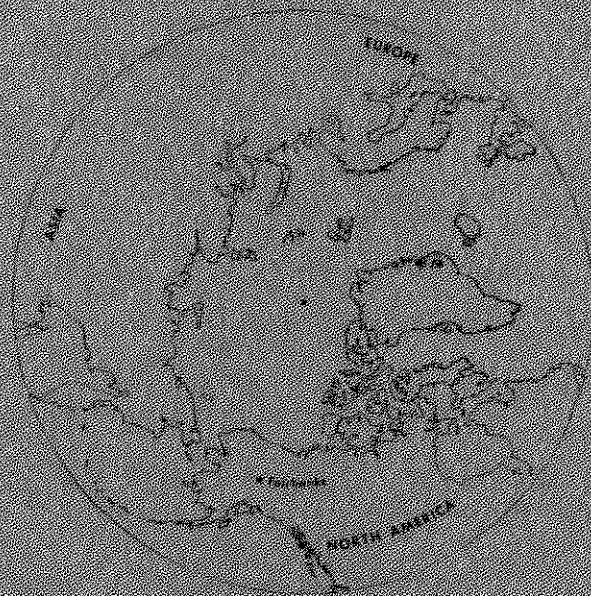


THE EFFECTIVENESS OF A CONTACT FILTER FOR THE
REMOVAL OF IRON FROM GROUND WATER

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Associate Professor of Environmental Health Engineering

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Kim, S.W., The effectiveness of a contact filter for the removal of iron from ground water, Inst. Water Res., Univ. Alaska, IWR 13, 46 p., Jan. 1971.

ABSTRACT

Various types of modified filters were investigated to replace greensand filters which clogged when removing ground water. A properly designed uniform-grain sized filter can increase the filtration time more than ten times that of ordinary sand or greensand filters.

The filter medium was obtained by passing commercial filter material between two standard sieves of a close size range, so that the resulting medium was of a uniform size.

The head loss rate on such a medium was independent of the filter depth and was inversely proportional to the almost $3/2$ power of the grain size. On the other hand, the filter depth was almost linearly proportional to the time of protective action. The effects of the grain size, filter depth, and filter material on the filter run were evaluated with a synthetic iron water; and optimum filter depths for each unisized material were determined. At identical filtration conditions, anthracite had a 70 to 110% longer filter run than the sand medium, and it was attributed to the greater porosity of the former. Expectedly, the time to reach initial leakage of the iron floc was greater with the coarse and more porous medium, but was reduced to an insignificant amount when the filter depth was increased to three to six feet.

The performance of unisized filters on permanganate-treated ground water was much better than that of fine-grained greensand.

Applicability of experimental data on an existing filtration theory was investigated.

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INTRODUCTION

Alaska is blessed with an abundant supply of surface water, but extreme winters make the installation and maintenance of a water transmission system very difficult and uneconomical, thus forcing most facilities to rely on ground water. Unfortunately, the ground water of interior and northwestern Alaska contains high concentrations of iron and hardness¹, requiring extensive treatment prior to domestic consumption.

Except for large treatment plants, the prevailing method of ground water treatment is oxidation of the dissolved iron by potassium permanganate, followed by filtration through greensand and/or hardness reduction by ion exchange.

The use of a fine-grained greensand medium (effective size: 0.33 mm) for the removal of precipitated iron rapidly clogs the filter, shortening the filtration and backwashing cycles. The objective of this study was to develop a filter that did not clog as readily as greensand but still produced a satisfactory water.

Two modes exist for solid-liquid separation by a granular filter². The first is "cake filtration" where the solid is mechanically removed by the mat formed from previously separated solids on top of (or within) the filter. The second, "standard filtration", removes the incoming solid by contact and physical (or physio-chemical) adhesion onto the filter grain (Figure 1). Since "standard filtration" is achieved by contact of the solid to the filter media it may be called contact filtration, although Mintz³ coined the latter phrase to mean only upflow filtration. Standard filtration is more desirable than cake filtration because of the lower head loss rate and the obvious advantages inherent in deep filters.

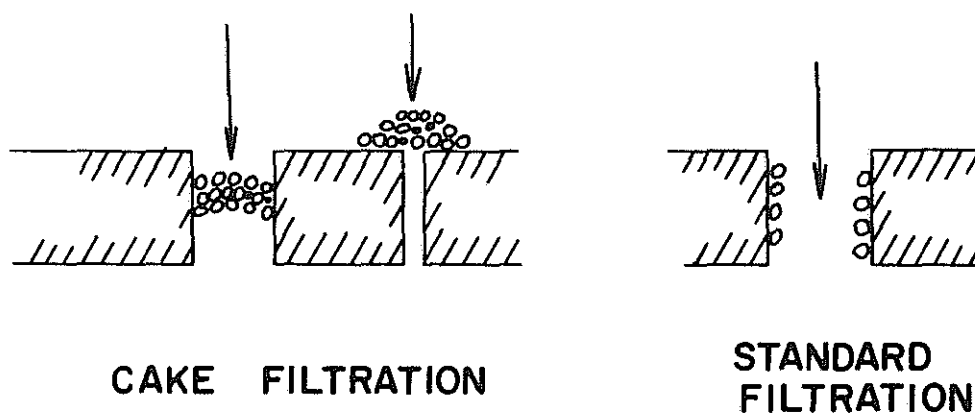


FIGURE 1 Two Modes of Filtration

A greensand filter clogs up much faster than a conventional sand filter due to the relatively fine size of the greensand particles. The primary reason for the use of such a fine-grained material is that manganese-treated greensand reacts with ferrous ions and oxidizes them to an insoluble ferric state. For completion of the chemical reaction, the finer grain size is advantageous because a larger number of reaction sites are available. With the development of the continuous permanganate feed process, however, the ferrous iron is directly oxidized by the oxidant chemical, and oxidation of iron by the greensand is not required.

Many other types of granular filters are superior to a greensand filter. These are: graded-sand filters; multimediuim filters; upflow filters; and unisized medium filters. Comparison led to the conclusion that the unisized medium filter offered many advantages; therefore, an in-depth study of it was conducted. The relative influences of grain size, type of material, and filter depth on the filtration of an iron floc suspension were investigated, and the applicability of an existing filtration equation to the results was explored. The results of these experiments are presented in this paper.

Though most of the experiments were conducted on a synthetic iron water, some tests were conducted using local ground water to which permanganate was added. The latter study proved that the uniform-sized anthracite filter was far superior to the greensand (or ferrosand) or commercial sand filters in the removal of iron in ground water.

REVIEW OF FILTRATION TECHNOLOGY

Theory of Filtration

Many theories and filtration equations have been developed in the past. Mintz⁴ assumed that floc deposited on a filter grain could subsequently be sheared off and redeposited in a lower layer. Based on the idea of these two opposing forces, detachment and attachment, he developed a filtration equation which contained many constants requiring a pilot plant test for their determination.

On the other hand, Ives⁵ maintained that there was no detachment of deposited floc during a filtration run. The mathematical relationship among filtration parameters developed by Diaper and Ives⁶ is extremely complex, requiring a computer for the exact solution. The most frequently criticized part of their theory is the unrealistic assumption of discrete, dense, unisized, and small floc. Fox and Cleasby⁷ tested the Ives equation on a suspension of hydrous ferric oxide floc and found that determination of the floc volume per unit weight (specific deposit) was a most difficult yet critical factor that limited the practicality of the equation.

The filtration equation of Heerje and Lerk⁸ was developed from the Hamaker equation of London - Van der Waal forces, the concept of a mixing model, and the phenomenon of laminar flow around filter particles. The derivation of the equation is very elegant, and its application requires the determination of only three constants. The validity of the Heerje-Lerk equation was investigated, and its applicability on the experimental results reported herein was tested.

Other empirical or semi-empirical equations were reported by Camp⁹, Hudson¹⁰, and Hsiung and Cleasby¹¹. All of them attempted to describe the physical aspects of filtration, such as the rate of filtration, grain size, depth of the filter, etc. O'Melia and Stumm¹², on the other hand, strongly emphasized the importance of the chemical aspects of filtration. If the functioning of a granular filter is divided into two steps, transport and adhesion, the chemical characteristics of floc strongly affect the latter. Once the quality of floc is altered by a change of pH, ionic strength, etc., the overall performance of the filter also changes; even though all the other physical parameters remain unchanged.

As pointed out by Cleasby¹³, there appears to be a gap between the physical and chemical theories of filtration. There must be a rational method to quantify the quality of floc and to relate it to filter performance. Until then, one must still rely on the results of a pilot plant study with the theory of filtration used only as a guide.

The following study was not undertaken to formulate another theory of filtration or an equation, but to evaluate the relative importance of some physical parameters such as grain size, filter depth, and the material used for a unisized medium. Studies were also made for optimizing the design of this particular filter.

Optimization Technique

Optimization of a filter design for a given suspension involves the correct choices of filtration rate, grain size, and filter depth. Cleasby and Baumann¹⁴ define an optimum rate of filtration as one that allows maximum production of filtered water. But this depends on the type of floc and is

difficult to predict without pilot plant studies.

Mintz⁴ proposed a method (Figure 2) for choosing a proper filter depth for a given filtration rate and grain size. After establishing the relationship between head loss and filtration time (Figure 2a), the time to reach a limiting head loss (T_2) was determined as shown. Once the filter head loss reaches a certain available gravity head, it can no longer filter at a constant rate and should be backwashed. This limiting head loss is in the range of 4.0 - 8.0 feet for most plants. Six feet was chosen to be the limit in the study reported herein.

There is another situation where a filter run has to be terminated; that is, when the effluent quality deteriorates beyond an acceptable limit. The filtration time to reach such a condition is called T_1 , the time for protective action. In case initial leakage of the floc is significant, T_1 has to be the difference between the time of breakthrough (T_n) and the duration of initial leakage (T_i), as shown in Figure 2b. In this study, the quality limit of the effluent was taken to be 0.3 mg/l of iron, the limit for standard drinking water set by the U.S. Public Health Service¹⁵.

As would be expected, T_1 increases as the filter depth increases, while the opposite is true for T_2 (Figure 2c). The optimum filter depth is reached when T_1 equals T_2 . However, this depth is optimum only for a given grain size, and the relationship among T_1 , T_2 , and filter depth changes for other grain sizes. One of the objectives of this study was to determine the above relationships with respect to grain size and type of material on uniform-sized filters.

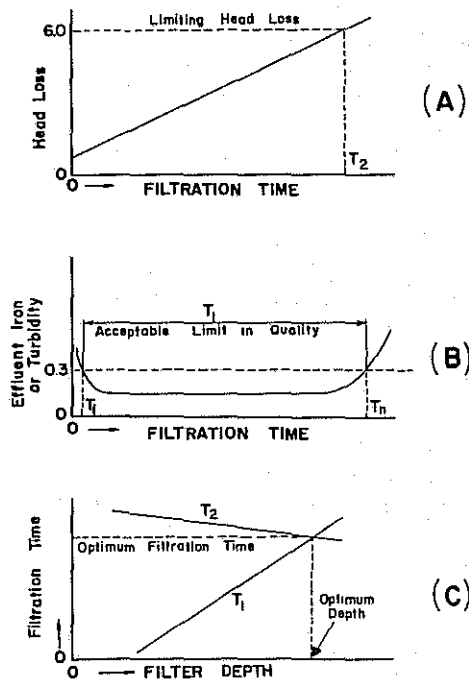


FIGURE 2 Method of Filter Optimization

Recent Developments

One of the drawbacks of a conventional rapid sand filter is its tendency to clog near the surface, resulting in a rapid increase of head loss. Many filter modifications have been proposed to overcome this imperfection. These will be discussed, and the rationale for choosing a unisized downflow filter will be described as well.

The new filters developed can be classified into two general categories, multiple layer and upflow.

Multiple Layer Filters. Conley and Pitman¹⁶ first advocated the use of a dual-medium filter composed of coarse but light anthracite on top of fine and dense sand to attain filtration in the direction of diminishing grain size. Dostal and Robeck¹⁷ used 24 inches of dual-medium for the clarification of Lake Erie water by feeding a coagulant on top of the filter. Since each medium has its own grain size gradation, the process tends to concentrate fine particles on top of each layer, where most of the head loss is realized. Dostal and Robeck recommended the use of relatively coarse and uniform-sized anthracite, possibly to avoid unfavorable geometry.

The Micro-Flow Process¹⁸ proposed a further modification by adding a layer beneath the sand. Ives¹⁹ even tested a five-layer filter using polystyrene, anthracite, sand, garnet, and magnetite from top to bottom in that order. Triple-medium and five-medium filters showed, respectively, 33 - 67% and 37 - 60% of the head loss of a flint sand bed of equal depth. In all these modifications the concentration of the fine grain at the top of each medium cannot be avoided. Also, the use of very heavy, small grain at the bottom requires extreme care in the composition of supporting gravel and may be much more costly than a conventional filter. Nevertheless, these filters are improvements over the conventional rapid sand filter.

Upflow Filters. The theories of filtration dictate that the filtration of floc should proceed in the direction of diminishing grain size. Since graded granular material, after backwash and resettling, has fine grain on top and coarse grain at the lower layer, downward filtration is obviously irrational. To achieve rational filtration, Mintz³ passed a suspension in the upward direction through a filter 6.5 feet deep with grain sizes ranging from 0.50 mm to 2.0 mm. This filter was to function not only as a solid-liquid separation unit but also as a flocculation device, which may account for its extraordinary depth. In order to prevent bed expansion the filtration rate had to be limited to less than 2.5 gpm/ft². Under the test conditions 20-25% of the coagulant was saved.

Because bed uplift was a problem with this device that limited the rate of filtration, several modifications were made. One of them was the addition of an AKX, or Biflow, filter as described by Ling²⁰. Embedding collection pipes near the top of the filter permitted suspensions to be elutriated from both the top and the bottom of the pipe. This tended to alleviate the problem of bed uplift at the beginning of a run, but the top layer clogged very rapidly. Under such circumstances, the entire flow is eventually upward, which may lead to a quicksand condition.

A more recent development for upflow filters is the Immedium filter patented by Boby Filter Co.²¹ A four-inch grid of stainless steel is placed near the top of an upflow filter to prevent uplift. It is claimed that this grid, together with deep (5.0 feet) and coarse (1.0 - 2.0 mm) sand, allows filtration rates up to 6.0 gpm/ft² at a final head loss of 17.0 feet. Nayler et al.²² compared five feet of an Immedium filter with three feet of a downflow rapid filter and obtained comparable effluent at a 50% higher flow rate. Clogging of the underdrain system was one shortcoming noted.

An Immedium filter also was investigated by Wood et al.²³ for solids removal from secondary effluent of an activated sludge plant. Even though the filter could remove about 99% of the suspended solids at a rate of 3.34 gpm/ft² when the plant was operating well, the removal efficiency dropped to 78.4% as soon as the floc became weak and small due to overload of the biological process (pin point floc). Based on their study, the desirability of using the finer grain size was recommended.

The use of the finer grain sized Immedium filter, however, was not successful in work done by Hamann and McKinney²⁴. When a commercial sand medium was used in upflow filtration at the rate of 3.9 - 4.2 gpm/ft², neither the increase of filter depth to six feet nor the use of a grid system was effective in preventing fluidization or uplift.

A seldom mentioned but serious problem is the handling of the low quality water remaining on top of the filter after backwashing²¹. In a downflow filter, this water poses little problem since it is clarified during its passage through the filter. In an upflow or Immedium filter, however, it has to be wasted to assure a satisfactory effluent. This reduces production and requires additional manipulation.

* * *

At the start of this study, tests were conducted on an upflow filter to observe its performance in relation to a conventional downflow filter. Lime floc from a settling tank at the University of Alaska Water Plant was used as influent on a 30-inch-deep commercial sand filter described in Table 1. Figure 3 shows downflow filtration resulted in a rate of head loss about 8.5 times faster than upflow filtration at a constant filtration velocity of 2.0 gpm/ft². The upflow filter, however, was disrupted at a head loss of three feet by bed uplift which caused deterioration of the effluent quality. When the filtration rate was increased from 2.0 to 4.0 gpm/ft², the top of the filter was fluidized and the effluent was of poor quality from the start of the run.

Both multimediuim and upflow filters have drawbacks. Underdrain clogging and handling the poor quality backwash water are intrinsic problems in upflow filtration. It is the author's opinion that these problems are too complex to justify further research at the present state-of-the-art. It was decided, therefore, that refinement of the downflow process would be of greatest value at this time.

The single most important problem with downflow filtration is the spread of maximum - minimum sizes of the medium that causes stratification. The problem could be greatly reduced if the spread of grain sizes could be limited. A uniform size medium is impossible to achieve in practice. A filter graded into the narrowest size range of available sieves should result in a nearly uniform sized medium. The spread of maximum and minimum sizes from the geometric mean would be only 19% and 16%, respectively, if the next nearest U.S. Standard sieve is used. This is a marked improvement over commercial sand and anthracite which have spreads of 43-131% from the average size if 1.0% and 99% sizes are compared with the 50% size.

It was anticipated that the more uniform sized medium would improve the rapid sand filtration process, causing fewer problems than the other modifications discussed in the preceding pages.

TABLE 1
 Characteristics of Commercial Filter Materials

	Commercial Sand	Anthracite	Greensand
10% size (mm)	0.50	0.68	0.33
50% size (mm)	0.68	1.1	0.47
60% size	0.72	1.2	0.51
Uniformity Coefficient	1.44	1.77	1.54
Porosity (%)	42.0	51.9	44.6
Bulk Sp. Gr.	2.57	1.52	2.25
Apparent Sp. Gr.	2.62	1.66	2.68
Sphericity*	0.86	0.63	-

* After Leva³³

Source: Monterey, Calif. Blue Coal Co., Wilkes-Barre, Pa.

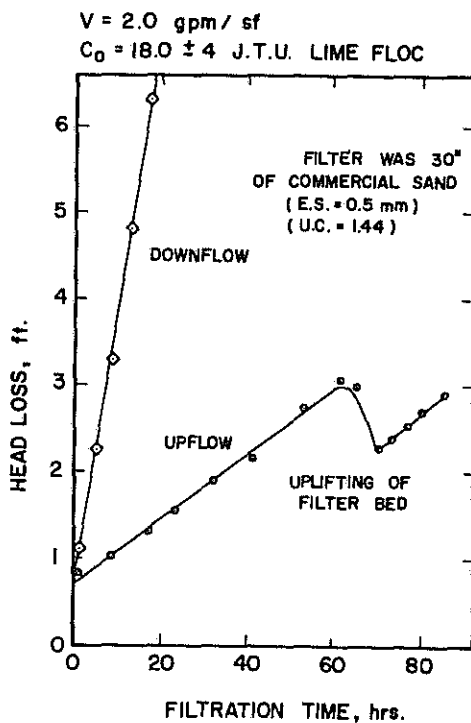


FIGURE 3 Effect of Flow Direction On Commercial Sand Medium

EXPERIMENTAL PROCEDURE

Experimental Filters.

The experimental apparatus is shown schematically in Figure 4. Three filter columns 6.5 feet long and 2.0 inches I.D. (inside diameter) were fabricated from plexiglass tubing. Each column had pressure taps fitted near the top and bottom for manometer connections. Influent water (either tap or raw) flowed into the constant head unit, received a chemical solution of ferric sulfate or potassium permanganate, and entered the test filters. The feed rate of the chemical solution was controlled by a peristaltic pump (Holter Pump). The concentration of the ferric sulfate stock solution was 1/30 molar; that of permanganate was 7.5 gm/l. The effluent from each column passed through a rotometer into the constant flow device depicted in Figure 5. The unit is similar to a device used by Ives and Pienvichitr²⁵, the rate of flow being adjusted by a tubing clamp. The float of the unit squeezes or relaxes the latex tubing, depending upon the rate of inflow, which, in turn, affects the water level in the cylinder and the float action. The rate of flow was very steady once it was set, as evidenced by frequent rotometer readings.

Filter Materials.

The three different filter materials (sand, anthracite, and greensand) used in the study are described in Table 1.

Sand and anthracite were sieved to the size range shown in Table 2 for the study of unisized filter media. Due to the original composition of anthracite, a 0.50 mm size could not be obtained in a sufficient amount for the filtration test. Each neighboring unisized medium had a size ratio of 1:2. The filter depth tested ranged from two inches to six feet.

Influent Quality.

Most of the testing was conducted with synthetic iron water by feeding ferric sulfate (technical grade) solution to tap water supplied by the University of Alaska Water Plant. The pilot plant was

TABLE 2
Size Range of Unisized Material

Geometric Mean (mm)	Sieve Opening (mm)		U.S. Sieve Number	
	Passing	Retained	Passing	Retained
0.50	0.59	0.42	30	40
0.70	0.84	0.59	20	30
1.0	1.19	0.84	16	20
1.4	1.68	1.19	12	16
2.0	2.38	1.68	8	12

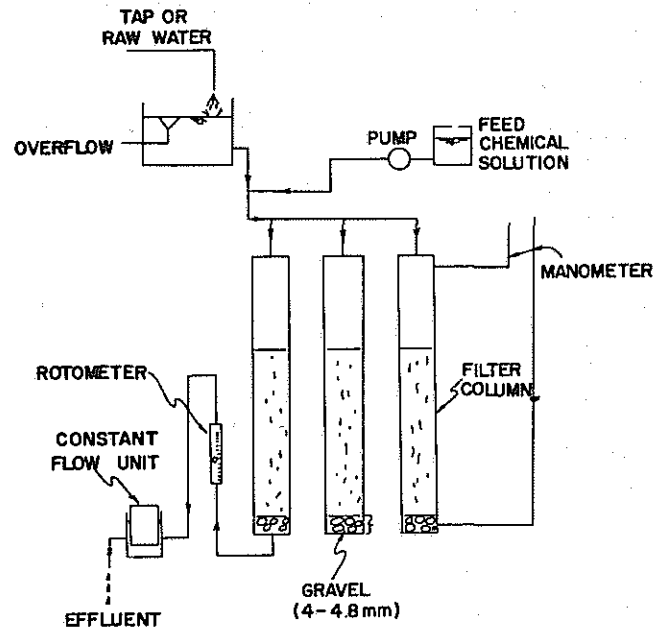


FIGURE 4 Flow Diagram of Pilot Filtration Unit

located at the Water Plant. As shown in Table 3, the quality of tap water was relatively constant, with occasional fluctuations in pH and hardness. Since raw ground water is used as a coolant for a power plant prior to entering the Water Plant, the temperature ranged from 14° to 17° C even though the temperature at the well head was below 10° C. The raw water was treated with lime for softening and iron removal, followed by coagulation, filtration, and recarbonation.

The feed rates of ferric sulfate were controlled so that an influent concentration of iron would be 3.5 mg/l. The choice of iron concentration was partly based on the result of Alaskan ground water surveys¹ and partly for convenient timing of data collection. No other concentration of iron was tested. Heerje²⁶ has reported the isoelectric pH of ferric hydroxide to be 8.3 and the size of floc 1 - 20 microns.

Method of Sampling.

Three filters were run in parallel while effluent samples were collected and head loss was read from the manometers. The testing was run at a fixed rate of 4.0 gpm/ft². The selection of this filtration rate was based on the following considerations:

1. The present trend of water technology is to increase the conventional filtration rate of 2.0 gpm/ft² to a higher rate.
2. A study by Cleasby and Baumann¹⁴ showed that the optimum rate of filtration on a stray floc is in the range of 3.0 to 5.0 gpm/ft².

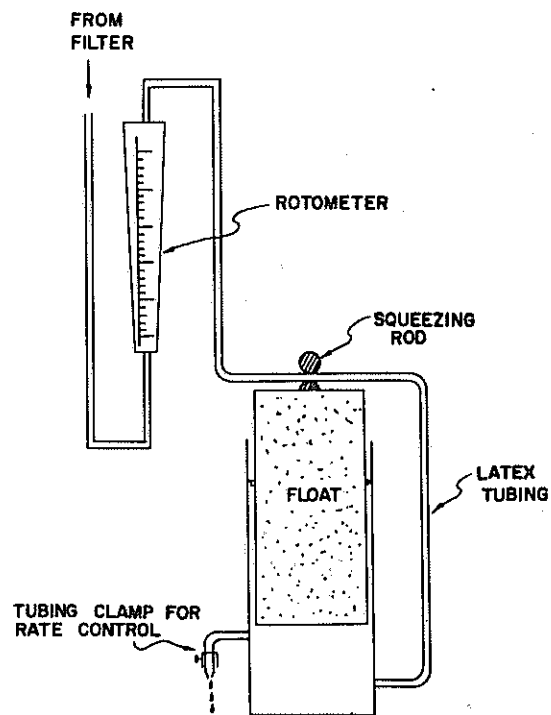


FIGURE 5 Constant Flow Unit

TABLE 3

Quality of Water Used in the Experiments

ITEMS		Tap Water	Tap Water + 3.5 ppm Fe	Raw Water	Raw Water + 14.0 ppm KMnO_4
pH	Range	7.6 ~ 8.1	7.2 ~ 7.5	6.9 ~ 7.0	6.9 ~ 7.0
	Average	7.8	7.3	7.0	7.0
Hardness (mg/l)	Range	96 ~ 120	-	330 ~ 348	-
	Average	110	-	335	-
Alkalinity (mg/l)	Range	94 ~ 120	-	262 ~ 285	-
	Average	106	-	272	-
Iron (mg/l)	Range	0 ~ 0.1	-	12.5 ~ 13.5	-
	Average	0.05	3.5	13.0	-
Manganese (mg/l)	Range	0	-	2.1 ~ 2.8	-
	Average	0	-	2.4	-
Temperature (°C)	Range	14 ~ 17	-	14 ~ 17	-
	Average	16	-	16	-

pH and iron were measured on collected samples, the former by an Orion pH meter and the latter by the tripyridine method²⁷. Sample collections and head loss readings were made at 10 minute to four hour intervals, depending on the length of the run. At the start of each test, however, samples were collected at the shorter interval to determine the time of the initial leakage (T_i).

Since a new filter medium behaves differently from a used medium, in that results cannot be reproduced, all the data reported herein were made only after a new filter was used and backwashed at least once.

Method of Data Analysis.

Graphic plots of head loss versus filtration time, and effluent iron concentration versus filtration time were made (See Figure 2) and the times T_2 , T_i , T_n , T_1 and S , were determined. Notation is as follows:

- T_2 : Filtration time to reach six feet head loss
- T_i : Time for initial leakage to reach 0.3 mg/l iron
- T_n : Time at which iron concentrations exceed 0.3 mg/l
- T_1 : Time of protective action ($T_1 = T_n - T_i$)
- S : Rate of head loss (ft/hr) expressed by the slope of head loss versus time plot.

After determining these parameters for a given size medium at different depths, a graph such as Figure 6 was plotted for each unisized material and the line of best fit was drawn that would relate T_1 , T_2 and filter depth. The reproducibilities of T_1 and T_2 were 3.6% and 4.0% respectively, expressed as the coefficient of variation.

As recommended by Johnson and Cleasby²⁸, the exhausted filters were backwashed to approximately 18% expansion until the wash water cleared.

1.0 mm ANTHRACITE FILTER
 $V = 4.0$ gpm/sf
 $C_0 = 3.5$ mg/l Fe

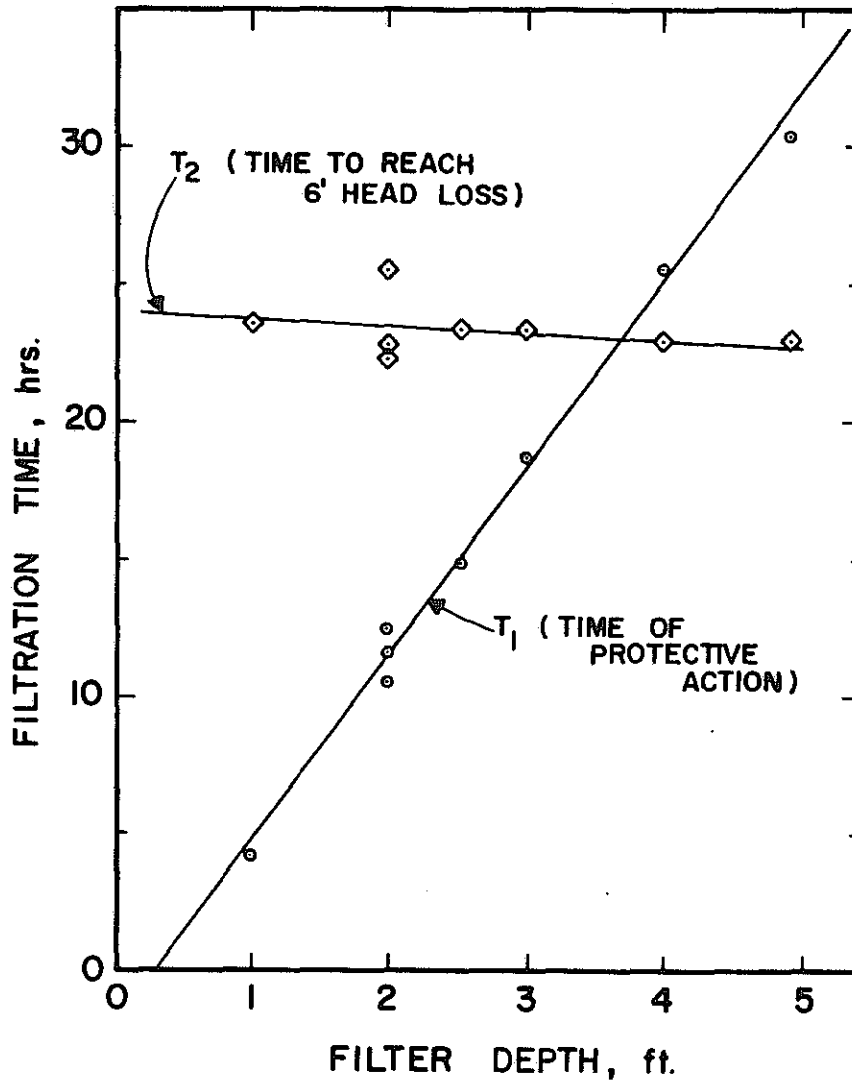


FIGURE 6 Relationship of T_1 , T_2 and Filter Depth

DISCUSSION OF RESULTS

Effect of Graded Size on Head Loss Rates

Commercial sand with an average size of 0.68 mm (uniformity coefficient 1.44) was compared with 0.70 mm unisized sand, the result shown in Figure 7 for a 30-inch filter. The head loss rate for a graded medium is about three times greater than for a unisized medium. Recalling the result by Ives¹⁹ on triple- and five-medium filters, which were 33 - 67%, and 37 - 40% of the head loss of flinted sand, the results in Figure 7 indicate a unisized filter medium might be quite satisfactory in comparison with multimedium filters. Also noteworthy is the effect of filter depth on the rate of head loss as depicted in Figures 8 and 9. The rate of head loss increased with the depth of commercial sand, while it was nearly independent of depth of unisized sand. This is an important advantage of a unisized medium because filter depth can be increased to prolong T_1 with only a slight effect on T_2 . The same cannot be said for graded (commercial) media, as an increase of filter depth as a means of increasing a filter run is impossible.

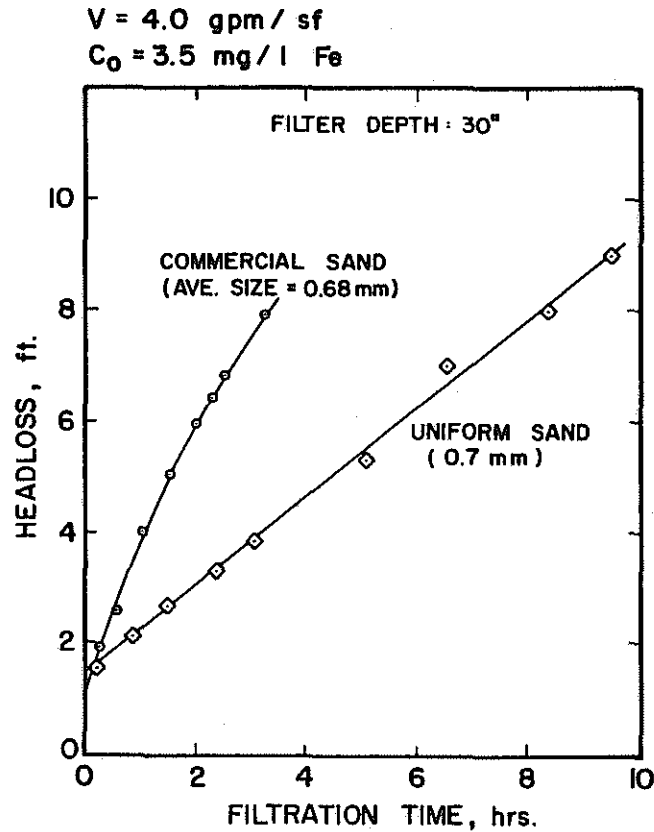


FIGURE 7 Effect of Size Gradation On Head Loss

Effect of Grain Size and Filter Depth for Unisized Media

As shown in Figures 7 and 9, for a unisized medium, the relationship between head loss and filtration time is linear. A similar result was obtained by Cleasby and Baumann¹⁶ on the filtration of iron floc. This linear relationship has some theoretical ramifications and will be discussed later.

The linear relationship, however, does not hold when the iron starts to leak and when filtration time exceeds T_1 (time of protective action). This is expected since head loss is the result of floc retention in the filter, and no head loss will occur if there is no removal of iron floc. Therefore, the head loss - time relationship beyond T_1 is neglected, and the time for six feet head loss T_2 is determined by the extension of the straight line when six feet are not reached before floc breakthrough. Each grain size of anthracite and sand was tested at varying filter depths, and graphs such as Figure 6 were developed for each unisized medium. These are summarized in Figures 10 and 11. The next section of the report discusses these figures.

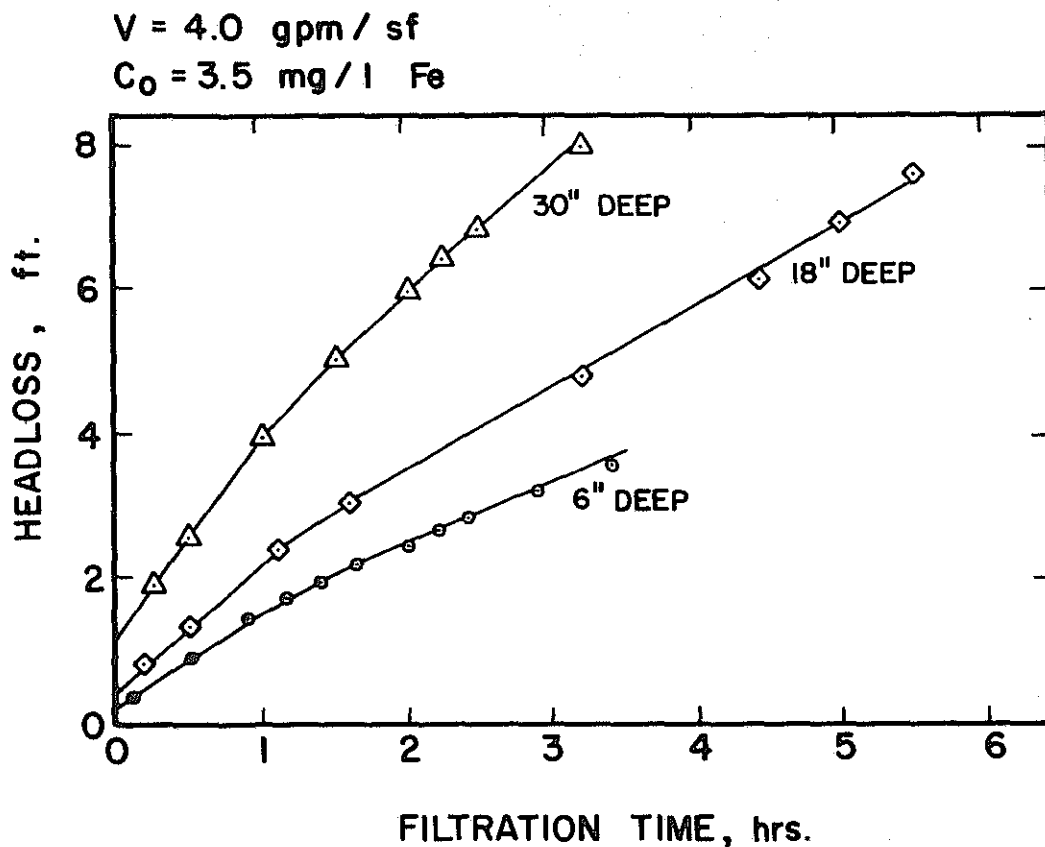


FIGURE 8 Head Loss Rate of Commercial Sand

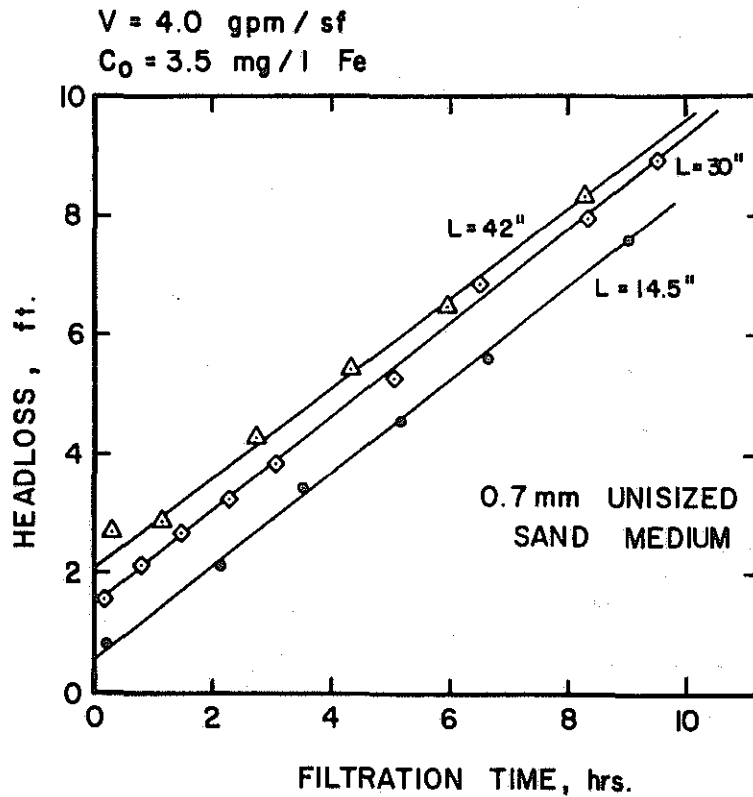


FIGURE 9 Head Loss Rate of Unisized Sand

Head Loss Rate. The relationship of head loss rate (S) and filter length was explored by determining the shape of the head loss - time regression line as shown in Figure 9. Figures 12 and 13 clearly prove that the rate of head loss is independent of filter depth and is some function of grain size for unisized media.

According to Heerje and Lerk⁶, T_2 has the following relationship with head loss rate and grain size:

$$T_2 = \frac{H_L - H_0}{\Delta h / \Delta t} = \frac{H_L - H_0}{S}; \quad (1)$$

$$S = \frac{\Delta h}{\Delta t} = P C_0 v = \frac{P'}{d^2} C_0 v; \quad (2)$$

$$\text{where } P = \frac{P'}{d^2} \quad (3)$$

- T_2 = Time to reach a limiting head loss
 H_L = Limiting head loss (six feet for these experiments)
 H_0 = Initial head loss
 Δh = Head loss increment
 Δt = Time increment
 S = Head loss rate
 P = Head loss constant
 P' = Constant
 C_0 = Initial floc concentration
 v = Filtration velocity
 d = Diameter of grain

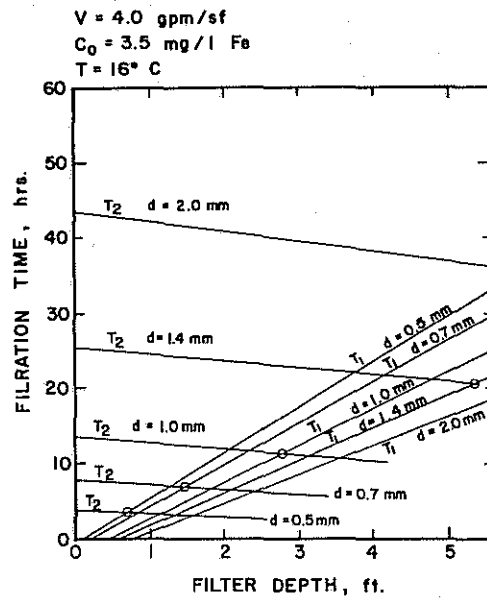


FIGURE 10 Filter Performance of Unisized Sand

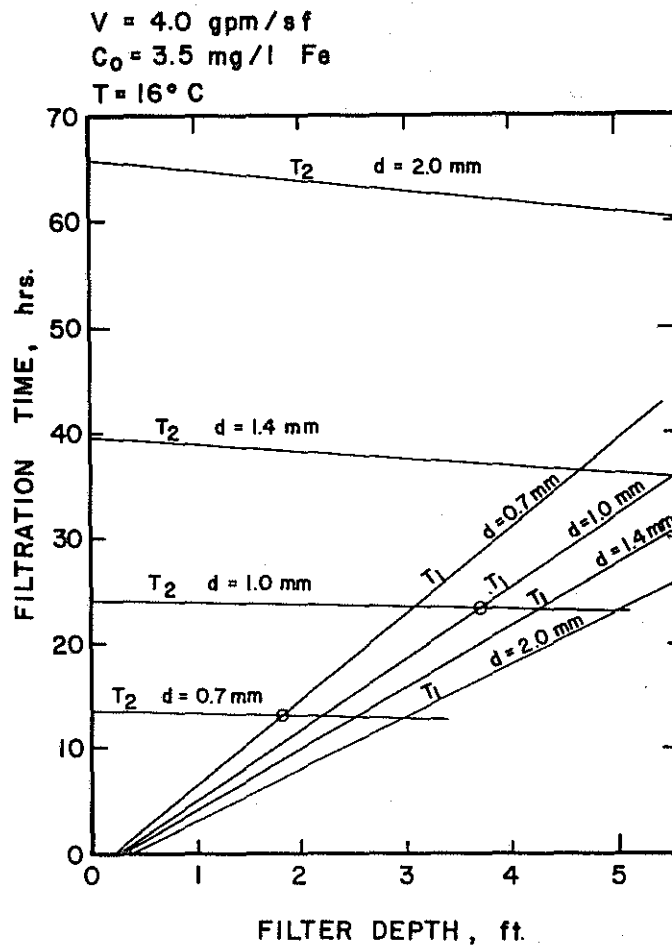


FIGURE 11 Filter Performance of Unisized Anthracite

Heerje and Lerk noted the following in regard to the head loss constant (P):

1. It is independent of filter depth.
2. It is independent of floc concentration.
3. It is independent of filtration rate.
4. It is inversely proportional to the square of grain size.

Since H_0 is a function of the measurable parameters of initial porosity, filtration rate, and grain size, it can readily be calculated by Ergun's Method²⁹. At a fixed value of filtration rate and floc concentration, the head loss rate (S) is a function of the diameter as in Equation 2. If the relationship of Equation 3 is correct, one filter run would be sufficient to calculate S and T_2 for any other grain size of a particular medium.

Even though the first assumption of Heerje and Lerk proved to be true as shown in Figures 12 and 13, the other assumptions must be tested if Equation 1 is to be applicable. The fourth assumption (the relationship expressed in Equation 3) was evaluated by relating the average rate of head loss against grain size (See Figure 14). A certain relationship exists between head loss rate (also head loss constant) and grain size, but the exponent of the inverse relationship was not 2.0 but 1.68 and 1.50 respectively for sand and anthracite, as expressed below:

$$P = \frac{P'}{d^{1.68}} \quad (\text{sand}) \quad (4)$$

$$P = \frac{P'}{d^{1.50}} \quad (\text{anthracite}) \quad (5)$$

According to Ergun's equation the head loss of a clean bed is proportional to $1/d^2$ (at Reynold's Number ≤ 20). This relationship apparently does not hold for a dirty bed, as the above result shows. The reason is not clear, but the probable explanation is that floc adhering to the filter grain is not discrete particles like sand or anthracite, but is very porous with more than 99% moisture as Lagvankar and Gemmel noted³⁰. Baylis²¹ observed it tends to compact slowly with time. If the above is true, the passage of water through the mixture of discrete sand grains and amorphous floc should be different from the flow in a clean bed.

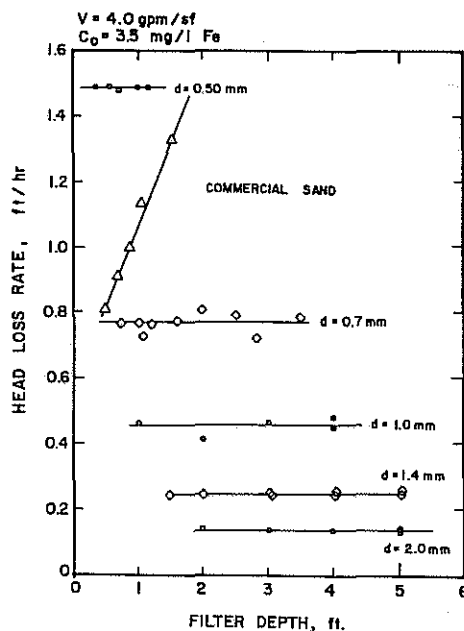


FIGURE 12 Effect of Grain Size On Head Loss Rate

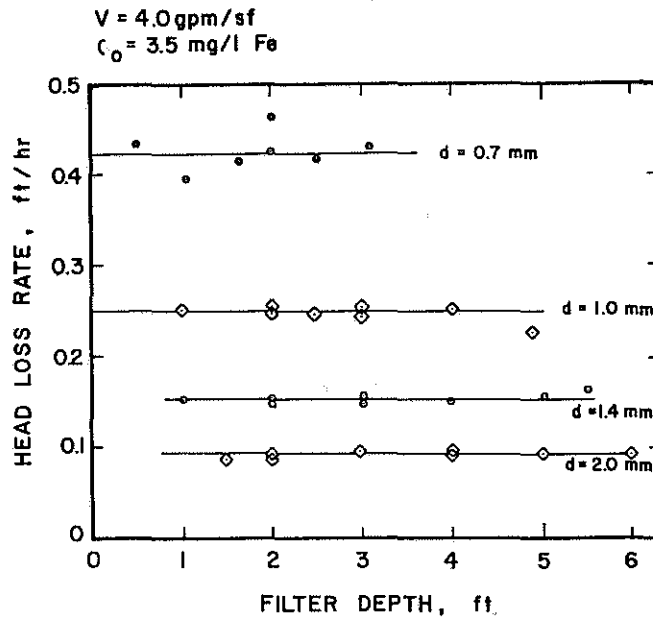


FIGURE 13 Effect of Anthracite Grain Size On Head Loss Rate

Effect of Grain Size on T_1 . The relationship between T_1 and the filter depth for each grain size is plotted on Figures 15 and 16 using the data of Figures 10 and 11. When the filter depth is greater than three feet, T_1 is inversely proportional to the 0.44 to 0.55 power of grain size as follows:

$$T_1 = \frac{K}{d^{0.44}} \sim \frac{K}{d^{0.55}} \quad (6)$$

Heerje and Lerk⁶ developed an equation for T_1 which relates the time of protective action with other filtration parameters:

$$T_1 = \frac{1}{vC_0b} \ln \frac{e^{bm_0L} - 1}{\frac{C_0}{C} - 1}$$

$$\text{which} = \frac{m_0}{vrC_{ow}} L - \frac{1}{rC_{ow}} K' \frac{d^3}{1 - m_0} \ln \left(\frac{C_{ow}}{C_w} - 1 \right) \quad (7)$$

where:

- T_1 = Time of protective action
 v = Filtration velocity
 b = Constant
 m_o = Initial porosity
 C_o = Initial volume concentration of floc
 C = Volume concentration of floc
 C_{ow} = Initial weight concentration of floc
 C_w = Weight concentration of floc
 r = Specific volume (volume of floc per unit weight of floc)
 K' = Constant
 d = Diameter of unisized media

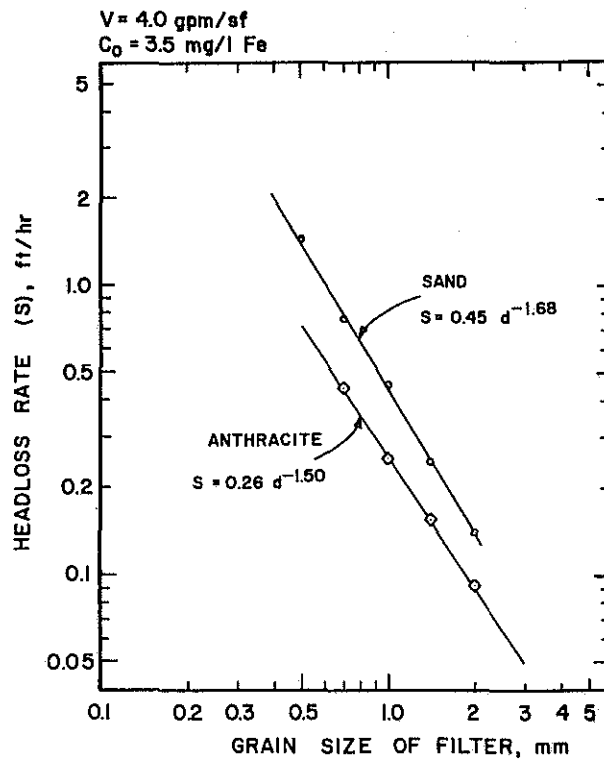


FIGURE 14 Effect of Grain Size On Head Loss Rate (Sand & Anthracite)

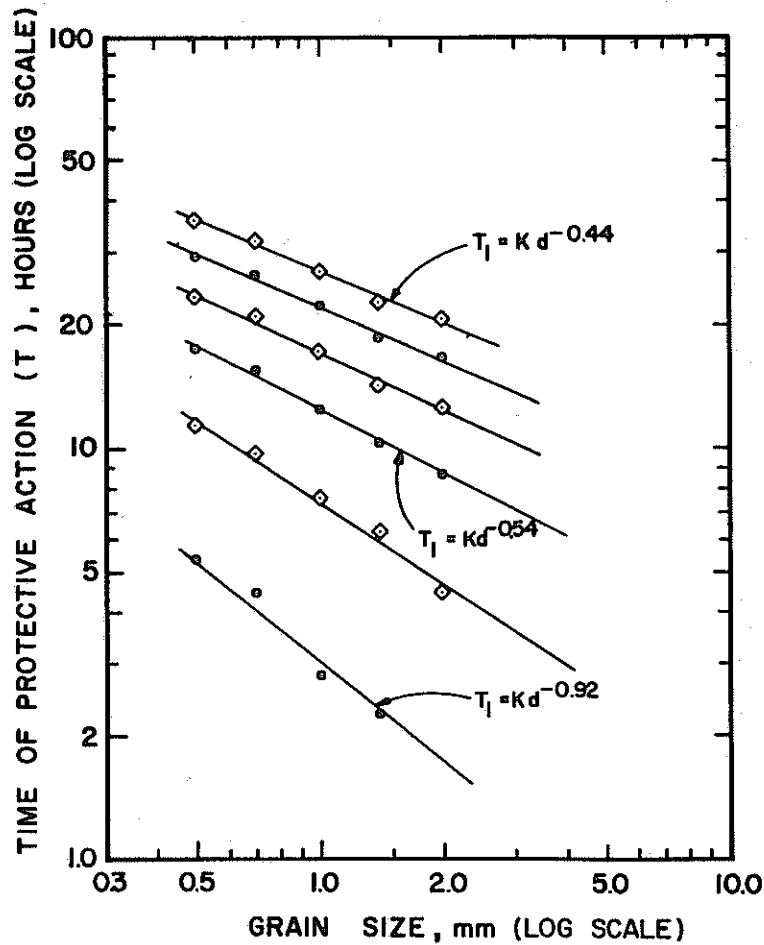


FIGURE 15 Effect of Grain Size On T_1 (Data From Figure 10)

Equation 7 relates the grain size with T_1 . There are only two unknowns for a given filtration condition, K' and r . To test the validity of Equation 7 on the experimental data, two unknown values were calculated, based on the measured value of T_1 at grain sizes of 0.7 mm and 2.0 mm of anthracite at a five-foot depth, taken from Figure 11. Then the T_1 values at the intermediate sizes, 1.0 mm and 1.4 mm, were calculated and compared with the actual value of T_1 as shown in Table 4 and Figure 17. It appears that the actual values and the calculated values of T_1 follow different equations. Equation 7 underestimates the effectiveness of both very large and very small grain sizes in retaining floc. Since the derivation of the equation presumes only a standard mode of filtration, any onset of local cake filtration on a very small size grain would give a longer T_1 than expected. The greater-than-predicted T_1 at the larger size range cannot be easily explained unless some mechanism of floc removal other than London - van der Waal forces is involved, which is quite possible.

TABLE 4

Test of Heerje - Lerk
Equation Relative to Grain Size

Filtration Rate = 4.0 gpm/sf
Iron Concentration = 3.5 mg/l
Filter Length = 5.0 ft

Grain Size of Anthracite	Actual T_1 (hrs)	Calculated T_1 (hrs)
1.0	32.0	37.3
1.4	27.5	33.4

Effect of Grain Size on the Initial Leakage of Floc. In the discussion of the use of coarse filter media, Hudson³² pointed out the importance of the duration of initial leakage. Immediately after the start of a filter run, the effluent quality is very poor (high iron concentration), but improves rapidly as was shown by Cleasby and Baumann¹⁴. This phenomenon is of considerable importance because the prolonged leakage period not only deteriorates the effluent quality but also reduces the effective period of filter run. As shown in Figure 3, the duration of initial leakage (T_1) was measured from the start of a run until the effluent iron content decreased to 0.3 mg/l. The

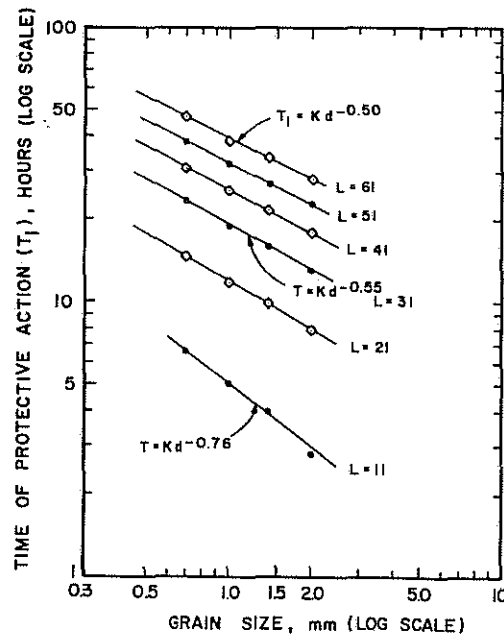


FIGURE 16 Effect of Anthracite Grain Size on T_1 (Data From Figure 11)

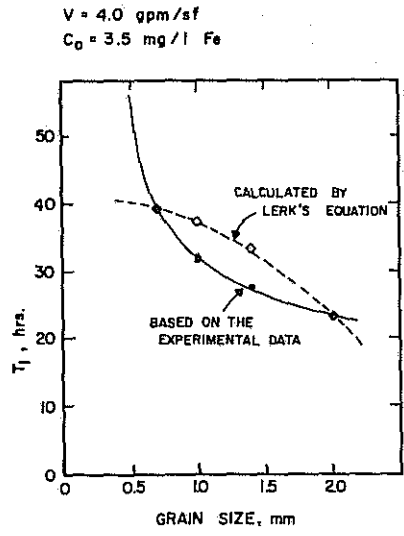


FIGURE 17 Test of Lerk's Equation on T_1 . Anthracite Filter 5' Long. Calculation Based on T_1 Data at $d=0.7, 2.0$ mm Grain Size.

relationship among T_i , grain size, and filter depth is shown in Figures 18 and 19. By using Figures 10 and 11, the boundary condition at which T_i/T_1 equals 2.0% was determined. According to the result shown, the coarser the medium and the shorter the filter depth, the longer was the duration of leakage. Also, anthracite had longer leakage time than sand of the same grain size and depth, but the difference was slight at the large grain size. Even with a coarse medium, however, the leakage duration reduced to an insignificant fraction of the total filtration time ($T_i/T_1 < 2.0\%$) when the length of the filter was increased.

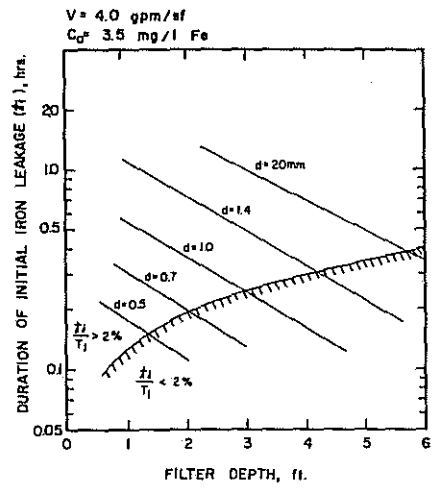


FIGURE 18 Leakage Duration of Sand Filters

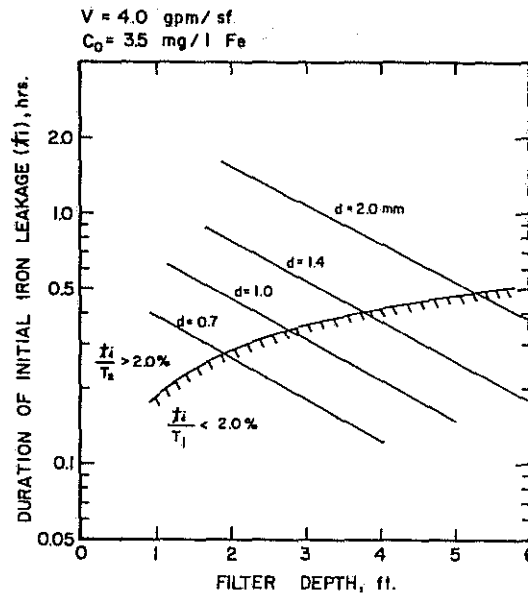


FIGURE 19 Leakage Duration of Anthracite Filters

Effect of Grain Size on Porosity. Porosity is an important factor bearing on rate and floc retention capacity¹⁰. Also, it is an important parameter in the calculation of initial head loss²⁹ and in the determination of T_1 ^{4,6,7}.

As shown by Leva³³, the porosities of sand and anthracite are not independent of grain size. His data, however, are limited to the grain sizes in the range 0.05 to 0.40 mm.

Therefore, porosity of each grain size of unisized media was measured. First, bulk specific gravity was measured following the AASHO method³⁴. With this result, porosity was determined as follows:

$$n = \frac{\bar{V}_o - \bar{V}_s}{\bar{V}_o} \times 100 \quad (8)$$

n = % Porosity

\bar{V}_o = Volume occupied by the solids in water

\bar{V}_s = Volume of solid including internal void (dry weight/bulk specific gravity)

The results are shown in Table 5. Figure 20 shows the plot of the results as well as the porosity data given by Leva³³. The extrapolated porosities of Leva's data are less than the measured values. The effect of grain size was obvious in both sand and anthracite media; that is, porosity decreased

TABLE 5
Porosity of Unisized Media

Geometric Mean of Grain Size (mm)	Sand (%)	Anthracite (%)
0.5	44.5	-
0.7	43.7	55.2
1.0	43.3	53.9
1.4	42.5	53.5
2.0	41.1	51.9

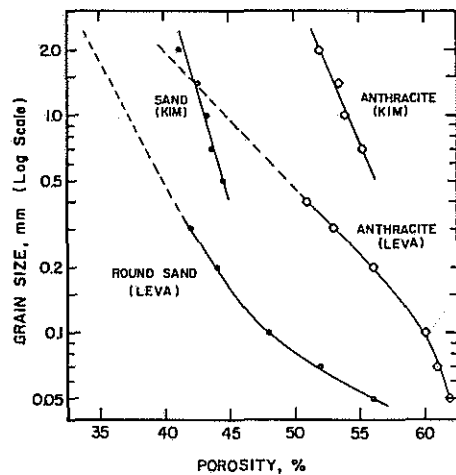


FIGURE 20 Effect of Grain Size on Porosity

with the increase of grain size. But the tendency was more pronounced in anthracite. The porosity data reported by Hudson³² was in the range of 42 - 43% for sand and 52 - 55% for anthracite, and are in good agreement with the measured results.

Effect of Grain Size on Backwash Rate. Backwashing is an essential step of filtration, and unless a filter is well cleared, the length of a filter run can be shortened prematurely. Hulbert³⁶ recommended expansion of the filter bed by 50% for cleaning filters. Later, Johnson and Cleasby²⁸ concluded that 16 - 18% expansion is optimum. They could get a cleaner filter than at the higher degree of expansion. The explanation of this apparent absurdity was based on the scouring action of colliding particles. Adhered floc is dislodged not only by the shearing force of uprising water but also by the scouring action of colliding particles. At a higher rate of backwash, the bed expands more and the shear force is greater, but the grains have less chance of collision,

and the scouring effect is less. Even to attain 16 - 18% bed expansion, the large grain may require too great a backwash velocity for a conventional filter plant to handle. Since the previous analysis favors the use of a coarse and deep medium, the backwash requirement of such a filter needs to be checked.

The degree of bed expansion of a 30-inch bed was measured by using tap water at 16°C. As shown in Figures 21 and 22, the degree of expansion had a linear relationship with the backwash rate except when the degree of expansion was very low. The required backwash rate for 18% bed expansion is listed in Table 6. Assuming an ordinary water plant is equipped to 50% expansion of commercial sand, the maximum backwash capacity will be 28 gpm/ft² or 44.8 inches/minute (Figure 21). If graded sand is replaced by a unisized medium, the new filter can handle sand of 1.0 mm or less, or anthracite of 2.0 mm or less without any difficulty, provided 18% bed expansion is sufficient.

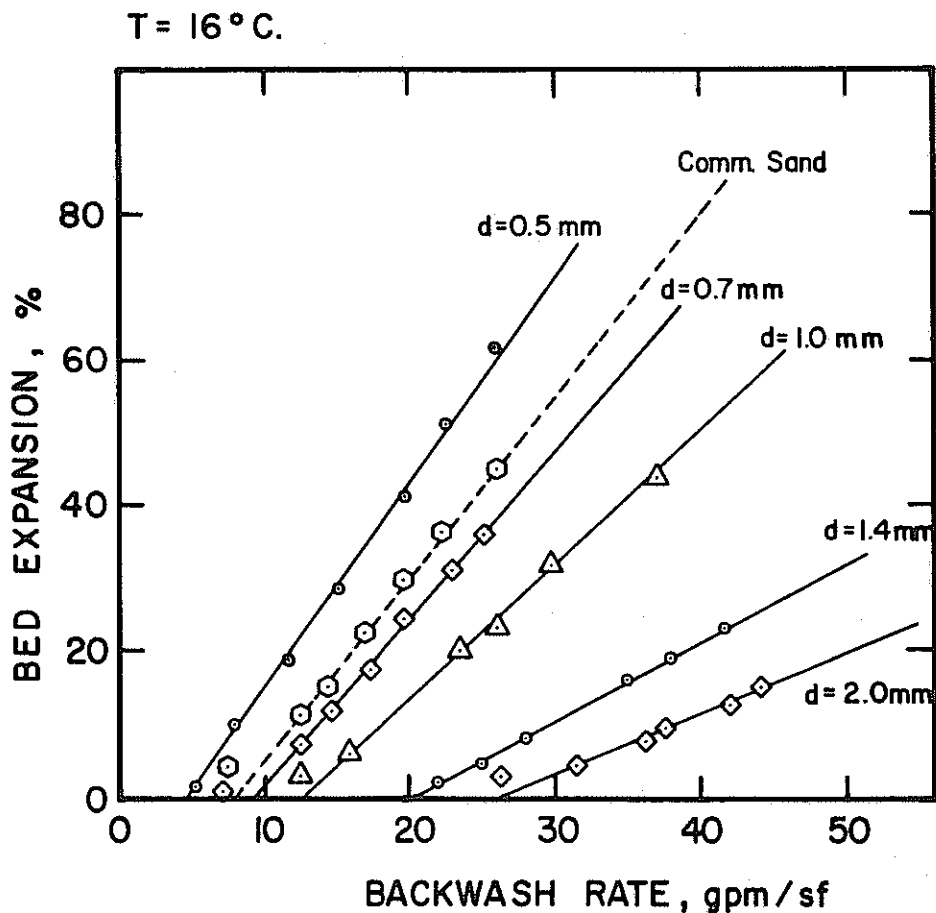


FIGURE 21 Backwashing of Unisized Sand. Commercial Sand E.S.=0.50 mm, Av. Size=0.68 mm, Unif. Coeff.=1.44.

TABLE 6

Rate of Backwash for 18% Bed Expansion

T = 16°C

Grain Size (mm)	Sand (gpm/sf)	Anthracite (gpm/sf)
0.50	11.0	-
0.7	17.2	10.5
1.0	22.8	16.0
1.4	37.0	18.5
2.0	48.0	26.3

T = 16°C.

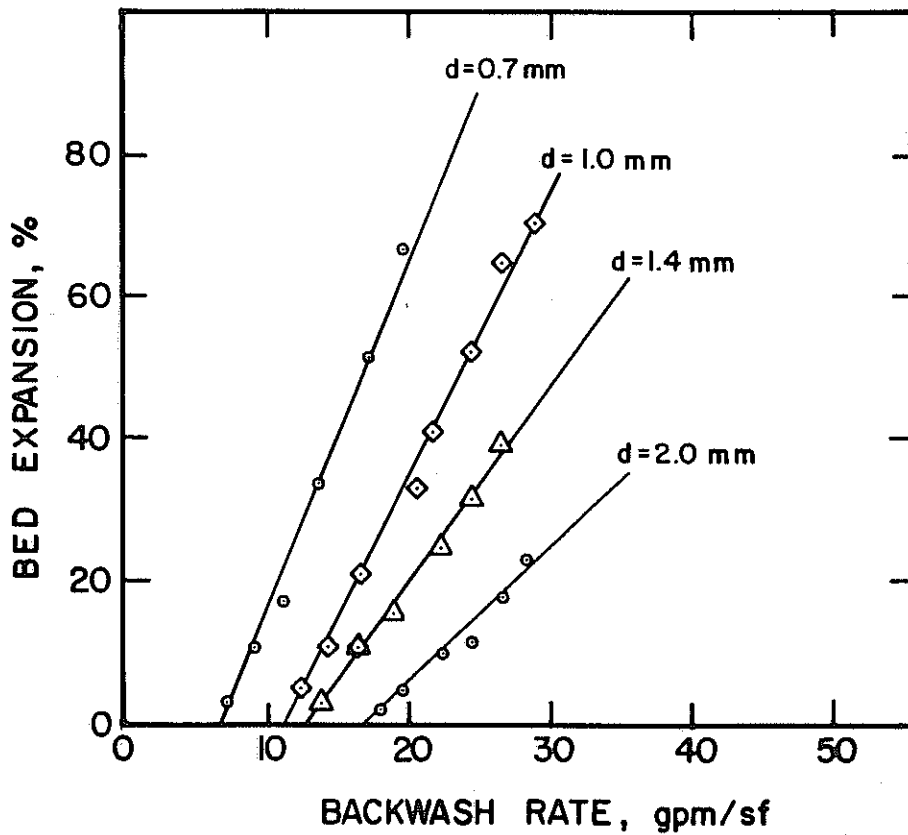


FIGURE 22 Backwashing of Unisized Anthracite

A by-product of backwashing studies is the determination of a critical or minimum fluidizing velocity. This is very important for upflow filtration because one of the limitations of the process is that a fine grain size cannot be used due to its fluidization at an increased filtration rate. The intersection of straight lines in Figures 21 and 22 with the abscissa of zero percent expansion is the approximate value of the minimum fluidization velocity. This velocity can also be calculated by an equation given by Kunii³⁷:

$$V_c = \frac{\Psi (d)^2}{150} \frac{\rho_s - \rho_l}{\mu} g \left(\frac{m_o^3}{1 - m_o} \right) \text{ at } N_R < 20. \quad (9)$$

- V_c = Minimum fluidization velocity
 Ψ = Sphericity
 d = Grain size
 ρ_s = Density of solid
 ρ_l = Density of liquid
 g = Gravity constant
 μ = Viscosity
 m_o = Porosity at the minimum fluidization velocity

In applying Equation 9, the following assumptions had to be made:

1. Sphericity of sand and anthracite are 0.86 and 0.63 respectively³³.
2. Porosity at the minimum fluidization velocity is identical with that formed under quiescent settling.
3. Porosity of each unisized medium is represented by the lines in Figure 20.

Calculated and measured values are shown in Table 7. The calculated velocity based on measured porosity is relatively close to that of actual velocity except in the case of the 2.0 mm size. The calculated values, using the extrapolated porosity of Leva, are much lower than the measured velocities.

In upflow filtration, the critical (or minimum) fluidization velocity is not equal to the allowable upflow velocity, because uplifting of the bed caused by bed clogging has to be considered for selection of the filtration rate. However, the minimum fluidization velocity is a measure of the degree of safety against uplifting at a given filtration rate; that is, the greater the difference

between the minimum fluidization velocity and filtration rate, the safer the filter is against uplifting.

Comparison of Sand and Anthracite

Filter performances and media characteristics of sand and anthracite are compared, and an example of a filter run of each medium is shown in Figure 23. Table 8 presents some of the pertinent information. A quantitative evaluation of deep filters (greater than three feet) of both media in the size range from 0.7 mm to 2.0 mm was made as follows:

1. An anthracite filter run was 29 - 51% longer than a sand run of the same size and depth in regard to the time of protective action (T_1).
2. The head loss rate of an anthracite bed was 55 - 62% of the corresponding sand bed.
3. T_2 of an anthracite filter was 1.6 - 3.1 times longer than the sand filter of identical characteristics.
4. Duration of initial leakage from an anthracite bed lasted only one to four minutes longer than that of a sand bed.
5. For 18% bed expansion, anthracite required a 50 - 70% lower backwash rate than a corresponding sand bed.

TABLE 7

Minimum Fluidizing Velocity of Unisized Media

$T = 16^\circ\text{C}$

Grain Size (mm)	V_c , Measured (gpm/sf)	V_c , by Kim (gpm/sf)	V_c , by Leva (gpm/sf)
SAND			
0.5	4.7	4.1	2.7
0.7	9.0	7.5	4.8
1.0	12.6	14.3	8.5
1.4	20.2	27.2	14.7
2.0	26.0	50.0	26.3
ANTHRACITE			
0.5	-	-	-
0.7	6.0	4.1	2.0
1.0	11.0	7.8	3.3
1.4	12.3	14.1	5.4
2.0	16.8	26.4	7.7

$V = 4.0 \text{ gpm/sf}$
 $C_0 = 3.5 \text{ mg/l Fe}$

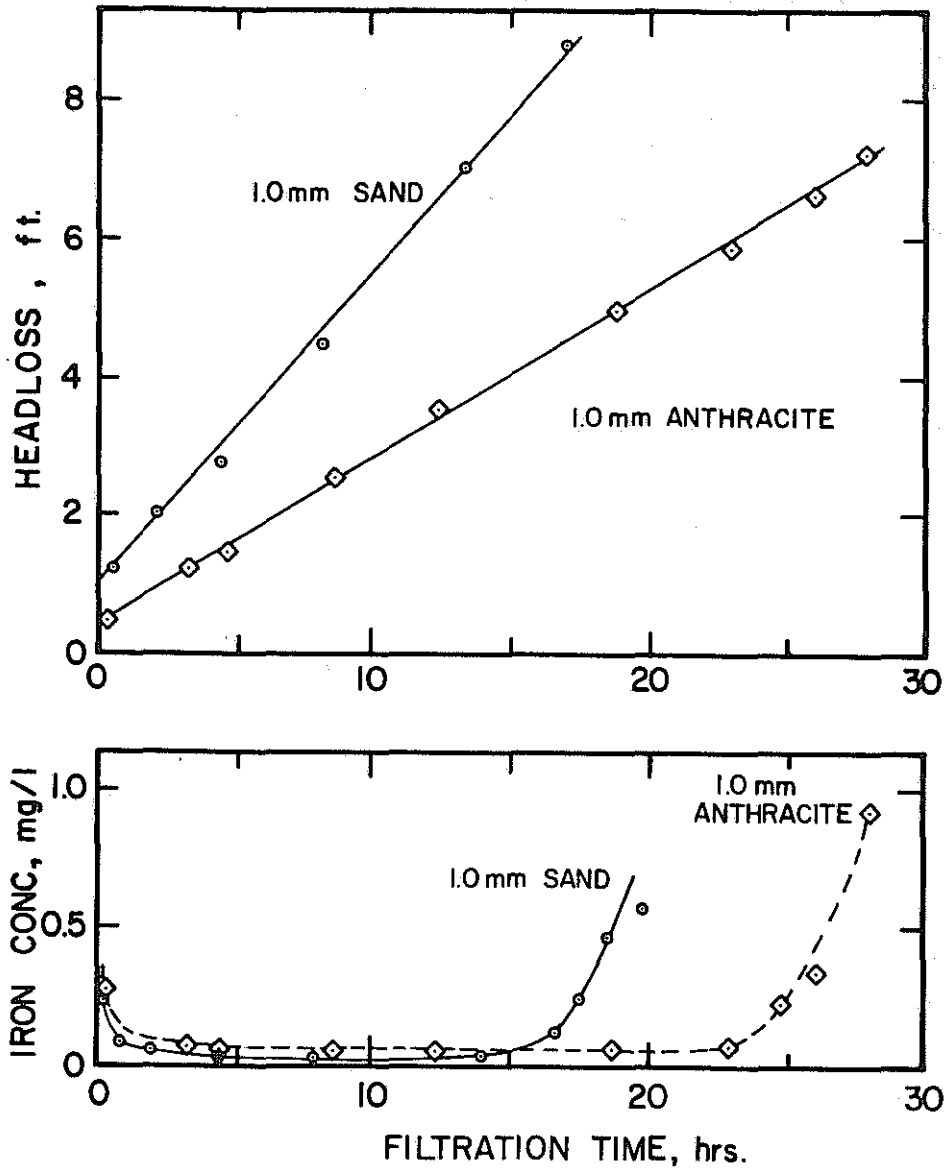


FIGURE 23 Effect of Filter Material On T_1 and T_2 . Filter Length=4.0'.

The greater porosity and higher angularity of anthracite render it superior to a sand medium in every aspect of filtration except the duration of initial leakage (T_i). Even the difference in T_i is negligible when filter depth is more than three feet.

The point of intersection of T_1 versus depth and T_2 versus depth regression lines expresses the optimum condition of filtration where T_1 equals T_2 . Such points were indicated by circles in Figures 10 and 11. Filtration time at the point of intersection was longest, and the corresponding depth was the optimum. Table 9 shows the results. The optimum filter run of anthracite was from 71% to 109% longer than sand of identical grain size. The results in Table 9 are, however, subject to variation depending on the criteria of limiting condition, floc concentration, filtration rate, and type of floc.

Comparison with Other Types of Filters

Comparison with Graded Commercial Sand. Since commercial sand has a 50% size of 0.68 mm, which is very close to the 0.70 mm size of unisized sand, the two media were compared to observe the effect of size gradation as shown in Figures 7, 8 and 9. The effect of filter depth on graded and unisized media was previously discussed. The results shown in Figure 12 more clearly indicate that

TABLE 8
Comparison of Sand and Anthracite Filters

$$\left. \begin{array}{l} V = 4.0 \text{ gpm/sf} \\ C_o = 3.5 \text{ mg/l Fe} \\ L = 4.0 \text{ ft} \\ d = 1.0 \text{ mm} \end{array} \right\} \text{Filter}$$

	Sand	Anthracite
Specific Gravity	2.62	1.66
Sphericity *	0.86	0.63
Porosity (%)	43.2	54.2
Moisture content at S.S.D. condition **	0.66	5.85
T_1 (hrs)	17.8	25.4
T_2 (hrs)	10.9	23.4
S (ft/hr)	0.45	0.25
T_i (hrs)	0.16	0.18
Backwash Rate for 18% expansion (gpm/sf)	22.8	16.0

* After Leva³³

** S.S.D. = Saturated Surface Dry³⁴

TABLE 9
Optimum Depth and Filter Run

Condition of Tests

$V = 4.0 \text{ gpm/sf}$
 $C_o = 3.5 \text{ mg/l Fe}$
 $T = 16^\circ\text{C}$

Grain Size (mm)	Optimum Filter Depth (ft)	Optimum Filter Run (hrs)
SAND		
0.5	0.65	3.5
0.7	1.45	6.7
1.0	2.8	11.0
1.4	5.3	20.3
2.0	8.8	31.2
ANTHRACITE		
0.5	-	-
0.7	1.8	11.5
1.0	3.7	23.0
1.4	6.3	35.0
2.0	11.2	55.0

the head loss rate of a graded medium changes with filter depth, while it does not for a unisized medium. The rate of head loss of commercial sand in Figure 12 is the average from the initial condition to six feet. If the initial rate of head loss depicted by the steepest slope in Figure 8 is used for such a plot, the tendency of the rate change with depth will still be the same, as can be seen in Figure 8.

Figure 24 shows the relationship among T_1 , T_2 and filter depth of the two sand media. At this particular experimental condition, the optimum depth and optimum filter run of commercial media were 1.06 feet and 5.3 hours respectively. Most water treatment plants use a two- to three-foot filter depth. If 2.5 feet are taken as average, the filter run will be only two hours, while the filter run of a corresponding unisized medium will be six hours. The fact that the conventional filter depth exceeds the optimum depth found in Figure 24 explains why head loss rather than floc leakage is usually the limiting condition of a filter run.

The dependency of head loss rate on the filter depth with commercial sand may be explained by considering grain size stratification. Commercially graded sand media after backwashing will have high concentrations of small particles on top of each filter column, which will promote clogging of pores and cause partial cake filtration. When the small size layer is thin, thickness of the cake will be thin and easily sheared, allowing a passage to open up for easier flow. The thickness of this fine

particle layer increases with filter depth, and the depth of the cake layer will thicken, and resistance to the shearing force needed to dislodge the floc and reopen the water passage will increase, leading to a greater head loss than expected from depth increase alone. In such a filter, the head loss will be governed by the finer particles on top (such as effective size), not by the average size.

$$V = 4.0 \text{ gpm/sf}$$

$$C_0 = 3.5 \text{ mg/l Fe}$$

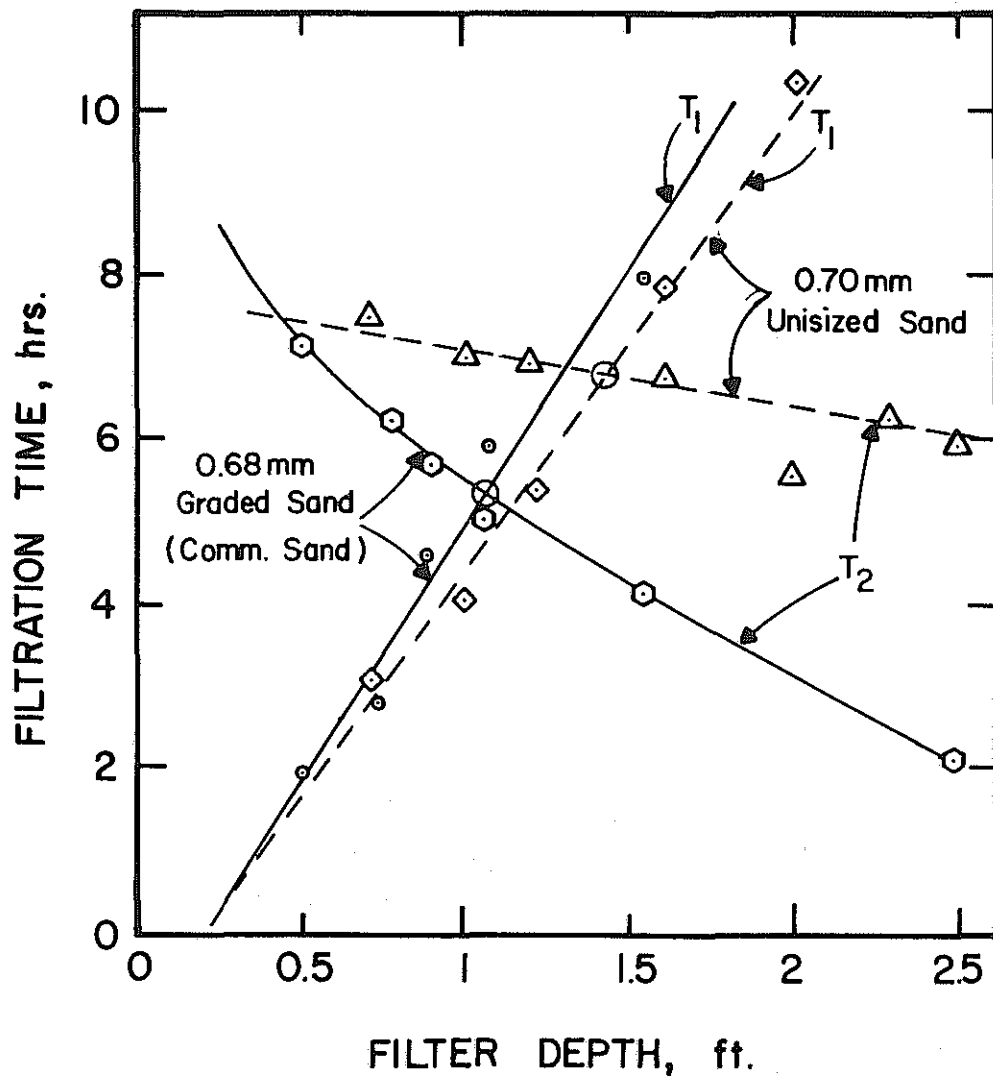


FIGURE 24 Comparison of Graded and Unisized Media

Comparison with Dual Medium. As proved by Conley and Pitman¹⁶ and Dostal and Robeck¹⁷, a dual-medium filter is one of the most practical innovations in filter design. To compare it with a unisized medium, a dual-medium filter with 18 inches of commercial anthracite on top of 12 inches of commercial sand was tested. The composition of each medium is shown in Table 1. Since the commercial anthracite had an average size of 1.1 mm, a unisized anthracite filter of 1.0 mm was compared with the dual-medium filter. As shown in Figure 25, T_1 of the dual-medium filter was 7% longer, but T_2 was only 57% of the unisized anthracite filter. This confirms the finding by Dostal and Robeck¹⁷ that most of the head loss in a dual-medium filter occurs at the topmost layers of anthracite and sand where very fine particles are concentrated, leading to a relatively faster head loss than expected from a standard mode of filtration. The presence of a coarser medium must have alleviated the fast clogging expected from the sand medium alone. Regarding the test presented in Figure 25, the actual filtration time (T_1 or T_2 , whichever is less) for a dual-medium filter would be 13.2 hours, while the same test of a unisized medium filter would be 16.0 hours. As shown in Figure 11, a further increase of a unisized medium filter depth would also increase the filter run up to 23 hours. With a dual-medium filter, however, a similar degree of filtration time increase is not likely because the increase of head loss may be much faster than the increase of T_1 .

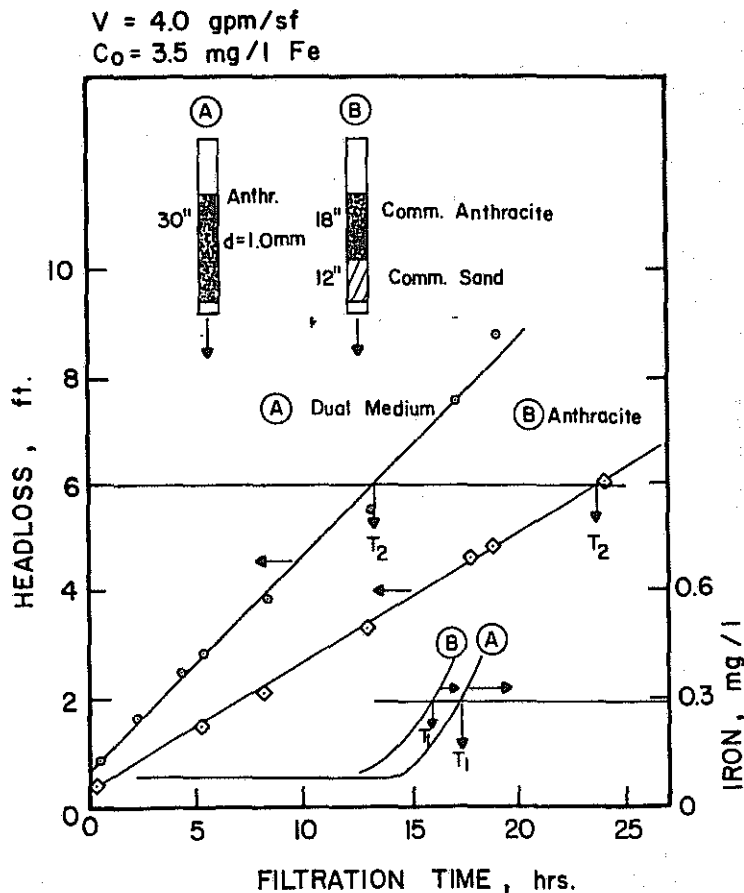


FIGURE 25 Comparison of Dual and Unisized Medium

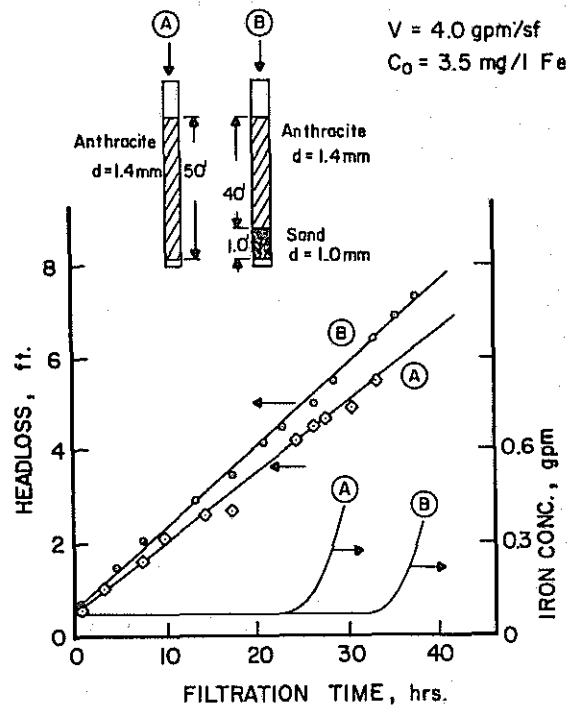


FIGURE 26 Effect of Dual Layer of Unisized Medium

Unisized Dual Medium Filter. Dostal and Robeck¹⁷ recommended the removal of fines smaller than 1.2 - 1.4 mm for use in a dual-medium filter. Even though this would be an improvement over a graded, commercial dual-medium filter, most of the head loss would still occur at the top portion of the commercial sand medium. This obstacle can be overcome by using unisized sand as well as unisized anthracite as the components of a dual-medium filter.

Such a filter, as shown in Figure 26, was compared with a unisized anthracite filter of the same grain size. The unisized dual-medium filter increased T_1 by 31%, while T_2 was reduced by 17% compared to the unisized filter. The choice of size and depth of the sand medium was quite arbitrary, and further improvement of the filter run (where $T_1 = T_2$) could be expected with the proper combination of size and depth of sand. The effect of using dual unisized media, however, is obvious. The addition of a sand layer resulted in the increase of a filter run from 27.5 hours to 30.7 hours. The main influence of the addition of the sand was the increase of T_1 , while the increase in head loss rate was slight. The advantage of a unisized medium is shown when the result in Figure 25 is compared with this test.

The optimum depth of 1.4 mm anthracite was 6.3 feet (Table 9), and the filter run was 35 hours. There will be situations where such a filter depth is impossible due to physical constraints. When the maximum filter depth is limited, the addition of heavier but finer unisized sand will reduce T_2 and increase T_1 , leading to an optimum condition ($T_1 = T_2$) for a given bed depth.

In such manipulations of filter design, the size of unisized sand should be chosen so that the two media, after repeated backwashings, will not mix. The proper size ratio should be selected based on two considerations, the protective action of a coarse medium against penetration, and their relative settling velocities.

In the construction of earth dams, a coarse granular medium is laid on top of a finer medium to prevent a quicksand phenomenon and the loss of fine material. It is called a protective filter, and the theoretical size ratio to prevent the penetration of fines is 1:6.5. In a real situation, however, the ratio is 1:10 before penetration can take place. This is due to the irregular shape of the grains³⁸.

Settling of particles after backwashing is affected by density, size, and sphericity. As long as the sand has a greater settling velocity than the anthracite, the duality of the filter will remain. Since Stoke's Law did not apply in the grain size considered herein, the settling velocity was calculated based on the curve for the transition zone given by Fair and Geyer³⁹ and listed in Table 10. The proper size combination of sand and anthracite will be the size ratio of $1:\sqrt{2}$ or 1:2. When the sand diameter is less than one half of the anthracite diameter, deep penetration of sand into anthracite will occur not because of the porosity relationship but because of the relative settling velocity. A certain degree of mixing at the interface may not be objectionable, but deep penetration would cause porosity reduction³⁵ and may not be desirable.

TABLE 10
Settling Velocity of Different Sized Filter Grain

$T = 16^\circ\text{C}$

Grain Size (mm)	Sand * (cm/sec)	Anthracite * (cm/sec)
0.5	7.0	2.4
0.7	10.4	3.7
1.0	15.6	5.8
1.4	20.3	8.7
2.0	26.8	12.4

* Assumed sphericities of sand and anthracite are 0.86 and 0.63 respectively³³

Comparison of Upflow and Downflow in Unisized Media. The effect of flow direction on unisized media was tested with 1.0 mm sand at the filtration rate of 4.0 gpm/ft². As shown in Figure 27, upflow filtration allowed 26% longer T_1 and 17% longer T_2 than downflow filtration. The slightly reduced head loss rate may be due to some gradation of grain size within the unisized bed. The 26% increase of T_1 is hard to explain. Possibly the upflow method may have enhanced the settling of floc. The settling of floc, however, is considered to play a minor role in the removal of floc⁴.

Since anthracite has a longer filter run than sand, but is not suited for upflow filtration due to its lower density, downflow anthracite media and upflow sand media should be compared for the most practical application. Downflow filtration with unisized anthracite media should be superior to an upflow of unisized sand in regard to the length of a filter run. Also, the intrinsic shortcomings of an upflow filter, such as clogging of the underdrain and dirty water after backwashing, would not be problems.

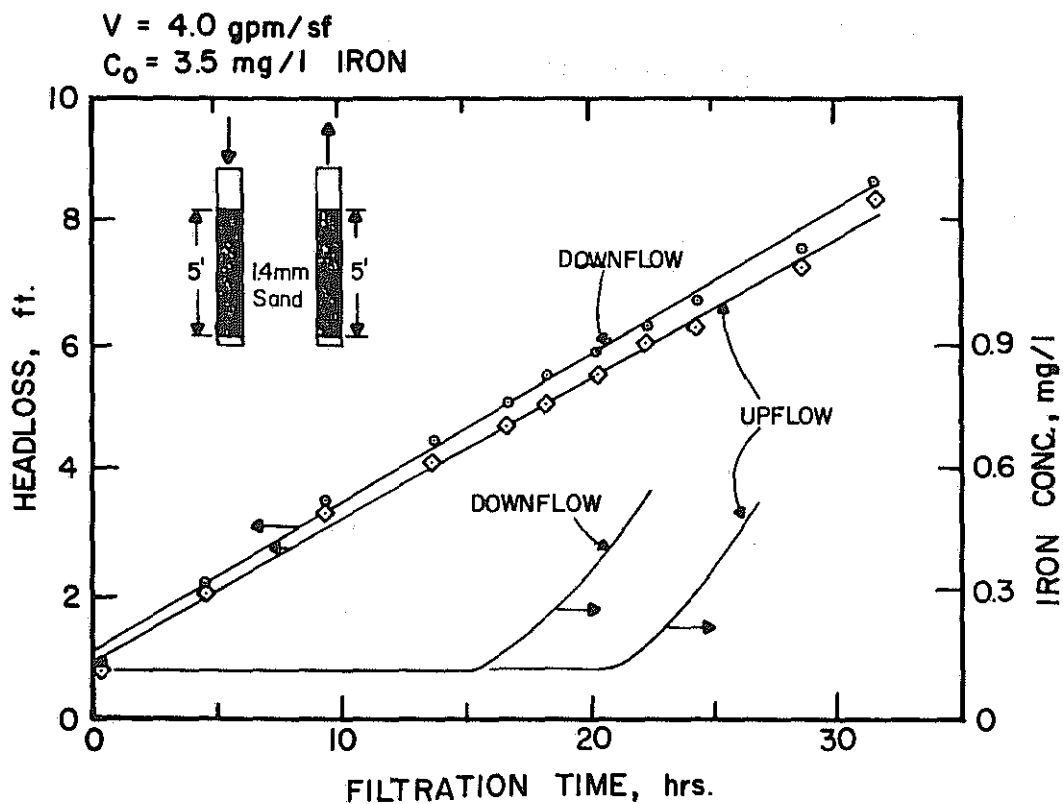


FIGURE 27 Effect of Flow Direction With Unisized Sand

Filtration of Permanganate-Treated Water

Due to the climatic and geological situation, many areas of interior Alaska obtain water from the ground. Ground water usually contains high iron concentration, and the most common method of deferrization is the precipitation of dissolved iron by potassium permanganate followed by greensand filters. The fines of a greensand medium, however, cause rapid clogging of the filter. The objective of this study was to find a filter medium that surpassed greensand.

Initially, greensand functioned as a medium of iron oxidation by prior treatment with permanganate⁴⁰. After each filter run, the exhausted greensand had to be regenerated by the oxidant. This intermittent method of permanganate feed was, however, replaced by the method of continuous permanganate feed, thereby oxidizing ferrous iron directly. Since then, greensand has functioned only as a separation medium, for which it is ill suited. A claim that greensand can buffer the fluctuation of iron concentration that causes overdosing or underdosing of the oxidant⁴⁰ has not been substantiated. It was therefore reasoned that any other type of filter could replace greensand if properly designed.

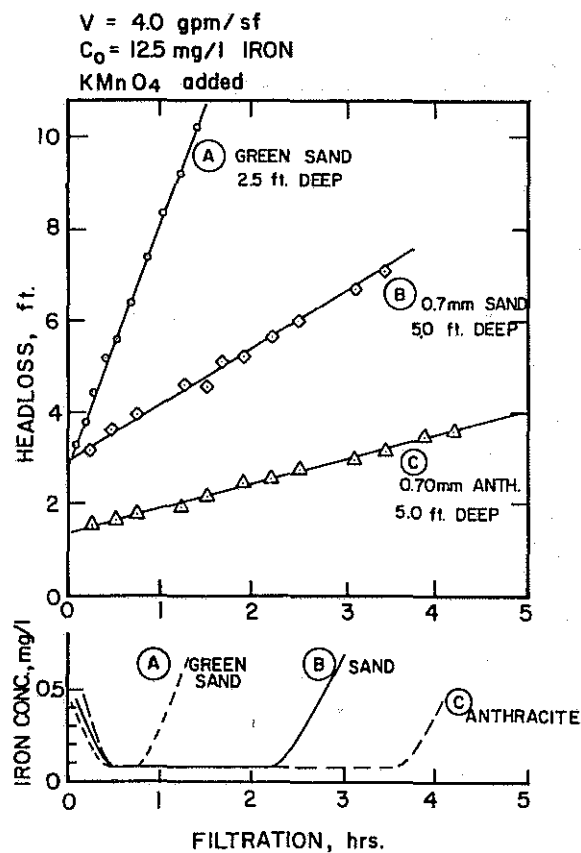


FIGURE 28 Comparison of Greensand and Unisized Media On Permanganate-Treated Water

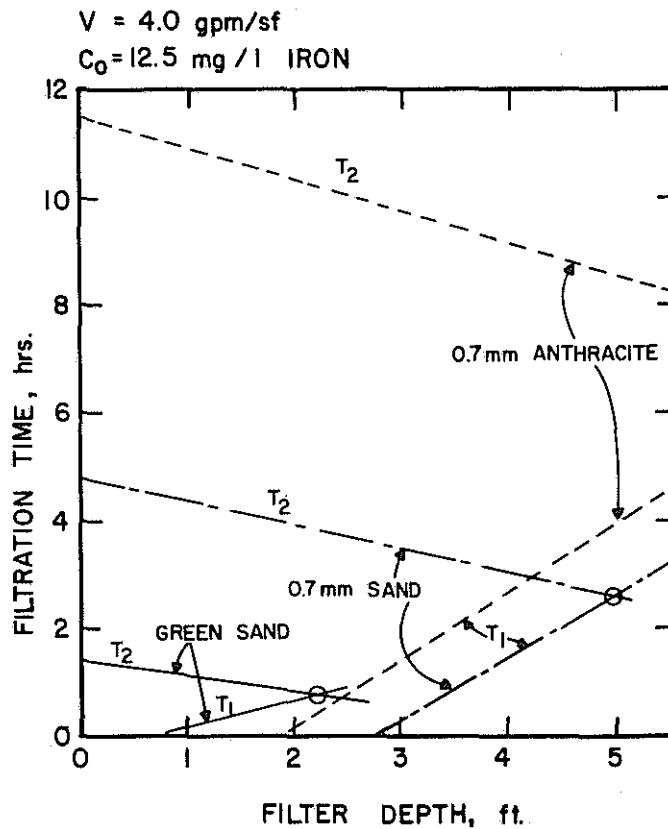


FIGURE 29 Effect of Filter Material On Filtration of Permanganate-Treated Water

The raw water used in this part of the study came from a local well that was used as a coolant for a power plant prior to entering the University Water Plant at about 16°C . The water contained 13.0 mg/l iron and 2.4 mg/l manganese on the average. Following the method proposed by Willey and Jennings⁴¹, a permanganate demand was found at 13.0 mg/l . In test runs, 14.0 mg/l of the oxidant were added to assure complete oxidation and precipitation of iron and manganese. The results of these tests are shown in Figures 28 and 29. Greensand showed extremely high head loss rate compared to unisized media. The optimum filtration time of greensand was only 0.8 hours, while for 0.7 mm sand and 0.7 mm anthracite optimum times were 2.6 hours and 7.2 hours respectively. If the greensand filter is run under a pressure filter system, the filter run will continue until 12.0 psig or 27.7 feet of head loss is reached⁴². Even so, the filter run will be only 3.4 hours at the optimum depth of 7.3 feet (by extrapolation of Figure 29), while 0.7 mm anthracite will run 6.8 hours at the same depth. The duration of the initial leakage was slightly shorter on greensand, but the difference was less than five minutes.

On the whole, unisized media, especially anthracite filters, gave much longer filter runs than greensand.

DESIGN OF AN OPTIMUM FILTER

As emphasized by Camp⁹, any application of a filtration equation for a rational design requires a pilot plant study. This is due to the uncertainty of the behavior of a given floc.

The results of this study, however, may aid in the improvement of a filter for longer filter runs.

First, the advantage of unisized media over graded media of the same average size was established. The uniqueness of unisized media lies in the head loss rate, since it is independent of the filter depth. On the other hand, the head loss rate of graded media increases with filter depth.

On a unisized medium filter, grain size affected both T_1 (time of protective action) and head loss rate. Grossly stated, T_1 was inversely proportional to \sqrt{d} (d =grain size), while the head loss was inversely proportional to $(\sqrt{d})^3$. Since T_2 (time to reach six feet head loss) was an inverse function of the head loss rate, the increase of the grain size led to a large increase of T_2 , while the same decreased T_1 to a limited extent.

On the other hand, the increase of the filter depth reduced T_2 slightly (for a unisized medium) but increased T_1 almost linearly.

Therefore, the use of a coarse and deep bed of a unisized medium resulted in prolonged T_1 and T_2 .

The higher porosity and angularity of anthracite were beneficial in the filter performance; that is, anthracite increased the filter run by more than 70% at an optimum depth compared to the performance of unisized sand of a corresponding grain size.

One of the possible problems in the use of a coarse and porous medium is the long duration of initial leakage. Hudson's observation^{10,32} on this point was pertinent. He showed that a coarse medium functioned very well as long as the floc was strong, but failed as soon as the floc strength was very low and the size of floc became small. He depicted the characteristics of weak and strong floc as shown in Figure 30⁴³. Iron floc used in this study, obviously, was weak because no result showed the convex curve of strong or adequate floc. Hudson's statement is right in regard to shallow (less than two feet) and coarse filters, as shown by the results in Figures 18 and 19. At an increased filter depth, the duration of leakage, however, was reduced to an insignificant amount.

When the depth of a filter is constrained by a physical limitation, the use of unisized sand underneath the unisized anthracite enables one to induce an optimum filtration condition ($T_1 = T_2$) and increases the filter run over the unisized, but less than optimum, anthracite depth. The size of the sand used for such a purpose should not be less than one half the grain size of the overlying anthracite.

There may be a few problems in the adoption of a deep, unisized anthracite filter; the cost of obtaining "unisized" or a narrowly sieved medium would be much greater than the use of a commercial medium. In the long run, however, the benefit of the former might be great enough to overcome the increased cost. The care needed for the composition of supporting gravel would be less for the unisized anthracite because of the lightness and coarseness of the latter.

For adequate cleaning of the bed after a filter run, deep filters require a longer backwash period than shallower, conventional filters. On the other hand, the relative volume of backwash water to the water production per cycle would be less on the unisized filters.

Another possible problem is the flaking of anthracite during repeated backwashings, leading to the accumulation of fine particles on top of the filter. Careful backwashing and periodic removal of the fine from the top would enable one to overcome the problem.

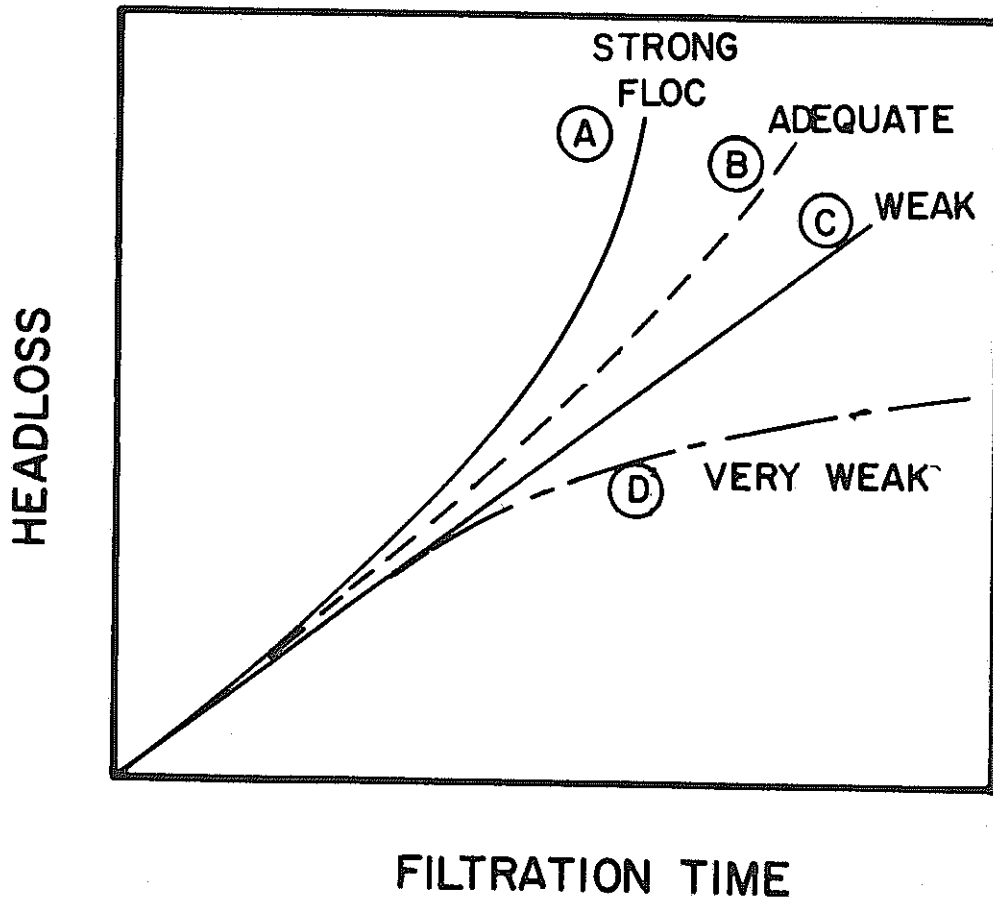


FIGURE 30 Strength of Floc Reflected In Head Loss Curves
(After Hudson⁴³ Except Curve D)

SUMMARY AND CONCLUSION

In an attempt to find a better filter than greensand for the removal of iron from ground water, several types of modified filters were investigated. Downflow, uniform sized (relatively speaking) filter media looked very promising, and an in-depth study of the filter under a fixed rate of filtration using a synthetic iron floc suspension was conducted. Also, the performance of the unisized medium filter was compared to other filters. The results can be summarized as follows:

1. An upflow contact filter was superior to a conventional downflow filter by reducing the rate of head loss. In spite of the advantages, there were a few important shortcomings which may restrict the wide-spread acceptance of the upflow method: the tendency of the bed to lift and fluidize limited the maximum rate and minimum grain size. Clogging of the underdrain and supporting gravel medium was a problem. Dirty water left on top of the filter after backwashing posed a disposal problem.

2. The head loss rate of a downflow, unisized bed was independent of the filter depth, allowing the use of a deep medium without significant reduction of T_2 (time to reach six feet head loss). The same could not be said for a graded commercial medium.

3. On unisized filters, the influence of the grain size was much more pronounced on the head loss rate than on the time of protective action (T_1). Filter depth, however, affected T_1 more than T_2 . Thus, a prolonged filter run was obtained by the use of a coarse and deep unisized medium. The filter run was increased more than ten times that of a conventional filter under the test conditions.

4. At the optimum filter depth, anthracite allowed a filter run 71 to 109% longer than a sand filter of the same grain size. This was attributed to the greater porosity and angularity of the former.

5. The duration of initial floc leakage after the start of a filter run was longer with the coarser grain size medium. Also, anthracite had a longer leakage period than sand. This problem could, however, be overcome by an increase in the filter depth, which would reduce the leakage period to an insignificant fraction of the total filtration time.

6. When the maximum filter depth is limited by a physical constraint, the use of a unisized dual-medium is recommended for optimization of the filter run. For such a filter, the size ratio of unisized anthracite and sand should not exceed two, in order to prevent mixing.

7. In the filtration of ground water treated with permanganate, a unisized medium performed much better than greensand; the latter clogged very fast due to the extremely fine grain size. For this floc anthracite was superior to sand of an identical grain size.

8. The validity of the filtration theory and equations developed by Heerje and Lerk⁶ was tested in regard to the relationship between T_1 (time of protective action) and grain size, and head loss rate and grain size. Experimental data did not fit the equations well.

9. The foregoing investigation was conducted at a fixed filtration rate and iron concentration. Quantitative extrapolation to another filtration condition would not be practical in view of the different characteristics of floc and the time lag in the floc compaction process within the filter.

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