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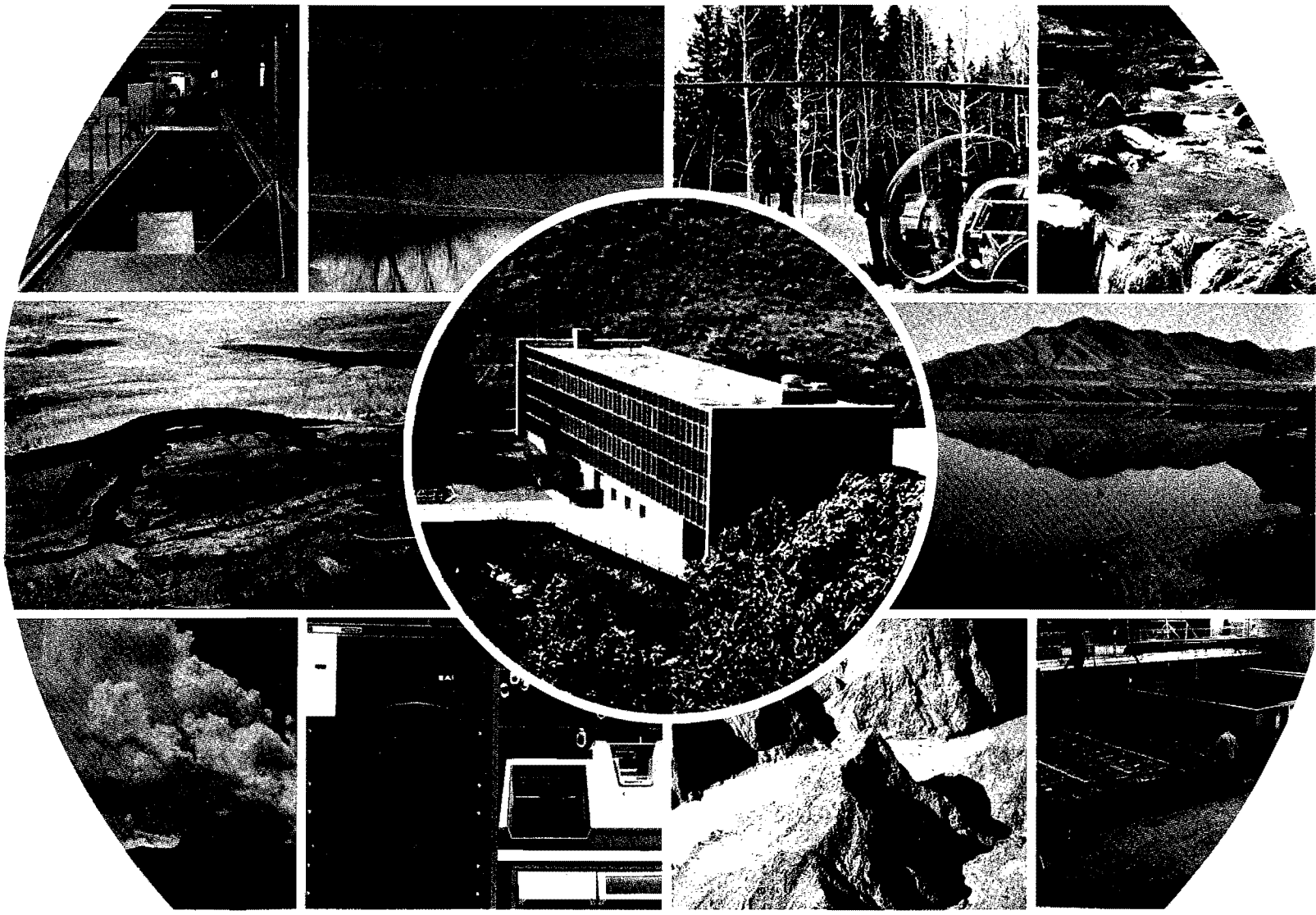

Utah Water Research Laboratory
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WATER QUALITY SERIES
UWRL/Q-79/04

EVALUATION OF IN-LINE DIRECT FILTRATION FOR VIRUS REMOVAL

by

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ABSTRACT

The purposes of this study were to evaluate virus removal in treatment of water supplies by an in-line direct filtration pilot plant system and to suggest a system design to enhance virus removal. Isotherm and jar tests were conducted to evaluate the effects of pH, sodium ion concentration, and coagulants (alum and cationic polyelectrolytes Cat-Floc T, Nalco 8101, 8102, and 8103) on the bacteriophage MS2 contained in water. Isotherm studies were also conducted to assess the kinetic adsorption of MS2 to sand, anthracite, and garnet. Rapid sand, dual-media, and multi-media filters were tested in continuous in-line direct filtration operations.

Approximately 95 percent reduction in virus concentration was observed at pH 9. Zero to 0.5 mg/l of sodium ion present in water had no significant effect on the virus. Alum dosages below 20 mg/l did not remove the bacteriophage MS2 from water, whereas 50 mg/l of alum removed 98 percent of the virus. Two mg/l of Nalco 8101 (the most efficient cationic polyelectrolyte with respect to virus removal) aggregated 96 percent of the virus. Sand and garnet were not found effective in virus removal from water by the isotherm tests. Anthracite, however, removed approximately 93 percent of the virus in 2 hours.

Based on the continuous filtration experiments, it was concluded that in-line direct filtration cannot be counted on to remove virus from water. In-line direct filtration, however, met the effluent turbidity standard of less than 1 NTU. No correlation existed between turbidity breakthrough and virus breakthrough in the effluent. Furthermore, these experiments showed that the effluent quality with respect to both turbidity and virus did not change when hydraulic loading rate was increased from 7.3 to 12.2 $m^3/hour/m^2$. On a more promising note, addition of 2 mg/l of Nalco 8101 to the rapid mix basin was suggested as a potential means of virus removal in a water treatment system.

ACKNOWLEDGMENTS

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INTRODUCTION

Surface waters designated as sources of potable water must be treated to remove contaminants which are potential hazards to public health. Conventional water treatment systems consist of a rapid mix basin, where chemical addition occurs and destabilization of colloid particles results; a flocculation basin, where the destabilized colloids agglomerate into the ensuing flocs results; and a sedimentation basin, where the agglomerated floc particles are gravimetrically removed. Subsequent filtration and disinfection of the water provide a product water ready for distribution to the public.

Certain aspects of conventional methods are expensive, and perhaps unnecessary, in communities which are treating low turbidity waters (< 50 NTU).[1] New technology has been developed and used which eliminates either the sedimentation or both the flocculation and sedimentation unit processes. These treatment methods are referred to as direct filtration water treatment systems. An In-Line Direct Filtration System is a direct filtration water treatment scheme which excludes both flocculation and sedimentation basins prior to filtration.

In In-Line Direct Filtration, the water containing the destabilized particles flows directly from the rapid mix basin to a granular media filter bed. Flocculation of the destabilized colloids occurs within the filtration process. The flocculation process is promoted and greatly accelerated within the filters because of the tremendous number of opportunities for contact as the water passes through the granular bed. In addition, turbulence caused by the passage of water through pumps and channels provides incidental flocculation (Stone 1979). Within the filter media, the floc particles become attached or adsorbed to the surface of the filter grains (Culp 1977). Product water turbidity levels less than 1 NTU have been obtained consistently from full scale in-line direct filtration systems (Spink and Monscvitz 1974; Tredgett 1974b; Harbert 1976).

The chief advantage of direct filtration is the capital cost savings of up to 30 percent while maintaining the same high effluent water quality (Willis 1972; Spink and Monscvitz 1973; Culp 1964; Harbert 1976). The cost saving results from elimination of sludge-collecting equipment, settling basin structures, flocculation equipment, and flocculation-basin structures. This cost reduction greatly eases the financial burden of water treatment for small communities having low turbidity raw water.

With direct filtration, there may also be savings of 10 to 30 percent in chemical costs. Generally less alum is required to produce a filterable floc than to produce a settleable floc (Culp 1977). The costs for coagulant aids, such as polymers, may be greater than in conventional plants, but these higher costs are more than offset by the lower costs for primary coagulant (Culp 1977). Operational and maintenance costs are also reduced because there is less equipment to operate and maintain.

The primary concern in treating water for human consumption is removal of pathogenic organisms such as viruses. In conventional water treatment facilities, higher coagulant dosages required to produce a floc particle which can be removed by sedimentation removes most viruses contained in the raw water prior to chlorination. It is yet to be demonstrated, however, whether direct filtration can achieve the same removal efficiency for virus. The purpose of this study is to test whether in-line direct filtration can or cannot remove water borne virus particles.

[1] NTU refers to Nephelometric Turbidity Unit.

OBJECTIVES

The overall objective of this study was to determine the effectiveness of an in-line direct filtration pilot plant system in removing virus. System variations included use of rapid sand, dual-media, and multi-media filters. Aluminum sulfate (alum) and polyelectrolytic polymers were employed as coagulant and coagulant aids, respectively. The following specific objectives of the study were accomplished:

1. The efficiencies of three different filter media (sand, anthracite and garnet) in removing a selected virus, bacteriophage MS2, from water were compared.

2. The virus removal efficiency of aluminum sulfate, over the dosage ranges used in both direct filtration plants (< 15 mg/l) and conventional treatment plants (> 20 mg/l) was evaluated.

3. The effectiveness of four cationic polyelectrolytes (substituted for the alum) in removing viruses from water was investigated.

4. A treatment scheme was developed to reduce potential transmission of virus through direct filtation water treatment systems.

LITERATURE REVIEW

Direct Filtration

Direct filtration is defined as a potable water treatment system in which filtration is not preceded by sedimentation (AWWA Water Quality Commission). This definition includes treatment systems that eliminate only the sedimentation basin as well as those that eliminate both the flocculation and sedimentation basins. Direct filtration systems which eliminate both the flocculator and sedimentation basin in the water treatment scheme are termed in-line direct filtration systems. The direct filtration process differs from the conventional flocculation-sedimentation-filtration system in that the total solids (both turbidity and coagulants) must be removed by, and stored in, the filter until it is backwashed.

The National Interim Primary Drinking Water Regulations of the Environmental Protection Agency now require filtration of all surface water used for public drinking water to remove virtually all particulate matter, whereas in the past disinfection was considered to be sufficient (EPA Federal Register 1975). To add to the burden of meeting this requirement, many existing plants are faced with a rapidly increasing water demand. Water supply utilities faced with costly expansion of their existing treatment facilities are very interested in turning to a water treatment system which is more economical than the conventional treatment plants, provided they can still achieve the same drinking water quality. Direct filtration water treatment systems were developed to produce an economical, high quality potable water. Direct filtration plants report overall savings of as much as 30 percent when compared to costs of conventional plants (Spink and Monscvitz 1973; Culp 1964; Harbert 1976).

Interest in direct filtration dates back to the turn of the century (Culp 1977). The first pilot plant systems were not successful due to the use of fine to coarse single medium (sand) filters, resulting in rapid headloss through the filter. The development of coarse to fine dual media and multimedia has enabled the filters to store greater quantities of flocculated matter without excessive headloss.

Anthracite, when used in combination with sand, or when used as a single media has proven very successful in direct filtration (Harbert 1976; Culp 1977; Hutchison 1976; DiDomenico 1976; Hutchison and Foley 1974; Spink and Monscvitz 1973). These filters make a greater portion of the filter bed available for storage of solids filtered. They allow deeper penetration of the deposit thus preventing surface clogging which reduces the rate of headloss developed. Mathematical models demonstrate that water production is maximized when the headloss is uniformly distributed across the filter bed (Letterman et al. 1967). Several studies have shown dual media filters (anthracite and sand) to have the best distribution patterns (least headloss) while maintaining high quality effluent (Harbert 1976; Culp 1977; Hutchison 1976; DiDomenico 1976; Hutchison and Foley 1974).

However, high rate direct filtration was not very successful until organic polymers were introduced as filter aids making higher flow rates and longer filter runs possible (Kleber 1973; Stumm and Morgan 1962; Shea et al. 1971; Adin and Rebhum 1974). These polyelectrolytes improve the bridging action of the primary coagulant (Stumm and Morgan 1962). Flocculation with the aid of polymers occurs in two stages: neutralization of the particles' negative charge by the positive hydroxo-metal complexes, followed by formation of flocs as a result of polymer-chain bridges which form between the particles and the polymer (Stumm and Morgan 1962). Polymer aids are most effective when added 30 seconds to 2 minutes after the primary coagulant has begun to form flocs, and at the height of 60 to 90 cm (2 to 3 feet) above the filter media, at the inlet to the filter (Hutchison 1976).

As a filtration run progresses, the shearing force increases and tends to disintegrate the flocs, driving them deeper into the filter media and eventually causing breakthrough (Kleber 1973). Polymers are able to strengthen the floc and thus delay breakthrough. Dosage of the polymer is a critical factor because if the flocs are too strong penetration into the filter bed is hindered and surface clogging results. Recommended polymer concentrations are usually in the range of 5 to 10 parts per

billion with the exact dosage depending on the turbidity of the influent water (Kleber 1973).

Studies have shown that polyelectrolytes, particularly the cationic types, are more effective than the hydrolyzing salts (including alum) used as primary coagulants (Shea et al. 1971; Adin and Rebhum 1974). When alum is used, often more than 50 percent of the sludge is composed of an aluminum hydroxide precipitate (Shea et al. 1971). Polyelectrolytes, however, produce flocs that have significantly less mass as the sludge is composed almost entirely of particles removed from the raw water. The use of polyelectrolytes, therefore, reduces both sludge handling and the cost of the sludge disposal.

The primary factor working against use of polyelectrolytes is that they have slower destabilization times than do hydrolyzing salts and, therefore, require more mixing, particularly rapid or flash mixing (Kleber 1973). Water plants designed to use hydrolyzing coagulants usually provide only 10 to 30 seconds of rapid mix at velocity gradients (G values) of 200 to 300 seconds-1. This duration is not sufficient when polyelectrolytes are used as primary coagulants (Kleber 1973). A rapid mixing time of 60 to 120 seconds at velocity gradients (G value) of 400-1000 sec-1 is required, followed by the conventional rapid mix at a G value of 300 sec-1 prior to flocculation. This provides excellent coagulation and clarification (Kleber 1973).

Although polyelectrolytes have proved to be outstanding primary coagulants, they are seldom used due to the high cost of conversion and the relatively high cost of the polymers themselves. Alum cannot produce a strong floc (Kleber 1973). Polyelectrolytes therefore are often employed as filter aids to render the necessary strength to the floc.

Conventional systems produce large flocs to enhance sedimentation prior to filtration, whereas, direct filtration systems cultivate the formation of pinpoint flocs which penetrate deeper into the filter media thus avoiding surface clogging. Pinpoint flocs are best achieved with low alum dosage (less than 20 mg/l) and a flocculation period of less than 10 minutes with a mixing velocity gradient (G value) of 20 to 100 sec-1 (Hutchison 1976; Hutchison and Foley 1974).

Both headloss and distribution of deposited solids within the filter bed are significantly influenced by the alum dosage and filter aid concentration. Thus an effective control system to regulate the coagulant dosage improves the filtration process. Pilot plant studies have been conducted using control systems to determine what dosage is adequate to filter specific raw water (Hutchison 1976; Letterman and Tanner 1974; Culp 1964). Three control methods were used: "zeta potential"; "filter control system"; and the "interface turbidity monitoring."

Zeta potential is a measurement of repulsive force between particles. A large zeta potential inhibits proper floc formation. Polymers reduce the zeta potential to the point where colloidal particles can aggregate into strong flocs. A recent correlation between zeta potential and the optimum polymer concentration showed that the highest quality effluent was achieved when the zeta potential was 14 millivolts (Letterman and Tanner 1974). By increasing or reducing the polymer concentration during periods of turbidity fluctuation, the optimum zeta potential can be maintained.

Direct filtration plants incorporating flocculation basins are able to monitor raw water filterability by means of a control filter (Culp 1964). After the addition of alum to the raw water, a small portion of the coagulated water is diverted to a pilot filter where the effluent turbidity is monitored constantly with a turbidometer. If the turbidity is beyond a satisfactory range, extra alum is added, and if the turbidity is below the acceptable range the alum dosage is decreased.

A third method monitors the quality of the water approximately midway through the filter (Hutchison 1976). A small amount of water is drawn off through a port located 8 cm (3 inches) above the coal-sand interface. Sample turbidity is checked and compared to the turbidity of the influent raw water. If 90 percent or more of the turbidity in the raw water has been removed by the time it reaches the monitoring port, it is assumed that the sand portion of the filter will collect the remaining particles. If less than 90 percent of the particles have been removed, then an extra dosage of polymer should be added (as filter aid) to correct the situation.

Raw water quality must be considered in design of a direct filtration system. Pilot plant studies should be conducted to determine the best combination of effective size and uniformity coefficient of the granular media, filter bed depth, coagulant type, hydraulic loading rates, flocculation periods and mixing intensities. Direct filtration is only suitable for raw waters of high quality. Application of direct filtration to municipal plants is feasible if 1) the raw water turbidity and color[1] are each less than 25 units, or 2) the color is low and the maximum turbidity does not exceed 200

[1]Color is determined by visual comparison of a water sample with known concentrations of colored solutions. The standard unit of color is the color produced by 1 mg/l of platinum (as K_2PtCl_6). A color series ranging from 0 to 70 color units is used.

turbidity units (TU), or 3) the turbidity is low and maximum color does not exceed 100 color units (Culp 1977). The presence of paper fiber or diatoms in excess of 1000 areal standard units per milliliter (asu/ml) require that settling be included in the treatment process (Culp 1977). Diatom levels in excess of 200 asu/ml may require the use of special coarse coal on top of the bed in order to extend filter runs (Culp 1977). Coliform M.P.N.'s (Most Probable Number) of 90 per 100 ml have been handled successfully in direct filtration plants (Culp 1977).

Direct filtration has proved successful in removing turbidity, color and coliforms (Hutchison 1976; Tate et al. 1979; Spink and Monscvitz 1974; Adin and Rebhum 1974; Culp 1964). The ability of a direct filtration system, however, to remove pathogenic virus has not been established.

Conventional Water Treatment Processes with Respect to Virus Removal

Coagulation

Extensive research has been conducted to determine the effectiveness of metal coagulants, synthetic polyelectrolytes, and water softening processes on the removal of viruses from water (Wentworth et al. 1968; Thayer and Sproul 1966; Manwaring et al. 1970; Chaudhuri and Engelbrecht 1970; Thorup et al. 1970; York and Drewry 1974). Water softening precipitation techniques have been shown effective in the removal of viruses (Wentworth et al. 1968; Thayer and Sproul 1966). Excess lime-soda ash softening process has been shown to be effective in removing up to 99.9 percent of the virus present in waters with initial total hardness of 300 mg/l as $CaCO_3$ if magnesium is present (Wentworth et al. 1968; Thayer and Sproul 1966).

Studies on the effectiveness of coagulation and flocculation on virus removal show contradictory results. Earlier investigators reported no appreciable virus removal with alum dosages ranging from 50 to 100 mg/l (Carlson et al. 1942; Kempf et al. 1942; Neefe et al. 1947) while more recent literature reports high (80 to 99 percent) virus removal with alum and ferric chloride dosages ranging from 20 to 50 mg/l (Chang et al. 1958; Pasco 1956; Manwaring et al. 1970; Chaudhuri and Engelbrecht 1970; Guy and McIver 1977)

The mechanisms whereby coagulation removes virus are not known, but the primary mechanism of virus destabilization is thought to be a formation of a complex between the virus and the metal coagulant (Chaudhuri and Engelbrecht 1970). When aluminum is used as the metal coagulant, it binds with the carboxyl group in the viruses' protein coat. The viruses, however, were not inactivated and could be eluted from the precipitate (Chaudhuri and Engelbrecht 1970). The presence of organic matter in water tends to decrease the virus removal efficiency of the coagulants (Chaudhuri and Engelbrecht 1970). The organic matter may compete with the virus particles in the complex process.

Cationic polyelectrolytes have been found superior with respect to virus removal to the anionic and non-ionic polyelectrolytes when used as a primary coagulant (Chaudhuri and Engelbrecht 1970; Thorup et al. 1970). Virus removals of 70 to 80 percent have been achieved using cationic polyelectrolytes as a primary coagulant with a dosage range of 0.5 to 1 mg/l (Chaudhuri and Engelbrecht 1970). Cationic polyelectrolytes, however, do not increase virus removal efficiency above those found with metal coagulants (Chaudhuri and Engelbrecht 1970; Thorup et al. 1970; York and Drewry 1974). Table 1 summarizes the relative effectiveness of various coagulants and coagulant aids in virus removal (York and Drewry 1974). These results were obtained using f_2 bacteriophage and a standard procedure (York and Drewry 1974).

Filtration

Single medium (sand) and dual media (sand and anthracite) filters are commonly used in potable water treatment processes to remove turbidity. These media remove pinpoint flocs which have not settled during the sedimentation process and have been evaluated as to their capacity to adsorb virus under various conditions. Virus removals greater than 90 percent have been achieved with a combination of coagulation, flocculation, sedimentation and filtration processes (Guy and McIver 1977; Robeck et al. 1962; Berg et al. 1968). Filtration alone, however, has not been very effective in virus removal (Guy and McIver 1977; Robeck et al. 1962; Jenkins 1978). In general the percentage of virus removed varies inversely with the flow rate (Robeck et al. 1962; Jenkins 1978). To enhance virus removal, Ca^{++} ion was used as a filter aid (Jenkins 1978). Removal of 70 to 80 percent of T_1 coliphage was achieved with 10^{-3} M Ca^{++} whereas the removal efficiency was only 20 percent without the calcium ion. A stoichiometric relationship existed between the virus titer and concentration of Ca^{++} necessary for producing effective removal of the virus by the sand filter. Calcium ion may specifically react with the hydroxyl sites of the protein and form positive sites. Such a reaction may be represented by the following formation reaction:

$$-\text{Virus}-\underset{\underset{0}{\|}}{\text{C}}-\text{OH} + Ca^{+2} \rightarrow -\text{Virus}-\underset{\underset{0}{\|}}{\text{C}}-\text{OCa}^{+} + H^{+}$$

The formation of positive sites may reduce the negative surface charge of the virus to a level that the electrostatic repulsive force

may be overcome by Van der Waals' forces of attraction. The virus can then be easily removed by filtration. Table 2 summarizes the results of various studies which have evaluated virus removal by filtration (modified from Amirhor and Engelbrecht 1975).

Table 1. Comparison of the effectiveness of various coagulants on bacteriophage f_2.[g]

Coagulants-Coagulant Aids	Dose mg/l	Maximum Virus Removal Percent	Dose mg/l	Maximum Turbidity Removal Percent	Dose mg/l	Maximum COD Removal Percent	Optimum Dosage* mg/l
$Al_2(SO4)3$	25	99.9	21	96.0	23	40	18
$FeCl_3$	50	99.4	23	92.5	40	38	21
$Fe_2(SO4)3 \times H2O$	50	92.0	49	89.0	-	-	47
$FeSO_4$ and $Ca(OH)_2$	36	93.5	-	-	-	-	39
$Al_2(SO4)3$ and	30	98.6	15	96.5	15	66	11
$Na_2OAL_2O_3$	23	-	12	-	12	-	8
Polyelectrolyte A[a]	2.0	76	1.8	40	-	-	2.3
$Al_2(SO4)3$ and	18	99.2	12	97.2	18	52	18
polyelectrolyte B[b]	1.0	-	0.5	-	0.5	-	0.5
Polyelectrolyte B	2.0	99.6	0.5	72	4.0	68	0.9
$Al_2(SO4)3$ and	18	99.8	18	98.2	10	57	18
polyelectrolyte B	0.7	-	0.2	-	0.2	-	0.1
$Al_2(SO4)3$ and	18	99.3	12	96.7	18	60	18
polyelectrolyte C[c]	0.4	-	0.5	-	0.4	-	0.5
$Al_2(SO4)3$ and	18	99.3	16	98.0	16	48	18
polyelectrolyte E[e]	0.1	-	0.1	-	0.1	-	0.3
$Al_2(SO4)3$ and	18	99.6	16	98.5	18	77	18
polyelectrolyte F[f]	0.1	-	0.1	-	0.4	-	0.3
$Al_2(SO4)3$ and	18	99.4	18	98.8	16	46	18
polyelectrolyte D[d]	1.0	-	0.7	-	0.1	-	0.6

*At isoelectric point as indicated by colloidal titration.
[a]Drewfloc 21, a product of Drew Chemical Co.
[b]Cat. Floc, a product of Calgon Corp.
[c]Coagulant aid 233, a product of Calgon Corp.
[d]Magnifloc 971, a product of Amer. Cyanamid Co.
[e]Coagulant aid 253, a product of Calgon Corp.
[f]Magnifloc 860, a product of Amer. Cyanamid Co.
[g]From York et al. (1974).

Table 2. Virus removal from water by filtration (modified from Amirhor and Engelbrecht 1975).

System	Flow Rate $l/sec/m^2$	(gpm/sq ft)	Virus	Virus Removed % (Or as Noted)	Reference
Rapid Sand Filtration	1.36	(2)	poliovirus	poor	Carlson et al. (1942)
Impregnated Filter with Alum	0.88	(1.3)	(pathogen for mice)	good	Kempf et al. (1942)
Flocc. & Rapid Sand Filter	1.36	(2)	poliovirus (strain DG)	poor	
Percolation of 3 ft Soil			Coxsackievirus	50	Gilcreas and Kelly (1955)
			bacterial virus T4	20	
Sand Filtration	0.14	(0.2)	Coxsackie and T4	99	
	1.36	(2)	Coxsackie	10	
Flocculation and Rapid Sand Filtration	1.36	(2)	bacterial virus T4	40	
Impregnated Rapid Sand Filter	1.36	(2)	Coxsackievirus	90	
			bacterial virus T4	99	
Sand Filtration			Coxsackievirus	90	Robeck et al. (1962)
Sand	0.02	(0.035)	poliovirus Type I	22-96	
Sand & Anthracite without Alum	1.36-4.07	(2-6)		1-50	
Sand & Anthracite with Alum without Settling				90-99	
Sand & Anthracite with Alum with Settling				>99.7	
Anthracite & Sand Excluding Flocculation & Sedimentation	0.75	1.1	Coxsackie & T4 Virus B_3 & B_5	37.5%	Guy and McIver (1977)
Anthracite & Sand Including Flocculation & Sedimentation	0.75	1.1	Virus B_3 & B_5	95%	
Sand Filtration with Ca^{++} as Filter Aid	0.68-1.36	(1-2)	T_1 Coliophage	70-85%	Jenkins (1978)
Sand Filtration Preceded by Lime Coagulation	1.36	(2)	Polio Type 1	80-99.8%	Berg et al. (1968)
Uncoated Diatomaceous-Earth Filter (DE)	0.68	(1)	MS2	Insignificant	
Polyelectrolyte Coated DE (0.2 - 0.4 mg/l)	0.68	(1)	MS2	good	Amirhor and Engelbrecht (1975)
Sand	1.36	(2)	MS2	96	Sriramulu and Chaudhuri (1976)
Sand & Anthracite	2.72	(4)	MS2	92	

MATERIAL AND METHODS

Virus Assay

Virus

Virus selected for this study was the bacteriophage MS2, which is specific for Escherichia coli (C#3000). MS2 was chosen as a model virus to represent the enteroviruses which include polio virus. These two virus types share similar physical characteristics (Table 3).

The initial stock of MS2 was obtained from American type culture in Rockville, Maryland. This stock was used to propagate necessary quantities of the phage. The method used for further propagation of virus was as follows:

1. Inoculate 10 ml of Escherichia coli (E. coli) culture with 1 ml of MS2 (1.7×10^{10} PFU/ml).[1] The optical density of the E. coli culture taken at wavelength 450 nm ($O.D._{450}$) on a Bausch and Lomb Spectrometer was 0.3.

2. Incubate for 4 to 5 hours at 37°C.

3. Dilute the virus culture with one liter of additional E. coli culture.

4. Incubate at 37°C with agitation for 12 hours.

5. Add chloroform to make a 1 percent solution, by volume, in order to lyse any remaining E. coli cells.

6. Centrifuge the suspension (10,000 rpm/20 minutes) to remove the lysed bacterial cells thereby leaving the virus particles in the supernatant. The above method yielded virus stock with concentration of 5.4×10^{12} PFU/ml.

Media

MS broth and MS agar were used as general growth and plating media for MS2 virus (Peifer et al. 1964). The MS broth contained 10 g of bactotryptone, 8 g of NaCl and 1 g of yeast extract per liter of distilled water. After autoclaving and cooling, the MS broth was supplemented with 10 ml of sterile glucose (10 percent solution), 2 ml of sterile 1 M $CaCl_2$, and 1 ml of thiamine (1 percent solution).

The bottom agar used for plating was MS broth with the addition of 10 g of agar per liter, before autoclaving. The top agar used

[1]PFU is Plaque Forming Unit.

Table 3. Properties of bacteriophage MS2 and enteroviruses.

Properties	MS2[a]	Enteroviruses[b]
Nucleic Acid	Single Stranded RNA	Single Stranded RNA
Size	26 nm	20-30 nm
Molecular Weight	3.6×10^6 Daltons	2.6×10^6 Daltons
Shape	Icosahedral	Icosahedral
Envelope	None	None
Tail	None	None
pH Stability	3.9	3.0

[a]Source: "An Introduction to Virology" by C. R. Goodheart. W. B. Saunders Co., Philadelphia (1969).

[b]Source: "The Biology of Animal Viruses" Second Edition by F. Fenner, B. R. Mcauslan, C. A. Mims, J. Sambrook, and D. White. Academic Press, New York, 1974.

was MS broth with the addition of 8 g of agar per liter, before autoclaving.

Bacteria

The host in this study was C#3000, a strain of E. coli. The original stock was obtained from the American Type Culture Collection, Rockville, Maryland. The E. coli culture used in the assays was prepared by inoculating sterile MS broth with bacteria from a slant tube. This inoculated MS broth was incubated at 37°C on a shaker table until it reached the optical density (O.D.) of from 0.2 to 0.3, as measured by the Bausch and Lomb spectrometer 20, at a wavelength setting of 450 nm. The concentration of the bacteria at O.D. of 0.3 was approximately 3 x 10^8 bacteria per milliliter.

Assay procedure

The plaque assay was used to determine the virus concentrations in the samples in all tests. In the plaque assay an appropriate dilution of a phage preparation was mixed with a large excess of bacterial suspension in a soft agar tube and the mixture was poured over an agar plate. During incubation the bacteria grew as a film, spotted with circular clear areas or plaques produced by lytic actions of the bacteriophage. Virus concentration was determined by counting the number of visible plaques (Adams 1959). The method used was:

1. Add 3 ml of liquified sterile soft agar to sterile tubes which were both maintained at 47°C in a water bath.

2. Add 0.5 ml of E. coli culture ($O.D._{450}$=0.3) with a concentration of about 3 x 10^8 cells/ml.

3. Add 0.1 ml of appropriate virus dilution to each tube.

4. Mix and pour the contents of the tube over a bottom agar plate to a uniform thickness.

5. Incubate the plates at 37°C for 8 to 12 hours.

6. Count the plaques.

In this study, three replicate plates were poured for each sample in order to have information on the variability of the results.

Batch Studies

Two types of batch tests were used to determine the ability of various coagulants and filter media to remove water borne virus. Jar tests were used to evaluate virus removal attributed to use of alternative coagulants. Isotherm tests were used to determine the removal associated with the various filter media.

Jar tests

Jar tests were used to determine the effect of coagulants (Aluminum Sulfate, Cat-Floc T, and Nalco 8101, 8102 and 8103)[1] on MS2 in tap water and turbid water. A water turbidity of 14 NTU was produced by adding locally available top soil to tap water. Jar tests were also used in determining the optimum dosage of alum for the continuous filter runs.

The number of jars (1 liter beakers) used in each test varied according to the objective of the particular test being conducted. Essentially, each jar consisted of one liter of either tap water or turbid tap water at room temperature. Initially, a virus concentration of 5.4 x 10^3 PFU/ml was introduced into the water sample. The coagulant was then added. Concentrations of alum ranged from 1 mg/l to 50 mg/l, while concentrations of polyelectrolytes ranged from 2 mg/l to 10 mg/l. Mixtures were stirred mechanically (laboratory stirrer, Phipps and Bird, Inc., Richmond, Virginia) at approximately 120 rpm for one minute (G value of 110 sec^{-1}), after which the stirring rate was reduced to 30 rpm for the remainder of the test. The G values introduced to the solutions by the stirrer at 30 rpm were calculated to be 14 sec^{-1}. The following formula by TeKippe (1969) was used to calculate the G. values:

$$G = 0.084\ N^{3/2}$$

where

G = root mean square velocity gradient, sec^{-1}

N = speed of rotation (rpm)

Samples of 0.5 ml were drawn from the jars periodically and assayed for virus concentrations.

Isotherm tests

The isotherm tests were used to assess the ability of different granular media (sand, anthracite, and garnet) to remove viruses from water. They were also used to determine the effect of turbidity and changes in pH levels on the virus. All isotherm tests were conducted in an agitated system, using a lab-line shaker table (Lab-line Instruments, Inc., Melrose Parks, Illinois) at a setting of 100 rpm.

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[1]The names and addresses of the venders which supplied the coagulants are listed under Chemicals.

Each granular material was washed, dried, and autoclaved before the tests. Because these materials had been dried, and were thus absorptive, a sufficient amount of tap water was added to saturate the media before the addition of virus suspension. A ratio of 1 g granular matter to 1 ml of virus suspension was used throughout the tests.

The virus suspension was added to the granular material and allowed to mix for a period of 24 hours. This time span was assumed to be sufficient to achieve the maximum possible adsorption of the virus to the granular matter. The solution was then assayed for virus concentration. Kinetic studies were conducted on anthracite only, using the same procedure as above, however the solution was assayed at specific time intervals during the 24 hour period.

The effect of pH on the viability of the virus was determined by adjusting the pH of tap water by either bubbling CO_2 gas through the water, or adding 0.01 N sodium hydroxide (NaOH). Virus was added to tap water at various pH levels (pH 5 to 9), in a closed system, and assayed after 24 hours. To ensure that the decrease in virus concentration was due solely to pH changes, and not sodium ion addition, a study was conducted in which the pH was held constant (7.9 $\pm$ 0.1) while the sodium ion concentration was varied. Sodium concentrations tested were equivalent to levels of sodium added as NaOH in the previous pH experiments.

In the turbidity studies, virus was added to turbid tap water and assayed after 24 hours, both before and after centrifugation (at 10,000 rpm for 5 minutes). The sample was centrifuged in order to determine if the virus had adsorbed to the colloidal matter, or had remained in the supernate. Turbidity, in all tests, was held constant at 14 NTU, as measured with Hach turbidimeter, model 2100 A.

An appropriate system of controls was used for the batch test being conducted. The controls consisted of either virus suspension in tap water, virus suspension in turbid water, or a mixture of tap water and the particular granular medium being studied without addition of virus.

The virus concentration used in all batch tests (jar and isotherm) and in the continuous run tests) described in the following section) was approximately 5.4 x 10^3 PFU/ml. This concentration is low enough to allow direct assay of the samples, and thereby reduce the error involved in making necessary serial dilutions before assaying. In order to improve reliability, each test was run at least twice with three replicate samples for each experimental condition.

Continuous Runs

Apparatus

A pilot scale system was designed to simulate the functions of an actual in-line direct filtration plant. The system was composed of three functional units: an injection system, a mix tank, and three filtration columns. Figure 1 shows the schematic design of the system.

The injection system consisted of three storage tanks containing separate concentrated stock solutions of either alum, virus, or turbidity. Parastaltic pumps (Monostat, New York) were used to inject calibrated amounts of these solutions into the mix tank.

Controlled volumes of the three stock solutions and tap water were introduced into the mix tank. Mechanical stirrers (Cole-Parmer, Chicago) were used to mix the injected stock solutions with the inflowing tap water in the mix tank. The average detention time was 2 to 5 minutes.

Three separate filter columns, fed by the common mix tank, were used to evaluate rapid sand, dual-media (anthracite and sand) and multimedia (anthracite, sand and garnet) filters concurrently. The plexiglass columns were equipped with 12 equidistant sample ports along the length of the filter bed (Figure 2). Each sample port was equipped with a toggle valve, and penetrated the filter media to the center of the column so that the fluid regime would not be disturbed during sampling. The filter media were supported by a plexiglass plate.

The underdrain system consisted of a Flexkleen/Mark II provided by EIMCO, Division of Envirotech Corporation, Salt Lake City, Utah. To avoid short circuiting and to ensure consistent backwash pressure across the base of the filter, holes were drilled in the plexiglass plate supporting the media, and a wire mesh was used to cover the supporting plates. The underdrain system is illustrated in Figure 3.

The filter media were purchased from Neptune Microfloc, Inc. Table 4 shows the effective size and the uniformity coefficient of the media. The rapid sand filter consisted of 81 cm (32 inches) of sand while the dual-media filter consisted of 38 cm (15 inches) of sand and 38 cm (15 inches) of anthracite, and the multi-media filter consisted of 23 cm (9 inches) of sand, 43 cm (17 inches) of anthracite and 13 cm (5 inches) of garnet.

Backwashing and air scouring were used to clean the filter media between tests. For backwashing, the bottom outlets of the

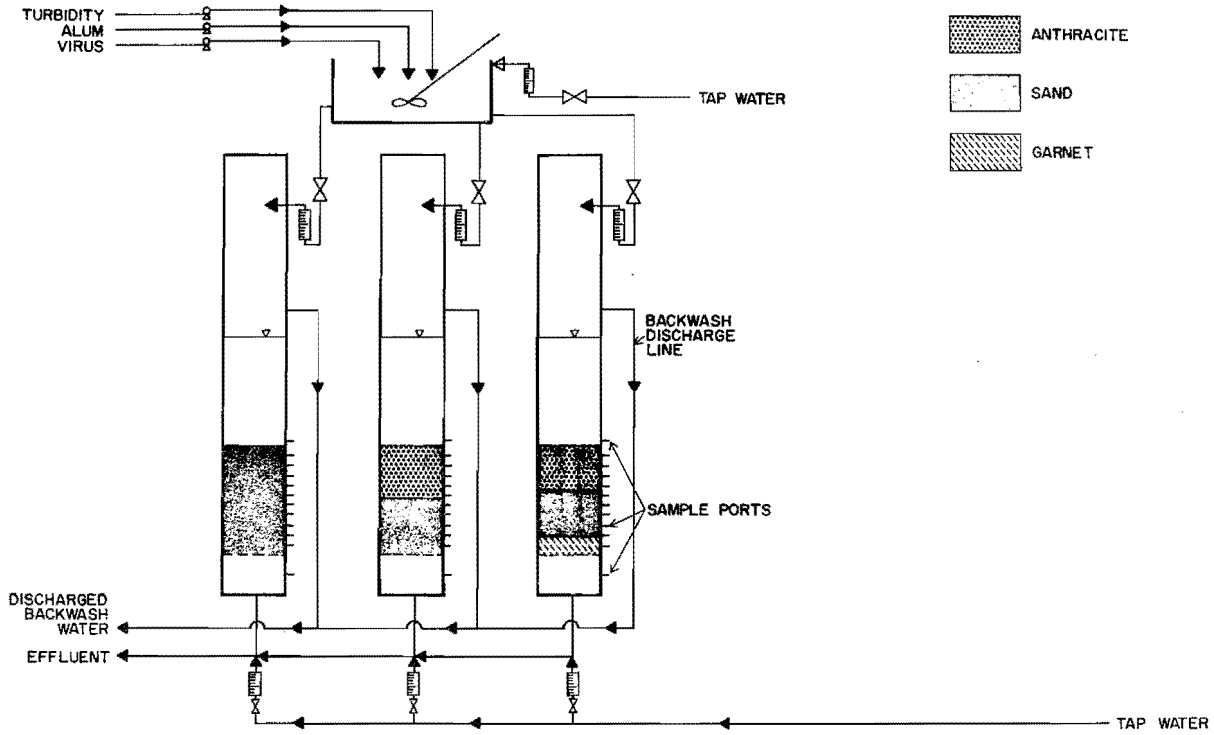


Figure 1. Schematic diagram of the laboratory in-line direct filtration system.

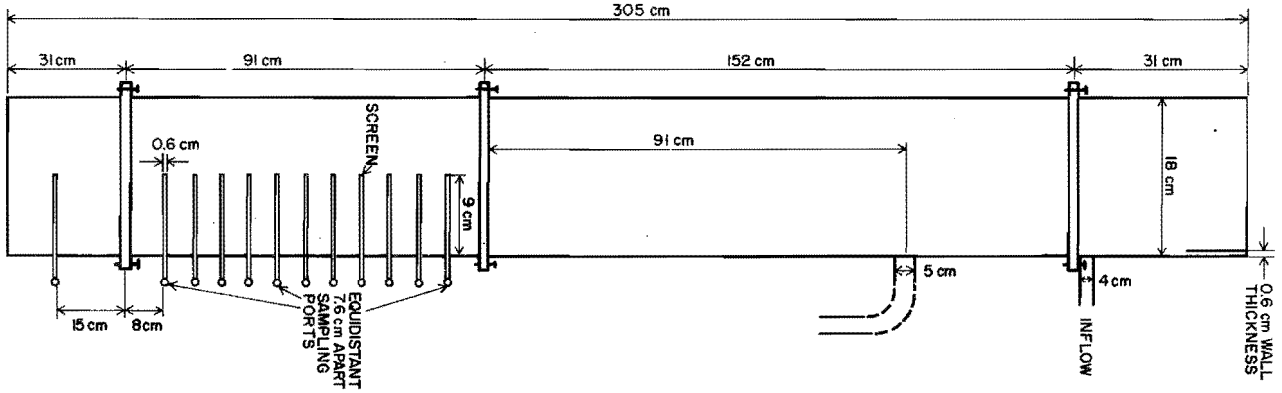


Figure 2. Dimensional details of each laboratory column.

Table 4. Media characteristics.

Media Design	Anthracite Coal		Sand		Garnet	
	Effective Size (mm)	Uniformity Coefficient	Effective Size (mm)	Uniformity Coefficient	Effective Size (mm)	Uniformity Coefficient
Single	-	-	0.4 - 0.5	< 1.4	-	-
Dual	1.5 - 1.6	< 1.8	0.4 - 0.5	< 1.4	-	-
Tri	1.0 - 1.1	< 1.7	0.4 - 0.5	< 1.4	0.18 - 0.28	$\leq$ 2

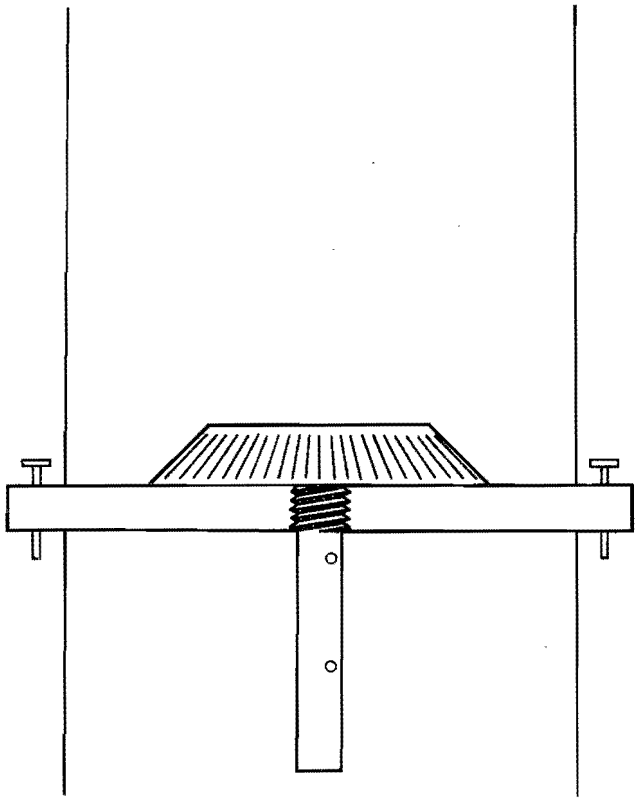


Figure 3. Schematic drawing of the underdrain system used in the filter columns.

columns were connected to a tap water line (Figure 1). Air scouring was achieved by forcing air through the filter bed. Compressed air was introduced in the bottom section of the filter below the media.

The backwash water was discharged from the filter through a 5 cm (2 inch) diameter PVC pipe located approximately 91 cm (36 inches) above the filter media (Figure 2). Filter effluent and backwash wastewater were piped to a 568 liter (150 gallon) reservoir. A water level actuated pump ultimately transported the wastewater to the Logan, Utah, municipal sewer system. All flow rates, in the pilot system, were controlled by means of valves and measured by flow meters (Fischer-Porter, Model 10A3500).

Column run procedure

To simulate surface water composition, modifications were made to the influent culinary tap water prior to filtration. Stock solutions of turbidity and virus were pumped and mixed with the influent tap water in the mixing tank. Logan, Utah, tap water, used in this study was derived from spring water. The spring water normally was not treated except for chlorination when needed. The tap water, however, was tested for residual chlorine periodically and the results were negative at all times.

Top soil was used to generate turbidity because its composition was representative of the turbidity found in the surface waters of this area. Top soil was obtained from the Utah State University Agricultural Farm, Logan, Utah. Table 5 presents the composition of the top soil used. Top soil was sterilized and graded with a #50 sieve. The stock turbidity solution was prepared by air mixing the top soil in tap water in a 49 liter holding tank. The virus stock solution consisted of suspension of MS2 (5.4×10^7 PFU/ml) in MS broth.

Table 5. Top soil composition which was used to generate turbidity.

Parameter	Value
pH	7.6
ECe, mmhos/cm	1.3
$NaHCO_3$-P, ppm	21
$NaHCO_3$-K, ppm	183
% O.C.	1.3
B, ppm	.76
NO_3-N, ppm	35.5
% $CaCO_3$	22.1
Fe, ppm	4.5
Zn, ppm	3.9
Cl, meq/l	1.3
HCO_3, meq/l	1.2
Extractable	
CEC, meq/100 g	11.3
Na, meq/100 g	< .1
K, meq/100 g	2.8
Ca, meq/100 g	*
Mg, meq/100 g	2.8
Water-soluble	
Na, meq/100 g	< .1
K, meq/100 g	< .1
Ca, meq/100 g	.4
Mg, meq/100 g	.1
Extractable	
Na, meq/100 g	< .1
K, meq/100 g	.8
Ca, meq/100 g	*
Mg, meq/100 g	2.7
SP, meq/100 g	35
Particle Size	
% Sand	25
% Silt	60
% Clay	15
Texture	Silt Loam

*When $CaCO_3$ is present in soils, extractable Ca is without meaning, and extractable Mg is often unreliable.

The stock solutions were pumped into the mix tank at rates which yielded final concentrations of 5.4×10^3 PFU/ml of virus and turbidity of approximately 14 NTU.

Aluminum sulfate (alum) was used as coagulant for the continuous runs. Stock solutions of alum were prepared by dissolving powdered alum (Stauffer Chemicals, Salt Lake City, Utah) in tap water. The stock solution was pumped into the mix tank to produce a final concentration of 6 mg/l of alum.

To establish whether pre-treatment of the filter media with polyelectrolytes would enhance the effluent water quality, an experiment was conducted treating the filter media by saturating it in a solution of Nalcolyte 8101 (20 mg/l) for 24 hours. Based on batch tests, Nalcolyte 8101 produced the greatest reduction of virus in water.

Before each run, the filters were backwashed for 15 minutes at a rate of approximately 61 $m^3/hour/m^2$ (25 $gal/min/ft^2$) followed by air-scouring for 5 minutes.

The efficiency of the pilot system was evaluated for both high hydraulic loading rates of 12.2 $m^3/hour/m^2$ (5 $gals/min/ft^2$) and low loading rates of 7.3 $m^3/hour/m^2$ (3 $gals/min/ft^2$). These rates were the total hydraulic loadings on each column. A constant head of approximately 91 cm (3 ft) was maintained above the filter bed during all runs.

Thirty minutes to one hour after the initiation of each run, samples were drawn from every other sampling port and assayed for virus concentration and checked for turbidity levels. The total volume of samples drawn from the ports each time was not more than 50 ml. A small volume (10-20 ml) was wasted from each port prior to obtaining samples. Turbidity was measured with a Hach turbimeter, Model 2100 A. All experiments were repeated twice to ensure reliability of results.

Chemicals

The following is a list of chemicals used in this study:

1. Bacto tryptone, Difco Laboratories, Detroit, Michigan.

2. Bacto Agar, Difco Laboratories, Detroit, Michigan.

3. Thiamine, Schering Corporation, New Jersey.

4. D. glucose, J. T. Baker Chemical Co., Phillipsburg, New Jersey.

5. Sodium Chloride, Mallinchrodt Chemical Works, St. Louis, Mo.

6. Yeast extract, Difco Laboratories, Detroit, Michigan.

7. Nalco 8101, 8102, 8103, Nalco Chemical Co., Salt Lake City, Utah.

8. Cat-Floc T, Calgon Corporation, Pittsburg, Pa.

9. Alum, Stauffer Chemicals, Salt Lake City, Utah.

10. Granular media (anthracite, sand, garnet), Neptune Microfloc, Inc.

Glassware

The following procedure was used in the preparation of all glassware used in this study.

1. Glassware was first soaked in a concentrated solution of chromic acid.

2. It was rinsed with a baking soda solution and tap water.

3. Deionized water was used for final rinsing.

4. Glassware was sterilized by means of autoclaving.

No special treatment was used to reduce adsorption, if any, of the virus to the glassware.

RESULTS AND DISCUSSION

Preceding the continuous pilot plant tests, batch studies were conducted to determine what effects, if any, factors such as pH, chemical coagulants, polyelectrolytes, and various filter media had on the bacteriophage MS2. Afterwards, continuous pilot plant tests were performed to determine the effectiveness of the system as a whole.

Data obtained from both batch studies and the continuous pilot plant runs, were statistically analyzed using the "Duncan Multiple Range Test" (Middlebrooks 1976). The data were the result of a biological assay procedure and thus inherently variable. The Duncan test was, therefore, used to determine if significant differences exist between the means of various treatments.

An observation was made that, in almost all cases, an initial decrease in virus concentration occurred with the addition of MS2 to tap water. This reduction of MS2 was probably due to virus aggregation that could be caused by the difference in the ionic strength of the tap water and the growth media. A previous study also showed aggregation of poliovirus and reovirus when these viruses were diluted with distilled water (Floyd and Sharp 1977). Aggregation was related to the lowering of the ionic strength of the solution. The basic underlying mechanism which governs the aggregation of virus particles, as reported by other investigators, involves 1) the nature of the soluble ionic groups in suspension with the virus, 2) the charged groups on the surface of the virus particle, 3) the isoelectric point of the virus, and 4) the ionic double layer which results from the interaction of one and two (Floyd and Sharp 1978). Floyd and Sharp emphasize that the conditions which induce aggregation of one virus will not necessarily induce aggregation of another. A minimum of two replicates of each experiment was conducted to verify results.

Effects of pH on MS2 Virus

The sensitivity of MS2 to pH was determined by isotherm batch studies. Approximately 5.4×10^4 PFU/ml of MS2 were added to tap water. The pH was varied either by bubbling CO_2 through the solution or by adding 0.01 N NaOH (sodium hydroxide). The virus was assayed after 24 hours. Results obtained from the experiment are presented in Figure 4. Virus concentrations increased as the pH increased from 5.5 to 7. The virus concentration, however, decreased at pH levels between 7 and 9. The isoelectric point of MS2 is at pH 3.9 (Goodhart 1969). Therefore, at pH above 3.9, MS2 has a net negative charge and at pH below 3.9 it has a net positive charge. Maximum aggregation would be expected to occur at the isoelectric point. When the surface charge is near neutrality, the repulsive forces between the virus particles approach zero. Therefore, the low concentration found at pH 5.5 probably resulted from virus particle aggregation. As the pH increased, from 5.5 to 7, repulsion of similarly charged virus particles inhibited aggregation. It should be emphasized, however, that aggregation is a very complex phenomena and may not be explained solely by colloidal chemistry.

Decrease in virus count from pH 7 to 9 may be due to the excessive negative charge on the virus and on the host cell, thus preventing attachment to the host cell. Another possibility would be irreversible structural changes in the virus' host specific attachment site. Decrease in virus concentration at pH 9 may be attributed to the virus protein coat rupture. The possibility of the protein coat rupture and denaturation, however, has been reported to occur at pH levels above 11 (Berg et al. 1970).

To ensure that the reduction in virus concentration at pH values above 7 was solely due to the pH change and not the sodium ion concentration, an experiment was conducted varying the sodium ion concentration while keeping the pH constant (7.9 ± 0.1). Sodium concentrations tested were equivalent to levels of sodium added as NaOH in the previous pH experiments. As shown in Figure 5, there was no significant difference at 95 percent confidence level between virus concentrations over the range of zero to 0.5 mg/l of sodium ion.

Virus removal by filter media - jar test

Virus sorption on anthracite, sand, and garnet was investigated. The resulting

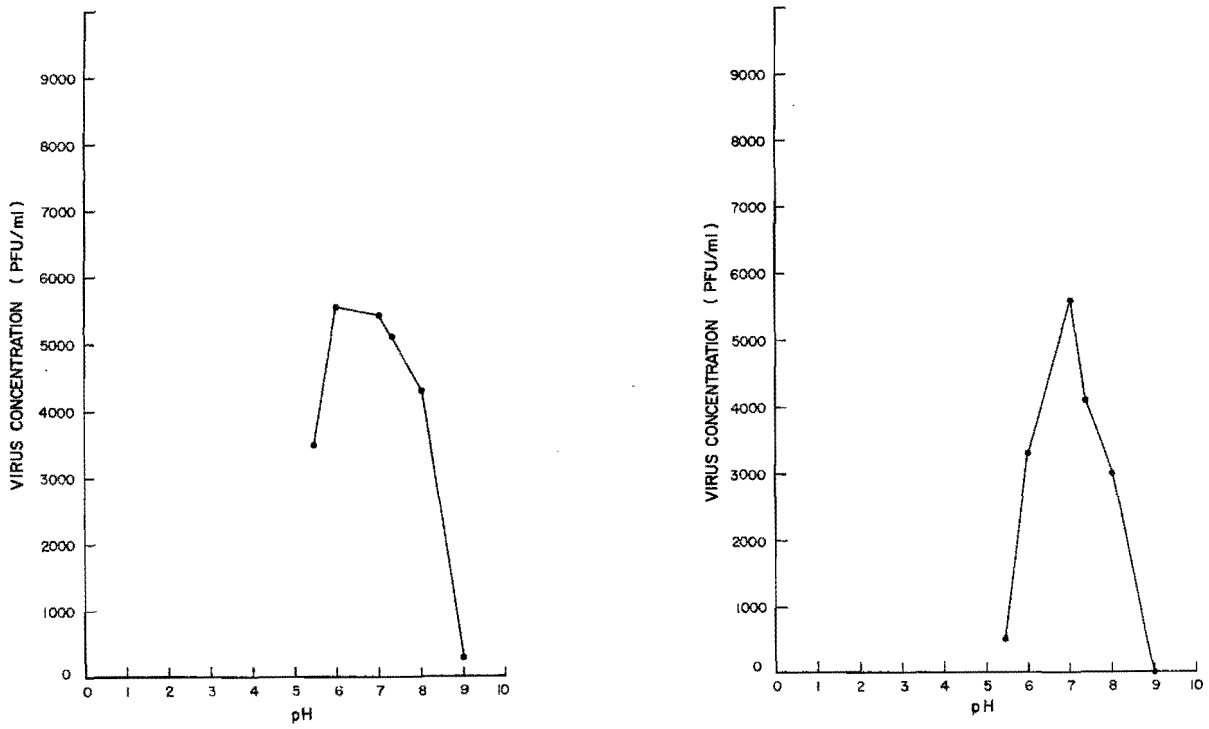


Figure 4. The effect of pH levels on MS2 bacteriophage (two replicate tests).

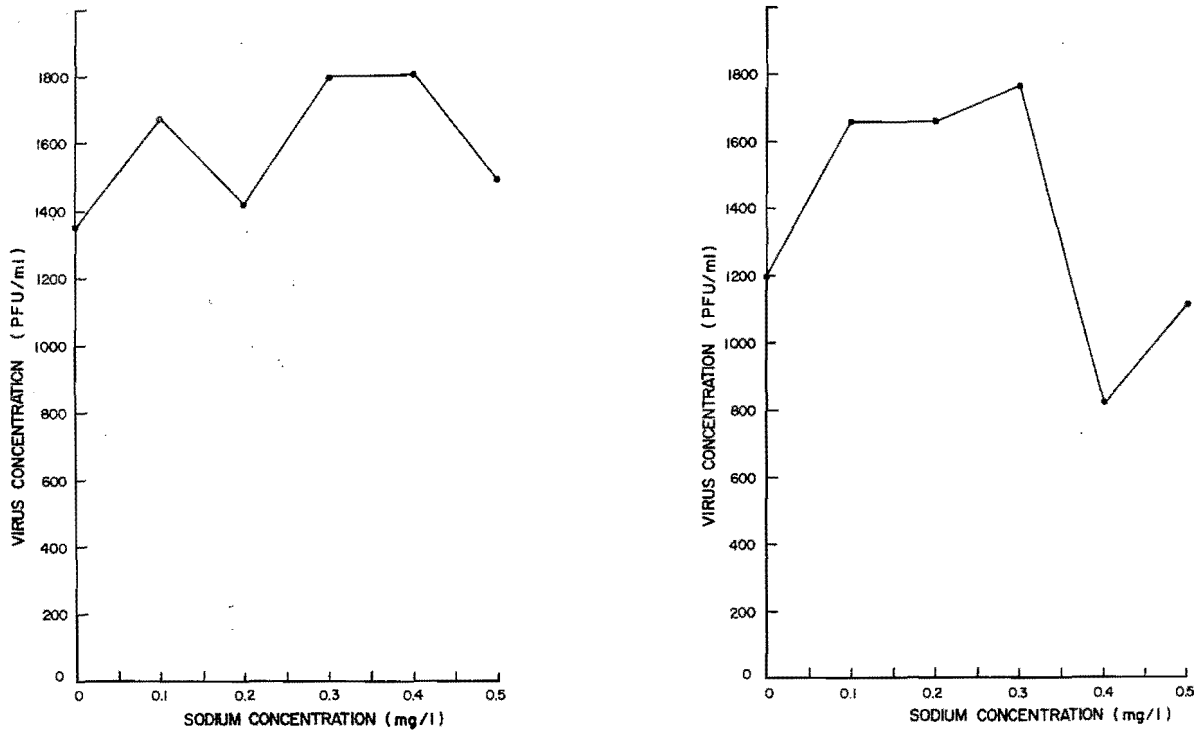


Figure 5. The effect of sodium ion levels on MS2 bacteriophage (two replicate tests).

kinetics of virus adsorption to the anthracite and sand are presented in Figure 6. Although the graphs appear to indicate some virus removal by the sand, the Duncan interpretation of the data show that the removal over time was insignificant at 95 percent confidence level.

The maximum virus removals achieved by the anthracite in Figure 6 was 93+ percent. Figure 7 also shows the virus adsorption to the anthracite as a function of time. The adsorption equilibrium was reached after 2 hours. The adsorption kinetics, however, showed that approximately 30 percent virus removal occurred within the first 10 minutes. During the pilot plant continuous experiments, the contact period between the filter media and the virus was less than 10 minutes. Therefore, adsorption kinetics limited the removal of virus by anthracite coal. Centrifugation of the fine colloidal particles from the supernatant yielded approximately 99 percent virus removal after 30 minutes of contact time (Figure 7). The increase in virus reduction was attributed to removal of the very fine particles of the anthracite which have virus associated with them. Although the Duncan test indicated that the difference between the centrifuged samples and noncentrifuged samples was not significant, the rate of virus removal for both samples was significant. It appeared that virus removal efficiency was improved with smaller size anthracite grains. The greater efficiency was probably due to increase in surface area.

The difference between the virus removal by sand and anthracite may be due to the difference in their surface area (Bitton 1975). Compared to anthracite, sand is relatively a poor adsorbent because of its smaller surface area. Previous study has shown that sand removes viruses mainly by adsorption which is enhanced by electrostatic attraction and Van der Waals forces between sand and virus particles (Bitton 1975). This finding was further confirmed by tests using egg albumin to compete with the bacteriophage for the limited amount of active sites on the sand surface (Bitton 1975).

The data obtained in this study describing the adsorption of virus to anthracite agree with similar data provided in the literature (Oza and Chaudhuri 1976, 1977). Virus-coal sorption interaction has been considered to involve some specific interaction between the surface functional groups of virus and coal (Oza and Chaudhuri 1976, 1977). This interaction has been presumed to involve hydrogen bonding. Coals with greater ratios of hydrogen to carbon (H/C) and hydrogen to oxygen (H/O) adsorbed greater numbers of MS2 virus (Oza and Chaudhuri 1976, 1977). Therefore, different degrees of removal would be achieved with different types of coal.

Since no virus removal was observed with garnet after a period of 24 hours, further kinetic studies with garnet were not conducted. In summary, anthracite coal was the most effective media in virus removal. Anthracite removed 93 percent of the bacteriophage MS2 at an initial titer of 5.4 x 10^3 PFU/ml. The removal of virus by the sand was insignificant at the 95 percent confidence level.

Virus adsorption to turbidity

Tap water and water containing turbidity were inoculated with approximately 5.4 x 10^3 PFU/ml of MS2 phage. Samples were agitated at 100 rpm for 24 hours. Samples were then assayed before and after centrifugation to ensure that virus particles were in the supernatant and not associated with the solids in the water. Table 6 presents the results of five repetitive jar tests.

Centrifugation did not reduce virus concentration (Table 6). Adsorption of MS2 to colloidal suspension was insignificant at 95 percent confidence level. Studies reported in the literature, however, have shown that colloidal particles present in water provide sites for virus attachment, thus decreasing the virus counts (Carlson et al. 1968; Moore et al. 1975; Bitton 1975; Berg 1973; Schaub and Sagik 1975; Bitton et al. 1976).

Table 6. Virus concentration in tap water and tap water containing turbidity for centrifuged and non-centrifuged samples.

Trial No.	Virus Conc. (PFU/ml) in tap water before centrifugation	Virus Conc. (PFU/ml) in tap water after centrifugation	Virus Conc. (PFU/ml) in tap water plus turbidity before centrifugation	Virus Conc. (PFU/ml) in turbidity water after centrifugation
1	347	503	520	187
2	730	657	628	588
3	392	389	364	420
4	358	460	337	438
5	383	367	370	368

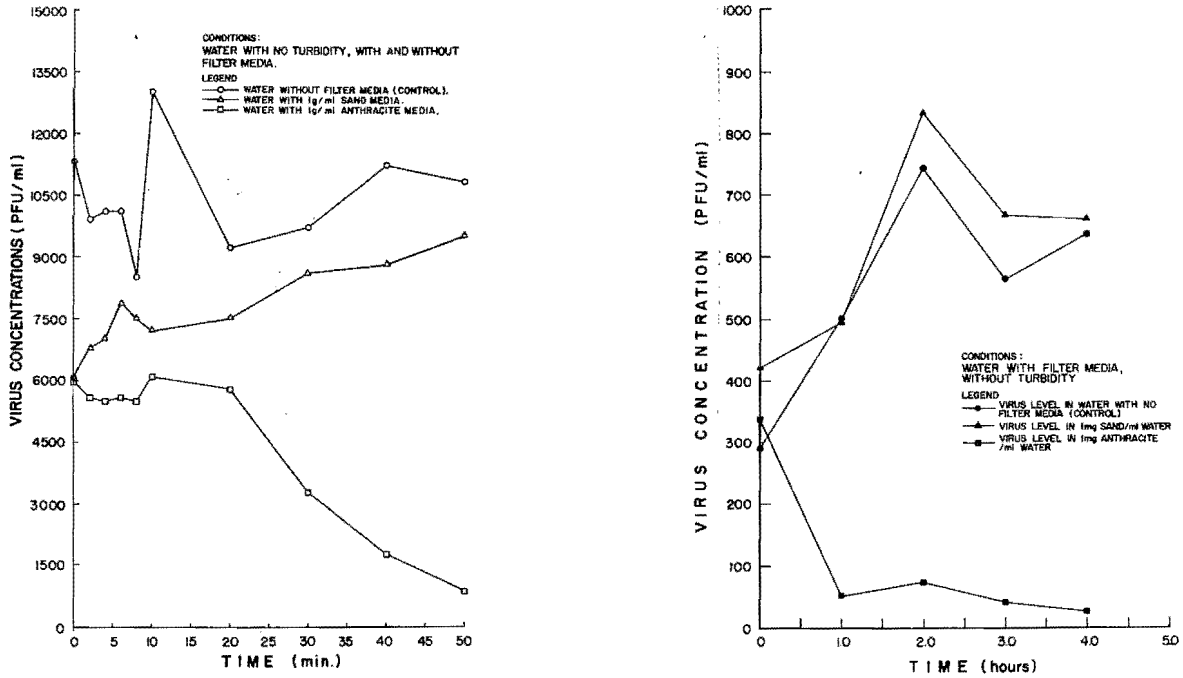


Figure 6. Virus adsorption to anthracite coal and sand at various times during kinetic studies.

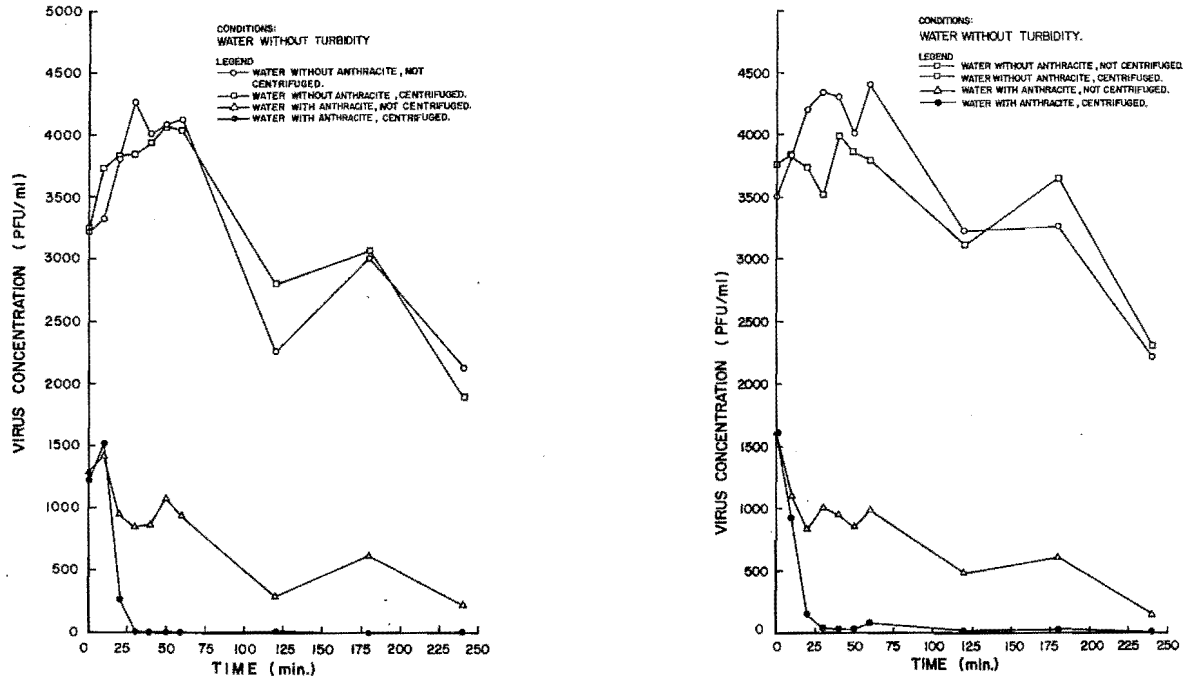


Figure 7. Virus adsorption to anthracite coal at various times during kinetic studies.

The discrepancy between these observed results and the literature results may be due to the difference in the nature of the colloidal matter, virus, and the cation species present. Carlson et al. (1968) made a detailed study on the adsorption of bacteriophage T_2 and type I poliovirus to Kaolinite, montmorillonite and illite. It was found that the sorption of these viruses depended on the type and concentration of cations present in the water. It was also concluded that clay minerals vary in their ability to adsorb virus particles. The surface exchange capacity, determined by the surface charge density and clay particle geometry, was an important factor which governed the adsorption process. Previous work reported that viral association to inorganic and organic suspended solids depended on the type of virus as well as the presence of cations (Moore et al. 1975). According to Moore, both T_2 and f_2 virus show great affinity for Bentonite in the presence of calcium. Their affinity for Kaolinite under the same condition, however, was much less.

Effects of Coagulants

Alum and cationic polyelectrolytes (Cat-Floc T, Nalco 8101, 8102, and 8103) were tested on the MS2 phage suspension in both tap water and turbid tap water. The purpose of using two types of water was to investigate the role of turbidity in the interaction between the bacteriophage and the coagulant. Cationic polyelectrolytes have been shown to be more effective at removing virus from water suspensions than are either anionic or non-ionic polyelectrolytes (Shea et al. 1971; Adin and Rebhum 1974; Chaudhuri and Engelbrecht 1970; Thorup et al. 1970).

Alum

Figures 8, 9, and 10 show the effect of various dosages of alum on the decrease of MS2 in tap water. No significant differences at the 95 percent confidence level was observed at alum dosages from 1 mg/l to 6 mg/l (Figures 8 and 9). The average removal of virus over time when compared to the control was 30 percent. When the dosage range was increased to between 7 and 10 mg/l, no significant difference at the 95 percent level was observed between each treatment, or the treatments and the control (Figure 10). When alum was added to virus suspension in turbid water, no significant reduction was achieved when compared to the control (Figures 11 and 12). In some cases the control actually had lower counts than the treatments achieved. The Duncan test indicated that there was no significant difference at the 95 percent confidence level between the results obtained at the different alum dosages (5 to 10 mg/l) and the controls.

Virus removal for alum concentrations up to 6 mg/l in tap water could be due to formation of a coordination complex between the virus and the metal coagulant. The aluminum may have been coordinated with the carboxyl groups in the virus' protein coat, thus resulting in a decrease in virus concentrations (Chaudhuri and Engelbrecht 1970).

In a turbid solution (14 NTU), virus removal did not occur at alum dosages from 5 to 10 mg/l (Figures 11 and 12). Turbidity appeared to interfere with the ability of alum to remove the virus at these low dosages.

Results presented in Figures 8 through 12 show a relative increase in virus counts with corresponding increases in the flocculation period in almost all cases. This increase may have been due to breaking up the virus aggregates by mechanical stirring. A more uniform distribution of the virus particles in the solution achieved by longer mixing could have also contributed to the increase in virus counts. The difference between virus concentration over the flocculation period of zero to 45 minutes was not significant at 95 percent confidence level. Thus it appears that virus reduction is not a function of the flocculation period.

Figure 13 plots virus removal for various alum dosages (up to 50 mg/l) after a flocculation period of 45 minutes. Following a 15 minute sedimentation period, three 0.1 ml supernatant samples were obtained and assayed for virus. Supernatant from the settled sample was centrifuged to determine if removal of the finer particles would improve virus removal. This sample was labeled "supernatant centrifuged." Having assayed the supernatant with and without centrifugation, the settled floc particles were resuspended in the water. Insufficient energy was introduced to the sample to disrupt the integrity of the floc particles. The resuspended samples were assayed to determine whether decrease in virus counts was due to virus aggregation on the floc's surface or enmeshment of the virus in the flocs particle.

Virtually no virus removal occurred with lower dosages of alum (5 - 10 mg/l), whereas dosages of 20 to 50 mg/l achieved nearly complete virus removal. Figure 13 clearly depicts the differences in virus removal by alum dosages used in direct filtration plants (usually less than 15 mg/l) and conventional treatment plants (greater than 20 mg/l). It appeared that the key to better virus removal efficiency was the alum dosages used. Flocculation period had no observed effect on virus removal. Alum dosage of 50 mg/l produced highest removal with maximum percent removals of 97, 98, and 93 for supernatant, supernatant centrifuged, and the resuspension, respectively. However, the Duncan analysis indicated that the differences in the percent removals for these three treatments were not significant at 95 percent confidence level. These results compare favorably with those reported by

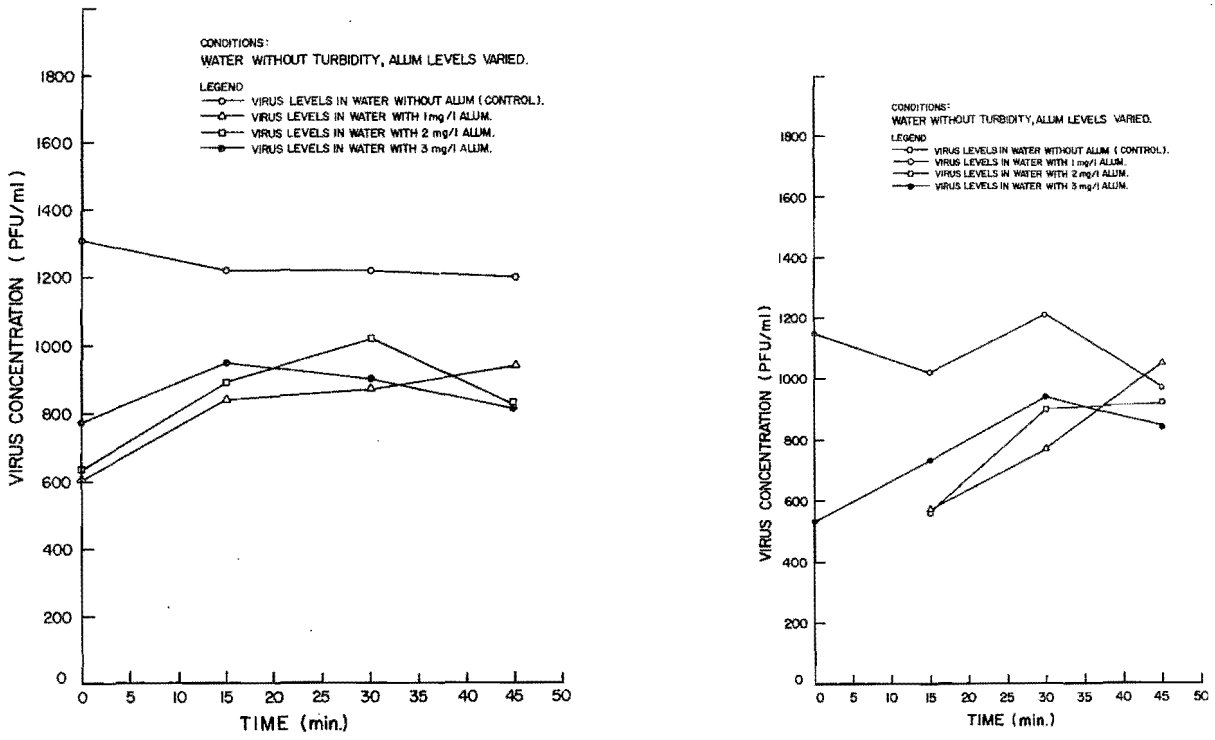


Figure 8. Effects of low concentration of alum (1,2,3 mg alum/l) on virus contained in water without turbidity.

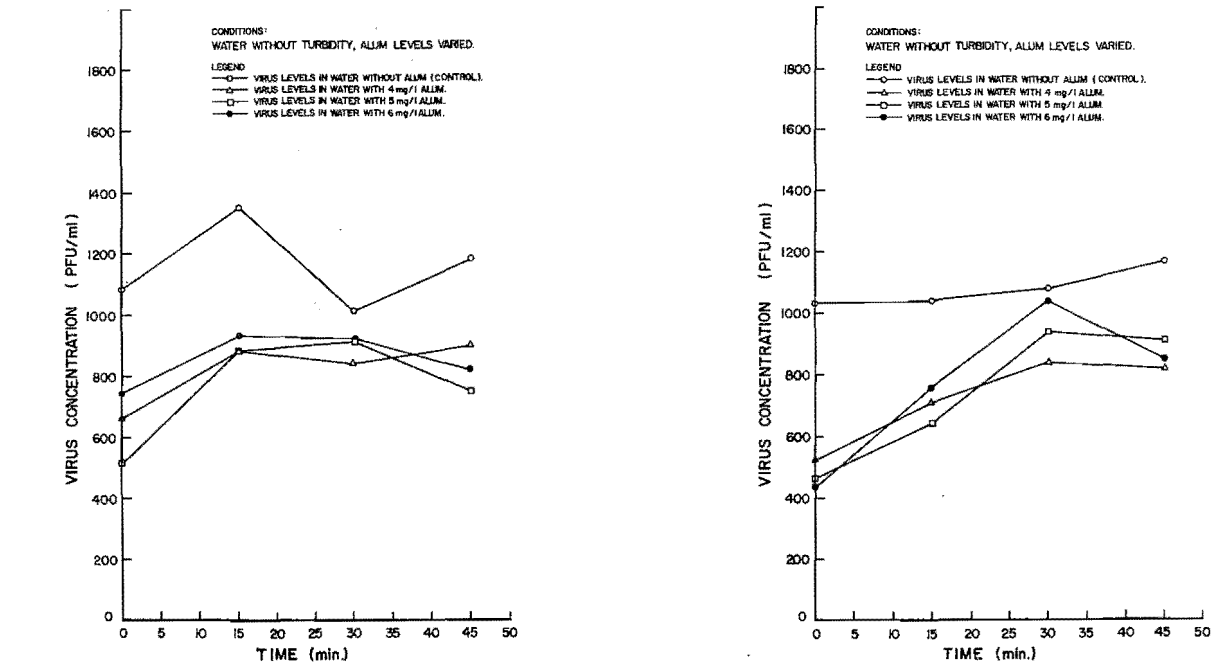


Figure 9. Effects of alum (4,5,6 mg alum/l) on virus contained in water without turbidity.

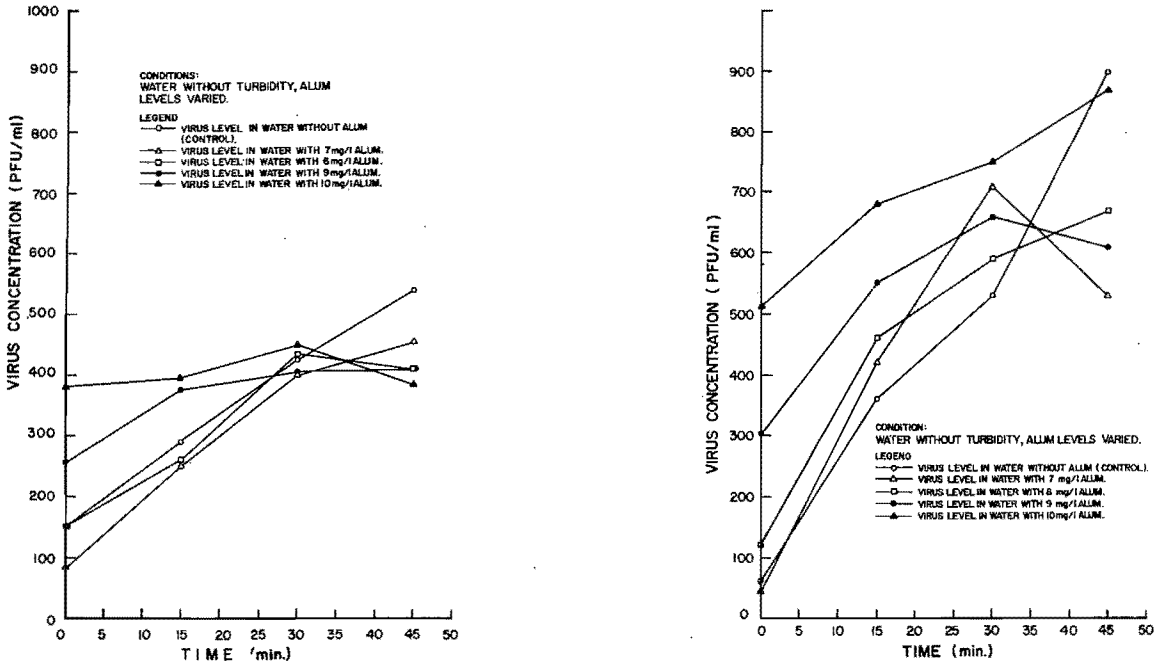


Figure 10. Effects of alum (7,8,9,10 mg alum/l) on virus contained in water without turbidity.

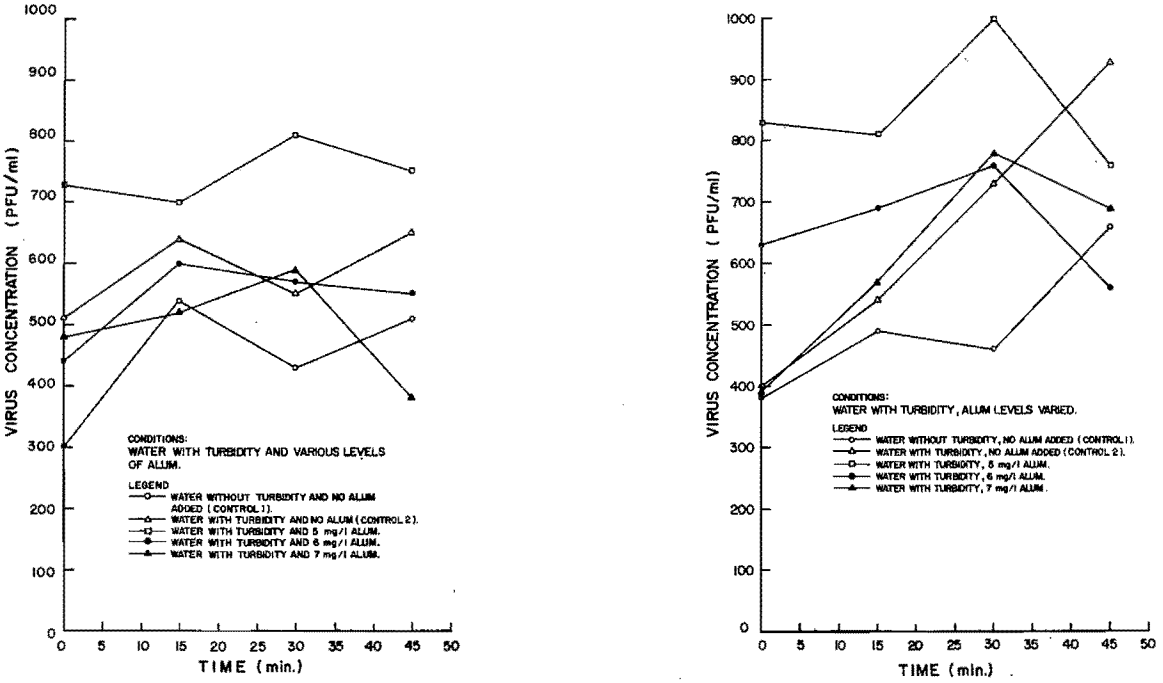


Figure 11. Effects of alum (5,6,7 mg alum/l) on virus contained in water with 14 NTU turbidity.

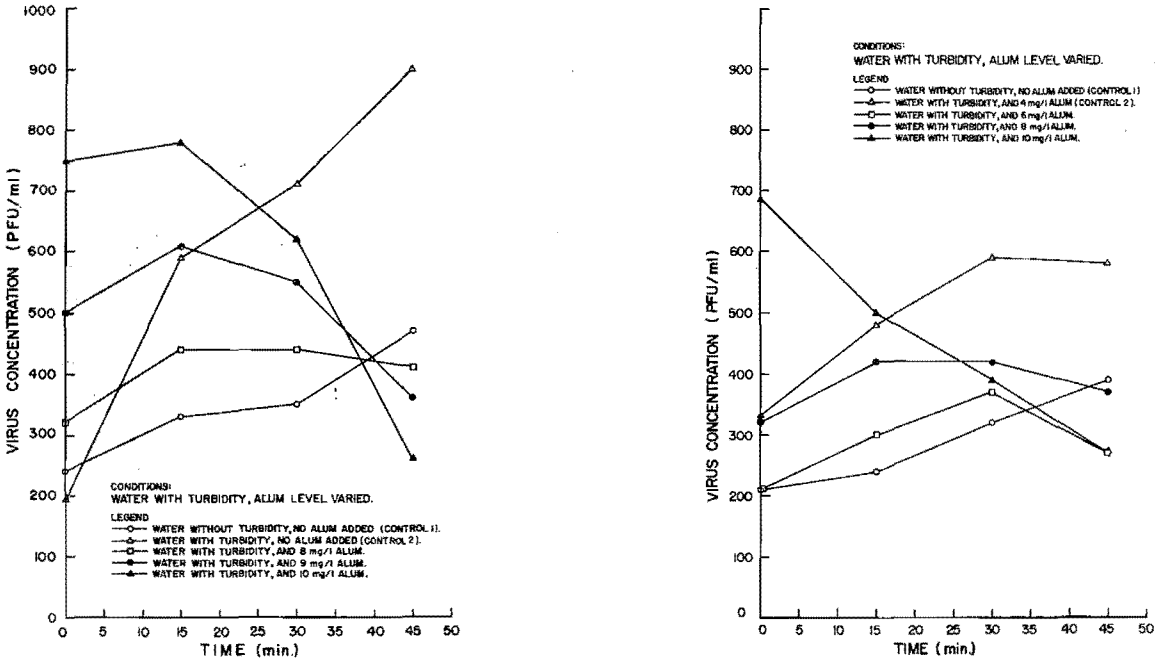


Figure 12. Effects of alum (4,6,8,9,10 mg alum/l) on virus contained in water with 14 NTU turbidity.

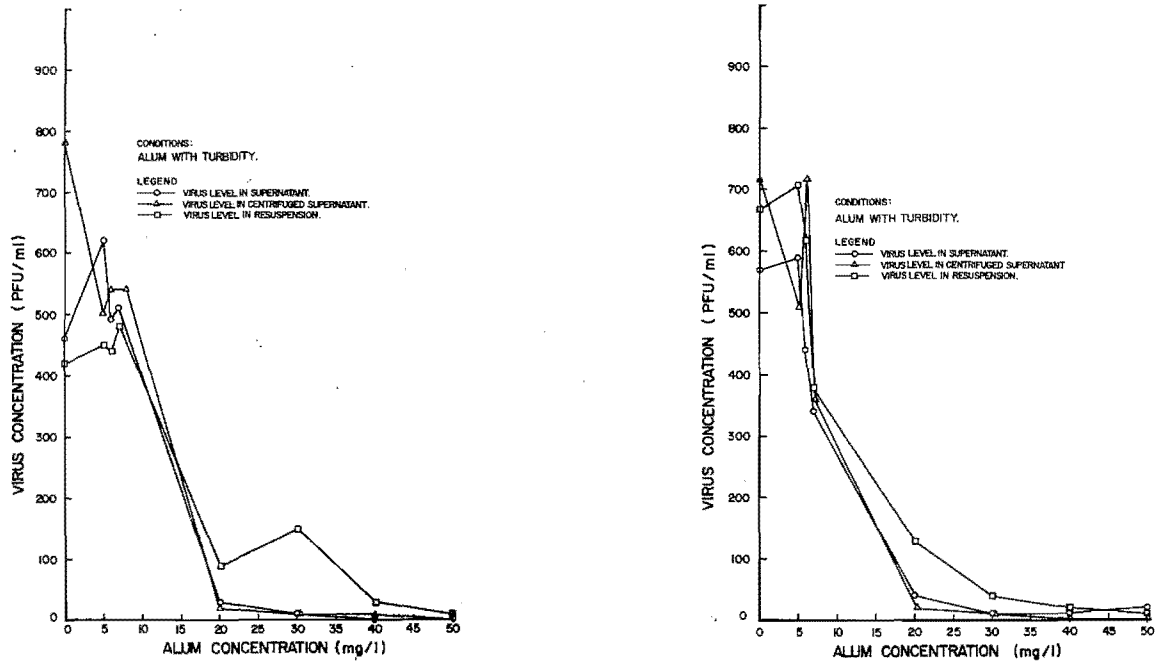


Figure 13. Effects of alum on virus contained in water with 14 NTU turbidity.

other investigators (Chaudhuri and Engelbrecht 1970; Chang et al. 1958; York and Drewry 1974). Since centrifugation and resuspension of the floc did not alter virus concentrations in the water sample, the removal may be due to the entrapment of the virus within the precipitating flocs. Furthermore, virus particles which were not entrapped in the flocs, remained in the supernatant and did not attach to the colloidal particles present.

Chaudhuri and Engelbrecht (1970) have presented evidence that metal coagulants initially form a coordination complex with the virus (T_2 and MS2 phages). The aluminum was believed to have coordinated with the carboxyl groups in the virus' protein coat. Subsequently the complex was incorporated into the precipitating hydrated aluminum oxide. The viruses were not inactivated but could be partially recovered from the sludge (Chaudhuri and Engelbrecht 1970). The presence of organic material was shown to decrease the amount of virus removed due to competition.

With respect to turbidity removal, 6 mg/l of alum was determined to be the optimum dosage. Optimum dosage is defined as the lowest dosage which produced pin point flocs while producing the lowest turbidity. Figure 14 represents the results of the jar test for turbidity removal at alum dosages of 1 to 10 mg/l.

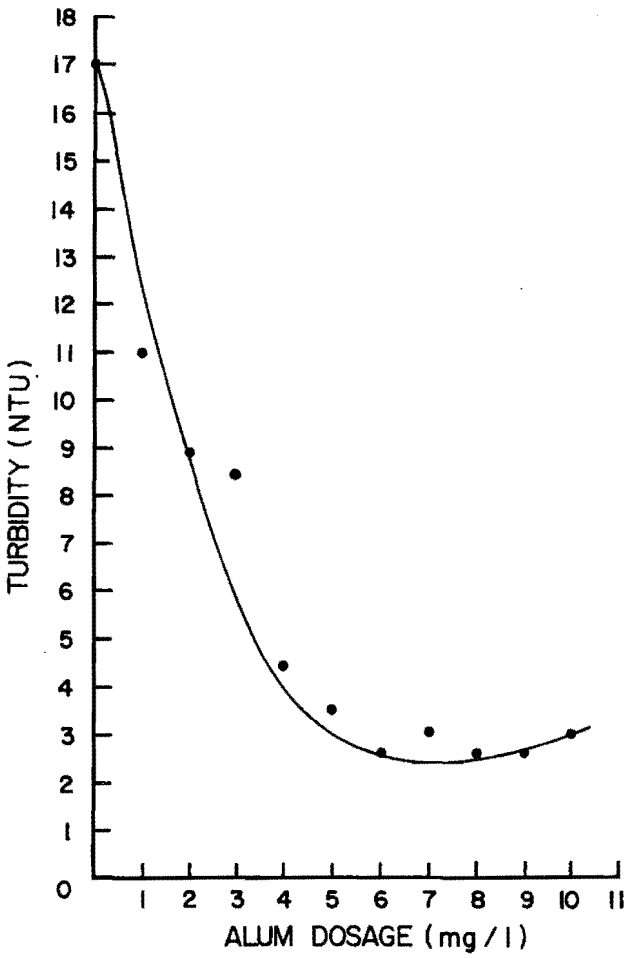


Figure 14. Turbidity removal at various alum dosages.

Virus and turbidity removal with polyelectrolytes

Figure 15 shows the effect of various dosages of Cat-Floc T (2 to 10 mg/l) on the virus suspended in tap water. There were no significant differences among the various Cat-Floc T dosages with regard to virus reduction. In each case, a 95 percent confidence level was used. In the presence of turbidity, greater removal was achieved (Figure 16). The effects of all the dosages were essentially the same except for the dosage of 10 mg/l which shows significantly less reduction (35 percent less). Optimum virus reduction was achieved by 2 mg/l of Cat-Floc T which reduced approximately 75 percent of the virus. The 75 percent removal was calculated based on arithmetic averages over time (Figure 7). These data further confirm the assumption that virus reduction was not a function of flocculation period. The maximum reduction, however, was 98 percent after a flocculation period of 45 minutes (Figure 17). Results with Cat-Floc T compare with virus removal data obtained using alum at higher concentrations (20 - 50 mg/l).

Figure 17 shows a definite trend toward colloidal restabilization as the dosages of Cat-Floc T were increased from 2 mg/l to 10 mg/l. This process was best explained by the work of O'Melia (1969) (Figure 18). Cationic polyelectrolytes bear positively charged amino groups which attract the negatively charged particles (virus in this case). When a polymer molecule comes into contact with a colloidal particle, some of these colloids adsorb at the positive sites, leaving the remainder of the molecule extending out into the solution. If a second particle with available adsorption sites contacts these extended segments, attachment can occur. A particle-polymer-particle complex is thus formed in which the polymer serves as a bridge. Dosages of polymer which are sufficiently large to saturate the colloidal surfaces produce a restabilized colloid, since no sites are available for the formation of interparticle bridges. The restabilization phenomena may explain why no virus removal occurred in the absence of turbidity. The dosage of polymer may have been so large that it saturated the virus surfaces, leaving no available sites for the formation of interparticle bridging. The addition of turbidity increased the number of colloidal particles present thus preventing saturation of colloidal surfaces and the virus.

Figures 19, 20 and 21 represent the results for virus removal with Nalco 8101. A 96 percent decrease in virus concentration was achieved when 2 mg/l Nalco 8101 was added to tap water, whereas 97 percent of the virus was reduced when this polymer was added to tap water containing turbidity. The Duncan test indicated no significant differences among the removal of virus at various dosages. The removal of the bacteriophage may be explained by formation of virus-polymer-virus complex, as previously explained, leading to aggregation.

A 2 mg/l concentration of Nalco 8102 removed 48 and 63 percent of the virus in tap water and turbid water, respectively (Figures 22 and 23). Restabilization of the virus particles occurred at 6 mg/l of Nalco 8102. Approximately 57 percent of the virus was reduced with the addition of 2 mg/l of Nalco 8103 to both tap water and turbid water (Figures 24 and 25). Restabilization was again observed at the concentration of 6 mg/l Nalco 8103 (Figure 24).

Reduction of virus levels obtained with Cat-Floc T, Nalco 8101, 8102, and 8103 futher confirmed the finding that flocculation period does not affect virus removal efficiency. None of the polyelectrolytes produced a visible floc with turbidity. Furthermore, they all failed to remove turbidity. These polyelectrolytes are not manufactured to be used as primary coagulants, rather they are intended as coagulant aids to coat filter media or be used in conjunction with another metal coagulant. Polyelectrolytes are usually added to the backwash water to cover the surface of the filter media. This process is referred to as "coating." Whether polyelectrolytes are used to coat filter media or in conjunction with metal coagulant, their function is to form strong bonds when floc is adsorbed on to the filter media.

Table 7 summarizes the efficiencies of the various coagulants evaluated to reduce the bacteriophage MS2. The dosages reported were the dosages which produced the highest virus reduction. The efficiencies in virus reduction were achieved for turbidity of 14 NTU's, initial virus titer of approximately 5.4 x 10^3 PFU/ml, and flocculation period of 45 minutes. No significant differences were observed between centrifuged, noncentrifuged, settled and nonsettled samples (Figures 13, 17, and 20). The percentages reported are, therefore, for samples without sedimentation or centrifugation because they are more representative of the processes in direct filtration systems. The percentages were calculated from the arithmetic averages of each dosage over time for two replicate tests. Because of the variability of results, the percentages based on averages over time were more accurate than maximum percent reduction. Maximum percent reduction would be calculated based on data obtained at a particular point in time during the test. Because the data were acquired by a biological assay procedure, and thus inherently variable, one data point was not reliable enough to be considered the result of a treatment.

Table 7. Reduction of bacteriophage MS2 concentrations in water by various coagulants without sedimentation.

	Optimum Dosage (mg/l)	Average % Virus Reduction Over Time
Alum	50	98
Cat-Floc T	2	75
Nalco 8101	2	96
Nalco 8102	2	63
Nalco 8103	2	57

Pilot Plant Studies

Initial conditions

Continuous filtration experiments were conducted to evaluate virus removal in a pilot scale in-line direct filtration system. Top soil was added to the culinary water of Logan, Utah, to simulate natural surface water. The turbidity of the simulated water ranged from 14 to 17 NTU in most cases. The flow rates used were 7.3 and 12.2 $m^3/hour/m^2$ with detention times in the rapid mix basin of 5 and 2 minutes respectively. A virus suspension was gravity fed to the mix tank to render a final virus concentration of 5.4 x 10^3 PFU/ml. A great deal of variability (0 to 5547 PFU/ml), however, was observed in the virus concentration in the rapid mix tank due to fluctuation in the flow from the virus feed system. Because the desired flow from the stock virus suspension in the rapid mix tank was only 1 ml/min., it was difficult to maintain a constant flow. An alum dosage of 6 mg/l was used in the continuous filteration runs. This optimum dosage for turbidity removal was determined by jar test (Figure 14). Four tests were run with alum alone at flow rates of 7.3 and 12.2 $m^3/hour/m^2$.

After the data had been collected with alum alone as the coagulant, the filters were coated with Nalco 8101 as described previously in the procedure. Two tests were then conducted with Nalco 8101 at a flow rate of 7.3 $m^3/hour/m^2$. In these studies, 2 mg/l of Nalco 8101 were added to the water approximately 61 cm (2 feet) above the coated filters after 6 mg/l of alum had been added in the rapid mix basin. Two mg/l as determined by the jar tests were the optimum dosage of Nalco 8101 for virus removal. The samples collected from each filter column were analyzed for turbidity and the bacteriophage MS2 concentration. The pilot plant

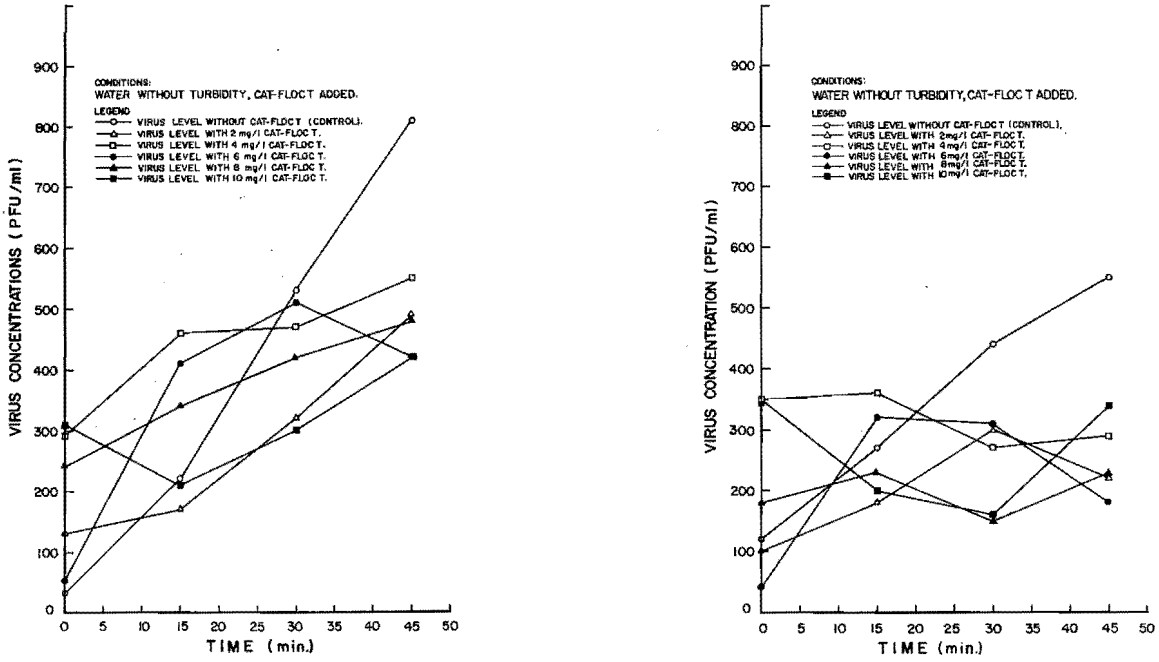


Figure 15. Effects of cationic polyeletrolyte, Cat-Floc T, on virus contained in water without turbidity.

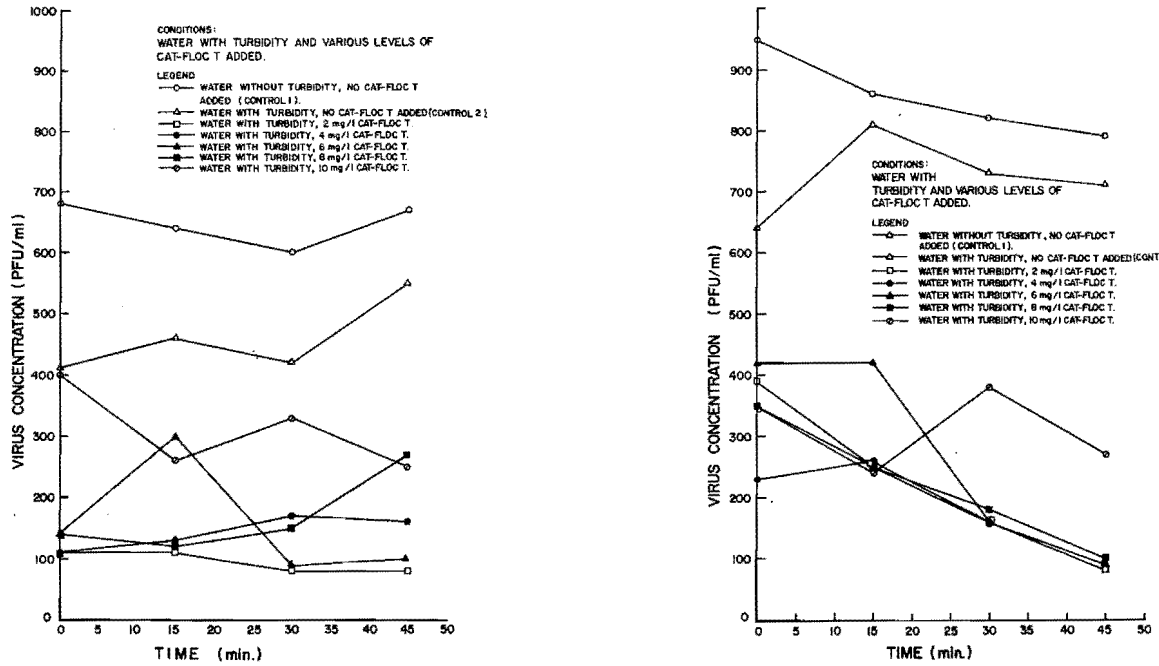


Figure 16. Effects of cationic polyelectrolyte, Cat-Floc T, on virus contained in water 14 NTU turbidity.

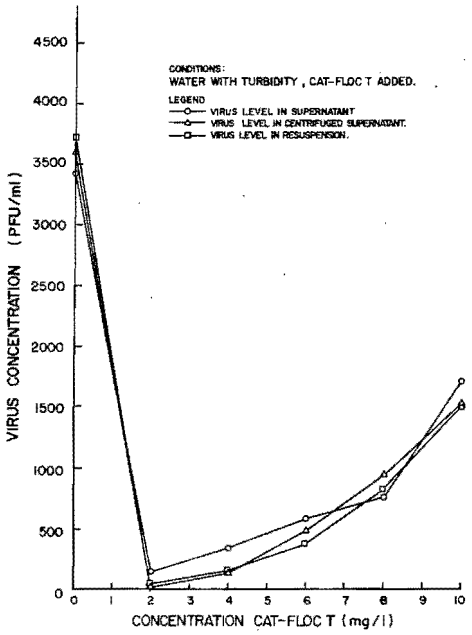


Figure 17. Effects of cationic polyelectrolyte, Cat-Floc T, on virus contained in water with 14 NTU turbidity.

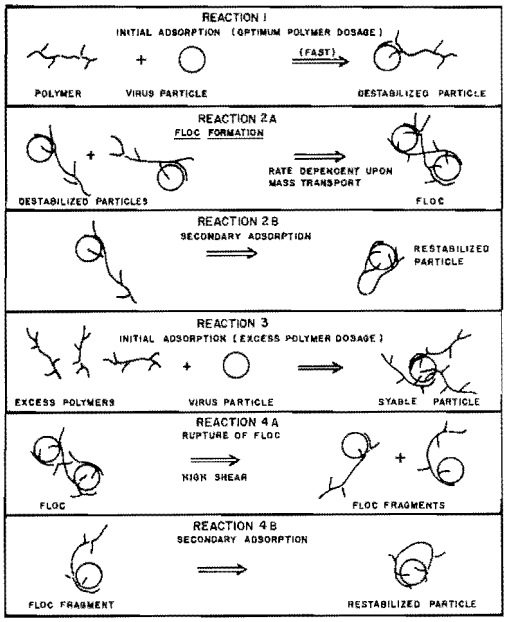
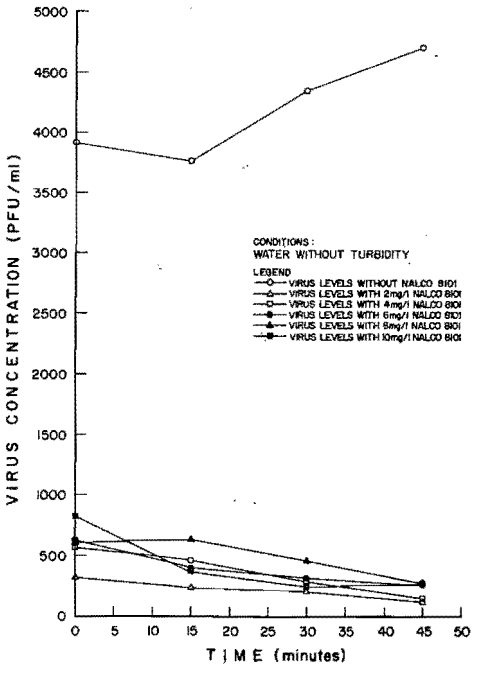


Figure 18. Reactions which may occur with virus particles and polymers (modified from O'Melia 1969).



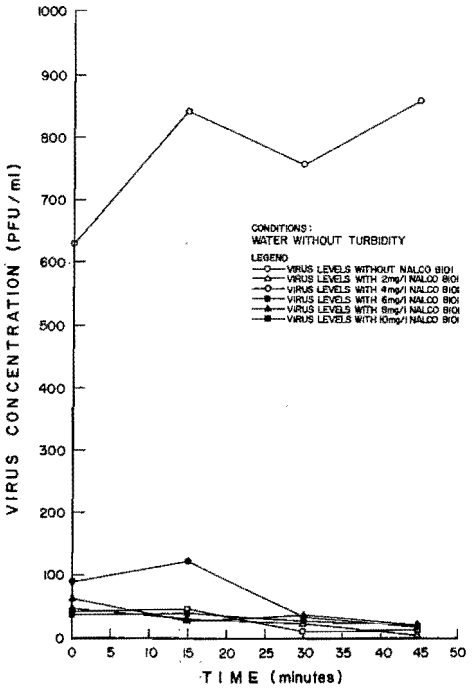


Figure 19. Effects of cationic polyelectrolyte, Nalco 8101, on virus contained in water without turbidity.

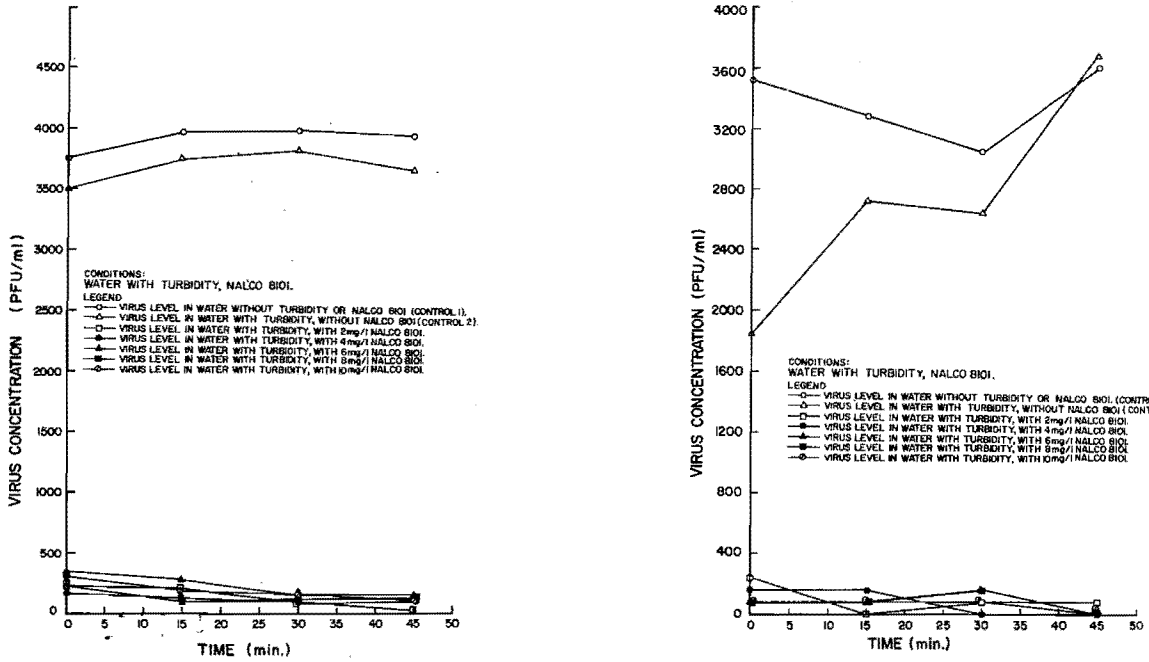


Figure 20. Effects of cationic polyelectrolyte, Nalco 8101, on virus contained in water with 14 NTU turbidity.

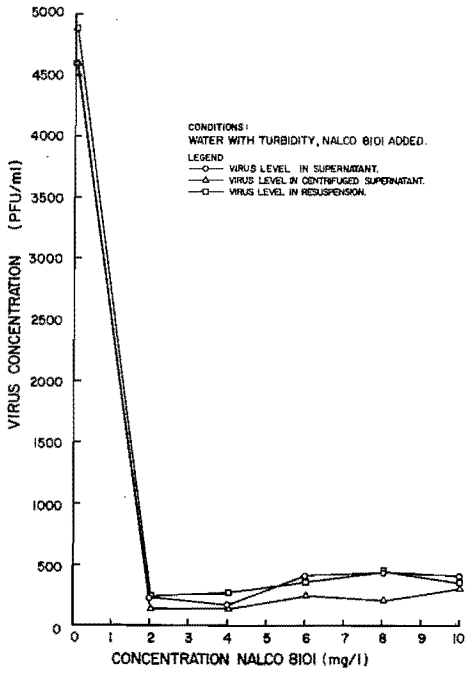


Figure 21. Effects of cationic polyelectrolyte, Nalco 8101, on virus contained in water with 14 NTU turbidity.

studies were repeated twice for each condition to ensure validity of the results.

The intent of these experiments was not to determine the optimum filtration length, but to determine the efficiency of virus removal. In all cases, first filter effluent samples assayed showed virus breakthrough. The filters were, therefore, operated for 9 hours which was considered sufficient to construct virus and turbidity profiles through the filter media.

Turbidity and virus removal by the filters

Single sand medium. The results of the continuous pilot plant operations for the single medium sand with alum alone as the coagulant, and at a flow rate of 7.3 m^3/hour/m^2 are presented in Figures 26 and 27. Turbidity values less than 0.5 NTU were achieved for 5 hours after system start up (Figure 26). During the first continuous filter operation, the filter plugged after 5 hours (Figure 26, Run #1). During the second continuous filtration experiment, the filter was operating for 9 hours (Figure 26, Run #2). The effluent turbidity standard of less than 1 NTU was achieved during the entire 9 hours. Nonetheless, virus breakthrough in the filter effluent was observed in the first sample (1 hour after the system start up). Figure 27 delineates

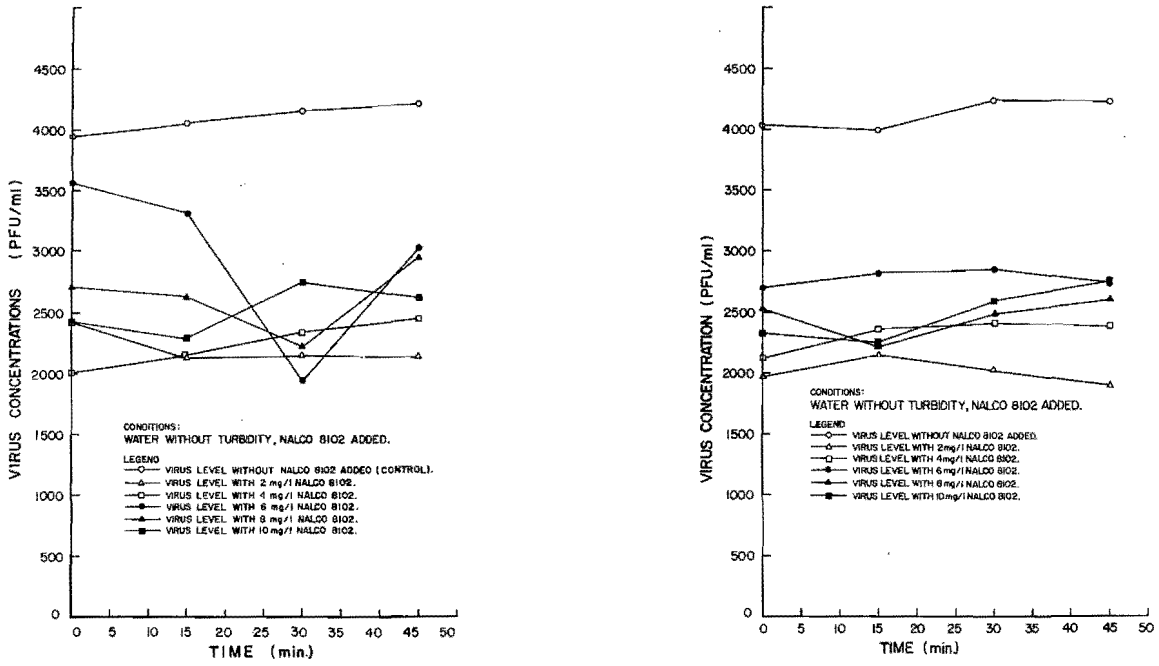


Figure 22. Effects of cationic polyelectrolyte, Nalco 8102, on virus contained in water without turbidity.

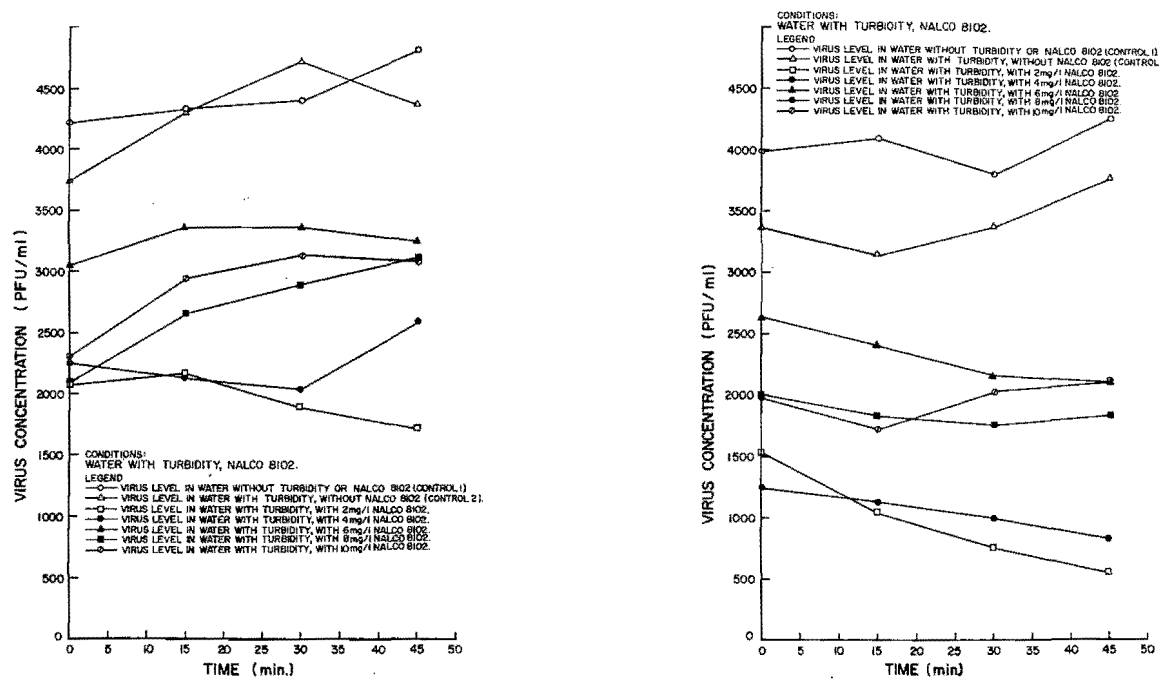


Figure 23. Effects of cationic polyelectrolyte, Nalco 8102, on virus contained in water with 14 NTU turbidity.

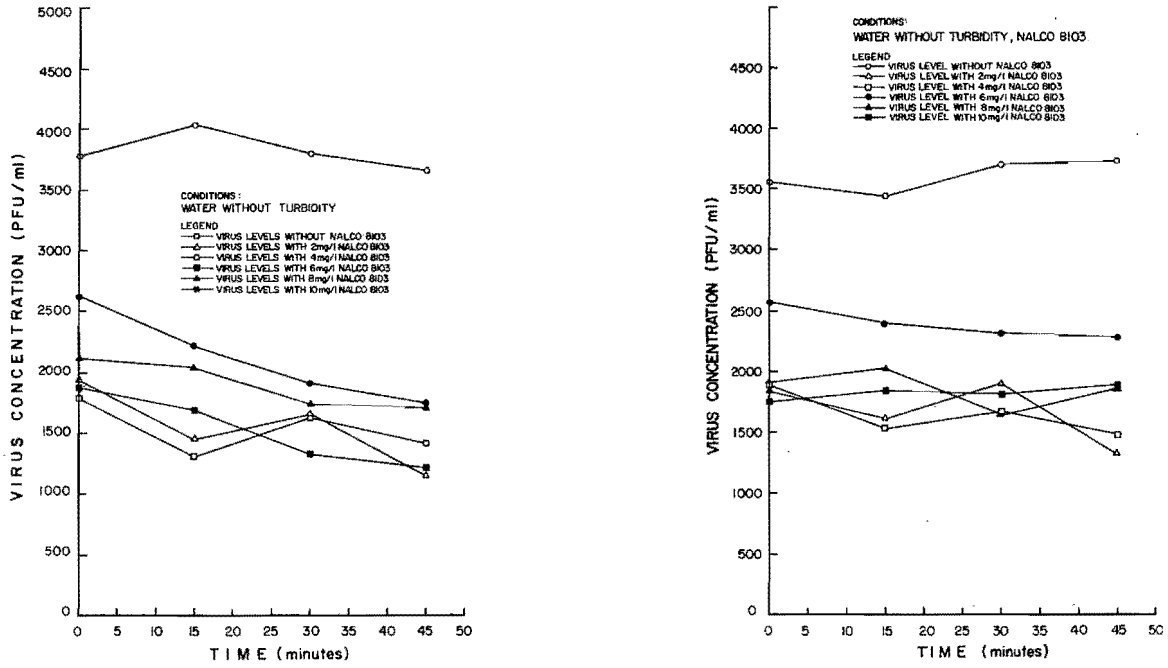


Figure 24. Effects of cationic polyelectrolyte, Nalco 8103, on virus contained in water without turbidity.

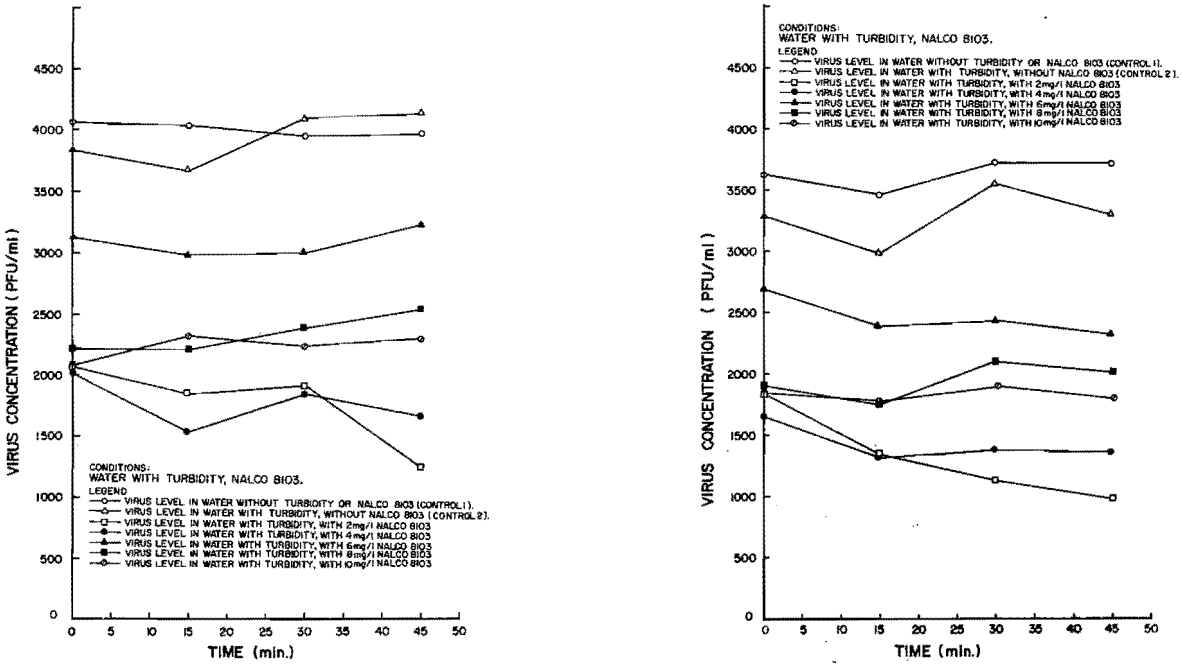


Figure 25. Effects of cationic polyelectrolyte, Nalco 8103, on virus contained in water with 14 NTU turbidity.

the differences between influent and effluent virus concentration over time. The first run in Figure 27 shows substantial virus removal (72 - 98 percent) while the second run shows relatively less (0 - 70 percent). The Duncan analysis showed significant difference between the influent and effluent virus concentrations over time. The Duncan analysis, however, may not be applied to the first run in Figure 27 due to the small number of data points. More data points were not obtained because of degradation in filter product water. Although Figure 27 showed virus removal by the sand filter, a meaningful average percentage was not established due to the high variability in the results between the two trials runs under the same conditions (Table 8).

The increase in the flow rate from 7.3 to 12.2 m^3/hour/m^2 did not change the effluent quality with respect to turbidity and virus (Figures 28 and 29). In one run, the effluent turbidity standard of less than 1 NTU was achieved during the first 5 hours (Figure 28, Run #2). In the other (Figure 28, Run #1), the sand filter met the effluent turbidity standard only during the first hour even though the filtration continued for 5 hours. The premature failure of the filter, during the first run, was due to supersaturation of the influent water with dissolved oxygen. At this column operation, the temperature of the influent was 14°C and dissolved oxygen was 20 mg/l. When supersaturated water enters the filter, if the head on the filter is less than the atmospheric pressure, oxygen bubbles are released and cause air binding. Air binding results in short circuiting and clogging of the filter, thus causing premature turbidity breakthrough.

Figure 29 shows virus removal by the sand filter at a flow rate of 12.2 m^3/hour/m^2. The Duncan analysis may not be applied to the results of either run due to the scarcity of data points. Virus removal in this experiment ranges from 39 to 96 percent (Table 9).

Figures 30 and 31 show the results when 2 mg/l of Nalco 8101 were added to the influent in addition to the 6 mg/l of alum. Alum was added in the rapid mix basin whereas Nalco 8101 was added just prior to filtration process, as prescribed by the Nalco Chemical Company (Salt Lake City). An initial high effluent turbidity (1.1 to 1.5 NTU) was observed, but 3 hours after the initiation of the operation the effluent turbidity decreased to less than 1 NTU (Figure 30). The initial high turbidity appeared to be the result of the excess of Nalco 8101 washout. Nalco 8101 was used to coat the filter media before each operation.

Figure 31 shows that reduction in virus concentration did not occur with Nalco 8101 as a coagulant aid. The contradiction in the virus removal results obtained by the jar tests and continuous filter runs was due to difference in treatment. In the jar test, Nalco 8101 was mechanically stirred with the virus (simulating rapid mix condition), whereas it was added just prior to filtration in the continuous runs. It may therefore be concluded that mechanical mixing is a very important factor in virus removal when Nalco 8101 is used.

Table 8. Virus removal by sand filter at 7.3 m^3/hour/m^2 flow rate.

Continuous Filter Operation Run Number	Time After Initiation of the Filter Operation (hour)	% Virus Removal
1	1	72
	3	98
	5	92
2	1	17
	3	0
	5	71
	7	24
	9	22

The turbidity profiles through the sand filter were typical of water treatment filters. Most of the turbidity accumulated in the top few centimeters (Figures 32, 33 and 34). The distribution of grain sizes for the sand medium after backwashing was from small to large. Removal resulted from the location of the smaller size grains in the top. It is very important, however, to bear in mind that filtration is not just a straining mechanism. It is a complex process involving attachment mechanisms such as electrostatic interactions, chemical bridging, or specific adsorption. All these mechanisms are affected by the coagulants used in the treatment system. Removal of floc within a bed is accomplished primarily by contact of the floc particles with the surface of the media or with floc already deposited thereon (Camp 1964). Contact is brought about by the convergence of streamlines, and by contractions in the pore channels and in the vicinity of curved surfaces of the media grains (Weber 1972).

Table 9. Virus removal by sand filter at a flow rate of 12.2 m^3/hour/m^2.

Trial	Time After Initiation of the Filter Operation (hour)	% Virus Removal
1	1	96
	3	92
2	1	55
	5	39

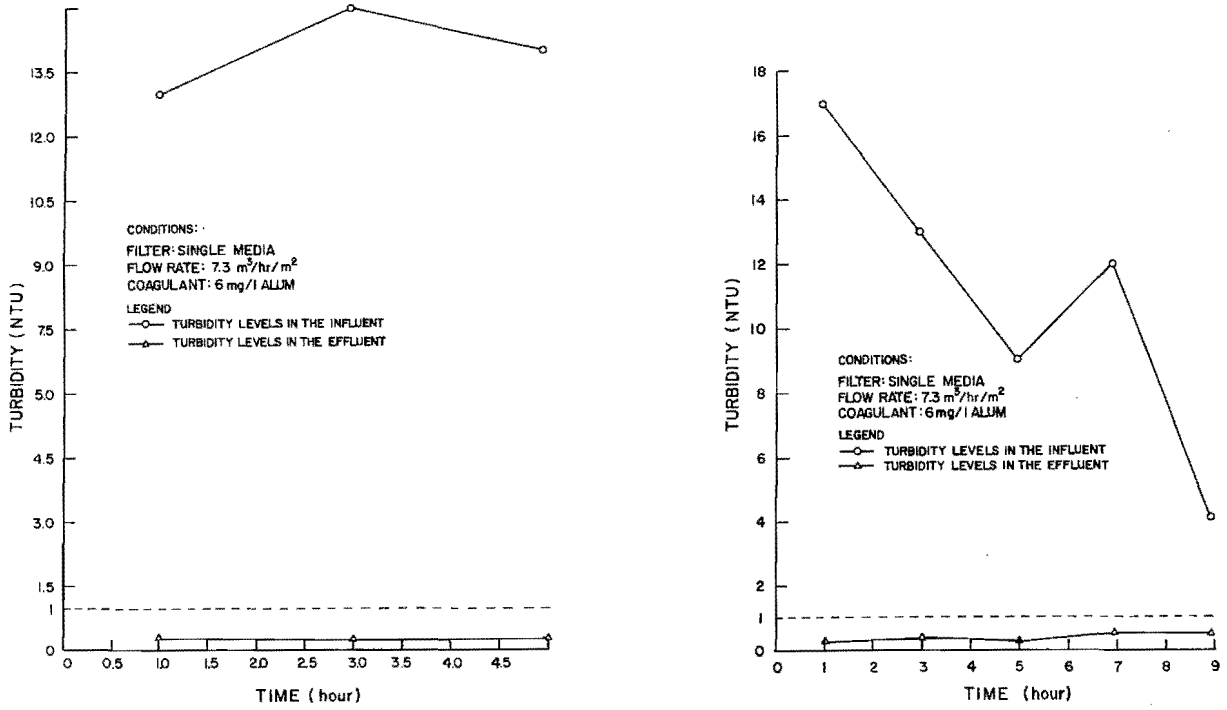


Figure 26. Influent and effluent turbidity measured during continuous filtration with sand medium experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

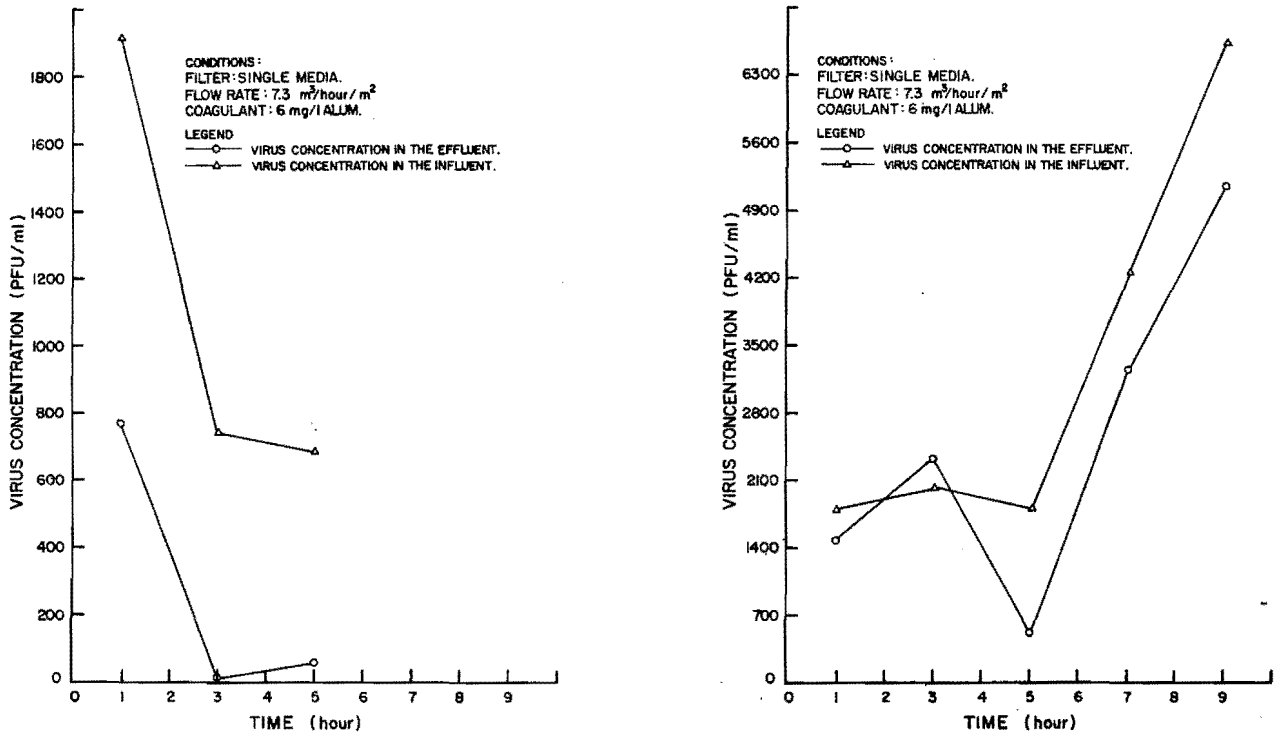


Figure 27. Influent and effluent virus concentrations measured during continuous filtration experiments with sand medium at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l of alum.

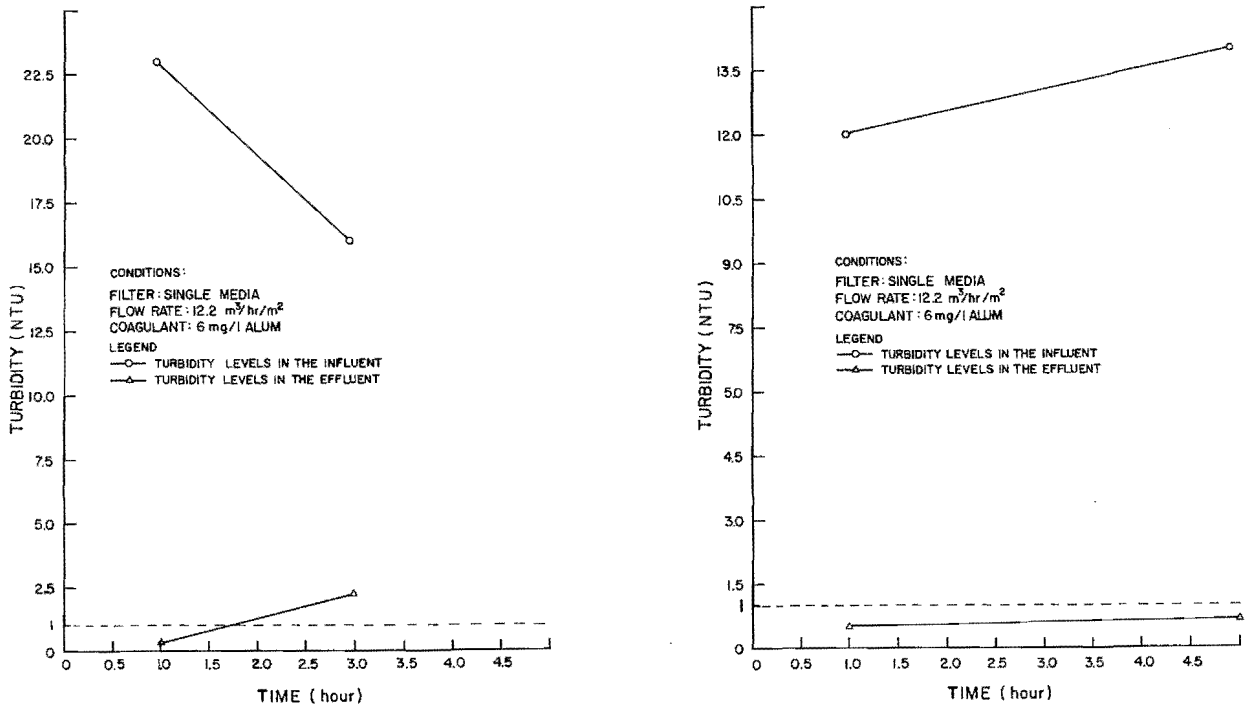


Figure 28. Influent and effluent turbidity measured during continuous filtration experiments with sand medium at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

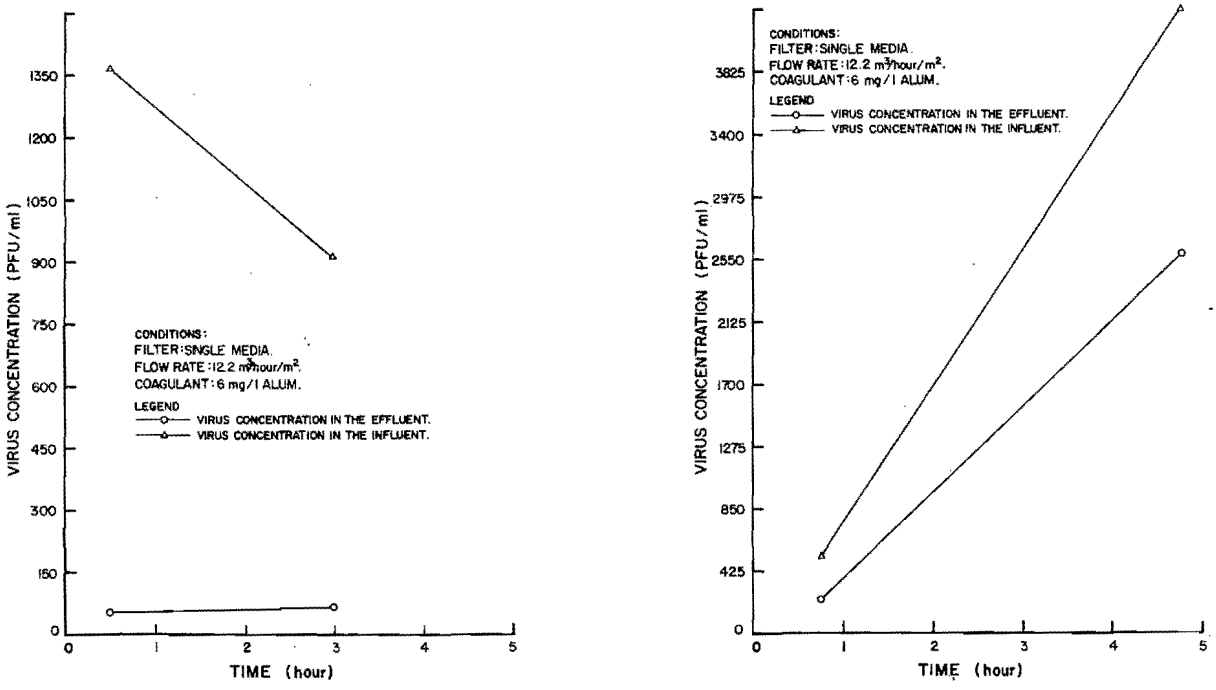


Figure 29. Influent and effluent virus concentrations measured during continuous filtration experiments with sand medium at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

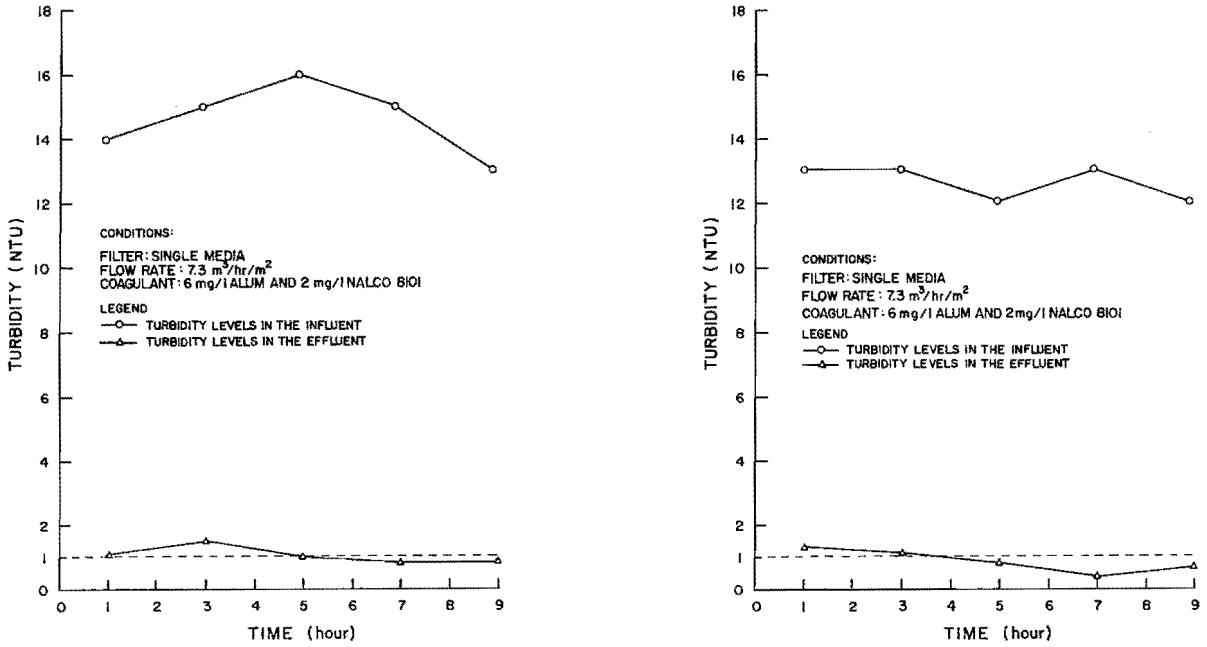


Figure 30. Influent and effluent turbidity measured during continuous filtration experiments with sand medium at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

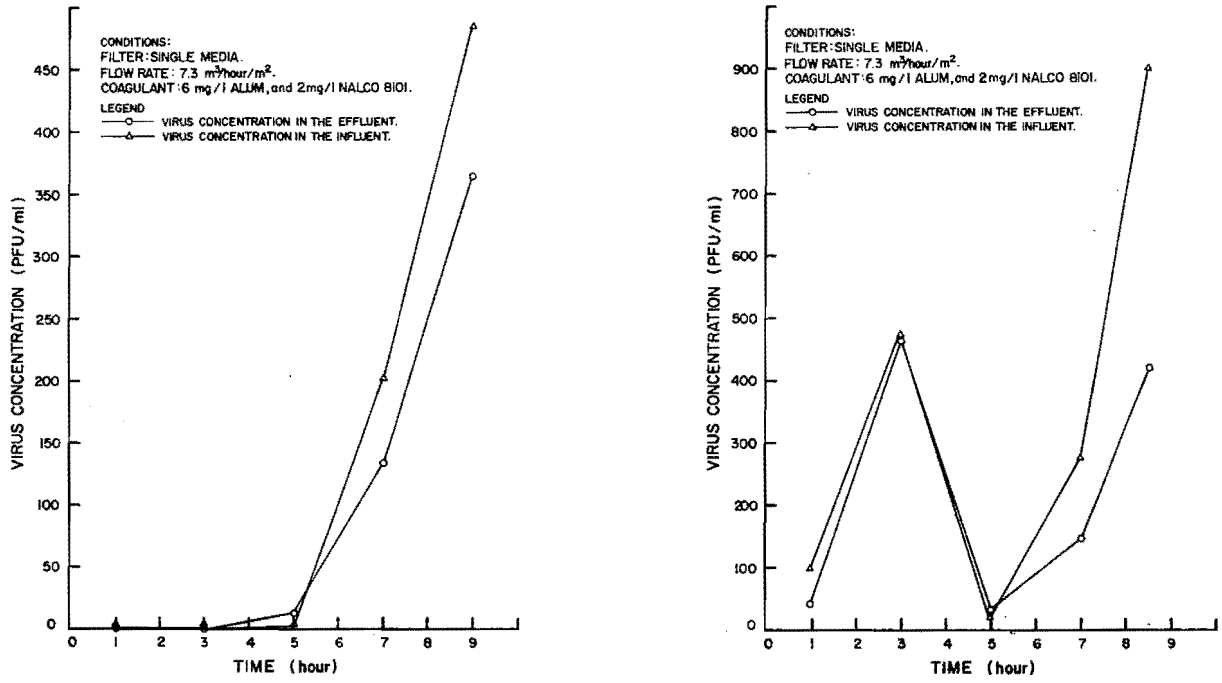


Figure 31. Influent and effluent virus concentrations measured during continuous filtration experiments with sand medium at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

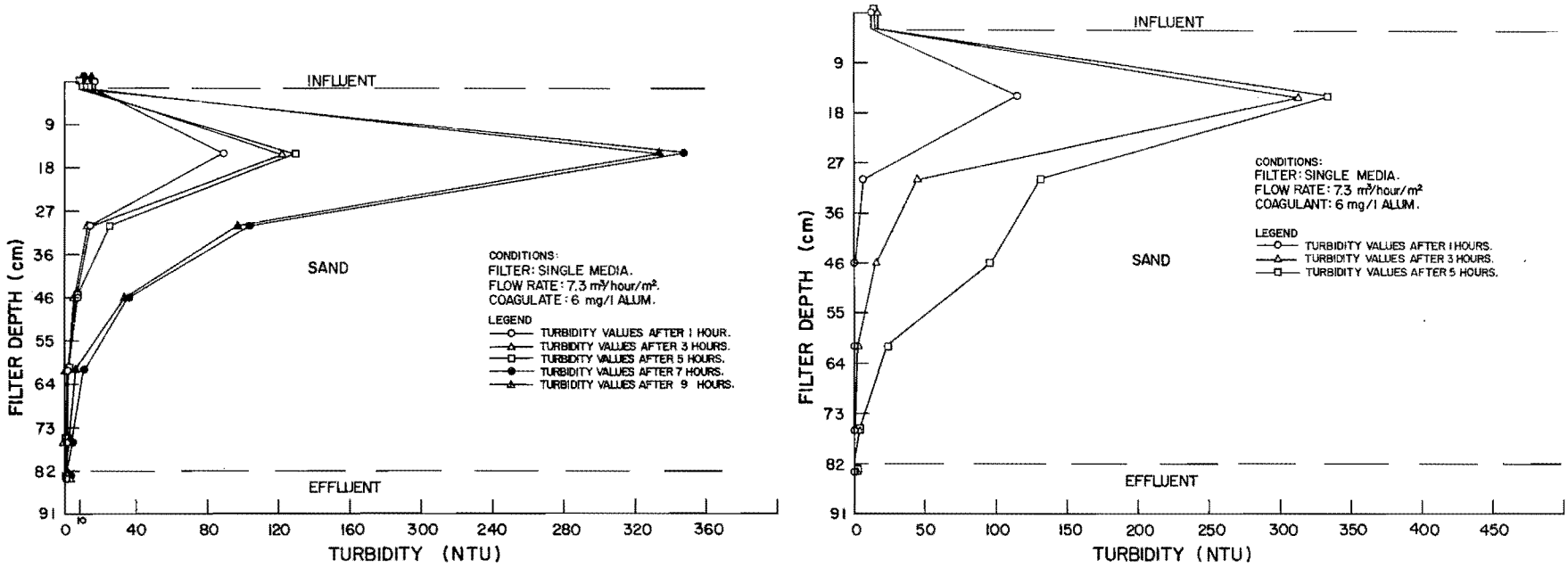


Figure 32. Turbidity profiles through sand filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

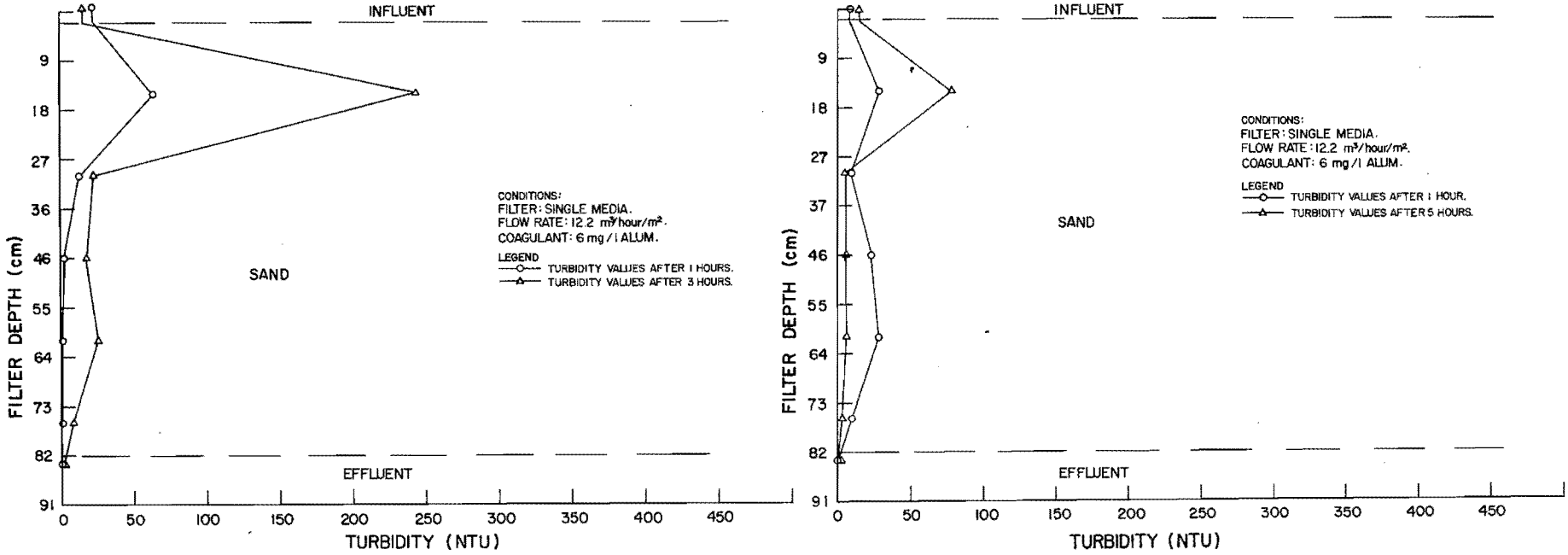


Figure 33. Turbidity profiles through sand filter at various times during continuous filtration experiments at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

The virus concentration profiles through the sand filter are presented in Figures 35, 36 and 37. These profiles are indicative of the pattern of movement of the virus through the filter media, however, some of the measured virus concentrations may be in error due to sampling procedure. The screened sample intake was located in the center of the column (Figure 2). Toggle valves were used to draw samples. Withdrawal of water samples may have influenced the fluid regime surrounding the sample intake screens. Hydraulic shear forces may have sheared off colloidal matter and the virus particles. The volume of the samples taken from each port was not more than 30 milliliters, nevertheless, hydraulic shearings of colloidal and virus particles were possible. Data, however, represent a relative amount of virus present through the filter profile.

At instances when significant virus removal was observed, the virus profiles followed the turbidity removal profiles closely (Figures 35, Run #1; 36, Run #1 except for effluent) in that most of the retained virus was in the top few centimeters of the sand filter column.

In summary, the sand filter met the effluent turbidity standard of less than 1 NTU at flow rates of 7.3 and 12.2 $m^3/hour/m^2$ (Figures 26 and 27) for a filtration period of 9 hours and 5 hours, respectively. Effluent quality, therefore, was not a function of hydraulic loading rate. Virus removal by the sand filter at the flow rates of 7.3 and 12.2 $m^3/hour/m^2$ (Tables 9 and 10) was independent of the flow rate. Furthermore, virus breakthrough was not related to turbidity breakthrough. Virus breakthrough was observed even though the effluent turbidity standard was met (Figures 27, 29 and 31).

Dual-media. Dual-media, anthracite and sand, filtation was also evaluated for its ability to remove virus. The results of the continuous pilot plant operations for the dual-media filter at a flow rate of 7.3 $m^3/hour/m^2$ are presented in Figures 39 and 40. The filter run lengths were predetermined 9-hour periods. Turbidity values less than 0.5 NTU were achieved (Figure 38). Figure 38 delineates the differences in the influent and effluent virus concentration over time. The Duncan analysis showed that there were no significant differences between the influent and effluent virus concentrations under the experimental conditions.

Table 10. Virus removal by sand filter at a flow rate of 12.2 $m^3/hour/m^2$.

Trial	Time After Initiation of the Filter Operation (Hour)	% Virus Removal
1	1	96
	3	92
2	1	55
	5	39

An increase in flow rate from 7.3 to 12.2 $m^3/hour/m^2$ did not deteriorate the effluent quality with respect to turbidity (Figure 40, Run #2). The dual-media filter was operating for 35 hours. The effluent turbidity less than 0.5 NTU, however, was achieved only during the first 9 hours. The influent turbidity in Figure 40, Run #2 fluctuated greatly (8 to 32 NTU) which may have shortened the operation length during which effluent quality standard was met.

Figure 40, Run #1 showed that the dual-media filter met the effluent turbidity standard of less than 1 NTU only during the first hour after the initiation of the filter operation. The filter plugged after 9 hours (far short of the 35 hours of second run). The premature failure of the filter, during the first run, was due to supersaturation of the influent water with dissolved oxygen as explained previously in the single-medium (sand) section. Run #1 is not, therefore, representative of the dual-media filter performance at a flow rate of 12.2 $m^3/hour/m^2$. Figure 41, Run #2 showed that significant virus removal was not achieved by the dual-media filter in this experiment. Duncan analysis may not be used to determine the significance of the reduction achieved in Run #1 because not enough data points were available, but superficial inspection of the results suggests that much greater reduction was achieved than in Run #2.

When Nalco 8101 was used as a coagulant aid, the initial effluent turbidity exceeded 1 NTU (1.3 to 1.9 NTU) in the first continuous filter operation (Figure 42, Run #1). The initial high finish water turbidity in the first run was due to Nalco 8101 washout as explained previously. The second filter operation (Figure 41, Run #2), however, met the effluent turbidity standard of less than one during the entire filter operation. Both filtration run lengths were terminated after the predetermined 9-hour period. The Duncan analysis showed that there were no significant differences between the influent and the effluent virus concentrations (Figure 43).

The failure of Nalco 8101 to decrease virus concentration in the continuous filter operation again contrasted with the results of the jar test. In the jar test the Nalco 8101 was mechanically mixed with the virus whereas in procedures outlined by the Nalco Chemical Company, the cationic polyelectrolyte was introduced immediately preceding the filtration process.

All three tests showed that the dual-media filter was not efficient in removing virus from water during continuous operation. Even though anthracite removed 93 percent

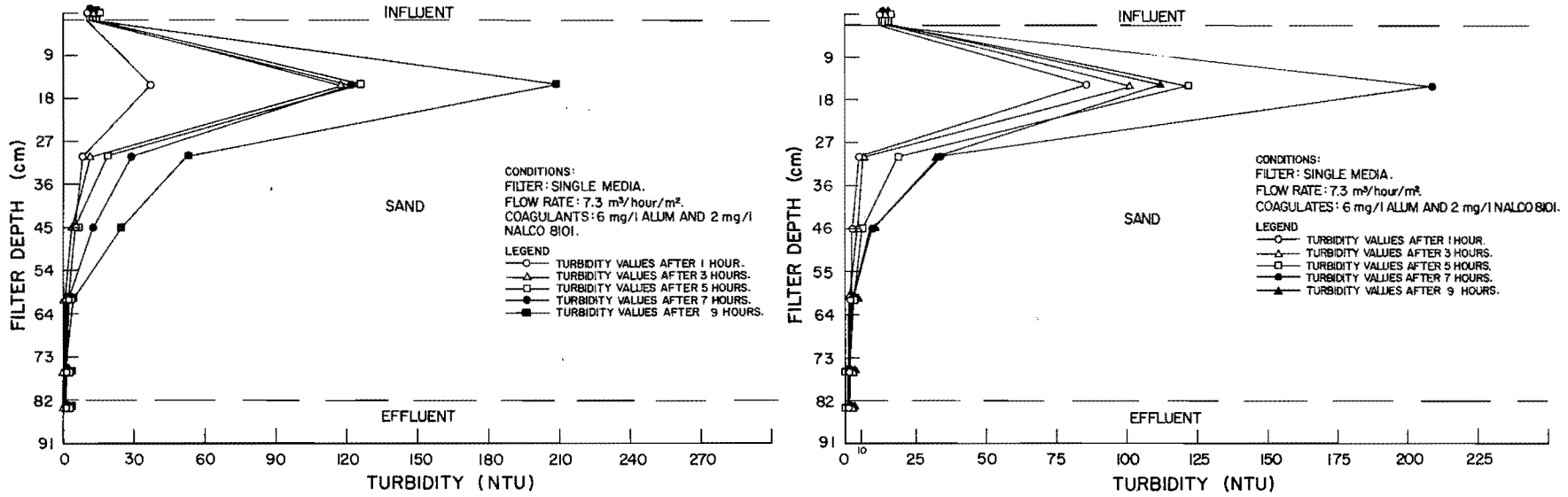


Figure 34. Turbidity profiles through sand filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

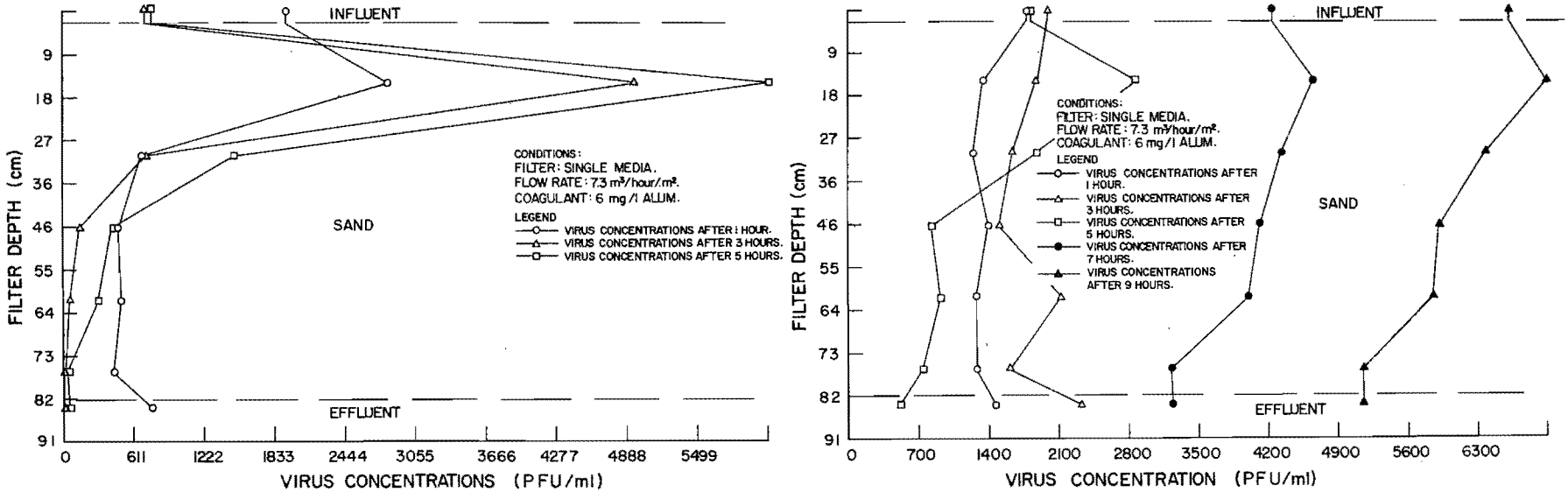


Figure 35. Virus concentration profiles through sand filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

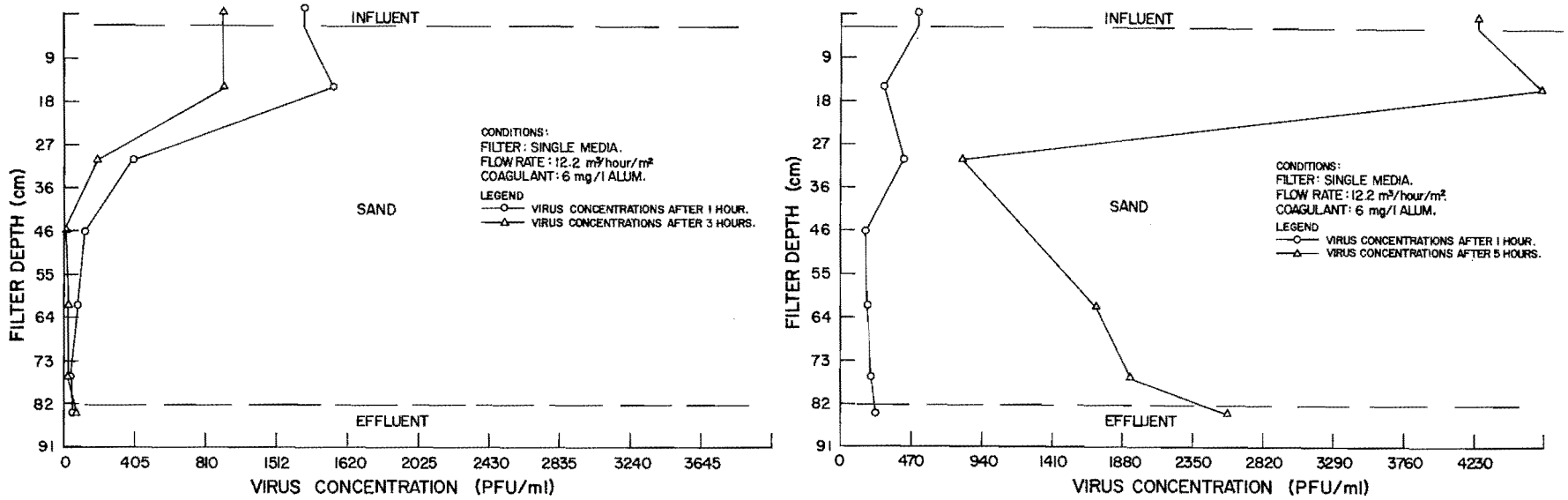


Figure 36. Virus concentration profiles through sand filter at various times during continuous filtration experiments at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

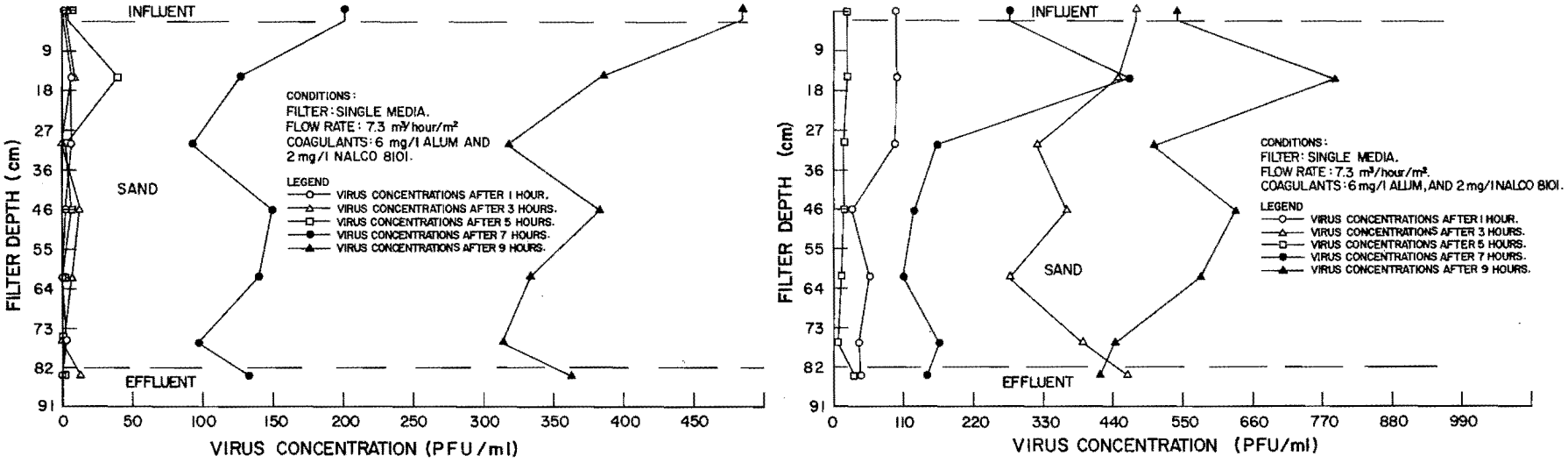


Figure 37. Virus concentration profiles through sand filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

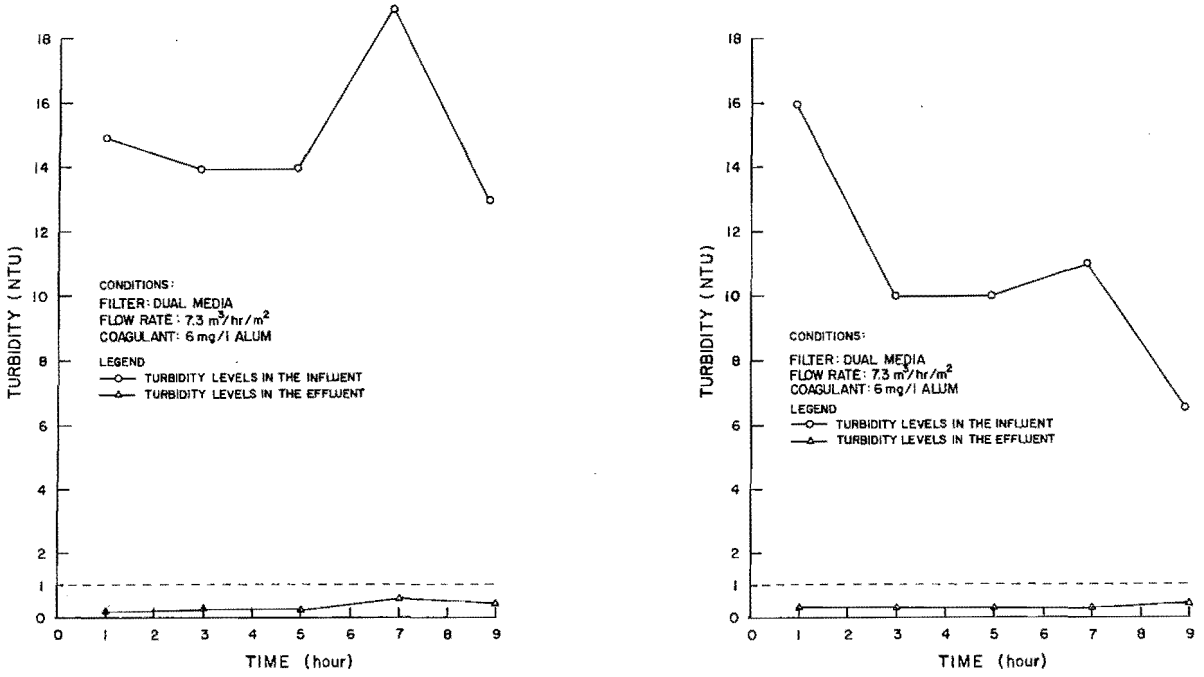


Figure 38. Influent and effluent turbidity measured during continuous filtration experiments with dual media at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

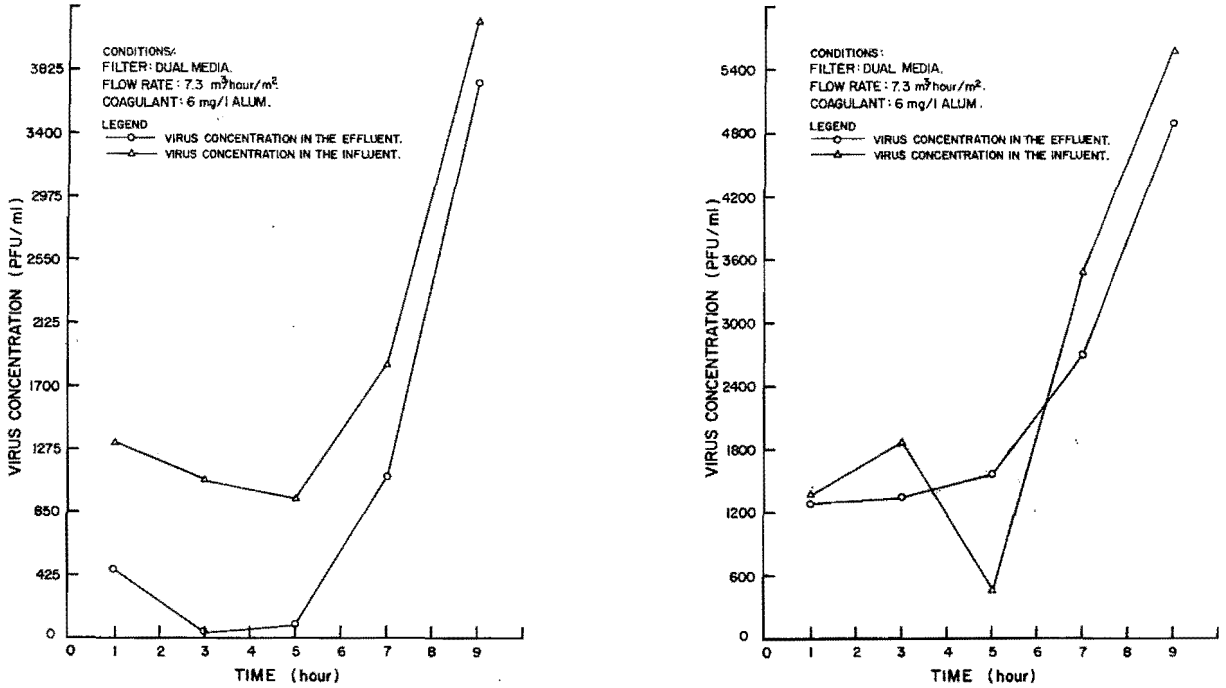


Figure 39. Influent and effluent turbidity measured during continuous filtration experiments with dual media at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

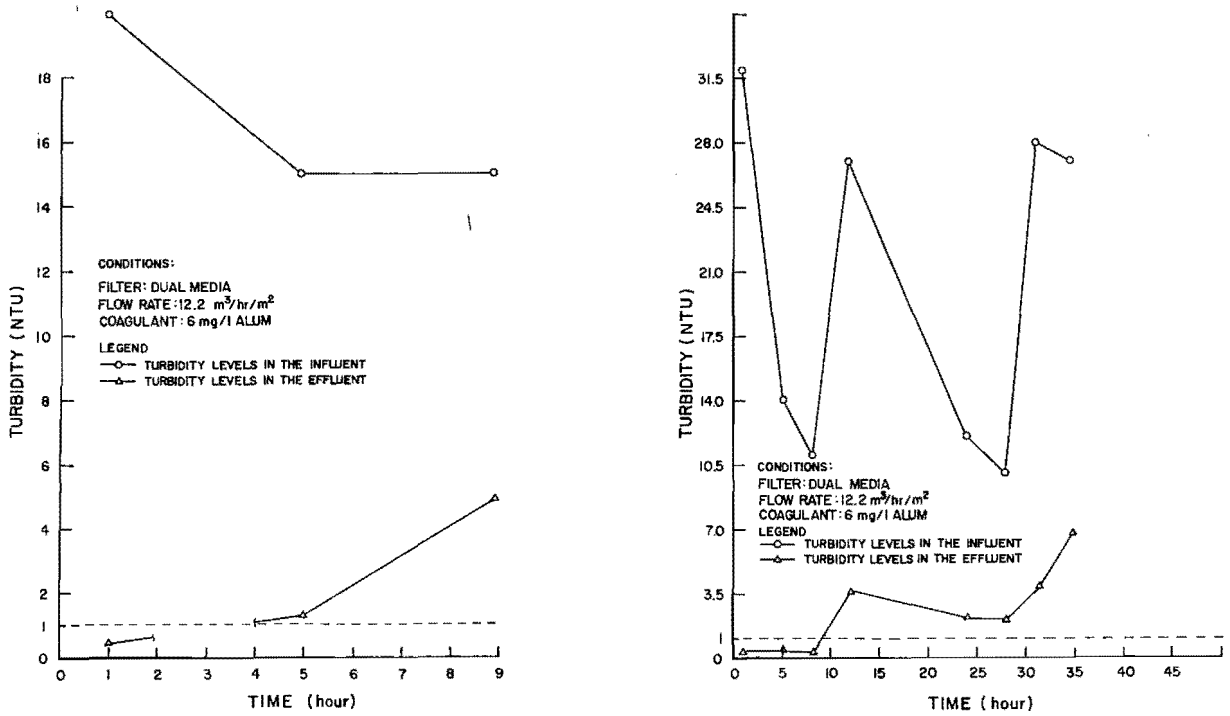


Figure 40. Influent and effluent turbidity measured during continuous filtration experiments with dual media at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

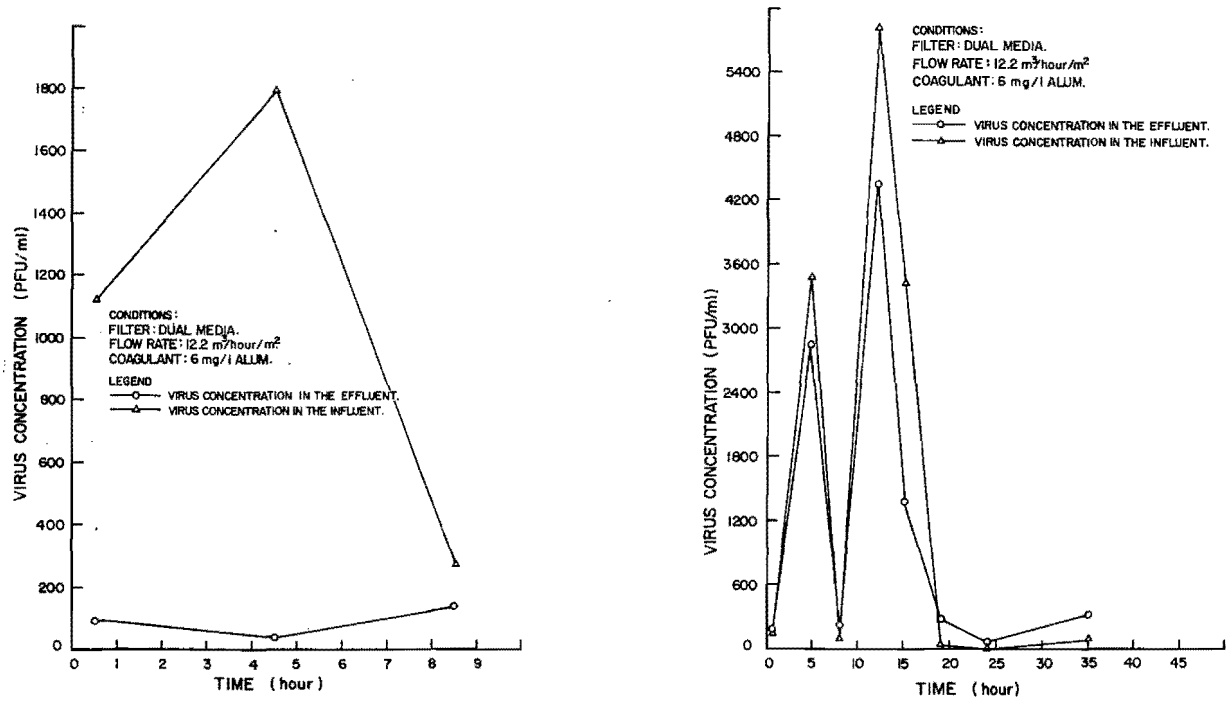


Figure 41. Influent and effluent virus concentrations measured during continuous filtration experiments with dual media at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

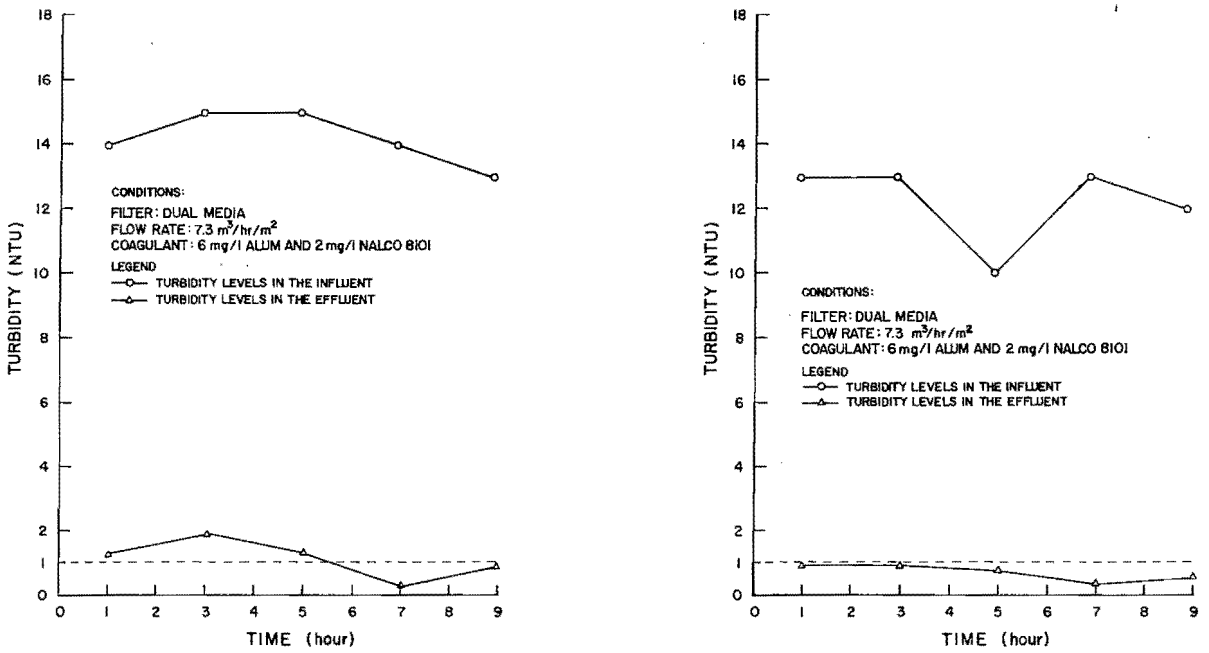


Figure 42. Influent and effluent turbidity measured during continuous filtration experiments with dual media at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

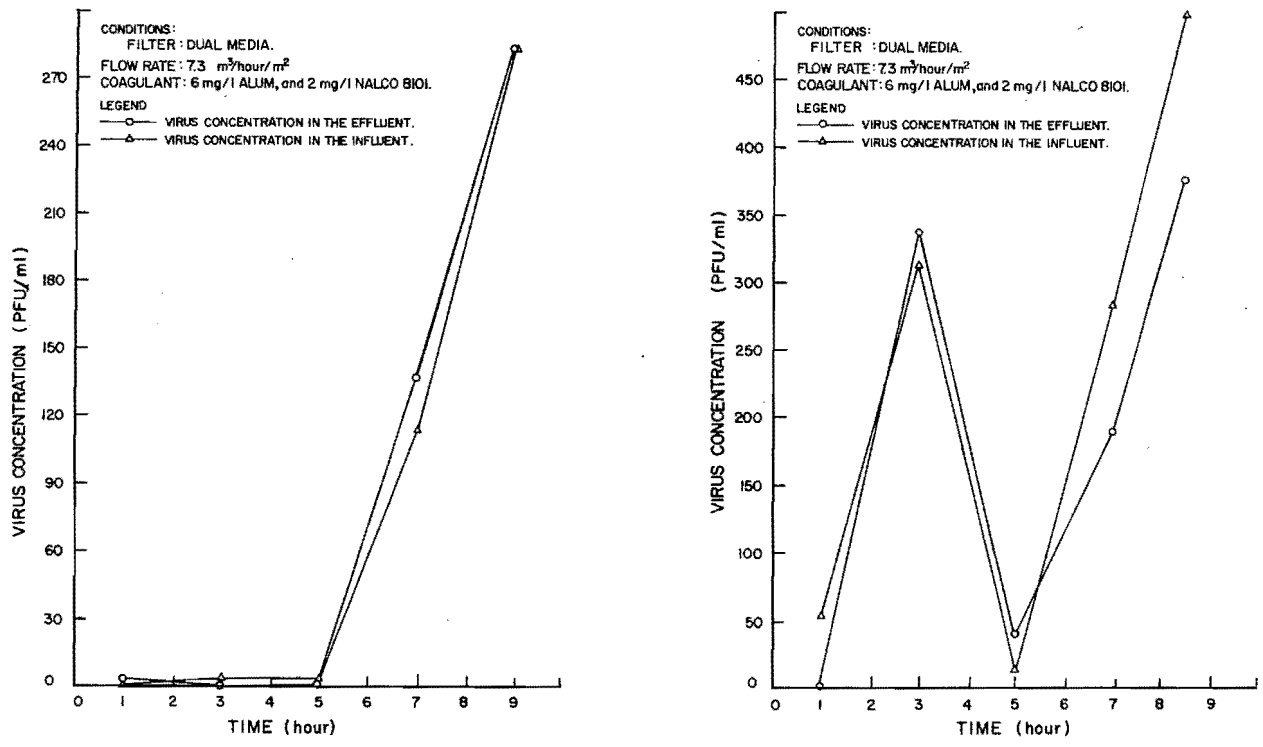


Figure 43. Influent and effluent virus concentrations measured during continuous filtration experiments with dual media at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

of the virus from water in the isotherm studies, the virus removal was kinetically limited. The failure of the virus to adsorb to the anthracite in the pilot-plant filtration study may have been due to the short contact time between the virus and the media. Shear forces caused by the flow velocity through pores may have also hindered adsorption.

The turbidity profiles through the dual-media filter showed that the turbidity removal occurred at the top of the filter and at the interface between anthracite and sand due to grain size changes (Figures 44, 45 and 46). The distribution of grain sizes for each medium after backwashing was from small to large. A certain degree of intermixing between the dual-media was observed with the amount depending on the density and size differences of the two media. Due to the higher porosity of the anthracite on top, the dual-media beds allow the suspended solids to penetrate further into the filter bed and thus use more of the solid-storage capacity available within the filter. The turbidity removal mechanism involves electrostatic interactions, chemical bridging, or specific adsorption as previously explained (Weber 1972).

Figures 47, 48 and 49 represent the virus concentration profiles through the dual-media. The general observation with the dual-media was that virus accumulation, as with turbidity accumulation, within the filter was observed in the anthracite layer and at the interface between the anthracite coal and sand (Figures 47, Run #1; 48, Run #1).

In summary, the dual media filter produced high effluent quality with respect to turbidity. At a flow rate of 12.2 m^3/hour /m^2 the dual-media filter met the water quality standard of less than 1 NTU for 9 hours whereas the sand filter met the standard for 5 hours. The difference between sand and dual-media filter operation lengths at flow rates of 7.3 m^3/hour/m^2 cannot be determined because all operations were terminated at a predetermined period of 9 hours. Furthermore, turbidity and virus removal by the dual-media was not a function of hydraulic loading rate. Dual-media filter did not show any significant virus removal.

Tri-media filter. Results obtained from the tri-media filter experiments were similar to those obtained for the dual-media filter with respect to turbidity and virus removal. Figures 50 and 51 show the results of turbidity and virus removal over time at a flow rate of 7.3 m^3/hour/m^2. Effluent turbidity of less than 0.4 NTU was achieved during the continuous filter operation for the predetermined run lengths of 9 hours. Although influent turbidity fluctuations (6 to 17 NTU) were observed in the first run, it did not affect the effluent quality (Figure 50, Run #1). Significant virus removal did not occur during this experiment (Figure 51).

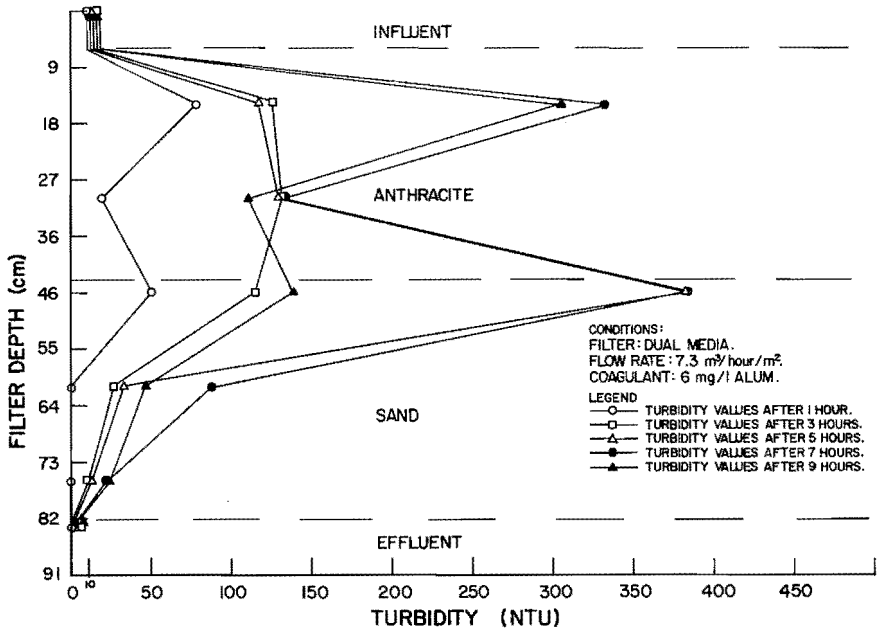
An increase in the flow rate from 7.3 to 12.2 m^3/hour/m^2 did not change the effluent quality with respect to both virus and turbidity (Figures 52 and 53). Figure 52, Run #1 may not be representative of the tri-media performance at 12.2 m^3/hour/m^2 loading rate. During this filter operation run, air binding occurred which resulted in premature turbidity breakthrough and short operation length as explained previously. During the second filter operation, however, effluent turbidity of less than 0.4 NTU was produced for 9 hours. There was no significant difference between the influent virus concentrations and effluent virus concentrations (Figure 55). A Type II statistical error may have occurred in Run #1 due to limited data (3 points). A Type II error results when the null hypothesis is assumed valid when it is not.

Figures 54 and 55 delineate the results when 2 mg/1 of Nalco 8101 was added to the influent water in addition to the 6 mg/1 of alum. Figure 54, Run #1 showed high effluent turbidity above 1 NTU (1.2 to 1.8 NTU) during the first 5 hours after the system start up, whereas the second operation run showed high effluent turbidity only during the first hour. The observed high turbidity was due to the excess Nalco 8101 washout as explained previously. Figure 55 shows the results of virus removal in this experiment. The failure of Nalco 8101 to decrease virus concentration in the continuous filter operation, was again due to the difference in the application procedure as explained previously.

The turbidity profiles in Figures 56, 57 and 58 show that most of the turbidity removal occurred in the upper few centimeters of the filter and at the interfaces between anthracite and sand due to grain size changes. As discussed previously, the distribution of grain sizes for each medium after backwashing was from small to large. A certain degree of intermixing in the tri-media beds was observed. Intermixing was dependent on the density and size differences of the various media. Filtration mechanism, however, is not simply due to straining mechanism but it involves electrostatic interactions, chemical bridging or specific adsorption.

Figures 59, 60 and 61 represent the virus profiles through the tri-media filter. The general observation was the same as for the sand and dual-media filters. Increases in virus concentrations occurred in the anthracite coal (Figure 60, Run #1).

In summary, the performance of the tri-media filter was very similar to dual-media filter. The tri-media met the effluent turbidity standard of less than 1 NTU for 9 hours at 12.2 m^3/hour/m^2 loading rate. At a flow rate of 7.3 m^3/hour/m^2, it also met the standard during the predetermined filter operation length of 9 hours. The



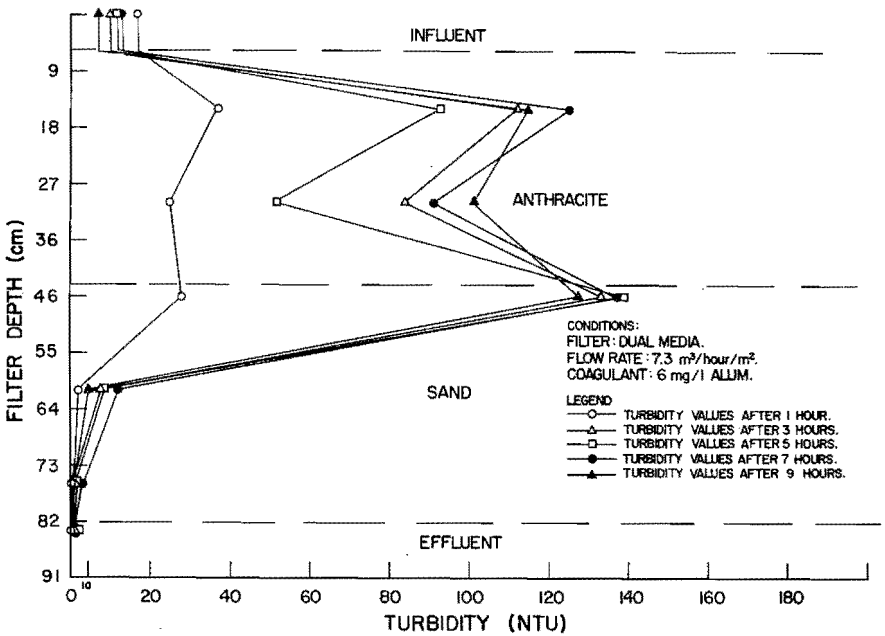
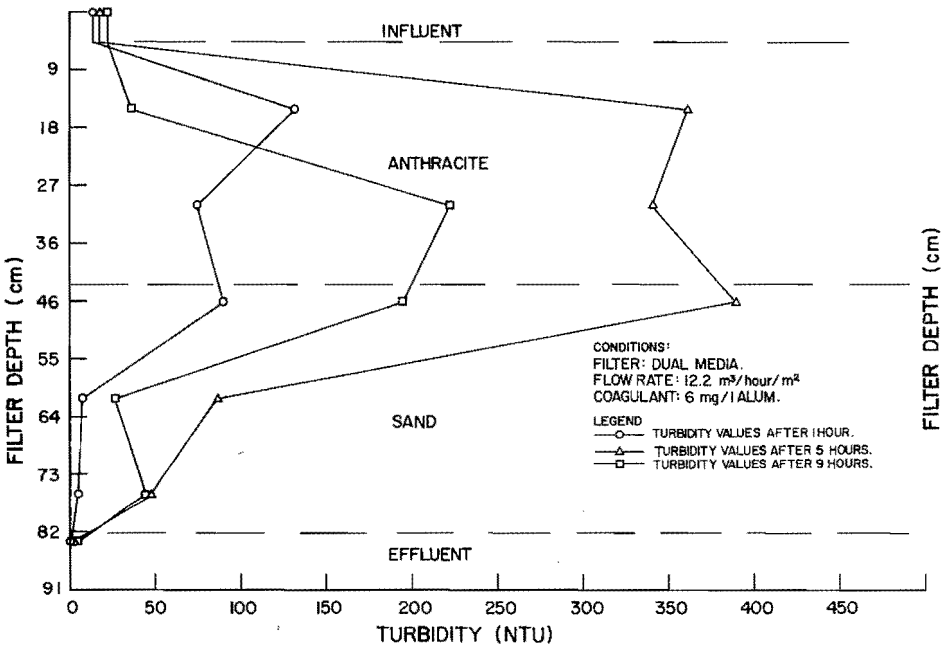


Figure 44. Turbidity profiles through dual media filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.



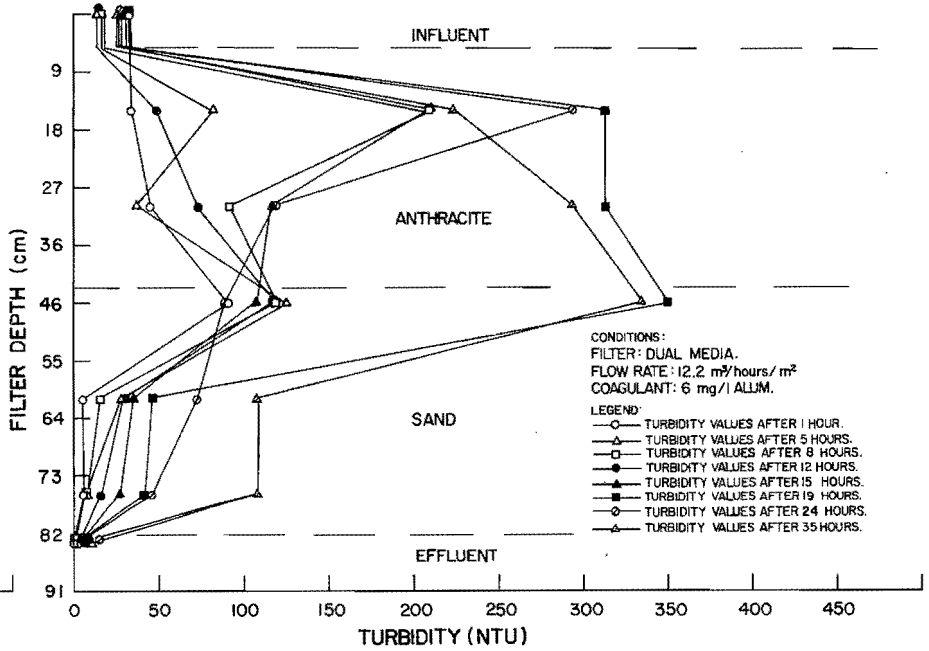


Figure 45. Turbidity profiles through dual media filter at various times during continuous filtration experiments at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

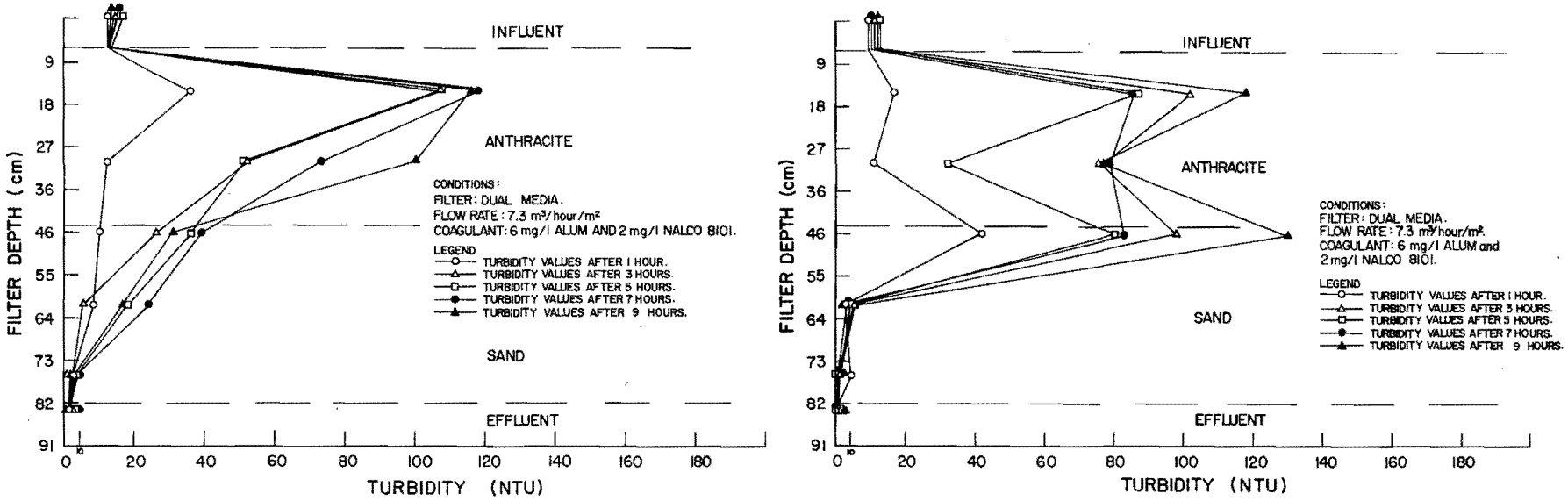


Figure 46. Turbidity profiles through dual media filter at variou times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

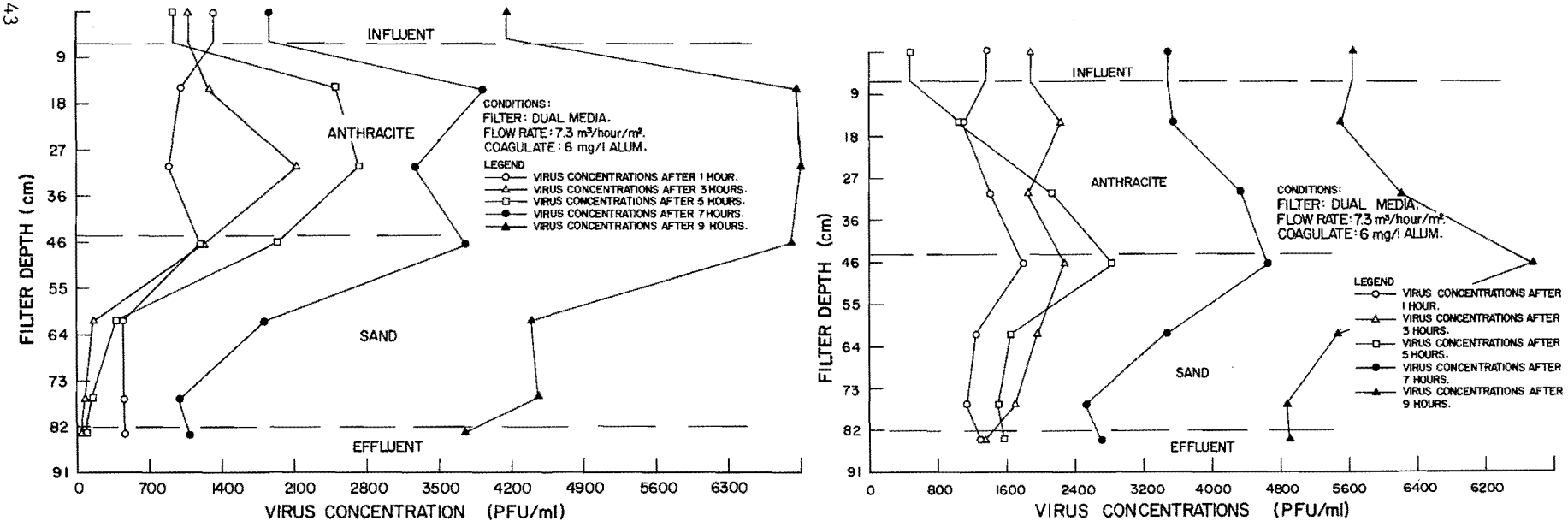


Figure 47. Virus concentration profiles through dual media filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

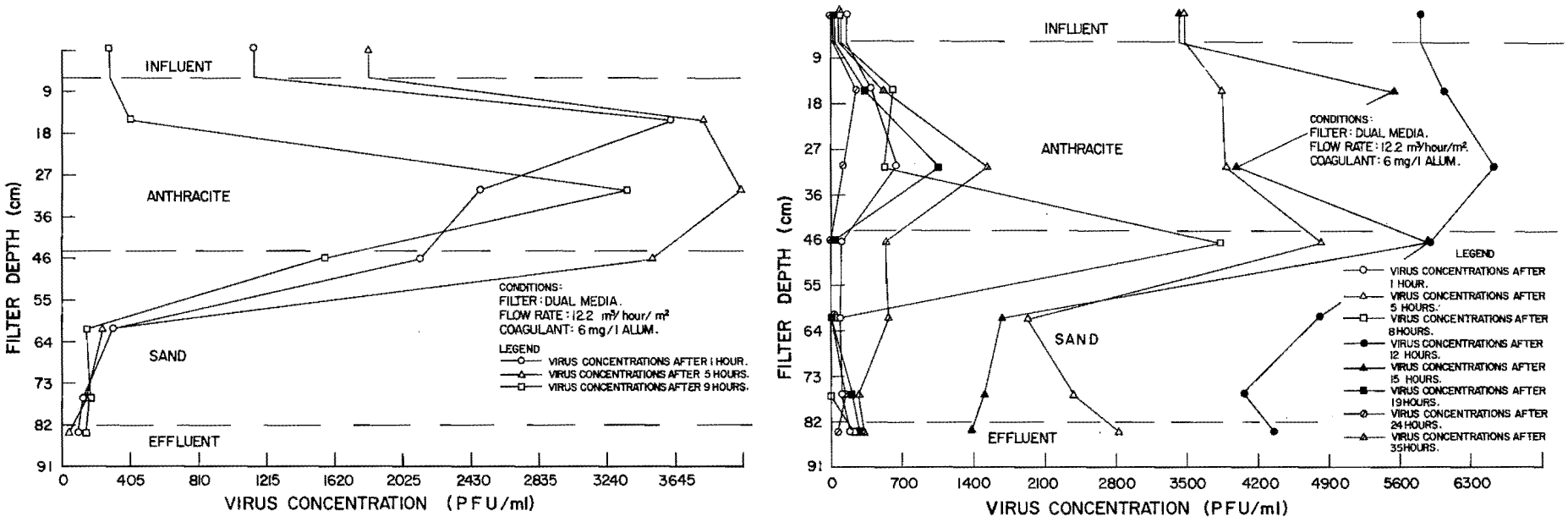


Figure 48. Virus concentration profiles through dual media filter at various times during continuous filtration experiments at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

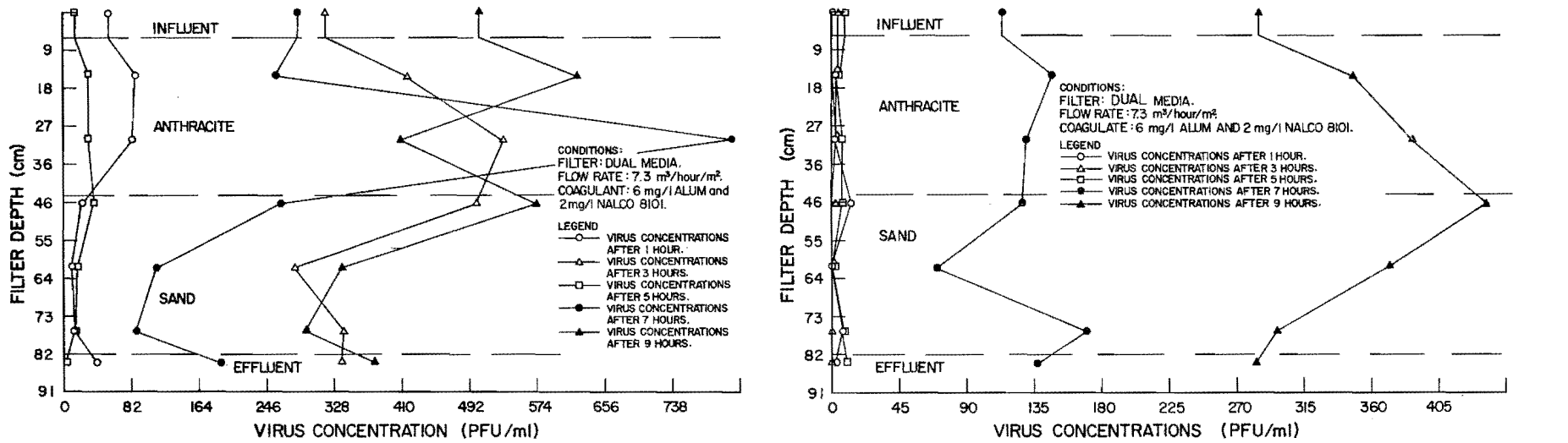


Figure 49. Virus concentrations through dual media filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

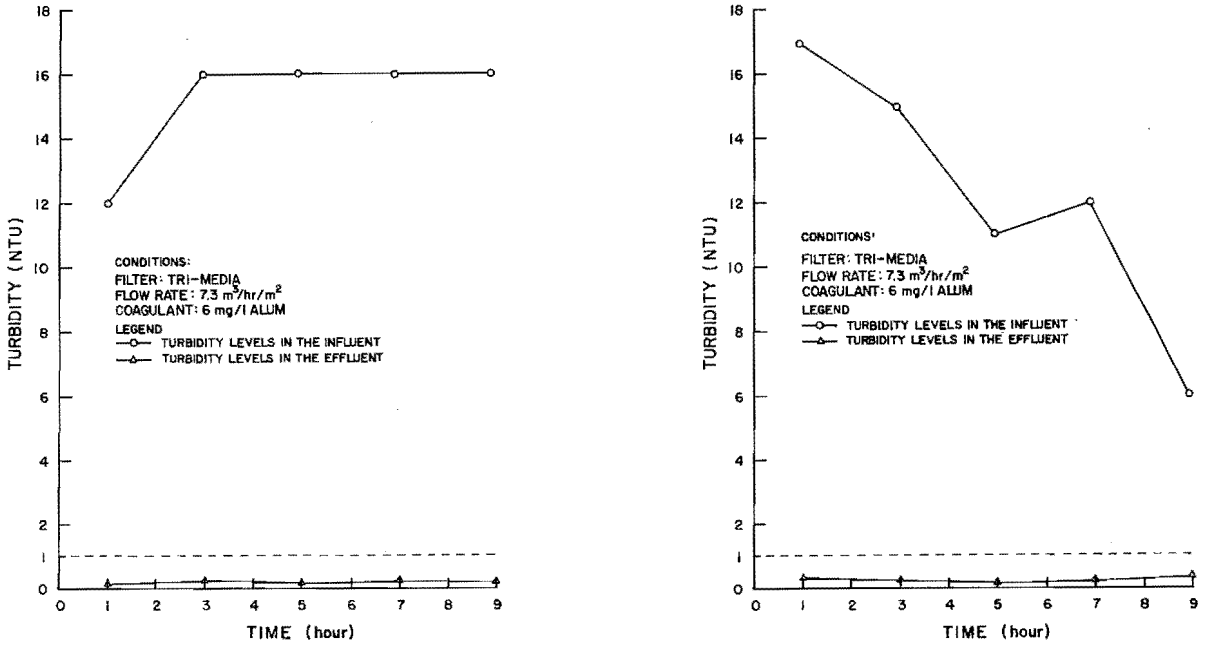


Figure 50. Influent and effluent turbidity measured during continuous filtration experiments with tri-media at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

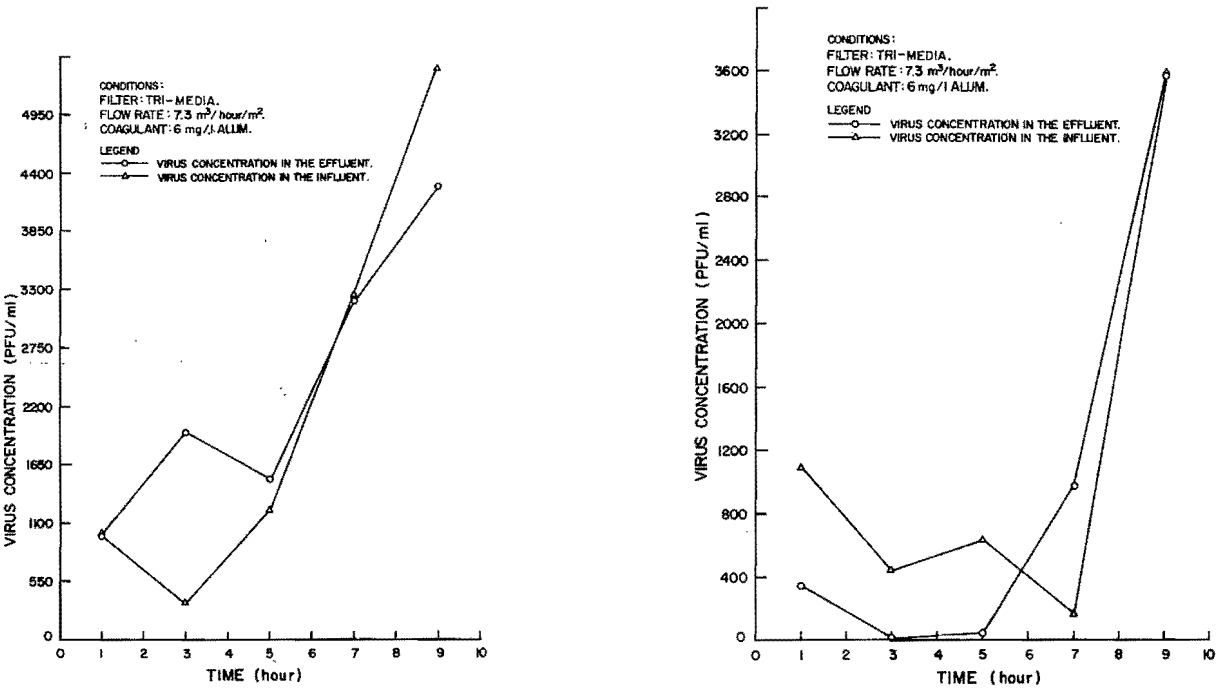


Figure 51. Influent and effluent virus concentrations measured during continuous filtration experiments with tri-media at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

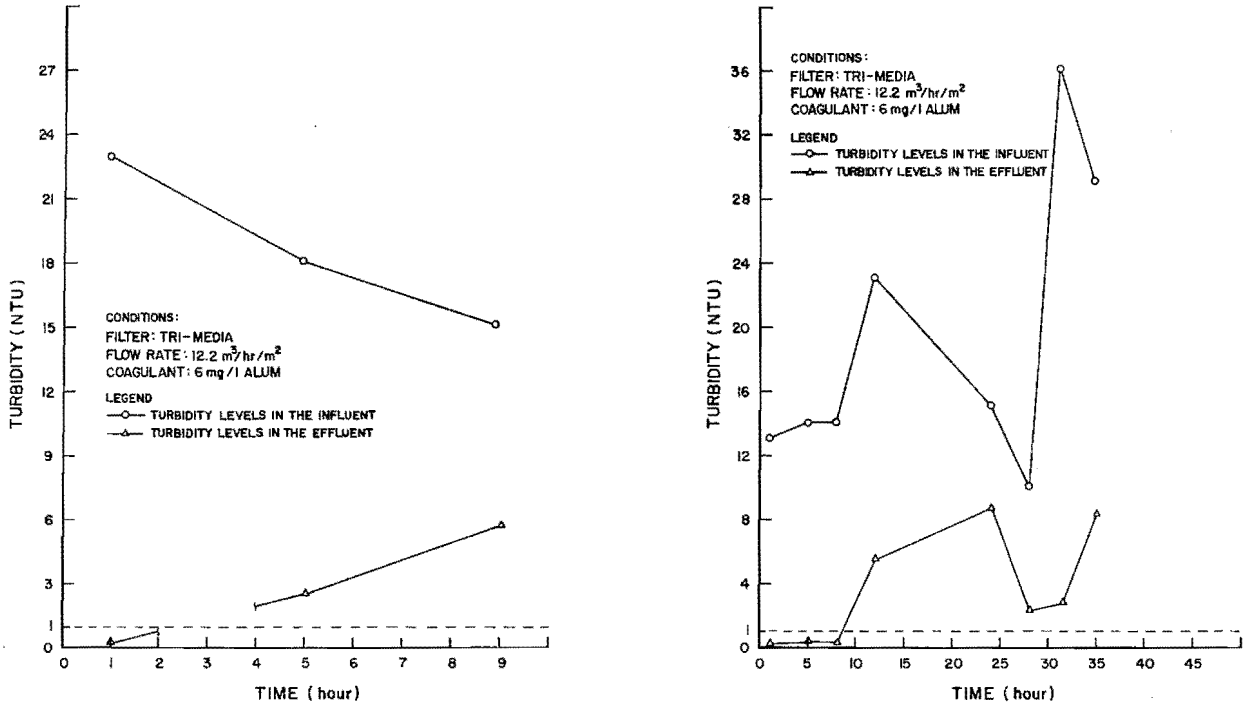


Figure 52. Influent and effluent turbidity measured during continuous filtration experiments with tri-media at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

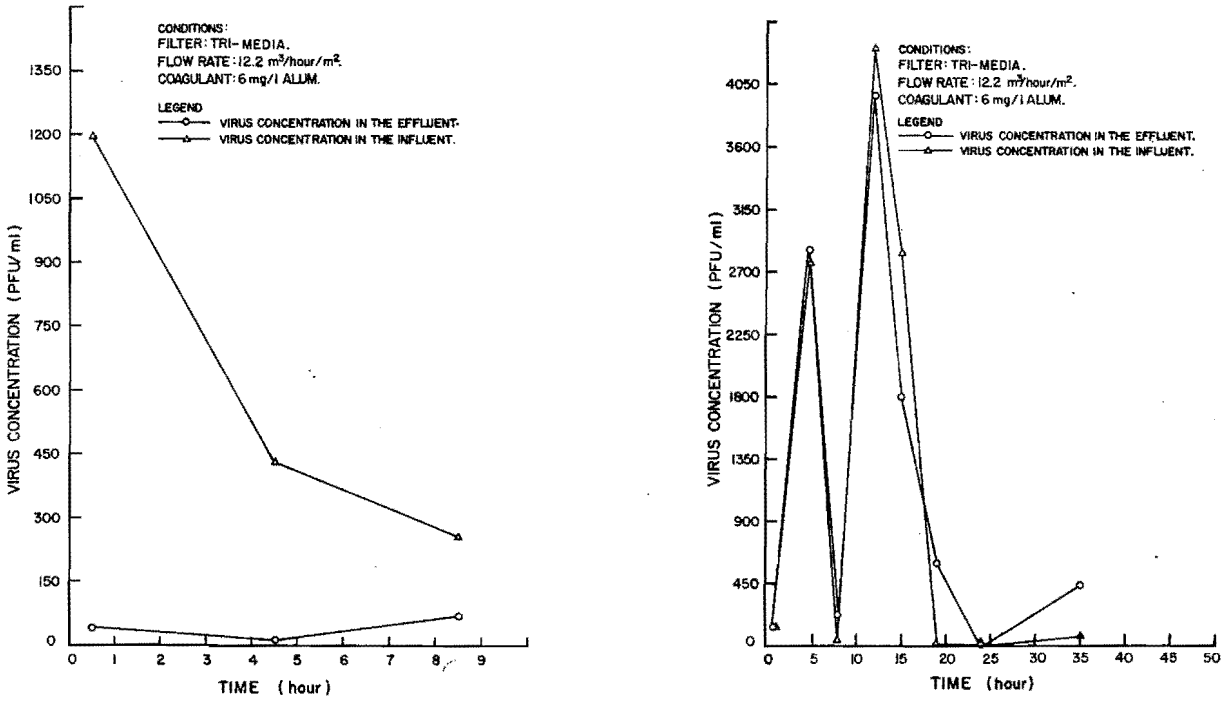


Figure 53. Influent and effluent virus concentrations measured during continuous filtration experiments with tri-media at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

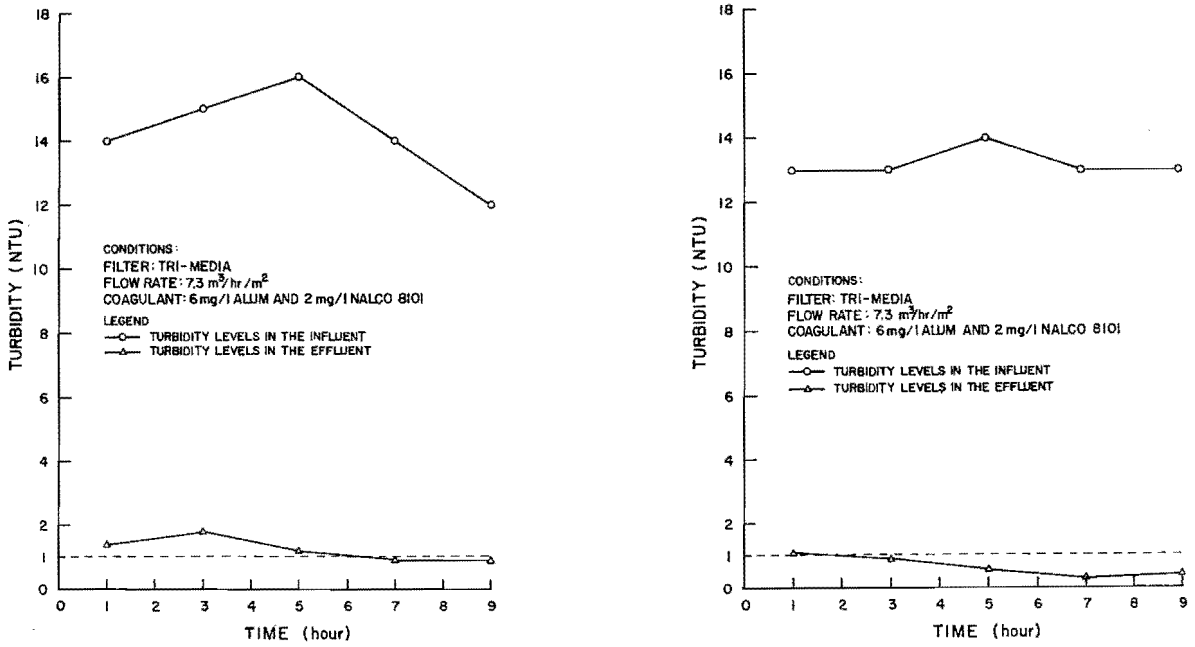


Figure 54. Influent and effluent turbidity measured during continuous filtration experiments with tri-media at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

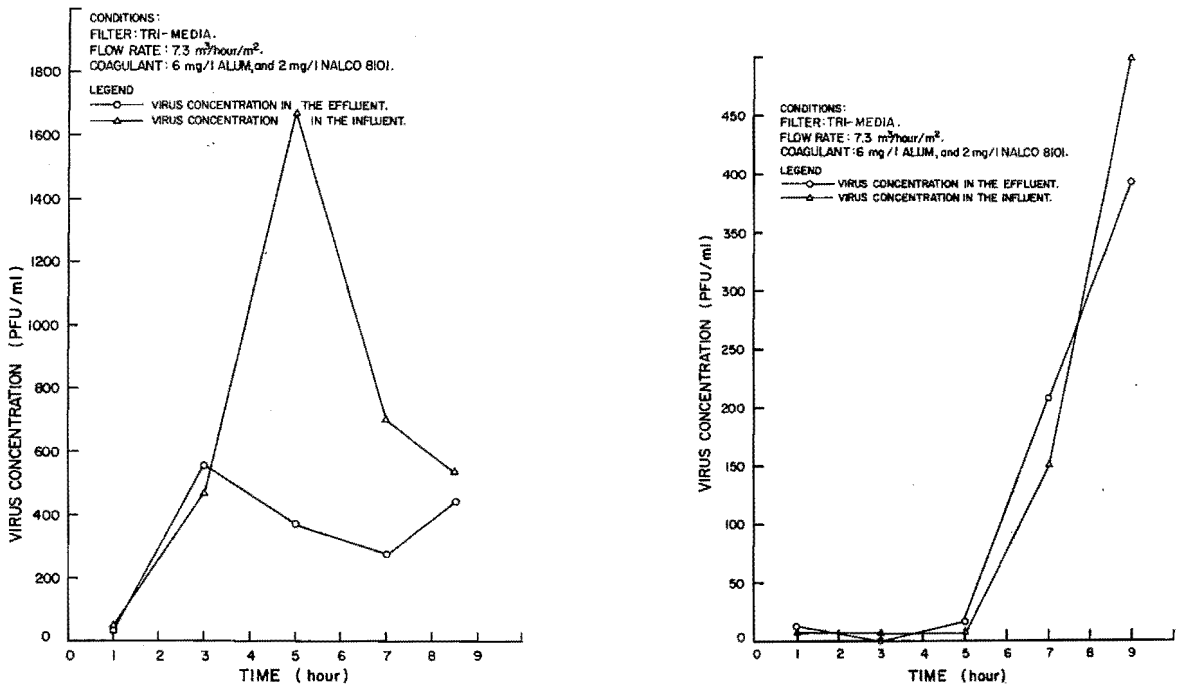
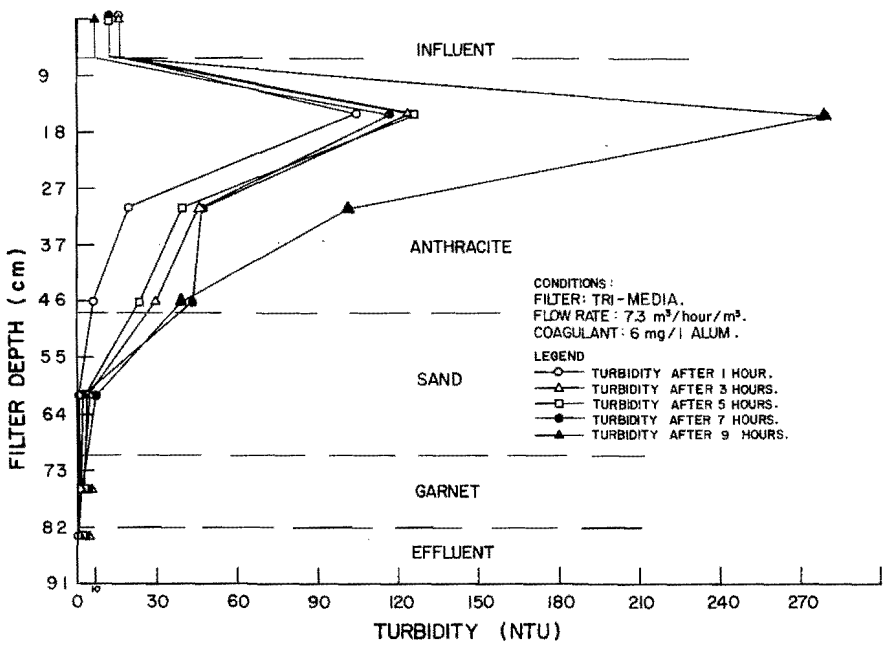


Figure 55. Influent and effluent virus concentrations measured during continuous filtration experiments with tri-media at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.



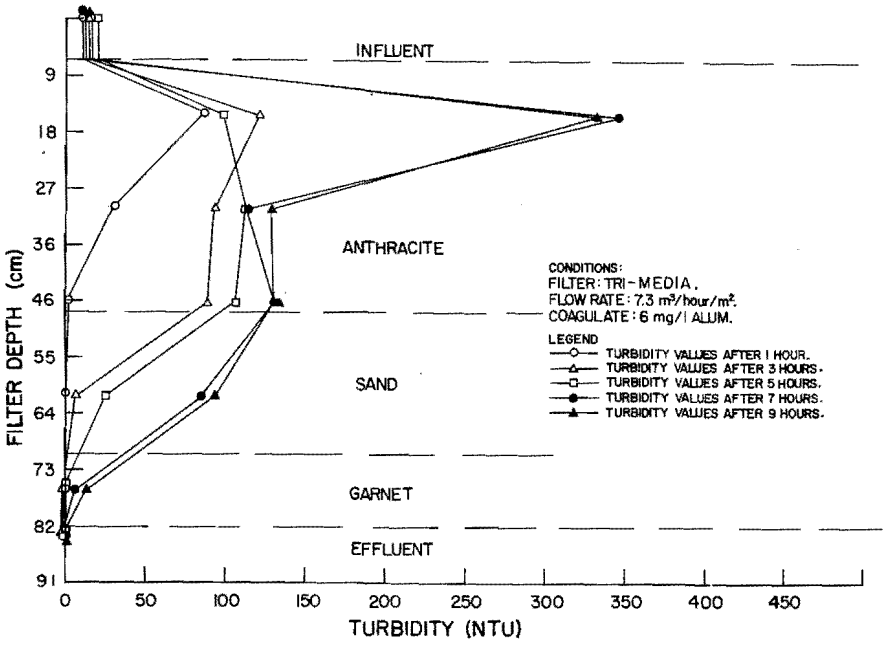
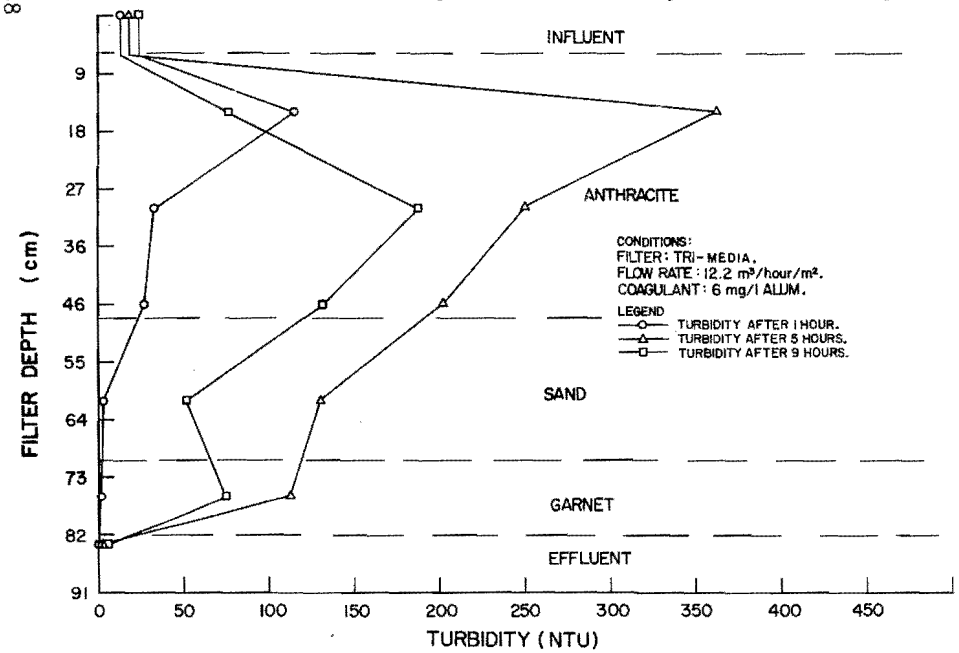


Figure 56. Turbidity profiles through tri-media filter at variou times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.



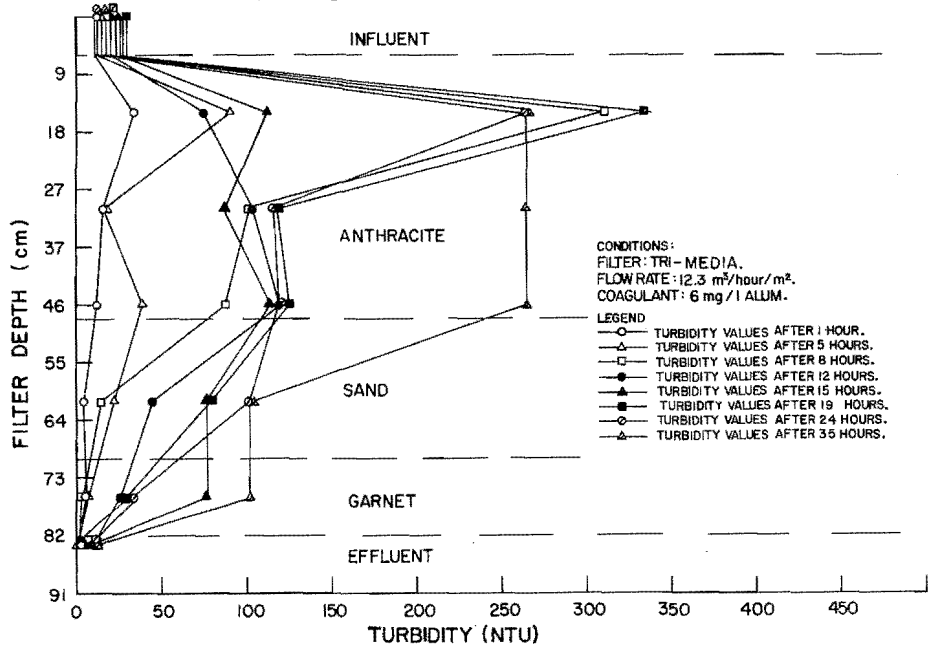


Figure 57. Turbidity profiles through tri-media filter at various times during continuous filtration experiments at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

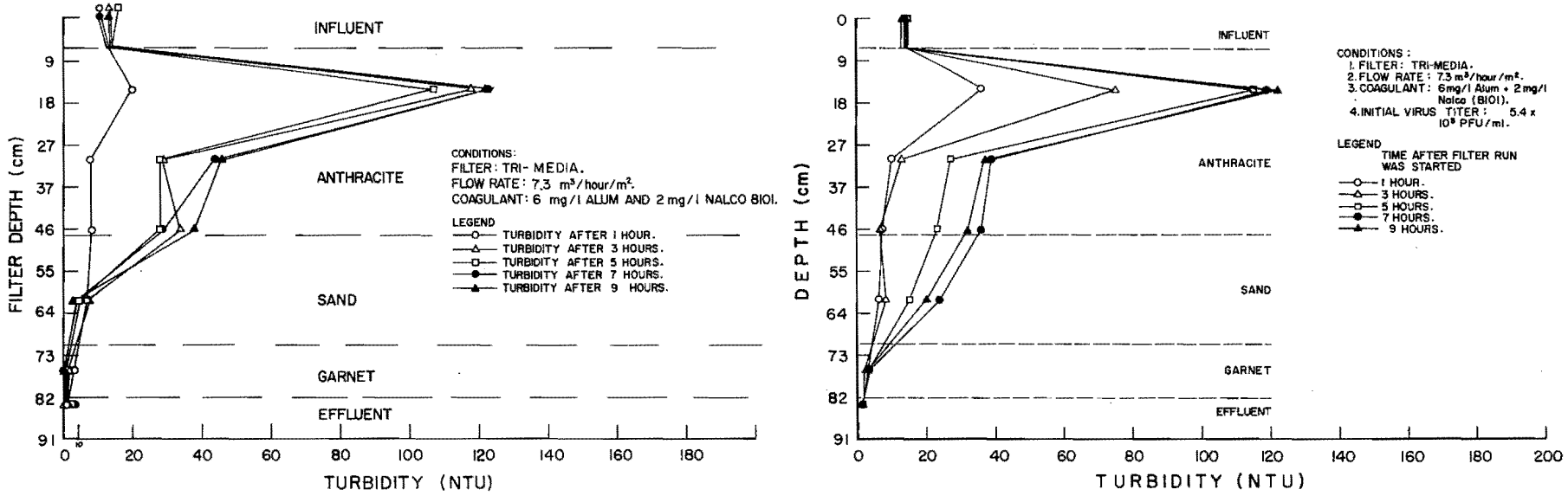


Figure 58. Turbidity profiles through tri-media filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

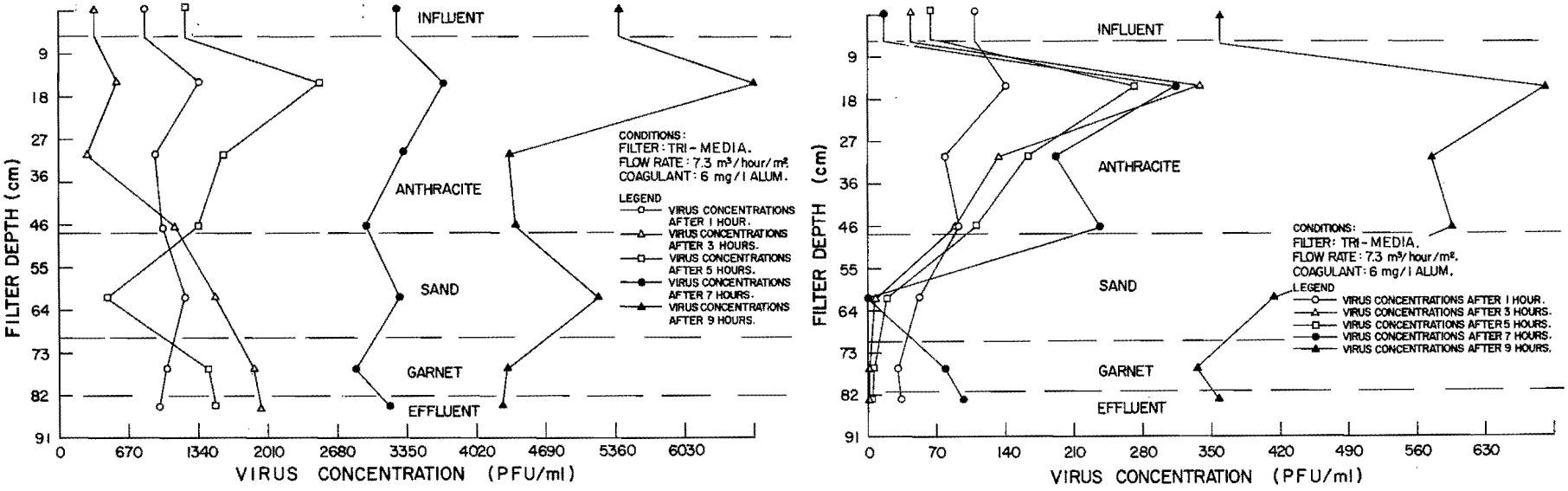


Figure 59. Virus concentration profiles through tri-media filter at various times during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum.

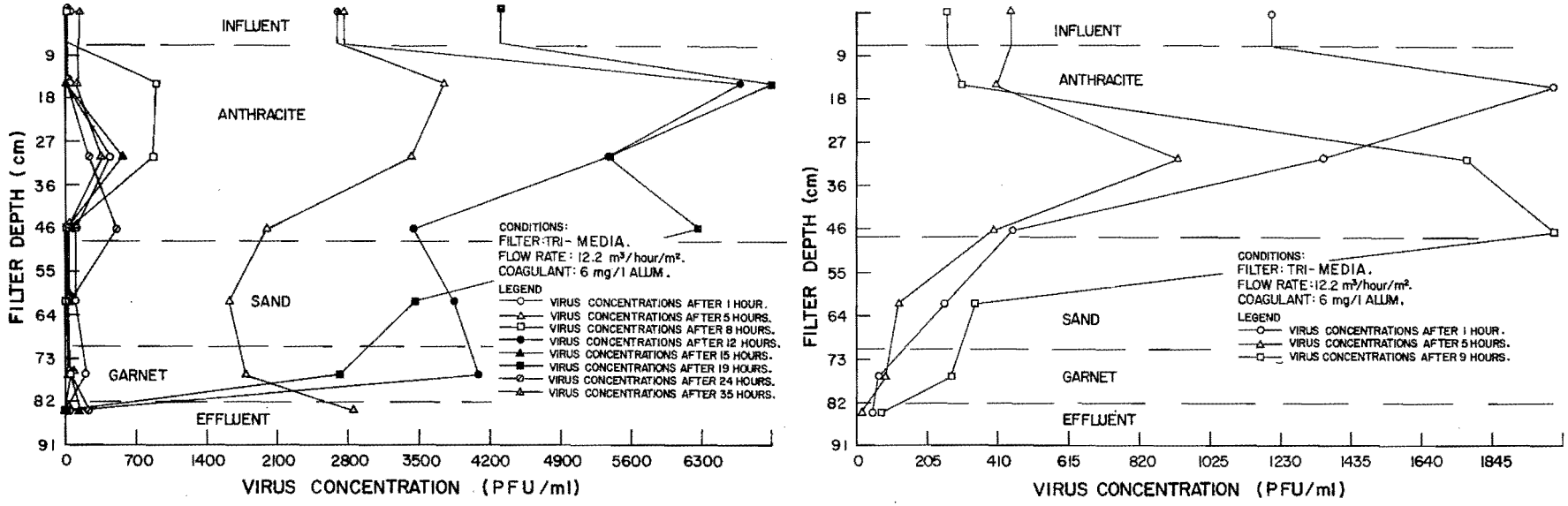


Figure 60. Virus concentration profiles through tri-media filter at various times during continuous filtration experiments at a hydraulic loading of 12.2 $m^3/hr/m^2$, using 6 mg/l alum.

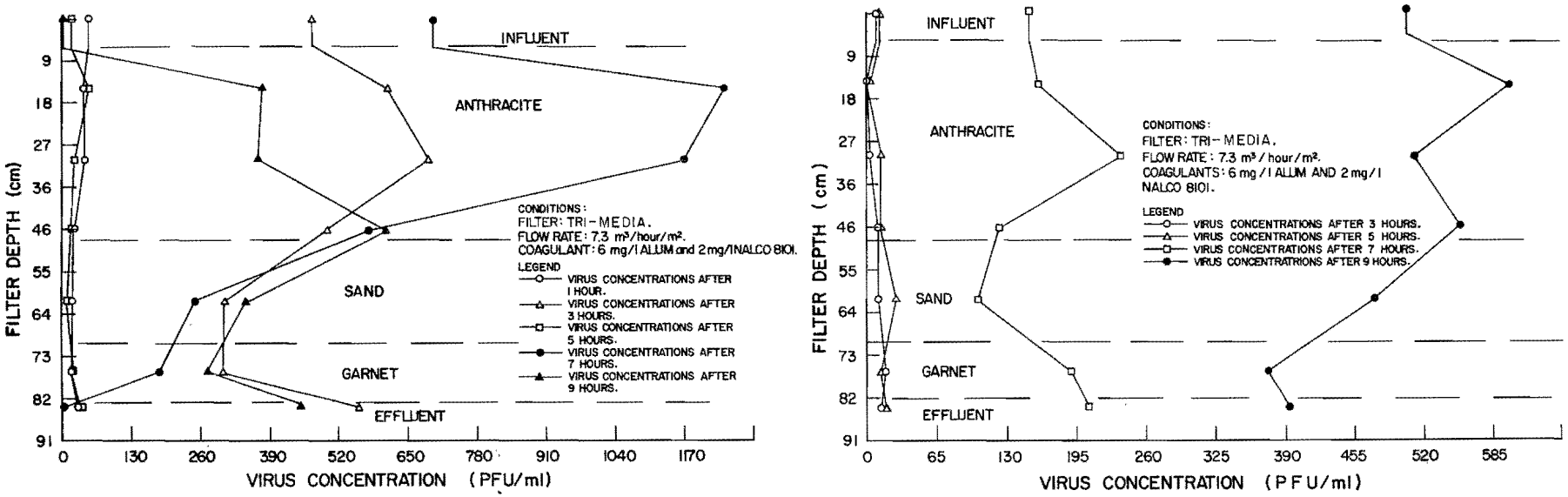


Figure 61. Virus concentration profiles through tri-media filter during continuous filtration experiments at a hydraulic loading of 7.3 $m^3/hr/m^2$, using 6 mg/l alum and 2 mg/l Nalco 8101.

effluent turbidity quality was not a function of hydraulic loading rate. Tri-media filter failed to remove virus from water.

The overall conclusion derived from the pilot plant studies was that while in-line direct filtration was efficient in producing low turbidity effluent (less than 1 NTU) it did not remove the bacteriophage MS2. Furthermore, the higher flow rate of 12.2 $m^3/hour/m^2$ did not influence the effluent quality with respect to either turbidity or virus.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The specific scope of this research was to conduct a pilot plant study to evaluate the effectiveness of in-line direct filtration in removing the bacteriophage MS2. Laboratory and continuous run data were collected to obtain information which can be used to develop a treatment system which will reduce not only turbidity but the potential hazard of pathogenic virus introduced into the water supply.

The overall conclusion derived from the pilot plant studies is that while in-line direct filtration is efficient in producing low turbidity effluent (less than 1 NTU) it does not remove the bacteriophage MS2. Furthermore, the higher flow rate of 12.2 $m^3/hour/m^2$ did not influence the effluent quality with respect to either turbidity or virus. The sand filter showed better virus removal efficiency than the dual-media and tri-media filters. Nevertheless, virus breakthrough was observed in the effluent at all times. Dual-media and tri-media met the effluent turbidity standard of less than 1 NTU for a longer period at 12.2 $m^3/hour/m^2$ loading rate by comparison to the sand filter. Dual-media and tri-media met the standard for 9 hours, whereas the sand filter met the standards for 5 hours.

From the results obtained in this study, the following conclusions were derived.

1. Virus breakthrough was observed in the effluent 30 minutes to 1 hour into the continuous filter run. The pilot plant system did not consistently succeed in removing the virus.

2. Pilot plant systems produced high quality effluent with respect to turbidity (less than 1 NTU).

3. Dual-media and tri-media filters performed 4 hours longer filtation length than a sand media filter at a higher flow rate (12.2 $m^3/hour/m^2$).

4. Aluminum sulfate was not effective in removing the bacteriophage MS2 over the range of doses from 4 to 10 mg/l. A dosage of 50 mg/l of aluminum sulfate reduced 98 percent of the virus present in water.

5. The cationic polyelectrolyte, Nalco 8101, was the most promising coagulant tested for decreasing virus concentrations in water. A dosage of 2 mg/l Nalco 8101 decreased virus concentration by 96 percent. Cat-Floc T was capable of reducing 75 percent of the virus while Nalco 8102 and 8103 reduced 63 and 57 percent of the virus respectively at a dosage of 2 mg/l.

6. In the jar tests, virus reduction was not enhanced by extending the flocculation period.

7. Anthracite adsorbed 92 percent of the virus after 2 hours of continuous mixing. Only 30 percent virus removal, however, was achieved during the first 10 minutes.

8. Removal of the virus by sand was insignificant at 95 percent confidence level.

9. Garnet did not remove any bacteriophage MS2.

10. Maximum virus concentration (4600 PFU/ml) was detected at pH 7.5 + 0.3, and the minimum virus counts (167 PFU/ml) were observed at pH's 5 and 9.

Engineering Significance

Based on the results obtained during this study, highest decrease in virus concentration was achieved by either high alum dosages (20 to 50 mg/l) or 2 mg/l of Nalco 8101. Virus removal from low turbidity water (approximately 14 to 17 NTU) by alum is believed to be due to the entrapment of the virus in the precipitating sweep flocs, whereas the mechanism involved in virus removal by Nalco 8101 was aggregation. The general observation was that virus removal was not a function of flocculation period, but rather a function of coagulant dosage (aluminum sulfate). Therefore, the limitation of in-line direct filtration to remove virus is the use of low dosages of alum. The results of the experiments conducted, however, indicate that addition of 2 mg/l of Nalco 8101 to the rapid mix basin may remove 98 percent of the virus in the raw water source.

Presently, the burden of virus removal, in in-line direct filtration, remains on disinfection. Since viruses show different degrees of susceptibility to chlorine (Engelbrecht et al. 1978), health hazard

remains a problem unless the suggested modification (addition of Nalco 8101 to the rapid mix basin) to full scale direct filtration system proves to be effective in virus removal.

Based on the turbidity results obtained during continuous filter operations, dual-media and tri-media filters met the effluent quality standard of less than 1 NTU for a longer period at a flow rate of 12.2 m^3/hour/m^2. Furthermore, the effluent quality with respect to turbidity and virus did not deteriorate with change in flow rate from 7.3 to 12.2 m^3/hour/m^2. The performance of all three filters with respect to virus removal was approximately the same. It is therefore recommended for the treatment plants to use dual-media filters at a rate of 12.2 m^3/hour/m^2.

Previous studies show that with low turbidity water, the flocculation time was not a critical factor in turbidity removal (Dostal et al. 1966; Conley 1965; Robeck 1964; and Tredgett 1974a). Tate et al. (1977) showed that the increase in flocculation (at G = 100 sec^{-1}) time from 13 to 26 minutes did not improve the water quality. Hutchison (1976) studied flocculation periods of 4.5 minutes to 28 minutes and found that flocculation periods beyond 4.5 minutes increased the likelihood of turbidity breakthrough. In a study by Tredgett (1974b), a hydraulic detention time of 30 sec with a G value of 140 sec^{-1} in a rapid mix basin gave a similarly excellent filtrate to that produced by a G value of 250 sec^{-1} for 90 seconds. In combination, these findings are important in suggesting system design retention times and G value.

Based on the data available in the literature and data obtained in this study, the water treatment schematic diagram of Figure 62 is suggested. This system will potentially result in significant virus removal (MS2) and yield low turbidity water.

Recommendations for Future Research

Based on the results of this investigation and a review of the literature, the following recommendations for research are made.

1. The effect of other metal coagulants and polyelectrolytes in virus removal on a prototype water treatment system needs to be investigated.

2. The effect of varying G values in the rapid mix basin on virus removal should be evaluated.

3. The ability of Nalco 8101 to remove virus when added to a full-scale rapid mix basin needs to be verified.

4. The evaluation of virus removal by the recommended direct filtration system as shown in Figure 62 should be made.

5. The effect of Nalco 8101 on other virus types should be examined.

6. The synergic effect of alum and Nalco 8101 should be evaluated to determine if alum interferes with Nalco 8101 to reduce virus concentration.

7. A research effort should be conducted to assess the viability of virus in chemical sludges and their potential public health hazard.

8. An investigation needs to be conducted concerning virus removal by coagulation-flocculation processes at various levels of turbidity with known composition.

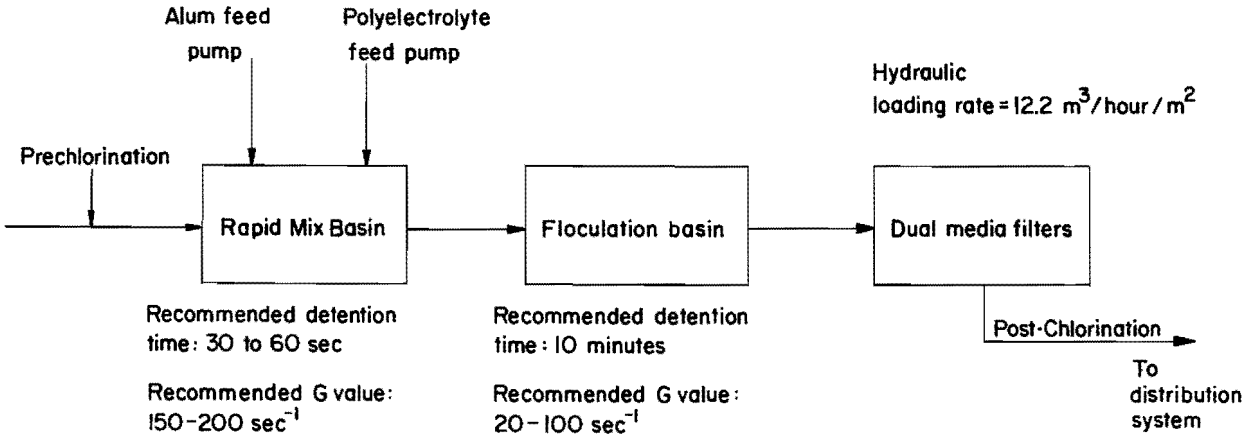


Figure 62. Flow sheet for a direct filtration plant for potential virus removal.

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APPENDICES

Appendix A

Table A-1. Experiment No. 1: Effect of pH on bacteriophage MS2.

Condition: pH varied with 0.01 NaOH or bubbling CO_2 through the solution

Initial Titer: ≈5.4 x 10^4 PFU/ml

Test No. 1

Replicate Samples	10^{-2} Dilution				
pH	Replicate Plates			Mean	Standard Deviation
	1	2	3		
MS_1 (broth)=	73	57	43		
MS_2	75	129	122	7183	2873
MS_3	63	52	69		
5.46	0	3	2		
5.46	5	8	15	467	447
5.46	3	4	2		
7.01	19	23	30		
7.01	37	48	58	3300	1265
7.01	25	27	30		
Tap_1 (pH=7.35)	56	43	45		
Tap_2	64	85	70	5589	1467
Tap_3	40	49	51		
8.01	33	30	30		
8.01	28	26	25	3044	416
8.01	32	39	31		
9.01	0	0	1		
9.01	1	0	0	44	53
9.01	1	0	1		

Test No. 2

Replicate Samples	10^{-2} Dilution				
pH	Replicate Plates			Mean	Standard Deviation
	1	2	3		
MS_1 (broth)=	65	62	75		
MS_2	122	135	146	8328	3052
MS_3	107	91	96		
5.46_1	22	33	31		
5.46_2	47	56	49	3478	1264
5.46_3	23	27	25		
5.99_1	34	36	55		
5.99_2	58	49	56	5556	2246
5.99_3	48	53	111		
7.01_1	51	52	59		
7.01_2	68	84	70	5433	1776
7.01_3	30	35	40		
Tap_1 (7.3)	31	47	40		
Tap_2 (7.3)	53	64	63	5111	1086
Tap_3 (7.3)	48	59	55		
8.01_1	41	42	36		
8.01_2	58	48	70	4300	1367
8.01_3	32	31	29		
9.01_1	2	2	0		
9.01_2	5	3	4	289	162
9.01_3	3	5	2		

Table A-2. Experiment No. 2: Effect of sodium ion concentration on MS2.

Condition: $Tap_{1,2,3}$ (Control): Tap water without sodium ion

Initial titer: ≈ 5.4×10^3 PFU/ml

Test No. 1						Test No. 2					
Replicate Samples	Replicate Plates			Mean	Standard Deviation	Replicate Samples	Replicate Plates			Mean	Standard Deviation
Sodium Ion Concentration (mg/l)	1	2	3			Sodium Ion Concentration (mg/l)	1	2	3		
Tap_1 (Control)	140	121	107			Tap_1 (Control)	112	149	168		
Tap_2	86	152	173	135	27	Tap_2	82	58	71	120	42
Tap_3	145	139	156			Tap_3	125	155	161		
0.1	256	216	197			0.1	118	109	157		
0.1	141	125	117	168	47	0.1	179	171	181	166	33
0.1	140	146	176			0.1	179	188	211		
0.2	132	85	63			0.2	212	179	181		
0.2	183	162	138	142	45	0.2	159	153	165	166	25
0.2	198	176	145			0.2	120	162	167		
0.3	296	216	193			0.3	194	196	199		
0.3	146	201	117	180	55	0.3	169	158	145	177	23
0.3	147	132	171			0.3	a	a	a		
0.4	248	257	228			0.4	45	60	44		
0.4	72	76	99	181	76	0.4	129	143	147	82	44
0.4	203	229	215			0.4	60	46	62		
0.5	142	113	231			0.5	110	138	81		
0.5	202	190	99	149	47	0.5	105	156	86	112	23
0.5	127	103	130			0.5	108	113	112		

[a]Contaminated.

Table A-3. Experiment No. 3: Kinetic study--adsorption of MS2 to anthracite and sand.

Condition: Tap (control): Virus suspension in tap water without any filter media. A_1,A_2: Replicate samples of 6 g anthracite in 6 ml virus suspension in tap water. S_1,S_2: Replicate samples of 6 g sand in 6 ml virus suspension in tap water.

Initial titer: $\approx 5.4 \times 10^3$ PFU/ml

Samples	Time in Hours	Dilution 10^{-1} Replicate Plates 1	2	3	Mean	Standard Deviation
Tap (Control)	0	37	30	20	29	9
A_1	0	36	24	20	34	7
A_2	0	38	30	31		
S_1	0	34	47	44	42	18
S_2	0	25	34	75		
Tap	1	53	46	51	50	4
A_1	1	7	8	5	5	2
A_2	1	4	3	4		
S_1	1	45	51	69	49	11
S_2	1	50	39	42		
Tap	2	74	83	66	74	8
A_1	2	7	12	11	8	3
A_2	2	6	4	5		
S_1	2	112	113	110	83	31
S_2	2	51	61	52		
Tap	3	65	42	62	56	12
A_1	3	4	6	4	4	2
A_2	3	3	2	6		
S_1	3	99	98	102	67	37
S_2	3	35	41	25		
Tap	4	80	56	55	64	14
A_1	4	3	5	3	3	1
A_2	4	2	1	2		
S_1	4	114	71	74	66	27
S_2	4	47	42	48		

Table A-4. Experiment No. 4: Kinetic study--adsorption of MS2 to anthracite and sand.

Condition: Tap (control): Virus added to tap water without any filter media. A_1,A_2: Replicate samples of 6 g anthracite in 6 ml virus suspension in tap water. S_1,S_2: Replicate samples of 6 g sand added to 6 ml virus suspension in tap water.

Initial titer: $\approx 5.4 \times 10^4$ PFU/ml

Samples	Time in Minutes	Dilution 10^{-2} Replicate Plates 1	2	3	Mean	Standard Deviation
Tap (Control)	0	125	101	a	113	12
A_1	0	46	52	41	60	19
A_2	0	85	53	81		

Table A-4. Continued.

Samples	Time in Minutes	Dilution 10^{-2} Replicate Plates 1	2	3	Mean	Standard Deviation
S_1	0	44	41	50	61	18
S_2	0	82	78	73		
Tap	2	96	101	a	99	4
A_1	2	32	32	42	56	24
A_2	2	65	84	82		
S_1	2	60	59	51	68	16
S_2	2	65	78	94		
Tap	4	103	99	a	101	2
A_1	4	48	44	31	55	20
A_2	4	54	64	89		
S_1	4	51	46	60	70	24
S_2	4	70	110	86		
Tap	6	110	92	a	101	13
A_1	6	31	47	33	56	26
A_2	6	56	68	100		
S_1	6	50	66	65	79	23
S_2	6	112	93	90		
Tap	8	75	95	a	85	10
A_1	8	39	42	33	55	23
A_2	8	69	94	54		
S_1	8	61	52	36	75	29
S_2	8	98	98	104		
Tap	10	123	138	a	130	11
A_1	10	33	40	53	61	23
A_2	10	73	83	86		
S_1	10	54	49	46	72	25
S_2	10	102	98	80		
Tap	20	98	87	a	92	8
A_1	20	34	31	48	58	25
A_2	20	96	67	69		
S_1	20	53	51	84	75	19
S_2	20	78	87	96		
Tap (Control)	30	97	97	a	97	-
A_1	30	42	26	33	33	7
A_2	30	25	37	36		
S_1	30	104	84	88	86	13
S_2	30	65	83	89		
Tap	40	124	101	a	112	16
A_1	40	19	15	29	13	5
A_2	40	17	18	9		
S_1	40	115	75	82	88	14
S_2	40	92	86	80		
Tap	50	110	105	a	108	-
A_1	50	13	5	a	9	-
A_2	50	a	a	a		
S_1	50	89	90	94	95	6
S_2	50	104	100	95		

[a]Contaminated.

Table A-5. Experiment No. 5: Kinetic study--adsorption of MS2 to anthracite.

Condition: Tap (Control): Virus added to tap water without any filter media. A_1,A_2: Replicate samples of 50 g anthracite in 50 ml virus suspension in tap water.

Initial titer: $\simeq 5.4 \times 10^4$ PFU/ml

Test No. 1

Samples	Time in Minutes	Before Centrifugation					After Centrifugation				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	371	382	371	875	6	371	342	327	347	22
A_1	0	186	158	172	161	16	233	190	157	166	40
A_2	0	142	162	146			120	37	159		
Tap	10	415	383	352	383	32	413	379	352	381	31
A_1	10	112	114	88	109	11	100	97	68	91	12
A_2	10	106	120	116			85	98	97		
Tap	20	427	407	426	420	11	401	354	364	373	25
A_1	20	101	79	76	82	10	4	12	5	14	8
A_2	20	81	78	74			18	23	20		
Tap	30	439	438	426	434	7	378	371	303	351	41
A_1	30	128	113	102	100	22	2	2	2	3	1
A_2	30	76	72	108			4	1	2		
Tap	40	472	420	397	430	38	395	436	366	399	35
A_1	40	116	113	119	94	26	1	0	0	2	2
A_2	40	90	56	72			6	1	1		
Tap	50	458	399	344	400	57	384	386	384	385	1
A_1	50	73	83	88	84	16	9	1	3	2	3
A_2	50	71	75	114			1	0	0		
Tap	60	453	452	415	440	22	398	387	352	379	24
A_1	60	116	106	98	98	20	13	17	10	7	7
A_2	60	90	63	116			1	0	0		
Tap	120	369	322	274	322	48	383	330	218	310	84
A_1	120	49	62	35	47	9	1	0	1	1	1
A_2	120	47	43	48			1	2	0		
Tap	180	323	369	285	326	42	364	387	344	365	22
A_1	180	65	56	58	60	9	1	0	0	2	2
A_2	180	46	62	73			1	2	0		
Tap	240	238	212	213	221	15	245	229	216	230	15
A_1	240	11	17	13	14	2	0	0	0	0	-
A_2	240	13	16	14			0	0	0		

Table A- 6. Experiment No. 6 : Kinetic study--adsorption of MS2 to anthracite.

Condition: Tap (Control): Virus added to tap water without any filter media. A_1,A_2: Replicate samples of 50 g anthracite in 50 ml virus suspension in tap water.

Initial titer: ≈ 5.4 x 10^4 PFU/ml

Test No. 2

Samples	Time in Minutes	Before Centrifugation					After Centrifugation				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	274	311	378	321	53	365	335	269	323	49
A_1	0	134	92	120	128	22	144	86	182	122	38
A_2	0	129	132	160			84	107	130		
Tap	10	342	344	312	333	18	395	392	338	375	32
A_1	10	158	144	142	142	16	103	386	119	153	115
A_2	10	116	160	135			95	107	106		
Tap	20	386	395	361	381	18	423	388	343	385	40
A_1	20	128	102	85	95	18	10	12	13	28	19
A_2	20	84	92	81			31	51	49		
Tap	30	413	418	450	427	20	365	395	399	386	19
A_1	30	98	100	90	85	15	1	0	3	2	1
A_2	30	73	87	62			3	3	4		
Tap	40	395	411	398	401	8	366	405	414	395	26
A_1	40	95	105	101	87	16	1	0	0	2	2
A_2	40	83	64	74			5	5	4		
Tap	50	431	428	368	409	36	392	413	421	409	15
A_1	50	129	107	141	108	24	3	4	6	2	2
A_2	50	88	78	102			0	1	0		
Tap	60	411	413	415	413	2	370	457	389	405	46
A_1	60	113	100	95	94	16	0	0	0	1	2
A_2	60	104	80	71			2	2	1		
Tap	120	284	211	184	226	52	328	275	241	281	44
A_1	120	34	33	20	29	6	5	0	1	2	2
A_2	120	34	26	29			0	0	0		
Tap	180	330	314	258	301	38	283	367	275	308	51
A_1	180	72	58	73	62	10	1	0	0	0	-
A_2	180	46	58	62			0	0	0		
Tap	240	240	226	173	213	35	210	186	172	189	19
A_1	240	16	26	30	22	7	0	0	0	0	-
A_2	240	24	12	24			0	0	0		

Table A- 7. Experiment No. 7 : Kinetic study--adsorption of MS2 to anthracite.

Condition: Tap (Control): Virus added to tap water without any filter media. A_1,A_2: Replicate samples of 50 g anthracite in 50 ml virus suspension in tap water.

Initial titer: ≃ 5.4 x 10^4 PFU/ml

Sample	10^{-1} Dilution										
	Time in Minutes	Replicate Plates			Mean	Standard Deviation	Time in Minutes	Replicate Plates			Mean	Standard Deviation
		1	2	3				1	2	3		
Tap_1	0	410	395	324	359	36	30	434	424	408	415	16
Tap_2	0	342	325	360			30	392	426	404		
A_1	0	241	270	326	288	32	30	164	173	207	154	36
A_2	0	319	298	276			30	102	129	149		
Tap_1	2	415	381	368	370	35	40	453	456	384	436	29
Tap_2	2	364	383	308			40	425	435	464		
A_1	2	241	205	243	223	20	40	149	121	115	106	28
A_2	2	228	192	227			40	73	88	88		
Tap_1	4	407	412	398	404	14	50	382	411	436	439	37
Tap_2	4	385	395	425			50	466	481	457		
A_1	4	262	259	247	245	24	50	141	101	98	100	21
A_2	4	214	217	269			50	94	85	84		
Tap_1	6	394	366	367	386	24	60	484	386	476	483	56
Tap_2	6	420	363	408			60	481	518	553		
A_1	6	186	229	287	229	38	60	93	100	121	112	13
A_2	6	202	259	213			60	115	113	129		
Tap_1	8	426	438	382	425	25	120	380	353	386	358	22
Tap_2	8	437	454	411			120	357	350	324		
A_1	8	217	210	218	201	17	120	78	44	60	60	13
A_2	8	185	197	179			120	72	58	48		
Tap_1	10	436	427	383	402	24	180	388	425	410	414	29
Tap_2	10	382	387	396			180	396	467	399		
A_1	10	238	217	205	198	26	180	55	68	64	60	8
A_2	10	177	174	176			180	63	46	66		
Tap_1	20	432	414	439	422	18	240	326	341	337	333	8
Tap_2	20	408	441	397			240	341	327	325		
A_1	20	198	201	209	190	27	240	40	33	50	41	6
A_2	20	145	170	215			240	40	47	37		

Table A-8. Experiment No. 8: Effects of alum on virus contained in water without turbidity.

Condition: Coagulant: Alum. Virus suspension in tap water without turbidity. Tap (Control): Virus suspension in tap water; no alum added.

Initial titer: ≈ 5.4×10^4 PFU/ml

Alum Dosage (mg/l)	Time in Minutes	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap (0 mg/l)	0	96	119	110	108	12	95	112	103	103	9
4	0	71	75	53	66	12	45	39	71	52	17
5	0	56	37	60	51	12	43	48	46	46	3
6	0	55	85	82	74	17	49	47	34	43	8
Tap	15	133	116	155	135	37	84	115	113	104	17
4	15	88	86	91	88	3	68	67	78	71	6
5	15	90	92	83	88	5	72	56	65	64	8
6	15	81	103	94	93	11	96	78	55	76	21
Tap	30	88	103	113	101	13	113	103	108	108	5
4	30	93	66	94	84	16	78	98	77	84	12
5	30	95	84	93	91	6	103	88	90	94	8
6	30	94	85	98	92	7	98	102	112	104	7
Tap	45	120	126	107	118	10	109	123	118	117	7
4	45	105	98	67	90	20	74	76	95	82	12
5	45	87	68	69	75	11	96	83	94	91	7
6	45	87	77	83	82	5	82	85	88	85	3

Table A-9. Experiment No. 9: Effects of alum on virus contained in water without turbidity.

Condition: Coagulant: Alum. Virus suspension in tap water without turbidity. Tap (Control): Virus suspension in tap water; no alum added.

Initial titer: ≈ 5.4×10^3 PFU/ml

Alum Dosage (mg/l)	Time in Minutes	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap (0 mg/l)	0	10	2	5	65	4	33	26	30	30	4
7	0	1	6	6	4	3	4	18	25	16	11
8	0	4	15	17	12	7	26	11	53	30	21
9	0	11	40	38	30	16	57	48	48	51	5
10	0	38	47	69	51	16	73	79	77	76	3
Tap	15	47	42	20	36	14	60	65	49	58	8
7	15	38	57	32	42	13	44	57	48	50	7
8	15	52	47	38	46	7	50	43	62	52	10
9	15	54	51	59	55	4	67	84	74	75	9
10	15	46	69	90	68	22	65	74	98	79	17
Tap	30	74	56	29	53	23	91	103	62	85	21
7	30	69	70	75	71	3	78	82	80	80	2
8	30	48	58	70	59	11	93	94	73	87	12
9	30	66	65	66	66	1	90	76	76	81	8
10	30	73	82	71	75	6	89	86	95	90	5
Tap	45	103	90	78	90	13	126	96	102	108	16
7	45	34	55	69	53	18	79	107	86	91	15
8	45	61	86	54	67	17	a	98	65	82	23
9	45	62	54	67	61	7	86	88	72	82	9
10	45	77	100	84	87	12	76	69	85	77	8

[a]Contaminated.

Table A-10. Experiment No. 10: Effects of alum on virus contained in water without turbidity.

Condition: Coagulant: Alum. Virus suspension in tap water without turbidity.

Initial titer: ≈ 5.4 x 10^3 PFU/ml

Alum Dosage (mg/l)	Time in Minutes	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap (0 mg/l)	0	112	130	152	131	20	115	122	131	123	8
1	0	79	47	53	60	17	a	a	a	-	-
2	0	67	58	65	63	5	a	a	a	-	-
3	0	74	76	80	77	3	51	55	a	53	1
Tap	15	125	105	137	122	16	102	a	a	102	-
1	15	66	87	98	84	16	60	48	62	57	8
2	15	90	95	81	89	7	62	65	42	56	8
3	15	97	106	81	95	13	67	82	69	73	8
Tap	30	110	138	119	122	14	99	129	134	121	19
1	30	94	85	81	87	7	83	81	68	77	8
2	30	101	117	88	102	15	91	89	89	90	1
3	30	86	97	87	90	6	88	86	109	94	13
Tap	45	113	119	127	120	7	94	96	102	97	4
1	45	92	91	98	94	4	109	104	101	105	4
2	45	78	88	81	82	5	90	90	96	92	3
3	45	70	94	78	81	12	99	79	74	84	13

[a]Contaminated.

Table A-11. Experiment No. 11: Effects of alum on virus contained in water with 14 NTU turbidity.

Condition: Coagulant: Alum. Virus suspension in turbid water (≈ 14 NTU). Tap (Control): Virus suspension in tap water; no alum added. Susp. (Control): Virus suspension in turbid water; no alum added.

Initial titer: ≈ 5.4 x 10^3 PFU/ml

Alum Dosage (mg/l)	Time in Minutes	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	34	27	29	30	4	42	38	35	38	4
Susp.	0	50	54	50	51	2	34	40	46	40	6
5	0	62	62	94	73	18	59	93	96	83	21
6	0	35	54	44	44	10	65	53	71	63	9
7	0	54	42	48	48	6	38	30	50	39	10
Tap	15	38	67	58	54	15	57	51	40	49	9
Susp.	15	71	48	73	64	14	41	56	64	54	12
5	15	81	67	61	70	10	69	75	98	81	15
6	15	68	57	54	60	7	58	78	71	69	10
7	15	58	61	38	52	13	66	51	54	57	8
Tap	30	38	46	44	43	4	52	43	44	46	5
Susp.	30	55	62	49	55	7	65	73	81	73	8
5	30	77	96	69	81	14	91	93	115	100	13
6	30	54	55	62	57	4	78	80	70	76	5
7	30	60	62	56	59	3	81	74	79	78	4
Tap	45	39	55	60	51	11	68	73	57	66	8
Susp.	45	63	75	57	65	9	106	82	90	93	12
5	45	77	72	77	75	3	83	73	71	76	6
6	45	60	54	52	55	4	61	62	46	56	9
7	45	34	45	34	38	6	71	59	77	69	9

Table A-12. Experiment No. 12: Effects of alum on virus contained in water with 14 NTU turbidity.

Condition: Coagulant: Alum. Virus suspension in turbid water (≈ 14 NTU). Tap (Control): Virus suspension in tap water; no alum added. Susp. (Control): Virus suspension in turbid water; no alum added.

Initial titer: ≈ 5.4×10^3 PFU/ml

Alum Dosage (mg/l)	Flocculation Time (min)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Samples			Mean	Standard Deviation	Replicate Samples			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	10	25	29	21	10	36	18	17	24	11
Susp.	0	37	22	39	33	9	18	21	17	19	2
8	0	8	26	28	21	11	27	44	26	32	10
9	0	35	33	28	32	4	48	64	38	50	13
10	0	62	56	89	69	18	58	74	93	75	18
Tap	15	19	29	24	24	5	32	32	34	33	1
Susp.	15	33	57	55	48	13	83	50	43	59	21
8	15	24	34	33	30	6	36	42	55	44	10
9	15	40	39	47	42	4	42	69	72	61	17
10	15	42	46	62	50	11	66	77	92	78	13
Tap	30	36	31	28	32	4	40	35	31	35	5
Susp.	30	59	68	51	59	9	64	84	65	71	11
8	30	36	28	46	37	9	35	46	50	44	8
9	30	38	49	40	42	6	58	42	64	55	11
10	30	41	46	29	39	9	54	73	59	62	10
Tap	45	45	36	37	39	5	47	56	37	47	10
Susp.	45	52	63	58	58	6	97	90	84	90	7
8	45	32	20	28	27	6	36	47	41	41	6
9	45	33	47	32	37	8	32	46	30	36	9
10	45	32	23	26	27	5	24	28	26	26	2

Table A-13. Experiment No. 13: Effects of alum on virus contained in water with 14 NTU turbidity.

Condition: Coagulant: Alum. Virus suspension in turbid water (≈ 14 NTU). Tap (Control): Virus suspension in tap water; no alum added. Susp. (Control): Virus suspension in turbid water; no alum added. Samples centrifuged at 10,000 rpm for 3 minutes.

Initial titer: ≈ 5.4×10^3 PFU/ml

Alum Dosage (mg/l)	Flocculation Period in Minutes	Before Centrifugation					After Centrifugation				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Samples			Mean	Standard Deviation	Replicate Samples			Mean	Standard Deviation
		1	2	3			1	2	3		
					Test #1						
Tap	45	10	10	9	10	1	5	2	4	4	2
Susp.	45	22	24	35	27	7	12	26	32	23	10
6	45	2	17	15	11	8	21	20	17	19	2
8	45	12	16	17	15	3	9	5	7	7	2
10	45	3	13	5	7	5	1	3	3	2	1
					Test #2						
Tap	45	12	8	9	10	2	10	7	6	8	2
Susp.	45	31	40	48	40	9	30	36	33	33	3
6	45	24	19	22	22	3	28	21	30	26	5
8	45	23	22	25	23	2	22	9	12	14	7
10	45	12	19	25	19	7	12	24	18	18	6

Table A-14. Experiment No. 14: Effects of alum on virus contained in water with 14 NTU turbidity.

Condition: Coagulant: Alum. Virus suspension in turbid water (≈ 14 NTU). Tap (Control): Virus suspension in tap water; no alum added. Susp. (Control): Virus suspension in turbid water; no alum added. Flocculation period 45 minutes. Settling Period: 15 minutes. Samples centrifuged at 10,000 rpm for 3 minutes.

Initial titer: ≈ 5.4×10^3 PFU/ml

Alum Dosage (mg/l)	Supernatant					Supernatant Centrifuged					Resuspension				
	10^{-1} Dilution					10^{-1} Dilution					10^{-1} Dilution				
	Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
	1	2	3			1	2	3			1	2	3		
							Test #1								
Tap	57	54	49	53	4	63	73	65	67	5	66	48	49	53	7
Susp.	47	59	31	46	14	72	72	90	78	10	48	34	43	42	7
5	51	75	60	62	12	58	49	44	50	7	38	45	52	45	7
6	55	41	51	49	7	54	51	51	52	2	39	46	47	44	4
7	42	58	53	51	8	53	47	57	52	5	56	42	46	48	7
20	5	1	3	3	2	3	1	1	2	1	10	12	4	9	4
30	1	1	2	1	1	1	1	1	1	0	10	15	20	15	5
40	0	0	0	0	-	1	0	0	0	-	1	4	5	3	2
50	0	0	1	0	-	0	0	1	0	-	1	1	2	1	1
							Test #2								
Tap	73	77	65	72	6	74	70	76	73	3	52	84	60	65	17
Susp.	60	64	46	57	9	75	63	78	72	8	54	75	72	67	11
5	65	62	51	59	7	58	47	48	51	6	73	51	89	71	19
6	45	44	44	44	1	79	76	62	72	9	59	72	56	62	9
7	41	27	35	34	7	36	39	32	36	4	35	45	35	38	6
20	5	2	6	4	2	1	2	4	2	2	17	14	7	13	5
30	1	3	0	1	2	2	0	0	1	1	4	1	8	4	4
40	0	0	2	1	1	1	0	0	0	-	3	2	0	2	2
50	2	3	0	2	2	0	0	0	0	0	2	0	1	1	1

Table A-15. Experiment No. 15: Effects of Cat-Floc T on virus contained in water without turbidity.

Condition: Polyelectrolyte: Cat-Floc T. Virus suspension in tap water without turbidity. Tap (Control): Virus suspension in water; no Cat-Floc T added.

Initial titer: ≈ 5.4×10^3 PFU/ml

Cat-Floc T (mg/l)	Flocculation Time (Minutes)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	15	14	6	12	5	0[a]	8	0[a]	3	5
2	0	9	6	14	10	4	9	17	14	13	4
4	0	26	31	48	35	12	28	32	28	29	2
6	0	1	1	9	4	5	2	1	11	5	6
8	0	23	18	14	18	5	33	16	24	24	9
10	0	33	34	37	35	2	19	30	45	31	13
Tap	15	30	32	18	27	8	41	15	10	22	17
2	15	17	17	21	18	2	10	19	21	17	6
4	15	44	31	34	36	7	31	65	43	46	17
6	15	37	27	32	32	5	53	30	39	41	12
8	15	26	22	21	23	3	37	30	35	34	4
10	15	15	19	17	20	4	30	24	10	21	10
Tap	30	49	38	46	44	6	76	47	35	53	21
2	30	29	36	25	30	6	21	39	37	32	10
4	30	17	28	36	27	10	29	45	68	47	20
6	30	44	25	25	31	11	37	57	60	51	13
8	30	11	25	10	15	8	27	45	55	42	14
10	30	16	11	20	16	5	33	30	27	30	3
Tap	45	55	67	44	55	12	93	68	83	81	13
2	45	17	23	27	22	5	45	33	68	49	18
4	45	24	26	37	29	7	44	52	69	55	13
6	45	22	10	22	18	7	42	39	46	42	4
8	45	25	18	27	23	5	42	55	47	48	7
10	45	26	37	39	34	7	43	36	48	42	6

[a]Contaminated.

Table A-16. Experiment No. 16: Effects of Cat Floc T on virus contained in water with 14 NTU turbidity.

Condition: Polyelectrolyte: Cat-Floc T. Virus suspension in turbid water (14 NTU). Tap (Control): Virus suspension in tap water; no Cat-Floc added. Susp. (Control): Virus suspension in turbid water; no Cat-Floc added.

Initial titer: ≈ 5.4×10^3 PFU/ml

Cat-Floc T (mg/l)	Flocculation Time (Minutes)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	84	67	54	68	15	109	88	87	95	12
Susp.	0	37	44	42	41	4	74	68	50	64	12
2	0	18	10	6	11	6	25	41	39	35	9
4	0	17	8	9	11	5	25	26	19	23	4
6	0	15	12	13	14	2	32	52	41	42	10
8	0	15	12	14	14	2	32	41	45	39	7
10	0	31	45	43	40	8	28	36	42	35	7
Tap	15	53	70	69	64	10	94	81	84	86	7
Susp.	15	40	51	46	46	6	86	85	72	81	8
2	15	9	14	10	11	3	23	20	31	25	6
4	15	14	9	16	13	4	24	26	27	26	2
6	15	26	27	37	30	6	42	42	42	42	0
8	15	10	12	14	12	2	30	23	21	25	5
10	15	32	17	28	26	8	19	23	31	24	6
Tap	30	55	62	63	60	4	85	92	70	82	11
Susp.	30	44	35	47	42	6	73	60	85	73	13
2	30	7	8	9	8	1	14	19	16	16	3
4	30	13	17	20	17	4	12	17	18	16	3
6	30	4	9	15	9	6	18	15	14	16	2
8	30	21	14	11	15	5	12	18	24	18	6
10	30	28	32	38	33	5	36	43	35	38	4
Tap	45	54	73	75	67	12	83	69	84	79	8
Susp.	45	39	61	65	55	14	79	72	61	71	9
2	45	9	8	8	8	1	6	9	9	8	2
4	45	13	12	22	16	6	10	9	7	9	2
6	45	11	16	4	10	6	11	8	8	9	2
8	45	25	30	26	27	3	1	13	17	10	8
10	45	24	23	29	25	3	35	32	15	27	11
Tap	45	57	60	66	61	5	67	68	76	70	5
Susp.	Samples centrifuged at 10,000 rpm for 3 minutes	43	44	49	45	3	61	80	76	72	10
2		1	4	3	3	2	8	1	1	3	4
4		9	7	8	8	1	3	1	8	4	4
6		11	7	5	8	3	10	a	a	10	–
8		19	18	16	18	2	13	11	24	16	7
10		21	9	12	14	6	27	14	12	180	8

[a]Top ajar had not solidified.

Table A-17. Experiment No. 17: Effects of Cat-Floc T on virus contained in water with 14 NTU turbidity.

Condition: Polyelectrolyte: Cat-Floc T. Virus suspension in turbid water (≈ 14 NTU). Tap (Control): Virus suspension in tap water; no Cat-Floc T added. Susp. (Control): Virus suspension in turbid water; no Cat-Floc T added. Flocculation period of 45 minutes, settling period of 15 minutes, samples centrifuged at 10,000 rpm for 3 minutes.

Initial titer: ≈ 5.4×10^3 PFU/ml.

Cat-Floc T Dosage (mg/l)	Supernatant					Supernatant Centrifuged					Resuspension				
	10^{-1} Dilution					10^{-1} Dilution					10^{-1} Dilution				
	Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
	1	2	3			1	2	3			1	2	3		
Tap	356	395	435	395	40	345	380	413	379	34	413	450	412	425	22
Susp.	342	355	330	342	13	310	378	406	365	49	375	352	407	378	28
2	16	9	18	14	5	1	1	2	1	1	5	3	4	4	1
4	32	39	32	34	4	10	14	16	13	3	9	17	20	15	6
6	55	62	58	58	4	38	45	62	48	12	33	48	30	37	10
8	84	80	64	76	11	92	112	78	94	17	85	74	88	82	7
10	128	214	170	171	43	159	144	155	153	8	142	146	162	150	11

Table A-18. Experiment No. 18: Effects of Nalco 8101 on virus contained in water with 14 NTU turbidity.

Condition: Polyelectrolyte: Nalco 8101. Virus suspension in turbid water (≈ 14 NTU). Tap (Control): Virus suspension in tap water; no Nalco 8101 added. Susp. (Control): Virus suspension in turbid water; no Nalco 8101 added. Flocculation period of 45 minutes, settling period of 15 minutes, samples centrifuged at 10,000 rpm for 3 minutes.

Initial titer: ≈ 5.4×10^3 PFU/ml

Nalco 8101 Dosage (mg/l)	Supernatant					Supernatant Centrifuged					Resuspension				
	10^{-1} Dilution					10^{-1} Dilution					10^{-1} Dilution				
	Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
	1	2	3			1	2	3			1	2	3		
Tap	462	441	457	453	11	491	508	467	489	21	499	511	456	489	29
Susp.	428	524	455	469	50	455	481	440	459	21	510	468	514	497	25
2	18	24	28	23	5	19	10	13	14	5	31	20	21	24	6
4	15	20	16	17	3	18	17	8	14	6	23	36	21	27	8
6	53	26	45	41	14	25	28	21	25	4	51	28	29	36	13
8	47	50	36	44	7	22	16	25	21	5	40	49	46	45	5
10	47	43	34	41	7	21	43	29	31	11	35	38	31	35	4

Table A-19. Experiment No. 19: Effects of Nalco 8101 on virus contained in water with 14 NTU turbidity.

Condition: Polyelectrolyte: Nalco 8101. Virus suspension in turbid water (14 NTU). Tap (Control): Virus suspension in tap water; no Nalco 8101 added. Susp. (Control): Virus suspension in turbid water; no Nalco 8101 added.

Initial titer: ≈ 5.4×10^3 PFU/ml

Nalco 8101 Dosage (mg/l)	Flocculation Time (min)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Samples			Mean	Standard Deviation	Replicate Samples			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	54	46	32	44	11	336	368	420	375	42
Susp.	0	23	27	20	23	4	342	351	357	350	8
2	0	4	2	4	3	1	19	30	21	23	6
4	0	4	0	2	2	2	17	16	19	17	2
6	0	1	1	2	1	1	29	31	44	35	8
8	0	1	0	3	1	1	15	25	30	23	8
10	0	1	3	1	1	1	33	35	26	31	5
Tap	15	55	27	0	41	20	352	435	402	396	42
Susp.	15	29	33	39	34	5	386	336	399	374	33
2	15	0	0	0	0	0	29	15	18	21	7
4	15	1	3	1	2	1	16	8	16	13	5
6	15	1	0	3	1	2	16	35	33	28	10
8	15	1	2	0	1	1	11	12	7	10	3
10	15	0	1	1	1	1	28	13	16	19	8
Tap	30	38	44	33	38	6	408	392	391	397	10
Susp.	30	34	34	31	33	2	397	368	379	381	15
2	30	2	0	0	1	1	9	10	5	8	3
4	30	0	0	1	0	1	12	6	13	10	4
6	30	4	0	1	2	2	11	18	17	15	4
8	30	2	3	1	2	1	12	12	11	12	1
10	30	0	2	0	1	1	16	13	19	16	3
Tap	45	40	47	48	45	4	366	425	386	392	30
Susp.	45	60	38	41	46	12	367	353	373	364	10
2	45	0	2	2	1	1	11	12	6	10	3
4	45	0	0	1	0	1	4	1	2	2	2
6	45	0	0	1	0	1	11	14	19	15	4
8	45	0	0	0	0	0	14	16	8	13	4
10	45	0	0	0	0	0	12	11	10	11	1
Tap	45	41	36	67	48	17	396	384	389	390	6
Susp.	Samples centrifuged at 10,000 rpm for 3 minutes	37	40	41	39	2	414	462	386	421	38
2		0	0	0	0	0	0	0	4	1	2
4		0	0	1	0	1	1	0	1	1	1
6		1	0	0	0	1	10	8	10	9	1
8		0	0	0	0	0	3	2	9	5	4
10		0	0	0	0	0	9	9	4	7	3

Table A-20. Experiment No: 20: Effects of Nalco 8101 on virus contained in water without turbidity.

Condition: Polyelectrolyte: Nalco 8101. Virus suspension in tap water without turbidity. Tap (Control): Virus suspension in tap water; no Nalco 8101 added.

Initial titer: $\approx 5.4 \times 10^3$ PFU/ml

Nalco 8101 Dosage (mg/l)	Flocculation Time (min)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	382	395	398	392	9	66	64	58	63	4
2	0	31	25	41	32	8	8	2	4	5	3
4	0	63	78	30	57	25	2	6	5	4	2
6	0	59	70	62	64	6	8	11	8	9	2
8	0	68	58	57	61	6	8	4	7	6	2
10	0	104	72	77	84	17	4	4	3	4	1
Tap	15	363	369	397	376	18	88	86	79	84	5
2	15	23	27	20	23	4	3	4	2	3	1
4	15	58	43	38	46	10	3	4	7	5	2
6	15	48	47	26	40	12	19	8	10	12	6
8	15	71	62	58	64	7	7	2	2	4	3
10	15	45	27	39	37	9	3	3	6	4	2
Tap	30	423	435	447	435	12	90	74	63	76	14
2	30	30	17	15	21	8	4	1	2	2	2
4	30	44	21	23	29	13	1	0	2	1	1
6	30	33	23	39	32	8	2	3	5	3	2
8	30	39	54	46	46	8	5	3	3	4	1
10	30	27	15	31	24	8	5	2	1	3	2
Tap	45	462	437	513	471	39	94	77	87	86	9
2	45	16	11	8	12	4	1	0	0	0	1
4	45	14	19	12	15	4	3	0	1	1	2
6	45	30	24	20	25	5	2	1	2	2	1
8	45	25	27	28	27	2	1	2	3	2	1
10	45	27	28	23	26	3	1	2	3	2	1

Table A-21. Experiment No. 21: Effects of Nalco 8102 on virus contained in water without turbidity.

Condition: Polyelectrolyte: Nalco 8102. Virus suspension in tap water without turbidity. Tap (Control): Virus suspension in tap water; no Nalco added.

Initial titer: ≈ 5.4 x 10^3 PFU/ml

Nalco 8102 Dosage (mg/1)	Flocculation Time (min)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	435	393	358	395	39	410	417	385	404	17
2	0	278	235	212	242	34	215	173	202	197	22
4	0	200	207	195	201	6	210	217	208	212	5
6	0	415	311	344	357	53	297	275	238	270	30
8	0	281	276	256	271	13	273	229	257	253	22
10	0	205	243	282	243	39	216	243	240	233	15
Tap	15	409	442	367	406	38	434	368	397	400	33
2	15	241	189	210	213	26	205	211	228	215	12
4	15	215	221	209	215	6	202	246	260	236	30
6	15	337	332	298	332	21	299	273	274	282	15
8	15	315	249	224	263	47	241	225	199	222	21
10	15	187	224	275	229	44	206	232	237	225	17
Tap	30	423	413	411	416	6	428	422	426	425	3
2	30	219	213	212	215	4	203	205	199	202	4
4	30	230	241	232	234	6	231	217	274	241	30
6	30	158	183	241	194	43	275	311	268	285	23
8	30	211	225	229	222	9	254	231	262	249	16
10	30	271	269	285	275	9	245	255	278	259	17
Tap	45	421	432	412	422	10	436	404	431	424	17
2	45	211	226	204	214	11	177	186	207	190	15
4	45	224	252	258	245	18	257	240	221	239	18
6	45	246	317	345	303	51	286	264	271	274	11
8	45	272	316	298	295	22	260	256	268	261	6
10	45	235	271	279	262	23	265	259	303	276	24

Table A-22. Experiment No. 22: Effects of Nalco 8102 on virus contained in water with 14 NTU turbidity.

Condition: Polyelectrolyte: Nalco 8102. Virus suspension in turbid water (≈ 14 NTU). Tap (Control): Virus suspension in tap water; no Nalco added. Susp. (Control): Virus suspension in turbid water; no Nalco added.

Initial titer: ≈ 5.4×10^3 PFU/ml

Nalco 8102 Dosage (mg/l)	Flocculation Time (min)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	395	402	398	398	4	442	414	406	421	19
Susp.	0	296	314	399	336	55	392	381	346	373	24
2	0	162	163	133	153	17	205	172	245	207	37
4	0	132	140	99	124	22	172	231	272	225	50
6	0	240	253	297	263	30	341	314	256	304	43
8	0	205	210	186	200	13	214	245	168	209	39
10	0	188	215	187	197	16	238	184	267	230	42
Tap	15	405	422	401	409	11	454	438	406	433	24
Susp.	15	301	282	355	313	38	434	435	421	430	8
2	15	104	105	103	104	1	201	244	205	217	24
4	15	132	104	104	113	16	171	210	258	213	44
6	15	215	244	262	240	24	366	356	286	336	44
8	15	201	172	177	183	16	287	281	228	265	32
10	15	189	142	186	172	26	280	289	312	294	17
Tap	30	357	358	422	380	37	435	423	463	440	21
Susp.	30	283	366	362	337	47	396	572	449	472	90
2	30	74	76	78	76	2	198	199	170	189	16
4	30	135	88	78	100	30	171	196	246	204	38
6	30	201	200	248	216	27	354	342	311	336	22
8	30	177	169	181	176	6	299	283	284	289	9
10	30	234	186	190	203	27	272	313	354	313	41
Tap	45	406	434	438	426	17	451	496	495	481	26
Susp.	45	367	385	379	377	9	435	448	426	436	11
2	45	57	36	72	55	18	158	156	203	172	27
4	45	90	85	73	83	9	224	271	282	259	31
6	45	215	199	219	211	11	312	325	336	324	12
8	45	189	148	215	184	34	314	296	323	311	14
10	45	273	172	188	211	54	285	299	339	308	28
Tap	45	425	421	464	437	24	455	506	491	484	26
Susp.	Samples centrifuged at 10,000 rpm for 3 minutes	423	400	354	392	35	578	450	485	504	66
2		17	16	31	21	8	76	85	90	84	7
4		37	32	23	31	7	203	225	216	215	11
6		111	141	158	137	24	326	310	256	297	37
8		173	182	147	167	18	264	325	248	279	41
10		196	177	193	189	10	284	302	294	293	9

Table A-23. Experiment No. 23: Effects of Nalco 8103 on virus contained in water without turbidity.

Condition: Polyelectrolyte: Nalco 8103. Virus suspension in tap water without turbidity. Tap (Control): Virus suspension in tap water; no Nalco added.

Initial titer: $\simeq 5.4 \times 10^3$ PFU/ml

Nalco 8103 Dosage (mg/l)	Flocculation Time (min)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	365	358	346	356	10	395	386	352	378	23
2	0	197	171	185	84	13	207	195	179	194	14
4	0	175	210	181	189	19	174	178	185	179	6
6	0	276	272	224	257	29	276	270	242	263	18
8	0	188	200	186	191	8	202	219	215	212	9
10	0	185	186	155	175	18	170	189	204	188	17
Tap	15	378	330	325	344	29	415	392	406	404	12
2	15	178	159	147	161	16	155	143	138	145	9
4	15	132	170	156	153	19	117	130	147	131	15
6	15	249	236	233	239	9	211	254	202	222	28
8	15	193	208	206	202	8	196	185	230	204	23
10	15	182	169	201	184	16	161	162	183	169	12
Tap	30	376	344	391	370	24	393	381	366	380	14
2	30	197	168	204	190	19	165	177	157	166	10
4	30	196	147	157	167	26	131	202	156	163	36
6	30	219	238	235	231	10	203	200	169	191	19
8	30	159	176	157	164	10	160	194	168	174	18
10	30	168	182	192	181	12	134	146	120	133	13
Tap	45	394	368	386	373	19	317	398	383	366	43
2	45	142	121	132	132	11	128	115	103	115	13
4	45	123	135	185	148	33	149	133	145	142	8
6	45	261	216	208	228	29	185	173	168	175	9
8	45	183	186	188	186	3	161	172	180	171	10
10	45	191	162	215	189	27	128	116	-	122	8

Table A-24. Experiment No. 24: Effects of Nalco 8103 on virus contained in water with 14 NTU turbidity.

Condition: Polyelectrolyte: Nalco 8103. Virus suspension in turbid water (≈ 14 NTU). Tap (Control): Virus suspension in tap water; no Nalco added. Susp. (Control): Virus suspension in turbid water; no Nalco added.

Initial titer: ≈ 5.4×10^3 PFU/ml

Nalco 8103 Dosage (mg/l)	Flocculation Time (min)	Test #1					Test #2				
		10^{-1} Dilution					10^{-1} Dilution				
		Replicate Plates			Mean	Standard Deviation	Replicate Plates			Mean	Standard Deviation
		1	2	3			1	2	3		
Tap	0	432	397	389	406	23	366	337	387	363	25
Susp.	0	395	406	349	383	30	383	247	359	330	73
2	0	224	202	192	206	16	175	198	183	185	12
4	0	184	239	179	201	33	132	192	173	166	31
6	0	344	312	281	312	32	309	239	261	270	36
8	0	232	218	212	221	10	177	217	179	191	23
10	0	199	218	204	207	10	170	189	197	185	14
Tap	15	415	405	388	403	14	361	365	312	346	30
Susp.	15	354	368	382	366	14	341	330	222	298	66
2	15	184	207	161	184	23	133	139	134	135	3
4	15	166	149	143	153	12	118	142	137	132	13
6	15	309	325	258	297	35	244	242	232	239	6
8	15	232	229	199	220	18	176	169	179	175	5
10	15	223	248	221	231	15	183	167	185	178	10
Tap	30	406	392	385	394	11	367	378	370	372	6
Susp.	30	426	411	389	409	19	393	315	358	355	39
2	30	230	184	159	191	36	112	106	122	113	8
4	30	189	179	185	184	5	114	156	145	138	22
6	30	341	303	254	299	44	255	246	228	243	14
8	30	259	215	239	238	22	186	217	228	210	22
10	30	187	241	242	223	31	168	187	214	190	23
Tap	45	398	406	383	396	12	385	372	356	371	15
Susp.	45	417	413	409	413	4	358	303	325	329	28
2	45	130	126	116	124	7	90	85	120	98	19
4	45	163	158	176	166	9	102	144	163	136	31
6	45	338	317	310	322	15	236	244	217	232	14
8	45	261	242	255	253	10	198	231	173	201	29
10	45	241	228	219	229	11	174	177	189	180	8
Tap	45	359	397	389	382	20	335	367	357	353	16
Susp.	Samples centrifuged at 10,000 rpm for 3 minutes	384	425	411	407	21	349	338	301	329	25
2		114	116	89	106	15	61	65	66	64	3
4		179	197	201	192	11	144	127	102	124	21
6		285	227	251	254	29	261	185	132	193	65
8		225	254	244	241	15	202	182	213	199	16
10		189	258	230	226	35	163	196	194	184	19

Appendix B

Table B-1. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum
Virus titer: ≈ 1397 to 1480 PFU/ml
Turbidity: ≈ 16 to 21 NTU
Filter: Single-medium Sand
Hydraulic loading rate on the filter: 12.2 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration, PFU/ml Replicate Plates 1	2	3	Virus Conc. PFU/ml $\bar{X}^a$	Standard Deviation
84	0.34	1	30	50	80	53	25
76	0.89	1	40	40	30	37	5
61	0.79	1	70	70	80	80	10
46	2.6	1	100	90	160	117	38
31	13	1	360	380	430	390	36
15	64	1	1470	1380	1750	1533	193
0	23	1	1520	1350	1220	1363	151
Rapid Mix Tank	21	1	1490	1540	1410	1480	66
84	2.2	3	20	100	80	67	42
76	8.4	3	30	10	30	23	11
61	26	3	50	10	10	23	23
46	18	3	10	0	0	3	5
31	23	3	160	200	200	187	23
15	244	3	550	1180	1010	913	326
0	16	3	660	1130	930	907	236
Rapid Mix Tank	16	3	1770	1270	1150	1397	329

[a]Mean of three replicate plates.

Table B-2. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum
Virus titer: ≈ 897 to 1480 PFU/ml
Turbidity: ≈ 15 to 21 NTU
Filter: Dual-media (anthracite and sand)
Hydraulic loading rate on the filter: 12.2 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration, PFU/ml Replicate Plates 1	2	3	Virus Conc. PFU/ml $\bar{X}^a$	Standard Deviation
84	0.46	1	80	90	110	93	15
76	4.7	1	130	150	90	123	30
61	7.7	1	350	190	350	297	93
46	90	1	2310	2110	1950	2123	180
31	75	1	2460	2380	2600	2480	111
15	132	1	3760	3790	3300	3617	275
0	20	1	1170	1130	1050	1117	61
Rapid Mix Tank	21	1	1490	1540	1410	1480	66
84	1.3	5	20	50	50	40	17
76	48	5	110	110	200	140	52
61	87	5	230	200	290	240	46
46	390	5	3200	2720	280	3500	265
31	341	5	4810	3600	3700	4037	672
15	362	5	2860	4330	4250	3813	826
0	15	5	1580	1670	2110	1787	284
Rapid Mix Tank	15	5	1770	1270	1150	1397	329
84	4.9	9	170	110	140	140	30
76	45	9	170	140	180	163	20
61	27	9	120	120	190	143	40
46	195	9	1300	1540	1750	153	225
31	223	9	3600	3250	320	3350	218
15	37	9	370	550	280	400	137
0	15	9	180	210	410	267	125
Rapid Mix Tank	16	9	910	950	830	897	61

[a]Mean of three replicate plates.

Table B-3. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l
Virus titer: ≈ 1397 to 8970 PFU/ml
Turbidity: ≈ 16 to 21 NTU
Filter: Tri-media (anthracite, sand, and garnet)
Hydraulic loading rate on the filter: 12.2 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml			Virus Conc. PFU/ml	Standard Deviation
			Replicate Plates				
			1	2	3	$\bar{X}$[a]	
84	0.25	1	40	60	30	43	16
76	1.2	1	50	80	60	63	16
61	2.7	1	250	160	350	253	95
46	27	1	370	470	510	450	72
31	33	1	1160	1570	1290	1340	210
15	115	1	1740	2200	2130	2023	248
0	23	1	1200	1080	1320	1200	120
Rapid Mix Tank	21	1	1490	1540	1410	1480	66
84	2.5	5	20	10	10	13	5
76	112	5	10	100	140	83	66
61	130	5	130	110	120	120	10
46	202	5	120	590	470	393	244
31	250	5	620	740	1430	930	437
15	362	5	350	270	570	397	156
0	18	5	450	490	360	433	66
Rapid Mix Tank	15	5	1770	1270	1150	1397	329
84	5.6	9	50	110	50	70	35
76	75	9	390	240	190	273	104
61	52	9	370	360	300	34.3	38
46	132	9	1490	1970	2610	2023	562
31	188	9	1860	1890	1560	1770	182
15	77	9	340	300	260	300	40
0	15	9	250	220	300	257	41
Rapid Mix Tank	16	9	910	950	830	8970	61

[a]Mean of three replicate plates.

Table B-4. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l
Virus titer: ≈ 33 to 4340 PFU/ml
Turbidity: ≈ 12 to 13 NTU
Filter: Single-medium (sand)
Hydraulic loading rate on the filter: 12.2 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml			Virus Conc. PFU/ml	Standard Deviation
			Replicate Plates				
			1	2	3	$\bar{X}$[a]	
84	0.5	1	290	230	180	233	55
76	9.8	1	200	200	210	203	5
61	29	1	170	260	110	180	75
46	24	1	120	210	170	167	45
31	10	1	470	460	330	420	78
15	30	1	350	260	250	287	55
0	12	1	490	460	610	520	790
Rapid Mix Tank	12	1	60	40	0	33	30
84	0.67	5	3120	2450	2170	2580	488
76	3.2	5	1850	2230	1720	1933	265
61	7.0	5	1880	1730	1490	1700	197
46	Plugged	5			Plugged		
31	6.2	5	620	740	1070	810	233
15	80	5	5180	4650	4210	4680	486
0	14	5	4240	4120	4390	4250	135
Rapid Mix Tank	13	5	4810	4550	3660	4340	603

[a]Mean of three replicate plates.

Table B-5. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l
Virus titer: ≈ 33 to 5547 PFU/ml
Turbidity: ≈ 10 to 18 NTU
Filter: Dual-media (anthracite and sand)
Hydraulic loading rate on the filter: 12.2 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml				Standard Deviation
			Replicate Plates			Virus Conc. PFU/ml	
			1	2	3	$\bar{X}$[a]	
84	0.46	1	210	180	160	183	25
76	5.8	1	170	40	110	107	65
61	5.5	1	0	200	70	90	101
46	91	1	90	120	100	103	15
31	45	1	890	600	440	643	228
15	34	1	450	430	330	403	64
0	32	1	140	160	150	150	10
Rapid Mix Tank	12	1	60	40	0	33	30
84	0.44	5	3530	2660	2330	2840	620
76	7.1	5	2680	2490	1980	2383	362
61	28	5	1890	2050	1860	1933	102
46	125	5	4380	4740	5370	483	501
31	37	5	4350	4100	3210	3887	600
15	82	5	3920	3730	3870	3840	98
0	14	5	2850	3260	4290	3467	742
Rapid Mix Tank	13	5	4810	4550	3660	4340	603
84	0.38	8	150	220	320	230	85
76	6.8	8	0	0	0	0	0
61	15	8	0	0	0	0	0
46	118	8	3470	3850	4150	3823	340
31	91	8	450	540	600	530	75
15	209	8	790	490	570	617	156
0	11	8	120	50	90	87	35
Rapid Mix Tank	12	8	100	150	170	140	36
84	3.7	12	4550	4290	4210	4350	178
76	27	12	4230	4300	3640	4057	363
61	35	12	4810	4580	4940	4790	201
46	107	12	5850	5670	6180	5900	259
31	116	12	6510	656	TNTC	6535	35
15	209	12	TNTC	654	554	6040	707
0	27	12	5810	5630	6010	5817	190
Rapid Mix Tank	18	12	5660	5560	5420	5547	121

[a]Mean of three replicate plates.

Table B-5. Continued.

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml				Standard Deviation
			Replicate Plates			Virus Conc. PFU/ml	
			1	2	3	$\bar{X}$[a]	
84	2.2	15	1690	1250	1200	1380	270
76	16	15	1430	1420	1690	1513	153
61	29	15	1860	1480	1700	1680	191
46	118	15	5740	6020	5920	5893	142
31	73	15	3850	4140	b	3995	205
15	49	15	5890	5340	5410	5547	300
0	12	15	3070	3580	3580	3410	294
Rapid Mix Tank	13	15	3150	2670	2860	2893	241
84	2.1	19	300	190	340	2770	78
76	41	19	250	300	70	207	121
61	46	19	0	0	0	0	0
46	350	19	0	0	0	0	0
31	313	19	1590	910	690	1063	469
15	313	19	650	330	30	337	310
0	10	19	20	30	40	30	10
Rapid Mix Tank	10	19	0	0	0	0	0
84	3.9	24	40	80	90	70	26
76	46	24	150	160	110	140	26
61	73	24	0	20	20	130	11
46	89	24	20	0	0	70	12
31	118	24	170	120	90	127	41
15	293	24	320	220	210	250	61
0	28	24	0	0	0	0	0
Rapid Mix Tank	15	24	0	0	0	0	0
84	6.8	35	420	250	310	327	87
76	108	35	260	320	240	273	41
61	108	35	540	900	270	570	316
46	334	35	730	630	260	540	248
31	293	35	1800	1570	1260	1543	271
15	223	35	530	560	480	523	40
0	27	35	90	50	140	93	45
Rapid Mix Tank	16	35	280	330	110	153	119

[a]Mean of three replicate plates.

[b]Contaminated.

Table B-6. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l
Virus titer: ≈ 0 to 5547 PFU/ml
Turbidity: ≈ 10 to 18 NTU
Filter: Tri-media (anthracite, sand and garnet)
Hydraulic loading rate on the filter: 12.2 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml			Virus Conc. PFU/ml	Standard Deviation
			Replicates Plates				
			1	2	3	$\bar{X}$ [a]	
84	0.23	1	160	130	130	140	17
76	5.6	1	30	80	50	53	25
61	4.0	1	60	0	10	23	32
46	12.0	1	0	60	0	20	35
31	16	1	310	350	450	370	72
15	34	1	140	100	110	117	21
0	13	1	80	200	190	157	67
Rapid Mix Tank	12	1	60	40	0	33	30
84	0.34	5	2350	3250	2980	2850	452
76	6.5	5	1590	1880	1850	1773	159
61	22	5	1780	1250	1830	1620	321
46	39	5	2360	2150	1450	1987	477
31	16	5	3940	3420	2920	3427	510
15	90	5	3550	3780	3920	3750	187
0	14	5	2680	2310	3270	2753	484
Rapid Mix Tank	13	5	4810	4550	3660	4340	603
84	0.30	8	300	100	290	230	113
76	4	8	80	30	70	60	26
61	15	8	40	120	60	73	41
46	88	8	0	30	40	23	20
31	101	8	1150	550	920	873	302
15	3.3	8	620	960	1150	910	269
0	14	8	40	60	20	40	20
Rapid Mix Tank	12	8	100	150	170	140	36
84	5.5	12	4330	3640	3920	3963	77
76	76	12	4350	3880	4030	4087	240
61	76	12	3920	3790	3820	3843	68
46	114	12	3350	3780	3190	3440	305
31	87	12	5480	5360	5260	5367	11
15	112	12	TNTC	TNTC	TNTC	6690	270
0	23	12	4560	4200	4170	4310	217
Rapid Mix Tank	18	12	5660	5560	5420	5547	121

[a]Mean of three replicate plates.

Table B-6. Continued.

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml			Virus Conc. PFU/ml	Standard Deviation
			Replicate Plates				
			1	2	3	$\bar{X}$ [a]	
84	8.7	15	1830	1950	1600	1793	178
76	26	15	2920	2750	2490	2720	217
61	45	15	3380	3450	3550	346	85
46	120	15	5670	6290	6830	6263	58
31	104	15	5160	5100	5260	5373	344
15	75	15	TNTC	TNTC	TNTC	7000	50
0	15	15	2640	2700	3140	2827	273
Rapid Mix Tank	13	15	3150	2670	2860	2893	241
84	2.3	19	740	600	450	597	145
76	29	19	100	0	50	50	50
61	79	19	10	50	10	23	23
46	125	19	0	0	0	0	0
31	118	19	910	420	390	573	292
15	334	19	10	0	30	13	15
0	10	19			Plugged		
Rapid Mix Tank	10	19	0	0	0	0	0
84	2.8	24	0	0	0	0	0
76	32	24	0	0	0	7	12
61	101	24	70	80	10	53	38
46	119	24	730	550	250	51	242
31	116	24	390	170	150	237	133
15	264	24	150	100	80	110	36
0	36	24	0	0	0	0	0
Rapid Mix Tank	15	24	0	0	0	0	0
84	8.3	35	460	620	240	440	191
76	102	35	300	180	130	203	87
61	102	35	90	70	140	100	36
46	265	35	230	50	60	113	101
31	265	35	510	380	460	450	66
15	265	35	140	300	530	323	196
0	29	35	70	70	60	67	6
Rapid Mix Tank	16	35	280	330	110	153	119

[a]Mean of three replicate plates.

Table B-7. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l
Virus titer: ≈ 997 to 1717 PFU/ml
Turbidity: ≈ 13 to 14 NTU
Filter: Single-medium (sand)
Hydraulic loading rate on the filter: 7.3 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml				Standard Deviation
			Replicate Plates			Virus Conc. PFU/ml	
			1	2	3	$\bar{X}$[a]	
84	0.26	1	790	810	710	770	53
76	9.2	1	430	480	400	437	41
61	0.72	1	540	560	420	507	76
46	1.0	1	310	410	730	483	219
31	6.6	1	740	720	600	687	76
15	115	1	3250	2790	2430	2823	411
0	13	1	2040	1650	2070	1920	234
Rapid Mix Tank	13	1	1100	1230	1050	1127	93
84	0.2	3	10	20	10	13	5
76	1.1	3	10	20	10	13	5
61	3.3	3	90	40	50	60	26
46	16	3	110	240	100	150	78
31	45	3	890	560	700	717	166
15	313	3	5150	5050	4630	4943	276
0	15	3	730	760	730	740	17
Rapid Mix Tank	14	3	1700	1560	1890	1717	166
84	0.27	5	40	90	50	60	26
76	4.8	5	60	20	40	40	20
61	24	5	450	260	210	307	127
46	97	5	320	520	440	427	101
31	132	5	1450	1470	1540	1487	48
15	334	5	5940	6260	6120	6107	161
0	14	5	600	760	690	683	80
Rapid Mix Tank	14	5	990	920	1080	997	81

[a]Mean of three replicate plates.

Table B-8. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l
Virus titer: ≈ 997 to 5227 PFU/ml
Turbidity: ≈ 12 to 14 NTU
Filter: Dual-media (anthracite and sand)
Hydraulic loading rate on the filter: 7.3 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml				Standard Deviation
			Replicate Plates			Virus Conc. PFU/ml	
			1	2	3	$\bar{X}$[a]	
84	0.18	1	600	410	390	467	116
76	0.39	1	480	340	550	457	107
61	0.64	1	350	600	400	450	132
46	51	1	110	1420	1070	1197	194
31	20	1	870	990	810	890	92
15	79	1	990	750	1290	1010	271
0	15	1	1640	1190	1120	1317	283
Rapid Mix Tank	13	1	1100	1230	1050	1127	93
84	0.25	3	40	30	40	37	6
76	14	3	50	110	80	80	30
61	34	3	160	170	160	163	5
46	383	3	1230	1140	1280	1217	71
31	130	3	2420	2010	1920	2117	267
15	118	3	1170	1410	1270	1283	12
0	14	3	1090	980	1120	1063	73
Rapid Mix Tank	14	3	1700	1560	1890	1717	166
84	0.23	5	90	90	80	87	6
76	12	5	150	120	180	150	30
61	28	5	440	390	310	380	66
46	116	5	1970	1440	2380	1930	471
31	133	5	2950	2790	2440	2727	261
15	127	5	2920	2640	1970	2510	488
0	14	5	940	1080	790	937	145
Rapid Mix Tank	14	5	990	920	1080	997	81
84	0.57	7	1200	1110	960	1090	121
76	23	7	830	1120	1020	990	147
61	89	7	1900	1790	1720	1803	90
46	383	7	4020	3910	3310	3747	382
31	0.32	7	3610	3120	3060	3263	301
15	334	7	4160	3930	3680	3923	24
0	19	7	1970	1750	1790	1837	118
Rapid Mix Tank	14	7	2540	2060	2010	2203	292
84	0.44	9	3820	3970	3420	3737	285
76	25	9	4280	4560	4540	446	156
61	47	9	4490	4780	3890	4387	454
46	139	9	6710	7100	6890	6900	195
31	111	9	6750	7320	7380	7150	348
15	306	9	7200	6640	7030	6957	287
0	13	9	4450	4240	3780	4157	343
Rapid Mix Tank	12	9	5350	5090	5240	5227	131

[a]Mean of three replicate plates.

Table B-9. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum
Virus titer: ≈ 997 to 5227 PFU/ml
Turbidity: ≈ 12 to 14 NTU
Filter: Tri-media (anthracite, sand and garnet)
Hydraulic loading rate on the filter: 7.3 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml			Virus Conc. PFU/ml	Standard Deviation
			Replicate Plates				
			1	2	3	$\bar{X}$[a]	
84	0.13	1	290	410	330	343	61
76	0.55	1	350	270	320	313	40
61	0.97	1	780	430	350	520	229
46	3.6	1	1160	860	790	937	197
31	32	1	830	870	650	783	117
15	88	1	1650	1380	1200	1410	226
0	12	1	1240	910	1110	1087	167
Rapid Mix Tank	13	1	110	1230	1050	1127	93
84	0.24	3	10	10	30	17	12
76	0.33	3	10	10	30	17	12
61	9.0	3	70	80	80	77	6
46	91	3	1010	800	870	893	107
31	95	3	1640	980	790	1137	446
15	123	3	3640	3410	3040	3363	302
0	16	3	480	440	390	437	45
Rapid Mix Tank	14	3	170	1560	1890	1717	166
84	0.14	5	70	40	30	47	21
76	1.3	5	70	110	30	70	40
61	28	5	260	150	190	200	56
46	109	5	1110	980	1210	1100	115
31	115	5	1720	1590	1550	1620	89
15	101	5	3020	2540	2630	2730	255
0	16	5	710	620	560	630	75
Rapid Mix Tank	14	5	990	920	1080	997	81
84	0.2	7	1120	980	830	977	145
76	8.4	7	720	850	790	787	65
61	87	7	890	920	1050	953	85
46	133	7	2510	2470	2130	237	209
31	116	7	1920	2070	1740	191	165
15	348	7	3550	260	3280	3143	489
0	16	7	180	150	160	163	15
Rapid Mix Tank	14	7	2540	2060	2010	2203	292
84	0.16	9	3570	3810	3340	3573	235
76	15	9	3640	3320	3090	3350	281
61	95	9	4020	3820	4560	4133	382
46	132	9	610	5710	6070	5960	217
31	130	9	6150	5880	5210	5747	484
15	334	9	6820	720	670	6907	26
0	16	9	3330	3720	3590	3547	199
Rapid Mix Tank	12	9	5350	509	524	5227	131

[a]Mean of three replicate plates.

Table B-10. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum
Virus titer: ≈ 1127 to 4047 PFU/ml
Turbidity: ≈ 7 to 17 NTU
Filter: Single-medium (sand)
Hydraulic loading rate on the filter: 7.3 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml			Virus Conc. PFU/ml	Standard Deviation
			Replicate Plates				
			1	2	3	$\bar{X}$[a]	
84	0.24	1	1650	1370	1400	1473	153
76	0.55	1	1270	1120	1480	1290	181
61	1	1	1000	1190	1630	1273	323
46	6.9	1	1340	1570	1310	1407	143
31	14	1	1350	1030	1370	1250	191
15	89	1	1240	1360	1540	1350	105
0	17	1	1760	1860	1730	1783	68
Rapid Mix Tank	17	1	730	1060	1590	1127	434
84	0.37	3	2590	2540	1830	2320	4250
76	0.48	3	1590	1400	1840	1610	221
61	2.1	3	1850	2280	2250	2127	24
46	6.0	3	1550	1590	1380	1507	112
31	14	3	1710	1560	1660	1643	76
15	123	3	1990	1730	1910	1877	133
0	13	3	1860	2160	1990	2003	15
Rapid Mix Tank	13	3	1290	1180	1860	1443	365
84	0.22	5	480	630	430	513	104
76	0.79	5	630	780	810	740	96
61	2.1	5	810	1250	710	923	287
46	7.4	5	830	820	850	833	15
31	26	5	1880	2290	1450	1873	42
15	130	5	3160	2760	2730	2883	24
0	9	5	1880	1890	1590	1787	171
Rapid Mix Tank	9	5	1810	1840	1890	1847	41
84	0.48	7	3260	3310	3140	3237	88
76	4.1	7	3220	3310	3150	3227	81
61	11	7	3690	4140	4160	3997	266
46	36	7	4560	3840	3930	4110	392
31	104	7	3990	4640	4370	4333	326
15	348	7	5210	4650	4100	4653	555
0	12	7	3530	4280	4880	4230	676
Rapid Mix Tank	12	7	3720	4420	3990	4043	353
84	0.48	9	5420	4840	5180	5147	292
76	1.1	9	4810	527	538	5153	302
61	5.9	9	527	618	611	5853	506
46	34	9	538	646	590	5913	540
31	97	9	6470	6040	6640	6383	309
15	334	9	7440	7600	7360	7467	123
0	4.1	9	6350	6750	6740	6613	228
Rapid Mix Tank	7.4	9	290	3020	4510	3477	897

[a]Mean of three replicate plates.

Table B-11. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum
Virus titer: ≈ 1127 to 4047 PFU/ml
Turbidity: ≈ 7 to 17 NTU
Filter: Dual-media (anthracite and sand)
Hydraulic loading rate on the filter: 7.3 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml Replicate Plates 1	2	3	Virus Conc. PFU/ml $\bar{X}$[a]	Standard Deviation
84	0.34	1	1510	1370	990	1290	269
76	0.75	1	1070	1280	1050	1133	127
61	2.2	1	1330	1380	1020	1243	195
46	28	1	1540	1860	1990	1797	232
31	25	1	1580	1480	1200	1420	197
15	37	1	1080	1130	1050	1087	41
0	16	1	1080	1380	1680	1380	300
Rapid Mix Tank	17	1	730	1060	1590	1127	434
84	0.32	3	1170	1260	1610	1347	233
76	0.73	3	1690	1860	1550	1700	155
61	7.7	3	1680	1870	2330	1960	334
46	133	3	2490	2400	1950	2280	289
31	84	3	2020	1720	1810	1850	154
15	112	3	2190	1910	2630	2243	363
0	10	3	1640	2110	1860	1870	235
Rapid Mix Tank	13	3	1290	1180	1860	1443	365
84	0.29	5	1750	1540	1410	1567	172
76	1.6	5	1350	1630	1520	1500	141
61	8.8	5	1540	1740	1690	1657	104
46	139	5	2710	2510	3290	2837	405
31	52	5	2060	2350	1980	2130	195
15	93	5	930	1140	1020	1030	105
0	10	5	440	490	440	457	29
Rapid Mix Tank	9	5	1810	1840	1890	1847	41
84	0.30	7	2690	3290	2120	2700	585
76	3.2	7	2550	2910	2130	2530	390
61	12	7	3120	3650	3610	3460	295
46	137	7	5080	4760	4140	4660	478
31	91	7	4410	4880	3730	4340	578
15	125	7	4080	3270	3290	3547	462
0	11	7	2930	330	4220	3483	664
Rapid Mix Tank	12	7	3720	4420	3990	4043	353
84	0.46	9	4850	4910	4960	4907	55
76	0.97	9	4690	4730	5190	4870	278
61	4.6	9	5740	5280	5360	5460	246
46	127	9	8340	7780	7170	7763	585
31	101	9	5810	6210	6650	6223	42
15	115	9	5380	5540	5630	5517	127
0	6.5	9	5250	5760	5780	5597	301
Rapid Mix Tank	7.4	9	290	3020	4510	3477	897

[a]Mean of three replicate plates.

Table B-12. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l
Virus titer: ≈ 1127 to 4047 PFU/ml
Turbidity: ≈ 7 to 17 NTU
Filter: Tri-media (anthracite, sand and garnet)
Hydraulic loading rate on the filter: 7.3 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml Replicate Plates 1	2	3	Virus Conc. PFU/ml $\bar{X}$[a]	Standard Deviation
84	0.36	1	980	1010	930	973	40
76	0.37	1	950	1100	1070	1040	79
61	1.6	1	1150	1120	1380	1217	143
46	6.2	1	1120	960	930	1003	102
31	19	1	940	980	880	933	50
15	104	1	1210	1390	1450	1350	125
0	17	1	No samples				
Rapid Mix Tank	17	1	730	1060	1590	1127	434
84	0.26	3	2150	1780	1910	1947	188
76	0.66	3	1680	2030	1920	1877	179
61	4.0	3	1410	1520	1590	1507	91
46	29	3	1030	1300	1030	1120	156
31	45	3	1340	1230	1270	1280	56
15	123	3	1800	1620	1270	1563	269
0	15	3	360	280	400	347	61
Rapid Mix Tank	13	3	1290	1180	1860	1443	365
84	0.16	5	1610	1460	1450	1507	90
76	0.78	5	1720	1180	1430	1443	270
61	2.6	5	440	490	480	470	26
46	23	5	1570	1130	1340	1347	220
31	39	5	1440	1490	1830	1587	213
15	125	5	2410	2380	2740	2510	200
0	11	5	1050	1160	1460	1223	212
Rapid Mix Tank	9	5	1810	1840	1890	1847	41
84	0.23	7	3400	2680	3450	3177	431
76	1.2	7	2560	3260	2750	2857	362
61	7.3	7	2960	3450	3430	328	277
46	39	7	3440	2680	2750	2957	420
31	101	7	2830	3300	3780	3303	475
15	279	7	4230	3410	3450	3697	463
0	12	7	2600	3540	3580	3240	555
Rapid Mix Tank	12	7	3720	4420	3990	4043	353
84	0.37	9	4760	3940	4060	4253	443
76	0.63	9	3840	4240	4830	4308	503
61	1.8	9	4750	5480	5350	5193	389
46	43	9	4810	4200	4150	4387	368
31	46	9	3840	4430	4690	4320	4360
15	116	9	6340	7070	6650	6687	367
0	6	9	5410	5090	5650	5383	281
Rapid Mix Tank	7.4	9	290	3020	4510	3477	897

[a]Mean of three replicate plates.

Table B-13. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum and 2 mg/l Nalco
Virus titer: ≈ 627 to 2697 PFU/ml
Turbidity: ≈ 12 to 15 NTU
Filter: Single-medium (sand)
Hydraulic loading rate on the filter: 7.3 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml Replicate Plates 1	2	3	Virus Conc. PFU/ml $\bar{X}$[a]	Standard Deviation
84	1.1	1	0	0	0	0	0
76	1.2	1	10	0	10	3	5
61	1.7	1	0	0	0	0	0
46	4.7	1	0	10	0	3	5
31	6.7	1	10	0	10	7	8
15	101	1	10	0	10	7	8
0	14	1	0	0	0	0	0
Rapid Mix Tank	13	1	1040	850	650	847	195
84	1.5	3	0	0	0	0	0
76	1.8	3	0	20	10	1	1
61	2.3	3	0	10	10	7	6
46	2.7	3	10	20	10	13	5
31	5.4	3	0	0	0	0	0
15	86	3	20	0	0	7	12
0	15	3	0	0	0	0	0
Rapid Mix Tank	15	3	760	700	420	627	182
84	1	5	0	10	30	13	15
76	1.5	5	0	0	0	0	0
61	3.1	5	0	0	0	0	0
46	6.3	5	0	10	10	7	6
31	19	5	0	0	10	3	5
15	122	5	10	0	110	40	61
0	16	5	10	0	0	3	5
Rapid Mix Tank	14	5	1050	690	610	783	234
84	0.80	7	110	110	180	133	40
76	1.1	7	140	60	90	97	41
61	2.7	7	210	110	100	140	61
46	10	7	160	180	110	150	36
31	34	7	40	110	130	93	47
15	209	7	190	110	80	127	57
0	15	7	280	140	180	200	72
Rapid Mix Tank	13	7	2460	2390	2380	2410	44
84	0.83	9	340	390	360	363	25
76	1.1	9	390	350	200	313	100
61	2.6	9	460	230	310	333	116
46	9.9	9	300	420	430	383	7
31	34	9	440	190	320	317	125
15	112	9	590	260	300	383	180
0	13	9	510	470	470	483	23
Rapid Mix Tank	12	9	2750	3010	2330	2697	343

[a]Mean of three replicate plates.

Table B-14. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum and 2 mg/l Nalco 8101
Virus titer: ≈ 627 to 2697 PFU/ml
Turbidity: ≈ 12 to 15 NTU
Filter: Dual-media (anthracite and sand)
Hydraulic loading rate on the filter: 7.3 $m^3/hour/m^2$

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml Replicate Plates 1	2	3	Virus Conc. PFU/ml $\bar{X}$[a]	Standard Deviation
84	1.3	1	0	0	10	3	5
76	2.1	1	0	10	10	7	6
61	5.4	1	0	0	0	0	0
46	26	1	0	40	0	13	14
31	52	1	0	10	0	3	5
15	107	1	0	0	0	0	0
0	14	1	0	0	0	0	0
Rapid Mix Tank	13	1	1040	850	650	847	195
84	1.9	3	0	0	0	0	0
76	2.2	3	0	0	0	0	0
61	8.1	3	0	0	0	0	0
46	10	3	0	0	0	0	0
31	12	3	0	0	10	3	5
15	36	3	0	0	10	3	5
0	15	3	10	0	0	3	5
Rapid Mix Tank	15	3	760	700	420	627	182
84	1.3	5	10	0	20	10	10
76	3.8	5	0	10	10	7	6
61	18	5	0	0	0	0	0
46	36	5	10	10	0	7	6
31	51	5	0	10	10	7	6
15	107	5	10	0	0	3	5
0	15	5	0	10	0	3	5
Rapid Mix Tank	14	5	1050	690	610	783	234
84	0.24	7	140	170	100	137	35
76	3.4	7	180	80	250	170	85
61	24	7	40	80	90	70	26
46	36	7	140	120	120	127	12
31	39	7	120	160	110	130	26
15	119	7	140	180	120	147	31
0	14	7	150	60	130	113	47
Rapid Mix Tank	13	7	2460	2390	2380	241	44
84	0.88	9	220	300	330	283	57
76	3.0	9	380	280	230	297	77
61	17	9	370	390	350	370	20
46	31	9	300	530	480	437	121
31	100	9	350	500	310	387	100
15	116	9	530	340	170	347	180
0	13	9	210	350	290	283	70
Rapid Mix Tank	12	9	2750	3010	2330	2697	343

[a]Mean of three replicate plates.

Table B-15. Continuous filter operation.

Run No. 1
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum and 2 mg/l Nalco 8101
Virus titer: ≈ 627 to 2697 PFU/ml
Turbidity: ≈ 12 to 15 NTU
Filter: Tri-media (anthracite, sand and garnet)
Hydraulic loading rate on the filter: 7.3 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml			Virus Conc. PFU/ml	Standard Deviation
			Replicate Plates				
			1	2	3	$\bar{X}$[a]	
84	1.4	1	10	10	20	13	5
76	2.1	1	10	20	20	17	6
61	8.3	1	10	10	10	10	0
46	6.6	1	10	10	10	10	0
31	13	1	10	0	0	3	5
15	75	1	0	0	0	0	0
0	14	1	0	10	10	7	6
Rapid Mix Tank	13	1	1040	850	650	847	195
84	1.8	3	0	0	0	0	0
76	3	3	0	0	0	0	0
61	6.2	3	0	0	0	0	0
46	7.3	3	0	0	0	0	0
31	10	3	0	0	0	0	0
15	36	3	0	0	0	0	0
0	15	3	0	10	10	7	6
Rapid Mix Tank	15	3	760	700	420	627	182
84	1.2	5	20	20	10	17	6
76	3.3	5	10	10	20	13	5
61	15	5	20	20	40	27	12
46	23	5	30	10	0	13	15
31	27	5	10	10	20	13	5
15	115	5	0	0	0	0	0
0	16	5	0	0	20	7	12
Rapid Mix Tank	14	5	105	690	610	783	234
84	0.93	7	150	180	290	207	74
76	3.4	7	130	190	250	190	60
61	24	7	130	60	120	103	38
46	36	7	150	130	90	123	30
31	39	7	210	220	280	237	30
15	119	7	160	140	180	160	20
0	14	7	160	140	150	150	10
Rapid Mix Tank	13	7	2460	2390	2380	2410	44
84	0.90	9	440	430	310	393	72
76	2.9	9	300	480	340	373	94
61	20	9	490	450	480	473	20
46	32	9	470	590	600	553	72
31	37	9	390	550	590	510	106
15	122	9	600	780	420	600	180
0	13	9	540	470	500	503	35
Rapid Mix Tank	12	9	2750	3010	2330	2697	343

[a]Mean of three replicate plates.

Table B-16. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum and 2 mg/l Nalco 8101
Virus titer: ≈ 213 to 4300 PFU/ml
Turbidity: ≈ 11 to 13 NTU
Filter: Single-medium (sand)
Hydraulic loading rate on the filter: 7.3 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml			Virus Conc. PFU/ml	Standard Deviation
			Replicate Plates				
			1	2	3	$\bar{X}$[a]	
84	1.3	1	30	60	40	43	15
76	1.4	1	50	30	40	40	10
61	2.2	1	60	60	50	57	6
46	4.5	1	10	30	50	30	20
31	8.2	1	130	60	100	97	35
15	37	1	90	140	70	100	36
0	13	1	130	110	50	97	42
Rapid Mix Tank	13	1	110	270	260	213	89
84	0.92	3	460	420	510	463	45
76	1.1	3	520	350	310	393	111
61	1.5	3	310	310	210	277	58
46	4.3	3	450	290	360	367	81
31	12	3	320	340	300	320	20
15	118	3	550	430	360	447	96
0	13	3	360	430	630	473	140
Rapid Mix Tank	12	3	2640	2870	2970	2827	170
84	0.79	5	30	30	40	33	5
76	0.87	5	10	0	10	7	6
61	1.7	5	0	30	10	13	15
46	5.4	5	20	0	30	17	16
31	19	5	30	20	0	17	16
15	126	5	50	20	0	23	25
0	12	5	10	30	20	20	10
Rapid Mix Tank	11	5	30	0	20	2333	391
84	0.37	7	130	180	130	147	29
76	0.53	7	120	180	200	167	42
61	2.4	7	170	100	60	110	56
46	13	7	130	80	170	127	45
31	29	7	190	180	120	163	38
15	122	7	480	430	490	467	32
0	13	7	280	230	320	277	45
Rapid Mix Tank	13	7	4210	3870	4660	4247	397
84	0.69	9	210	460	590	420	193
76	1	9	450	410	470	443	30
61	4.6	9	600	420	710	577	147
46	25	9	460	580	860	633	205
31	53	9	450	430	630	503	110
15	209	9	1010	1190	1020	1073	101
0	12	9	No sample				
Rapid Mix Tank	13	9	4280	4610	4010	4300	300

[a]Mean of three replicate plates.

Table B-17. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum and 2 mg/l Nalco 8101
Virus titer: ≈ 213 to 4300 PFU/ml
Turbidity: ≈ 11 to 13 NTU
Filter: Dual-media (anthracite and sand)
Hydraulic loading rate on the filter: 7.3 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml Replicate Plates 1	2	3	Virus Conc. PFU/ml $\bar{X}$[a]	Standard Deviation
84	0.94	1	10	0	0	30	5
76	1.6	1	20	10	10	13	5
61	2.7	1	10	10	10	10	0
46	42	1	10	40	20	23	15
31	11	1	110	90	50	83	3
15	17	1	100	100	60	87	23
0	13	1	50	80	30	53	25
Rapid Mix Tank	13	1	110	270	260	213	89
84	0.91	3	310	290	410	337	65
76	1.2	3	420	310	290	340	70
61	5.4	3	230	310	300	280	44
46	130	3	380	440	680	500	159
31	77	3	780	350	470	533	222
15	102	3	450	410	380	413	35
0	13	3	310	340	290	313	25
Rapid Mix Tank	12	3	2640	2870	2970	2827	170
84	0.74	5	60	50	10	40	26
76	1	5	10	20	10	13	5
61	3.9	5	10	10	30	17	12
46	80	5	40	50	60	37	16
31	32	5	30	40	20	30	10
15	87	5	10	20	60	30	26
0	10	5	0	40	0	13	23
Rapid Mix Tank	11	5	2740	2300	1960	2333	391
84	0.32	7	160	190	220	190	30
76	0.68	7	100	60	100	87	23
61	3.3	7	130	150	60	113	47
46	83	7	330	230	230	263	57
31	79	7	750	1180	500	810	344
15	86	7	220	230	320	257	55
0	13	7	310	240	300	283	38
Rapid Mix Tank	13	7	4210	3870	4660	4247	397
84	0.53	9	330	470	330	377	81
76	0.93	9	320	200	360	293	83
61	5.2	9	330	320	360	337	21
46	98	9	450	510	760	573	164
31	76	9	470	220	530	407	165
15	118	9	490	480	900	623	239
0	12	9	480	470	550	500	44
Rapid Mix Tank	13	9	4280	4610	4010	4300	300

[a]Mean of three replicate plates.

Table B-18. Continuous filter operation.

Run No. 2
Conditions in the rapid mix basin:
Coagulant: 6 mg/l alum and 2 mg/l Nalco
Virus titer: ≈ 213 to 4300 PFU/ml
Turbidity: ≈ 11 to 13 NTU
Filter: Tri-media (anthracite, sand and garnet)
Hydraulic loading rate on the filter: 7.3 m^3/hour/m^2

Filter Depth (cm)	Turbidity (NTU)	Time After System Start Up	Virus Concentration PFU/ml Replicate Plates 1	2	3	Virus Conc. PFU/ml $\bar{X}$[a]	Standard Deviation
84	1.1	1	40	30	20	30	10
76	3.1	1	20	30	0	17	16
61	6.8	1	20	20	20	20	0
46	8.3	1	40	0	20	20	20
31	7.8	1	30	60	40	43	15
15	20	1	30	30	60	40	17
0	13	1	70	20	60	50	26
Rapid Mix Tank	13	1	110	270	260	213	89
84	0.89	3	630	560	480	557	75
76	1.7	3	320	310	290	301	10
61	7.3	3	340	280	300	307	31
46	34	3	490	450	560	500	56
31	29	3	770	590	710	690	92
15	118	3	560	680	600	613	61
0	13	3	610	450	350	470	131
Rapid Mix Tank	12	3	2640	2870	2970	2827	170
84	0.56	5	70	20	20	37	29
76	0.99	5	10	30	10	16	11
61	4.6	5	10	0	20	10	10
46	28	5	10	20	20	16	5.8
31	28	5	20	30	20	23	5.7
15	107	5	50	50	40	46	5.8
0	14	5	30	0	20	16	15
Rapid Mix Tank	11	5	2740	2300	1960	2333	391
84	0.28	7	160	340	330	277	101
76	0.58	7	180	110	260	183	75
61	4.1	7	230	210	310	250	53
46	29	7	490	750	490	577	150
31	44	7	1200	1000	1310	1170	157
15	123	7	1370	1200	1170	1247	108
0	13	7	360	720	1030	703	335
Rapid Mix Tank	13	7	4210	3870	4660	4247	397
84	0.44	9	290	580	460	443	145
76	0.68	9	160	360	300	273	102
61	4.4	9	370	340	330	347	21
46	38	9	440	710	690	613	15
31	46	9	310	430	370	370	60
15	122	9	560	370	200	377	180
0	12	9	430	440	740	537	176
Rapid Mix Tank	13	9	4280	4610	4010	4300	300

[a]Mean of three replicate plates.

Appendix C

D U N C A N
= = = = = =

```
                                                                      START OF SEGMENT 002
      DIMENSION GROW (75,30),SQ(75),P(16) ,R(100),SIG(75,75,1),ID(75)  C  002:0000:0
     ? , ALPHA(75,4)                                                  C  002:0000:0
      Data SIG/5625*' '/                                              C  002:0000:0
      READ(5,/,END=1)P                                                C  002:0000:6
                                                                        FIB IS 0006 LONG
    1 CONTINUE                                                        C  002:0006:0
      READ(5,/)ITREAT,ITIME                                           C  002:0008:6
      DO 5 J=1,ITIME                                                  C  002:0012:0
      DO 10 I=1,ITREAT                                                C  002:0013:0
      READ(5,100)GROW(I,J)                                            C  002:0014:0
C*****************************************************************   C  002:001C:2
C                                                                     C  002:001D:2
C                              FORMAT STATEMENT                       C  002:001D:2
C                                                                     C  002:001D:2
  100 FORMAT(30X,F4.0)                                                C  002:001D:2
C                                                                     C  002:001D:2
C                                                                     C  002:001D:2
C*****************************************************************   C  002:001D:2
      SQ (J)=SQ(J)+GROW(I,J)                                          C  002:001D:2
      TOT=TOT+GROW(I,J)**2                                            C  002:0021:2
   10 CONTINUE                                                        C  002:0024:5
      XSQJ=XSQJ+SQ(J)**2                                              C  002:0027:0
      CORR= CORR+SQ(J)                                                C  002:002A:2
      SQ(J)=0                                                         C  002:002B:2
    5 CONTINUE                                                        C  002:002C:5
      DO 6 I=1,ITREAT                                                 C  002:002F:0
      READ (5,500)(ALPHA(I,J),J=1,4)                                  C  002:0030:6
  500 FORMAT(5X,4A6)                                                  C  002:003E:2
    6 CONTINUE                                                        C  002:003E:2
      CORR=CORR**2                                                    C  002:0040:3
      DO 15 I=1,ITREAT                                                C  002:0041:4
      DO 20 J=1,ITIME                                                 C  002:0043:0
      SQ(I)=SQ(I)+GROW(I,J)                                           C  002:0044:0
   20 CONTINUE                                                        C  002:0048:0
      ID(I)=(I)                                                       C  002:004A:1
      XSQI=XSQI+SQ(I)**2                                              C  002:004C:0
      SQ(I)=SQ(I)/ITIME                                               C  002:004E:2
   15 CONTINUE                                                        C  002:0050:3
      DO 2 I=1,9                                                      C  002:0052:4
      R(I)=P(I)                                                       C  002:0054:0
    2 CONTINUE                                                        C  002:0056:2
      R(10)=P(9)                                                      C  002:0058:3
      K=0                                                             C  002:005A:1
      DO 3 I=10,13                                                    C  002:005A:5
      K=K+1                                                           C  002:005C:0
      J=I+K                                                           C  002:005D:2
      L=J+1                                                           C  002:005E:5
      R(J)=P(I)                                                       C  002:005F:5
      R(L)=P(I)                                                       C  002:0062:1
    3 CONTINUE                                                        C  002:0064:3
      DO 4 J=19,34                                                    C  002:0066:4
      R(J)=P(14)                                                      C  002:0068:0
    4 CONTINUE                                                        C  002:006A:0
      DO 40 J=35,73                                                   C  002:006C:1
      R(J)=P(15)                                                      C  002:006D:0
```

```
   40 CONTINUE                                                          C  002:006F:6
      DO 45 J=74,100                                                    C  002:0071:1
      R(J)=R(16)                                                        C  002:0072:0
   45 CONTINUE                                                          C  002:0074:0
      DFERR=(ITREAT-1)*(ITIME-1)                                        C  002:0076:1
      CORR=CORR/(ITREAT*ITIME)                                          C  002:0078:1
      TOT=(TOT-CORR)                                                    C  002:007A:1
      TREAT=(XSQI/ITIME-CORR)                                           C  002:007D:2
      BLOCK=(XSQJ/ITREAT-CORR)                                          C  002:0070:1
      ERR=(TOT-(TREAT+BLOCK))/DFERR                                     C  002:007F:1
      DFTRE=ITREAT-1                                                    C  002:0081:2
      SM=SQRT(ERR/DFTRE)                                                C  002:0086:3
      DO 25 M=1,ITREAT                                                  C  002:0084:3
      DO 30 I=1,DFTRE                                                   C  002:0086:0
      K=I+1                                                             C  002:0087:0
      IF(SQ(I).LT.SQ(K)) GO TO 30                                       C  002:008A:2
      SAVE=SQ(I)                                                        C  002:008B:0
      SQ(I)=SQ(K)                                                       C  002:008C:3
      SQ(K)= SAVE                                                       C  002:008E:5
      ISAVE=ID(I)                                                       C  002:0090:3
      ID(I)=ID(K)                                                       C  002:0092:0
      DO 7 J=1,4                                                        C  002:0094:2
      SAVE = ALPHA(I,J)                                                 C  002:0095:0
      ALPHA(I,J)= ALPHA(K,J)                                            C  002:0097:4
      ALPHA(K,J)=SAVE                                                   C  002:009C:2
    7 CONTINUE                                                          C  002:009F:1
      ID(K)=ISAVE                                                       C  002:00A1:2
   30 CONTINUE                                                          C  002:00A3:0
   25 CONTINUE                                                          C  002:00A5:1
      ITREA=ITREAT+1                                                    C  002:00A7:2
      DO 50 I=1,ITREA                                                   C  002:00A8:4
      R(I)=R(I)*SM                                                      C  002:00AA:0
   50 CONTINUE                                                          C  002:00AC:1
      K=0                                                               C  002:00AE:2
      DFTREA=DFTRE                                                      C  002:00AF:0
      DO 70 I=1,DFTREA                                                  C  002:00AF:5
      N=ITREAT-K                                                        C  002:0081:0
      TEST=SQ(N)-R(N-1)                                                 C  002:00B2:3
      KOUNT=0                                                           C  002:00B5:0
      DO 75 J=1,N                                                       C  002:00B5:4
      IF(TEST-SQ(J)) 200,300,400                                        C  002:00B7:0
  200 IF(KOUNT.EQ.0.AND.J.EQ.ICHECK)GO TO 17                            C  002:00BB:0
      IF(KOUNT.EQ.0)ICHECK=J                                            C  002:00BD:1
      KOUNT=KOUNT+1                                                     C  002:00BF:1
      SIG(I,J,1)='*'                                                    C  002:00C0:3
      GO TO 75                                                          C  002:00C4:1
  300 SIG(I,J,1)=' '                                                    C  002:00C4:4
      GO TO 75                                                          C  002:00C9:1
  400 SIG(I,J,1)=' '                                                    C  002:00C9:4
   75 CONTINUE                                                          C  002:00CE:1
      GO TO 18                                                          C  002:00D0:2
   17 I=I-1                                                             C  002:00D0:5
      DFTREA=DFTREA-1                                                   C  002:00D2:1
   18 K=K+1                                                             C  002:00D3:2
   70 CONTINUE                                                          C  002:00D4:4
      WRITE(6,2000)                                                     C  002:00D6:5
                                                                          FIB IS 00D6 LONG
 2000 FORMAT(T51,'DUNCANS MULTIPLE RANGE TEST')                         C  002:00DF:2
      WRITE(6,2500)                                                     C  002:00D6:2
 2500 FORMAT('0',T48,'TREATMENT',T74,'AVERAGE',T85,'RANKING')           C  002:00DF:2
      DO 8 I=1,ITREAT                                                   C  002:00DF:2
```

```
      WRITE(6,2400)ID(I),(ALPHA(I,J),J=1,4),SQ(I),I                    C  002:00E0:0
 2400 FORMAT(' ',T38,I2,4X,4A6,4X,G11.5,4X,I2)                         C  002:00F5:2
    8 CONTINUE                                                         C  002:00F5:2
      WRITE(6,2300)                                                    C  002:00F5:3
 2300 FORMAT('1')                                                      C  002:00F9:2
      DO 90 J=1,ITREAT                                                 C  002:00F9:2
      WRITE(6,2200)ID(J),(ALPHA(J,I),I=1,4),(SIG(1,J,1),I=1,DFTREA)    C  002:00FA:0
 2200 FORMAT(' ',I2,1X,4A6,1X,75(A1,1X))                               C  002:0111:2
      WRITE(6,2100)(SIG(I,J,1),I=1,DFTREA)                             C  002:0111:2
 2100 FORMAT(' ',28X,75(A1,1X))                                        C  002:011E:2
   90 CONTINUE                                                         C  002:011E:2
      END                                                              C  002:0120:5
      002:0122:0  IS THE LOCATION FOR EXCEPTIONAL ACTION ON THE I/O STATEMENT AT 002:0006
      002:0125:1  IS THE LOCATION FOR EXCEPTIONAL ACTION ON THE I/O STATEMENT AT 002:0000
                                                  SEGMENT 002 IS 0130 LONG
```