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DIRECT FILTRATION OF LAKE SUPERIOR WATER FOR ASBESTIFORM FIBER REMOVAL

Appendix I

National Environmental Research Center
Office of Research and Development
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Cincinnati, Ohio 45268

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DIRECT FILTRATION OF LAKE SUPERIOR WATER FOR ASBESTIFORM FIBER REMOVAL

Appendix I

Diatomite Filters for Asbestiform Fiber Removal from Water

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for

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment -- air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

This report and its appendices present the results of pilot plant filtration research for the removal of asbestiform fibers from drinking water. The several appendices present detailed information on water quality, pilot plant equipment and operation, individual filter run data, asbestiform fiber and amphibole mass concentrations in raw and filtered water, and diatomite filter optimization. Appendix I contains the diatomite filter optimization study.

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ABSTRACT

Pilot plant research conducted in 1974 at Duluth, Minnesota, demonstrated that asbestiform fiber counts in Lake Superior water could be effectively reduced by municipal filtration plants. During the study, engineering data were also obtained for making cost estimates for construction and operation of both granular and diatomaceous earth (DE) filtration plants ranging in size from 0.03 to 30 mgd.

During one phase of the pilot plant investigation, the diatomite filters were operated in a way that yielded data used for computer optimization of the DE filtration process. the POPO (Program for Optimization of Plant Operation) results are presented in Appendix I.

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DIATOMITE FILTERS FOR ASBESTIFORM FIBER REMOVAL FROM WATER

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April 1, 1975

This paper is a summary of the results from vacuum and pressure diatomite filter pilot plants operated by Black and Veatch, Consulting Engineers of Kansas City, Missouri, for the removal of asbestiform fibers from Lake Superior water at Duluth, Minnesota. The work was conducted under contract with the U.S. Environmental Protection Agency in cooperation with the U.S. Army Corps of Engineers and the City of Duluth. The author served as a consultant to the engineers in planning and interpreting the pilot-plant results.

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DIATOMITE FILTERS FOR ASBESTIFORM FIBER REMOVAL FROM WATER

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Introduction

During the period from May through September, 1974, two diatomite filter pilot plants (10 gpm) were operated at Duluth Minnesota, for the removal of suspended solids, including asbestiform materials, from Lake Superior water. A total of 86 runs was made using a pressure diatomite filter (ERD-2), and a total of 122 runs was made using a vacuum diatomite filter (BIF-2). All runs were made with filtration rates between about 0.8 and 1.6 gpm/sq ft of filter area. The raw water turbidity varied from 0.5 to about 1.2 FTU, and the water temperature was between 33 ^{o}F and 48 ^{o}F.

Data of the following type were collected during each filter run:

1. Filtration rate (constant),
2. Head loss every half-hour,
3. Water temperature,
4. Precoat and body feed types and amounts and filter media coating types and amounts used,
5. Raw and filtered water turbidity every half-hour.

Raw and filtered water samples were taken during about every fifth run for detailed analysis for asbestiform fibers.

During the series of filter runs, the variables which could be controlled included:

1. Filtration rate,
2. Grade and amount of precoat filter aid used,
3. Grade and amount of body feed filter aid used,
4. Coating type and amount applied to the body feed and/or precoat filter aid used,
5. Type and amount of polymer used as a coagulant during the filter run.

The test series were conducted in three phases:

1. A preliminary test series conducted to train the operators, develop test and data recording procedures, and gain plant operating experience,
2. An "asbestiform fiber removal" efficiency series of runs to determine which treatments gave promise of effectively removing asbestiform fibers from suspension (This series was designed to narrow down the treatment possibilities.),
3. An "optimum-design" series of runs to determine filter cake resistance measurements using treatment techniques found most successful in the phase two runs. Cake resistance measurements are necessary to optimize the design of diatomite filters to provide least-cost filtration of the Lake Superior water. These runs were also used to evaluate the expected suspended solids (asbestiform fiber) removal to be accomplished by diatomite filtration.

This paper provides a brief summary of the results of the significant runs on which the optimum design of a diatomite filtration plant for removal of asbestiform fibers are based. The paper will consider the following items:

1. The quality of the raw water,
2. The potential treatments that might be expected to produce the desired quality of filtered water,
3. The results achieved,
4. The determination of filtration resistance,
5. The determination of optimum plant designs,
6. Conclusions and recommendations.

Quality of Raw Water

The design of a filter plant must be based both on the quantity of the filtered water which must be produced and on the quality of the raw water that must be filtered. In optimizing filter plant operating costs, it is <u>not</u> necessary to design a diatomite filter plant to operate under the <u>worst</u> raw water conditions that will be encountered. If it were, the plant might operate under optimum conditions during only a few days per year. On all other days, it would be overdesigned. It is more satisfactory to design a filtration plant for optimum operation using a raw water quality that will be equalled or exceeded, say 90 or 95 per cent of the time. The economics of doing this will be explained in more detail later in this paper.

The main purpose of filtering Lake Superior water, for example, for use as a public water supply would be for the reduction of suspended solids, principally the suspended solids in the form of asbestos fibers. Unfortunately, it is not customary to routinely measure suspended solids levels in water supply sources, and interest in asbestos fibers in Lake Superior waters has been generated only recently (1973). Thus, adequate data on levels of suspended solids and asbestos fibers in Lake Superior water are not available. Such data are necessary for predicting the quality of raw water which will have to be filtered. The turbidity of water, however, is related to the level of suspended solids present and is a reliable indicator of the presence of suspended solids.

Until 1962 the U.S. Public Health Service drinking water standards limited the turbidity of drinking water to a value less than 10 JTU*. In 1962 a new drinking water standard was issued in which the allowable drinking water turbidity was reduced to 5 JTU [1]. With the recent passage of the "Safe Drinking Water Act" by the U.S. Congress in December, 1974, it is expected that the Environmental Protection Agency will again revise the drinking water turbidity standard by requiring a drinking water turbidity less than 1.0 JTU. In 1968 the American Water Works Association adopted a turbidity "goal" (which water works should seek to achieve) of only 0.1 JTU [2]. Fortunately, the Duluth water works has collected Lake Superior raw water turbidity data at the Lakewood Pumping Station for a number of years. These records can be used

---

*Jackson Turbidity Units. In this study, a formazin turbidity standard was used and thus the turbidity results are expressed in Formazin Turbidity Units (FTU).

to evaluate the quality of water which a filtration plant must be designed to handle.

Table 1 summarizes the raw water turbidity of Lake Superior water measured at the Lakewood Pumping Station from 1952-1972. Each year, the turbidity of the Lake water is recorded during those hours when the turbidity exceeds 1 JTU. The number of hours during which the turbidity is in the range 1-5, 6-10, 11-15, 16-20, etc. are recorded by year. There were only 4 hours in 21 years that the turbidity was as high as the 76-100 range, and a total of only 124 hours in 21 years that it exceeded a turbidity of 20 JTU. During the 21 years the water turbidity was below 1.0 JTU 89.95 per cent of the time.

Figure 1 is a plot of Lake Superior water turbidity as a function of the per cent of time the turbidity was equal to or less than a given value. Figure 1 shows the data on logarithmic probability paper so that the data plots as a straight line. Table 2 lists the per cent of time that the water has a turbidity less than the given value. Ninety per cent of the time the raw water has a turbidity less than 1.0 JTU and 95 per cent of the time the turbidity is less than 1.9 JTU. The working values at the bottom of Table 2 will be used in evaluating diatomite filter plant design and operating costs. During the phase three pilot plant tests, the lake water turbidity was between 0.5 and 1.4 FTU, values that are exceeded only about 8 per cent of the time.

Table 1. City of Duluth water supply, Lakewood Pumping Station raw water turbidity data, 1952-1972

Year	No. of Pumping Hours	Total Hours Turbidity Recorded*	Per Cent Time Turbidity < 1	Number Hours Turbidity Within Indicated JTU Ranges								
				1-5	6-10	11-15	16-20	21-30	31-40	41-50	51-75	76-100
1952	6062	244	96.0	106	90	26	12	10	0	0	0	0
1953	5871	315	94.6	233	46	36	0	0	0	0	0	0
1954	5815	281	95.2	263	12	3	3	0	0	0	0	0
1955	5913	172	97.1	128	41	0	3	0	0	0	0	0
1956	6076	108	98.2	93	15	0	0	0	0	0	0	0
1957	6050	81	98.7	55	10	0	10	6	0	0	0	0
1958	5705	31	99.4	10	21	0	0	0	0	0	0	0
1959	5964	232	96.1	143	59	13	10	7	0	0	0	0
1960	5806	422	92.7	315	68	15	24	0	0	0	0	0
1961	5907	147	97.5	123	18	0	0	8	0	0	0	0
1962	6049	508	94.1	478	26	4	0	0	0	0	0	0
1963	5556	530	90.5	445	59	25	0	1	0	0	0	0
1964	5457	376	93.1	326	38	7	1	4	0	0	0	0
1965	5668	656	88.4	635	21	0	0	0	0	0	0	0
1966	5786	284	95.1	263	21	0	0	0	0	0	0	0
1967	5766	744	87.1	538	136	22	14	21	2	2	5	4
1968	5821	866	85.1	547	143	84	52	20	14	6	0	0
1969	5949	892	85.0	727	111	29	8	17	0	0	0	0
1970	6310	772	87.1	689	67	7	0	0	1	2	6	0
1971	5814	1315	77.4	1034	167	96	15	3	0	0	0	0
1972	5826	3406	41.5	3271	108	23	0	0	4	0	0	0
Totals	123,171	12,384	Mean 89.95	10,422	1,277	390	152	97	21	10	11	4
Turbidity			< 1	< 5	< 10	< 15	< 20	< 30	< 40	< 50	< 75	< 100
Percent of Time Turbidity Less than Given Value			89.95	98.41	99.45	99.76	99.88	99.96	99.97	99.988	99.997	100.0

*Only hours with turbidity greater than 1.0 were monitored.

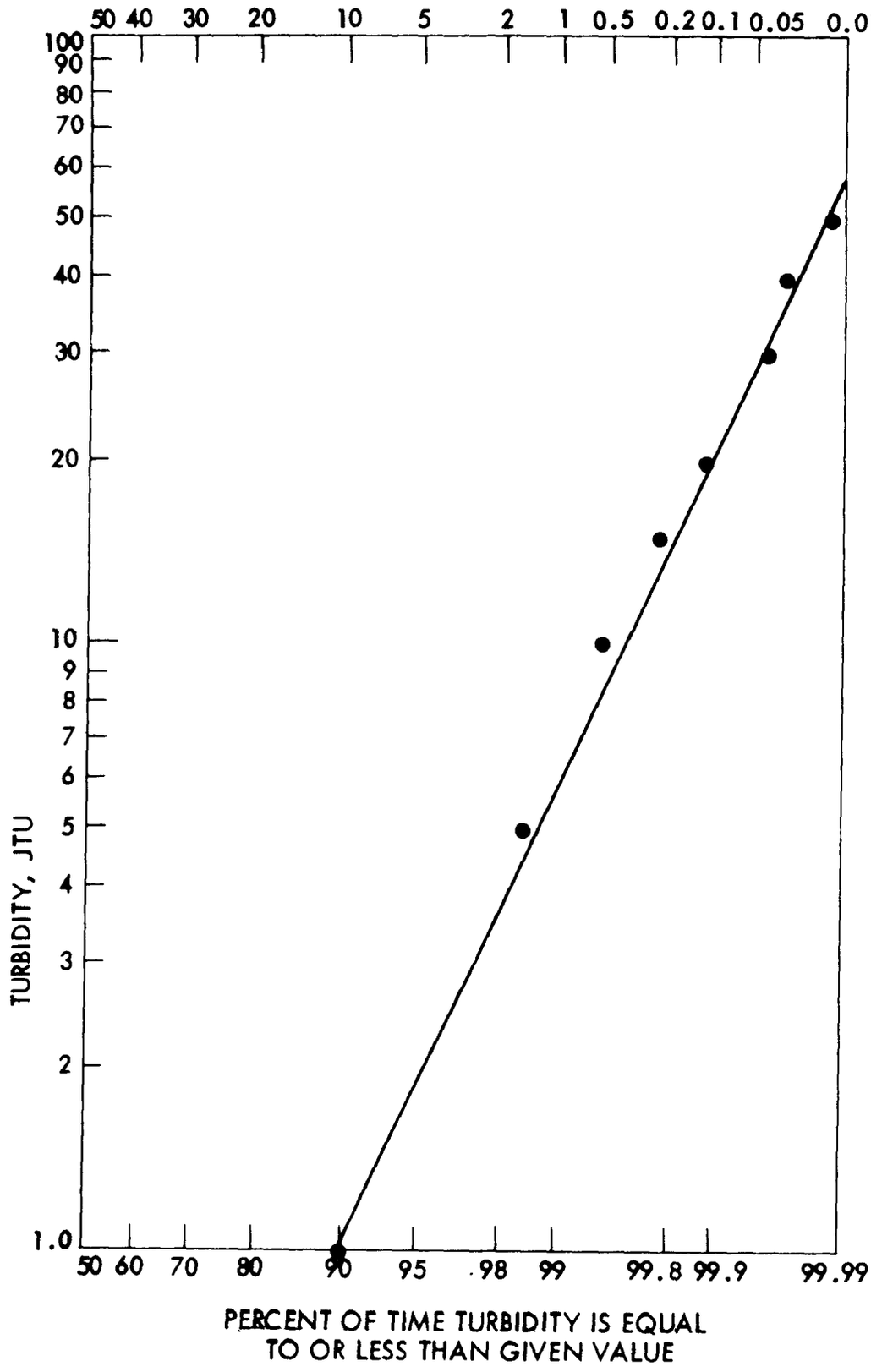


Fig. 1. City of Duluth, Minnesota, Lakewood Pumping Station, Lake Superior raw water turbidity, 1952–1972.

Table 2. Percentage of time given raw water turbidity is equalled or exceeded, City of Duluth, Lakewood Pumping Station, 1952-1972.

Raw Water Turbidity, JTU	Per Cent of Time Equal or Less than
1.0	89.95
2.0	95.3
3.0	97.2
4.0	98.2
5.0	98.7
10.0	99.6
20.0	99.9
30.0	99.99
50.0	99.985

Working values from Fig. 1

1	90.0
1.9	95.0
5.8	99.0
20.5	99.9
57.5	99.99

Potential Treatments with Diatomite Filters

Diatomite filter aids are produced by several manufacturers in several grades. Table 3 is a table of filter aid grades currently available on the market. The table lists the trade name of filter aid grades from several manufacturers that are approximately "equivalent." Filter aids are considered "equivalent" when they produce approximately the same flow rate and filtered solution clarity under the same operating conditions when filtering a standard sugar solution. Grades that produce the highest clarity will also produce the lowest flow rate. In general, the high clarity filter aids are composed of very small particles of filter aid (mean size in the range of 3-6 μm) and high flow rate filter aids are composed of larger particles (mean size in the range of 20-40 μm). High clarity filter aids are cheaper, produce a better clarity of filtered water, and produce the highest rate of pressure drop increase across the filter and, therefore, shorter filter runs.

In the pilot plant work, therefore, the filter aids and/or filter aid treatments are selected which will produce the desired clarity of filtered water or the desired removal of asbestiform fibers with the lowest rate of head loss increase. The rate of head loss increase is measured by a filter cake resistance index, β [3,4]. In the pilot plant studies all grades of filter aid were <u>not</u> available; filter aid purchases were made periodically of grades that were found to be potentially useful. The principal grades used in the study, in order of

Table 3. Filter aid ratings.

Standard Ratios[a]				
Flow Rate	Clarity	Eagle-Picher	Johns-Manville	Dicalite
100	1000	Celatom FP-2	Filter Cel	215
125	1000	Celatom FW-2	Celite 505	Superaid, UF
200	995	Celatom FP-4	Standard Super-Cel	Speedflow
300	986	Celatom FW-6	Celite 512	Special Speed-flow, 231
400	983	Celatom FW-10	---	341
700	970	Celatom FW-12	Hyflo Super Cel	Speedplus, 689 CP-100
800	965	Celatom FW-14	---	375
950	963	Celatom FW-18	Celite 501	CP-5
1000	960	Celatom FW-20	Celite 503	Speedex, 757
1800	948	Celatom FW-40	---	---
2500	940	Celatom FW-50	Celite 535	4200, CP-8
3000	936	Celatom FW-60	Celite 545	4500
4500	930	Celatom FW-70	Celite 550	5000
5500	927	Celatom FW-80	Celite 560	---

[a]Based on bomb filter tests with 60^0 Brix raw sugar solution, 80 ^oC.

decreasing water clarity achieved, were (Table 3):

FW-6, Celite 512

FW-10

FW-12, Hyflo Super Cel

FW-20, Celite 503

FW-50, Celite 535 (Aquacel)

As the mean particle size of the filter aid gets smaller, the total surface area of a given weight of material increases. In order to remove very small particles of suspended solids such as asbestiform fibers, the particles must be transported through the fluid over to the surface of the filter media, and then the particles must become attached to the surface of the filter media. Both particle transport and attachment are enhanced as filter media particle size is decreased. Diatomite filter aid normally carries a negative surface potential. Also, most normally encountered suspended solids also carry negative surface potentials. When such particles are filtered through negatively charged filter media, the transport forces have more difficulty in moving the particles to the media surface where attachment can take place. Thus pretreatment of the water or pretreatment of the filter aid can be designed and used to change the surface potential either of the suspended solids or of the filter media. One must be changed to carry a surface charge opposite to that of the other.

The removal of asbestiform fibers by such treatments presents an anomaly. Two types of asbestiform fibers are found in Lake Superior - amphibole particles and chrysotile particles. Amphibole particles have fiber diameters (or widths) from 0.1 to about 2 to 3 μm. Chrysotile

particles have a fiber diameter that is consistently less than 0.08 to 0.1 μm. Asbestiform fibers, by definition, are particles which have a length/width ratio equal to or greater than three. Both fiber forms are usually present in roughly equivalent numbers (see Table 4). Thus, because of the different sizes of the two asbestiform particles, the mass of amphibole particles is consistently and significantly greater than the mass of chrysotile particles.

Unfortunately, current analytical techniques do not always produce the same fiber count when identical samples are analyzed by two or more laboratories. An order of magnitude difference in such results is not unusual. If a series of samples is processed by the same laboratory, however, more consistent results can be achieved. Standard laboratory procedures are still under development.

During this study, several methods were used to evaluate the quality of the raw and filtered water:

Amphibole fibers per liter	(Transmission Electron Microscope Count)
Chrysotile fibers per liter	(" " " ")
Total fibers per liter	(" " " ")
Mass of suspended solids, mg/l	(X-Ray Diffraction)
Mass of amphibole fibers, mg/l	(X-Ray Diffraction)
Turbidity, FTU	(Hach 2100A Turbidimeter)

Amphibole asbestos fibers are negatively charged (Fig. 2) [5], whereas chrysotile asbestos fibers are positively charged. Thus water or media treatments that are designed to enhance removal of one species will interfere with the removal of the other species. In general, transport forces are a minimum when particles are about 0.5-2.0 μ in

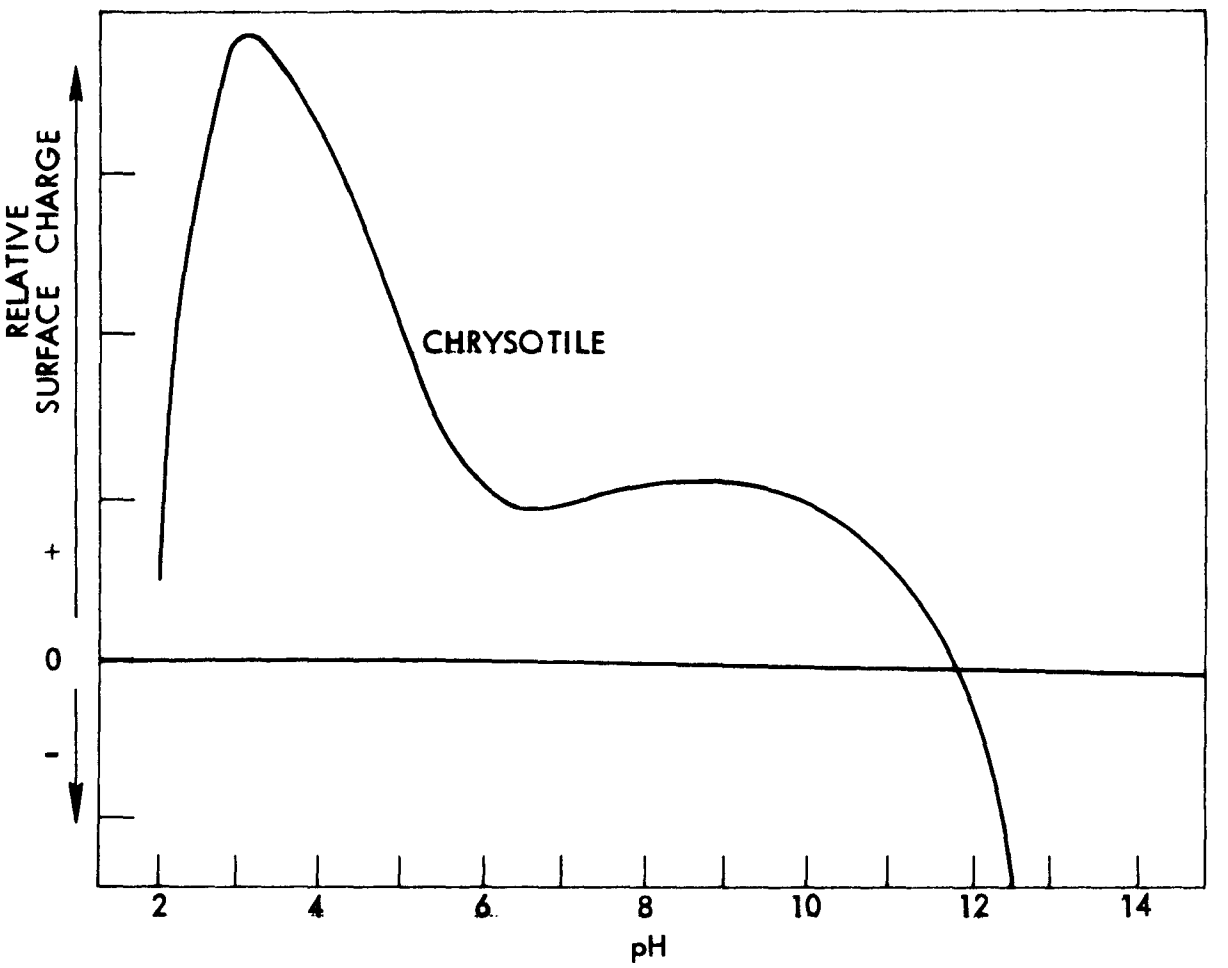


Fig. 2. Surface charges on Chrysotile fibers.

size. Significantly smaller particles are transported effectively by diffusion forces. Since the size of the amphibole particles is in the size range that would be difficult to transport and since they are present in larger numbers, water and filter media treatments used were designed to enhance removal of these negatively charged particles.

In diatomite filtration, the prime filter media consists of a precoat layer of filter aid with a thickness of about 1/8 in. (0.1-0.2 lb of filter aid/sq ft filter). The addition of body feed filter aid throughout a filter run is designed primarily to maintain a desirable permeability of the case which is formed (suspended solids removed by the filter plus the body feed filter aid). It does, however, also provide an increasing depth of filter media as the run progresses and thus serves to increase both the area of media surface available for particle adsorption and the opportunities for transport of particles to the media surface.

There are only a limited number of water and/or media treatments that can be expected to improve solids removal on a diatomite filter:

Use of filter media without chemical treatment of the water or the media.

- Use of a finer grade of media as precoat to improve retention, but with a greater rate of head loss increase.
- Use of a greater depth of precoat, but at an increased cost for the filter aid.
- Use of two filter media, a fine media for the precoat to improve solids retention and a coarser media for the body feed to improve the hydraulic characteristics of the case. The operation of the

filter would be slightly more complicated by the use of two filter media.

Use of chemical pretreatments of the filter media [6].

- Application of an organic or inorganic coating to the filter media used as precoat to improve particle retention.
- Application of an organic or inorganic coating to the filter media used as body feed to improve particle retention.
- Application of such a coating to both precoat and body feed filter aid.

Use of chemical treatment of the raw water.

- Use of inorganic and/or organic coagulants to change the particle characteristics to improve their retention in the diatomite filter media.

In view of the normally expected effectiveness of diatomite filters for the removal of suspended solids from low turbidity waters (0-30 FTU), no provision was made for the coagulation-flocculation-sedimentation normally provided with single, dual, or multi-media granular filters. When used, coagulants were added immediately prior to the main filter pump without provision for more than a few seconds of mixing time before the water reached the filter media.

Since the amphibole particles had a negative surface (zeta) potential, it was expected that a positive coating applied to the filter media would be most effective. Two such coatings had been used in previous studies - a cationic polymer, C-31, manufactured by the Dow Chemical Company, and alum. Figures 3 and 4 show the effect of coating level at a pH of 6.5 on the surface potential of Celite filter media

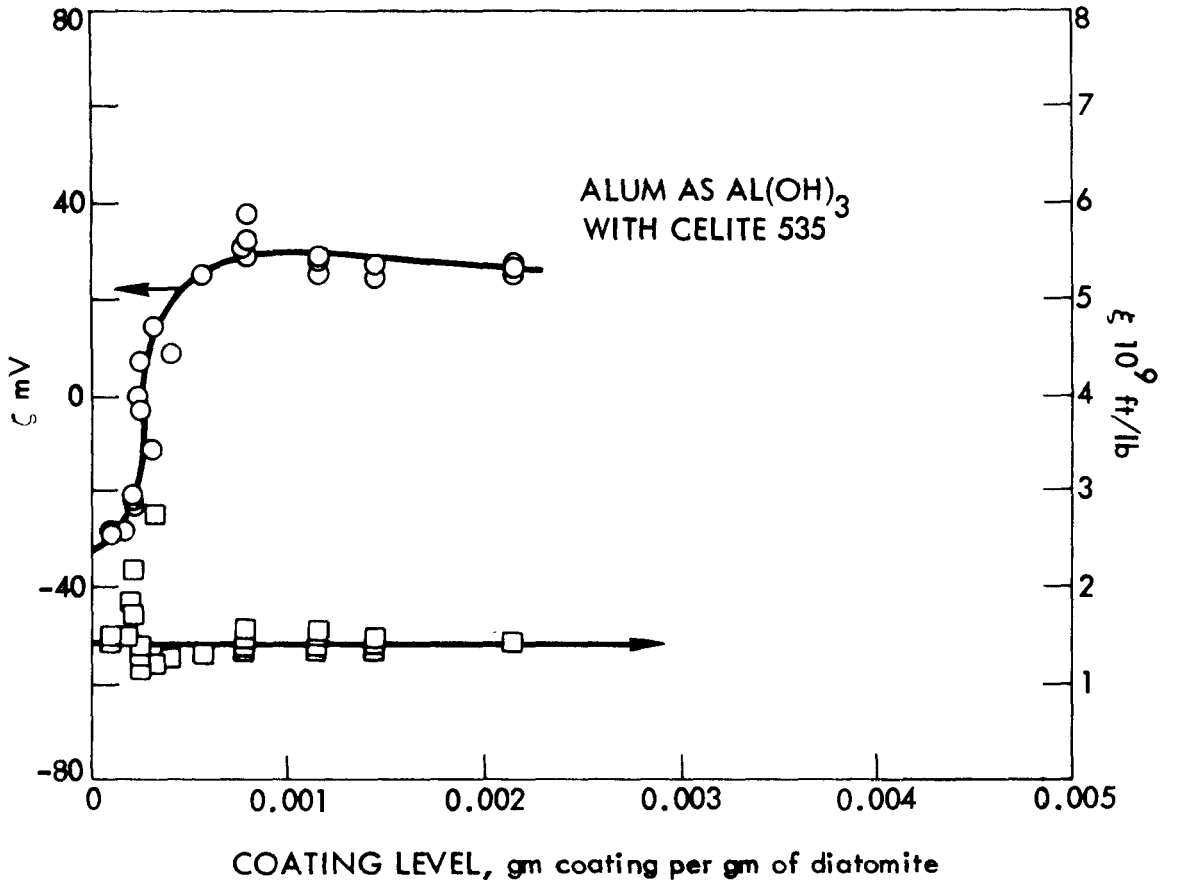


Fig. 3. Zeta potential, ζ, and filter case resistance, ξ, as a function of coating level for Alum coated on Celite 535 (6).

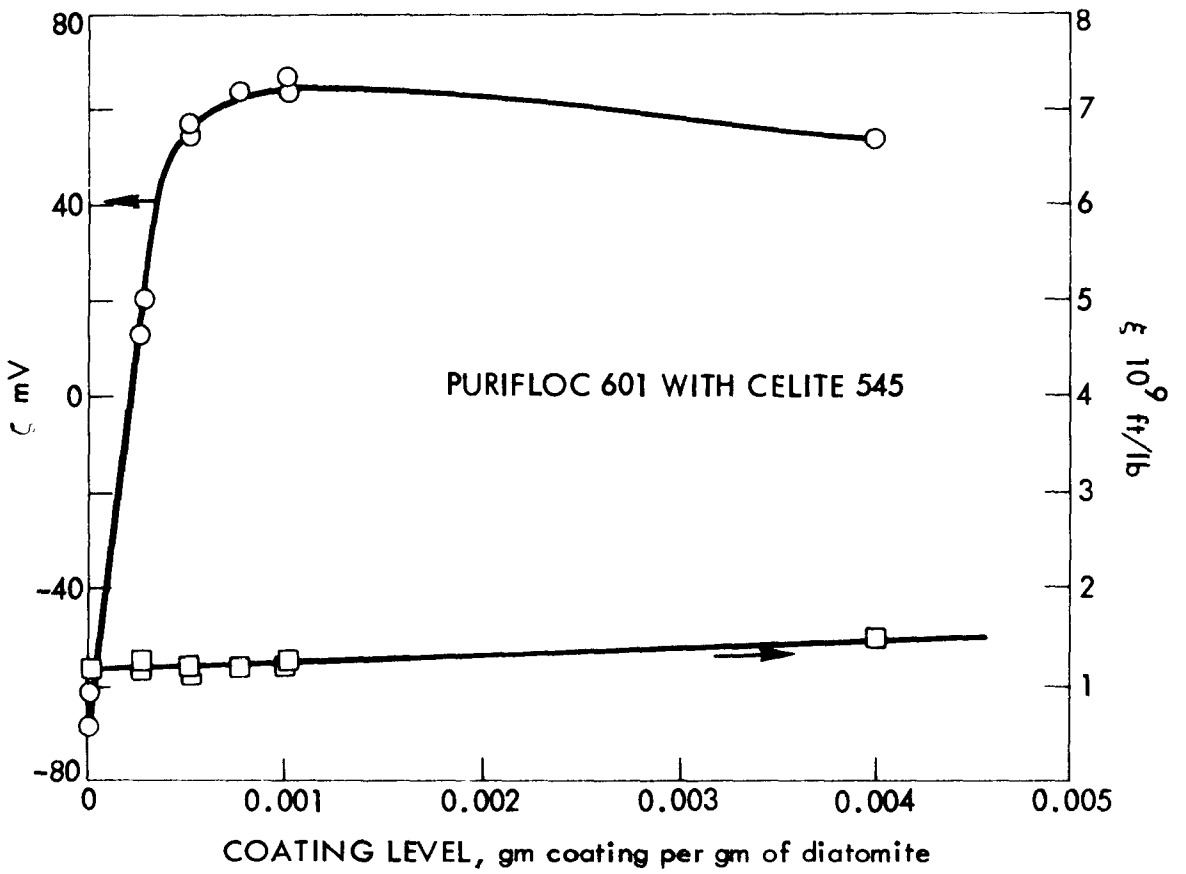


Fig. 4. Zeta potential, ζ, and filter case resistance, ξ, as a function of coating level for C-31 coated on Celite 545 (6).

coated with alum and C-31, respectively. Both coatings effectively provide a positive surface characteristic to the filter media at a water pH of 6.5. At Duluth, the water in Lake Superior during the period of the pilot plant operations had a normal pH from seven to eight. Previous studies had demonstrated that C-31-coated media had a negative surface potential at pH values above 7.0 and a positive surface potential at pH values below 7.0 [6]. Figure 2 indicates that chrysotile asbestiform particles carry a positive surface potential at pH values between about two and thirteen. No similar data is available to evaluate the effect of pH on the surface potential of amphibole particles or of alum-coated filter media. It was hypothesized, however, that alum-coated filter medias would carry a positive surface potential, and the amphibole particles would carry a negative surface potential in the Lake Superior water pH range of seven to eight. Use of other media coatings was based on an "Edisonian" approach (try it and see if it would work) rather than on detailed knowledge of the coating characteristics.

The treatments designed and used for the removal of amphibole particles included:

Using different grades of filter aid.

Celite 535

Celite 503

Hyflo Super Cel

Celite 512

etc.

Coating precoats and/or body feed with

C-31 (a Dow cationic polymer)

Alum

573-C

A-23 (a Dow anionic polymer)

Magnifloc 985N (a Cyanamid non-ionic polymer)

Coagulation of the water prior to filtration

Cat-Floc B (Calgon Corporation cationic polymer)

Of all the treatments used, the treatments listed in Table 4 offered the most potential for use in a diatomite filtration plant at Duluth based on the pilot plant studies.

Pilot Plant Results

As the pilot plant runs were made, routine analyses were made of the run results. A number of problems were encountered which seriously affected the ability to interpret adequately the test results. These included the following:

1. The time required for analysis of samples collected for asbestos fiber determinations was so long (four to six weeks frequently) that the periodic results available were of little use in adjusting the test schedule.
2. The early test results indicated serious passage of filter aid into the filter effluent due to the fact that the filter septa were not fine enough to retain the finer precoat filter aids. Subsequently, a two-layer precoat was used. The first

Table 4. Water and/or filter media treatments tested for optimization runs.

Case	Treatment[a,b]	
1	Precoat	Alum-coated C-512
	Body Feed	C-512
	Coagulant	None
2	Precoat	Alum-coated C-512
	Body Feed	Hyflo Super Cel
	Coagulant	None
3	Precoat	Alum-coated Hyflo Super Cel
	Body Feed	Alum-coated Hyflo Super Cel
	Coagulant	None
4	Precoat	Alum-coated Hyflo Super Cel
	Body Feed	Hyflo Super Cel
	Coagulant	Cat-Floc B (0.59 mg/l)
5	Precoat	Alum-coated C-512
	Body Feed	Aquacel (C-535)
	Coagulant	Cat-Floc B (0.33 mg/l)

[a] All alum coatings at 1% by weight of Al^{+++}.

[b] All filter aids produced by Johns-Manville Products Corp. Cat-Floc B is a cationic (primary coagulant) polyelectrolyte produced by the Calgon Corporation.

layer consisted of coarse filter aid (FW-50 or C-535) used to retain the finer precoats found necessary for good filtration. The second layer consisted of the grade of filter aid considered necessary to achieve successful suspended solids reduction. Only the second precoat layer was ever coated. The first precoat layer was considered to be a part of the septum.

3. In early runs, the major problem encountered concerned the consistency of suspended solids removal. In many runs, the turbidity level (used as a measure of suspended solids) remained low for only a portion of the filter run and then increased to levels approaching turbidity levels in the raw water.

The phase two series of runs conducted to determine which treatments gave promise of removing asbestiform fibers were made under fairly standard conditions:

Filtration rate ------	1.0 ± gpm/sq ft
Precoat weights ------	0.1 lb/sq ft of coarse media (part of septum) 0.1 lb/sq ft of test media
Body feed rate -------	50-70 mg/l (more or less only to provide run of at least 12 hours and no more than 2 days)

In order to classify success or failure in achieving the desired water quality, the primary objective was to vary precoat, body feed, and filter aid coating treatments until the average filtered water turbidity reached a consistent goal of 0.1 FTU or better. That goal was reached when either the C-512 or Hyflo Super Cel (or other equivalent filter aids) were used with an alum coating. Other coatings did

not consistently produce such water quality. For example, the C-31 polymer coatings used in the basic Lake Superior water did not prove consistently effective in turbidity reduction.

Once it was established that alum-coated filter aids used as precoats could produce the desired water quality, additional studies were made to evaluate the use of various types and amounts (mg/l) of body feed for providing both better turbidity removal and better cake hydraulic characteristics during the filter run. In this series of runs, the body feed rate was different in each of four or five runs in the series. The variation in the body feed rate made it possible to optimize the filter design for use with that "treatment." When the asbestos fiber analyses were ultimately evaluated, the five cases described in Table 4 were found to provide the suspended solids removal summarized in Table 5. The average turbidity of the final effluent in each series of runs was as follows:

	Filtered Water Turbidity, FTU
Case 1	0.09 (Runs 59-62)
Case 2	0.10 (Runs 55, 57, 58)
Case 3	0.05 (Runs 67, 68, 69)
Case 4	0.05 (Runs 73, 74, 75)
Case 5	0.06 (Runs 79, 80, 81)

Analysis of the data in Table 5 indicated that amphibole asbestos fiber removal generally was above 80 per cent, and when finished water turbidity was 0.05 or 0.06 FTU fiber removal was over 95 per cent. In most cases the amphibole fiber removal was significantly better than chrysotile fiber removal. This may be due to several conditions:

Table 5. Suspended solids removal in selected series of filter runs.

Treatment Case	Suspended Solid	Concentration in Raw Water	Concentration in Filtered Water	Per Cent Removal
1	ORF - Amphibole fibers/liter	300,000	0	100
	ORF - Chrysotile fibers/liter	720,000	170,000	76
	NWQL - SS, mg/l	0.81	0.04	95
	NWQL - Amphibole fibers, mg/l	0.02	< 0.003	85
	UMD - Total fibers/liter	25,300,000	810,000	97
	B&V - Turbidity, FTU	0.73	0.09	88
2	ORF - Amphibole fibers/liter	10,000	40,000	?+
	ORF - Chrysotile fibers/liter	170,000	40,000	77
	NWQL - SS, mg/l	0.81	0.16	80
	NWQL - Amphibole fibers, mg/l	0.06	< 0.003	95
	UMD - Total fibers/liter	8,980,000	1,530,000	83
	B&V - Turbidity, FTU	0.70	0.10	86
3	ORF - Amphibole fibers/liter	780,000	0	100
	ORF - Chrysotile fibers/liter	330,000	540,000	?+
	NWQL - SS, mg/l	0.41	0.008	98
	NWQL - Amphibole fibers, mg/l	0.07	< 0.003	96
	UMD - Total fibers/liter	17,800,000	270,000	99
	B&V - Turbidity, FTU	0.58	0.05	91
4	ORF - Amphibole fibers/liter	1,000,000	0	100
	ORF - Chrysotile fibers/liter	500,000	1,000,000	?+
	NWQL - SS, mg/l	0.6	0.03	95
	NWQL - Amphibole fibers, mg/l	0.04	< 0.003	93
	UMD - Total fibers/liter	15,400,000	640,000	96
	B&V - Turbidity, FTU	0.58	0.05	91
5	ORF - Amphibole fibers/liter	900,000	20,000	98
	ORF - Chrysotile fibers/liter	100,000	60,000	40
	NWQL - SS, mg/l	0.31	0.04	87
	NWQL - Amphibole fibers, mg/l	0.08	< 0.003	96
	UMD - Total fibers/liter	20,300,000	810,000	96
	B&V - Turbidity, FTU	0.48	0.06	88

ORF = Ontario Research Foundation
NWQL = EPA National Water Quality Laboratory, Duluth
UMD = University of Minnesota, Duluth
B&V = Black and Veatch

1. The precoat coating used was designed for the removal of negatively charged particles similar to the amphibole particles;
2. The chrysotile fibers are very small and positively charged, and their removal was undoubtedly retarded by the precoat treatments used;
3. There must be an anomaly in the measurement techniques used to count chrysotile fibers, since the results frequently showed more (by a factor of two) fibers leaving in the filter effluent than there were present in the raw water (Cases 3 and 4).

To date no criteria have been established for evaluating what removal of asbestos fibers is desired. Accordingly, the results of all five cases were analyzed in detail to determine the optimum design characteristics of the diatomite filtration plant needed in each case to produce the lowest cost of filtered water.

Determination of Filtration Resistance

The design of a diatomite filtration plant requires specification of the following items:

1. The design filtration rate, gpm/sq ft,
2. The terminal pressure drop to be built up across the filter cake, feet of water,
3. The precoat type and weight,
4. The body feed type and amount to be used.

The research group at Iowa State University has developed and published mathematical models for and described techniques which can be used in the optimum design and operation of diatomite filtration plants [3,4,7].

In order to optimize filter design, it is first necessary to evaluate the filter cake resistance that is generated when any given ratio of suspended solid to body feed exists in a filter cake. In order to accomplish this, it is necessary to have a record of:

1. The head loss generated across the filter cake as a function of time during a filter run,
2. The average raw water turbidity during the filter run,
3. The average body feed rate, CD, in mg/l, during the filter run.

These data were collected routinely in each run (Fig. 5).

The data for head loss vs time from each run in all five cases were fed into a computer, and the filter cake resistance of each filter cake (B, in ft^{-2}) was calculated. The BID (Beta Index Determination) program developed at Iowa State University was used for this purpose. The results of each run provided two related parameters:

1. The cake resistance, represented by B,
2. The proportion of solids to body feed in the cake as represented by the ratio, T/CD (Turbidity, FTU/Body feed, mg/l)

If two or more (preferably many more) runs are made under similar conditions using different T/CD ratios, it is possible to determine a so-called <u>Beta prediction equation</u> which can be used to predict the filter cake resistance that will result for any "reasonable" ratio of T/CD in the filter cake. For example, Fig. 6 shows a plot of Beta as

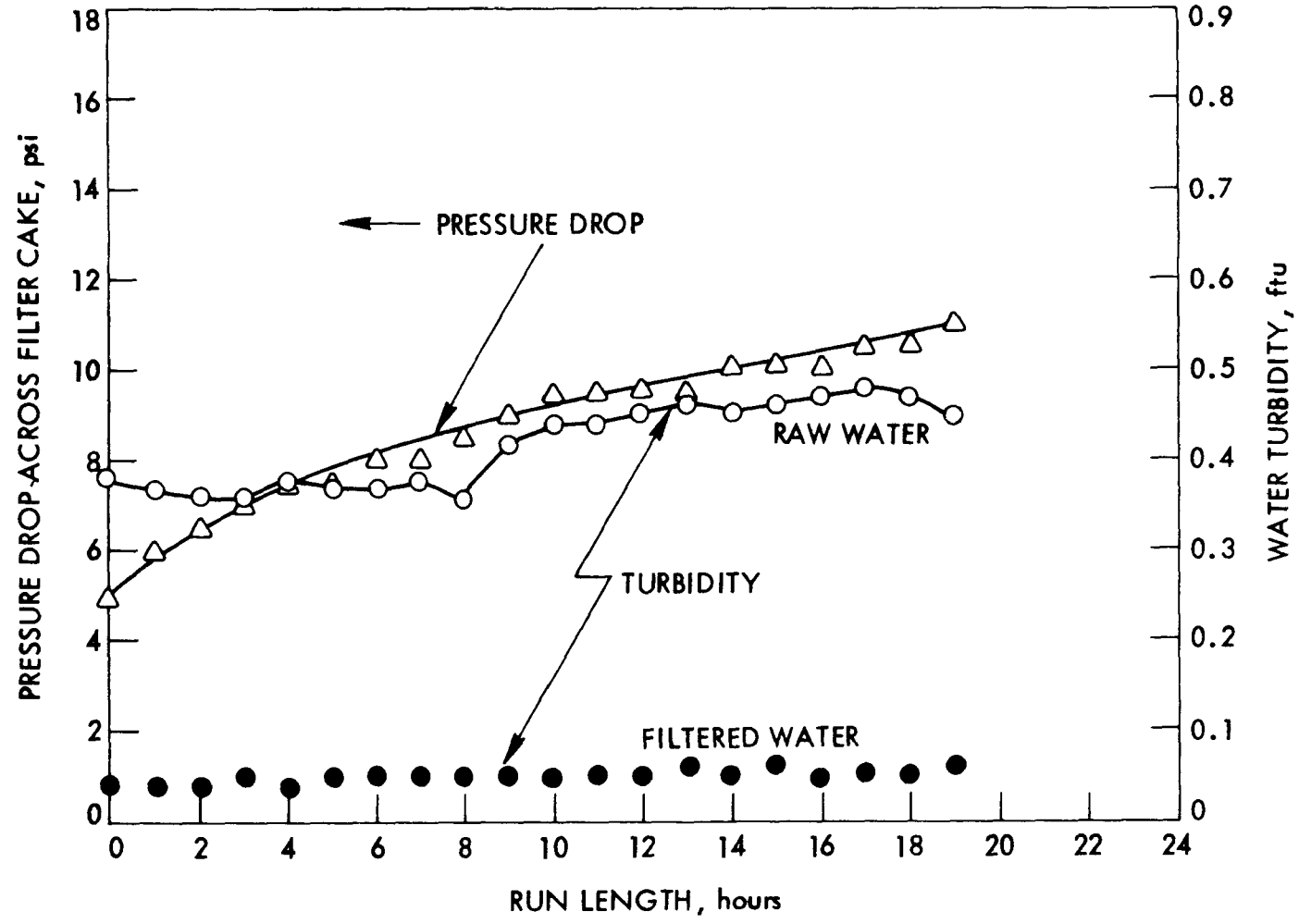


Fig. 5. Turbidity and pressure drop as a function of run length, Run 79, Case 5.

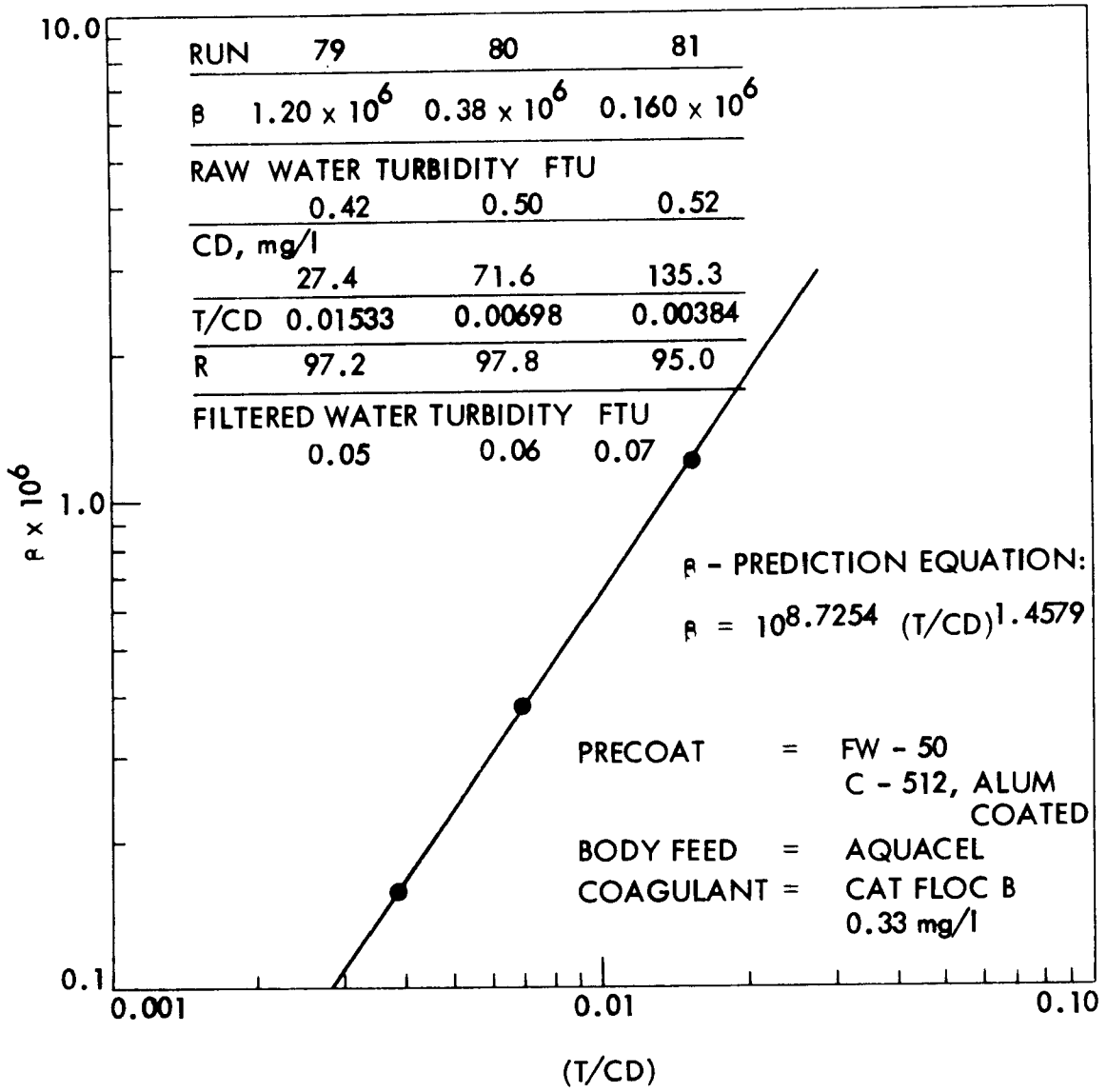


Fig. 6. Development of a Beta prediction equation for Case 5.

a function of T/CD for Case 5. The figure includes the calculated value of B, the raw water turbidity, the body feed, the run T/CD value, and R, the correlation coefficient describing the statistical fit of the head loss to time data for the run. An R value of 100 would indicate perfect correlation. The results of the three runs shown in Fig. 6 were used to determine a Beta prediction equation.

The Beta prediction equation is frequently expressed in the form $\text{Beta} = 10^a (T/CD)^b \, CD^c \, \xi^d$ where ξ is a measure of the cake resistance of the clean filter aid. However, in this study the Beta prediction equations are expressed in the form

$$\text{Beta} = 10^a (T/CD)^b$$

The Beta prediction equation exponents determined in each case are as follows:

	a	b
Case 1	7.207	0.735
Case 2	6.987	0.760
Case 3	9.252	1.393
Case 4	9.053	1.628
Case 5	8.725	1.458

Figure 7 shows a plot of the Beta vs T/CD for Cases 1-4. Case 5 is not shown since it falls very close to Case 4. The results for Cases 1 and 2 are typical of Beta prediction curves obtained in other studies using filter aids without chemical treatment of the body feed

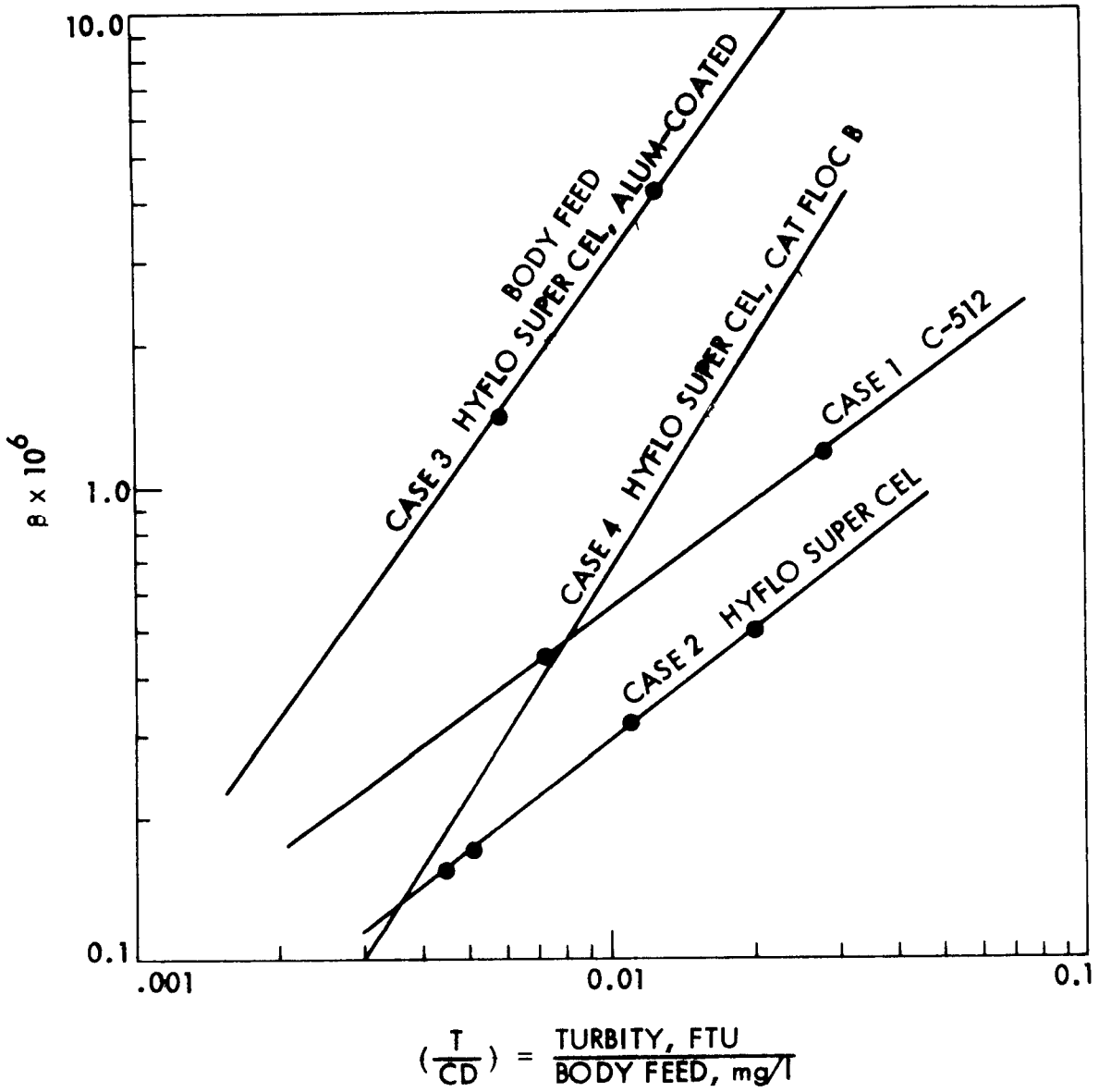


Fig. 7. Beta prediction relationships for Cases 1-4.

filter aid. Use of C-512 for body feed provides a higher cake resistance at the same T/CD ratio than does Hyflo Super Cel because it is a finer filter aid. When the Hyflo Super Cel used as body feed is coated with alum, the cake resistance increases, and increases at a faster rate with increasing values of T/CD. It does, however, provide the best effluent quality. Case 3, because of the higher cake resistance, should also provide the highest filtration cost. In both Cases 4 and 5 the use of Cat-Floc B as a coagulant provides excellent water quality, but the filter cake resistance is less than in Case 3. Both cases should provide nearly the same filtration cost. The data for Case 5 is probably the most reliable, since there was a better fit of the individual Beta values to the curve. With the 5 Beta prediction equations, it was possible to design the optimum diatomite filtration plants for each case so that each plant would operate with maximum economy.

Determination of Optimum Plant Designs

Diatomite filters can be designed as pressure filters (head losses across filter cakes to about 200 ft of water maximum) or as vacuum filters (head loss across filter cakes of 20-22 ft). Vacuum filters are easier to operate and maintain, but the cake is under a pressure less than atmospheric, and dissolved gases in the water can come out of solution and collect in the cake causing an unnecessary resistance increase. This was observed to happen in the pilot filter runs, particularly with water at about 33-40 $^{\circ}$F. In general, pressure filters are more economical than vacuum filters under higher turbidity loadings

and/or where power costs are relatively low. The filter cake resistances should be the same using vacuum or pressure filters provided gases are not collected in the cake. Therefore, the Beta prediction equations listed in the previous section were used to optimize the design of both pressure and vacuum diatomite filtration plants.

A computer "Program for Optimization of Plant Operation" (POPO), developed at Iowa State University, was used to find the optimum design characteristics of the plants in each case. It was assumed initially that the design flow of the plant was 30 mgd, and costs are based on the production of 30 mgd during each day of operation.

The operation of POPO requires the input of 20 items of data. Tables 6 and 7 list the data input into the computer for pressure and vacuum diatomite plant design, respectively. In general, the data are self explanatory, but some items deserve some additional comment (see Table 6).

Item 4. This is the assumed rate of interest that cities on Lake Superior might pay on the bonded indebtedness of the first cost.

Item 6. The turbidity of the raw water varies up to about 57.6 FTU. A turbidity of 1.0 is exceeded only 10 per cent of the time. The plant design is repeated using other turbidity values to provide the least possible <u>yearly</u> plant operating costs.

Items 7, 10, 12, and 16 These will be explained later.

Table 6. Input Data, POPO (Program for Optimization of Plant Operation), asbestos-turbidity removal, Lake Superior water, Pressure Diatomite Filter Plant.

1.	Design Flow		30 mgd
2.	Salvage Value		30% First Cost
3.	Energy Conversion		70%
4.	Interest Rate		6.68%
5.	Plant Life		20 Years
6.	Solids, C_s		1.0 FTU (by turbidity)
7.	XI Index		ft/lb
8.	Temperature		33 °F
9.	Precoat Weight		0.15 lb/sq ft
10.	Precoat Density		lb/cu ft
11.	Septum Diameter		3.5 in
12.	Beta Prediction		
13.	Unit Flow Rate		0.5/0.1/6.0 gpm/sq ft
14.	Body Feed		10/5/150 mg/l
15.	Terminal Head		20/5/150 ft
16.	Diatomite Cost		$/ton
17.	First Cost	Area, sq ft	$/sq ft
		1,000	$616
		3,472	376
		6,944	259
		20,832	155
		41,667	134
		80,000	122
		100,000	120
18.	Power Cost		1.627 ¢/KWH
19.	Labor Cost	Area, sq ft	$/sq ft per month
		1,000	$1.87
	($5/hr)-1.25 men	3,472	1.30
	2.0 men	6,944	1.04
	4.0 men	20,832	0.69
	6.0 men	41,667	0.52
		80,000	0.40
		100,000	0.35
20.	Backwash Cost		10,30 gal/sq ft, min

Table 7. Input data, POPO (Program for Optimization of Plant Operation), asbestos-turbidity removal, Lake Superior water, vacuum diatomite filter plant.

1.	Design Flow		30 MGD
2.	Salvage Value		30% First Cost
3.	Energy Conversion		70%
4.	Interest Rate		6.68%
5.	Plant Life		20 Years
6.	Solids, C_s		1.0 FTU (turbidity)
7.	XI Index		ft/lb
8.	Temperature		33 ^{o}F
9.	Precoat Weight		0.15 lb/sq ft
10.	Precoat Density		lb/cu ft
11.	Septum Diameter		Flat
12.	Beta Prediction		
13.	Unit Flow Rate		0.5/0.1/6.0 gpm/sq ft
14.	Body Feed		10/5/150 mg/l
15.	Terminal Head		20 ft
16.	Diatomite Cost		$/ton
17.	First Cost	Area, sq ft	$/sq ft
		3,472	$479
		6,944	355
		20,832	257
		41,667	237
18.	Power Cost		1.627 ¢/KWH
19.	Labor Cost	Area, sq ft	$/sq ft per month
	($5/hr) 1.25	3,472	1.17
		6,944	0.936
		20,832	0.621
		41,667	0.468
20.	Backwash Cost		10,30 gal/sq ft, min

Item 8. This is the temperature of the water under the worst plant operating conditions. When the water is warmer, the operating costs will be lower.

Item 11. This is the diameter of the septa in pressure filters. For vacuum filters, flat septa are specified.

Item 13. This tells the computer to compute filtration costs for filtration rates from 0.5 to 6.0 gpm/sq ft in increments of 0.1 gpm/sq ft.

Item 14. This tells the computer to compute filtration costs for body feed rates from 10 to 150 mg/l in increments of 5 mg/l.

Item 15. This tells the computer to compute filtration costs for terminal head losses from 20 ft to 150 ft in increments of 5 ft.

Item 17. This tells the computer the cost per square foot of the filter area required as related to the total filter area requirement. The computer interpolates between these values when other areas are required. The cost of the pressure filters was derived from Table 8 and the cost of the vacuum filter was derived from Table 9.

Item 19. This tells the computer the monthly cost per square foot of the filter area required as related to the total filter area requirement. The computer interpolates between these values when other areas are required. The pressure filter labor requirement is shown at a wage rate of $5/hr. It is assumed that each man indicated is

Table 8. Capital construction costs[a] of pressure diatomaceous earth or diatomite water filtration plants with varying filter rates, plant design for 30 mgd.[b]

Item	Filter Flow Rate, gpm/sq ft			
	0.5 ($x10^6)	1.0 ($x10^6)	3.0 ($x10^6)	6.0 ($x10^6)
Building and associated costs	2.288	1.430	1.144	0.858
Filter equipment	2.150	1.075	0.350	0.189
Body feed and precoat slurry feeders and storage tanks	0.500	0.400	0.200	0.200
Equipment set-up and assembly	0.645	0.324	0.105	0.058
Totals	$5.583	$3.229	$1.800	$1.305

[a]Cost data from Black and Veatch, Consulting Engineers.

[b]Based on lowest cost filtration equipment currently commercially available.

Table 9. Capital construction costs[a] of vacuum diatomaceous earth or diatomite water filtration plants with varying filter rates, plant design for 30 MGD.[b]

Item	Filter Flow rate, gpm/sq ft			
	0.5 ($x10^6)	1.0 ($x10^6)	3.0 ($x10^6)	6.0 ($x10^6)
Building and associated costs	2.288	1.430	1.114	0.858
Filter equipment	5.437	2.718	0.937	0.468
Body feed and precoat slurry feeders and storage tanks	0.500	0.400	0.200	0.200
Equipment set-up and assembly	1.631	0.815	0.218	0.140
Totals	$9.856	5.363	2.469	$1.666

[a]Cost data from Black and Veatch, Consulting Engineers.

[b]Based on costs of filtration equipment currently commercially available.

required 24 hrs per day. More men are required with larger filter areas. The vacuum filter labor costs are assumed to be 90 per cent of those needed for pressure filters.

Item 20. This tells the computer that 10 gal of water are required for backwashing each square foot of filter and that for 30 min the filter will be out of service for backwashing.

In each computer run, the costs are computed as if the water always had the turbidity and temperature shown. In general, lower operating costs will be obtained since the turbidity is less than 1 FTU 90 per cent of the time, and the water temperature is more than 33 $^{\circ}$F (and easier to filter) for some of the year.

Items 7, 10, and 16 refer to the characteristics of the filter aid grade used. In all POPO runs the characteristics of the body feed filter aid were used in these items. Table 10 lists the appropriate values for the filter aids used in Cases 1-5. The ξ index (item 7) measures the cake resistance of the pure diatomite without any suspended solids. The filter aid density (item 10) is used to measure the thickness of filter cake that builds up during filtration. The per ton cost of filter aid (item 16) represents the December 1974 cost delivered to the Lake Superior region.

The following computer runs were made to determine the optimum plant design and operating costs at each given turbidity level:

Table 10. POPO input data, filter aid characteristics (approximate values).

Filter Aid	Cost, $/ton	ξ, ft/lb	Density, lb/cu ft
Celite-512	132	5.5×10^9	21.0
Hyflo Supercel	134	4.74×10^9	20.7
Celite-503	146	3.05×10^9	19.9
Celite-545 (Aquacel)	152	1.77×10^9	19.7
FW-20	144	2.57×10^9	20.7

	Turbidity Level Assumed[a], FTU	
	Pressure Filter	Vacuum Filter
Case 1	1.0	1.0
Case 2	1.0	1.0
Case 3	1.0, 1.9, 5.8, 20.5	1.0
Case 4	1.0, 1.9, 5.8, 20.5, 57.5	1.0
Case 5	1.0, 1.9, 5.8, 20.5, 57.5	1.0

[a]Working values from Table 2.

In the solution of the POPO runs on the computer, two items of computer output were usually requested.

1. A listing of the data input into the computer,
2. A list of the ten cheapest operating combinations of filter design (filtration rate, terminal head loss, body feed rate), the Beta value of cake resistance produced, the filter area required, the optimum length of filter run, the thickness of the filter cake at the end of the run, and the filter operating costs. The operating costs ($/mg) include the following separately indicated items:
   - Total Cost
   - First Cost
   - Operating Costs
     - Labor and Maintenance
     - Power
     - Filter Aid
   - Total Cost, $/Month

In order to evaluate the changes that would occur in plant design and operating costs if the Beta resistance varied above and below the predicted value, the same data as outlined above were output for Beta resistance values of 50, 75, 100, 125, 150 and 175 per cent of the Beta prediction equation computed values. An example of the data input and the (100 per cent β value) computer printout is shown in Tables 11 and 12. Table 11 shows the computer input data required by the computer to optimize the design of pressure diatomite filters for the removal of 1.9 FTU of turbidity at a water temperature of 33 °F using Case 5 precoat and body feed treatments. Table 12 shows the 100 per cent β value computer output data for this input. All ten least-cost combinations of design data show about the same per 1000 gallon filtration cost of 5.89-5.90 cents. In all cases the economic filtration rate is 1.5-1.7 gpm/sq ft. In all cases the body feed rate is 6 or 8 mg/1. In general, the optimum terminal head varies from 120 to 140 ft, with the best optimum (lowest monthly cost) showing a terminal head of 130 ft of water. These values are, therefore, probable best operating conditions and are entered into a summary table (Table 13) in the appropriate place, as follows:

Case 5, turbidity 1.9 FTU

Optimum filtration rate	1.60 gpm/sq ft
Optimum terminal pressure	130 ft of water
Optimum body feed	8 mg/1
Predicted length of run	14.6 hr
Predicted terminal cake thickness	0.14 in

Table 11. Data input to POPO, pressure diatomite filter, Case 5, raw water turbidity of 1.9 FTU.

```
C JOB X5. ASBESTOS-TURBIDITY REMOVAL; DULUTH, MINNESOTA
C         TRIAL 1
C         RUNS 79,80,81 AQUACEL + CATFLOC B
C         PRESSURE D. E. PLANT
C         FINAL TURBIDITY: 0.06
C
 1 DESIGN FLOW                 30        MGD
 2 SALVAGE VALUE               30        PERCENT FIRST COST
 3 ENERGY CONVERSION           70        PERCENT
 4 INTEREST RATE                6.68     PERCENT
 5 PLANT LIFE                  20        YEARS
 6 SOLIDS  (CS)                 1.9      MG/L (BY TURBIDITY)
 7 XI INDEX                  1.77E9      FT/LB
 8 TEMPERATURE                 33        DEGREES F
 9 PRECOAT WEIGHT              0.15      LB/SF
10 PRECOAT DENSITY             19.7      LB/CF
11 SEPTUM DIAMETER              3.5      INCHES
12 BETA PREDICTION          8.725/1.45800/0/0
13 UNIT FLOW RATE           0.4/0.1/1.8              GSFM
14 BODY FEED (CD)           6/2/30                   MG/L
15 TERMINAL HEAD            100/10/200               FT
16 DIATOMITE COST                152      $/TON
17 FIRST COST               AREA         $/SF
                               1000       616
                             3472         376
                             6944         259
                             20832        155
                             41667        134
                             80000        122
  *                         100000        120
18 POWER COST                    1.627   CENTS/KWH
19 LABOR COST               AREA         $/SF PER MONTH
                               1000       1.87
                             3472         1.30
                             6944         1.04
                             20832        0.69
                             41667        0.52
                             80000        0.40
  *                         100000        0.35
20 BACKWASH COST             10, 30       GAL/SF, MIN
  BEGIN
```

Table 12. Computer output for data input shown in Table 11.

FLOW GSFM	TERM HEAD FT	CF PPM	B E T A 4 -2 10 FT	TIME HR	AREA SQ FT	THICK IN	* --- COSTS, $ PER MILLION GALLONS -- * TOTAL COST $/MO							
							* TOTAL	1ST	OPER	LAB+ MAIN	POWR	PAID	*	
BETA INDICES = 75 PERCENT OF PREDICTED VALUES														
1.60	120	6	5549	15.6	13545	0.13	* 56.3	22.2	34.0	13.5	8.8	11.7	*	51309
1.70	130	6	5549	15.0	12763	0.13	* 56.3	21.9	34.4	13.2	9.5	11.6	*	51315
1.70	120	6	5549	13.8	12807	0.13	* 56.3	21.9	34.3	13.3	8.8	12.3	*	51326
1.60	130	6	5549	16.9	13503	0.14	* 56.3	22.2	34.1	13.5	9.5	11.1	*	51341
1.70	120	8	3648	15.9	12733	0.15	* 56.3	21.9	34.4	13.2	8.8	12.4	*	51342
1.80	130	6	5549	13.4	12108	0.13	* 56.3	21.7	34.6	13.3	9.5	12.1	*	51354
1.80	120	8	3648	14.2	12077	0.15	* 56.3	21.6	34.7	13.0	9.8	12.9	*	51355
1.50	120	6	5549	17.7	14384	0.14	* 56.3	22.5	33.8	13.9	8.8	11.2	*	51366
1.70	110	8	3648	14.6	12778	0.15	* 56.3	21.9	34.4	13.2	8.1	13.1	*	51377
1.60	110	8	3648	16.4	13517	0.15	* 56.3	22.2	34.2	13.5	8.1	12.6	*	51384
BETA INDICES = 100 PERCENT OF PREDICTED VALUES														
1.60	130	8	4864	14.6	13583	0.14	* 58.9	22.2	36.7	13.5	9.6	13.6	*	53730
1.50	130	8	4864	16.5	14421	0.15	* 58.9	22.6	36.4	13.8	9.5	13.1	*	53744
1.60	140	8	4864	15.7	13541	0.15	* 58.9	22.2	36.7	13.5	10.3	13.0	*	53760
1.50	120	8	4864	15.3	14467	0.14	* 59.0	22.6	36.4	13.8	8.8	13.7	*	53772
1.70	140	8	4864	13.9	12804	0.14	* 59.0	21.9	37.0	13.3	10.3	13.5	*	53778
1.70	130	8	4864	12.9	12848	0.14	* 59.0	22.0	37.0	13.3	9.6	14.2	*	53791
1.50	140	6	7399	15.5	14457	0.13	* 59.0	22.6	36.4	13.8	10.3	12.3	*	53803
1.60	120	8	4864	13.5	13632	0.14	* 59.0	22.3	36.7	13.5	8.8	14.3	*	53807
1.50	130	6	7399	14.4	14502	0.13	* 59.0	22.6	36.4	13.8	9.6	13.0	*	53815
1.50	140	8	4864	17.8	14381	0.15	* 59.0	22.5	36.5	13.8	10.3	12.5	*	53816
BETA INDICES = 125 PERCENT OF PREDICTED VALUES														
1.50	140	8	6080	14.3	14509	0.14	* 61.1	22.6	38.5	13.8	10.3	14.4	*	55752
1.40	140	8	6080	16.3	15466	0.14	* 61.1	23.0	38.2	14.1	10.3	13.7	*	55761
1.50	150	8	6080	15.3	14466	0.14	* 61.2	22.6	38.6	13.8	11.0	13.7	*	55774
1.40	130	8	6080	15.2	15512	0.14	* 61.2	23.0	38.1	14.2	9.6	14.4	*	55786
1.60	150	8	6080	13.5	13631	0.14	* 61.2	22.3	38.9	13.5	11.0	14.3	*	55809
1.40	150	8	6080	17.5	15425	0.15	* 61.2	23.0	38.3	14.1	11.0	13.1	*	55828
1.50	130	8	6080	13.3	14558	0.14	* 61.2	22.7	38.5	13.9	9.6	15.1	*	55831
1.60	140	8	6080	12.6	13676	0.14	* 61.2	22.3	38.9	13.6	10.3	15.0	*	55834
1.30	130	8	6080	17.6	16619	0.14	* 61.2	23.4	37.8	14.5	9.6	13.7	*	55849
1.60	160	8	6080	14.4	13592	0.14	* 61.3	22.3	39.0	13.5	11.8	13.7	*	55872

Required filter area	13,583 sq ft
Operating cost	5.89 ¢/1000 gal
Monthly operating cost	$53,730 (30 mgd)

If cake resistance goes up or down from the predicted value, the optimum design conditions will change slightly, producing the new conditions shown in Table 12. In general, if unusual operating conditions result the computer output will readily indicate what they are. Without such conditions the optimum design condition would be considered acceptable; it has been transferred to the summary Table 13.

Tables 13 and 14 list the optimum design conditions for pressure and vacuum filters, respectively, for various levels of influent water turbidity when the plant is optimized for <u>that turbidity</u> (see Fig. 8). The data indicate that under <u>similar</u> conditions, the pressure filters are significantly more economical than vacuum filters. For example, when the plants are designed to remove 1.0 FTU of turbidity under optimum conditions, the comparison of plant operating costs shown in Table 15 results. Any of the treatments (cases) might be used successfully, depending on the quality desired in the filtered water. The costs follow the range predicted previously on the basis of cake resistance. Since the vacuum filter is limited in terminal pressure drop to 20-22 ft of water and cannot take advantage of the relatively low power costs to reduce overall filtration costs, the costs of vacuum filtration will increase <u>faster</u> than the costs of pressure filters designed for higher water turbidity levels. On this basis, vacuum filters were eliminated from further consideration.

Table 13. POPO output, pressure filter, all cases.

	Turbidity, FTU		Optimum Operation Conditions				
Case	Raw	Filtered	Q, gpm/ sq ft	HL[a]	CD	Cost, ¢/1000 gal	Run Length, hours
1	1.0	0.09	3.05	50	5	3.97	20-22

2	1.0	0.10	3.20	40	5	3.83	28.4
3	1.0	0.05	1.30	155	9	6.47	13.4
	1.9	----	1.10	195	10	7.29	13.0
	5.8	----	0.80	200	20	9.47	11.0
	20.5	----	0.50	200	35	13.64	10.0
4	1.0	0.05	1.80	110	10	5.52	14.1
	1.9	----	1.50	130	12	6.10	14.3
	3.5	----	1.30	150	14	6.75	13.1
	5.8	----	1.10	180	16	7.37	14.5
	20.5	----	0.90	200	28	9.65	9.8
	57.5	----	0.60	200	42	12.60	10.2
5	1.0	0.06	1.80	110	6	5.32	16.1
	1.9	----	1.60	130	8	5.89	14.6
	5.8	----	1.10	180	10	7.16	15.5
	20.7	----	0.80	200	18	9.51	12.1
	57.5	----	0.50	200	26	12.62	13.1

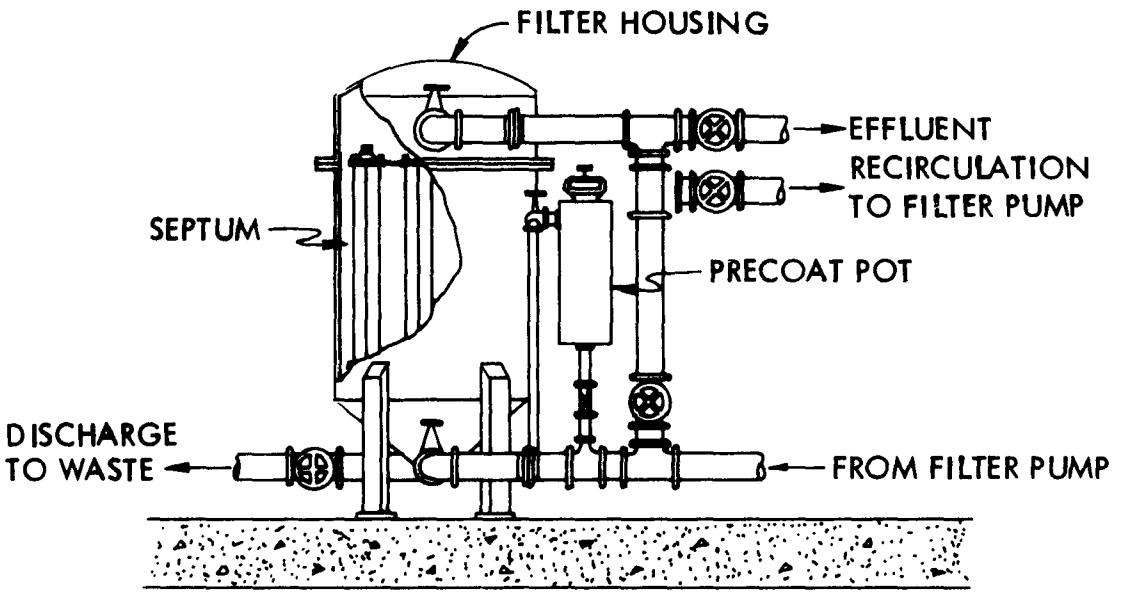
[a]HL = terminal pressure drop across filter cake.

Table 14. POPO output, vacuum filters, all cases.

	Turbidity, FTU		Optimum Operating Conditions				
Case	Raw	Filtered	Q,gpm/sq ft	HL	CD	Cost ¢/1000 gal	Run Length, hours
1	1.0	0.09	2.65	20	5	5.04	9.9
2	1.0	0.10	3.15	20	5	4.63	12.0
3	1.0	0.05	0.75	20	30	12.44	7.5
4	1.0	0.05	1.20	20	25	8.64	8.8
5	1.0	0.06	1.20	20	15	8.39	8.9

Table 15. Comparison of pressure and vaccum diatomite filtration costs optimized to remove 1.0 FTU turbidity.

	Total Operating Costs, ¢/1000 gal		Ratio: Vacuum Filter Cost / Pressure Filter Cost
Case	Pressure Filters	Vacuum Filters	
1	3.97	5.04	1.27
2	3.83	4.63	1.21
3	6.47	12.44	1.92
4	5.52	8.64	1.57
5	5.32	8.39	1.58



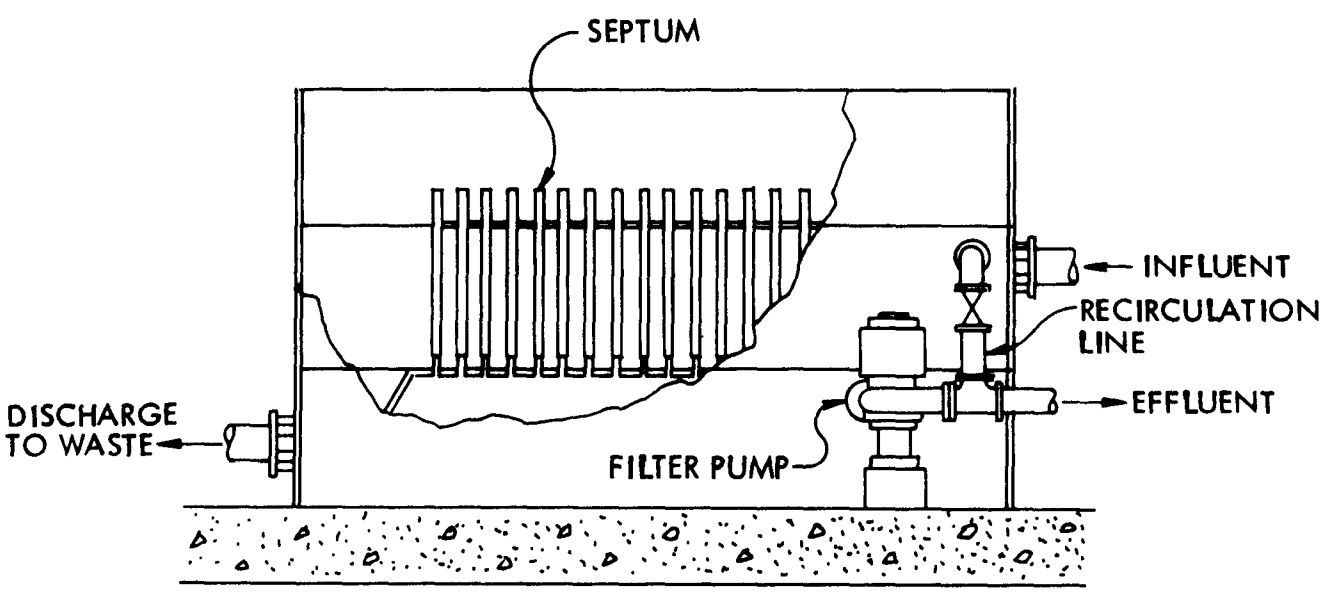


Fig. 8. Sections through typical pressure and vacuum diatomite filters (Table 15), Case 5.

Table 13 lists data for three cases for which the filters are optimized for higher turbidity levels. In Case 3, when the water turbidity is at 20.5 FTU, the least cost of filtration proved to be 13.64 ¢/1000 gallons. (In all cases the terminal pressure drop in pressure filters was limited to 200 ft of water.) With optimized plants Cases 4 and 5 can filter the same turbidity of water (20.5 FTU) for 9.65 and 9.51 ¢/1000 gallons, respectively. Figure 9 shows the optimum filter operating characteristics as related to raw water turbidity for Case 5 pressure filters. Since Case 5 filter operation produces essentially the same filtrate quality as did the Case 3 and Case 4 treatment, further study was made to determine the approximate average operating cost of Case 5 filters over a period of a year where the filter might encounter raw water turbidities as high as 57.5 FTU for a short period of time.

In the plant design procedure the next question of concern is, "What base turbidity should be used for plant optimization to minimize the total annual operating costs of the plant?" A study of this question was made for Case 5. Table 13 indicates the following design conditions for raw water turbidities of 1.0, 1.9, and 5.8 FTU:

Raw Water Turbidity, FTU	Filtration Rate, gpm/sq ft	Terminal Head, ft of water	Run Length, hours
1.0	1.80	110	11.0
1.9	1.60	130	14.6
5.8	1.10	180	15.5

Let us assume, for example, that the plant design is based on a raw water turbidity of 1.9 FTU and the filters are designed to operate at 1.60 gpm/sq ft to a terminal head of 130 ft of water. When the turbidity

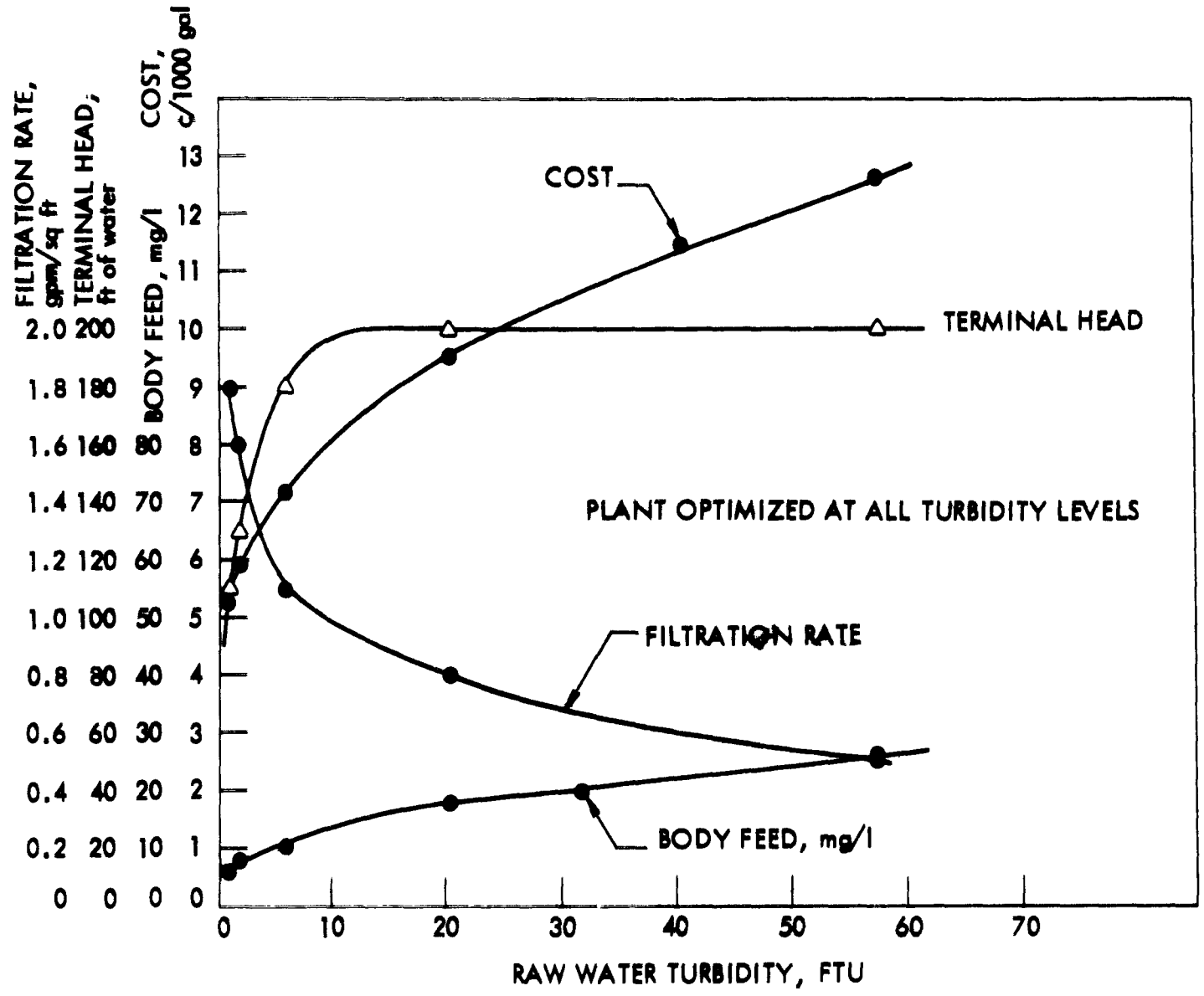


Fig. 9. Optimum design characteristics of pressure diatomite filters (Table 12), Case 5.

is either more or less than 1.9 FTU, the only operating change that can be made to provide minimum operating costs under the fixed flow rate-terminal pressure drop conditions is to adjust the body feed to a new level which provides minimum operating costs for the fixed filter plant and the new turbidity conditions. POPO can be used for this purpose. For example, Table 16 shows the new computer input data for Case 5 when the plant designed to handle 1.9 FTU turbidity water actually handles a 1.0 FTU turbidity water. The computer printout data indicated that a body feed of 5 mg/l will provide a 22-hr run and a filtration cost of 5.37 ¢/1000 gallons. When the plant was designed to filter 1.0 FTU turbidity water, the plant operating cost was only 5.32 ¢/1000 gallons (Table 13).

The results of this series of POPO runs is shown in Table 17. When the plant design is based on a 1.0 FTU trubidity, the optimum run lengths become shorter and filtration costs become greater as turbidity increases. It is doubtful whether plant operators could keep up with backwashing duties during the 3.65 days a year (Table 2) that water turbidity is greater than 5.8 FTU and the filter runs are less than 3-4 hours long, unless the filter backwash operation were automated.

When the plant design is based on a turbidity of 1.9 FTU or 5.8 FTU (instead of on 1 FTU), the cost of filtration with lower turbidities goes up and the cost of filtration with higher turbidities goes down. In general, plants designed on the basis of a 1.9 or 5.8 turbidity would be easier to operate, since both give longer runs with higher turbidities. However, a more detailed analysis can be made to determine the average annual filtration costs, assuming the normal

Table 16. Data Input to POPO, pressure diatomite filter, Case 5, turbidity of 1.0 FTU when plant is designed for 1.9 FTU.

Asbestos-Turbidity Removal: Lake Superior Water, Design Based on Turbidity of 1.9 FTU, Final Turbidity: 0.06 FTU

1	Design Flow	30 MGD
2	Salvage Value	30% First Cost
3	Energy Conversion	70%
4	Interest Rate	6.68%
5	Plant Life	20 years
6	Solids (CS)	1.0 FTU (by turbidity)
7	XI Index	1.77E9 ft/lb
8	Temperature	33 °F
9	Precoat Weight	0.15 lb/sq ft
10	Precoat Density	19.7 lb/cu ft
11	Septum Diameter	3.5 in.
12	Beta Prediction	8.725/1.45800/0/0
13	Unit Flow Rate	1.60/0/0 gpm/sq ft
14	Body Feed (CD)	5/1/20 mg/l
15	Terminal Head	130/0/0 ft
16	Diatomite Cost	152 $/ton
17	First Cost	Area, sq ft / $/sq ft
		1,000 / $616
		3,472 / 376
		6,944 / 259
		20,832 / 155
		41,667 / 134
		80,000 / 122
		100,000 / 120
18	Power Cost	1.627 ¢/KWH
19	Labor Cost	Area, sq ft / $/sq ft per month
		1,000 / $1.87
		3,472 / 1.30
		6,944 / 1.04
		20,832 / 0.60
		41,667 / 0.52
		80,000 / 0.40
		100,000 / 0.35
20	Backwash Cost	10,30 gal/sq ft, min

Table 17. Final optimization of Case 5 pressure diatomite filters operated at full range of water turbidity to be encountered.

Raw Turbidity, FTU	Q, gpm/sq ft	HL, ft of water	CD, mg/l	Cost, ¢/1000 gal	Run Length, hours
Plant Based on 1.0 FTU Turbidity Optimization					
1.0	1.8	110	6	5.32	16.1
1.9	1.8	110	9-10	5.96	10.4-10.9
5.8	1.8	110	20	8.04	5.2
20.5	1.8	110	49	13.59	2.5
57.5	1.8	110	104	24.18	1.5
PPlant Based on 1.9 FTU Turbidity Optimization					
1.0	1.60	130	5	5.37	22
1.9	1.60	130	8	5.89	14.6
5.8	1.60	130	16	7.59	6.8
20.5	1.60	130	40	12.08	3.2
57.5	1.60	130	84	20.56	1.9
Plant Based on 5.8 FTU Turbidity Optimization					
1	1.10	180	3	5.82	50.5
1.9	1.10	180	3	6.13	33.8
5.8	1.10	180	10	7.16	15.5
20.5	1.10	180	25	9.87	6.9
57.5	1.10	180	50	14.92	3.7

water quality variations. During a year the plant will filter a total of 30 million gal/day x 365 days or 10,950,000 thousand gallons per year. The gallons filtered when the turbidity is at each level would be:

Turbidity, FTU	Per cent of Time Turbidity Experienced	Fraction	Thousand Gallons
0-1	90.0	0.90	9,855,000
1-1.9	5.0	0.05	547,500
1.9-5.8	4.0	0.04	438,000
5.8-20.5	0.9	0.009	98,550
20.5-57.5	0.09	0.0009	10,950
		Total water filtered -	10,950,000

When these gallons of water filtered at each turbidity level are multiplied by the unit cost of filtering water at that turbidity level (Table 17), the total annual unit costs of filtering water in plants optimized for operation at turbidity levels of 1.0, 1.9, and 5.8 FTU are shown in Table 18. The results of this table indicate that the annual unit filtration cost is essentially the same for plant designs based on 1.0 and 1.9 FTU turbidities. Filtration costs in a plant designed on the basis of a raw water turbidity of 5.8 FTU would be only 6.24 per cent higher. This would indicate that the final filtration plant design should be based on a turbidity between 1.9 and 5.8 FTU and the annual unit filtration cost would be between 5.56 and 5.93 ¢/1000 gallons.

Once a filtration plant has been built, the first cost and the power requirements of the plant are fixed. The major plant operating

Table 18. Total annual pressure diatomite filtration costs, Case 5, when plants are designed on raw water turbidities of 1.0, 1.9, and 5.8 FTU.

		Plant Design Based on Turbidity					
		1.0 FTU		1.9 FTU		5.8 FTU	
Turbidity, FTU	1,000 Gallons Filtered Yearly	Unit Cost, $/1000 gal	Yearly Cost, $	Unit Cost, $/1000 gal	Yearly Cost, $	Unit Cost, $/1000 gal	Yearly Cost, $
0-1.0	9,855,000	0.0532	$524,286	0.0537	$529,214	0.0582	$573,561
1.0-1.9	547,000	0.0596	32,631	0.0589	32,248	0.0613	33,531
1.9-5.8	438,000	0.0804	35,215	0.0759	33,244	0.0716	31,361
5.8-20.5	98,550	0.1359	13,393	0.1208	11,905	0.0987	9,777
20.5-57.5	10,950	0.2418	2,648	0.2056	2,251	0.1492	1,634
		(Table 17)		(Table 17)		(Table 17)	
Total	10,950,000		$608,173		$608,862		$649,814
	Yearly	0.0555		0.0556		0.0593	

costs that can escalate with the passage of time due to inflation involve power costs, labor costs, and the costs of filter aid. With the higher turbidities encountered, from 60-80 per cent of the total plant operating costs are involved in the cost of filter aid. A study was made, therefore, to determine what effect a 20 per cent increase in filter aid cost would have on the total cost of filtration. The results are summarized in Table 19. The results indicate that such an increase in filter aid costs, a probable increase in the years ahead, would make the plant design based on a 1.9 FTU turbidity the most economical plant to build. The probability of further filter aid cost increases would tend to suggest that the plant be based on a raw water turbidity of about 2.5-3.5 FTU.

If the plant design were based on a turbidity of 1.9 FTU, the operator would control the turbidity/body feed ratio by measuring water turbidity at say 4-hr intervals (more frequently under rapidly changing conditions) and could determine the optimum body feed required from Fig. 10. The filter run lengths expected at various turbidities are shown in Table 17. When the turbidity exceeds about 20.5 FTU (about 10 hr/yr), the runs would be less than 3.2 hr long. In such cases it might be necessary to forego operating economy in order to obtain an operable filter run length. Figure 11 shows how much body feed would have to be added to obtain filter run lengths of various time periods at raw water turbidities of 5.8, 20.5 and 57.5 FTU. An alternative to operation with such high water turbidity would be to:

1. Provide a raw water storage basin to store low turbidity water that could be used during storms when water turbidity might increase for short periods,

Table 19. Effect of 20 percent increase in filter aid cost on annual unit filtration cost of three plant designs.

Plant Design Based on Turbidity	Water Turbidity Range	Unit Cost Before Filter Aid Price Increase, $/1000 gal	Filter Aid Cost $/1000 gal		New[a] Unit Cost, $/1000 gal	Total Annual Cost, $
			Original	With Price Increase		
1 FTU	0-1	0.0532	0.0106	0.1272	0.05532	$545,178
	1-1.9	0.0596	0.0165	0.1980	0.0629	34,438
	1.9-5.8	0.0804	0.0360	0.0432	0.0876	38,369
	5.8-20.5	0.1359	0.0880	0.1056	0.1535	15,127
	20.5-57.5	0.2418	0.1881	0.22572	0.27942	3,060
			Annual Cost		5.81¢/1000 gal	$636,172
1.9 FTU	0-1	0.0537	0.0087	0.01044	0.05544	546,361
	1-1.9	0.0589	0.0136	0.01632	0.06162	33,737
	1.9-5.8	0.0759	0.0294	0.03528	0.08178	35,820
	5.8-20.5	0.1208	0.0717	0.08604	0.13514	13,318
	20.5-57.5	0.2056	0.1517	0.18204	0.23594	2,584
			Annual Cost		5.77¢/1000 gal	$631,820
5.8 FTU	0-1	0.0582	0.0054	0.00648	0.05928	584,204
	1-1.9	0.0613	0.0084	0.01008	0.06298	34,482
	1.9-5.8	0.0716	0.0181	0.02172	0.07522	32,946
	5.8-20.5	0.0987	0.0436	0.05232	0.10742	10,586
	20.5-57.5	0.1492	0.0907	0.10884	0.16734	1,832
			Annual Cost		6.06¢/1000 gal	$664,050

[a]Assuming the same level of body feed is used.

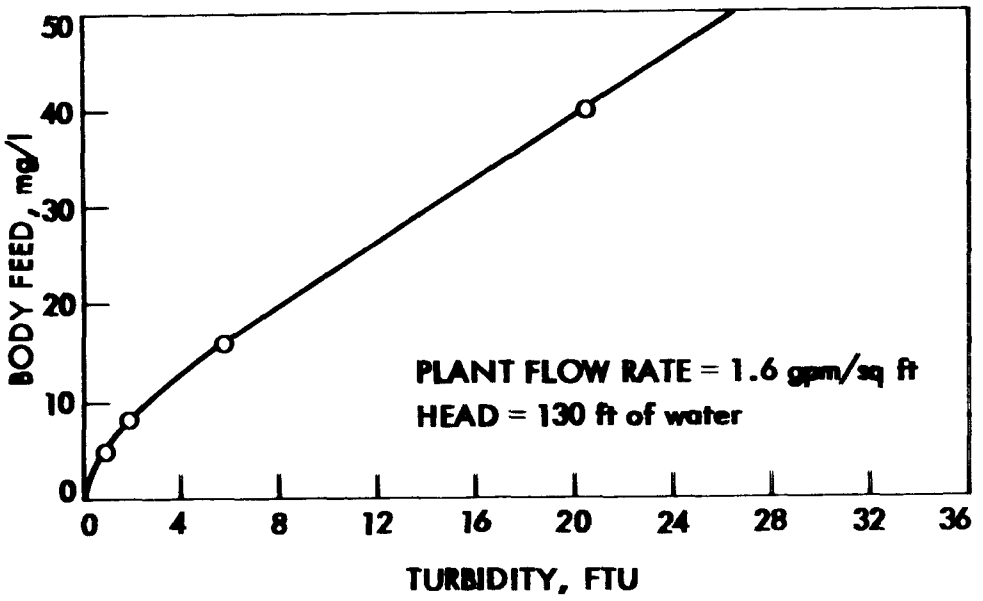


Fig. 10. Body feed required for optimum plant operation, Case 5 plant based on raw water turbidity of 1.9 FTU.

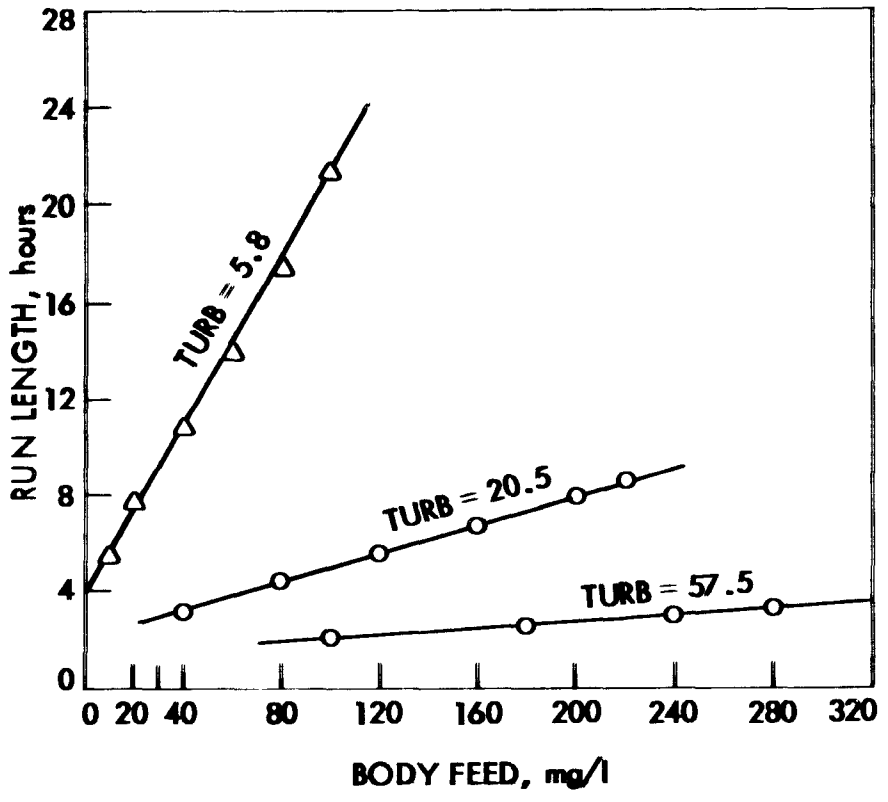


Fig. 11. Body feed levels required to provide a given run length, Case 5 plant optimized for handling 1.9 FTU turbidity water.

2. Provide several days of filtered water storage capacity so that the plant flow rate could be reduced during the rare periods of peak raw water turbidity.

Final Cost Comparisons

In order to bring the costs developed to this point in this paper to the same comparative basis used in developing costs of direct-filtration, granular media filters for the removal of asbestiform fibers from Lake Superior water, several design assumptions had to be adjusted. These included the following design bases:

- The pressure filter costs were to be based on use of filters incorporating 1-in diameter filter septa.
- The plant operating costs were to be based on the 30 mgd capacity plant producing an <u>average</u> plant output of only 20 mgd.
- The plant was to be designed for a 50-yr life with an interest rate of 5.625 per cent. (This represented an interest rate reduction from the federal government interest rate estimated to be 6.68 per cent to a tax-free municipal bond interest rate of 5.625 per cent.)
- The plant costs were to include a sludge disposal cost of $0.01 per pound of sludge produced and provide for higher operating and maintenance costs.

In accomplishing a final cost comparison on the adjusted bases, it was decided that the <u>final plant design</u> and <u>annual operating costs</u> should be based on use of a pressure, diatomite filtration plant optimized to filter raw Lake Superior water when the plant turbidity was

2.5 FTU. Table 20 lists the revised cost data used to determine the per square foot cost of the final plant design. Table 21 shows the basic information used to determine the plant first cost and the plant operation and maintenance costs for use in the POPO computer program. These data were then input into the computer to accomplish the following:

- To determine for Cases 1-5 the optimum design characteristics of the final diatomite pressure filtration plant to have a capacity of 30 mgd.
- To use the plant size determined for the 30 mgd plant to determine the costs of operating that plant under optimum operating conditions to produce 20 mgd of filtered water.

Table 22 is a summary of the costs of the filters for each case. These data are not comparable to any previous data cited in this paper. These costs must be increased to provide for the cost of the chemicals used to treat the filter media and the raw water and to cover the cost of sludge disposal. Table 23 lists the total cost of filtering 2.5 FTU Lake Superior water through pressure diatomite filters having a 50-yr useful life.

A more useful estimate of the annual average cost of filtering water was obtained for Case 5. Table 24 lists the amount of water which would have to be filtered at each turbidity level during the year as a function of yearly plant production. Rather than assume that all of the water filtered would be at the level in the top of the range, as was done in Tables 18 and 19, a mean turbidity for the range was assumed. The Case 5 pressure filter characteristics optimized for filtering water at a turbidity of 2.5 FTU (Table 22) were then used to

Table 20. Revised cost data[a], total capital construction costs for pressure (De Laval) diatomite filtration plant with various filtration rates, plant capacity of 30 mgd.

Item	Filter Flow Rate, gpm/sq ft			
	0.5 ($x10^6)	1.0 ($x10^6)	3.0 ($x10^6)	6.0 ($x10^6)
Building and Associated Costs	2.288	1.430	1.114	0.858
Filter Equipment	5.824	2.953	0.984	0.492
Body Feed and Precoat Slurry Feeders and Storage Tanks	0.800	0.600	0.400	0.300
Equipment Set-up and Assembly	1.747	0.886	0.295	0.148
Piping and Wiring Equipment	0.874	0.443	0.148	0.074
Present Worth of 50-year Life Replacement Items	0.255	0.129	0.043	0.022
TOTAL	$ 11.788	$ 6.441	$ 2.984	$ 1.894

[a]Cost data supplied by Black and Veatch, Consulting Engineers.

Table 21. Unit filter and labor costs for De Laval pressure filters and the estimated plant labor requirements.

Plant Capacity, MGD	Filtration Rate, gpm/sq ft	Filter Area, sq ft	Cost, $/sq ft	No. of Filters[a]
30	0.5	41,667	282.90	72
30	1.0	20,833	309.17	36
30	3.0	3,944	429.72	12
30	6.0	3,472	545.51	6

[a]Largest commercial filter has 585 sq ft.

Plant Labor Requirements

Plant Operation	No. of Filters 72	36	12	6
Body Feed	1 man	1 man	1 man	1 man
Laboratory	1 man	1 man	1 man	1 man
Maintenance	1 man	1 man	1 man	½ man
Filter Floor	4 men	2 men	1 man	½ man
Total Manpower per Shift ----	7 men	5 men	4 men	3 men
Cost per Year	$ 241,500	$ 172,500	$ 138,000	$ 103,500
Cost per Month per sq ft	$ 0.48	$ 0.69	$ 1.66	$ 2.48

Table 22. POPO optimum design of pressure filters (1 in. diameter septa), raw water turbidity of 2.5 FTU.

Case	Plant Output, mgd	Raw Water turb, FTU	Q, gpm/sq ft	HL, ft of water	CD, mg/l	Cost[a] ¢/1000 gal	Length of run, hrs.
1	30	2.5	2.50	60	4	5.13	23.5
	20	2.5	1.66	60	4	6.27	56.0
2	30	2.5	2.70	50	4	4.94	29.6
	20	2.5	1.80	50	4	6.06	71.4
3	30	2.5	1.15	195	12	8.32	13.0
	20	2.5	0.77	195	9	9.71	25.6
4	30	2.5	1.60	135	13	7.05	14.3
	20	2.5	1.06	135	10	8.29	27.2
5	30	2.5	1.60	135	8	6.85	15.6
	20	2.5	1.06	135	6	8.11	30.6

[a]Does not include chemical (except filter aid) or the sludge disposal costs.

Table 23. Average cost per thousand gallons for pressure filtration of 2.5 FTU turbidity water, Cases 1-5, 50-year plant life.

Case	Plant Production, mgd	Optimized Cost ¢/1000 gal	Chemical and Sludge Disposal Cost, ¢/1000 gal	Total Filtration Cost, ¢/1000 gal
1	30	5.13	0.111	5.24
	20	6.27	0.083	6.35
2	30	4.94	0.090	5.03
	20	6.06	0.069	6.13
3	30	8.32	0.558	8.88
	20	9.71	0.450	10.16
4	30	7.05	0.480	7.53
	20	8.29	0.415	8.71
5	30	6.85	0.346	7.20
	20	8.11	0.288	8.40

Table 24. Amount of water filtered at each turbidity level as a function of daily plant production.

Raw Water Turbidity, FTU		Annual Plant Production at Each Range, 1000 gal	
Range	Assumed Mean	20 mgd	30 mgd
0-1	0.75	6,570,000	9,855,000
1-1.9	1.50	364,667	547,000
1.9-5.8	3.85	292,000	438,000
5.8-20.5	13.15	65,700	98,550
20.5-57.5	39.0	7,300	10,950
	Total	7,300,000	10,950,000

evaluate the per unit cost of filtering water at other assumed mean turbidity levels representative of the ranges of turbidity to be encountered throughout the year. The costs for producing water at rates of 30 mgd and 20 mgd are listed in Table 25. Since Table 24 lists the volumes of water which must be filtered at each turbidity range in a year and Table 25 lists the unit cost of filtering water at each turbidity range, it is possible to calculate the total annual average unit cost for pressure filtration of 30 mgd and 20 mgd of Lake Superior water when the plant was originally designed to filter water with a turbidity of 2.5 FTU. Tables 26 and 27 show the calculations required to determine the average annual cost of filtering Lake Superior water. The total cost for filtering 20 mgd and 30 mgd through the 30 mgd plant were 7.81 and 6.40 ¢/1000 gal, respectively.

Conclusions & Recommendations

The pilot plant studies of diatomite filtration for the removal of asbestiform fibers from Lake Superior water indicate that the following conclusions may be drawn.

1. Several filter operating conditions are capable of consistently producing a filtered water turbidity in the range of 0.05-0.07 FTU and also can accomplish 95-98 per cent removal of asbestiform fibers.
2. The filter operating conditions considered most satisfactory for providing best filtered water quality would involve either the use of:

Table 25. POPO optimized plant operation for different mean levels of turbidity expected in Lake Superior during a year.

Turbidity, FTU	Body Feed, mg/l	Run Length, hr	Unit Filtration Cost[b], ¢/1000 gal
	Average Plant Production - 30 mgd[a]		
0.75	4	37.7	6.06
1.50	6	22.7	6.43
3.85	11	11.8	7.34
13.15	26	5.4	9.89
39.00	56	2.9	15.03
	Average Plant Production - 20 mgd[c]		
0.75	4	89.7	7.53
1.50	4	41.9	7.79
3.85	8	22.8	8.47
13.15	19	10.2	10.38
39.00	41	5.2	14.19

[a]Filtration rate = 1.60 gpm/sq ft, Head = 135 ft of water.

[b]Exclusive of chemical costs and sludge disposal costs.

[c]Filtration rate = 1.06 gpm/sq ft, Head = 135 ft of water.

Table 26. Approximate total annual pressure diatomite filtration costs, Case 5, when plant is designed for producing 30 mgd using raw water containing 2.5 FTU of turbidity and operated at 30 mgd.

Mean Turbidity, FTU	Run Length, hrs	Precoat Usage: Precoats Per Year	Precoat, lb/sq ft	Per Cent of Year	Precoat Used, lb/sq ft/yr	Body Feed Usage: Body Feed, mg/l	Thousand Gallons Per Year	Pounds Per Year	Cost: Unit Filtration Cost ¢/1000 gal	Total Cost $
0.75	38.2	229.3	34.4	0.900	30.96	4	9,855,000	328,369	6.06	597,213
1.50	23.2	377.6	56.6	0.050	2.83	6	547,000	27,339	6.43	35,172
3.85	12.3	712.2	106.8	0.040	4.272	11	438,000	40,134	7.34	32,149
13.15	5.9	1484.7	222.7	0.009	2.004	26	98,550	21,344	9.89	9,747
39.0	3.4	2576.5	386.5	0.0009	0.347	56	10,950	5,108	15.03	1,646
				Total	40.413		10,950,000	422,294		

$$\text{Cat-Floc B Cost} = \frac{0.00274\ \text{lb}}{1000\ \text{gal}} \times 10{,}950{,}000\ \text{thousand gal} \times \$0.35 = 10{,}501$$

$$\text{Alum Cost} = 40.413\ \frac{\text{lb}}{\text{sq ft}} \times 13{,}546\ \text{sq ft} \times \frac{49.6\ \text{lb}}{453.6\ \text{lb}} \times \frac{\$0.0335}{\text{lb}} = 2{,}017$$

$$\text{Soda Ash Cost} = 40.413\ \frac{\text{lb}}{\text{sq ft}} \times 13{,}546\ \text{sq ft} \times \frac{25\ \text{lb}}{453.6\ \text{lb}} \times \frac{\$0.0791}{\text{lb}} = 2{,}387$$

$$\text{Sludge Disposal Cost} = \left(40.413\ \frac{\text{lb}}{\text{sq ft}} \times 13{,}546\ \text{sq ft} + 422{,}294\ \text{lb}\right) \times \frac{\$0.01}{\text{lb}} = 9{,}697$$

Total Annual Cost = $ 700,529

$$\text{Annual Unit Cost, ¢/1000 gal} = \frac{70{,}052{,}900\ ¢}{10{,}950{,}000\ \text{thousand gal}} = 6.40\ ¢/1000\ \text{gal}$$

Table 27. Approximate total annual pressure diatomite filtration costs, Case 5, when plant is designed for producing 30 mgd using raw water containing 2.5 FTU of turbidity but operated at 20 mgd.

Mean Turbidity, FTU	Precoat Usage: Run Length, hrs	Precoat Usage: Precoats Per Year	Precoat Usage: Precoat, lb/sq ft	Precoat Usage: Percent of Year	Precoat Usage: Precoat Used, lb/sq ft/yr	Body Feed Usage: Body Feed, mg/l	Body Feed Usage: Thousand Gallons Per Year	Body Feed Usage: Pounds Per Year	Cost: Unit Filtration Cost, ¢/1000 gal	Cost: Total Cost, $
0.75	90.2	97.1	14.6	0.900	13.14	4	6,570,000	218,912	7.53	494,721
1.50	42.4	206.6	31.0	0.500	1.55	4	364,667	12,133	7.79	28,408
3.85	23.3	376.0	56.4	0.040	2.26	8	292,000	19,466	8.47	24,732
13.15	10.7	818.7	122.8	0.009	1.11	19	65,700	10,402	10.38	6,820
39.0	5.7	1,536.8	230.5	0.0009	0.21	41	7,300	2,494	14.19	1,036
				Total	18.27		7,300,000	263,407		

$$\text{Cat-Floc B Cost} = \frac{0.00274\ \text{lb}}{1000\ \text{gal}} \times 7{,}300{,}000 \text{ thousand gal} \times \$0.35 = \quad 7{,}001$$

$$\text{Alum Cost} = 18.27\ \frac{\text{lb}}{\text{sq ft}} \times 13{,}546 \text{ sq ft} \times \frac{49.9\ \text{lb}}{453.6\ \text{lb}} \times \frac{\$0.0335}{\text{lb}} = \quad 912$$

$$\text{Soda Ash Cost} = 18.27\ \frac{\text{lb}}{\text{sq ft}} \times 13{,}546 \text{ sq ft} \times \frac{25\ \text{lb}}{453.6\ \text{lb}} \times \frac{\$0.0791}{\text{lb}} = \quad 1{,}079$$

$$\text{Sludge Disposal} = (18.27\ \frac{\text{lb}}{\text{sq ft}} \times 13{,}545 \text{ sq ft} + 263{,}407 \text{ lb}) \times \frac{\$0.01}{\text{lb}} = \quad 5{,}109$$

Total Annual Cost = $ 569,818

$$\text{Annual Unit Cost, ¢/1000 gal} = \frac{56{,}918{,}800\ ¢}{7{,}300{,}000} = \quad 7.81\ ¢/\text{gal}$$

Alum-coated Hyflo Super Cel (or equivalent grade) as body feed and precoat or

Alum-coated C-512 filter aid (or equivalent grade) as precoat plus a continuous coagulant feed to the filter influent water of Cat-Floc B polymer.

3. The analysis of filter operating data indicates that vacuum diatomite filters are significantly more expensive in producing low per unit cost filtered water and would be very difficult to operate under high turbidity conditions in the raw water.
4. Pilot plant data were used in least cost design of several alternate plants. The results suggest that a low-cost plant designed for a 20-yr life and on the basis of the turbidity (1.9 FTU) equalled or exceeded only 5 per cent of the time could produce 30 mgd of filtered water at a cost of 5.56 ¢/1000 gal.
5. Once such a plant is constructed, the major item contributing to increased cost of plant operation will be increases in the cost of power, labor, and filter aid. A 20 per cent increase in filter aid cost will increase the annual average unit cost of water filtration to 5.77 ¢/1000 gal, an increase of 3.78 per cent. This increase could be reduced by reoptimizing the body feed using the POPO computer program each time a significant labor, power, or filter aid cost increase was encountered. Further computer analysis would probably indicate that the best protection against filter aid price increases significantly affecting unit filtration costs would occur if the filtration

plant were designed on the basis of a water turbidity of about 2.5-3.5 FTU.

6. A pressure diatomite filter with a 50-yr life can be optimized to filter water with a turbidity of 2.5 FTU and operated over an average year to produce 20 mgd or 30 mgd of low turbidity water at an average annual unit cost of 7.81 or 6.40 ¢/1000 gal, respectively. The costs include the cost of chemical and sludge disposal.

7. All optimized diatomite filtration plants would experience short filter runs and a difficult operating experience during periods of high water turbidity. These difficulties during such periods can be reduced by:

   - Providing raw or filtered water storage adequate to carry the plants over peak lake water turbidity periods. A raw or filtered water storage period of 0.5-1.5 days would be required in the example cited in this paper,
   - Abandoning the concept of economic filter aid use during high turbidity periods and increasing the rate of body feed to secure longer than optimum length runs during periods of short filter cycles obtained with optimum body feed rates.

8. The annual per unit filter operating costs cited are conservative since they are based on a constant level of turbidity during each time period and on a constant water temperature of 33 °F. The water turbidity is a <u>maximum</u> of 1.0 FTU 90 per cent of the time, not an <u>average</u> of either 1.0 or 0.75, as

used in calculating filtration costs. With warmer summertime water, the filtration costs would be lower since longer filter runs would occur with the better water viscosity. The optimized costs cited in this paper are probably accurate to within a $\pm$ 5 per cent range. Any diatomite filtration plant designed, built, and operated without such optimization could be expected to experience operating costs significantly higher than the costs developed here.

9. For maximum operating economy the availability of a computer and the computer programs used in this study would permit plant personnel to adjust plant operation to changes that occur naturally with time (power, chemical, labor costs, etc.), including evaluations of conditions that were not encountered in the pilot-plant operations.

10. The margin for error in plant design can be significant when extrapolation of pilot-plant data is made significantly beyond the conditions existing during the pilot plant period. It would be comforting, prior to final plant design, to operate a pilot plant with raw water turbidities in the 5-20 range, with lower body feed rates than were used (down to 4 mg/l when turbidity is in the range of 0.5 FTU) and with a wider range of alum coating levels on the precoat filter aid and Cat-Floc coagulant dosages. Such additional pilot plant experience could provide better plant operating guidance but probably would not significantly alter the costs determined in this paper.

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This paper is a summary of the results from vacuum and pressure diatomite filter pilot plants operated by Black and Veatch, Consulting Engineers of Kansas City, Missouri, for the removal of asbestiform fibers from Lake Superior water at Duluth, Minnesota. The work was conducted under contract with the U.S. Environmental Protection Agency in cooperation with the U.S. Army Corps of Engineers and the City of Duluth. The author served as a consultant to the engineers in planning and interpreting the pilot plant results.

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6. ABSTRACT

Pilot plant research conducted in 1974 at Duluth, Minnesota, demonstrated that asbestiform fibers counts in Lake Superior water could be effectively reduced by municipal filtration plants. During the study engineering data were also obtained for making cost estimates for construction and operation of both granular and diatomaceous earth (DE) filtration plants ranging in size from 0.03 to 30 mgd. During one phase of the pilot plant investigation, the diatomite filters were operated in a way that yielded data used for computer optimization of the DE filtration process. The POPO (Program for Optimization of Plant Operation) results are presented in Appendix I.

7. KEY WORDS AND DOCUMENT ANALYSIS

DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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