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Seattle Tolt Water Supply Mixed Asbestiform Removal Study

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August 1979

SEATTLE TOLT WATER SUPPLY
MIXED ASBESTIFORM REMOVAL STUDY

by

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Grant No. 804422

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report presents the results obtained and conclusions drawn from pilot plant filtration research on the removal of naturally occurring asbestiform fibers from a protected mountain water source. Appendixes not contained in this report are available separately and present detailed information on water quality, pilot plant equipment and operation, individual filter runs, ambient conditions and cost.

Francis T. Mayo, Director
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ABSTRACT

In 1975, the U.S. Environmental Protection Agency (EPA) discovered naturally occurring asbestos fibers in the Tolt River, a 100 million gallon per day (MGD) source of water supply for the City of Seattle. Two types of fibers were detected - amphibole and chrysotile. These fibers are in the sub-micron size range and are thought to have opposite surface charges. Although earlier research had been conducted on amphibole fiber removal from Lake Superior, little was known about methods of removal for chrysotile. To reduce lead time should fiber removal become necessary, the Seattle Water Department obtained research funding from EPA to develop methods of removal for these contaminants.

The research study gathered strong field evidence that both types of asbestos can be removed if certain operating conditions are met. Simply meeting the 1.0 nephelometric turbidity unit (NTU) specified by the National Interim Primary Drinking Water Regulations is not adequate to insure fiber removal; the American Water Works Association goal of 0.10 NTU must be met.

The pilot plant research was conducted to learn what combinations and variations of unit processes would effectively remove amphibole and chrysotile. Those studies confirmed that a static mixer could be used to blend chemicals with the raw waters and that a short period of flocculation was needed to properly condition floc particles during the winter months when waters were cold and turbidities were highest. Direct filtration of the conditioned water through granular media filters was effective at rates as high as 10 gallons per minute per square foot (gpm/ft^2). The most effective pretreatments developed for asbestos removal include alum at 10 milligrams per liter (mg/l) with lime for pH control, alum at 3 mg/l along with cationic polymer at 2 mg/l, and cationic polymer alone at 3 mg/l. Using these treatments, amphibole counts can consistently be reduced down to the detection limit of 0.01(10^6) fibers/liter. Chrysotile removal is much more difficult to achieve. However, when finished water turbidity was $\leq$0.10 NTU, 50% of the time chrysotile counts were reduced from an average of 7.1(10^6) fibers/liter in the raw water down to not statistically significant levels [$\leq$0.02(10^6) fibers/liter] in the finished water.

Removal of asbestos fibers by filtration was found to be quite sensitive to changes in the treatment process. Turbidity spikes in the filtered water of less than 0.35 NTU have caused increases in asbestos counts from levels which were not statistically significant, to over 12 million fibers/liter. Thus, vigilant control over the chemical additions and filter breakthrough is a necessity to insure consistent asbestos removal. To enable continuous process control, relationships between finished water asbestos counts and

turbidity were developed. The turbidimeter can be calibrated easily by the treatment plant operator and can be used to indicate if asbestos is being successfully removed. Thus, the operator does not have to wait for days or sometimes weeks to get asbestos results from an electron microscope and can take corrective action immediately if needed. Also, by relying on the turbidimeter, the utility can substantially reduce the number of asbestos analyses, which now cost about $400 per sample.

The conceptual design of the asbestos removal treatment plant for the Tolt includes static mixers, flocculators and granular media filters; no sedimentation basins are needed. Project costs are estimated at $25 million and operating costs are about $1.2 million per year. The plant would be capable of removing amphibole down to the detection limit and chrysotile down to levels which are not statistically significant.

This report was submitted in fulfillment of Grant No. 804422 by the Seattle Water Department under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from May, 1976 to November, 1978 and work was completed March, 1979.

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ACKNOWLEDGMENTS

The execution of this study involved the "team" approach in which representatives from health and regulatory agencies, consultants, analysts and manufacturers met and/or conversed via conference calls periodically to give advice and direction to the City's project officer. The cooperation and assistance of all participants is gratefully acknowledged.

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SECTION I

INTRODUCTION

BACKGROUND INFORMATION

Seattle Service Area

The Seattle Water Department's service area includes Seattle proper and also most of the metropolitan area. It extends from Edmonds on the north to just south of Des Moines and easterly from Puget Sound to Lake Sammamish at the foot of the Cascade range. Approximately 992,000 people are served directly or indirectly by the Seattle Water Department, which is about 83% of the population of King County. Average total water consumption is 161 MGD and summer peak day use has reached 350 MGD. Approximately two-thirds of this water is sold directly to the Seattle Water Department retail customers and the remaining portion is delivered at wholesale rates to suburban water districts and municipalities, who in turn sell it to their direct service customers.

Water Sources

The primary sources of Seattle water are the Cedar and Tolt rivers on the western slope of the Cascade Mountains in eastern King County. These two rivers furnish high quality mountain water of unusual clarity. The Cedar River system, which has been in operation since 1901, serves the southern region of Seattle and parts of South King County; the Tolt, which was added to the City system in 1964, generally serves the area north of the Ship Canal and the water purveyors on the east side of Lake Washington. The two sources feed the distribution system from opposite ends, a feature which affords excellent hydraulic characteristics. Figure 1 illustrates the major facilities of the system.

Water Treatment

Currently, the treatment of both water supplies consists of intake screening, chlorination and fluoridation. Prior to distribution, the water is rechlorinated as it leaves the open in-town reservoirs to assure the free chlorine residual necessary to maintain adequate levels of disinfection. Compared to most other major water utilities in this country, the present treatment is minimal. Many are required to extensively treat their water with coagulation and filtration techniques to render it safe to drink. The

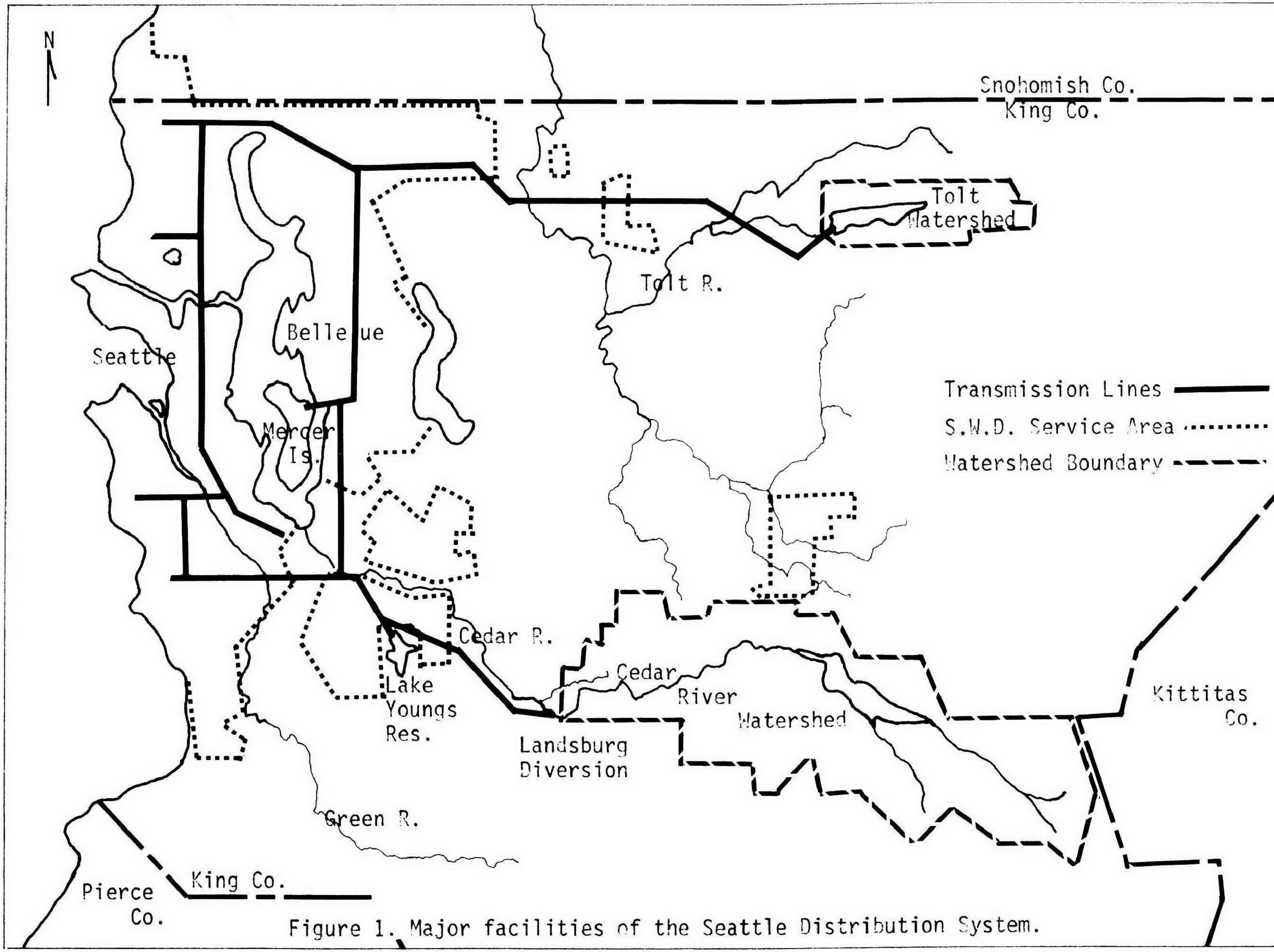

Figure 1. Major facilities of the Seattle Distribution System.

Water Department's emphasis on watershed protection, coupled with the large storage reservoir system to meet demands during periods of high turbidity, has enabled Seattle to meet National Interim Primary Drinking Water Regulations[1] without major modifications to the existing facilities.

Existing Facilities on the Tolt

Water originates in a 13,390 acre area watershed, which is narrow and steep and has been prone to slide activity. Ownership in the watershed is about equally divided between Weyerhaeuser Company, the Forest Service and the Water Department. Ten major streams feed the South Fork Tolt Reservoir, a 56,000 acre-feet, man-made storage reservoir with a maximum pool elevation at 1760 ft. The water enters a 33-inch diameter, 4.8-mile pipeline through one of three intakes, which are located at different depths in the reservoir. Upon discharge from the pipeline, water enters the pressure Regulating Basin, a 88 acre-feet reservoir at an elevation of 760 ft. The purpose of the pipeline and the Regulating Basin is to dissipate 1000 ft of head so that the water is at an acceptable pressure prior to chlorination. Water then enters a 66-inch diameter transmission line where it is chlorinated and fluoridated and subsequently discharged into the Seattle distribution system. The firm yield flow on the Tolt is 60 MGD with a design hydraulic capacity of 100 MGD. It is critical that water enter the transmission line at an elevation of 760 ft; otherwise, the necessary peak flow of 100 MGD would be unattainable. There is a proposal at this time by Seattle City Light Department to construct a second pipeline parallel to the existing line between the South Fork Tolt Reservoir and the Regulating Basin to enable generation of power rather than dissipating the excess head. Presently, there is a small turbine which supplies power to the existing treatment station located on the pipeline just upstream from the Regulating Basin.

Internal Corrosion Problem

The Seattle Water Department has recognized the existence of a corrosion problem for some time. In 1964, when the Tolt supply was brought into full operation, customer complaints concerning "rusty" water and fixture staining in that service area had doubled in frequency within a short period of time. Consequently, the Tolt supply was considered much more aggressive than the older Cedar source.

The corrosiveness of the water is a result of several related factors:

1. The dissolved oxygen concentration is very high; often at saturated conditions due to the low water temperature, the turbulence in the system and the lack of oxygen-consuming material in the water.

2. The water is very soft and has a low pH. The hardness is only 9.0 mg/l as $CaCO_3$ and after chlorination with gaseous chlorine and fluoridation with fluosilicic acid, the pH of the Tolt water is in the range of 5.8-6.2.

3. There is insufficient natural calcium and bicarbonate alkalinity in the water to form protective calcium carbonate scale on the pipe surfaces.

4. There is a relatively high halogen/alkalinity ratio, 1.5-2.5, which causes areas of low pH to develop and results in conditions favorable to pitting type corrosion which is prevalent in much of the old galvanized pipe.

A recently completed study[2] has recommended a comprehensive corrosion control plan with two features - a water treatment program and a material selection program. The treatment program will raise the pH and alkalinity of both supplies and possibly supplement silicates on the Tolt supply. Treatment facilities should be on line in 1981. The material selection program will help the customers choose corrosion resistant materials and will initiate plumbing code changes to allow the expanded use of materials such as plastic pipe. Since filtration techniques can increase the corrosivity of a water supply, a treatment plant for turbidity or asbestos removal must include provisions for addition of corrosion control chemicals.

Discovery of the Asbestos Fibers

In January of 1975, the U.S. Environmental Protection Ageny (EPA) was asked to determine if a water system utilizing asbestos cement (A/C) pipe could be located and sampled to supplement information for a loop study which was being conducted at the Municipal Environmental Research Laboratory in Cincinnati. A water district served by the Seattle Tolt supply was contacted and they agreed to participate in the sampling program. Samples were gathered from two locations within the water district's distribution system and at a control point from the Tolt transmission pipeline prior to any exposure to the A/C pipe. Analysis indicated that there were no statistical differences between fiber concentrations found in samples collected from the water district and those from the Tolt pipeline. Follow-up sampling confirmed the presence of both amphibole and chrysotile fibers in the Tolt transmission line and in the South Fork Tolt Reservoir. Samples from ten major streams which feed the supply reservoir were gathered and analyzed to determine if a point source existed, results of these analyses are contained in Appendix A. All of the feeder streams contained asbestos fibers in varying concentrations. Since the Tolt supply serves up to 100 MGD to a large population of the Pacific Northwest, the Seattle Water Department applied for and was awarded a $150,000 EPA research grant to study methods of fiber removal to reduce lead time should a treatment plant become necessary.

Related Asbestos Removal Study

In June, 1973, the EPA reported the discovery of a large amount of asbestos in Lake Superior - the source of drinking water for Duluth, Minnesota. Subsequent electron microscope analysis revealed up to one billion amphibole fibers/liter. A Federal Court ruling indicated that these fibers resulted from a mining company which had been dumping talconite tailing waste directly into the lake at its iron ore processing plant in Silver Bay, 50 miles northeast of Duluth. The discovery of these fibers in the lake and in the Duluth tap water prompted many environmental and epidemiological studies. Methods to remove these fibers were developed in a joint study conducted by Black and Veatch Consulting Engineers, the EPA and the Corps of Engineers.[3] Today, a water treatment facility is in operation and is removing amphibole fibers from the Duluth drinking water.

Health Implications

Occupational studies indicate that a human health hazard may exist for ingested asbestos since the death rates due to digestive system cancer are elevated in asbestos workers. This finding may be related to the swallowing of fibers that were inhaled and cleared from the respiratory system via the respiratory clearance mechanism.[4] One investigator has found the incidence of gastrointestinal (GI) cancer in asbestos workers to be 2-3 times the level in the general population; other researchers have also found significant increases in GI cancer.[4] The effect is more evident after 20 years or more from first exposure. The dose-response relationship between occupational exposure to asbestos and the risk of GI cancer is poorly defined. Therefore, it is difficult to evaluate the potential health hazard of low levels of ingested asbestos.

It appears that the physical and fibrous properties of asbestos, rather than its chemical composition or presence of trace elements, determines its carcinogenity.[4] Studies involving autopsies of asbestos workers are generally inconclusive but do suggest that asbestos may penetrate digestive system tissue. A recent study in Minnesota indicates that asbestos fibers were found in the urine of people drinking water containing fibers. Studies involving the feeding of asbestos to animals are generally inconclusive mainly because insufficient numbers of test and control animals were used.[4] However, there is again some evidence that asbestos may penetrate digestive system tissue and migrate to other locations in the body.[4]

There have been at least four epidemiological studies conducted to determine if ingestion of asbestos fibers is a possible health hazard. Three of the studies, which were conducted in Duluth, MN,[5] Quebec, Canada[6] and in Connecticut,[7] indicated no correlation between fiber count and cancer incidence. A fourth study[8] conducted in the San Francisco Bay Area is the first study to suggest a link between asbestos ingestion and cancer incidence. EPA indicates that results from the San Francisco study are not definitive enough to justify extensive modifications in water supply treatment and distribution and that additional studies should indicate more clearly whether there is a need for changes in drinking water practices.[9]

An epidemiological study is presently being conducted locally by the Fred Hutchinson Cancer Research Center in the Puget Sound Area. It will compare cancer rates of persons ingesting various quantities of asbestos fibers from drinking water in Everett, Seattle, Tacoma and an area on the Kitsap Peninsula where industrial exposure to asbestos was known to exist.

In summary, the potential hazards associated with asbestos ingestion through drinking water are not well defined at this time. The National Academy of Sciences indicates that no acute hazard exists but they do suggest minimizing exposure through effective coagulation and filtration of water containing asbestos.[10] EPA has set no standard for asbestos in drinking water.

STUDY OBJECTIVES

The formal objective of this research effort was to determine the most feasible method for reducing asbestiform count in the Tolt water. The scope of work included:

1. Developing methods to improve chrysotile removal by the use of three-stage mixing in combination with three conditioning chemicals in granular media filtration;

2. Optimizing asbestos removal using anionic, cationic and nonionic polymers;

3. Conducting filtration experiments at 5-6 gpm/ft^2 with granular media filters;

4. Determining the effect of mixing intensity on filtration and comparing back mixing with in-line mixing techniques;

5. Developing an operating tool which indicates quickly and economically if asbestos removal is occurring;

6. Collecting design data and developing cost information; and

7. Confirming amphibole results gathered during the Duluth asbestos removal study.[3]

Once the grant was approved, a literature review of the properties of asbestos fibers and methods for their removal was conducted. CH2M/Hill Consulting Engineers was awarded a contract to help with the collection of design data and cost information and the University of Washington agreed to perform the asbestos analysis. A study plan was developed, bench scale filtration studies were conducted and pilot testing was then undertaken.

SCOPE OF THE STUDY

During the period from January 1977 through September 1978, a small scale water filtration plant was operated at the Regulating Building on the Tolt supply. The primary goal of the pilot filtration study was to investigate various filtration systems to remove amphibole and chrysotile asbestos from the raw Tolt water. In-line, direct and conventional filtration processes were investigated. Various mixing intensities were tested with different chemical coagulants and dosages. Several granular medias were compared at filter loading rates up to 10 gpm/ft^2.

The study was conducted using a "team" approach where the consultant, the EPA, the Washington State Department of Social and Health Services, and the University of Washington, met or conversed via conference calls several times during the pilot study. This approach enabled the principal investigator to modify the study as needed and insured that all necessary information had been collected by the end of the pilot study.

ELEMENTS OF THE STUDY

The study consisted of the following six primary elements that included various secondary topics.

Water Quality

1. Seasonal Variation of Water Quality Parameters.
2. Relationship of Raw Water Turbidity with Asbestiform Counts.
3. Asbestos Size Distribution.

Methods of Analysis

1. Comparison of Asbestos Analysis Methods.
2. Particle Counting Techniques.
3. Development of Turbidimeter as Operational Tool.

Pretreatment for Filtration

1. Effectiveness of Alum, Ferric Salts and Polymers.
2. Mixing Requirements Including Flocculation.

Filtration Process

1. Comparison of Granular Media Filters.
2. Direct Filtration Techniques.
3. Filter Loading Rates Up to 10 gpm/ft^2.
4. Rate of Headloss Build-Up.
5. Air Binding Problems.

Backwash Water

1. Sludge Production.
2. Sludge Settling Characteristics.
3. Sludge Treatment Train.

Engineering Analysis

1. Preferred Techniques for Asbestos Removal.
2. Development of Design and Operating Criteria.
3. Cost Estimates.

SECTION II

CONCLUSIONS

RAW WATER

Asbestos

Two types of naturally occurring asbestos fibers contaminate the Seattle Tolt water supply - amphibole and chrysotile. Amphibole fiber counts averaged $1.6(10^6)$ fibers/liter and ranged from $< 0.04(10^6)$ up to $5.7(10^6)$ fibers/liter; chrysotile fiber counts averaged $7.1(10^6)$ fibers/liter and ranged from $1.2(10^6)$. fibers/liter up to $25.8(10^6)$ fibers/liter.

Turbidity

The turbidity of the raw water fluctuates from about 0.10 nephelometric turbidity unit (NTU) up to about 5 NTU throughout the year depending upon the season. Asbestos counts are positively correlated with turbidity.

FINISHED WATER

Turbidity Removal

Finished water turbidities can consistently be reduced down to $\leq$0.10 NTU with granular media filtration if proper pretreatment is applied.

Chemical Dosages

The most effective pretreatment combinations are as follows:

Chemical	Dosage	Chemical	Dosage	Chemical	Dosage
Aluminum Sulfate (Alum)	7-10 mg/l	Alum	3-5 mg/l	Cationic Polymer	3 mg/l
Lime [$Ca(OH)_2$] (pH range = 6.1-6.7)	1-4 mg/l	Cationic Polymer	2 mg/l	Filter Aid (Nonionic or anionic polymer)	0.1-0.3 mg/l
Filter Aid (Nonionic or anionic polymer)	0.02-0.25 mg/l	Filter Aid (Nonionic or anionic polymer	0.1-0.3 mg/l		

mg/l = Milligrams per liter

pH control is very critical when using alum and pH must be maintained between about 6.1 and 6.7 units for effective destabilization to occur.

Preferred Treatment Train

The preferred treatment train includes static mixers, flocculators and granular media filters; no sedimentation basins are needed. Direct filtration techniques are capable of meeting both process and water quality goals.

Static mixers functioned as well as mechanical mixers in dispersing chemicals into the process stream and they use less energy and require less maintenance.

A flocculator must be included in the process train to meet both water quality and process goals at low water temperatures and turbidities which exceed 1.5 NTU.

Filtration Considerations

All filter medias which were tested met both water quality and process goals.

As the filter loading rate increased, the unit filter run volume (filter efficiency) dropped and net water produced per 24 hours increased.

Filter loading rates up to 10 gallons per minutes per square foot (gpm/ft^2) were found to be effective at reducing finished water turbidity down to $\leq$ 0.10 NTU and at reducing asbestos fiber concentrations down to not detectable (ND) or not statistically significant (NSS) levels.

When filter loading rates were between 5.5 gpm/ft^2 and 7.5 gpm/ft^2, there was little difference noted in the water production efficiencies among the various filter medias tested. At loading rates less than 5.5 gpm/ft^2, the dual media with a coarse coal was most efficient and at rates greater than 7.5 gpm/ft^2, the mixed media demonstrated a higher efficiency.

The air binding problems, which were encountered with the cold, oxygen saturated water during pilot testing, can be eliminated in the full-scale plant by increasing the depth of water over the top of the filter surface thereby maintaining a positive head throughout the filter media.

Asbestos Removals

Amphibole --

When amphiboles were detected in the raw water and when finished water turbidity was $\leq$ 0.10 NTU, 52 out of 57 asbestos results (91%) had levels of amphibole which were at or less than the detection limit of $0.01(10^6)$ fibers/liter. In all 5 cases where amphiboles were greater than $0.01(10^6)$ fibers/liter, 4 or fewer fibers were counted, indicating that results were NSS.

Turbidity spikes and poor destabilization were consistently associated with high amphibole counts in the finished water.

Chrysotile --

Chrysotile fibers are more difficult to remove than amphibole; nevertheless, when finished water turbidities were $\leq$ 0.10 NTU, 50% of the time, chrysotile counts were $\leq$ 0.02(10^6) fibers/liter. When turbidities were >0.10 NTU, 50% of the time, chrysotile was $\leq$ 0.27(10^6). This indicates that there was ten times more asbestos present in the finished water when turbidity was >0.10 NTU than when turbidity was $\leq$ 0.10 NTU.

Turbidity spikes, filter breakthrough and poor destabilization were consistently associated with very high finished water chrysotile counts.

Removal Techniques --

Direct filtration techniques using standard water treatment chemicals can consistently remove amphibole down to ND levels and chrysotile down to NSS levels if certain operating conditions are met.

Analysis Procedures --

Both Millipore and Nuclepore asbestos analysis methods yielded virtually the same results on raw and finished water samples.

Trihalomethane Reduction

Levels of trihalomethanes in the filtered water were on the order of 60-70% less than in the unfiltered water.

High Turbidity Removal

Direct filtration techniques can be used to reduce raw water turbidities of about 20 NTU down to levels of 0.5 NTU.

BACKWASH CONSIDERATIONS

Volume

Backwash water to clean the filters will be drawn from a 5 million gallon (MG) finished water storage reservoir and will comprise an estimated 3.1% of the plant production water at nominal flow rates.

Treatment

Treatment for the backwash wastewater must be provided to meet the state pollution control requirements. Due to the high quality water of the receiving streams in the area, complete recycle of the liquid waste and land disposal of the solids will most likely be required.

DESIGN CONSIDERATIONS

Treatment Train

The preferred treatment train includes an energy dissipating system; three static mixers; four flocculation chambers, each with three stages of mixing; eight granular media filters; a backwash wastewater treatment system; and a finished water storage clearwell with provisions for addition of corrosion control chemicals.

Filtration System

Either dual or mixed media filters will meet both process and water quality goals.

The suggested nominal filter loading rate is 4.2 gpm/ft^2 at 60 million gallons per day (MGD) and 6.9 gpm/ft^2 at 100 MGD.

Rates up to 10 gpm/ft^2 can produce water with turbidities of $\leq$ 0.10 NTU and can consistently remove asbestos fibers down to NSS levels; however, filter production efficiency is significantly decreased at the higher filter loading rates.

Deep filter boxes are needed to prevent air binding problems from reducing filter efficiency and creating problems during backwashing.

Water Quality

The preferred treatment train and filtration system will meet the National Interim Primary Drinking Water Regulations,[1] will remove asbestos, turbidity, color, trihalomethane precursors, aluminum, will fulfill state guidelines regarding direct filtration plants and will meet state pollution control requirements.

Monitoring

Each filter will be equipped with continuously recording turbidimeters and the proposed plant should include a gravity flow pilot filter identical to the full-scale plant along with a coagulant control center.

Construction Materials

Asbestos-bearing products should be avoided when selecting construction materials.

OPERATING PARAMETERS

Water Quality

To insure asbestos removal, the finished water turbidity should be maintained at or preferably below 0.10 NTU and backwash procedures should be initiated at the first sign of turbidity breakthrough.

Headloss

The plant should be operated to a terminal headloss of 10 feet (ft).

COST

The estimated project costs are $24,747,000 with annual operation and maintenance costs of $1,212,000. This equates to an annual cost of $3,019,000.

SECTION III

RECOMMENDATIONS

This section of the report makes specific recommendations concerning additional research needs and further evaluations in the area of asbestiform removal and filtration capabilities.

Analyze the Seattle asbestiform count data to determine the size distribution of asbestos particles in the raw and filtered water.

Determine if high rate, coarse media, deep bed filtration is effective at removing asbestos fibers.

Compare a continuous recording turbidimeter with a continuous recording particle counter on a filter effluent to determine if there are any advantages to using a particle counter as an operational tool over the simple turbidimeter.

Compare the effluent from a declining rate versus a constant rate filter to determine the advantages and disadvantages of each.

Determine what problems may arise from an overdose of a filter aid.

Determine why filtration of a surface water can cause it to be more corrosive and what measures can be taken to reduce the resulting problems.

Develop a standard procedure for the asbestiform analysis.

Publish a state of the art manual on removal of asbestiform particles from the water to enable water utilities to modify either plant facilities or operations to remove the fibers.

SECTION IV

EQUIPMENT DESIGN, INSTALLATION AND OPERATION

GENERAL

The pilot study was conducted on a 20 gallon per minute (gpm) Waterboy (WB-27) package plant, which is manufactured by Neptune Microfloc, Inc. The unit was installed in the chlorine room at the Tolt Regulating Basin. Since the unit was designed to operate as a conventional filtration plant, modifications were made to the basic unit to enable several different treatment trains to be tested. Because of a serious air binding problem which developed in the filter media due to insufficient water over the top of the filter, three additional filter columns were constructed and operated in parallel with the Waterboy filter. Photographs of the pilot plant apparatus are presented in Appendix B.

RAW WATER SOURCE

Water was supplied to the pilot unit by tapping the injector water supply for the chlorinators and running a 2-inch supply line to the pilot unit. Injector water is pumped from the forebay of the Regulating Basin up to an elevated storage tank and then it flows by gravity to the injectors. This is the same water which is supplied directly to the customers of the Seattle Water Department except that the water had not been fluoridated or chlorinated at that point.

PERSONNEL

The Tolt Regulating Building is manned 24 hours per day, 7 days per week, by a trained operator. The operators, who are employees of the Seattle Water Department, were given all drawings and manuals for the pilot unit. They became quite familiar with the operation of the unit and gathered all necessary operating data such as headloss, turbidity, flow rate, chemical feed rates, etc.

The study was conducted in three phases. First, there was an initial "break-in" period where all personnel became familiar with the operation of the pilot apparatus. Next was a lengthy "intensive testing" period during which numerous different treatment trains and dosages were evaluated to determine the feasible asbestos removal methods. Lastly, there was an "optimal design" phase in which filter loading rates up to 10 gpm/ft^2 were tested and special studies were made involving excessive raw water turbidities and sludge treatment techniques.

AMBIENT CONDITIONS

To determine what relationship existed, if any, between ambient conditions in the watersheds and raw water quality, and to document conditions during the study, several readings including the water level in the South Fork Tolt Reservoir, the turbidity, the precipitation, valve operations, water use, the wind direction and velocity, and the temperature were collected These are contained in Appendix B.

PILOT PLANT

Waterboy

The unit processes on the package plant included a hydraulic rapid mix chamber, a flocculation basin with picket flocculators, tube settlers and a granular media filter. Media installation and initial start-up were supervised by a representative of Neptune Microfloc, Inc. The plant is rated at 20 gpm and can be operated either on a manual or automatic basis.

Modifications

Since the unit was to be used as a pilot plant, Neptune Microfloc, Inc., provided a variable speed flocculator so that various mixing intensities could be investigated. Several other modifications were made on the unit by the Seattle Water Department. Additional piping was installed to enable any unit process to be by-passed or eliminated simply by operating a valve or removing a pipe or fire hose. Figure 2 illustrates the possible flow schematics and Table 1 lists pertinent dimensions.

Three 2-inch static mixers were supplied by EPA and they were installed with the unit. Mechanical mixers and 55-gallon drums were also part of the flexible treatment train. Water would flow under pressure into the first drum and then could discharge by gravity into a second drum or into any other unit process in the treatment train.

A flow controller, which would maintain a preset flow rate regardless of incoming line pressure, was installed on the raw water pipe and an effluent meter was placed on the finished water line. These devices provided assurance that a constant flow rate entered the plant and was discharged from the filter.

Two turbidimeters were installed, one on the raw water and one on the finished water. These meters fed information to a strip chart recorder to insure that a permanent record of turbidity was kept. Bubble traps were later installed on each turbidimeter to prevent air bubbles from giving false turbidity readings.

Filtered water was discharged to an 8,000-gallon storage tank with an overflow near the top of the tank. Excess water discharged to a small stream

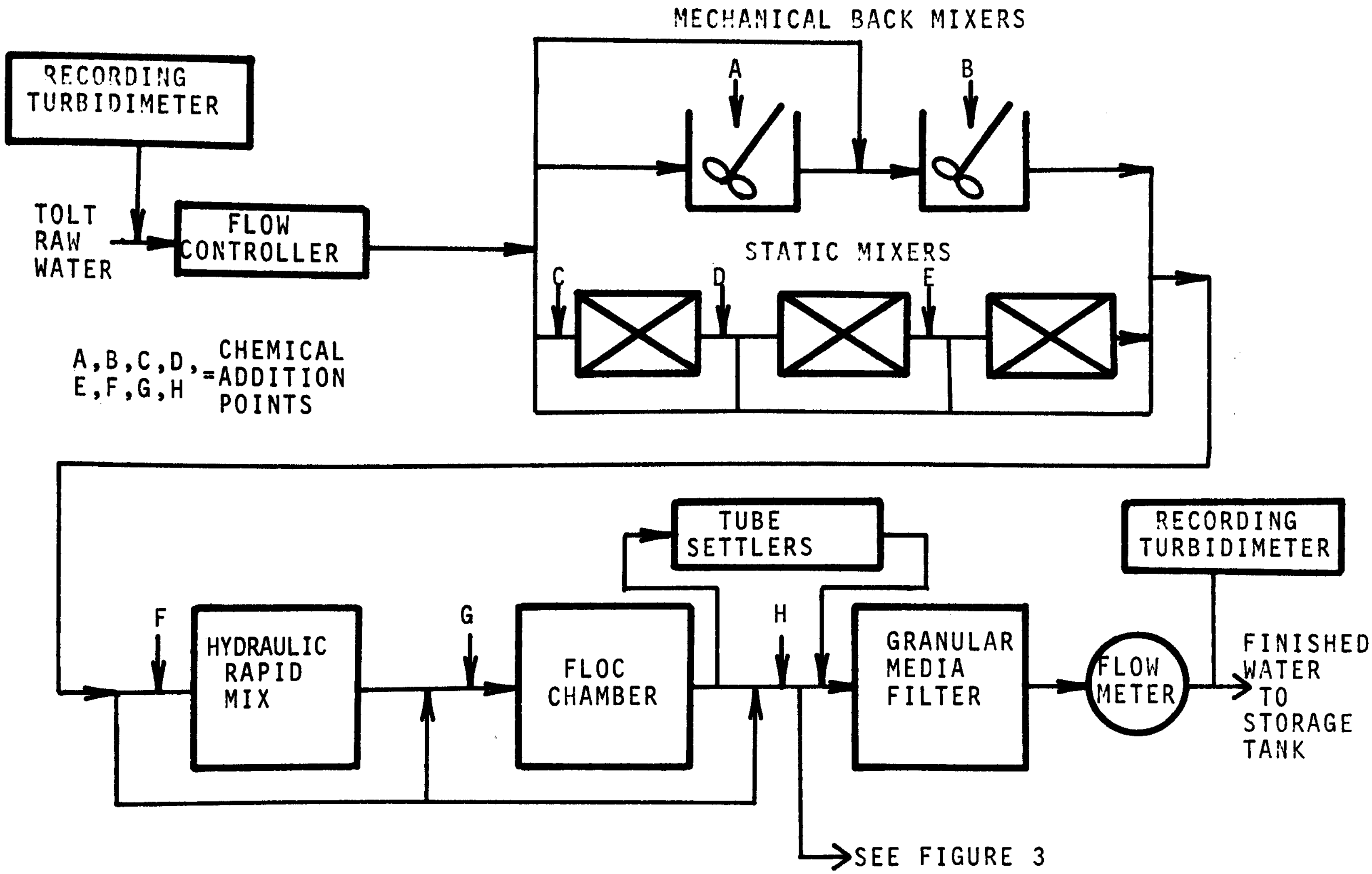

Figure 2. Pilot plant flow schematic.

TABLE 1. DIMENSIONS OF UNIT PROCESSES

Unit Process	Length (cm)	Width or Diameter (cm)	Depth (cm)	Volume Units as Indicated	Detention Time*
Hydraulic Rapid Mixing Chamber	62.9 cm 24-3/4 in	27.3 cm 10-3/4 in	165.1 cm 65 in	.028 m^3 10 ft^3	4.7 min
Mechanical Back Mixing Chamber	N/A	58.4 cm 23 in	7.1 cm 28 in	0.19 m^3 6.7 ft^3	3.1 min
Static Mixing Pipe	45.7 cm 18 in	5.1 cm 2 in	N/A	933 cm^3 0.033 ft^3	0.92 sec
Flocculation Chamber	62.9 cm 24-3/4 in	57.1 cm 22-1/2 in	165.1 cm 65 in	0.59 m^3 20.9 ft^3	9.8 min
Backwash Settling Chamber	6.1 m 20 ft	1.2 m 4 ft	0.53 m 1.75 ft	3.88 m^3 140 ft^3	N/A
Finished Water Storage Tank	N/A	3.1 m 10 ft	2.13 m 7 ft	16.1 m^3 549.5 ft^3	N/A

*Theoretical detention time at 60.5 l/min (16 gpm).

cm = centimeter
cm^3 = cubic centimeter
m = meter
m^3 = cubic meter
in - inch
N/A = not applicable
gal = gallon
ft^3 = cubic foot
min = minute
sec = second

adjacent to the Regulating Building and stored water was used for backwashing the Waterboy filter.

Early in the pilot studies, air binding in the Waterboy filter became a serious problem. Apparently, the pressure in the filter would drop below one atmosphere and dissolved gases, which were present in the raw water, would come out of solution and plug the voids in the filter media. This caused two problems: (1) rapid build-up of headloss as the filter run progressed, and (2) loss of anthracite media during filter backwash because of air bubble release at the start of backwash.

Since headloss was rising so rapidly, it became evident that filter design data could not be gathered from the Waterboy filter. To collect representative design data, three 4¼-inch diameter filter columns were installed in the basement of the Regulating Building (see Figure 3). A small stream of water was diverted from the chamber above the Waterboy media to the filter columns to maintain a column of water about 10 ft high over the top of the filter media. Maintaining a positive head throughout the column filter media held the gases in solution and prevented the air binding problem. Having three columns in parallel also allowed comparisons to be made among three different types of filter media at one time.

The loss of media during backwash of the Waterboy filter due to entrapped air was minimized by modifying backwashing procedures. The anthracite coal was stirred mechanically to release as much air as possible before backwash water was brought into the filter underdrain system. Electronic modifications also gave the plant operator complete control over the amount of backwash water allowed to the unit at any time. Water was brought into the filter chamber very slowly to prevent anthracite coal from being carried out with the backwash water.

Backwash Wastewater

Backwash wastewater from the Waterboy was discharged to a weir box and then into a plywood settling basin (see Figure 4). Emergency overflows from the settling basin were discharged to an earthen lagoon. Water was normally held in the settling basin until the solids had settled and then the clarified water was discharged to the North Fork Tolt River. Solids were periodically removed from the basin and tests were performed to determine treatment techniques for the sludge.

Mixing Intensities

Mixing intensities for each unit process were estimated using both field data and empirical calculations. A discussion of this information follows.

Hydraulic Rapid Mixing Chamber --

This chamber is part of the WB-27 pilot filtration unit. Water enters the bottom of the chamber under pressure and flows upward spilling over a rectangular weir into the flocculation chamber. Mixing intensity is estimated using the following formula:

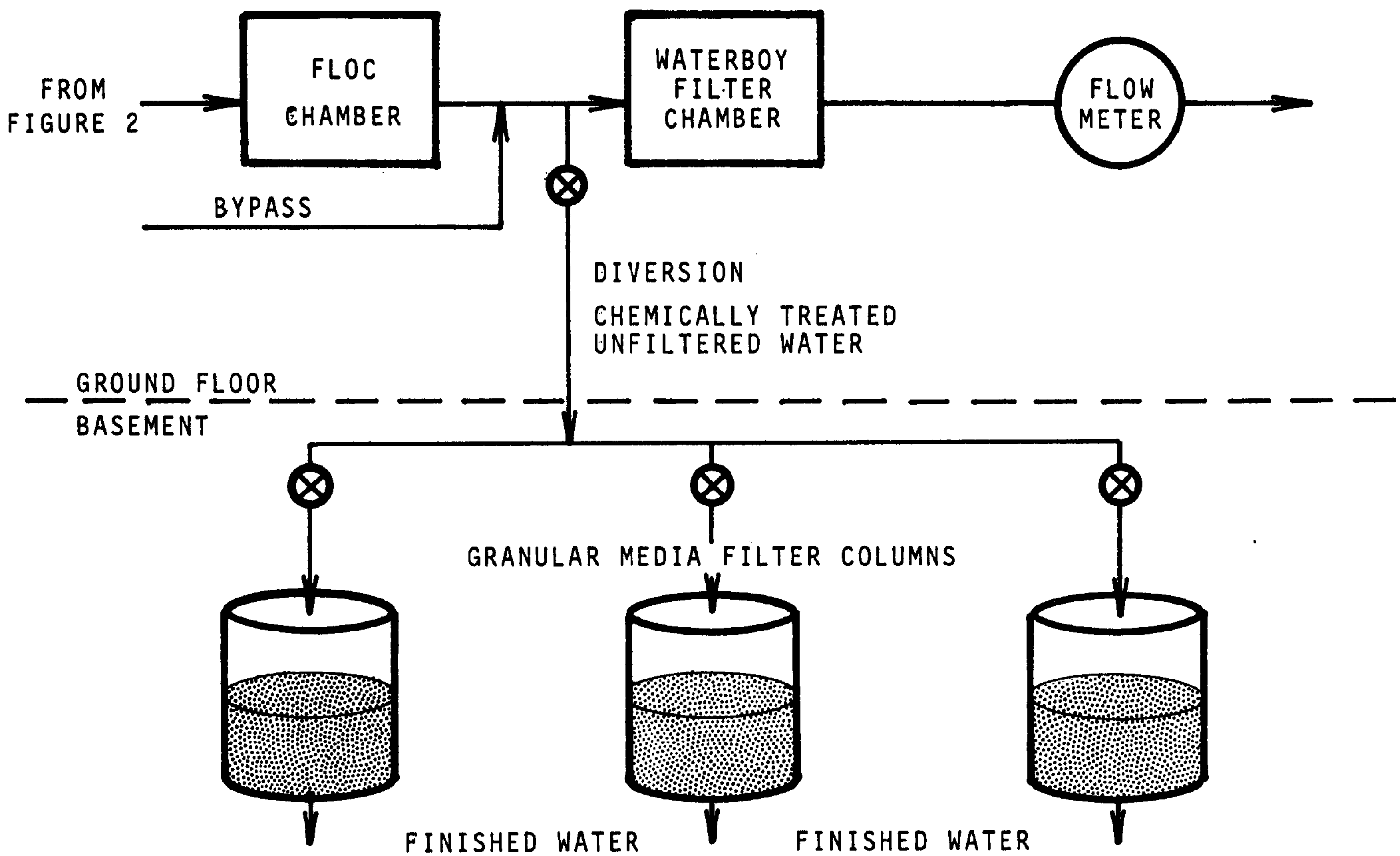

Figure 3. Flow diagram for filter columns.

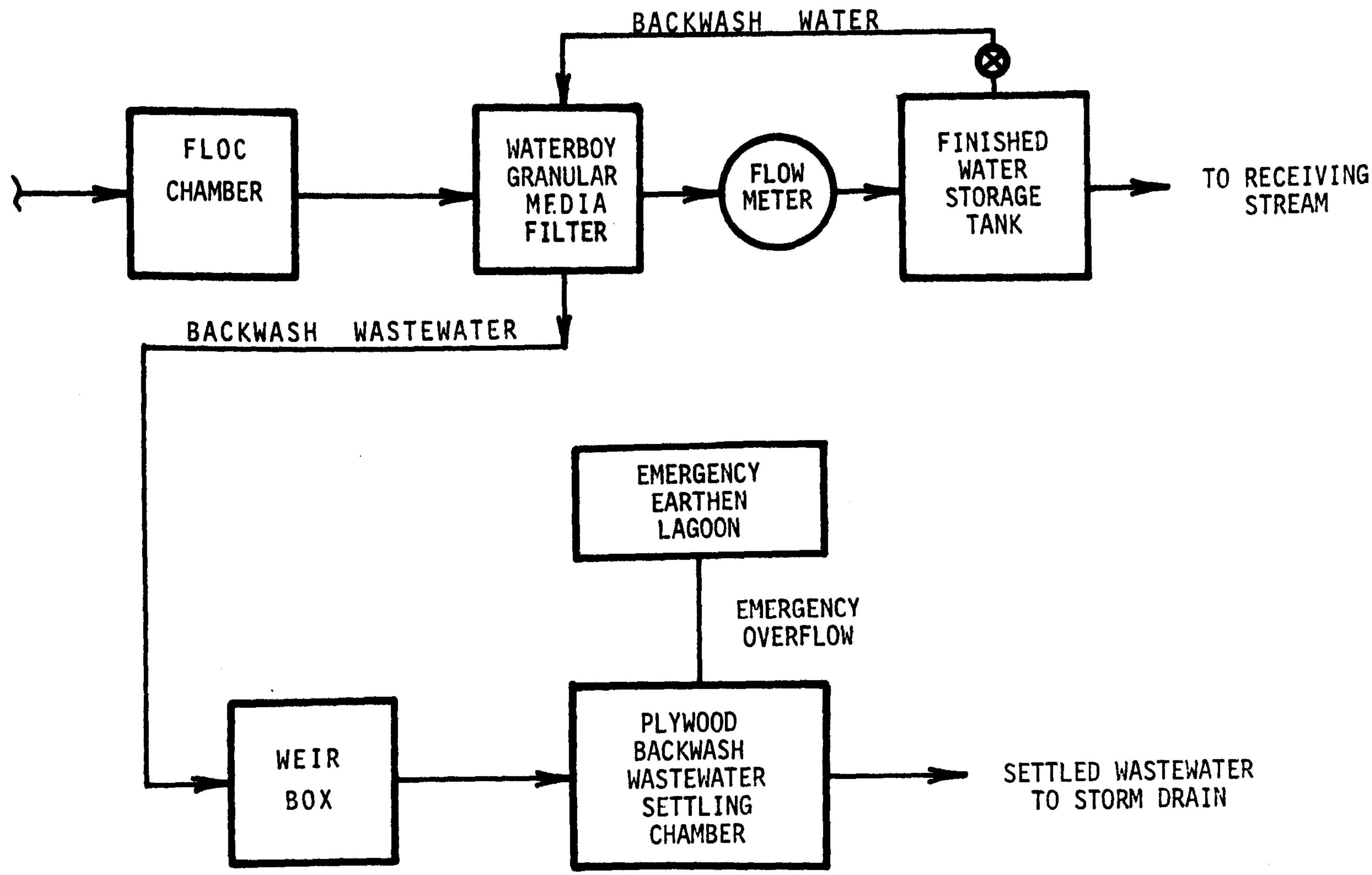

Figure 4. Flow diagram for backwash wastewater treatment system.

$$G = \sqrt{\frac{62.4\ (H)}{T\mu}}$$

where G = Velocity Gradient in seconds^{-1} (sec $^{-1}$)

H = Headloss in ft

μ = Viscosity in pounds - seconds per square foot $\left(\frac{\text{lb - sec}}{\text{ft}^2}\right)$

T = Time in seconds (sec)

Assumptions/Data:

H = 5.4 ft

μ at 8.5°C = $2.883(10^{-5})\left(\frac{\text{lb - sec}}{\text{ft}^2}\right)$

T = 282 sec from Table 1

$$G = \sqrt{\frac{62.4(5.4\ \text{ft})}{2.883(10^{-5})\left(\frac{\text{lb - sec}}{\text{ft}^2}\right)\ 282\ \text{sec}}} = 203\ \text{sec}^{-1}$$

This also yields a GT value = 57246.

Mechanical Back Mixing Chambers --

Two 55-gallon drums with mechanical mixers were used as back mixing chambers. Four baffles were placed in each drum to insure that a vortex was not formed. Information found on the mixer motor name plate or gathered from the manufacturer is presented below.

TABLE 2. MOTOR DESCRIPTION

HP	= 1/3	Phase	= 1
Revolutions per Minute	= 1725	Ampere	= 6.2
Volts	= 115	Hertz	= 60

TABLE 3. POWER FACTOR INFORMATION

Loading	Amperes	Power Factor	Efficiency
Full Load	6.2	0.63	54%
3/4 Load	5.9	0.56	59%
1/2 Load	5.6	0.47	42%
0 Load	5.0	-	-

The following data was gathered by varying the number of propellers on the motor shaft and then measuring the voltage and current drawn.

TABLE 4. FIELD ELECTRICAL DATA ON MIXER MOTOR

No. of Propellers on Shaft	Amperes Drawn (Amps)	Voltage (Volts)	Comments Regarding Motor
7	11.0	108	Very warm.
6	9.5	110	Very warm.
5	8.0	111	Marginal.
4	7.0	112	Good.
3	6.2	113	Good.
2	5.5	114	Good.
1	5.0	115	Good.
0	5.0	116	----

The formula used to estimate "G" factors is as follows:

$$G = \sqrt{\frac{550P}{V\mu}}$$

where G = Velocity Gradient in sec^{-1}

μ = Absolute Viscosity in $\frac{lb - sec}{ft^2}$

V = Volume of Basin (ft^3)

P = Water Horse Power = $\frac{Amps * Volts * PF}{746}$

PF = Power Factor

Assumptions/Data:

μ at $8.5^{o}C = 2.883(10^{-5})\ \frac{lb - sec}{ft^2}$

$V = 6.7\ ft^3$ = Volume used in drum

3 propellers and 2 propellers.

For 3 propellers:

$$G = \sqrt{\frac{550(6.2\ amps)(113\ volts)0.63}{(6.7\ ft^3)746\left[2.883(10^{-5})\ \frac{lb - sec}{ft^2}\right]}} = 1298\ sec^{-1}$$

also yielding a dimensionless GT value = 245113.

For 2 propellers:

$$G = \sqrt{\frac{550(5.5\ amps)(115\ volts)0.46}{(6.7\ ft^3)746\left[2.883(10^{-5})\right]}} = 1049\ sec^{-1}$$

also yielding a dimensionless GT value = 195114.

Static Mixing Pipes --

Three Kenics static mixers were loaned to the Seattle Water Department by the Municipal Environmental Research Laboratory, EPA, for use during the pilot studies. EPA performed hydraulic testing on the mixers which allowed calculation of pressure drop and mixing intensity at various flow rates. The formula used to calculate mixing intensity is:

$$G = \sqrt{\frac{62.4\ H}{\mu * T}}$$

where G = Velocity Gradient in sec^{-1}

H = Headloss in ft

μ = Absolute Viscosity in $\frac{lb - sec}{ft^2}$

T = Time in sec

Assumptions/Data:

μ at $8.5^{o}C = 2.883(10^{-5})\ \frac{lb - sec}{ft^2}$

Table 5 contains mixing information at various flow rates.

TABLE 5. MIXING INFORMATION ON 2-INCH KENICS STATIC MIXER

Flow Rate (gpm)	Time (sec)	Velocity (ft/sec)*	Headloss unit mmHg**	ft H_2O	Velocity Gradient (sec^{-1})	Dimensionless GT Value
8	1.8	0.83	4.8	0.21	502	904
12	1.2	1.25	11	0.49	940	1128
16	0.92	1.63	19	0.85	1414	1301
20	0.73	2.05	30	1.34	1993	1455
24	0.61	2.46	44	1.96	2637	1609
28	0.53	2.83	58	2.59	3252	1724

*ft/sec = feet per second.

**mmHg = millimeters of mercury.

Flocculator --

The flocculator is powered by a variable speed motor with an adjustable rheostat. The flocculator paddles (area = 6.5 ft^2) are attached to a vertical shaft and rotate in a clockwise direction. Two methods were employed to estimate the energy input to the water by the paddles: (1) Substitution into an empirical formula and (2) field measurements made with a torque meter.

The empirircal formula is presented as follows:

$$G = \sqrt{\frac{\frac{Cd}{2} A \rho v^3}{\mu V}}$$

where Cd = Coefficient of Drag of Flocculator Paddles Moving Perpendicular to Fluid

A = Area of Paddles in ft^2

ρ = Mass Fluid Density, slugs/ft^3

v = Relative Velocity of Paddles in Fluid in ft/sec, usually about 0.7 to 0.8 of Paddle Tip Speed

G = Velocity Gradient in sec^{-1}

V = Volume of Flocculation Chamber in ft^3

μ = Absolute Viscosity $\frac{lb - sec}{ft^2}$

Assumptions/Data:

$A = 6.5\ ft^2$

$\rho = 1.94\ slugs/ft^3$

$v = 0.7$ Tip Velocity (Tip Velocity varied from 0 to 1.78 ft/sec)

μ at $8.5^oC = 2.883(10^{-5})\ \frac{lb - sec}{ft^2}$

$V = 20.9\ ft^3$

$Cd = 1.8$

Information gathered on the flocculator is summarized in Table 6.

The second method of estimating energy input involved measuring torque with the torque meter, calculating actual power input to the water, and then tabulating G and GT factors. The formula used is as follows:

$$G = \sqrt{\frac{2\ \pi\ (RPM)Tq}{60\ \ \mu\ V}}$$

where RPM = Revolutions/min

Tq = Torque in ft - lb

μ = Absolute Viscosity in $\frac{lb - sec}{ft^2}$

V = Volume in ft^3

G = Velocity Gradient in sec^{-1}

Assumptions/Data:

RPM = 0-19

Tq = 0-23 ft - sec as measured on torque meter

μ at $8.5^oC = 2.833(10^{-5})\ \frac{lb - sec}{ft^2}$

$V = 20.9\ ft^3$

TABLE 6. MIXING INTENSITIES FOR FLOCCULATOR

% on Flocculator Rheostat	Paddle RPM	Tip Velocity ft/sec	Empirical Calculations		Transducer Output (Tq)			Torque Meter Data	
			G, sec^{-1}	GT*	Without Water ft - lb	With Water ft - lb	$\triangle$ Output	G, sec^{-1}	GT*
0	0	0	0	0	0	0	0	0	0
10	1-3/4	0.16	5	2940	2 - 10	2 - 10	0	0	0
20	3-1/2	0.33	15	8820	2 - 10	4 - 11	1.5	30	17640
30	5-1/2	0.52	30	17640	2 - 10	5 - 13	3	53	31164
40	8	0.75	52	30576	2 - 10	6 - 16	7	98	57624
50	10	0.94	73	42924	2 - 10	8 - 19	7.5	114	67032
60	12	1.13	96	56448	2 - 10	9 - 22	9.5	140	82320
70	14	1.31	120	70560	2 - 10	11 - 26	12.5	174	102310
80	15	1.41	134	78792	2 - 10	14 - 30	16	204	119950
90	18	1.69	176	103488	2 - 10	20 - 25	21.5	259	152290
100	19	1.78	193	113484	3 - 10	20 - 28	23	276	162290

*Detention time assumed to be 9.8 minutes at 16 gpm from Table 1.

Review of Table 6 indicates that actual field measurements with the torque meter resulted in "G" and "GT" values that were consistently higher than those from the empirical relationship; however, the differences are remarkably small when one considers the many variables which were included in the evaluation.

Filter Media Tested

Media Characteristics --

There were four different types of filter media evaluated during the pilot tests and the characteristics of each as supplied by the manufacturer are presented in the following tables.

TABLE 7. CHARACTERISTICS OF MEDIA TESTED

Table 7A

	Neptune Microfloc Mixed Media					
	Type MM			Type CMM		
	Effective Size (mm)	Uniformity Coefficient	Thickness (cm)	Effective Size (mm)	Uniformity Coefficient	Thickness (cm)
Anthracite Coal	1.0 - 1.1	1.7	45.7	1.0 - 1.1	1.7	53.3
Sand	0.42 - 0.55	1.8	22.9	0.42 - 0.52	1.4	17.8
Fine Garnet	0.18 - 0.32	2.2	7.6	0.18 - 0.32	2.2	5.1

Table 7B

	Turbitrol Dual Media					
	Type FC			Type CC		
	Effective Size (mm)	Uniformity Coefficient	Thickness (cm)	Effective Size (mm)	Uniformity Coefficient	Thickness (cm)
Anthracite Coal	0.92	1.28	50.8	1.1	1.31	50.8
Sand	0.40	1.30	25.4	0.40	1.30	25.4

Notes: MM = Mixed media, sand MS-6.

CMM = Mixed media, sand MS-18.

FC = Dual media with fine coal.

CC = Dual media with coarse coal.

mm = Millimeter.

Other pertinent information on the medias may be found in Appendix B. The media in the Waterboy (Type MM) was installed under the direction of the Neptune Microfloc Service Representative. The media in the filter columns was installed by the principal investigator. The placement was accomplished by adding about 1" more media to the bottom layer than was actually needed, backwashing the filter, skimming about one-half of the excess, backwashing again, and then skimming the remainder of the excess media.

Water Production Efficiencies --

Three methods were used to evaluate filter efficiencies: The Unit Filter Run Volume (UFRV)[11], Percent Efficiency and Net Water Produced per 24 hours.

The UFRV is the volume of water passing through a given filter surface area during the course of a filter run. The units are gallons per square foot per run. Trussell[11] suggests a minimum UFRV of 5000 gal/ft^2/run because filter production efficiency begins to drop off rapidly below that value. The formula for UFRV is as follows:

$$UFRV = LR * T$$

where UFRV = Unit Filter Run Volume, $\frac{gal/ft^2}{run}$

LR = Average Filter Loading Rate, gpm/ft^2

T = Time, Length of Filter Run in minutes

The Percent Efficiency (%) is the net water produced per filter run divided by the total water produced times 100. The formula is presented below:

$$\text{\% Efficiency} = 100 \left[\frac{(LR * T) - BW}{LR * T} \right]$$

where LR = Average Filter Loading Rate, gpm/ft^2

T = Time, Length of Filter Run in minutes

BW = Amount of Backwash Water used, 200 gallons per ft^2 per backwash.

The Net Water Produced per 24 hours is the total volume of water produced per unit of filter area in 24 hours less the amount of backwash water used to clean the filter per 24 hours. This term also accounts for filter down time during backwash. The formula is presented below:

$$NP = (LR * 1440) - NBW \left[BW + (LR * T) \right]$$

where NP = Net Water Produced, gallons/ft^2/24 hours

LR = Average Filter Loading Rate, gpm/ft^2

NBW = Number of Backwashes per 24 hours

BW = Amount of Backwash Water Used, 200 gallons per ft^2 per backwash

T = Time, 15 minutes down time per backwash

Method of Operation --

The Waterboy filter was operated as a constant rate filter to a headloss of 8 ft while filter columns were operated in either one of two modes - constant or declining rate. Filter runs on the columns were terminated at a headloss of 10 ft and loading rates as high as 10 gpm/ft^2 were tested.

Chemical Additions

Several types and combinations of inorganic and organic chemical coagulants were investigated and the chemicals used are listed below.

TABLE 8. CHEMICALS TESTED

Name	Type of Chemical or Use	Manufacturer
Alum	Inorganic Coagulant	-
Ferric Chloride	Inorganic Coagulant	-
Lime, Hydrated	pH Control	-
1986N	Nonionic Polymer	American Cyanamid Co.
1849A	Anionic Polymer	American Cyanamid Co.
573C	Cationic Polymer	American Cyanamid Co.
N-17	Nonionic Polymer	Dow Chemical Co.
A-23	Anionic Polymer	Dow Chemical Co.
CA253	Anionic Polymer	Calgon Corp.
CA233	Nonionic Polymer	Calgon Corp.
CATFLOC T-1	Cationic Polymer	Calgon Corp.

SECTION V

SAMPLING AND ANALYSIS

SAMPLING PROCEDURES

Grab samples were gathered during the filter runs and analyses were performed on these samples. pH and temperature measurements were performed at the pilot plant location. Other analyses including aluminum, calcium, conductivity, alkalinity, tannin and lignin, color, iron, dissolved oxygen, suspended solids and particle counts were conducted in the Seattle Water Department laboratory according to the 14th edition of Standard Methods[12] (where applicable). Asbestos analyses were performed by an electron microscopist at the University of Washington. Trihalomethane analyses were performed by the Laboratory Branch, Region X, EPA.

TURBIDITY

During normal filtration runs, turbidity information was taken directly from in-line, Model 1720, Hach turbidimeters. When asbestos samples were gathered, turbidity analysis was performed directly on a portion of each individual water sample using the laboratory, Model 2100A, Hach turbidimeter. Thus, correlations between turbidity and other parameters such as asbestos and particle counts could be defined if they existed. The on-line field turbidimeters (Model 1720) were calibrated against the laboratory turbidimeter (Model 2100A), which is calibrated using formazin standards.

Early in the pilot studies, air bubbles which were formed in the granular media filter would become entrained in the finished water and give false turbidity readings. This situation was eliminated by installing bubble traps on the lines which lead to the recording turbidimeters.

PARTICLE COUNTER

A HIAC particle counter was loaned to the Seattle Water Department by Pacific Scientific Company for use during the early portion of the pilot studies. The counter was equipped with 12 separate channels and had a sensor that could detect and count particles which were between 1 and 60 microns in diameter. The instrument was calibrated using a stock solution of spheres with a known particle distribution which were provided by the manufacturer. All samples were de-gassed prior to being analyzed. Normally finished water samples were run directly on the instrument; however, raw water often had to be diluted prior to analysis.

ASBESTOS FIBER ANALYSIS

General

The samples were gathered in quart cubitainers and were normally delivered to the University of Washington within 24 hours after the time of collection; thus, preservation techniques were not used. Concerning analysis, suspended material in the water is collected on a Millipore filter, which is later dried in an asbestos-free oven. A small disc is cut from the filter and it is then placed upside down on a carbon-coated specimen grid. The filter is gently dissolved in a condenser washer, leaving the asbestos and other suspended material on the grid. The grid is then placed in the electron microscope (EM) and magnified for counting. Before a fiber can be counted, it must be identified as being asbestos, preferably by type. There were two types of asbestos fibers found in the Tolt water - amphibole and chrysotile. The identification of these fibers is based on three factors: Morphology (size, shape and appearance), crystal structure and elemental composition.[13]

Identification

Since asbestos fibers generally appear to have sharp edges and often ragged or broken ends, they can be readily distinguished from most biological debris and many inorganic fibers. Identifying fibers by their crystal structure is done in the EM using selected area electron diffraction. An intense beam of electrons penetrates a section of a selected fiber, and if a diffraction spot pattern appears on the screen, the substance is crystalline. The arrangements of the spots depend on the atom layers in the crystal and are therefore a sort of identifying fingerprint. Diffraction spots from the amphibole fibers form rows of uniformly spaced dots while the three double-dot diffraction pattern is an important way to identify chrysotile asbestos. The elemental composition is determined by the X-ray energy dispersive analysis system (EDS) attached to the EM. The electron beam is focused on the fiber of interest and X-rays are produced as a result of the interaction between the electrons and the atoms on the surface of the fiber. A lithium drifted silicon [Si(Li)] detector converts the X-rays into voltage pulses proportional to their X-ray energies. After accumulating X-rays for a preset period of time, the EDS unit displays the data graphically as a spectra of peaks. Since atoms of different elements produce X-rays having different energies, the positions of the peaks show which elements are present in the fiber. The height of the peaks gives an indication as to the amount of each element present. Since all types of fibers have a basic silicone structure but differ in the amount of magnesium, iron, calcium and sodium which they contain, the EDS can differentiate among the types of asbestos present. Identifying and counting the fibers on a significant portion of the sample grid requires between 1 and 4 hours. The number of fibers per liter present in the sample is determined by multiplying the average number of fibers per grid opening by a factor that contains the ratio of the area of the grid opening to the filter area and the sample volume.

Laboratory Analyst

The samples were analyzed by a team of microscopists at the University of Washington (UW) headed by Dr. Edwin Boatman, School of Public Health. The capability to analyze for waterborne asbestos was developed at the UW shortly before the pilot studies began and since that time, the EPA has utilized that capability in several asbestos surveys. Sample results were normally available within a couple weeks after collection and the cost of each analysis was $250 per sample.

SECTION VI

RESULTS AND DISCUSSION

RAW WATER

Quality

The Tolt water supply is a high quality source of water originating from rainfall and snowmelt runoff in the north Cascade mountains and possesses the following water quality characteristics. (A complete chemical analysis sheet may be found in Appendix A.)

TABLE 9. RAW WATER QUALITY CHARACTERISTICS

Parameter	Value
pH	6.65 (units)
Alkalinity	5.0 (mg/l $CaCO_3$)
Hardness	9.0 (mg/l $CaCO_3$)
Conductivity	24 (micromhos)
Dissolved Oxygen	13 (mg/l, Saturated)
Temperature	2-10 [°Centigrade (°C)]
Aluminum	0.21 (mg/l)
Color	18 (units)
Tannin/Lignin	0.25 (mg/l)
Corrosivity	Highly Corrosive
Turbidity	Range: 0.10-5 NTU; Average = 0.75 NTU
Bacteriological Counts	Range: 1-65/100 milliliters (ml); Average = 9/100 ml
Amphibole	Range <0.04-5.7 (10^6) fibers/liter; Average = 1.6(10^6) fibers/liter
Chrysotile	Range 1.2(10^6)-25.8 (10^6) fibers/liter; Average = 7.1(10^6) fibers/liter

The water is quite soft, with little buffering capacity and currently meets the maximum contaminant level for turbidity set forth by the National Interim Primary Drinking Water Regulations[1] without filtration. Disinfection is accomplished with gaseous chlorine.

Turbidity

Turbidity exceeds the desirable goal of 1.0 NTU on a seasonal basis. It normally drops throughout the summer months to near 0.10 NTU and then begins to rise slowly with the fall precipitation. Highest turbidities normally occur during January, February, March, April and December. The turbidity has not exceeded the 5 NTU maximum contaminant level since the National Interim Primary Drinking Water Regulations[1] became effective in June of 1977.

The Tolt watershed is narrow and steep and has been prone to landslides for many years. Roads have been built and intensive logging activity has been carried out. This activity has increased the potential for high turbidity, especially during heavy fall and winter precipitation. Further, fluctuations in reservoir levels, especially the lower levels during the winter months, cause large areas of bank to be exposed. These bare, muddy banks are extremely vulnerable to erosion by heavy rains and wind and wave action. Fortunately, during periods of high turbidity, the bacteriological quality of the water has been excellent.

Asbestiform Counts

Table 10 lists the results of both raw water amphibole and chrysotile counts which were gathered during the study. Appendix B contains micrographs of both types of asbestos fibers found in Tolt water. These fibers are present naturally in the streams which feed the South Fork Tolt Reservoir and have been found in several water supplies throughout western Washington.

Amphibole fibers range in length from 0.3 to 7.5 microns and counts have ranged from $<0.04(10^6)$ fibers/liter up to $5.7(10^6)$ fibers/liter. Amphibole counts fluctuate with the season of the year and appear to be related to raw water turbidity as indicated by the statistical correlations developed below.

Statistical evaluation including all data points

Average Turbidity = 0.99 NTU

Standard Deviation = 0.82 NTU

Average Amphibole = $1.28(10^6)$ fibers/liter

Standard Deviation = $1.58(10^6)$ fibers/liter

Linear Regression: $A = 1.0 + 0.25\ (TURB)$

where A = Amphibole in fibers/liter * 10^{-6}

TURB = Turbidity in NTU

TABLE 10. RAW WATER ASBESTOS COUNTS

Date of Collection	Filter Run Number	Turbidity NTU	Amphibole fibers/liter	Chrysotile fibers/liter
Jan. 24, '77	3	1.4	5.70(10^6)	8.89(10^6)
Feb. 2, '77	4	1.4	3.31(10^6)	5.12(10^6)
Feb. 9, '77	5	1.4	3.06(10^6)	16.39(10^6)
Feb. 17, '77	6	1.3	3.46(10^6)	13.0 (10^6)
Feb. 23, '77	11	1.15	4.33(10^6)	13.29(10^6)
Mar. 3, '77	12	1.0	1.76(10^6)	13.14(10^6)
Mar. 25, '77	21	0.66	2.18(10^6)	25.80(10^6)
Apr. 11, '77	24	0.60	2.4 (10^6)	9.40(10^6)
Apr. 21, '77	29	0.62	0.94(10^6)	4.25(10^6)
May 6, '77	33	0.61	0.65(10^6)	3.82(10^6)
May 18, '77	44	0.56	0.90(10^6)	2.80(10^6)
June 1, '77	51	0.54	<0.29(10^6) (ND)	8.40(10^6)
June 9, '77	53	0.50	0.70(10^6) (NSS)	3.60(10^6)
June 29, '77	62	0.35	<0.12(10^6) (ND)	2.52(10^6)
July 13, '77	70	0.35	<0.07(10^6) (ND)	2.81(10^6)
Sept. 2, '77	89	0.35	<0.05(10^6) (ND)	1.20(10^6)
Oct. 6, '77	93	0.38	<0.07(10^6) (ND)	3.60(10^6)
Nov. 7, '77	108	0.55	<0.14(10^6) (ND)	3.61(10^6)
Nov. 16, '77	111	0.85	<0.14(10^6) (ND)	4.62(10^6)
Jan. 12, '78	120	3.30	0.19(10^6) (NSS)	5.38(10^6)
Jan. 12, '78	120	3.40	<0.10(10^6) (ND)	11.56(10^6)
Feb. 14, '78	135	1.80	<0.07(10^6) (ND)	3.90(10^6)
June 8, '78	161	0.30	<0.04(10^6) (ND)	2.00(10^6)
Sept. 4, '78	174	0.36	0.07(10^6) (NSS)	1.84(10^6)

Correlation Coefficient (R) = 0.13

Standard Error of Estimate (Se) = 1.57(10^6) fibers/liter

Statistical evaluation excluding two outlying data points collected on January 12, 1978

Average Turbidity = 0.77 NTU

Standard Deviation = 0.42 NTU

Average Amphibole = $1.38(10^6)$ fibers/liter

Standard Deviation = $1.62(10^6)$ fibers/liter

Linear Regression: A = -0.5 + 2.5 (TURB)

Correlation Coefficient (R) = 0.67

Standard Error of Estimate (Se) = $1.20(10^6)$ fibers/liter

As these regressions indicate, when all data points are included in the statistical analysis, the correlation coefficient is very weak, 0.13. After exclusion of two samples collected during unusually turbid water conditions (3.3, 3.4 NTU), the correlation coefficient increases to 0.67, which gives a good indication that there is a positive relationship between raw water turbidity and amphibole counts. Figure 5 contains a graph of the data with the line of best fit.

Concerning chrysotile, these fibers range in length from 0.1 up to 8 microns and counts have ranged from $1.2(10^6)$ up to $25.8(10^6)$ fibers/liter. Statistics relating chrysotile counts to raw water turbidity are listed below.

Statistical evalution including all data points

Average Turbidity = 0.99 NTU

Standard Deviation = 0.82 NTU

Average Chrysotile = $7.1(10^6)$ fibers/liter

Standard Deviation = $5.6(10^6)$ fibers/liter

Linear Regression: C = 5.5 + 1.6 (TURB)

where C = Chrysotile in fibers/liter * 10^{-6}

TURB = Turbidity in NTU

Correlation Coefficient (R) = 0.23

Standard Error of Estimate (Se) = $5.45(10^6)$

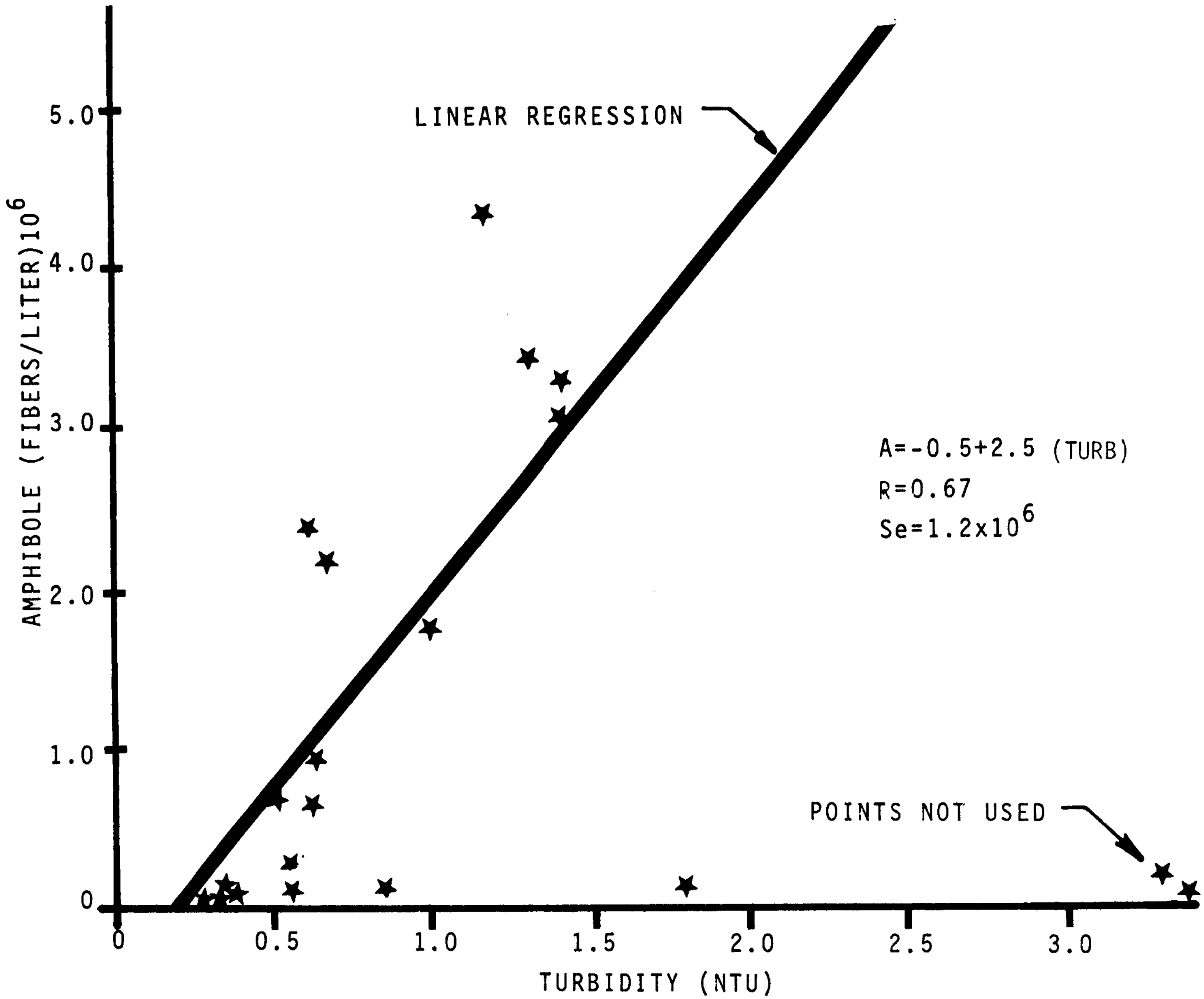

Figure 5. Raw water amphibole vs. turbidity.

Statistical evalution excluding outlying data points collected on January 12, 1978 and March 25, 1978

Average Turbidity = 0.78 NTU

Standard Deviation = 0.41 NTU

Average Chrysotile = $6.10(10^6)$ fibers/liter

Standard Deviation = $4.3(10^6)$ fibers/liter

Linear Regression: $C = 1.36 + 6.1$ (TURB)

Correlation Coefficient (R) = 0.66

Standard Error of Estimate (Se) = $3.2(10^6)$ fibers/liter

As with the amphibole, when outlying data points are excluded from the analysis, there is a positive correlation ($R = 0.66$) between raw water chrysotile counts and turbidity. Figure 6 contains a graph of the data with the line of best fit.

FINISHED WATER

General

This section discusses goals for the quality of the finished water and treatment trains needed to meet these goals. It deals with asbestos removal techniques, develops relationships between finished water asbestiform counts and turbidity and documents the removal of trihalomethane precursors while using direct filtration treatment methods. Conditions surrounding each filter run (i.e., flow rate, chemicals used, dosage, etc.) are presented in Appendix C. Headloss and turbidity information have been plotted for each filter run and these figures may be found in Appendix D.

Water Quality Goals

Removal of all amphibole and chrysotile asbestos was the primary goal of the research effort. To effect good fiber removal, a finished water turbidity goal of $\leq$ 0.10 NTU was established. Turbidities of 0.10 NTU are readily attainable with filtration and such techniques had been effective at removing amphibole fibers down to the detection limit at Duluth, Minnesota.[3] To preclude problems with reflocculation in the distribution system, the American Water Works Association (AWWA) goal of $\leq$ 0.05 mg/l for aluminum in the finished water was also established. It should be noted that EPA has set no standard for asbestos levels in drinking water at this time and as such, complete fiber removal was a self-imposed goal.

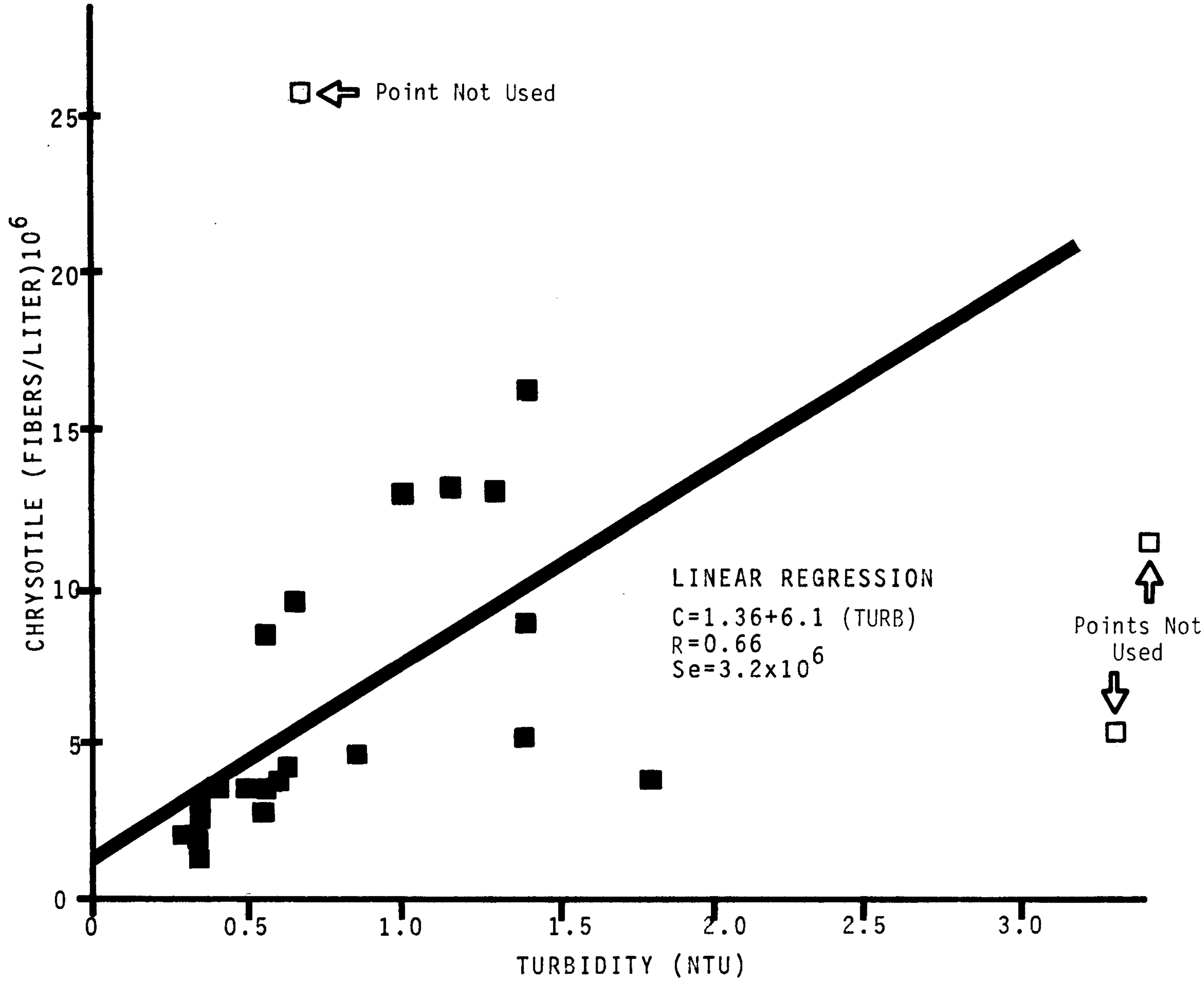

Figure 6. Raw water chrysotile vs. turbidity.

Chemical Treatments to Remove Turbidity

Alum Coagulation --

Soft, unbuffered, low turbidity waters are one of the most difficult to destabilize and aggregate.[14] To determine what effects the addition of alum would have on the pH of this water, titrations were performed and Figure 7 was developed. pH is of concern because alum is only effective over a relatively narrow pH range. It was evident that even very low dosages of alum significantly depressed the pH and that a buffer of some type was needed to properly pretreat the water before filtration. Lime is normally used for pH control and Table 11 lists estimates of lime dosages required to maintain a preselected pH at various alum dosages.

TABLE 11. ESTIMATED LIME DOSAGES* [mg/l $Ca(OH)_2$]

Alum mg/l	pH = 6.7	pH = 8.2
5	1.9	5.8
10	3.7	7.7
15	5.6	9.6
30	11.2	15.1
50	18.7	22.6

*Calculated values.

With an alkalinity of only 5 mg/l as $CaCO_3$, the water is very sensitive to both alum and lime addition and numerous filter runs did not meet water quality goals due to a slight under or over feed of lime. Since the problem persisted, tests were initiated to better define the optimum pH range for destabilization. Figure 8 was developed and indicates that pH should be maintained between 6.1 and 6.7 pH units. Field data indicated that between 1 and 4 mg/l of $Ca(OH)_2$ is required to maintain the pH in this range at a dosage of 10 mg/l of alum. This compares favorably with the estimated dosage of 3.7 mg/l of $Ca(OH)_2$ which is listed in Table 11. The AWWA goals of 0.05 mg/l for aluminum and 0.10 NTU for turbidity in the finished water can consistently be met in this pH range. Although these data were collected from numerous filter runs conducted under various water quality conditions, they indicate that pH is a very critical factor in the destabilization of Tolt water.

Based on laboratory jar tests, an alum dosage of 10 mg/l was chosen as a starting point for the pilot filter runs. This dosage, in conjunction with granular media filtration, was very successful at removing turbidity from the raw water under practically all conditions encountered during the testing phase. Finished water turbidity would normally drop rapidly to $\leq$ 0.10 NTU within a half an hour and would remain at that level until breakthrough or terminal headloss occurred. The addition of lime for pH control was critical for consistent removal as was the use of a filter aid. (Approximately 100 filter runs were conducted at a dosage of 10 mg/l of alum.)

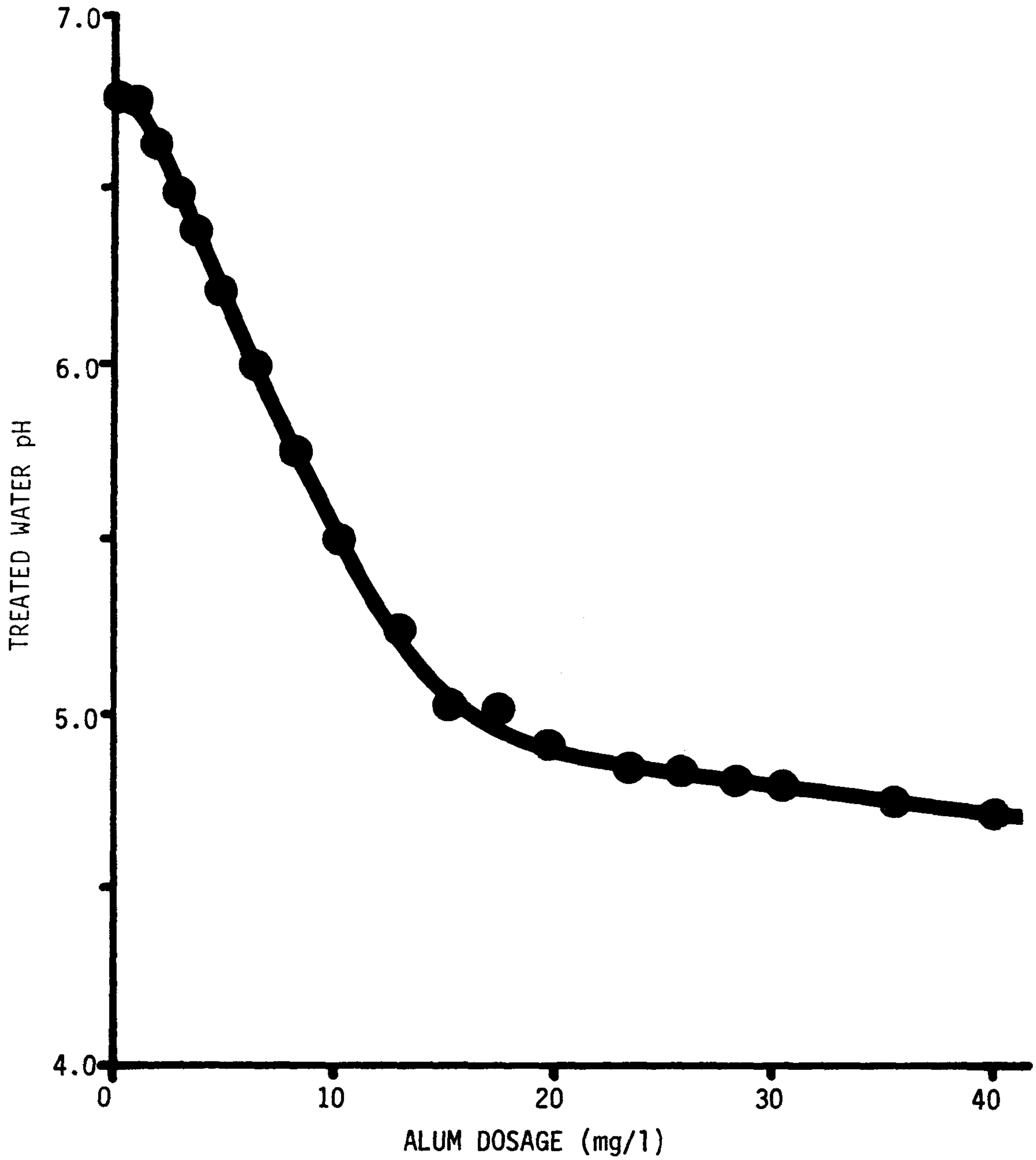

Figure 7. pH vs. alum dosage for raw Tolt water.

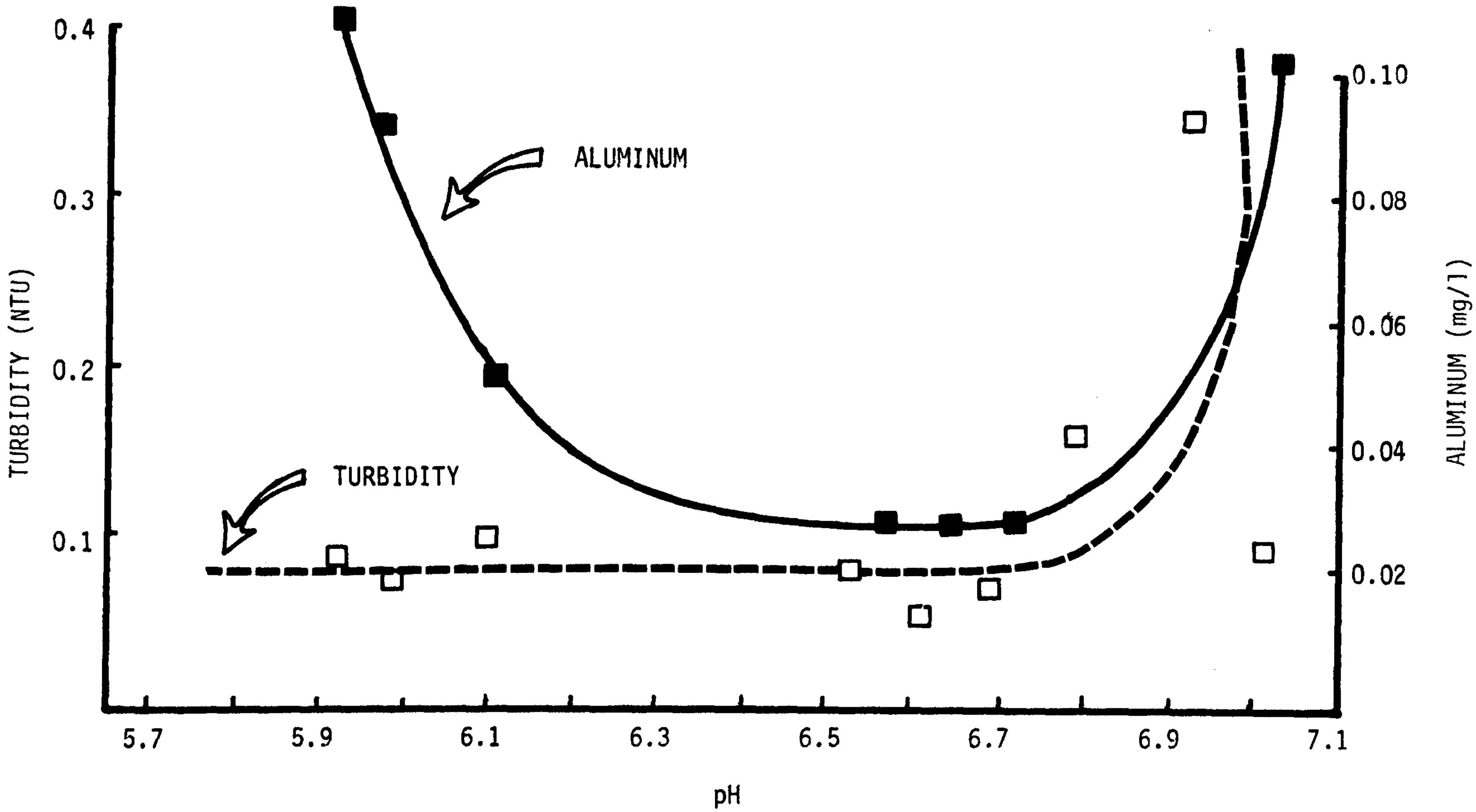

Figure 8. Finished water turbidity and aluminum residual vs. pH.

To determine minimum dosages for effective turbidity removal, several filter runs were conducted at dosages ranging from 3 to 10 mg/l. The information from these runs is summarized in Table 12 and in Figure 9.

TABLE 12. ALUM DOSAGE VS. OPERATING PARAMETERS

Run #	Raw Water Turbidity NTU	Alum Dose mg/l	Finished Water Turbidity NTU	Time to Steady State or 0.10 NTU	Comments
9	1.1	5.0	0.11	3 hours	Slow break-in period.
10	1.15	3.0	0.9	<1 hour	No break-in period.
11	1.12	5.9	0.20	3 hours	Slow break-in period.
22	0.62	5.6	0.1	2½ hour	Slow break-in period.
23	0.63	6.0	0.1	2 hours	Slow break-in period.
24	0.60	7.0	0.1	<1 hour	Quickly reached steady state.
25	0.65	7.5	0.1	<1 hour	Quickly reached steady state.
26	0.60	7.0	0.1	<1 hour	Quickly reached steady state.
27	0.62	7.0	0.1	<1 hour	Quickly reached steady state.
28	0.63	7.0	0.1	1½ hours	Slow break-in period.
29	0.69	7.0	0.1	2 hours	Slow break-in period.
50	0.56	8.0	0.1	<1 hour	Quickly reached steady state.
104	0.46	8.5	0.1	<1 hour	Quickly reached steady state.
105	0.48	8.5	0.1	<1 hour	Quickly reached steady state.
107	0.61	8.5	0.1	<1 hour	Quickly reached steady state.
108	0.70	8.5	0.1	<1 hour	Quickly reached steady state.
124	2.5	10.0	0.1	<1 hour	Quickly reached steady state.

Dosages as low as 5 mg/l were successful at removing turbidity to ≤ 0.10 NTU; however, results at this dosage did not appear to be as consistent as at the higher dosages. In addition, the lower dosages normally required a much longer break-in period to reach steady state conditions.

Several dosages between 10 and 20 mg/l of alum were also tested and were successful at removing turbidity down to ≤ 0.10 NTU. However, these higher dosages did not appear to offer any significant advantages over the 10 mg/l dose.

Several nonionic and anionic polymers were used as filter aids. These polymers included 1986N, 1849A, N-17 and A-23, and were fed directly onto the top of the filter at dosages ranging from 0.020 to 0.25 mg/l. Generally, the higher dosages were used to prevent filter breakthrough during periods when raw water turbidity exceeded 1.0 NTU and at filter loading rates above 5 gpm/ft^2.

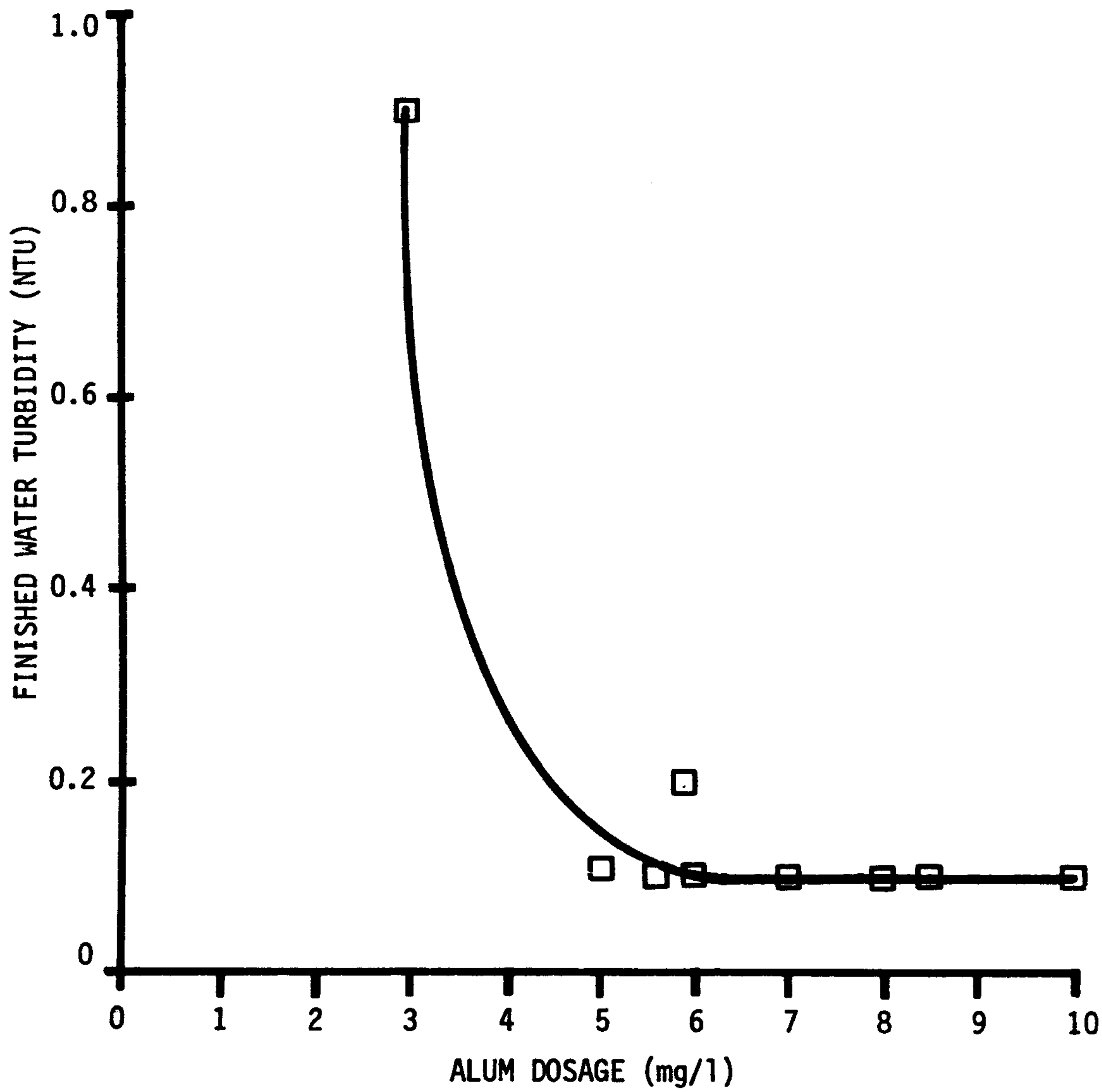

Figure 9. Finished water turbidity vs. alum dosage.

Based on these pilot tests, the removal of turbidity down to levels $\leq$ 0.10 NTU is attainable using alum, lime and a filter aid in conjunction with granular media filtration. The preferred dosage ranges and chemicals are listed in Table 13.

TABLE 13. PREFERRED CHEMICAL TREATMENTS - ALUM

Chemical	Dosage
Alum	7-10 mg/l
Lime $[Ca(OH)_2]$ to pH between 6.1 and 6.7; alkalinity 4 mg/l.	1-4 mg/l
Nonionic or anionic filter aid.	0.02-.25 mg/l

Alum and Cationic Polymer --

One of the objectives set forth by the EPA was to investigate the effectiveness of three conditioning chemicals in conjunction with granular media filtration. To determine the optimum chemical dosages; various combinations of alum, lime, cationic polymer and filter aids were investigated and are listed in Table 14.

TABLE 14. ALUM AND LIME DOSAGE VS. CATIONIC POLYMER DOSAGE

Alum Dosage mg/l	CATFLOC T-1 Dosage mg/l				
2	.2	.4	.8	1.6	3.2
4	.2	.4	.8	1.6	3.2
8 + Lime	.2	.4	.8	1.6	3.2
16 + Lime	.2	.4	.8	1.6	3.2

Based on these screening tests, a combination of 3-5 mg/l of alum, 2 mg/l of CATFLOC T-1 and a filter aid was found to be quite effective at removing turbidity down to $\leq$ 0.10 NTU. The major advantage associated with this chemical and dosage combination is that pH adjustment with lime is not necessary. Since much smaller amounts of alum are used, both pH and alkalinity are only slightly affected.

Several nonionic and anionic filter aids including 1986N, CA-233, CA-253, and A-23 were tested during this portion of the pilot studies. These aids prevented rapid breakthrough of the floc particles from occurring. For example, filter runs #64 and #81 indicated that although turbidity was removed to $\leq$0.10 NTU with a dosage of 0.1 mg/l of CA-233, breakthrough would occur several hours before reaching terminal headloss. Increasing the dosage to 0.3 mg/l (filter runs #65 and #82) prevented breakthrough from occurring until terminal headloss was reached.

The preferred dosages for the alum, cationic polymer and filter aid combination are listed in Table 15.

TABLE 15. PREFERRED CHEMICAL TREATMENTS - ALUM PLUS CATIONIC POLYMER

Chemical	Dosage
Alum	3-5 mg/l
Cationic Polymer	2 mg/l
Filter Aid (Nonionic or Anionic Polymer)	0.1-0.3 mg/l

Cationic Polymer Alone --

Pilot tests were run to determine the effectiveness of using a cationic polymer without alum. The dosages of cationic polymer, CATFLOC T-1 and 573C, were increased slowly at set intervals during separate filter runs with the following results.

TABLE 16. CATFLOC T-1 DOSAGES AND TURBIDITY

CATFLOC T-1 Dosage (mg/l)	Finished Water Turbidity (NTU)
0.12	0.35
0.20	0.34
0.40	0.34
0.60	0.32
0.80	0.33
1.2	0.25
2.0	0.15
3.0	0.1

TABLE 17. 573C DOSAGES AND TURBIDITY

573C Dosage (mg/l)	Finished Water Turbidity (NTU)
0.12	0.19
0.20	0.18
0.40	0.18
0.60	0.19
0.80	0.14
1.6	0.095
2.4	0.10
3.2	0.08

As indicated in these tables and in Figures 10 and 11, additions of CATFLOC T-1 and 573C were effective at removing turbidity down to $\leq$ 0.10 NTU if the dosage was increased to about 3 mg/l. The advantages associated with this chemcail treatment are two-fold. First, it does not affect the pH or alkalinity of the water; thus, pH control with lime is not necessary. Secondly, the sludge generated from cationic polymers is normally denser and easier to dewater than an alum sludge.

Ferric Chloride --

A limited amount of testing was conducted using ferric chloride at dosages ranging from 3 to about 20 mg/l. Results were not very encouraging. A dosage of 6-9 mg/l with a filter aid could reduce turbidity to about 0.2 NTU for a short period of time. Breakthrough would normally occur rapidly and results were inconsistent.

Unit Processes

Static Mixers --

Several filter runs were conducted to determine if static mixers would effectively blend the treatment chemicals with the raw water and if so, how many units would be needed to accomplish this task. Efficiency data from filter runs #6A, B, C and D are listed in the following table and can be used to compare results when different numbers of mixers were in use.

TABLE 18. COMPARISON OF ONE WITH THREE STATIC MIXERS

Run No.	No. of Static Mixers	Filter Efficiencies: UFRV (gal/ft^2/run)	Filter Efficiencies: Net Water Produced / 24 Hours (gal/ft^2/24 hours)	Filter Efficiencies: Efficiency (%)
6A	3	1980	3785	89.9
6B	3	2160	3830	90.7
6C	1	2340	3868	91.5
6D	1	2430	3884	91.8

Review of the filter efficiencies resulting from the use of one or three static mixers indicates that there was little or no discernable difference in the results. A single static mixer appeared to mix the treatment chemicals with the raw water as well as three mixers in series; thus, most runs conducted during the study utilized only one mixer.

Back Mix Systems --

Several back mix systems were investigated including hydraulic and mechanical mixers with and without the flocculator in the treatment train. There appeared to be little difference among the various back mix systems tested. Filter runs conducted with these systems would normally be terminated due to turbidity breakthrough well before terminal headloss was reached.

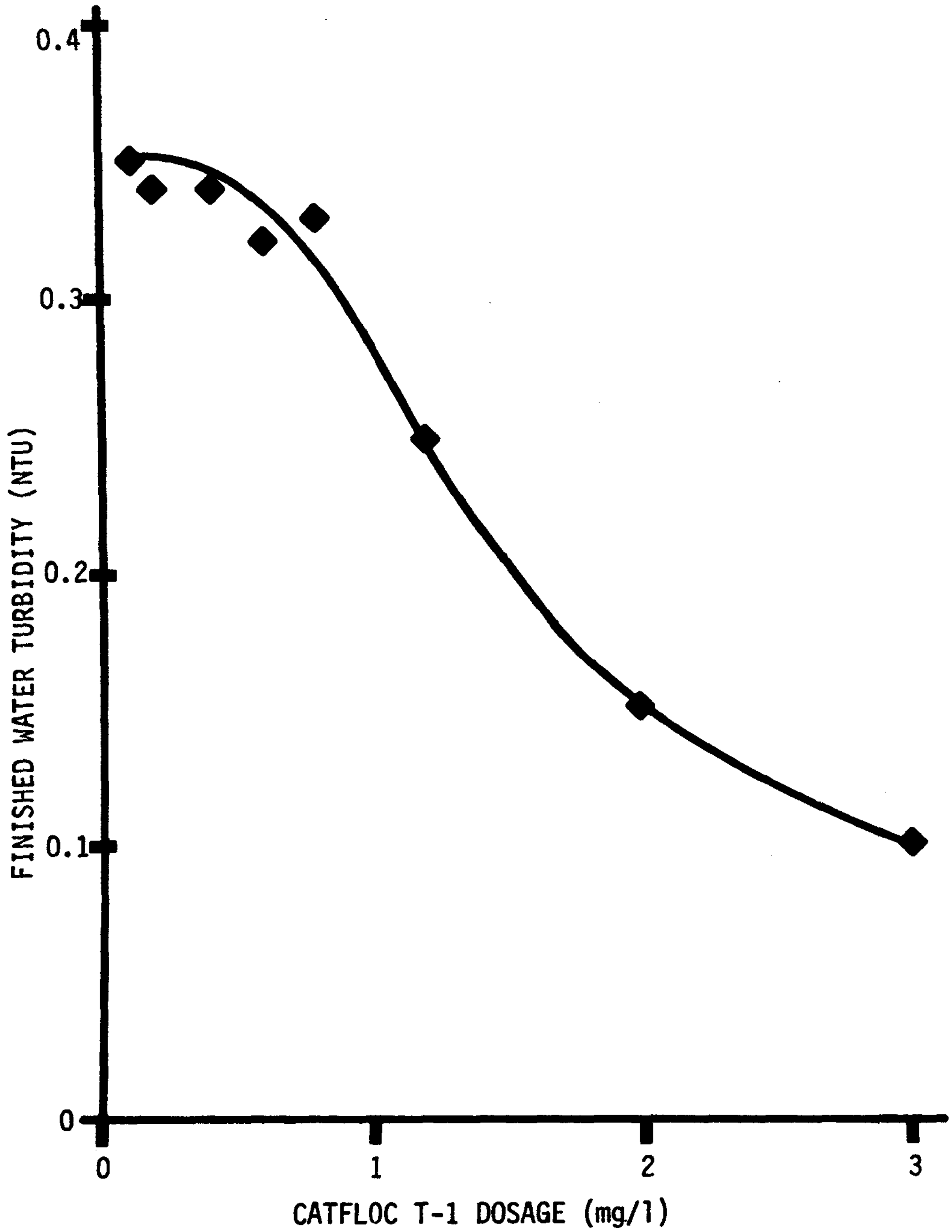

Figure 10. Finished water turbidity vs. Catfloc dosage.

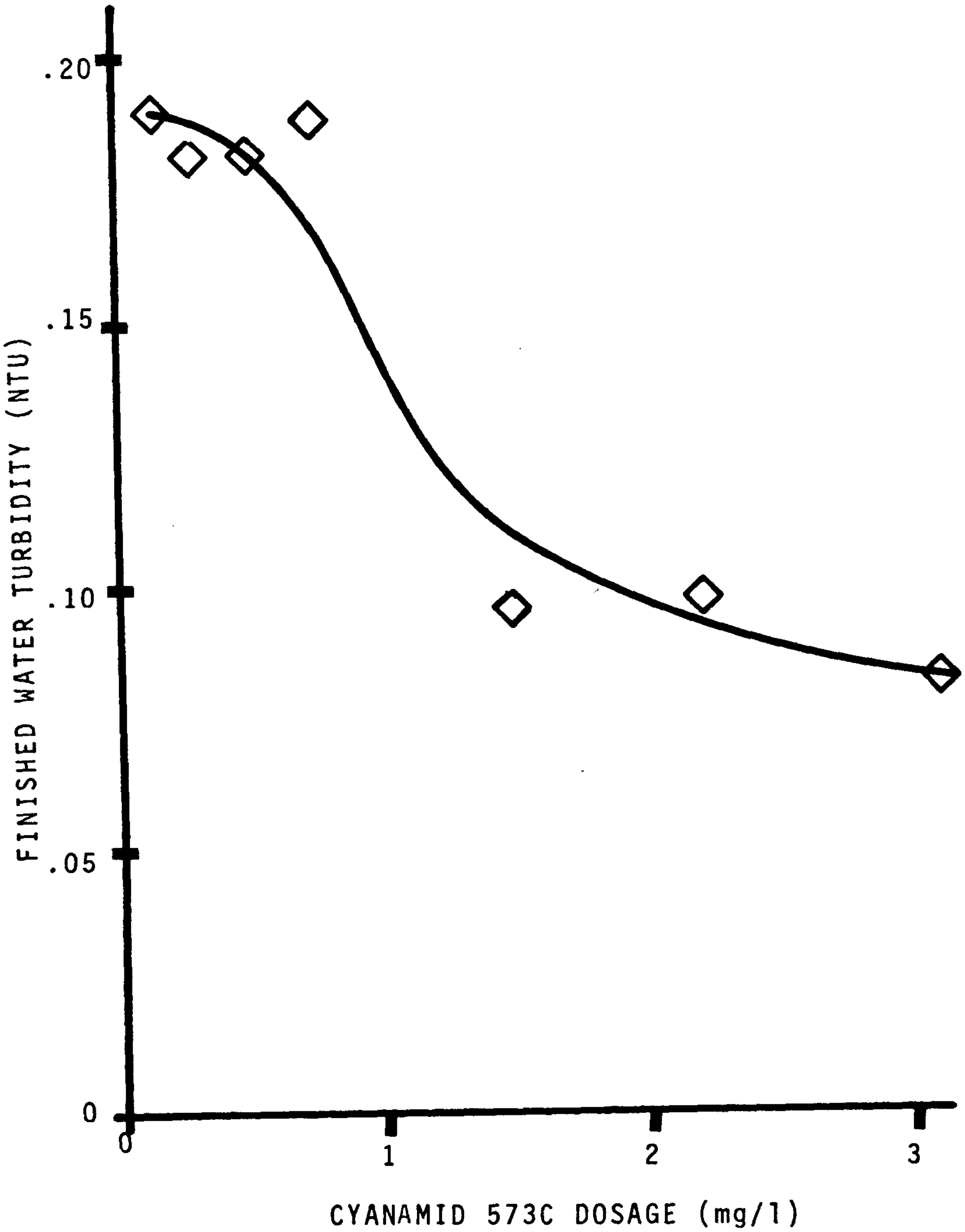

Figure 11. Finished water turbidity vs. 573C dosage.

Comparison of Static and Back Mix Systems --

Both static and back mix systems could be operated to produce an acceptable quality finished water. One difference that was noted was the reason for terminating a filter run. With the static mixers, there appeared to be a quicker build-up of headloss and the run would be terminated because the headloss reached 8 ft, rather than because of turbidity breakthrough. The opposite was true with the back mix systems, headloss would build at a slower rate and the run would normally be stopped because of turbidity breakthrough not because it reached terminal headloss. The reason for this difference in operational characteristics was not determined.

Flocculator --

To determine if a flocculation basin should be included in the full-scale treatment plant, the following set of filtration runs was conducted with and without this unit process in the treatment train.

TABLE 19. RESULTS FROM FILTER RUNS WITH AND WITHOUT FLOCCULATION

Filter Run No.	Flocculator Yes/No	Filter Loading Rate gpm/ft^2 Maximum	Filter Loading Rate gpm/ft^2 Average	Number of Hours ≤0.10 NTU	UFRV gal/ft^2/run	Filter Efficiency %	Comments
127M	Yes	7.0	6.8	10	4080	95.1	
128M	Yes	8.0	6.5	16	6240	96.8	
129M	No	6.1	6.1	0	0	0	Turbidity >0.10 NTU
130M	No	6.0	6.0	0	0	0	Turbidity >0.10 NTU
131M	No	4.0	4.0	8	1915	89.6	
132M	No	5.0	5.0	5	1500	86.7	
133M	No	6.0	6.0	0	0	0	Turbidity >0.10 NTU
134M	Yes	4.0	4.0	25	5985	96.7	
135M	Yes	4.0	4.0	23	5506	96.3	
136M	Yes	5.0	5.0	16	4781	95.8	
137M	Yes	6.0	6.0	22	7405	97.3	

Review of the data indicates that when the flocculator was deleted from the treatment train, water production efficiencies were consistently much lower. The runs conducted at 5-6 gpm/ft^2 were unable to remove turbidity down to ≤0.10 NTU and even the runs conducted at 4 gpm/ft^2 experienced rapid breakthrough.

When the flocculator was placed back into the treatment train, the UFRV and the filter efficiency rose immediately to much higher levels. Efficiencies exceeded 95% and the turbidity was normally held to ≤ 0.10 NTU until terminal headloss occurred. The reason for the increased efficiency with the flocculator in place was not determined but the differences in operational capabilities were evident. These differences were most noticeable when the raw water turbidity was >1.5 NTU and water temperatures were cold, 5-6°C. The cold water conditions may have required more contact or reaction time before filtering.

Filter Media

Loading Rates and Mode of Operation --

One of the initial objectives established by the EPA was to conduct filtration experiments at loading rates of 5-6 gpm/ft^2; loading rates as high as 10 gpm/ft^2 were investigated during the study using various filter medias. The granular filters were operated in either a constant or declining rate mode up to a terminal headloss of 10 ft.

Water Production Efficiencies --

Methods used to evaluate filter efficiencies were described in detail in SECTION IV, EQUIPMENT DESIGN, INSTALLATION AND OPERATION, and included the Unit Filter Run Volume, Percent Efficiency and Net Water Produced per 24 hours. The minimum goal for the UFRV was set at 5000[11] gal/ft^2/run for the nominal flow rate of 60 MGD, which is equivalent to a filter efficiency of 96%. Rather than setting a goal for Net Water Produced per 24 hours, this parameter was used to establish the filter area required to produce the maximum daily flow of 100 MGD.

As mentioned earlier in this report, air binding in the Waterboy filter was a serious problem. It shortened filter runs to the point that very few of the runs ever approached the minimum UFRV or percentage efficiency goals. The headloss would progress at a normal rate until about 4 ft of headloss; then, as the gases rapidly began coming out of solution, the rate of headloss build-up would accelerate. Review of Figure 12 illustrates the two headloss rates. To address the problem, three filter columns were designed and installed to maintain a positive head throughout the media for the duration of the filter run. A comparison of the headloss build-up in the Waterboy filter and in a filter column (Figure 12) illustrates the seriousness of the air binding problem. In addition to a reduced rate of headloss build-up, the columns demonstrated much higher UFRV's and percentage efficiencies than the Waterboy filter. Fortunately, the air binding problem can be eliminated in the full-scale plant simply by insuring that an adequate depth of water is maintained over the surface of the filter media. Other cold waters with high dissolved oxygen and gas content occur in many areas of the Northwest and would probably cause similar problems upon filtration. The problem is especially acute where direct filtration techniques are used and extra freeboard in the filter boxes ought to be considered in all such applications.

After the filter columns were installed, several typical filter runs were selected and measures of water production efficiencies were calculated (see Appendix A). Filter runs were terminated when turbidity was >0.10 NTU or at 10 ft of headloss, whichever came first. Most of the runs analyzed had average filter loading rates of 6 gpm/ft^2 or above, and rates at the beginning of declining rate runs were as high as 10 gpm/ft^2. To simulate filter conditions which would occur at peak summer flows of 100 MGD, data from four declining rate runs (#153, #156, #157 and #161) were also analyzed in a slightly different manner. The rate at the beginning of these runs was 10 gpm/ft^2 and

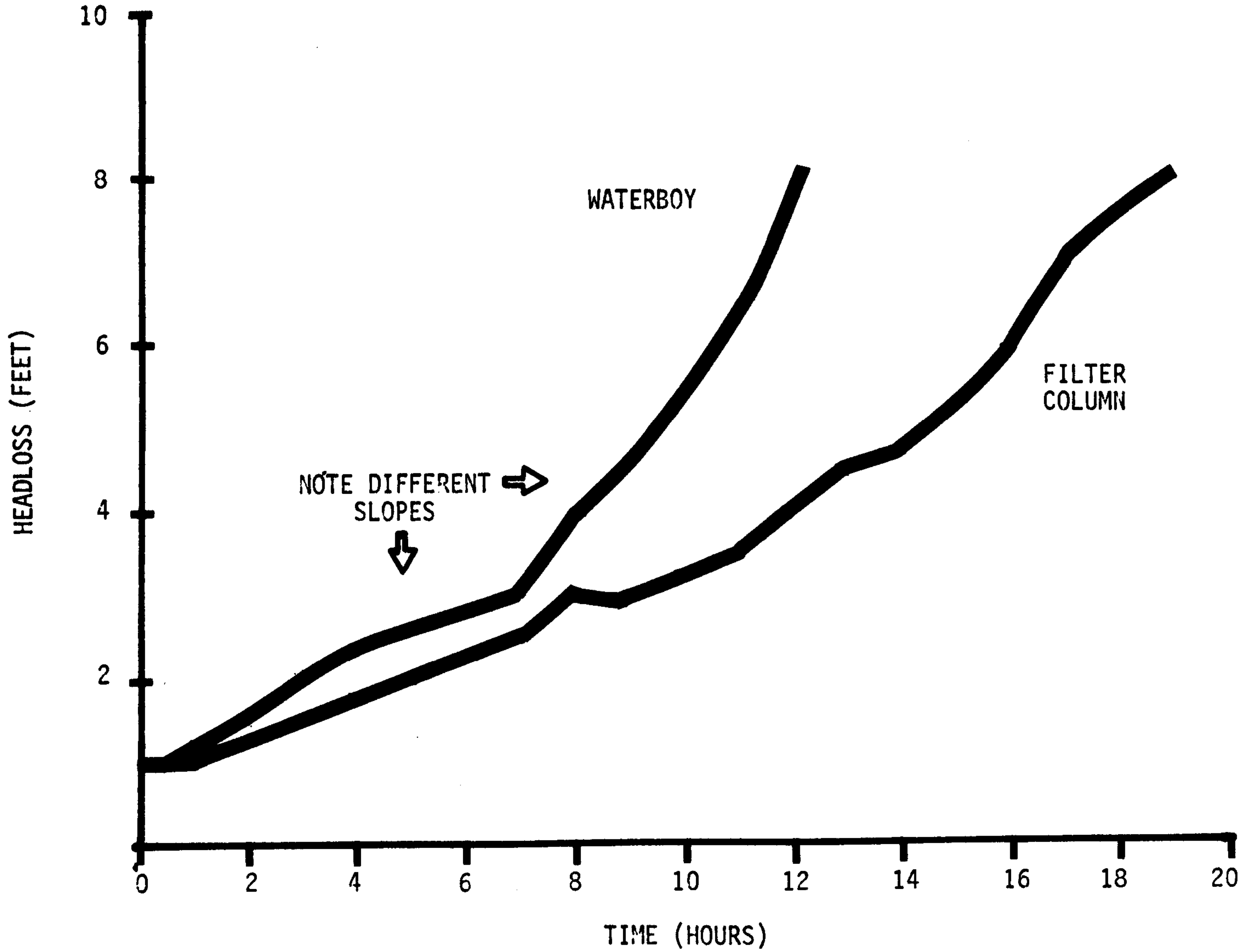

Figure 12. Headloss vs. time - runs #93 & #93M.

it was assumed that the filter run would terminate when the loading rate had decreased to 6 gpm/ft^2 rather than allowing the run to progress to 10 ft of headloss. This data provides a better picture of the filters operating under stressed conditions. To evaluate data from the various medias under consideration, side-by-side testing of the three filter columns was undertaken and measures of water production efficiency for runs #139, #140, #141, #145, #147, #153*, #156*, #157*, and #161* were plotted in Figures 13 and 14 and linear regressions are presented in the following table.

TABLE 20. LINEAR REGRESSION EQUATIONS FOR THE VARIOUS FILTER MEDIAS

	Filter Media		
	MM	FC	CC
UFRV gal/ft^2/run	= 6620 - 197(LR$^+$)	= 8442 - 488(LR)	= 9308 - 610(LR)
Net Water Produced per 24 Hours gal/ft^2/24 hours	= 197 + 1323(LR)	= 151 + 1322(LR)	= 397 + 1283(LR)

$^+$LR = Average Filter Loading Rate in gpm/ft^2.

Review of the Figures and the regression equations indicates that when filter loading rates are between about 5.5 gpm/ft^2 and 7.5 gpm/ft^2, there is little difference in the UFRV's of the different medias. Assuming the data can be extrapolated outside that range, the differences become more exaggerated. At loading rates less than 5.5 gpm/ft^2, the dual media with coarse coal (CC) would produce more water per filter run and is more efficient than either dual media with fine coal (FC) or the mixed media (MM). At rates exceeding 7.5 gpm/ft^2, the mixed media (MM) produced more water per filter run. This finding may be related to a more even distribution of floc particles throughout the mixed media which becomes evident at the higher loading rates. The linear regressions for the net water produced per 24 hours were about the same for all three medias.

By analyzing all the data contained in Appendix A-3, the following linear regressions are obtained.

UFRV (gpm/ft^2/run) = 8773 - 572(LR)

Net Water Produced per 24 Hours (gal/ft^2/24 hours) = 665 + 1239(LR)

where LR = Average Filter Loading Rate (gpm/ft^2)

*Efficiencies were calculated as if filter runs were terminated at 10 ft of headloss and then at 6 gpm/ft^2.

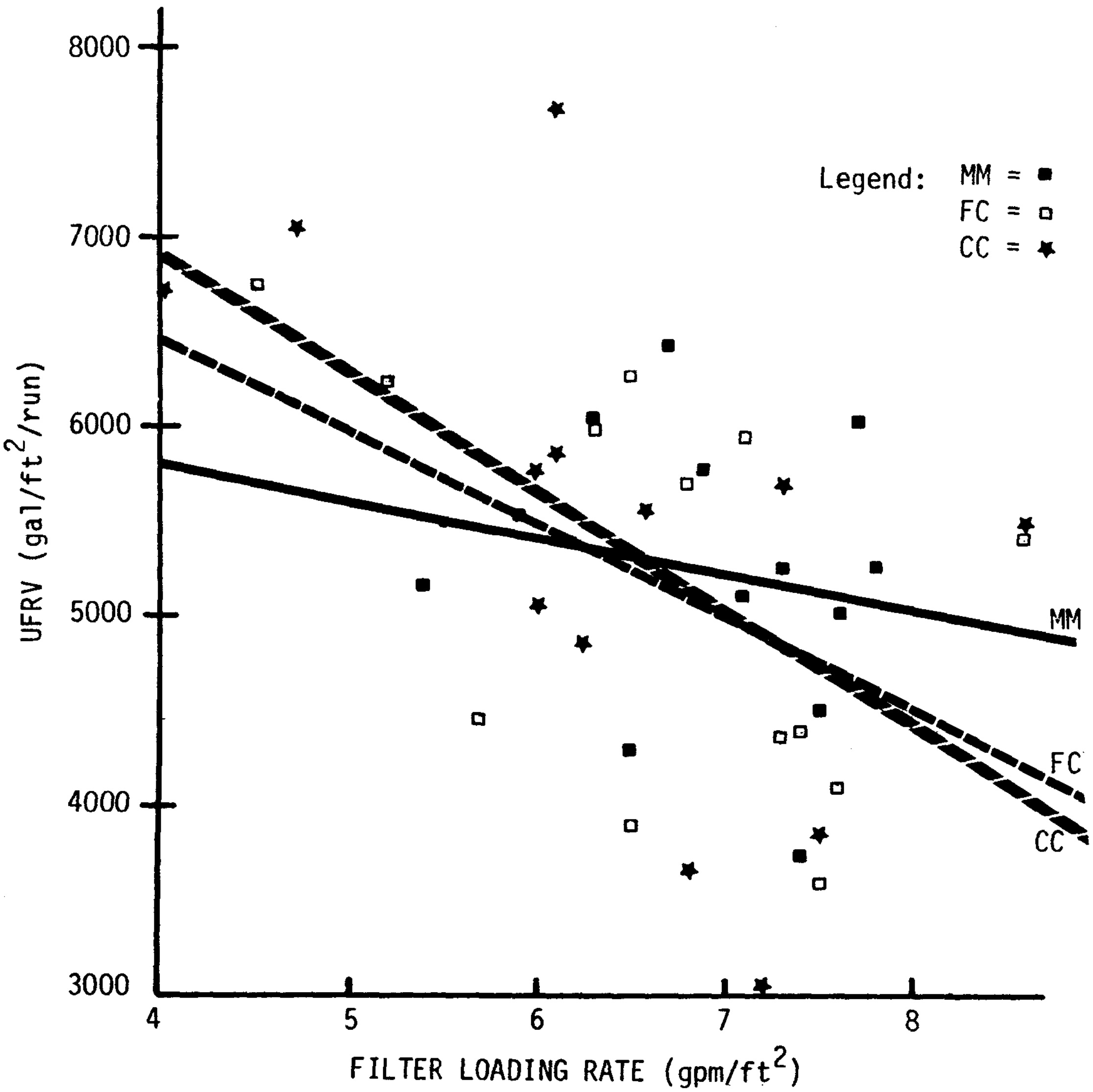

Figure 13. UFRV vs. filter loading rate.

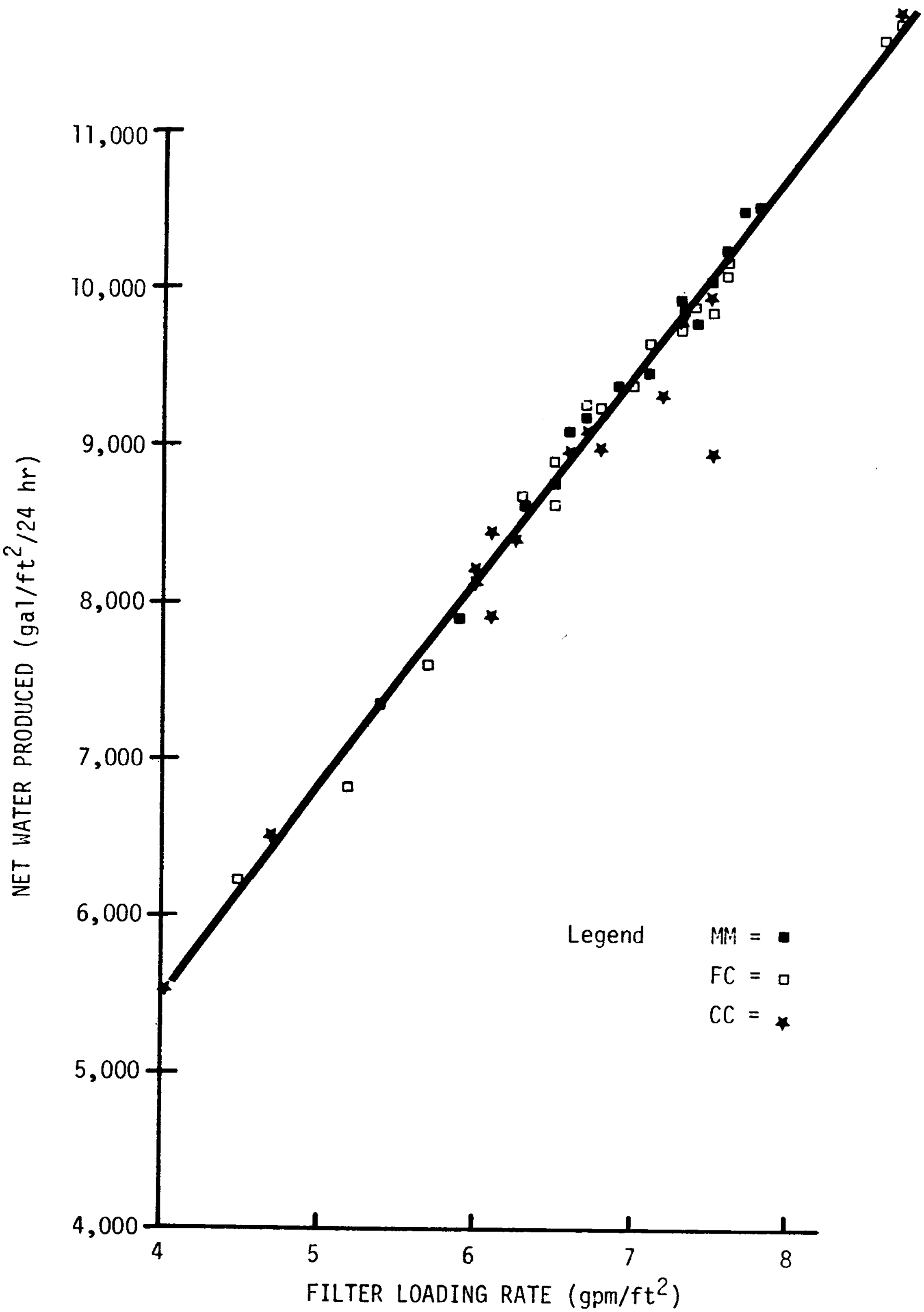

Figure 14. Net water produced per 24 hours vs. the filter loading rate.

These equations combine data from all filter medias tested, are quite similar to the ones found in Table 20 and will be used to estimate the required filter surface area in SECTION VII, DESIGN CONSIDERATIONS.

One filter run, #174, was conducted using a different combination and depth of the various mixed media components. To reduce the rate of headloss build-up, the depth of garnet and sand was reduced and the depth of anthracite was increased. In addition, the uniformity coefficient of the sand was slightly lower, 1.4 for filter media CMM, as opposed to 1.8 for filter media MM. Results of that run indicated that there were virtually no differences between average filter loading rates, the UFRV's and the net water produced per 24 hours for the various medias. Figures 15, 16 and 17 illustrate the operating parameters throughout the filter run for each media as well as water quality data which is discussed in the following section.

In summary, there were advantages and disadvantages associated with both dual and mixed media filters. Both types of filters met process goals and efficiencies were practically the same when the filter loading rate was between 5.5 and 7.5 gpm/ft^2. Below 5.5 gpm/ft^2, the coarse coal dual media (CC) was more efficient and above 7.5 gpm/ft^2, the mixed media (MM) demonstrated a higher efficiency.

Water Quality Generated --

Since removal of asbestos fibers was a prime consideration of the study, a comparison of the chrysotile counts in the finished water generated from the various medias was made and results are shown below.

TABLE 21. CHRYSOTILE RESULTS FROM VARIOUS FILTER MEDIAS

		Filter Column			
Run No.	Hour Into Run	MM 10^6 fibers/liter	FC 10^6 fibers/liter	CC 10^6 fibers/liter	CMM 10^6 fibers/liter
161	1	0.01 (NSS)	<0.01 (ND)	<0.01 (ND)	-
	4	0.02 (NSS)	0.04 (NSS)	<0.01 (ND)	-
	10	<0.01 (ND)	0.02 (NSS)	0.01 (NSS)	-
	13	<0.01 (ND)	0.03 (NSS)	<0.01 (ND)	-
	15	<0.01 (ND)	<0.01 (ND)	<0.01 (ND)	-
174	0	0.07	-	0.01 (NSS)	0.09
	1	0.1	-	0.04 (NSS)	0.02 (NSS)
	1½	0.36	-	<0.03 (ND)	0.94
	2	0.03 (NSS)	-	0.01 (NSS)	<0.01 (ND)
	3	<0.01 (ND)	-	<0.01 (ND)	0.03 (NSS)
	4	<0.01 (ND)	-	<0.01 (ND)	0.01 (NSS)
	5	0.01 (NSS)	-	<0.01 (ND)	0.06 (NSS)
	6	0.01 (NSS)	-	<0.01 (ND)	0.02 (NSS)
	7	0.01 (NSS)	-	0.06 (NSS)	0.01 (NSS)
	14	<0.01 (ND)	-	<0.01 (ND)	0.01 (NSS)

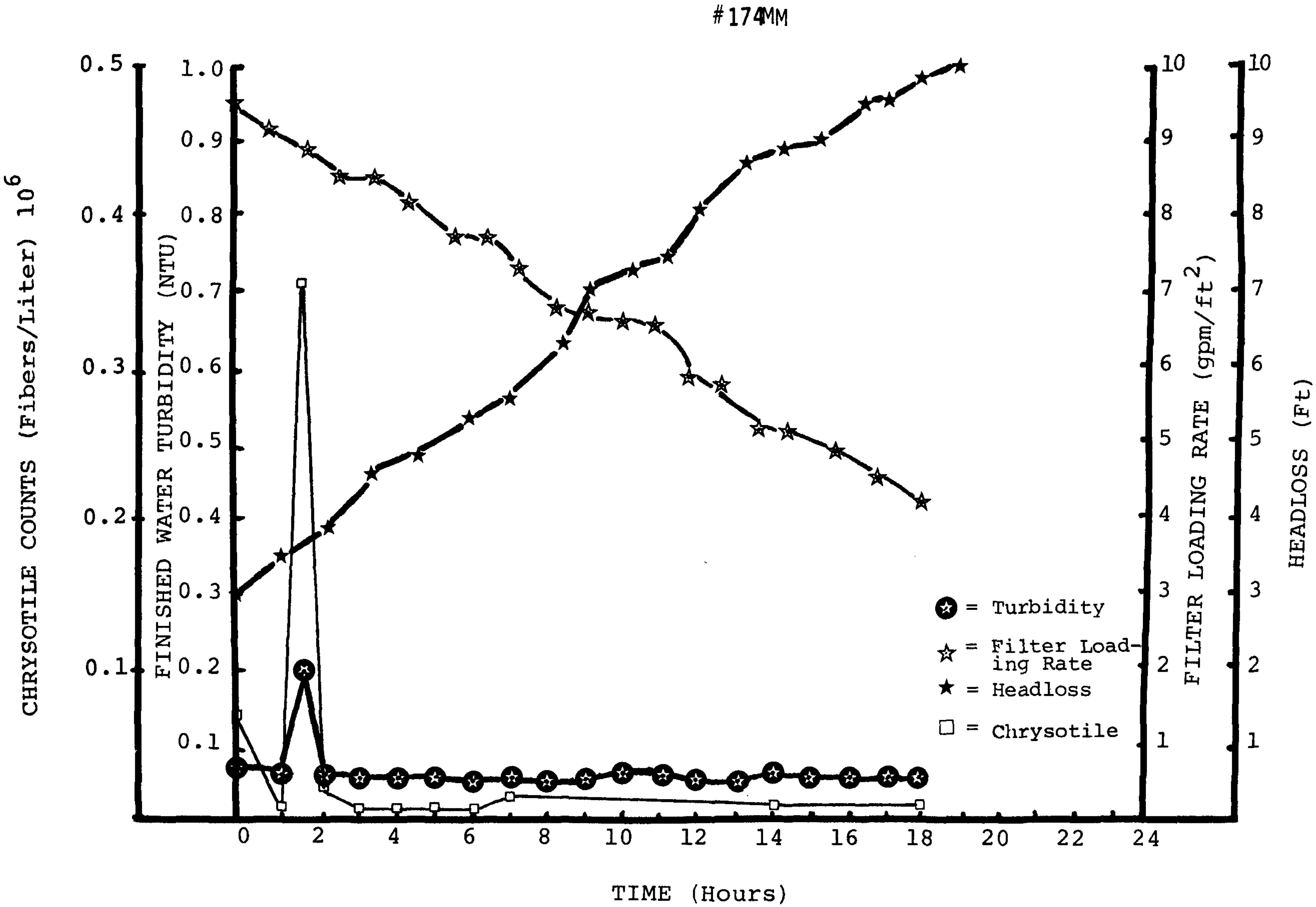

Figure 15. Operating data for run #174MM.

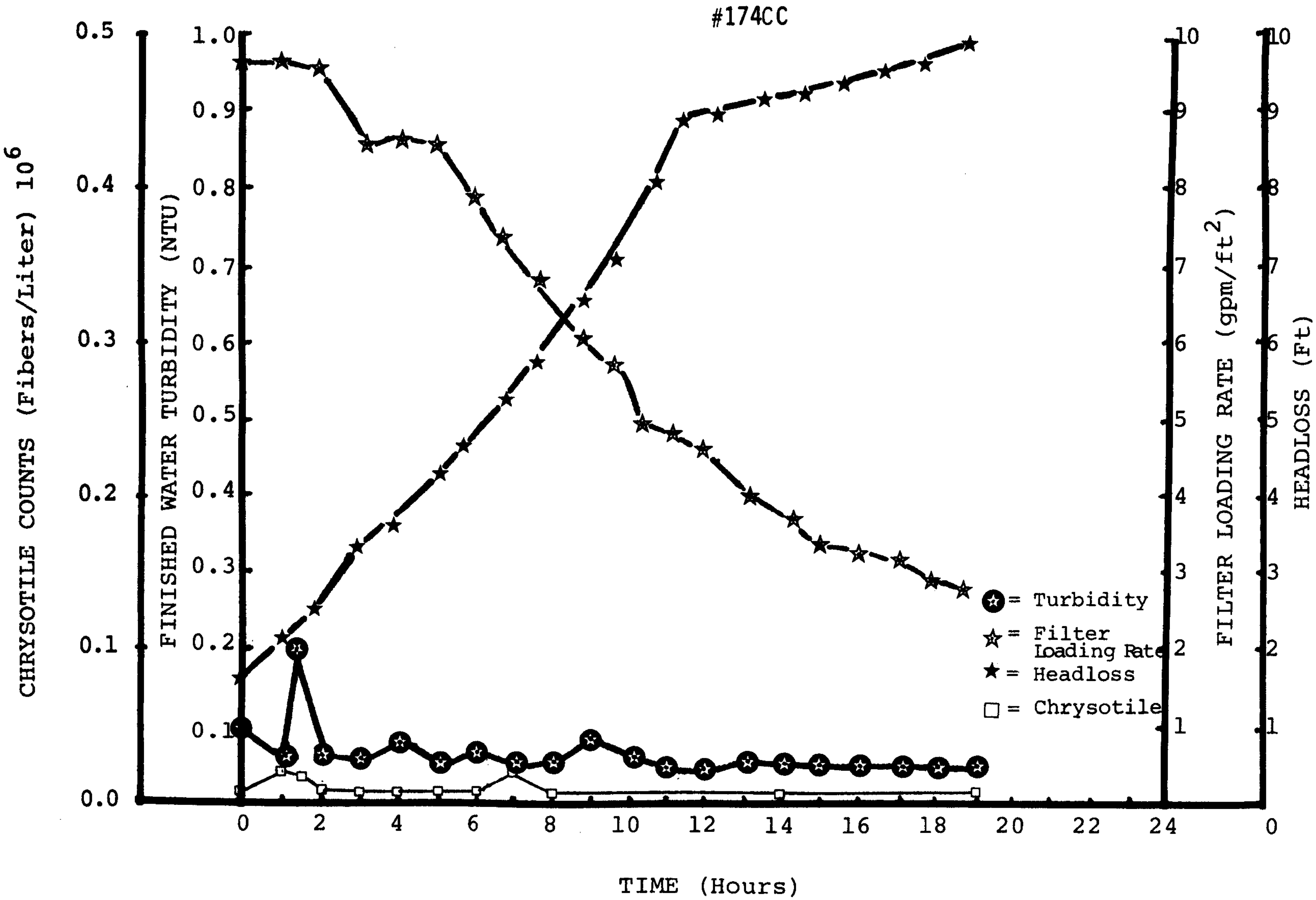

Figure 16. Operating data for run #174CC.

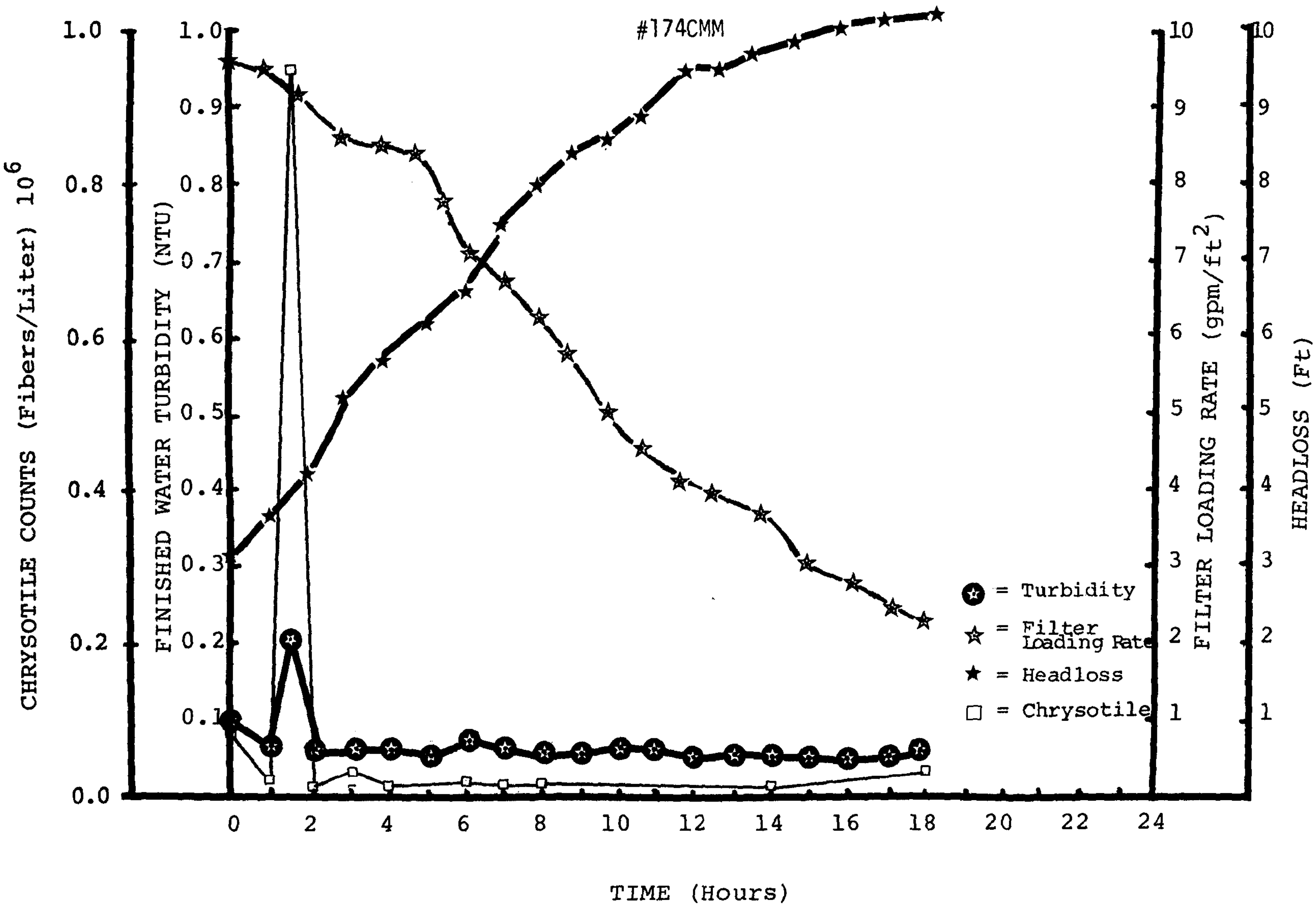

Figure 17. Operating data for run #174CMM.

When one considers the complexity of the asbestos analysis, the data indicate that all filter medias are equally effective at removing asbestos fibers during the normal course of a filter run. With the exception of samples collected during a turbidity spike and at the very beginning of the filter run #174, all samples had ND or NSS levels of chrysotile. Finished water turbidities were also virtually the same for all of the medias being tested.

Asbestos Removals

Two objectives established by the EPA at the outset of the study were to: (1) confirm earlier amphibole removal results gathered during the Duluth asbestos removal study,[3] and (2) develop methods for chrysotile removal. Finished water asbestos results are contained in Appendix A.

Amphibole --

Review of the removal data indicates that amphibole fibers can consistently be removed down to the detection limit of $0.01(10^6)$ fibers/liter. Removal efficiencies were between 98.3 and 100%. Where amphiboles were detected in the raw water and when turbidity was $\leq$ 0.10 NTU, 52 out of 57 results (91%) had levels of amphibole which were at or less than the detection limit. In all 5 of the cases where amphibole fibers were $> 0.01(10^6)$ fibers/liter, 4 or fewer fibers were counted by the analyst, which means that the results were not statistically significant. 3 out of the 5 cases occurred when alum without lime addition was being employed as a treatment method and the other 2 occurred at an alum dosage of about 7 mg/l rather than the optimal 10 mg/l. These are possible explanations for the outlying data points but by no means are they conclusive evidence. As indicated in Figure 18, when the finished water turbidities exceed 0.10 NTU, amphibole counts are much higher and there is a noticeable scatter to the data. These data points represent times when either poor destabilization was occurring or when turbidity breakthrough had already taken place. In conclusion, amphibole fibers can consistently be removed down to the detection limit if certain operating conditions are met. This confirms the earlier amphibole research and operating data at Duluth, Minnesota.[3]

Chrysotile --

Review of the chrysotile data listed in Appendix A indicates that although excellent removals can be achieved, it is more difficult to remove than amphibole and results are more variable. Figure 19 indicates that there is a very tight pattern of data when finished water turbidity is $\leq$ 0.10 NTU and considerable scatter above that point. As with the amphibole results, the scattered chrysotile data above 0.10 NTU are normally associated with either poor destabilization, turbidity spikes or breakthrough. Data from filter runs #111, #120, #161 and #174 indicate that chrysotile can consistently be removed down to not detectable or not statistically significant levels when good filtration is occurring (i.e., $\leq$ 0.10 NTU). Figure 20 can be used to estimate what levels of chrysotile were present at any given time when finished water turbidity was $\leq$0.10 NTU. For example, 50% of the time when turbidity was $\leq$ 0.10 NTU, finished water chrysotile counts were $\leq 0.02(10^6)$ fibers/liter. Figure 21 estimates levels of chrysotile present when turbidity was $>$0.10 NTU and indicates than 50% of the time, chrysotile counts were $\leq 0.27(10^6)$

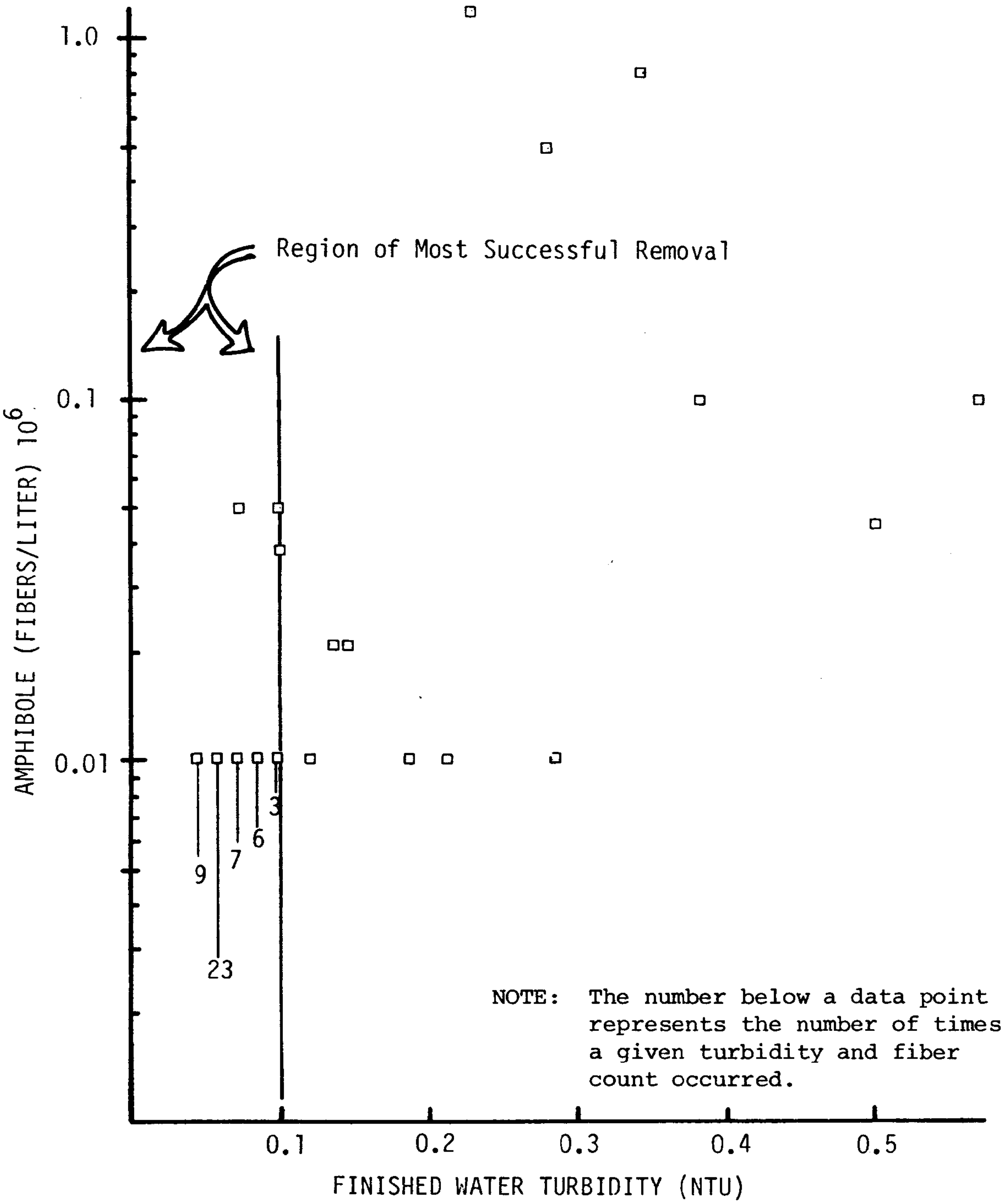

Figure 18. Amphibole vs. finished water turbidity.

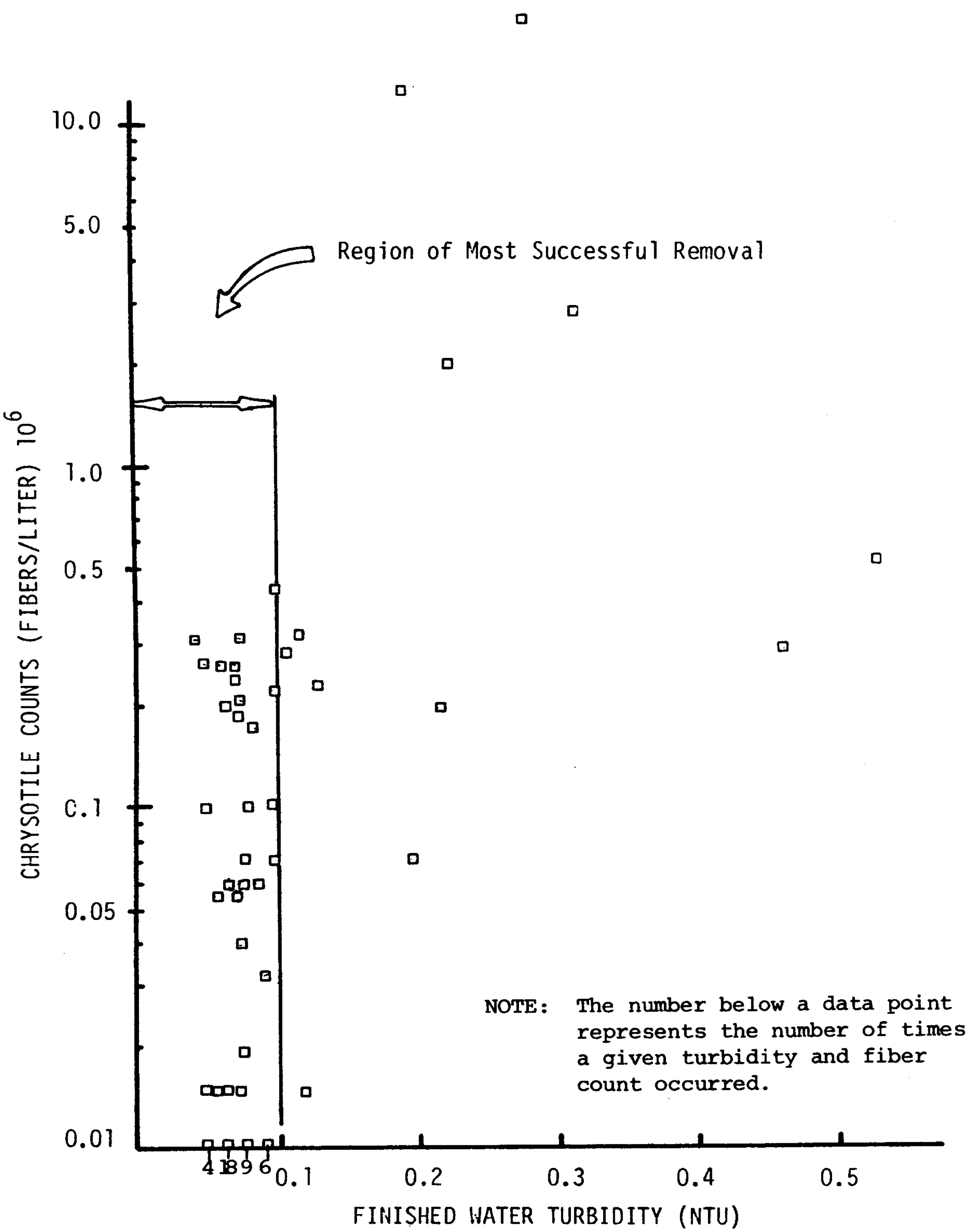

Figure 19. Chrysotile count vs. finished water turbidity.

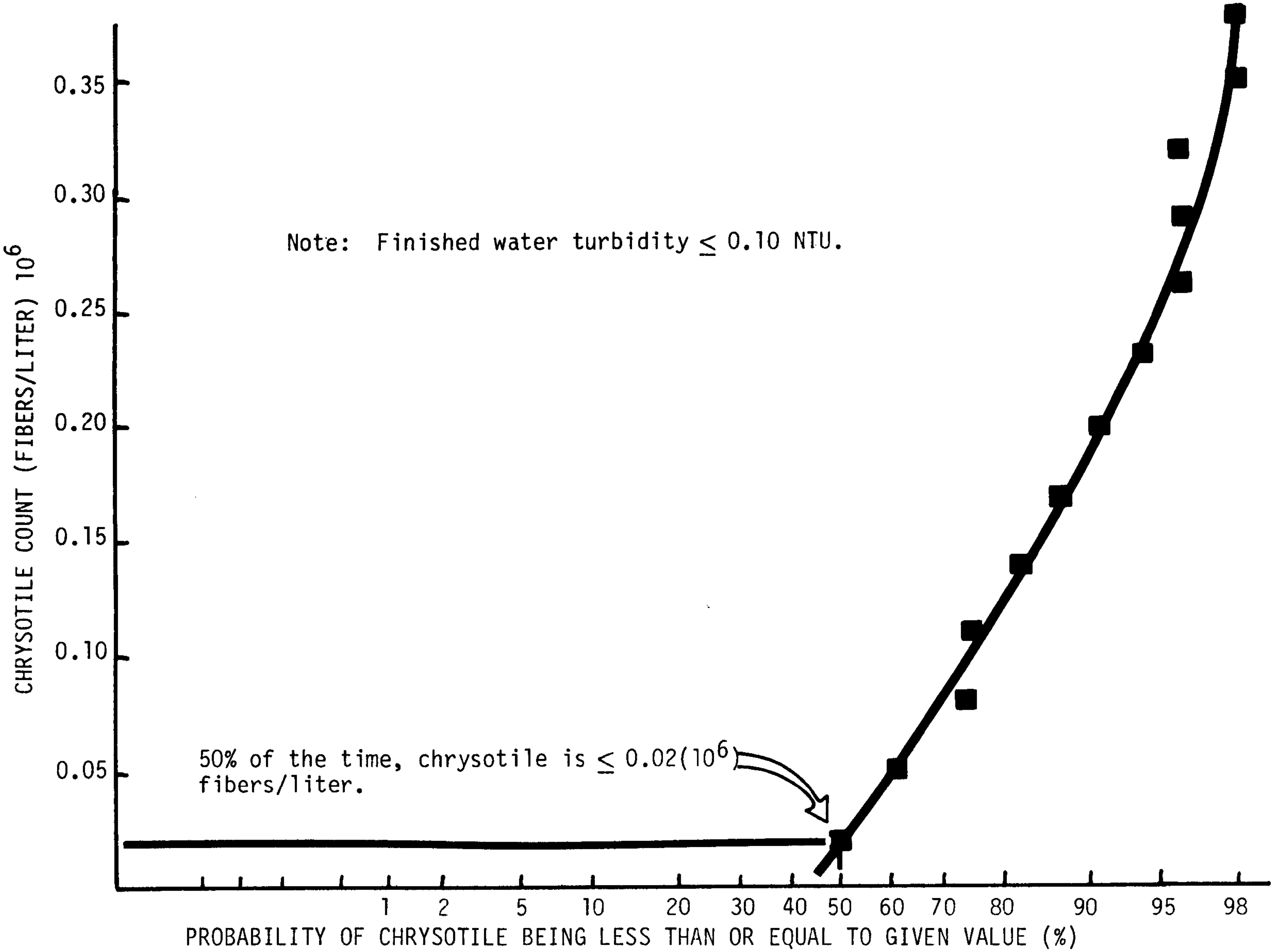

Figure 20. Probability plot for chrysotile when finished water turbidity is ≤ 0.10 NTU.

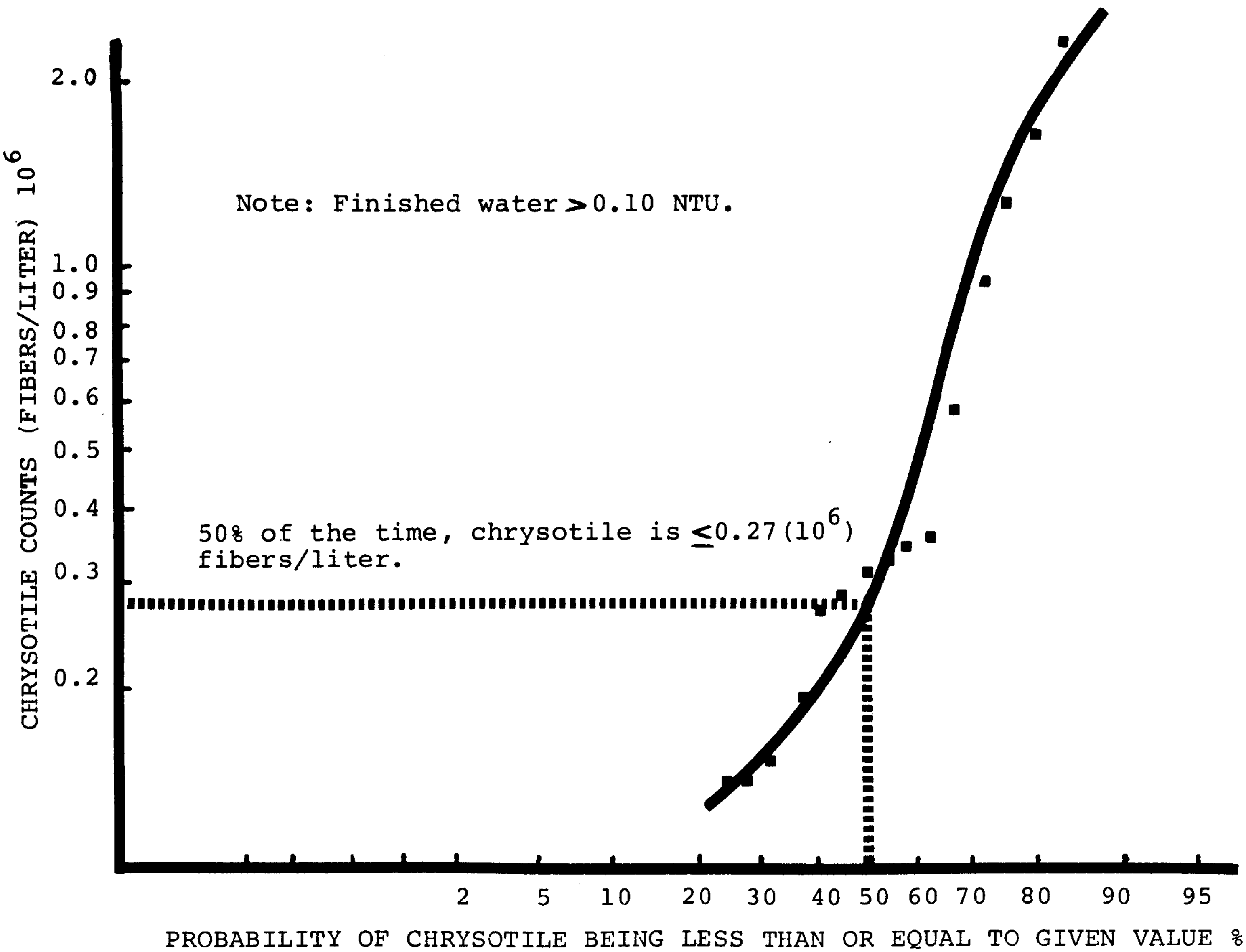

Figure 21. Probability plot for chrysotile when turbidity is >0.10 NTU.

fibers/liter. Thus, over 10 times more asbestos was present in the finished water when turbidity was >0.10 NTU as compared to when turbidity was ≤0.10 NTU. In conclusion, chrysotile fibers can consistently be removed to levels which are NSS if certain operating conditions are met. This accomplishes the most important objective established by the EPA for this study.

Relationship to Turbidity --

One of the objectives of the study established by the principal investigator was to develop an operating tool which would indicate quickly when effective asbestos removal was occurring. To be an operating tool, it needed to be simple to calibrate and operate and had to give immediate results. An on-line turbidimeter would fit the criteria if it could be correlated with asbestos removal. To provide the background for development of this relationship, several filter runs and asbestos counts are reviewed in detail.

Filter Run #11. This filter run was conducted at 5.9 mg/l of alum and never reached the finished water goal of 0.10 NTU. Chrysotile results are presented in the following table.

TABLE 22. RESULTS FROM RUN #11

Sample Location	Hour Into Run	Turbidity, NTU	Chrysotile Counts fibers/liter
RAW	6	1.15	$13.39(10^6)$
FINISHED	6	0.20	$1.64(10^6)$

Although the finished water was meeting the 1.0 NTU maximum contaminant level established by the National Interim Primary Drinking Water Regulations,[1] these results indicate that asbestos removal efficiencies were poor, only 87.7% and that chrysotile counts were extremely high in the finished water.

Filter Runs #21 and #24. These filter runs were conducted using 7 and 9.2 mg/l of alum, respectively, along with lime for pH control and a polymer as a filter aid. Results are presented in the following table and in Figures 22 and 23.

These results indicate that when finished water turbidity was ≤ 0.10 NTU, then chrysotile removal was excellent (99.3-99.8%). At Hour 7 when the finished water turbidity spiked at 0.34 NTU, the finished water chrysotile rose from NSS levels up to $12.25(10^6)$ fibers/liter (removal efficiency = 52.5%). The spikes probably occurred because of a temporary overfeed of lime causing pH to increase to levels that were not conducive to proper floc formation. Even though 0.34 NTU is well within the 1.0 NTU maximum contaminant level, poor destabilization was occurring and this resulted in very high asbestos counts in the filtered water. High levels of chrysotile also coincided with the turbidity spike in run #24.

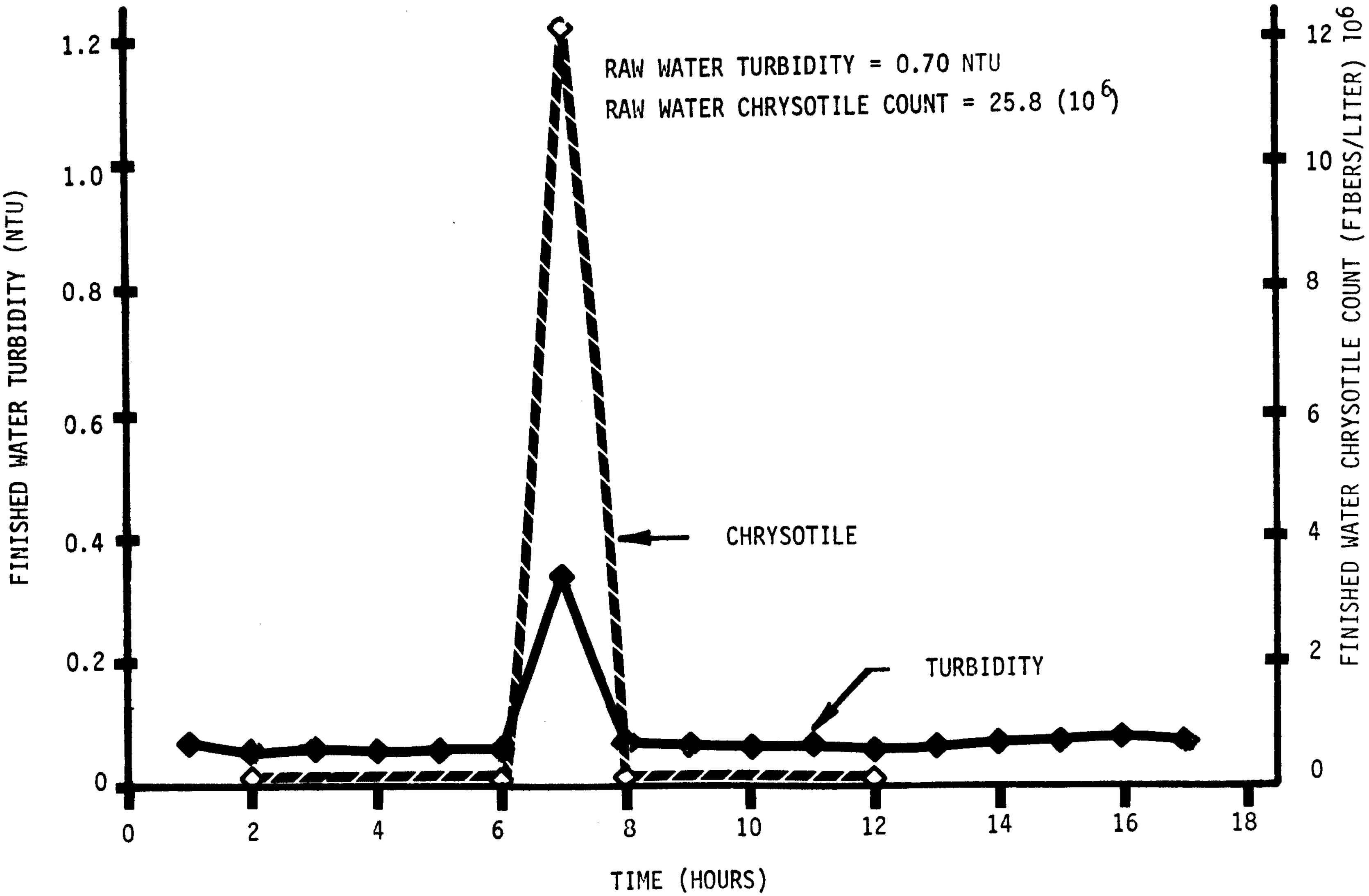

Figure 22. Finished water turbidity and chrysotile vs. time - run 21.

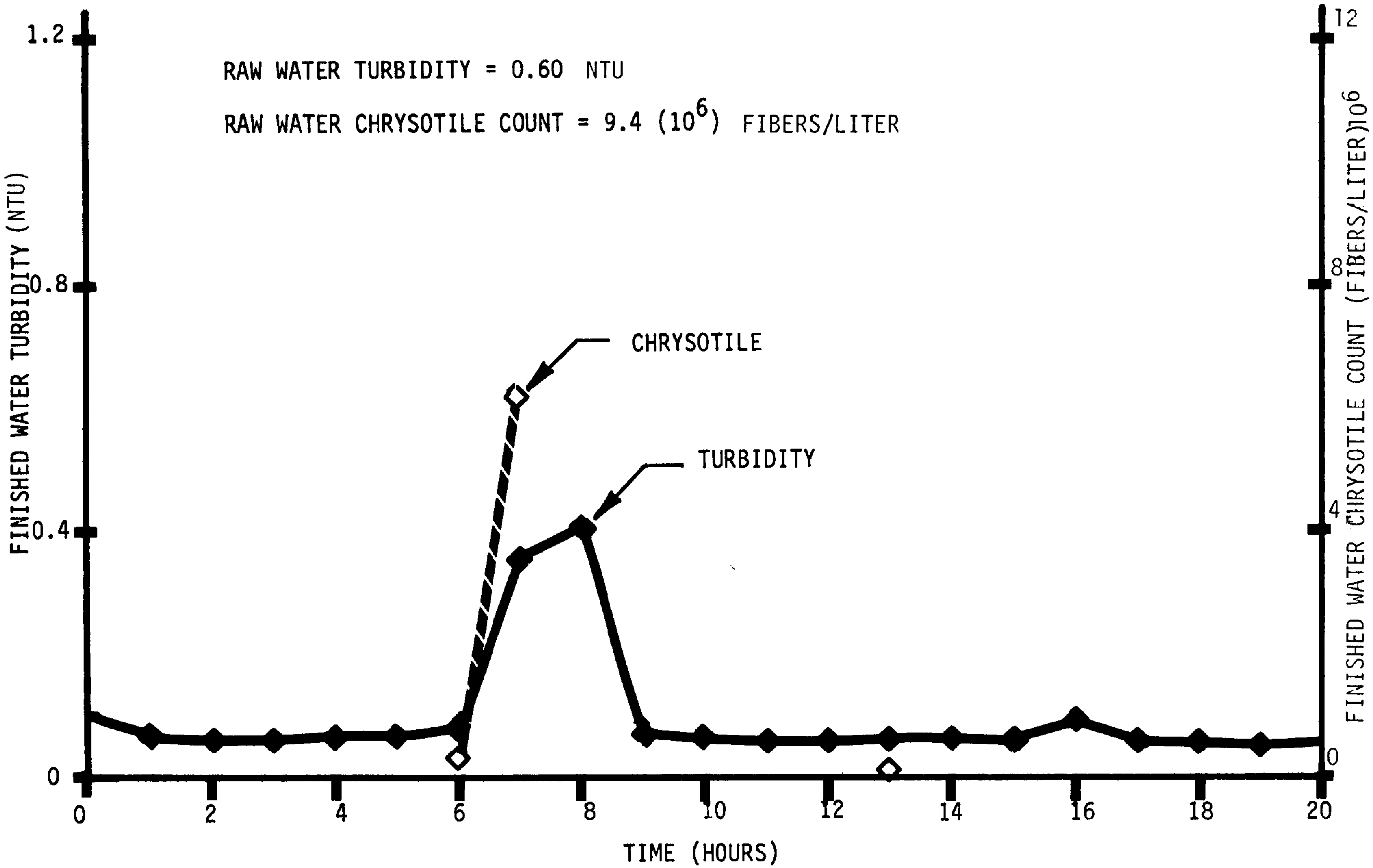

Figure 23. Finished water turbidity and chrysotile vs. time - run 24.

TABLE 23. RESULTS FROM RUNS #21 and #24

Sample Location		Hour Into Run	Turbidity, NTU	Chrysotile Counts fibers/liter
RAW	(Run #21)	7	0.66	25.8 (10^6)
FINISHED	(Run #21)	2	0.065	0.16(10^6)
FINISHED	(Run #21)	6	0.06	0.06(10^6)
FINISHED	(Run #21)	7	0.34	12.25(10^6)
FINISHED	(Run #21)	8	0.07	9.19(10^6)
FINISHED	(Run #21)	12	0.059	0.09(10^6)
RAW	(Run #24)	7	0.60	9.4 (10^6)
FINISHED	(Run #24)	6	0.085	0.34(10^6)
FINISHED	(Run #24)	7	0.36	6.2 (10^6)
FINISHED	(Run #24)	13	0.07	0.13(10^6)

Filter Run #53. This filter run was conducted using 3 mg/l of CATFLOC T-1 without a filter aid. Asbestos results are presented below.

TABLE 24. RESULTS FROM RUN #53

Sample Location	Hour Into Run	Turbidity NTU	Chrysotile fibers/liter	Amphibole fibers/liter
RAW	9	0.50	3.0 (10^6)	0.70(10^6) (NSS)
FINISHED	3	0.13	0.27(10^6)	<0.02(10^6) (ND)
FINISHED	9	0.24	11.2 (10^6)	1.2 (NSS)

Turbidity in the Hour 3 sample was slightly >0.1 NTU and asbestos removals were good for amphibole but only marginal for chrysotile. The Hour 9 sample was collected during a turbidity spike and it contained higher levels of both amphibole and chryosile than did the raw water. This indicates that the floc particles, which contain concentrated levels of asbestos, were probably sheared from the media and entered the filtered water. Thus, operations tending to break the floc should be avoided.

Filter Run #62. This filter run was conducted using 3 mg/l of alum, 2 mg/l of CATFLOC T-1 and 0.1 mg/l of a nonionic polymer as a filter aid. Finished water turbidities were just at the 0.10 NTU goal until breakthrough began to occur late in the run. Asbestos results are presented in Table 25.

TABLE 25. RESULTS FROM RUN #62

Sample Location	Hour Into Run	Turbidity NTU	Chrysotile fibers/liter	Amphibole fibers/liter
RAW	16	0.35	$2.52(10^6)$	$<0.1\ (10^6)$ (ND)
FINISHED	3	0.1	$0.34(10^6)$	$<0.02(10^6)$ (ND)
FINISHED	9	0.105	$0.24(10^6)$	$<0.02(10^6)$ (ND)
FINISHED	16	0.37	$2.28(10^6)$	$0.1\ (10^6)$

It is interesting to note that although amphibole fibers were not detected in the raw water, one fiber was found in the finished water after breakthrough occurred. The filtration process was evidently concentrating the fibers to the point that they were detected in the finished water after breakthrough had occurred. The sample that had detectable amphibole also indicated a very poor removal efficiency for chrysotile, only 9.5%.

Filter Run #120. This filter run provides an excellent example of how finished water turbidity and asbestos counts track during filter breakthrough. The results are presented in the following table and in Figure 24.

TABLE 26. RESULTS FROM RUN #120

Sample Location	Hour Into Run	Turbidity, NTU	Chrysotile Count fibers/liter
RAW	9	3.3	$5.38(10^6)$
FINISHED	1	0.14	$0.14(10^6)$
FINISHED	2	0.090	$0.19(10^6)$
FINISHED	6	0.08	$0.07(10^6)$
FINISHED	9	0.065	$<0.01(10^6)$ (ND)
FINISHED	12	0.06	$0.01(10^6)$ (NSS)
FINISHED	13	0.07	$<0.01(10^6)$ (ND)
FINISHED	15	0.062	$0.01(10^6)$ (NSS)
FINISHED	16	0.071	$0.01(10^6)$ (NSS)
FINISHED	17	0.071	$0.02(10^6)$ (NSS)
FINISHED	18	0.115	$<0.01(10^6)$ (ND)
FINISHED	10	0.14	$0.19(10^6)$
FINISHED	20	0.28	$0.14(10^6)$ (NSS)
FINISHED	21	0.48	$0.28(10^6)$
FINISHED	22	0.57	$0.57(10^6)$
FINISHED	23	1.2	$1.25(10^6)$

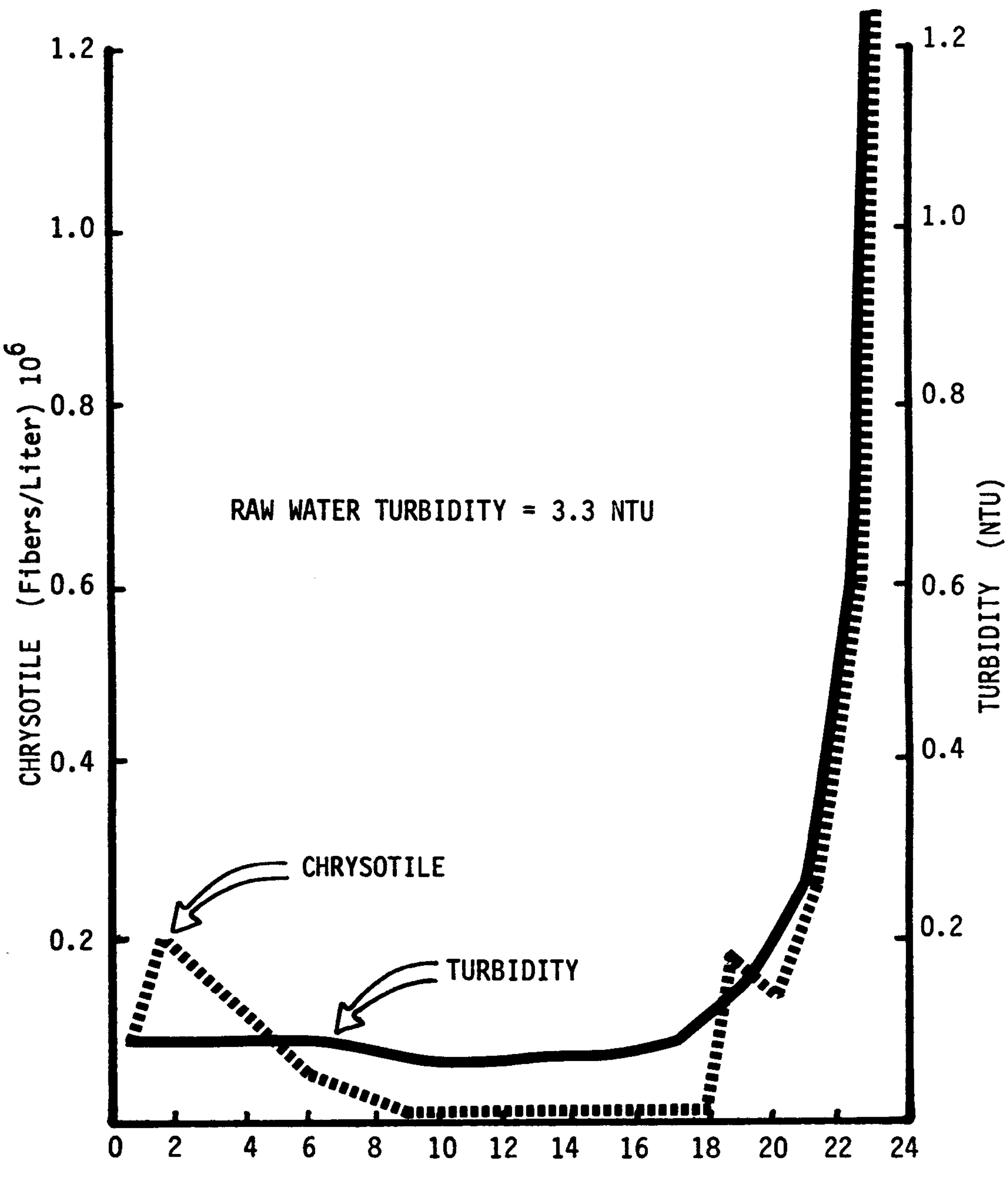

Figure 24. Finished water chrysotile counts and turbidity vs. time-run #120.

This filter run indicates that high chrysotile counts in the filtered water coincide with filter breakthrough as indicated by a rising finished water turbidity. This run also illustrates that direct filtration techniques can consistently remove chrysotile down to ND or NSS levels even during periods of high raw water turbidities (3.3-3.4 NTU).

Filter Run #174. Filter run #174 was conducted using 10 mg/l of alum, lime for pH control and a nonionic polymer as a filter aid. Initial filter loading rates were as high as 10 gpm/ft^2 and the declining rate filtration mode of operation was used. To test the sensitivity of the turbidimeter in detecting changes in the operation of the filter, the alum feed pump was discontinued and finished water turbidity was monitored continuously during the process. Within about 15 minutes after disconnecting the pump, the finished water turbidity began to rise rapidly. By adding the estimated detention time of the water in the flocculation chamber and in the free space above the filter media, a time of about 13.5 minutes is obtained. Although both chambers are complete mix systems as opposed to plug flow reactors, a comparison of these two times, 15 vs. 13.5 minutes, indicates that the simple turbidimeter functions exceptionally well as a "troubleshooting" instrument which could have alerted an operator that something was wrong somewhere in the system. Within 15 minutes after the alum pump was placed back into operation, the finished water turbidity returned to $\leq$ 0.10 NTU and stayed at that low level for the duration of the filter run. Asbestos analyses conducted before, during and after pump shutdown are presented in Table 27 and in Figure 25. These data indicate that when the alum pump was off and finished water turbidity had risen only to 0.20 NTU, there was a noticeable increase in chrysotile counts from the very low levels previously occurring.

TABLE 27. RESULTS FROM RUN #174MM

Sample Location	Hour Into Run	Turbidity NTU	Chrysotile fibers/liter	Alum Pump On/Off
RAW	1½	0.36	1.84(10^6)	
FINISHED	0	0.089	0.07(10^6)	On
FINISHED	1	0.075	0.1 (10^6)	On
FINISHED	1½	0.20	0.36(10^6)	Off
FINISHED	2	0.079	0.03(10^6) (NSS)	On
FINISHED	3	0.078	<0.01(10^6) (ND)	On
FINISHED	4	0.075	0.01(10^6) (NSS)	On
FINISHED	5	0.079	0.01(10^6) (NSS)	On
FINISHED	6	0.072	0.01(10^6) (NSS)	On
FINISHED	7	0.075	0.02(10^6) (NSS)	On
FINISHED	14	0.078	<0.01(10^6) (ND)	On
FINISHED	18	0.075	<0.01(10^6) (ND)	On

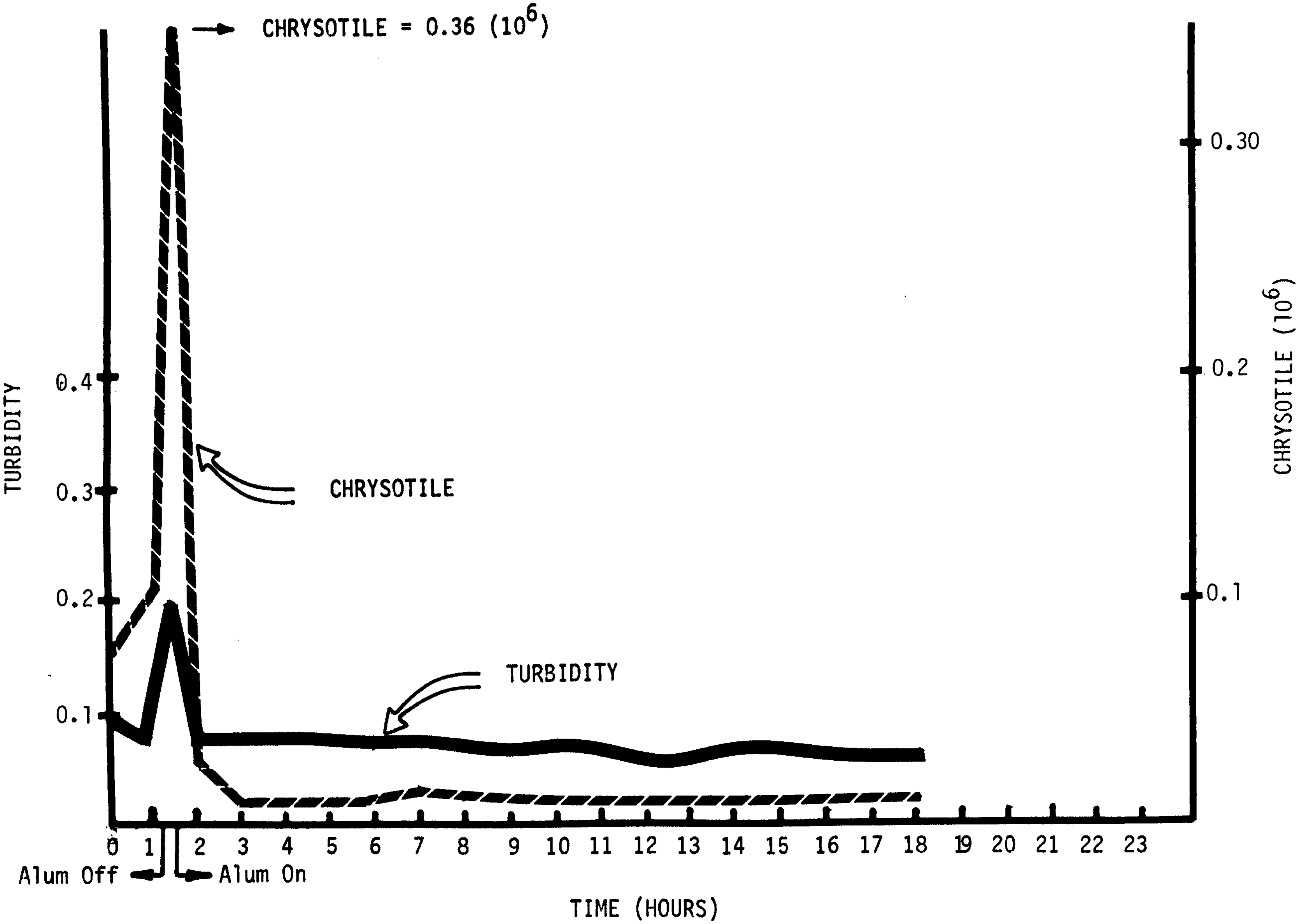

Figure 25. Finished water turbidity and chrysotile vs. time-run #174MM.

In conclusion, the data from numerous filter runs indicate that the continuous, on-line turbidimeter can be used as an operational tool to indicate when excellent asbestos removals are occurring. The turbidimeter does not necessarily relate to specific asbestos concentrations in the finished water but nevertheless it can alert the treatment plant operator when poor destabilization, a turbidity spike or breakthrough are occurring. These conditions invariably cause both turbidity and asbestos counts to increase in the finished water.

Comparison of Different Methods of Asbestos Analysis --

About two-thirds of the way through the research study, the EPA project officer asked if the scope of work might be expanded to compare the results obtained from two different analysis methods - the Millipore[15] and the Nuclepore[15]. There are several procedural differences in the analysis methods, the major ones being that filters with different pore sizes are used and in the Nuclepore method, the fibers are coated with carbon. The Millipore procedure uses a filter that has a pore size of 0.45 microns whereas the Nuclepore filter has a pore size of 0.1 microns. To make the comparison, one raw water sample and ten finished water samples were gathered, split and analyzed by each method. Results of analysis are presented in Table 28.

TABLE 28. COMPARISON OF MILLIPORE AND NUCLEPORE ANALYSIS METHODS

Run No.	Hour Into Run	Turbidity	Amphibole Millipore 10^6	Amphibole Nuclepore 10^6	Chrysotile Millipore 10^6	Chrysotile Nuclepore 10^6
161-CC	1	0.092	<0.01(ND)	<0.03(ND)	<0.01(ND)	0.03(NSS)
161-CC	10	0.069	<0.01(ND)	<0.03(ND)	0.01(NSS)	<0.03(ND)
161-FC	1	0.095	<0.01(ND)	<0.14(ND)	<0.01(ND)	<0.14(ND)
161-MM	1	0.135	<0.01(ND)	<0.14(ND)	0.01(NSS)	<0.14(ND)
161-MM	10	0.079	<0.01(ND)	<0.03(ND)	<0.01(ND)	0.03(NSS)
171-R	1½	0.36	0.07(NSS)	<0.18(ND)	1.84	2.16
174-MM	2	0.078	<0.01(ND)	<0.07(ND)	0.03(NSS)	0.07(NSS)
174-CMM	2	0.068	<0.01(ND)	<0.07(ND)	<0.01(ND)	0.07(NSS)
174-CC	1	0.070	<0.01(ND)	<0.03(ND)	0.04(NSS)	<0.03(ND)
174-CC	1½	0.20	<0.03(ND)	<0.14(ND)	<0.03(ND)	0.71
174-CC	2	0.07	<0.01(ND)	<0.07(ND)	0.01(NSS)	<0.07(ND)

Although the detection levels for the fibers analyzed by the two methods differ slightly, amphibole results on the finished water consistently show nondetectable levels by both methods. Raw water chrysotile results were practically the same - $1.84(10^6)$ fibers/liter by Millipore and $2.16(10^6)$ fibers/liter by Nuclepore. With one exception, chrysotile counts were also very consistent on the finished water. Water collected 1½ hours into run #174 from the CC column was the only sample to indicate any significant difference in chrysotile counts as measured by the two analysis methods. That sample was collected during a turbidity spike and based on previous results should have had detectable chrysotile. The Millipore method indicated non-detectable levels whereas Nuclepore filtration indicated that $0.71(10^6)$ fibers/liter were present. Samples collected during the same turbidity spike from other filter columns indicated that chrysotile was present when analyzed by Millipore methods. Overall, the results of analysis by both methods were virtually the same.

Particle Counts

Early in the pilot testing phase, the particle counts on hourly samples throughout filter runs were measured and results are contained in Appendix B. This data indicates that particle counts tracked fairly well with turbidity; however, there were some unexplained spikes in the counts. The particle counter is undoubtedly much more sensitive to treatment changes than the turbidimeter and the former could be used to optimize chemical dosages and fine tune treatment plant operations. The particle counter is more difficult to calibrate and maintain and requires a much higher level of skill to operate than a turbidimeter; therefore, the particle counter was not judged suitable as an on-line tool for indicating the acceptability of filter effluent.

High Turbidity Removal

Since direct filtration techniques were being employed and were quite effective at removing turbidity and asbestos fibers from the raw water, it became desirable to determine the capability of these same techniques during abnormally high raw water turbidities (>5 NTU). Therefore, tests were conducted to determine (1) if the process flow schematic, which included a static mixer, a flocculator and granular media filters, would remove high levels of turbidity; (2) what practical upper limit of raw water turbidity could be removed; and (3) which of the test filter medias was most effective under the stressed turbidity conditions.

As determined from previous pilot tests, a finished water turbidity level of $\leq$ 0.10 NTU was needed to effectively remove asbestos fibers. For this series of tests, meeting the National Interim Primary Drinking Water Regulations[1] for turbidity was the primary goal; therefore, a finished water goal of $\leq$0.5 NTU was established. Occurrences causing high turbidity, such as landslides or flooding, are considered short term phenomena and asbestos fiber removal would likely be of secondary importance during these brief periods. It should be noted that the Tolt rarely, if ever, will exceed a turbidity of 5 NTU at the outlet from the Regulating Basin.

To achieve the high turbidities, soil from the banks of the South Fork Tolt Reservoir was gathered and mixed with raw Tolt water. The slurry was allowed to settle to remove heavy suspended material and the supernatent was decanted into another container for feeding into the pilot plant. Equipment limitations prohibited the investigator from injecting the slurry at a point upstream of the static mixer and consequently it was fed directly into the head end of the flocculation chamber. Turbidities between 5 and 34 NTU were tested and results were encouraging. (Data for runs #150, #151, #154, #159, #160, #162 and #163 are listed in Appendix C.)

As expected, the filter run efficiencies would decrease substantially as raw water turbidities were increased; nevertheless, 10 mg/l of alum along with lime and nonionic polymer could reduce finished water turbidity to 0.5 NTU when raw water turbidities were less than about 20 NTU. Run #160 yielded interesting results and these are illustrated in Figure 26. Raw water turbidities were fairly constant at about 15 NTU and finished water was normally $\leq$ 0.10 NTU. At Hour 6, the raw water turbidity spiked at 34 NTU and finished water turbidity rose immediately above the 0.5 NTU goal. As the raw water turbidity was lowered to its original level, the finished water turbidity concurrently dropped back to acceptable levels. Dual media filters with coarse coal normally yielded more water per 24 hours than either the dual media with fine coal or the mixed media filters. Results under the high raw water turbidity conditions were favorable and indicate that direct filtration techniques would produce an acceptable finished water for short periods of time until the turbidity receded to lower levels.

Organic Removal

The Tolt River supply has been plagued with color problems since it was brought on line in the mid-1960's, although the color has been steadily decreasing since that time. Some of the color probably results from naturally occurring organic material originating in the watershed and from swampy areas within the reservoir itself. Since color-causing organic precursors in the water, such as tannins and lignins, could form chloroform and other trihalomethanes (THM's) upon chlorination, the efficiency of filtration at removing these materials was documented and is listed in Table 29.

TABLE 29. ORGANIC REMOVAL DATA

Run No.	Sample Location	Color Units	Tannin/Lignin mg/l	% Removal
111	RAW	-	0.17	53%
	FINISHED	-	0.08	
120	RAW	17	0.25	68%
	FINISHED	8	0.08	
130	RAW	17	0.25	72%
	FINISHED	5	0.07	
135	RAW	17	0.23	70%
	FINISHED	3	0.07	
174	RAW	16	0.08	56%
	FINISHED	12	0.035	
175	RAW	17	0.08	-
	FINISHED	12	0.03	62%
	FINISHED	12	0.03	62%
	FINISHED	14	0.025	69%
175	RAW	15	0.075	-
	FINISHED	12	0.03	60%
	FINISHED	12	0.03	60%
	FINISHED	12	0.03	60%

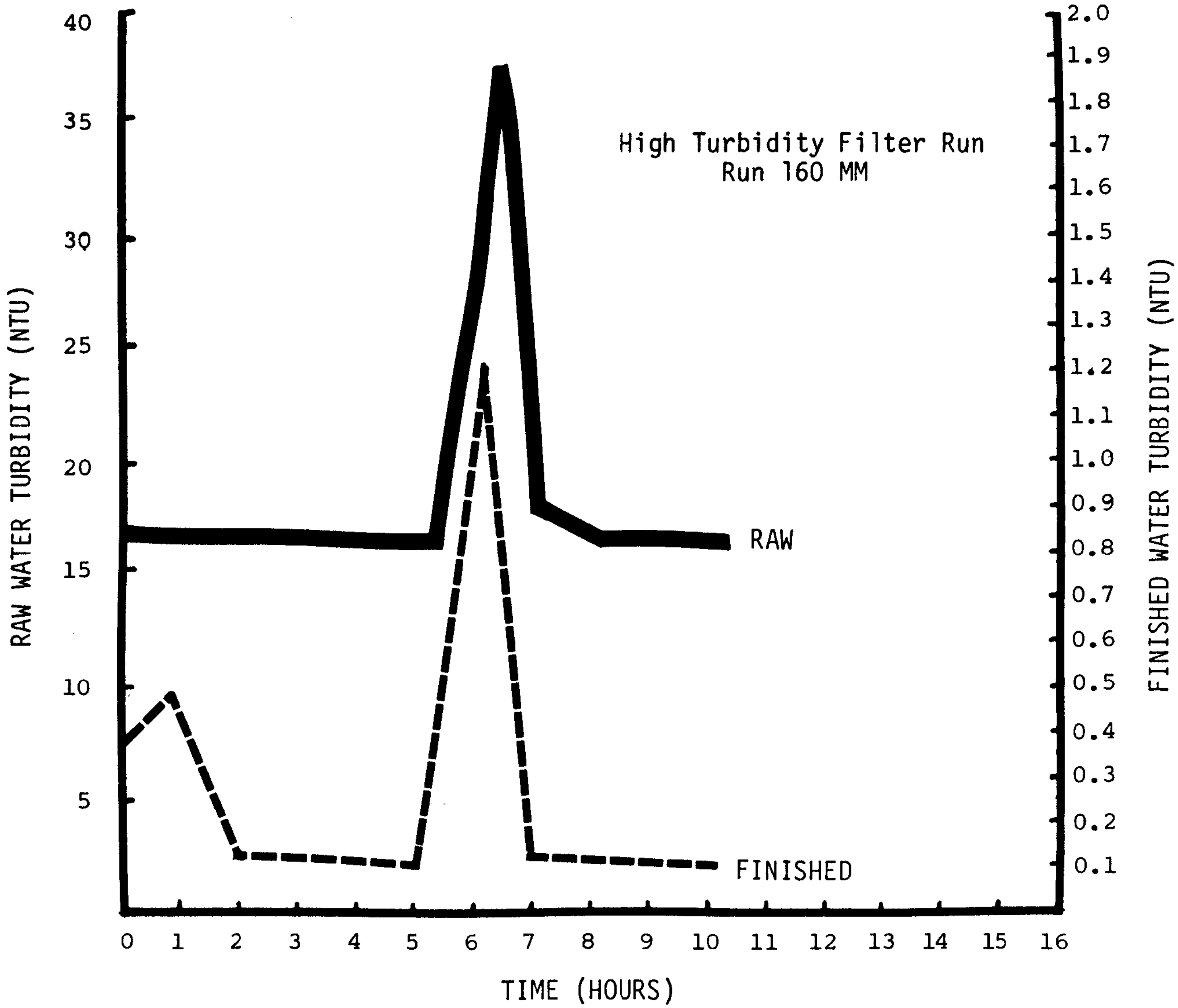

Figure 26. Raw and finished water turbidity vs. time for run #160 MM.

These data indicate that from one-half to two-thirds of the tannins and lignins can consistently be removed using direct filtration techniques. Based on these encouraging results, further testing was performed to document actual THM concentrations before and after filtration and results are contained in Table 30.

TABLE 30. TRIHALOMETHANE RESULTS ON UNFILTERED AND FILTERED TOLT WATER*

		7°C			25°C		
Day	Parameter**	Unfiltered Water pH = 8.25	Filtered Water pH = 8.0	Total THM % Removal	Unfiltered Water pH = 8.25	Filtered Water pH = 8.0	Total THM % Removal
0	$CHCl_3$	27	9.5	61%	35	5.5	80%
	$CHBrCl_2$	1.4	1.0		1.4	1.1	
	Total THM	28	11		36	7	
	Residual Cl_2† (mg/l)	1.8	2.4		1.8	2.4	
1	$CHCl_3$	50	15	68%	75	26	63%
	$CHBrCl_2$	2.8	2.4		3.0	2.7	
	Total THM	53	17		78	29	
	Residual Cl_2† (mg/l)	1.5	2.0		0.8	2.0	
3	$CHCl_3$	65	21	68%	60	30	48%
	$CHBrCl_2$	2.1	1.8		2.9	2.6	
	Total THM	67	23		63	33	
	Residual Cl_2† (mg/l)	1.2	1.5		0.3	1.8	
7	$CHCl_3$	65	19	70%	135	45	66%
	$CHBrCl_2$	3.1	0.7		4.2	1.8	
	Total THM	68	20		139	47	
	Residual Cl_2† (mg/l)	0.8	2.0		0.05	1.6	
10	$CHCl_3$	90	25	71%	140	60	55%
	$CHBrCl_2$	3.4	2.3		4.4	4.7	
	Total THM	93	27		144	65	
	Residual Cl_2† (mg/l)	0.7	2.0		0.05	1.2	

*All results in micrograms per liter unless otherwise noted.
**$CHBr_2Cl$ and $CHBr_3$ were detected in none of the sample ($<0.1\ \mu g/l$).
†Free residual chlorine.

The unfiltered water used in these tests was raw Tolt water gathered from a tap in the Regulating Building. The filtered water was collected from the Waterboy pilot plant and had been pretreated with 10 mg/l of alum, lime and a nonionic polymer prior to filtration. The flow schematic included a single static mixer, a flocculator and a mixed media granular filter. The filtration rate was 4 gpm/ft^2 and the raw and finished water turbidities were 1.0 NTU and 0.14 NTU respectively. All samples were transported to the Seattle Water Department laboratory in specially prepared glass containers, where they were adjusted to a pH of about 8 and an alkalinity of 25 mg/l with lime, sodium bicarbonate and sodium silicate. Water was then fluoridated to 1 mg/l and dosed with about 2.5 mg/l of chlorine. After these treatments were applied, the water was placed into vials that were capped with Teflon seals and the samples were taken to the Region X, EPA, laboratory, incubated at 7°C or 25°C and analyzed by the EPA/Bellar purge and trap method[16] for THM.

The results indicate that the same techniques that are used to remove asbestos down to ND or NSS levels, will also substantially reduce THM precursors in Tolt water. Removal efficiencies for THM are highly consistent and are typically on the order of 60-70%. The removal efficiencies for tannin and lignin are very similar to the THM removals although one cannot be certain that they are the actual precursors. The chlorine demand of filtered water is significantly less than the demand exerted by unfiltered water.

WASTEWATER TREATMENT

Quantity

The volume of wastewater to be treated depends upon the quantity used to backwash the granular media filters and has been conservatively estimated at 200 gal/ft^2/backwash. The number of backwashes per unit of time will depend on the efficiency of the filter at different filter loading rates. These parameters are selected in SECTION VII, DESIGN CONSIDERATIONS, and they will provide the basis for estimating the total volume of backwash wastewater generated at various plant flows.

Quality

The solids that are removed from the filters during backwash result from two sources - the alum added during the treatment process and the suspended material present in the raw water.

An estimate of the solids produced from the addition of alum can be made based on the following reaction.[17]

$$Al_2(SO_4)_3 \cdot 14\ H_2O + 3\ Ca(HCO_3)_2 \longrightarrow$$

$$\underline{2\ Al(OH)_3} + 3\ CaSO_4 + 6\ CO_2 + 14\ H_2O$$

The molecular weights of $Al_2(SO_4)_3 \cdot 14\ H_2O$ vs. $2\ Al(OH)_3$ are in a ratio of 3.8 to 1. Thus, if 10 mg/l of alum is used in the treatment process, it will result in approximately 2.63 mg/l of sludge being generated. This equates to 0.022 pounds of sludge per 1000 gallons (lb/1000 gal) of water treated.

The concentration of suspended solids in raw Tolt water fluctuates throughout the year but is normally 1 to 2 mg/l and never exceeds 3 mg/l. Since filtration techniques are removing even the micron size asbestos particles, it is probably removing most other suspended matter as well. If the suspended solids concentration is 2 mg/l, then the solids removed amount to approximately

0.017 lb/1000 gal treated. The total sludge generated from both the chemical additives and the solids in the raw water is approximately 0.039 lb/1000 gal water treated. This estimate falls within the range of values (0.038-0.061 lb/1000 gal) found by Black and Veatch Consulting Engineers during their evaluation of Lake Superior water.[3]

Based on the 0.039 lb/1000 gal water treated estimate, a UFRV of 5000 gal/ft^2/run, and a volume of 200 gal/ft^2/backwash; the suspended solids concentration in the backwash water would be an estimated 117 mg/l. A range in suspended solids concentrations from 106 mg/l to 227 mg/l was obtained by Black and Veatch Consulting Engineers;[3] thus, the 117 mg/l concentration appears to be a reasonable estimate. Suspended solids tests were performed on the backwash water from the Waterboy filter and the filter columns and the solids concentrations were only about one-half of the 117 mg/l estimate. Proportionately larger quantities of backwash water are normally required to clean filter columns and relatively small filters when compared to large scale filters and this may have diluted the solids concentrations in these samples. This is one possible explanation for the discrepancy between the field values and the theoretical estimate.

Settleability

Tests were performed to determine the settling characteristics of sludge that had been generated from backwashing the Waterboy filter and held in the settling basin. Although the sludge resulted from several different water treatment techniques, holding and concentrating the solids was the only method that would provide enough quantity of sludge for the tests. Using a 6-inch diameter settling column to minimize wall effects and a mechanical stirring device that rotated at 1 RPM to enable water to move more freely upward through the solids, interface settling velocities (ISV's) were documented at various sludge concentrations (Figure 27). Based on these tests, Figure 28, a batch flux curve was prepared and it can be used to estimate the limiting flux at various underflow concentrations.[14] Review of the flux curve indicates that underflow concentrations of 2-3% are feasible using gravity thickening techniques. Details of these tests are presented in Appendix B.

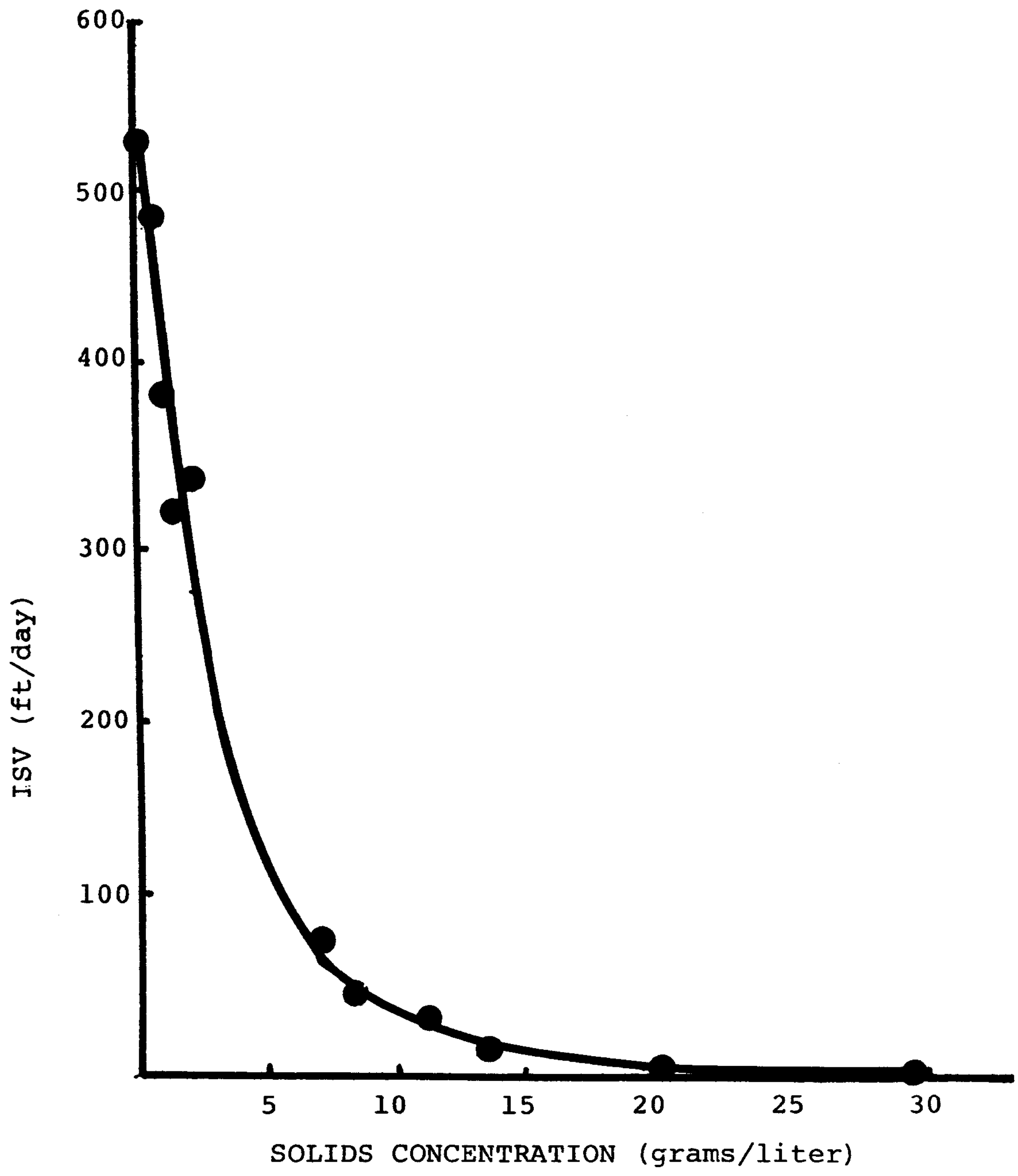

Figure 27. Interface settling velocity vs. solids concentration.

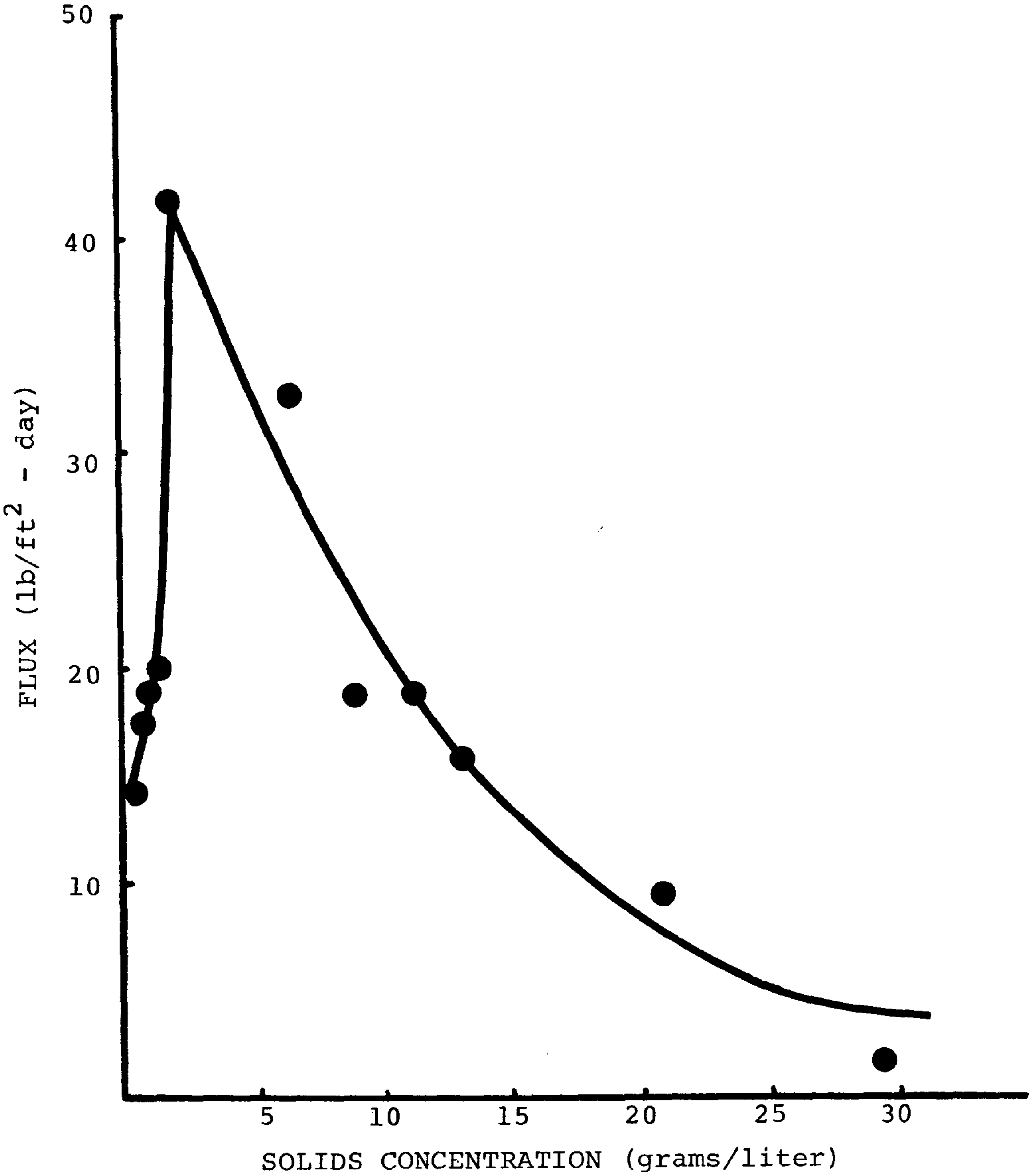

Figure 28. Batch settling curve for waste solids.

SECTION VII

DESIGN CONSIDERATIONS

PREFERRED TREATMENT TRAIN

The preferred treatment train includes static mixers, flocculators and granular media filters. The plant will have a maximum hydraulic capacity of 100 MGD and a nominal flow rate of 60 MGD. Since the study demonstrated that direct filtration techniques met both process and water quality goals, no settling basins will need to be incorporated into the design. The proposed plant will remove amphibole fibers to ND levels, chrysotile fibers to NSS levels, turbidity to $\leq$ 0.10 NTU, tannins and lignins to $<$0.07 mg/l, 60-70% of the THM precursors, color to $<$15 units, and will incorporate corrosion control apparatus and a coagulant control center. The design also includes provisions for treatment of backwash wastewater which will comply with the discharge requirements of the state pollution control agencies. Asbestos-free materials will be used in construction of the plant. The design criteria is summarized in Table 31 and the unit processes are illustrated in Figure 29. A brief description of the unit processes is presented below.

FILTRATION PLANT

Energy Dissipators

To reduce the pressure head off of the Tolt pipeline between the South Fork Tolt Reservoir and the Regulating Basin, energy disspiators will be constructed ahead of the static mixers to reduce pressure from the existing head of 160-900 ft down to between 20-40 ft. It will be equipped with both fine and coarse controls to enable accurate adjustment of head exiting the unit. If Seattle City Light Department decides to develop power on the Tolt supply, water would flow through their proposed turbines into a stilling basin and would then discharge into the existing Water Department Regulating Basin. In this case, the water would need to be pumped from the Regulating Basin to the static mixers rather than flowing through the energy dissipators as is assumed at this time.

Static Mixers

To provide initial mixing of chemicals into the process stream, three static mixers are planned to provide flexibility throughout the flow range. Characteristics of these units, which require no outside power source and very little maintenance, are described in Table 32.

GENERAL DESIGN CRITERIA

PLANT CAPACITY MGD	
NOMINAL	60
DESIGN HYDRAULIC CAPACITY	100
PRIMARY TREATED WATER QUALITY GOALS	
TURBIDITY UNITS	≤0.1
COLOR UNITS	<15
TASTE	0
ODOR	0
FLUORIDE	1.0
PH UNITS	8.3
ASBESTIFORM COUNT 10^6 FIBERS/LITER	
AMPHIBOLE	≤0.01
CHRYSOTILE	≤0.01
ALKALINITY mg/l	20-25
SILICATE mg/l	9
ALUMINUM mg/l	≤0.05

RAPID MIX DESIGN CRITERIA

NUMBER, STATIC TYPE	2 OR 3

FLOCCULATION BASIN DESIGN CRITERIA

NUMBER OF BASINS	4
NOMINAL CAPACITY, MGD	
EACH	15
COMBINED	60
DESIGN HYDRAULIC CAPACITY, MGD	
EACH	25
COMBINED	100
FLOCCULATION BASINS	
DETENTION TIME AT NOMINAL DESIGN FLOW, MINUTES	15
WATER DEPTH	20
STAGES OF FLOCCULATION	3
PADDLE WHEEL DIAMETER FT	15
VELOCITY GRADIENT, G. FT SEC/FT	
1ST STAGE	70
2ND STAGE	50
3RD STAGE	30
BASIN INLET VELOCITY, FT/SEC	1.0
BASIN OUTLET (DIFFUSION WALL) VELOCITY, FT/SEC	0.25
AVAILABLE SPEED VARIATION RATIO	2:1

FILTRATION SYSTEM DESIGN CRITERIA

NUMBER OF FILTERS (DUAL)	8
FILTER AREA EACH FT^2	1250
FILTRATION RATE, GPM/FT^2	
NOMINAL	4.2
DESIGN HYDRAULIC CAPACITY	10.0
FILTER CAPACITY, EACH, MGD	
NOMINAL	7.5
DESIGN HYDRAULIC CAPACITY	12.5
SYSTEM CAPACITY, MGD	
NOMINAL (4.2 GPM/FT^2)	60
PEAK (6.9 GPM/FT^2)	100
TOTAL STATIC HEAD ACROSS FILTER, FT	14
NET AVAILABLE INDICATED HEAD, FT(1)	
AT 4.2 GPM/FT^2	12.7
AT 6.9 GPM/FT^2	12.1
AT 10.0 GPM/FT^2	11.1
DESIGN MAXIMUM BACKWASH RATE GPM/FT^2	12
DESIGN BACKWASH WATER USAGE AS PERCENT OF RAW WATER (MAX.)	5
BACKWASH SUPPLY RESERVOIR, MG	5
CAPACITY EACH BACKWASH PUMP(2) GPM	15,000
NUMBER OF AIR WASH BLOWERS(2)	2
CAPACITY AIR WASH BLOWERS(2) EACH SCFM	4375

(1) AS MEASURED FROM FILTER WATER SURFACE TO CENTER LINE OF EFFLUENT PIPE AHEAD OF FLOW TUBE.

(2) ONE PUMP REDUNDANT

CLEARWATER RESERVOIR DESIGN CRITERIA

NUMBER	1
CAPACITY, MG	5
MAXIMUM DEPTH, FT	25

CHEMICAL STORAGE AND DOSAGE

CHEMICAL	FORM AND METHOD OF DELIVERY	ANTICIPATED DOSAGE RANGE, mg/l			
		MIN.	AVG.	MAX.2-WEEKS	PEAK
ALUM	LIQUID-TANK TRUCK	2	10	20	30
POLYMER					
CATIONIC	LIQUID-TANK TRUCK OR DRUM	0.5	2	5	7
ANIONIC/NONIONIC	LIQUID-TANK TRUCK OR DRUM	0.01	0.1	0.2	0.3
LIME: FILTRATION PLUS CORROSION	BULK QUICKLIME (CaO) PNEUMATIC CONVEYOR TRUCK	1.3	10.3	12	18
CHLORINE: PRE PLUS POST	LIQUID - CL_2 1 TON CYLINDER	0.5	1.5	3	5
FLUORIDE	LIQUID FLUOSILICIC ACID - TANK TRUCK	0.5	1.0	1.0	1.0
SODIUM SILICATE	LIQUID-TANK TRUCK	1	4	10	15
SODIUM BICARBONATE		3	7.5	15	30

SOLIDS HANDLING

2–100' SURGE/CLARIFIER/THICKER

2–2000 GPM RETURN PUMPS

2–100 GPM UNDERFLOW PUMPS

2–30' THICKENER/CONDITIONER

2–75 GPM UNDERFLOW PUMPS

2–SOLID BOWL CENTRIFUGES, 75 GPM

TABLE 31

FILTRATION SYSTEM DESIGN CRITERIA

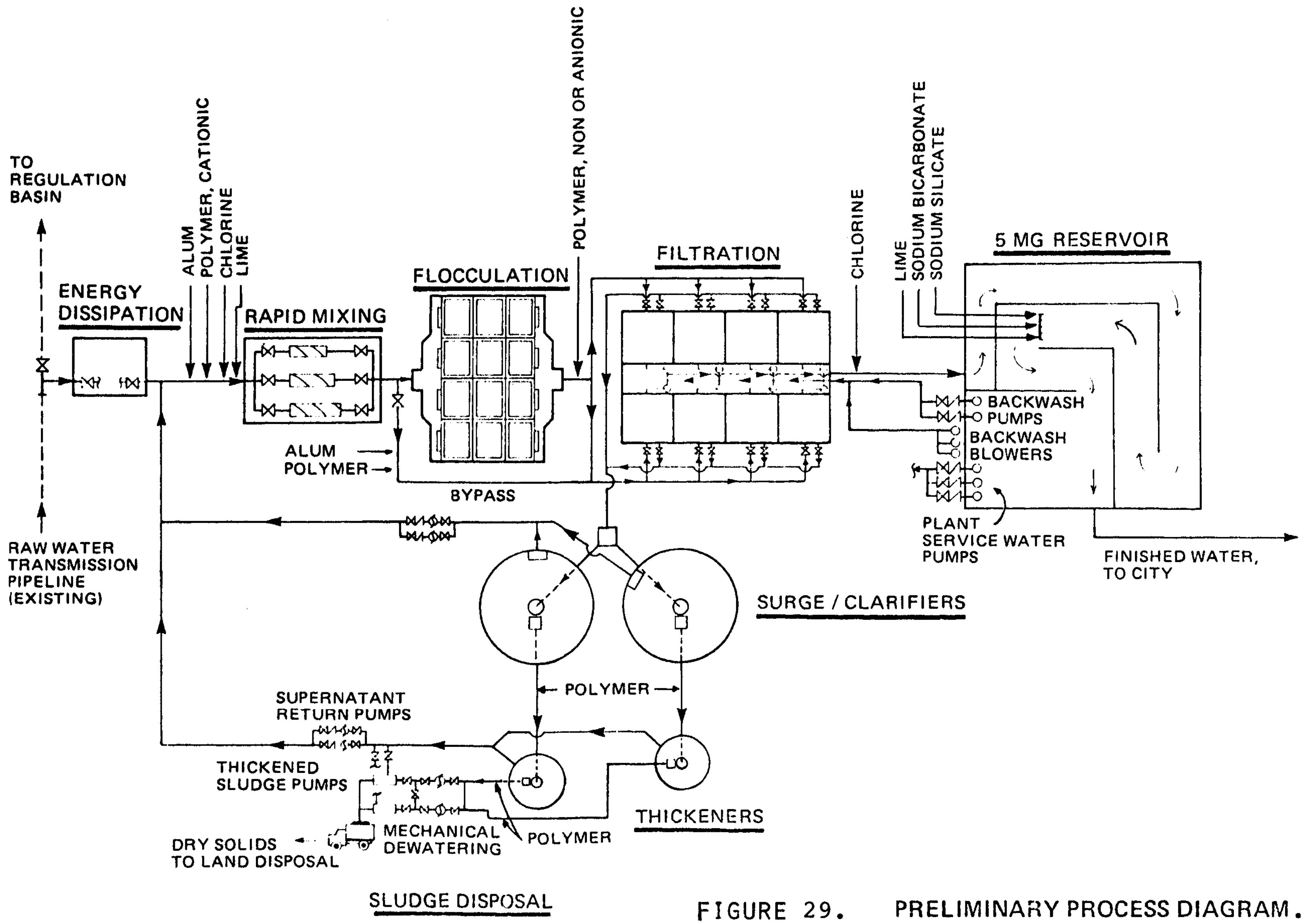

FIGURE 29. PRELIMINARY PROCESS DIAGRAM.

TABLE 32. CHARACTERISTICS OF STATIC MIXERS

No. of Units	Flow Capacity	Diameter	Length	Pressure Drop	No. of Elements	Approximate Weight of Unit (lb)
2	25 MGD	3 ft	9 ft, 6 in	6.3 ft	3	2500
1	50 MGD	4 ft	12 ft, 6 in	8.4 ft	3	4000

Flocculators

When water temperatures were cold and turbidity was $>$ 1.5 NTU, use of the flocculators demonstrated certain advantages including better turbidity removal and longer filter runs. In addition, the Washington State Department of Social and Health Services suggests a minimum contact time of 15 minutes before filtration in direct filtration treatment plants,[18] thus the flocculation chambers will also satisfy these requirements. Four flocculation chambers are proposed, each with a 15-minute detention time at the design hydraulic capacity of 100 MGD. A tapered three-stage system with variable speed flocculator paddles is suggested.

Filtration Gallery

Filter Loading Rates --

Based on the filtration rate studies and the equations and criteria listed below, the proposed filter loading rates are developed and presented in Table 33.

Equations Used:

$$UFRV = 8773 - 572(LR)$$

$$NP = 665 + 1239(LR)$$

where UFRV = Unit Filter Run Volume (gal/ft^2/run)
NP = Net Water Produced (gal/ft^2/24 hours)
LR = Average Filter Loading Rate (gpm/ft^2)

Minimum Criteria:

UFRV = 5000 gal/ft^2/run[11] at 60 MGD

UFRV = 4000 gal/ft^2/run at 100 MGD

Filter must produce a net volume of 100 MG/24 hours.

TABLE 33. DETERMINING THE FILTER AREA

Assuming a Minimum UFRV of	at a Capacity of	Average Filter Loading Rate	Net Water Produced	Filter Area Required
5000 gal/ft^2/run	60 MGD Nominal Rate	6.6 gpm/ft^2	8850 gal/ft^2/24 hours	6780 ft^2
4000 gal/ft^2/run	100 MGD Design Hydraulic Capacity	8.3 gpm/ft^2	10950 gal/ft^2/24 hours	9130 ft^2

Based on these calculations, the limiting factor is the flow rate at design hydraulic capacity, not the nominal rate; thus, a minimum of 9130 ft^2 of filter area is required to produce 100 MGD. Assuming that there will be 10,000 ft^2 of filter surface area divided into 8 filter boxes, the following filter loading rates are developed.

TABLE 34. RESULTING FILTER LOADING RATES.

Flow	8 Filters Operating (Average Rate) gpm/ft^2	7 Filters Operating* gpm/ft^2
60 MGD	4.2	4.8
100 MGD	6.9	7.9**

*One filter down for backwashing.
**Filter will be designed to handle hydraulic loading rates up to 10 gpm/ft^2.

Extra freeboard in the filter boxes must be provided for two reasons. First, it will be needed to maintain a positive head throughout the filter media up to 10 ft of headloss and secondly, to accommodate fluctuations in water levels inherent in declining rate filters. Rate controls will be of the type that either constant or declining rate filtration will be attainable. Continuous recording turbidimeters will be installed on the effluent from each filter as well as the clearwell effluent.

Filter Media --

Measures of water production efficiency including the UFRV, net water produced per 24 hours and % efficiency indicate little differences among the various medias evaluated in the loading rate range between 5.5 gpm/ft^2 and 7.5 gpm/ft^2. Below 5.5 gpm/ft^2, the coarse coal, dual media (CC) filter produced more water and above 7.5 gpm/ft^2, the mixed media filter (MM) exhibited the best efficiency. Most of the year, the plant will operate within the range of 5.5-7.5 gpm/ft^2 or less and as such any of the filter medias tested would be acceptable from a process or water quality standpoint. To continue side-by-side testing of dual and mixed media filter, to encourage lower bids for the filter media, and to take advantage of the benefits of both dual and mixed media; it may be desirable to specify both types of filter media in the full-scale plant. Listed below in Table 35 are selected guidelines for media selection. (This information is general in nature and should not be used as is for bidding purposes.)

TABLE 35. SUGGESTED GUIDELINES FOR GRANULAR MEDIA FILTERS

	Mixed Media			Dual Media		
	Effective Size (mm)	Uniformity Coefficient	Thickness (cm)	Effective Size (mm)	Uniformity Coefficient	Thickness (cm)
Anthracite Coal	1.0 - 1.1	1.7	53	0.9 - 1.1	1.3	51
Sand	0.42 - 0.52	1.4	18	0.40	1.3	25
Garnet	0.18 - 0.32	2.2	5	-	-	-

Backwash System

Since polymer additions were necessary to meet both water quality and process goals, it is especially important to have a good backwashing system to insure removal of the soft, adherent floc particles from the filter media. An air scour, water rinse type system is suggested. Provisions should be made for addition of a polymer to the backwash water to precoat the filter to preclude a turbidity spike as the clean filter is placed back into operation. Backwash water will be drawn from the finished water storage reservoir at the plant. Assuming that 200 gallons of water per ft^2 of filter will be used per backwash for cleaning the filter,[11] the backwash volume requirements are estimated to be 3.1% of the water produced at the nominal filtration rate of 4.2 gpm/ft^2 (60 MGD) and 4.2% at the design hydraulic capacity of 6.9 gpm/ft^2 (100 MGD). The figure of 200 gal/ft^2/backwash is considered to be a conservative estimate since air scour backwash systems normally require significantly less volume of water than simply hydraulic or fluidized washes.[11] The assumptions made in sizing the filter were based on the premise that the volume of backwash water would not exceed 5% of the water produced (95% filter efficiency) at the peak loading rate; thus, a volume up to about 5 MGD could periodically be required for backwashing purposes.

FILTERED WATER STORAGE AND CORROSION TREATMENT

To provide backwashing water and to dampen pipeline flow fluctuations, a 5 MG finished water storage reservoir is proposed. It would be baffled and will provide contact time for chlorine disinfection. In addition, the Tolt is known to be a very corrosive water at this time and since filtration would likely increase the problem, provisions for adding corrosion control chemicals to the storage basin would be included. The overflow elevation of the clear-well must be no less than elevation 760 ft to provide enough water at an adequate head to the Tolt supply line.

WASTEWATER TREATMENT

Characteristics

Based on the filter loading rates selected previously and the associated filter efficiencies, the wastewater characteristics are listed in the following table.

TABLE 36. BACKWASH WASTEWATER CHARACTERISTICS

Water Produced MGD	Efficiency %	Wastewater Produced MGD	lb Solids / 1000 gal Produced	lb Solids / Day	Estimated Solids Concentration (mg/l)
60	3.1	1.86	0.039	2340	151
100	4.2	4.2	0.039	3900	111

Thickening

Using the batch flux curve shown in Figure 28, thickener area estimates for several underflow concentrations are presented in the following table.

TABLE 37. CLARIFIER/THICKENER AREA REQUIREMENTS BASED ON BATCH FLUX CURVES

Water Produced MGD	Wastewater Volume MGD	Underflow Concentration (gram/liter)	Limiting Flux ($lb/ft^2/day$)	Solids Production (lb of Solids / Day)	Minimum Surface Area Required (ft^2)
60	1.86	20	42	2340	56
		25	33	2340	71
		30	25	2340	94
		35	18	2340	130
100	4.2	20	42	3900	93
		25	33	3900	118
		30	25	3900	156
		35	18	3900	217

In addition to the thickening requirements as dictated by the batch settling curves, there are also hydraulic requirements that must be met to enable a clarifier/thickener to operate properly. These requirements are normally based on an allowable surface overflow rate and have been developed by designers based on field experience. Textbooks normally list values between 600 and 1800 gallons per day per square foot (gpd/ft^2).[14] Using the lower value of 600 gpd/ft^2 and the peak wastewater flow of 4.2 MGD, this yields a minimum surface area of 7000 ft^2. Comparing 7000 ft^2 with 217 ft^2 (Table 37); the surface overflow rates, not the thickening requirements, govern the surface area of clarifier/thickener. With two circular clarifiers in operation, each would need to be a minimum of 66 ft in diameter. To absorb periodic slugs of wastewater from the backwashing system; to provide a smooth, even flow of clarified wastewater back to the head of the plant; and to provide some extra storage before the dewatering process; the suggested design includes two 100 ft diameter surge/clarifiers in parallel followed by two 30 ft diameter thickeners with provisions for chemical treatment. Assuming the waste was thickened to a 2% solids concentration, this would amount to about 60 tons of sludge per day. Consideration should also be given to the method for recycling of the clarified wastewaters. Since directly recycled waters can change the raw water characteristics, provisions for discharging the clarified water to the Regulating Basin prior to recycle should be considered.

Dewatering

Several methods of sludge dewatering are available and they normally involve the use of centrifuges, press filters or vacuum filters. These devices can produce a cake with a solids concentration of 15-40%. If the waste was dewatered to a 15% solids concentration, this would result in about 2920 tons of sludge per year that would require ultimate disposal. For purposes of cost estimation, two centrifuges were included in the waste treatment train to dewater the thickened sludge. More thorough studies of this subject need to be undertaken before an actual dewatering method can be chosen.

SECTION VIII

OPERATIONAL CONSIDERATIONS

To insure that asbestos fibers will be removed down to ND or NSS levels, optimizing the operation of the filtration plant is of utmost importance. To aid in the operations and monitoring functions, the facility should include a gravity flow pilot plant of not less than 20 gpm capacity which is identical to the full-scale plant. A coagulant control center and a computer would facilitate treatment plant operation as would a particle counter. Turbidimeters on the effluent from each filter and on the finished water storage reservoir should be mandatory and the finished water turbidity should be maintained at $\leq$ 0.1 NTU. Backwash should be initiated at terminal headloss of 10' or when the effluent turbidity curve on the recorders begins to rise upward indicating that turbidity breakthrough is beginning to occur.

SECTION IX

COST ANALYSES

Construction and operating cost estimates have been developed by CH2M/Hill Consulting Engineers for a 60 MGD (100 MGD peak flow) water filtration plant for the Tolt supply. The American Association of Cost Engineers divides construction estimating into three categories.[19] To better understand the level of confidence to be placed in the estimates presented herein, a brief description of those categories is listed below.

1. Order of Magnitude - Approximate, prepared without detailed data, prepared from cost curves with various factors applied to scale up or down, considered accurate within +50% or -30%.

2. Budget Estimate - Prepared from flow sheets, lay-outs and equipment details, considered accurate within +30% or -15%.

3. Definitive Estimate - Prepared from explicit engineering data such as near complete set of plans and specifications, considered accurate within +15% or -5%.

CONSTRUCTION COSTS

The estimate prepared and presented here reflects an anticipated level of confidence which would fall between categories 1 and 2 above, or accurate within +40% or -20%. Table 38 outlines the project costs and Appendix B contains more detailed documentation of cost information.

OPERATING COSTS

Table 39 shows a breakdown of operation and maintenance costs. It has been assumed that the plant is manned continuously and that labor costs carry a 50% overhead burden. No allowance has been made for vehicles or resident housing.

TABLE 38. PLANT CONSTRUCTION COSTS

General*	$ 6,152,000
Landscaping	145,000
Headworks and Energy Dissipation	358,000
Flocculation Basins	638,000
Filtration Complex	3,091,000
Chemical Complex	1,290,000
Control Building	230,000
Sludge Disposal	
Surge Clarifiers	731,000
Thickeners	97,000
Dewatering Complex	562,000
Pump Station	68,000
Reservoir, 5 MG	815,000
Backwash and Service Water	184,000
Electrical	1,679,000
Instrumentation and Control	
Base	582,000
Data Logging Computer	75,000
Base Cost	$16,697,000
Move-in, Bond & Insurance (4%)	668,000
Subtotal	17,365,000
Contingency Allowance (25%)	4,341,000
TOTAL CONSTRUCTION COST	$21,706,000
Final Engineering Design (6½% of Construction Cost)	1,408,000
Resident Inspection	310,000
Surveying	54,000
Soils Analysis	75,000
Sales Tax (5½% of Construction Cost)	1,193,830
TOTAL PROJECT COST	$24,747,000**

*The general category includes all cleaning and grubbing of stumps, brush, etc., after the logging operation; all structural excavation for all facilities and storage reservoir; all trench excavation for piping, etc; concrete for sidewalks, curbs and any other concrete not specific to a particular facility; all asphaltic concrete for paving, parking spaces and driveways; miscellaneous metals not specific to a particular facility, for example, handrails, etc., some allowance for equipment not specific to any facility - for example, maintenance of grounds equipment; instrumentation controls, electrical, etc., not specific to a particular facility; all yard piping, fittings, valves, etc., not specific to a particular facility; and drainage ditch for environmental safety of nearby reservoir.

**Costs are based on October 1978 dollars, Engineering News Record (ENR) index for Seattle, Washington, 3194. Estimates do not include costs for land (8-12 acres), logging the proposed site, escalation during design and construction, mileage allowances for workers or permit fees. Assumptions include bridges and roads meet weight capacities needed to transport supplies and workers; labor availability - reasonable; scope of work as defined; contractor availability - reasonable; and good access on current roads to site.

TABLE 39. ANNUAL PLANT OPERATING COSTS

1. Labor			
Chief Operator & Chemist	2 @ $33,000	= $ 66,000	
Operators & Maintenance	10 @ $27,000	= 270,000	
			$336,000
2. Chemicals			
Alum	912 ton/yr @ $100/ton	= $ 91,200	
Lime	759 ton/yr @ $57/ton	= 53,600	
Polymer	383,250 lb/yr @ $0.70/lb	= 268,300	
Sodium bicarbonate	686 ton/yr @ $230/ton	= 157,800	
Sodium silicate	365 ton/yr @ $330/ton	= 120,400	
Chlorine	137 ton/yr @ $270/ton	= 37,000	
Fluoride (25% strength)	461 ton/yr @ $83/ton	= 38,750	
			767,000
3. Power (Average 72,400 kilowatt-hours/month)			22,900
4. Maintenance and Repairs			
Assume 3%/yr of initial cost of major equipment			86,100
ANNUAL OPERATING COST			$1,212,000

TOTAL ANNUAL COSTS

The amortized project costs plus the annual operating costs are presented below as the estimated total annual costs in October 1978 dollars for the Tolt treatment plant.

$$CR = (P - L)\ (crf - i\% - n) + Li^{20}$$

where CR = Annual cost of capital recovery

P = Present worth

L = Salvage value at $\underline{n}$ years

crf - i% - n = Capital recovery factor at $\underline{i}$% interest rate after $\underline{n}$ years assuming $i = 7\%$

$n = 40$ years (yr)

$L = 40\%$ of first cost

$$CR = \left[24{,}747{,}000 - 0.4(24{,}747{,}000)\right](0.07501) + \left[0.4(24{,}747{,}000)\right](0.07)$$

$$= 1{,}113{,}763 + 692{,}916$$

$$= \$1{,}806{,}679$$

TOTAL ANNUAL COST = CAPITAL RECOVERY + ANNUAL OPERATING COSTS

= \$1,806,679 + \$1,212,000 = \$3,018,679

or approximately \$3,019,000/yr

SECTION X

REFERENCES

1. National Interim Primary Drinking Water Regulations, Federal Register, Vol. 40, No. 248; Wednesday, December 24, 1975; pgs 59566-59574; and Background Used to Develop Regulations, EPA-570/9-76-003, Office of Water Supply, U.S. Environmental Protection Agency.

2. Seattle Water Department, City of Seattle, Final Environmental Impact Statement for the Proposed Seattle Corrosion Control Plan, SEPA Entry No. 1246, November 14, 1978.

3. Black and Veatch Consulting Engineers. Direct Filtration of Lake Superior Water for Asbestiform Fiber Removal, EPA-670/2-75-050a, U.S. Environmental Protection Agency, Cincinnati, Ohio, June, 1975.

4. Hallenbech, W. H. and C. S. Hesse. A Review of the Health Effects of Ingested Asbestos, Reviews on Environmental Health, Vol. II, No. 3, 1977.

5. Levy, Barry S., Eunice Sigurdson, Jack Mandel, Emaline Laudon and John Pearson, Investigating Possible Effects of Asbestos in City Water: Surveillance of Gastrointestinal Cancer Incidence in Duluth, Minnesota, American Journal of Epidemiology, Vol. 103, No. 4, 1976.

6. Wigle, D. T., Cancer Mortality in Relation to Asbestos in Municipal Water Supplies, Archives of Environmental Health, Vol. 32, pgs 185-190 1977.

7. Harrington, J. Malcolm and Gunther F. Craun, J. Winter Meigs, Philip J. Landrigan, John T. Flannery and Richard S. Woodhull. An Investigation of the Use of Asbestos Cement Pipe for Public Water Supply and the Incidence of Gastrointestinal Cancer in Connecticut 1935-1973, American Journal of Epidemiology, Vol. 107, No. 2, pgs 96-103, 1978.

8. Kanarek, Marty Steven, Draft Interim Report entitled, Asbestos in Drinking Water and Cancer Incidence, University of California, Berkeley, 1978.

9. EPA Position Paper on Draft Interim Report entitled, Asbestos in Drinking Water and Cancer Incidence (see Reference #8), September 26, 1978.

10. National Academy of Sciencies, Drinking Water and Health, Safe Drinking Water Committee, 1977 (Library of Congress #77-089284), prepared at the request of and funded by the U.S. Environmental Protection Agency, Contract No. 68-01-3139.

11. Trussell, R. Rhodes, Application of Treatment Technology, prepared for U.S.E.P.A. Environmental Research Center - Technology Transfer Seminar on Designing and Upgrading Drinking Water Systems, Portland, Oregon, May 25-26, 1977.

12. American Public Health Association, American Water Works Association and Water Pollution Control Federation, Standard Methods for the Examination of Water and Wastewater, Fourteenth Edition, 1975.

13. Millette, James R. Analyzing for Asbestos in Drinking Water. News of Environmental Research in Cincinnati, Municipal Environmental Research Laboratory, U.S.E.P.A., January 16, 1976.

14. Weber, Walter J., Jr. Physiochemical Processes for Water Quality Control. Wiley - Interscience, A Division of John Wiley & Sons, Inc. New York, 1972, Library of Congress Catalog Card No. 77-37026.

15. Anderson, C. H. and J. M. Long, Preliminary Interim Procedure for Fibrous Asbestos, Transmission Electron Microscopy Method, EPA Analytical Chemistry Branch, Athens, Georgia, July, 1976.

16. Bellar, EPA/Bellar Purge and Trap Method for THM Analysis.

17. Sawyer, Clair N. and Perry L. McCarty, Chemistry for Sanitary Engineers, Second Edition, McGraw-Hill Book Company, New York, 1967, Library of Congress Catalog Card No. 67-20179.

18. Kirner, John C., Regional Engineer, Washington State Department of Social and Health Services, Memorandum, Subject: Proposed Criteria for the Acceptance of Direct Filtration Water Treatment Plants, To: Water Supply and Waste Section - Operations Staff, February 16, 1977.

19. American Association of Cost Engineers, The Cost Engineers Notebook, Section AA-4.000, pg 10, January, 1978.

20. Grant, Eugene L. and W. Grant Ireson. Principles of Engineering Economy, Fourth Edition, The Ronald Press Company, New York, 1964, Library of Congress Catalog Card No. 64-66236.

SECTION XI

GLOSSARY

A/C - Asbestos cement
alum - Aluminum sulfate.
amp - Amperes.
A - Area of paddles.
BW - Amount of backwash water used, 200 gal/ft^2/backwash.
^oC - Degree Centrigrade.
CC - Dual media with coarse coal.
CMM - Mixed media, sand MS-18.
Cd - Coefficient of drag.
cm - Centimeter.
CR - Capital recovery.
crf - Capital recovery factor.
EDS - Energy dispersive analysis system.
EM - Electron microscope.
EPA - U.S. Environmental Protection Agency.
FC - Dual media with fine coal.
ft - Foot or feet.
ft^2 - Square foot.
ft/sec - Foot per second.
G - Velocity gradient.
gal - Gallon.
GI - Gastrointestinal.
gpd/ft^2 - Gallons per day per square foot.
gpm - Gallons per minute.
gpm/ft^2 - Gallons per minute per square foot.
GT - Velocity gradient times the time.
H - Headloss in feet.
i - Interest rate.
in - Inch
ISV - Interface settling velocity.
L - Salvage value.
LR - Average filter loading rate, gpm/ft^2.
lb - Pound.
lb/1000 gal - Pounds per 1000 gallons.
m - Meter.
m^2 - Square meter.
m^3 - Cubic meter.
MG - Million gallon.
MGD - Million gallons per day.

mg/l - Milligram per liter.
min - Minute.
mm - Millimeter.
MM - Mixed media, sand MS-6.
mmHg - Millimeter of mercury.
n - Number of years.
N/A - Not applicable.
NBW - Number of backwashes per 24 hours.
ND - Not detectable.
NP - Net water produced, gal/ft^2/24 hours.
NSS - Not statiscally significant.
NTU - Nephelometric turbidity units.
P - Water horsepower.
PF - Power factor.
pH - Negative logarithm of the hydrogen ion concentration.
R - Correlation coefficient.
RPM - Revolutions per minute.
Se - Standard error of estimate.
sec - Seconds.
sec^{-1} - Seconds^{-1}.
T - Time.
THM - Trihalomethane.
ton/yr - Ton per year.
Tq - Torque.
TURB - Turbidity.
μ - Absolute viscosity.
UFRV - Unit Filter Run Volume.
UW - University of Washington.
ν - Relative velocity of paddles in fluid.
V - Volume of basin.
yr - Year.
ρ - Mass fluid density, slugs/ft^3.
% - Percent.

SECTION XII

APPENDIX A

A-1 RESULTS OF ASBESTIFORM ANALYSES ON STREAMS FEEDING THE SOUTH FORK TOLT RESERVOIR.

A-2 COMPLETE CHEMICAL ANALYSIS OF SOUTH FORK TOLT RIVER WATER SUPPLY.

A-3 WATER PRODUCTION EFFICIENCIES FOR SELECTED FILTER RUNS.

A-4 SUMMARY OF RAW AND FILTERED WATER ASBESTIFORM COUNTS.

APPENDIX A-1. RESULTS OF ASBESTIFORM ANALYSES ON STREAMS FEEDING THE SOUTH FORK TOLT RESERVOIR.

Sample Point		Description
TW 1	CONSULTANT CREEK	Consultant Creek; east bank, 100' upstream from Spur 70 culvert; R 9E, T 26N, Sec 29, SW¼. Lat. 47°, 42'15"; Long. 121°, 41'15".
TW 2	RAINBOW CREEK	Rainbow Creek, west bank, 5' upstream from Spur 70 culvert; R 9E, T 26N, Sec 29, SE¼. Lat. 27°, 42'14"; Long. 121°, 40'18".
TW 3	HORSESHOE CREEK	Horseshoe Creek; east bank, 15' upstream from Spur 70 culvert; R 9E, T 26N, Sec 28, SE¼. Lat. 47°, 42'16"; Long. 121°, 39'17".
TW 4	SOUTH FORK TOLT RIVER	South Fork Tolt River; north bank, 50' upstream from Spur 70 bridge; R 9E, T 26N, Sec 25, SW¼. Lat. 47°, 42'25".
TW 5	PHELPS CREEK	Phelps Creek; north bank, 75' upstream from Spur 50 bridge; T 9E, T 26N, Sec 25, SW¼. Lat. 47°, 42'18"; Long. 121°, 36'02".
TW 6	SKOOKUM CREEK	Skookum Creek; east bank, 25' upstream from Spur 50 bridge; R 9E, T 26N, Sec 26, SW¼. Lat. 47°, 42'04"; Long. 121°, 37'24".
TW 7	SIWASH CREEK	Siwash Creek; west bank, 10' upstream from Spur 50 sulvert; R 9E, T 26N, Sec 34, NW¼. Lat. 47°, 42'00"; Long. 121°, 38'21".
TW 8	DOROTHY CREEK	Dorothy Creek, west bank, 10' upstream from Spur 50 culvert; R 9E, T 26N, Sec 33, NW¼. Lat. 47°, 41'50"; Long. 121°, 39'47".
TW 9	CRYSTAL CREEK	Crystal Creek; west bank, 75' south of Spur 50, above concrete dam; R 9E, T 26N, Sec 32, SW¼. Lat. 47°, 41'29"; Long. 121°, 41'08".
TW 10	SOUTH FORK TOLT RESERVOIR	

APPENDIX A-1 (CONTINUED)

RESULTS OF ANALYSES*

Date	Location	Chrysotile fibers/liter	Possible Amphibole fibers/liter	Sample Vol., ml	Lower Limit of Detection	Comments
June 15, 1975	TW 1	-	5×10^4		2.5×10^4	
"	TW 2	ND	ND		5×10^4	
"	TW 3	ND	ND		2.5×10^4	
"	TW 4	ND	ND		2.5×10^4	
"	TW 5	ND	ND		2.5×10^4	
"	TW 6	ND	ND		2.5×10^4	
"	TW 7	-	2.5×10^4		2.5×10^4	
"	TW 8	-	2.5×10^4		2.5×10^4	
"	TW 9	ND	ND	100	2.5×10^4	
July 29, 1975	TW 10	1.3×10^6	1.7×10^6	50	1×10^5	Preserved with $HgCl_2$.
"	TW 10	1.3×10^6	1.9×10^6	50	1×10^5	Not Preserved.
Sept. 28, 1975	TW 1	2.3×10^5	2.8×10^5	200	2.5×10^4	
"	TW 2	2×10^5	1.5×10^5	100	5×10^4	
"	TW 3	ND	ND	100	5×10^4	
"	TW 4	5×10^4	7.5×10^4	200	2.5×10^4	
"	TW 5	1.5×10^5	7.5×10^4	200	2.5×10^4	
"	TW 6	ND	ND	100	5×10^4	
"	TW 7	ND	ND	200	2.5×10^4	
"	TW 8	7.5×10^4	ND	200	2.5×10^4	
"	TW 9	7.5×10^4	1.3×10^5	200	2.5×10^4	
"	TW 10	1.6×10^6	9×10^5	50	1×10^5	
Cubetainer Blank	-	ND	ND	1000	5×10^3	

*Analyses performed by Mr. Jack Murchio, University of California at Berkeley.
ND = Not Detected.

APPENDIX A-2. COMPLETE CHEMICAL ANALYSIS OF SOUTH FORK TOLT RIVER WATER SUPPLY - JANUARY 20, 1978*

	Raw	Treated
Alkalinity, Total (as $CaCO_3$)	4.5	1.4
Alkalinity, bicarbonate (as $CaCO_3$)	4.5	1.4
Aluminum	.21	.21
Barium	<0.015	<0.03
Cadmium	<0.002	<0.002
Calcium	2.9	3.3
Carbon Dioxide, free (calc.)†	3.0	-
Chloride	1.8	2.6
Chromium	<0.006	<0.006
Color, standard units	18	18
Copper	<0.008	<0.008
Fluoride	<0.1	1.01
Hardness (as $CaCO_3$)	8.0	9.0
Hardness, grains per gallon	0.47	0.53
Iron	0.18	0.20
Lead	<0.015	<0.015
Lithium, µg/l	<0.15	<0.15
Magnesium	0.50	0.43
Manganese	0.013	0.005
Mercury, inorganic leachable, µg/l	<0.1	<0.08
Mercury, total, µg/l	<0.05	<0.05
Nitrogen - Nitrate (as N)	0.13	0.45
Nitrogen - Ammonia (as N)	<0.01	<0.01
Nitrogen - Organic (as N)	0.065	0.04
Nickel	<0.01	<0.01
Oxygen, Dissolved	13.0	12.4
Oxygen, % of saturation	101	105
pH	6.65	-
Phosphorus, Total Orthophosphate	<0.002	0.002
Phosphorus, Filtrable Orthophosphate	<0.002	<0.002
Phosphorus, Acid Hydrolysable	0.011	0.014
Potassium	0.27	0.22
Residue, Total	24	23.5
Residue, Non-filtrable	1½	1
Silica, Reactive	3.8	4.2
Silver	<0.001	<0.001
Sodium	1.15	1.02
Specific Conductance, micromhos	24½	27½
Strontium	0.009	0.010
Sulfate	1.9	1.95
Temperature, °C	4	6
Turbidity, NTU	3.8	3.1
Tannin-Lignin	0.25	0.20
Zinc	<0.004	0.008

*Results in mg/l, except as noted.
†Calculated.

APPENDIX A-3. WATER PRODUCTION EFFICIENCIES FOR SELECTED FILTER RUNS.

Run #	Column	Maximum Filter Loading Rate gpm/ft^2	Average Filter Loading Rate gpm/ft^2	UFRV $\frac{gal}{ft^2\text{-run}}$	Net Water Produced per 24 Hours	Filter Efficiency %
84	MM	6	6	3600	7944	94.4
85	MM	8	8	2880	10240	93.1
86	MM	6	6	4026	8017	95.0
87	MM	6	6	4464	8098	95.5
88	MM	6	6	4836	8121	95.9
90	MM	6	6	6480	8253	96.9
91	MM	8	8	2400	9984	91.7
95	MM	6	6	3960	8007	95.0
96	MM	8	8	2880	10240	93.1
98	MM	6	6	3600	7944	94.4
99	MM	8	8	2880	10240	93.1
101	MM	6	6	3960	8007	95.0
102	MM	8	8	2880	10240	93.1
104	MM	6	6	4320	8060	95.4
105	MM	8	8	3840	10560	94.8
109	MM	6	6	2880	7770	93.1
110	MM	6	6	4298	8057	95.3
112	MM	6	6	5040	8143	96.0
123	MM	6	5.8	5905	7930	96.6
124	MM	6	5.2	6500	7100	96.9
125	MM	7	4.5	5152	6171	96.1
127	MM	7	6.8	4080	9072	95.1
128	MM	8	6.5	6240	8914	96.8
137	MM	6	5.6	7405	7768	97.3
138	MM	7	6.7	4020	8930	95.0
138	FC	7	6.5	4680	8760	95.7
139	MM	7	6.5	4303	8739	95.4
139	FC	7	6.5	3900	8640	94.9
139	CC	7	6.25	4875	8400	95.9
140	MM	8	7.1	5112	9470	96.1

(continued)

APPENDIX A-3 (CONTINUED).

Run #	Column	Maximum Filter Loading Rate gpm/ft^2	Average Filter Loading Rate gpm/ft^2	UFRV $\frac{gal}{ft^2\text{-run}}$	Net Water Produced per 24 Hours	Filter Efficiency %
140	FC	8	7.4	4440	9888	95.5
140	CC	8	7.3	5690	9872	96.5
141	MM	6	5.9	5568	7902	96.4
141	FC	6	5.7	4446	7608	95.5
141	CC	6	6.0	5760	8190	96.5
145	MM	6	5.4	5184	7355	96.1
145	FC	6	4.5	6750	6223	97.0
145	CC	6	4.7	7050	6508	97.2
147	MM	8	7.7	6060	10520	96.7
147	FC	8	6.3	6048	8630	96.7
147	CC	8	6.1	7686	8451	97.4
153	MM	10	7.3	5256	9893	96.2
153	FC	10	6.8	5712	9248	96.5
153	CC	10	6.0	5040	8143	96.0
156	MM	10	6.9	5796	9390	96.5
156	FC	10	7.1	5964	9672	96.6
156	CC	10	6.6	5544	8991	96.4
157	MM	10	6.3	6048	8630	96.7
157	FC	10	5.2	6240	6820	96.8
157	CC	10	4.0	6720	5537	97.0
161	MM	10	6.7	6432	9197	96.9
161	FC	10	6.5	6280	8916	96.6
161	CC	10	6.1	5856	7909	96.6
174	MM	10	6.6	7128	9115	97.2
174	CMM	10	6.7	7236	9257	97.2
174	CC	10	6.7	7638	9257	97.4

(continued)

APPENDIX A-3 (CONTINUED)

Run #*	Column	Maximum Filter Loading Rate gpm/ft^2	Average Filter Loading Rate gpm/ft^2	UFRV $\frac{gal}{ft^2\text{-run}}$	Net Water Produced per 24 Hours	Filter Efficiency %
153	MM	10	7.6	5016	10253	96.0
153	FC	10	7.3	4380	9769	95.4
153	CC	10	6.8	3672	8976	94.5
156	MM	10	7.5	4500	10050	95.5
156	FC	10	7.6	4104	10096	95.1
156	CC	10	7.5	3825	9925	94.8
157	MM	10	7.4	3774	9785	94.7
157	FC	10	7.5	3600	9862	94.4
157	CC	10	7.2	3024	9321	93.4
161	MM	10	7.8	5244	10540	96.2
161	FC	10	8.6	5418	11627	96.3
161	CC	10	8.7	5481	11768	96.3
174	MM	10	7.3	4270	9902	95.3
174	CMM	10	7.6	4560	10190	95.6
174	CC	10	7.5	3600	8925	94.4

NOTES:

*Runs terminated at 6 gpm/ft^2 instead of 10' headloss.

MM = Finished Sample from Mixed Media Filter Column with MS-6 Sand.
FC = Finished Sample from Dual Media Filter Column with Fine Coal
CC = Finished Sample from Dual Media Filter Column with Coarse Coal
CMM = Finished Sample from Mixed Media Filter Column with MS-18 Sand.

APPENDIX A-4. SUMMARY OF RAW AND FINISHED WATER ASBESTIFORM COUNTS.

Run #	Hour Into Run	Turbidity (NTU)	Raw (fibers/liter) Amphibole (10^6)	Raw Chrysotile (10^6)	Finished (fibers/liter) Amphibole (10^6)	Finished Chrysotile (10^6)	Removal Amphibole (%)	Removal Chrysotile (%)
3-R	8	0.1	5.7	8.9	--	--	--	--
3-F	8		5.7	8.9	0.04(NSS)	0.09	99.4	99.0
4c-R	5	1.4	3.31	5.12	--	--	--	--
4c-F	5	0.1	3.31	5.12	0.05(NSS)	0.09	98.5	98.2
5c-R	5	1.4	3.06	16.39	--	--	--	--
5c-F	5	0.08	3.06	16.39	<0.01(ND)	0.15	100	99.1
6-R	4	1.3	3.46	13.0	--	--	--	--
6-F	4	0.07	3.46	13.0	0.05(NSS)	0.15	98.6	98.8
11-R	6	1.15	4.33	13.29	--	--	--	--
11-F	6	0.28	4.33	13.29	0.42	1.64	90.3	87.7
12d-R	7	1.0	1.76	13.14	--	--	--	--
12d-F	7	0.09	1.76	13.14	0.01(NSS)	0.13	99.4	99.0
21-R	7	0.66	2.18	25.8	--	--	--	--
21-F	2	0.065	2.18	25.8	0.01(NSS)	0.16	99.5	99.4
21-F	6	0.06	2.18	25.8	0.01(NSS)	0.16(NSS)	99.5	99.4
21-F	7	0.34	2.18	25.8	0.72(NSS)	12.25	67.0	52.5
21-F	8	0.07	2.18	25.8	<0.01(ND)	0.19	100.0	99.3
21-F	12	0.059	2.18	25.8	<0.01(ND)	0.09	100.0	99.7
24-R	7	0.60	2.4	9.4	--	--	--	--
24-F	6	0.085	2.4	9.4	0.04(NSS)	0.34	98.3	96.4
24-F	7	0.36	2.4	9.4	0.6(NSS)	6.2	75.0	72.3
24-F	13	0.062	2.4	9.4	0.04(NSS)	0.13	98.3	98.6
29-R	10	0.62	0.94	4.25	--	--	--	--
29-F	10	0.090	0.94	4.25	<0.01(ND)	0.07	100.0	98.4
29-F	17	0.10	0.94	4.25	<0.01(ND)	0.22	100.0	94.8

(continued)

APPENDIX A-4 (CONTINUED).

Run #	Hour Into Run	Turbidity (NTU)	Raw (fibers/liter)		Finished (fibers/liter)		Removal	
			Amphibole (10^6)	Chrysotile (10^6)	Amphibole (10^6)	Chrysotile (10^6)	Amphibole (%)	Chrysotile (%)
33-R	6	0.61	0.65	3.82	--	--	--	--
33-F	6	0.062	0.65	3.82	<0.01(ND)	0.06(NSS)	100	98.4
33-F	9	0.053	0.65	3.82	<0.01(ND)	0.22	100	94.2
44-R	11	0.56	0.90	2.8	--	--	--	--
44-F	11	0.042	0.90	2.8	<0.01(ND)	0.26	100.0	90.7
44-F	13	0.09	0.90	2.8	<0.01(ND)	<0.01(ND)	100.0	100.0
51-R	9	0.54	<0.29(ND)	8.4	--	--	--	--
51-F	3	0.07	ND	8.4	<0.01(ND)	0.06(NSS)	--	99.3
51-F	3	0.07	ND	8.4	<0.01(ND)	0.20	--	97.6
53-R	9	0.50	0.70(NSS)	3.6	--	--	--	--
53-F	3	0.13	0.70	3.6	<0.02(ND)	0.27	--	92.5
53-F	9	0.24	0.70	3.6	1.2(NSS)	11.2	--	+211.1
62-R	16	0.35	<0.12(ND)	2.52	--	--	--	--
62-F	3	0.10	ND	2.52	<0.02(ND)	0.34	--	86.5
62-F	9	0.105	ND	2.52	<0.02(ND)	0.24	--	90.5
62-F	16	0.37	ND	2.52	0.1(NSS)	2.28	--	9.5
70-R	15	0.35	<0.07(ND)	2.81	--	--	--	--
70-F	5	0.085	ND	2.81	<0.01(ND)	0.06(NSS)	--	97.9
70-F	11	0.072	ND	2.81	<0.01(ND)	0.26	--	90.7
70-F	15	0.08	ND	2.81	<0.01(ND)	0.17	--	94.0
89-R	9	0.35	<0.05(ND)	1.2	--	--	--	--
89-F	9	0.064	ND	1.2	<0.01(ND)	0.014(NSS)	--	98.8
89-MM	9	0.06	ND	1.2	<0.01(ND)	0.043(NSS)	--	96.4
89-MM	15	0.049	ND	1.2	<0.01(ND)	0.04(NSS)	--	96.7
89-MM	19	0.065	ND	1.2	<0.01(ND)	0.17	--	85.8

(continued)

APPENDIX A-4 (CONTINUED).

Run #	Hour Into Run	Turbidity (NTU)	Raw (fibers/liter) Amphibole (10^6)	Raw (fibers/liter) Chrysotile (10^6)	Finished (fibers/liter) Amphibole (10^6)	Finished (fibers/liter) Chrysotile (10^6)	Removal Amphibole (%)	Removal Chrysotile (%)
93-R	18	0.38	<0.07(ND)	3.6	--	--	--	--
93-MM	3	0.098	ND	3.6	<0.02(ND)	0.09(NSS)	--	97.5
93-MM	12	0.10	ND	3.6	<0.01(ND)	0.53	--	85.3
93-MM	14	0.065	ND	3.6	<0.01(ND)	0.07	--	--
93-MM	17	0.074	ND	3.6	<0.01(ND)	0.18	--	98.9
93-F	18	0.08	ND	3.6	<0.01(ND)	0.04(NSS)	--	98.9
108-R	4	0.55	<0.14(ND)	3.61	--	--	--	--
108-MM	2	0.12	ND	3.61	<0.02(ND)	0.34	--	90.6
108-MM	10	0.073	ND	3.61	<0.01(ND)	0.03(NSS)	--	99.2
108-MM	15	0.081	ND	3.61	<0.01(ND)	0.14	--	96.1
108-MM	16	0.068	ND	3.61	<0.01(ND)	0.07(NSS)	--	98.1
108-F	18	0.082	ND	3.61	<0.01(ND)	0.13	--	96.4
111-R	12	0.85	<0.14(ND)	4.62	--	--	--	--
111-MM	7	0.084	ND	4.62	<0.01(ND)	0.09	--	98.1
111-MM	12	0.19	ND	4.62	<0.02(ND)	0.07(NSS)	--	98.5
111-MM	16	0.082	ND	4.62	<0.01(ND)	0.07(NSS)	--	98.5
111-MM	17	0.09	ND	4.62	<0.01(ND)	0.03(NSS)	--	99.4
111-MM	18	0.10	ND	4.62	<0.02(ND)	0.07(NSS)	--	98.5
111-MM	19	0.22	ND	4.62	<0.02(ND)	0.15	--	96.8
111-F	19	0.072	ND	4.62	<0.01(ND)	0.04(NSS)	--	99.1
120-R	9	3.3	0.19(NSS)	5.38	--	--	--	--
120-R	15	3.4	<0.10(ND)	10.1	--	--	--	--
120-MM	1	0.14	0.19(NSS)	5.38	<0.02(ND)	0.14	—	97.4
120-MM	2	0.096	0.19(NSS)	5.38	<0.02(ND)	0.19	—	96.5
120-MM	6	0.08	0.19(NSS)	5.38	<0.01(ND)	0.07	—	98.7
120-MM	9	0.065	0.19(NSS)	5.38	<0.01(ND)	<0.01(ND)	—	100.0
120-MM	12	0.06	0.19(NSS)	5.38	<0.01(ND)	0.1(NSS)	—	99.8
120-MM	13	0.07	0.19(NSS)	5.38	<0.01(ND)	<0.01(ND)	—	100.0
120-MM	15	0.062	0.19(NSS)	5.38	<0.01(ND)	0.01(NSS)	—	99.8
120-MM	16	0.071	0.19(NSS)	5.38	<0.01(ND)	0.01(NSS)	—	99.8
120-MM	17	0.071	0.19(NSS)	5.38	<0.01(ND)	0.02(NSS)	—	99.6
120-MM	18	0.115	0.19(NSS)	5.38	<0.01(ND)	<0.01(ND)	—	100.0
120-MM	19	0.14	0.19(NSS)	5.38	<0.02(ND)	0.19	—	96.5
120-MM	20	0.28	0.19(NSS)	5.38	<0.04(ND)	0.14(NSS)	—	97.4

(continued)

APPENDIX A-4 (CONTINUED).

Run #	Hour Into Run	Turbidity (NTU)	Raw (fibers/liter) Amphibole (10^6)	Raw (fibers/liter) Chrysotile (10^6)	Finished (fibers/liter) Amphibole (10^6)	Finished (fibers/liter) Chrysotile (10^6)	Removal Amphibole (%)	Removal Chrysotile (%)
120-MM	21	0.48	0.19(NSS)	5.38	<0.04(ND)	0.28	—	94.8
120-MM	22	0.57	0.19(NSS)	5.38	<0.07(ND)	0.57	—	89.4
120-MM	23	1.2	0.19(NSS)	5.38	<0.08(ND)	1.25	—	76.8
135-R	9	1.8	<0.07(ND)	3.9	--	--	--	--
135-MM	0	0.28	ND	3.9	<0.02(ND)	0.31	--	92.1
135-MM	1	0.14	ND	3.9	<0.02(ND)	0.32	--	91.8
135-MM	2	0.10	ND	3.9	<0.01(ND)	0.14	--	96.4
135-MM	3	0.096	ND	3.9	<0.01(ND)	0.2	--	94.9
135-MM	4	0.090	ND	3.9	<0.01(ND)	0.08	--	97.9
135-MM	11	0.074	ND	3.9	<0.01(ND)	0.04(NSS)	--	99.0
135-MM	13	0.11	ND	3.9	<0.01(ND)	0.05(NSS)	--	98.7
135-MM	21	0.065	ND	3.9	<0.01(ND)	0.02(NSS)	--	99.5
135-MM	22	0.089	ND	3.9	<0.01(ND)	<0.01(ND)	--	100.0
135-MM	23	0.072	ND	3.9	<0.01(ND)	0.01(NSS)	--	99.7
135-MM	24	0.065	ND	3.9	<0.01(ND)	0.01(NSS)	--	99.7
161-R	6	0.34	<0.04(ND)	2.0	--	--	--	--
161-CC	1	0.092	ND	2.0	<0.01(ND)	<0.01(ND)	--	100.0
161-CC	4	0.085	ND	2.0	<0.01(ND)	<0.01(ND)	--	100.0
161-CC	10	0.069	ND	2.0	<0.01(ND)	0.01(NSS)	--	100.0
161-CC	13	0.082	ND	2.0	<0.01(ND)	<0.01(ND)	--	99.5
161-CC	15	0.082	ND	2.0	<0.01(ND)	<0.01(ND)	--	100.0
161-FC	1	0.095	ND	2.0	<0.01(ND)	<0.01(ND)	--	100.0
161-FC	4	0.071	ND	2.0	<0.01(ND)	0.04(NSS)	--	100.0
161-FC	10	0.069	ND	2.0	<0.01(ND)	0.02(NSS)	--	98.0
161-FC	13	0.072	ND	2.0	<0.01(ND)	0.03(NSS)	--	99.0
161-FC	15	0.073	ND	2.0	<0.01(ND)	<0.01(ND)	--	98.5
161-MM	1	0.135	ND	2.0	<0.01(ND)	0.01(NSS)	--	100.0
161-MM	4	0.082	ND	2.0	<0.01(ND)	0.02(NSS)	--	99.5
161-MM	10	0.079	ND	2.0	<0.01(ND)	<0.01(ND)	--	99.0
161-MM	13	0.089	ND	2.0	<0.01(ND)	<0.01(ND)	--	100.0
161-MM	15	0.081	ND	2.0	<0.01(ND)	<0.01(ND)	--	100.0
174-R	1.5	0.36	0.07(NSS)	1.84	--	--	--	--
174-MM	0	0.089	--	--	<0.01(ND)	0.07	—	96.2
174-MM	1	0.075	--	--	<0.01(ND)	0.1	—	94.5
174-MM	1.5	0.20	--	--	<0.03(ND)	0.36	—	80.4

(continued)

APPENDIX A-4 (CONTINUED).

Run #	Hour Into Run	Turbidity (NTU)	Raw (fibers/liter) Amphibole (10^6)	Raw (fibers/liter) Chrysotile (10^6)	Finished (fibers/liter) Amphibole (10^6)	Finished (fibers/liter) Chrysotile (10^6)	Removal Amphibole (%)	Removal Chrysotile (%)
174-MM	2	0.079	--	--	<0.01(ND)	0.03(NSS)	–	98.4
174-MM	3	0.078	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-MM	4	0.075	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-MM	5	0.079	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-MM	6	0.072	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-MM	7	0.075	--	--	<0.01(ND)	0.02(NSS)	–	98.9
174-MM	14	0.078	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-MM	18	0.075	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-CMM	0	0.095	--	--	<0.01(ND)	0.09	–	95.1
174-CMM	1	0.070	--	--	<0.01(ND)	0.02(NSS)	–	98.9
174-CMM	1.5	0.21	--	--	<0.02(ND)	0.94	–	48.9
174-CMM	2	0.068	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-CMM	3	0.070	--	--	<0.01(ND)	0.03(NSS)	–	98.4
174-CMM	4	0.071	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-CMM	5	0.062	--	--	<0.01(ND)	0.06(NSS)	–	96.7
174-CMM	6	0.089	--	--	<0.01(ND)	0.02(NSS)	–	98.9
174-CMM	7	0.075	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-CMM	8	0.070	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-CMM	14	0.065	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-CMM	18	0.079	--	--	<0.01(ND)	0.05(NSS)	–	97.3
174-CC	0	0.097	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-CC	1	0.07	--	--	<0.01(ND)	0.04(NSS)	–	97.8
174-CC	1.5	0.20	--	--	<0.03(ND)	<0.03(ND)	–	100.0
174-CC	2	0.070	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-CC	3	0.071	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-CC	4	0.090	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-CC	5	0.071	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-CC	6	0.081	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-CC	7	0.068	--	--	<0.01(ND)	0.06(NSS)	–	96.7
174-CC	8	0.070	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-CC	14	0.070	--	--	<0.01(ND)	<0.01(ND)	–	100.0
174-CC	19	0.070	--	--	<0.01(ND)	<0.01(ND)	–	100.0

NOTES:

R = Raw Sample
F = Finished Sample from Waterboy
MM = Finished Sample from Mixed Media Filter Column with MS-6 Sand
CMM = Finished Sample from Mixed Media Filter Column with MS-18 Sand
FC = Finished Sample from Dual Media Filter Column with Fine Coal
CC = Finished Sample from Dual Media Filter Column with Coarse Coal
ND = None Detected
NSS = Not Statistically Significant (4 or fewer fibers actually counted)

SECTION XIII

INDEX OF UNATTACHED APPENDIXES

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-79-125	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE SEATTLE TOLT WATER SUPPLY MIXED ASBESTIFORM REMOVAL STUDY		5. REPORT DATE August 1979 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Gregory J. Kirmeyer		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Water Quality Division Seattle Water Department 1509 South Spokane Street Seattle, Washington 98144		10. PROGRAM ELEMENT NO. 1CC614 Sos 1 Task 06 11. CONTRACT/GRANT NO. R-804422
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research & Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final 5/76 - 11/78 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES Appendices B and C, EPA-600/2-79-153, are supplementary to this main report. Additional supplementary material is in Appendix D, EPA-600/2-79-126. Project Officer: Gary Logsdon 513/684-7345.

16. ABSTRACT

For 1 1/2 years the Seattle Water Department conducted direct filtration pilot plant studies at the Tolt Reservoir, obtaining data on techniques to remove amphibole and chrysotile asbestos from drinking water. Research showed that filtered water turbidity should be 0.1 ntu or lower in order to effectively remove fibers. Flocculation was necessary but sedimentation was not. Amphibole fibers are more readily removed than chrysotile, but both types could be reduced to below detectable limits or to not statistically significant counts by treatment with alum, lime and a filter aid (nonionic or anionic polymer); or alum, cationic polymer and a filter aid; or cationic polymer and a filter aid. Asbestos fiber content of filtered water increased sharply when filtered water turbidity rose above 0.1 ntu because of filtration rate changes, interruption of chemical feed, or turbidity breakthrough associated with the end of the filter run. Asbestos fibers in the concentrations encountered in this study (raw up to 20×10^6 f/L, filtered down to 0.01×10^6 f/L) can not be detected by a turbidimeter; however, the association of rising fiber counts and turbidities in filtered water would enable a plant operator to estimate fiber removal by observing turbidity if the filter was operated in the manner done in this work.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Asbestos, Coagulation, Electron microscopes, Filtration, Pilot plants, Potable water, Turbidity, Water treatment	Seattle, Washington Tolt Reservoir Fiber removal, Chrysotile, Amphibole, Direct filtration, Flocculation	13 B

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