A LABORATORY STUDY OF FACTORS AFFECTING THE APPLICABILITY OF DIRECT FILTRATION WATER TREATMENT

by

William T. Amy

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APPROVED:

Paul H. King, Chairman

Clifford W. Randall

Gregory D. Boardman

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INTRODUCTION

With the passage of Public Law 93-523, the Safe Drinking Water Act, maximum contaminant levels, commonly called MCL's, have been established for all community water systems. The MCL set for turbidity was 1.0 Nephelometric turbidity unit (Ntu). This level was appreciably more stringent than the 5.0 Ntu guideline suggested by the United States Public Health Service in 1962 and was the result of an effort to insure that disinfection processes were not compromised by suspended particulates in the treated water intended for delivery to the consumer.

Communities which had been meeting the 5.0 Ntu guideline by utilizing high quality raw water sources without providing conventional filtration treatment were suddenly faced with the prospect of a substantial capital investment for a water treatment facility. Because direct filtration treatment has been used successfully with high quality raw water, increased interest in the United States in direct filtration water treatment schemes was one result of the PL-93-523 legislation.

As defined by a committee of the American Water Works Association, direct filtration is a water treatment scheme in which filtration is not preceded by a sedimentation step. Chemical pretreatment of the water is intended, and a flocculation step may or may not be included. The elimination of the sedimentation basin--and possibly the flocculation basin as well—would represent a significant savings in the cost of constructing a new water treatment plant. Governmental officials able to draw upon any relatively high quality raw water source would naturally be interested in realizing such savings for their constituents. In addition, direct filtration schemes have been contemplated for water sources of appreciably poorer quality than those meeting a 5.0 Ntu turbidity standard.

Research on the factors which affect the design and operation of direct filtration treatment plants has been undertaken by investigators in various nations. Thus far, laboratory studies and the operating experience of existing direct filtration facilities would appear to indicate that direct filtration may be a particularly attractive water treatment option for many communities.

Many raw water, filter, and process operating characteristics have been studied as design limiting factors. The requirement that the filters must store all of the material removed from the water applied to them has led to general acceptance of the suggestion that turbidity might be the most immediately decisive factor limiting the use of direct filtration treatment schemes. Maximum raw water turbidity limits suggested by various investigators have ranged from less than 15 Ntu to over 100 Ntu.

Other factors which may influence the efficiency of direct filtration treatment are raw water color, total dissolved solids, hardness, tastes and odors, biological characteristics, pH, temperature, and alkalinity, the nature of the suspended particulates, the chemical and physical characteristics of the coagulant added, the size, shape, density, depth, and porosity of the filter media, the hydraulic loading rate applied to the filter, and the mixing characteristics of the specific flow scheme contemplated.

The laboratory study reported in the following pages was intended to allow conclusions about some--though not all--of the parameters cited. The variables of interest were the raw water turbidity, the coagulant choice, the use of a flocculation step, and the hydraulic loading rate applied to the filter. Because the raw water used during the study was not a strictly controlled "synthetic" water, other parameters were quantified to ensure that variations in the raw water characteristics did not go unnoticed. The objectives of the research were to determine, for a specific surface water source and a specific, dual media, granular bed filter, the raw water turbidity which limited the applicability of selected direct filtration treatment schemes and to compare the results of direct filtration treatment with the results of conventional treatment employing the same water source and filter.

LITERATURE REVIEW

The treatment process steps conventionally used for the production of municipal potable water supplies might appear to be exceedingly well established technologies which have seen little change for some time. As pointed out by King et al (1), a less casual observer can distinguish several, if not many, important refinements developed in recent years. In some cases, the progress made was constrained simply by considerations of economics. Recent changes in conventional plant design have been discussed by Culp (2), and the flow schemes shown in Figure 1 evidence several such economically constrained changes. The 2 gpm/sf production rates of older designs have given way to much higher filtration rates, such as the 5 gpm/sf rate noted for many California plants and the 4 gpm/sf rate currently permitted in Virginia (3). Improved cost control and treatment reliability through better coagulant control have been found necessary and have been made available using such means as the indicated pilot filter.

Direct Filtration Schemes

Direct filtration treatment is another refinement in water treatment technology motivated by considerations of economics. The idea itself is not recent, but interest in it has been only recently revived. For raw water sources of low turbidity, the flocculation and sedimentation steps provided in conventional treatment are kinetically and economically inefficient (2,4-7). Safe and reliable water

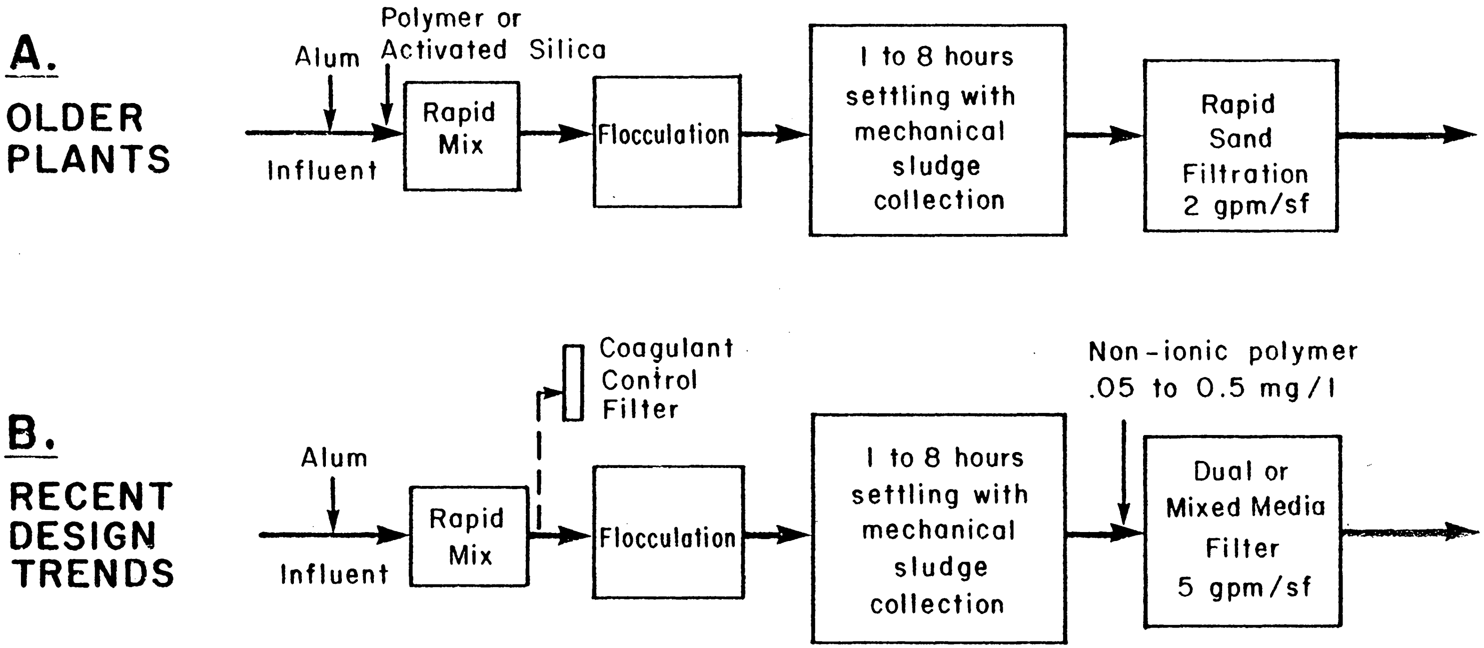


Figure 1. Conventional Water Treatment Flow Schemes, (after Culp) (2)

treatment appears to be possible without these steps, and their elimination from the process chain evidently can result in attractive savings in the cost of building and operating a water treatment facility (2,8-12). Direct filtration flow schemes that have been studied are shown in Figure 2. The elimination of the sedimentation step is the key aspect to this treatment alternative. Elimination of the flocculation step may or may not be appropriate, but rapid mixing is always included. Venema (12) suggested the use of a flow scheme without rapid mixing that he called in-line filtration. Such a process, identified as contact flocculation, was studied with good bench scale results by Adin and Rebhun (4). Lee (13), of the Nalco Chemical Company, patent-holder for an in-line filtration scheme using proprietary coagulants, has indicated that such flow patterns are generally unsatisfactory. He, along with a rather substantial number of other investigators (14-17), has found that intense rapid mixing is essential to the success of direct filtration treatment.

Relation of Coagulation Theory to Direct Filtration

Current coagulation theory, as developed by Stumm and Morgan (18) and others (19-21), emphasizes both the physical and chemical aspects of colloidal destabilization. Chemical coagulation produces, by chemical reaction and by charge neutralization and double layer compaction, a microscopic floc. This floc, under the influence of Van der Waals forces and chemical bridging mechanisms, coalesces readily. It can be removed from the water being treated either by flocculation and sedimentation as in conventional treatment or,

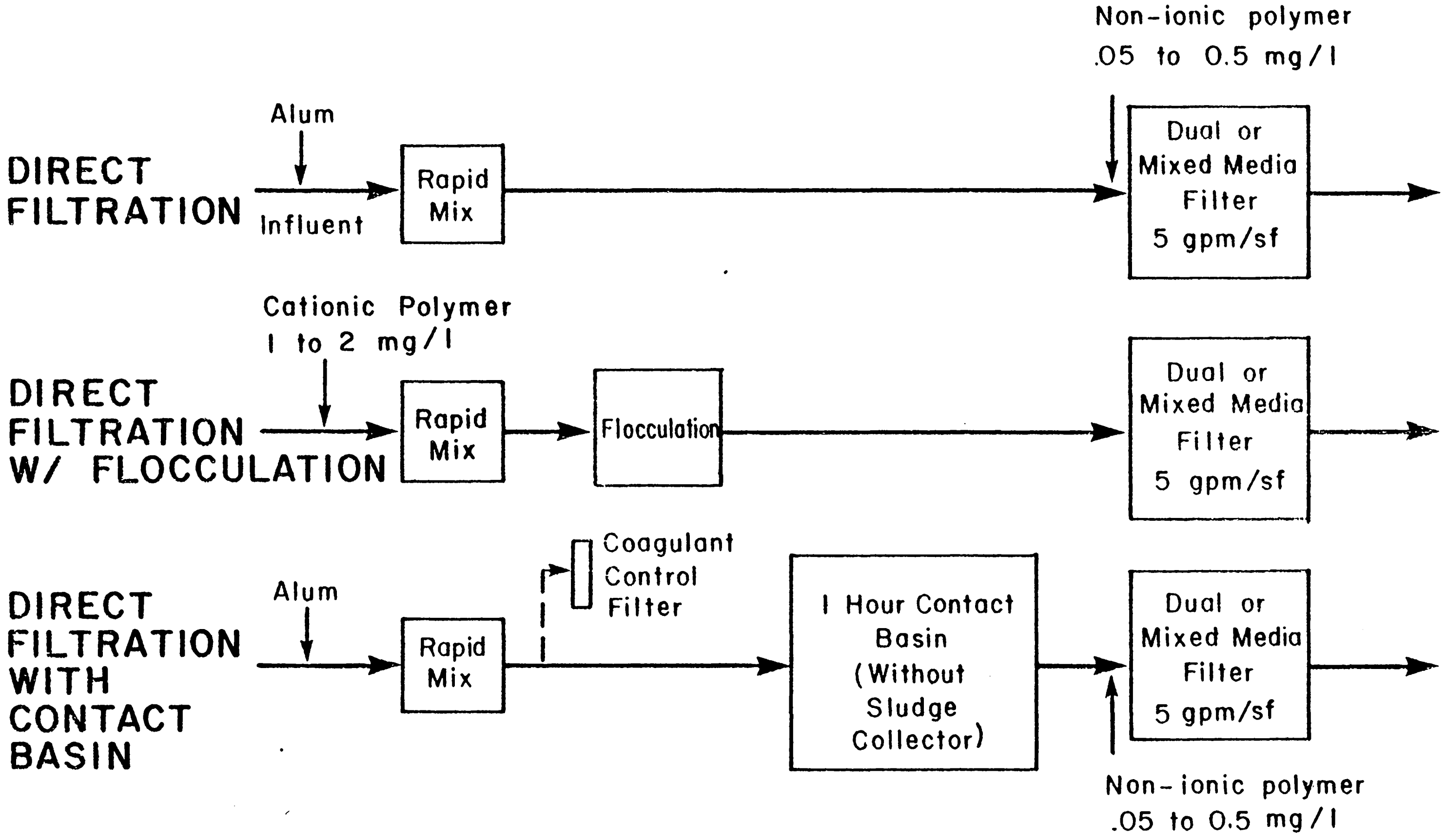


Figure 2. Direct Filtration Flow Schemes, (after Culp) (2)

under appropriate conditions, by direct filtration. The filterable floc required for direct filtration success is not necessarily settleable. The goal of producing a floc that is filterable may allow in some circumstances the elimination of the flocculation step as well as the sedimentation step. Although the favorability of eliminating a flocculation step is indicated by current theory, the experience of several investigators and designers has led to the inclusion of flocculation at many direct filtration plants.

Current filtration theory, as developed by O'Melia and Stumm (22) and others (23-27), satisfactorily accounts, qualitatively at least, for filtration removals by direct filtration processes. But use of the theory does not allow delineation of the circumstances under which direct filtration schemes are appropriate or workable.

Relation of Raw Water Characteristics to Direct Filtration

High suspended solids concentrations cause short filtration times and high backwash requirements. No consensus, however, has yet been reached as to how high suspended solids concentrations can be before direct filtration treatment becomes uneconomical. Kawamura (28) suggested that when the average raw water turbidity exceeds about 10 Ntu, direct filtration usually is not efficient. An AWWA survey by Letterman and Logsdon (29) appeared not to contradict this limit. Eighty per cent of the plants responding had average raw water turbidities less than 10 Ntu. It was also reported, however, that 50 per cent of the respondents had an average raw water of less than

3 Ntu. The experience of Culp (2,30) in California has led him to suggest different water quality limits. He has suggested that direct filtration treatment may be an attractive option when a) color and turbidity are both less than 25 units, or b) with low color, maximum turbidity is less than 200 Ntu, or c) with low turbidity, maximum color is less than 100 APHA units. Additionally, he felt there should be no paper fiber or diatom concentrations greater than 500-1000 asu/ml, and no coliform concentrations greater than 90 coliforms/100 ml.

Operational Parameters

In addition to the limitations imposed by raw water characteristics, water treatment engineers must consider the conditions under a direct filtration treatment scheme would be operated. Media composition, size, and depth must be chosen, as must the flow rates at which the plant should be operated, the type and amount of coagulant, and the minimum acceptable filtration time between backwashings. These considerations are not unrelated, but the effect of one choice on the others can generally be anticipated only qualitatively. Engineers designing direct filtration plants have found that pilot studies are almost always a desirable first step (2,5,7-16,30-39). As described in the literature, pilot studies and the designs resulting from those studies apparently vary rather widely from one situation to another. As experience with direct filtration is gained in a given region, the need for extensive direct filtration pilot studies may become less critical. It is hoped that this report will contribute to the body of knowledge available to engineers contemplating direct filtration treatment alternatives in Virginia.

MATERIALS AND METHODS

Laboratory Procedures

A bench scale water treatment plant was constructed in the laboratory to allow for data collection and to facilitate the comparisons indicated earlier. In general, the treatment units used were vessels available in the laboratory and did not require extensive modification. The treatment units and the flow schemes employed are as shown in Figure 3. The raw water reservoir was a painted steel, 55 gallon drum. Two 10" diffuser stones, approximately 1/2" square in cross section, were placed on the bottom of the drum. These were connected to the laboratory air supply, and sufficient air was bubbled through the raw water to keep it well mixed and to prevent the settling out of the suspended particulates. Water was pumped out of the drum with a Monostat peristaltic action pump and supplied to a constant head tank. The pumping rate was generally about twice the rate of flow desired for the remainder of the treatment plant. Excess flow was returned to the raw water reservoir through a hose connected to an overflow port at the top of the constant head tank. No mixing was provided in the constant head tank, but sedimentation in the 11-liter plexiglass vessel was minimal.

A rapid mix unit was constructed from a piece of plexiglass column 4 cm inside diameter by approximately 10 cm in height. An 8 mm plexiglass base plate was fastened to one end of the column, and a

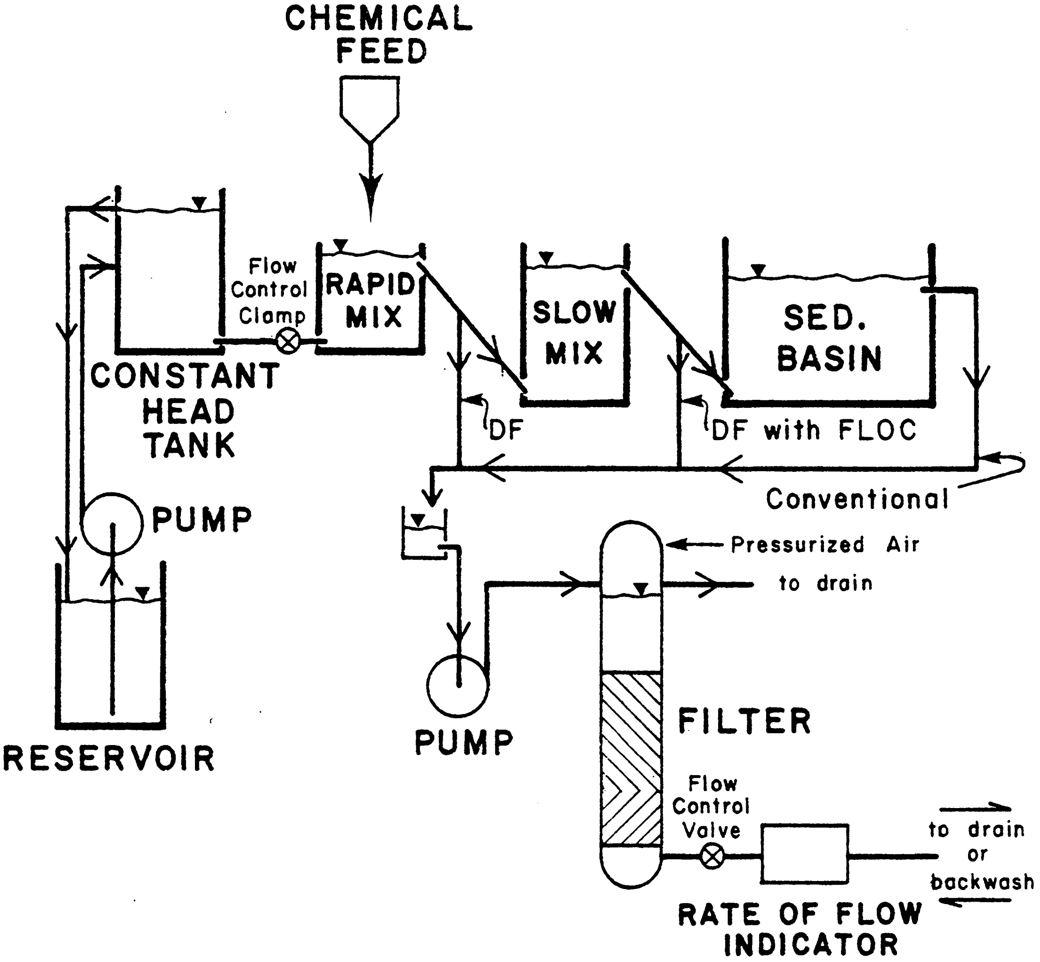


Figure 3. Laboratory Water Flow Schemes

side tap of approximately 10 mm inside diameter was provided about 5 mm from the base plate. The other end of the column was closed with a two-hole rubber stopper containing a glass thistle tube and a plastic tee. The thistle tube was used to deliver coagulant solution to a point approximately level with the side tap. The tee was oriented with the run vertical and the branch, or side outlet, horizontal and was connected to an effluent line. The high end of the run of the tee was open, and, by allowing atmospheric pressure at the branch, prevented pulsing, siphon-action flow when the mixing unit was full of water. A magnetic stirring bar approximately 5 mm in diameter by about 25 mm in length provided mixing and was powered by a Fischer Flexamix laboratory stirrer. Although the stirrer was operated near its maximum speed for long periods of time, no heat buildup occurred, and the plexiglass base plate of the rapid mix vessel was allowed to rest on the stirrer surface. The velocity gradient afforded was not measured, but mixing was vigorous and was assumed to be adequate.

Because the rapid mix vessel volume was not altered for the flow rates studied, the detention time in the mixer was different for each flow rate. At a flow rate equivalent to 5 gallons per minute per square foot of filter surface area, the calculated detention time was 25 seconds. At flow rates equivalent to 3 and 8 gallons per minute per square foot of filter surface area, the detention times were 41 seconds and 15 seconds respectively. The coagulant, either alum or Cat-Floc T-1 polymer, was added to the water flowing through the rapid mix unit by means of a constant rate drip flow into the glass thistle tube mentioned earlier. The coagulant solution flow represented only about 1% of the raw water flow. It was dispensed through a dropper connected to a constant head reagent bottle called a Marriott flask. After it was determined that 20 drops were equal to 1 ml at the 2 ml per minute flow rate contemplated, metering the flow was done by timing 10 drops with a stop watch. Adjustments to the flow were made with a ground glass valve in the line. Coagulant dosage was determined by means of the Riddick Zeta-Meter for alum coagulated trials and by use of the jar test for polymer coagulated trials.

Water flowed out of the rapid mixer into a plastic wye that allowed the water to be directed either to a flocculation step or directly to the filtration step. The flocculator unit was a 20 cm inside diameter by 50 cm tall plexiglass vessel similar to the vessel used as a constant head tank. Flows from the rapid mix unit entered the flocculator vessel at the bottom and travelled upward to an overflow port approximately 25 cm above the inlet. A calculated detention time of 30 minutes was provided, and the velocity gradient afforded was an average of about 30 cm per second per cm (sec^{-1}). Mixing was provided by a rheostat controlled blade mixer with 6 stirrer paddles attached to a single brass rod. Variations in the speed of the mixer caused the velocity gradient to vary somewhat, and the range of gradients employed was 20 sec^{-1} to 50 sec^{-1}. This range was, however, acceptable, particularly in light of the fact that the variations were not abrupt. Mixing efficiency in the circular cross sectioned tank was enhanced by the presence of 4 baffles projecting about 25 mm from the side wall and dividing the cross section into quadrants. While sedimentation within the flocculator was negligible, the upflow mode of operation was not entirely satisfactory due to the apparent increase in the suspended solids concentration within the vessel as a given trial progressed.

The effluent from the flocculator entered another plastic wye that allowed the flow to be directed either to the filtration step or to a sedimentation step. The sedimentation unit was a 15 gallon (approximately 55 liter) polyethylene container with an internal, adjustable weir provided. Coagulated effluent entered the container through an opening in the bottom and traveled in a discernable current part way across the bottom. Precise modelling of the hydraulic regime was not attempted, but flows were sufficiently slowed and dispersed through the container that adequate solid-liquid separation took place. Water flowed up from the bottom of the tank and over a plexiglass weir approximately 120 mm long. The weir formed one (low) side of an open topped plexiglass box with a bottom outlet. A tightly sealed hose carried the water down to the bottom of the container to an outlet near the bottom of the can. From thence the water was conducted to the suction side of the filter feed pump.

The filter employed in the study was a dual media, coal-sand filter, 36" in height. Silica sand was obtained from VPI's concrete laboratory and was sieved wet and dry several times to obtain the desired size fraction. The sand used in the filter passed through a screen with 0.589 mm openings and was retained on a screen with

0.420 mm openings. Assuming an approximately linear gradation between these two sizes, the effective size of the sand was 0.44 mm with a coefficient of uniformity of 1.2. The coal used was "Anthrafilt" anthracite coal obtained from what is now Carbon Sales Inc. of Wilkes Barre, PA. It, too, was sieved wet and dry to obtain the size fraction desired. Coal used in the filter passed through a seive with 1.19 mm openings and was retained on a sieve with 0.84 mm openings. Again assuming an approximately linear gradation between these two sieve sizes, the effective size of the coal was 0.88 mm with a uniformity coefficient of 1.2. Work by Cleasby & Sejkova (40) might lead to the expectation that because the coal size was only twice that of the sand, the coal and sand would form a sharp interface when placed in the filter. Apparent impurities and specific gravity variations in both media and the angularity of the coal caused a zone of intermixing of about 4" to form when the two materials were placed in the filter column and backwashed. The depth of sand placed in the filter column was 11". Sufficient coal was then added that the total depth of the filter after it was backwashed and drained several times was 36". The undergrain material was quartz pebbles graded from 1/8" sieve size at the interface with the sand layer to 1/2" at the drilled plexiglass plate which formed the bottom of the filter.

The plexiglass filter column was 4.1 cm inside diameter by about 180 cm (about 6') tall. A flanged joint with a rubber O-ring seal was provided at midheight to allow the filter media to be packed more readily. The column had side taps immediately above and below the drilled plate that supported the underdrain and media. Additional side taps were provided 9" on center to the midheight flange then 6" on center to the top of the column. Most of the taps were not used during the course of this laboratory study. It is expected, however, that they contributed significantly to any wall effects that may have resulted from the rather small size of the filter cross section.

Manometer taps to a mercury U-tube manometer were provided just above the unexpanded filter and just below the filter media in the underdrain gravel. The manometer allowed measurements of the total amount of headloss across the entire height of the filter but did not, of course, allow a headloss profile at multiple points through the bed. The measurement error introduced because the lower tap was in the underdrain gravel was estimated to be less than 1 per cent of the headloss measured, even during the clean bed phases of filtration.

Pretreated water was applied to the filter using a Monostat peristaltic action pump identical to the pump supplying the constant head tank. A 1-liter reagent bottle collected the effluent water at the suction side of the pump. The average retention time in the catch bottle was generally about 1/3 of the 2 min to 5 min retention time above the filter media. The water was pumped to a point about 6" above the surface of the water column over the media. The height of the water above the media was generally about 2'.

Because of drain height constraints and minor losses, the total headloss that could be expended in the filter was only about 4'. A higher terminal headloss in the filter was desired, and the column volume above the media was pressurized to 2.6 psig using a Gast laboratory pressure/vacuum pump. The 2' height of the water column over the media should theoretically have led to air binding in the media as soon as the headloss exceeded the depth of the water at any given point. Apparently, the gas transfer rate at the air-water interface was sufficiently slow that dissolved gas concentrations were appreciably below equilibrium when the water left the interface. The net effect of pressurizing, then, was to increase the effective height of the water column above the filter media.

Flow through the filter was controlled by means of a needle valve and rotameter on the outflow line from the filter to the drain. As the headloss in the filter increased, the headloss in the needle valve was decreased, i.e., the valve was opened, and the height of the rotameter indicator remained constant. This method of controlling the flow was not entirely satisfactory. Ideally, the valve would have been opening continuously as the run progressed. Instead, periodic adjustments of the flow were made, causing flow surges that would presumably be roughly similar to the "hunting" action of an improperly operating rate of flow controller in a full scale plant. Between upward adjustments of the flow, the filter would have functioned as a declining rate filter rather than as a constant rate filter as intended. These flow surges were never substantial, however, and rarely amounted to as much as 10 per cent of the desired flow rate. The main result of the non-ideality of the flow control system was the need for constant monitoring of the rotameter.

Backwashing of the filter was accomplished using Blacksburg tap water. To allow use of the rotameter for indicating backwash flow rates, the outflow lines from the filter were disconnected from the rotameter inflow tap and reconnected to its outflow tap. A hose connection was made from the city water tap to the rotameter inflow, and the backwash water then flowed through the rotameter before flowing up through the filter media. A backwash flow of about 20 gallons per minute per square foot of filter surface area was sufficient to expand the bed almost 50 per cent, and no accumulation of mudballs was noted throughout the time of the study. Measurements of the amount of backwash water used were not attempted, partly because one of the apparent wall effects observed was difficulty in fluidizing the bed when it was dirty.

Raw Water Source and Handling

The water used for the study was taken from the influent of the Blacksburg-Christiansburg-VPI Water Authority Treatment Plant. This plant is located on Virginia State Route 114 between Blacksburg and Radford, and it draws its raw water from the New River at a point above the Radford Arsenal and below the city of Radford. Although subject to rather wide fluctuations in turbidity, the quality of the water is generally good, and the turbidity is not uncommonly less than 5 Ntu. Water for the study was collected in 5 gallon Nalgene carboys at the pumping station located at the river intake or at the booster station located about midway between the plant and the river. In general, not less than 50 gallons of water were collected on each trip. The turbidity of the water was adjusted upward as required by the addition of bentonite from the American Colloid Company of Chicago, Illinois. Approximately 25 grams of bentonite was suspended in a liter of tap water at least 24 hours before it was used to adjust the turbidity of the river water. This procedure was employed to insure that the clay was fully hydrated before use. Approximately 5 mg/l of bentonite were generally required to raise the turbidity of the water about 1 Ntu. This was appreciably more than anticipated, since the original silica standard was based on 40 mg/l of specially graded silica yielding a turbidity of 40 units. This unexpectedly high ratio of concentration to turbidity may indicate some deficiency in the bentonite used.

The matrix of variables studied is presented in Table 1. The parameters varied were influent turbidity, the hydraulic loading rate and the treatment flow scheme. A total of 23 differing combinations of treatment conditions were studied, and the results herein reported.

Analytical Methods

The tests used to characterize the raw and filtered water and the analytical procedures employed are summarized in Table 2. The basic procedures referred to are described in the Fourteenth Edition of APHA's

TABLE 1

LABORATORY TREATMENT RUNS ATTEMPTED: MATRIX OF VARIABLES STUDIED

Mode	Hyd. Loading	Raw Water Turbidity in Ntu:								
		Alum Coagulant			Polymer Coagulant			Alum + Polymer		
		5	10	15	5	10	15	5	10	15
Direct Filtration	5 gpm/ft^2	x	x	x	x	x	x	-	x	-
	8 gpm/ft^2	-	x	x	-	x	x	-	x	-
	3 gpm/ft^2	-	-	x	-	-	-	-	-	x
Direct Filtration w/Flocculation	5 gpm/ft^2	x	-	x	x	x	x	-	-	-
Conventional	5 gpm/ft^2	x	-	x	x	-	x	-	-	-

TABLE 2

TESTS & ANALYTICAL PROCEDURES

Alkalinity - Titration w/ 0.02 N H_2SO_4

Algae - Sedgwick Rafter Counting Chamber and Whipple Eyepiece
Color - APHA Platinum-Cobalt Standard in Klett Colorimeter (Apparent and True)
Total Coliform - Membrane Filtration on .45µ Filters Incubated on LES Endo Agar
Total Hardness - EDTA Titration Method
Total Dissolved Solids - Gravimetric Method
Turbidity - Hach 2100 A Nephelometer

Standard Methods for the Examination of Water and Waste Water. Deviations from some of the procedures specified were as follows. The end point of the titration for alkalinity determination was occasionally determined using methyl purple indicator instead of a pH meter. Color, both apparent and true, was measured using a Klett-Summerson Colorimeter rather than the visual or spectrophotometric methods recommended. Turbidity is an interference, particularly for apparent color determinations, but a reasonable comparison between raw and filtered waters was thought to be more important than precise color measurements. True color samples were prepared by filtration of a water sample through washed, glass fiber filters such as required for dissolved solids determinations. True color is thus expected to be accurately reported. The Klett-Summerson Colorimeter allowed quick color determinations of greater accuracy than would be expected from visual comparisons. A standard curve was developed for the particular instrument and cuvettes employed using platinum-cobalt standards. Values for color were then interpolated from the standard curve.

The filter holders and funnels for membrane filtration analysis were not autoclaved between sampling intervals of the same experiment. Sterilization was accomplished with ultraviolet light, and incubation of control filters demonstrated the efficacy of this method.

Turbidity measurements for later experiments were made using secondary standards prepared by Hach Chemical Company. The accuracy of the secondary standards was checked against primary, Formazin standards and was thought to be adequate. The secondary standards were in sealed cuvettes and matching those cuvettes with the sample cuvettes was not possible. Accuracy greater than 0.05 Ntu in the range of 0-1 Ntu was not anticipated by the writers of Standard Methods, and data in this range were recorded to the nearest 0.05 Ntu.

EXPERIMENTAL RESULTS

The data resulting from 29 filtration trials are summarized in Tables 3-16. Tables 3-7 are a summary of the results related to the physical description of the filter's performance. Tables 9-15 summarize the characteristics of the raw and filtered water as tested at various intervals. Table 8 presents essentially all of the turbidity and headloss values measured for each filtration trial, and Table 16 provides a comparison of the results of the three flow schemes studied.

As shown in Table 3, the results of conventional treatment filtration were uniformly satisfactory for both 5 Ntu and 15 Ntu raw water samples. A settleable floc could be produced with both alum and polymer coagulants and the clarity of the filtered water ranged from values below detectable limits to about 0.2 Ntu. These values are well below the 1.0 Ntu MCL set for turbidity by EPA, and in only one case was the 0.1 Ntu goal suggested by AWWA exceeded. Breakthrough appeared to be beginning at the end of only one of the four trials, the alum coagulated 15 Ntu raw water sample. In these conventional treatment trials, the filter was essentially employed as a polishing step. The turbidity of the applied water was fairly low and generally decreased as the solids concentration in the sedimentation tank increased. Applied water turbidity averaged from about 2.0 Ntu to about 3.5 Ntu for the four trials reported.

TABLE 3

FILTRATION DATA: CONVENTIONAL TREATMENT

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant:	Alum	Alum	T-1	T-1
Coagulant Dose (mg/l)	20	25	1.0	1.5
Influent Turbidity (Ntu)	5	15	5	15
Applied Turbidity (Ntu)	2.3	3.5	2.0	2.3
Effluent Turbidity (Ntu)	0.0	0.05	0.10	0.20
Run Time to B.T. or h_L = 8 (hrs)	>10	>10	>10	>10
Actual Run Time (hrs)	10	11.5	7	4
Final Effluent Turbidity (Ntu)	0.0	0.40	0.10	0.20
Final Headloss (ft)	3.5	3.8	4.8	2.5
Remarks:	ZP to -3 from -13	ZP to -3 from -12		ZP to -10 from -13

TABLE 4

FILTRATION DATA: DIRECT FILTRATION w/ALUM COAGULANT

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant:	Alum	Alum	Alum	Alum	Alum + CA233
Coagulant Dose: (mg/l)	15	25	15	15	20 + 0.10
Influent Turbidity (Ntu)	5	10	15	25	10
Effluent Turbidity (Ntu)	0.15	0.10	0.20	0.25	0.05
Run time to B.T. or h_L = 8 (hrs)	>10	<1.5	>3.5	--	3
Actual Run Time (hrs)	10	1.5	3.5	1	3.75
Final Effluent Turbidity (Ntu)	0.15	1.2	0.2	B.T.	0.05
Final Headloss (ft)	7.3	2.9	4.2	3.1	11.5
Remarks	dose by jar test	ZP to -5 from -16	w/o pressure, h_L limit reached	B.T. at filter pressurizing dose by jar test	visible floc penetr. to sand; B.W. difficult

TABLE 5

FILTRATION DATA: DIRECT FILTRATION w/POLYMER COAGULANT

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant:	T-1	T-1	T-1	T-1	T-1
Coagulant Dose (mg/l)	0.75	0.75	0.75	0.25	1.0
Influent Turbidity (Ntu)	5	10	15	15	15
Effluent Turbidity (Ntu)	0.10	0.10	0.10	0.35	0.15
Run time to B.T. or h_L = 8 (hrs)	<7	3.5	<3	<2	2.5
Actual Run Time (hrs)	8	4.5	3	4	2.5
Final Effluent Turbidity (Ntu)	0.05	4.5	7.6	12.0	1.0
Final Headloss (ft)	10.3	7.8	8.6	9.3	9.7
Remarks	ZP to -12 from -14	h_L = 6.6 at B.T.		dose increase at 2 hrs ineffective	ZP to - 12.5 from -14

TABLE 6

FILTRATION DATA: DIRECT FILTRATION PLUS FLOCCULATION

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant	Alum	Alum	T-1	T-1	T-1
Coagulant Dose (mg/l)	20	20	1.25	0.75	2.0
Influent Turbidity (Ntu)	5	15	5	10	15
Effluent Turbidity (Ntu)	0.05	0.10	0.10	0.10	0.10
Run Time to B.T. or h_L = 8 (hrs)	>10	<2	>10	3	<7
Actual Run Time (hrs)	11	3.5	11	3	8
Final Effluent Turbidity (Ntu)	0.05	5.4	0.10	1.8	0.10
Final Headloss (ft)	7.8	3.5	7.6	5.6	10.0
Remarks	ZP -3	ZP -5; h_L = 2.8 at B.T.	ZP to -13.5 from -16; 0.75 mg/l T-1 til 3 1/2 hrs	raw water added at 2 1/2 hrs	ZP to -10 from -15; air pump on at 2 hrs at h_L = 2.8 ft

TABLE 7

FILTRATION DATA: DIRECT FILTRATION AT OTHER FLOWRATES

Hydraulic Loading Rate: 8 gpm/ft^2

Coagulant	Alum	Alum	T-1	T-1	Alum +	Alum	Alum +
Coagulant Dose (mg/1)	25	20	1.25	0.75	25+ 0.01	20	20+ 0.10
Influent Turbidity (Ntu)	10	15	10	15	10	15	15
Effluent Turbidity (Ntu)	0.05	B.T.	0.10	0.05	0.05	0.10	0.05
Run time to B.T. or h_L = 8 (hrs)	1.5	--	2	<1.5	<1.5	2	4
Actual Run Time (hrs)	2	1	2.5	1.5	1.5	3	4
Final Effluent Turbidity (Ntu)	3.5	7.0	0.05	4.8	0.05	1.8	2.7
Final Headloss (ft)	8.8	3.7	10.4	9.4	10.3	2.4	5.7
Remarks	ZP to -5 from -16; B.T. at h_L = 7	ZP -7			dose by jar test	ZP test to -6.5 R.M. to -8 from -11	

TABLE 8

EFFLUENT TURBIDITY AND FILTER HEADLOSS DATA

Mode	hlr gpm/ft^2	Inf turb (Ntu)	Coag	Dose mg/1		Elapsed Time 0	1	2	3	4	5	6	7	8	9	10
Conv	5	5	Alum	20	Ntu	-	0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
					ft	1.6	1.9	2.0	2.2	2.4	2.5	2.6	2.3	3.0	3.2	3.5
Conv	5	15	Alum	25	Ntu	-	0.05	0.05	-	0.05	0.05	0.05	-	0.10	0.20	0.25
					ft	1.6	1.8	2.0	-	2.2	2.4	2.6	-	3.0	3.3	3.4
Conv	5	5	T-1	1.0	Ntu	-	0.15	0.10	0.10	0.10	0.10	0.10	0.10	-	-	-
					ft	1.4	2.1	2.6	3.0	3.4	3.9	4.4	4,8	-	-	-
Conv	5	15	T-1	1.5	Ntu	-	0.25	0.2	0.2	0.2	-	-	-	-	-	-
					ft	1.4	1.7	2.0	2.2	2.5	-	-	-	-	-	-
					E.T.:	0	1	1 1/2	2	2 1/2	3	3 1/2	4	6	8	10
DF	5	5	Alum	15	Ntu	-	0.25	-	0.20	-	-	-	0.15	0.15	0.15	0.15
					ft	1.7	2.1	-	2.6	-	-	-	3.5	5.0	6.5	7.3
DF	5	10	Alum	25	Ntu	-	0.05	1.2*	2.3	-	-	-	-	-	-	-
					ft	1.6	2.5	2.9	3.3	-	-	-	-	-	-	-
DF	5	15	Alum	15	Ntu	-	0.05	-	0.2	-	0.2	0.2	-	-	-	-
					ft	1.8	2.8	-	-	-	4.0	4.2*	Limit w/O pressure			-
DF	5	25	Alum	15	Ntu	-	0.25	15.0*	B.T. w/air pump on			-	-	-	-	-
					ft	1.7	3.1	-	-	-	-	-	-	-	-	-
DF	5	10	Alum + CA233	20 + 0.10	Ntu	-	0.05	0.05	0.05	-	0.05	0.05	0.05	-	-	-
					ft	1.6	2.9	3.5	4.4	-	8.3*	9.5	11.5	-	-	-
					E.T.	0	1	1 1/2	2	2 1/2	3	4	5	6	7	8
DF	5	5	T-1	0.75	Ntu	-	0.15	-	0.10	-	0.10	0.10	0.10	0.10	0.05	0.05
					ft	1.5	2.4	-	3.3	-	4.0	5.0	6.0	7.2	8.9*	10.3
DF	5	10	T-1	0.75	Ntu	-	0.10	0.10	0.10	-	0.10	1.0*	3.5	-	-	-
					ft	1.6	2.6	2.9	3.8	-	5.6	6.6	7.3	-	-	-
DF	5	15	T-1	0.75	Ntu	-	0.10	-	0.10	-	7.6*	-	-	-	-	-
					ft	1.7	2.9	-	5.7	-	8.6*	-	-	-	-	-
DF	5	15	T-1	0.25	Ntu	-	0.35	-	2.5*	-	7.0	-	12.0	-	-	-
					ft	1.6	3.3	-	4.8	-	6.9	-	9.3	-	-	-
DF	5	15	T-1	1.0	Ntu	-	0.15	-	0.15	1.0*	-	-	-	-	-	-
					ft	1.4	3.6	-	7.3	9.7*	-	-	-	-	-	-

TABLE 8 (Continued)

Mode	hlr gpm/ft^2	Inf turb (Ntu)	Coag	Dose mg/l		Elapsed Time										
					E.T.	0	1	2	3	4	5	6	7	8	9	10
DF+F	5	5	Alum	20	Ntu	-	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
					ft	1.6	1.9	2.2	2.5	3.0	3.5	4.1	4.6	4.8	5.8	6.9
DF+F	5	15	Alum	20	Ntu	-	0.1	3*	4.3	-	-	-	-	-	-	-
					ft	1.5	2.2	2.3	3.3	-	-	-	-	-	-	-
DF+F	5	5	T-1	1.25	Ntu	-	0.25	0.35	0.40	0.35	0.25	0.20	0.15	0.10	0.10	0.10
					ft	1.6	1.8	2.2	2.5	2.8	3.2	3.7	4.3	5.1	5.9	7.1
DF+F	5	10	T-1	0.75	Ntu	-	0.10	0.10	1.8*	-	-	-	-	-	-	-
					ft	1.6	2.5	3.9	5.6	-	-	-	-	-	-	-
DF+F	5	15	T-1	2.0	Ntu	-	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.10	-	-
					ft	1.4	2.0	2.8	4.3	5.4	6.5	7.6	8.8*	10.0	-	-
					E.t.	0	1/2	1	1 1/2	2	2 1/2	3	3 1/2			
DF	8	10	Alum	25	Ntu	-	0.05	0.05	0.90*	3.5	-	-	-			
					ft	2.6	3.9	5.2	7.0	8.8*	-	-	-			
DF	8	15	Alum	20	Ntu	-	4.2*	-	-	-	-	-	-			
					ft	2.6	2.9	-	-	-	-	-	-			
DF	8	10	T-1	1.25	Ntu	-	0.05	0.10	0.10	0.10	0.05					
					ft	2.6	3.8	5.0	6.2	8.0*	10.4	-	-			
DF	8	15	T-1	0.75	Ntu	-	0.05	0.05	4.8*	-	-	-	-			
					ft	2.6	4.8	7.4	9.4*	-	-	-	-			
DF	8	10	Alum + CA233	25 + 0.10	Ntu	-	0.05	0.05	0.05	-	-	-	-			
					ft	2.6	3.9	6.7	10.3*	-	-	-	-			
					E.T.	0	1	2	3	4						
DF	3	15	Alum	20	Ntu	-	0.10	1.0*	1.8	-						
					ft	0.9	1.4	2.0	2.4	-						
DF	3	15	Alum + CA233	20 + 0.10	Ntu	-	0.05	0.05	0.05	2.7*						
					ft	0.9	1.5	2.5	4.2	5.7						

TABLE 9

WATER CHARACTERISTICS: CONVENTIONAL TREATMENT w/ALUM COAGULANT

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant & Dose	20 mg/l Alum			25 mg/l Alum		
Sample Interval (hrs)	1	6	10	1	6	10
Turbidity (Ntu)						
Raw	5	5	5	15	15	15
Filtered	0.05	0.0	0.0	0.05	0.05	0.25
% Removal	99	99+	99+	99+	99+	98
Algae (cells/ml)						
Raw	340	300	400	0	100	0
Filtered	30	0	0	0	0	0
% Removal	91	99+	99+	--	99+	--
Total Coliforms (cells/100 ml)						
Raw	470	510	570	1030	850	1050
Filtered	71	29	24	6	16	24
% Removal	85	94	96	99+	98	98
True Color (APHA @ pH 7.4)						
Raw	13	12	11	11	6	13
Filtered	5	8	5	8	10	5
% Removal	62	33	55	27	<67>	62
Alkalinity (mg/l as $CaCO_3$)						
Raw	48	49	48	45	44	45
Filtered	37	39	40	33	35	34
pH						
Raw	7.8	7.7	7.8	8.0	8.0	7.9
Filtered	7.1	7.0	7.2	7.3	7.2	7.3
Hardness (mg/l as $CaCO_3$)						
Raw	56	56	56	52	50	50
Filtered	56	54	56	52	48	50
Total Dissolved Solids (mg/l)						
Raw	92	88	83	66	72	64
Filtered	87	88	88	72	70	71

TABLE 10

WATER CHARACTERISTICS: CONVENTIONAL TREATMENT w/POLYMER COAGULANT

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant & Dose	1.0 mg/l T-1		1.5 mg/l T-1
Sample Interval (hrs)	1	6	1
Turbidity (Ntu)			
Raw	5	5	15
Filtered	0.15	0.10	0.25
% Removal	97	98	98
Algae (cells/ml)			
Raw	380	340	120
Filtered	0	0	0
% Removal	99+	99+	99+
Total Coliforms (Cells/100 ml)			
Raw	380	>800	450
Filtered	2	0	66
% Removal	99+	99+	85
True Color (APHA @ pH 7.4)			
Raw	13	16	17
Filtered	11	14	11
% Removal	15	12	35
Alkalinity (mg/l as $CaCO_3$)			
Raw	41	44	43
Filtered	41	44	38
pH			
Raw	7.8	8.0	7.8
Filtered	7.5	7.8	7.4
Hardness (mg/l as $CaCO_3$)			
Raw	52	52	48
Filtered	52	52	46
Total Dissolved Solids (mg/l)			
Raw	70	75	66
Filtered	70	74	66

TABLE 11

WATER CHARACTERISTICS: DIRECT FILTRATION w/ALUM COAGULANT

Hydraulic Loading Rate:	5 gpm/ft^2						
Coagulant and Dose	15 mg/l Alum			25 mg/l Alum	15 mg/l Alum	15 mg/l Alum	20 mg/l Alum + 0.1 mg/l CA233
Sample Interval	1	6	10	1	1	1	1
Turbidity (Ntu)							
Raw	5	5	5	10	15	25	10
Filtered	0.25	0.15	0.15	0.05	0.05	0.25	0.05
% Removal	95	97	97	99+	99+	99	99+
Algae (cells/ml)							
Raw	240	-	-	-	-	-	960
Filtered	0	-	-	-	-	-	10
% Removal	99+	-	-	-	-	-	99
Total Coliforms (Cells/100 ml)							
Raw	650	560	270	2890	1230	-	30,700
Filtered	6	5	10	17	5	-	32
% Removal	99	99	96	99	99+	-	99+
True Color (APHA @ pH 7.4)							
Raw	10	10	10	16	11	10	13
Filtered	2	2	8	9	5	0	7
% Removal	80	80	20	56	55	99+	46
Alkalinity (mg/l as $CaCO_3$)							
Raw	45	47	50	44	39	50	44
Filtered	43	46	47	33	33	35	33
pH							
Raw	8.2	8.0	6.7	7.7	7.8	7.8	7.9
Filtered	7.3	7.5	6.6	7.0	7.4	7.1	7.2
Hardness (mg/l as $CaCO_3$)							
Raw	60	58	56	52	22	54	52
Filtered	60	60	58	50	22	52	52
Total Dissolved Solids (mg/l)							
Raw	79	82	91	91	58	85	106
Filtered	86	82	95	97	57	79	99
Remarks					headloss limit reached	failed at pressuring of filter	

TABLE 12

WATER CHARACTERISTICS: DIRECT FILTRATION w/POLYMER COAGULANT

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant and Dose	0.75 mg/l T-1		0.75 mg/l T-1	0.75 mg/l T-1	0.25 mg/l T-1	1.0 mg/l T-1
Sample Interval	1	6	1	1	1	1
Turbidity (Ntu)						
Raw	5	5	10	15	15	15
Filtered	0.15	0.10	0.10	0.10	0.35	0.15
% Removal	97	98	99	99+	98	99
Algae (cells/ml)						
Raw	180	340	200	120	90	320
Filtered	0	0	0	0	0	0
% Removal	99+	99+	99+	99+	99+	99+
Total Coliforms (Cells/100 ml)						
Raw	450	490	2900	530	710	1190
Filtered	0	3	17	28	140	85
% Removal	99+	99+	99+	99+	80	93
True Color (APHA @ pH 7.4)						
Raw	16	16	16	13	16	16
Filtered	11	11	11	11	13	6
% Removal	31	31	31	15	19	63
Alkalinity (mg/l as $CaCO_3$)						
Raw	47	47	46	46	44	43
Filtered	44	44	45	45	43	42
pH						
Raw	8.1	7.6	8.0	7.7	7.9	7.6
Filtered	7.8	7.5	7.6	7.4	7.7	7.4
Hardness (mg/l as $CaCO_3$)						
Raw	52	54	52	52	50	50
Filtered	52	54	48	48	48	48
Total Dissolved Solids (mg/l)						
Raw	79	77	93	83	79	72
Filtered	72	77	101	79	72	74

TABLE 13

WATER CHARACTERISTICS: DIRECT FILTRATION w/ALUM COAGULANT

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant & dose	20 mg/l Alum			20 mg/l Alum
Sample Interval	1	6	10	1
Turbidity (Ntu)				
Raw	5	5	5	15
Filtered	0.05	0.05	0.05	0.1
% Removal	99	99	99	99+
Algae (cells/ml)				
Raw	540	180	280	--
Filtered	60	100	60	--
% Removal	89	45	79	--
Total Coliforms (cells/100 ml)				
Raw	880	620	680	126,000
Filtered	44	53	42	1,120
% Removal	95	91	94	99
True Color (APHA @ pH 7.4)				
Raw	19	14	10	19
Filtered	5	11	4	6
% Removal	74	21	60	68
Alkalinity (mg/l as $CaCO_3$)				
Raw	46	46	46	43
Filtered	36	37	36	36
pH				
Raw	8.1	7.9	7.7	8.0
Filtered	7.2	7.2	7.0	7.1
Hardness (mg/l as $CaCO_3$)				
Raw	52	52	52	52
Filtered	52	52	52	50
Total Dissolved Solids (mg/l)				
Raw	74	74	76	78
Filtered	80	79	79	75
Remarks				ZP = 5 mv

TABLE 14

WATER CHARACTERISTICS: DIRECT FILTRATION PLUS FLOCCULATION w/POLYMER COAGULANT

Hydraulic Loading Rate: 5 gpm/ft^2

Coagulant & dose	1.25 mg/l T-1			0.75 mg/l T-1	2.0 mg/l T-1	
Sample Interval	1	6	10	1	1	6
Turbidity (Ntu)						
Raw	5	5	5	10	15	15
Filtered	0.25	0.20	0.10	0.1	0.20	0.10
% Removal	95	96	98	99	96	99
Algae (cells/ml)						
Raw	220	230	940	960	780	780
Filtered	0	0	0	40	0	20
% Removal	99+	99+	99+	96	99+	97
Total Coliforms (cells/100 ml)						
Raw	100	50	160	1070	1120	630
Filtered	0	3	4	7	76	31
% Removal	99+	94	98	99	93	95
True Color (APHA @ pH 7.4)						
Raw	16	15	14	17	17	17
Filtered	8	10	9	14	11	11
% Removal	50	33	36	18	35	35
Alkalinity (mg/l as $CaCO_3$)						
Raw	43	44	45	45	38	40
Filtered	43	43	42	45	36	39
pH						
Raw	8.1	7.9	7.7	7.9	7.9	7.9
Filtered	7.9	7.8	7.7	7.7	7.7	7.7
Hardness (mg/l as $CaCO_3$)						
Raw	52	50	60	50	44	44
Filtered	50	52	56	48	42	44
Total Dissolved Solids (mg/l)						
Raw	71	75	92	70	67	71
Filtered	69	74	86	73	60	60
Remarks	0.75 mg/l T-1 until 3 1/2 hrs				pressure pump on after 2 hrs.	

TABLE 15

WATER CHARACTERISTICS: DIRECT FILTRATION AT OTHER FLOWRATES

Hydraulic Loading Rate:	8 gpm/ft^2	8	8	8	3 gpm/ft^2	3
Coagulant & Dose	25 mg/l Alum	1.75 mg/l T-1	0.75 mg/l T-1	25 mg/l Alum +0.10 CA233	20 mg/l Alum	20 mg/l Alum +0.10 CA233
Sample Interval (hrs)	1	1	1	1	1	1
Turbidity (Ntu)						
Raw	10	10	15	10	15	15
Filtered	0.05	0.10	0.05	0.05	0.10	0.05
% Removal	99+	99	99+	99+	99	99+
Algae (cells/ml)						
Raw	1300	1080	--	1300	940	860
Filtered	0	80	--	0	0	0
% Removal	99+	93	--	99+	99+	99+
Total Coliforms (cells/100 ml)						
Raw	3	40	530	1680	>8000	>80,000
Filtered	0	15	18	17	>80	>80
% Removal	99+	63	97	99	--	--
True Color (APHA @ pH 7.4)						
Raw	14	14	19	16	9	11
Filtered	5	11	14	9	3	5
% Removal	64	21	26	44	67	55
Alkalinity (mg/l as $CaCO_3$)						
Raw	45	45	48	45	44	44
Filtered	35	44	47	34	34	35
pH						
Raw	7.7	7.8	8.0	7.7	7.9	7.9
Filtered	6.9	7.6	7.9	7.2	7.1	7.1
Hardness (mg/l as $CaCO_3$)						
Raw	46	50	54	52	50	52
Filtered	46	48	40	50	48	48
Total Dissolved Solids (mg/l)						
Raw	125	75	84	119	69	72
Filtered	122	72	87	112	71	74

TABLE 16

COMPARING MODES AT 5 GPM/FT^2 FLOW RATE

	Conventional	Direct Filtration	Direct Filtration w/Flocculation
Alum Coagulated Trials:			
Maximum Raw Water Turbidity (Ntu)	15	5-8	5-8
Applied Water Turbidity (Ntu)	2.0-5.0	-	-
Effluent Turbidity (Ntu)	0.0-0.2	0.05-0.25	0.05-0.10
Run Time (hrs)	>10	>10	>10
Headloss at 10 hrs (ft)	~3.5	~7	~7
Polymer Coagulated Trials:			
Maximum Raw Water Turbidity (Ntu)	15	5	10-15
Applied Water Turbidity (Ntu)	2.0-5.0	-	-
Effluent Turbidity (Ntu)	0.10-0.20	~0.10	~0.10
Run Time (hrs)	>10	~8	~8
Headloss at 10 hrs (ft)	~5-6	≥8	≥8

From Tables 9 and 10, it can be seen that the polymer coagulated trial with 0.25 Ntu effluent turbidity after the first hour had a substantial number of bacteria in the filtered water. This result, however, was similar to that experienced with the first sample taken during the alum coagulated trial that had a filtered water turbidity below detectable limits for most of the experiment. Color and color removal seemed somewhat inconsistent, but for the alum coagulant, an average raw water true color of 11 units was reduced to an average filtered water true color of less than 7 units. For the polymer coagulated trials, an average true color of 15 units was reduced to 12 units. Alkalinity destruction for the alum coagulated trials was on the order of 0.5 mg/l per 1.0 mg/l of alum added, but varied rather widely from that value.

The results of runs with a hydraulic loading rate of 5 gpm/ft^2 utilizing direct filtration with alum as coagulant are presented in Table 4. The turbidity of the filtered water range from 0.05 Ntu to 0.25 Ntu. Only the 5 Ntu influent, however, allowed a filtration time greater than the 10 hour period desired and the headloss after 10 hours was just over 7 feet. Treatment of water with higher than 10 Ntu of turbidity was generally unsatisfactory. During the first trial with 25 Ntu influent water, breakthrough resulted from pressurizing the airspace over the filter. Subsequent trials with the filter pressurized at the beginning of the run evidenced prompt breakthrough, and further testing with 25 Ntu influent was not pursued. As shown in Table 11, the direct filtration scheme allowed coliform removals similar to the removals accomplished by conventional treatment, and color removal averaged over 60 percent.

Polymer coagulated direct filtration at 5 gpm/ft^2, reported in Tables 5 and 12, produced filtered water of excellent clarity. For two-thirds of the total filtration time in this series of experiments, the turbidity of the filtered water was at or below the 0.1 Ntu level recommended by AWWA. None of the trials, however, were of the desired duration. The longest run lasted only 7 hours. Breakthrough occurred in four of the five trials reported; for the fifth trial, the effluent turbidity dropped to and remained at 0.05 Ntu while the headloss reached 10.3 feet. Coliform removals were satisfactory, ranging from 80 per cent removal for one sample to over 99 per cent removal for three samples. Algae, present in fairly low concentrations in the raw water, were not found in any of the filtered water samples examined. Color removals ranged from 16 per cent to 62 per cent and were roughly comparable to the results of conventional treatment with polymer coagulation.

Adding a flocculation step to direct filtration treatment led to the results shown in Tables 6, 13, and 14. Effluent clarity was generally excellent, and effluent turbidity was at or below the 0.1 Ntu concentration suggested by AWWA for almost three-fourths of the total time during which the treatment unit was operating. Both the alum coagulated and polymer coagulated trials with 5 Ntu influent turbidity ran longer than the desired ten hours. In addition, seven hours of filtration time were obtained with 15 Ntu influent turbidity with the raw water coagulated with an overdose of polymer. Algae were found in five of the nine samples examined, although coliform removals averaged over 95 percent. Color removal once again was generally better for alum coagulated samples than for polymer coagulated samples.

Direct filtration at flow rates other than 5 gpm/ft^2 yielded the results shown in Tables 7 and 15. Loading the filter at 8 gpm/ft^2 produced finished water of excellent clarity, but filtration times were extremely short, even when coagulant doses were near optimum. The two trials at a flow rate of 3 gpm/ft^2 were seriously underdosed even though zeta potential measurements were used for dose selection. The substantial effect of a filter aid was evident, however, since the run time of the polymer added trial was doubled. Clarity of the filtrate at 3 gpm/ft^2 was good, but similar results were possible at both 5 and 8 gpm/ft^2 flow rates. As shown in Table 15, this similarity of results extended to the other water characteristics as well.

The comparison of treatment processes in Table 16 summarizes the results from the preceding tables. In general, the data show that for the filter employed, direct filtration schemes provided a satisfactory effluent for reasonable filtration times for water of influent turbidity of 5 Ntu. Direct filtration of polymer coagulated water with a flocculation step included appeared to allow a higher influent turbidity to be treated.

DISCUSSION

Factors Affecting Filtration Results

In general, the performance of the laboratory filter employed in these studies was excellent with regard to turbidity removal and limited, or even somewhat unsatisfactory, with respect to floc storage capacity. Limitations in floc storage capacity may have been caused by a combination of two factors, first, an unacceptably low filter porosity resulting from the use of relatively fine filter media that may have been packed too tightly in the filter column and, second, the nature of the bentonite clay which had been used for turbidity additions.

Packing of the filter media in the column was done in a fashion similar to that used by Cleasby and Sejkora (40). To insure that the filter media had approximately the same porosity from one filtration trial to the next, Cleasby and Sejkora reported that after backwashing, the backwash valve was closed abruptly. After the media had settled, it was then "shocked" by rapidly opening and closing the backwash valve. This method reportedly provided an equally dense bed for all their experiments. For the particular laboratory unit set up for the experiments herein reported, shocking the bed in the manner described seemed impractical because rubber tubing provided all of the required connection lines. Instead, the media was returned to its original packed height after backwashing by tapping the bottom portion of the filter column. It was intended that both media be returned to the heights originally packed, and it appeared that the sand was generally somewhat more compacted than was the anthracite. While it did seem that the bed had approximately the same appearance from run to run, this same compaction procedure was used to pack the bed originally and may have resulted in a low porosity bed. As a consequence, the floc storage capacity of the bed may have been lessened substantially.

The second factor that may have contributed to the limited floc storage capacity of the bed was the bentonite clay used for turbidity addition. As indicated earlier, the bentonite used required approximately 5 mg/l to cause a change of 1 Ntu. This amount of mass would presumably result in a proportionately greater volume of coagulated floc solids requiring storage in the filter. If the floc strength were unchanged, a one-to-one ratio of clay concentration to turbidity units could hypothetically allow for approximately five times more influent turbidity to be treated successfully. Referring to Table 16, it can be seen that multiplying the results by a factor of five would increase the upper limit of influent turbidity for alum coagulated direct filtration schemes to 25-40 Ntu. This range is very nearly the same as the 25-50 Ntu range suggested by Culp (2). Similarly, the polymer coagulated direct filtration schemes with flocculation included might have an upper limit of influent turbidity of 75 Ntu or so. This result, too, is much more nearly comparable to the experience of West coast engineers. It would appear, then, that the particular bentonite sample used for turbidity addition did indeed provide a worst case condition for treatment.

Coagulant Dosage Selection

The filter media employed were within the range of sizes found in direct filtration plants in the survey by Logsdon (11). The coal in particular, however, was on the low side of the reported range and is relatively much finer than candidate media studied by some investigators (7). Because of the relative fineness of the media and the experience of West coast engineers with less-than-conventional coagulant doses, it was anticipated that coagulant doses would need to be reduced to as low a level as possible to avoid excessive headlosses through the filter. The results of these experiments would appear to indicate that this expectation was incorrect, particularly with regard to alum coagulation.

For optimum filter performance, breakthrough should occur just after the limiting headloss is reached. Of 24 trials carried to terminal headloss or breakthrough or both, 12 were underdosed with coagulant, 7 were overdosed, 5 were optimally dosed. Chemical overdosing was most often associated with polymer coagulated or polymer aided trials. Only one alum coagulated sample appeared to have been too heavily dosed.

The reasons for this problem relative to coagulant dose and breakthrough were likely related to the strength of polymer coagulated floc particles and the relative fineness of the filter media. Other investigators have already noted the difficulty of using polymer coagulation with fine grained media, although the size limitations of "fine" media do not seem to be well-defined. Less than optimum mixing may magnify the tendency to overdose polymer, in particular, it would appear, when coupled with a lack of flocculation time.

Use of either the Riddick Zeta-Meter or the jar test apparatus to estimate the needed polymer dose seemed to lead to the overestimation of coagulant needs. Several factors may have contributed to the apparent weakness of these two methods. The short floc development time normally anticipated for direct filtration schemes would presumably not be well modelled by a 15 to 45 minute jar test. Further, since the floc desired need not be readily visible or settleable, it is difficult to select the proper coagulant dose based on the appearance of the water in the jars. Theoretically, the use of a Riddick Zeta-Meter would overcome both of these two problems. However, following the rule of thumb of adding enough polymer to bring the zeta potential of influent colloids to - 10 mv appeared to lead to a substantial overdose of coagulant. The direct filtration with flocculation trial with 15 Ntu of influent turbidity can be cited as an example. The zeta potential of the raw water was brought to about - 10 mv from about - 15 mv. After 8 hours of filtration time, the headloss was 10 feet, but the effluent turbidity was still 0.10 Ntu. Higher (i.e. more negative) coagulated water zeta potentials were tried with varying degrees of success. The problem encountered was the distribution of measured zeta potentials in a given water sample.

A typical raw water sample might have a zeta potential of about - 15 mv with a range of values from - 10 mv to over - 25 mv. After the addition of polymer, the average zeta potential of the water may have been reduced to - 13.5 mv but with a standard deviation--assuming, incorrectly, a normal distribution--of 1-3 mv. Choosing the desired polymer dosage based on small, difficult-to-measure differences in zeta-potential did not seem to be a very satisfactory method. For these reasons the use of the Zeta-Meter was abandoned for polymer coagulated trials. The results of a jar test and of previous filtration trials were used to select coagulant doses for polymer coagulated polymer-aided trials.

The Zeta-Meter did appear to be satisfactory, however, for alum coagulated trials, since the desired change in ZP was much larger. The reduction in coagulant dosage over conventional treatment noticed by west coast engineers was not apparent in this series of experiments. Spink and Monscvitz (38) reported that an alum coagulated floc with a zeta potential of about - 20 mv, lowered from about - 25 to - 35 mv with 5 mg/l of liquid alum, resulted in filtrate of satisfactory clarity for a direct filtration water treatment plant in Nevada. The media used for their work was of roughly comparable fineness to that used in this series of experiments. For the Virginia surface water studied and with the lab filter employed, however, it was found that alum coagulated floc would break through the filter even at very low headlosses when the zeta potential was more negative than about - 3 mv. As a result, coagulant doses for alum coagulated trials were generally appreciably more than the 12 mg/l dosage recommended by Hutchinson (34) as a maximum level for consideration of direct filtration schemes. Despite apparently large doses of alum and fairly low zeta potentials, underdosing was generally a problem with alum coagulated trials.

In addition, it appeared that factors other than zeta potential had an influence on floc strength. Referring to Tables 1 and 4, it was noted that, at 5 Ntu of raw water turbidity, particulates in coagulated water with a zeta potential of - 3 mv did not break through the filter for either conventional or flocculated, direct filtration treatment. Although zeta potential was not measured for the non-flocculated direct filtration trial, the similarity of water characteristics, coagulant dose, and treatment results was noted. Headloss for these latter two trials reached more than 7 feet. However, with a raw water turbidity of 15 Ntu, coagulated water with a zeta potential of - 3 mv showed the start of breakthrough during conventional treatment at a headloss less than 4 feet. At a zeta potential of - 5 mv, floc broke through the filter at less than three feet for flocculated and non-flocculated direct filtration trials with 15 and 10 Ntu of influent turbidity, respectively. From Table 7, for direct filtration at a flowrate of 8 gpm/ft^2, water with an influent turbidity of 10 Ntu brought to a ZP of - 5 did not show breakthrough until the headloss reached 7 feet.

Raw Water Characteristics

Because the raw water used in the study was not a strictly controlled "synthetic" water, it is possible that variations and anomalies in treatment results were caused by changes in either the chemical or physical characteristics of the raw water. It should be noted, however, that the chemical and physical characteristics of the raw water which were measured for each filtration trial did not in general vary beyond acceptable limits. The temperature of the water varied from about 21°C to about 30°C. The average temperature was near 27°C. The true color of the raw water ranged from 9 APHA units to 17 APHA units with a mean of 13 units & a median value of 15 units. Values for the alkalinity content of the raw water were generally very close to about 45 mg/l as $CaCO_3$. Two thirds of the samples tested were within 2.5 mg/l of this value. The pH of the raw water was generally within 0.2 units of a value of 7.9. The hardness of the water was generally very close to 50 mg/l as $CaCO_3$, and only ranged from 44 to 58 mg/l as $CaCO_3$. Most of the values for total dissolved solids fell within 15 mg/l of an average of 80 mg/l.

The two parameters which varied most widely were the algae concentration and the total coliform concentration. The distribution of algae concentrations for the samples examined ranged from 0 cells/ml to a high of 1,300 cells/ml. The mean algae concentration was 480 cells/ml, but the median concentration was only 340 cells/ml. For nearly half of the samples examined, the algae concentration was between 120 and 400 cells/ml. While the algae concentrations of the raw water samples varied over a wider range than would have been preferred, no causal relationship was noted between high algae concentrations and filtration difficulties.

The raw water total coliform concentrations varied from a low value of only 3 cells/100 ml to a value of 126,000 cells/100 ml. Forty per cent of the samples examined had coliform concentrations between 400 and 700 cells/100 ml. The median concentration was 350 cells/100 ml, while the mean concentration was 5300 cells/100 ml. The higher values are greater than would normally be preferred for a surface source for drinking water. The very high values, however, are thought to be the result of bacterial multiplication between the time the water was taken from the river and the time it was sampled for coliforms. High values also resulted when raw water was withdrawn from the river shortly after a storm event. As the time from the most recent storm event increased, steady decline in the number of total coliform bacteria in the raw water was noted. This result would lead to the expectation that most of the coliform bacteria in the samples examined were of soil origin rather than sewage origin. A preponderance of soil coliforms is almost always anticipated in surface water samples. Fecal coliform testing was not done, since total coliform counts are of greater interest in testing disinfected water. As indicated earlier, bacterial concentrations in the raw water are of interest mainly because of the effect they may have on coagulation. The goal of filtration is not bacteria removal per se. The goal of filtration is sufficient turbidity removal that subsequent disinfection steps are completely and reliably effective in bacteria destruction.

Since the bacterial removal efficiencies of rapid sand filters were anticipated by Weber (41) generally to be about 80-85 per cent, the bacteria removal efficiencies noted were very good. It is expected that this result was related to the very low turbidities generally attainable by the filter used. Although coliform concentrations varied over a wide range, treatment results seemed not to be influenced adversely.

Limitations of Laboratory Design

It is possible that some of the filtration difficulties encountered could have been avoided if the velocity gradient afforded by the rapid mixer had been higher. A buildup of sludge occurred near the outlet of the rapid mixer. This sludge buildup, coupled with the rather wide range of zeta potentials measured in many coagulated water samples, would give support to the suspicion that rapid mixing might reasonably have been more vigorous.

The most likely source of filtration difficulties may well have been the flow control provided. Not only would surges in flow cause greatly increased hydraulic stresses inside the filter, but coagulant doses would also be varied. Such a variation, a reduction in dose in the case of a raw water flow surge, might lead to the filtration of undercoagulated water. This would enhance, of course, the likelihood of breakthrough of the suspended colloids.

Filtration Results

In general, the changes in the water characteristics were in agreement with the findings of other investigators. Color removal, for example, was generally better with alum coagulation than with polymer coagulation. This result is thought to be due to chemical reactions between color colloids and alum which are not possible between color colloids and the synthetic polymer employed. Alkalinity destruction by alum was near 0.5 mg of alkalinity per 1.0 mg alum as found by Eberly (43) using similar surface sources. Finally, the pH depressions noted were about as expected and would be related to the alkalinity destruction cited above.

The most important aspects of the results obtained during the study are as summarized in Table 16. As indicated initially, the variables of greatest interest were the raw water turbidity, in particular, the limiting raw water turbidity that could be treated with the specific treatment units studied, the coagulant choice, the use of flocculation, and the hydraulic loading rate onto the filter.

Hydraulic Loading Rate .

As indicated in Table 1, most of the trials which were made during this study were made at a hydraulic loading rate of 5 gpm/sf. Trials at flowrates other than 5 gpm/sf were also attempted. However, the data are sufficiently limited to require caution in reaching conclusions about the effect of varying the hydraulic loading rate. Comparing the filtration results obtained with alum coagulated direct filtration treatment at 5 and 8 gpm/sf would appear to support the contention that higher hydraulic loading rates allow greater filter production between backwashings. The results of filtration trials at 3 gpm/sf were generally unsatisfactory, but in comparing these results with the results of filtration at 5 and 8 gpm/sf, it would appear that, for the filter studied, the value of the limiting influent turbidity is not greatly affected by a change in hydraulic loading rate. Apparently, neither were the values of effluent turbidity that were attainable.

Effect of Coagulant Choice

For the values of influent turbidity that were successfully treated during this study, it would appear that alum was a more satisfactory coagulant that was the Cat-Floc T-1 polymer both for conventional and direct filtration treatment. While effluent clarity was comparable for both coagulants, differences in headloss accumulation seem to support this conclusion. No sludge treatment comparisons were considered. It is possible that additional accuracy in polymer dosing would tend to reduce the differences that were noted, but, in general, the headloss accumulation was much more rapid for polymer coagulated water. At 5 Ntu and 15 Ntu raw water turbidity for both conventional and direct filtration trials, a more rapid rise in rate of headloss for polymer coagulated water was noted. Graphs of these headloss accumulations are presented in Figures 4, 5 and 6. Apparently similar results led Adin and Rebhun (4) to conclude that polymer was not suitable for use in a medium grained bed with low approach velocities. The high shear strength of polymer coagulated floc was discussed earlier, and evidently was the cause of this effect. It is important to note, however, that this difference was not noticed with the flocculated

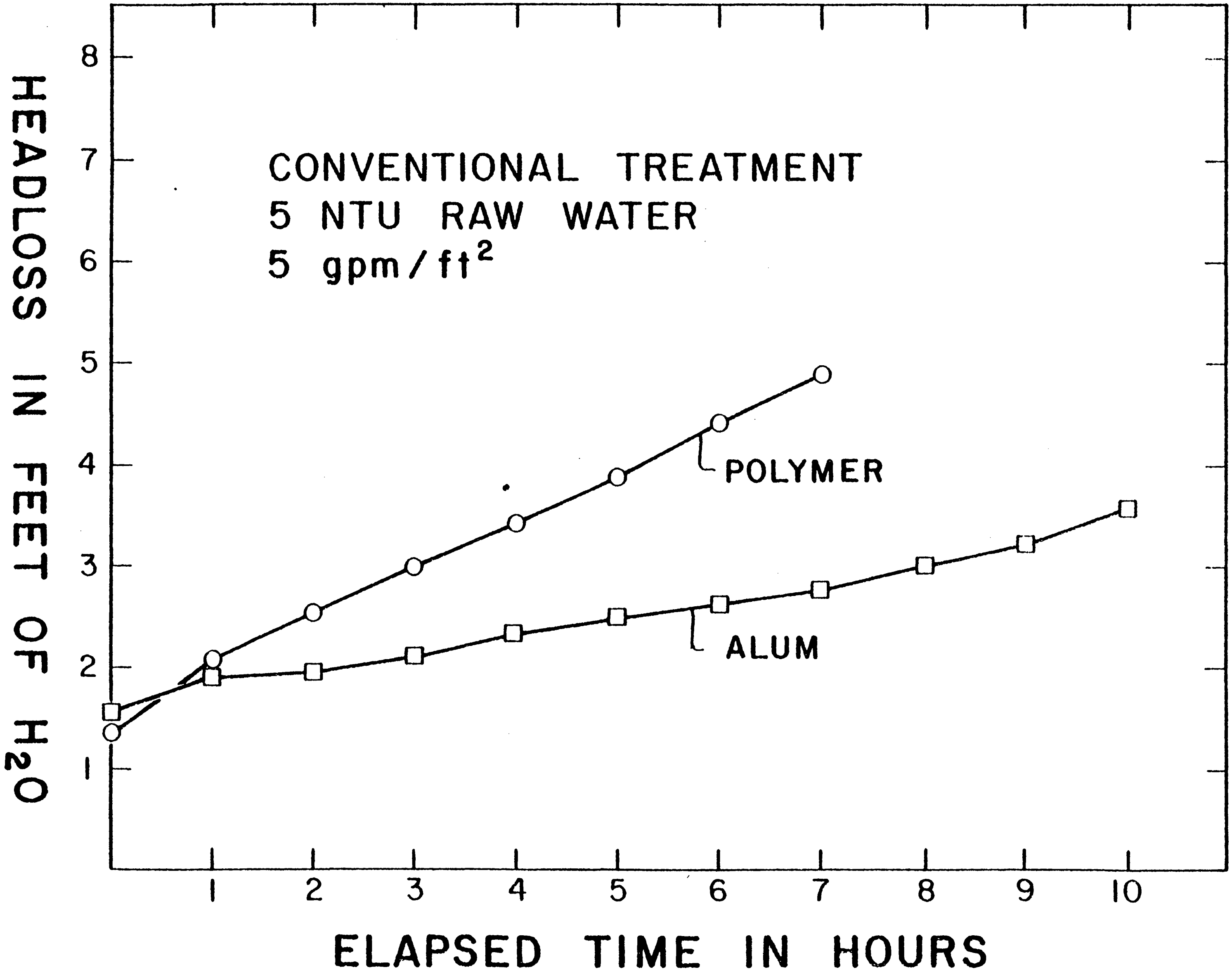
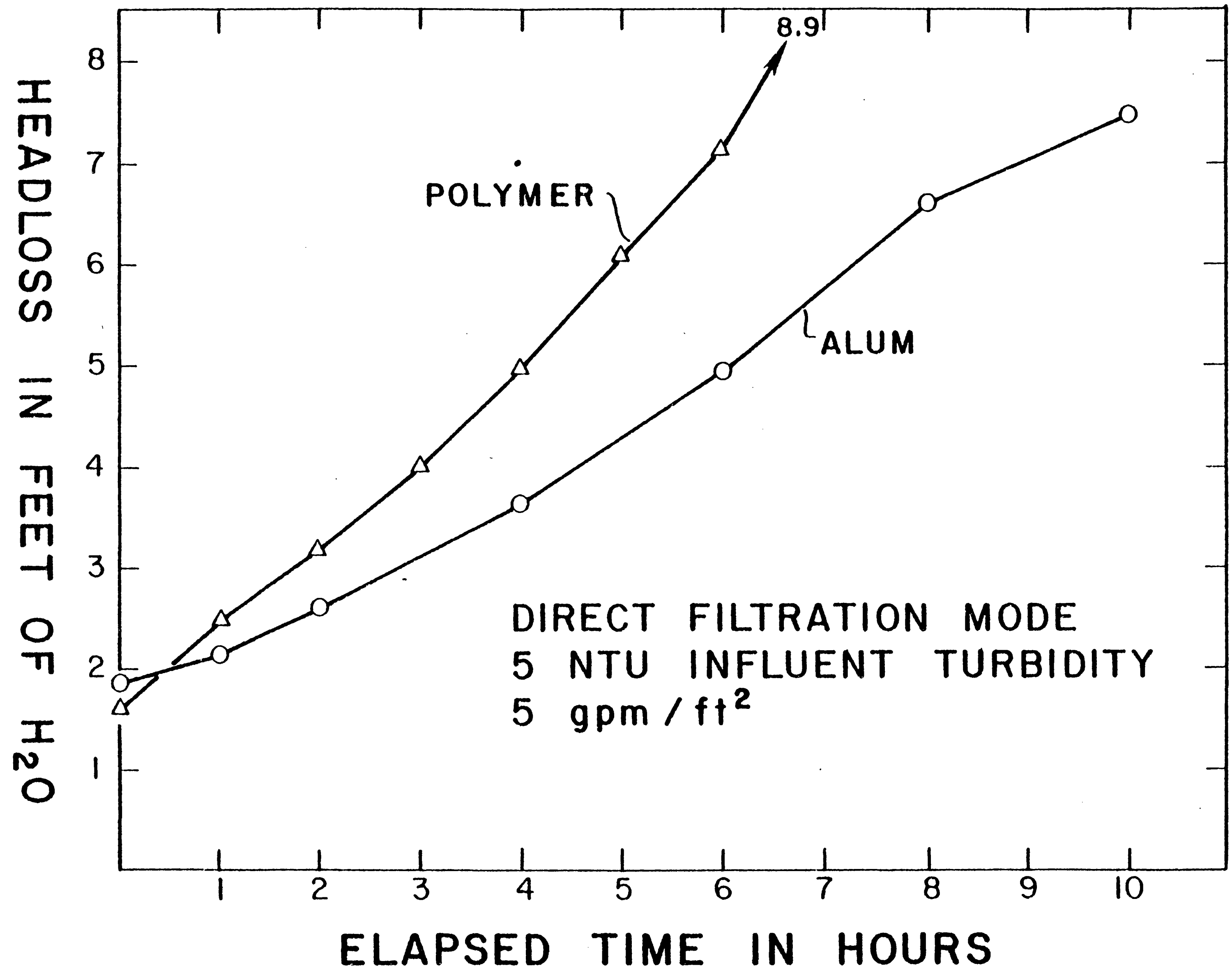


Figure 4. Headloss vs. Elapsed Time: Conventional Treatment

Figure 5. Headloss vs. Elapsed Time: Direct Filtration with 5 Ntu



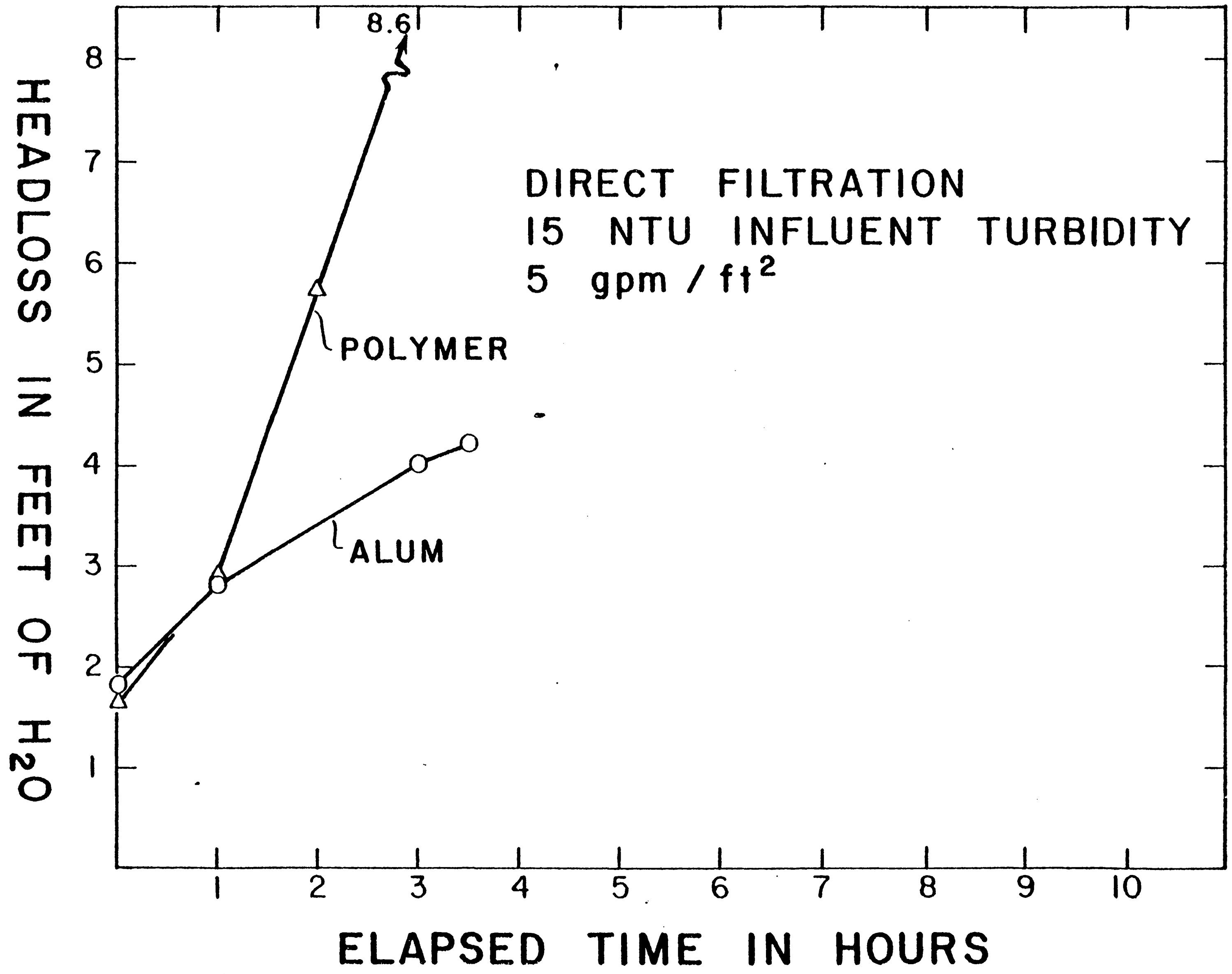


Figure 6. Headloss vs. Elapsed Time:
Direct Filtration with 15 Ntu

direct filtration trials. Comparing the 5 Ntu influent turbidity, flocculated direct filtration trials, as graphed in Figure 7, it can be seen that the headloss accumulations were nearly identical for alum and polymer coagulated waters.

The effect of the addition of a flocculation step in direct filtration treatment for this study seemed substantial and would appear to indicate that further investigation may be appropriate. A total of only five flocculated trials were attempted and the strength of the conclusions drawn from the results is therefore obviously limited.

Recalling that chemical overdosing was most often associated with polymer coagulation, it would appear that the flocculation step provided greatly mitigated the effect of this polymer overdose. A comparison of the flocculated and non-flocculated polymer coagulated trials at 5 Ntu influent turbidity would seem to support this contention. For the non-flocculated run, a polymer dosage of 0.75 mg/1 was sufficient to bring the zeta potential to about - 12 mv from about - 14 mv. After 8 hours of filtration time, the headloss had reached 10.3 feet, while the effluent turbidity was only 0.05 Ntu. For the flocculated trial, 1.25 mg/1 of polymer reduced the zeta potential to about - 13.5 mv from about - 16 mv. After 11 hours of filtration time, the effluent turbidity was 0.10 Ntu, but the headloss had reached only 7.6 feet.

Based on the assumption that even for moderate weight cationic polymers, the polymer molecule is a long strand, it would appear that the flocculation step caused more of the available adsorption sites

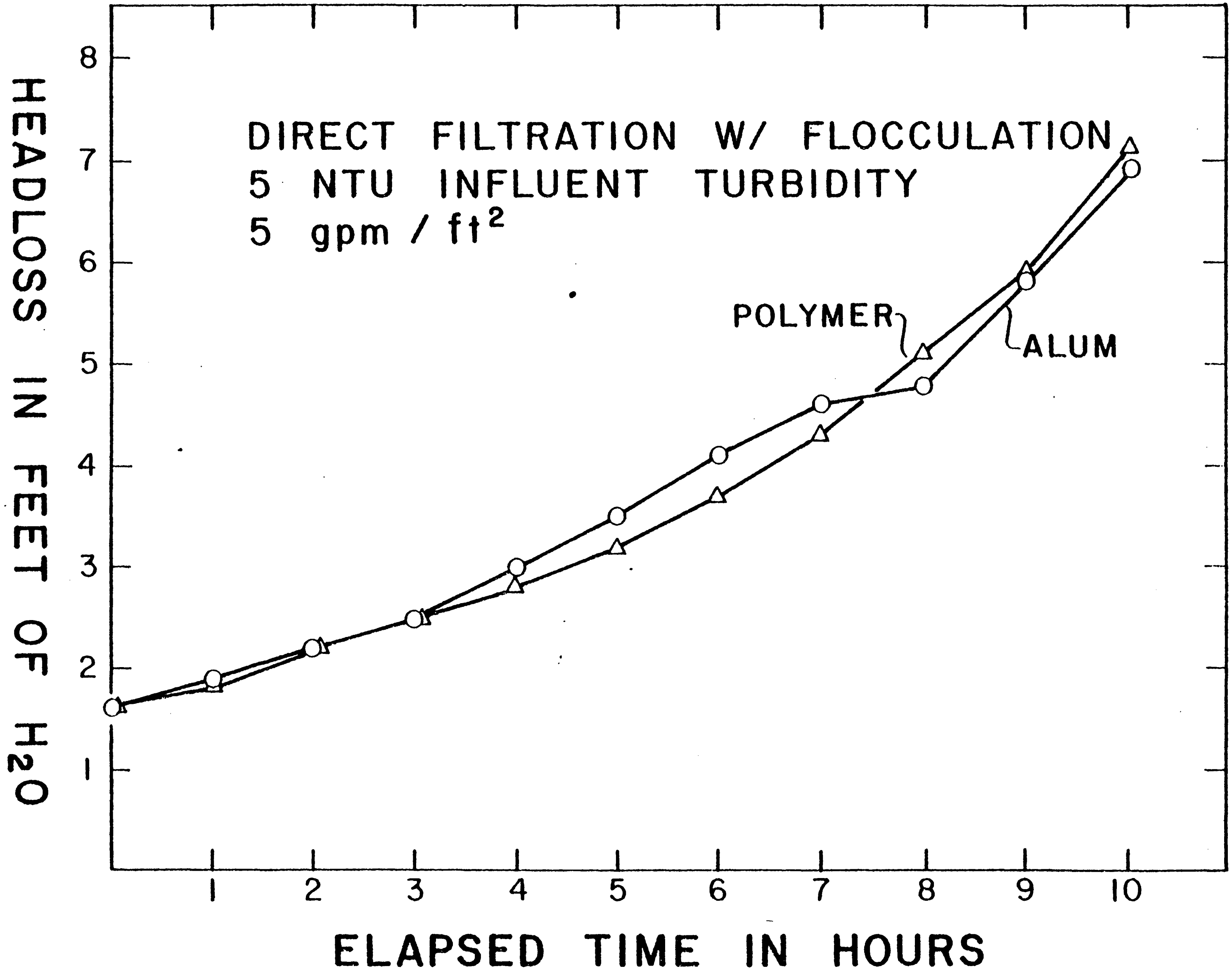


Figure 7. Headloss vs. Elapsed Time: Direct Filtration with Flocculation

on both the colloid and the polymer molecule to interact. This interaction may have made the colloid less "active" as it passed through the filter. As a consequence, flocs were not always captured near the top of the filter, avoiding rapid headloss due to surface accumulation. These flocs could thus pass deeper into the bed, allowing more efficient use of the filter depth.

It may be that flocculation not only mitigated the effect of a polymer overdose, but actually enhanced the filterability of the coagulated floc. A comparison of the flocculated and non-flocculated direct filtration trials with 15 Ntu of influent turbidity seemed to support this possibility. Although clearly overdosed, as discussed earlier, the flocculated trial ran for seven hours before the terminal headloss of 8 feet was reached. The non-flocculated trial, however, ran only 2.5 hours before reaching both terminal headloss and breakthrough. Since the dose at the non-flocculated trial was half the dose of the flocculated trial, it would have seemed more likely that the headloss accumulation would be slower for the non-flocculated trial. Since the opposite was true, and since the bed in the non-flocculated trial was presumably "full," flocculation may have caused a beneficial conditioning effect.

The removal of solids in the flocculation vessel could also account for the slower rates of headloss accumulation observed and must be considered a possibility. It is believed, however, that such solids removal was not a significant factor. As shown at Figure 8, a comparison of the flocculated and non-flocculated alum coagulated direct

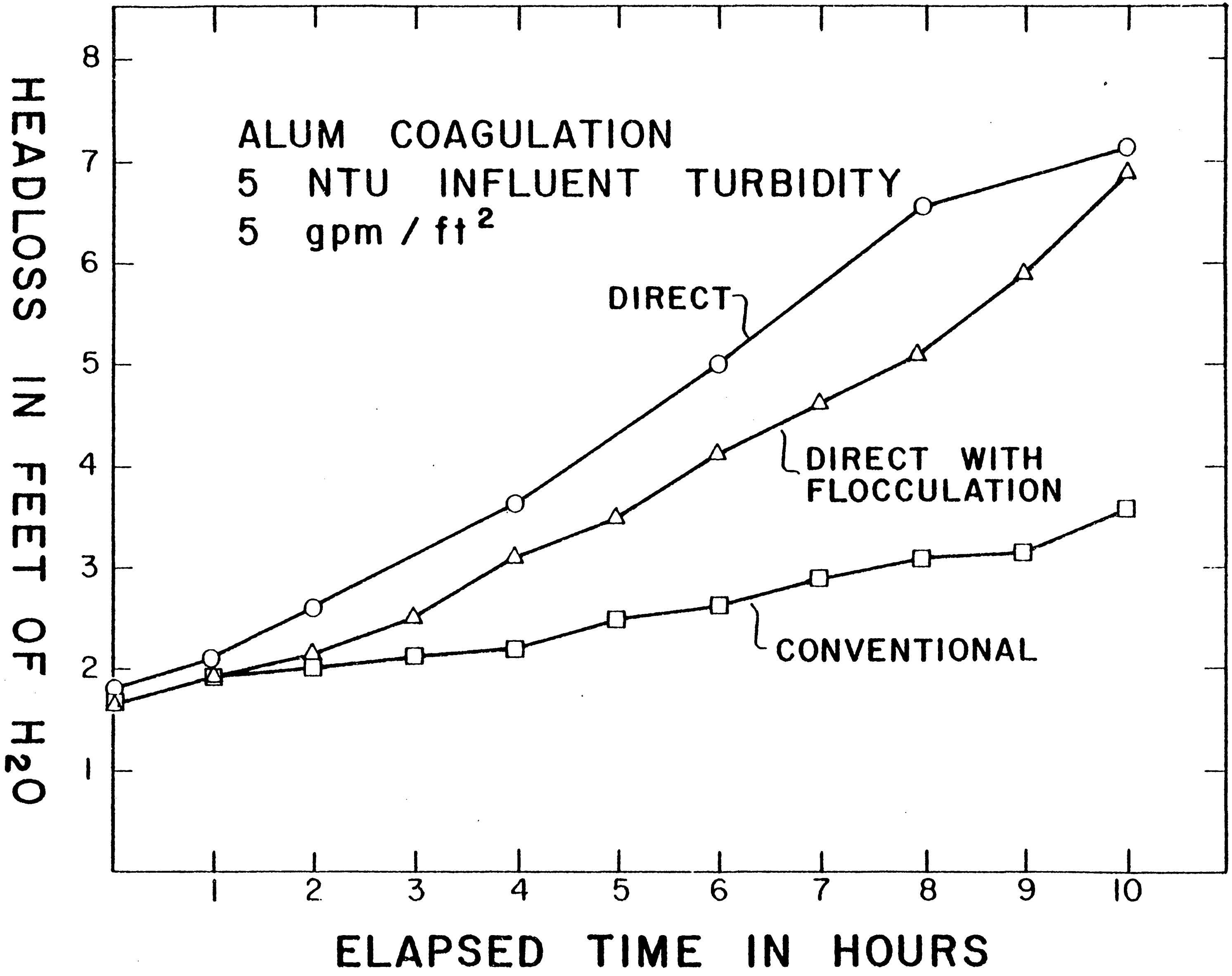


Figure 8. Headloss vs. Elapsed Time: Alum Coagulation

filtration trial with 5 Ntu of influent turbidity seemed to support this contention. The headloss in the non-flocculated trial was consistently higher than the corresponding headloss in the flocculated trial. At the end of the trial, however, the difference was less than 0.5 ft. Some removal of solids in the flocculator evidently occurred initially, but a quasi-equilibrium condition was apparently reached fairly quickly. This equilibrium condition might be indicated by the fact the difference between the two headlosses was fairly uniform throughout most of the filtration time. The equilibrium condition would presumably be reached very quickly with more concentrated suspensions such as the 15 Ntu sample discussed earlier.

Raw Water Turbidity

The raw water turbidity was likely the most important variable studied. The possible adverse effects of using bentonite for turbidity addition have been mentioned.

The results obtained appear to indicate that 5 mg/l of bentonite addition to achieve a 1 Ntu turbidity increase caused a worst case condition for direct filtration treatment despite the fact that bentonite clays are sometimes employed as coagulant aids for conventional treatment at low turbidity water. The large surface area present in colloidal suspensions of bentonite improves conventional orthokinetic flocculation and widens the range of acceptable coagulant doses. Substantially all of the coagulant aid added is removed in the sedimentation basin, however, due to the greater size and weight of the resulting floc. For direct filtration, all of the added bentonite must be stored in the filter. The advantages of increased surface area are thus offset by the comparatively large storage volume required and by the increased coagulant doses required to destabilize the bentonite in addition to the naturally occurring colloids.

The limiting influent turbidity for the particular filter studied was appreciably lower than had been anticipated based on the results of other laboratory studies and on the operating experience of existing direct filtration treatment facilities. Because the treatment conditions were more difficult than would normally be encountered with Virginia surface waters, it seems reasonable to conclude that the results obtained represented a conservative estimate of the potential applicability of direct filtration treatment.

Applicability of Results

Referring to Table 14, the results of these experiments appear to confirm the attractiveness of direct filtration treatment only for those water systems currently providing only chlorination treatment, but with raw water turbidities in excess of 1 Ntu. With the particular filter employed, both alum coagulated and polymer coagulated direct filtration treatment schemes were able to produce very low filtered water turbidities with filtration times that were not prohibitively short. Providing a flocculation step for alum coagulated, direct filtration treatment did not seem to have any effect on filtrate clarity, total filtration time, or the upper limits of treatable influent turbidity.

For polymer coagulated trials, however, somewhat limited data would appear to indicate that providing a flocculation step in direct filtration treatment allowed treatment of appreciably higher influent turbidities. Improvements in the effluent turbidity were not noticed, but the effluent turbidities attained were excellent for both flocculated and non-flocculated trials.

With the particular system studied and for low influent turbidities, filtration times between backwashings were in excess of ten hours at a flow rate of 5 gpm/sf. This is well within the range of theoretical acceptability. Production at this rate would allow 10 minutes of 18 gpm/sf backwash flow at the end of each filter run with such flow representing only 6 per cent of the total water produced.

CONCLUSIONS

The most important conclusions derived from the results of the study were as follows:

1) Direct filtration treatment was a potentially attractive treatment alternative for water of influent turbidity less than about 5 to 8 Ntu.

2) For the particular, relatively fine filter media employed in the study, the more satisfactory choice of coagulant appeared to be alum rather than Cat-Floc T-1 polymer.

3) The provision of a flocculation step in direct filtration treatment did not appear to be advantageous for alum coagulated water, but seemed appreciably to increase the amount of influent turbidity that could be satisfactorily treated for polymer coagulated water samples.

4) Increasing the hydraulic loading rate appeared to increase the filtrate volume produced between backwashings.

5) At the limiting influent turbidity, lowering the hydraulic loading rate did not seem to be advantageous.

6) Color, algae, and coliform removals appeared to be comparable for direct filtration and conventional treatment schemes.

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A LABORATORY STUDY OF FACTORS AFFECTING THE APPLICABILITY OF DIRECT FILTRATION WATER TREATMENT

by

William T. Amy

(ABSTRACT)

The purposes of the study reported in this thesis were to determine the limiting raw water turbidity that could be treated using selected direct filtration treatment schemes and to compare the results of direct filtration and conventional water treatment. A dual media, granular filter employing coal and sand was used to treat New River water with turbidity adjusted by addition of bentonite. Besides influent turbidity, other variables of interest were coagulant choice, inclusion of flocculation with direct filtration, and the hydraulic loading rate applied to the filter.

Results indicated that direct filtration treatment may be an attractive treatment alternative for raw water of influent turbidity less than 5-8 Ntu. Alum appeared to be the coagulant of choice because the selected high molecular cationic polymer system exhibited too rapid headloss in the relatively fine grained filter. Flocculating the coagulated water for 30 minutes allowed direct filtration treatment of raw water with turbidity of 15 Ntu when polymer coagulant was used.