flocculation within the filter pores may change particle character to such a degree that other mechanisms are affected. Furthermore flocculation within the filter bed becomes more pronounced when either a coagulant or flocculant is applied directly to the filter. The authors have noted that floc of substantial size appears in the filter effluent of shallow filters after breakthrough occurs, while the influent water contains no visible floc. Based on a similar observation, Mints defended his hypothesis of detachment, which has been questioned by others.[9] For steady flow conditions, the visible flocs may be the unattached flocculated particles or the previously deposited particles that have been detached. For extreme flow changes, the effluent can contain more floc[1] than the influent. Obviously, this floc must have been previously deposited material.

During filtration, the typical pattern of the change of concentration of effluent-suspended solids as a function of filter depth and operating time was first reported by Elliassen.[4] This has also been described in many mathematical models, including one by Ives.[7] The practical application of the filtration equations, however, is still limited in several respects. One major limitation is that many coefficients involved in the equations should be determined experimentally for a given system, and the usefulness of the equations depends largely on the accuracy of the determination of such coefficients. The analysis becomes more complicated when system conditions change. In this paper, an extension of Hsiung's work on single media filters[6,12] is presented that has been found to be useful to optimize the design of multimedia filters.

Design Variables

There are many variables affecting filtration efficiency: flow rate, media grain size, filter depth, and the properties of the suspension. The characteristics of the influent, relative to the filter media, can be depicted in two performance curves (shown in Fig. 1 and 2). These curves can be developed through pilot plant study by first evaluating the effect of each variable on the filter performance for a given system. The pilot unit may consist of several multimedia filters having different grain sizes and depths. The effect of one variable can be evaluated while other variables are kept constant. Although some interaction exists among these variables, they can be neglected under practical considerations. The method of developing the performance curves and the design procedures using these curves have been presented in detail in Hsiung's work. When the method is applied to multimedia filters, a modification must be made by using an equivalent grain size that can be approximated as follows:

$$d_e = X_1 d_1 + X_2 d_2 + X_3 d_3$$

Where d_e is the equivalent grain size of a three-media filter, d_1, d_2, and d_3 are the mean size of individual media, and X_1, X_2, and X_3 are the percentage by volume of individual media respectively.

For example, for a coal-sand-garnet filter, if

$d_1 = 1.30$ mm $\quad X_1 = 60$ per cent
$d_2 = 0.55$ mm $\quad X_2 = 30$ per cent
$d_3 = 0.28$ mm $\quad X_3 = 10$ per cent

then

$$d_e = 0.60 \times 1.30 + 0.30 \times 0.55 + 0.10 \times 0.28 = 0.973 \text{ mm}$$

Figures 1 and 2 show the typical pattern of performance for a synthetic muddy water after coagulation and settling. The deposit index, U, that reflects the effluent turbidity is obtained from Fig. 3, where C and C_0 are the turbidity of the effluent and influent, respectively, and t is the time scale of any unit. In these figures, 15

A paper presented on Jun. 4, 1968, at the Annual Conference, Cleveland, by Walter R. Conley (Active Member, AWWA), Director of Research, Neptune Microfloc, Inc., Corvallis, Ore., and Kou-ying Hsiung (Active Member, AWWA), Research Engr., Neptune Microfloc, Inc., Corvallis, Ore. [Q]

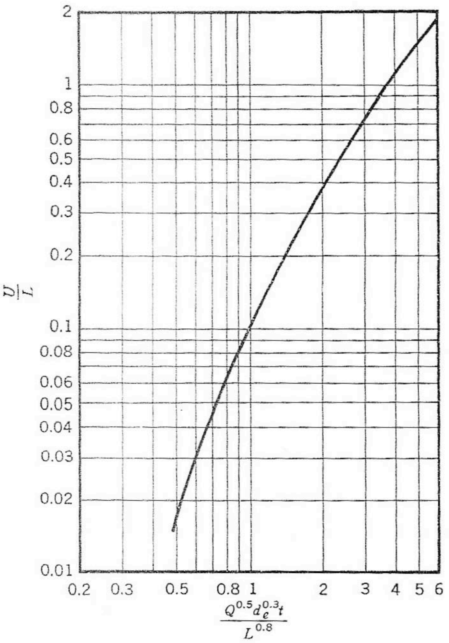

Fig. 1. Synthetic Muddy Water Performance Curve 1

Key: U, *deposit index;* Q, *flow rate (gpm/sq ft)*; d_e *equivalent media size (mm)*; t, *time unit of filtration period (15 min)*; *and* L, *depth of filter bed (in.). The constants on grouped terms change with changes in raw water quality. A secondary flocculent was not used.*

min have been used as one time unit. Q is the filtration rate in gallons per minute per square foot; d is the media grain size in millimeters; L is the filter depth in inches. Figure 1 shows that the effluent turbidity at a given time varies directly with the flow rate, influent turbidity, and grain size and inversely with the depth. Figure 2 shows that the headloss increase varies directly with flow rate, filtration time, and influent turbidity and inversely with grain size.

Therefore, based on the effluent criterion, a selection of higher rate should be accompanied with a finer grain size, a shorter run, or a deeper bed, but, based on the headloss criterion, a coarser grain and shallower bed should be used instead. Increasing flow rate is preferable to extending the filter run. It is obvious that a relatively coarse and deep bed made of uniform material is desirable for high-rate filtration. One way to reduce the filter depth, without adversely affecting the effluent quality and the headloss increase, is to use a bed having decreasing particle size in the flow direction. This can be done by using materials of different specific gravity and size. Filters of this kind merit particular attention for both theoretical and practical reasons.

At present the available commercial media to be used in multimedia filters are anthracite coal, sand, garnet, and ilmenite with an average specific gravity of 1.5, 2.6, 4.2, and 4.8, respectively. Because of the difference in specific gravity, it is possible to have the coarser, lighter material on top of the bed and finer, denser material on the bottom, accomplishing the coarse-to-fine gradation in the direction of flow. This can be achieved, however, only by proper selection of the relative sizes of different media. Controlled mixing among the materials is allowable and also beneficial, but too much intermixing would defeat the purpose of the multimedia concept.[2, 3] The ideal degree of mixing results in a gradual reduction in effective size from top to bottom in the filter.[18]

Performance Curves

A filter should be designed according to the type of influent suspension. Filter performance curves tell the typical characteristics of the given influent suspension and, therefore, can serve as guides for the selection of design variables. With the equivalent size, depth, and flow rate first assumed, the effluent quality and the headloss at a given time can be estimated from the performance curves. If the effluent standard and terminal headloss are fixed, other variables can be determined in a similar manner.

The desirable size ratios of media can be determined satisfactorily by the principle of equal settling.[8] A large grain of lighter material may have the same velocity of settling as a small grain of denser material. At the end of backwashing, the bed is compacting gradually, and the settling of grains may be considered as hindered settling. The grains interfering with each other as they settle act as a sorting bed of a higher density than water. If the average porosity of the mixing interface (two adjacent media) of the expended bed near the end of backwashing is assumed to be e, the apparent density of the solid-liquid mixture can be approximated as follows:

$$P_m = eP + \tfrac{1}{2}(P_1 + P_2)(1-e)$$

Where P is the density of water, P_1 and P_2 are the density of media to be compared; P_m is the density of the mixture, and e is the average porosity of the expanded media.

Then the critical size ratio (equal settling velocity) will be:

$$\frac{d_1}{d_1} = \left(\frac{P_2 - P_m}{P_1 - P_m}\right)\frac{1}{1.6}$$

Assuming $e = 0.85$ for a coal-sand-water mixture,

$$P_m = 0.85 \times 1.0 + \tfrac{1}{2}(1.5 + 2.6) \times 0.15 = 1.16$$

$$\frac{d_1}{d_2} = \left(\frac{2.60 - 1.16}{1.50 - 1.16}\right)\frac{1}{1.6} = 2.47$$

For a sand-garnet-water mixture, assuming $e = 0.80$,

$$P_m = 0.80 \times 1.0 + \tfrac{1}{2}(2.6 + 4.2) \times 0.20 = 1.48$$

$$\frac{d_1}{d_2} = \left(\frac{4.20 - 1.48}{2.60 - 1.48}\right)\frac{1}{1.6} = 1.74$$

Any size ratio less than the foregoing critical value can be used to accomplish satisfactory separation.

Because of the assumptions required in the use of the foregoing equations, it is necessary to modify the results indicated by the equations. This is done by taking core samples of a completed filter and noting the relative position of the various media components in the filter. Although the equations are used for a first approximation, final designs are based on observed experimental data.

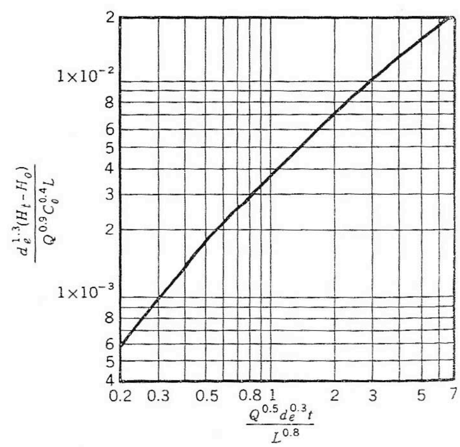

Fig. 2. Synthetic Muddy Water Curve 2

Key: Q, *flow rate;* d_e, *equivalent media size (mm)*; t, *time unit of filtration period (15 min)*; L, *depth of filter bed (in.)*; H_t, *head loss at time* t *(ft)*; H_o, *initial head loss (ft)*; *and* C_o, *influent concentration (JTU).*

Proportioning Different Media

A good start for proportioning the different media may be based on the following conditions:

$$\frac{d_1}{X_1} = \frac{d_2}{X_2} = \frac{d_3}{X_3} \text{ or } \frac{d_1}{d_2} = \frac{X_1}{X_2}, \frac{d_2}{d_3} = \frac{X_2}{X_3}$$

and $X_1 + X_2 = X_s = 100$ per cent

For example, if

$d_1 = 1.2$ mm, $d_2 = 0.5$ mm, and $d_3 = 0.3$ mm

then,

$X_1 = 60$ per cent, $X_2 = 25$ per cent, and $X_3 = 15$ per cent.

A change in the proportion may be needed following the performance analyses.

The performance curves indicate that there are many alternate combinations in selecting the flow rate, filter depth, and grain size. For best economy the highest practical flow rate and minimum length of run should be analyzed first.

Secondary Flocculants

The addition of polymers to the filter influent to increase the efficiency of filtration is common practice and yet is not well understood. In order to improve understanding of the use of these materials, filtration tests were run. Experimental data show that the influent suspension, as characterized in Fig. 1 and 2, is not highly filterable and represents difficult operating conditions. When a secondary flocculant (polyacrylamide) was applied immediately ahead of the filter, however, the performance was changed substantially (shown in Fig. 4 and 5). For example, with an influent of 30 standard turbidity units and a 24-in. multimedia bed operated at a rate of 5 gpm/sq ft without polyacrylamide, the effluent turbidity was 17 Jackson turbidimeter units (JTU) at the end of 4 hr. The effluent turbidity was 0.2 JTU under the same conditions, when 0.10 mg/l of polyacrylamide was applied immediately ahead of the filter. The headloss was changed from 3 to 6 ft when using the secondary flocculant.

The dramatic effect of secondary flocculants on filter performance is apparent. Although this effect has been reported previously,[2] it has not generally been considered in filter design. The best use of secondary flocculants can be achieved by an integral consideration of other design and operating variables. Plant results obtained with secondary flocculants will be shown in the following section.

Multimedia Designs

This is a 50-mgd filter plant at Wauna, Ore. The raw water supply is the lower Columbia River. The raw water turbidity varies from a normal 2–15 units to a high in normal years of approximately 100 units and, on rare occasions, to several hundred units. Organic color ranges from 10–20 units. Industrial wastes are present, and coagulation is difficult. Alum feed requirements vary from 10–50 ppm. Polyacrylamide is fed as a secondary flocculant during the winter and spring. There is no flocculation or settling at this plant. The raw water is treated with chemicals, passed through a flash mixer with a retention time of approximately 5 min, and then goes directly to the filters without flocculation or settling. The filters consist of 3 in. of −40 +80 garnet (passing No. 40 and retained on No. 80 US sieves), 9 in. of −20 +40 sand, and 24 in. of −10 +20 anthracite coal. The total filter depth is 36 in., and the filtration rate is 5 gpm/sq ft.

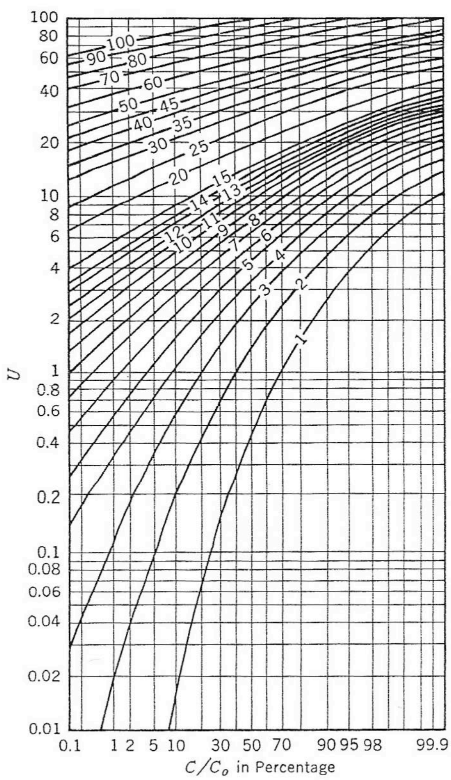

Fig. 3. Relationship Between U Values and C/C_o

Key: U, deposit index; C, filtrate concentration; and C_o, influent concentration. The numbers in the figure represent time units of filtration from the beginning of the run.

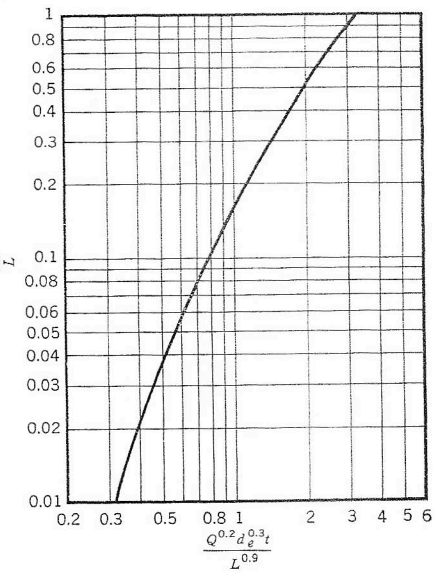

Fig. 4. Performance Curve 1 for a Synthetic Muddy Water

Polyelectrolyte was added ahead of the filter as a secondary flocculent. Key: U, *deposit index;* Q, *flow rate (gpm/sq ft);* d_e, *equivalent media size (mm);* t, *time unit of filtration period (15 min);* *and* L, *depth of filter bed (in.).*

Operating data from the plant are presented in Table 1. In the winter and spring, the total load increases because of the normal spring runoff, and operation is somewhat more difficult than for the summer. During the summer the plant is subjected to large concentrations of filter-clogging diatoms. Operation of this plant has been described by Moulton *et al.*[10] There are no operators stationed at the plant, but remote instrumentation signals operators when there is difficulty at the plant. The operators also periodically visit the plant to monitor the operation.

The plant at Fort St. John is for treating water for oil field flooding, the basic requirement being that the filtered water will be suitable for underground injection without clogging the aquifer. The raw water supply to be filtered contains organic color ranging from 500–600 standard units. The appearance of the water resembles strong tea. Occasionally small amounts of turbidity are present, but the basic problem is removal of organic color. The raw water contains only 10–15 mg/l of alkalinity, and the pH is about 5. The optimum pH zone of coagulation of this water is approximately 4.5, and the alum requirements are gener-

TABLE 1

Wauna Data

Season	Raw Water		Filtered Water		Alum—*ppm*		Item		
	Color	Turbidity	Color	Turbidity	Plant	Floc Test	Polymer *ppm*	Filter Run *Hr*	Flow *gpm/sq ft*
Summer	10	2	5	0.2	15	15	0	12	5
Winter	12	3	5	0.3	27	25	0.2	8	5
Spring	10	25	5	0.4	32	25	0.2	12	5

TABLE 2

Fort St. John Data

Raw Water Standard Units		Alum	Polymer	Chlorine	Filtered Water Standard Units		Filter	
Color	Turbidity	*ppm*			Color	Turbidity	Runs *hr*	Rate *gpm/sq ft*
500	5	80	5	0	35	0.8	2½	4½
500	5	80	5	15	15	0.5	2½	4½

ally in the range from 80–120 mg/l. The filter for this plant was unusually deep, 42 in. The filter consists of 8 in. of −40 +80 garnet, 12 in. of −20 +40 sand, and 22 in. of −10 +20 anthracite coal. The filtration rate averaged approximately 4.5 gpm/sq ft, and there was no flocculation or settling. Operating data from the plant are presented in Table 2. Note that color removal is improved when chlorine is added.

Although an installation of this kind could not normally be justified because of the short filter runs, in this particular situation it met the design objective of a compact plant that could be delivered quickly and be capable of maintaining the required quality and quantity of water. At a later time settling facilities were added, and filter runs were lengthened.

Buffalo Pound

The raw water at Buffalo Pound is unusual because of heavy algal growth. The chemist at the plant has presented an interesting theory that the luxuriant growth of organisms in the lake produces a natural polymer, making the resulting alum floc very sticky and very tough. This is the first raw-water supply observed by the authors that does not require polymer to strengthen floc at high filtration rates and cold temperature. Because of the high organic content and alkalinity, the alum feed ranges normally from 80–100 mg/l.

Laboratory tests indicate that even higher alum feeds are necessary to remove the final traces of colloidal turbidities. The floc forms quickly and settles readily but is so strong that the normal size filter sand rapidly clogs at the surface, and operations at high rate with normal size filter media are impractical. A series of filtration tests and pilot plant tests at the site were run. Data from these tests are shown in Table 3. As a result of these tests, the final filter design was 3 in. of −20 +40 garnet, 12 in. of −10 +20 sand, and 15 in. of −10 +16 anthracite coal. Filters of this design are now being built, but plant operating data are not yet available.

The raw water supply at Peoria contains from 0.5–1 ppm iron and manganese. The iron and manganese are oxidized with chlorine and potassium permanganate, and a polyacrylamide is added just before filtration. There is no mechanical flocculation or settling.

The media for the filters at Peoria consisted of 3 in. of −40 +80 garnet, 9 in. of −20 +40 sand, and 18 in. of −10 +20 anthracite coal. Operating data from the plant are shown in Table 4. Note that the design filtration rate is 8 gpm/sq ft. The plant is a 10 mgd plant.

Operating Problems

Loss of coal is a potential although controllable problem. Loss can be minimized by excluding air from the backwash system and paying careful attention to the design and operation of the surface wash system. Loss of coal is a function of the amount of air in the backwash water, the kind and duration of surface wash, the skill of the operator, and frequency of backwash. Under favorable conditions, there will be less than a 1-in. loss of coal a year. Under unfavorable conditions, there can be substantial coal loss. This loss is not necessary and can be avoided by paying attention to the necessary details. There is some attrition loss of coal, but it is quite small, less than 0.1 in. a year.

The garnet used for filtration, being very fine and very dense, must be supported on gravel sized garnet to prevent loss. This coarse garnet is used as the final gravel layer. Not only does the coarse garnet prevent loss of fine garnet, but it stabilizes the gravel and reduces the chance of an upset filter, which is caused by air in the backwash water or by improper operation.

Core samples have been taken from a number of operating filter plants using multimedia designs. A typical core analyses is shown in Table 5. This particular analysis was taken after the plant had been in operation for a period of approximately 2 years. The analysis shows that there has been no detectable loss of any of the three components: coal, sand, and garnet. The analysis also shows typical distribution of materials from top to bottom in the filter.

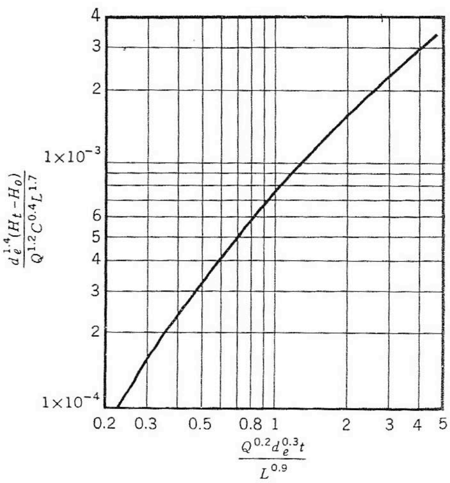

Fig. 5. Performance Curve 2 for a Synthetic Muddy Water

Polyelectrolyte was added ahead of the filter as a secondary flocculent. Key: Q, *flow rate (gpm/sq ft)*; d_e, *equivalent media size (mm)*; t, *time unit of filtration period (15 min)*; L, *depth of filter bed (in.)*; H_t, *head loss at time* t *(ft)*; H_o, *initial head loss (ft)*; *and* C_o, *influent concentration (JTU)*.

TABLE 3

Regina Data

No.	Sand		Coal		Garnet		Alum	Headloss	Filtered Water
	Size	Depth	Size	Depth	Size	Depth	*ppm*	*ft/hr*	*turbidity units*
1	−10+20	15	−8+12	13	−40+50	2	85	0.25	1.5
2	−20+40	30	—	—	—	—	85	0.71	1.5
3	−20+30	6	−10+14	21	−20+40	3	71	0.29	2.1*
4	−20+30	15	−10+14	10	−20+40	3	71	0.34	2.1*
5	−20+40	30	—	—	—	—	71	1.64	1.8*

* When alum was at 102 ppm, the filtered turbidity was 1.5, 1.5 and 1.3. Laboratory tests show that filtered water turbidity is a function of alum feed. At 150 ppm, the turbidity was reduced to 0.3 ppm with No. 1 filter media. In all cases, the water being filtered was from the plant clarifier.

TABLE 4

Peoria Data

Flow	Filter	Raw Water		Filtered Water		Chemical Feeds—*ppm*		
gpm/sq ft	Run—*hr*	Fe	Mn	Fe	Mn	Cl_2	KmO_4	Polymer
7.8	9	0.3	0.5	0.01	0.02	1.1	0.8	0.006
6.2	14	0.3	0.5	0.01	0.03	1.2	0.8	0.005
4.6	30	0.4	0.5	0.01	0.02	1.3	0.8	0.005
3.5	35	0.3	0.6	0.02	0.02	0.9	0.8	0.006

TABLE 5

Typical Core Analysis

Depth *in.*	Volume Retained on US Sieve by Percentage				
	20	30	40	60	80
3	32	24	7	35	1
6	34	35	12	15	4
9	50	23	17	7	3
12	67	6	21	5	2
15	74	3	16	5	2
18	77	2	13	8	T
21	80	2	9	8	T
24	82	5	6	6	T
27	85	6	4	4	T
30	53	41	4	1	T

Summary

The variables that affect filtration efficiency and headloss, such as flow rate, media size, filter depth, and amount of suspension in the influent, are arranged in grouped terms. Experimental data are then used to establish the proper exponentials to be used in these terms. It is then possible to evaluate with satisfactory precision the effect of changing any of the pertinent variables within the practical range. The method proposed in this paper can be used to optimize the design of multimedia filters.

Various alternative designs using media of different specific gravities and sizes have been built and tested on various kinds of raw water supplies and different synthetic suspensions. Some of these data are presented and discussed. Operating results from various plant designs are also presented and discussed.

It is concluded that:

1. A practical rational method developed for uniform single media filters can also be used for filters made of three or more non-uniform and different materials.
2. Polyacrylamides drastically change the filter performance for all filters tested and should be considered in filter design.
3. Filter design should not be limited by rule of thumb standards and should be specific to individual water sources. Operating results of many plants show that custom design for specific situations is reasonable.
4. Flocculation within filter pores may play an important role and needs to be re-evaluated.

Acknowledgment

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