MEMORANDUM

MWH

To:	Bill Lynard	**Date:**	November 25, 2005
From:	Geno Lehman	**File No.:**	
CC:	Darren Giles		
Subject:	NAWS Pretreatment Design Criteria Study – Bench Scale Treatability Study		

MWH's Applied Research Department conducted a series of bench-scale tests to evaluate the efficiency of a coagulation/sedimentation process in reducing turbidity to target levels (goals) prior to treatment by UV irradiation for water reaching the divide between the Missouri River and Hudson Bay Basins. The bench-scale studies were focused to develop information used to select coagulants, determine settleability, and predict sedimentation performance. This memorandum summarizes the experimental methods used throughout the bench-scale study, discusses results obtained during the testing period, and presents conclusions from the study.

Experimental Approach

Twenty gallons each of ambient and turbid lake water were collected from Lake Sakakawea and the U.S. Bureau of Reclamation Snake Creek Pumping Plant, respectively, and delivered to the MWH Applied Research Department testing laboratory in Monrovia, CA. The ambient was sample was collected from the lake, in the entrance channel just outside of the pump plant embankment. The turbid sample was collected inside the pump plant from the service water system that pumps water from the fore bay of the facility. The turbid sample was collected while the pump plant was running at approximately 1700 cubic feet per second to stir up as much turbidity as possible. The raw water samples were analyzed for turbidity, total organic carbon (TOC), dissolved organic carbon (DOC), UV_{254} absorbance, color, pH, alkalinity, ammonia and hardness.

Several series of bench-scale tests were conducted, using a Phipps and Bird stirrer apparatus. All tests were conducted at 5°C and were designed to evaluate:

- Coagulant Selection. Jar tests were conducted on raw water to select the optimal coagulant for formation of settleable floc. Tests were conducted with varying doses of alum and ferric chloride. A representative flocculation energy gradient of 30 sec^{-1} (mixing speed of 44 rpm) for 15 minutes was used.

- Optimal Flocculation Energy and Settleability. Using the preferred coagulant and an anticipated dose, selected from the previous test, settling curves were developed over a detention time of 60 minutes with a flocculation energy gradient of 30 sec^{-1} for 15 minutes. Additional tests were also performed to determine if flocculation mixing conditions could be further optimized.

- TOC Reduction Using Enhanced Coagulation. This series of tests identified the optimal coagulant dose to satisfy the enhanced coagulation requirements of the Stage 1 D/DBP Rule (i.e., TOC, DOC and UV_{254} absorbance removal).

- UV transmittance and solids production. Throughout the testing, UV transmittance (UVT) was monitored for selected data points and compared to the raw water UVT. For each data point, an unfiltered and filtered UVT was measured. Additionally, the total solids production was determined from the sequence of doses applied during enhanced coagulation testing.

Raw Water Quality

The results of the water quality analyses on the two raw waters utilized in this testing are presented in Table 1 below. As expected, the turbid sample had a higher TOC, UVT, and turbidity, compared to the ambient lake sample. In particular, hardness, alkalinity, and sulfate levels were noticeably higher in the turbid sample.

Table 1
Raw Water Quality

Parameter	Unit	Ambient Sample	Turbid Sample
Turbidity	NTU	3.1	6.2
TOC	mg/L	4.1	5.4
DOC	mg/L	3.8	5.2
UVT (unfiltered)	% transmittance	80.5	70.8
UVT (filtered)	% transmittance	84.3	77.7
SUVA	L/mg-m	1.9	2.2
Apparent Color	Pt Co C.U.	21	53
True Color	Pt Co C.U.	0	7
pH	-	8.4	7.8
Alkalinity	mg/L as $CaCO_3$	159	365
Ammonia	mg/L as N	<0.1	<0.1
$Hardness_{Total}$	mg/L as $CaCO_3$	240	365
Chloride	mg/L	13.1	15.9
Nitrate	mg/L	0.25	0.32
Sulfate	mg/L	211	398

Coagulant Selection – Alum versus Ferric Chloride

An initial jar test was performed with the ambient lake water sample to determine whether aluminum- or ferric-based coagulants would allow for improved water quality with respect for turbidity and TOC removal. Two-liter samples of water were coagulated with 10, 30, and 60 mg/L equivalent alum doses with reagent grade aluminum sulfate and ferric chloride. For purposes of this initial experiment, the mixing scheme was as follows: rapid mix (100 rpm) for 1 min, flocculation energy of 30 sec^{-1} (44 rpm) for 15 minutes, and 60 minutes settling.

Figure 1 shows that turbidity removal was enhanced when ferric chloride was applied compared to alum, when less than a 30-mg/L equivalent alum dose was used. Beyond a 30-mg/L equivalent alum dose, turbidity removals are similar, most likely due to an overdose of coagulant for the specific water quality conditions. *Hence, ferric chloride was chosen as the desired coagulant for all consecutive tests (with ambient and turbid water samples).* It is important to note that from this initial test and using preliminary mixing conditions, the required dose was expected to fall between 10 and 30 mg/L equivalent alum (5 and 15 mg/L ferric chloride). This was used as guidance for the additional tests described below.

Further analysis of the 60 minute settled water revealed that TOC removals were similar when using either alum or ferric chloride. In fact, TOC removal capability of this water appeared to be minor, even at a high coagulant dose of either alum or ferric, as shown in Figure 2. The TOC removal of the source water is detailed in a later section.

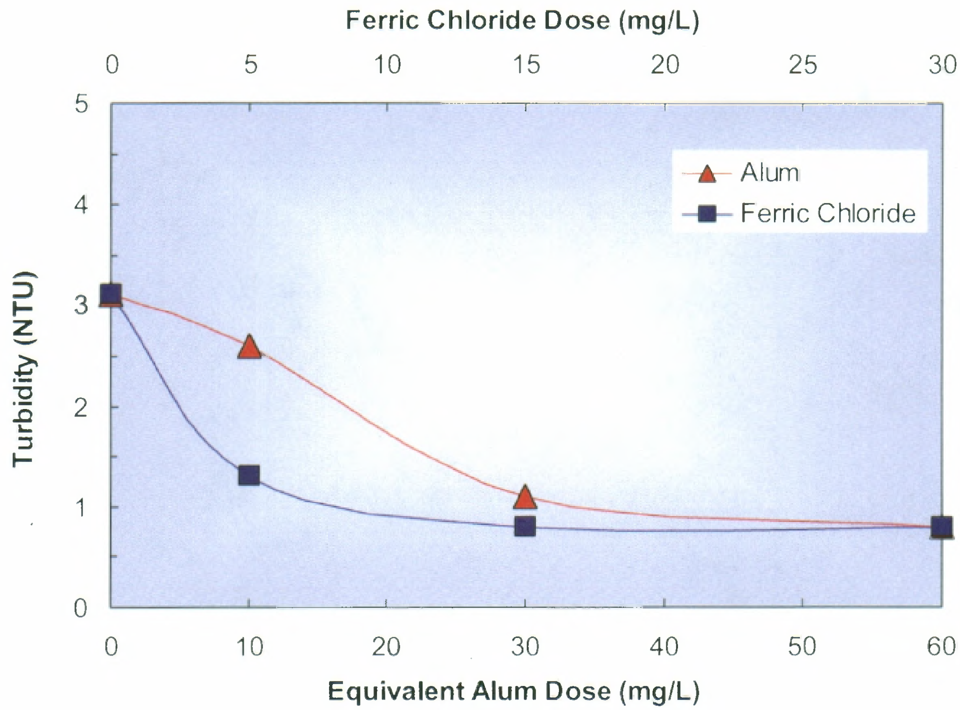

Figure 1
Settled Water Turbidity – Alum versus Ferric Chloride

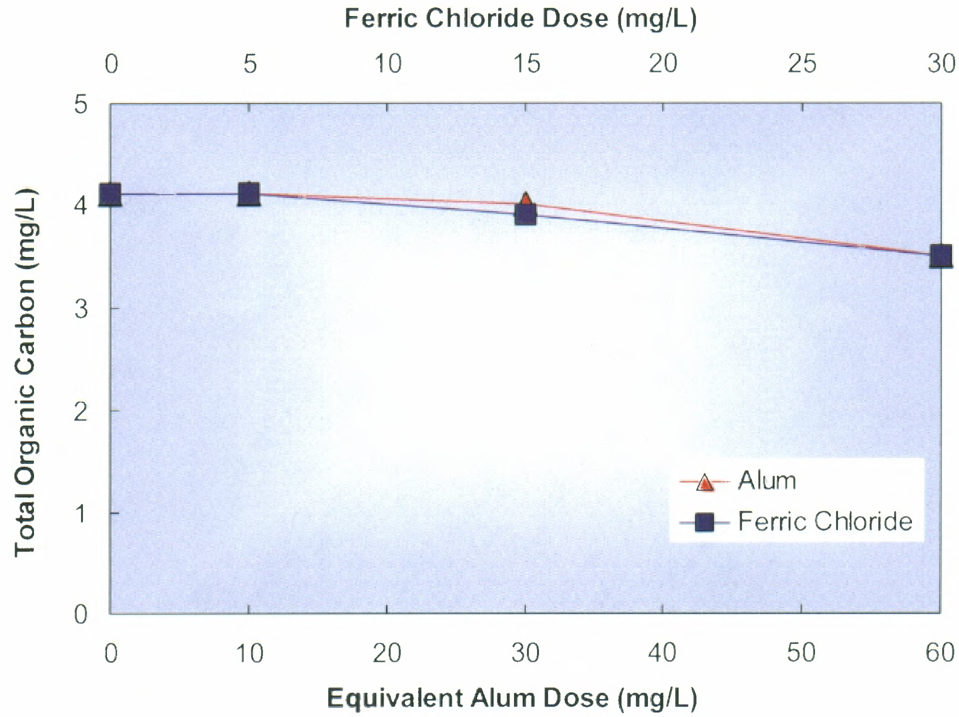

Figure 2
Settled Water TOC levels – Alum versus Ferric Chloride

Determination of Optimal Mixing and Settling Conditions

Impact of Settling Time. Results from the coagulant selection test indicated that settled water turbidities below 1.0 NTU could be achieved when at least 15 mg/L of ferric chloride was used with 60 minutes of settling time. In order to analyze the settling characteristics further, a settling curve was establish by dosing a sample of ambient lake water with 15 mg/L ferric chloride and collecting turbidity samples at defined time intervals over a period of 60 minutes. Again, the mixing scheme used during this experiment included rapid mix (100 rpm) for 1 min and a single-stage flocculation energy of 30 sec^{-1} (44 rpm) for 15 minutes. Figure 3 shows that given the applied mixing condition and ferric chloride dose, the floc aggregates required at least 20 minutes of settling time before effective turbidity removal was observed. After 30 minutes of settling, the settled water turbidity was 1.3 NTU and further dropped to below 1.0 NTU after 60 minutes of settling. *Based on these results, a minimum of 30 minutes settling time was determined to provide significant removal of turbidity.*

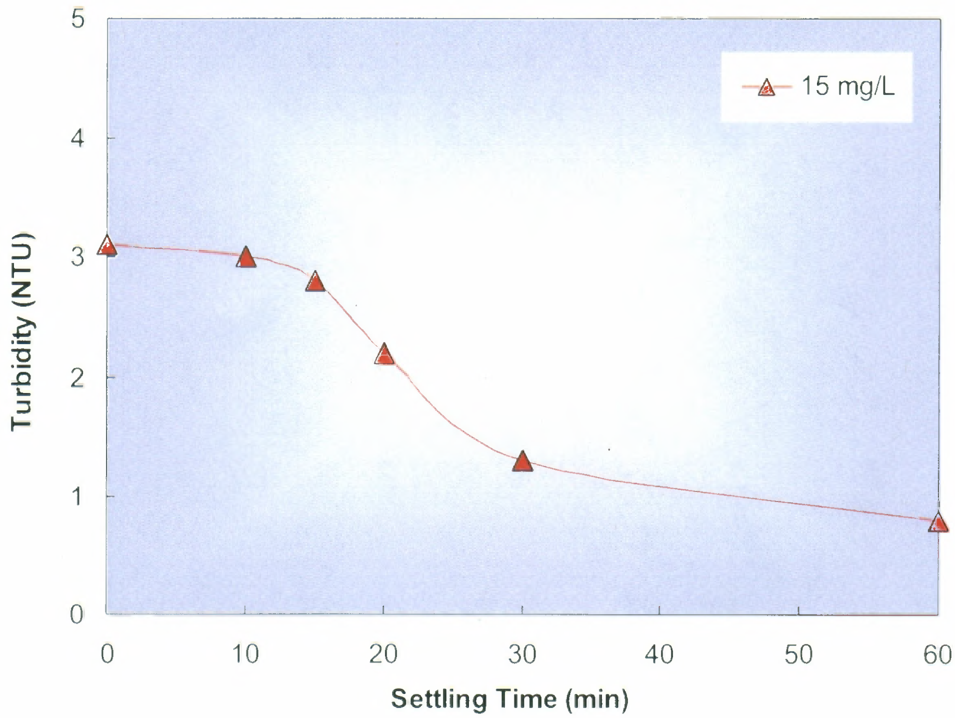

Figure 3
Settleability Curve for Turbidity Removal Using 15 mg/L Ferric Chloride

Impact of Dose and Settling Time. An additional test was performed to establish settling curves for increasing ferric chloride doses to determine if improve settled water turbidities could be achieved at a higher dose and decrease settling time condition. As shown in Figure 4, again it appears that even at higher dose of ferric chloride, settleable floc is removed after 20 minutes of settling. Increasing the dose more than two-fold to 30 and 40 mg/L improves the settled water turbidity by 20%. Final turbidity values after 60 minutes of settling are essentially equivalent for all ferric chloride doses applied. *As a result of these settleability experiments, 30 minutes of settling time was chosen as the baseline for the remaining test to be conducted.*

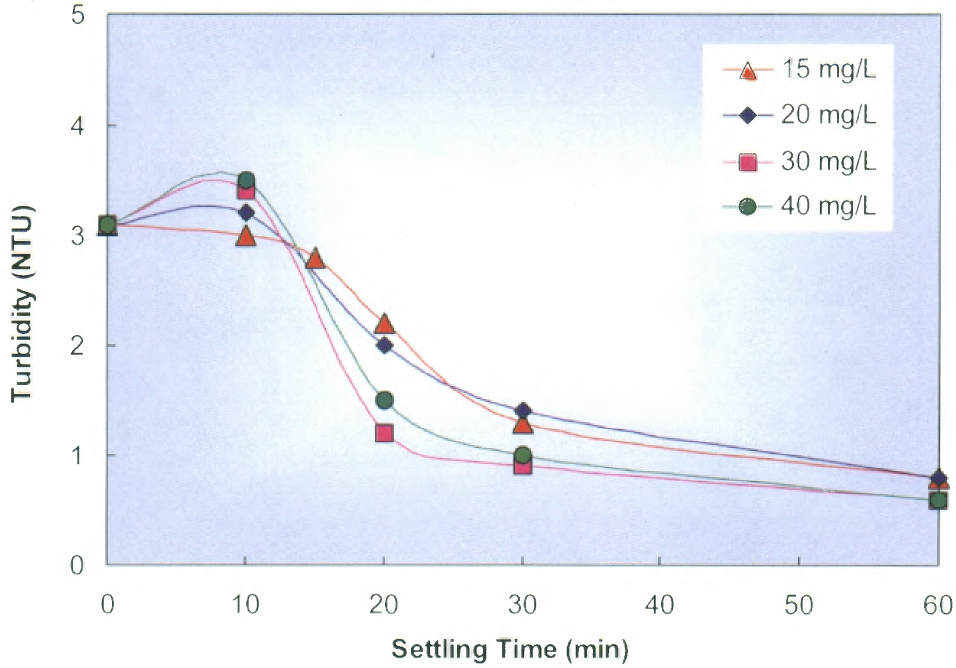

Figure 4
Settleability Curves for Turbidity Removal Using Increasing Ferric Chloride Doses

Impact of Mixing Energy. Frequently, some form of tapered flocculation can improve the formation of floc particles compared to single stage mixing. Tapered flocculation usually involves two or three stages, in which the mixing energy is decreased incrementally per stage. Typical detention times observed per stage range from 5 to 10 minutes, allowing for a total of 15 to 30 minutes of flocculation. An additional experiment was conducted to evaluate enhancements to mixing performance using tapered flocculation. A standard 30 minute tapered flocculation, which included 1 min flash mix (100 rpm) followed by three 10-minute stages with mixing energy G-values of 40, 18, and <5 sec^{-1} (60, 30, 10 rpm), was used. This test was compared to the 15 mg/L ferric chloride dose with 15 and 30 minutes of single stage mixing at 30 sec^{-1} (44 rpm). Figure 5 shows that the settled water turbidity after 30 minutes decreased by 30% from 1.3 to 0.9 when the single-stage mixing time was increased to 30 minutes. When tapered flocculation was used, an even further 50% decrease in turbidity was achieved – measured below 0.6 NTU. *As a result, it is recommended that some form of tapered flocculation be used to achieve the maximum turbidity removal during full-scale operation.*

Although enhanced turbidity removal would be beneficial for operation of the post UV disinfection process, the governing parameter for UV design is the UV transmittance (UVT) of the water to be treated. For the three experiments comparing different forms of flocculation (15 min single-stage, 30 min single-stage, 30 min tapered), filtered and unfiltered UVT was measured and is presented in Figure 6. It can be seen in this figure that both increasing the flocculation time (from 15 to 30 minutes) and use of tapered flocculation has a minimal impact on the settled water unfiltered UVT values (from 79% to 81%). Interestingly, Figure 6 also reveals that filtered UVT values are only 8-13% higher than unfiltered samples, indicating that the majority of UV absorbing constituents are in the dissolved phase.

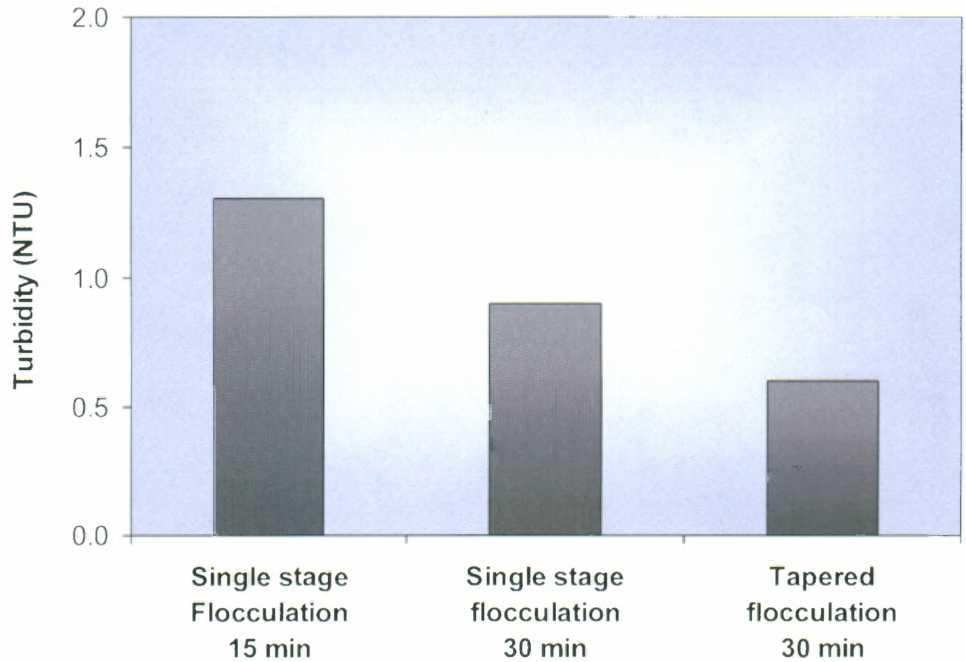

Figure 5
Settled Water Turbidity After Single-stage and Tapered flocculation

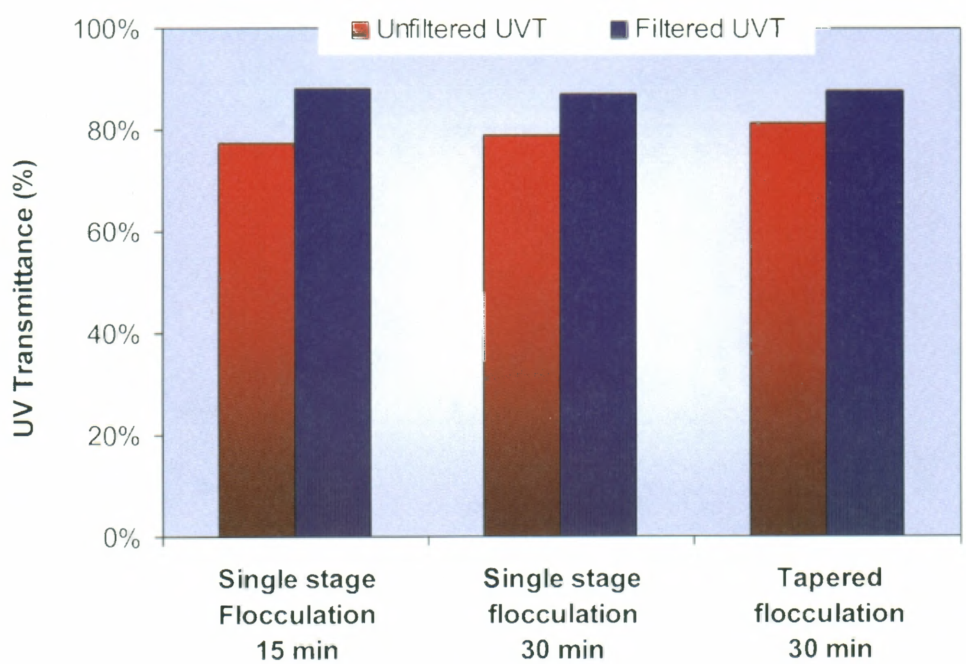

Figure 6
Settled Water UV Transmittance After Single-stage and Tapered Flocculation

TOC Reduction Using Enhanced Coagulation

Enhanced coagulation is defined as the "...addition of sufficient coagulant for improved removal of disinfection by-product precursors", (TOC). The following sections present results from enhanced coagulation testing for both ambient and turbid lake samples. The enhanced coagulation characteristics of the water were established without a coagulant aid. Mixing conditions used were based on optimization jars results from the flocculation and settleability tests: 1 minute flash mix (100 rpm), 30 minute tapered flocculation (60, 30, 10 rpm), and 30 minutes settling.

Ambient Lake Sample. The TOC removal achieved on the ambient lake sample over a range of coagulant doses is shown in Figure 7. TOC removal held at a consistent level of about 7 percent reduction up to a dose rate of 15 mg/l Ferric Chloride. TOC removal increased as coagulant dosed increased from 15 to 30 mg/l of Ferric Chloride. The maximum TOC reduction achieved on this water sample was about 1.1 mg/l, or about a 27 percent reduction.

Turbid Lake Sample. The TOC removal achieved on the_turbid lake sample over a range of coagulant doses is shown in Figure 8. The turbid water sample was more difficult to treat for TOC removal. This is related to the higher alkalinity and hardness compared to the ambient lake sample. The initial coagulant dose of 5-mg/l ferric chloride resulted in a TOC reduction of about 0.6-mg/l, or about an 11 percent reduction. From a dose of 5 to 25-mg/l, only marginal improvements in TOC reduction were observed. The maximum TOC removal achieved on this water sample was about 1-mg/l, or about a 19 percent reduction. Further coagulant optimization using polymer flocculant aids and increasing the settling time may help to achieve improved TOC removals.

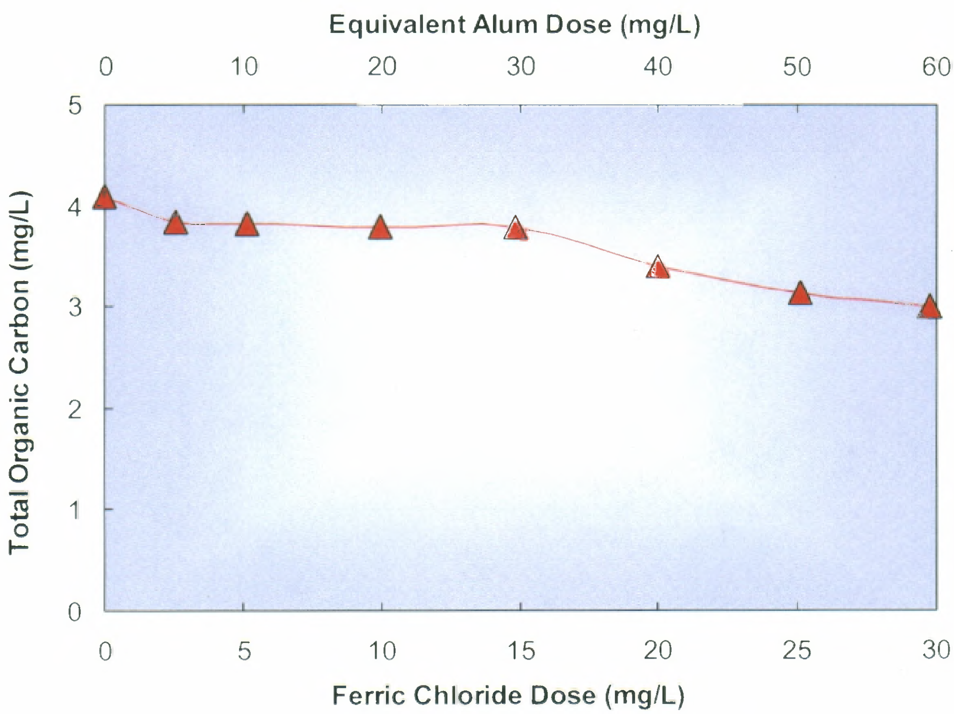

Figure 7
Enhanced Coagulation – Ambient Sample

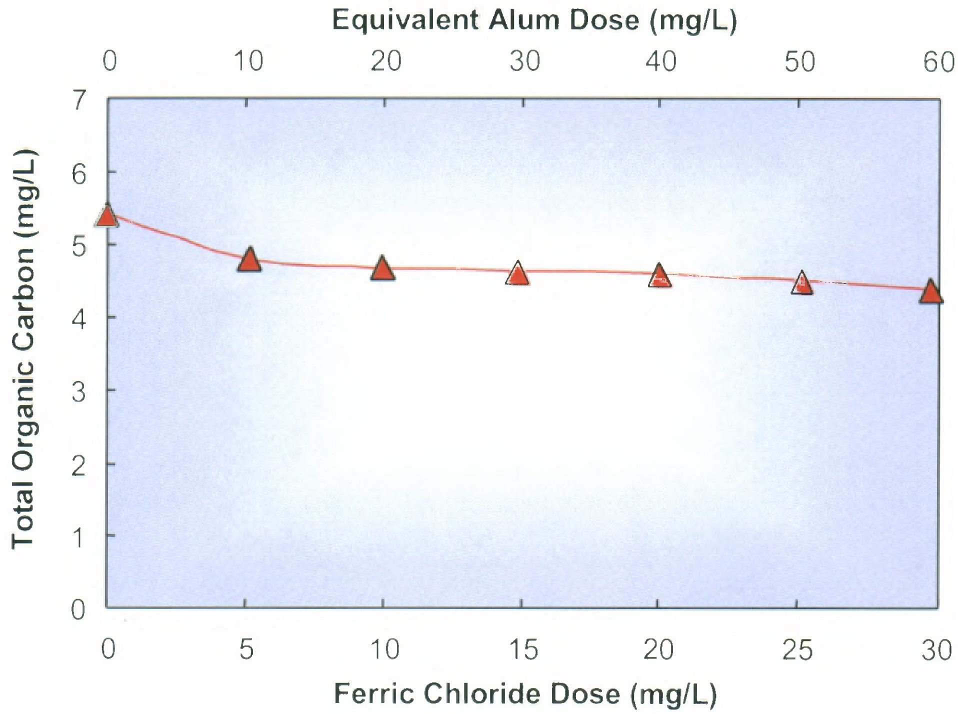

Figure 8
Enhanced Coagulation – Turbid Sample

Water Quality - UV Transmittance, Turbidity, and Solids Production

Samples of treated water were also collected from the enhanced coagulation tests to provide additional water quality data per applied dose (5 to 30 mg/L ferric chloride). The following presents water quality profiles for UVT, turbidity, and a measure of the total solids production.

Ambient Lake Sample. In this testing, turbidity was used as the main surrogate for assessing jar testing performance. Figure 9 shows the turbidity removal of the optimized jar tests at varying ferric chloride doses. Previously, it was determined that at least 15 mg/L ferric chloride was required to achieve desired settled water turbidities. However, the enhanced coagulation testing demonstrated that at optimized mixing conditions and settling times, turbidities <1.0 NTU can be achieved at a ferric chloride dose as low as 5 mg/L. An additional jar test coagulated with 2.5 mg/L ferric showed that the coagulant dose was insufficient to effectively form a settleable floc.

Figure 10 shows filtered and unfiltered UVT values for the same 2.5 to 30 mg/L ferric chloride doses. At a low ferric chloride dose of 5-mg/L, the unfiltered UVT was 81% and was observed as high as 84% at the higher coagulant dosages. Based on these results, it can be seen that it may not be economical to use as high a ferric chloride dose (25-30 mg/L) to achieve only a 4% increase in unfiltered UVT. Additionally when using higher ferric chloride dose, sludge production may be an issue as seen in the profile of total solids (dry weight basis) generated from samples of coagulated water, shown in Figure 11. At a 5 mg/L ferric dose, 9 mg/L of total solids was produced from the sample (or 18 mg dry weight solids for the 2-L sample). This is compared to 24 mg/L of solids at a 25 mg/L ferric dose (or 48 mg of solids for the 2-L sample).

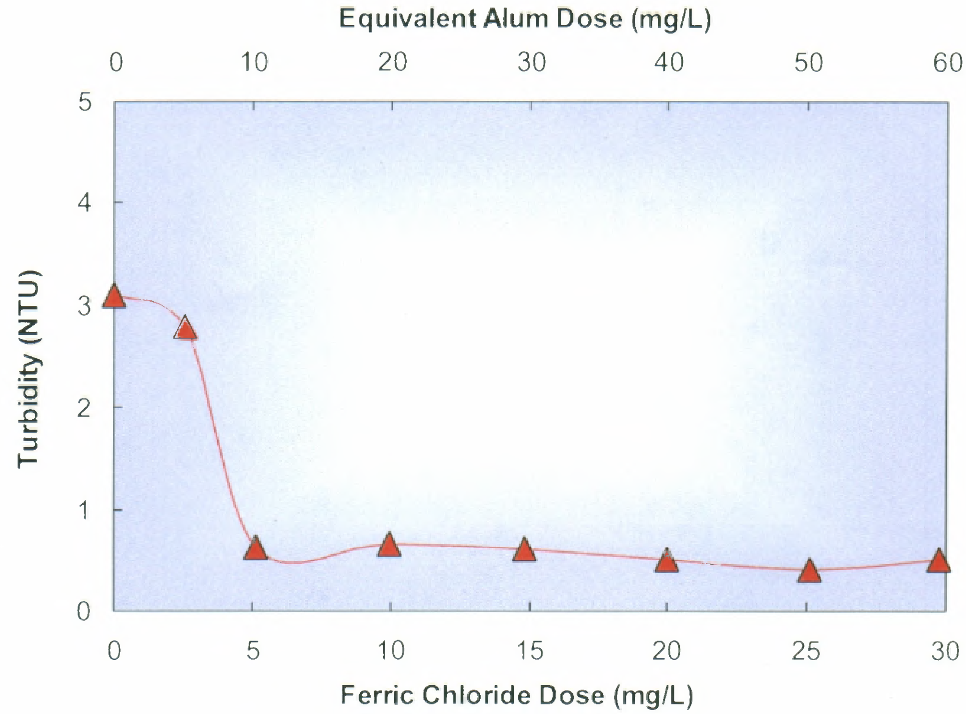

Figure 9
Reduction of Turbidity – Ambient Sample

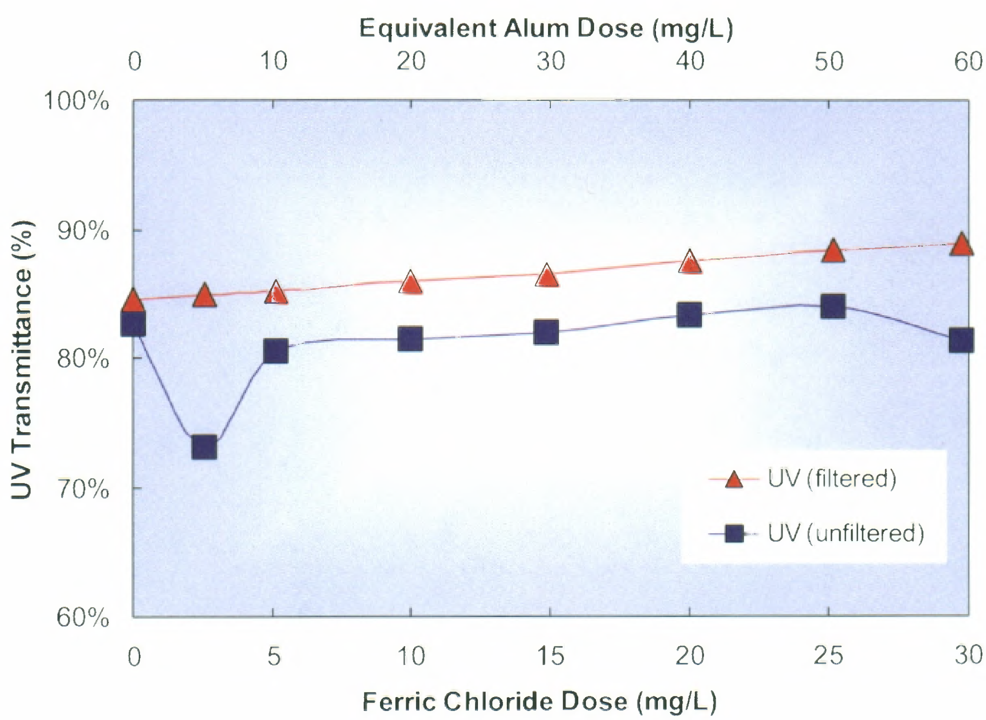

Figure 10
Filtered and Unfiltered UV Transmittance – Ambient Sample

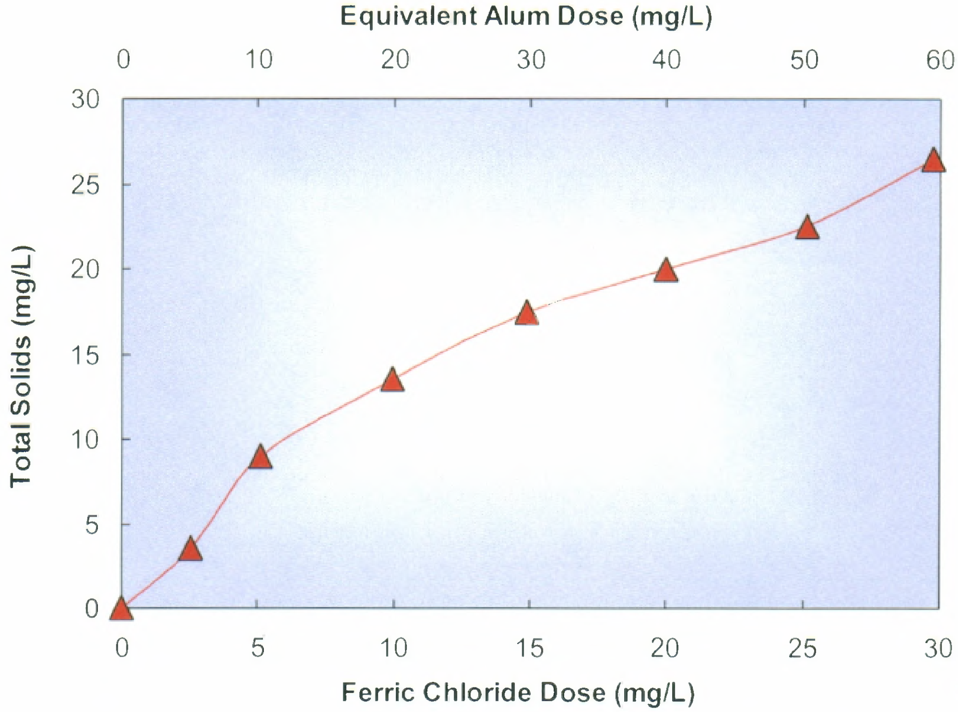

Figure 11
Total Solids Production (dry weight basis for 2 liter water sample)– Ambient Sample

<u>Turbid Lake Sample.</u> Similarly, Figure 12 shows the turbidity removal of the optimized jar tests at the varying ferric chloride doses. With the ambient lake sample, it was determined that a minimum 5 mg/L ferric chloride is required to maintain settled water turbidities below 1.0 NTU. However, due to the more challenging water quality of the turbid sample (i.e., higher turbidity, TOC, alkalinity, sulfate, etc.), *results demonstrated that a much higher coagulant dose would be required to achieve the similar treated water quality of the ambient sample (i.e., turbidity <1.0 NTU, UVT > 80%).*

Figure 13 also shows UVT values were also lower at 71-74% and 78-81% for unfiltered and filtered UVT, respectively. Finally, total solids production for these jars was slightly lower than the ambient lake samples at coagulant doses greater than 5-mg/l, as shown in Figure 14. This was most likely due to inability of the coagulant to remove the majority of the turbidity in the form of settleable floc. Based on these results, it was clear that additional treatment or optimization may be necessary to improve the treated water quality further. Hence, the following set of experiments focused on determining if the application of flocculation aids or polymers could improve the coagulation efficiency.

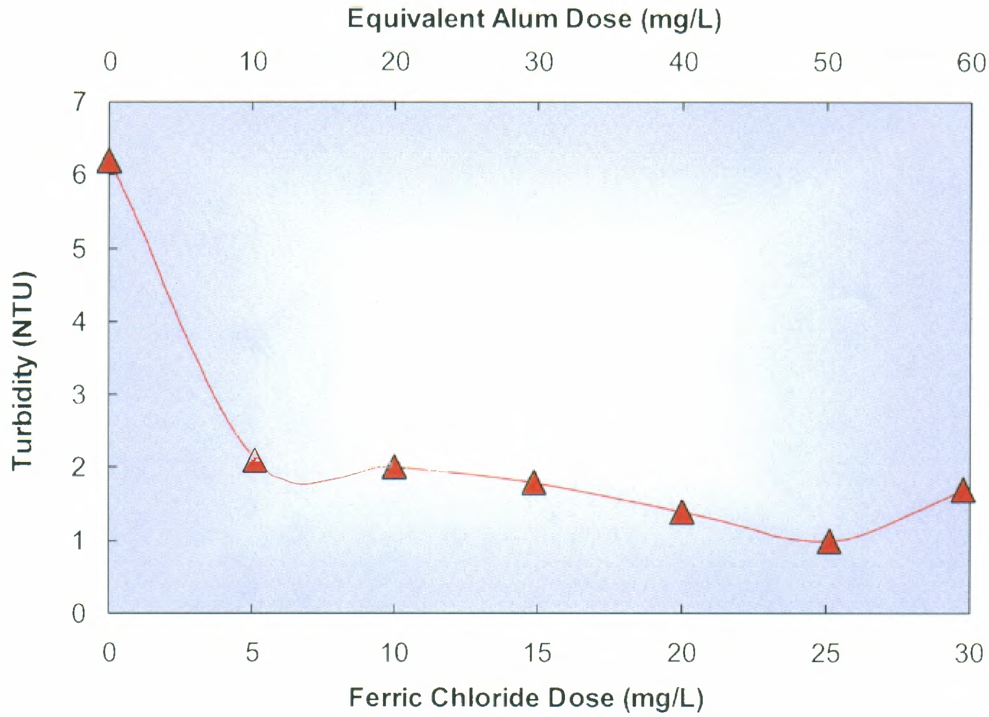

Figure 12
Reduction of Turbidity – Turbid Sample

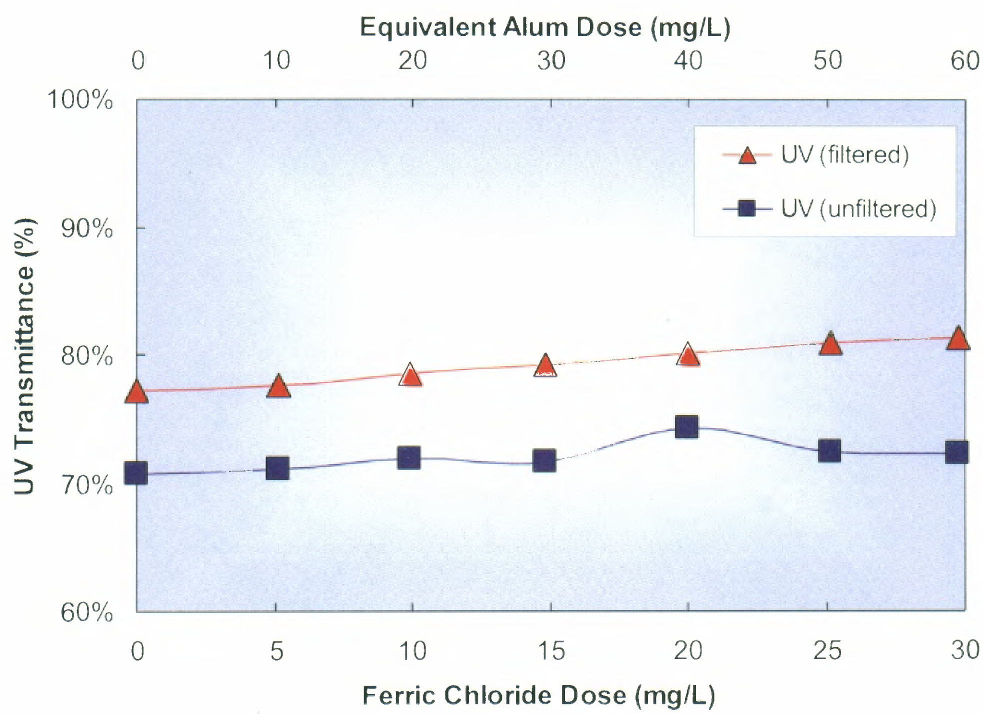

Figure 13
Filtered and Unfiltered UV Transmittance – Turbid Sample

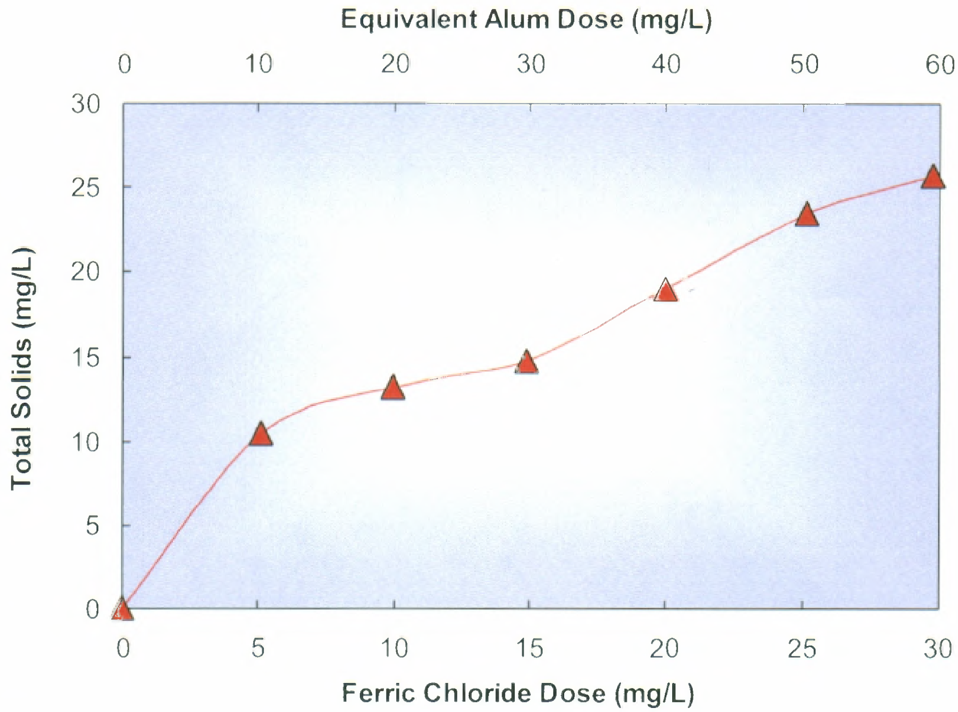

Figure 14
Total Solids Production (dry weight basis for 2 liter water samples) – Turbid Sample

Jar Test Optimization and Impact of Polymer Addition

In an effort to further optimize the use of coagulant for turbidity removal prior to the UV disinfection system and determine mechanisms to improve the treated water quality of the more challenging raw water qualities (i.e., turbid lake sample), jar testing experiments were performed with the simultaneous addition of cationic polymer (DADMAC) with ferric chloride. Previously, the enhanced coagulation characteristics of the water were established without a coagulant aid as dictated by the Stage 1 D/DBP Rule. The proposed WTP, however, provides the ability to use floc aids or polymers in conjunction with the coagulant.

Ambient Lake Sample. With the ambient water sample, results demonstrated that a low ferric dose of 5 mg/L was effective at removing turbidity to below 1.0 NTU, when 30 min tapered flocculation was used. Since polymer addition is unnecessary given these results, a jar test was conducted to investigate the effect of reducing the tapered flocculation time (therefore reducing the size of the full-scale flocculation basins), and determine if polymer addition would be necessary to maintain treated water quality. As shown in Figure 15, reducing the mixing to 5 minutes per stage (15 minute tapered floc) resulted in poor treated water quality conditions as the settled turbidity was 1.7 NTU, compared to 0.6 NTU when 10 min stages were used. However, when 3-mg/L polymer was added with the 5 mg/L ferric chloride dose, floc formation and settleability improved and resulted in a treated water turbidity of < 1.0 NTU. Similarly, Figure 16 shows the resulting filtered and unfiltered UVT values for the same samples. *The main conclusion of this subset of experiments is that the use of polymer may be required for the ambient lake sample at the same 5-mg/L ferric chloride dose, if shortened flocculation stages is utilized. Otherwise, polymer addition provides no additional benefit when full 10 minute stages for 30 minute tapered flocculation is used.*

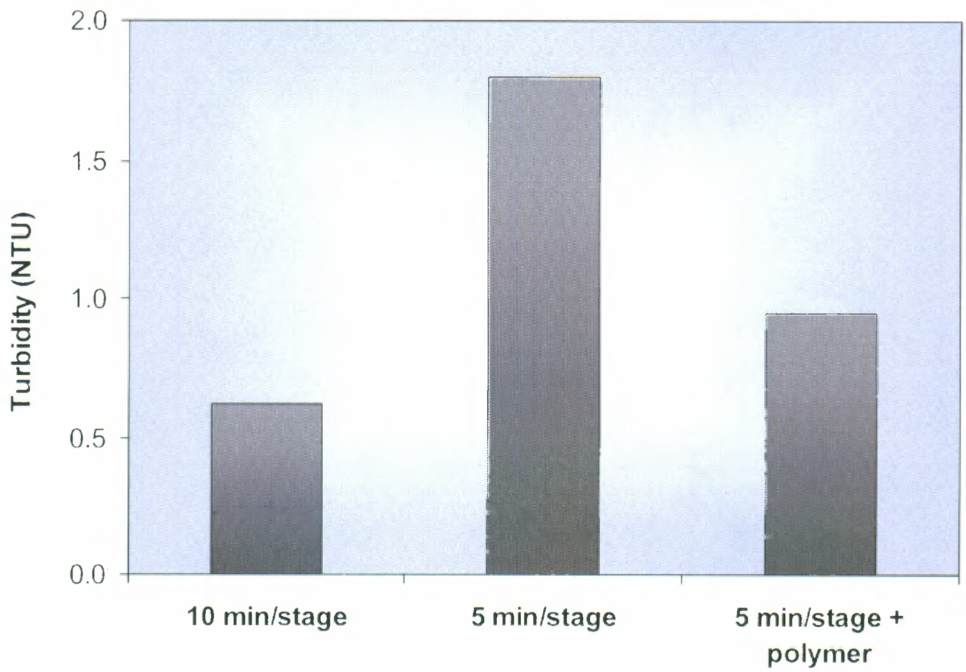

Figure 15
Impact of Mixing Time and Polymer on Turbidity Removal - Ambient Lake Sample

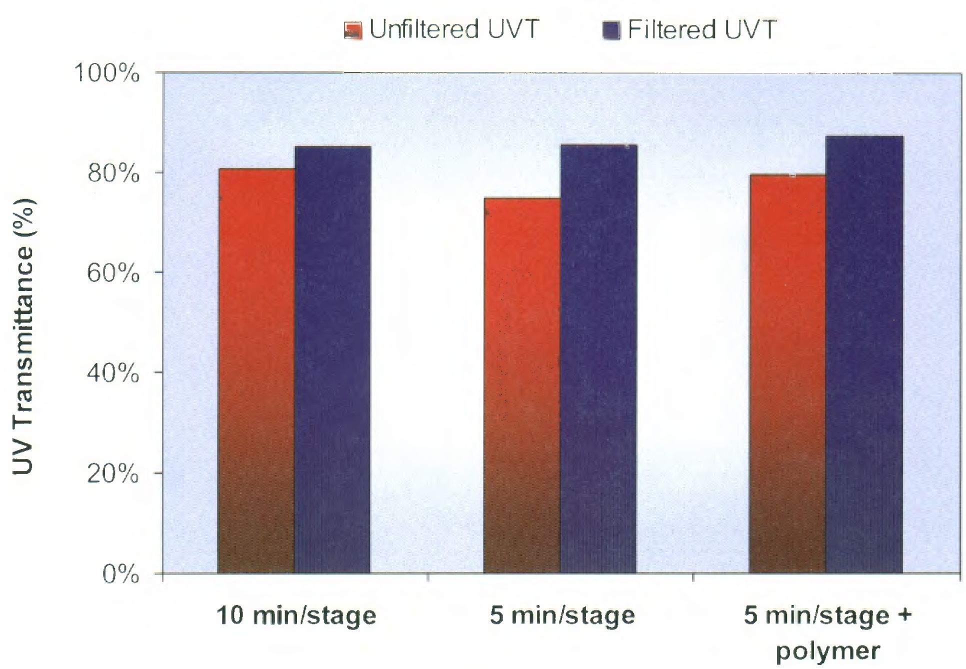

Figure 16
Impact of Mixing Time and Polymer Addition on UVT - Ambient Lake Sample

Turbid Lake Sample. Based on the enhanced coagulation results, it is difficult to determine the optimal dose due to the inability of the ferric chloride, alone, to produce similar water quality as experienced during the ambient lake water tests. Therefore, a series jar tests were conducted to further optimize the treatment process by simultaneously investigating a spread of coagulant doses, the impact of polymer addition, and effect on required settling time. Figure 17 shows results from the optimization jar test in which three ferric chloride doses (5, 15, 25 mg/L) were used with the addition of 3-mg/L cationic polymer. Results are also presented for samples collected at 30 and 60 minute settling times. As a point of reference, the dose versus treated turbidity after 30 minutes of settling is presented as green circle points. It can be seen in this figure, that holding the mixing condition constant, the settled water turbidities were much improved when polymer was used as a floc aid. Even at a low coagulant dose of 5 mg/L, finished water turbidities below 1.0 NTU were achieved. Additionally, an additional 30 minutes of settling (60 minutes total) provide a marginal improvement in the finished turbidities, confirming the 30 minutes of settling time determined in the prior experiments. Since it was determined that 30 minutes of settling time is the minimum required HRT, 60 minutes of extra detention time would provide a good safety factor for achieve treated water quality goals. Finally, in Figure 18, unfiltered UVT values are presented for the same dose/polymer conditions. When polymer was used, unfiltered UVT values increased on average by 7% (UVT = 77-79%).

An additional jar test was also conducted to determine if, similar to ambient lake water, a 15-minute tapered flocculation could be used with the addition of polymer, and still achieve finished water turbidities less than 1.0 NTU. Figure 19 presents results of this experiment, which demonstrate that, treated water turbidities are slightly improved when polymer is used and 5-minute tapered floc stages are used. However, 60 minutes of settling would be required to approach a settled water turbidity of 1.0 NTU. In order to achieve less than 1.0 NTU, a large amount of coagulant with polymer would be required.

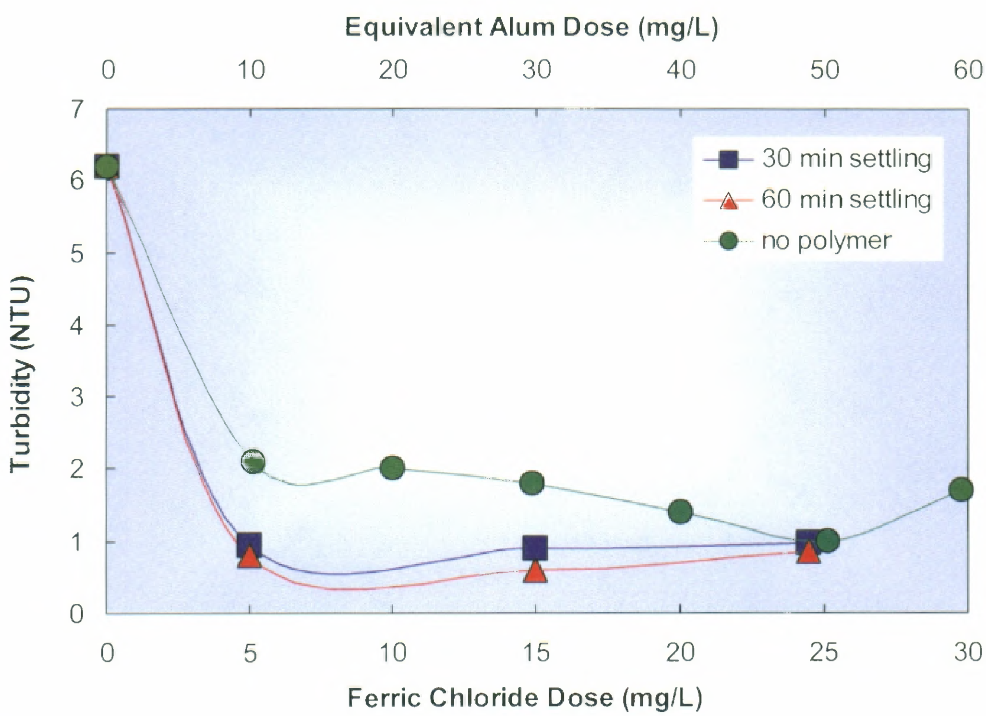

Figure 17
Effect of Polymer and Settling Time on Turbidity Removal - Turbid Lake Sample

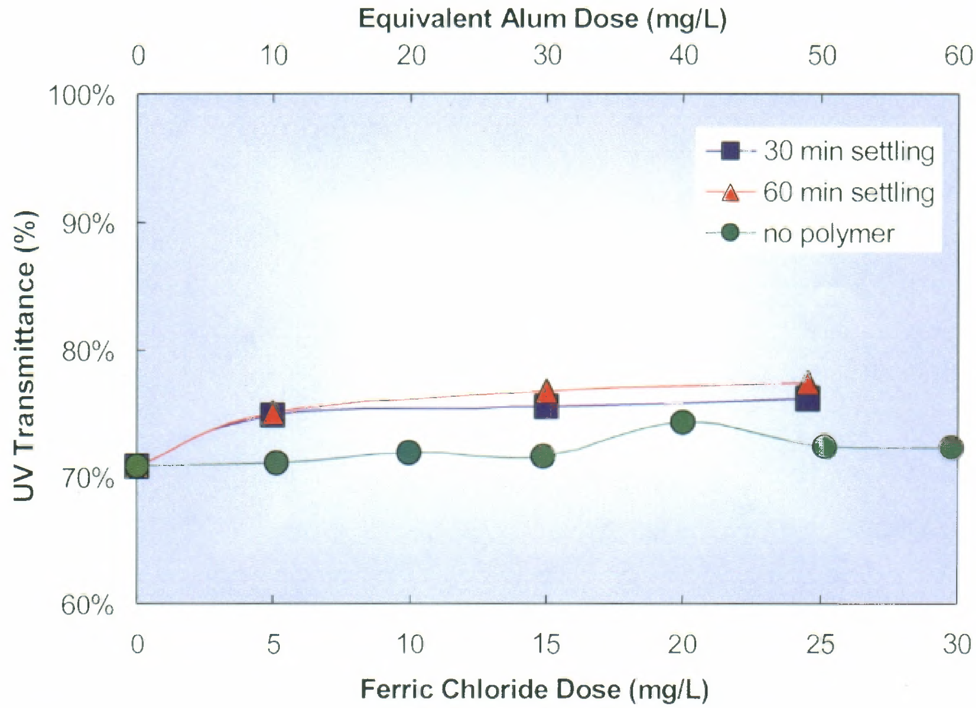

Figure 18
Effect of Polymer and Settling Time on UVT - Turbid Lake Sample

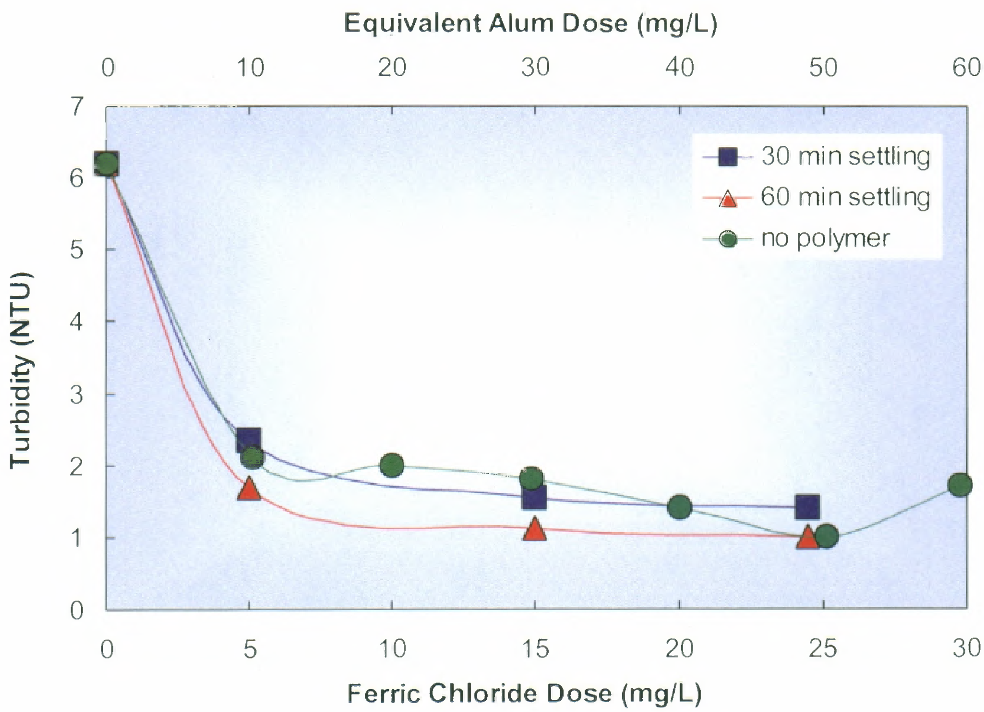

Figure 19
Effect of Polymer and Settling Time on Turbidity Removal with Decrease Flocculation Time- Turbid Lake Sample

Conclusions and Recommendations

These data indicate that the tested source waters can easily achieve pre-UV disinfection turbidities of <1.0 NTU and unfiltered UVT values of approximately 70-80 percent. It is important to note that the results presented in this technical memorandum are representative only of the raw water grab sample collected for purposes of this testing. Although two lake sample with different water qualities were collected, it is recommended that pilot-scale testing be performed to confirm coagulant doses and mixing condition required to achieve water quality goals under real-world conditions (temperature, turbidity spikes, high organic content episodes, seasonal effects, etc.). At a minimum, routine (i.e., quarterly) bench-scale testing should be conducted to maintain and confirm full-scale operational conditions.

Based on the results of this bench-scale testing the following brief conclusions can be made for the two batches of raw water received:

- An initial jar test verified that the ferric chloride performed better than alum, at the same metal mole applied dose. Turbidity removal was enhanced when ferric chloride was applied compared to alum, when less than a 30-mg/L equivalent alum dose was used. After 30-mg/L equivalent alum, turbidity removals were similar, most likely due to an overdose of coagulant for the specific water quality conditions.

- A minimum of 30 minutes settling time is required to obtain the best settled water quality. Settleability curves were generated for a variety of ferric chloride doses and settled time between 10 and 60 minutes. The majority of turbidity removal occurs after 20 minutes of settling. Therefore, 30 minute of settling would be required to allow floc aggregates sufficient time to settle. 60 minutes of detention time would ensure maximum settleability of floc particles and provide finished water turbidities of less than 1.0 NTU.

- Using tapered flocculation improves the settled water quality compared to single stage mixing. Results demonstrated that providing 30 minute three-stage tapered flocculation improves settled water turbidities by more than 50 percent, when the same coagulant dose is applied. The tapered flocculation used in these experiments represented mixing energy G-values of 40, 18, and <5 sec^{-1} for per 10 minute stage.

- TOC removal is minimal for the sample lake water, unless very high dose of coagulant is used. Bench-scale testing indicated that the source water is not amenable to enhanced coagulation. TOC reduction was minimal as the point of diminishing returns is achieved after only 10-mg/L equivalent alum dose, representing less than 6% reduction in TOC. Stage 1 D/DBP enhanced coagulation requirement necessitate a 25% reduction in TOC. However, several of the alternative compliance criteria are applicable to this source water.

- Polymer addition can effectively be used as a floc aid to improved settled water turbidity and UVT. Test results with ambient lake water samples indicated that settled water quality is not further improved when polymer is added with coagulant. However, experiments performed with the turbid lake sample (high turbidity, alkalinity, TOC, etc.) demonstrated that the use of polymer improved settled water turbidities by up to 50% - settled water turbidities < 1.0 NTU. It is important to note, however, that a single polymer dose (3 mg/L) was used in these experiments. Further bench- or pilot-scale testing would be required to optimize the polymer dose and/or type for achieving water quality goals.

- The required ferric chloride dose to achieve optimal water quality is as low as 5 mg/L. Based on used of optimal mixing conditions (tapered flocculation), settling time (30-60 minutes), and polymer addition (cationic polymer), settled water turbidities of less than 1.0 NTU and up to 83% UVT can be achieved. Use of a low dose of ferric coagulant is favorable is sludge production will be minimized.