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MIT JAR TESTS OF WACHUSETT RESERVOIR WATER USING THE NATURAL POLYMER CHITOSAN WITH BENTONITE

APRIL, 1993

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MITSG 93-23

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Cambridge, Massachusetts 02139

Grant No: NA90AA-D-SG424

Project No: 92-A-5

#4

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MIT JAR TESTS OF WACHUSETT RESERVOIR WATER USING THE NATURAL POLYMER CHITOSAN WITH BENTONITE

APRIL, 1993

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Funded by MIT Sea Grant

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1. INTRODUCTION

Although drinking water in the MWRA system is of very good quality with minimal treatment,[1] new Safe Drinking Water Act regulations, including surface water treatment, volatile organic contaminant, copper and lead, and pathogen removal requirements are compelling the MWRA Water Division to build a large water treatment plant at Wachusett Reservoir unless a waiver is obtained. In preliminary 1991 - 1992 planning studies a Pilot Treatment Program, conducted by MWRA Water Division's engineering consulting firm CH2M Hill, tested a variety of chemical coagulants and coagulant aids in 3 different pilot systems: a direct filtration system, a dissolved air flotation system, and a contact adsorption clarification system.

Alum, aluminum chloride, poly-aluminum chloride, and ferric chloride were the primary coagulants tested in the Wachusett Pilot Treatment Program. In addition, various polymers such as Magnifloc 1986N (a nonionic polyacrylamide), Magnifloc #573C (a cationic polyamine) and Magnifloc #587C (a cationic polyacrylamide) were tested as coagulant aids. Metal salts and polymers were added at the influent end of all 3 pilot systems at the same location. Metal salts were not added ahead of the synthetic polymers. Performance of alum and ferric chloride were about equal, although alum had a slight edge for all measured parameters except UV absorbance (CH2M Hill, 1992a). Chemical coagulant doses varied seasonally, but were typically 3 mg/l to 10 mg/l metal salt with 0 mg/l to 3.0 mg/l polymer.

At present the MWRA treats its water by pH adjustment with sodium hydroxide, disinfection with chloramines, and the addition of fluoride. pH adjustment occurs at 2 locations: at "Shaft 4" in Southboro, where pH is adjusted to 9, and, at Spot Pond, in Stoneham. The disinfectant is added at Westboro near Route 128.

1.1 Use of Chemical Coagulants in Water Treatment

Common sense as well as pollution prevention principles suggest that drinking water treatment coagulant chemicals should ideally be organic, non-toxic, biodegradable chemicals or inorganic substances with low residual metals content. A holistic or systems approach to water treatment processes implies that attention be paid not only to chemical coagulant quality, performance, and cost but also to sludge quantity and quality. Non-toxic chemicals will not contaminate drinking water. Organic and biodegradable chemicals will contribute to a beneficial, reusable sludge. The benefits and proven efficacy of aluminum salts in drinking water treatment are offset by the possible problems with residual metals contamination, performance problems at low temperatures, and the disposal of alum sludges. Ferric salts have been the coagulant of choice in at least one large U.S. water municipality (Tampa, Fl.) because the iron-based sludge had some land value on the local iron-poor soils (Matteo, J. 1992). The popularity of synthetic organic polymers such as polyacrylamides and polyamines have the drawback of possible toxicity problems. Toxicity concerns have led to a ban on the use of certain synthetic polymers in drinking water treatment in Germany, (Jackson, 1992), the Netherlands (Jackson, 1992), and Japan (Aizawa, T. et.al. 1990). Elsewhere, their dose is regulated to control potential problems with impurities (National Sanitation Foundation, 1990)

Today, organic polymers, whether natural or synthetic, are of interest in water treatment for the following reasons:

1. They are effective in very low dosages as compared to metal salts;
2. Low dosages of polymers reduce the volume of sludge produced;
3. Their effectiveness is less pH dependent than for metal salts;

4. Polymers improve the sludge dewatering process as compared with alum or iron salts (i.e. high sludge density and good dewaterability);
5. Polymers are generally more biodegradable than alum or iron salt sludges and therefore ease sludge digestion by microorganisms;
6. They are non-corrosive and easy to handle;
7. Polymers do not have residual metals contamination problems.

The natural polymer, chitosan, examined in this study, has some additional favorable characteristics:

1. It is an abundant and renewable resource;
2. It is biodegradable and has been shown to stimulate plant growth (Brzeski, M. 1987), making it a desirable component of a beneficial sludge;
3. It is non-petroleum-based;
4. It is non-toxic.

Natural organic polymers such as chitosan may provide an alternative to the use of metal salts and synthetic organic polymers in the coagulation process. In common with other chemical coagulants, the performance of chitosan can be evaluated through jar tests, an effective tool for comparing alternate chemical types, dosages and mixing regimes.

1.2 What is Chitosan?

Chitosan is a modified form of chitin, the second most abundant natural polymer after cellulose. Typically derived from the chitin found in the organic exoskeleton of crustacea such as crabs, shrimps, prawns and lobsters, chitosan is a polysaccharide, composed of poly-N-acetyl-glucoamine units, linked by beta 1-4 bonds into a linear polymer.

Chitosan would provide a beneficial component to sludge, as it is biodegradable and has even been approved for use in animal feeds, as outlined by the American Feed Control officials:

> Chitosan is a cationic carbohydrate polymer intended for use as a precipitation agent of proteinaceous material from food processing plants. It is chemically derived by deacetylation of naturally occurring chitin in crab and shrimp shells. It may be used in an amount not to exceed that necessary to accomplish its intended effect. Chitosan, when fed as a component of feed to livestock, shall be present at no more than 0.1% of the feed. Proteinaceous material coagulated with chitosan must have safety and efficacy data approved before it can be registered or offered for sale.
>
> (87.16: Adopted, 1985)

2. PURPOSE

The purpose of the MIT jar tests of chitosan at Wachusett Reservoir was to demonstrate the effectiveness of chitosan as a primary coagulant substitute for alum or ferric chloride. The approach was to compare the performance of the chitosan to the performance of alum and other chemical coagulants in terms of the parameters turbidity, color, pH and alkalinity. Over 30 jar test series were conducted during the months of February, March, and April, 1993, on water sampled from the aqueduct beneath the Wachusett Administration Building (Power House). Tests and analyses were performed on site in a laboratory which was set up by permission of the MWRA and the MDC.

3. PROCEDURE

Over the past four years, researchers at Parsons Laboratory working under Professor Donald Harleman, have gained extensive experience in jar testing and full-plant testing of a wide range of coagulants and coagulant aids. Preliminary procedural steps include selection of a mixing regime, sampling protocol, and an understanding of the raw water characteristics.

3.1 Mixing Regime

A standard AWWA jar test procedure is as follows: Six jars are filled with raw water and alum is added to each jar in a range of appropriate concentrations. The alum is mixed rapidly for 2 minutes at 150 rpms, then the jars are stirred slowly for 30 minutes at 25 rpms. After 30 minutes of settling, a sample from each jar and also a raw water sample are analyzed for turbidity, color, and pH. This mixing regime is referred to in this report as the "AWWA standard mixing procedure" (AWWA, 1978).

According to some studies, energy input during the rapid mixing stage should be higher with organic polymers than with metal salts as primary coagulants (Fettig, J.et.al. 1990; Murcott, S. and Harleman, D. 1993). Therefore, the AWWA standard mixing procedure was followed in some of the MIT jar tests and modified in others. Two basic mixing regimes (described fully in Appendix A) were established:

1) The AWWA standard mixing procedure;
2) A modification of the AWWA standard mixing procedure based on increasing the time and speed of the rapid mixing step.

However, experiments were also conducted at various other mixing times and speeds in order to determine the optimal conditions.

3.3 Sample Analyses

MIT jar tests were conducted on a Phipps & Bird 6-paddle stirrer. Turbidity was analyzed using a HACH Model 2100P portable turbidimeter according to EPA Method 180.1 (nephelometric). Apparent color[2] was analyzed using a Hach Model DR/2000 spectrophotometer according to the Platinum-Cobalt Standard Method (Hach Method 8025). This procedure assigns the wavelength of 455 nm as the dominant wavelength. pH was analyzed using a Hach One pH Meter. Alkalinity (as CaCO3) was determined using a HACH Digital Titrator.

3.4 Raw Water Characteristics

During the February through April, 1993 test period, the average raw water characteristics as measured by MIT were as follows:

Turbidity = 0.53 NTU
Apparent Color = 14 CU
pH = 6.8
Alkalinity = 4.2 mg/l (as CaCO3)
Temperature = 3 degrees C

Additional information on raw water characteristics was obtained from Edzward (1991):

Total Organic Carbon (TOC) = 3.1 mg/l
Dissolved Organic Carbon (DOC) = 3.0 mg/l
UV Absorbance (254nm) = 0.70 cm^{-1}
Trihalomethane Formation Potential (THMFP) = 155 ug/l

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[2] Apparent color does not filter the sample through a 0.45 micron filter membrane prior to analysis. True color does filter the sample through a 0.45 micron filter membrane. All color values determined in the analysis of MIT jar tests are apparent color results.

When we consider typical concentrations of turbidity and color in surface waters, as shown in Table 1, we can see that generally, a river has the lowest water quality and a reservoir the highest. Comparing these typical values to raw water turbidity and color values of Wachusett Reservoir, we see that Wachusett Reservoir is of a very high quality prior to any treatment.

TABLE 1
RAW WATER QUALITY AS A FUNCTION OF WATER SOURCE

	Turbidity (NTU)	Color (CU)
Reservoir	11	18
Lake	16	28
River	26	44

(Cornwell, D. and Susan, J., 1979)

In regard to Wachusett Reservoir water, we note in particular that raw water turbidity is already near to the 0.5 NTU standard required for surface water treatment.[3] It is this characteristic that influenced the choice of chitosan with bentonite as a viable chemical coagulant combination for the MWRA water system. Polymers have been found to be effective primary coagulants in low turbidity waters (Fettig, J. et.al., 1990) and cationic polymers such as chitosan can be effective in coagulating negatively charged clay particles (Culp, 1986). Electrostatic forces or ion exchange are the primary mechanisms by which polymers become attached to clay particles, which is then followed by bridging (Culp, 1986).

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[3] Specifically, treatment by conventional or direct filtration must achieve a turbidity level of less than 0.5 NTU in at least 95% of the samples taken each month.

Bentonite

Clays are hydrated aluminosilicates of calcium, sodium, magnesium and iron, commonly used as coagulant aids in water treatment. Bentonite is a fine-grained inorganic clay of the mineral montmorillonite that assists in increasing the rate and efficiency of coagulation. It has a slight negative charge and can add weight to the flocs, joining them together to produce larger, tougher, faster settling flocs. That bentonite acts as a coagulant aid rather than as a coagulant is evidenced by the fact that turbidity and color increased rather than decreased when bentonite was tested by itself.

4. RESULTS

4.1 Factors Affecting Coagulation

The principal factors affecting coagulation include:

- raw water characteristics
- chemical type
- chemical dose
- mixing time and speed
- order of chemical addition
- pH and alkalinity
- temperature

We have already mentioned raw water characteristics. The following discussion of MIT test results will be organized according to these other major factors. First, the results will be summarized and then discussed in detail below:

4.2 Summary of Results

- Chitosan Dose: Optimal chitosan dose is 1.0 mg/l;

- Bentonite Dose: Optimal bentonite dose is 8 mg/l;

- Mixing time and speed: Chitosan with bentonite may benefit from slight modifications of mixing time and speed of the standard mixing procedure, however, these are not necessary adjustments

- Order of chemical addition: Chitosan and bentonite can be added sequentially or simultaneously without affecting performance.

- pH: pH is decreased by 0.1 unit relative to the raw water pH at the optimal chitosan/bentonite dose. In contrast, pH is reduced by 1.4 units at the optimal alum concentration.

- Alkalinity: Alkalinity (as $CaCO_3$) decreases by 12% from 4.2 mg/l to 3.7 mg/l at the optimal dose of 1.0 mg/l chitosan with 10 mg/l bentonite. Alkalinity decreases by 64% from 4.2 mg/l to 1.7 mg/l at the optimal alum dose of 10 mg/l.

- Temperature: Chitosan with bentonite performs very well, and alum performs very poorly, in terms of turbidity removal in the cold water conditions of the winter. Both chemical regimes perform well in terms of color removal under cold water conditions.

4.3 Chitosan/Bentonite Optimal Dose

Optimal dose was determined on the basis of turbidity and color concentration and percent removals. In terms of these parameters, chitosan, in combination with the clay product bentonite, showed good results.

Chitosan was tested in a concentration range from 0.2 to 3.0 mg/l. The optimal chitosan concentration range was from 0.5 to 1.5 mg/l; the recommended chitosan concentration for the MWRA is 1.0 mg/l. Figures 1 and 2 are representative results showing the range of chitosan concentrations tested versus the concentration and % removal of turbidity and color.

Bentonite was tested in a concentration range from 2 to 40 mg/l. The optimal bentonite concentration range was from 5 to 12 mg/l; the recommended bentonite concentration for the MWRA is 8 mg/l. Figures 3 and 4 are representative results showing the range of bentonite concentrations tested versus the concentration and % removal of turbidity and color.

4.4 Alum with and without Synthetic Polymer Aids - Optimal Dose

In the MIT tests, the optimal dose of alum as a primary coagulant ranged from 5 mg/l to 20 mg/l. Several cationic polymers, Magnifloc #573C and #587C, the same polymers used in the MWRA Pilot Test Program, were tested as coagulant aids in conjunction with alum. At an optimal polymer dose of 2 mg/l, the cationic polymers tested were inconsistent in aiding turbidity removal and usually provided no improvement in color removal. Although these polymers may have been successfully used as filtration aids, they were generally ineffective in improving coagulation of Wachusett Reservoir water under winter conditions. Bentonite did not improve the performance of alum at any dose. Figures 5 and 6 are representative results showing the range of concentrations of alum alone and alum with polymer versus the concentration and % removal of turbidity and color.

4.5 Comparison of Optimal Results: Alum versus Chitosan/Bentonite

Optimal chemical type and concentration tests were performed on a weekly basis throughout the 3-month test period. The data from this set of coagulation tests is summarized in Appendix B. The average results from these coagulation tests are presented below in Tables 2 and 3:

TABLE 2
CHEMICAL TYPE AND CONCENTRATION
AVERAGE TURBIDITY RESULTS FOR 3 MONTH COAGULATION TESTS

Chemical Type	**Chemical Concentration (mg/l)**		**Turbidity % Removal**
Chitosan/Bentonite	0.9	8	49
Alum	11		21
Alum/Polymer	15	2	25

TABLE 3
CHEMICAL TYPE AND CONCENTRATION
AVERAGE COLOR RESULTS FOR 3 MONTH COAGULATION TESTS

Chemical Type	**Chemical Concentration (mg/l)**		**Color % Removal**
Chitosan/Bentonite	1.0	7	61
Alum	9		69
Alum/Polymer	20		47

We see from these average results that about 1.0 mg/l chitosan and 8 mg/l bentonite gave significantly better turbidity removal and good color removal compared to the metal salt regimes. 9 mg/l alum gave a somewhat better color removal. However, about the same dosage of alum (11 mg/l) provided poor turbidity removal. Alum with polymer, although recommended by CH2M Hill to the MWRA as a result of their 4-season pilot study, did not perform well in the MIT winter season coagulation studies. Overall, chitosan with bentonite gave the best coagulation performance.

Other chemicals were tested and compared to chitosan with bentonite or alum. These chemicals included ferric chloride, a variety of chitosan products, a variety of clay products, and some synthetic polymers, including Dadmac, polyacrylamides, and polyamines.

Figures 7 and 8 are representative results showing all of the primary coagulants tested (including ferric chloride) versus the concentration and % removal of turbidity and color.

4.6 Mixing Regime

The primary coagulant tests indicated in Figures 7 and 8 were all performed at the standard AWWA mixing procedure. From these results we see that chitosan with bentonite performed better then the metal salts according to the mixing procedure developed for metals salts. Other tests indicated that the modified mixing procedure did not improve alum's performance. However, as shown in Figure 9, slight increases in rapid mixing time promotes improved turbidity and color removal for chitosan with bentonite. Overall, the MIT mixing time and speed tests showed that chitosan with bentonite may benefit from slight modifications of the standard mixing procedure, however, these are not necessary adjustments.

4.7 Order of Chemical Addition

Chitosan and bentonite can be added sequentially or simultaneously without affecting performance. Figure 10 shows this result.

4.8 pH and Alkalinity

In contrast to metal salts, chitosan with bentonite does not decrease pH. This characteristic means that the use of this chemical regime offers a decided advantage for the treatment of low alkalinity waters such as Wachusett Reservoir water. Figure 11a shows that alum or alum with polymer significantly decreases pH by 1.4 units from 6.8 to 5.4 over the range of effective coagulation concentrations. Figure 11b shows that chitosan with bentonite decreases pH by only 0.1 units from 6.9 to 6.8 over the range of effective bentonite concentrations.

Alkalinity declines sharply with the increased addition of alum. At the effective alum dose of 10 mg/l, the raw water alkalinity concentration of 4.2 mg/l drops 64% to 1.5 mg/l. In contrast, alkalinity drops by only 12% at the effective chitosan dose of 1.0 mg/l with 10 mg/l bentonite. Figures 12a and 12b present these alkalinity results.

4.9 Temperature

Turbidity removal using alum was poor at low water temperatures of 3 degrees centigrade, the typical raw water temperature throughout the MIT winter testing season. This result corresponds with the CH2M Hill result. In their synopsis of summer test results, CH2M Hill found "less difficulty optimizing chemistry due to warmer water" (CH2M Hill, 1992a). However, CH2M Hill would have been referring to <u>metal salt chemistry</u>; chitosan with bentonite was very successful at removing turbidity in cold water. In contrast, both alum and chitosan with bentonite successfully removed color at low raw water temperatures. Chitosan with bentonite showed an unusual pattern of decreasing color removal with increasing temperature. Alum showed improved color removal with increasing water temperature. Figure 13a and 13b show the effect of temperature on turbidity and color removal.

5. COMPARISON OF MIT AND CH2M HILL JAR TEST RESULTS

Jar tests were a part of the Pilot Treatment Program performed by CH2M Hill during 1991 and 1992. Table 4 lists the chemical coagulants tested during that 4-season pilot study at Wachusett Reservoir, the manufacturer, and the type of polymers used.

TABLE 4
COAGULANT CHEMICALS TESTED IN CH2M HILL 4-SEASON PILOT STUDY

Chemical	Manufacturer	Polymer Type
Alum	Holland	
Aluminum Chloride	VWR Scientific	
Poly-Aluminum Chloride (PAC)	Westwood Chemical Corp	
Ferric Chloride	Gulbrandsen Co.	
Magnifloc #1986N	American Cyanamid	nonionic polyacrylamide
Magnifloc #573C	American Cyanamid	cationic polyamine
Magnifloc #587C	American Cyanamid	cationic polyacrylamide

Although the CH2M Hill Pilot Treatment Program Report has not yet been made public (and therefore this report could not benefit from CH2M Hill results or comment upon their work), some of the general results of the pilot study as regards the use of chemical coagulants include the following (CH2M Hill, 1992a):

1) Alum and ferric chloride are effective primary coagulants and their performance is about equal. Effective concentrations range from 3 mg/l to 10 mg/l, depending on the season, water characteristics, and the particular primary coagulant. Alum had the edge for all measured parameters except UVA-254.

2) Cationic or nonionic polymers are required to assist primary coagulants. Effective concentrations range from to 3 mg/l.

3) Summer conditions provided less difficulty in optimizing coagulation chemistry due to warmer water and greater stability in raw water pH and alkalinity.

Table 5 compares the 4-season pilot study chemicals and their optimal concentrations with those from the MIT jar test study:

TABLE 5
COMPARISON OF CH2M HILL AND MIT OPTIMAL CHEMICALS AND DOSES

	PRIMARY COAGULANT	COAGULANT AID
CH2M Hill	Alum @ 3 - 10 mg/l	Magnifloc #573C or #587C @ 2 mg/l
CH2M Hill	Ferric Chloride @ 3 mg/l	Magnifloc #573C or #587C @ 1.5 mg/l
MIT	Chitosan @ 1.[illegible] mg/l	Bentonite @ 8 mg/l

(CH2M Hill, 1992a; 19[illegible]b; Murcott, S. and Harleman, 1993a)

For the sake of comparison, in the discussion of sludge production and cost in Sections 6 and 7 below, we will assume a CH2M Hill chemical recommendation of 10 mg/l alum and 1.5 mg/l polymer and an MIT chemical recommendation of 1.0 mg/l chitosan and 8 mg/l bentonite for use in a water treatment plant at Wachusett Reservoir.

6. SLUDGE PRODUCTION

A simple equation to evaluate sludge production is given as follows:

M_s = 86.4 Q(0.44A + SS + M) (Equation 1)

where

M_s = dry sludge produced (kg/day)
Q = plant flow (m^3/sec) (13.1 m^3/sec)
A = alum or bentonite dose (mg/l)
SS = suspended solids in raw water (mg/l)
M = miscellaneous chemical additions such as polymers pH neutralizing chemical, etc. (mg/l)

The insoluble aluminum hydroxide complex $Al(H_2O)_3(OH)_3$ is thought to predominate in most water treatment plant sludges. This species results in the production of 0.44 kg of chemical sludge for each kg of alum added. Any suspended solids present in the water will produce an equal amount of sludge. Polymers and clays will produce about one kg of sludge per kg of chemical addition (Davis, M, and Cornwell, D., 1985). Turbidity, especially in low turbidity waters such as at Wachusett Reservoir, makes an insignificant contribution to sludge quantity.

Based on equation 1, 1.0 mg/l chitosan plus 8 mg/l bentonite will produce about the same amount of sludge as 15 mg/l alum plus 1.5 mg/l polymer. The additional quantity of chitosan/bentonite sludge produced is offset by its beneficial characteristics.

7. COST COMPARISON

A rough estimate can be made of the relative costs of using alum and a polymer versus using chitosan and bentonite at Wachusett Reservoir. The following assumptions pertain:

Flow = 300 mgd (1.1 x 10^9 l/day)
Alum concentration = 10 mg/l
Polymer concentration = 1.5 mg/l
Chitosan concentration = 1.0 mg/l
Bentonite concentration = 8 mg/l

Cost of alum = $0.10/lb ($0.22/kg)
Cost of polymer = $1.70/lb (($3.74/kg)
Cost of chitosan = $3.00/lb ($6.60/kg)[4]
Cost of bentonite = $0.10/lb ($0.22/kg)

Alum + Polymer Cost

Alum

$$\frac{10\ \text{mg}}{\text{L}} \times \frac{\$0.22}{\text{kg}} \times \frac{10^{-6}\ \text{kg}}{\text{mg}} \times \frac{1.1 \times 10^{9}\ \text{l}}{\text{day}} = \frac{\$2,400}{\text{day}}$$

Polymer

$$\frac{1.5\ \text{mg}}{\text{L}} \times \frac{\$3.74}{\text{kg}} \times \frac{10^{-6}\ \text{kg}}{\text{mg}} \times \frac{1.1 \times 10^{9}\ \text{l}}{\text{day}} = \frac{\$6,200}{\text{day}}$$

$$\textbf{TOTAL} = \frac{\$8,600}{\text{day}}$$

Chitosan + Bentonite Cost

Chitosan

$$\frac{1.0\ \text{mg}}{\text{L}} \times \frac{\$6.60}{\text{kg}} \times \frac{10^{-6}\ \text{kg}}{\text{mg}} \times \frac{1.1 \times 10^{9}\ \text{l}}{\text{day}} = \frac{\$7,300}{\text{day}}$$

Bentonite

$$\frac{8\ \text{mg}}{\text{L}} \times \frac{\$0.22}{\text{kg}} \times \frac{10^{-6}\ \text{kg}}{\text{mg}} \times \frac{1.1 \times 10^{9}\ \text{l}}{\text{day}} = \frac{\$1,900}{\text{day}}$$

$$\textbf{TOTAL} = \frac{\$9,200}{\text{day}}$$

In terms of the chemical cost alone, the chitosan/bentonite cost is slightly more expensive than the alum/polymer cost. However, besides the chemical cost, the chitosan plus bentonite chemical combination would have other operating cost implications. Because chitosan plus bentonite has only a slight impact on pH, cost savings would occur from reduced demand for neutralizing agents.

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[4] Estimate provided by Lee Johnson, Vanson Chemicals, 7/92.

A significant cost savings from the use of chitosan and bentonite would be in sludge handling and disposal. The increased options for disposal of a beneficial sludge would outweigh the slight additional chemical cost. Column 2 of Tables 6 and 7 gives total present worth cost estimates provided by CH2M Hill evaluating various sludge handling and disposal alternatives (CH2M Hill, 1992b). Based on the CH2M Hill sludge production estimate of 11,500 lb/day, column 3 of Tables 6 and 7 give the dollar cost per dry ton of sludge. These 2 tables illustrate the wide range of sludge handling and disposal costs. The better the sludge, the greater the likelihood that the lower land application costs of Table 7 could pertain. Chitosan plus bentonite could well offer the MWRA a more desirable sludge for land application. This is an important subject which requires further investigation.

TABLE 6
COST ESTIMATES OF SLUDGE PROCESSING AND LANDFILL

Option	Total Present Worth ($ million)	Cost ($/dry ton of sludge)
D1 Freeze/Thaw Lagoons	17.0	405
D2 Plate and Frame	25.9	617
D3A Belt Press + F/T Lagoons	18.0	429
D3B Belt Press + Drying Lagoons	19.2	457

TABLE 7
COST ESTIMATES OF SLUDGE PROCESSING AND LAND APPLICATION

Option	Total Present Worth ($ million)	Cost ($/dry ton of sludge)
D1 Freeze/Thaw Lagoons	13.3	317
D2 Plate and Frame	19.5	463
D3A Belt Press + F/T Lagoons	14.3	341
D3B Belt Press + Drying Lagoons	12.7	302
D3 Belt Press	10.7	254

8. CONCLUSIONS

1. Performance: Low doses of the natural polymer, chitosan, plus bentonite give better overall performance than alum or alum with synthetic polymer in turbidity and color concentration and % removal in jar tests of Wachusett Reservoir water during winter conditions.

2. Mixing: The AWWA standard mixing procedure could be applied to either alum or chitosan with bentonite. A modified mixing regime using a slightly longer rapid mixing time and a slightly higher slow mixing speed had no impact on alum performance but showed some improvement in the performance of chitosan with bentonite.

3. Order of Chemical Addition: Chitosan with bentonite can be added sequentially or simultaneously.

4. pH: In the range of optimal doses, alum reduces pH by 1.4 units; chitosan with bentonite lowers pH by 0.1 units. Water treated with chitosan/bentonite will require less subsequent chemical treatment to neutralize the water.

5. Alkalinity: Alkalinity (as $CaCO_3$) decreases by 12% from 4.2 mg/l to 3.7 mg/l at the effective dose of 1.0 mg/l chitosan with 10 mg/l bentonite. Alkalinity decreases by 64% from 4.2 mg/l to 1.7 mg/l at the effective alum dose c 10 mg/l.

6. Temperature: Chitosan with bentonite performs very well, and alum performs very poorly in terms of turbidity removal in the cold water conditions of the winter. Both chemical regimes perform well in terms of color removal under cold water conditions.

7. Sludge: A 1.0 mg/l chitosan plus 8 mg/l bentonite chemical dose will produce about the same amount of sludge as a 15 mg/l alum plus 1.5 mg/l polymer dose. Increased sludge quantity with chitosan/bentonite is offset by improved sludge quality.

8. Chemical Cost: The chemical cost of chitosan plus bentonite would be a little more expensive than alum plus polymer. Chemical costs alone do not give the complete picture. Effects of chitosan plus bentonite on the reduced need for pH adjustment chemicals, and sludge disposal options also need to be considered in computing the overall operating costs. Regardless of which chemical regime is ultimately selected, a coagulant chemical cost to MWRA ratepayers of approximately $8,000 to $10,000 per day argues for the importance of careful chemical coagulation studies to optimize the chemical type and dose as part of any future design planning. This subject will be addressed more fully in an enclosed proposal for future work.

9. FUTURE WORK

Chitosan with bentonite has some distinct advantages in the treatment of Wachusett Reservoir water. It performs favorably in jar tests and is a non-toxic chemical regime that would produce a beneficial sludge. Future work would correlate MIT jar test results with CH2M Hill jar test results and conduct additional studies during the fall, spring, and summer seasons. Tests on the effect of chitosan/bentonite on organics and inorganics, including TOC, THMs, and residual metals would be undertaken. Laboratory scale dissolved air flotation and filtration tests of chitosan with bentonite are proposed. Chitosan/bentonite could also be tested in the pilot system in storage at the Wachusett Dam Power Station and/or in a pilot dissolved air flotation unit to which MIT has access. Detailed estimates of sludge production, and overall costs would also be ascertained, based on data provided to MIT by CH2M Hill and the MWRA. A proposal for such a project is given as a separate document.

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APPENDIX A
MIXING PROCEDURES

American Water Works Standard Jar Test Mixing Procedure

1. Fill each of the 6 beakers with raw water.
2. Add alum to each beaker in appropriate incremental concentrations.
3. Mix at 150 rpm for 2 minutes.
4. Add polymer if desired and mix for 150 rpm for 30 seconds
4. Mix at 25 rpm for 30 minutes.
5. Turn the mixer off and let flocs settle for 30 minutes.

Modified Standard Mixing Procedure

1. Fill each of the 6 beakers with raw water.
2. Add bentonite and chitosan.
3. Mix at 150 rpm for 4 minutes.
4. Mix at 50 rpm for 30 minutes.
5. Turn the mixer off and let flocs settle for 25 minutes.

APPENDIX B
OPTIMAL* CHITOSAN/BENTONITE CONCENTRATION TESTS
TURBIDITY & COLOR

DATE	RUN #	Concentration Chitosan (mg/l)	+ Bent. (mg/l)	Turb. % Rem.	Concentration Chitosan (mg/l)	+ Bent. (mg/l)	Color % Rem.
2/11	1	0.3	9	64			
2/18	2	1.0	6	63	1.0	6	59
2/18	3	1.0	5	84	1.0	4	100
3/2	2	0.5	6	45			
3/2	3	0.5	5	26			
3/2	4	0.5	12	26			
3/18	1	0.5	6	28	0.5	6	40
3/18	2	0.5	8	17	0.5	8	25
3/18	3	1.5	6	72	1.5	6	72
4/6	1	1.0	10	52	1.0	10	73
4/6	2	2.0	10	39	1.5	10	80
4/13	3	1.0	10	49	1.0	10	38
4/13	2	1.0	10	72	1.0	9	60
AVE		**0.9**	**8**	**49**	**1.0**	**7**	**61**

* NOTE: Each value shown represents the best result of a single run (6 jars) in which a range of chitosan or bentonite concentrations were tested.

APPENDIX B

OPTIMAL* ALUM +/- POLYMER JAR TESTS CONCENTRATIONS -- TURBIDITY

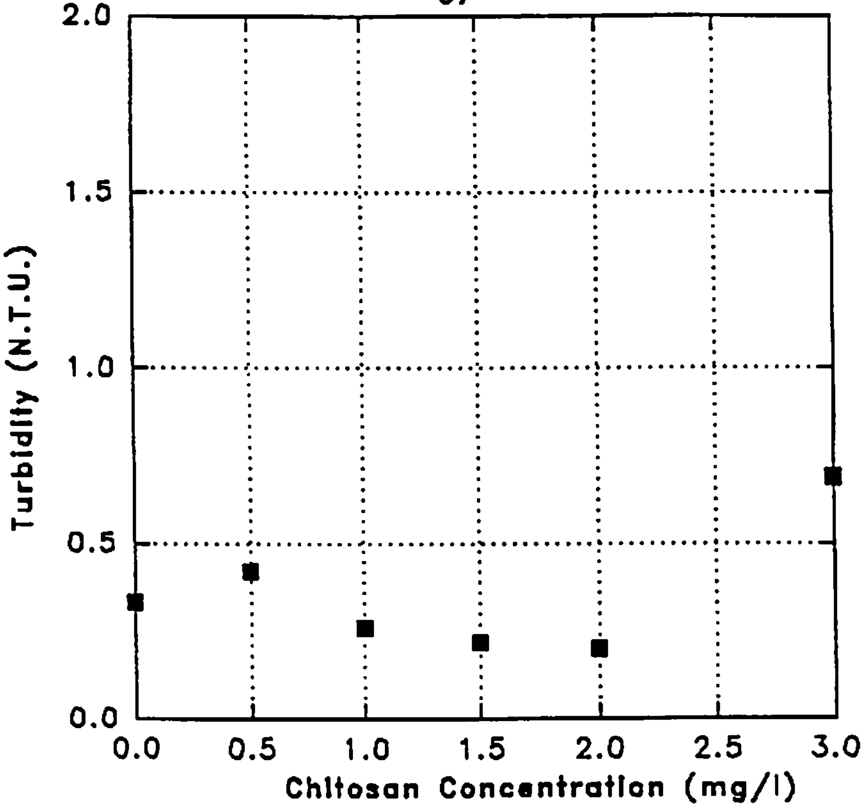
Date	Run #	Conc Alum mg/l	Turbidity % Removal	Concentration Alum + Polymer (mg/l) (mg/l)	Turbidity % Removal
2/18	1	5	-2		
2/25	1			10 2 (#573C)	21
3,9	1			20 2 (#573C)	-13
3/16				20 2 (#587C)	16
3/16	2	10	54		
3/16	3			10 2 (#587C)	50
4/6	3	10	-11		
4/13	3	20	33		
4/29	1	10	29		
AVE		**11**	**21**	**15 2**	**25**

OPTIMAL* ALUM +/- POLYMER JAR TESTS CONCENTRATIONS -- COLOR

Date	Run #	Conc Alum mg/l	Color % Removal	Concentration Alum + Polymer (mg/l) (mg/l)	Color % Removal
2/18	1	5	100		
3/9	1			20 2 (#573C)	47
3/16	1, 2	10	69		
3/16	3	10	67		
4/6	3	10	64		
4/13	3	10	46		
4/29	1	10	67		
AVE		**9**	**69**	**20 2 (#573C)**	**47**

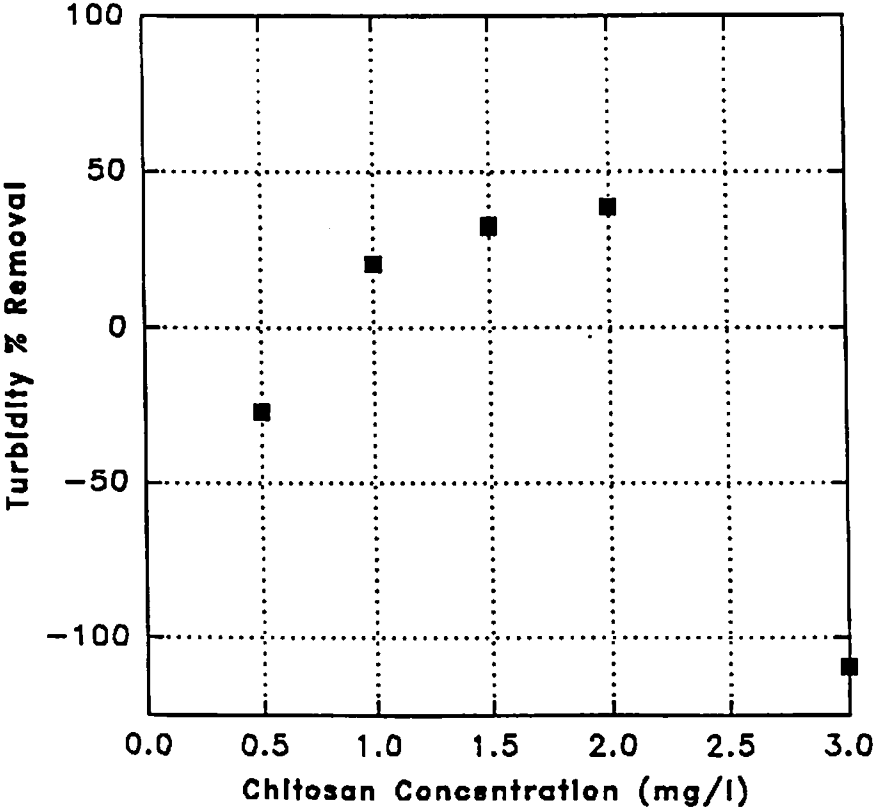
* NOTE: Each value shown represents the best result of a single run (6 jars) in which a range of alum or alum + polymer concentrations were tested.

Figure 1a
Chitosan Concentration vs. Turbidity Concentration
With 10 mg/l Bentonite



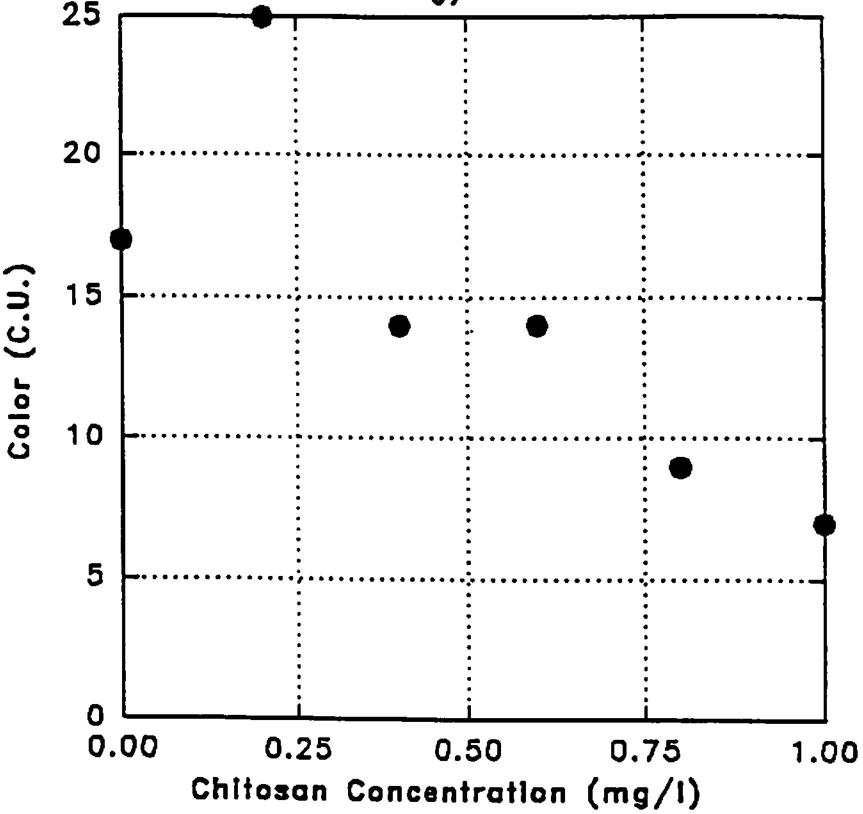
April 6, 1993

Figure 1b
Chitosan Concentration vs. Turbidity % Removal
With 10 mg/l Bentonite



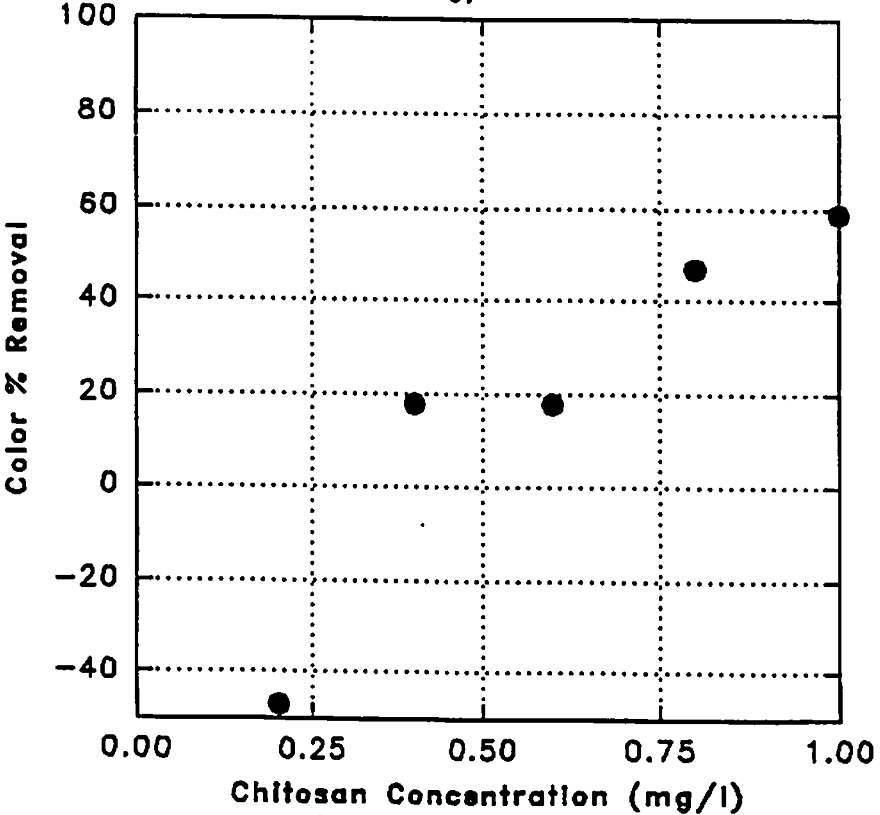
April 6, 1993

Figure 2a
Chitisan Concentration vs. Color Concentration
With 6 mg/l Bentonite



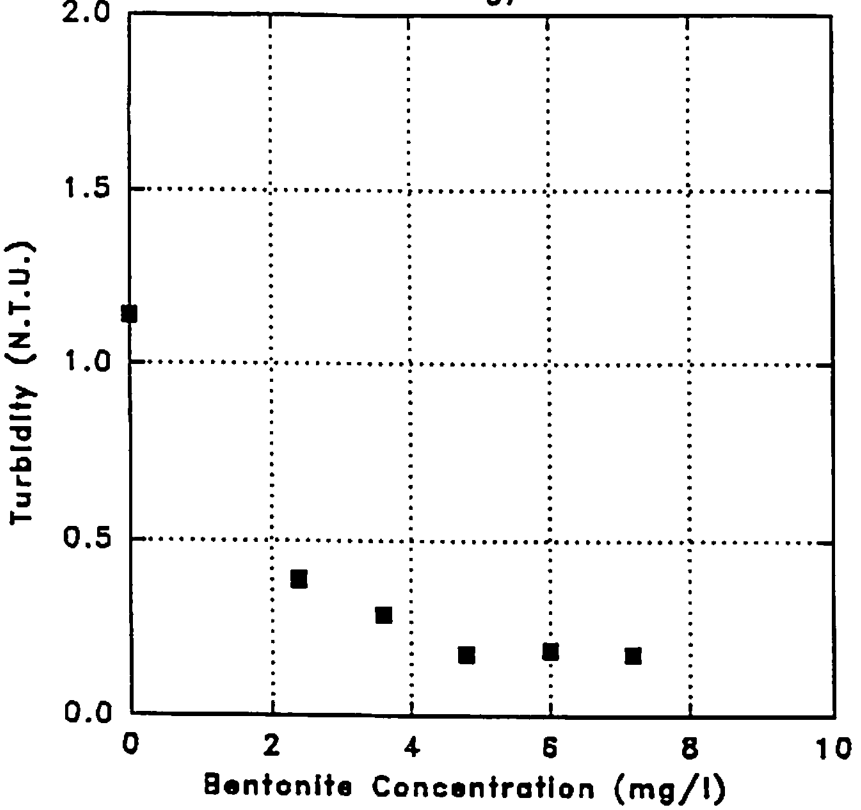
February 18,1993

Figure 2b
Chitosan Concentration vs. Color % Removal
With 6 mg/l Bentonite



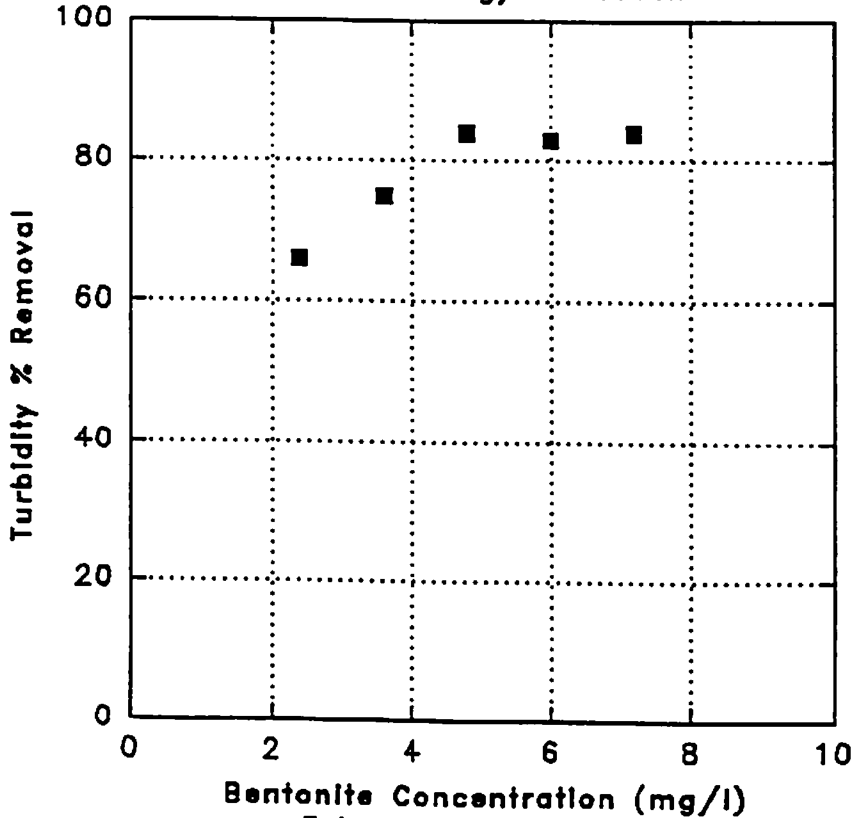
February 18, 1993

Figure 3a
Bentonite Concentration vs. Turbidity Concentration
With 1.0 mg/l Chitosan



February 18, 1993

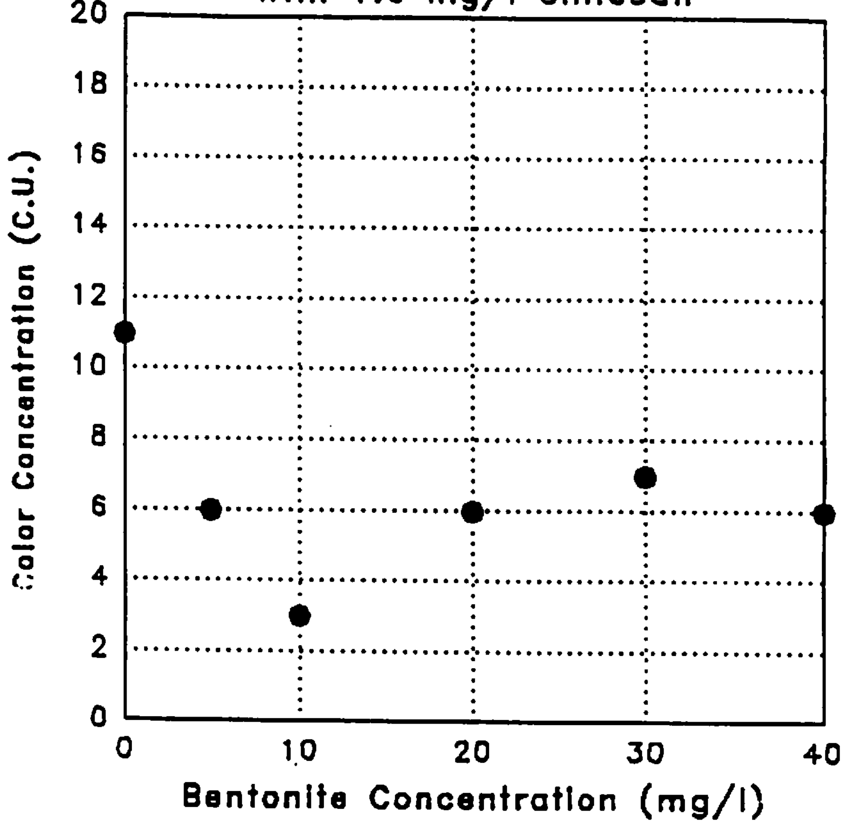
Figure 3b
Bentonite Concentration vs. Turbidity % Removal
With 1.0 mg/l Chitosan



February 18, 1993

Figure 4a

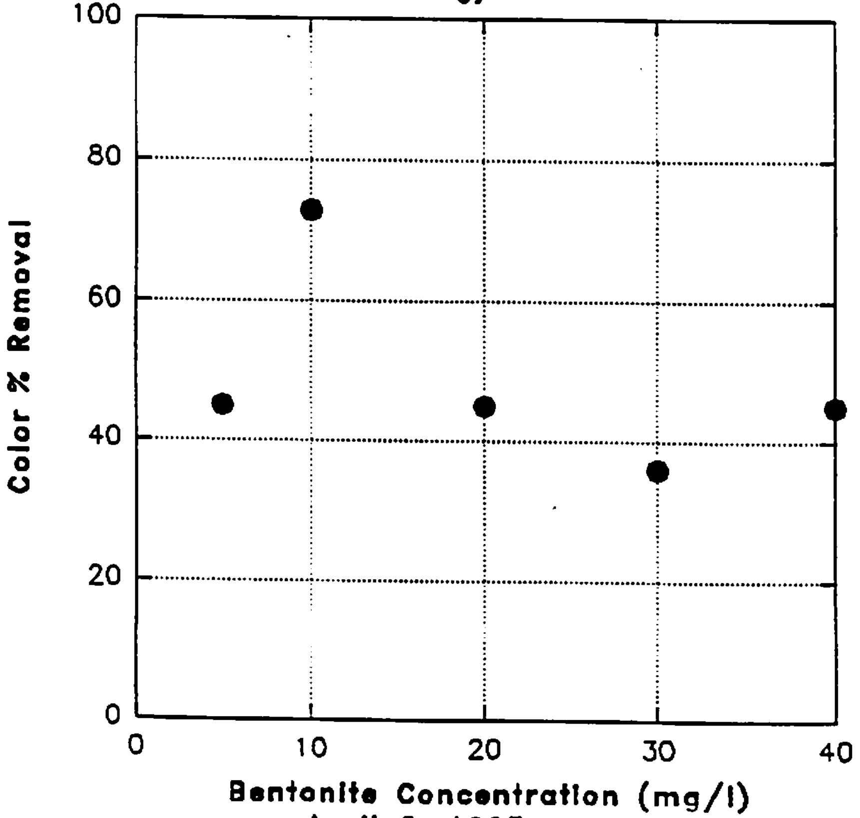
Bentonite Concentration vs. Color Concentration
With 1.0 mg/l Chitosan



April 6, 1993

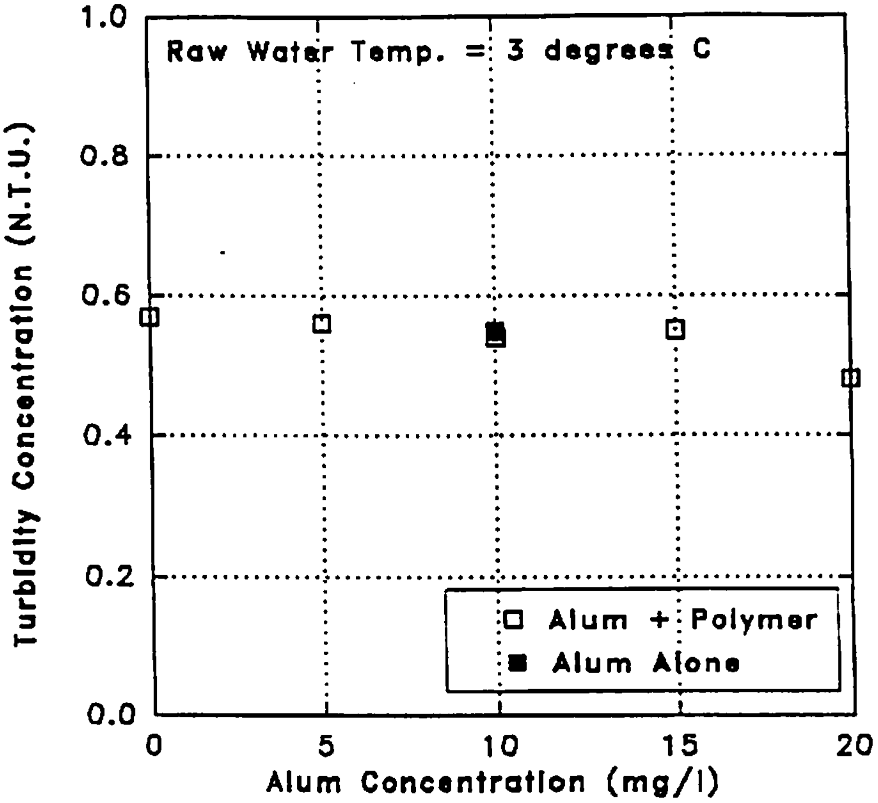
Figure 4b

Bentonite Concentration vs. Color % Removal
With 1.0 mg/l Chitosan



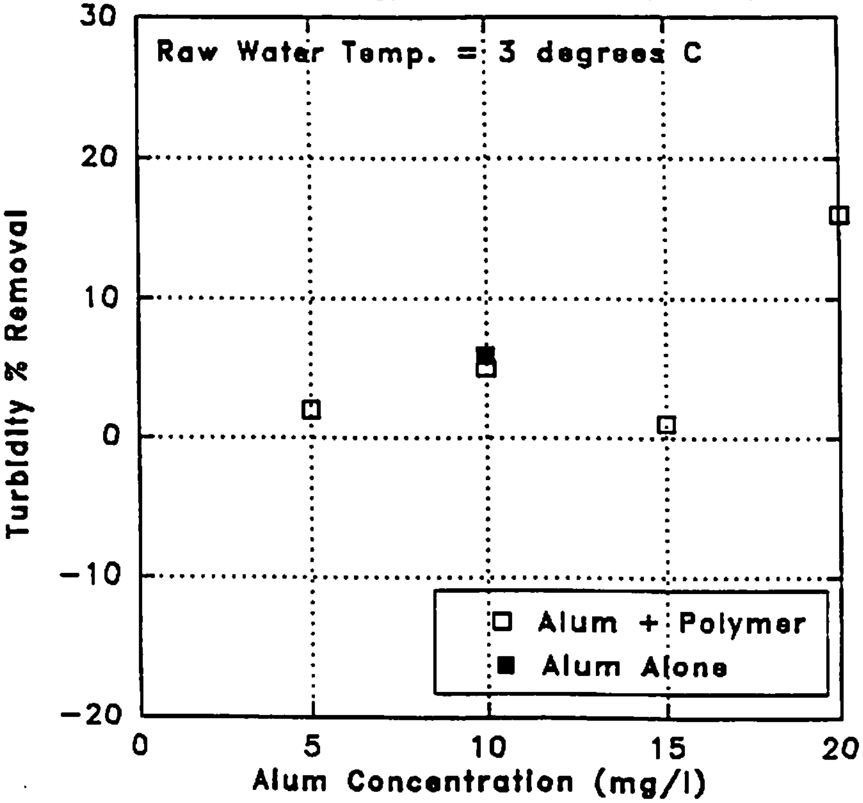
April 6, 1993

Figure 5a
Alum Concentration vs. Turbidity Concentration
Alum Alone or with 2 mg/lCationic Polymer (Magnifloc #587C)



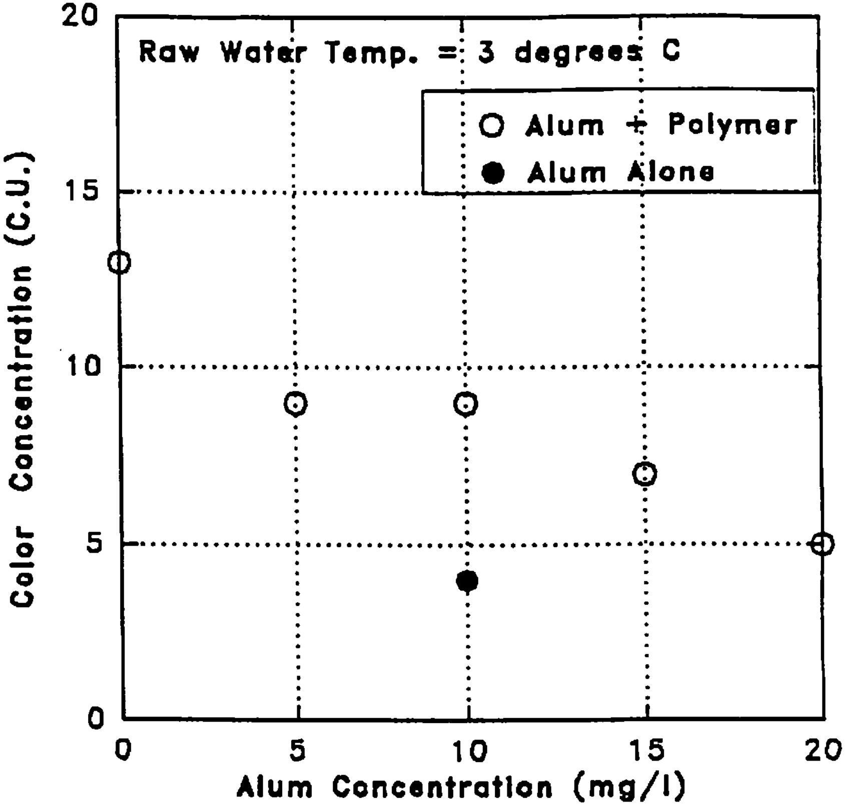
March 16, 1993

Figure 5b
Alum Concentration vs. Turbidity % Removal
Alum Alone or with 2 mg/l Cationic Polymer (Magnifloc #587C)



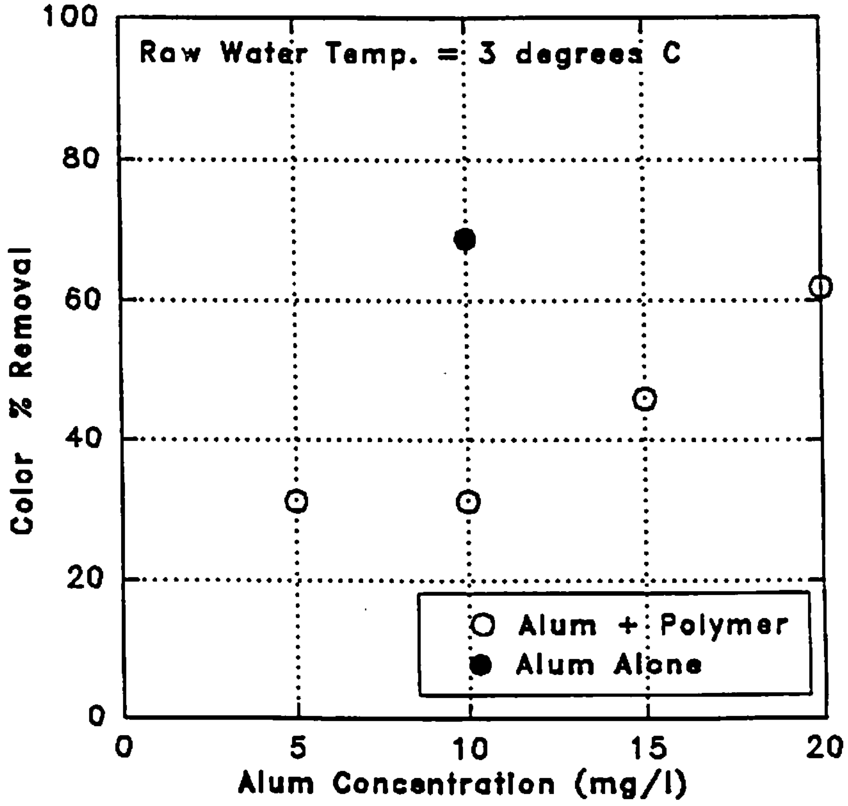
March 16, 1993

Figure 6a
Alum Concentration vs. Color Concentration
Alum Alone or with 2 mg/l Cationic Polymer (Magnifloc #587C)



March 16, 1993

Figure 6b
Alum Concentration vs. Color % Removal
Alum Alone or with 2 mg/l Cationic Polymer (Magnifloc #587C)

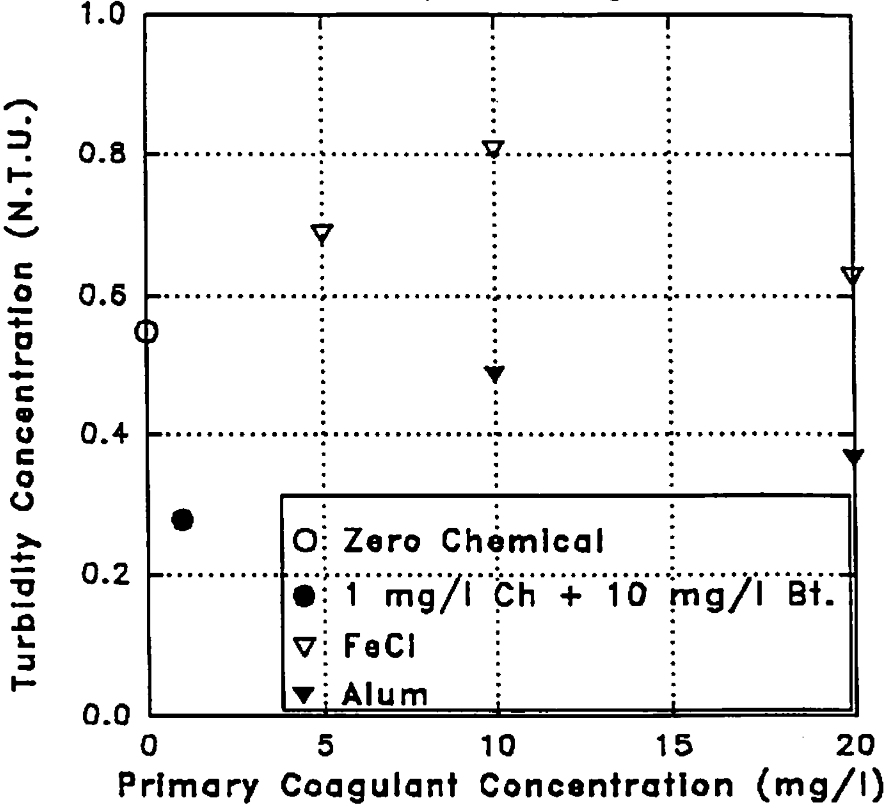


March 16, 1993

Figure 7a

Primary Coagulant Concentration vs. Turbidity Concentration

Raw WaterTemp. = 11 degrees C

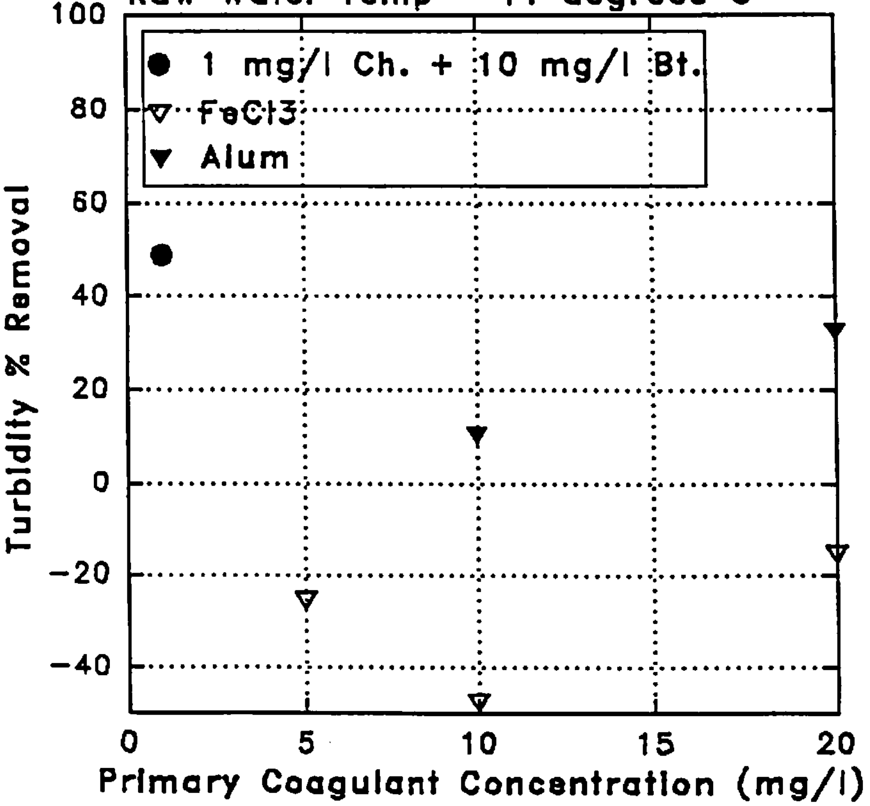


April 13, 1993

Figure 7b

Primary Coagulant Concentration vs. Turbidity % Removal

Raw Water Temp = 11 degrees C

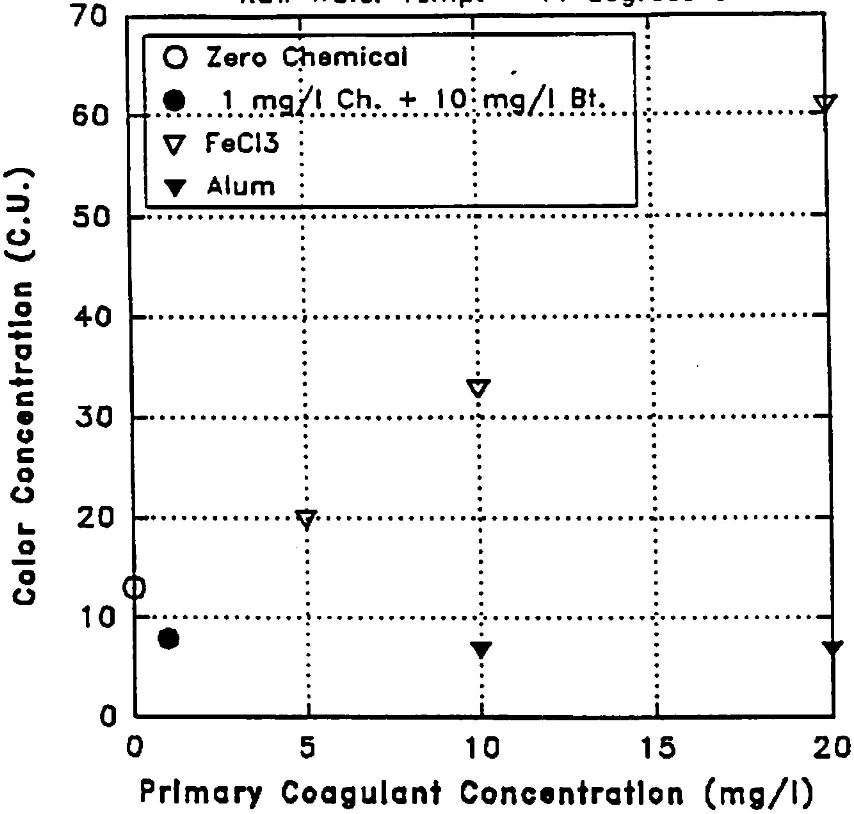


April 13, 1993

Figure 8a

Primary Coagulant Concentration vs. Color Concentration

Raw Water Temp. = 11 degrees C

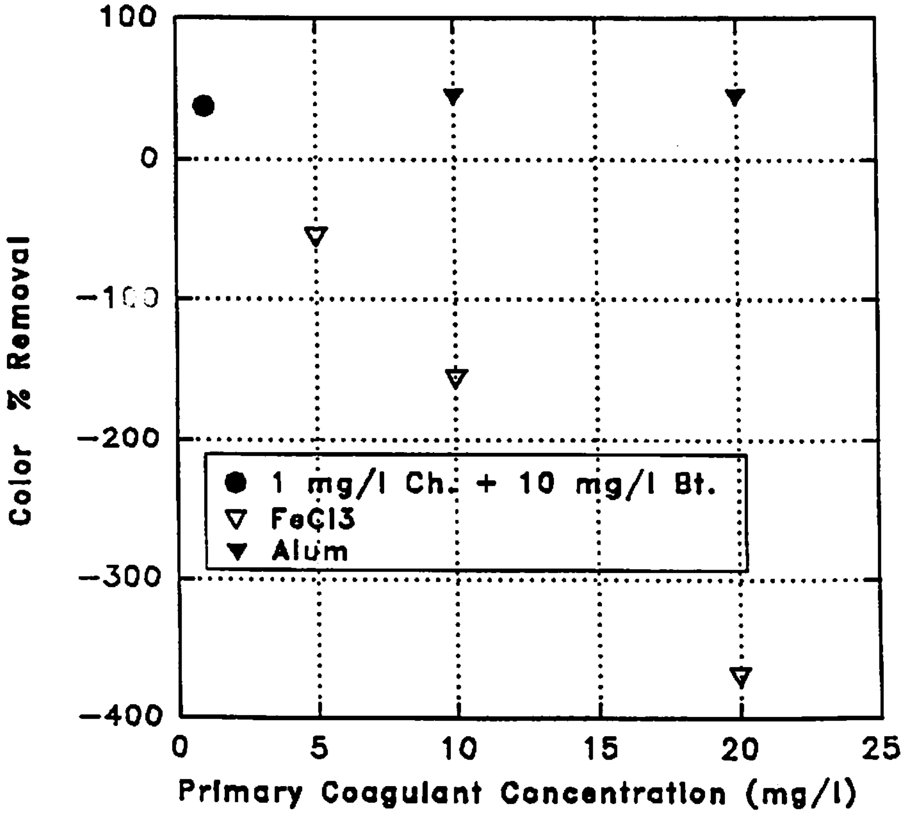


April 13, 1993

Figure 8b

Primary Coagulant Concentration vs. Color % Removal

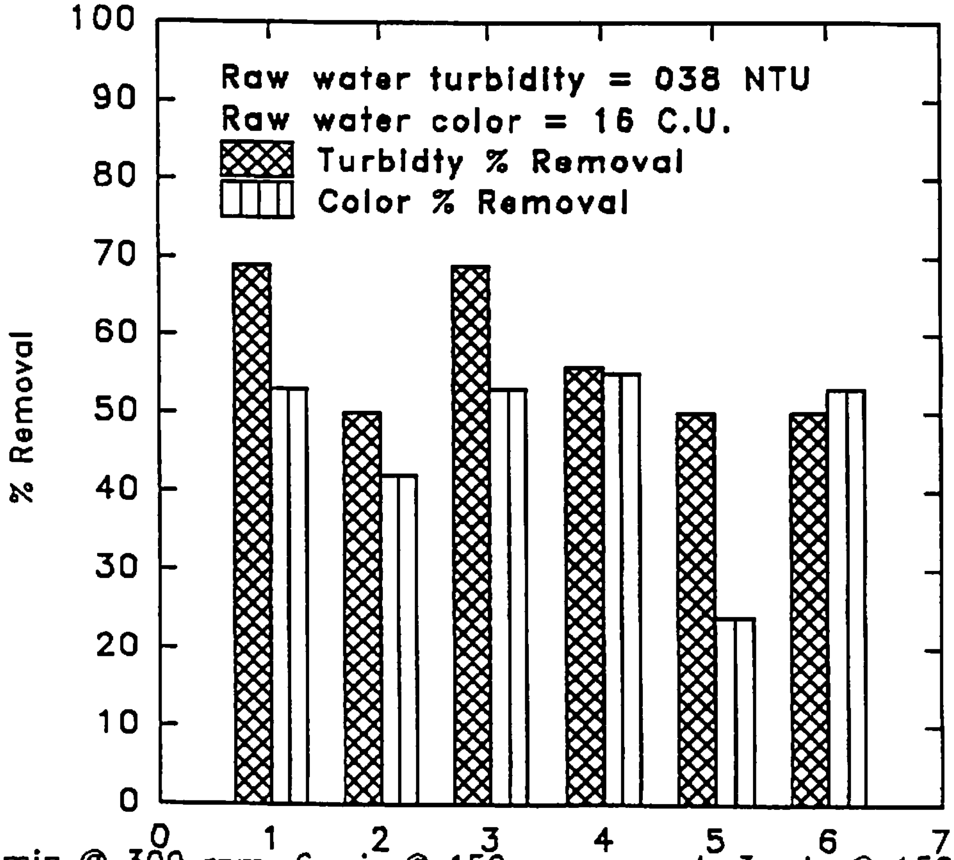
Raw Water Temp. = 11 degrees C



April 13, 1993

Figure 9

% Removal of Turbidity and Color at Various Mixing Times and Speeds With 1.0 mg/l Chitosan + 10 mg/l Bentonite



1. 2 min @ 300 rpm, 6 min @ 150 rpm
2. 1 min @ 300 rpm, 4 min @ 150 rpm
3. 4 min @ 150 rpm
4. 3 min @ 150 rpm
5. 2 min @ 150 rpm
6. 1 min @ 150 rpm

Figure 10
% Removal of Turbidity and Color
With Sequential or Simultaneous Addition of Chemicals
Using 1.0 mg/l Chitosan + 10 mg/l Bentonite

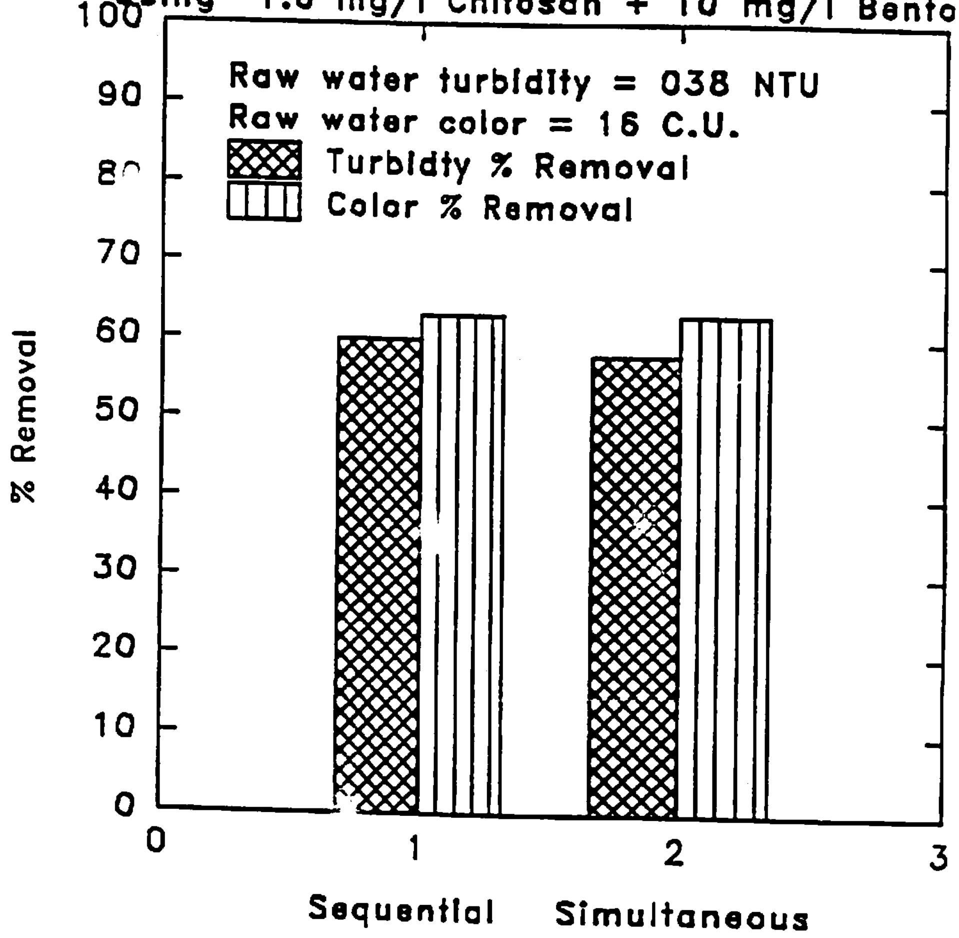
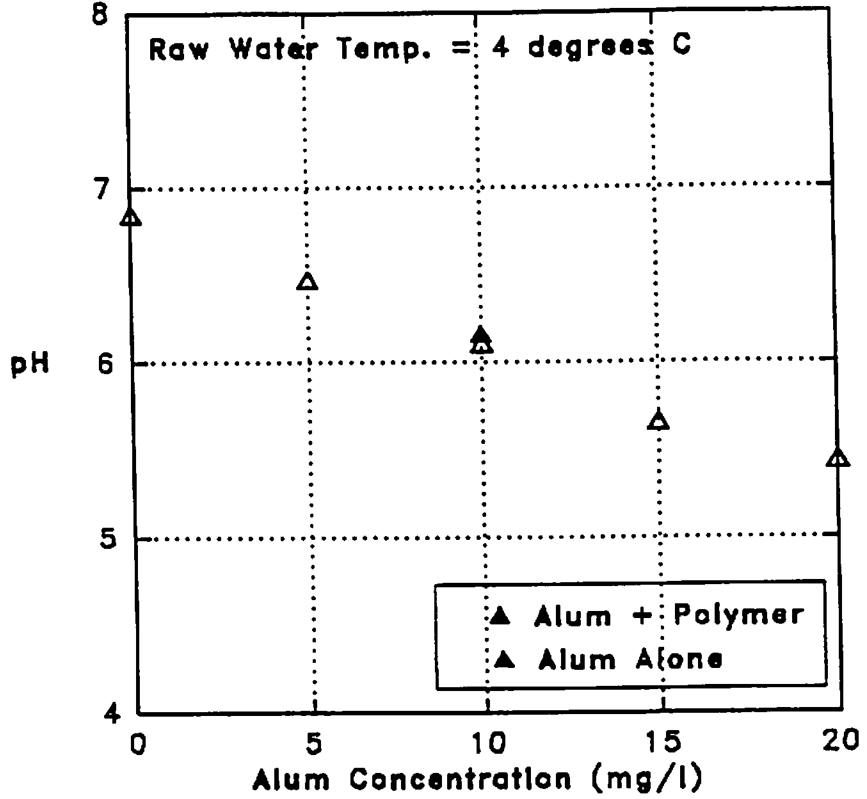
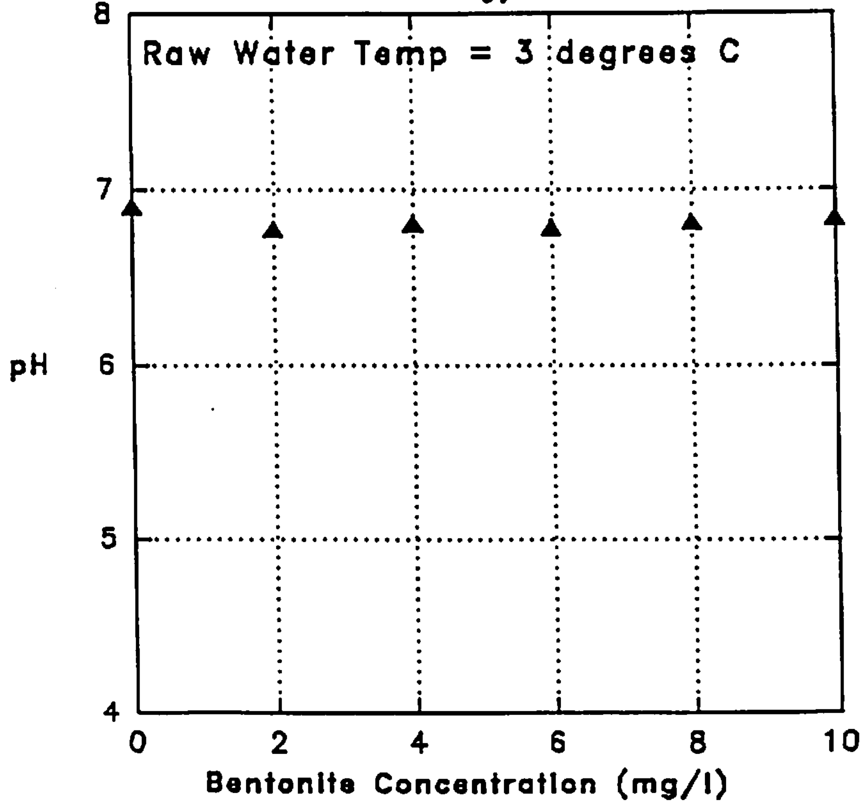


Figure 11a
Alum Concentration vs. pH
Alum Alone or with 2 mg/l Cationic Polymer (Magnifloc #573C)



March 9, 1993

Figure 11b
Chitosan with Bentonite vs. pH
With 0.5 mg/l Chitosan

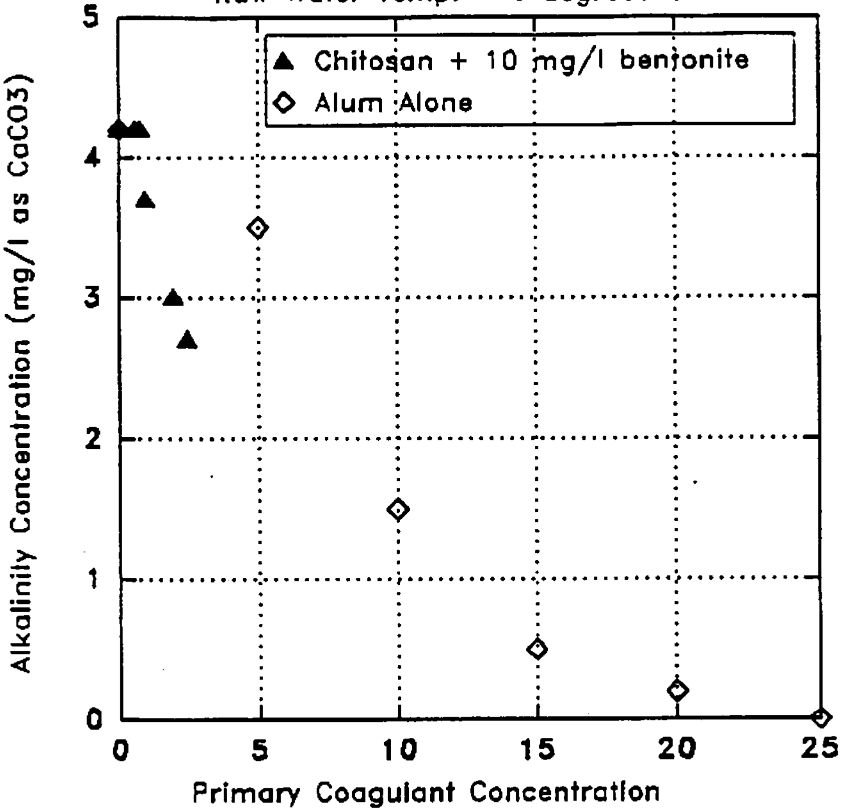


March 18,1993

Figure 12a

Primary Coagulant Concentration vs. Alkalinity Concentration

Raw Water Temp. = 6 degrees C

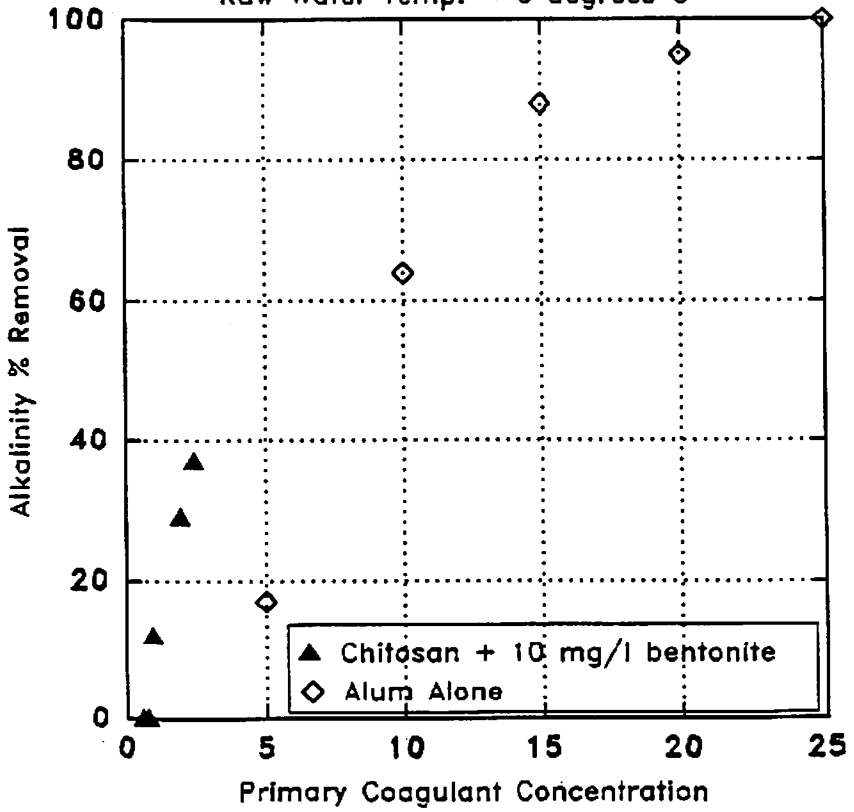


April 29, 1993

Figure 12b

Primary Coagulant Concentration vs. Alkalinity % Removal

Raw Water Temp. = 6 degrees C



April 29, 1993

Figure 13a

Effect of Temperature on Turbidity % Removal

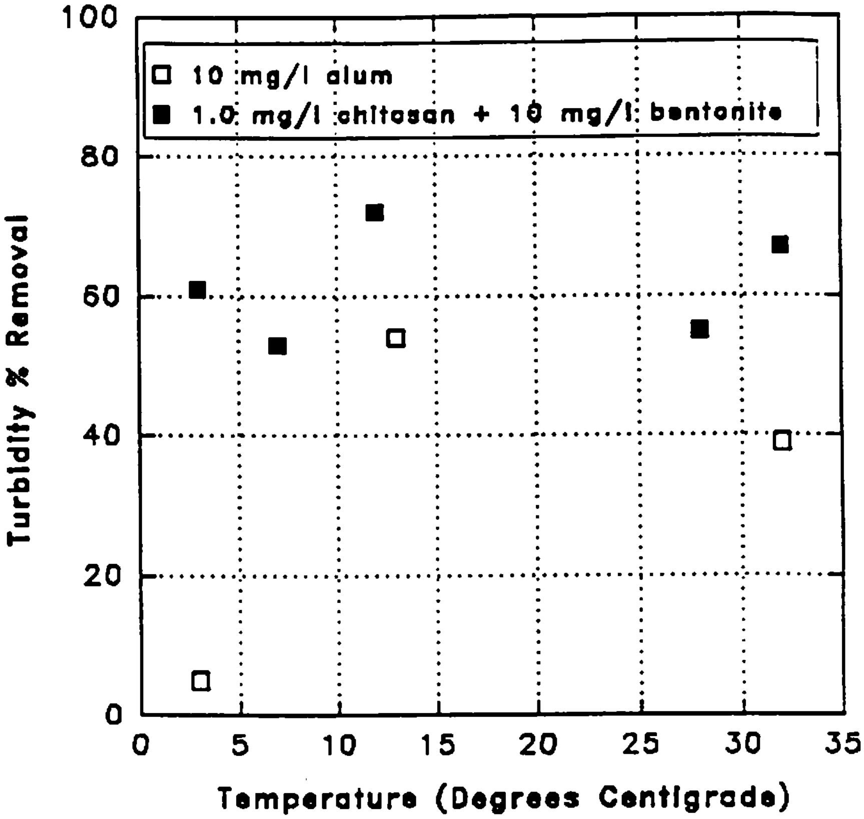


Figure 13b

Effect of Temperature on Color % Removal