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Water Filtration for Asbestos Fiber Removal

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WATER FILTRATION FOR ASBESTOS FIBER REMOVAL

by

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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 for minimizing 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 shows that granular media filtration and diatomaceous earth filtration can remove as much as 99.99 percent of the asbestos fibers from drinking water. Fiber counts below the limit of detection by the transmission electron microscope method can often be achieved. The report presents results of research conducted at Duluth, Minnesota and Seattle, Washington as well as monitoring data from Silver Bay and Two Harbors, Minnesota; Philadelphia, Pennsylvania; Chicago, Illinois; and the San Francisco Bay area in California. Even though data were collected under diverse conditions, the relationship of low turbidity and low fiber count in filtered water is seen as a unifying factor.

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PREFACE

The Safe Drinking Water Act (P.L. 93-523) gives the Administrator of the Environmental Protection Agency authority to issue regulations if a substance may pose a health hazard in drinking water. Inhaled asbestos is a known carcinogen, and ingested asbestos may be hazardous to health. Therefore information about asbestos in drinking water should be of interest to public health officials, the water utility industry, and the Environmental Protection Agency.

During the 1970's the results of electron microscope examination of water samples showed that some waters contained asbestos fibers. Early Canadian efforts created both concern and curiosity in other investigators, and gradually knowledge about asbestos fibers in drinking water increased. Because the fibers might constitute a health hazard in drinking water, monitoring efforts were carried out to assess the capability of water filtration plants to remove asbestos, and engineering research was funded to provide more detailed knowledge about water filtration for asbestos removal.

Information about asbestos in drinking water and about fiber removal by filtration is scattered throughout the engineering and scientific literature. Results have been reported by numerous investigators, concerning a variety of waters and locations, based upon a number of different variations of analytical technique. Because of such diversity, those who review the literature can expect to find results that appear contradictory or difficult to explain. Therefore the Drinking Water Research Division has undertaken a comprehensive review of asbestos in drinking water, in order to summarize and interpret the work of the many investigators who have made contributions to present day knowledge of the problem.

The goal of this report is to present a unified concept of water filtration for asbestos fiber removal that can be used to explain past results as well as to guide filtration plant designers as they plan new facilities and to help water filtration plant operators as they strive to reduce the concentration of asbestos fibers in drinking water.

ABSTRACT

This report was prepared so that concepts of water filtration for asbestos fiber removal could be presented in a manner that would explain results reported by other investigators, to provide information for designers of water filtration plants, and to give guidelines for the successful operation of filtration plants that are removing asbestos fibers from drinking water. This document reviews the literature of other investigators, (mostly Canadian), summarizes filtration studies funded by U.S. EPA at Duluth and Seattle, and presents monitoring data gathered at water treatment plants in Philadelphia, Chicago, and the San Francisco Bay area.

Results of treatment for asbestos removal presented herein cover not only a number of widely separated geographic locations from coast to coast in the United States and Canada, but also from a wide range of source waters, from a pristine mountain lake to turbid rivers and estuarine waters, as well as variations in flow from 10 gallons per minute or smaller to more than 200 million gallons per day and several modifications of granular media filtration. Although the results are presented on the basis of geographic location, the discussion of results is based upon the type of filtration used, because of the substantial differences between granular media filtration and diatomaceous earth filtration.

Data from Seattle and Duluth show that chrysotile and amphibole fiber concentrations in drinking water can be substantially reduced by granular media filtration. Reductions of up to 99.99 percent were reported during storm conditions at Duluth, Minnesota. Effective granular media filtration required very diligent plant operation with careful control of pH, coagulant doses, and filtered water turbidity.

Even though turbidity can not directly measure asbestos fibers in the concentrations found at water treatment plants, when a granular media filtration plant is properly operated, turbidity readings can be used as a guide to plant operation. Filtered water turbidity should be 0.10 nephelometric turbidity units (ntu) or lower to maximize fiber removal. Turbidity increases of 0.1 or 0.2 ntu above this value generally were accompanied by large increases in asbestos fiber concentrations.

Some of the results presented suggest that fiber removal is more easily accomplished when source waters have turbidities greater than 1 ntu, the raw water turbidity typical at Duluth and Seattle.

Diatomaceous earth filtration was found effective for asbestos fiber removal in bench-scale and pilot plant studies. A full scale diatomite filtration plant has not yet been evaluated for fiber removal efficiency.

Research to date indicates that coating the diatomaceous earth filter aid with aluminum hydroxide substantially increases the removal of both amphibole and chrysotile fibers. Duluth results indicate that filtered water turbidity should be 0.10 ntu for most effective fiber removal.

The principal studies on which this report is based were performed during the period from March, 1974 to June, 1979. This report was completed in September 1979.

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LIST OF METRIC CONVERSIONS

Filter area	1.0 ft^2 = 0.093 m^2
Filter box depth	1.0 ft = 0.30 m
Filter head loss	1.0 ft of water = 0.30 m water
Filtration rate	1.0 gal/min/sq ft = 2.4 m/hr
Flocculator paddle velocity	1.0 ft/sec = 0.30 m/sec
Plant capacity	1.0 mgd = 3800 m^3/day
River flow rate	1.00 cu ft/sec = 0.028 m^3/sec
Torque	1.0 ft-lb = 1.36 N-m
Unit costs	1.0¢/1000 gal = 0.26¢/m^3
Volume	1 million gallons = 3800 m^3
Water production of a filter	1.0 gal/sq ft/day = 0.041 m^3/m^2/day
Water flow in treatment process	1.0 gal/min = 0.063 L/sec
Weir overflow	1.0 gal/ft/day = 0.00014 L/m/sec

ACKNOWLEDGMENTS

This report is based upon the efforts of many persons and a large number of organizations, but special consideration is due to the Canadian scientists and engineers who conducted the first studies that revealed the problem of asbestos in drinking water and suggested that water filtration could provide the solution.

Contributors to the effort at Duluth and the Lake Superior north shore include Black & Veatch, the Ontario Research Foundation, EPA Environmental Research Laboratory at Duluth, University of Minnesota-Duluth, Lake Superior Basin Studies Group, RREM Inc. Consulting Engineers, and the Duluth Department of Water and Gas.

The Seattle pilot plant study was performed by the Seattle Water Department. Electron microscope analysis of water samples was done by the University of Washington.

Data for the San Francisco Bay area came from research done at the University of California, Berkeley, with much supplemental treatment plant data furnished by the Sanitary Engineering Section, Department of Health, State of California. Asbestos samples were analyzed at the University of California, Berkeley.

Chicago data were furnished by the Chicago Department of Water and Sewers. The Chicago Water Purification Laboratory analyzed the samples for asbestos.

The Philadelphia Water Department provided information on Philadelphia's water treatment plants. Asbestos samples from Philadelphia were analyzed at the University of Washington.

SECTION 1

INTRODUCTION

Asbestos is used in many ways in the world today. It has found many successful commercial and industrial applications for numerous decades. Over a period of years, public health officials and medical experts have learned that inhaled asbestos is an occupational health hazard. When Cunningham and Pontefract (1) reported in 1971 that they had found asbestos fibers in drinking water in Canada, asbestos came to the attention of regulatory officials and the water utility industry. Health effects data for ingested asbestos fibers were not available, so no basis for immediate regulatory action existed. Because this was the first report of asbestos in drinking water, additional investigation would be needed to describe the nature of the problem.

Asbestos in drinking water suddenly became a serious environmental problem in the United States in the summer of 1973, as a result of studies done at the Environmental Research Laboratory in Duluth (2). Involved in litigation with the Reserve Mining Company, the Environmental Protection Agency contended that amphibole fibers originating in tailings being dumped into Lake Superior at Silver Bay, Minnesota were traveling with the lake current and could be detected in the unfiltered drinking water of Duluth.

The Lake Superior problem stimulated much interest in asbestos in drinking water, especially in the USA. Studies were made to improve analytical methods for asbestos, to learn more about the health effects of ingested asbestos, and to develop information about ways to remove asbestos fibers from drinking water by filtration. Since 1973, much money and many hours of work have been expended to find some answers to the problem of asbestos in drinking water.

The purpose of this report is to assess the efficacy of water filtration processes for asbestos fiber removal. This has been done by reviewing published reports of work done by others and by studying in depth the results of work done by or sponsored in some way by EPA. A heavy reliance is placed on EPA-related work because generally these studies are more recent, and a greater amount of additional engineering and water quality data could be obtained. Having the engineering and water quality data is especially important for the purpose of advising design engineers and water utility operators how to design and run water filtration plants so that asbestos fibers can be efficiently removed.

SECTION 2

CONCLUSIONS

MONITORING

Analysis of water samples by transmission electron microscope is the only method that provides asbestos fiber counts, but this technique can not be used for control of treatment plant operation because of the long time delay between collection of samples and receipt of results.

A laser-illuminated optical detector has been developed and regression equations can be used to convert detector signal output to estimates of amphibole fiber count. This device could be adapted to on-line operation in water filtration plants.

Turbidimeters do not detect asbestiform fibers in the range of concentrations of interest for drinking water - 0.01 to 1000 X 10^6 fibers/liter. When water is properly conditioned for granular media filtration, changes of turbidity of the filtered water usually signal changes in the fiber concentration of filtered water.

GRANULAR MEDIA FILTRATION

Asbestiform fiber removal by granular media filtration has exceeded 99.99 percent.

Proper conditioning of raw water is essential for effective fiber removal. Adequate coagulant must be used to completely destabilize all particles. Filter aids may be needed to prevent turbidity breakthrough.

After filtered water turbidity has stabilized at the recommended goal of 0.10 nephelometric turbidity unit (ntu) or lower, an increase of even 0.1 ntu in filtered turbidity is usually associated with a very large increase in filtered water fiber concentration, because granular media filters can store and then slough large numbers of fibers in filter upset situations. Loss of chemical feed and rapid filtration rate increases must be avoided. Careful control of coagulation pH is needed, especially for low alkalinity waters. Very careful attention to coagulation chemistry and filter operation will be required for effective filtration plant operation.

Granular media filters can remove chrysotile fibers at filtration rates of 2 to 10 gpm/sf. Depending on local circumstances, both back mix and in-line or static mix techniques can be effective. Some waters require flocculation for effective filtration. Sedimentation removes asbestos fibers but it is not needed for relatively clear, 1 ntu or less, surface waters.

The principal types of granular media currently in use - sand,dual media, and mixed media - have been shown to be effective for filtering out asbestos fibers.

Designing filters with seven or more feet of water over the filter media prevents air binding problems.

DIATOMACEOUS EARTH FILTRATION

Diatomaceous earth filtration can remove both amphibole and chrysotile fibers, with demonstrated removals as high as 99.99 percent.

Diatomaceous earth (DE) coated with aluminum hydroxide is more effective for removal of asbestos fibers than uncoated DE.

Filtered water turbidity should be 0.10 ntu or lower to attain maximum filter efficacy for fiber removal.

Use of vacuum DE filters to treat cold, oxygen-saturated water may result in formation of air bubbles in the filter cake. This problem can cause deterioration of filtered water quality. Because of design differences, pressure DE filters would not experience the air bubble problem.

COSTS

Cost of filtration for surface waters containing asbestos fibers should be very similar to the cost of filtering other surface waters. Meeting the 0.10 ntu goal for water quality is economically and technically feasible. This is demonstrated by the ability of plants such as the Contra Costa County Water District's Bollman plant and Duluth's Lakewood plant to meet such a turbidity goal.

SECTION 3

RECOMMENDATIONS

Water treatment plants that filter water for the purpose of removing asbestos fibers should continuously monitor the effluent turbidity from each filter.

Filtered water turbidity should be 0.10 ntu or lower.

A small increase in turbidity (0.1 to 0.2 ntu) may be associated with a very large increase in asbestos fiber count in filtered water. For this reason plant operators should backwash filters long before the 1 ntu Maximum Contaminant Limit for turbidity is reached during turbidity breakthrough.

At granular media filtration plants, very careful control of chemical feed rates should be maintained to assure that proper coagulant dose and pH are maintained at all times.

Filtration rate should not be changed abruptly during a filter run.

Filters should be designed to avoid problems caused by formation of air bubbles in the filter media. Use of pressure diatomaceous earth filters or deep granular media filter boxes (about seven feet of water over media) is recommended to prevent air binding problems in locations where they could occur.

Usually a pilot plant study should be carried out before a water filtration plant is designed for asbestos fiber removal to help designers select optimum filtration rates, coagulant dose and type, filter aid and dose and type if needed, media type and so forth.

SECTION 4

REVIEW OF LITERATURE

HEALTH EFFECTS

A considerable amount of controversy in the Reserve Mining Company trial was related to the health effects of ingested asbestos. Asbestos is acknowledged to be a carcinogen when inhaled, but in the early 1970's very little was known about the health effects of ingested asbestos. Presenting a detailed review of the health effects questions is not the purpose of this paper, but a brief review of the health effects controversy will show why work on asbestos in water is continuing. A more detailed paper on health effects was recently prepared by McCabe and Millette (3).

One of the questions debated by scientists has been whether ingested asbestos fibers could migrate through the gastrointestinal wall to the peritoneum and cause cancer. This possibility had been suggested because of the association of peritoneal mesotheliomas with asbestos exposure, according to Gross et. al. (4). The authors further stated that their report on ingested mineral fibers was being published in response to the desire of public health officials to learn whether or not ingested asbestos might present a health hazard. In three separate laboratories investigators fed rats asbestos fibers in butter or margarine, or introduced amosite fibers and taconite tailings into the stomach of rats by means of a stomach tube.

Gross and the co-authors reported no incontrovertible proof of transmigration of the fibers. They also attacked a study by Pontefract and Cunningham (5) in which the latter authors found amosite fibers widely disseminated in tissues outside the gastrointestinal tract. Pontefract and Cunningham had injected asbestos fibers through the stomach wall, and Gross et. al. contended that the hole made by the needle allowed fibers to leak from the stomach and contaminate the abdominal cavity. Thus controversy surrounded the issue of the fate of ingested asbestos in the early 1970's.

In an attempt to resolve some of the controversy, EPA researchers recently have sponsored or conducted studies. In a paper entitled "Ingested Mineral Fibers: Elimination in Human Urine," Cook and Olson describe research on the excretion of amphibole fibers in urine of persons drinking unfiltered water (6). Cook and Olson found from 300 to 1200 amphibole fibers per milliliter (0.3 to 1.2 X 10^6 fibers/liter) in the urine of persons who drank unfiltered Lake Superior water. They estimated that the amphibole fiber content of the unfiltered lake water ingested by the persons who voluntarily provided urine samples would have been 50 X 10^6 (fibers/liter), or more in certain cases. Cook and Olson stated, "These observations provide the first direct evidence for the passage of mineral fibers through the human gastrointestinal mucosa under normal conditions of the alimentary canal."

At the University of Illinois School of Public Health in Chicago, researchers studied the fate of ingested chrysotile by bottle feeding a suspension of chrysotile in milk formula to a newborn baboon that was kept in an infant incubator under conditions of controlled temperature, humidity, and air supply (7). The asbestos dose was about 3 X 10^{13} fibers per kilogram of body weight. Chrysotile fibers were found in the kidney cortex tissue of the exposed baboon, but were below limits of detection in the unexposed control. Analysis of fiber size data showed very little difference in the size frequency distributions for the fibers used in the study and the fibers found in the cortex tissue. The investigators stated that no fiber selection process seemed to be occurring in the gastrointestinal tract of the newborn baboon. The maximum length of fiber found in the cortex tissue was 35 μm.

The recent findings on the migration of asbestos fibers across the gastrointestinal barrier do not in any way prove that the fibers cause gastrointestinal cancer or mesothelioma. The findings do, however, disprove the argument that ingested asbestos could not cause peritoneal mesothelioma because asbestos fibers do not migrate across the intestinal wall.

Because of findings like these, public health officials continue to be concerned about the possible health hazards related to ingested asbestos. The information on removal of asbestos fibers by water filtration processes is presented in this context.

SOURCES OF ASBESTOS FIBERS IN DRINKING WATER

Asbestos fibers are contaminants in some drinking waters. They occur when fibers contaminate raw waters or when aggressive waters dissolve the cement in asbestos cement water mains.

Sometimes asbestos fibers are found in raw waters because natural weathering action causes disintegration and erosion of rock formations that contain asbestos. This occurs in the Cascade Mountains, for example, and is the reason for the high concentration of asbestos fibers in the Tolt Reservoir.

Human activity can result in high concentrations of asbestos fibers in water. The Reserve Mining Company's disposal of about 67,000 tons per day of tailings into Lake Superior caused the concentration of amphibole fibers in the lake water at Duluth to range from tens of millions per liter to about one billion fibers per liter during severe storms. Liquid wastes discharged from industries that manufacture products that contain asbestos may be sources of contamination. An assessment of sources of environmental contamination has been published by EPA (8).

Another source of asbestos fibers in drinking water is the pickup of asbestos in water that flows through asbestos-cement pipes. In 1974 H. L. Olson wrote, "Water flowing through asbestos-cement pipe does not increase the level of fiber content significantly" (9). Olson's statement is correct in some cases, but unfortunately in other instances it is wrong. Buelow et. al., in a paper presented at the 1979 Annual Conference of the American Water Works Association state, ". . . asbestos-cement pipe behaves much like other piping materials, excepting plastic, that are in common use for distribution of drinking water. If aggressive conditions toward the piping material exist, the pipe will corrode and deteriorate. If aggressive conditions do not exist toward the piping material the pipe will not corrode and deteriorate" (10).

Water quality conditions that cause deterioration of asbestos-cement pipe and conditions that do not cause the deterioration are not completely understood at the present time (1979). Further studies on this problem are needed. Buelow et. al. gave a list of conditions indicative of situations in which water is not attacking A/C pipe, and also a list of conditions in which the water is probably attacking A/C pipe. Among the signs of likely attack was inlet water screens at coin operated laundries becoming plugged with asbestos fibers.

Water filtration often occurs before water is pumped into a water utility's distribution system. Although filtration would not improve a water quality problem caused by deterioration of A/C pipe, overall water treatment practice can influence the extent to which a water attacks pipes in the distribution system. The influence can be adverse if addition of alum and chlorine exhausts most of the natural alkalinity in a water and drastically reduces the pH. The treatment influence can be positive, however, if the utility recognizes the importance of corrosion control and adjusts the quality of the treated water so that it does not attack pipes in the distribution system.

This report does not deal with corrosion control, but it is mentioned here so that filtration plant operators will be aware that they should not treat water in a way that removes asbestos at the filtration plant but then causes the water to deteriorate asbestos-cement pipe in the distribution system.

ASBESTOS FIBERS IN RAW AND FILTERED WATERS

Since the early 1970's investigators have published data on the concentration of asbestos in various raw and filtered waters. A review of some of these data is presented in this document. For a more complete report on asbestos in drinking waters, readers should obtain a report by Millette, Clark, and Pansing (11). As the authors carefully explain, analytical methods for asbestos fibers in water have been different from laboratory to laboratory. Also, techniques have improved since analysts first began searching for asbestos in water. Therefore, caution must be applied by anyone who wants to make comparisons of data between laboratories. A single example should be sufficient to illustrate the point. During the pilot plant filtration research conducted at Duluth in 1974, the Ontario Research Foundation reported amphibole counts in the range from less than 1×10^6 to 4×10^6 fibers per liter (f/L) for raw Lake Superior water (Reference 12, Appendix E). From 1977 through 1979 the Lake Superior Basin Studies Group at the

University of Minnesota-Duluth generally found amphibole fiber concentrations to vary from tens to hundreds of million per liter (13). Because the discharge of tailings occurred in 1974 and also in recent years, the most likely explanation for the difference in results would be different fiber recoveries by the methods used in 1974 and in the monitoring done since 1977.

Even though comparisons of data between laboratories can cause problems, fiber counting data for samples done within a single laboratory should be comparable if the interval of time between counting samples is not too great. Care should be taken when looking at 1974 vs. 1979 data, because the counting method has been improved recently, but sample data collected in a one-year or two-year study should be comparable if the analyst did not change or improve methods during the study.

In their study of asbestos fibers in water, Cunningham and Pontefract reported finding on the order of 1 to 10 X 10^6 f/L in tap waters in some Canadian towns and cities (1). They reported, " . . . Ottawa tap water, drawn from the Ottawa river, had considerably fewer fibres than unfiltered river water." Cunningham and Pontefract thus gave engineers reason to expect that water filtration could remove the fibers.

Stimulated by the Cunningham and Pontefract paper, the Ontario Ministry of the Environment began a program of water analysis. Samples were collected at 22 Ontario cities in August, 1972 and analyzed by the Ontario Research Foundation. Results of the study were published by G. H. Kay in Water and Pollution Control in 1973 (14) and in JAWWA in 1974 (15). Of particular interest was Kay's report that fiber count was reduced about 92 percent by the filtration plant at Windsor, Ontario. Counts there dropped from about 20 X 10^6 f/L to less than 2 X 10^6 f/L when the water was subjected to what Kay called "complete treatment filtration" (14). The Windsor plant utilizes coagulation, flocculation, sedimentation, and filtration through dual media. In a letter to O. J. Schmidt of Black & Veatch in 1974, Kay mentioned coagulation, flocculation, and filtration as a technique to remove fibers to below 1 X 10^6 f/L (16).

Wigle published some data on raw and filtered municipal water supplies in the communities of Asbestos and Drummondville in Quebec (17). At one location the fiber count was reduced from 1,200 X 10^6 f/L to 200 X 10^6 f/L by filtration. At another the reduction was from 680 X 10^6 f/L to 1.1 X 10^6 f/L. Wigle was a medical doctor writing about cancer mortality in relation to water supplies, and he included no engineering information in his paper other than whether or not a municipal water was filtered.

In the United States, Sargent should be recognized for his early concern about levels of asbestos in Vermont drinking waters (18). Unfortunately, Sargent's fiber counts were made by optical microscope at a 450-power magnification, and that method is no longer used for water analysis.

In an epidemiological study made to determine if a link existed between cancer incidence and exposure to asbestos in drinking water, Kanarek reported the results of an extensive sampling and analysis program carried out in the San Francisco Bay area (19). Kanarek included data on filtered and unfiltered waters, as well as on water quality at many locations in the distribution systems in the Bay area. Some of his data on filter plant performance are presented and discussed later in this report.

A long-term electron microscope investigation of water quality was carried out at the Water Purification Laboratory at Chicago. McMillan, Stout, and Willey reported on asbestos in raw and treated water at Chicago, and presented a graph showing monthly average raw and treated water fiber counts for the July, 1974 - December, 1975 time period (20). The Chicago water filtration plants employ coagulation, flocculation, sedimentation and filtration. The authors stated that the plants " . . . remove 70 to 90% of the asbestos fibers present in the raw water of Lake Michigan" (20).

The monitoring program begun in 1974 has been continued. Fiber counting data for 1976 through 1978 were provided by McMillan, and these are presented and discussed later in this report.

TREATMENT STUDIES REPORTED BY OTHERS

Canadian Research

Much of the work on water filtration for asbestos removal has been done with the assistance of the Environmental Protection Agency. Of the studies done independently of EPA, work in Canada has probably been more extensive than that done anywhere else. The Ontario Ministry of the Environment and Canada Centre for Inland Waters sponsored research studies over a period of years.

In the first research reported upon, Lawrence et. al. performed laboratory tests of flocculation and sand filtration (21). They reported 99.8 percent fiber removal when treating a lake water containing 12.3 X 10^6 f/L. Later Lawrence and Zimmerman reported that with respect to fiber removal, an optimum dose for polymer existed (22). Either an overdose or an underdose of polymer resulted in a higher residual fiber count in water that had been flocculated and filtered. An optimum dose for polymers has been reported by other researchers who assessed filter behavior in terms of turbidity removal and particle counting (23-26).

Lawrence and Zimmerman reported on use of mixed media filtration and diatomaceous earth (DE) filtration in a study of asbestos mine effluent water treatment (27). They reported that although mixed media filtration could reduce the asbestos fiber concentration by a factor of 40 to 100, DE filtration could reduce the asbestos fiber concentration by a factor of 10^3. Diatomite coated with aluminum hydroxide according to a Johns-Manville technique was even more effective, reducing the fiber count from 10^9 f/L to less than 10^5 f/L.

The Ontario Ministry of the Environment set up a pilot plant in its Research Test Facility in Toronto in order to evaluate the efficacy of water treatment processes for asbestos fiber removal. The authors reported on problems experienced in diluting chrysotile and adding it to the pilot plant flow stream (28) and on results of the pilot plant study (29). The pilot plant was similar to conventional plants, having rapid mix, flocculation, sedimentation, and filtration. The plant operated at the rate of 0.4 L/s (6.3 gpm). The plant had three 14 cm inside diameter filter columns, two of which had dual media, while the third filter contained only sand. The authors reported that optimized conventional treatment could significantly reduce asbestos levels in potable water. In the most successful experiments fiber reductions through the complete treatment train ranged from 95 to 99.3 percent. Foley and Missingham presented data showing that in one experiment at the test facility, 99.5 percent reduction of fibers (from 7.8 X 10^6 to 0.038 X 10^6 f/L) had taken place (30).

Everett, Washington

Water treatment pilot plant research was conducted at Everett, Washington in 1977. Filter performance evaluation was usually based upon turbidity or particle counting data. Watkins, Ryder, and Persich did present a limited amount of asbestos fiber data, however (31). The data are shown in Table 1.

TABLE 1. ASBESTOS COUNT CORRELATIONS - EVERETT PILOT PLANT

		Asbestos Count			Particle Count		
		10^6 Fibers/Liter		Turbidity	10^6/liter		
Run*	Sample	Chrysotile	Amphibole	ntu	1-5μm	5-60μm	1-60μm
Conventional Treatment	Raw	143	4.68	1.05	12.11	1.24	13.35
	#3 Eff.	0.07	<0.01	0.06	0.44	0.06	0.50
Direct Filtration	Raw	71.6	1.7	0.73	7.08	0.38	7.46
	#3 Eff.	1.12	<0.01	0.05	0.037	0.003	0.040
In-Line Filtration	Raw	35.9	2.12	0.60	5.71	0.23	5.94
	#3 Eff.	0.39	<0.01	0.15	0.17	0.01	0.18

*Based on a 5 GPM/Sq. Ft. Filter loading

The pilot plant, as described in detail by the authors, could operate with conventional treatment (rapid mix, tapered flocculation, sedimentation, rapid sand filtration), direct filtration (sedimentation omitted),and in-line filtration (both flocculation and sedimentation omitted). The pilot plant was rated at 1.6 gpm. Conventional treatment and direct filtration (with flocculation) were processes capable of producing filtered water with a turbidity of 0.10 ntu or less. Filtration preceeded by rapid mix only (in-line filtration) did not attain the 0.10 ntu level. The filtration processes were effective for removing both amphibole and chrysotile fibers.

FIBER REMOVAL BY FILTRATION

The literature reviewed, when considered as a whole, suggests that water filtration processes can be quite effective for reducing the concentrations of asbestos fibers under certain circumstances. On the other hand, some results show that fiber removal efficiency was not especially good. A basic premise of this report is that reasons do exist for differences in water filtration efficacy. Finding the reasons and explanations for differences in filter performance is an objective that will be pursued in further sections of this report.

Research on filtration for asbestos fiber removal has been sponsored by EPA since 1973. The following portion of this report describes such research on a location-by-location basis. Data are available for Duluth, Minnesota; other communities on the north shore of Lake Superior; Seattle, Washington; Philadelphia, Pennsylvania; and the San Francisco Bay area (through Kanarek's study).

SECTION 5

WATER UTILITIES ON LAKE SUPERIOR'S NORTH SHORE

DULUTH

In June, 1973 the Environmental Protection Agency announced that its Environmental Research Laboratory in Duluth had found asbestos fibers in the drinking water of Duluth. At the time the water was disinfected and fluoridated but not filtered. In the summer of 1973 EPA began a program of research on asbestos fibers in drinking water, and activity continues to the present time. The first research, performed in Cincinnati with Lake Superior water that had been shipped from Duluth via air freight, indicated that dual media filtration could reduce the concentration of larger amphibole fibers by as much as ninety percent. However, nearly all of the asbestos analysis was done by light microscopy at a magnification factor of 450. This technique was soon shown to be inadequate for such work, so details of the Cincinnati research were not published.

During the summer of 1973, the U. S. Army Corps of Engineers conducted a brief program of filtration research at Duluth. This work was described by Schmitt, Lindsten and Shannon (32). They reported that polymer coagulation followed by diatomaceous earth filtration was effective for removal of asbestos. The authors reported that all the asbestos was removed in one run. The analytical method in 1973 probably has a practical detection limit of 0.05 to 0.1 X 10^6 f/L, however, so 100 percent removal of fibers was not actually demonstrated. Nevertheless, DE filtration on a scale of 7 gpm appeared promising.

Pilot Plant Research

In the fall and early winter of 1973 an interagency agreement for studies of the problem was formulated and signed by the EPA and the U.S. Army Corps of Engineers. Under this agreement, EPA funded the pilot plant research on asbestos fiber removal and the Corps funded a study of alternative water sources and sites for construction of a filtration plant or plants for the Duluth-Cloquet-Superior area.

Black & Veatch conducted the pilot plant research at the Lakewood pumping station in Duluth, Minn., with the assistance of the Department of Water and Gas of the City of Duluth during the period from April through September, 1974. In this time, a total of 227 granular media and 228 diatomaceous earth (DE) filter runs were performed.

Pilot Plant Equipment--

The apparatus used in the research has been described in Appendix B of the report on the project (12). Two types of filters -- granular media and DE -- were used. All units were situated in the Lakewood pump station. Total water flow through individual filter systems generally ranged from 10 to 20 gpm.

Two granular filters were employed. Both units were package plants* with 4.0 sq. ft. of filter surface. Equipment variations with these units included use of dual media; mixed media (tri-media); no settling; tube settlers; single-stage rapid mix and two-stage rapid mix with propellor mixers; two-stage and three-stage rapid mix with in-line mixers; alum or ferric chloride as the primary coagulant; anionic, cationic, and non-ionic polymers; and filtration rates of 2 - 7 gpm/sq ft.

Two kinds of DE filter systems were employed. In the pressure filtration unit† the clear Lake Superior water merely was passed through the pretreatment portions of the filter on its way to the pressure filter. The filter had two pressure vessels, each containing six cylindrical septa. Total filter-surface area for one pressure vessel was 10.0 sq. ft. After the filter septum was precoated, body feed could be added dry or in slurry form.

The gravity or vacuum DE filter unit# consisted of an open rectangular tank with flat septa. The driving force for filtration was the difference between atmospheric pressure and the pressure at the pump intake on the effluent side of the filter. Filter surface was also 10.0 sq. ft. on this unit. Body feed could be added dry or in slurry form.

Both kinds of DE filters were operated in various ways to evaluate conditioning of DE with alum, cationic polymer, and anionic polymer. On some runs, a cationic polymer was added to the raw water. Single-step vs two-step precoat was studied. Conditioned DE was used in precoat situations as well as for body feed. Various grades of DE, from fine to coarse, were evaluated.

Study Results--

The two principal objectives of the research were (1) to obtain information on asbestos fiber removal and (2) to operate pilot plants in such a way as to generate data for engineering design and cost estimates. These objectives were accomplished. Fiber removal results are discussed in the following sections of this report. Cost estimates based on the pilot plant work are not presented because actual construction cost data are now available.

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*Neptune - Microfloc WB-27

†Erdlator, The U.S. Army water filtration system developed by the Engrg. R&D Lab. at Ft. Belvoir, Va.

#A product of BIF Industries

Amphibole data--Analysis of the data showed that certain filtration techniques were effective for amphibole removal as measured by x-ray diffraction at the National Water Quality Laboratory (NWQL, now the Environmental Research Laboratory) and by transmission electron microscopy. Data are summarized in Tables 2-4.

TABLE 2. AMPHIBOLE MASS AND FIBER REMOVAL BY DUAL MEDIA FILTRATION - DULUTH PILOT PLANT

Treatment Technique	NWQL Amphibole Mass Number of Samples: Total Analyzed	NWQL Amphibole Mass Number of Samples: $\leq$.005 mg/L	Ontario Research Foundation Amphibole Fibers Number of Samples: Total Analyzed	Ontario Research Foundation Amphibole Fibers Number of Samples: At or Near BDL*
Filtration without sedimentation				
Alum & nonionic polymer† 2 gpm/sq ft	3	3	3	2
Alum & nonionic polymer# 4 gpm/sq ft	5	4	10	9
Alum & nonionic polymer† 6-8 gpm/sq ft	-	-	3	2
$FeCl_3$ and cationic polymer§ 4 gpm/sq ft	-	-	2	2
Filtration with sedimentation tube settlers, 4 gpm/sq ft				
Alum and nonionic polymer†	12	12	12	12
$FeCl_3$ and nonionic polymer†	2	1	2	2

*At or near BDL (below detectable limits) is defined as $\leq$ 0.04 X 10^6 f/L
†985 N, Nonionic polymer by American Cyanamid, Wayne, N.J.
#N-17, Dow Chemical Co., Midland, Mich.
§C-31, Dow Chemical Co., Midland, Mich.

From Black & Veatch (12)

TABLE 3. AMPHIBOLE MASS AND FIBER REMOVAL BY MIXED MEDIA FILTRATION - DULUTH PILOT PLANT

	NWQL Amphibole Mass Number of Samples		Ontario Research Foundation Amphibole Fibers Number of Samples	
Treatment Technique	Total Analyzed	≤.005 mg/L	Total Analyzed	At or Near BDL*
Chemicals added to mixing chamber:				
Alum and nonionic polymer,† 4 gpm/sq ft	1	1	1	1
Chemicals added to two flash mixers:				
Alum and nonionic polymer,† 4 gpm/sq ft	5	5	5	5
Alum and anionic# and cationic§ polymers, 4 gpm/sq ft	2	2	2	2
Alum and anionic# and nonionic† polymers, 4 gpm/sq ft	2	2	2	2
Alum and nonionic polymer,† 2 gpm/sq ft	1	1	1	1
In-line mixers:				
Alum and nonionic polymer,† 4 gpm/sq ft	1	1	1	1
Alum and nonionic† and anionic# polymers, 4 gpm/sq ft	2	2	2	2
Alum and anionic# and cationic§ polymers, 4 gpm/sq ft	1	1	1	1
Alum and nonionic polymer† 6 gpm/sq ft	2	2	2	2
Alum and cationic polymer,§ 4 gpm/sq ft	1	1	1	1

*At or near BDL (below detectable limits) is defined as $\leq 0.04 \times 10^6$ f/L.
†985 N, Nonionic polymer by American Cyanamid, Wayne, N.J.
#A-23, Dow Chemical Co., Midland, Mich.
§C-31, Dow Chemical Co., Midland, Mich.

From Black & Veatch (12)

TABLE 4. AMPHIBOLE MASS AND FIBER REMOVAL BY DIATOMITE FILTRATION - DULUTH PILOT PLANT

Treatment Technique	NWQL Amphibole Mass Number of Samples: Total Analyzed	NWQL Amphibole Mass Number of Samples: ≤.005 mg/L	Ontario Research Foundation Amphibole Fibers Number of Samples: Total Analyzed	Ontario Research Foundation Amphibole Fibers Number of Samples: At or Near BDL*
Pressure filtration; two-step precoat, 1 gpm/sq ft				
Anionic polymer† to second step of precoat; alum & soda ash to body feed	1	1	1	1
Alum & soda ash to second step of precoat	6	6	6	3
Alum & soda ash to second step of precoat and to body feed	3	3	3	3
Cationic polymer# to raw water	5	5	5	5
Alum & soda ash to second step of precoat; cationic polymer# to raw water	3	3	3	3
Vacuum filtration; one-step precoat, 1 gpm/sq ft:				
Anionic polymer† to precoat	2	1	3	2
Vacuum filtration; two-step precoat, 1 gpm/sq ft:				
Anionic polymer† to total precoat	0	0	1	1
Anionic polymer† to second step of precoat	1	0	1	1
Anionic polymer† to second step of precoat; alum & soda ash to body feed	5	4	5	5
Alum & soda ash to second step of precoat	2	2	2	0
Alum & soda ash to second step of precoat and to body feed	2	2	3	2
Cationic polymer# to raw water	1	1	3	3
Alum & soda ash to second step of precoat; cationic polymer# to raw water	4	4	4	4

*At or near BDL (below detectable limits) is defined as $\leq 0.04 \times 10^6$ f/L.
†A-23, Dow Chemical Co., Midland, Mich.
#Catfloc-B, Calgon Corp., Pittsburgh, Pa.

From Logsdon and Symons (33)

Data in Tables 2-4 indicate that amphibole asbestos fibers can be removed readily by filtration. Additional evidence to confirm the efficacy of filtration was found in the amphibole mass data. Many of the filter runs that were sampled contained 0.005 mg/L or less in the filter effluent. Based on the amphibole mass concentration in the raw water, this represented amphibole mass reductions of tenfold to fortyfold. Treatment of the raw water with alum and a nonionic polymer was considered to be the most effective for amphibole fiber removal by granular media filtration. Techniques most effective for removing amphiboles by diatomaceous earth filtration involved conditioning the DE filter aid with alum or a polymer, or conditioning the raw water with cationic polymer. Pressure DE filtration was more effective than vacuum DE filtration, probably because air bubbles would form and collapse within the diatomite filter cake when the cold, highly oxygenated Lake Superior water experienced a pressure drop to less than one atmosphere in the pilot plant vacuum DE filter.

In late 1974 personnel from the Johns-Manville Research and Engineering Center performed DE filtration tests at Duluth. The results are described in a Johns-Manville report (34) that was prepared in response to the Interim Report on Water Supply for the Duluth-Cloquet-Superior Area (35). The Johns-Manville report indicates that diatomaceous earth filtration is very effective for asbestos fiber removal. Analysis by optical phase contrast microscopy at 1000 X showed that 99.80 and 99.93 percent removal of amphibole fibers with a length of 5 um or greater. These results, although limited in scope, agree with the other results from Duluth and elsewhere.

Reevaluation of chrysotile data--Both the project report prepared by Black & Veatch (12) and the analysis of fiber data by Logsdon and Symons (33) included data on chrysotile fibers, as well as on amphibole fibers. The data were reported in good faith by the electron microscope laboratory, and although the chrysotile counts were questioned at the time by EPA personnel working in Duluth, filtration researchers did not have enough fiber data from other sources to decide to discard or disregard the chrysotile data.

A more recent analysis of chrysotile data suggests they should be disregarded. Originally data were evaluated in groups according to the type of treatment, including treatment chemicals used. The basis for evaluation was to consider the number of filtered water samples with chrysotile equal to or less than 0.04×10^6 f/L. Raw water fiber counts were not considered. A new analysis of the chrysotile data takes into account recent Duluth and Seattle experience. The data in Table 5 are grouped according to whether or not filtered fiber counts are less than raw water fiber counts, with only those samples having filtered water turbidity of 0.10 ntu or less included. Seattle results showed consistent removal of chrysotile at this turbidity level but these data did not.

The hypothesis for analysis is that all data are random and filtered water fiber counts would be expected to be less than raw water counts for 50 percent of the observations. At the 0.05 level the hypothesis can not be rejected for any of pilot filter units employed at Duluth.

TABLE 5. COMPARISON OF RAW AND FILTERED WATER CHRYSOTILE DATA FOR DATA PAIRS WITH FILTERED WATER TURBIDITY EQUAL TO OR LESS THAN 0.10 ntu - DULUTH PILOT PLANT

Treatment Unit	Data Pairs	Comparison of Chrysotile Fiber Count Data		
		raw exceeds filtered	raw less than filtered	raw equals filtered
MM1 (granular media)	15	11	4	0
MM2 (granular media)	25	13	8	4
vacuum DE	3	0	3	0
pressure DE	17	8	7	2

In addition to the statistical analysis, other EM data support disregarding the earlier Lake Superior chrysotile data. Chrysotile fibers are seldom found by the University of Minnesota-Duluth laboratory (13) and by the EPA laboratory in Duluth. Therefore, chrysotile data from the Duluth pilot plant study are not presented in this report.

A number of publications resulted from the Duluth pilot plant study. Conclusions related to design and cost factors have been given by Robinson et. al. (36). A paper on DE filtration optimization has been presented by Baumann (37). EPA published the results of the pilot plant study (12). Logsdon and Symons published an analysis of the pilot plant performance data (33).

Filtration Plant Design and Construction

After the pilot plant research was completed, the City of Duluth hired Black & Veatch to prepare an engineering report on the design of a filtration plant. The consultant recommended building a gravity, granular media filtration plant with mixed media (tri-media) filters. In February, 1975 the City Council approved the report and authorized Black & Veatch to prepare plans and specifications of a 30 mgd plant (38). This was done during the spring and summer of 1975.

The City of Duluth worked through the Minnesota congressional delegation to obtain a demonstration grant for water filtration. The efforts were successful, and EPA awarded a $4,000,000 demonstration grant on October 6, 1975 (retroactive to June 27 of that year). This has been described by Peterson (39).

Construction progress was unusually rapid. Ground was broken in August,

1975. The plant dedication ceremony was held in 1976 at the end of November. Construction management techniques have been described by both Patton (38) and Peterson (39). The filtration plant, as dedicated in 1976, was a direct filtration plant providing rapid mixing and filtration. A basin used as a chlorine contact basin until November, 1976 was converted for use as a flocculation and sedimentation basin. The rebuilt basin was completed and put into use in the process flow stream in June, 1977. Patton described the plant in detail (38). A flow diagram for the plant, shown in Figure 1, reveals that an unusual amount of process flexibility exists at Duluth. Rapid mixing can be accomplished in three stages, chemical addition can be done at numerous locations, and any or all of the unit processes prior to filtration - rapid mixing, flocculation, and sedimentation - can be bypassed. Hydraulic information on the plant, as given by Patton, can be found in Table 6.

TABLE 6. PLANT HYDRAULIC INFORMATION - DULUTH

	Plant Design Rate (30 mgd)	Plant Overload Rate (36 mgd)
Rapid mix chambers		
Detention each, seconds	30	25
G value sec^{-1}	500	
Flocculation Facilities		
Detention, min	40	33
Sedimentation Facilities		
Detention, min	140	117
Surface loading rate, gpm/sf	1.1	1.3
Weir overflow rate, gal/lin ft/day	20,000	24,000
Filters		
Filtration rate, gpm/sf	4.9	5.9
Wash Water		
Design rise rate, in/min	30	-
Duration, min	10	-
Recovery storage, gal.	240,000	-
Wash water recovery facilities		
Detention, min	285	240
Surface loading rate, gpm/sf	0.5	0.6
Flocculation zone, min	30	25

From Patton (38)

The plant has four filters, each with 1067 square feet of surface area. Filtration rate is 4.9 gpm/sf at 30 mgd. Three filters have mixed media. For purposes of comparison, one filter has dual media. Surface wash was provided for all filters. Media specifications are given in Table 7.

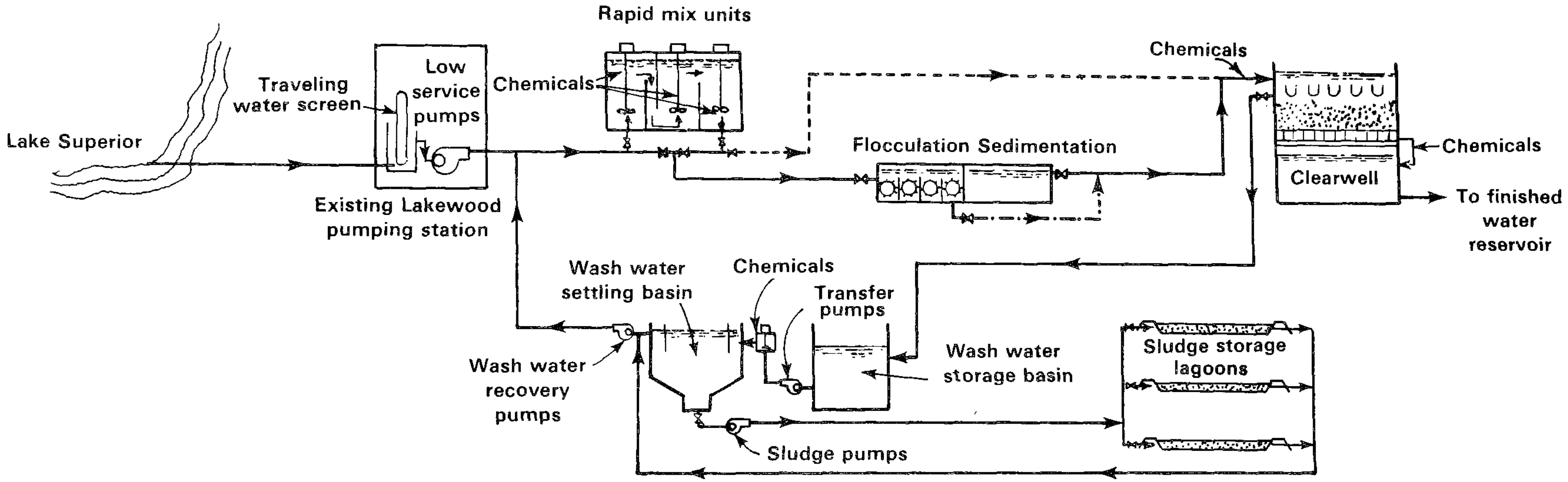


Figure 1. Flow diagram for filtration plant at Duluth, showing treatment train options.

From Logsdon (40)

TABLE 7. DULUTH FILTER MEDIA

	Depth	Size	Uniformity coefficient
Mixed Media			
Coal	16.5"	1.0-1.1 mm	1.7 max
Sand	9"	0.42-0.45 mm	1.35 to 1.70
Garnet	4.5"	0.21-0.32 mm	1.8 max
Dual Media			
Coal	21"	1.0-1.1 mm	1.7 max
Sand	9"	0.42-0.45 mm	1.35 to 1.70

Operating Results

Primary Coagulant, pH Control, and Polymers--

As a result of the pilot plant research, the plant was designed to use liquid aluminum sulfate as a primary coagulant with liquid sodium hydroxide for subsequent pH control, nonionic polymer for amphibole fiber removal and anionic polymer for chrysotile fiber removal.

Because EM analysis of water samples indicated no chrysotile fibers in raw or finished water, Duluth Filtration Plant personnel decided to discontinue the use of anionic polymers. After successfully eliminating the anionic polymer from pilot plant runs, it was eliminated on a trial basis in the main filter plant.

As a result of the pilot plant and full scale studies, anionic polymer is no longer used at the Filtration Plant. The water is conditioned with alum, and the nonionic polymer strengthens the floc so that turbidity breakthrough is less likely to occur.

Turbidity is monitored continuously at each filter. The continuous flow turbidimeters are used to detect changes in filter effluent quality. A laboratory turbidimeter is used to calibrate the flow-through turbidimeters and to obtain the daily filter plant effluent turbidity value that must be recorded to satisfy the Interim Primary Drinking Water Regulations.

Water Quality--

Monitoring--The Duluth filtration plant was built to remove asbestos fibers from Duluth drinking water. The water quality data collected since January, 1977 show that the plant performance has exceeded expectations. The operating goal at Duluth has been to produce the best possible filtered water quality. The plant consistently produces filtered water turbidities in the 0.04 to 0.06 ntu range, as shown in Figure 2. Turbidity of filtered water is almost always below 0.10 ntu except when changes in chemical feed or filtration rate cause higher turbidity. Raw water turbidity in Lake Superior at the Duluth intake was 1 ntu or less about ninety percent of the time from 1952 to 1972 (37).

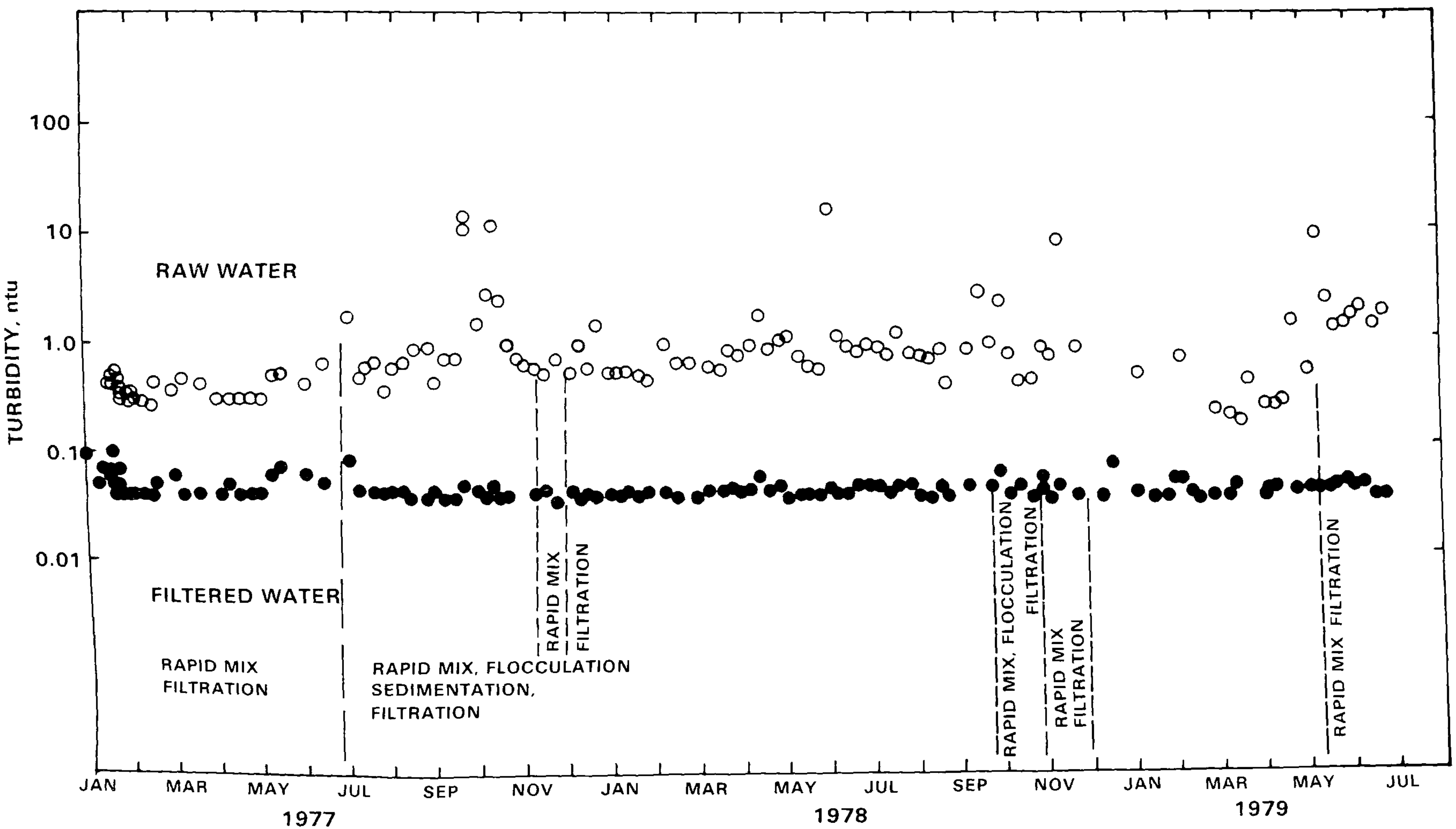


Figure 2. Lakewood filtration plant turbidity data

Raw and filtered amphibole fiber counts are shown in Figure 3. Filtered water amphibole fiber counts have consistently been below 0.1 X 10^6 f/L since the plant operation started. Monitoring data are tabulated and presented in Appendix A-1.

Amphibole fiber concentrations in filtered water were higher in January, 1977 than in later months. In fact, fiber counts through September, 1977 seem to be higher than subsequent counts. This trend may have occurred because as local personnel gained experience in their jobs they could improve plant operating techniques as well as electron microscope (EM) analysis techniques. Training operators in the finer points of plant operation at a specific plant might take a number of months. Also, eliminating little problems that usually occur in a totally new plant takes time. The lowest reported concentration for amphibole fibers decreased from 0.19 X 10^6 in January, 1977, to 0.067 in February, to 0.030 in May, and to 0.010 X 10^6 f/L in September. The lower concentrations were made possible by improved analytical procedures (analyzing a greater surface area of the sample grid) and by production of water with a fewer particulates (resulting in filtration of larger sample volumes for EM analysis).

Because progessive improvement in operating and analytical capabilities took place during the first year of operation, a comparison of direct filtration data and conventional treatment data should not be made with 1977 results. Determining how much improvement in water quality was caused by flocculation and sedimentation and how much was caused by the improvement of skills that occurred in the first nine months is not possible.

Results during storms--During the five months of pilot plant studies in 1974, the raw water turbidity did not exceed 5 ntu. A key question related to the efficacy of the filtration process when Lake Superior was turbid and amphibole fiber counts were on the order of one billion fibers per liter. In the fall of 1977, storms on Lake Superior caused raw water turbidity and asbestos fiber count to increase sharply. The efficacy of the filtration plant was tested twice when amphibole fiber counts were very high, and on both occasions plant performance exceeded expectations and confirmed the soundness of the plant design and the capabilities of plant operating personnel. Data obtained during the storms are shown in Table 8.

The treatment plant effectively removed as much as 99.996 percent of the asbestos fibers during storm conditions. Fiber removal was enhanced by adjusting the chemical feed after raw water quality had changed. The data show that maintaining adequate chemical dose is important to attain maximum fiber removal and to provide assurance that the plant is very effective for fiber removal during storms.

Distribution systems--Unfiltered water containing amphibole asbestos fibers was pumped into the Duluth distribution system for nearly twenty years. While the filtration plant was under construction, a program of water main flushing was carried out. Duluth has numerous water storage reservoirs in the distribution system. About three days' supply can be stored. This type of distribution system was developed in past years so that drinking water could be provided without pumping lake water when storms caused high turbidity.

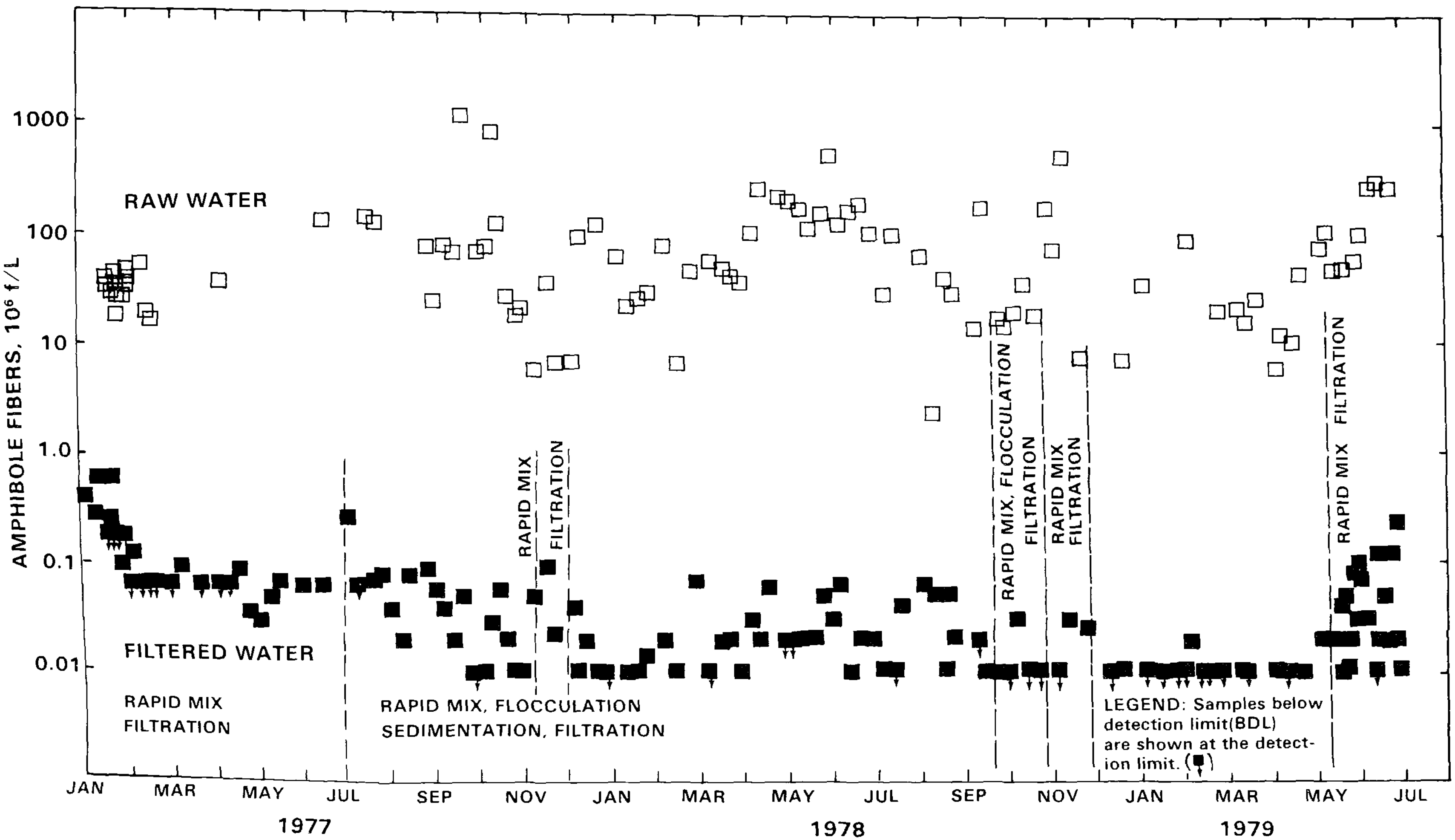


Figure 3. Lakewood filtration plant amphibole fiber data.

TABLE 8. DULUTH FILTRATION PLANT PERFORMANCE DURING STORMS

Date	Sample Description	Raw Water Turbidity ntu	Raw Water Amphibole Fibers 10^6 f/L	Filtered Water Turbidity ntu	Filtered Water Amphibole Fibers 10^6 f/L
9/19/77	Raw water	14.0	1200		
9/19/77	Filtered water			0.045	0.048
10/8/77	Raw water 8:30 pm	11.0	830		
	Filtered water 8:10 pm just before chemical feed adjustments			0.05	0.12
10/8/77	Filtered water midnight 3 1/2 hours after chemical feed adjustment			0.045	0.029

Flushing the reservoirs has been done as a part of normal distribution system operation. When the filter plant operation started, a substantial reduction of fibers took place, in the reservoirs, from hundreds or tens of millions, to less than ten million. In March, 1977 amphibole fibers were generally less than 1 X 10^6 in reservoirs. In April, 1979 amphibole fiber counts in the distribution system were similar to amphibole fiber counts of filtered water at the Lakewood plant. These results are summarized in Table 9.

Effects of rate changes on filtered water quality--When a change in filtration rate occurs, the quality of filtered water can also change. At Duluth, a number of circumstances bring about rate changes of different types. Some are related to filter backwashing, and others are caused by plant production changes.

Raw water pumps at Duluth have capacities of 20 mgd and 30 mgd, so the plant operates at one or the other of those flow rates. A 50 percent rate increase would occur if production was boosted from 20 mgd to 30 mgd (3.2 to 4.9 gpm/sf). Since the plant was built, Duluth water consumption has typically been less than 20 mgd. Thus the plant is operated on an intermittent basis, being shut down when additional water production is not needed. Starting the plant results in a rate increase of 0 to 3.2 gpm/sf. With flocculation and sedimentation basins in use, filter rate changes caused by production changes are gradual, because of the design of the sedimentation basin effluent collectors. These changes are considerably more abrupt when the treatment process consists of rapid mixing followed by filtration.

When one filter is removed from service for backwash, the other three filters experience a 33 percent rate increase (3.2 to 4.3 gpm/sf) in a 30 to 60 second time period. After backwashing is completed, the clean filter is returned to service. This causes a very rapid rate increase in the clean filter.

TABLE 9. AMPHIBOLE FIBER CONCENTRATIONS IN DULUTH DISTRIBUTION SYSTEM RESERVOIRS

Reservoir	Distance from Plant	1977 2/11 10^6 f/L	1977 3/10 10^6 f/L	1977 3/17 10^6 f/L	1977 3/22 10^6 f/L	1977 10/25 10^6 f/L	1978 6/08 10^6 f/L	1978 9/19 10^6 f/L	1979 4/30 f/L
"A"	Nearest	0.61	N.T.	0.36	0.32	0.15	BDL(0.032)	0.22	N.T.
Endion		1.8	0.21	0.11	3.0	0.27	N.C.	0.11	0.13
Woodland		3.4	0.21	0.16	BDL(0.48)	BDL(0.87)	0.024	0.17	0.09
Highland		N.T.	1.2	1.3	1.3	BDL(0.12)	N.C.	0.13	0.04
Middle		9.7	N.T.	0.50	0.50	1.2	0.048	0.095	0.02
W. Duluth	Farthest	4.4	0.42	N.T.	0.48	1.4	N.C.	0.21	BDL (0.019)

N.T. - no sample taken
BDL - below detectable limits (detection limit in parentheses)
N.C. - sample could not be counted because of excessive debris

Data have been collected for various types of filter rate changes. Work on this is not yet completed. Data obtained and reported by the Duluth Department of Water and Gas are presented in the Appendix A-2. Data used to evaluate water quality changes were filtered water turbidities and amphibole fiber counts. Quality of the water after filter rate changes was compared to quality before the rate change occurred. Results in Appendix A-2 suggested that fiber count and turbidity generally increase only slightly when a clean filter is started after it is backwashed.

At Duluth, because all backwash water is discharged to a washwater treatment plant, operating practice is to shut down the plant without washing all filters immediately before treatment stops. On a few occasions, filters were restarted at head losses of greater than 6 feet. This resulted in much higher fiber counts in the filtered water for a brief period (less than on hour) on two occasions.

Additional work

Studies of plant performance and monitoring of water quality for asbestos fiber concentration will continue at Duluth into mid-1980, at which time the research requirements for the demonstration grant should be met.

OTHER NORTH SHORE PLANTS

In addition to Duluth, a number of other communities along the Lake Superior shore were affected by the taconite tailings discharge at Silver Bay. Of these, Silver Bay and Two Harbors have built water filtration plants. Construction was being completed on the filtration plant at Beaver Bay during the summer of 1979, so no data are included for Beaver Bay.

Before comparisons of water quality at filtration plants in Duluth, Two Harbors and Silver Bay are made, the nature of Lake Superior currents and their effect on water quality needs to be explained. Along the north shore of Lake Superior, in the western portion of the lake, the current in the lake flows from the northeast, past Silver Bay, then Two Harbors, and then past the Duluth intake. The current turns at the head of the lake at Duluth, Minnesota and Superior, Wisconsin, and flows along the shore past northern Wisconsin and the Upper Peninsula of Michigan. The current flows past the Silver Bay intake before tailings from the Reserve Mining Company are dumped into Lake Superior. The Silver Bay intake is close enough to Reserve's flume to be affected, but amphibole fiber counts at Silver Bay tend to be lower than counts at Two Harbors or Duluth. Because Two Harbors is closer to Reserve's flume than Duluth, amphibole fiber counts are higher at Two Harbors. Raw water quality at all three plants is similar, but fiber counts differ for the above reason.

Two Harbors

The two Harbors plant is a 2.6 mgd direct filtration plant designed by RREM, Inc. It employs two-stage rapid mix, two-stage flocculation, and filtration through mixed media. A flow diagram is shown in Figure 4. Plant hydraulic information is given in Table 10. The plant has three filters,

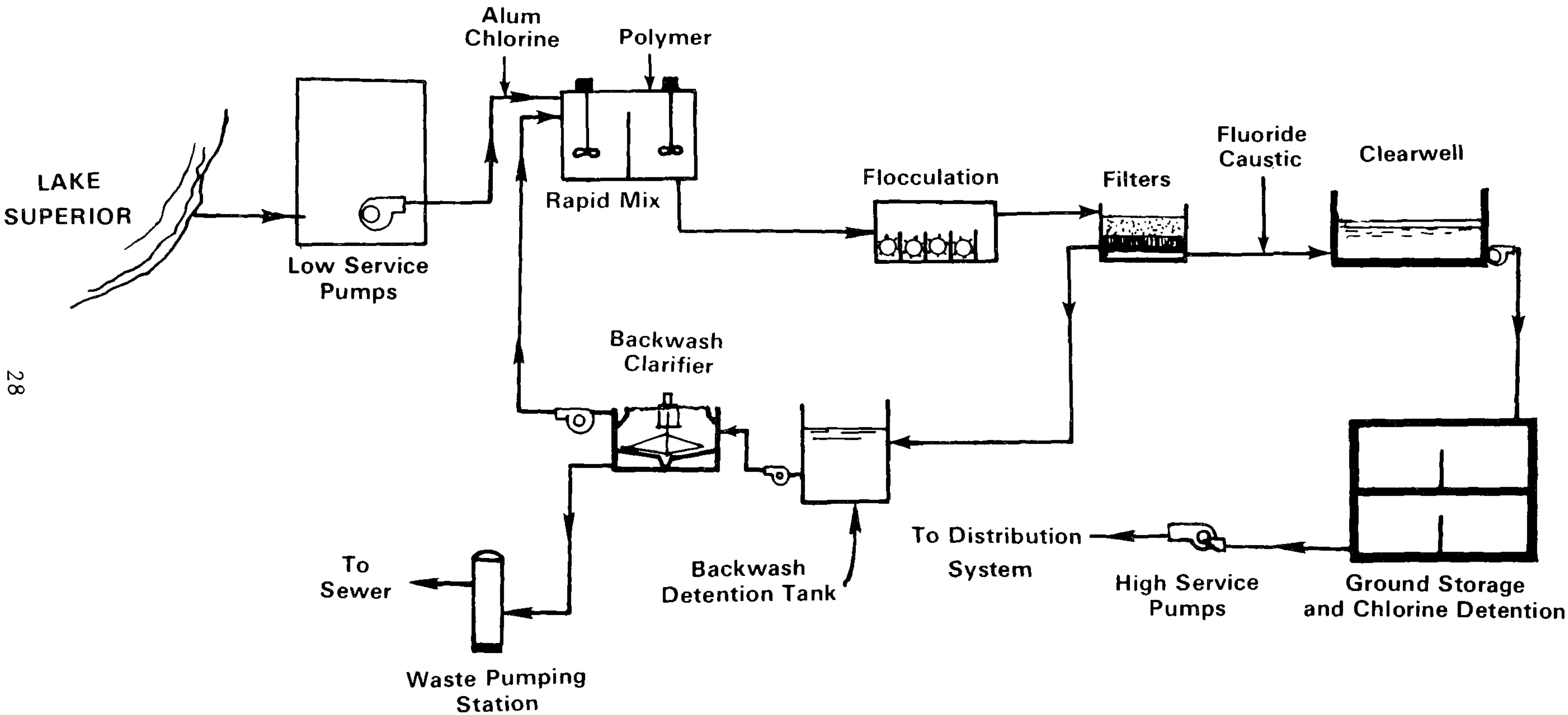


Figure 4. Flow diagram for filtration plant at Two Harbors.

each with 150 square feet of surface area. Media design is given below:

Material	Specification	Depth
Coal	Neptune - Microfloc MS - 4	16.5"
Sand	Neptune - Microfloc MS - 6	9.0"
Illmenite	Neptune - Microfloc MS - 21	4.5"

The Two Harbors filtration plant design was based upon results from the Duluth pilot plant study. The plant uses alum and a nonionic polymer to condition the water for filtration. Both of these chemicals are added at the rapid mixers. Caustic soda is added in the clearwell to adjust pH before the water is pumped to the distribution system. Turbidity is monitored continuously at each filter, and grab samples are taken periodically so that turbidity can also be measured with a laboratory turbidimeter.

TABLE 10. PLANT HYDRAULIC INFORMATION - TWO HARBORS

	Plant Design Rate, 2.6 mgd
Rapid mix chambers (4)	
(2 in series each side)	
Total detention time, minutes	4.2
Flocculation basins (4)	
(2 in series each side)	
Total detention time, minutes	20
Filters (3)	
Filtration rate, gpm/sf	4
Wash water	
Design rate, gpm/sf	15
Duration, minutes	10

The plant at Two Harbors was started early in 1978. Two Harbors obtained some money for construction from the State of Minnesota, but an extensive water quality monitoring program of the type undertaken at Duluth was not possible. Therefore, only a limited amount of data on fiber removal at Two Harbors is available. The results obtained to date are given in Table 11. Filtered turbidity at Two Harbors generally ranges from 0.10 to 0.20 ntu, and fiber counts typically have been from 0.4 to 2 X 10^6 f/L. These values are somewhat higher than the values for Duluth and Silver Bay, although they were taken with a different instrument and may not be comparable. Substantial reductions in fiber count are consistently attained.

TABLE 11. TWO HARBORS AMPHIBOLE DATA

Date	Lab	Raw Water Turbidity ntu	Raw Water Fibers 10^6 f/L	Filtered Water Turbidity ntu*	Filtered Water Fibers 10^6 f/L	Percent Reduced Turbidity	Percent Reduced Fibers
4/28/78	EPD	0.6	141	-	-	-	-
5/15/78	MDH	1.2	44	0.14	0.43	88	99.0
6/22/78	MDH	1.0	111	0.16	0.80	84	99.3
6/27/78	EPD	0.78	200	-	-	-	-
7/3/78	EPD	1.3	177	-	-	-	-
7/18/78	EPD	1.5	84	0.10	1.6	93	98.1
7/27/78	MDH	0.8	19	0.15	0.56	81	97.1
8/1/78	EPD	1.0	53	0.20	2.3	80	95.7
9/1/78	EPD	0.66	356	0.10	0.45	85	99.9
9/7/78	MDH	1.0	22	0.15	< 0.07	85	> 99.7
10/6/78	EPD	1.2	61	0.14	1.9	88	96.9
1/9/79	MDH			0.13	0.37		
6/26/79	MDH	0.96	65	0.14	0.28	85	99.5

EPD = EPA-Duluth MDH = Minn. State Health Dept. *May not compare with Duluth and Silver Bay

Silver Bay

The Silver Bay treatment plant was modified and put into service in its present configuration in May, 1978. The filters, clearwell, and both low lift and high left pumping facilities existed before the modification. New facilities added in 1978 were rapid mixing and flocculating basins as well as chemical feed and storage facilities. A schematic diagram of the modified plant is shown in Figure 5. Design information for the plant from RREM, Inc., is given in Table 12. The plant has dual media filters, with 15 inches of 1.16 mm effective size coal (U.C. = 1.43) and 15 inches of 0.45 mm effective size sand (U.C. = 1.41).

Amphibole fiber and turbidity data for the Silver Bay plant are given in Table 13. Because of the circulation pattern in Lake Superior, raw water fiber counts at Silver Bay are lower than counts at Two Harbors and Duluth. The limited amount of data available indicate that the Silver Bay plant is effective in removing amphibole fibers from water.

Future North Shore Activity

Additional monitoring for amphibole fibers is planned for Two Harbors and Silver Bay. Monitoring will also be done at the Beaver Bay plant to determine amphibole fiber concentrations in filtered water at the plant most influenced by the tailings discharge from the Reserve Mining Company.

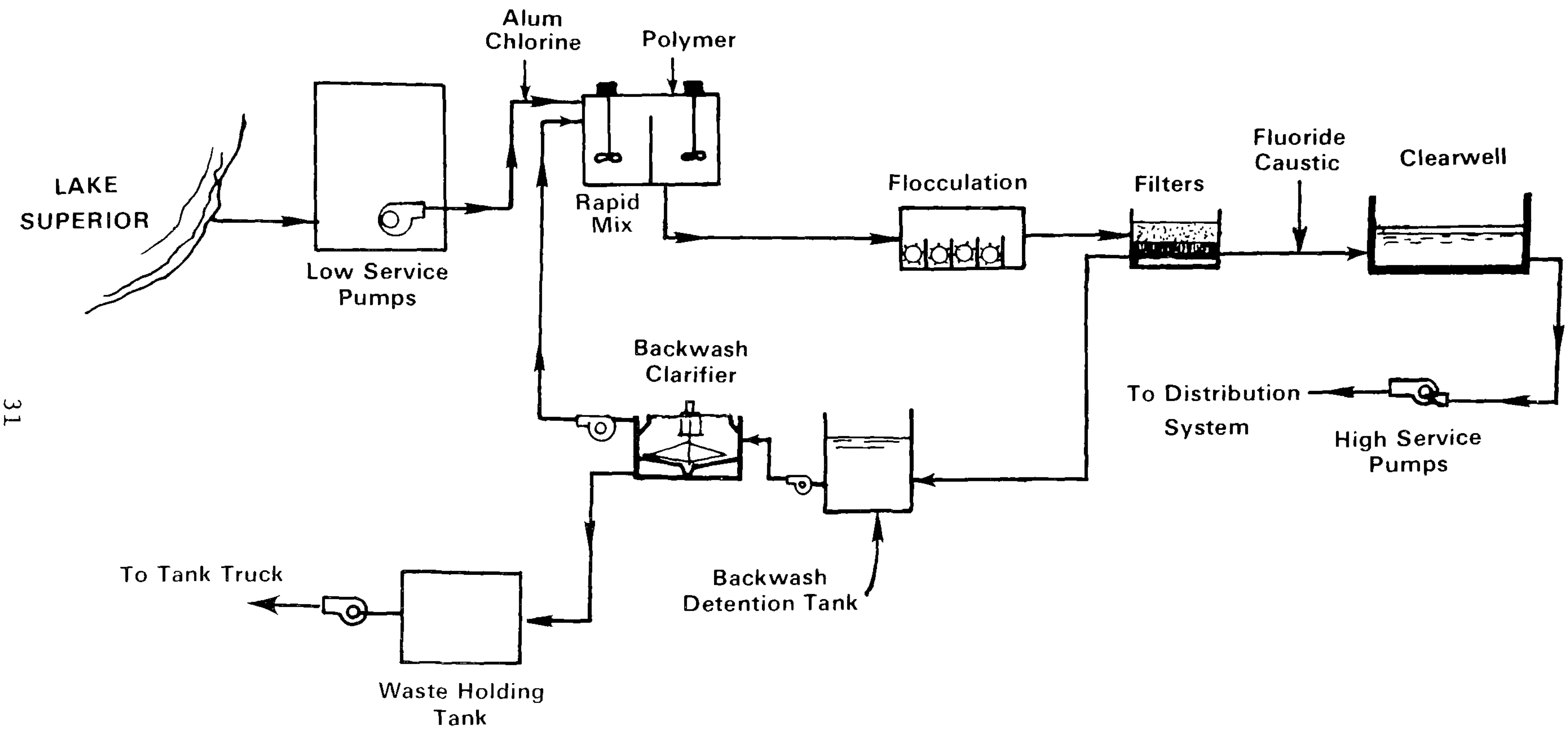


Figure 5. Flow diagram for filtration plant at Silver Bay.

TABLE 12. PLANT HYDRAULIC INFORMATION - SILVER BAY

	Plant Design Rate, 2.3 mgd
Rapid mix chambers (4)	
(2 in series each side)	
Total detention time, minutes	8.1
Flocculation basins (4)	
(2 in series each side)	
Total detention time, minutes	40.5
Filters (2)	
Filtration rate, gpm/sf	2.6
Wash water	
Design rate, gpm/sf	7.4
Duration, minutes	7

TABLE 13. SILVER BAY AMPHIBOLE DATA

Date	Lab	Raw Water Turbidity ntu	Raw Water Fibers 10^6 f/L	Filtered Water Turbidity ntu	Filtered Water Fibers 10^6 f/L	Percent Reduced Turbidity	Percent Reduced Fibers
6/22/78	MDH	0.41	25.3	0.05	0.18	88	99.29
7/27/78	MDH	0.41	8.4	0.05	< 0.13	88	> 98.4
9/5/78	MDH	0.32	1.8	0.07	< 0.13	78	> 92.8
1/9/79	MDH	-	-	0.05	0.18	-	-
6/26/79	MDH	0.28	14.3	0.06	0.33	79	97.7

SECTION 6

SEATTLE PILOT PLANT STUDY

In 1975 amphibole and chrysotile fibers were found in the South Fork Tolt Reservoir, which supplies up to 100 mgd to a portion of the Seattle metropolitan area. The clear, clean mountain water is distributed to consumers after screening, disinfection and fluoridation. After the fibers were discovered, the Seattle Water Department applied for and received a research grant to study filtration of the Tolt water. Results of this work were summarized by Kirmeyer et. al. (41). The following section is adapted from Kirmeyer's report (42).

DESCRIPTION OF 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.

Study Objectives

The formal objective of the Seattle research effort was to determine the most feasible method for reducing asbestos 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 (12).

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.

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 Asbestos 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.

MATERIALS AND METHODS

Pilot Plant Equipment

The pilot study was conducted on a 20 gallon per minute (gpm) (WB-27) package plant, manufactured by Neptune Microfloc, Inc. The unit was installed in the chlorine room at the Tolt Regulating Basin. Because 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 package plant filter.

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.

Modifications of Equipment--

Because the unit was to be used as a pilot plant, the manufacturer 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 6 illustrates the possible flow schematics and Table 14 lists pertinent dimensions.

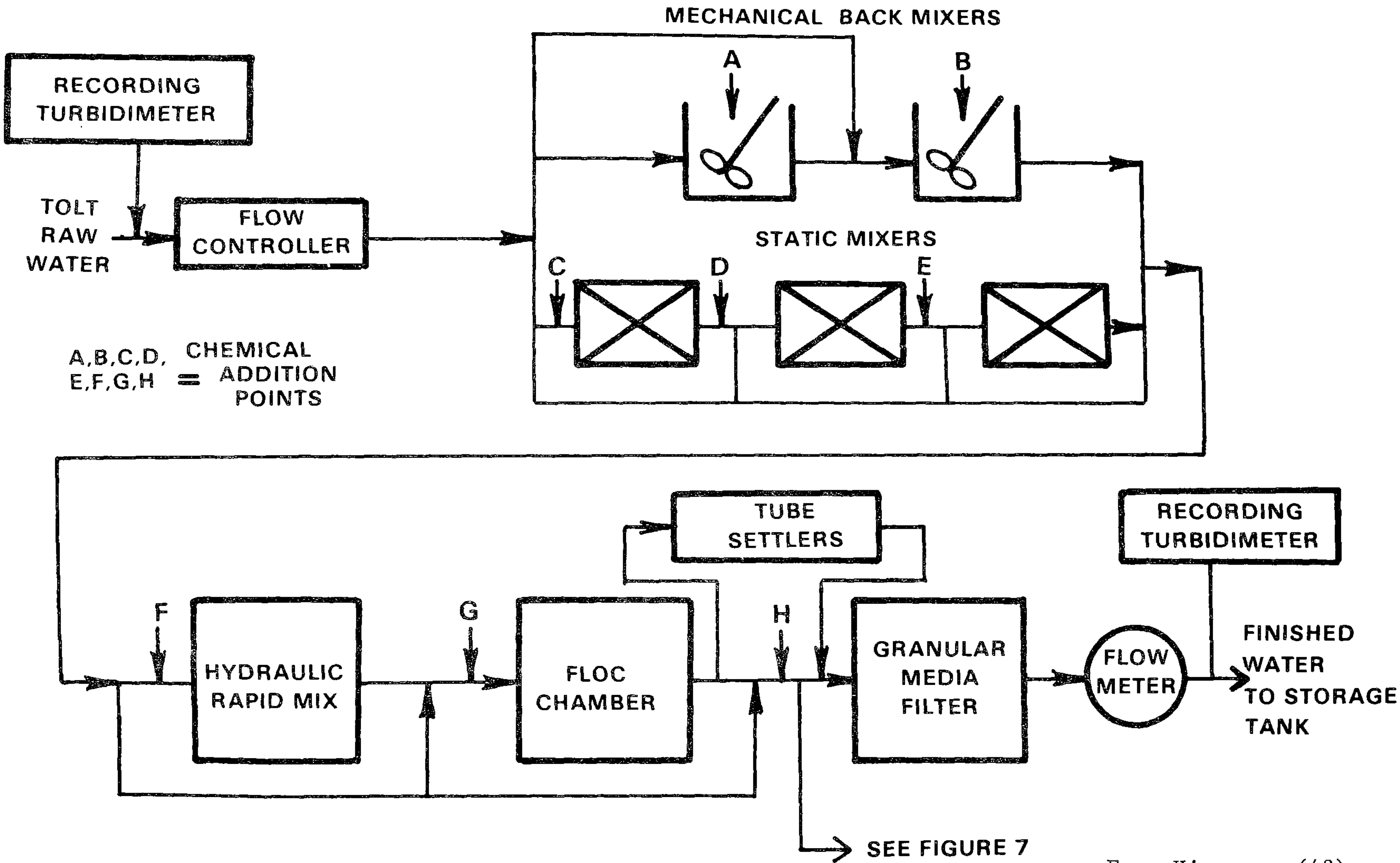
Three 2-inch static mixers were installed with the unit. Mechanical mixers and 55-gallon drums were also part of the flexible treatment train. Water would flow under pressure into the first drum and then could discharge by gravity into a second drum or into any other unit process in the treatment train.

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.

Early in the pilot studies, air binding in the package plant 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.

To remedy this situation, three 4 1/4-inch diameter filter columns were installed in the basement of the Regulating Building (see Figure 7). A small stream of water was diverted from the plant, above the filter 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.



From Kirmeyer (42)

Figure 6. Pilot plant flow schematic — Seattle.

TABLE 14. DIMENSIONS OF UNIT PROCESSES - SEATTLE PILOT PLANT

Unit Process	Length	Width or Diameter	Depth	Volume	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	0.28 m^3 10 ft^3	4.7 min
Mechanical Back Mixing Chamber	N/A	58.4 cm 23 in	71 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; N/A = not applicable; m^3 = cubic meter; min = minute
cm^3 = cubic centimeter; gal = gallon; in = inch; sec = second
m = meter; ft^3 = cubic foot

From Kirmeyer (42)

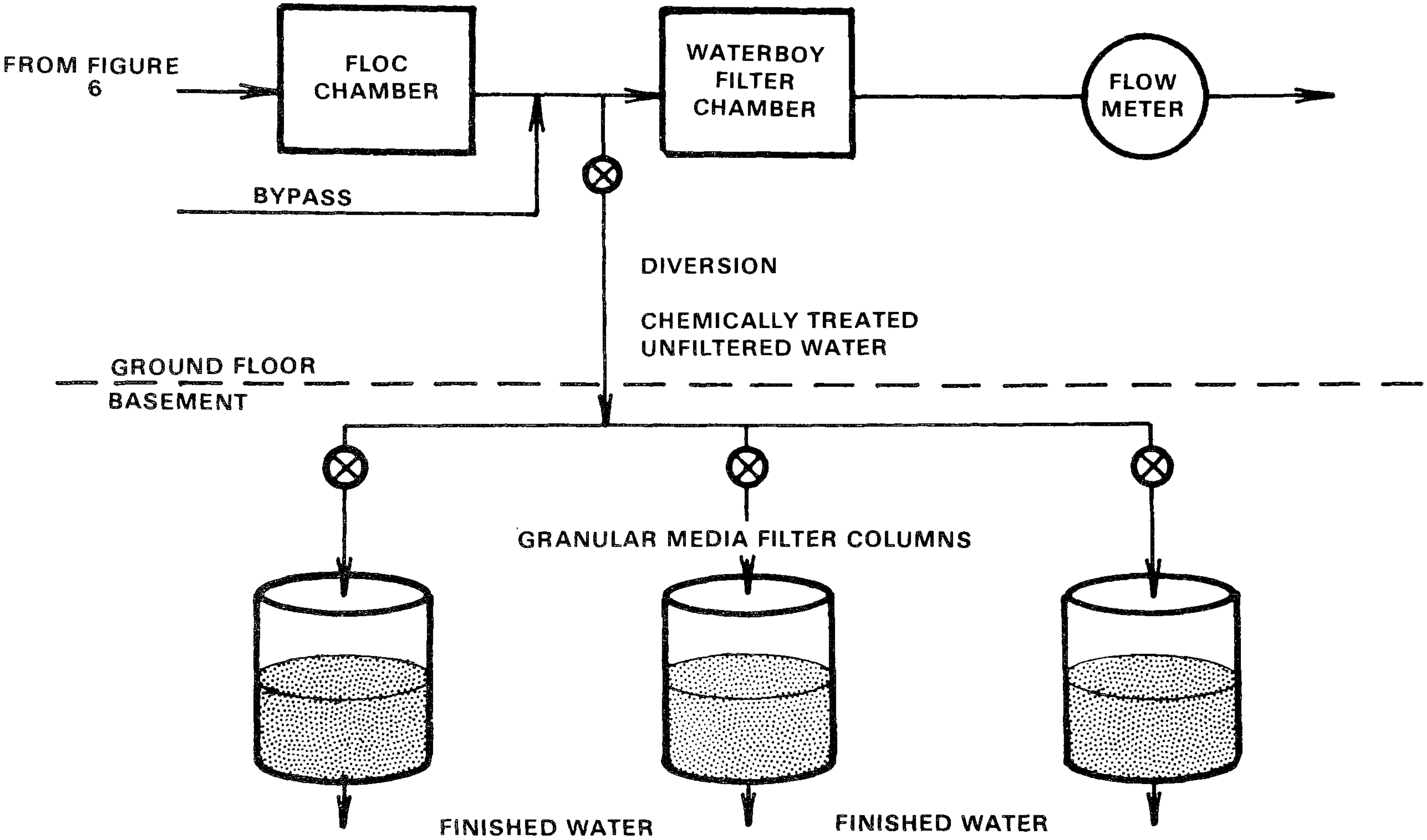


Figure 7. Flow diagram for filter columns — Seattle pilot plant.

From Kirmeyer (42)

Having three columns in parallel also allowed comparisons to be made among three different types of filter media at one time.

Mixing Intensities--

Mixing intensities for each unit process were estimated using both field data and empirical calculations. The data are tabulated and presented in Tables 15 and 16. Detailed information on velocity gradient calculations and measurements can be found in the EPA report written by Kirmeyer (42).

TABLE 15. VELOCITY GRADIENT DATA - SEATTLE PILOT PLANT

Unit	Calculated G sec^{-1}	Measured G sec^{-1}	Gt at 20 gpm
Rapid mix on WB-27	203	-	57,000
External rapid mixers using 1/3 HP motor and baffled 55 gallon drums			
with 2 propellors	-	1050	195,000
with 3 propellors	-	1300	245,000
Kenics static mixer 2" diameter*	-	1990	1,450

*A product of Kenics Corporation, Danvers, Mass.

Filter Media Tested-

Four different types of filter media were evaluated during the pilot tests. The characteristics of each as supplied by the manufacturer are presented in the Table 17.

Sampling and Analysis

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 (43) (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.

During normal filtration runs, turbidity information was taken directly from in-line turbidimeters. When asbestos samples were gathered, turbidity analysis was performed directly on a portion of each individual water sample using the laboratory 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 were calibrated against the laboratory turbidimeter, which was calibrated using formazin standards.

TABLE 16. MIXING INTENSITIES FOR FLOCCULATOR - SEATTLE PILOT PLANT

Flocculator Rheostat Percent	Paddle RPM	Tip Velocity ft/sec	Empirical Calculations G, sec^{-1}	Empirical Calculations GT*	Transducer Output (Tq) Without Water ft - lb	Transducer Output (Tq) With Water ft - lb	Transducer Output (Tq) Avg Net Output ft - lb	Torque Meter Data G, sec^{-1}	Torque Meter Data 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.

From Kirmeyer (42)

TABLE 17. CHARACTERISTICS OF MEDIA TESTED - SEATTLE PILOT PLANT

	Effective Size (mm)	Uniformity Coefficient	Thickness inches	Effective Size (mm)	Uniformity Coefficient	Thickness inches
	Neptune Microfloc Mixed Media*					
	Type MM			Type CMM		
Anthracite Coal	1.0 - 1.1	1.7	18	1.0 - 1.1	1.7	21
Sand	0.42 - 0.55	1.8	9	0.42 - 0.52	1.4	7
Fine Garnet	0.18 - 0.32	2.2	3	0.18 - 0.32	2.2	2
	Turbitrol Dual Media†					
	Type FC			Type CC		
Anthracite Coal	0.92	1.28	20	1.1	1.31	20
Sand	0.40	1.30	10	0.40	1.30	10

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

*Neptune Microfloc, Corvallis, Ore.
†Taulman Co., Atlanta, Georgia

From Kirmeyer (42)

Early in the pilot studies, air bubbles that 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 that led to the recording turbidimeters.

Asbestos fiber count of the water samples was determined by the transmission electron microscope method as recommended by EPA (44). Analytical work was done by the University of Washington School of Public Health.

STUDY RESULTS

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 water quality characteristics, as shown in Table 18.

TABLE 18. RAW WATER QUALITY CHARACTERISTICS - SEATTLE

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 X 10^6 - 5.7 X 10^6 fibers/liter; Average = 1.6 X 10^6 fibers/liter
Chrysotile	Range 1.2 X 10^6 - 25.8 X 10^6 fibers/liter; Average = 7.1 X 10^6 fibers/liter

From Kirmeyer (42)

Turbidity--

Turbidity exceeds the Seattle Water Department's 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 became effective in June of 1977.

Asbestos Counts--

Table 19 lists the results of both raw water amphibole and chrysotile counts which were gathered during the study. 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.

TABLE 19. RAW WATER ASBESTOS COUNTS - SEATTLE PILOT PLANT

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	$< 0.29(10^6)$(BDL)	$8.40(10^6)$
June 9, '77	53	0.50	$0.70(10^6)$(NSS)	$3.60(10^6)$
June 29, '77	62	0.35	$< 0.12(10^6)$(BDL)	$2.52(10^6)$
July 13, '77	70	0.35	$< 0.07(10^6)$(BDL)	$2.81(10^6)$
Sept. 2, '77	89	0.35	$< 0.05(10^6)$(BDL)	$1.20(10^6)$
Oct. 6, '77	93	0.38	$< 0.07(10^6)$(BDL)	$3.60(10^6)$
Nov. 7, '77	108	0.55	$< 0.14(10^6)$(BDL)	$3.61(10^6)$
Nov. 16, '77	111	0.85	$< 0.14(10^6)$(BDL)	$4.62(10^6)$
Jan. 12, '78	120	3.30	$0.19(10^6)$(NSS)	$5.38(10^6)$
Jan 12, '78	120	3.40	$< 0.10(10^6)$(BDL)	$11.56(10^6)$
Feb. 14, '78	135	1.80	$< 0.07(10^6)$(BDL)	$3.90(10^6)$
June 8, '78	161	0.30	$< 0.04(10^6)$(BDL)	$2.00(10^6)$
Sept. 4, '78	174	0.36	$0.07(10^6)$(NSS)	$1.84(10^6)$

BDL = Below Detectable Limits
NSS = Not Statistically Significant

From Kirmeyer (42)

Amphibole fibers range in length from 0.3 to 7.5 microns and counts have ranged from $<0.04 \times 10^6$ 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. Chrysotile 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.

Filtered Water Quality

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 (12). 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. Because EPA had set no standard for asbestos levels in drinking water at the time of the Seattle study, the water quality goals were selected by the Seattle Water Department.

Alum Coagulation--

The first treatment technique tried for conditioning the water for filtration was alum coagulation. Lime was used for pH control. With an alkalinity of only 5 mg/L as $CaCO_3$, the water was very sensitive to both alum and lime addition, and numerous filter runs did not meet water quality goals because of a slight under or over feed of lime. The problem persisted so 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. 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.)

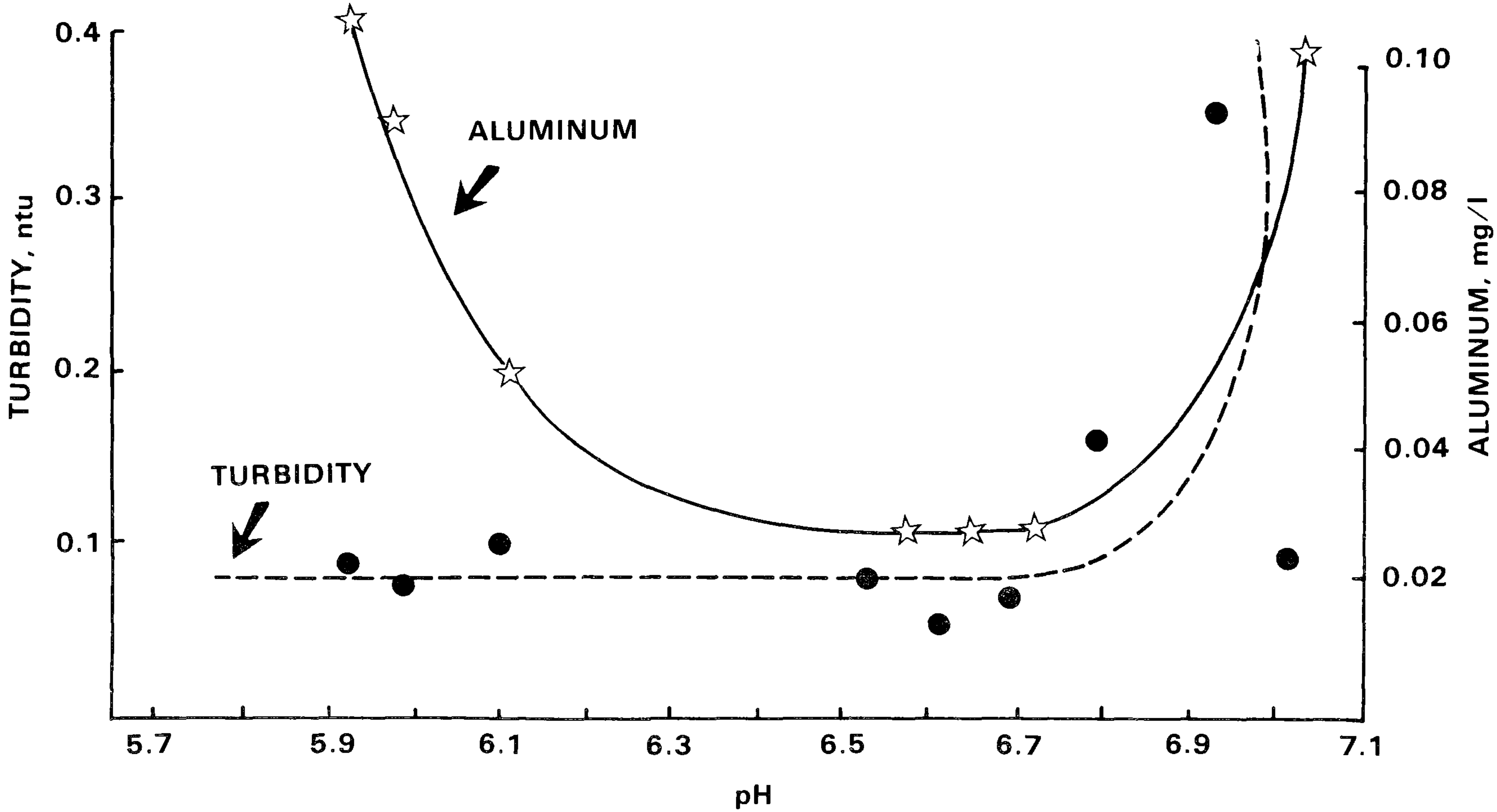
To determine minimum dosages for effective turbidity removal, several filter runs were conducted at dosages ranging from 3 to 10 mg/L. The information from these runs is summarized in Figure 9.

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 20.

TABLE 20. SEATTLE PILOT PLANT 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

From Kirmeyer (42)



From Kirmeyer (42)

Figure 8. Finished water turbidity and aluminum residual vs. pH — Seattle pilot plant.

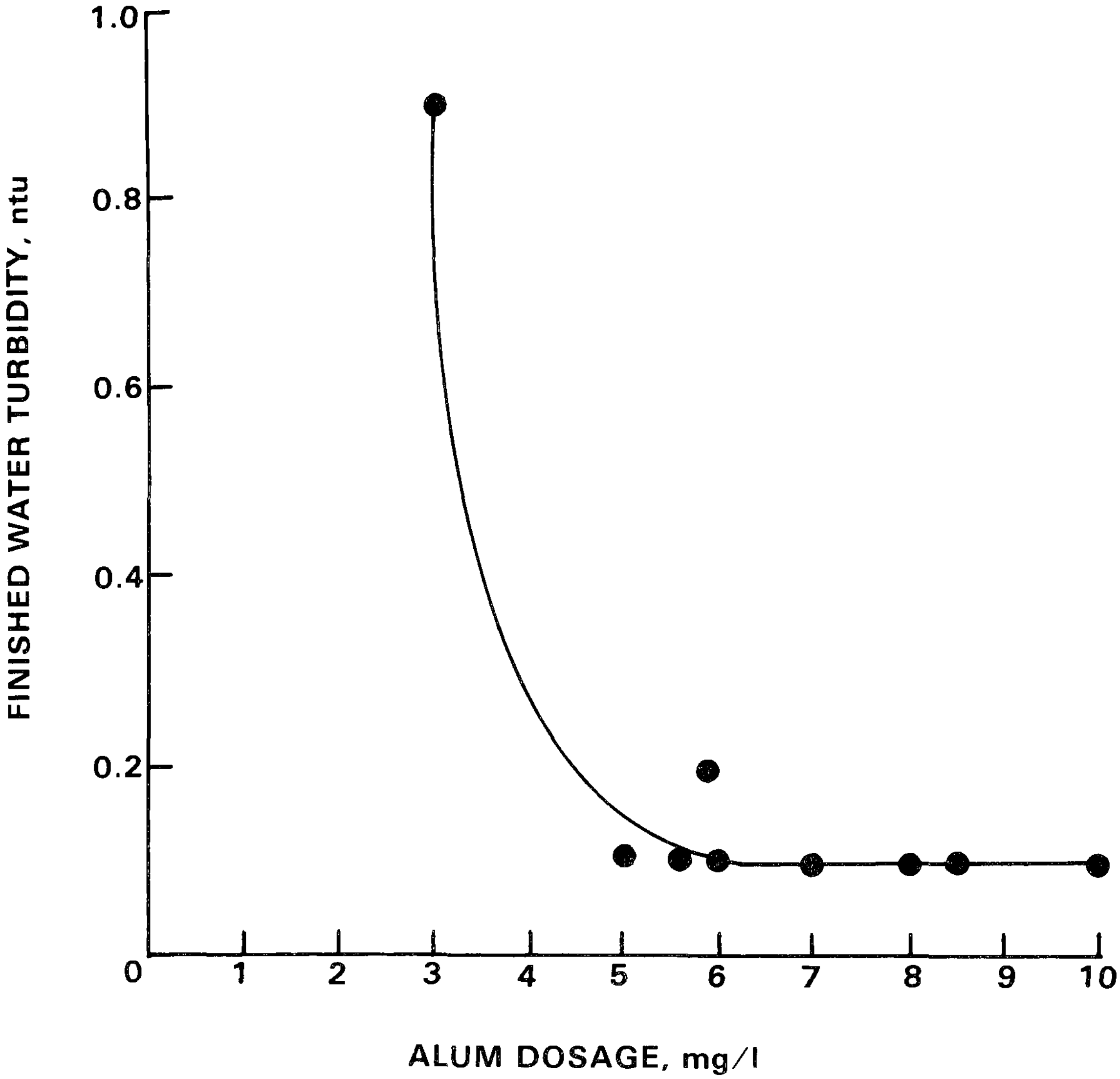


Figure 9. Finished water turbidity vs. alum dosage — Seattle pilot plant

From Kirmeyer (42)

Alum and Cationic Polymer--

One of the objectives of the study 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 21.

TABLE 21. ALUM AND LIME DOSAGE VS. CATIONIC POLYMER DOSAGE - SEATTLE PILOT PLANT

Alum Dosage mg/L	CATFLOC T-1* Dosage mg/L				
2	0.2	0.4	0.8	1.6	3.2
4	0.2	0.4	0.8	1.6	3.2
8 + Lime	0.2	0.4	0.8	1.6	3.2
16 + Lime	0.2	0.4	0.8	1.6	3.2

*Calgon Corporation, Pittsburgh, Pa. From Kirmeyer (42)

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 for 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. Because 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, two filter runs 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 in two other runs prevented breakthrough from occurring until terminal headloss was reached. Table 22 shows the preferred doses for alum and polymers.

TABLE 22. SEATTLE PILOT PLANT 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

†American Cyanimid, Wayne, N.J. From Kirmeyer (42)
#Dow Chemical Co., Midland, Mich.

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.

As indicated in Tables 23 and 24 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 chemical 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.

TABLE 23. CATFLOC T-1 DOSAGES AND TURBIDITY - SEATTLE PILOT PLANT

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

*Calgon Corporation, Pittsburgh, Pa. From Kirmeyer (42)

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. Note, ferric chloride results were not encouraging at Duluth either.

Evaluation of Unit Process and Treatment Train Variations

Several aspects of pretreatment and the filtration process were investigated to determine their influence on both asbestos fiber removal and treatment cost. Rapid mixing and flocculation were evaluated. Four different

†American Cyanamid, Wayne, N.J.

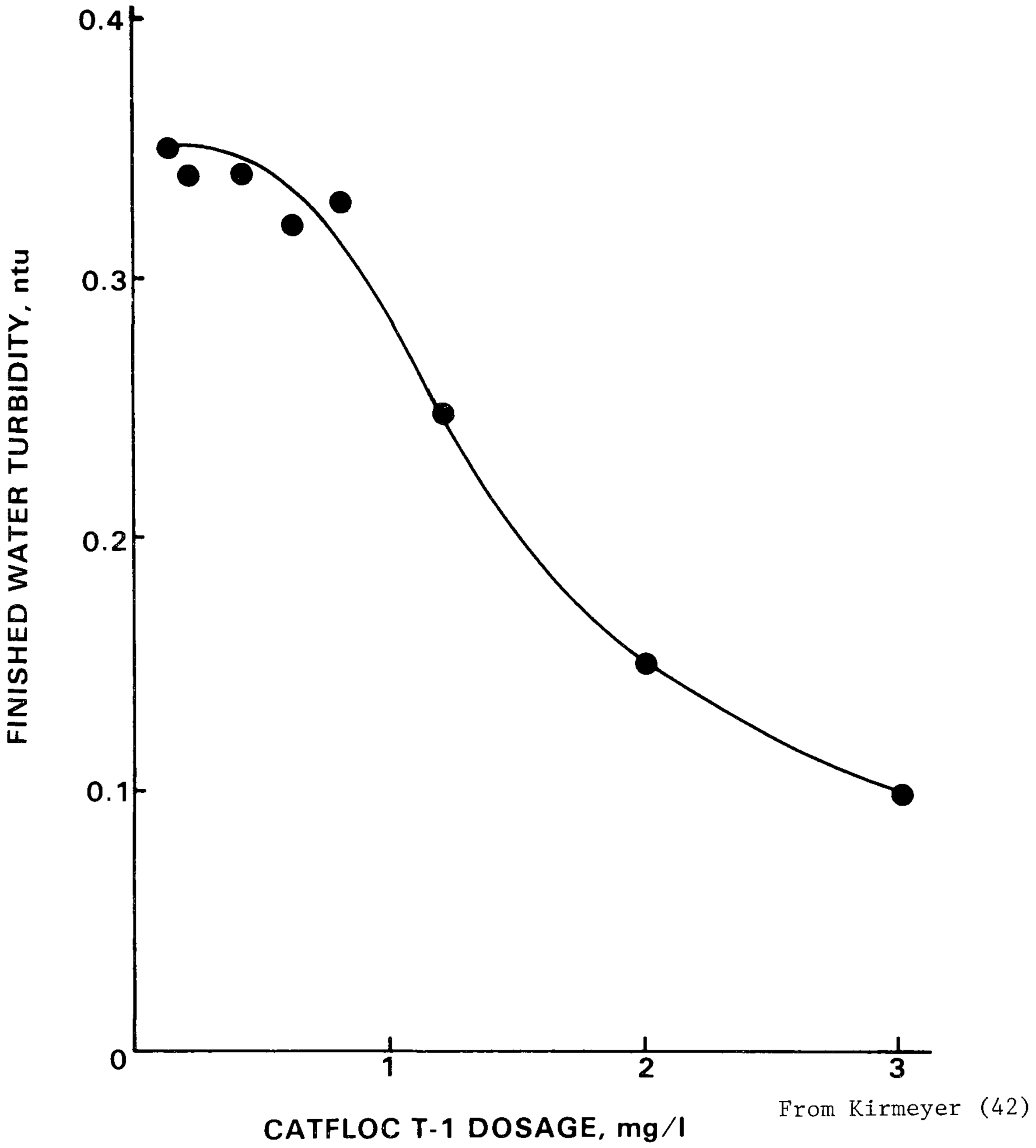


Figure 10. Finished water turbidity vs. Catfloc dosage – Seattle pilot plant.

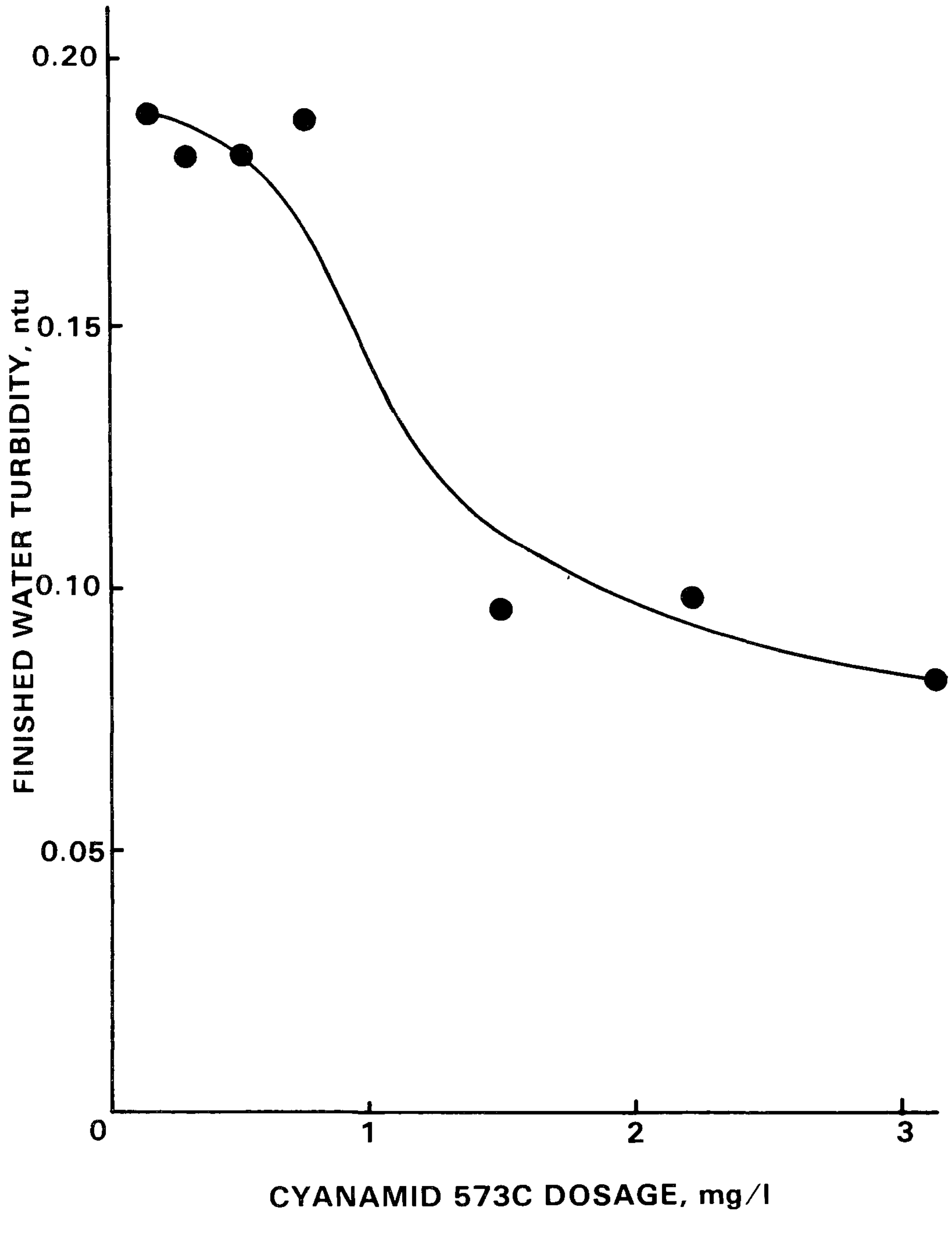


Figure 11. Finished water turbidity vs. 573C dosage Seattle pilot plant.

From Kirmeyer (42)

TABLE 24. 573C DOSAGES AND TURBIDITY - SEATTLE PILOT PLANT

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

†American Cyanamid, Wayne, N.J. From Kirmeyer (42)

filter medias were used during the research, and a wide range of filtration rates was employed. Data were obtained for both fixed rate and declining rate modes of filtration.

Water Production Efficiencies--

A major factor in determining the cost of a filtration plant is the surface area of the filters. Filter surface area needed for production of a given amount of water in a day's time is a function of filtration rate and production efficiency. Three different methods, Unit Filter Run Volume (UFRV), Percent Efficiency, and Net Water Produced per 24 Hours were used by Kirmeyer (42). Each method involves a somewhat different approach to evaluation of filter efficiency.

In this report, net water production was evaluated. This was defined as the amount of usable water produced per unit surface area of a filter per 24 hours. Net water produced includes corrections for water used during backwash and for production lost during the time of the backwash cycle. This was Net Water Produced per 24 Hours as calculated by Kirmeyer. For this report a correction was also made for water above 0.10 ntu produced at the beginning of a filter run during the filter ripening period that should be filtered to waste. The formula is:

$$NP = (LR \times 1440)(h/H) - NBW[BW + (LR \times T)]$$

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 = 24/H

BW = Amount of backwash water used (200 gallons per ft^2 per backwash, for Seattle data analysis)

T = Time, 15 minutes down time per backwash

h = Hours of production of water with turbidity $\leq$ 0.10 ntu

H = Length of run to termination or turbidity of 0.2 ntu, hours

Because production of water with a turbidity of 0.10 ntu or less was a goal of this study, water with higher turbidity was not included as net water produced, even though filter run length was taken as time from start of run to termination or 0.2 ntu turbidity in the filtered water. The calculation is made as if the plant operated in a filter-to-waste mode when turbidity was high at the start of a filter run.

The amount of water used per backwash was estimated at 200 gallons by Kirmeyer (42), because the filters used in the pilot plant study were too small to yield backwash data that would be representative of performance at a large filtration plant. Actual backwash water used could vary with different treatment modifications, particularly coagulant chemicals used (alum vs. polymer), filter media sizes and filtration rate, so the limitations of this concept should be kept in mind as it is applied to pilot plant data. In spite of these limitations, net water produced is a useful benchmark against which to evaluate the effects of treatment modifications.

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 four consecutive filter runs are listed in Table 25 and can be used to compare results when different numbers of mixers were in use.

TABLE 25. COMPARISON OF ONE VS. THREE STATIC MIXERS - SEATTLE PILOT PLANT

Run No.	No. of Static Mixers	Net Water Produced / 24 Hours (gal/ft^2/24 hours)
6A	3	3785
6B	3	3585
6C	1	3868
6D	1	3759

Review of the filter efficiencies resulting from the use of one or three static mixers indicates little difference in the results. Because a single static mixer appeared to mix the treatment chemicals with the raw water as well as or better than three mixers in series, most runs conducted during the study utilized only one mixer.

Back mixers--Several back mix systems were investigated including hydraulic and mechanical mixers with and without the flocculator in the treatment train. Little difference could be detected among the various back mix systems tested. Filter runs conducted with these systems would normally be terminated because of turbidity breakthrough well before terminal headloss was reached.

Comparison of mixing 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, head loss built up more quickly, 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, filter runs 127M to 137M were conducted with and without this unit process in the treatment train.

Review of the data in Table 26 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 $\leq$ 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 net water produced rose immediately to much higher levels. The turbidity was normally held to $\leq$ 0.10 ntu until terminal headloss occurred. The reason for the increased production 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 exceeded 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 Comparison--

Removal of asbestos fibers was a prime consideration of the study, so a comparison of the chrysotile counts in the finished water generated from the various medias was made and results are shown in Table 27.

When the complexity of the asbestos analysis is taken into consideration, 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 BDL or NSS levels of chrysotile. Finished

TABLE 26. RESULTS FROM FILTER RUNS WITH AND WITHOUT FLOCCULATION - SEATTLE PILOT PLANT

Filter Run No.	Flocculator Yes/No	Filter Loading Rate gpm/ft^2 Maximum	Filter Loading Rate gpm/ft^2 Average	Number of Hours $\leq$0.10 ntu	Hours to End of Run or 0.2 ntu	Net Production $gal/ft^2/day$	Comments
127M	Yes	7.0	6.8	10	13	6970	
128M	Yes	8.0	6.5	16	16	8910	
129M	No	6.1	6.1	0	-	0	Turbidity >0.10 ntu
130M	No	6.0	6.0	0	-	0	Turbidity >0.10 ntu
131M	No	4.0	4.0	8	10	3980	
132M	No	5.0	5.0	5	7	4200	
133M	No	6.0	6.0	0	-	0	Turbidity >0.10 ntu
134M	Yes	4.0	4.0	25	26	5300	
135M	Yes	4.0	4.0	23	24	5260	
136M	Yes	5.0	5.0	16	16	6790	
137M	Yes	6.0	6.0	15	16	7660	

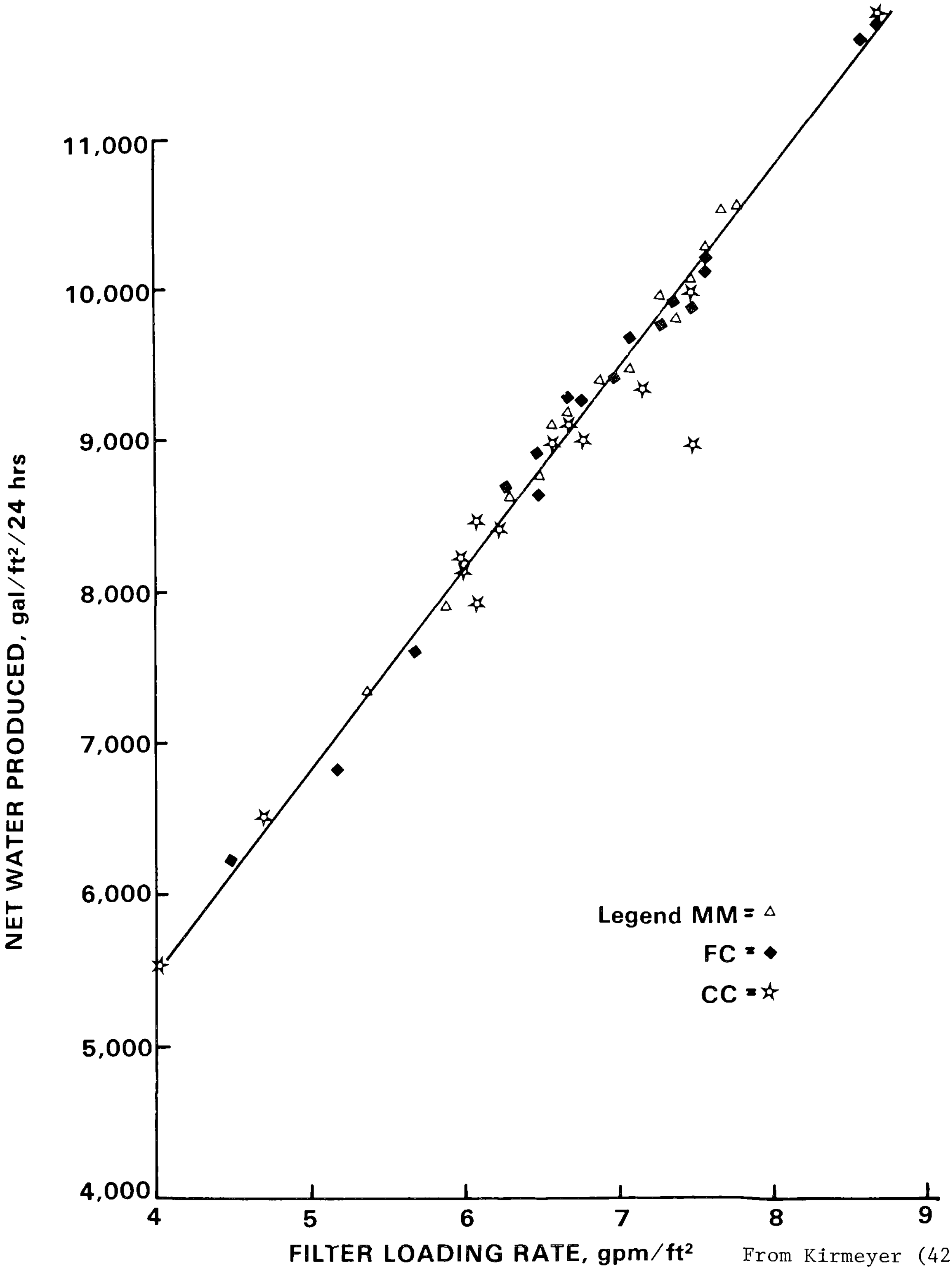
TABLE 27. CHRYSOTILE RESULTS FROM VARIOUS FILTER MEDIA - SEATTLE PILOT PLANT

		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
	1	0.01(NSS)	< 0.01(BDL)	< 0.01(BDL)	-
	4	0.02(NSS)	0.04(NSS)	< 0.01(BDL)	-
161	10	< 0.01(BDL)	0.02(NSS)	0.01(NSS)	-
	13	< 0.01(BDL)	0.03(NSS)	< 0.01(BDL)	-
	15	< 0.01(BDL)	< 0.01(BDL)	< 0.01(BDL)	-
	0	0.07	-	0.01(NSS)	0.09
	1	0.1	-	0.04(NSS)	0.02(NSS)
	1 1/2	0.36	-	< 0.03(BDL)	0.94
	2	0.03(NSS)	-	0.01(NSS)	< 0.01(BDL)
	3	< 0.01(BDL)	-	< 0.01(BDL)	0.03(NSS)
174	4	< 0.01(BDL)	-	< 0.01(BDL)	0.01(NSS)
	5	0.01(NSS)	-	< 0.01(BDL)	0.06(NSS)
	6	0.01(NSS)	-	< 0.01(BDL)	0.02(NSS)
	7	0.01(NSS)	-	0.06(NSS)	0.01(NSS)
	14	< 0.01(BDL)	-	< 0.01(BDL)	0.01(NSS)

*Data on filter media are on p. 41 of this report. From Kirmeyer (42)

water turbidities were also virtually the same for all of the medias being tested.

Kirmeyer calculated water production data for a large number of filter runs made with filters utilizing mixed media with sand MS-6, dual media with fine coal, and dual media with coarse coal. Data are presented as net water produced per day vs. filter loading rate in Figure 12. Differences in water production for the three kinds of media are slight, if any exist. Water production data in Figure 12 were not adjusted for production of filtered water having turbidity above 0.10 ntu. In the runs used as a data base for Figure 12, filtered water turbidity was almost always $\leq$ 0.10 ntu, so any correction



From Kirmeyer (42)

Figure 12. Net water produced per 24 hours vs. filter loading rate

factor for the net production would be small. Filter performance was affected more by pretreatment conditions than by media types in experiments with Tolt Reservoir water.

Summary of Treatment Results

Fiber count data from the Seattle study are compiled in Appendix B of this report. A summary of the appendix data is presented in Table 28. It shows that chrysotile removal exceeded 99.0 percent in 50 of 125 samples. Removal was greater than 95.0 percent for 100 of 125 samples. Amphibole removal exceeded 99.0 percent in 6 of 18 samples and 95.0 percent in 15 of 18 samples. Chrysotile fiber counts were below detectable limits (BDL) or not statistically significant (NSS) for 46 of 125 filtered water samples. Amphibole fiber counts were BDL or NSS for 15 of 18 filtered water samples. Most of the samples with filtered turbidity above 0.10 ntu had fiber removals of 95.0 percent or lower.

The Seattle study confirmed the Duluth pilot plant research results. In addition, the work at Seattle included runs to provide simultaneous comparison of different kinds of filter medias and extensive asbestos sampling throughout certain filter runs to give a better understanding of fiber removal by granular media filters.

TABLE 28. SUMMARY OF FIBER COUNT DATA FOR SEATTLE STUDY

Filtered Water Fiber Removal percent	Number of samples in this category	Percent of samples in this category	Number of samples with filtered turbidity ≤ 0.10 ntu	Number of samples with filtered turbidity > 0.10 ntu	Number of samples with BDL fiber count	Percent with BDL fiber count	Number of samples with NSS fiber count	Percent with NSS fiber count
Chrysotile Data Base: 125 filtered water samples paired with statistically significant raw water chrysotile counts								
> 99.0	50	40%	48	2	11	22%	15	30%
> 95.0 to 99.0	50	40%	43	7	3	6%	17	34%
> 90.0 to 95.0	13	10%	7	6	0	0%	0	0%
≤ 90.0	12	10%	3	9	0	0%	0	0%
Amphibole Data Base: 18 filtered water samples paired with statistically significant raw water amphibole counts								
> 99.0	6	33%	6	0	3	50%	3	50%
> 95.0 to 99.0	9	50%	9	0	6	67%	3	33%
> 90.9 to 95.0	1	6%	0	1	0	0%	0	0%
≤ 90.0	2	11%	0	2	0	0%	0	0%

SECTION 7

SAN FRANCISCO BAY AREA

During the course of preparing a doctoral dissertation entitled, "Asbestos in Drinking Water and Cancer Incidence," Kanarek incidentally obtained some data on asbestos fiber removal at water filtration plants (19). Collecting information about treatment was not the main purpose of Kanarek's work, so only a portion of the treatment plant data he obtained could be used in this report. Data from nine treatment plants owned and operated by seven utilities were compiled. The water sources, as well as the raw water asbestos fiber counts, varied greatly.

Kanarek's data are most useful for the present effort when both raw and filtered water fiber counts are given. Removal percentages can not be calculated without raw water data, nor can adequacy of treatment be discussed with confidence if treated water fiber counts are very low but raw water counts are unknown, and possibly also very low. For these reasons caution must be used in interpreting the data presented by Kanarek.

Treatment performance data to supplement Kanarek's asbestos data were furnished by the Sanitary Engineering Section of the Department of Health Services, Health and Welfare Agency, State of California. The data, although incomplete, show that treatment practice varies in the Bay area. Some plants receive raw water of excellent quality, as measured by usual parameters such as turbidity. Some of these are direct filtration plants. At times some of the plants filter this high quality raw water with little or no coagulant chemical added to condition the water. Other plants in the area, such as those in Contra Costa County, treat turbid waters that are subject to wastewater contamination by upstream outfalls. These plants employ complete treatment, and they tend to strive for the best possible filtered water quality.

TREATMENT PLANTS IN CONTRA COSTA COUNTY

Three of the treatment plants for which some data are available are located in Contra Costa County. According to Kanarek (19), filtration plants for the City of Antioch, City of Pittsburg, and Contra Costa County Water District (Bollman Plant) draw raw water from the Contra Costa Canal, the Sacramento River, or the San Joaquin River (Fig. 13).

Design and Operating Information

Bollman Plant--

The Bollman plant is the largest of the plants in Contra Costa County for

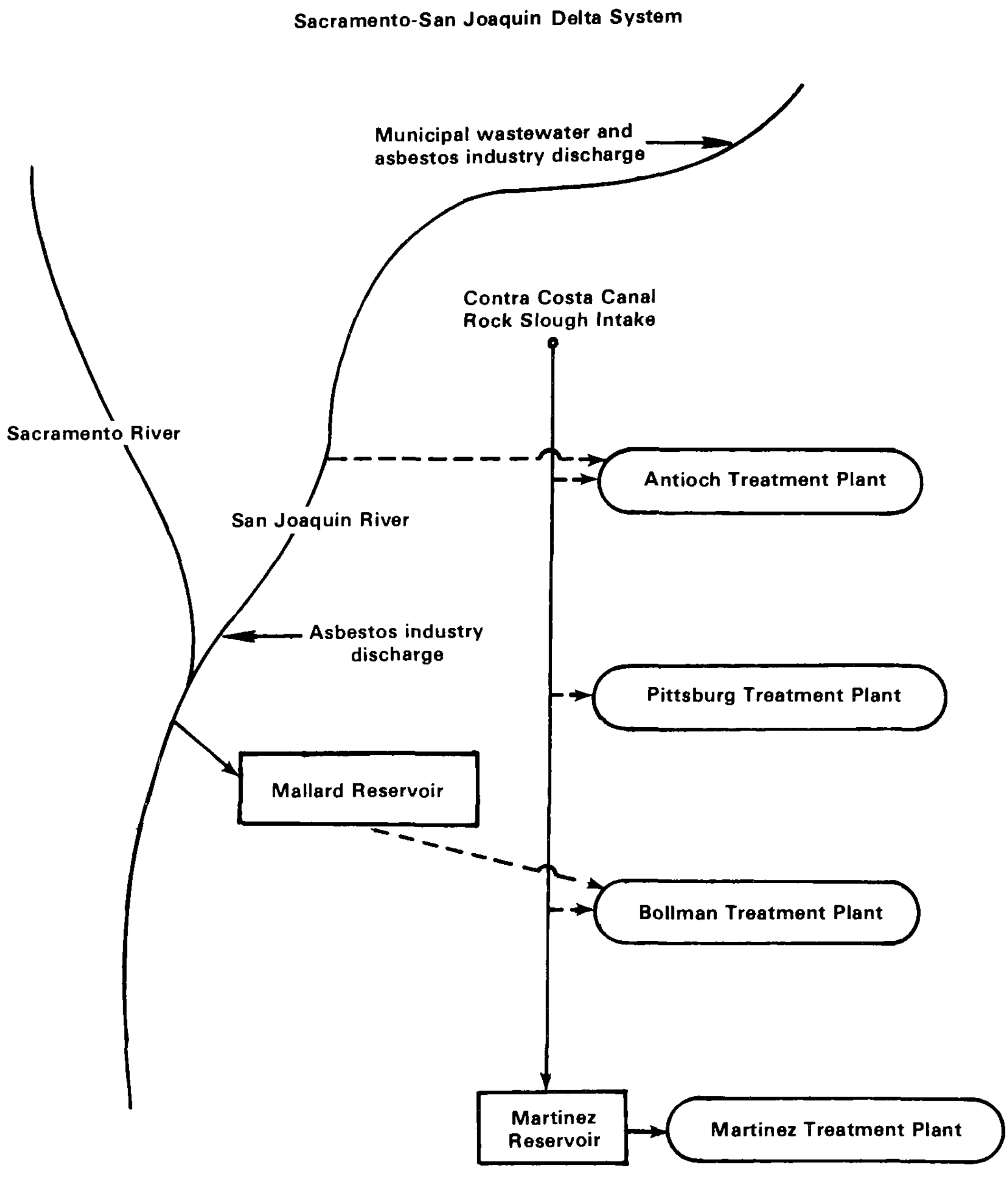


Figure 13. Water sources for water treatment plants. —Contra Costa County

which data are available. Stone indicated that this plant could pump water from the Sacramento River when flows were great enough to overcome tidal effects from San Francisco Bay (45). According to Harris the turbidity of the raw water at the Bollman Plant was expected to range from 25 to 300 ntu (46). He wrote that the drainage of the Sacramento and San Joaquin River systems contributed considerable amounts of industrial, municipal, and industrial wastes to the source water.

Because of the raw water quality, the Bollman Plant was designed to provide very thorough treatment to the water. Treatment includes coagulation, flocculation, sedimentation and filtration. Plant design criteria as given by Stone are shown in Table 29. The Bollman Plant was designed so that alum, lime, caustic soda, and polymer could be fed to adjust pH and condition the water for filtration.

Filter media were evaluated in pilot filter studies. Media selection is given in Table 30. The combined media depth after backwashing was 31 inches. Stone noted that the top of the filter media was 7.1 feet below the surface of the water when the filter was in operation. This design was used so that a positive head could be provided in the filter media under all operating conditions.

Antioch and Pittsburg Plants--

Engineering information about the Antioch and Pittsburg plants was provided by the Sanitary Engineering Section of the Department of Health Services, State of California. The Antioch plant uses upflow clarifiers with sludge recirculation. The floc zone provides about 15 minutes detention time. Detention time in the settling zone is about 50 minutes. The surface loading for the upflow clarifier is about 2 gpm/sf. Alum is used as the primary coagulant, and polyelectrolytes are used as both coagulant and filter aids. The filters consist of 20 inches of anthracite on top of 10 inches of sand. During 1976-77 the filtration rate ranged from 1.5 to 3 gpm/sf. The treatment plant at Pittsburg is of conventional design with rapid mix, flocculation, about 4 hours of detention time in the settling basins, and filtration through dual media at 2 to 2.5 gpm/sf. Specifications for the media are:

i. 10 inches of anthracite 1.5-1.6 mm, U.C.$\leq$1.70
ii. 20 inches of crystal Monterey sand, graded as follows:

Sieve Size	% Passing Sieve
U.S. #16	96-99%
U.S. #20	68-89%
U.S. #30	19-58%
U.S. #40	2-7%
U.S. #50	0-1%

TABLE 29. DESIGN AND HYDRAULIC INFORMATION FOR BOLLMAN PLANT, CONTRA COSTA COUNTY WATER DISTRICT

Plant capacity, mgd	80
Rapid mix, minutes	0.9
Flocculation	
high energy, minutes	11
low energy, minutes	7.5
Sedimentation, minutes	60
Filters	
Number (with 2 bays each)	4
Square feet per filter	1447
Flow per filter, mgd	20
Maximum Filtration rate, gpm/sf	9.6

TABLE 30. BOLLMAN PLANT FILTER MEDIA

		Specific Gravity	Depth inches	Effective Size mm
Top Layer	Anthracite	1.48	16	1.58
Intermediate Layer	Anthracite	1.58	8	0.89
Lower Layer	Silica Sand	2.6	10	0.3

Water Quality

Raw Water--

Asbestos fiber counts and turbidity data for the Contra Costa County raw water samples are given in Table 31. The fiber data contain only three statistically significant chrysotile values, and this at first appears to make an assessment of treatment efficacy difficult or impossible. Careful consideration of the data, however, reveals a tendency for raw water samples to contain asbestos fibers in the range of 10^6 f/L to 10^7 f/L. The three samples that did contain statistically significant fiber counts had 8, 4, and 17 X 10^6 f/L.

Two samples of raw water taken at the CCCWD had fiber counts that were not statistically significant, but because of the debris present in the raw water and the small amount of water that could be filtered for analysis, the finding of a single fiber represented 2.5 or 5 X 10^6 f/L. These sample results, although not statistically significant, suggest that the raw water fiber count was in the millions. Of the 8/13/76 samples from the canal, one

TABLE 31. RAW WATER DATA FOR CONTRA COSTA CANAL AND OTHER SURFACE WATERS IN CONTRA COSTA COUNTY

Date	Location	pH	Turbidity ntu	Chrysotile 10^6 f/L	Amphibole 10^6 f/L
12/10/74	Mallard Reservoir CCCWD	7.7	23	0.03 NSS (0.03)	BDL(0.03)
10/13/75& 10/14/75	North Inlet Mallard Reservoir	7.7	40	0.6 NSS (0.2)	0.2 NSS (0.2)
5/8/76	Pittsburgh raw	-	42	21	BDL(4.3)
5/8/76	Antioch raw	-	-	BDL(4.3)	BDL(4.3)
8/13/76	Contra Costa Canal @ Clyde	7.7	32	present, impossible to count	present impossible to count
8/13/76	Contra Costa Canal @ Pittsburg	7.5	28	present, impossible to count	present impossible to count
8/12/76& 8/13/76	Contra Costa Canal @ Antioch	7.6	18	8	0.8 NSS (0.8)
4/18/77	Clyde, CCCWD intake on Canal	7.7	25-19	10 NSS (2.5)	BDL (2.5)
4/18/77	Contra Costa Canal @ Pittsburg	7.4	21	-	-
4/18/77	Contra Costa Canal @ Antioch	8.2	25	-	-
4/18/77	Clyde - CCCWD settled 8 days	7.9	3	0.6 NSS (0.2)	BDL (0.2)
5/11/77	Contra Costa Canal @ Clyde	7.7	29	15 NSS (5)	BDL (5)
1/9/78	Mallard Reservoir from canal @ Clyde settled 3 days	7.6	22	4	BDL (0.5)
4/4/78	Mallard Reservoir from Mallard Slough	7.6	38	17	3.3 NSS (1.7)

Detection limit in parenthesis
CCCWD = Contra Costa County Water District

was counted and had 8×10^6 f/L. Fibers were present in two other samples taken that day, but determining the number of fibers per liter was not possible. Nevertheless, on the basis of the Antioch sample, suggesting that the other two 8/13/76 samples contained asbestos fibers in the range of 10^6 to 10^7 f/L seems reasonable.

Filtered Water--

Data for turbidity and fiber counts of raw and filtered water samples from Antioch, Pittsburg, and CCCWD are shown in Tables 32 to 34. The Bollman plant consistently produces filtered water with a turbidity of less than 0.10 ntu. Turbidity reduction was 99.7 percent or higher. Chrysotile fiber count reduction exceeded 99 percent twice, and on two other instances it probably was 98 percent or more. The chrysotile count in the filtered water ranged from below 0.02 to 0.7×10^6 f/L. Filtered water turbidities at the Antioch and Pittsburg plants are slightly higher than at the Bollman plant, and fiber count reduction is slightly lower. Fiber counts in the filtered water ranged from 0.05 to 0.8×10^6 f/L, values similar to those reported at the Bollman plant.

SAN FRANCISCO

Both water quality and coagulation practice are more variable at the San Andreas plant. This plant is a conventional plant, employing rapid mixing, coagulation, sedimentation and filtration. During periods of low turbidity, a low alum dose is used to destabilize particulates and form tiny floc particles that do not settle but are removed in the filtration process. With respect to the water quality characteristics in the existing EPA Drinking Water Regulations, raw water quality at this plant is excellent. Turbidity before filtration sometimes meets the 1 ntu limit in the Regulations. Before the Kanarek study was made, coagulant chemical feed was often shut off if the water met the 1 ntu limit before filtration. Since Kanarek's findings were made known, treatment practice calls for the use of a coagulant chemical whenever water is filtered, regardless of raw water turbidity, in order to achieve more effective fiber removal.

As the treatment information indicates in Table 35, the plant was sometimes operated without any coagulant chemicals. Because of the characteristics of the raw water, the doses of alum and polymer, when used, are low. During the 1975 to early 1977 period of operation, asbestos fiber counts were higher by a factor of 2 to 4 than they have been since May, 1977.

MARIN COUNTY

Kanarek's study included data on the Marin Municipal Water District's San Geronamo and Bon Tempe plants. According to Kanarek, these are conventional plants, employing flocculation, sedimentation, and filtration (19). Sources of raw water are shown in Figure 14. Water for the District comes from local runoff from the Coast Range. It is collected in reservoirs in the Mt. Tamalpais region and treated at the two filtration plants. Raw water data are limited to two samples taken at the San Geronamo plant (see Table 36). Samples of treated water show that both turbidity and fiber counts are lower at the Bon Tempe plant. Filtered water turbidities as high as 1.0 ntu were

TABLE 32. TREATMENT DATA FOR ANTIOCH PLANT

Date	Coagulation		Raw Water Data				Finished Water Data				% Reduced	
	Chemical Used	mg/L	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	Turbidity	Chrysotile
5/8/76	Alum Polymer Caustic*	40 0.0061	-	25	BDL (4.3)	BDL (4.3)	-	0.14	0.13	BDL (0.02)	99.4	-
8/12/76	Alum Polymer Lime*	41 0.0077	7.6	18			7.4	0.21			98.8	
8/13/76					8	0.8 NSS (0.8)			0.26	BDL (0.02)		96.7
4/18/77	Alum Polymer Lime*	45 0.0058	8.2	25	-	-	8.0	0.26	0.13	BDL (0.025)	99	-

*Used to adjust pH
Detection limit shown in parenthesis

TABLE 33. TREATMENT DATA FOR BOLLMAN PLANT

Date	Coagulation			Raw Water Data			Finished Water Data				% Reduced	
	Chemical Used	mg/L	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	Turbidity	Chrysotile
12/10/74	Alum Polymer Lime & Caustic*	41 0.02	7.7	23	0.03 NSS	BDL (0.03)	8.1	0.04	BDL (0.005)	BDL	99.8	
10/13/75					0.6 NSS	0.2 NSS (0.2)			0.13	BDL (0.005)		
10/14/75	Alum Polymer† Lime & Caustic*	41.5 0.017	7.7	40			8.06	0.04			99.9	
8/13/76	Alum Polymer† Lime & Caustic*	45.6 0.019	7.7	32	Present can't count		8.2	0.05	0.16	0.01 NSS	99.8+	
4/18/77	Alum Polymer† Lime & caustic* (settled 8 days)	47.8 0.022	7.7	25-19 3	10 NSS 0.6 NSS	BDL (2.5) BDL (0.2)	8.15	0.055	0.025§ NSS BDL# (0.025)	BDL§ (0.025) BDL# (0.025)	99.7+	could be 99.75%
5/11/77	Alum Polymer† Lime & Caustic*	49.6 0.026	7.7	29	15 NSS	BDL (5)	8.11	0.05	0.18	BDL (0.025)	99.8+	could be 98.8%
8/5/77	Alum Polymer† Lime & Caustic*	54.1 0.032	7.7	35	-	-	8.1	0.053	0.7	BDL (0.05)	99.8+	

(continued)

TABLE 33. (continued)

Date	Coagulation			Raw Water Data			Finished Water Data				% Reduced	
	Chemical Used	mg/L	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	Turbidity	Chrysotile
1/9/78	Alum Polymer† Lime & Caustic*	49.8 0.032	7.6	22	4	BDL (0.5)	8.45	0.05	BDL (0.025)	BDL (0.025)	99.7+	99.37+
4/4/78	Alum Polymer† Lime & Caustic*	46.8 0.032	7.63	38	17	3.3 NSS(1.7)	8.3	0.061	0.15	0.025 NSS	99.8+	99.1

*Used to adjust pH
†Generally nonionic polymer used as a filter aid
Detection limit shown in parenthesis
§After filtration
#After clearwell

TABLE 34. TREATMENT DATA FOR PITTSBURG PLANT

Date	Coagulation Chemical Used	Raw Water Data pH	Raw Water Data Turbidity (ntu)	Raw Water Data Chrysotile (10^6 f/L)	Raw Water Data Amphibole (10^6 f/L)	Finished Water Data pH	Finished Water Data Turbidity (ntu)	Finished Water Data Chrysotile (10^6 f/L)	Finished Water Data Amphibole (10^6 f/L)	% Reduced Turbidity	% Reduced Chrysotile
5/8/76	Data Unavailable	8.3	42	21	BDL (4.3)	8.0	0.28-0.38	BDL (0.26)	BDL (0.26)	99.2	98.7+
8/13/76	Alum Lime	7.5	28	Present	Present	7.5	0.27	0.76	0.04 NSS	99	-
4/17/77& 4/18/77	Alum Lime	7.4	21	-	-	7.4	0.10	0.05 NSS	BDL (0.025)	99.5+	-

Detection limit shown in parenthesis

TABLE 35. TREATMENT DATA FOR SAN ANDREAS PLANT

Date	Coagulation: Chemical Used	Coagulation: mg/L	Raw Water Data: pH	Raw Water Data: Turbidity (ntu)	Raw Water Data: Chrysotile (10^6 f/L)	Raw Water Data: Amphibole (10^6 f/L)	Finished Water Data: pH	Finished Water Data: Turbidity (ntu)	Finished Water Data: Chrysotile (10^6 f/L)	Finished Water Data: Amphibole (10^6 f/L)	% Reduced: Turbidity	% Reduced: Chrysotile
5/5/75	Alum Magnafloc[†] Caustic*	2.1 0.23	7.6	1.1	3.5	BDL	8.6	0.12	1.4	BDL	89	60
12/14/76	None		7.6	0.64	3.7 estimate	BDL (0.08)	8.7	0.32	3.4[§] 1.4[#]	NSS 0.08[§] 0.32[#]	50	8 62
2/17/77	Alum Catfloc-T[@] Caustic*	0.75 0.69	7.5	0.75	-	-	8.6	0.15	1.9 (1.5 EPA)	BDL (0.25)	80	-
5/26/77	Alum Catfloc-T	2.0 0.75	7.5	1.2	-	-	8.8	0.12 0.12 0.11	0.4 0.8 0.32	BDL(0.025) 0.05 NSS BDL(0.025)	90 90 91	- - -
8/17/77	Alum Catfloc-T	3.0 0.75	7.6	0.9 to 0.76	-	-	8.6	0.20	0.93	0.05 NSS (0.025)	78 to 74	-
1/11/78	Alum Catfloc-T	2.1 0.75	7.5	1.4	-	-	7.9	0.14	0.7	BDL (0.025)	90	-
4/12/78	Alum Polymer Caustic*	12.5 none	7.6	2.2	1.5	BDL (0.13)	8.7	0.22	0.32	BDL (0.064)	90	79

[†]American Cyanamid, Wayne, N.J.
*Used for pH adjustment
[@]Calgon Corporation, Pittsburgh, PA

[§] after filtration
[#] after clear well

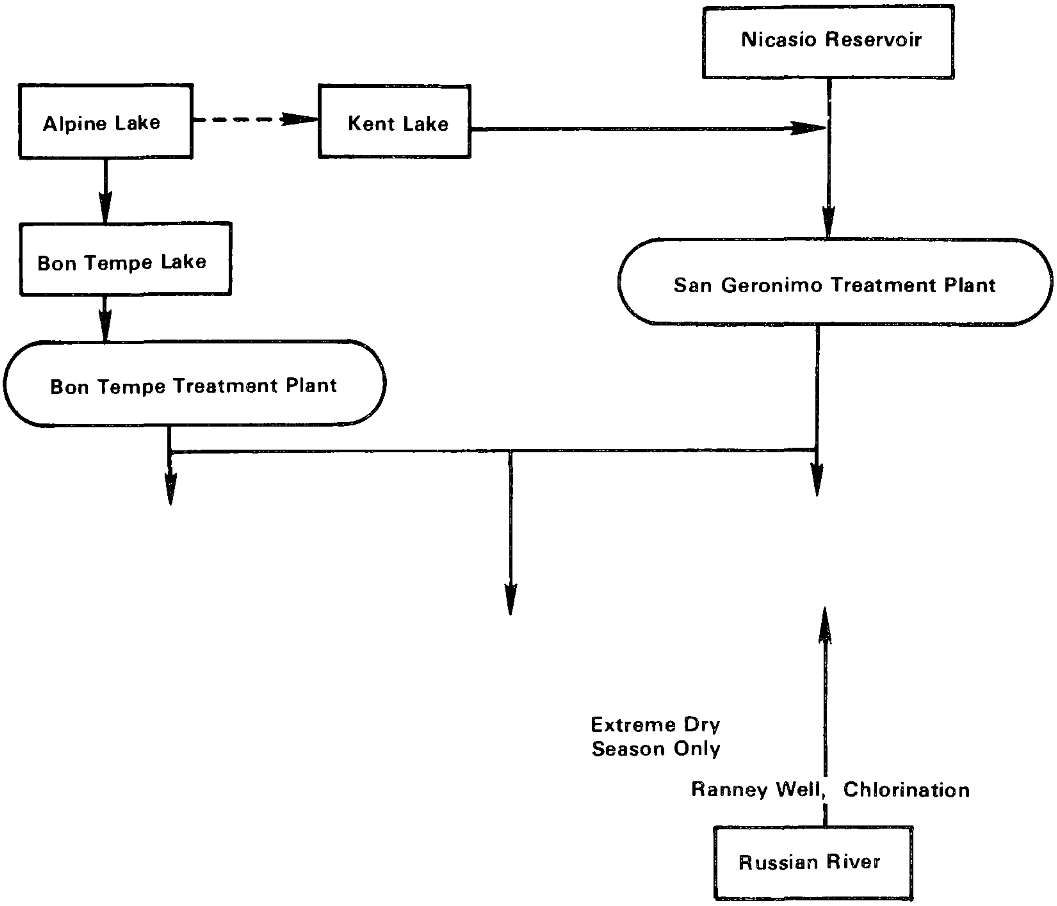


Figure 14. Water sources for Marin Municipal Water District plants.

TABLE 36. TREATMENT DATA FOR MARIN MUNICIPAL WATER DISTRICT AND NORTH MARIN WATER DISTRICT

Date	Coagulation			Raw Water Data			Finished Water Data				% Reduced	
	Chemical Used	mg/L	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	Turbidity	Chrysotile
San Geronomo Plant, Marin Municipal Water District												
12/2-3/74	-	-	-	-	2	-	-	-	-	--	-	-
3/6/75	Alum Lime	23 12	7.7	8-6	11	-	8.6	1.0-0.82			83-90	
3/7/75	Alum Lime	25 17	7.2-7.6	5	-	-	8.6	1.0-0.57	2	--	80-89	82
2/25/76	Alum Polymer Lime	9 1.0 8	7.2	8	0.3 0.25	 -	8.6	0.55	0.14	--	93	53 44
11/12/76	Alum Polymer Lime	14.3 1.6 0	7.6	19-2.1	-	-	7.1	0.16	0.04 NSS	0.04 NSS	92-99	-
12/13/76	Alum Polymer Lime	7.8 0.6 10		2.5	-	-	-	0.41	BDL (0.02)	BDL (0.02)	84	-
8/17/77	Alum Lime	6.1 0	6.6	14	-	-	7.9	0.29	0.7	0.1 NSS	98	-
1/10/78	Alum Lime	51 0	6.8	46	-	-	8.2	0.64-0.28	12	BDL (0.5)	99	-

Detection limit in parenthesis

(continued)

TABLE 36. (continued)

Date	Coagulation		Raw Water Data				Finished Water Data				% Reduced	
	Chemical Used	mg/L	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	pH	Turbidity (ntu)	Chrysotile (10^6 f/L)	Amphibole (10^6 f/L)	Turbidity	Chrysotile
						Bon Tempe Plant, Marin Municipal Water District						
12/13/76	Alum Lime	22.6 14	7.7	1.0	-	-	8.4	0.25	0.2 NSS	BDL (0.05)	75	-
8/10/77	Alum Lime	14.1 13	8.0	0.70	-	-	8.8	0.17	BDL (0.1)	BDL (0.1)	76	-
1/14/78	data unavailable		7.3	23	-	-	7.4	0.12	BDL (0.1)	BDL (0.1)	99+	-
						Stafford Plant, North Marin Water District						
3/15/78	Alum Lime Polymer	60 24 0.03	7.3	65	5 NSS (5)	BDL (5)	8.4	<0.05	BDL (0.025)	BDL (0.025)	99.9+	-

Detection limit in parenthesis

reported at San Geronomo, vs. 0.25 ntu at Bon Tempe. The highest filtered water fiber count at San Geronomo was 12 X 10^6 f/L, but it was only 0.2 X 10^6 f/L (NSS) at Bon Tempe.

The Stafford treatment plant of the North Marin Water District was sampled one time. Both the finished water fiber count and filtered water turbidity were quite low (Table 36). Data suggest that the raw water may contain asbestos fibers, this would be expected at Stafford.

The San Francisco Bay area has many water treatment plants, with a variety of types, including direct filtration, upflow clarification, and conventional flocculation-sedimentation-filtration plants. Although additional data would have been very useful for interpreting the fiber removal results, the availab information is very interesting and shows, in general, that water filtration plants can remove asbestos fibers under proper operating conditions.

SECTION 8

PHILADELPHIA

The City of Philadelphia has three water treatment plants, Torresdale on the Delaware Estuary, and Belmont and Queen Lane on the Schuylkill River. About half of Philadelphia's drinking water is supplied by the Torresdale Plant and the other half is supplied by the Queen Lane and Belmont Plants. Generally the portion of Philadelphia east of Broad Street receives treated Delaware Estuary water while the section west of Broad Street receives treated Schuylkill River water.

DESIGN AND OPERATING INFORMATION

The three treatment plants are typical of plants east of the Rocky Mountains that have been designed for turbidity removal. All three treatment facilities are coagulation plants of the rapid sand filter type, with automatic and semi-automatic controls.

Torresdale Plant

The Torresdale Plant receives raw water to a pre-sedimentation basin via a difference in pre-sedimentation basin and estuary water levels. Raw water from the pre-sedimentation basin is pumped by eight 60-MGD pumps to eight separate rapid mix chambers. Coagulant addition takes place in these chambers. Beyond the rapid mix chambers the Torresdale Plant is operated as two parallel facilities, a North and South section. Each section contains two 2.3 million gallon flocculation basins, two 10 million gallon sedimentation basins and 47 rapid sand filters. Finished water is stored in two clear wells with a total storage of 194 million gallons. The Torresdale Plant has a rated capacity of 282 MGD and a hydraulic capacity of 423 MGD.

Chemical treatment at the Torresdale Plant includes marginal chlorination at the presedimentation basin, breakpoint chlorination during rapid mix, and post addition of ammonia to form chloramines. Lime is added for pH stabilization to facilitate coagulation with ferric chloride. Post chemical treatment includes addition of fluoride. Occasionally powdered carbon and chlorine dioxide are used for taste and odor control.

Queen Lane Plant

The Queen Lane Plant receives raw water via four 40 MGD and two 20 MGD pumps located on the Schuylkill River just below the confluence of the Wissohickon Creek. The intake pumps are protected by a floating boom and vertical bar screens. The raw water is delivered to a 177 million gallon raw water storage reservoir. Raw water from the storage reservoir flows by gravity into the pretreatment building which contains four rapid mix chambers. The Queen Lane Plant is divided into a north and south section. Each section contains two 1.0 million gallon flocculation basins and two 4.3 million gallon sedimentation tanks stacked to accomplish primary settling in the upper level and secondary settling in the lower level. The north section contains 21 rapid sand filters and the south section contains 19 rapid sand filters, with each filter rated at 3 MGD. Filter water flows to north and south bi-level clear wells, with a total combined storage of 83 million gallons. The Queen Lane Plant has a rated capacity of 120 MGD and a hydraulic capacity of 160 MGD.

Chemical treatment at Queen Lane includes breakpoint prechlorination at the raw water storage reservoir. Ammonia is added after filtration to form chloramines. Coagulation is achieved through the addition of ferric chloride and lime. Post chemical treatment also includes the addition of fluoride and zinc phosphate for corrosion control. Occasionally powdered carbon is used for taste and odor control.

Belmont Plant

The Belmont Plant receives raw water through submerged intakes on the Schuylkill river. Each intake is equipped with primary and secondary vertical bar screens. Water is pumped by two 40 MGD and two 20 MGD pumps to two raw water reservoirs operated in series with a total capacity of 72 million gallons. Raw water flows by gravity to rapid mixing facilities each containing three chambers. The Belmont Plant is divided into a north and south section. The north section contains two 0.55 million gallon flocculation basins followed by two 2.36 million gallon sedimentation basins, and 12 rapid sand filters rated at 3 MGD each. The south section contains two 0.66 million gallon flocculation basins, followed by two 3.24 million gallon sedimentation basins, and 14 rapid sand filters. Filtered water flows into a 1.8 million gallon clear well and then into a 21.7 million gallon finished water reservoir. The Belmont Plant has a rated capacity of 78 MGD and a hydraulic capacity of 108 MGD.

Chemical treatment at Belmont includes marginal pre-chlorination followed by breakpoint chlorination. Ammonia is added after filtration to form chloramines. Coagulation is achieved through the addition of alum and lime. Post-chemical treatment includes the addition of fluoride, and zinc phosphate for corrosion control. Occasionally powdered carbon and chlorine dioxide are used for taste and odor control.

Performance for all three plants is summarized in Table 37.

WATER QUALITY DATA

A cooperative study between the Philadelphia Water Department and EPA was undertaken after a limited sampling program had indicated that raw and filtered waters in Philadelphia contained asbestos. Two phases of this study have been completed, and a third is under way.

TABLE 37. DESIGN AND OPERATING INFORMATION FOR PHILADELPHIA PLANTS, 1977-1978

	Torresdale	Queen Lane	Belmont
Rated Capacity			
Peak MGD	423	160	108
Average MGD	282	120	78
Daily Output			
Peak MGD	306	159	90
Average MGD	224	110	73
Flocculation Time at Average Rated Capacity, minutes	47	48	44 North section 45 South section
Sedimentation Time at Average Rated Capacity, minutes	204	206	188 North section 222 South section
Filtration Rate at Average Rated Capacity, gpm/sf	2	2	2
Coagulant			
Type	Ferric Chloride	Ferric Chloride	Alum
Dosage (avg) mg/L	13.3	7.3	15.5
Typical pH(Finished)	8.5	6.9	7.2
Turbidity			
River			
Average, ntu	12	14	19
Range, ntu	3-80	2-230	2-390
Finished			
Average, ntu	0.24	0.10	0.44
Range, ntu	0.1-1.4	0.01-1.3	0.2-1.8

During the first phases of sampling and analysis, monitoring of raw and filtered water quality during normal plant operation was emphasized. Seven day composite samples of raw and filtered waters were collected at all plants. In addition, so that effects of storms and high runoff could be evaluated, some twenty-four hour composite samples were taken during periods of rising river flow and falling river flow.

Effects of Storms

Because early sampling activities had produced conflicting data on asbestos in raw and finished waters, effects of storm flow were studied in order to learn if asbestos concentrations in the rivers were influenced by scouring and deposition during flow changes. In December, 1977 two storms occurred in the area, and the sampling was carried out.

On December 14, 0.9 inches of rain fell, according to the U.S. Weather Station at Philadelphia International Airport. The second storm occurred on December 21, when 1.0 inches of rain fell at the airport. Figure 15 shows the variation of Delaware Estuary flow as measured at Trenton, New Jersey, and raw water turbidity at the Torresdale Plant during the time period that included both storms. Figure 16 shows similar data for the Schuylkill River at the Belmont Plant. Substantial increases in flow occurred at both plants after the December 14 precipitation fell at Philadelphia. The variations in flow on December 15-20 probably were the result of precipitation in the watersheds in areas upstream from Philadelphia. The trends that occurred during sampling were rising flow and turbidity followed by falling flow and turbidity. Results of the storm sampling program are given in Table 38.

Asbestos fiber counts in the rivers are higher at the beginning of a storm, when flow is rising and sediment previously deposited on the river bed is picked up and carried by the higher flow.

Treatment Plant Performance

In plant performance evalution studies at Philadelphia plants, 7-day composite samples have generally been collected. Sampling for filtered water generally has been delayed by 24 hours to allow for time of flow through the plants. Results are shown in Tables 39-41. The results show that conventional water treatment plants with coagulation, flocculation, sedimentation and filtration can remove a high percentage of the asbestos fibers found in the raw water. Substantial removal by sedimentation was observed when raw, settled, and filtered water samples were analyzed. Sedimentation at Torresdale reduced the fiber count from 15.8 to 0.7×10^6 f/L. At Belmont, sedimentation reduced the fiber count from 10 to 1.7×10^6 f/L, but the filtered water contained 1.35×10^6 f/L. These samples were taken as 24-hour composite samples during a period when 7-day composite samples were taken. The 7-day composite for the Belmont plant had 8.6×10^6 f/L in the raw water and 0.28×10^6 f/L (NSS) in the filtered water. The significance of the 1.35×10^6 f/L filtered water sample is uncertain because no other filtered waters had such a high fiber count. Additional composite sampling of raw, settled, and filtered water is needed.

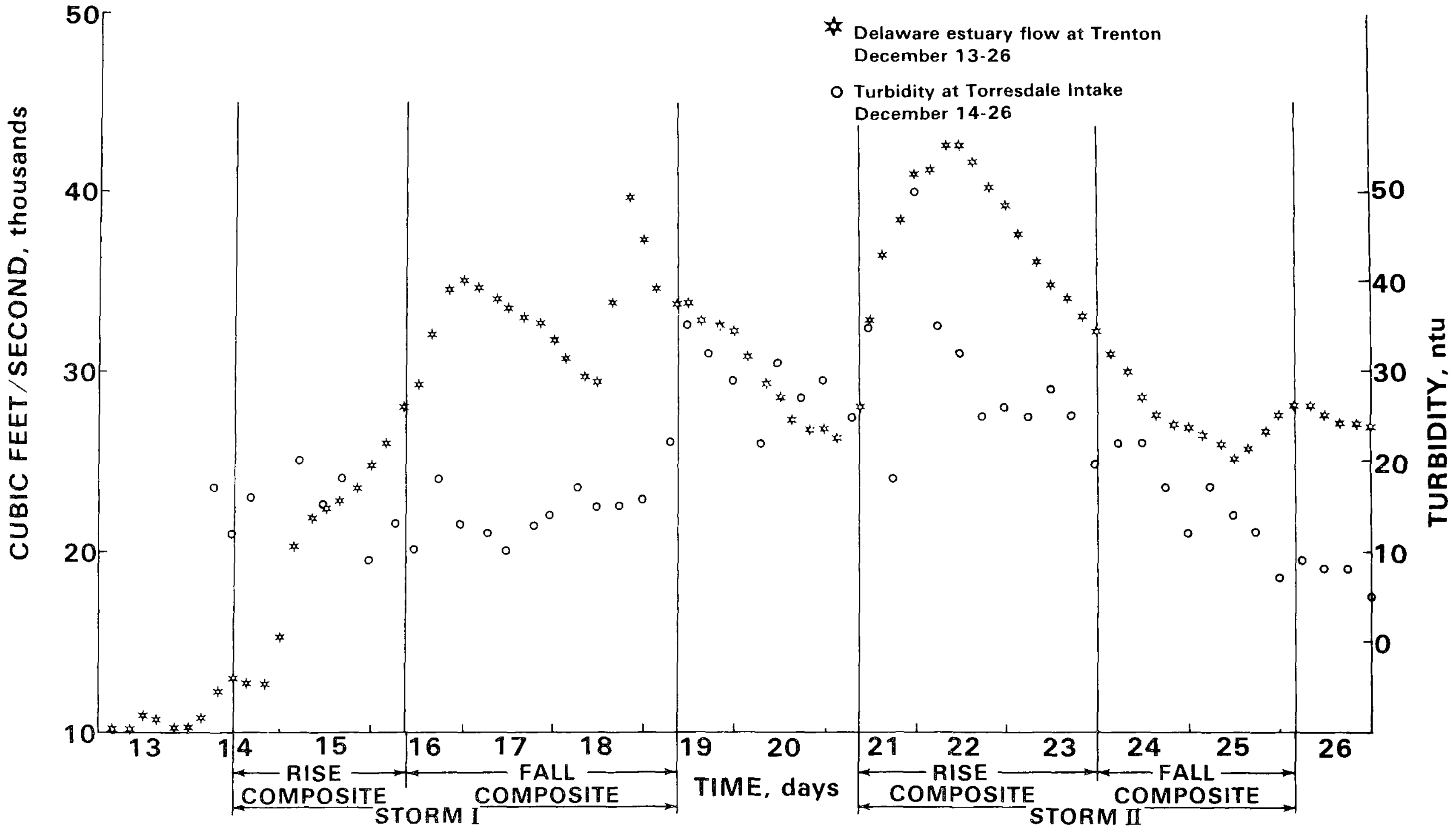


Figure 15. Flow and turbidity during Torresdale plant storm sampling.

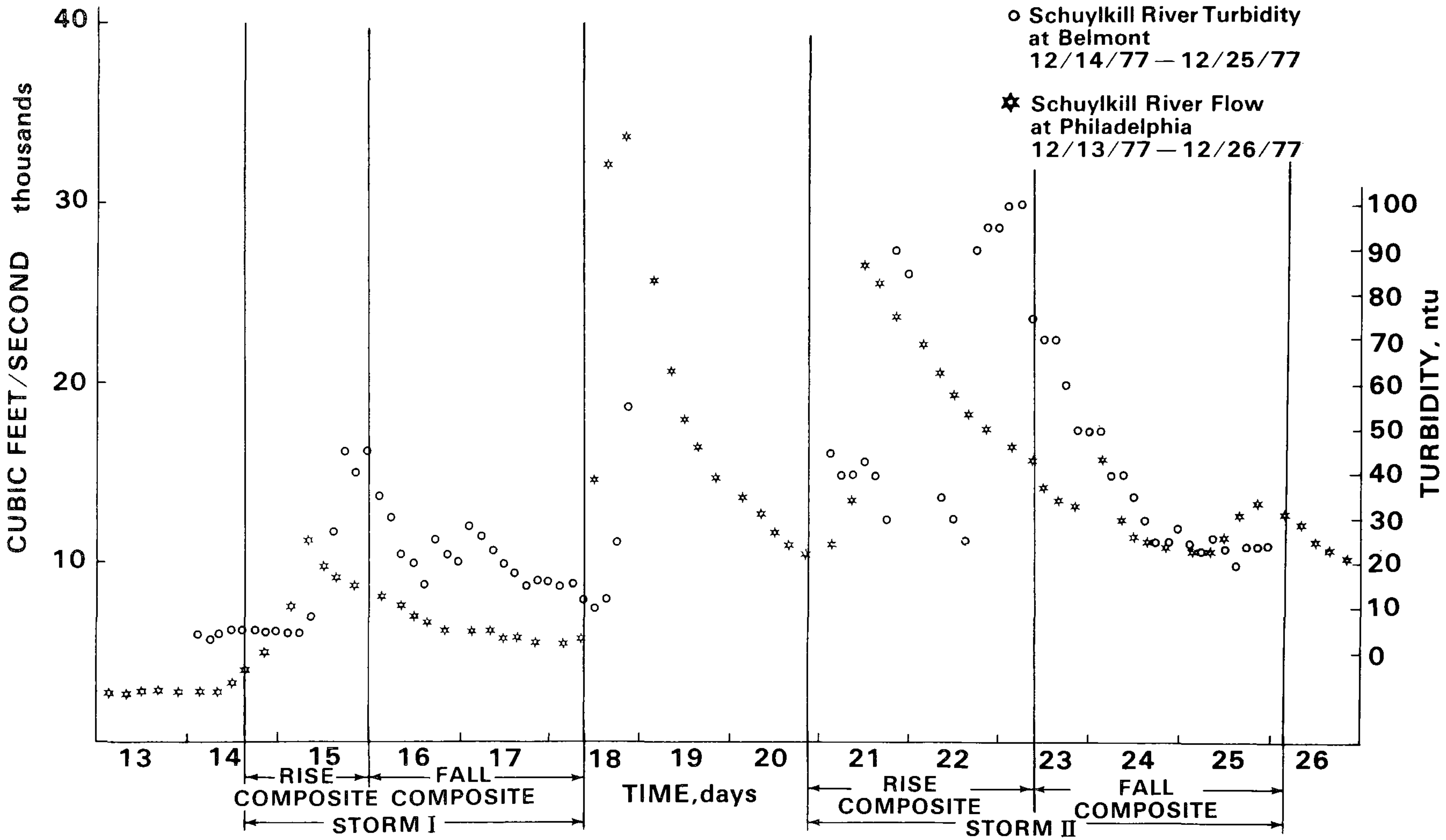


Figure 16. Flow and turbidity during Belmont plant storm sampling.

TABLE 38. STORM FLOW SAMPLING RESULTS AT PHILADELPHIA

				Torresdale		Belmont	
River/ Fin.	Storm No.	Date	Type	Storm Rise Asbestos 10^6 f/L	Storm Fall Asbestos 10^6 f/L	Storm Rise Asbestos 10^6 f/L	Storm Fall Asbestos 10^6 f/L
River	1	12/14/77	C	2.9	NSS(0.3)	7.6	5.4
			A	BDL(0.3)	BDL(0.3)	BDL(0.3)	BDL (0.3)
Fin.	1	12/14/77	C	-	-	BDL(0.01)	-
			A	-	-	BDL(0.01)	-
River	2	12/21/77	C	6.1	4.7	14.6	1.7
			A	BDL(0.3)	BDL(0.3)	BDL(0.7)	BDL (0.3)
Fin.	2	12/21/77	C	0.1	-	NSS(0.02)	-
			A	BDL(0.01)	-	BDL(0.02)	-

C: Chrysotile
A: Amphibole
NSS: Not Statistically Significant
BDL: Below Detectable Limit
Detection Limit in parenthesis

TABLE 39. WATER QUALITY DATA - TORRESDALE PLANT

Date	Raw Water Turbidity Avg. ntu	Raw Water Turbidity Range ntu	Raw Water Chrysotile fibers 10^6 f/L	Filtered Water Turbidity Avg. ntu	Filtered Water Turbidity Range ntu	Filtered Water Chrysotile fibers 10^6 f/L	Percent Reduction Turbidity	Percent Reduction Chrysotile
12/28/77-1/3/78	8	7-12	3.6	0.13	0.11-0.17	0.02 NSS (0.02)	98.3	may exceed 99.4
12/21/77 Storm Rise	29	18-50	6.1	0.19	0.16-0.23	0.1	98.9	98.3
2/22-28/78	7	5-8	1.2 NSS	0.13	0.11-0.14	0.03 NSS (0.01)	98.1	may exceed 97.5
11/13-19/78	6	4-9	2.2	0.27	0.23-0.30	0.28 NSS (0.14)	95.5	may exceed 87.2
1/8-9/79	34	27-40	15.8	See data below				
settled water to sand filter				3.7	3.0-4.9	0.7 NSS (0.7)	89.1	may exceed 95.5
sand filter effluent				0.38	0.34-0.40	(0.14) BDL	99.1	>99.1
settled water to GAC filter				3.7	3.0-4.9	0.7 NSS (0.7)	89.1	may exceed 95.5
GAC filter effluent				0.38	0.34-0.40	0.43 NSS (0.14)	99.1	may exceed 97.2

Note: Detection Limit in Parenthesis

TABLE 40. WATER QUALITY DATA - QUEEN LANE PLANT

Date	Raw Water Turbidity Avg. ntu	Raw Water Turbidity Range ntu	Raw Water Chrysotile fibers 10^6 f/L	Filtered Water Turbidity Avg. ntu	Filtered Water Turbidity Range ntu	Filtered Water Chrysotile fibers 10^6 f/L	Percent Reduction Turbidity	Percent Reduction Chrysotile
12/7-13/77	4	2-10	2.9	0.11	0.06-0.23	0.2	97.2	93.1
12/28/77-1/3/78	8	4-24	5.5	0.20	0.17-0.22	0.1 NSS (0.1)	97.5	98.1
2/22-28/78	3	3-4	3.6	0.06	0.05-0.08	(0.01) BDL	98	>99.7
11/13-19/78	6	4-9	19.5	0.11	0.09-0.15	0.84	98.1	95.6
1/8-15/79	30	11-110	86	0.10	0.07-0.14	0.43 NSS (0.14)	99.6	may exceed 99.5

Note: Detection Limit in parenthesis

TABLE 41. WATER QUALITY DATA - BELMONT PLANT

Date	Raw Water Turbidity Avg. ntu	Raw Water Turbidity Range ntu	Raw Water Chrysotile fibers 10^6 f/L	Filtered Water Turbidity Avg. ntu	Filtered Water Turbidity Range ntu	Filtered Water Chrysotile fibers 10^6 f/L	Percent Reduction Turbidity	Percent Reduction Chrysotile
10/31/77-11/6/77	4.5	4-5	7.6	0.45	0.35-0.55	0.03 NSS (0.01)	90	may exceed 99.6
12/14/77 Storm	13	5-45	7.6	0.15	0.15	(0.01) BDL	98.8	>99.8
12/21/77 Storm Rise	60	24-100	14.6	0.23	0.21-0.24	0.02 NSS (0.02)	99.6	may exceed 99.8
2/22/78-2/28/78	4	4	2.5	0.35	0.30-0.55	0.03 NSS (0.03)	91.2	may exceed 98.8
11/13-19/78	4.6	3.6-5.3	8.6	0.42	0.35-0.50	0.28 NSS (0.14)	90.8	may exceed 96.7
1/8-15/79	53	5-160	15.2	0.36	0.15-0.65	(0.14) BDL	99.3	>99.0
11/13-14/79	4.2	4.0-4.3	10	see data below				
settled water to sand filter				1.7	1.4-2.0	1.7	59.5	83.0
filter effluent				0.29	0.25-0.35	1.35	93.0	86.5

Detection Limit in Parenthesis

SECTION 9

CHICAGO

The City of Chicago operates two very large water filtration plants, the South District Filtration Plant rated at 480 mgd and the Jardine Water Filtration Plant rated at 960 mgd. Total peak filtration capacity of the two plants is 2500 mgd. The peak filtration capacity of the Jardine Plant, formerly called the Central District Filtration Plant, is 1,700 mgd, making this the world's largest water filtration plant. The Jardine Plant was described in American City (47) and in Water Works and Wastes Engineering (48). Both of Chicago's plants are conventional rapid sand filtration plants filtering at 2 gpm/sf at rated capacity. Alum is used as the primary coagulant chemical.

Data on asbestos in raw and filtered water at Chicago have been obtained in a long-range analytical program carried out by the Water Purification Laboratory of the City of Chicago. The report of McMillan, Stout and Willey was included in the literature review (20). More recent data furnished by McMillan are plotted in Figures 17 and 18, which show raw and filtered water asbestos concentrations from January 1976 through December, 1978 for the Jardine and South Plants, respectively.

The figures show that raw water generally contained 1 to 2 million fibers per liter. Filtered water generally had 0.1 to 0.3 million fibers per liter. Fiber reduction is similar to the percentage reported earlier (20), about 70 to 90 percent.

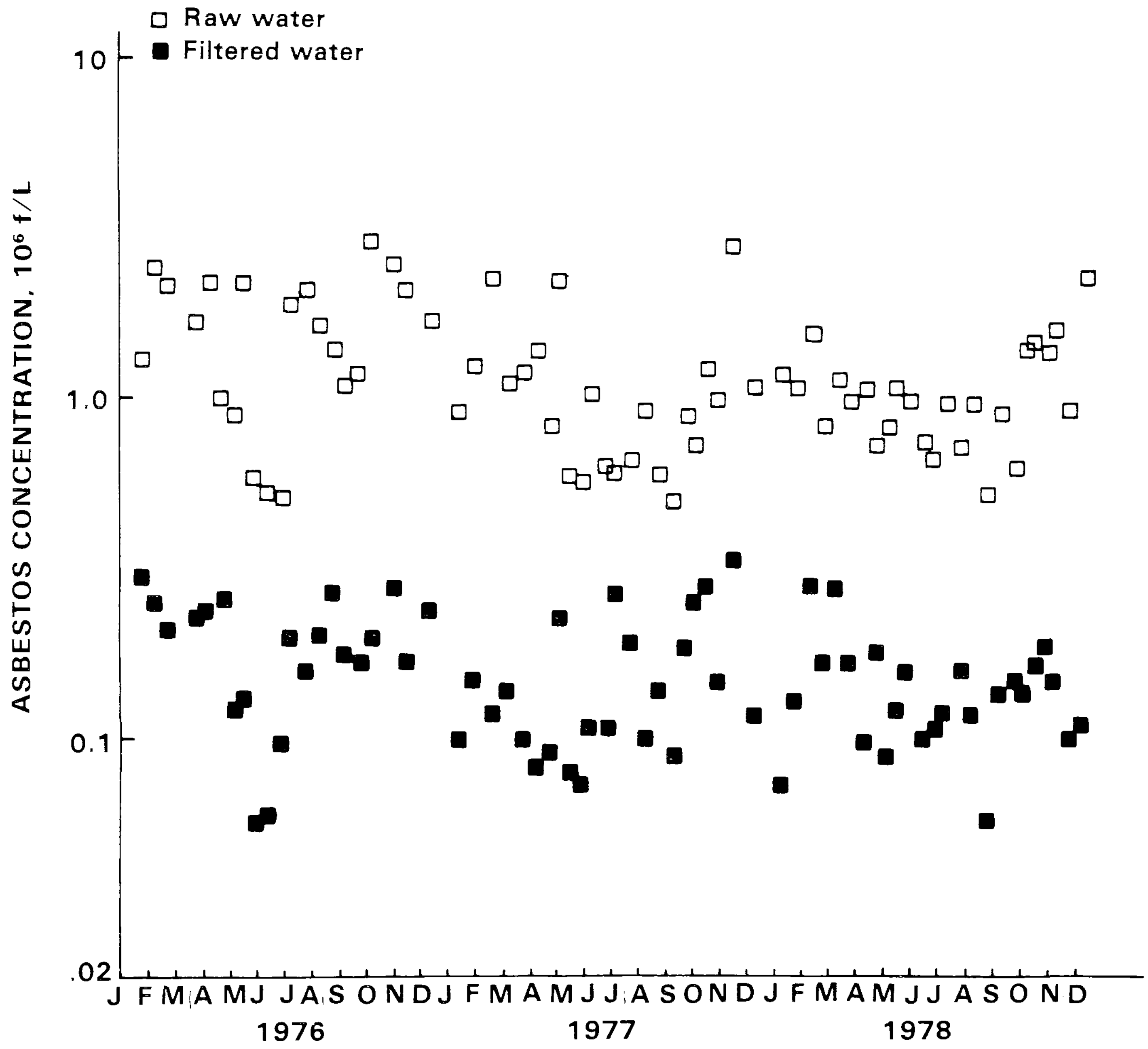


Figure 17. Chicago asbestos monitoring data — Jardine water filtration plant.

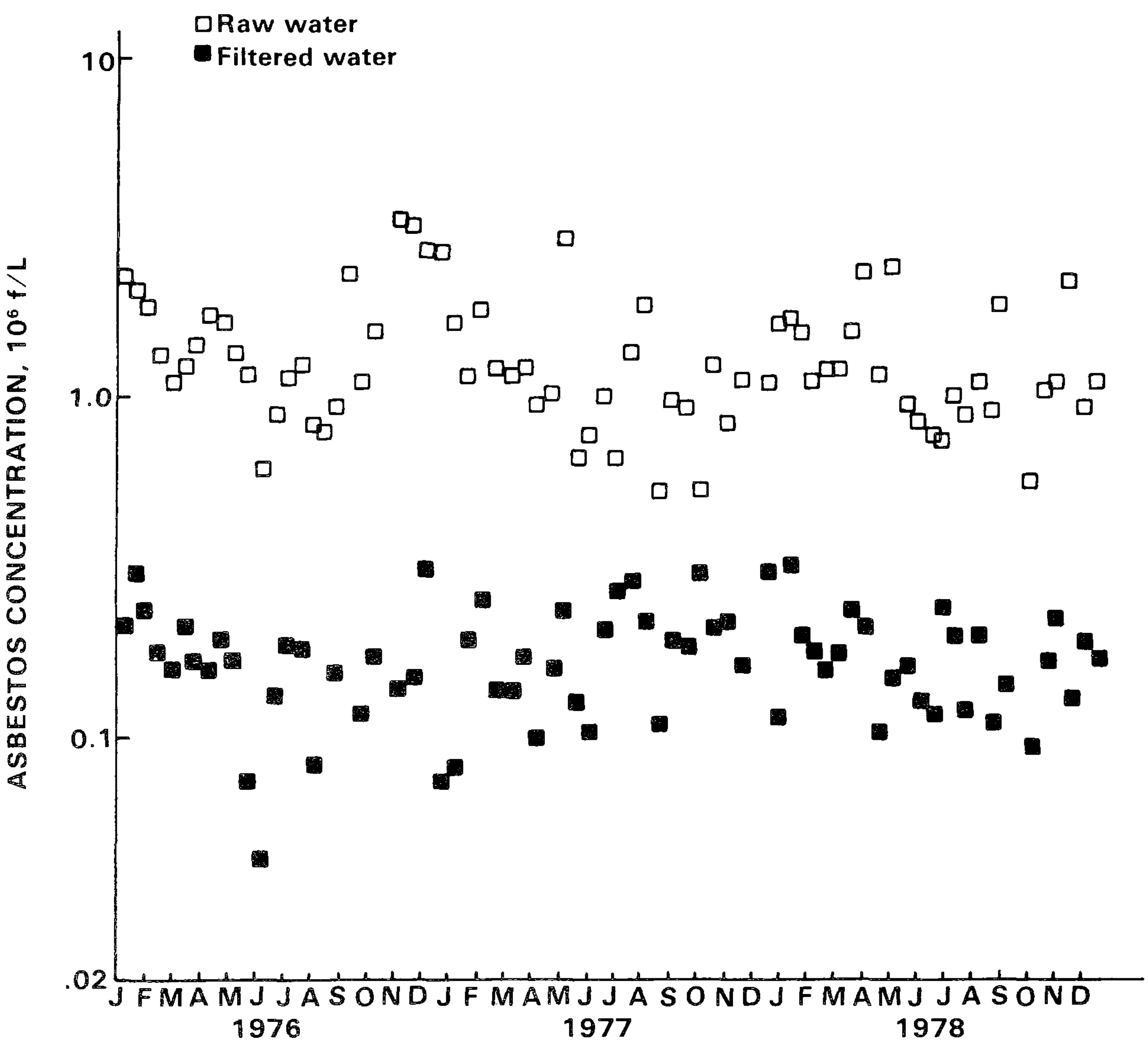


Figure 18. Chicago asbestos monitoring data — South water filtration plant.

SECTION 10

DISCUSSION

As the data for treatment plants in the literature review and results sections indicated, some treatment plants have been very effective for fiber removal, whereas others have not been effective. This section of the report will present some possible reasons for the differences and suggestions for plant operating techniques to enhance fiber removal.

MONITORING METHODS

Electron Microscope

The only method of analysis that provides positive identification of asbestos fibers is the transmission electron microscope (TEM) method. Electron microscopy is both slow and expensive. Sample analysis generally takes more than one working day, including all preparation steps, although analysis of a single sample usually does not require more than eight hours of an analyst's time. Asbestos analysis by TEM generally costs $300 or more per sample.

Because of the work load, most electron microscope laboratories (in 1979) are not able to provide results in less than three or four weeks after receipt of samples. Thus electron microscope results can not be used to monitor ongoing plant performance. They are very valuable, however, for reviewing past plant performance to decide if treatment practice was effective for fiber removal.

X-ray Diffraction

The measurements of amphibole mineral in Duluth's drinking water in 1973 were made by X-ray diffraction (2). The method is quicker than TEM analysis and costs about one-fifth to one-tenth of the electron microscope method. Amphibole mass measurements were used during the Duluth pilot plant study and have continued to be used by the EPA laboratory in Duluth.

One disadvantage of amphibole mass measurement by X-ray diffraction is that the technique measures the mass of material and not the number of fibers. The presence of some very large pieces of amphibole could greatly increase the mass detected by the technique without increasing significantly the number of fibers.

X-ray diffraction has not been used to determine the mass of chrysotile in any water supply with chrysotile contamination. Work has been done on the measurement of chrysotile by X-ray diffraction, but many technical problems must be resolved before this could provide a less-expensive method for detection of chrysotile in drinking water.

Particle Counters

A limited amount of work has been done with HIAC particle counters* in efforts to learn if numbers of larger particles (cross-sectional area equal to that of a sphere of 1.0 µm or 2.5 µm or larger) correlate with numbers of asbestos fibers. Results are limited and inconclusive and sample contamination may exist. Results from Seattle, Everett, and Duluth suggest that an in-line system with the filtered water piped directly to the counter would minimize contamination and offer the best prospects for successful application of this device.

Laser-Illuminated Optical Detector

Under a research grant from the U.S. Environmental Protection Agency, a laser-illuminated optical particle detector was developed at the University of Minnesota-Duluth. This device was described in an EPA report (49). A multiple detector system uses differences in the scattering signatures of different types of particulates to identify the particulates. This detector was used to study red clay, taconite tailings, amphibole fibers, and chrysotile fibers. Detector output was related to electron microscope counting data so that the instrument could be used to estimate the concentration of fibers in water. Fiber levels as low as 0.05×10^6 f/L could be detected. An important advantage of the detector was that results could be obtained in a matter of minutes. Even when fiber counts are very low (under 0.01×10^6 f/L) results should be available in less than one hour. This instrument provides a rapid estimate of the number of fibers in water and is capable of identifying the types of particles present if the water does not contain particles that were absent when the calibration was done.

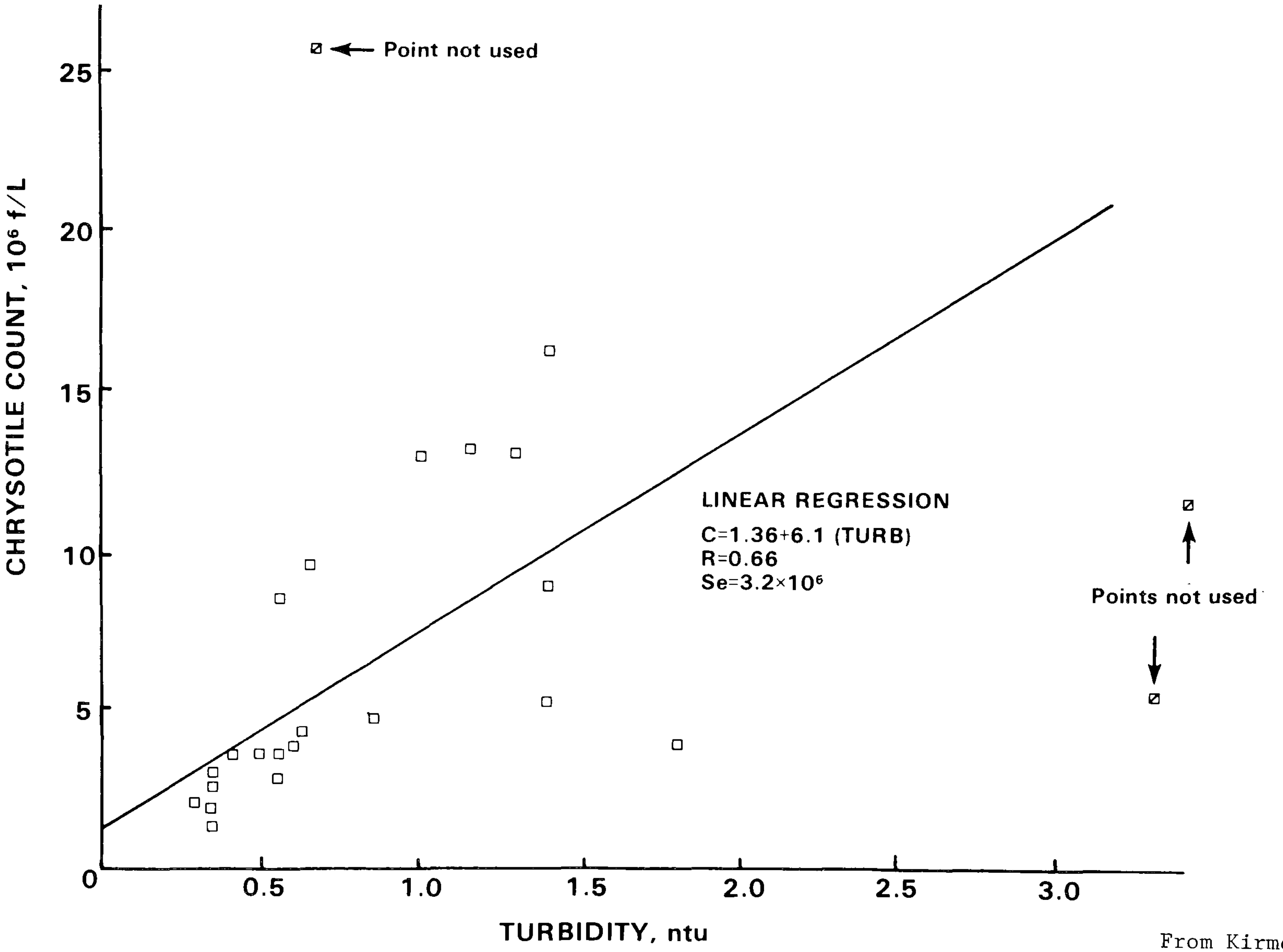
Turbidity Measurement

Of the methods described in this section of the report, turbidity measurement has perhaps the most disadvantages. Turbidimetry is not specific for asbestos fibers and can not differentiate between light scattered by fibers or clay or diatoms or any other particulates. Furthermore, Lawrence's data on measurement of asbestos fibers show that fiber counts below 10^{10} f/L are not readily detected by a turbidimeter (27). Asbestos fibers in concentrations found in most raw waters and nearly all filtered waters are too low to cause a turbidimeter to register any light scatter. A turbidimeter alone can not be used to detect and quantify asbestos fibers in drinking water.

Correlation of Turbidity and Fibers in Raw Water--

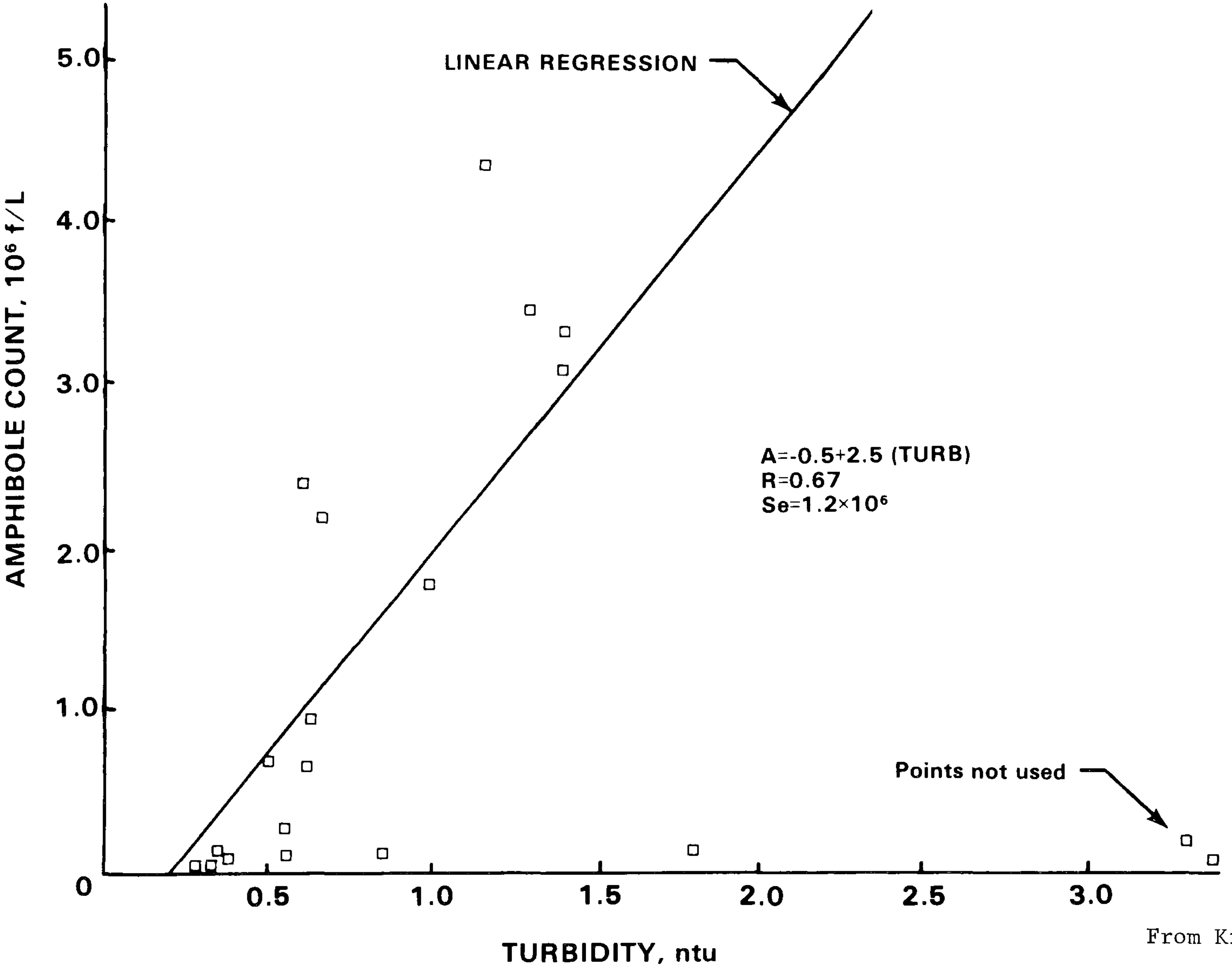
Turbidity and asbestos fiber counts in unfiltered waters may correlate weakly or very poorly. A weak relationship existed for Seattle raw water chrysotile or amphibole and turbidity (Figures 19,20). Little or no relationship was observed for amphibole fiber counts and raw water turbidity in the

*Pacific Scientific, Montclair, CA.



From Kirmeyer (42)

Figure 19. Raw water chrysotile vs. turbidity — Seattle pilot plant.



From Kirmeyer (42)

Figure 20. Raw water amphibole vs. turbidity — Seattle pilot plant.

Duluth pilot plant study (Figure 21). These figures show why trying to associate a fiber count with a given turbidity value often would not give a satisfactory estimate of the asbestos concentration.

Turbidity Measurements for Evaluating Plant Operation--

Turbidity measurements have been very useful for monitoring the filtration process even though the fibers in the filtered water do not affect the turbidimeter reading. As a monitoring device the turbidimeter is used to assess the overall efficacy of the granular media filration process,and this appears to be related to asbestos fiber removal.

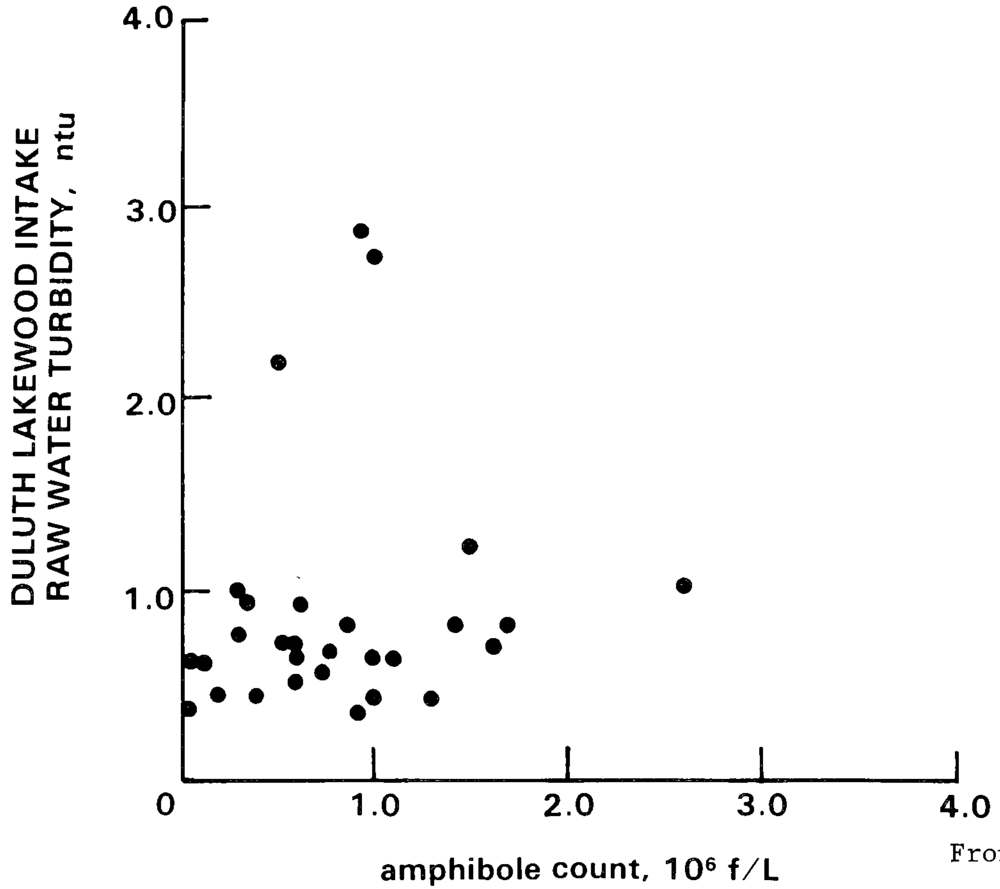
Seattle pilot plant filter run data--Kirmeyer showed that turbidity measurements could be used as an indicator of whether or not a granular media filter was removing asbestos fibers (42).

Filter runs #21 and #24 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 Figures 22 and 23.

These results indicate that when finished water turbidity was $\leq$ 0.10 ntu, then chrysotile counts were 0.34 X 10^6 f/L or less. At hour 7 of run #21 when the finished water turbidity spiked at 0.34 ntu, the finished water chrysotile rose from NSS levels up to 12.25 X 10^6 fibers/liter. High levels of chrysotile also coincided with the abrupt rise in turbidity in run #24.

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 temporarily discontinued after the first hour of operation and finished water turbidity was monitored continuously during the process. Within about 15 minutes after the pump was disconnected, the finished water turbidity began to rise rapidly. The detention time of the water in the flocculation chamber and in the free space above the filter media can be estimated at about 13.5 minutes. 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 that 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 Figure 24. These data indicate that when the alum pump was off and finished water turbidity had risen only to 0.20 ntu, a noticeable increase in chrysotile counts occurred, as compared to the very low levels previously measured.

Figure 25 provides an excellent example of how finished water turbidity and asbestos counts track during filter breakthrough. This filter run indicates that high chrysotile counts in the filtered water coincide with filter breakthrough as indicated by a rising finished water turbidity.



From Black & Veatch (12)

Figure 21. Relationship between raw water turbidity at Duluth Lakewood intake and ORF amphibole fiber counts.

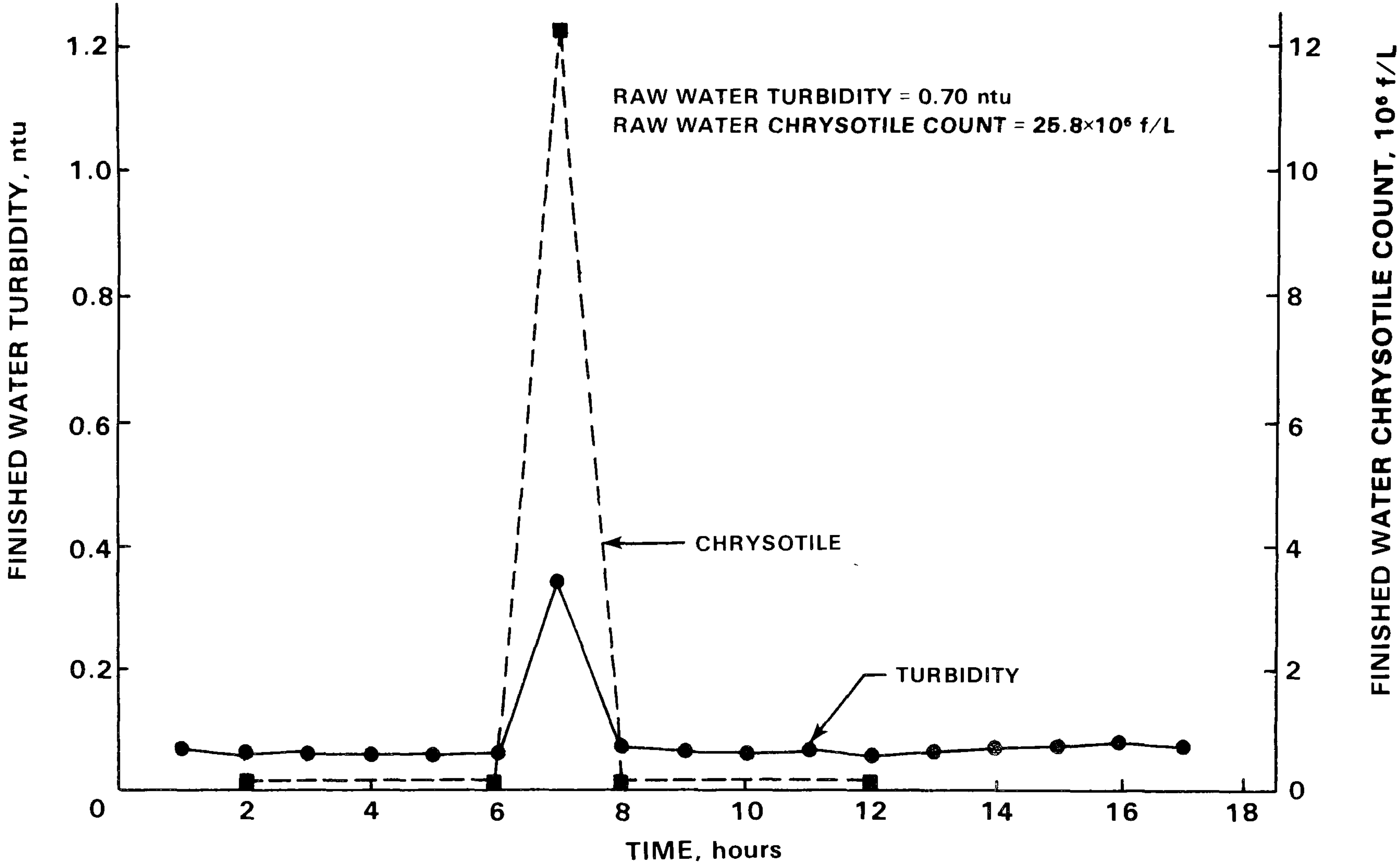
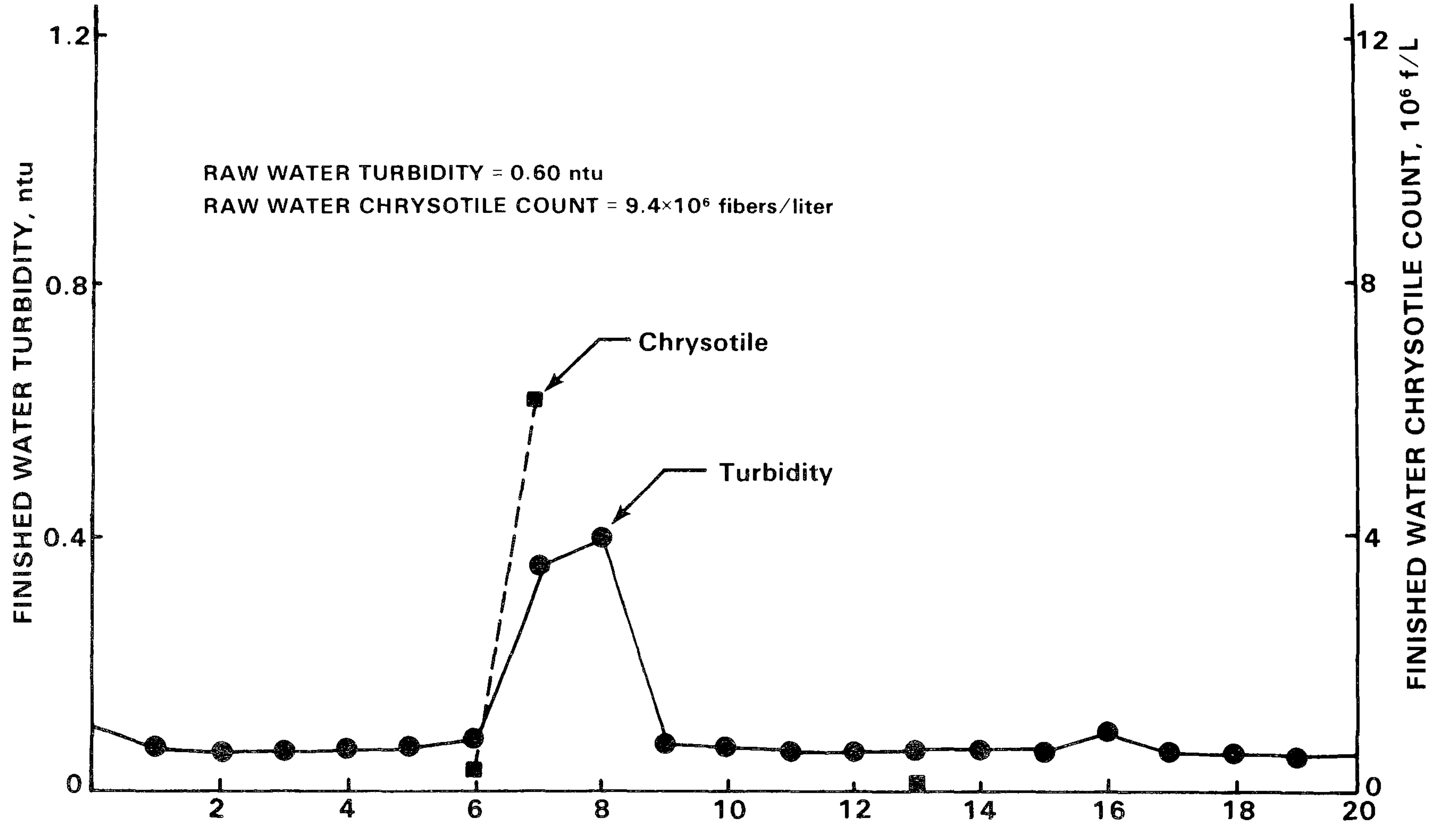


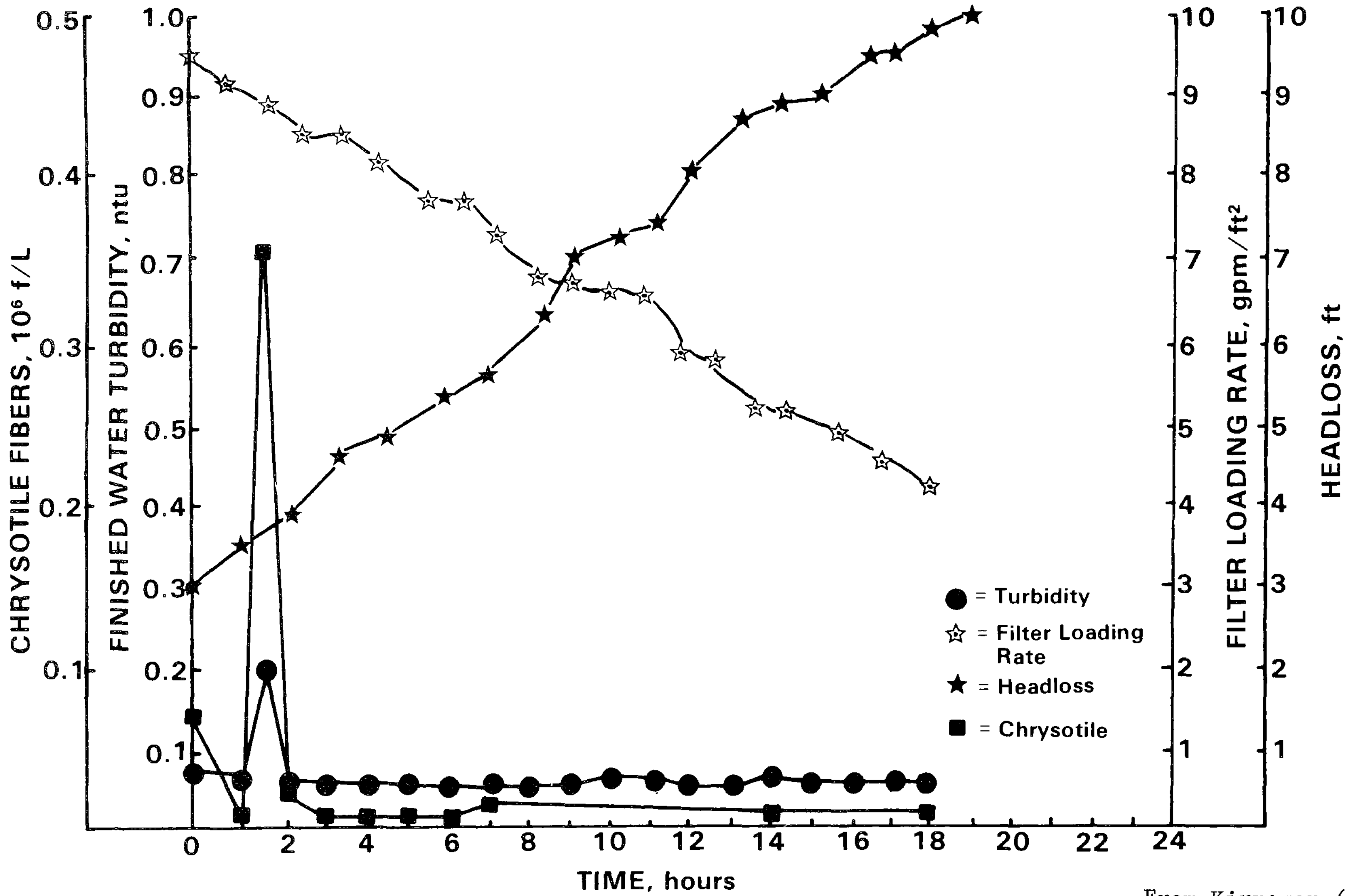
Figure 22. Finished water turbidity and chrysotile vs. time-run #21 — Seattle pilot plant.

From Kirmeyer (42)



From Kirmeyer (42)

Figure 23. Finished water turbidity and chrysotile vs. time - run #24 — Seattle pilot plant.



From Kirmeyer (42)

Figure 24. Operating data for run #174MM — Seattle pilot plant.

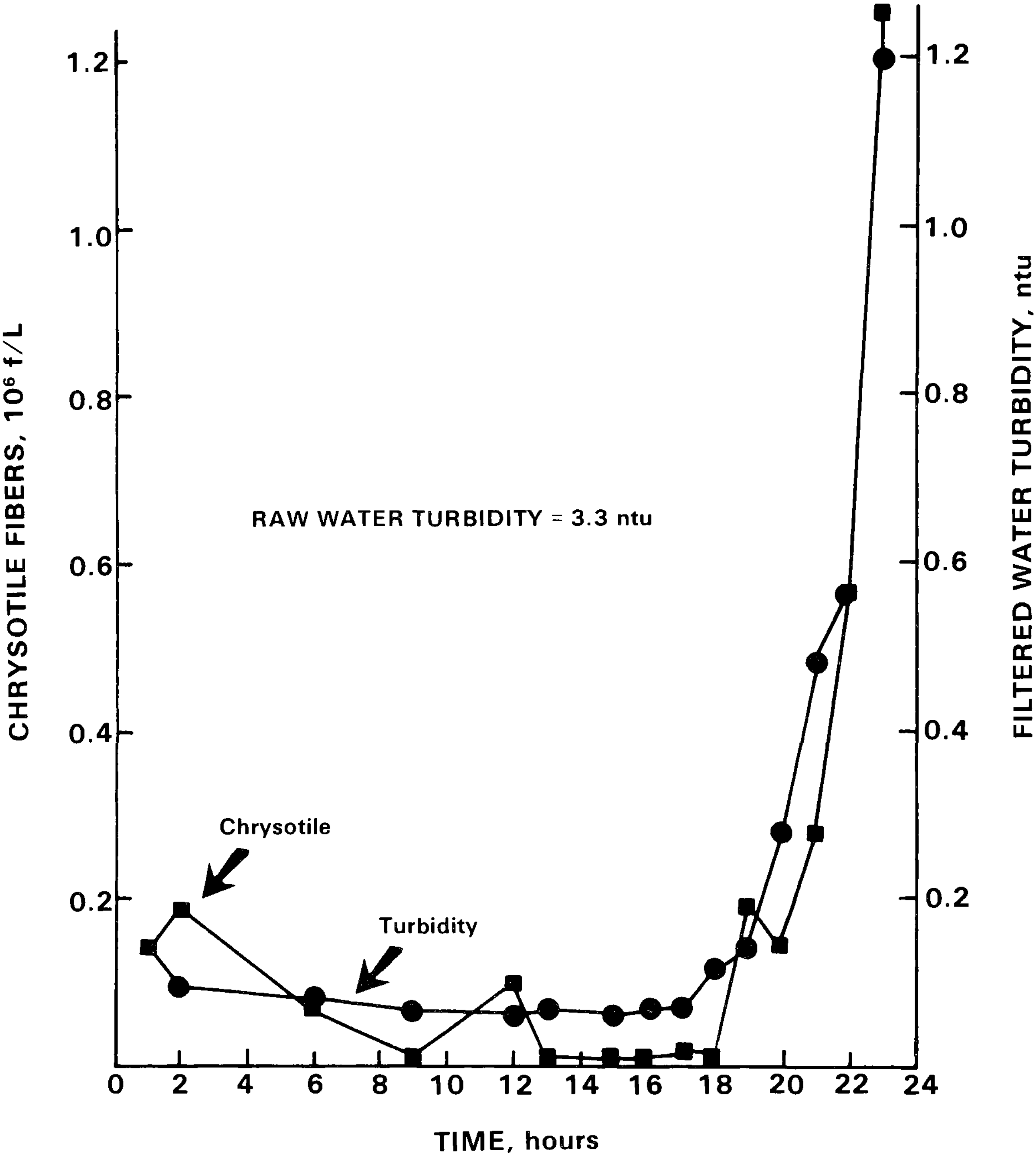


Figure 25. Finished water chrysotile counts and turbidity vs. time-run #120 — Seattle pilot plant.

From Kirmeyer (42)

Turbidity-fiber count relationship in filtered water--The nature of the turbidity-fiber relationship for filtered water could perhaps be compared to the coliform-pathogen relationship. The presence of coliforms is a signal that pathogens might be present. It is, however, not certain proof of pathogen presence and no direct proportional ratio for the two kinds of microorganisms exists. Similarly, when a raw water contains asbestos fibers, a rise in filtered water turbidity very probably is a sign of an increase in filtered water fiber count, but the fiber count can not be estimated on the basis of the abnormally high turbidity reading. Data from the Seattle study are presented in Table 42 to illustrate this. One sample with 0.24 ntu turbidity had 11 X 10^6 f/L, whereas another with 0.28 ntu had a not statistically significant count of about 0.14 X 10^6 f/L.

When a granular media filter has been operating for a period of time and has been producing a stable quality of effluent as measured by turbidity, a rise in filtered turbidity should be interpreted as a sign that some operator action is required. This may mean an adjustment of chemical doses or a filter backwash. When a granular media filter is removing a contaminant in particulate form, such as asbestos fibers, a rise in filtered water turbidity is a strong indication that the particles that had been captured within the filter are now being released.

Table 43 contains data on fiber counts during Seattle filter Runs 53 and 62. In Run 53, when the turbidity rose after nine hours of filter operation, the chrysotile count in the filtered water was nearly four times that in the raw water. In Run 62, when turbidity rose to 0.37 ntu at 16 hours, chrysotile counts in raw and filtered water were quite similar. Amphibole data for Run 62 give additional evidence that granular media filters can store and then slough particulate contaminants. Amphibole fibers were not detected in raw water or in filtered water during normal operation in this run, but when turbidity rose at hour 16, amphibole fibers that apparently had been removed and concentrated in the filter were released in a concentration high enough to be detected in the filtered water.

The sloughing and discharge of asbestos fibers from filters that previously had removed them from the raw water is a potential problem that filter plant operators must consider. At the present time, the best way to prevent the discharge of a concentrated amount of fibers into filtered water seems to be to avoid any significant rises in turbidity after a granular media filter has ripened and effluent turbidity is stable.

The extent of a turbidity rise that could cause a problem is not well defined, but in Run 53 an increase from 0.13 ntu to 0.24 ntu resulted in a forty-fold increase in the chrysotile count. For a filter producing 0.10 ntu filtered water, a rise of 0.1 ntu is probably sufficient cause to backwash the filter. Controlling the operation of a filter in this manner is being accomplished at some filtration plants, but for many others it would represent a considerable modification of operating procedures.

TABLE 42. SEATTLE PILOT PLANT CHRYSOTILE FIBER COUNTS IN FILTERED WATER WHEN TURBIDITY ROSE ABOVE 0.10 ntu

Run #	Hours Into Run	Filtered Turbidity ntu	Fibers 10^6 f/L
21	7	0.34	12.25
24	7	0.36	6.2
53	9	0.24	11.2
62	16	0.37	2.28
120	1	0.14	0.14
120	19	0.14	0.19
120	20	0.28	0.14 (NSS)
120	21	0.48	0.28
120	22	0.57	0.57
120	23	1.2	1.25

TABLE 43. RELEASE OF ASBESTOS FIBERS BY FILTERS AT SEATTLE PILOT PLANT

Run	Sample Location	Hour Into Run	Turbidity ntu	Chrysotile fibers/liter	Amphibole fibers/liter
53	RAW	9	0.50	3.0×10^6	0.70×10^6 (NSS)
53	FINISHED	3	0.13	0.27×10^6	$<0.02 \times 10^6$ (BDL)
53	FINISHED	9	0.24	11.2×10^6	1.2×10^6 (NSS)
62	RAW	16	0.35	2.52×10^6	$<0.1 \times 10^6$ (BDL)
62	FINISHED	3	0.1	0.34×10^6	$<0.02 \times 10^6$ (BDL)
62	FINISHED	9	0.105	0.24×10^6	$<0.02 \times 10^6$ (BDL)
62	FINISHED	16	0.37	2.28×10^6	0.1×10^6

From Kirmeyer (42)

GRANULAR MEDIA FILTRATION FOR ASBESTOS FIBER REMOVAL

The ability of granular media filters to remove asbestos fibers has been demonstrated repeatedly in filtration experiments at Duluth and Seattle. Operating data from the water treatment plants at Duluth, Two Harbors, and Silver Bay confirm pilot plant studies that showed that the fibers can be removed on a routine, day-to-day basis. Because a properly operated filter can reduce the concentration of asbestos fibers in water by as much as 99 to 99.9 percent, or even more in some instances, the problem of efficiently removing fibers from water becomes a problem of achieving proper filter operation. In this section of the report, operating techniques are discussed. Certain aspects of filter plant design were shown to be important in the pilot plant studies, and these are also presented.

Filtered Water Turbidity Value for Effective Fiber Removal

Turbidimeters are used to monitor filter performance in many water treatment plants. Because turbidity changes are associated with changes in the asbestos fiber concentration of filtered water under certain circumstances, turbidity and asbestos fiber count data have been analyzed in the search for a relationship between filtered water turbidity and fiber concentration. Such a relationship was found for the Seattle pilot plant and for the water filtration plants on the north shore of Lake Superior. Because of the differences in fiber counting, the 1974 Duluth pilot plant data are analyzed and discussed separately from data collected since January, 1977.

Filtered Water Turbidity vs. Fiber Count--

Duluth amphibole data--The Duluth pilot plant study (12) showed that amphibole fiber counts were likely to be at or near the detection limit when filtered water turbidity was below 0.2 ntu. In Figure 26, of the 41 BDL counts reported, 31 occurred when filtered water turbidity was 0.10 ntu or lower. Logsdon and Symons (33) recommended that quality control for filter operation at Duluth should be based on producing finished water with a turbidity of not more than 0.10 ntu with the run being terminated when the turbidity reached 0.2 ntu.

Seattle amphibole data--One of the goals of the Seattle pilot plant study was to confirm the Duluth findings. To do this the Seattle Water Department focused upon turbidity and fiber removal. A summary of the results of an extensive program of testing, sampling, and analysis is presented in Appendix B. This appendix gives turbidity and fiber count data for the pilot plant runs that were sampled for electron microscope analysis.

Review of the Seattle fiber 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%. When amphiboles were detected in the raw water and when turbidity was < 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 $> 0.01 \times 10^6$ fibers/liter, 4 or fewer fibers were counted by the analyst, which means that the results were not statistically significant. Three out of the five cases

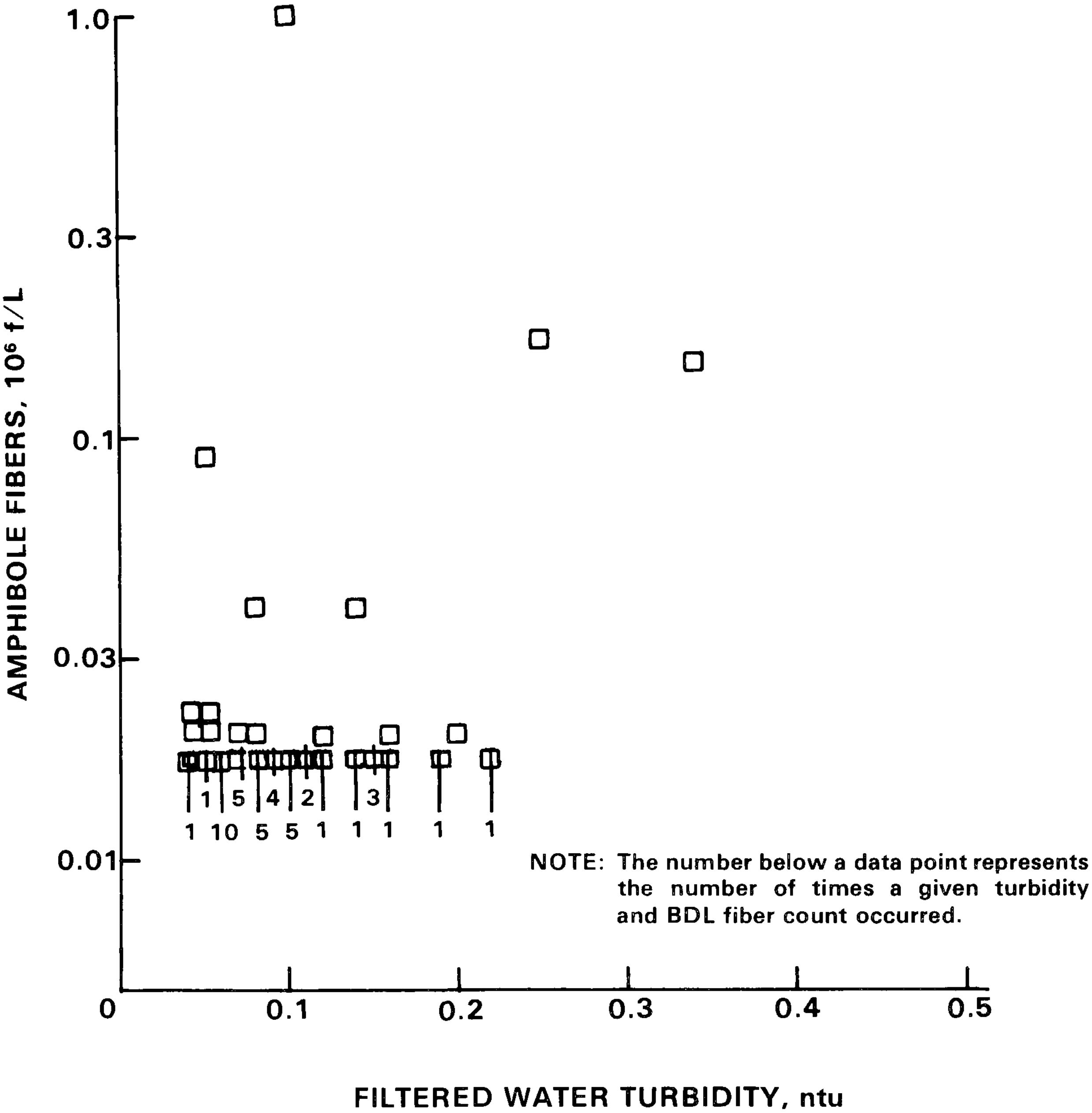


Figure 26. Effluent turbidity vs. amphibole fiber count, Duluth granular media pilot plants.

occurred when alum without lime addition was being employed as a treatment method and the other two 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 27, when the finished water turbidities exceed 0.10 ntu, amphibole counts are much higher and the data show a noticeable scatter. 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 (12).

Seattle chrysotile data-- Review of the chrysotile data listed in Appendix B indicates that although excellent removals can be achieved, it is more difficult to remove than amphibole and results are more variable. Figure 28 shows 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. Both Figures 27 and 28 are very similar to results obtained in the Duluth pilot plant study.

Turbidity and Probability of High Fiber Counts--

Lake Superior results-- In the operation of the Lakewood Filtration Plant at Duluth, filtered water turbidity for plant monitoring samples was routinely 0.04 to 0.06 ntu. The lower turbidity values approach the detection limit for the nephelometer employed, and asbestos results are frequently at or near the detection limit too. A direct comparison of filtered water turbidity vs. fiber count would not be very useful, so another approach was taken (13). Filtered water fiber count data from Duluth were grouped according to turbidity and operating conditions. Differences in the fiber counts for the data groups are apparent in Figure 29, which shows the probability of occurrence of fiber counts for the various operating conditions. Lowest fiber counts were likely to occur during routine operating conditions when turbidity was below 0.10 ntu. Highest counts were likely to occur when filter rate changes took place and turbidity was 0.10 ntu or greater.

In this figure and in Figures 30 and 31, when a BDL fiber count was reported, the data point was plotted at the detection limit. This resulted in clusters of data points at certain fiber count values and is a conservative approach to data analysis, because actual fiber counts could have been below the BDL values.

In this report an effort is made to extend this comparison to the Silver Bay plant. Data from this plant are included in the probability plots of Figure 30. In this figure, data are divided according to filtered water turbidity (equal to or below 0.10 ntu vs. greater than 0.10 ntu), and amphibole fiber counts were tabulated in order. Figure 30 shows the probability of occurrence of fiber count according to the circumstances of sampling as well as filtered turbidity. The samples likely to have the highest fiber counts were those from the new 10 gpm pilot plant with turbidity above 0.10 ntu. Samples from the treatment plants with turbidity above 0.10 ntu can be seen to have a likelihood of higher amphibole counts than samples

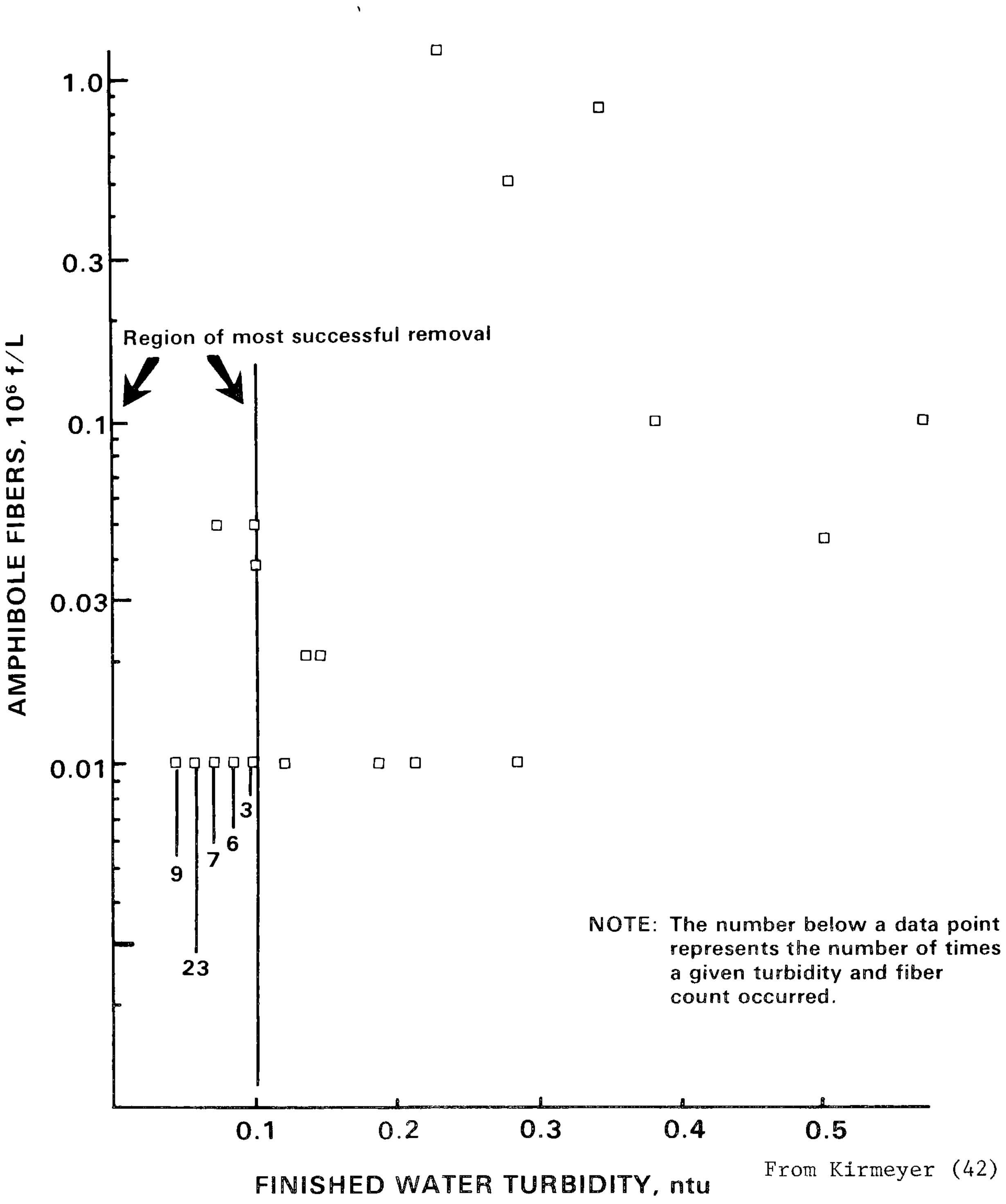
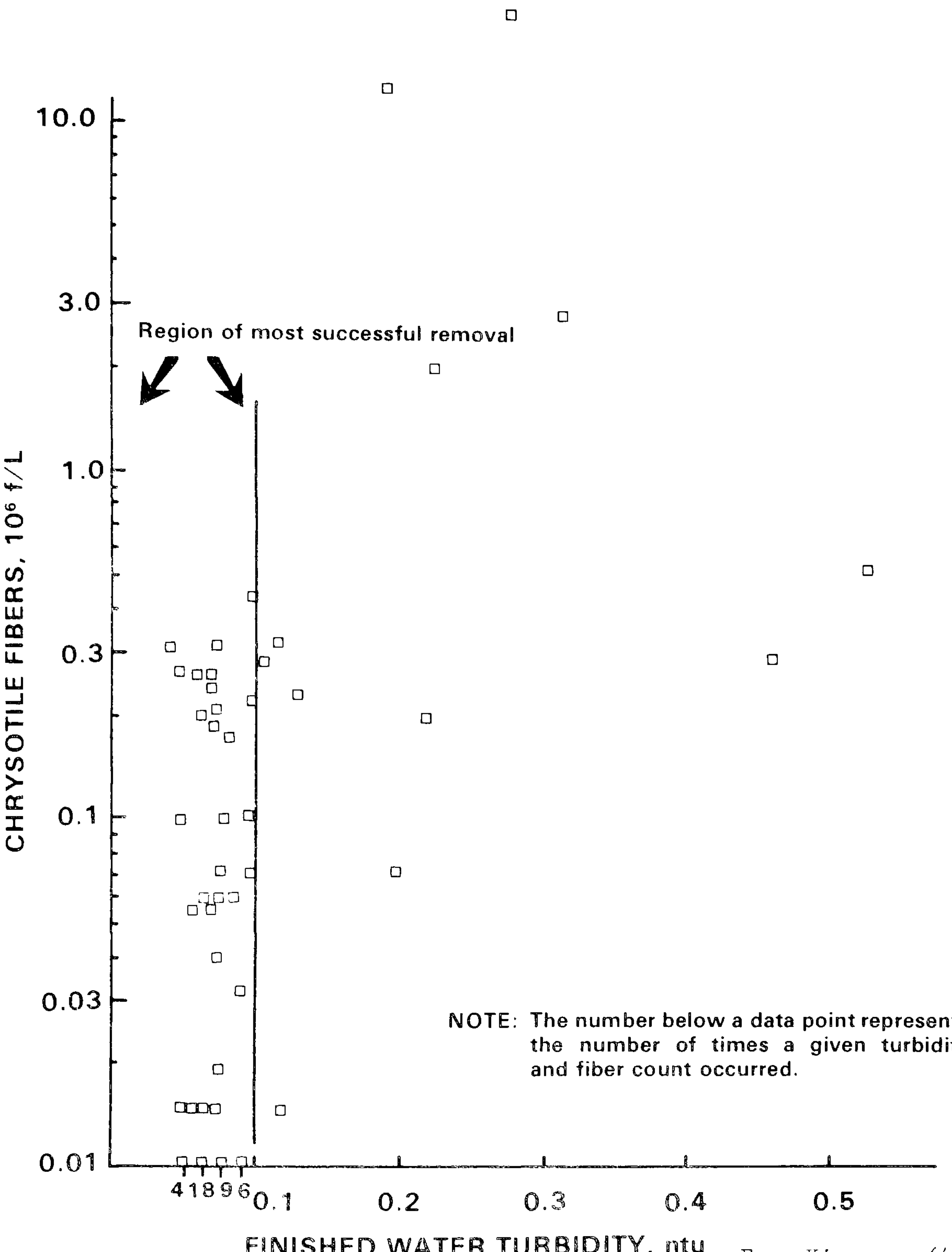


Figure 27. Amphibole count vs. finished water turbidity — Seattle pilot plant.



From Kirmeyer (42)

Figure 28. Chrysotile count vs. finished water turbidity —Seattle pilot plant.

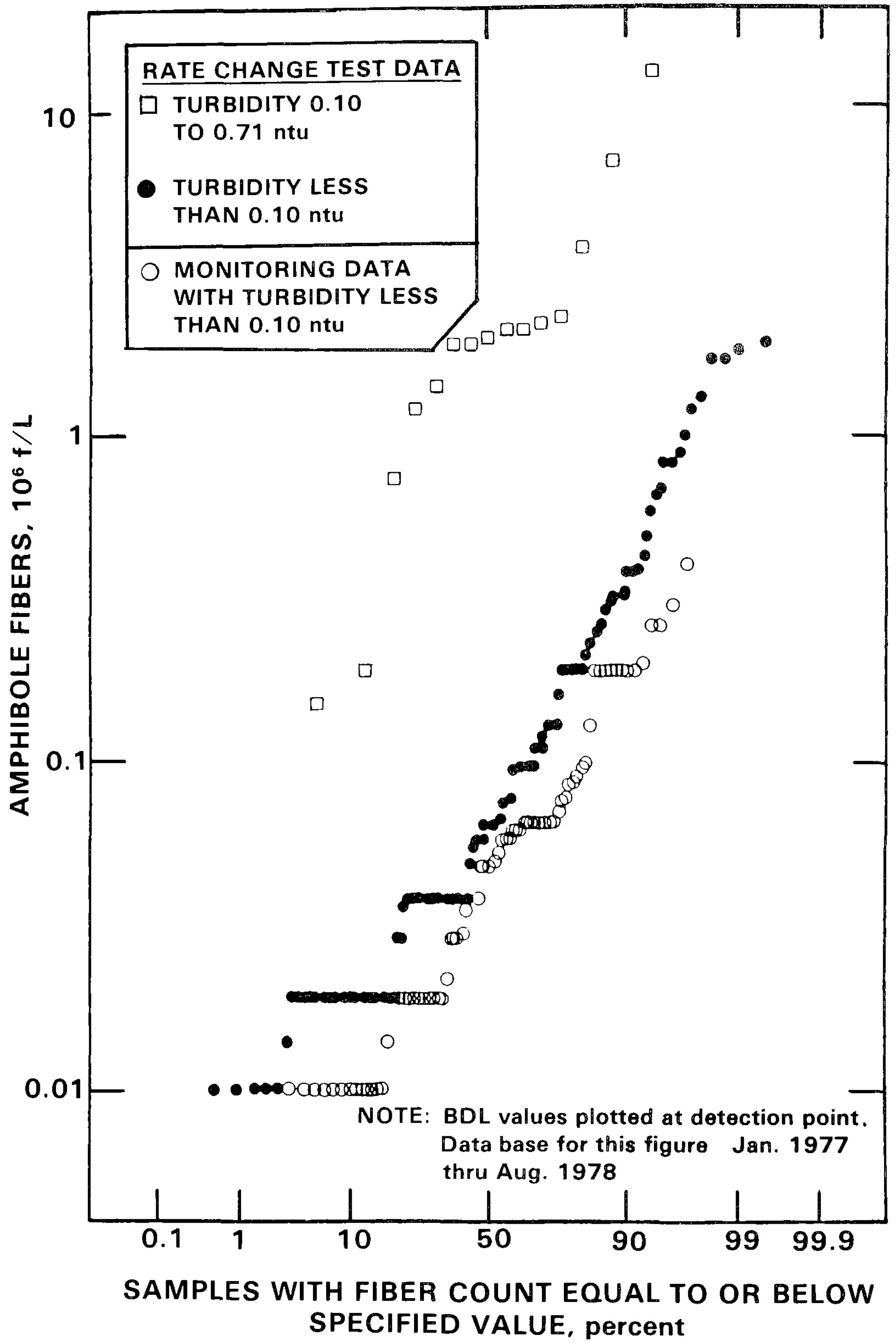


Figure 29. Comparison of frequency distributions of fiber counts of filtered water sample groups, Lakewood Plant — Duluth.

From Logsdon, Schleppenbach and Zaudtke (13)

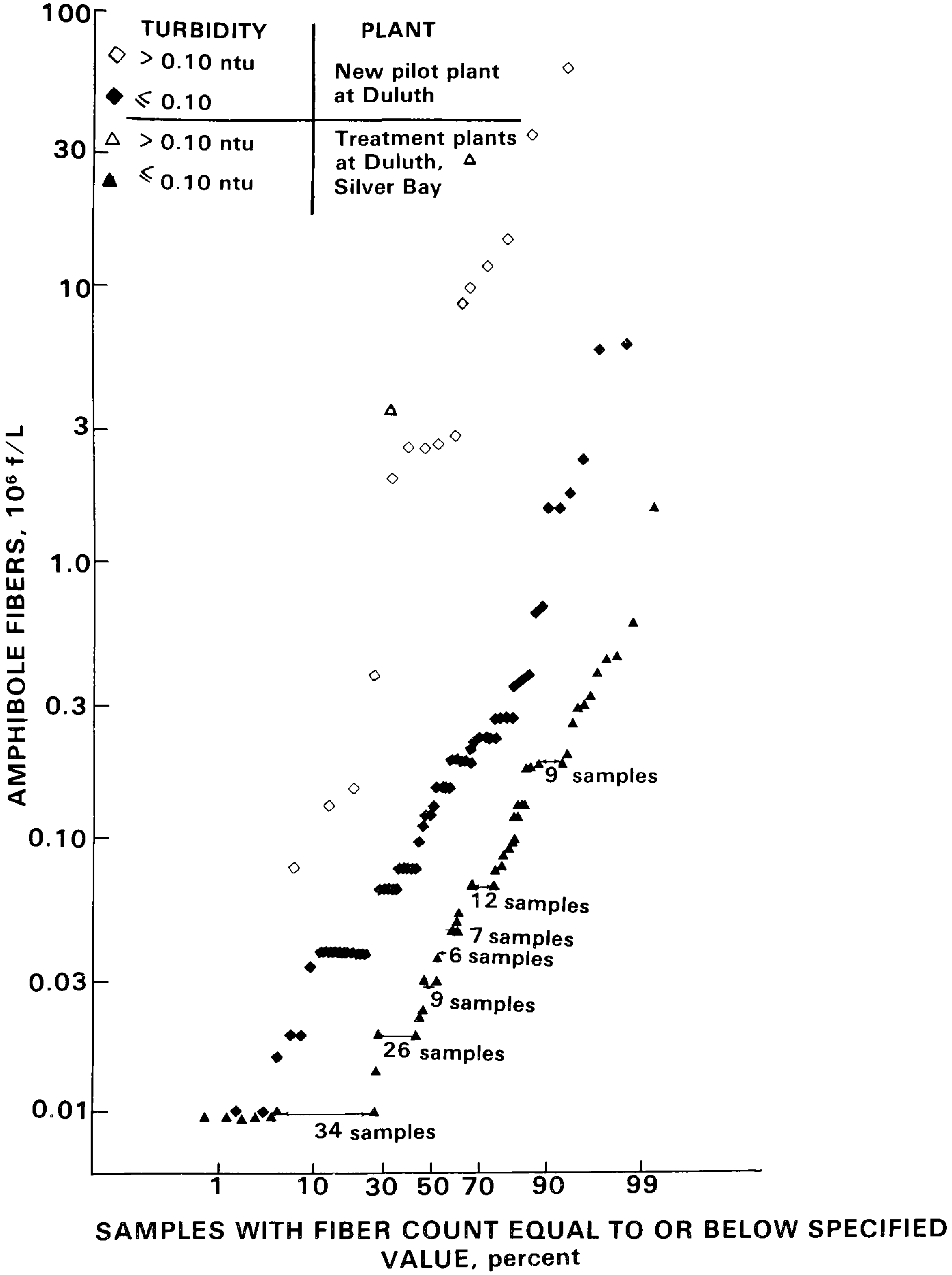


Figure 30. Frequency distributions of amphibole fiber counts for filtered waters from plants on Lake Superior. Data base — January 1977 thru June 1979

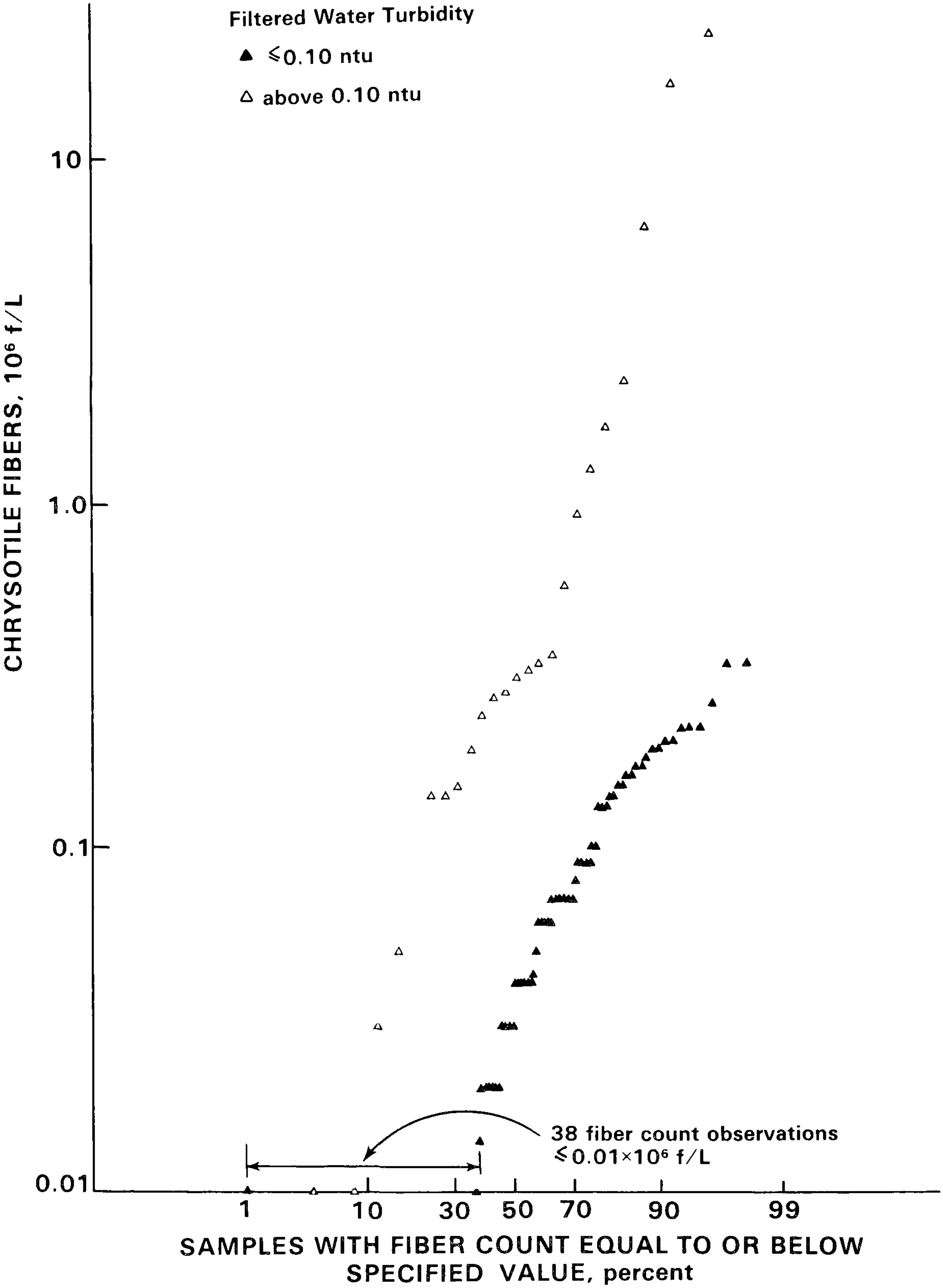


Figure 31. Frequency distribution of chrysotile fiber counts for filtered water sample groups — Seattle pilot plant.

taken at the treatment plants when turbidity was 0.10 or less. The high turbidity monitoring data consist of two samples taken at Duluth when an upset of coagulation chemistry caused very high fiber counts. These samples were not taken during a special rate change test so they were included as high turbidity monitoring samples.

Figure 30 clearly shows that lower fiber counts are more likely to occur when the turbidity of filtered water is 0.10 ntu or lower. In this turbidity range, amphibole fiber counts were 0.03 X 10^6 f/L or less half of the time for the filtration plants. For this reason, the recommendation is made that water filtration plants treating Lake Superior water should attempt to produce filtered water meeting a goal of 0.10 ntu.

Seattle results--Kirmeyer (42) showed a similar trend with Seattle chrysotile data. Figure 31 can be used to estimate what levels of chrysotile were present at any given time when finished water turbidity was $\leq$ 0.10 ntu or above 0.10 ntu. For example, 50 percent of the time when turbidity was $\leq$ 0.10 NTU, finished water chrysotile counts were $\leq$ 0.03 X 10^6 fibers/liter. When turbidity was > 0.10 ntu, 50 percent of the time, chrysotile counts were $\leq$ 0.3 X 10^6 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 $\leq$ 0.10 ntu. In conclusion, chrysotile fibers can consistently be removed to levels which are NSS if certain operating conditions are met.

As a further test of the relationship of fiber removal and filtered water turbidity, a statistical analysis was performed using Seattle data in Appendix B. Fiber removal percentages were calculated, and data were placed into four fiber removal categories: > 99.0 percent, > 95.0 to 99.0 percent, > 90.0 to 95.0 percent, and 90.0 percent or less. Then the number of each of these samples with filtered water turbidity above 0.10 ntu and 0.10 ntu or less was placed in a table (Table 44). This was done separately for amphibole and chrysotile results. The hypothesis in each case was that the frequency of observation of the various fiber removal percentages was independent of filtered water turbidity. The results were statistically different from the expected (null hypothesis) at the 0.01 level for both amphibole and chrysotile. Thus the Seattle results also showed that the degree of fiber removal is related to filtered water turbidity.

Filtered Turbidity and Fiber Reduction at Seattle--

In another test of the relationship of fiber removal and turbidity, fiber removal data for chrysotile were placed into the four percentage categories used in the chi square analysis. Then data for each category were arranged in order according to filtered water turbidity. The results were plotted on logarithmic probability paper, showing the percentage of samples of a given fiber removal having turbidity equal to or less than a certain value. Results are shown in Figure 32. This figure clearly shows that higher filtered water turbidities are associated with lower percentages of chrysotile removal.

Because the relationship shown in Figure 32 is very important, a careful explanation of what it does show and what it does not show is appropriate. The figure does not show that the percentage of chrysotile removal is always higher when turbidity is lower, because this is not what happened in the pilot plant

TABLE 44. CHI SQUARE ANALYSIS OF FIBER REMOVAL AND TURBIDITY - SEATTLE

Chrysotile Data

Turbidity of Filtered Water	> 99.0%	> 95.0 to 99.0%	> 90.0 to 95.0%	≤ 90.0%
	Fiber Removal Percentage Categories			
	Number of samples with fiber removal percentage in category			
≤ 0.10 ntu	48	43	7	3
> 0.10 ntu	2	7	6	9

$\chi^2 = 38.5$

Amphibole Data

Turbidity of Filtered Water	> 99.0%	> 95.0 to 99.0%	> 90.0 to 95.0%	≤ 90.0%
	Fiber Removal Percentage Catagories			
	Number of samples with fiber removal percentage in category			
≤ 0.10 ntu	6	9	0	0
> 0.10 ntu	0	0	1	2

$\chi^2 = 18.0$

study. For example, one filtered water sample with a removal percentage of 90 percent or less had a turbidity of 0.06 ntu. Some fluctuation occurs from time to time, partly because of the variation in analytical methods and partly because of the variation in treatment efficacy. Figure 32 shows the trends that occur as many samples are taken over a period of time. It shows the distribution of filtered water turbidities for a given level of fiber removal.

An example of how the figure could be used follows. If, on the basis of raw water data, a water department chose to operate a filtration plant to attain at least 99 percent reduction in the fiber count, producing water with a filtered turbidity of 0.10 or less would be necessary 95 percent of the time. Filtered water turbidity, over a long period of time, could be allowed to exceed 0.10 ntu only 5 percent of the time in order to consistently attain 99 percent fiber reduction. On the other hand, if only a 90 percent reduction of chrysotile was needed, turbidity would have to remain below 0.35 ntu 95 percent of the time. If chrysotile removal was of no consequence, and less than 90 percent was acceptable, meeting the 1 ntu limit of the Drinking Water Regulations could be an operating goal.

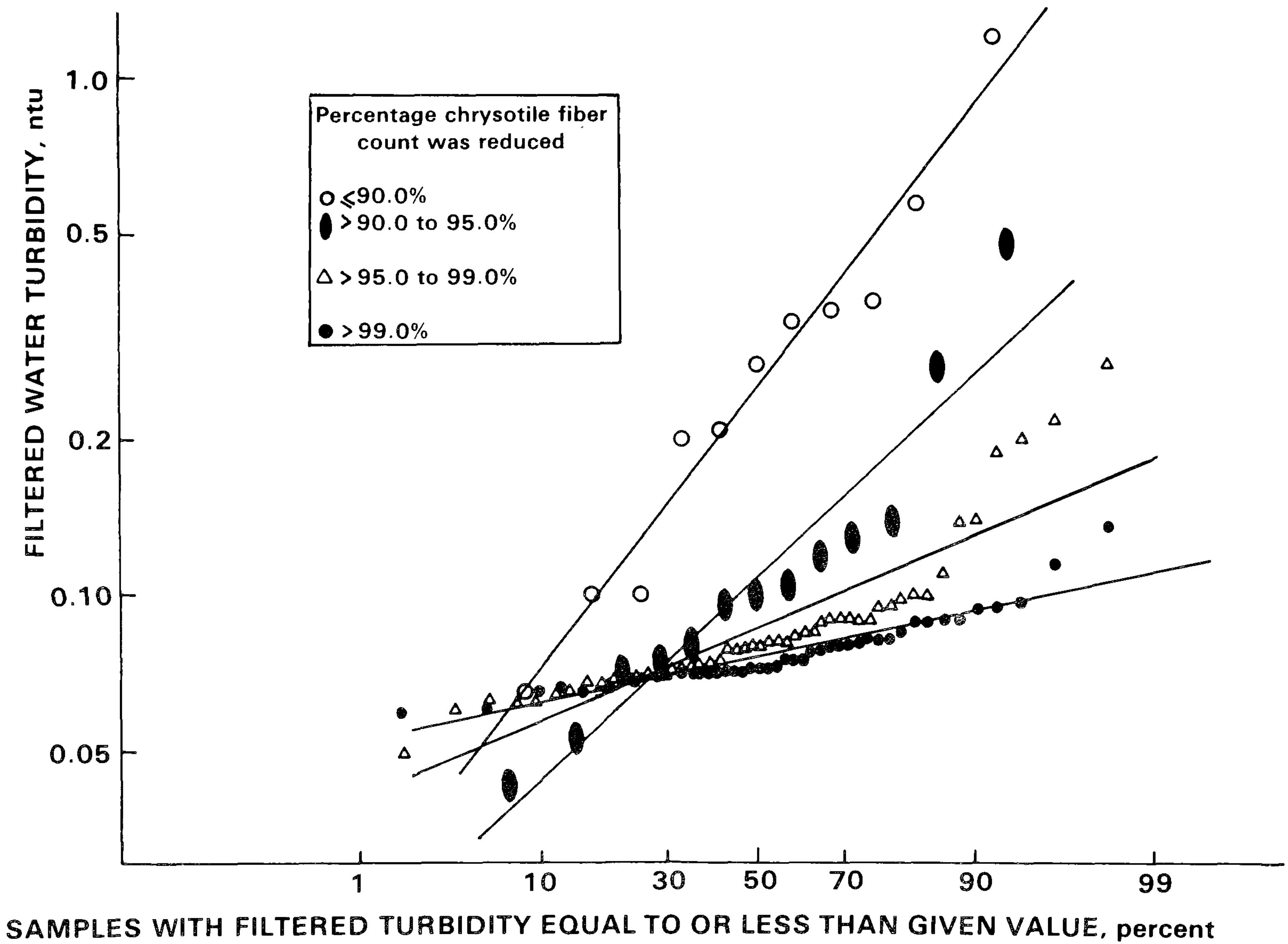


Figure 32. Relationship of turbidity and chrysotile removal by granular media filtration — Seattle pilot plant.

Aspects of Plant Design and Operation

Adequate Pretreatment Unit Processes--

Water must be properly conditioned before filtration if the filter is to achieve its maximum treatment efficiency. The need to prepare water for filtration is generally acknowledged by sanitary engineers, and much research has been conducted on rapid mix, flocculation, and sedimentation. Some aspects of pretreatment were investigated in filtration research on asbestos fiber removal.

Rapid mixing--Rapid mix variations were tried at Duluth, and the three-stage rapid mix at the filtration plant was designed on the basis of pilot plant studies. Rapid mixing was studied in greater depth at Seattle. Adequate head is available at Seattle, so in-line mixers were used in the pilot study. A comparison of back mixers and in-line or static mixers was made. The usual cause for run termination with static mixers was excessive head loss, whereas use of back mixers resulted in run termination because of turbidity breakthrough. Because control of turbidity breakthrough is very important, and head is available to permit use of static mixers, in-line or static mixers would probably be used if a full scale plant is built at Seattle.

Flocculation--The effect of flocculation was studied in Seattle by conducting a series of filter runs with and without the flocculator. The results in Table 26 showed that flocculation greatly increased the length of filter runs, in terms of operating hours when the water quality goal was met. Preconditioning by both rapid mixing and flocculation resulted in production of lower filtered water turbidity. Some runs in the rapid mix-filtration mode had no filtered water with turbidity equal to or below 0.10 ntu, and so had no hours of production of acceptable water quality.

Similar results with Cascade Mountain water were observed in the Everett pilot plant study (31). Watkins et. al. reported that when raw water turbidity was high (10-20 ntu in this case) filtration preceeded by rapid mixing and flocculation (direct filtration) was more effective than filtration preceeded by rapid mix only (in-line filtration).

Sedimentation--Sedimentation for asbestos fiber removal has been given little consideration because the pilot plant studies conducted so far have been conducted with clear water sources that did not require sedimentation for effective filtration. Sedimentation was studied to a limited degree at Everett (31), and the Duluth filtration plant can use this process, and in fact does so a majority of the time.

Because the purpose of sedimentation is considered to be the same as that of pretreatment processes for direct filtration - preparation of raw water for filtration - emphasis in asbestos sampling has been on raw and filtered water quality. Only limited sampling to evaluate asbestos removal in the sedimentation process has been done. Canadian pilot plant studies (29) showed as much as 60 to 80 percent removal of spiked chrysotile in the sedimentation process. Two sets of samples collected at Philadelphia show 60 and 90 percent reduction of chrysotile. Philadelphia data include the effect of storage in presedimentation basins at the Torresdale and Belmont plants.

Even though primary concern is on filtered water fiber count, the amount of asbestos fibers removed in sedimentation vs. granular media filtration may be of interest. For example, decisions on treatment, disposal or recycle of backwash water would involve consideration of asbestos fiber levels in the wash water. Decisions on water plant sludge disposal may be affected by concern for the fiber content of the sludge and the need to avoid recontaminating the environment with the fibers after they have been removed from drinking water. The fate of coagulated fibers in filter washwater or sedimentation basin sludge is not clearly defined at this time.

Process Control--

In order for the necessary treatment processes, described in the previous section, to remove asbestos fibers at maximum efficacy, they must be operated properly. Careful control of water chemistry is essential for attaining effective coagulation and filtration. Two key elements of effective coagulation are control of pH and use of the correct doses of coagulants and filter aids. The optimum combination of treatment chemicals will vary from plant to plant as well as from time to time at one plant. Techniques for determining appropriate chemical doses have been discussed in the literature for many years. This report will consider how process control affects fiber removal.

pH control--The necessity for careful control of pH was shown by Kirmeyer (42). Figure 8 shows the effect of pH on filtered water turbidity and aluminum content when the primary coagulant was alum. Kirmeyer concluded that pH should be between 6.1 and 6.7 pH units to treat Tolt Reservoir water and meet the goals of 0.05 mg/L of aluminum and 0.10 ntu turbidity. He stated, "... pH is a very critical factor in the destabilization of Tolt water." (42)

Control of pH is also very important for plants treating Lake Superior water. At Duluth the optimum pH for treatment is influenced by the raw water temperature, ranging from 7.2 or 7.3 at 1°C to 7.05 at 7°C and 6.8 at 13°C. When sedimentation is employed, a deviation of $\pm$ 0.1 pH unit from the optimum value is acceptable. For filtration without sedimentation, plant operators try to maintain pH within $\pm$ 0.05 unit of the optimum value.

Use of adequate treatment chemical dose--In addition to the need for careful control of pH during coagulation, another very important aspect of treatment process control is maintaining the proper doses of treatment chemicals. Polymers generally have a range of concentration that gives optimum efficacy, with reduced effectiveness resulting from either an overdose or an underdose of coagulant aid or filter aid. Inorganic coagulants must be used in doses adequate to assure that particulates are destabilized before filtration.

When very clear water (close to 1 ntu) is filtered, meeting the 1 ntu Maximum Contaminant Limit for turbidity can sometimes be accomplished without the addition of coagulant chemical. Often 1 ntu filtered water can be produced with a very small coagulant dose, such as 2 to 5 mg/L of alum. Producing very low turbidity filtered water, 0.10 ntu or below, requires higher doses of treatment chemicals and more careful filter operation.

Data available now suggest that the turbidity-asbestos relationship holds only for waters treated with enough coagulant either to agglomerate particles so they will settle or to destabilize all or nearly all of the particles in the raw water so they will be removed in the filter. San Andreas plant data (Table 35) show that when very low coagulant doses or no coagulants were used, fiber counts were in the range of 1 to 2 X 10^6 f/L even though filtered turbidities were 0.1 to 0.3 ntu. Kirmeyer (42) also reported that use of a low alum dose (6 mg/L) resulted in filtered water turbidity of 0.20 ntu but a chrysotile count of 1.6 X 10^6 f/L. Apparently filtration plant operators trying to maximize asbestos fiber removal should not try to minimize application of coagulant chemical.

A review of Chicago data suggests that the use of low doses of coagulant chemical can result in the removal of a large portion of the asbestos fibers (70 to 90 percent usually), but the relationship between turbidity and fiber count is weak or non-existent when less than optimum coagulant doses are used. Since 1976, typical coagulant use at the Jardine Water Filtration Plant has been in the range of 2 to 8 mg/L of alum plus 0.2 to 0.4 mg/L of cationic polymer as a coagulant aid. At the South Water Filtration Plant typical alum doses range from 2 to 8 mg/L, with 0.1 to 0.3 mg/L of cationic polymer generally used. These doses are not now nor ever have been designed specifically for asbestos fiber removal and are lower than doses of chemical used successfully for asbestos removal at Lake Superior (10 to 15 mg/L of alum and 0.05 to 0.1 mg/L of nonionic polymer). Chemical doses employed at Chicago result in production of filtered water that has a turbidity of 0.15 to 0.25 ntu most of the time, although occasional samples may be as low as 0.10 ntu or as high as 0.35 ntu. The turbidity limit set by Chicago was intended to keep the distribution system clean, and this has been in effect for two decades.

That the chemical doses used are not intended to destabilize all of the particles in the raw Lake Michigan water is possibly shown by the variation of filtered water turbidity. It is also evident in the lack of chrysotile counts below detectible limits (BDL) at Chicago. BDL counts were frequently observed at Seattle and Duluth, where the higher coagulant chemical doses used resulted in lower filtered water turbidity. Lake Michigan water at Chicago is at times as clear as Lake Superior (1 ntu), but the Chicago filtration plants use lower doses of coagulant chemicals than filtration plants at Duluth, Two Harbors and Silver Bay.

The differences in chemical use at the two locations are related to variations in raw water quality, water quality goals, and economics. Because of the low fiber count in filtered water at Chicago (0.1 to 0.3 X 10^6 f/L), and because EPA has not established any limit for asbestos fibers in water, management in Chicago does not now (Fall, 1979) see any need or reason to concern itself about asbestos removal. In contrast, treatment plants on Lake Superior must treat water with amphibole fibers often in the 10 to 100 X 10^6 f/L concentration range so deliberate efforts are made to maximize fiber removal.

The turbidity goal at Chicago, 0.2 ntu, is well below the 1 ntu Maximum Contaminant Level for turbidity, but above the 0.10 ntu goal recently established for Duluth, Silver Bay and Two Harbors. Filtered water with 0.10 ntu turbidity could be produced at Chicago. However, because of the large and presently difficult to justify extra cost for chemicals this is not done.

The Chicago monitoring data show that coagulant doses that produce water that always meets the 1 ntu turbidity MCL may not achieve maximum asbestos fiber removal.

Filter Design--

A number of factors related to filter design have been observed or evaluated with respect to fiber removal. These include type of filter media, rate of filtration, type of rate control, and depth of water over the media. These are discussed in this section of the report.

Media--The various kinds of granular media generally used for water filtration have been shown to remove asbestos fibers. Conventional rapid sand filters operated at 2 gpm/sf (like those at Philadelphia) are seldom chosen by design engineers, because of the advantages and benefits of filtration with dual or mixed (tri) media. Therefore, efforts to evaluate filter media have been concentrated on dual and mixed media.

Dual and mixed media were compared in the 1974 Duluth pilot plant study. When Black & Veatch designed the filtration plant at Duluth, mixed media was selected. Dual media was placed in one of the four filters at the Lakewood plant, however, so a full-scale comparison could be made. Results suggest that in instances when filtered water quality deteriorated as a result of a filtration rate change, the quality of the mixed media filter effluent was generally better than the quality of the dual media filter effluent.

Kirmeyer compared dual and mixed media for both asbestos fiber removal and water production efficiency in Seattle. Comparisons for fiber removal involved both coarse and fine dual and mixed media. Details were given by Kirmeyer (42). In the fiber removal evaluation, two sets of three simultaneous filter runs were carried out, and 45 water samples were analyzed for asbestos. Kirmeyer concluded that under normal operating conditions, all of the different media tested were equally effective for asbestos fiber removal.

Concerning water production, Kirmeyer found little difference in net water produced per day for dual media and mixed media in a range of filtration rates from 5.5 gpm/sf to 7.5 gpm/sf. Data on water production efficiency are likely to be specific for the raw water source, so pilot plant tests with local water would be needed before a decision could be made on media types and water production efficiency at other locations.

Rate and rate control--During the 1974 pilot plant study in Duluth, the filters were operated in a flow range from 2 to 8 gpm/sf, but only a limited number of runs with rates above 4 gpm/sf were sampled for asbestos fibers. On the basis of the limited data, Black & Veatch concluded that filtration at 5 gpm/sf would be effective for amphibole fiber removal (12). In the Seattle pilot plant study, filtration rates as high as 10 gpm/sf were found to be effective for asbestos fiber removal.

At Seattle, filters were operated in both declining rate mode and constant rate mode. Both modes were effective for asbestos fiber removal. Selection of type of rate control for a treatment plant would probably be influenced by factors such as experience of the design engineer with variable and constant rate control and willingness of state regulatory engineers to approve variable rate filtration. One possible advantage of variable rate filtration is that abrupt rate changes are avoided. As noted before, Duluth studies of rate changes showed that fiber counts could increase during abrupt rate increases so these disturbances should be prevented to the extent possible.

Air binding of filters--In pilot plant studies at both Duluth and Seattle, air binding of the filters occurred, as indicated by air bubbles rising out of the filter media when the filters were shut off at run termination. In both locations the raw water was cold and nearly saturated or supersaturated with dissolved gases. These can be released during filtration, especially when water depth over the media is only 2 or 3 feet and the filter is operated to 7 or 8 feet of head loss.

Because of the air binding problem in 1974, the filtration plant at Duluth was designed to prevent this. The filter overflow is 9 feet above the top of the media so that 7 feet of water normally will be over the top of the media during filtration. This design feature has prevented repetition of the air binding problems that occurred in the pilot plant study.

Influence of Source Water Turbidity on Treatment Results

The source waters at Seattle and along the north shore of Lake Superior, where extensive filtration studies have been carried out, are very clear and generally unpolluted waters (except for the asbestos fiber content). Filtration of very clear water requires diligent operator attention if the treatment process is to attain maximum efficiency. Particles must be completely destabilized and low filtered water turbidity must be achieved to remove asbestos fibers.

When turbid raw water is treated, the presence of a large number of particulates in the water seems to aid the agglomeration of particles, and some water plant operators have observed that turbid waters may be easier to treat than very clear waters. Some of the data presented in this report were obtained from filtration plants that treat water sources that are not as clear as Lake Superior and the Tolt Reservoir. These include a number of surface waters in the San Francisco Bay area and the water sources for Philadelphia. Turbidity for some of these was as low as 3 to 5 ntu during some sample times. Turbidities in excess of 100 ntu were also observed. In contrast with the clear (equal to or less than 1 ntu) lake waters, these sources are considered turbid.

The relationship between filtered water turbidity and fiber count may be different in waters that are more turbid than Lake Superior and the Tolt

Reservoir. For example, in Contra Costa County, the Antioch and Pittsburg plants had effluent turbidities between 0.1 and 0.4 ntu (Tables 32 and 34) while effluent turbidity at the Bollman Plant was 0.06 ntu or lower (Table 33). Nevertheless fiber counts in filtered water were similar for all three plants, below 0.3 X 10^6 f/L in 12 of 14 instances. Two of these samples were in the 0.7 - 0.8 X 10^6 f/L range, and six samples had BDL or NSS values. Raw water turbidities generally were between 20 and 40 ntu.

At the San Geronomo plant (Table 36) two samples had counts above 1 X 10^6 f/L (2 X 10^6 and 12 X 10^6). These samples had filtered water turbidities of 1.0 - 0.6 ntu and 0.6 - 0.3 ntu. Raw water turbidity at the San Geronomo plant was 5 ntu for one of the above samples and 46 ntu for the other.

All three plants at Philadelphia effectively remove asbestos fibers, generally to NSS or BDL levels, as shown in Tables 39 - 41. This occurred even though average filtered water turbidity varied from 0.06 to 0.20 ntu, at Queen Lane, from 0.13 to 0.29 ntu at Torresdale, and from 0.15 to 0.45 ntu at Belmont. Raw water turbidities were as low as 3-4 ntu and as high as 160 ntu.

The results from Philadelphia, Contra Costa County, and Marin County suggest that attaining a filtered water turbidity of 0.10 ntu or less is not as important when the raw water is not exceptionally clear, meeting the 1 ntu MCL, before filtration. Perhaps when raw water contains enough clays, algae, bacteria, and other particulates to raise the turbidity significantly above 1 ntu, the asbestos fibers become associated with the other particulates and are removed along with them. This might occur especially with chrysotile, which has a positive zeta potential at usual raw water pH values.

Data suggest that asbestos fiber removal can be accomplished when filtered turbidity exceeds 0.10 if the raw water turbidity is greater than 1 ntu. Sufficient data to define "turbid" waters for which this is true have not been obtained, however, nor is the upper limit for filtered water turbidity that is associated with good fiber removal apparent. Limited data suggest that 0.4 ntu might be adequate, but 0.6 ntu might not.

Too little data and too much uncertainty exist now to suggest an operating goal other than 0.10 ntu, or the AWWA Quality Goal of 0.1 (no trailing zero) ntu. The AWWA goal technically can be met with a turbidity of 0.14 ntu because of rounding. Treating to attain the AWWA Quality Goal or 0.10 ntu would require careful operation and excellent equipment performance at plants treating turbid water. A distinct advantage of such an exacting quality goal is that to achieve it, fluctuations in filtered water quality would not be permitted. A rise in turbidity, caused by run-terminating breakthrough or by a coagulant feed malfunction, could be a signal for immediate corrective action by the plant operator. Preventing the production of higher turbidity water would prevent the sloughing of asbestos fibers from filters and would thus improve filtered water quality.

Recommended Treatment Technique

On the basis of results presented in this report, granular media filters can be operated to dependably remove asbestos fibers. The most important factor involved is properly conditioning the raw water before filtration so that a very low effluent turbidity is produced. Alum and cationic polymers have usually been used for coagulation. Two plants in Philadelphia successfully use ferric chloride however. Polymers often are used as coagulant aids or filter aids. Control of coagulant dose, to assure thorough and complete particle destabilization, is essential, as is careful control of process pH. Filter rates from 2 to 10 gpm/sf have removed asbestos fibers, but abrupt rate changes must be avoided, particularly if floc is not strong and could pass through the filter as a result of a rate increase. An appropriate goal for filtered water turbidity is 0.10 ntu, a goal that is now being met at some water filtration plants. Asbestos fiber counts are likely to increase very substantially as filtered water turbidity rises, so increases in turbidity over 0.10 ntu should be interpreted as a signal for corrective action by filter plant operators. Because turbidity is only an indicator of the presence of particulates in water, attaining the lowest possible filtered water turbidity is perhaps the best way to assure that a filtration plant is operating at maximum effectiveness.

DIATOMITE FILTRATION FOR ASBESTOS FIBER REMOVAL

Amphibole Removal

Amphibole fibers were effectively removed by diatomaceous earth filtration at Duluth. In their reviews of the Duluth pilot plant study, both Baumann (37) and Logsdon and Symons (33) cited the use of alum-coated diatomite as particularly effective. Baumann suggested that alum-coated filter media would have a positive surface potential, and that amphibole particles in the pH range of 7 to 8 (Lake Superior raw water pH) would be negatively charged. This charge difference would enhance the attraction of amphiboles to the diatomite filter aid particles. Surface attachment could occur, facilitating the removal of amphibole fibers too small to be removed by straining.

The use of both pressure and vacuum diatomite filters at Duluth permitted comparison of the two kinds of equipment. Pressure filtration was more effective than vacuum filtration for removing amphiboles and turbidity-causing particulates. This may have been the result of raw water quality and a fundamental difference in the two types of filters. The pressure filter pump was on the influent side of the filter. It provided a positive pressure, or driving force through the filter, of up to 100 feet of water, as observed in head loss measurements in some early long filter runs. Water passed through the pressure filter and was discharged at atmospheric pressure.

In the vacuum filter operation, the driving force was the difference between atmospheric pressure at the influent side of the filter and the suction at the pump on the effluent side of the filter. Head loss for the vacuum filter runs was less than 15 feet of water in most runs.

When the clear, cold, oxygen-saturated water from Lake Superior passed through the vacuum filter and pressure dropped below one atmosphere, the dissolved gases tended to come out of solution and form bubbles in the filter cake. These bubbles could grow and collapse, permitting solids to bleed through the filter cake. From June 21 to August 27, according to pilot plant operators' notes, bubbles were observed on the vacuum filter septum in 18 out of 67 runs. Because of the air bubble problem associated with filtering very cold waters, pressure filtration is better suited to such situations.

During the last half of the Duluth pilot plant study, pressure D.E. filtration repeatedly produced water with turbidity of 0.10 ntu or lower. For amphibole removal, the use of pressure filtration with alum coated diatomaceous earth would be recommended. The grade of diatomite selected should be fine enough to produce a filtered water of 0.10 ntu or lower, because high fiber counts were usually associated with turbidities above 0.10 ntu (Fig. 33). Nine of twelve BDL counts occurred with turbidities of 0.10 or lower.

If the septum pores are too large to permit effective precoating with the fine diatomite, a two-stage precoating process could be used, with the coarser DE coated on the septum and then a second layer of fine DE placed over the first precoat layer. Only the second layer of precoat in such a case would need to be alum-coated. Two-stage precoat was used often at Duluth.

Chrysotile Removal

Lawrence and coauthors have presented the best available information on the use of diatomaceous earth filtration for removing chrysotile fibers from water (21, 27). A reduction of 99.9 percent could be attained when waters with 100 X 10^6 f/L to 1000 X 10^6 f/L were treated by filtraton through ordinary diatomaceous earth. Hyflo-supercel* was used in their early work (21). The type of diatomaceous earth used for later laboratory and field studies was not identified.

Lawrence and Zimmerman (27) reported that the chrysotile fiber count in a synthetic (laboratory-prepared) suspension could be reduced from 1000 X 10^6 f/L to less than 0.1 X 10^6 f/L when it was filtered through diatomaceous earth coated with aluminum hydroxide. This is more than a 99.99 percent reduction, about the same degree of reduction that was attained by the filtration plant at Duluth during storms on Lake Superior.

Field tests at Asbestos, Quebec, verified the efficacy of diatomite filtration. Raw water contained 1000 X 10^6 f/L. Water filtered through uncoated diatomite had 3 X 10^6 f/L, and water filtered through alum coated DE had 0.08 X 10^6 f/L, for a reduction exceeding 99.99 percent.

Alum coated diatomaceous earth is obviously more effective for chrysotile than uncoated DE. Because both the coated diatomite and the individual chrysotile fibers are probably positively charged, the improved filter performance would not be explained merely on the basis of surface potential. The Seattle granular media filtration results, in which alum and cationic polymers removed chrysotile may help explain this finding. Such removal would not be explained on the basis of surface change alone, but it could be explained if chrysotile fibers were associated with negatively charged particles, such as clays, and were removed with them.

*Johns-Manville Products Corp., Denver, Colorado

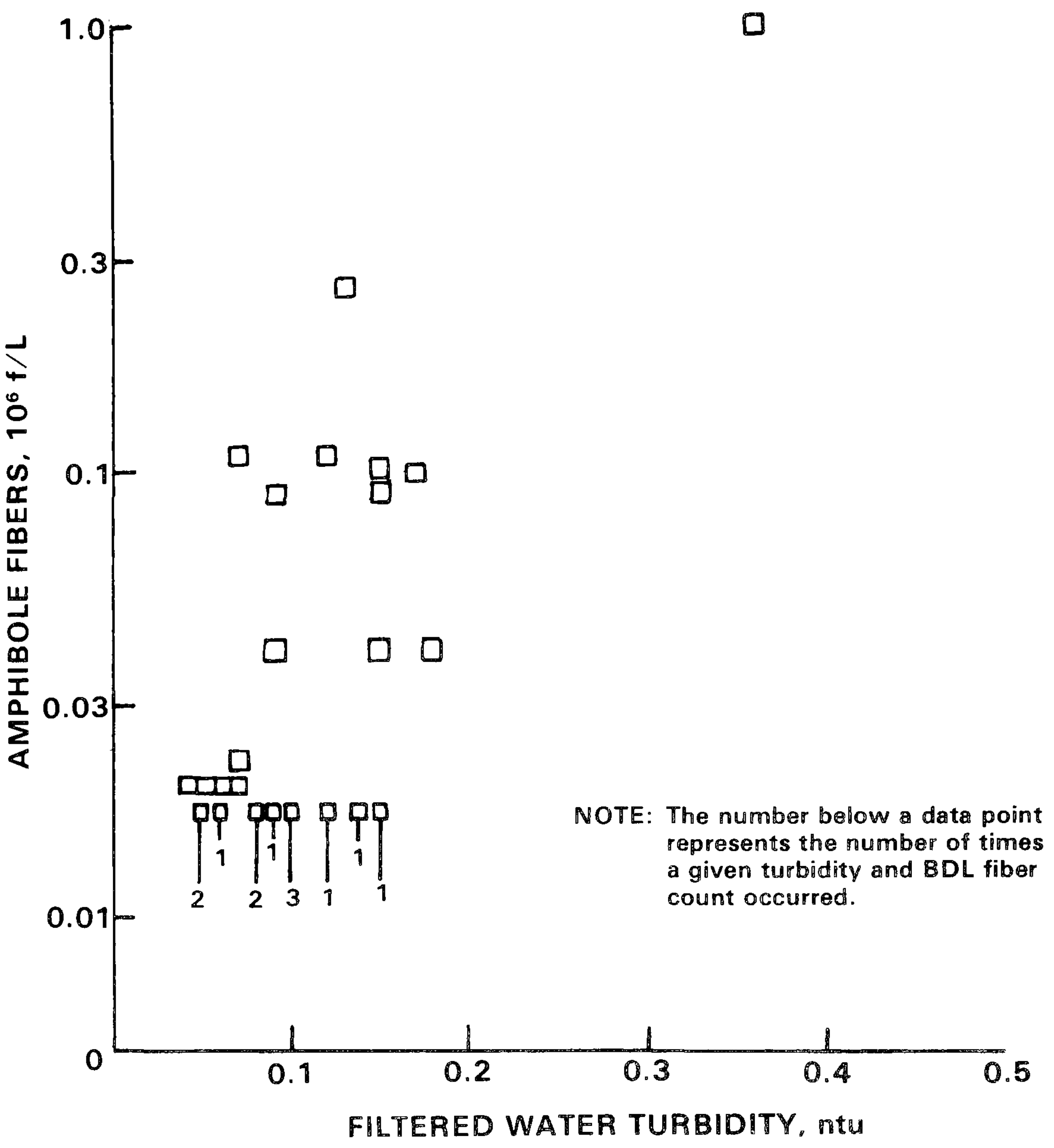


Figure 33. Effluent turbidity vs. amphibole fiber count for pressure diatomite filtration — Duluth pilot plant.

Other Applicatons for D.E. Filtration

Diatomaceous earth filtration has been used for many years in industry to filter both process flow streams and waste streams. Because of the advantages of low capital cost and ease of operation, industries that need to filter waste streams containing asbestos fibers are likely to adopt diatomite filtration. Both the Canadian research and the Duluth results suggest that this process should be effective for treating industrial waste discharges and potable waters.

COSTS

The cost of water treatment to attain water quality goals is an important consideration in selecting a treatment technique. Cost aspects also may be evaluated when quality goals are set; for example, the amount of hardness removed at a softening plant. Because of the importance of costs, they will be discussed in this portion of the report.

Treatment Costs Attributed to Asbestos

In Volume 2 of a report prepared for EPA, Gumerman, Culp and Hansen discussed added treatment costs for asbestos fiber removal (50). They emphasized the need to produce finished water turbidities of 0.1 to 0.2 ntu to accomplish virtually complete removal of asbestos fibers. Because consistently producing high quality water would be necessary, the authors stated, ". . .a need may arise for more highly skilled operators. Such additional cost would also have to be charged to asbestos removal."

Gumerman et al. (50) listed a number of potential modifications to existing plants to enhance asbestos removal. These should also be considered for new plants built for asbestos removal. They are:

1. Multi-stage rapid mix
2. Provision to feed polymers
3. Use of a pilot filter or coagulant control center
4. Use of mixed-media filters
5. Turbidity monitoring equipment for each filter
6. Higher than normal backwash rates
7. Washwater recovery
8. Lagoon or landfill disposal of sludge
9. Laboratory instrument to measure asbestos fiber removal (a particle counter)

Some of the above items may have been incorporated into water filtration plants constructed or modified in the 1960's or 1970's. Most were used at Duluth and Two Harbors. An explanation of how to estimate the cost of the above items is given by the authors in Volume 1 (50).

Capital Costs--

Cost estimates for direct filtration plants by Gumerman et al. (50) were compared with actual plant costs by Logsdon, Clark and Tate (51). Application of direct filtration is promising when raw water is of such good quality that it previously was not filtered before being distributed to consumers. This is the most likely situation in which discovery of asbestos in drinking water would necessitate building a new filtration plant. Emphasis is placed on direct filtration, therefore, in a discussion of plant costs.

Data on plant costs are available for Duluth, Two Harbors, and Silver Bay. Duluth and Two Harbors have new filtration plants. The plant at Silver Bay was upgraded, as described earlier. Costs for these plants, and a cost estimate prepared by CH2M-Hill for a Seattle Tolt treatment plant, are given in Table 45. The Minnesota cost data are updated to a May, 1979 Engineering News-Record construction Cost Index of 2981. The Seattle ENR index of 3215 was used for the Tolt plant. In Table 45 a column for maximum plant capacity normalized to a filtration rate of 5 gpm/sf is also shown. The rationale for this, given by Logsdon, Clark, and Tate (51), was discussed in an earlier paper by Dickson (52).

TABLE 45. TREATMENT PLANT CAPITAL COSTS

Treatment Plant	Maximum Capacity mgd	Capacity at 5 gpm/sf mgd	Cost million $	Year	Cost Adjusted to May, 1979 million $
Silver Bay (modification of existing plant)	2.3	4.4	1.0	1978	1.1
Two Harbors	2.6	3.2	1.5	1977	1.7
Duluth	36	30	6.2	1976	7.7
Seattle (estimated)	100	72	-	-	25*

*Seattle CCI used

When the costs for the four plants are updated and plotted on a capacity-cost curve with the EPA estimate (50) also updated and shown, the specific costs tend to be greater than the EPA estimates (Fig. 34). The differences in costs may reflect a number of factors. Provision of sludge handling and disposal at the plants was omitted in the EPA estimate, although it could be calculated and included in the curve because CWC Engineers included waste disposal cost curves in their report. Construction costs in Minnesota may be higher than the national average because of winter conditions. Construction costs are definitely higher than the national average in Seattle, and the Seattle project cost estimate even included a $1.2 million item for state sales tax. The Seattle conceptual design and the three plants built on Lake Superior were intended specifically for asbestiform fiber removal. Design engineers may have been more careful to provide process flexibility and redundancy so that the plants would perform at a very high fiber removal efficiency on a dependable basis.

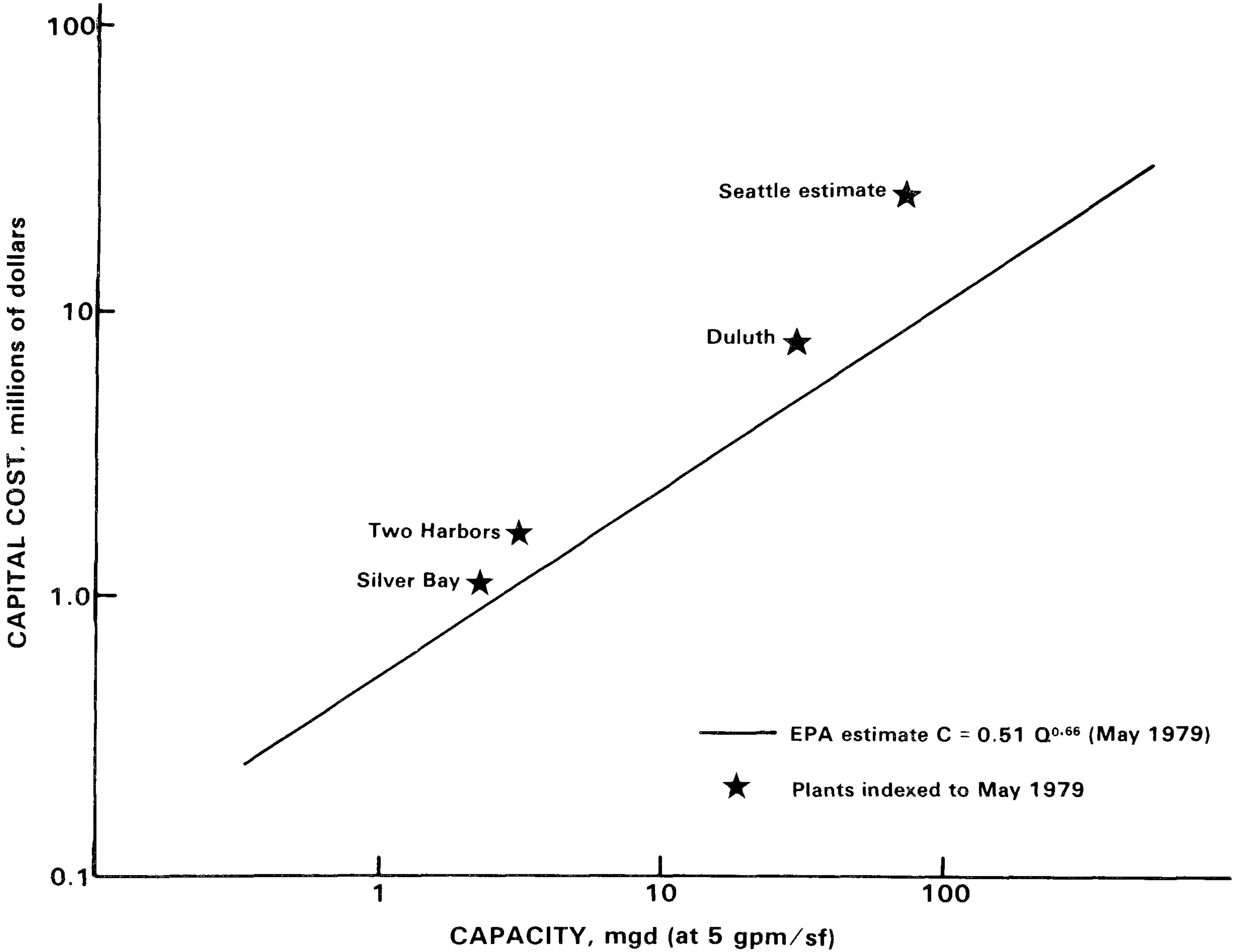


Figure 34. Direct filtration plant capacity vs. cost.

Operating Costs--

Plant operating costs vary over a wide range, so the extent to which asbestos removal would add to the costs is not readily defined. Certainly additional costs would occur at a plant that in normal operating practice was barely meeting the 1 ntu limit. At a plant already producing filtered water at the 0.1 ntu level, extra operating costs would be much lower.

Examples of actual costs for operation and maintenance for a number of plants were given in the paper on costs of direct filtration. Those data are shown in Table 46 and shown in Figure 35 which shows the downward trend in costs as plant size increases. Costs were updated from July, 1977 to May, 1979 using the Wholesale Price Index ratio of 239/196.

TABLE 46. WATER FILTRATION PLANT OPERATION AND MAINTENANCE COSTS

Utility and Location	Water Production Average MGD	Water Production Maximum MGD	Average/Maximum percent	O&M Costs Indexed to 5/79 ¢/1000 gallons
Clackamas Water Dist., Clackamas, Oregon	5.3	20	26.5	5.7
Duluth, Minnesota	17	36	47.2	5.5
Bellingham, Washington	9.8	36	27.2	7.2
Metropolitan Water Board, Oswego, N.Y.	19	54	35.2	5.1
East Bay MUD Oakland, Calif. Walnut Creek Plant	10*	60	16.7	7.2*
Springfield, Mass.	26	60	43.3	3.2
Southern Nevada Water System, Las Vegas	67	200	33.5	3.7

*EBMUD data reflect California drought conditions and water conservation. At a more typical 12 to 13 mgd, filtration O&M costs would have been close to 6.2 ¢/1000 gallons.

The cost of treatment chemicals would be one of the concerns of plant operators and managers who would need to filter water to remove asbestos fibers. Chemical prices vary according to type and strength, quantity purchased, and shipping costs. No prices are given here. However, actual chemical doses used at some treatment plants or pilot plants removing asbestos fibers are given so treatment plant personnel can formulate judgments on the nature of the chemical costs they might experience. These are shown in Table 47. Chemical doses are low for the very clear waters and certainly not unreasonably high for the turbid waters. In fact, the chemical costs for the

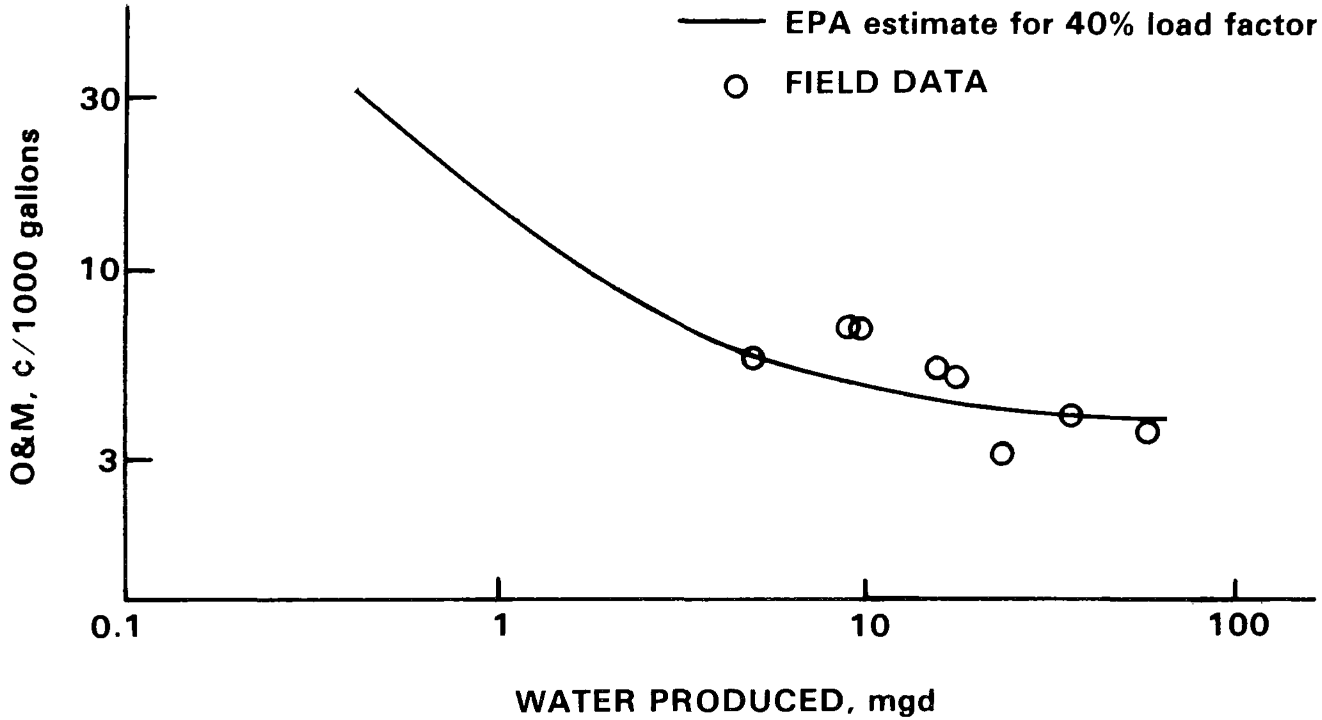


Figure 35. Operation and maintenance cost vs. water production for direct filtration. (May 1979)

plants cited are probably a lot lower than chemical costs at a number of lime softening plants.

Extensive cost data are not yet available because plants have not been operated specifically for asbestos fiber removal for very long at this time. As more years of operating experience are acquired, defining costs more closely will be easier.

Monitoring Costs

Although capital and operating costs for filtration plants intended to remove asbestos fibers might not be much greater than costs normally associated with filtration plants, the cost of monitoring could be an overwhelming financial burden. In 1979 the only method that yields actual asbestos fiber counts in water samples is the transmission electron microscope method. The annual cost of submitting only two samples per week to a laboratory for analysis would be in the range of $30,000 to $40,000. Only the largest utilities can absorb such a high analytical cost.

Even if TEM analysis could be afforded, the results often are returned to the water utility from the analyst four to six weeks after a sample was submitted. Therefore, electron microscopy is suitable only for providing historical records of water quality.

Day-to-day and minute-to-minute quality monitoring must be done by use of turbidimeters. For most effective monitoring of filtered water turbidity, a continuous recording turbidimeter with an alarm should be installed on each filter, or a valving and timer arrangement should be installed so that one continuous turbidimeter could monitor three or four filters once each hour on a rotating basis.

Economic Burden of Filtration for Asbestos Removal

Adopting new or improved treatment technology for contaminant removal generally results in higher water treatment costs. Water utilities that build filtration plants to remove asbestos fibers will incur significant capital and operating costs. Utilities that have filtration plants that need adjustments to operating procedures in order to attain greater reduction of the fiber counts will also face increased expenses, but these will be much lower than the costs of new plant construction.

In this century many water utilities have demonstrated that filtration is affordable by building, operating, and maintaining water filtration plants. A number of water utilities that filter surface waters meet the AWWA Quality Goal of 0.1 ntu for filtered water, thus showing that attaining this degree of clarity in filtered water is economically feasible. The degree to which water utilities go to remove asbestos fibers from drinking water may depend more upon their perception of the need for asbestos removal than on the economic factors involved.

TABLE 47. CHEMICAL DOSES FOR ASBESTOS FIBER REMOVAL

Treatment Plant	Raw Water Source	Raw Water Turbidity, ntu	Treatment Chemical	Dose mg/L
Lakewood(Duluth)	L. Superior	1 (10-15 max)	Alum	10-15
			Nonionic Polymer	1.5-4
			Sodium Hydroxide	0.07-012
Two Harbors	L. Superior	1 (10-15 max)	Alum	15
			Nonionic Polymer	0.4
			Sodium Hydroxide	11-12
Seattle pilot plant	Tolt Reservoir	1 (5 max)	Alum	7-10
			Lime	1-4
			Nonionic Polymer	0.02-0.25
			or	
			Alum	3-5
			Cationic Polymer	2
			Nonionic Polymer	0.1-0.3
			or	
			Cationic Polymer	3
Bollman plant CCCWD	Contra Costa Canal or Sacramento R.	20-40	Alum	40-55
			Polymer	0.02-0.03
			Lime	3-6
			Sodium Hydroxide	9-15
Torresdale plant	Delaware R.	5-10 (max > 50)	Ferric Chloride	about 10
			Lime	
Queen Lane plant	Schuylkill R. and Wissohickon Creek	5-10 (max > 170)	Ferric Chloride	about 10
			Lime	
Belmont plant	Schuylkill R.	5-10 (max > 400)	Alum	about 20
			Lime	

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APPENDIX A-1. DULUTH MONITORING DATA FROM LAKEWOOD FILTRATION PLANT

	Plant Influent		Plant Effluent	
Date	Turbidity (ntu)	Amphibole (10^6 fibers/liter)	Turbidity (ntu)	Amphibole (10^6 fibers/liter)
1977				
1/1	-	-	0.09	0.40
1/11	-	-	0.05	0.30
1/13	-	-	0.07	0.62
1/18	0.43	37	0.07	BDL(0.19)
1/18	0.43	41	0.06	"
1/20	0.41	31	0.10	0.60
1/21	0.52	40	0.05	0.26
1/22	0.39	43	0.04	BDL(0.19)
1/23	0.54	44	0.05	"
1/24	0.45	44	0.07	"
1/25	0.36	35	0.04	"
1/26	0.33	38	0.04	"
1/27	0.30	19	0.04	0.20
1/28	0.38	29	0.04	0.10
1/29	0.37	35	0.04	BDL(0.19)
1/30	0.35	42	0.04	"
2/01	0.30	29	0.04	0.067
2/03	0.36	49	0.04	BDL(0.067)
2/05	0.28	41	0.04	0.13
2/12	0.28	55	0.04	BDL(0.067)
2/17	0.26	20	0.04	"
2/19	0.44	17	0.05	"
3/02	0.37	-	0.06	"

APPENDIX A-1. (Continued)

Date	Plant Influent Turbidity (ntu)	Plant Influent Amphibole (10^6 fibers/liter)	Plant Effluent Turbidity (ntu)	Plant Effluent Amphibole (10^6 fibers/liter)
1977				
3/09	0.47	-	0.04	0.096
3/21	0.41	-	0.04	BDL(0.067)
4/04	0.30	38	0.04	"
4/11	0.30	-	0.05	BDL(0.067)
4/18	0.30	-	0.04	0.091
4/25	0.30	-	0.04	0.036
5/02	0.30	-	0.04	0.030
5/10	0.50	-	0.06	0.050
5/16	0.50	-	0.07	0.070
6/02	0.40	-	0.06	0.064
6/14	0.62	134	0.05	0.064
7/01	1.6	-	0.08	0.26
7/08	0.45	-	0.042	BDL(0.064)
7/13	0.56	145	-	-
7/18	0.60	130	0.04	0.067
7/25	0.33	-	0.04	0.078
8/01	0.55	-	0.04	0.038
8/08	0.60	-	0.04	0.019
8/15	0.80	-	0.035	0.077
8/24	0.82	75	0.035	0.086
8/30	0.40	24	0.04	0.058

Date 1977	Plant Influent Turbidity (ntu)	Plant Influent Amphibole (10^6 fibers/liter)	Plant Effluent Turbidity (ntu)	Plant Effluent Amphibole (10^6 fibers/liter)
9/06	0.68		0.035	0.038
9/14	0.68		0.035	0.019
9/19	10.0		0.045	0.048
9/19	14.0	1200		
9/28	1.3	69	0.04	BDL(0.010)
10/04	2.6	72	0.035	0.010
10/08	11.0	830	0.045	0.029
10/12	2.3	120	-	-
10/14	-	-	0.033	0.053
10/19	0.85	26	0.035	0.019
10/25	0.63	18	-	0.010
10/31	0.56	20	-	0.010
11/07	0.51	5.6	0.038	0.048
11/16	0.47	34	0.039	0.088
11/22	0.62	6.6	0.031	0.022
12/02	0.48	6.5	0.038	0.038
12/07	0.83	90	0.034	0.010
12/14	0.52	3.8	0.037	0.019
12/20	1.4	120	0.035	0.010
12/28	0.48	27	0.036	BDL(0.010)

APPENDIX A-1. (Continued)

Date	Plant Influent Turbidity (ntu)	Plant Influent Amphibole (10^6 fibers/liter)	Plant Effluent Turbidity (ntu)	Plant Effluent Amphibole (10^6 fibers/liter)
1978				
1/04	0.46	60	0.036	0.029
1/10	0.47	21	0.038	0.010
1/18	0.42	24	0.035	0.010
1/24	0.40	27	0.038	0.014
2/06	0.86	75	0.038	0.019
2/14	0.56	6.1	0.034	0.010
2/24	0.57	44	-	-
2/27	-	-	0.034	0.067
3/06	0.51	55	0.038	BDL(0.010)
3/16	0.48	48	0.039	0.019
3/21	0.72	40	0.039	0.019
3/28	0.68	36	0.037	0.010
4/05	0.82	100	0.039	0.029
4/11	1.5	250	0.051	0.019
4/17	0.73	-	0.038	0.058
4/25	0.89	210	0.041	BDL(0.019)
5/1	0.94	200	0.033	BDL(0.019)
5/8	0.62	160	0.034	0.019
5/15	0.52	110	0.033	0.019
5/23	0.49	160	0.034	0.048
5/30	15.0	500	0.039	0.029
6/5	1.0	130	0.035	0.058
6/12	0.80	170	0.034	0.010

Date	Plant Influent Turbidity (ntu)	Plant Influent Amphibole (10^6 fibers/liter)	Plant Effluent Turbidity (ntu)	Plant Effluent Amphibole (10^6 fibers/liter)
1978				
6/19	0.72	180	0.041	0.019
6/26	0.81	99	0.040	0.019
7/5	0.77	27	0.040	0.010
7/11	0.67	96	0.035	BDL(0.010)
7/17	1.05	45	0.040	0.038
7/25	0.68	46	0.041	-
8/02	0.64	59	0.032	0.058
8/09	0.61	2.2	0.031	0.048
8/17	0.75	36	0.039	0.048
8/22	0.35	27	0.032	0.019
9/06	0.71	12	0.041	0.019
9/13	2.4	160	0.04	0.0096
9/22	0.84	15	0.04	0.0096
9/28	2.0	13	0.052	BDL(0.0096)
10/5	0.67	16	0.003	0.029
10/12	0.37	33	0.04	BDL(0.0096)
10/20	0.38	16	0.031	BDL(0.0096)
10/27	0.73	150	0.048	0.010
11/3	0.65	68	0.031	BDL(0.010)
11/10	7.7	460	0.04	0.029
11/22	0.74	6.5	0.032	0.023
12/08	-	-	0.031	BDL(0.010)
12/15	-	-	0.065	BDL(0.010)

APPENDIX A-1. (Continued)

Date	Plant Influent Turbidity (ntu)	Plant Influent Amphibole (10^6 fibers/liter)	Plant Effluent Turbidity (ntu)	Plant Effluent Amphibole (10^6 fibers/liter)
1979				
1/5	0.43	34	0.039	BDL(0.010)
1/16	-	-	0.033	BDL(0.010)
1/25	-	-	0.033	BDL(0.010)
1/30	-	-	0.048	BDL(0.010)
2/5	0.65	81	0.048	0.019
2/13	-	-	0.036	BDL(0.010)
2/19	-	-	0.031	BDL(0.010)
2/27	0.21	18	0.033	BDL(0.010)
3/8	-	-	0.033	0.010
3/9	0.19	19	-	-
3/14	0.16	14	0.043	BDL(0.010)
3/20	-	-	0.040	BDL(0.010)
3/22	0.39	24	-	-
4/3	-	-	0.033	0.010
4/5	0.24	5.4	-	-
4/12	0.35	11	0.038	0.010
4/17	0.26	9.6	0.040	BDL(0.010)
4/24	1.3	40	0.039	0.010
5/4	0.44	70	0.039	0.019
5/10	8.4	96	0.036	0.019
5/17	2.2	47	0.037	0.019
5/18	-	-	0.038	0.0096
5/18	-	-	0.038	0.0096

APPENDIX A-1. (Continued)

Date	Plant Influent Turbidity (ntu)	Plant Influent Amphibole (10^6 fibers/liter)	Plant Effluent Turbidity (ntu)	Plant Effluent Amphibole (10^6 fibers/liter)
1979				
5/22	1.2	46	0.040	0.010
			0.039	0.038
5/23	-	-	0.052	0.019
			0.038	0.048
			0.048	0.077
5/29	1.3	56	0.043	0.029
5/31	-	-	0.038	0.086
			0.043	0.067
6/4	1.5	96	0.044	*
6/4			0.039	*
6/6	-	-	0.045	*
			0.040	0.029
6/11	1.8	150	0.043	0.010
6/11			0.041	BDL(0.010)
6/12	-	-	0.051	0.12
			0.041	0.019
6/19	1.3	180	0.033	0.048
			0.031	0.029
6/21	-	-	0.033	0.019
			0.033	0.12
6/25	1.6	170	0.036	0.31
			0.032	0.010

*These samples are in the process of being analyzed.

APPENDIX A-2. EFFECTS OF FILTRATION RATE CHANGES ON WATER QUALITY AT DULUTH

Date	H_L at rate change ft water	Media	Filtered Water Quality: Equilibrium during Normal Operation ntu	Equilibrium during Normal Operation Amphibole 10^6 f/L	Highest during Rate Change ntu	Highest during Rate Change Amphibole 10^6 f/L	Approximate Average for 30 minutes During Rate Change Amphibole 10^6 f/L	Unit Processes Employed Before Filtration: Rapid Mix	Floccu-lation	Sedimen-tation
Rate Increased From 3.25 to 4.33 gpm/sf When One Filter Was Shut Down for Backwash										
5/24/77	2.0	dual	0.09	0.07	0.16	0.38	0.2	X		
6/1/77	2.0	dual	0.06	0.06	0.07	0.38	0.2	X		
6/9/77	7.2	dual	0.10	0.06	0.44	12.8	3-4	X		
9/28/77	7.5	dual	0.04	0.04	0.08	0.06	0.04	X	X	X
10/4/77	2.0	dual	0.04	0.04	0.05	0.30	0.1	X	X	X
5/25/77	2.1	mixed	0.06	0.06	0.06	0.32	0.2	X		
6/2/77	2.3	mixed	0.06	0.06	0.06	0.096	0.1	X		
6/14/77	6.7	mixed	0.05	0.06	0.06	0.13	0.1	X		
10/14/77	4.5	mixed	0.034	0.05	0.04	0.05	0.05	X	X	X
2/27/78	2.8	mixed	0.07	0.07	0.04	0.07	0.05	X	X	X

APPENDIX A-2. EFFECTS OF FILTRATION RATE CHANGES ON WATER QUALITY AT DULUTH

Date	H_L at rate change ft water	Media	Filtered Water Quality: Equilibrium during Normal Operation ntu	Equilibrium during Normal Operation Amphibole 10^6 f/L	Highest during Rate Change ntu	Highest during Rate Change Amphibole 10^6 f/L	Approximate Average for 30 minutes During Rate Change Amphibole 10^6 f/L	Unit Processes Employed Before Filtration: Rapid Mix	Floccu-lation	Sedimen-tation
Rate Increased From 0 to 3.25 gpm/sf When Entire Plant Started Up										
7/6/77	2.0	dual	0.04	0.06	0.05	0.48	0.2	X	X	X
9/20/77	2.5	dual	0.05	0.02	0.05	0.19	0.05	X	X	X
11/11/77	3.5	dual	0.04	0.07	0.04	0.09	0.05	X		
11/28/77	9.0	dual	0.07	0.03	0.71	3.7	1	X		
8/10/77	2.0	mixed	0.07	0.05	0.05	0.11	0.1	X	X	X
8/17/77	9.0	mixed	0.05	0.08	0.12	2.2	1	X	X	X
11/22/77	2.7	mixed	0.04	0.02	0.04	0.12	0.05	X		
11/28/77	6.9	mixed	0.04	0.03	0.04	0.04	0.05	X		

APPENDIX A-2. EFFECTS OF FILTRATION RATE CHANGES ON WATER QUALITY AT DULUTH

Date	H_L at rate change ft water	Media	Filtered Water Quality: Equilibrium during Normal Operation ntu	Filtered Water Quality: Equilibrium during Normal Operation Amphibole 10^6 f/L	Filtered Water Quality: Highest during Rate Change ntu	Filtered Water Quality: Highest during Rate Change Amphibole 10^6 f/L	Filtered Water Quality: Approximate Average for 30 minutes During Rate Change Amphibole 10^6 f/L	Unit Processes Employed Before Filtration: Rapid Mix	Unit Processes Employed Before Filtration: Floccu-lation	Unit Processes Employed Before Filtration: Sedimen-tation
Rate Increased From 0 to 3.25 gpm/sf in One Filter When Operation Resumed After Backwash										
6/22/77	2.0	dual	0.05	0.03	0.10	2.3	2	X		
3/6/78	2.5	dual	0.04	0.01	0.04	0.25	0.1	X	X	X
11/23/77	2.0	mixed	0.04	0.03	0.05	0.10	0.05	X		
3/10/78	2.4	mixed	0.04	0.02	0.04	0.21	0.1	X	X	X

APPENDIX B. SUMMARY OF SEATTLE PILOT PLANT ASBESTOS DATA

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 (%)
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	>99.6	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	>99.5	99.3
21-F	12	0.059	2.18	25.8	<0.01(ND)	0.09	>99.5	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	>98.9	98.4
29-F	17	0.10	0.94	4.25	<0.01(ND)	0.22	>98.9	94.8

(continued)

APPENDIX B (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 (%)
33-R	6	0.61	0.65	3.82	--	--	--	--
33-F	6	0.062	0.65	3.82	<0.01 (ND)	0.06 (NSS)	>98.4	98.4
33-F	9	0.053	0.65	3.82	<0.01 (ND)	0.22	>98.4	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	>98.8	90.7
44-F	13	0.09	0.90	2.8	<0.01 (ND)	<0.01 (ND)	>98.8	>99.6
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 B (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	--	98.0
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)	—	>99.8
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)	—	>99.8
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)	—	>99.8
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 B (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)	--	>99.7
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)	--	>99.5
161-CC	4	0.085	ND	2.0	<0.01(ND)	<0.01(ND)	--	>99.5
161-CC	10	0.069	ND	2.0	<0.01(ND)	0.01(NSS)	--	>99.5
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)	--	>99.5
161-FC	1	0.095	ND	2.0	<0.01(ND)	<0.01(ND)	--	>99.5
161-FC	4	0.071	ND	2.0	<0.01(ND)	0.04(NSS)	--	98.0
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)	--	>99.5
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)	--	>99.5
161-MM	15	0.081	ND	2.0	<0.01(ND)	<0.01(ND)	--	>99.5
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 B (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)	–	>99.4
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)	–	>99.4
174-MM	18	0.075	--	--	<0.01(ND)	<0.01(ND)	–	>99.4
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)	–	>99.4
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)	–	> 98.3
174-CC	2	0.070	--	--	<0.01(ND)	0.01(NSS)	–	99.4
174-CC	3	0.071	--	--	<0.01(ND)	<0.01(ND)	–	>99.4
174-CC	4	0.090	--	--	<0.01(ND)	<0.01(ND)	–	>99.4
174-CC	5	0.071	--	--	<0.01(ND)	<0.01(ND)	–	>99.4
174-CC	6	0.081	--	--	<0.01(ND)	<0.01(ND)	–	>99.4
174-CC	7	0.068	--	--	<0.01(ND)	0.06(NSS)	–	96.7
174-CC	8	0.070	--	--	<0.01(ND)	<0.01(ND)	–	>99.4
174-CC	14	0.070	--	--	<0.01(ND)	<0.01(ND)	–	>99.4
174-CC	19	0.070	--	--	<0.01(ND)	<0.01(ND)	–	>99.4

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)

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

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16. ABSTRACT

This report presents a comprehensive review of data on removal of asbestos fibers by granular media filtration and diatomaceous earth filtration. It summarizes data obtained in pilot plant studies at Duluth and Seattle, in research program carried out at Duluth's Lakewood filtration plant, and monitoring at Silver Bay and Two Harbors, Minnesota plants, Chicago, Philadelphia, and in the San Francisco Bay area.

Chrysotile and amphibole fiber concentrations in drinking water can be substantially reduced by granular media filtration. Reductions of up to 99.99 percent were reported during storm conditions at Duluth, Minnesota. Effective granular media filtration required careful control of pH, coagulant doses, and filtered water turbidity.

Research to date indicates that coating the diatomaceous earth filter aid with aluminum hydroxide substantially increases the removal of both amphibole and chrysotile fibers. Duluth results indicate that filtered water turbidity should be 0.10 ntu for most effective fiber removal.

When a granular media filtration plant is properly operated, turbidity readings can be an indicator of fiber removal efficiency even though turbidity cannot directly measure asbestos fibers in the concentrations found at water treatment plants. Filtered water turbidity should be 0.10 nephelometric turbidity units (ntu) or lower to maximize fiber removal. Turbidity increases of 0.1 or 0.2 ntu above this value generally were accompanied by large increases in fiber concentrations.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Asbestos, filtration, potable water, turbidity, water treatment, amphiboles	Seattle, Lake Superior, San Francisco Bay area, Philadelphia, Chicago, fiber removal, chrysotile, diatomaceous earth filter, granular media filter	13 B

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