

Removal of Dissolved Organic Carbon and Organic

Halide Precursors by Enhanced Coagulation

by

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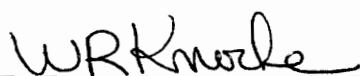
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(ABSTRACT)

Raw water samples from nine utilities were received, and water-quality analyses, bench-scale water treatment, and chlorination were performed to determine the effectiveness of enhanced coagulation at removal of dissolved organic carbon (DOC) and organic halide precursors. Bench-scale treatment included: 1) baseline treatment, defined as the coagulant dose and pH at which the specific utility's water treatment plant was operating on the day the samples were collected, and 2) enhanced treatment, which was determined on the basis of bench-scale studies. Enhanced treatment is defined in the proposed Disinfectant/Disinfection By-Products (D/DBP) Rule as the coagulant dose at which a 10 mg/L increase in coagulant dose does not produce greater than a 0.3 mg/L decrease in dissolved organic carbon (DOC) or total organic carbon (TOC) concentration over the previous dose (Federal Register 1994). The treated samples were then chlorinated and analyzed for disinfection by-products (DBPs), including trihalomethanes (THMs) and non-purgeable dissolved organic halides (NPDOX).

Specific objectives included: 1) an evaluation of the effectiveness of enhanced coagulation for TOC reduction, 2) determination of the effectiveness of surrogate parameters; such as raw water DOC and specific ultraviolet absorbance (SUVA); for

predicting TOC removal by enhanced coagulation, and 3) determination of the relationship between DOC and NPDOX concentration in raw and treated waters.

For all of the utilities, enhanced coagulation was effective at meeting the proposed TOC removal requirements contained in the D/DBP Rule, which range from 20 percent to 50 percent removal based on the alkalinity and TOC of the raw water. Raw water SUVA was the best indicator of the expected TOC removal by enhanced coagulation, with raw water SUVA values > 3.0 L/mg-m typically indicating greater TOC removal. Organic content was a good indicator of DBP formation. The average non-purgeable dissolved organic halogen formation potential (NPDOXFP) yields, based on DOC, were $155 \mu\text{g as Cl}^-/\text{mg DOC}$ for raw water samples and ranged from 110-138 $\mu\text{g as Cl}^-/\text{mg DOC}$ for treated water samples.

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Chapter I

INTRODUCTION

The United States Environmental Protection Agency (USEPA) has proposed new regulations requiring many water treatment facilities to demonstrate the use of enhanced coagulation prior to continuous disinfection for disinfectant contact time (CT) credit (Federal Register 1994). Enhanced coagulation describes coagulation designed for "enhanced" removal of organic matter using conventional coagulation processes (i.e. coagulation, flocculation, and filtration) (Federal Register 1994). The proposed regulations require utilities to remove a prescribed percentage of their influent total organic carbon (TOC), that is dependent on the individual raw water alkalinity and total organic carbon concentrations. The removal of TOC from the water is intended to decrease the formation potential of disinfection by-products (DBPs) such as trihalomethanes (THMs), which are currently regulated under the Safe Drinking Water Act, and total organic halides (TOX), which may be regulated in the future. The purpose of this study was to determine the effectiveness of enhanced coagulation in removing TOC and how it related to the reduction of THMs and TOX.

Chlorine has been used as a disinfectant for water supply systems for many years. Rook (1974) and Bellar et al. (1974) discovered that chlorination of water containing natural organic substances such as humic material can form THMs, which have been shown to be carcinogenic, as well as other DBPs. Other specific DBPs include haloacetic acids, haloacetonitriles, and haloketones (Bellar et al. 1974; Rook 1974; Symons et al. 1975; Stevens et al. 1976; Rook 1977; Trehy et al. 1986). Several strategies for reducing DBP formation during water treatment have been investigated, including replacement of chlorine with other oxidants such as ozone or chlorine dioxide, removal of organic matter prior to chlorination (focus of this study), or removal of DBPs after formation.

The specific objectives of this study were to:

1. Evaluate the reproducibility of dissolved organic carbon (DOC) data obtained in bench-scale jar testing to determine if anticipated regulations defining enhanced coagulation are feasible. Also, compare the results of bench-scale jar testing to pilot-scale and full-scale facilities in terms of removal of TOC and reduction of ultraviolet absorbance at 254 nm (UV254).
2. Evaluate TOC removal and UV254 reduction by enhanced coagulation and compare the TOC results to the proposed regulations concerning TOC removal.
3. Evaluate the effect of optimization of pH for removal of TOC on the amount of dissolved residual coagulant remaining in treated waters. Also, evaluate the effects of temperature on the optimum pH for organics removal, TOC removal, and residual coagulant concentrations.
4. Evaluate apparent molecular weight distribution (AMWD) of DOC for raw and treated waters to determine what, if any, specific fraction of DOC is typically removed.
5. Evaluate raw water DOC and specific UV absorbance (SUVA), defined as the ratio of UV254/DOC, as indicators of TOC removal by enhanced coagulation. Describe the relationship between DOC and THM or non-purgeable dissolved organic halides (NPDOX) in raw and treated waters.

6. Describe the relationship between THM and both NPDox and total dissolved organic halides (DOX) in both raw and treated waters.
7. Compare the effectiveness of aluminum and iron salts as coagulants for removal of DOC.

Chapter II

LITERATURE REVIEW

This chapter contains a review of previous research pertaining to organics removal by coagulation processes and also formation of disinfection by-products (DBPs), specifically trihalomethanes (THMs) and total organic halides (TOX), following chlorination during drinking water treatment. First, a historical review of the regulations governing chlorinated disinfection by-products and organics removal will be presented. Included is a discussion of the Safe Drinking Water Act (SDWA), the Information Collection Rule (ICR), and the Disinfectant/Disinfection By-Products (D/DBP) Rule.

Next, coagulation of organics will be discussed, including removal of total organic carbon, reduction of ultraviolet light absorbance, apparent molecular weight distribution of organics in raw and treated waters, temperature effects on organics removal, and residual coagulant in treated waters. Coagulation utilizing both aluminum and iron salts will be discussed.

The final section of this chapter will discuss DBP formation, including THMs and TOX. Water quality factors and treatment conditions that affect removal of DBP precursors and formation of DBPs will be discussed. Also, parameters that are good indicators of DBP formation will be discussed, as will the relationship between THM and TOX formation.

A glossary of the abbreviations used in this chapter is contained in Appendix P.

REGULATORY FRAMEWORK

In 1974, THMs were discovered in chlorinated water containing dissolved organic matter (DOM). The THMs include chloroform (CHCl_3), bromodichloromethane (CHCl_2Br), dibromochloromethane (CHClBr_2), and

bromoform (CHBr_3) (Rook 1974). Other researchers have also shown the presence following chlorination of natural water of other chlorinated by-products including haloacetic acids (HAAs), haloacetonitriles (HANs), and haloketones (HKs) (Bellar et al. 1974; Rook 1974; Symons et al. 1975; Stevens et al. 1976; Rook 1977; Trehy et al. 1986).

The National Organics Reconnaissance Survey and the National Organics Monitoring Survey were conducted in the 1970's to determine the existence and concentration of these chlorinated organics in water supplies. These surveys indicated the existence of chlorinated organics, in particular THMs, in most finished waters (Symons et al. 1975; Cortruvo and Wu 1978).

The health effects of THMs were investigated by the National Cancer Institute and the National Academy of Sciences in the late 1970's. The results from toxicity tests on laboratory mice and rats showed that chloroform, normally the most prevalent THM seen in drinking water, is a human carcinogen (Cortruvo 1981). The three brominated haloforms (bromodichloromethane, dibromochloromethane, and bromoform) are suspected carcinogens (Schnoor et al. 1979). Based on this information, the United States Environmental Protection Agency (USEPA), as part of the Safe Drinking Water Act (SDWA) Amendments of 1979, established a maximum contaminant level (MCL) of 0.10 milligram per liter (mg/L) for total trihalomethanes (TTHMs), which is the sum of the four primary trihalomethanes. Utilities must collect quarterly THM samples from representative points in the distribution system. The MCL of 0.10 mg/L is based on the four quarter running average of these samples (Cortruvo and Wu 1978).

In the early 1990's the Disinfectant/Disinfection By-Products (D/DBP) Rule and the Information Collection Rule (ICR) were proposed. The D/DBP Rule is to be implemented in two stages, and will set limits on various disinfection by-products, as well as set limits on various disinfectants (e.g., chlorine, chloramines, and chlorine dioxide). Included in the proposed D/DBP Rule Stage 1 regulations are MCLs for

TTHMs, total haloacetic acids (THAAs), bromate (BrO_3^-), and chlorite (ClO_2^-), as well as maximum residual disinfectant levels (MRDLs) for chlorine, chloramines, and chlorine dioxide (ClO_2). Table 2.1 includes the proposed Stage 1 MCLs for disinfection by-products and MRDLs for certain disinfectants (Federal Register 1994).

In addition, the proposed D/DBP Rule requires surface water systems or groundwater systems under the influence of surface water (classified as Subpart H systems) using conventional filtration treatment to demonstrate the use of enhanced coagulation. "Enhanced coagulation is defined in the proposed D/DBP Rule as the addition of excess coagulant for improved removal of DBP precursors by conventional filtration treatment." (Crozes *et al.* 1995). The proposed rule requires a specified level of precursor removal, with TOC serving as a surrogate measure of DBP precursors. The TOC removal requirement must be accomplished prior to continuous disinfection for CT credit. (Crozes *et al.* 1995; Shorney *et al.* 1996) The required TOC removals by enhanced coagulation for Subpart H systems for Stage 1 of the D/DBP Rule are shown in Table 2.2.

The information contained in Table 2.2 is commonly referred to as the "3 x 3 matrix." The first step for utilities is to meet the requirements of the 3 x 3 matrix. If utilities can not meet the required TOC removals in step 1, the utility can use a step 2 procedure to determine enhanced coagulation. Step 2 requires a coagulant dose and a coagulation pH where TOC removal is less than 0.3 mg/L per 10 mg/L coagulant. Step 2 also requires a coagulation pH less than or equal to a maximum value determined by raw water alkalinity (Crozes *et al.* 1995; Shorney *et al.* 1996).

The ICR will be used to collect data on organics, disinfectants, disinfection by-products, and microorganisms for use in establishing the Stage 2 D/DBP regulations. Monitoring requirements under the ICR for DBPs apply to groundwater systems serving $\geq 50,000$ people (TOC monitoring only), and Subpart H systems serving $\geq 100,000$ people (TOC and DBP monitoring). Microbial monitoring under the ICR applies to Subpart H systems serving $\geq 10,000$ people. The information collected will

Table 2.1
D/DBP Rule
Proposed Stage 1 and Anticipated Stage 2 Requirements

Constituent	Stage 1 MCL or MRDL (mg/L)	Stage 2 MCL or MRDL (mg/L)
TTHMs*	0.080	0.040
THAAs†	0.060	0.030
BrO ₃ ⁻	0.010	0.010
ClO ₂ ⁻	1.0	1.0
Chlorine	4.0	4.0
Chloramines	4.0	4.0
ClO ₂	0.080	0.080

Source: Adapted from Federal Register 1994.

* Sum of four trihalomethanes (chloroform, bromodichloromethane, dibromochloromethane, and bromoform)

† Sum of five haloacetic acids (mono-, di-, and trichloroacetic acids, and mono- and dibromoacetic acids)

Table 2.2
D/DBP Rule
Revised Stage 1 Required Removal of TOC
by Enhanced Coagulation for Subpart H Systems

TOC (mg/L)	Alkalinity (mg/L as CaCO ₃)		
	0-60	>60-120	>120
0-2	NO ACTION	NO ACTION	NO ACTION
>2-4	40%	30%	20%
>4-8	45%	35%	25%
>8	50%	40%	30%

Source: Federal Register 1994.

aid in balancing the requirements of microbial control with the control of disinfectants/disinfection by-products (Federal Register 1994). The anticipated D/DBP Rule Stage 2 requirements are included in Table 2.1.

The final ICR was signed on May 1, 1996 and included in the Federal Register on May 14, 1996. Monitoring for the ICR is expected to begin in summer 1997 (Pontius 1996; Robertson 1997).

For additional information, Pontius has written several good summary papers on the proposed regulations (Pontius 1994; Pontius 1995; Pontius 1996).

COAGULATION OF ORGANICS

Natural organic matter (NOM) is found in surface water supplies and consists largely of humic substances which are derived from the soil or are produced in the water. Humic substances have typically been divided into three fractions based on the solubilities of the fractions. These fractions are humic acids, fulvic acids, and humin. Humic acids are soluble in base and insoluble in acid. Fulvic acids are soluble in base and acid, while humin is insoluble in both base and acid (Edzwald 1987). Under the pH conditions seen in most natural surface waters, humic materials are negatively charged due to functional groups such as carboxylic (COOH) and phenolic (OH), thus allowing these organics to be removed by positively charged metal hydrolysis species during the coagulation process (Edwards and Amirtharajah 1985).

The removal of aquatic humics is important in water treatment because humics can react with chlorine and other disinfectants to form DBPs, can transport other organic and inorganic pollutants, can cause biological regrowth in distribution systems, can cause taste and odor problems, and/or can cause color in treated water (Collins et al. 1985; Owen et al. 1995). The main factors which affect removal of organic material by coagulation are coagulation pH, coagulant dose, and molecular size and concentration of organics (Qasim et al. 1992).

TOC Removal and UV254 Reduction

Removal of TOC and reduction of ultraviolet light (UV) absorbance by coagulation with metal salts occurs by the interaction of the metal hydrolysis species with NOM. The exact metal hydrolysis speciation varies depending on water quality characteristics; however, several monomers are typically present along with some polymers. Typical hydrolysis equations for aluminum and iron are shown in Table 2.3. Figures 2.1 and 2.2 contain typical coagulation diagrams for aluminum and iron coagulation (Johnson and Amirtharajah 1983; Edwards and Amirtharajah 1985).

Dempsey *et al.* (1984) proposed the following sequence of speciation following simultaneous addition of aluminum salts and base to a water containing fulvic acid:

1. Formation of monomers occurs rapidly.
2. Competing reactions include:
 - Fulvic acid-aluminum monomer complexes
 - Al polymer formation
 - Al solids formation ($\text{Al}(\text{OH})_3(\text{s})$)

As pH is increased, fulvic acid-aluminum monomer complexes and Al polymer formation occur more rapidly. At higher alum doses $\text{Al}(\text{OH})_3(\text{s})$ forms more rapidly.

Randtke (1988) distinguished between the following three mechanisms of organics removal by coagulation:

1. Colloid destabilization
2. Precipitation
3. Coprecipitation

Table 2.3
Iron and Aluminum Equilibrium Equations

Reaction	log K(25°C)
Iron	
1. $\text{Fe}^{3+} + \text{H}_2\text{O} = \text{FeOH}^{2+} + \text{H}^+$	-2.2
2. $\text{FeOH}^{2+} + \text{H}_2\text{O} = \text{Fe}(\text{OH})_2^+ + \text{H}^+$	-3.5
3. $\text{Fe}(\text{OH})_2^+ + \text{H}_2\text{O} = \text{Fe}(\text{OH})_3 + \text{H}^+$	-6
4. $\text{Fe}(\text{OH})_3 + \text{H}_2\text{O} = \text{Fe}(\text{OH})_4^- + \text{H}^+$	-10
5. $2\text{Fe}^{3+} + 2\text{H}_2\text{O} = \text{Fe}_2(\text{OH})_2^{4+} + 2\text{H}^+$	-2.9
6. $3\text{Fe}^{3+} + 4\text{H}_2\text{O} = \text{Fe}_3(\text{OH})_4^{5+} + 4\text{H}^+$	-6.3
7. $\text{Fe}(\text{OH})_3 (\text{am}) = \text{Fe}^{3+} + 3\text{OH}^-$	-38.7
Aluminum	
1. $\text{Al}^{3+} + \text{H}_2\text{O} = \text{AlOH}^{2+} + \text{H}^+$	-4.97
2. $\text{AlOH}^{2+} + \text{H}_2\text{O} = \text{Al}(\text{OH})_2^+ + \text{H}^+$	-4.3
3. $\text{Al}(\text{OH})_2^+ + \text{H}_2\text{O} = \text{Al}(\text{OH})_3 + \text{H}^+$	-5.7
4. $\text{Al}(\text{OH})_3 + \text{H}_2\text{O} = \text{Al}(\text{OH})_4^- + \text{H}^+$	-8.0
5. $2\text{Al}^{3+} + 2\text{H}_2\text{O} = \text{Al}_2(\text{OH})_2^{4+} + 2\text{H}^+$	-7.7
6. $3\text{Al}^{3+} + 4\text{H}_2\text{O} = \text{Al}_3(\text{OH})_4^{5+} + 4\text{H}^+$	-13.94
7. $13\text{Al}^{3+} + 28\text{H}_2\text{O} = \text{Al}_{13}\text{O}_4(\text{OH})_{24}^{7+} + 32\text{H}^+$	-98.73
8. $\text{Al}(\text{OH})_3 (\text{am}) = \text{Al}^{3+} + 3\text{OH}^-$	-31.5

Source: Pontius 1990.

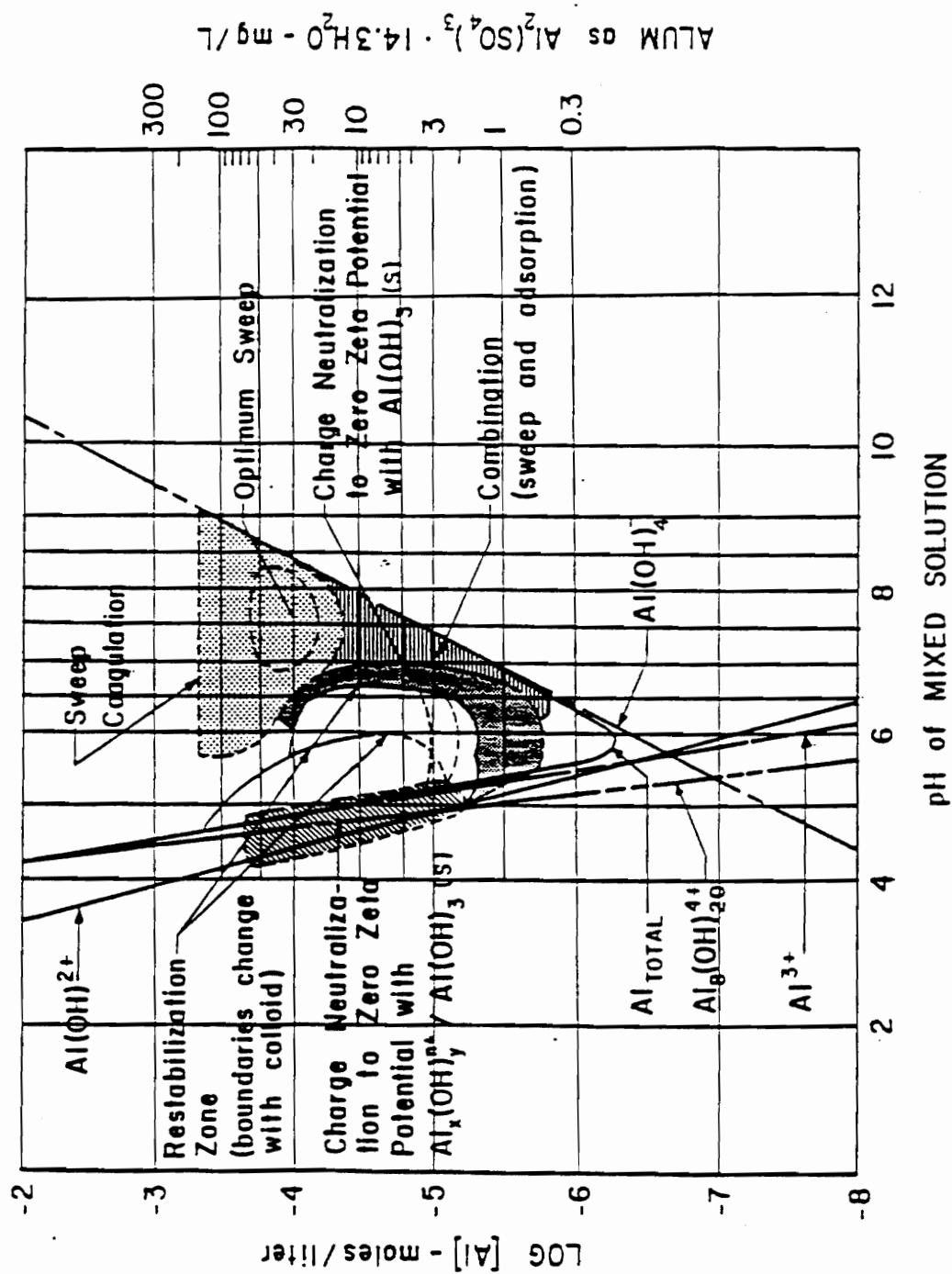


Figure 2.1. Alum coagulation diagram (Edwards and Amirtharajah 1985)

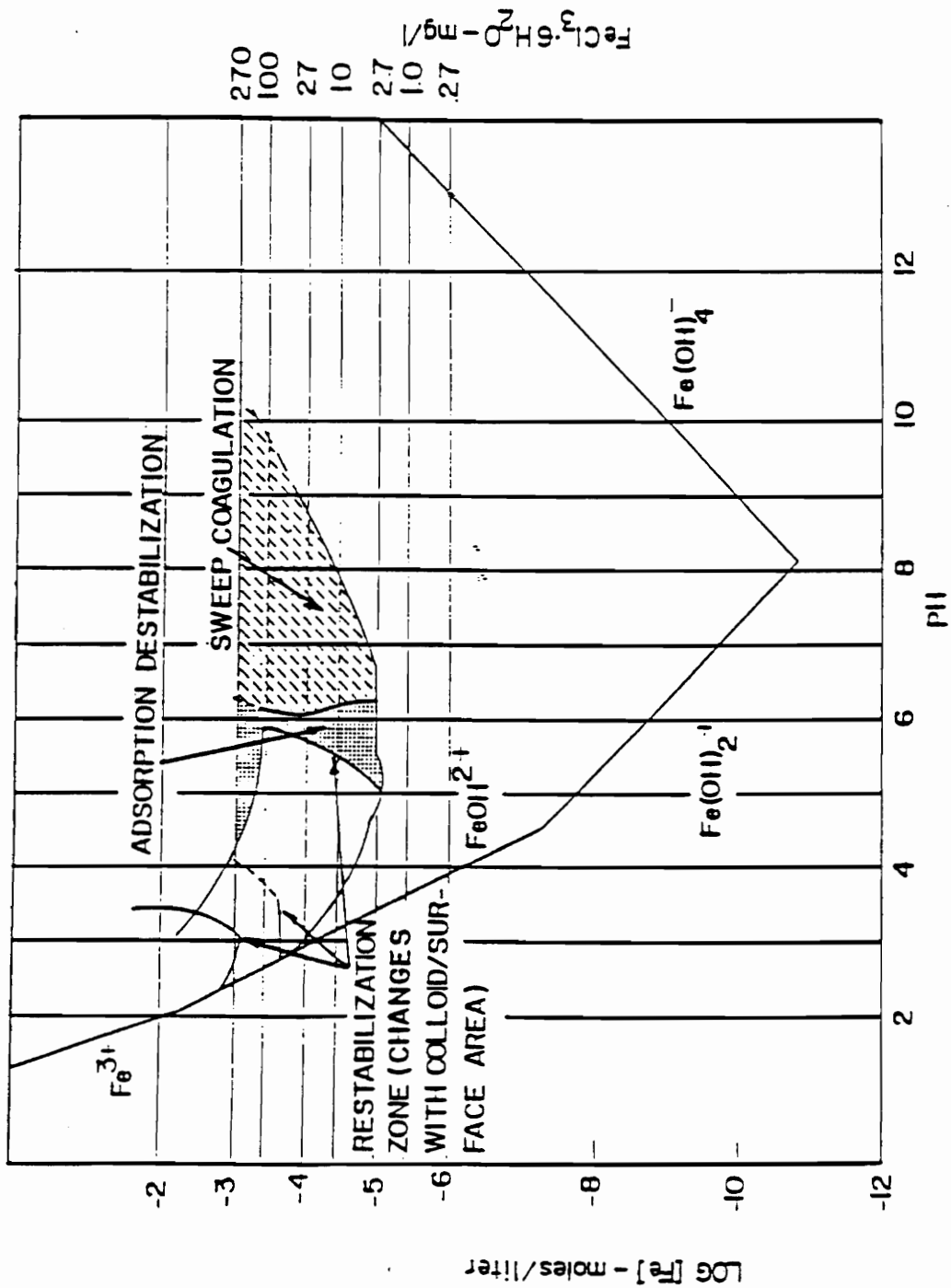


Figure 2.2. Iron coagulation diagram (Johnson and Amirtharajah 1983).

Colloid destabilization can further be divided into electrical double layer compression, adsorption/charge neutralization, adsorption/bridging, and sweep floc. Colloid destabilization involves removal of particulate NOM only.

Precipitation and coprecipitation are mechanisms for removal of dissolved organic matter (DOM). Precipitation was defined by Randtke (1988) as exceeding the solubility product (K_{sp}) for an aluminum-fulvate species. Coprecipitation was defined as the contamination of a precipitate by a species that is otherwise soluble. Coprecipitation is most likely the removal mechanism for DOM, and involves adsorption onto metal hydroxides. These metal hydroxides are typically amorphous with a large surface area which makes them conducive to adsorbance of DOM (Randtke 1988).

The optimum pH for organics removal typically ranges from 5-6 for aluminum salts and from 4-5 for iron salts (Hubel and Edzwald 1987 quoting Hall and Packham 1965; Vik *et al.* 1985; Hubel and Edzwald 1987). Hubel and Edzwald (1987) performed coagulation studies on 5 mg/L synthetic humic acid at an alum dose ranging from 3 mg/L to 7.5 mg/L and a solution pH of 5.5 and determined that the formation of aluminum-fulvates was the removal mechanism. At higher alum doses and at a pH of 5-6, the removal mechanism is most likely a combination of aluminum-fulvate formation and adsorption onto $Al(OH)_3$ (s). Edwards and Amirtharajah (1985) investigated the coagulation of color in natural waters and found that at pH values less than 5.75, the removal mechanism is either charge neutralization/precipitation for particulate NOM or formation of aluminum fulvates for dissolved NOM. At pH values greater than 5.75, the removal mechanism appears to be adsorption onto $Al(OH)_3$ (s).

Randtke (1988) summarized the influence of pH on DOM removal by metal ion coagulation as a competitive process, including the competition between hydrogen (H^+) ions and metal hydrolysis species for organic ligands and competition between hydroxyl (OH^-) ions and organic ions for metal hydrolysis species. At low pH values

when considering precipitation of metal fulvates, sufficient coagulant must be added to dislodge and outcompete the H^+ ions for the organic ligand sites. If the solution pH is too low, H^+ ions will outcompete metal hydrolysis species and aluminum-fulvates will not form. A similar competition occurs at high pH between OH^- ions and organic ligands for metal species. Also, as pH increases, metal species become less positively charged and organics less negatively charged, making adsorption efficiency decrease.

UV absorbance at a wavelength of 254 nanometers (nm) (UV254) has been investigated as a surrogate parameter for TOC due to its ease of measurement. UV254 reduction and TOC removal are typically similar but not identical, since not all of the TOC absorbs light at 254 nm (Van Benschoten and Edzwald 1990b). The ratio of UV254/TOC is commonly referred to as specific ultraviolet absorbance (SUVA). Specific UV absorbance values vary between different raw water sources. A SUVA value of 4-5 L/mg-m is typical for naturally occurring organics which are largely humic in nature (Edzwald *et al.* 1985). If a greater percentage of humic material is present, then the SUVA value will increase. Fulvic acid has a SUVA value of 7.1.

Specific UV absorbance values have been shown to be a good indicator of the expected removal of DOC from natural waters. Generally, if SUVA values are a minimum of 4-5 L/mg-m, the DOC is largely aquatic humic material, and DOC removals of 50 percent to 70 percent can be expected. For SUVA values less than 3 L/mg-m, the DOC is composed largely of non-humics, and DOC removals of 20 percent to 50 percent can be expected (Edzwald *et al.* 1985; Edzwald 1993).

Typically, coagulation will cause a greater reduction of UV254 than TOC, causing SUVA values to decrease after treatment (Edzwald *et al.* 1985; Edzwald 1993). Previous research has also shown the reduction of THMFP following coagulation to be greater than TOC reduction, but less than UV254 reduction (Reckhow and Singer 1990; Edzwald 1993; Owen *et al.* 1995). In addition, Reckhow and Singer (1990) found TOXFP reduction following coagulation to be greater than THMFP reduction, but less than UV254 reduction.

Both aluminum and iron salts, as well as polymers, have been investigated for removal of organics by coagulation. There is not a consensus on which metal coagulant is more effective. Aluminum salts have been shown to be more effective in some cases, while iron salts have been more effective in others (Randtke 1988). When used as primary coagulants, polymers are not as effective as aluminum or iron salts for removal of DOM. However, the use of polymers as a coagulant aid can improve TOC removal by improving liquid-solid separation (Jacangelo et al. 1995).

Sinsabaugh et al. (1986b) investigated the optimum coagulant dose required for TOC removal using iron salts. The optimum iron dose occurred at a molar ratio of Fe(III) to TOC of 0.5, which corresponded to a 50 mg/L ferric sulfate dose for a TOC concentration of 6.5 mg/L. The corresponding alum dose for a molar ratio of Al(III) to TOC of 0.5 is 85 mg/L.

Additional information on organics removal can be found in a number of sources (Edzwald 1987; Hubel and Edzwald 1987; Randtke 1988; Jacangelo et al. 1995).

Apparent Molecular Weight Distribution

The removal of organic substances during coagulation is related to the apparent molecular weight (AMW) of the organic substances. Fulvic acids typically have molecular weights ranging from 200 amu to 10,000 amu, while humic acids have molecular weights >10,000 amu (Edzwald 1987). Sinsabaugh et al. (1986b) studied Harwood's Mill Reservoir water in Newport News, Virginia and found that 75 percent of the TOC had an AMW less than 10,000 amu at a mean TOC concentration of 4 mg/L. At a mean TOC concentration of 6.3 mg/L, 82 percent of the TOC contained in Harwood's Mill Reservoir had a molecular weight less than 10,000 amu, with 20 percent less than 0.5 amu (Sinsabaugh et al. 1986a). El-Rehaili and Weber (1987) found Huron River water to contain organics in the 1,000-6,000 amu range.

Collins et al. (1986) studied Colorado River Water and found approximately 45 percent of organics had a molecular weight less than 1,000 amu, with 24 percent in the 500-1,000 amu range.

Typically, higher molecular weight NOM is more easily removed by coagulation than lower molecular weight material. Amy et al. (1992) found that alum preferentially removed higher molecular weight material, and removed only small amounts of low molecular weight (<500 amu) material. Collins et al. (1986) studied four different water supplies, and found that neither conventional treatment nor direct filtration removed significant portions of NOM less than 500 amu, and in only one case was a substantial portion of the organics in the 500-1,000 amu removed. Lower molecular weight material may be more difficult to remove due to properties such as functional group densities, or the small molecular weight material may be nonhumic in nature (Collins et al. 1985).

Ultrafiltration or gel chromatography are typically used to measure the AMW of NOM. Ultrafiltration was used in the current study; therefore, gel chromatography will not be discussed here. Ultrafiltration consists of filtration through small pore filters under pressure, and is actually a measure of molecular size rather than molecular weight, although the two parameters are obviously related. Ultrafiltration depends on molecular properties, and has the following inherent drawbacks (Aiken 1984):

1. Nominal molecular weight cutoff is size that will be 90 percent retained because pores are not of equal size.
2. During filtration, a concentration gradient can form near the filter surface causing subsequent breakthrough of organic material.
3. Organic matter can interact with other species in the water causing properties to change.
4. Organic matter can interact with the filter surface.

Despite these drawbacks, if ultrafiltration experiments are consistently performed, the results provide a relative comparison between different waters, or between waters before and after treatment (Amy *et al.* 1992).

The effect of AMW on disinfection by-product formation will be discussed in the Disinfection By-Products section of this chapter.

Temperature Effects

Lower temperatures typically do not significantly affect the removal of organic matter in conventional filtration treatment. However, colder temperatures can affect individual water treatment processes, in particular the sedimentation process, which is hindered by the increased viscosity of water at colder temperatures. The decreased sedimentation efficiency at lower temperatures may increase loading rates to filters, but generally will not adversely affect finished water quality (Pontius 1990).

Knocke *et al.* (1986) investigated the effects of low temperatures on the removal of THM precursors (measured as TOC) by coagulation, and found similar overall TOC removal results at 2°C versus 22°C. However, the removal of low molecular weight organics (<1,000 amu) was adversely affected by colder temperatures. Morris and Knocke (1984) investigated the removal of turbidity at low temperatures, and found that turbidity removal was less at 2°C than at 22°C. The results from these two studies suggest that low temperatures have a greater effect on the removal of particulate matter, and affect to a lesser degree the removal of DOM during coagulation processes (Knocke *et al.* 1986).

Low temperatures can affect the optimum pH for organics removal due to the change in the ion product of water from 10^{-14} at 25°C to $10^{-14.78}$ at 4°C. As a result, at a constant pH, the concentration, or activity, of the hydroxyl ion will change greatly. Consequently, at lower temperatures the minimum solubility of aluminum will be

shifted to a higher pH value, with a subsequent shift of the optimum pH for organics removal to a higher pH value (Van Benschoten et al. 1994).

Residual Coagulant

The occurrence of high levels of residual coagulant in finished waters can lead to the formation of a precipitate in distribution systems, which can decrease pipe capacity and can increase turbidity (Letterman and Driscoll 1988 quoting Costello 1984). Also, ingestion of high levels of aluminum has been hypothesized to cause neurological disorders, including Alzheimers disease and presenile dementia (Letterman and Driscoll 1988 quoting Crapper et al. 1973; Davidson et al. 1982). In 1968, the American Water Works Association (AWWA) set a maximum contaminant level goal (MCLG) of 0.050 mg/L for total residual aluminum (Qureshi and Malmberg 1985 quoting AWWA 1968). However, as of 1997, a maximum contaminant level (MCL) for aluminum has not yet been enacted

A survey of 186 water utilities by Miller et al. (1984) indicated that 55 percent of the raw waters tested had an Al concentration greater than 0.05 mg/L, while 69 percent of finished surface waters which utilized alum and 29 percent of finished surface waters not utilizing alum had an Al concentration greater than 0.05 mg/L. Aluminum concentrations increased in 43 percent of the surface waters which had been treated with alum. A survey of 91 utilities by Letterman and Driscoll (1988) indicated that approximately 75 percent, 60 percent, and 30 percent of the utilities had treated water Al concentrations less than 0.2, 0.1, and 0.05 mg/L, respectively. The survey indicated that some utilities utilized pH adjustment to reduce aluminum residuals, with pH ranging from 5.1 to 7.0. The reduction of finished water turbidity seems to be the most effective way to decrease aluminum residuals in finished waters because the residual turbidity can contain a large amount of precipitated aluminum.

Van Benschoten et al. (1994) examined the effects of temperature and pH on residual aluminum in treated waters. At colder temperatures, the minimum solubility of aluminum shifts to a higher pH; therefore, a higher treatment pH at lower temperatures would tend to minimize residual aluminum. The effects of temperature and pH on residual aluminum can be defined in terms of pOH since pOH is directly related to residual aluminum and is mostly independent of temperature (Van Benschoten et al. 1994).

DISINFECTION BY-PRODUCTS

Disinfection by-products (DBPs) are formed when chlorine is added to waters containing NOM. Chlorine can react with NOM by oxidation of the organics or by substitution into the organic matrix. Generally, the oxidation reaction removes the organic compounds, while the substitution reaction produces DBPs (Johnson and Jensen 1986). Chlorination by-products can be broadly classified into volatile and non-volatile fractions. Trihalomethanes (THMs) constitute the largest portion of the volatile fraction, while haloacetic acids (HAAs) generally constitute the largest portion of the non-volatile fraction. The sum of all the chlorination by-products formed is termed total organic halides (TOX). The non-volatile portion of TOX is termed the non-purgeable TOX (NPTOX). As of the mid-1990's, only approximately 50 percent of the compounds which are part of TOX were accounted for (Pourmoghaddas and Stevens 1995).

Only the sum of the concentrations of the four trihalomethanes, as opposed to the concentrations of the individual species, has been regulated as of the mid-1990's. From a public health concern, control of individual species may be important also. Bromodichloromethane (CHCl_2Br) may be the most carcinogenic trihalomethane; therefore, control of that compound may be more important than control of the other THMs (Krasner et al. 1994). Source and concentration of organic halide precursors,

form and dose of chlorine, reaction time, pH, Br⁻ concentration, and temperature can affect the formation and speciation of DBPs (Fleishacker and Randtke 1983; Krasner *et al.* 1994; Najm *et al.* 1994).

The apparent molecular weight of organics in raw and treated waters can affect the TOX or THM yields per unit of TOC. Sinsabaugh *et al.* (1986a) reported higher TOX yields per unit of TOC for the molecular weight fraction between 1,000 daltons and 10,000 daltons than for the molecular weight fraction less than 1,000 daltons. Owen *et al.* (1995) studied seven source waters and found that relatively higher molecular weight organics are responsible for UV absorbance and relatively lower molecular weight organics are responsible for THMFP.

The concentrations of TOX and THM increase with reaction time. Non-purgeable TOX typically forms more rapidly than THMs; therefore, the ratio of NPTOX/THM will typically decrease over time (Fleishacker and Randtke 1983). Trihalomethanes and total organic halides respond differently to pH changes, with THMs increasing with increasing pH, and TOX decreasing with increasing pH (Johnson and Jensen 1986). This decrease in TOX with increase in pH may be due to decreased formation of HAAs at higher pH values (Pourmoghaddas and Stevens 1995).

Total organic halide and total trihalomethane concentrations are often reported in terms of formation potential (FP), which is a standardized test (chlorination at 25°C for 7 days, chlorine residual after 7 days of 2-5 mg/L). These tests are time-consuming and expensive; therefore, the correlation of TOX, NPTOX, and THM to other parameters such as TOC or UV254 is important. These relationships have been investigated by a number of authors. Fleishacker and Randtke (1983) reported a ratio of chloroform (CHCl₃)/TOX of 24 percent for a chlorination period of 100 hours and a NPTOX yield of peat fulvic acid based on TOC of 220 - 280 micrograms as Cl⁻ per milligram TOC (µg as Cl⁻/mg TOC). Reckhow and Singer (1984) found that the ratio of (CHCl₃)/TOX for humic and fulvic extracts from five surface waters was approximately 20 percent after a chlorination period of 72 hours (3 days), and that the

approximate average NPTOX yield with respect to TOC was 230 μg as Cl^-/mg TOC, with yields ranging from 138 μg as Cl^-/mg TOC to 333 μg as Cl^-/mg TOC.

Sinsabaugh et al. (1986a) found a TOXFP yield (chlorination period of 168 hours) based on TOC (TOXFP/TOC) of 281 μg as Cl^-/mg TOC and a THMFP yield based on TOC (THMFP/TOC) of 97 μg TTHMs/mg TOC for Harwood's Mill water (TOC = 6.37 mg/L) and a TOXFP yield of 404 μg as Cl^-/mg TOC and a THMFP yield of 126 μg TTHMs/mg TOC for Occoquan Reservoir water (TOC = 8.86 mg/L). Singer and Chang (1989) found an average THM/TOX ratio of 24 percent for the distribution systems of six utilities, and also reported the following linear regressions for raw waters from twelve full-scale treatment plants:

- $\text{THMFP } [\mu\text{g/L}] = 0.342 * \text{TOXFP } [\mu\text{g/L as Cl}^-] - 3.57$
- $\text{TOXFP } [\mu\text{g/L as Cl}^-] = 152 * \text{TOC } [\text{mg/L}] + 222$
- $\text{THMFP } [\mu\text{g/L}] = 54.0 * \text{TOC } [\text{mg/L}] + 46.6$

Reckhow and Singer (1990) reported average raw water TOXFP/TOC ratios (chlorination period of 72 hours) of 215 μg as Cl^-/mg TOC and average THMFP/TOC ratios of 52 μg TTHMs/mg TOC for seven utilities, and average THMFP/TOXFP ratios of 22.2 percent for 11 raw waters. Krasner et al. (1994) conducted formation potential tests at a chlorination pH of 8.2 for 7 days at 25°C on delta waters in California and reported a molar yield of TTHMs per unit of TOC of 0.75-1.2 percent. The molar yield increased with increasing UV:TOC ratio and also increased with increasing Br^- concentration.

The Uniform Condition (UFC) test was developed in the early 1990's as a counterpart to the FP test. The UFC test was standardized in 1996 at the following

conditions, which are more representative than the FP test of conditions present in full-scale distribution systems (Summers et al. 1996):

- Chlorination pH: 8.0 ± 0.2
- Temperature: $20.0 \pm 1.0^{\circ}\text{C}$
- Incubation time: 24 ± 1 hour
- Chlorine residual: 1.0 ± 0.4 mg/L as free chlorine after 24 hours

Summers et al. (1996) determined specific DBP-to-TOC mass concentration ratios under UFC conditions of $29.4 \mu\text{g}/\text{mg}$ TOC for TTHMs, $18.9 \mu\text{g}/\text{mg}$ TOC for HAA6 (six haloacetic acids including mono-, di-, and trichloroacetic acid, mono- and dibromoacetic acids, and bromochloroacetic acid) and $99.4 \mu\text{g}$ as Cl/mg TOC for DOX.

Chapter III

METHODS AND MATERIALS

In this chapter, the techniques used during bench-scale treatment of nine raw water sources to determine the effects of enhanced coagulation on removal of dissolved organic carbon and organic halide precursors will be presented. Details will also be given of the chlorination experiments performed on bench-scale treated samples, as well as on pilot-scale and full-scale treated samples. Data analysis procedures for all samples will also be presented.

A glossary of the abbreviations used in this chapter is contained in Appendix P.

EXPERIMENTAL OVERVIEW

Water samples from nine utilities which treat surface waters by either conventional filtration (eight utilities) or direct filtration (one utility) were transported to the Virginia Tech Environmental Engineering Laboratory for water quality analyses, bench-scale water treatment, and chlorination to determine the effects of enhanced coagulation on removal of dissolved organic carbon (DOC) and organic halide precursors. In addition, full-scale samples were obtained after sedimentation and after complete treatment (clearwell) from each of the utilities for analysis of a number of water quality parameters in order to compare the bench-scale treatment results with full-scale treatment plant performance.

Initial analyses for the raw waters included alkalinity, pH, turbidity, and total organic carbon (TOC). The optimum pH for organics removal was determined by jar testing at various pH values but at a constant coagulant dose. The optimum pH was the pH at which the largest amount of organics (measured as TOC) was removed. Dose optimization followed pH optimization using various coagulant doses at the

optimum pH value. The dose optimization study identified the enhanced and optimized doses, which were defined as:

- Enhanced - The dose at which a 10 mg/L increase in coagulant dose does not produce greater than a 0.3 mg/L decrease in DOC or TOC over the previous dose (Federal Register, 1994)
- Optimized - The dose at which a 10 mg/L increase in coagulant dose does not produce a noticeable decrease in DOC or TOC over the previous dose (Virginia Tech definition)

Another dose, the "baseline dose" was defined as the coagulant dose and pH at which the specific utility's water treatment plant was operating on the day the samples were collected. Large batches of raw water were then treated at the optimum pH value at the enhanced and optimized doses, as well as at the baseline dose.

The bench-scale coagulant treated waters, as well as the corresponding filtered raw water samples, were then chlorinated, incubated for seven days, and analyzed for DBPs including total trihalomethanes (TTHMs), total haloacetic acids (THAAs), non-purgeable dissolved organic halides (NPDOX), haloacetonitriles (HANs), and haloketones (HKs). In addition, enhanced and baseline treated samples were chlorinated according to the Uniform Formation Condition (UFC) test and analyzed for TTHMs, THAAs, and NPDOX.

Jar testing (and subsequent chlorination) was performed using both aluminum and iron salts as coagulants for six of the raw waters (VT-3, VT-4, VT-6, VT-7, VT-8, and VT-9). Temperature effects on the jar test results only were investigated for two raw waters (VT-6 and VT-9). Additional large batch jar tests were performed at the optimum pH value with two coagulant doses other than the enhanced and optimized

doses for one raw water (VT-6). Chlorination and DBP analyses were performed on the samples treated at these two additional coagulant doses.

A complete list of the analyses performed on each of the raw and treated waters is contained in Table 3.1.

DESCRIPTION OF WATER TREATMENT FACILITIES

A summary of the raw water characteristics and geographic location for each utility that participated in this project is included in Appendix A. Flow diagrams of the water treatment plants for each utility are included in the respective appendix for each utility. Throughout the main text of this report the utilities will be referred to as Utility VT-#, with the # ranging from one to nine in the order of receipt at the Virginia Tech Environmental Engineering Laboratory.

CHEMICALS AND SOLUTIONS

All water-based solutions were prepared by dilution with deionized, distilled, carbon-filtered water (Milli-Q water) (Milli-Q Corporation, Bedford, MA). Table 3.2 contains a list of some of the less common chemicals used during this project.

GLASSWARE PREPARATION

All glassware was initially cleaned with chromic acid, which was made by combining a 9 lb bottle of sulfuric acid with a 25 milliliter (mL) bottle of Chromerge® (Fisher Scientific, Springfield, NJ). New glassware was contacted with chromic acid for a minimum of 2 hours, while previously used glassware was contacted overnight. Daily cleaning involved immersing glassware in a 10 percent nitric acid solution for a minimum of 10 minutes, rinsing three times with tap water, and then soaking

Table 3.1
Analysis List for Raw and Treated Water Samples

Analysis	Sample					Clearwell
	Raw	Coagulated/Settled (Bench-Scale)			Settled (Full-Scale)	
		Baseline	Enhanced	Optimized		
Unfiltered:						
pH	X	X	X	X	X	X
Alkalinity	X					X
Turbidity	X	X	X	X	X	X
TOC	X					X
Filtered:						
Alkalinity		X				
Hardness	X					
Anions	X					
DOC	X	X	X	X	X	
UV254	X	X	X	X	X	X
Color	X	X			X	X
Al/Fe	X	X	X	X		
AMWD	X		X			
THMFP	X	X	X	X		
HAAFP	X	X	X			
DOXFP	X	X	X	X		
HANFP	X	X	X			
HKFP	X	X	X			
UFC THMs		X	X			
UFC HAAs		X	X			
UFC DOX		X	X			

Table 3.2
Partial List of Chemicals and Solutions

Chemical	Supplier and Stock No.	Purity or Strength	Grade
Aluminum Sulfate Octadecahydrate	Aldrich (22,761-7)	98%	A.C.S.
Iron(III) Sulfate Pentahydrate	Aldrich (30,771-8)	97%	A.C.S.
Platinum Cobalt Color Standards	Fisher (SP120-500)	500 NTU	---
Sodium Hypochlorite	Fisher (SS-290-1)	4-6%	Purified
Sodium Phosphate Dibasic	Fisher (S374-500)	100.2%	A.C.S.
Potassium Phosphate Monobasic	Fisher (P285-3)	99.5%	A.C.S.
3,5-Dihydroxybenzoic Acid	Aldrich (D11,000-0)	97%	---
Sodium Sulfite	Fisher (S-430)	99.1%	A.C.S.
Sodium Chloride	Fisher (S-271)	---	A.C.S.
Methanol	Aldrich (17,933-7)	99.9%	A.C.S.
Chloroform	Aldrich (31,998-8)	99.8%	A.C.S.
Bromodichloromethane	Aldrich (13,918-1)	98+%	---
Chlorodibromomethane	Aldrich (20,632-6)	98%	---
Bromoform	Aldrich (13,294-2)	96%	---
2,4,6-Trichlorophenol	Sigma	98%	---

overnight in an approximately 0.1 percent chlorine bath. Finally, glassware was rinsed six times with Milli-Q water and dried in a drying oven.

GENERAL LABORATORY PROCEDURES

Water Quality Characteristics

Alkalinity

Alkalinity titrations followed Method 2320B, Titration Method, from 18th Edition, *Standard Methods* (APHA, AWWA, and WPCF 1992). An alkalinity titration curve was developed for the raw water samples by measuring the pH of the sample at incremental levels of acid addition up to the alkalinity endpoint. This titration curve was used in determining necessary acid addition amounts for pH adjustment of the raw water prior to jar testing.

pH

Sample pH was measured using a Fisher Scientific (Springfield, NJ) Accumet pH meter, model 610A. The meter was calibrated before each use with standard buffer solutions of pH 4, 7, and 10.

Turbidity

Samples for turbidity analyses were collected after coagulation, flocculation, and settling. Samples were collected by carefully dipping a glass cuvet into the square jar test jars, so as not to disturb the settled floc. Sample volumes of 25 ± 1 mL were collected and analyzed using a Hach (Ames, Iowa) Model 2100A Turbidimeter.

Turbidity standards employed were 0.6, 10, and 100 nephelometric turbidity units (NTU).

Anions

Anion analyses were completed using a Dionex (Sunnyvale, CA) Ion Chromatograph with a Dionex Ion Pac AS9 anion column according to U.S. EPA Method 300.0 (A) (EPA 1979). Samples were analyzed for chloride (Cl^-), sulfate (SO_4^{2-}), and bromide (Br^-) concentrations.

Hardness

Calcium and magnesium hardness analyses involved use of a Perkin Elmer (Norwich, CT) Model 703 flame atomic absorption spectrophotometer. Calcium hardness was determined according to U.S. EPA Method 215.1 (EPA 1979); magnesium hardness determined according to U.S. EPA Method 242.1 (EPA 1979).

Organic Carbon Determinations

Total Organic Carbon

Total organic carbon (TOC) concentrations were measured using a Dohrmann (Xertex, Santa Clara, CA) Carbon Analyzer, Model DC-80. Samples were collected in 40 mL glass vials and analyzed according to manufacturer's recommendations. Prior to analysis, samples were acidified to pH 2 with 85 percent phosphoric acid and purged with oxygen for 5 minutes to remove any inorganic carbon present.

The Carbon Analyzer required a 10 mg/L calibration standard, which was made by dilution with Milli-Q water of a 2000 mg/L TOC stock solution to 200 mg/L,

followed by dilution of the 200 mg/L standard to 10 mg/L. The 2000 mg/L stock solution was prepared monthly; the 200 mg/L standard was prepared weekly; and the 10 mg/L standard was prepared every other day.

Samples were analyzed in duplicate for TOC. A third sample was analyzed if the TOC concentration of the duplicates differed by more than 10 percent.

UV254

Ultraviolet (UV) absorbance at 253.7 nm (UV254) was quantified using a Beckman (Irvine, CA) DU 640 Spectrophotometer according to Method 5910, UV-Absorbing Organic Constituents, from 18th Edition, *Standard Methods* (APHA, AWWA, and WPCF 1992). A known quantity of pH 7 phosphate buffer was added to the samples to adjust them to pH 7 prior to analysis. Samples were analyzed in duplicate.

Color

Color was analyzed by measuring sample absorbance using a Beckman (Irvine, CA) DU 640 Spectrophotometer at a visible wavelength of 420 nm. Calibration standards of 5, 10, 25, 50, 100, and 150 primary color units (PCU) were analyzed to produce a standard curve which was used to later quantify the color of the samples. The standards were made by the appropriate dilution with Milli-Q water of a 500 PCU platinum cobalt color standard. Milli-Q water was used as the blank solution during analysis.

Apparent Molecular Weight Distribution

Apparent molecular weight distribution (AMWD) was determined using ultrafiltration through an Amicon (Amicon Division, W. R. Grace & Co., Canvers, MA) Model 8200 ultrafiltration cell apparatus. Amicon ultrafilters with nominal molecular weight cutoffs of 10,000 (Amicon Model YM10), 3,000 (Amicon Model YM3), 1,000 (Amicon Model YM1), and 500 (Amicon Model YC05) atomic mass units (amu) were utilized.

The ultrafilters were cleaned prior to use by first soaking them in Milli-Q water for one day, and then passing Milli-Q water (typically approximately 500 mL) through the filters until the effluent DOC from the filters was less than 0.2 mg/L greater than the DOC of the Milli-Q water. Ultrafilters were cleaned in a similar way between treated and raw samples. Separate sets of ultrafilters were cleaned for each type of coagulant (iron or aluminum) and for each set of tests for a given utility.

Ultrafiltration cells were pressurized to 40-45 pounds per square inch (psi) using nitrogen gas. Approximately 150 mL of a 200 mL sample was passed through the filter. Samples were processed in parallel through the four ultrafilters of different molecular size. Three filtrate samples were collected from each ultrafilter during processing. These samples were then analyzed for TOC concentration as previously described. The average of the TOC values from the three samples collected was the recorded DOC concentration for each molecular weight. The DOC results for each of the three samples collected are contained in Appendix K.

Trace Metal Ion Analysis

Analysis for sample aluminum content was conducted using a Perkin Elmer (Norwich, CT) Zeeman 5100 PC graphite furnace atomic absorption spectrophotometer using the method recommended by the equipment manufacturer.

Iron analysis involved use of a Perkin Elmer (Norwich, CT) Model 703 flame atomic absorption spectrophotometer according to U.S. EPA Method 236.1 (EPA 1979).

Jar Test Procedures

As previously discussed in this chapter, numerous jar tests with each raw water were conducted. These included pH optimization and dose optimization, plus baseline, enhanced, and optimized coagulation. In addition, temperature effects on pH and dose optimization were examined for two raw waters. Additional jar tests were performed at coagulant doses other than the enhanced and optimized doses for one raw water. Table 3.3 summarizes the jar test conditions utilized. Jar testing was performed using a Phipps and Bird (Richmond, VA) six-paddle stirrer at 25° C unless otherwise noted.

Various pH values were utilized for the jar tests. Either 0.2 N or 1 N H₂SO₄ was used for pH adjustment, with the amount of acid required to decrease the raw water pH to a certain level determined based on the alkalinity titration curve developed for each raw water. Sample pH was maintained at a constant value throughout each jar test in order to better report and evaluate pH effects on coagulation. The raw water sample was first adjusted to the desired pH, followed by a 10 minute mixing period to allow equilibration of dissolved carbon dioxide (CO₂(aq)) with the atmosphere. Minor adjustments were then made with either acid or base to achieve the required initial pH; this pH was recorded. Coagulant was added during the rapid mix stage which caused a decrease in sample pH. Base (NaOH) was added immediately following coagulant addition in order to increase the pH to approximately its initial value.

During 1st stage flocculation minor pH adjustments were made with either acid or base in order to achieve the desired pH range for the test; this pH was recorded. Sample pH was also recorded following flocculation (prior to settling), but no

Table 3.3
Jar Test Conditions

Stage	Paddle Speed (rpm)	Time (min)
Rapid Mix	Max speed	2
1st Stage Flocculation	40	10
2nd Stage Flocculation	30	10
3rd Stage Flocculation	20	10
Settling	---	60

adjustment of pH was made at that time. This approach was used for all jar testing except for baseline jar testing. The baseline jar testing was performed according to the operation of the full-scale plant. To minimize dilution effects, less than 3 percent of the original sample volume was added in the form of *acid + base + coagulant* for all jar tests.

Typically, a 10 mg/mL coagulant solution was used for coagulant addition. Therefore, 1 mL of the coagulant solution added to 1 L of raw water produced a coagulant dose of 10 mg/L. For higher coagulant doses, a 50 mg/mL coagulant solution was sometimes used. For alum, the coagulant solutions were prepared in order that the coagulant dose be based on alum in the form of $\text{Al}_2(\text{SO}_4)_3 \cdot 14.3\text{H}_2\text{O}$, which is a standard commercially available form of alum. For the ferric sulfate jar testing, the coagulant solutions were prepared based on ferric sulfate in the form of $\text{Fe}_2(\text{SO}_4)_3 \cdot 5\text{H}_2\text{O}$.

Following coagulation, samples were then filtered for all analyses except turbidity, which was taken on the unfiltered sample. Filters were cleaned prior to sample filtration with Milli-Q water until the DOC passing through the filter was less than 0.2 mg/L greater than Milli-Q water. For pH optimization and dose optimization jar tests, samples were filtered through a 1.5 micrometer (μm) Whatman (Maidstone, England) 934-AH glass fibre filter, while all other treated samples were filtered through a 0.45 μm Gelman (Ann Arbor, Michigan) #12175 filter cartridge. Inherent in this procedure was the assumption that an insignificant amount of organics (between 1.5 μm and 0.45 μm) remained in the treated water. The results indicated that typically < 4 percent of the total TOC was in the size range between 0.45 μm and 1.5 μm in size.

Most raw water samples were filtered through a 0.45 μm Gelman #12175 filter cartridge. For the higher turbidity waters (>15 NTU), a 0.45 μm Whatman Polycap 75 AS filter cartridge with prefilter was utilized. These filters were cleaned prior to sample filtration in the same manner as previously described.

Determination of Optimum pH for TOC Removal

Initially, for each raw water sample, the optimum pH for organics removal was determined by jar testing at a constant coagulant dose and varying pH value. The jar test pH range employed was 5.3-6.7 for alum and 4.5-6.1 for ferric sulfate.

Turbidity samples were collected following settling, but prior to filtration. Residual coagulant, DOC, and UV254 were analyzed using filtered water samples. Prior to collecting the samples from each jar test jar, a small amount of treated water was flushed through the filter to prevent bias from the previous jar. Typically, samples from three jar test jars were filtered through one filter and then the filter was replaced.

The DOC data collected from the pH optimization jar tests were then used to determine the optimum pH range, typically the pH value (± 0.1 pH units) at which the greatest amount of TOC was removed.

For the pH optimization jar tests on the utilities for which aluminum and iron coagulants were both investigated, the coagulant doses for alum and ferric sulfate were chosen so that approximately the same molar amount of aluminum or iron was added to the water for each coagulant. For the specific coagulants used in this study, 0.83 g ferric sulfate yielded an equivalent molar metal coagulant concentration to 1 g alum.

Dose Optimization

Dose optimization jar testing was performed by maintaining pH constant (at the optimum pH value) and varying coagulant doses. Coagulant dose was typically varied in 10 mg/L increments. In order to keep the dilution effects equivalent across each jar, Milli-Q water was added to some of the jars, so that an equal volumetric amount of *Milli-Q + coagulant + acid + base* was added to each jar.

Turbidity, residual coagulant, DOC, and UV254 samples were collected in the same manner as previously described under Determination of Optimum pH for TOC Removal.

The DOC data collected from the dose optimization jar tests were used to establish the enhanced and optimized doses (previously defined).

Baseline Jar Testing

A large batch of water was treated at the coagulant dose and pH used at the specific utility's water treatment plant on the day which the samples were collected. These conditions were defined as the baseline conditions. Typically six jars, each containing 1.25 liters (L) of raw water, were treated at this dose. This produced a usable volume of treated water of approximately 6 L. The treated water was filtered through a previously cleaned 0.45 μm filter cartridge prior to collection. The filter cartridge was used to filter each of the 6 jars, unless the flow rate through the filter substantially decreased, in which case an additional filter was used. This quantity of treated water was used to perform the required sample analyses and chlorination procedures.

A turbidity sample was collected from one jar prior to filtration. In addition, DOC and UV254 samples were collected from each jar following filtration to determine the reproducibility between identical jars. A residual coagulant sample was collected from the filtered, homogenized baseline water.

Enhanced Jar Testing

A large batch of water was treated at the enhanced dose and optimum pH value previously determined from the pH optimization and dose optimization jar testing.

Typically six jars, each containing 1.25 L of raw water, were treated at this dose. The treated water was filtered similar to the large batch treated at the baseline dose.

Turbidity, DOC, UV254, and residual coagulant samples were collected in the same manner as previously described under Baseline Jar Testing.

Optimized Jar Testing

A large batch of water was treated at the optimized dose and optimum pH value previously determined from the pH optimization and dose optimization jar testing. Typically three jars, each containing 1.25 L of raw water was treated at this dose. This produced a usable volume of treated water of approximately 3 L. Only 3 L was required for the optimized treated water since the number of tests to be run on the optimized sample was less than the number for the baseline or enhanced samples (see Table 3.1). The treated water was filtered similar to the large batches treated at the baseline and enhanced doses.

Turbidity, DOC, UV254, and residual coagulant samples were collected in the same manner as previously described under Baseline Jar Testing.

DBP Removal Optimization

For Utility VT-6, a DBP removal optimization was performed. This involved treating large batches of water at the optimum pH value at two doses other than the enhanced and optimized doses and performing the DBP analyses on these additional doses. These large batch jar tests were performed similar to the procedure described previously under Enhanced Jar Testing.

Temperature Effects

Temperature effects on organics removal were investigated in studies conducted using water samples from Utilities VT-6 and VT-9. For each of these utilities, additional pH optimization and dose optimization jar testing was performed at approximately 4° C. To achieve a temperature of approximately 4° C, the six square jar test vessels were placed into a large pyrex container containing an ice bath. To account for the temperature of the samples, the pH standards were refrigerated to 4° C prior to use.

The pH optimization jar test at 4° C was performed similar to the 25° C test, except the pH ranges utilized were altered. The pH range at 4° C for alum coagulation was approximately 5.7-7.6 and the pH range at 4° C for ferric sulfate coagulation was 4.8-6.8. The coagulant dose used for the 4° C pH optimization was identical to the dose used for the 25° C pH optimization for that utility. Turbidity, residual coagulant, DOC, and UV254 samples were collected for analysis as previously discussed under Determination of Optimum pH for TOC Removal.

The dose optimization jar test at 4° C was performed at varying coagulant doses and at the optimum pH value determined from the 4° C pH optimization jar testing. The coagulant doses used were identical to those used for the 25° C dose optimization for that utility. Turbidity, residual coagulant, DOC, and UV254 samples were collected for analysis as previously discussed under Determination of Optimum pH for TOC Removal.

Sample Chlorination Procedures and Analyses

Chlorine Solutions and Buffers

For both the seven-day formation potential (FP) tests and the Uniform Formation Condition (UFC) tests, approximately 5 mg/mL chlorine solutions were prepared by dilution of NaOCl with Milli-Q water. The chlorine solutions were adjusted to pH 7 for the FP tests and pH 8 for the UFC tests with 10 percent HNO₃. The exact strength of the chlorine solutions was determined by the DPD method (described later).

The following phosphate buffers were prepared for the different analyses:

- Seven-day formation potential tests: 0.5 M pH 7 phosphate buffer (Method 5170B, Trihalomethane Formation Potential, 18th edition, *Standard Methods* (APHA, AWWA, and WPCF 1992)).
- Uniform Formation Condition tests: 1 M pH 8 phosphate buffer (1.0 M boric acid (ACS grade) and 0.26 M sodium hydroxide (ACS grade) in Milli-Q water).

Seven-day Formation Potentials

The chlorination procedures for the seven-day formation potentials were performed according to Method 5170B, Trihalomethane Formation Potential, 18th edition, *Standard Methods* (APHA, AWWA, and WPCF 1992). Slight variations from this standard method were made for HAAs. As described in the method, four hour chlorine demands were first determined for each sample. The chlorine dose used for the four hour chlorine demand evaluation was three times the sample DOC

concentration. The doses for the seven-day formation potentials were then determined by adding 3,6,9, and 12 mg/L of additional free chlorine to the four hour chlorine demand of the water. If this chlorine dose range did not bracket three times the DOC of the sample, then the range was shifted so that three times the DOC was bracketed. The dose used for the disinfection by-product analyses was that one which produced a free chlorine residual of 3 to 5 mg/L at the end of the seven day incubation period.

Once the appropriate chlorine doses were determined, samples for THMFP, DOXFP, HANFP, and HKFP were buffered according to Method 5170B (1 mL of pH 7 phosphate buffer/50 mL sample). Samples for HAAFP were buffered at a rate of 1 mL of pH 7 phosphate buffer/500 mL sample due to the interference of large amounts of phosphate buffer with the HAA analysis. Samples were then dosed with the appropriate volume of chlorine solution and placed into head-space free containers. Samples were sealed with teflon-lined caps and incubated at 25° C for seven days.

Uniform Formation Condition (UFC)

The UFC test for this study was designed to produce a free chlorine residual between 0.7 and 1.3 mg/L following a one day incubation period at pH 8 and 20° C. This varies from the current UFC test (developed in 1996) which allows a free chlorine residual between 0.6 and 1.4 mg/L following the one day incubation period at pH 8 and 20° C (Summers et al. 1996). To accomplish the requirements of the UFC test, approximately five chlorine doses were selected initially for each sample. These initial chlorine doses were based on the four hour demands determined during the formation potential tests, and the chlorine demand of the full-scale clearwell sample observed after one day. Once these five initial doses had been chosen, five 40 mL samples were buffered at a rate of 0.5 mL pH 8 phosphate buffer/500 mL sample and chlorinated at the appropriate chlorine dose. Each sample was sealed head-space free in 40 mL vials with TFE-lined caps and stored for one day at the previously stated

conditions. The DPD method was used to determine the free chlorine residual in the samples after 24 hours. The initial dose which produced a free chlorine residual between 0.7 and 1.3 mg/L after one day was chosen as the dose for the UFC testing.

Once the appropriate dose to produce a chlorine residual between 0.7 and 1.3 mg/L was determined, larger volumes (approximately 500 mL) were chlorinated at the appropriate dose and buffered to produce adequate sample volume to perform the disinfection by-product analyses (THMs, HAAs, and DOX) required. This volume was then incubated at pH 8 and 20° C for one day.

Chlorine Residual Measurement

Either amperometric titration or the DPD method was used to determine the free chlorine residual remaining in samples. Initially, both methods were used, but early in the project it was decided to only use the DPD method in order to attain more consistent results.

Amperometric titrations were conducted following Section 408.C, Chlorine (Residual) - Amperometric Titration Method, 18th edition, *Standard Methods* (APHA, AWWA, and WPCF 1992). A Fisher Scientific (Pittsburgh, PA) Model 465 Computer-Aided Titrimeter was used for the titration, with 0.00564 N phenylarsine oxide (PAO) used as the titrant.

The DPD method utilized an Orbeco-Hellige (Orbeco Analytical Systems, Inc., Farmingdale, NY) pocket comparator based on N,N-Diethyl-p-Phenylendiamine (DPD) Method 4500-Cl G, Chlorine (Residual) - DPD Colorimetric Method, 17th Edition, *Standard Methods* (APHA, AWWA, and WPCF 1989). A low-range DPD color disc was used which contained free chlorine standards of 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, and 4.0 mg/L free chlorine.

Two identical distortion-free tubes were utilized in the DPD method, each containing 10 mL of sample. One tube contained the blank (Milli-Q water), while the

other contained the sample. An indicator tablet (Tablet No. 1, Fisher Scientific (Springfield, NJ) catalog number 15-398-102A) was added to the sample, causing a color change proportional to the amount of free chlorine remaining in the sample. The tubes were then placed into the Orbeco-Hellige comparator and the color disc rotated until the sample color matched the color of the standard. The free chlorine content was then read directly from the comparator. Samples were typically diluted by one-half when the chlorine residual was greater than approximately 3 mg/L free chlorine so that the sample color could be more easily compared to the standard.

Quenching Procedure

Free chlorine residuals for the seven-day formation potential tests were determined by measuring the residual in the chlorinated samples using the DPD procedure, beginning with the sample which had been dosed at the lowest chlorine concentration. If the free chlorine residual of that sample was between 3 and 5 mg/L, the sample was quenched to stop the chlorine reaction. Otherwise, the chlorine residual in the sample which had been dosed at the next highest chlorine concentration was measured. If the free chlorine residual in that sample was between 3 and 5 mg/L, the sample was quenched to stop the chlorine reaction. This procedure was repeated until the chlorine residual in a sample was determined to be between 3 and 5 mg/L.

The free chlorine residual for the UFC samples was measured after the 24 hour incubation period using the DPD procedure. If the chlorine residual was not between 0.7 and 1.3 mg/L, then the UFC procedure was repeated at an adjusted dose until the residual was determined to be within the acceptable range.

Samples for THM analysis were quenched and acidified according to Method 5170B, Trihalomethane Formation Potential, 18th edition, *Standard Methods* (APHA, AWWA, and WPCF 1992).

Samples for DOX analysis were quenched and acidified according to Method 5320, Dissolved Organic Halogen, 18th edition, *Standard Methods* (APHA, AWWA, and WPCF 1992) and manufacturer's recommendations. Typically, DOX samples were quenched with 0.1 M sodium sulfite using a dose ratio of 1 mL of sodium sulfite solution per 500 mL sample. Samples were acidified to pH 2 with concentrated HNO₃ by adding approximately 1 mL of nitric acid (HNO₃) per 500 mL sample.

All samples were refrigerated prior to analysis.

Disinfection By-Product Analysis

THM Analysis

Samples for THM analysis were analyzed according to EPA Method 501.1, Trihalomethane Formation Potential. A Tekmar (Tekmar-Dohrmann, Cincinnati, OH) 3000 purge and trap system, Tracor (Finnegan Corporation, Austin, TX) 560 gas chromatograph, Tracor 1000 Hall detector, Hewlett-Packard (Palo Alto, CA) 3390A integrator, and a Supelco 1 % SP 1000 on a 60/80 carbopack B packed column were used for these analyses.

A standard curve was analyzed prior to analysis of each set of samples as outlined in method 501.1. Instrument precision was checked by analyzing duplicate samples out of each sample vial. Replicate sample vials were also analyzed to check human precision.

Quality Assurance/Quality Control samples were prepared for each set of samples according to Method 5170B, Trihalomethane Formation Potential, 18th edition, *Standard Methods* (APHA, AWWA, and WPCF 1992). In addition, a Milli-Q blank was also chlorinated, incubated, and quenched along with the other samples.

DOX Analysis

DOX analyses were performed according to Method 5320, Dissolved Organic Halogen, 18th edition, *Standard Methods* (APHA, AWWA, and WPCF 1992) and manufacturer's recommendations. The micro-column adsorption-pyrolysis-titrimetric method was utilized. An Envirotech/Dohrmann (Santa Clara, CA) Total Organic Halide Analyzer System was utilized for the DOX analyses.

The standard stock solution for DOX analyses was a 10 µg as Cl⁻/µL solution prepared by adding 1.856 g 2,4,6-trichlorophenol and diluting to 100 mL with methanol. A 1 µg as Cl⁻/µL solution was prepared by diluting 2.5 mL of the 10 µg as Cl⁻/µL stock solution to 25 mL with Milli-Q water. Stock solutions were stored in amber vials, refrigerated, and the top wrapped with teflon tape. New stock solutions were prepared for each utility.

For each utility, check samples and matrix spike recovery samples were analyzed. Typically, a minimum of one nonvolatile organic halide calibration standard was analyzed each day when DOX analyses were conducted. As a minimum, matrix spike recovery samples were analyzed every tenth sample. For each set of samples analyzed, a system blank and a standard blank (as defined in Method 5320) were also analyzed. Standard curves were prepared for five of the nine utilities. The nonvolatile organic halide calibration standards for the utilities for which a standard curve was not prepared correlated well with the standard curves developed for the other utilities. The standard curves and the data for check samples and matrix spike duplicate samples are contained in Appendix L.

A minimum of duplicates were analyzed for each sample. Due to the large number of samples to be analyzed, two different dilutions of the same sample were not analyzed for each utility as described in Standard Method 5320. However, for some of the utilities, two different dilutions of the same sample were analyzed to determine

if the dilution affected the analysis. Samples using different dilutions typically varied by less than 5 percent.

Prior to DOX analysis, samples were purged to remove all volatile organic halides. This was performed by purging approximately 100 mL of sample with nitrogen gas at 800 cc/min for 10 minutes (Fleischacker and Randtke, 1983). Therefore, unless otherwise noted, all reported DOX values for this study are non-purgeable dissolved organic halogen (NPDOX) concentrations.

Chapter IV

RESULTS

This chapter presents the results obtained from the experiments described in the Methods and Materials section. The first section of this chapter presents data on jar test reproducibility, along with a comparison of bench-scale results, pilot-scale results, and full-scale results. Next, the bench-scale results from each utility are presented, including: (1) pH optimization results, (2) dose optimization results, including enhanced and optimized dose determination, (3) residual coagulant results, (4) apparent molecular weight distribution results, and (5) disinfection by-product (THM and DOX) precursor removal results. The final section of this chapter presents the effects of temperature on pH optimization results, dose optimization results, and residual coagulant results.

In the sections for each utility, the raw water characteristics are briefly discussed. These data are presented in greater detail in Appendix A. In determining an optimum pH and enhanced and optimized doses, often the data did not present a clearly defined conclusion. Best judgment and consideration of actual full-scale plant operation were used, particularly in choosing the optimum pH.

A glossary of the abbreviations used in this chapter is contained in Appendix P.

REPRODUCIBILITY OF JAR TEST PROCEDURES

The reproducibility of the jar testing procedure was evaluated when the large batches of baseline, enhanced, and optimized samples were treated. This was done by measuring the residual DOC and UV254 concentrations in each individual jar test vessel treated at a specific dose. Table 4.1 contains DOC data for each utility for each of the jars treated at the baseline and enhanced doses for both alum and ferric sulfate. The DOC data from the optimized jar tests as well as the UV254 data for the baseline,

Table 4.1

Jar Test Reproducibility for Alum Baseline (ABL), Alum Enhanced (AEN),
 Ferric Baseline (FBL), and Ferric Enhanced (FEN) Treatment
 (Determined from Parallel Treatment in Six Different Jar Test Vessels)

Sample	Coag	DOC1	DOC2	DOC3	DOC4	DOC5	DOC6	Avg	Std Dev	% Error
	Dose									
(mg/L)		(mg/L)								
<u>VT1</u>										
ABL	40	2.47	2.51	2.63	2.45	2.61	2.54	2.53	0.073	2.89
AEN	40	2.33	2.16	2.22	2.32	2.29	2.20	2.25	0.070	3.10
<u>VT2</u>										
ABL	17	1.36	1.28	1.40	1.23	1.31	---	1.32	0.067	5.06
AEN	30	1.00	1.27	1.19	1.16	1.08	1.15	1.14	0.093	8.13
<u>VT3</u>										
AEN	100	4.60	4.53	4.98	4.25	4.44	4.27	4.51	0.268	5.94
FBL	122	2.76	2.80	2.78	3.22	2.78	2.87	2.87	0.176	6.15
FEN	65	3.56	3.65	3.83	3.64	3.78	3.78	3.70	0.105	2.83
<u>VT4</u>										
AEN	20	2.03	1.40	1.55	1.50	1.52	1.66	1.61	0.222	13.80
FBL	5.6	2.38	2.47	2.27	2.28	2.47	2.15	2.34	0.126	5.41
FEN	20	1.26	1.24	1.54	1.25	1.35	1.74	1.39	0.203	14.51
<u>VT5</u>										
ABL	120	4.62	5.00	4.99	5.34	4.56	4.51	4.84	0.327	6.76
AEN	50	3.82	3.73	3.65	3.60	3.95	3.75	3.75	0.125	3.33

(continued)

Table 4.1 (continued)

Sample	Coag Dose	DOC1	DOC2	DOC3	DOC4	DOC5	DOC6	Avg	Std Dev	% Error
	(mg/L)	(mg/L)								
<u>VT6</u>										
ABL	40	2.96	3.02	3.03	3.19	3.28	2.92	3.07	0.139	4.54
AEN	30	2.28	2.53	2.51	2.55	2.52	2.50	2.48	0.100	4.04
FEN	30	1.96	2.19	1.97	1.93	2.07	2.08	2.03	0.098	4.83
<u>VT7</u>										
ABL	35	2.86	2.87	2.87	2.86	2.95	2.93	2.89	0.039	1.37
AEN	30	3.43	2.96	2.90	2.97	2.97	2.91	3.02	0.202	6.67
FEN	40	2.55	2.33	2.19	2.10	2.20	2.10	2.24	0.172	7.65
<u>VT8</u>										
ABL	3	2.99	2.86	2.77	2.86	---	---	2.87	0.091	3.16
AEN	30	2.15	2.04	1.98	1.91	1.94	1.98	2.00	0.086	4.28
FEN	25	1.89	1.78	2.09	1.79	1.87	---	1.88	0.125	6.63
<u>VT9</u>										
ABL	36	3.32	3.10	3.11	3.24	3.24	3.31	3.22	0.095	2.96
AEN	60	3.60	3.78	3.77	3.83	3.59	3.64	3.70	0.104	2.80
FEN	60	3.60	3.24	3.41	3.20	3.48	---	3.39	0.167	4.92

enhanced, and optimized jar tests for each utility are contained in Appendix M. The percentage errors of the standard deviations for the DOC results with respect to the average DOC concentration for the baseline and enhanced jar tests ranged from 1.4 percent to 14.5 percent.

COMPARISON OF PILOT-SCALE AND FULL-SCALE TREATMENT TO BENCH-SCALE TREATMENT

Pilot-Scale Treatment

For Utilities VT-1, VT-6, and VT-8, pilot-scale treatment was performed to compare the removal of disinfection by-product precursors between pilot-scale and bench-scale treatment. The pilot-plant treatment was not performed on raw water identical to that used for the bench-scale treatment; therefore, raw water characteristics and formation potentials were analyzed on the raw water utilized for both bench-scale and pilot-scale treatment. The pilot-plant testing was performed at the enhanced coagulant dose determined by the bench-scale treatment.

Utility VT-1

For Utility VT-1, the pilot-plant testing was performed at the enhanced alum dose of 40 mg/L. However, unlike the bench-scale jar testing, 0.35 mg/L of coagulant-aid polymer was added to the water, which is typical of the utility's treatment plant operation. Also unlike the bench-scale jar testing, pH adjustment was not performed during the pilot-scale testing. Therefore, the pH change between the raw and finished water during the pilot-scale testing was only due to the addition of coagulant. For the pilot-scale testing, the raw water pH value was 6.82, and the finished water pH value was approximately 6.58.

By comparison, the raw water utilized for the bench-scale treatment had a pH value of 7.8. The coagulation pH range for the enhanced bench-scale treatment was 5.8-6.0.

Table 4.2 contains a comparison between the raw water data and enhanced treated water data for the bench-scale and pilot-scale testing. The DOC, THMFP, and NPDOXFP reductions for the bench-scale treatment exceeded the corresponding reductions for the pilot-scale treatment.

Utility VT-6

For Utility VT-6, pilot-plant testing was performed using both alum and ferric chloride as coagulants. Four pilot-plant tests were performed, and for each pilot-plant test a raw water sample and a treated water sample were collected. The treated water samples consisted of an alum baseline sample, alum enhanced sample, ferric baseline sample, and a ferric enhanced sample. The baseline samples for Utility VT-6 pilot-plant treatment were samples treated at the enhanced dose, but without pH adjustment. The enhanced samples were treated at pH values approaching the optimum pH values for TOC removal determined during the bench-scale testing. This allowed for comparison of identical treatment with and without pH adjustment.

The coagulation pH for the enhanced treated pilot-scale samples was adjusted in a slightly different manner than the method utilized during the bench-scale treatment. The bench-scale samples were adjusted to the desired pH prior to treatment, and coagulant and NaOH were added simultaneously to maintain the sample pH at the initial value. For the pilot-plant samples, the sample pH was partially adjusted to the desired value, and the addition of coagulant was used to reduce the pH to the desired level. The coagulant dose utilized for both alum and ferric chloride treatment and for both baseline and enhanced treatment was 30 mg/L. The pH values for the raw water samples used for pilot-scale treatment were approximately 7.9. The

Table 4.2
Comparison of Pilot-Scale and Bench-Scale Treatment
for Utility VT-1 Alum Treatment

Sample	DOC (mg/L)	TOC* Reduction (%)	THMFP (µg/L)	THMFP Reduction (%)	DOXFP† (µg/L as Cl⁻)	DOXFP† Reduction (%)
<u>Bench-Scale Treatment</u>						
Raw	5.32‡	---	414	---	847	---
Enhanced§	2.25	58	175	58	343	60
<u>Pilot-Scale Treatment</u>						
Raw	4.79‡	---	374	---	593	---
Enhanced**	2.77	42	202	46	299	50

* TOC reduction is based on TOC of raw waters and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

‡ Values for raw waters are TOC values.

§ 40 mg/L alum, coagulation pH = 5.8-6.0.

** 40 mg/L alum, 0.35 mg/L coagulant aid polymer, coagulation pH = 6.58.

pH value for the pilot-scale alum baseline treatment was 7.6, while the pH value for the pilot-scale alum enhanced treatment was 6.6. The pH value for the pilot-scale ferric baseline treatment was 7.2, while the pH value for the pilot-scale ferric enhanced treatment was 5.8.

By comparison, the raw water utilized during bench-scale treatment had a pH value of 8.1. The optimum pH range for the bench-scale alum enhanced treatment was 5.5-5.6 and for the bench-scale ferric enhanced treatment was 5.0-5.2.

For the alum pilot-plant treatment, formation potentials were analyzed for the raw waters used for both baseline and enhanced treatment. For the ferric chloride pilot-plant treatment, the TOC of the raw waters used for baseline and enhanced treatment was compared and the values were similar. Therefore, formation potentials were analyzed only for the raw water used for ferric enhanced treatment.

Table 4.3 contains a comparison between the data for the bench-scale and pilot-scale aluminum treatment. Table 4.4 contains the data for bench-scale and pilot-scale iron treatment. The DOC, THMFP, and NPDOXFP reductions were similar for the enhanced bench-scale and enhanced pilot-scale treatment for both coagulants. The reductions for pilot-scale enhanced treatment were greater than those for the pilot-scale baseline treatment for both coagulants.

Utility VT-8

For Utility VT-8, pilot-plant testing was performed using ferric sulfate only. On each day of pilot-plant testing, both raw water and treated water samples were collected. The treated water samples consisted of a ferric baseline sample and a ferric enhanced sample. The pilot-scale baseline and enhanced samples for Utility VT-8 were treated similarly to the procedure outlined in the previous paragraph for Utility VT-6, but at a coagulant dose of 25 mg/L. The pH values for the raw water samples

Table 4.3
Comparison of Pilot-Scale and Bench-Scale Treatment
for Utility VT-6 Alum Treatment

Sample	DOC (mg/L)	TOC* Reduction (%)	THMFP (µg/L)	THMFP Reduction (%)	DOXFP† (µg/L as Cl⁻)	DOXFP† Reduction (%)
<u>Bench-Scale Treatment</u>						
Raw	4.02‡	---	217	---	482	---
Enhanced§	2.48	38	187	14	233	52
<u>Pilot-Scale Treatment</u>						
Raw**	3.95‡	---	257	---	338	---
Baseline††	2.89	27	250	3	320	5
Raw‡‡	4.63‡	---	291	---	461	---
Enhanced§§	2.47	47	238	18	279	39

* TOC reduction is based on TOC of raw waters and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

‡ Values given for raw waters are TOC values.

§ 30 mg/L alum, coagulation pH = 5.5-5.6.

** Raw water used for baseline treatment.

†† 30 mg/L alum, coagulation pH = 7.6.

‡‡ Raw water used for enhanced treatment.

§§ 30 mg/L alum, coagulation pH = 6.6.

Table 4.4
Comparison of Pilot-Scale and Bench-Scale Treatment
for Utility VT-6 Iron Treatment

Sample	DOC (mg/L)	TOC* Reduction (%)	THMFP (µg/L)	THMFP Reduction (%)	DOXFP† (µg/L as Cl⁻)	DOXFP† Reduction (%)
<u>Bench-Scale Treatment</u>						
Raw	4.02‡	---	217	---	482	---
Enhanced§	2.03	50	119	45	237	51
<u>Pilot-Scale Treatment</u>						
Raw**	2.89‡	---	265	---	369	---
Baseline††	1.68	42	175	34	246	33
Enhanced‡‡	1.09	62	146	45	196	47

* TOC reduction is based on TOC of raw waters and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

‡ Values given for raw waters are TOC values.

§ 30 mg/L ferric sulfate, coagulation pH = 5.0-5.2.

** Raw water used for enhanced treatment.

†† 30 mg/L ferric chloride, coagulation pH = 7.2.

‡‡ 30 mg/L ferric chloride, coagulation pH = 5.8.

used for pilot-scale treatment were approximately 7.9. The pH value for the baseline treatment was 7.6 and the pH value for the enhanced treatment was 6.5.

By comparison, the raw water utilized during bench-scale treatment had a pH value of 8.1. The optimum pH range for ferric enhanced bench-scale treatment was 5.6-5.7.

For the pilot-plant samples, the TOC concentrations of the raw waters used for baseline and enhanced treatment were compared, and the values were similar. Therefore, formation potentials were analyzed only for the raw water used for ferric enhanced treatment.

Table 4.5 contains a comparison between the data for the bench-scale and pilot-scale iron treatment. The DOC and NPDOXFP reductions for the enhanced bench-scale and pilot-scale treatment were generally similar, with both being greater than the reductions for the pilot-scale baseline treatment.

Full-Scale Treatment

For each of the raw water samples received, a sample of full-scale settled (unfiltered) water and a sample of full-scale clearwell (filtered) water were also received. Water quality characteristics were analyzed for these full-scale treated waters, including DOC and UV254. The full-scale settled samples were filtered in the laboratory through a 1.5 μm filter prior to DOC or UV254 analysis. The clearwell samples (which had already been filtered at the water treatment plant) were not filtered in the laboratory prior to DOC or UV254 analysis. Table 4.6 contains a comparison of the DOC values for the bench-scale baseline treated waters, and the full-scale settled and clearwell waters. A comparison of the bench-scale UV254 values and the full-scale settled and clearwell UV254 values is contained in Appendix N. Formation potentials were not analyzed for the full-scale samples. The percentage differences between the DOC values for the bench-scale baseline treatment and the full-scale

Table 4.5
Comparison of Pilot-Scale and Bench-Scale Treatment
for Utility VT-8 Iron Treatment

Sample	DOC (mg/L)	TOC* Reduction (%)	THMFP (µg/L)	THMFP Reduction (%)	DOXFP† (µg/L as Cl⁻)	DOXFP† Reduction (%)
<u>Bench-Scale Treatment</u>						
Raw	2.79‡	---	116	---	194	---
Enhanced§	1.88	33	82	29	113	42
<u>Pilot-Scale Treatment</u>						
Raw**	3.22‡	---	128	---	191	---
Baseline††	2.33	28	117	9	149	22
Enhanced‡‡	1.30	60	245	(91)	104	46

* TOC reduction is based on TOC of raw waters and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

‡ Values given for raw waters are TOC values.

§ 25 mg/L ferric sulfate, coagulation pH = 5.6-5.7.

** Raw water used for enhanced treatment.

†† 25 mg/L ferric sulfate, coagulation pH = 7.6.

‡‡ 25 mg/L ferric sulfate, coagulation pH = 6.5.

Table 4.6
Comparison of Residual DOC Values for Bench-Scale Baseline Treatment
and Full-Scale Treatment

Sample	Raw Water TOC (mg/L)	Bench-Scale	Full-Scale		% Difference [†] (%)
		Finished DOC (mg/L)	Settled DOC* (mg/L)	Finished DOC* (mg/L)	
VT-1	5.32	2.53	2.91	3.18	-20.4
VT-2	2.56	1.32	1.30	1.21	9.1
VT-3	11.8	2.87	4.33	3.88	-26.0
VT-4	2.65	2.34	1.60	1.42	64.8
VT-5	9.41	4.84	5.35	6.02	-19.6
VT-6	4.02	3.07	2.92	3.03	1.3
VT-7	5.64	2.89	2.81	2.53	14.2
VT-8	2.73	2.87	2.66	2.50	14.8
VT-9	8.54	3.22	2.59	2.78	15.8

* Settled full-scale samples were filtered in laboratory through a 1.5 μ m filter prior to DOC analysis. Finished full-scale samples were not filtered in the laboratory prior to DOC analysis.

† Percentage difference is the difference between the bench-scale and the full-scale finished water results as a percentage of the full-scale finished water results.

finished water samples (as a percentage of the full-scale finished water DOC values) varied from -20 percent to 65 percent.

JAR TESTING AND DISINFECTION BY-PRODUCT FORMATION RESULTS

Utility VT-2

The drinking water supply for Utility VT-2 is a reservoir/river combination with low alkalinity, low TOC, average turbidity of less than 2 NTU, and average hardness of approximately 20 mg/L as CaCO₃. For the bench-scale testing of Utility VT-2, alum was the only coagulant utilized. The complete set of jar test and DBP results for Utility VT-2 is contained in Appendix B.

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-2 are presented in Figure 4.1. The pH optimization test was performed at an alum dose of 30 mg/L. Both DOC and UV254 results are included in Figure 4.1. These results indicate a minimum residual DOC concentration at a solution pH range of approximately 5.9-6.1, which was chosen as the optimum pH range.

Dose Optimization

The dose optimization procedure for Utility VT-2 was performed at coagulant doses ranging from 0 to 110 mg/L in 10 mg/L increments at the previously determined optimum pH range of 5.9-6.1. Both DOC and UV254 results are presented in Figure 4.2. The residual DOC begins to approach a constant minimum value (horizontal line) at an alum dose of approximately 30 mg/L. Residual DOC is at its lowest value at an

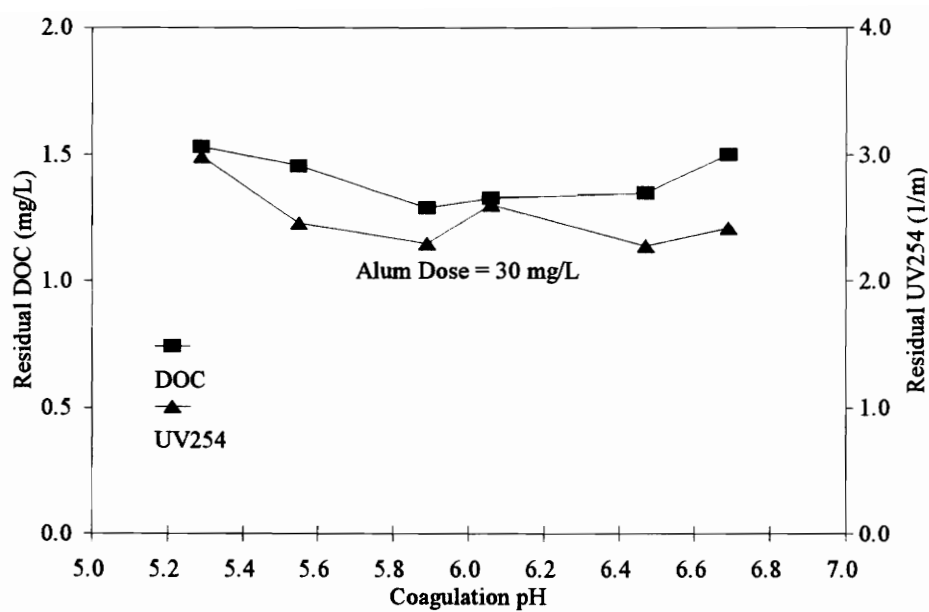


Figure 4.1. Residual DOC and UV254 as a function of coagulation pH for Utility VT-2 alum treatment.

alum dose of approximately 80 mg/L. The residual UV254 values follow the same trend. Alum doses of 30 mg/L and 80 mg/L were selected for the enhanced and optimized doses, respectively.

Figure 4.3 contains the specific UV absorbance (UV254/DOC) as a function of coagulant dose for Utility VT-2. The initial specific UV absorbance (SUVA) value was approximately 2.4 L/mg-m, with the value decreasing with increasing alum dose.

Residual Aluminum

The residual aluminum results for Utility VT-2 are presented in Figures 4.4 and 4.5. Figure 4.4 presents residual aluminum as a function of coagulation pH, while Figure 4.5 presents residual aluminum as a function of coagulant dose. Residual aluminum concentrations were at a minimum near pH 6.0. Likewise, residual aluminum concentrations following coagulation were generally comparable to the background aluminum level in the raw water.

Apparent Molecular Weight Distribution

The AMWD results for Utility VT-2 are presented in Figures 4.6 and 4.7. Figure 4.6 presents the DOC values for both raw and alum enhanced samples for each of the molecular weight fractions. Figure 4.7 presents the percentage removal of each weight fraction of organic material. With the exception of the <3K fraction, DOC values for the various molecular weight fractions decreased with treatment. The percentage reductions in DOC concentration of the higher molecular weight fractions were generally greater than the percentage reductions of the lower molecular weight fractions. The percentage removal of the 1K-3K fraction was negative and is not shown in Figure 4.7.

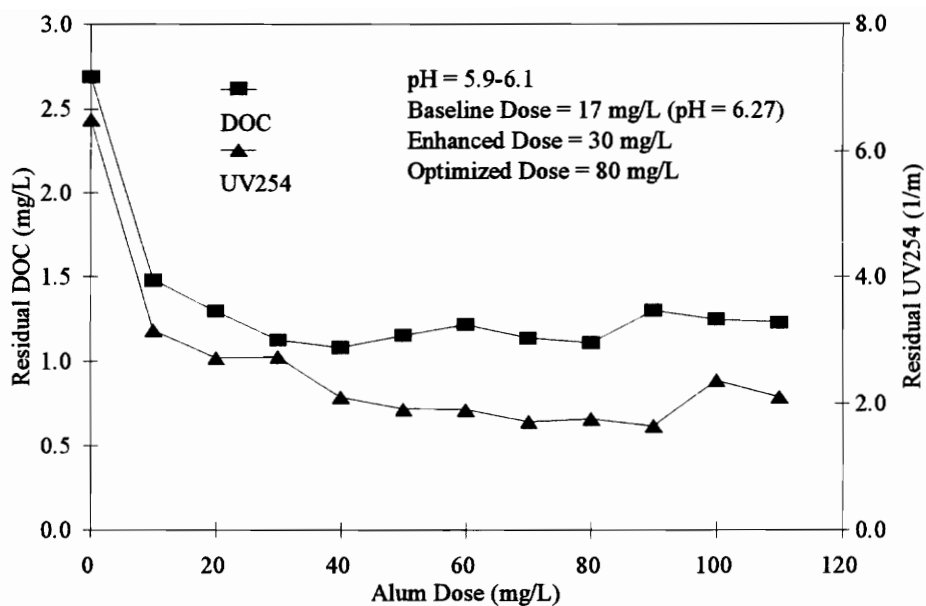


Figure 4.2. Residual DOC and UV254 as a function of alum dose for Utility VT-2 alum treatment.

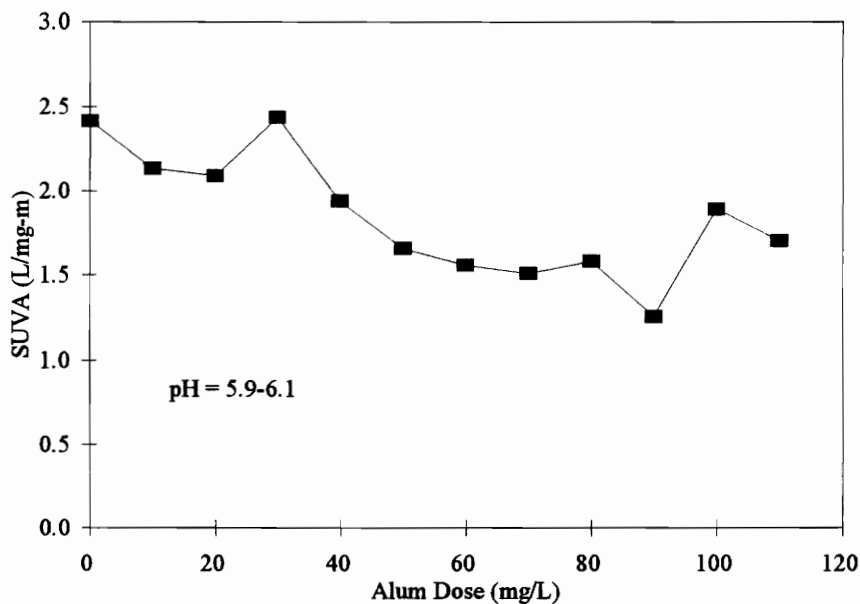


Figure 4.3. Specific UV absorbance as a function of alum dose for Utility VT-2 alum treatment.

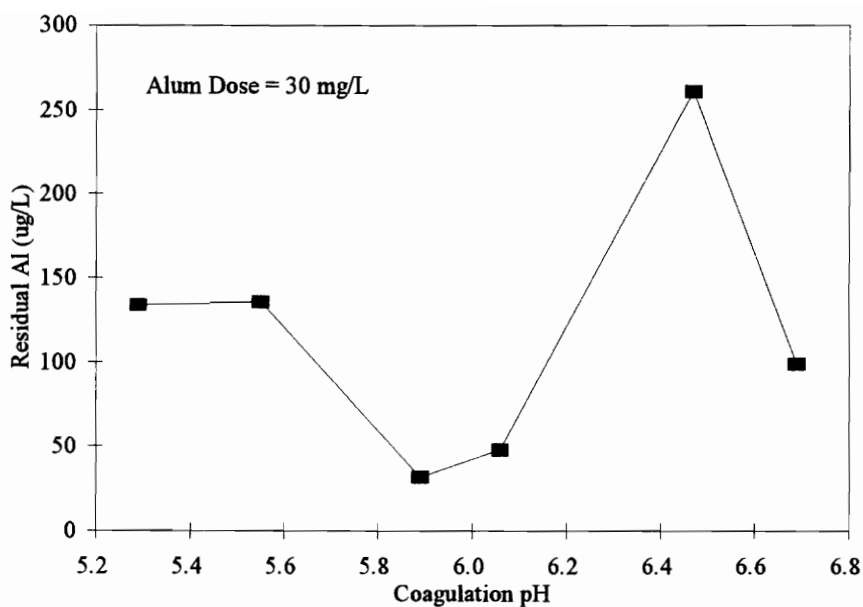


Figure 4.4. Residual aluminum as a function of coagulation pH for Utility VT-2 alum treatment.

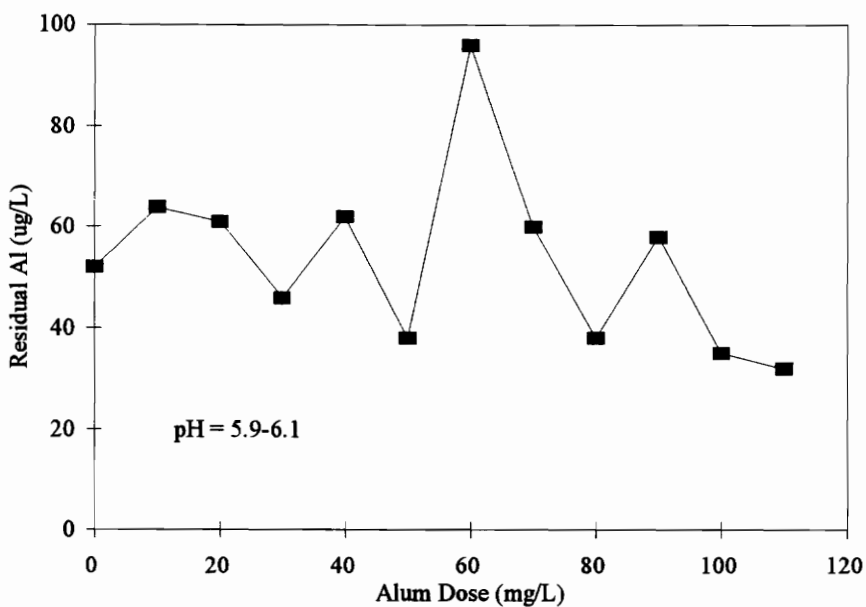


Figure 4.5. Residual aluminum as a function of coagulant dose for Utility VT-2 alum treatment.

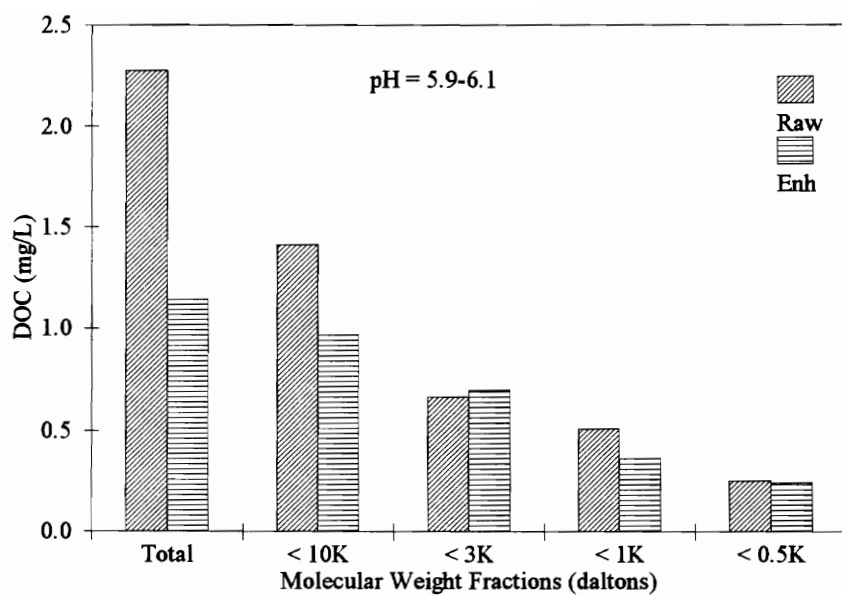


Figure 4.6. Apparent molecular weight distribution for raw and alum enhanced samples for Utility VT-2.

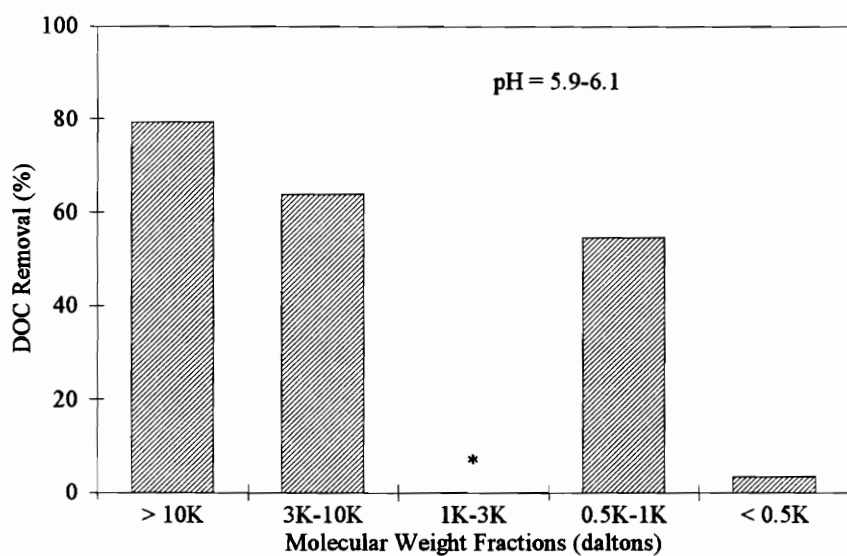


Figure 4.7. Percentage removals of DOC at alum enhanced dose for molecular weight fractions for Utility VT-2. (Note: * indicates values which were negative and are not included in this figure.)

Disinfection By-Product Formation

Table 4.7 includes the NPDOX and THM results for Utility VT-2 raw, baseline, enhanced, and optimized samples, while Table 4.8 correlates the NPDOX results with residual DOC, UV254, SUVA, and THMs. Table 4.9 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline, enhanced, and optimized treated samples. NPDOX and THM UFC and FP values generally decreased with increasing alum doses and corresponding decreasing DOC and UV254 values. NPDOX yield based on DOC generally decreased with treatment. For Utility VT-2, THMFP reduction was the largest, with TOC, UV254, and NPDOXFP reduction approximately equal, but less than THMFP reduction.

Utility VT-4

The drinking water supply for Utility VT-4 is a reservoir with low alkalinity, low TOC, average turbidity of approximately 1-2 NTU, and average hardness of approximately 25 mg/L as CaCO₃. Utility VT-4 utilizes direct filtration for treatment. For the bench-scale testing of Utility VT-4, both alum and ferric sulfate were examined. The complete set of jar test and DBP results for Utility VT-4 is contained in Appendix C.

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-4 for both alum and ferric sulfate treatment are presented in Figure 4.8. The DOC results only are included in Figure 4.8. The UV254 results are contained in Appendix C. The pH optimization was performed at a coagulant dose of 20 mg/L for alum and 15 mg/L for ferric sulfate. Minimum residual DOC values were seen at a solution pH range of approximately

Table 4.7
DOX and THM Values for Utility VT-2

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	2.56 (TOC) 2.28 (DOC)	4.25	---	---	226	409
Std. Dev.	---	---	---	---	3.0	48
Baseline						
Avg.	1.32	3.02	42	126	70	208
Std. Dev.	---	---	3.0	9.3	12	18
Enhanced						
Avg.	1.14	1.87	32	89	59	144
Std. Dev.	---	---	1.3	38	3.5	6.8
Optimized						
Avg.	1.09	2.02	---	---	66	209
Std. Dev.	---	---	---	---	2.0	20

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.8

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-2

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^-*\text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^-*$ $\text{mg}*m$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	96	42	55	3.0
Enhanced UFC	78	48	54	2.9
Raw FP	180	96	219	1.8
Baseline FP	158	69	91	3.0
Enhanced FP	126	77	88	2.4
Optimized FP	192	103	113	3.2

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.9

Percentage Reduction of TOC, UV254, THMFP and DOXFP for Treated Samples for Utility VT-2

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	48	29	69	49
Enhanced	55	56	74	65
Optimized	57	52	71	49

* TOC reduction is based on TOC of raw water and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

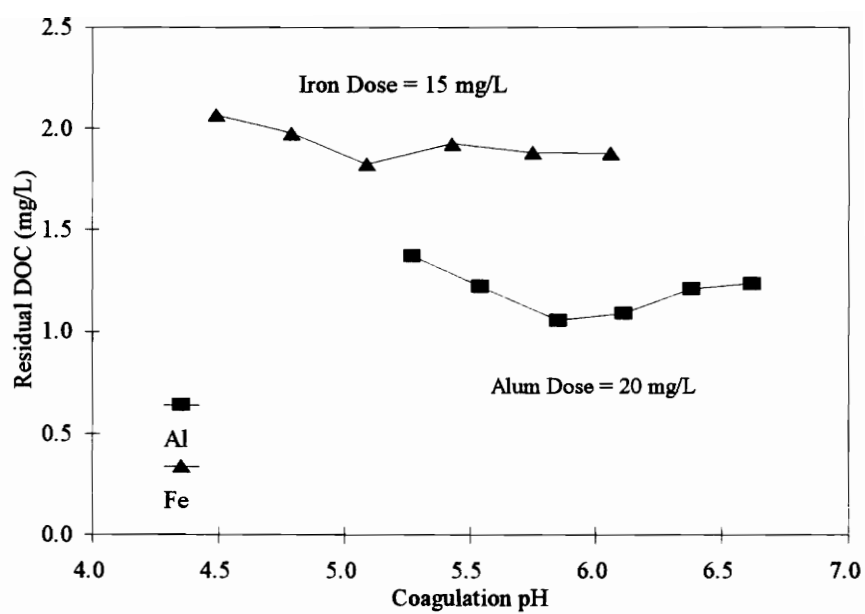


Figure 4.8. Residual DOC as a function of coagulation pH for Utility VT-4 alum and ferric sulfate treatment.

5.8-6.0 for alum and 5.0-5.2 for ferric sulfate. These pH ranges were chosen as the optimum pH ranges.

Dose Optimization

The dose optimization procedure for Utility VT-4 was performed at coagulant doses ranging from 0 to 110 mg/L in 10 mg/L increments for alum and from 0 to 80 mg/L in 10 mg/L for ferric sulfate, each at the respective optimum pH ranges. Both DOC and UV254 results are presented in Figure 4.9 for alum, and in Figure 4.10 for ferric sulfate. The DOC curves begin to approach a constant minimum value at an alum dose of approximately 20 mg/L and a ferric sulfate dose of approximately 20 mg/L. These coagulant doses were chosen as the enhanced doses. The DOC curves for alum and ferric sulfate reach a minimum at a coagulant dose of approximately 50 mg/L. This was chosen as the optimized dose for both coagulants. A spike in residual UV254 was present at low ferric sulfate doses.

Specific UV absorbance as a function of both alum and ferric sulfate dose is presented in Figure 4.11. Initial SUVA was approximately 2.2 L/mg-m. A spike in SUVA was seen at low ferric sulfate doses due to the spike in residual UV254 at these low doses.

Residual Coagulant

The residual coagulant results for Utility VT-4 are presented in Figures 4.12 and 4.13. Figure 4.12 presents residual coagulant as a function of coagulation pH, while Figure 4.13 presents residual coagulant as a function of coagulant dose. Both residual iron and residual aluminum results are contained in Figures 4.12 and 4.13. Residual aluminum concentrations following coagulation were at a minimum near a pH value of 6.2. Likewise, aluminum concentrations following coagulation were

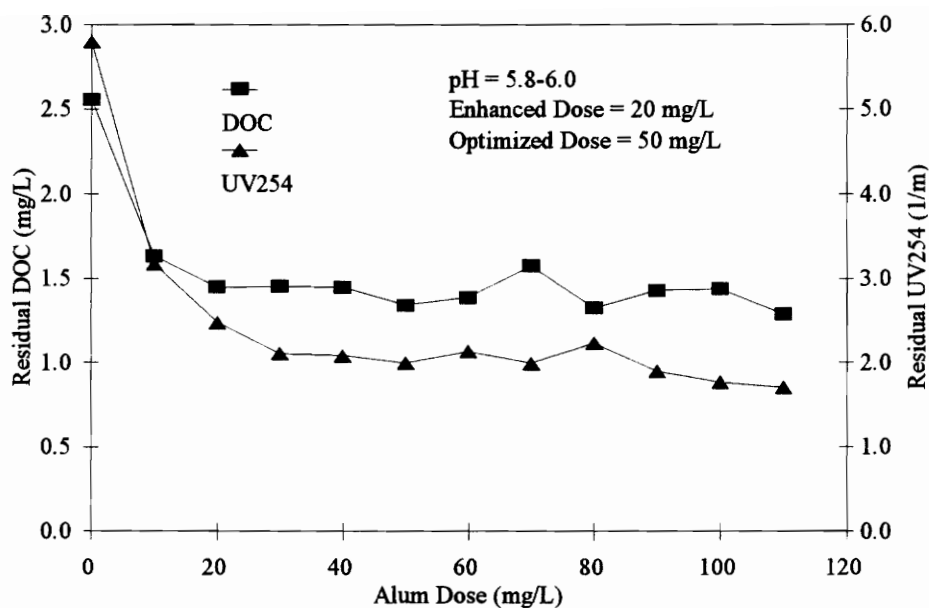


Figure 4.9. Residual DOC and UV254 as a function of alum dose for Utility VT-4 alum treatment.

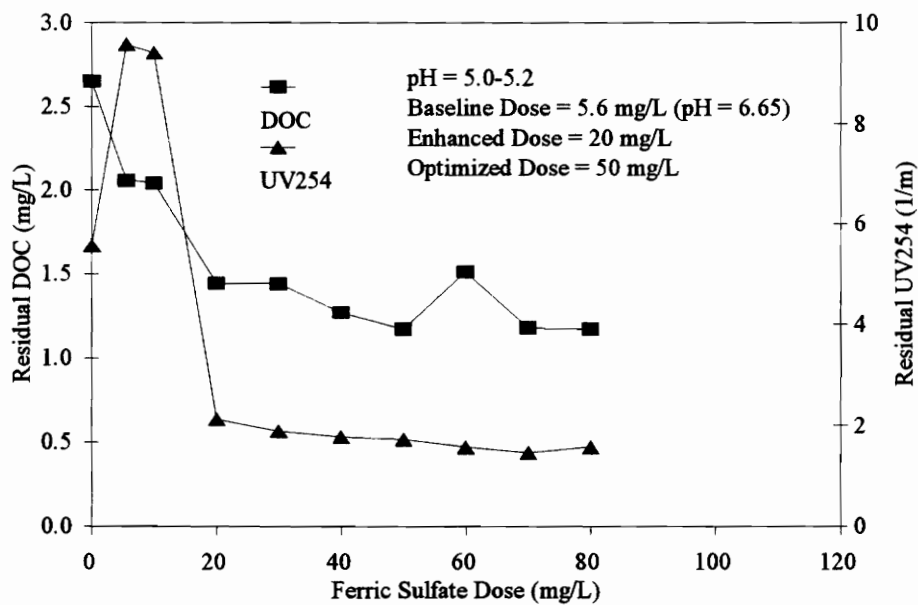


Figure 4.10. Residual DOC and UV254 as a function of ferric sulfate dose for Utility VT-4 ferric sulfate treatment.

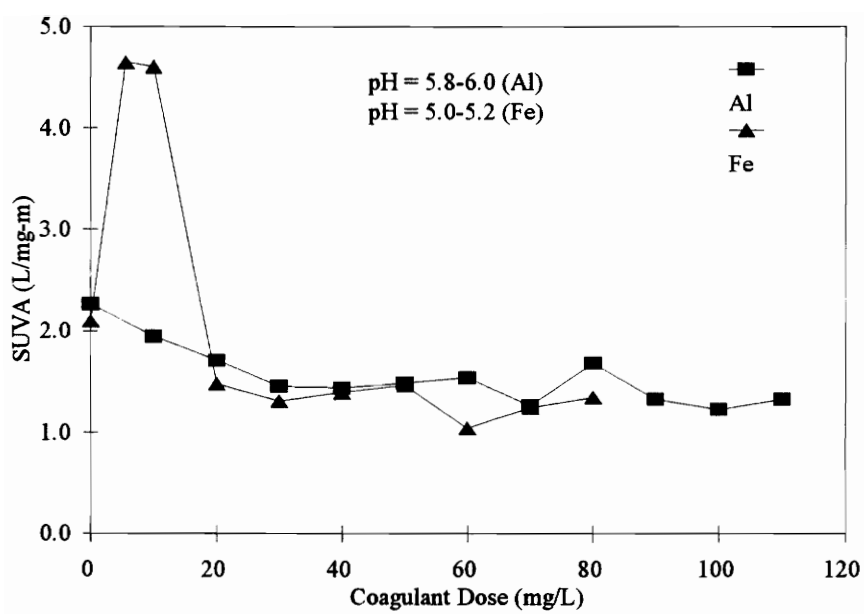


Figure 4.11. Specific UV absorbance as a function of coagulant dose for Utility VT-4 alum and ferric sulfate treatment.

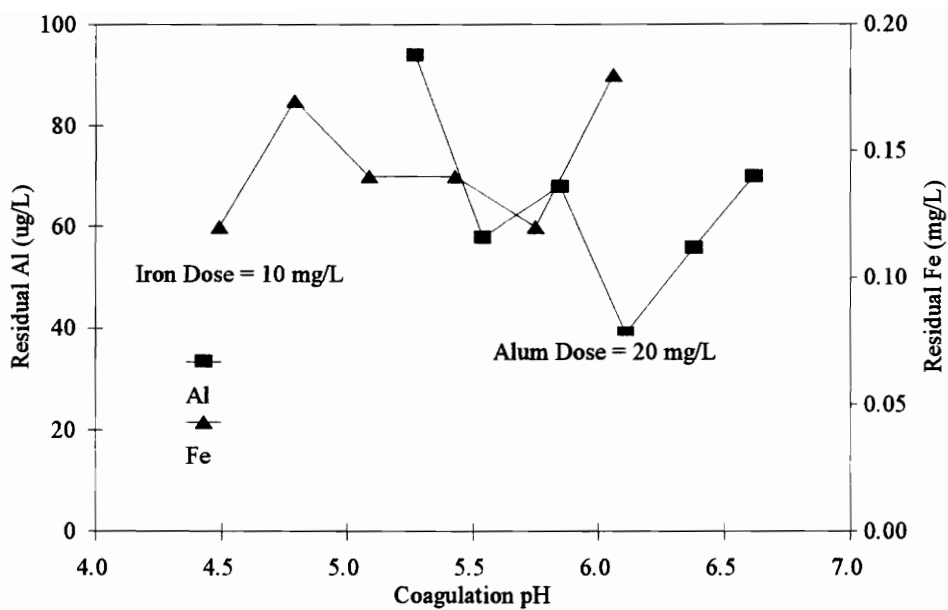


Figure 4.12. Residual coagulant as a function of coagulation pH for Utility VT-4 alum and ferric sulfate treatment.

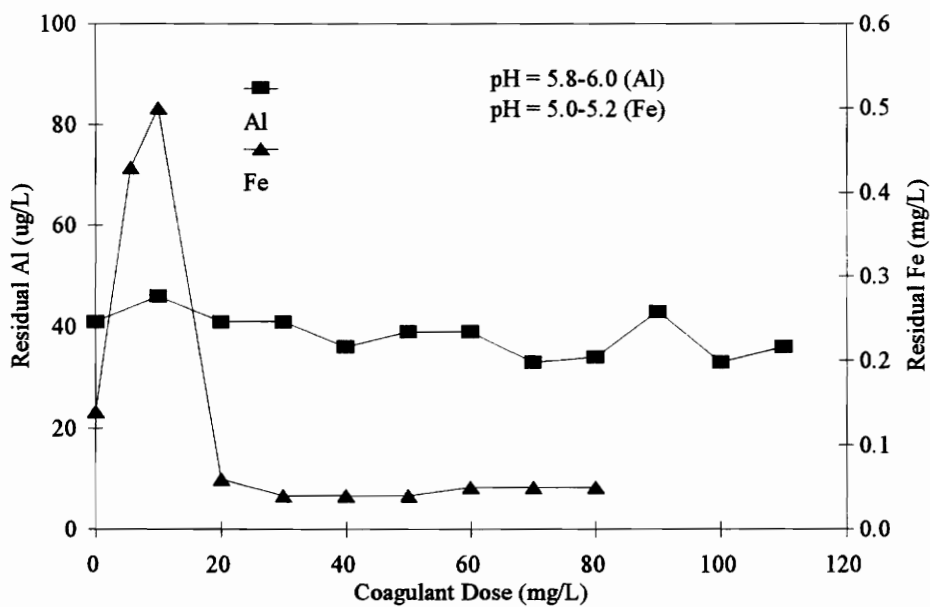


Figure 4.13. Residual coagulant as a function of coagulant dose for Utility VT-4 alum and ferric sulfate treatment.

generally comparable to background aluminum concentrations. Residual iron concentrations did not follow a distinct trend with pH although the minimum residual iron concentration occurred at a pH of approximately 5.7. Residual iron concentrations decreased with increasing ferric sulfate dose, with a spike in residual iron concentrations occurring at low ferric sulfate doses.

Apparent Molecular Weight Distribution

The AMWD results for both coagulants for Utility VT-4 are presented in Figures 4.14 and 4.15. Figure 4.14 presents the DOC values for both raw and enhanced samples for each of the molecular weight fractions. Figure 4.15 presents the percentage removal of each weight fraction of organic material. Treatment decreased the amount of higher molecular weight fractions for both alum and ferric sulfate. The percentage removals in each molecular weight fraction were greater for ferric sulfate coagulation than for alum coagulation.

Disinfection By-Product Formation

Table 4.10 includes the NPDOX and THM results for Utility VT-4 raw, baseline, enhanced, and optimized samples, while Table 4.11 correlates the NPDOX results with residual DOC, UV254, SUVA, and THMs. Table 4.12 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline, enhanced, and optimized treated samples. Results for both aluminum and iron coagulation are included in each table. NPDOX and THM values for both the UFC and FP tests generally decreased with decreasing organic content of the waters. The UV254 values at the baseline ferric sulfate dose (5.6 mg/L) were greater than the UV254 values for the raw water. NPDOX correlated well with DOC, with the NPDOX/DOC ratio approximately 50 $\mu\text{g}/\text{mg}$ TOC for the UFC tests and approximately 100-120 $\mu\text{g}/\text{mg}$

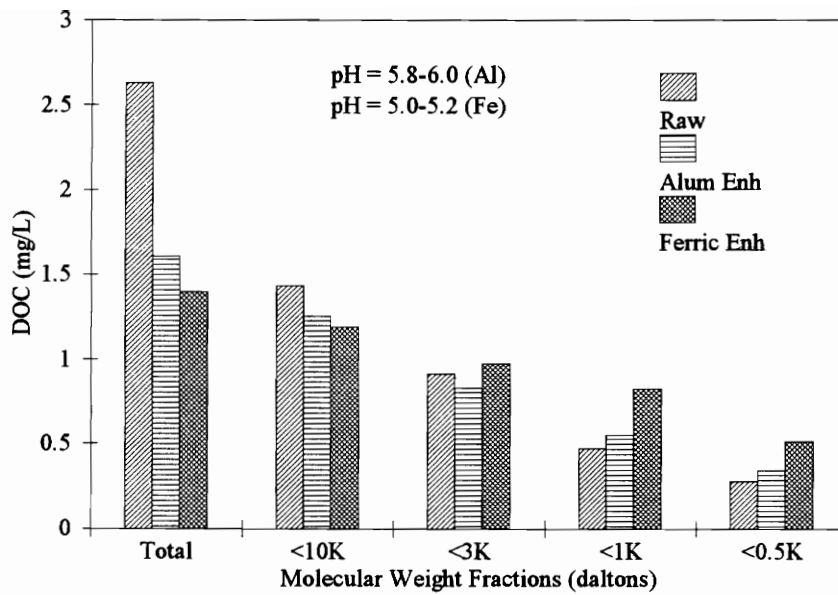


Figure 4.14. Apparent molecular weight distribution for raw, alum enhanced, and ferric enhanced samples for Utility VT-4.

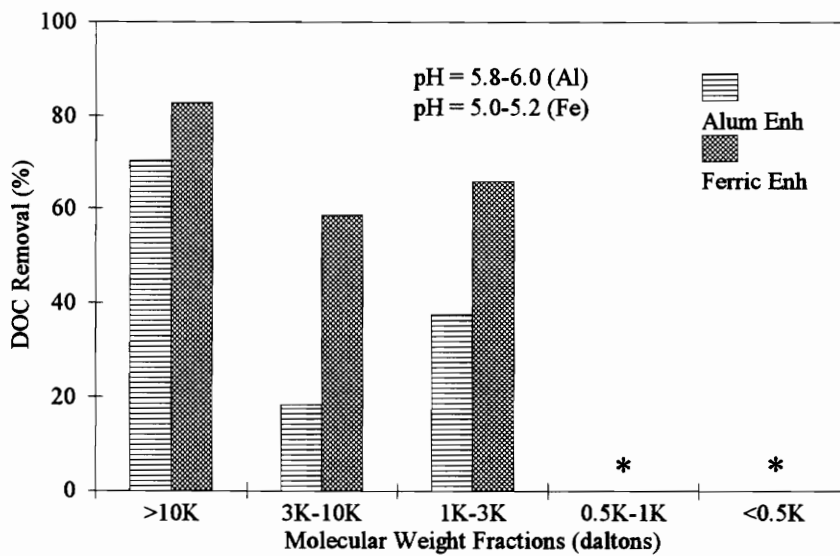


Figure 4.15. Percentage removals of DOC at alum enhanced and ferric enhanced doses for molecular weight fractions for Utility VT-4. (Note: * indicates values which were negative and are not included in this figure.)

Table 4.10
DOX and THM Values for Utility VT-4

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	2.65 (TOC) 2.63 (DOC)	5.75	---	---	138	262
Std. Dev.	---	---	---	---	2.9	9.2
Baseline						
Avg.	2.34	7.03	72	119	127	234
Std. Dev.	---	---	2.4	1.4	5.8	26
Alum Enh						
Avg.	1.61	2.64	35	87	75	195
Std. Dev.	---	---	1.1	11	4.4	25
Ferric Enh						
Avg.	1.39	2.07	51	65	70	161
Std. Dev.	---	---	10	15	1.7	7.1
Alum Opt						
Avg.	1.38	1.97	---	---	72	165
Std. Dev.	---	---	---	---	1.8	7.1
Ferric Opt						
Avg.	1.09	1.71	---	---	59	135
Std. Dev.	---	---	---	---	2.0	38

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.11

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-4

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^-*\text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^-*$ $\text{mg}* \text{m}$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	51	17	39	1.6
Alum Enh UFC	54	33	53	2.5
Ferric Enh UFC	47	31	44	1.3
Raw FP	99	45	119	1.9
Baseline FP	100	33	78	1.8
Alum Enh FP	121	74	119	2.6
Ferric Enh FP	116	77	107	2.3
Alum Opt FP	120	84	116	2.3
Ferric Opt FP	124	79	86	2.3

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.12
Percentage Reduction of TOC, UV254, THMFP and DOXFP for
Treated Samples for Utility VT-4

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	12	(22)	8	11
Alum Enh	39	54	46	25
Ferric Enh	48	64	49	39
Alum Opt	48	66	48	37
Ferric Opt	59	70	57	48

* TOC reduction is based on TOC of raw water and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

TOC for the FP tests. NPDOX yield based on DOC was slightly less for the raw water than for the treated water. The relative percentage reductions of the four parameters generally corresponded to the following trend: UV254 > THMFP = TOC > NPDOXFP.

Utility VT-7

The drinking water supply for Utility VT-7 is a river with low alkalinity, moderate TOC, average turbidity of approximately 10 NTU, and average hardness of approximately 80 mg/L as CaCO₃. For the bench-scale testing of Utility VT-7, both alum and ferric sulfate were examined. The complete set of jar test and DBP results for Utility VT-7 is contained in Appendix D.

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-7 for both alum and ferric sulfate treatment are presented in Figure 4.16. The DOC results only are included in Figure 4.16. The UV254 results are contained in Appendix D. The pH optimization was performed at a coagulant dose of 25 mg/L for alum and 20 mg/L for ferric sulfate. Although the residual DOC values continue to decrease slightly at lower pH values, the residual DOC values for alum coagulation level out at a pH value of approximately 5.9-6.1. Therefore, an optimum pH range of 5.9-6.1 was chosen for alum. For ferric sulfate coagulation, the residual DOC values also decrease as pH decreases over the entire range of pH values. An optimum pH range of 4.9-5.1 was chosen for ferric sulfate because a full-scale water treatment plant could not lower the coagulation pH below this value due to corrosion considerations. The optimum pH ranges chosen for both coagulants were consistent with optimum pH values seen for other utilities.

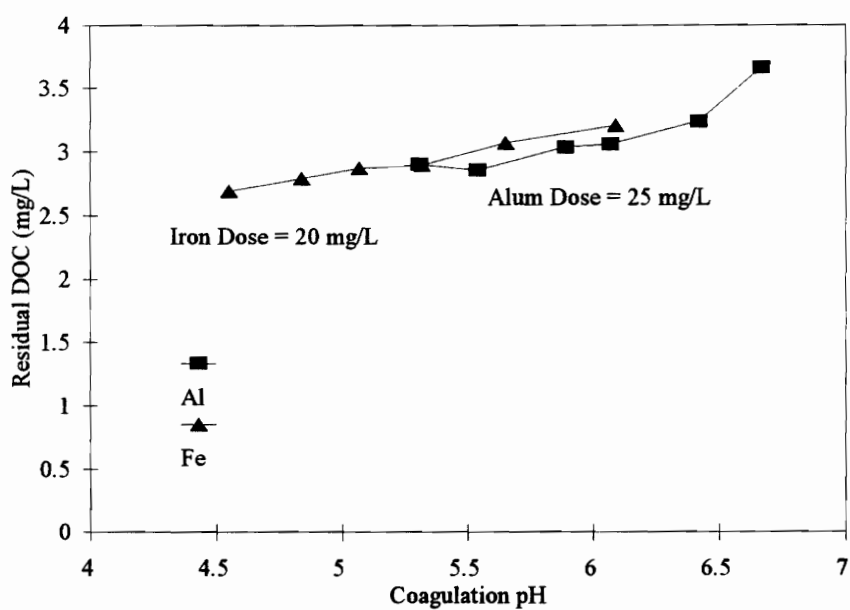


Figure 4.16. Residual DOC as a function of coagulation pH for Utility VT-7 alum and ferric sulfate treatment.

Dose Optimization

The dose optimization procedure for Utility VT-7 was performed at coagulant doses ranging from 0 to 110 mg/L in 10 mg/L increments for both alum and ferric sulfate at the previously described optimum pH ranges. Both DOC and UV254 results are presented in Figure 4.17 for alum, and in Figure 4.18 for ferric sulfate. The DOC and UV254 results followed closely the same trend for both alum and ferric sulfate except for a spike in residual UV254 at low ferric sulfate doses. The DOC curves begin to approach a constant minimum value at an alum dose of approximately 30 mg/L and a ferric sulfate dose of approximately 40 mg/L; these coagulant doses were chosen as the enhanced doses. The DOC values reach a minimum at an approximate coagulant dose of 90 mg/L for alum and 80 mg/L for ferric sulfate. These doses were chosen as the optimized doses.

Specific UV absorbance as a function of both alum and ferric sulfate dose is presented in Figure 4.19. The SUVA value for Utility VT-7 raw water was approximately 2.5 L/mg-m. The SUVA values decreased with treatment. A spike in SUVA was seen at low ferric sulfate doses due to the spike in residual UV254 at these low doses.

Residual Coagulant

The residual coagulant results for Utility VT-7 are presented in Figures 4.20 and 4.21. Figure 4.20 presents residual coagulant as a function of coagulation pH, while Figure 4.21 presents residual coagulant as a function of coagulant dose. Both residual iron and residual aluminum results are contained in Figures 4.20 and 4.21. Residual aluminum concentrations were at a minimum near pH 6.0, which was the optimum pH for organics removal. Likewise, residual aluminum concentrations following coagulation generally decreased below background aluminum concentrations,

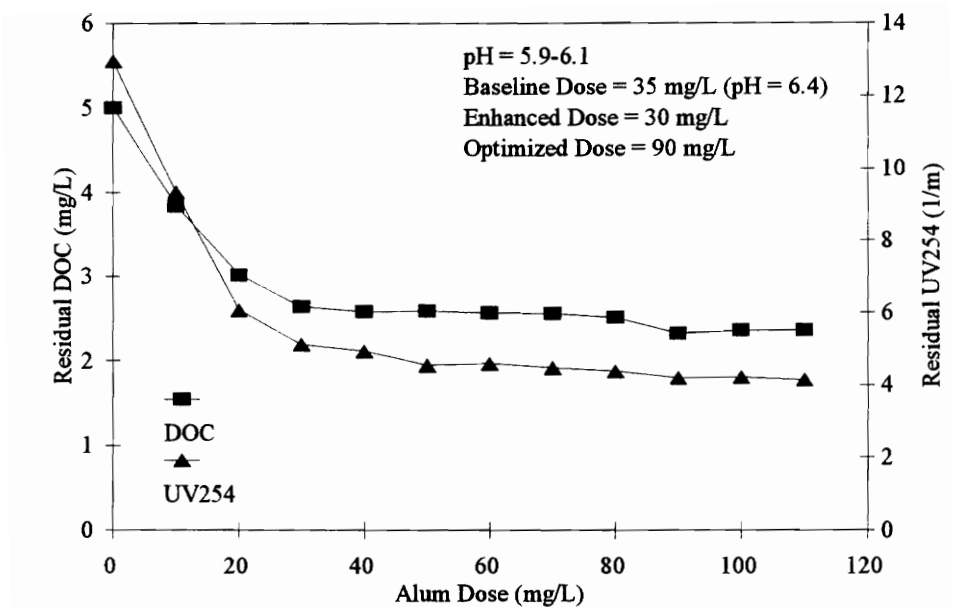


Figure 4.17. Residual DOC and UV254 as a function of alum dose for Utility VT-7 alum treatment.

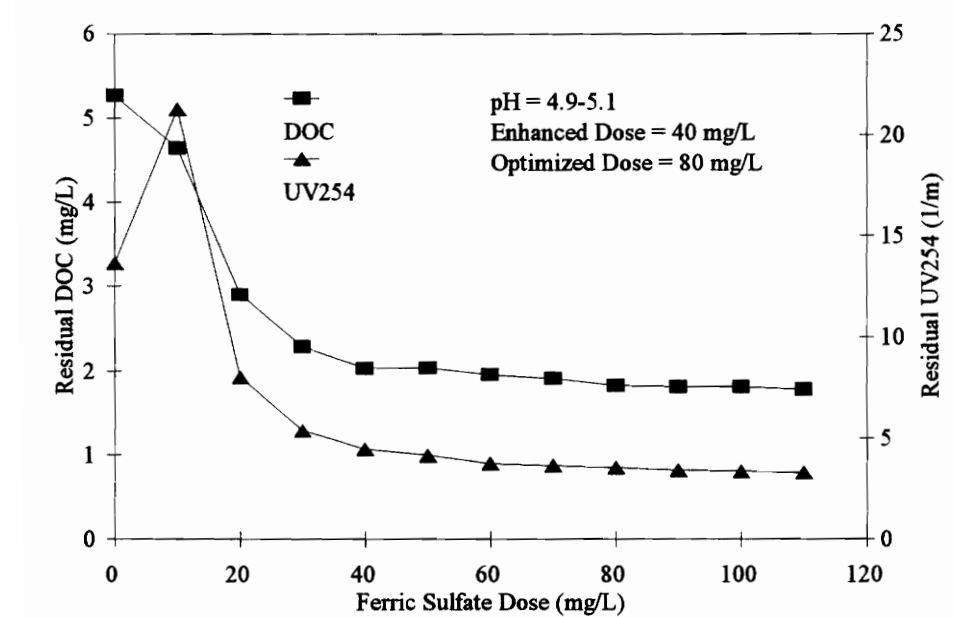


Figure 4.18. Residual DOC and UV254 as a function of ferric sulfate dose for Utility VT-7 ferric sulfate treatment.

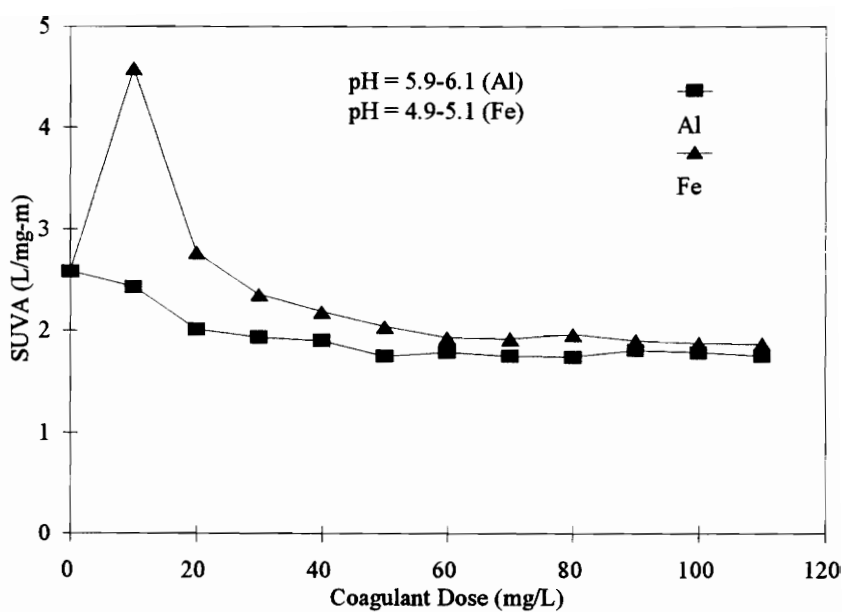


Figure 4.19. Specific UV absorbance as a function of coagulant dose for Utility VT-7 alum and ferric sulfate treatment.

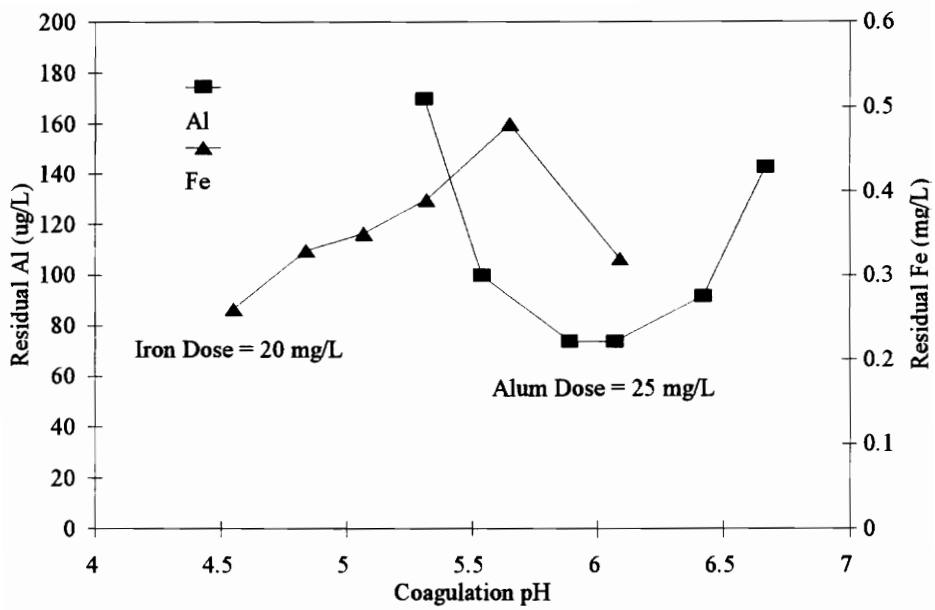


Figure 4.20. Residual coagulant as a function of coagulation pH for Utility VT-7 alum and ferric sulfate treatment.

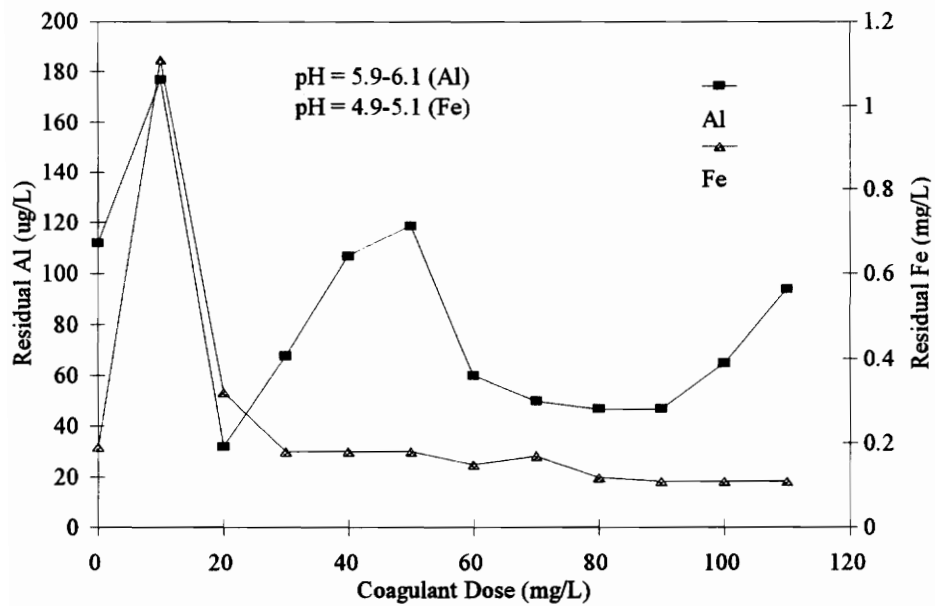


Figure 4.21. Residual coagulant as a function of coagulant dose for Utility VT-7 alum and ferric sulfate treatment. (File: vt7jarpr.wb1:doserescoag)

with a spike in residual aluminum at low coagulant doses. Residual iron concentrations generally decreased with decreasing pH and no minimum value was seen, similar to the trend seen for the residual DOC results as a function of pH. Residual iron concentrations following treatment were generally comparable to background iron concentrations, with a spike in residual iron concentrations occurring at low ferric sulfate doses.

Apparent Molecular Weight Distribution

The AMWD results for both coagulants for Utility VT-7 are presented in Figures 4.22 and 4.23. Figure 4.22 presents the DOC values for both raw and enhanced samples for each of the molecular weight fractions. Figure 4.23 presents the percentage removal of each weight fraction of organic material. Treatment removed a large percentage of the higher molecular weight fractions, but removed only a small percentage of the DOC fraction less than 1,000 daltons. The percentage removals in each molecular weight fraction were higher for ferric sulfate coagulation than for alum coagulation.

Disinfection By-Product Formation

Table 4.13 includes the NPDOX and THM results for Utility VT-7 raw, baseline, enhanced, and optimized samples, while Table 4.14 correlates the NPDOX results with residual DOC, UV254, SUVA, and THMs. Table 4.15 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline, enhanced, and optimized treated samples. Results for both aluminum and iron coagulation are included in each table. NPDOX and THM values for both the UFC and FP tests generally correlated well with the organic content of the waters. NPDOX correlated well with THM values, with the NPDOX/THM ratio approximately 4.2 $\mu\text{g as Cl}^-/\mu\text{g}$

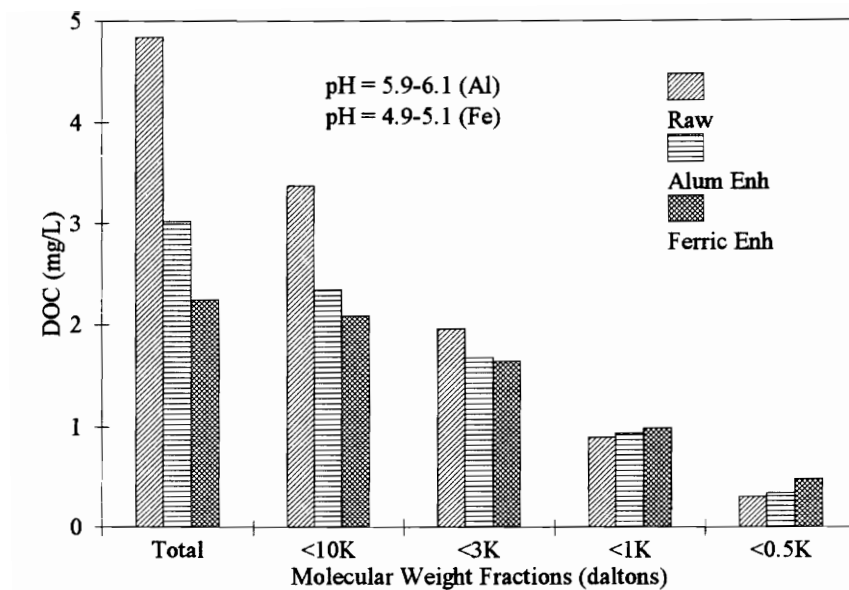


Figure 4.22. Apparent molecular weight distribution for raw, alum enhanced, and ferric enhanced samples for Utility VT-7.

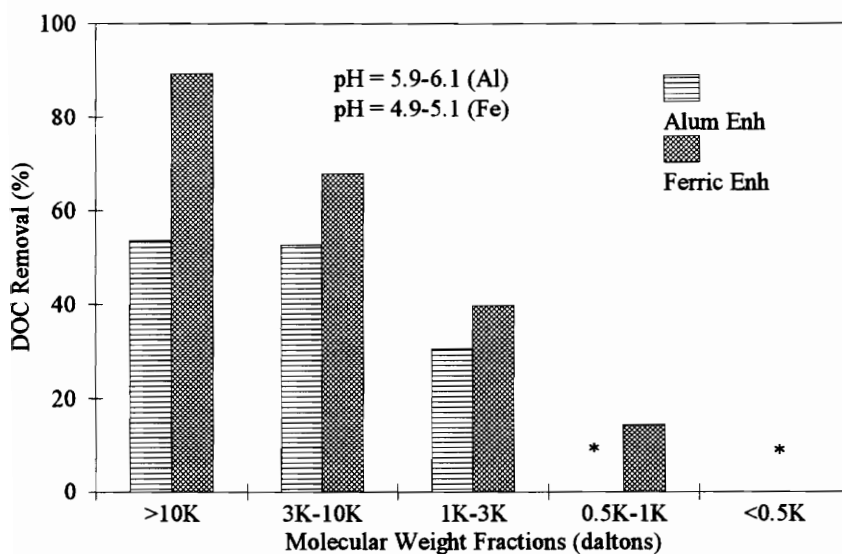


Figure 4.23. Percentage removals of DOC at alum enhanced and ferric enhanced doses for molecular weight fractions for Utility VT-7. (Note: * indicates values which were negative and are not included in this figure.)

Table 4.13
DOX and THM Values for Utility VT-7

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	5.64 (TOC) 4.84 (DOC)	13.3	---	---	326	916
Std. Dev.	---	---	---	---	6.8	69
Baseline						
Avg.	2.89	5.79	70	305	202	375
Std. Dev.	---	---	1.2	8.8	4.5	13
Alum Enh						
Avg.	3.02	5.83	69	298	203	454
Std. Dev.	---	---	7.1	1.4	3.6	24
Ferric Enh						
Avg.	2.24	4.31	53	222	139	302
Std. Dev.	---	---	1.2	3.9	6.7	11
Alum Opt						
Avg.	2.51	4.73	---	---	165	385
Std. Dev.	---	---	---	---	5.2	12
Ferric Opt						
Avg.	2.46	3.63	---	---	128	278
Std. Dev.	---	---	---	---	3.3	4.6

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.14

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-7

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^- \cdot \text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^- \cdot \text{mg} \cdot \text{m}$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	106	53	152	4.4
Alum Enh UFC	99	51	155	4.3
Ferric Enh UFC	99	52	116	4.1
Raw FP	190	69	333	2.8
Baseline FP	130	65	187	1.9
Alum Enh FP	150	78	236	2.2
Ferric Enh FP	135	70	157	2.2
Alum Opt FP	152	82	207	2.3
Ferric Opt FP	113	77	190	2.2

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.15
Percentage Reduction of TOC, UV254, THMFP and DOXFP for
Treated Samples for Utility VT-7

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	48	56	38	59
Alum Enh	46	56	38	50
Ferric Enh	60	68	58	67
Alum Opt	55	65	50	58
Ferric Opt	56	73	61	70

* TOC reduction is based on TOC of raw water and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

for the UFC tests and approximately 2.2 µg as Cl⁻/µg for the FP tests for the treated waters. NPDOX yield based on DOC generally decreased with treatment. The relative percentage reductions of the four parameters generally corresponded to the following trend: UV254 > NPDOXFP > TOC > THMFP.

Utility VT-9

The drinking water supply for Utility VT-9 is a reservoir with low alkalinity, high TOC, average turbidity of approximately 20 NTU, and average hardness of approximately 20 mg/L as CaCO₃. For the bench-scale testing of Utility VT-9, both alum and ferric sulfate were examined. The complete set of jar test and DBP results for Utility VT-9 is contained in Appendix E.

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-9 for both alum and ferric sulfate treatment are presented in Figure 4.24. The DOC results only are included in Figure 4.24. The UV254 results are contained in Appendix E. The pH optimization was performed at a coagulant dose of 25 mg/L for alum and 20 mg/L for ferric sulfate. Minimum residual DOC values were seen at a solution pH range of approximately 6.0-6.2 for alum coagulation. This pH range was chosen as the optimum pH range. Residual DOC values were approximately constant below a pH of approximately 5.7 for ferric sulfate. Therefore, an optimum pH range of 5.5-5.7 was chosen for ferric sulfate.

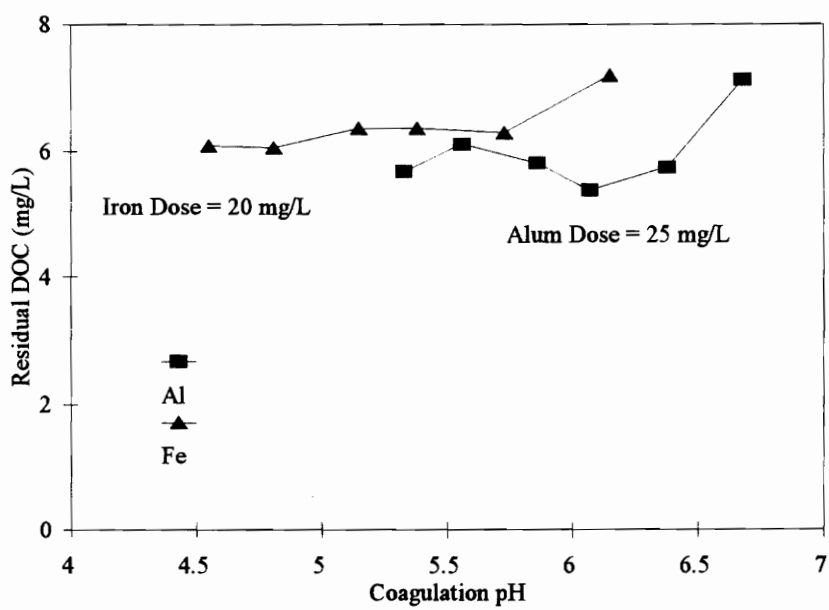


Figure 4.24. Residual DOC as a function of coagulation pH for Utility VT-9 alum and ferric sulfate treatment.

Dose Optimization

The dose optimization procedure for Utility VT-9 was performed at coagulant doses ranging from 0 to 150 mg/L for both alum and ferric sulfate at the previously determined optimum pH ranges. Both DOC and UV254 results are presented in Figure 4.25 for alum, and in Figure 4.26 for ferric sulfate. The DOC and UV254 results followed closely the same trend for both alum and ferric sulfate, except for a spike in residual UV254 which was seen at a ferric sulfate dose of 30 mg/L. A spike in residual UV254 was not seen at a ferric sulfate dose of 20 mg/L. The DOC and UV254 curves begin to approach a constant minimum value at an alum dose of approximately 60 mg/L and a ferric sulfate dose of approximately 60 mg/L; therefore, these coagulant doses were chosen as the enhanced doses. The DOC values reach a minimum at an approximate coagulant dose of 130 mg/L for alum and 110 mg/L for ferric sulfate. These doses were chosen as the optimized doses.

Specific UV absorbance as a function of both alum and ferric sulfate dose is presented in Figure 4.27. The SUVA value for Utility VT-9 raw water was approximately 6.0 L/mg-m. The SUVA values decreased with treatment. A spike in SUVA was seen at a ferric sulfate dose of 30 mg/L due to the spike in residual UV254.

Residual Coagulant

The residual coagulant results for Utility VT-9 are presented in Figures 4.28 and 4.29. Figure 4.28 presents residual coagulant as a function of coagulation pH, while Figure 4.29 presents residual coagulant as a function of coagulant dose. Both residual iron and residual aluminum results are contained in Figures 4.28 and 4.29. Residual aluminum concentrations were at a minimum near pH 6.0, while residual iron concentrations were at a minimum near pH 5.7. These pH values were also the

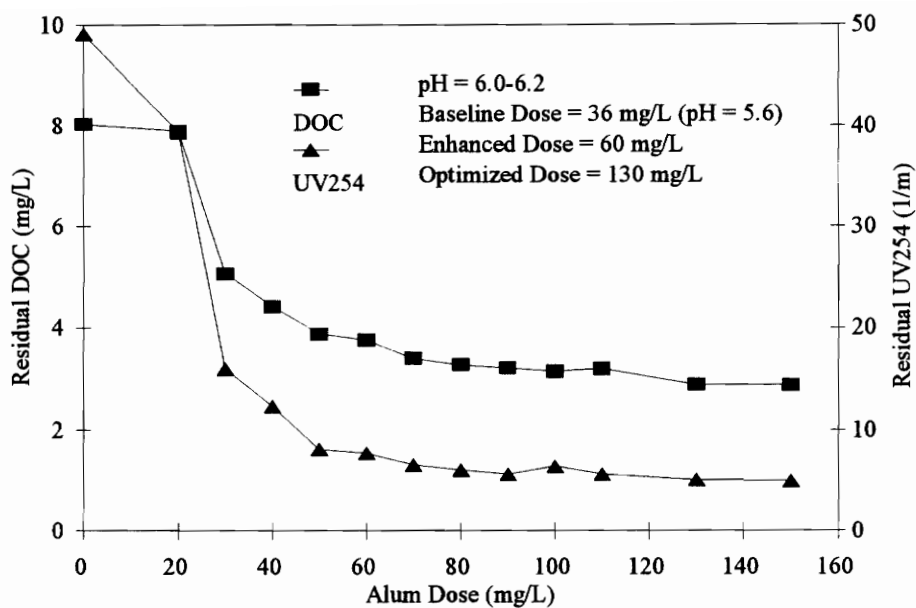


Figure 4.25. Residual DOC and UV254 as a function of alum dose for Utility VT-9 alum treatment.

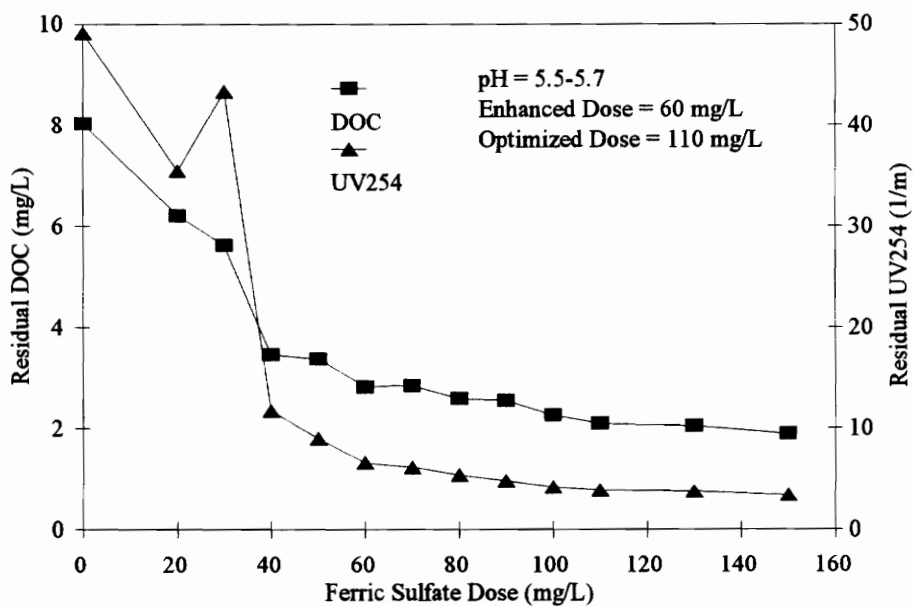


Figure 4.26. Residual DOC and UV254 as a function of ferric sulfate dose for Utility VT-9 ferric sulfate treatment.

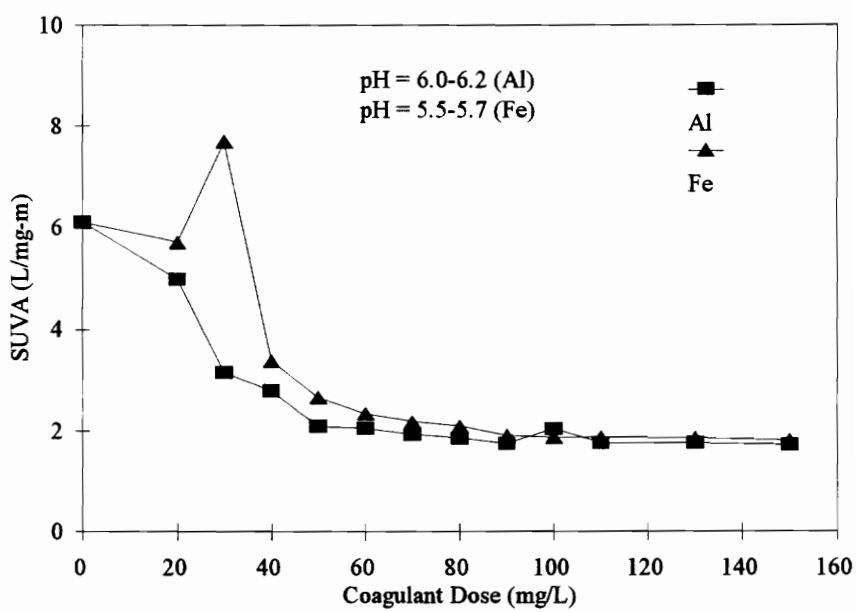


Figure 4.27. Specific UV absorbance as a function of coagulant dose for Utility VT-9 alum and ferric sulfate treatment.

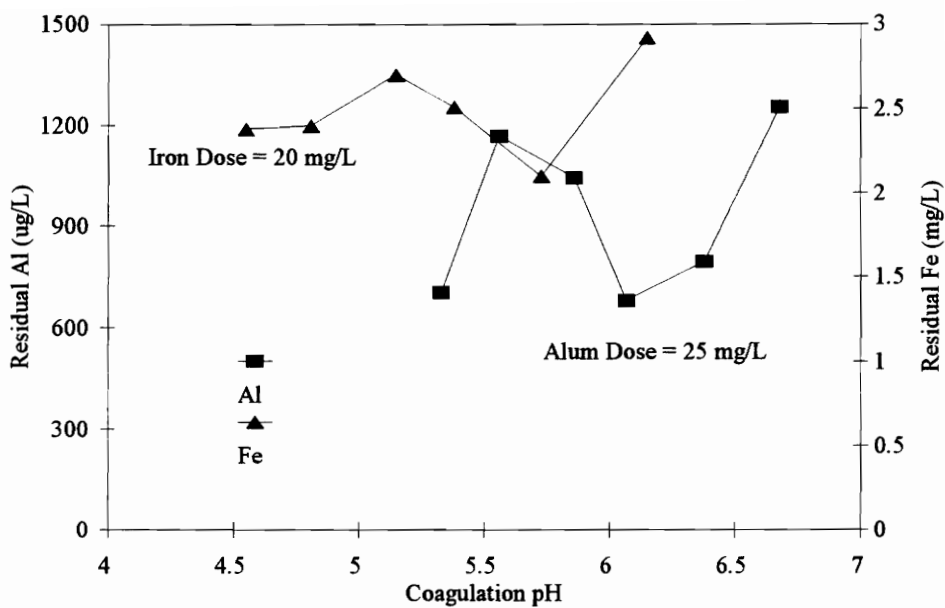


Figure 4.28. Residual coagulant as a function of coagulation pH for Utility VT-9 alum and ferric sulfate treatment.

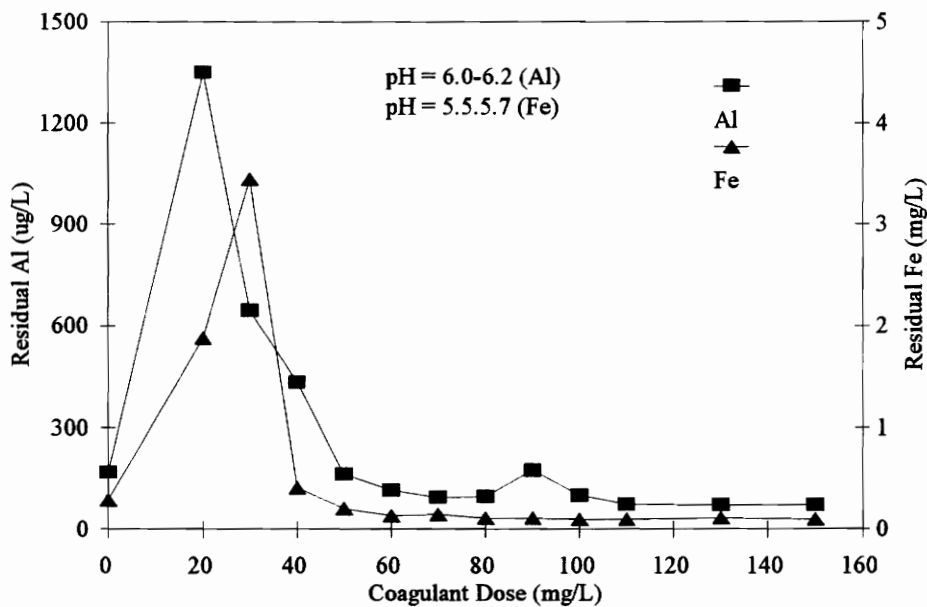


Figure 4.29. Residual coagulant as a function of coagulant dose for Utility VT-9 alum and ferric sulfate treatment.

optimum pH values for organics removal. Aluminum and iron concentrations were generally comparable to background concentrations except at low coagulant doses, for which high residual coagulant levels were seen.

Apparent Molecular Weight Distribution

The AMWD results for both coagulants for Utility VT-9 are presented in Figures 4.30 and 4.31. Figure 4.30 presents the DOC values for both raw and enhanced samples for each of the molecular weight fractions. Figure 4.31 presents the percentage removal of each weight fraction of organic material. Treatment generally decreased the amount of higher molecular weight fractions for both alum and ferric sulfate, with the greatest removal occurring in the DOC range greater than 10,000 daltons.

Disinfection By-Product Formation

Table 4.16 includes the NPDOX and THM results for Utility VT-9 raw, baseline, enhanced, and optimized samples, while Table 4.17 correlates the NPDOX results with residual DOC, UV254, SUVA, and THMs. Table 4.18 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline, enhanced, and optimized treated samples. Results for both aluminum and iron coagulation are included in each table. NPDOX and THM values generally decreased with decreasing organic content. NPDOX correlated well with both DOC and THM values, with the NPDOX/DOC ratio ranging from approximately 65-80 $\mu\text{g as Cl}^-/\text{mg TOC}$ for the UFC tests and ranging from approximately 120-140 $\mu\text{g as Cl}^-/\text{mg TOC}$ for the FP tests for the treated waters. The NPDOX yield based on DOC generally decreased with treatment, and was almost 200 $\mu\text{g as Cl}^-/\text{mg TOC}$ for the raw water. The relative

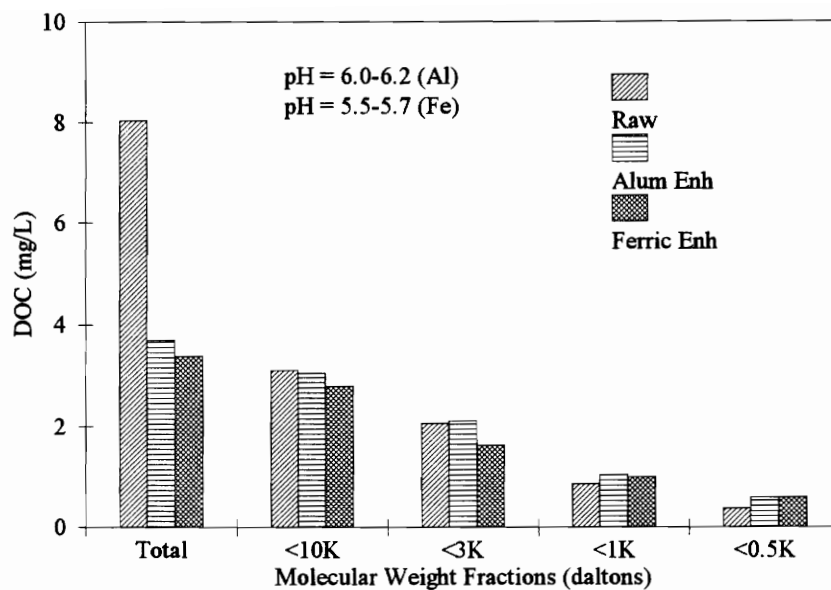


Figure 4.30. Apparent molecular weight distribution for raw, alum enhanced, and ferric enhanced samples for Utility VT-9.

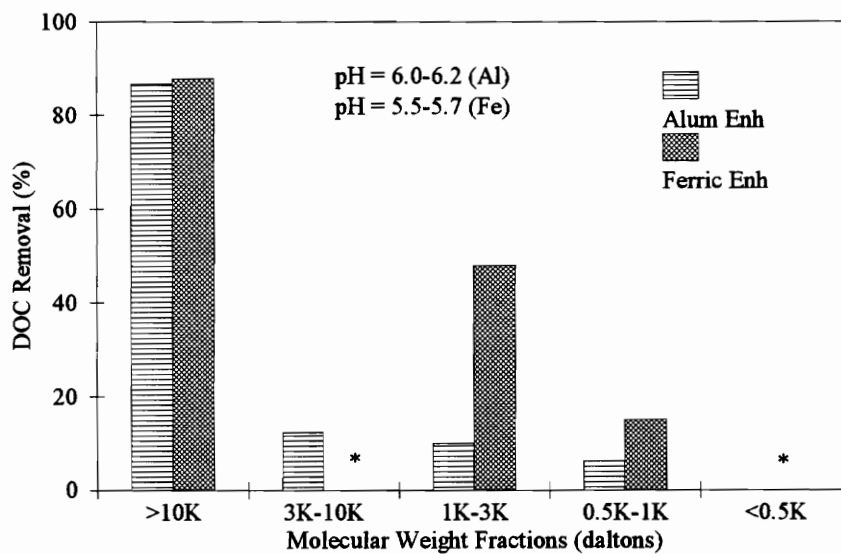


Figure 4.31. Percentage removals of DOC at alum enhanced and ferric enhanced doses for molecular weight fractions for Utility VT-9. (Note: * indicates values which were negative and are not included in this figure.)

Table 4.16
DOX and THM Values for Utility VT-9

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	8.54 (TOC) 8.03 (DOC)	49.1	---	---	432	1570
Std. Dev.	---	---	---	---	9.2	38
Baseline						
Avg.	3.22	6.80	85	253	186	404
Std. Dev.	---	---	2.9	7.0	4.0	29
Alum Enh						
Avg.	3.70	8.32	94	296	247	526
Std. Dev.	---	---	9.0	12	13	24
Ferric Enh						
Avg.	3.39	6.44	64	225	193	431
Std. Dev.	---	---	4.9	12	1.9	17
Alum Opt						
Avg.	3.18	5.97	---	---	158	423
Std. Dev.	---	---	---	---	82	31
Ferric Opt						
Avg.	2.68	4.09	---	---	142	287
Std. Dev.	---	---	---	---	2.1	27

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.17

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-9

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^- \cdot \text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^- \cdot \text{mg} \cdot \text{m}$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	79	37	120	3.0
Alum Enh UFC	80	36	132	3.2
Ferric Enh UFC	66	35	118	3.5
Raw FP	196	32	257	3.6
Baseline FP	125	59	191	2.2
Alum Enh FP	142	63	234	2.1
Ferric Enh FP	127	67	227	2.2
Alum Opt FP	133	71	225	2.7
Ferric Opt FP	107	70	188	2.0

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.18
Percentage Reduction of TOC, UV254, THMFP and DOXFP for
Treated Samples for Utility VT-9

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	62	86	57	74
Alum Enh	57	83	43	67
Ferric Enh	60	87	55	73
Alum Opt	63	88	63	73
Ferric Opt	69	92	67	82

* TOC reduction is based on TOC of raw water and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

percentage reductions of the four parameters generally corresponded to the following trend: UV254 > NPDOXFP > TOC > THMFP.

Utility VT-1

The drinking water supply for Utility VT-1 is a reservoir with low to moderate alkalinity, moderate TOC, average turbidity of less than 1 NTU, and average hardness of approximately 70 mg/L as CaCO₃. For the bench-scale testing of Utility VT-1, alum was the only coagulant examined. The complete set of jar test and DBP results for Utility VT-1 is contained in Appendix F.

Determination of Optimum pH for TOC Removal

The results from the pH optimization for Utility VT-1 are presented in Figure 4.32. The pH optimization was performed at an alum dose of 30 mg/L. Both DOC and UV254 results are included in Figure 4.32. Residual DOC results were fairly constant over the pH range studied, with a minimum value at a solution pH of approximately 5.8-6.0. This was chosen as the optimum pH range.

Dose Optimization

The dose optimization procedure for Utility VT-1 was performed at coagulant doses ranging from 0 to 140 mg/L at the previously determined optimum pH range of 5.8-6.0. Both DOC and UV254 results are presented in Figure 4.33. The residual DOC begins to approach a constant minimum value at an alum dose of approximately 40 mg/L, which was selected as the enhanced dose. An optimized dose was not chosen for Utility VT-1.

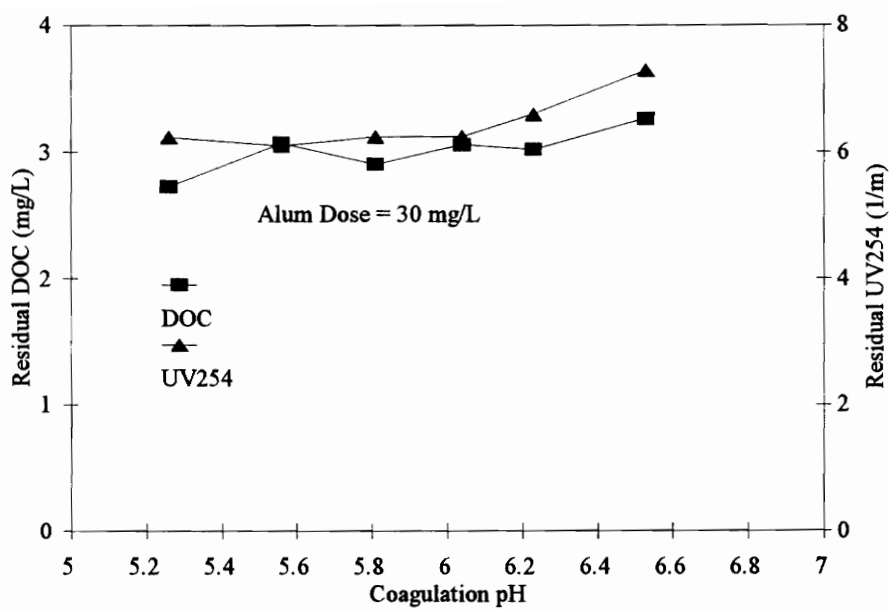


Figure 4.32. Residual DOC and UV254 as a function of coagulation pH for Utility VT-1 alum treatment.

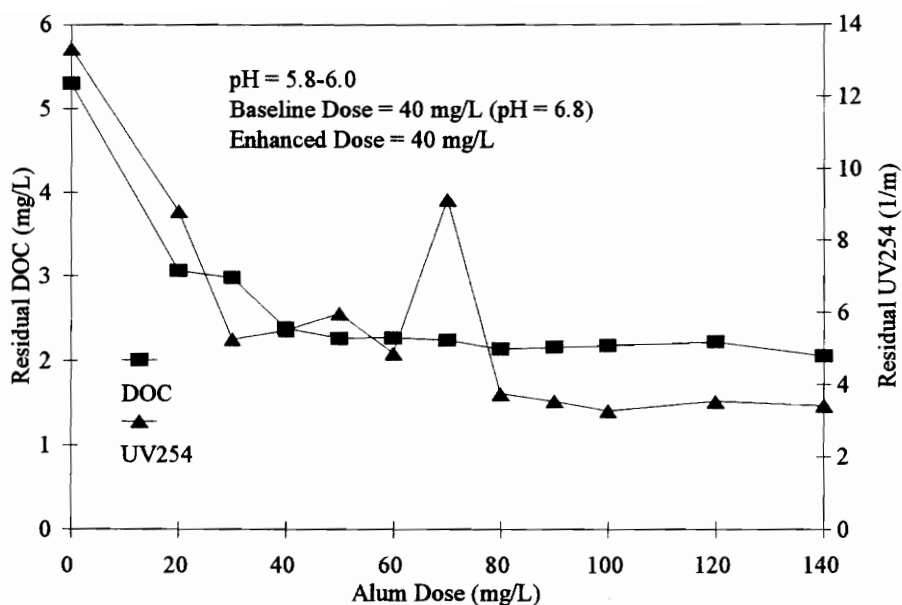


Figure 4.33. Residual DOC and UV254 as a function of alum dose for Utility VT-1 alum treatment.

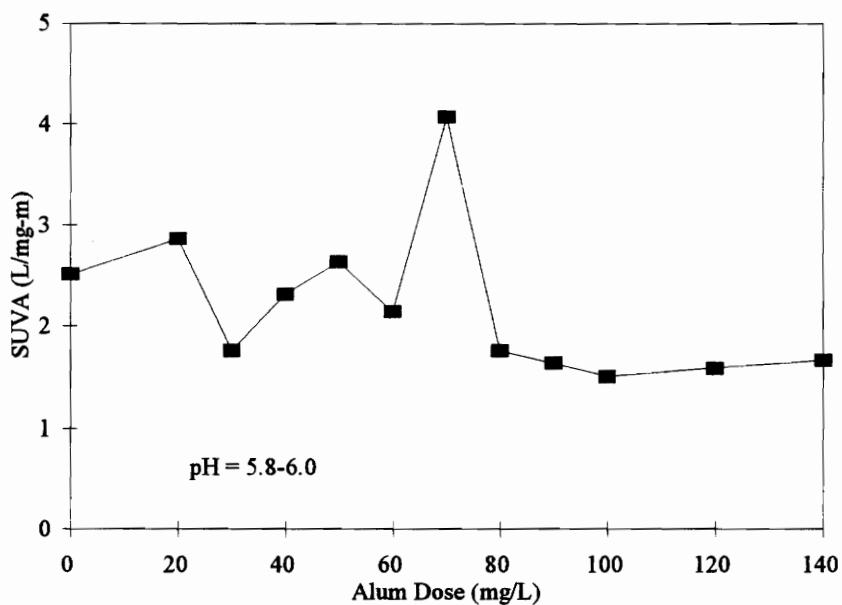


Figure 4.34. Specific UV absorbance as a function of alum dose for Utility VT-1 alum treatment.

Specific UV absorbance as a function of coagulant dose for Utility VT-1 is presented in Figure 4.34.. The initial SUVA value was approximately 2.5 L/mg-m, with the value decreasing with treatment.

Residual Aluminum

Residual aluminum samples were not collected for Utility VT-1.

Apparent Molecular Weight Distribution

The AMWD results for Utility VT-1 are presented in Figures 4.35 and 4.36. Figure 4.35 presents the DOC values for both raw and enhanced samples for each of the molecular weight fractions. Figure 4.36 presents the percentage removal of each weight fraction of organic material. The DOC concentrations for the various molecular weight fractions decreased with treatment, with the greatest reduction seen in the molecular weight fractions greater than 3,000 daltons.

Disinfection By-Product Formation

Table 4.19 includes the NPDOX and THM results for Utility VT-1 raw, baseline, and enhanced samples, while Table 4.20 correlates the NPDOX results with residual DOC, UV254, SUVA, and THMs. Table 4.21 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline and enhanced treated samples. NPDOX and THM UFC and FP values decreased with increasing alum doses and corresponding decreasing DOC and UV254 values. NPDOX corresponded best with THM values, with the NPDOX/THM ratio approximately 3.1 $\mu\text{g as Cl}^-/\mu\text{g}$ for the UFC tests, and ranging from 2.0-2.6 $\mu\text{g as Cl}^-/\mu\text{g}$ for the FP tests. Reduction

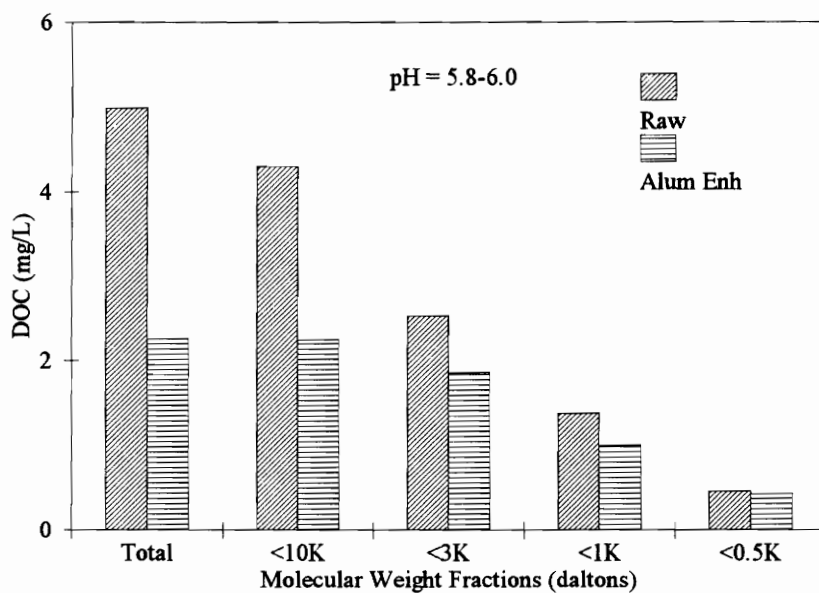


Figure 4.35. Apparent molecular weight distribution for raw and alum enhanced samples for Utility VT-1.

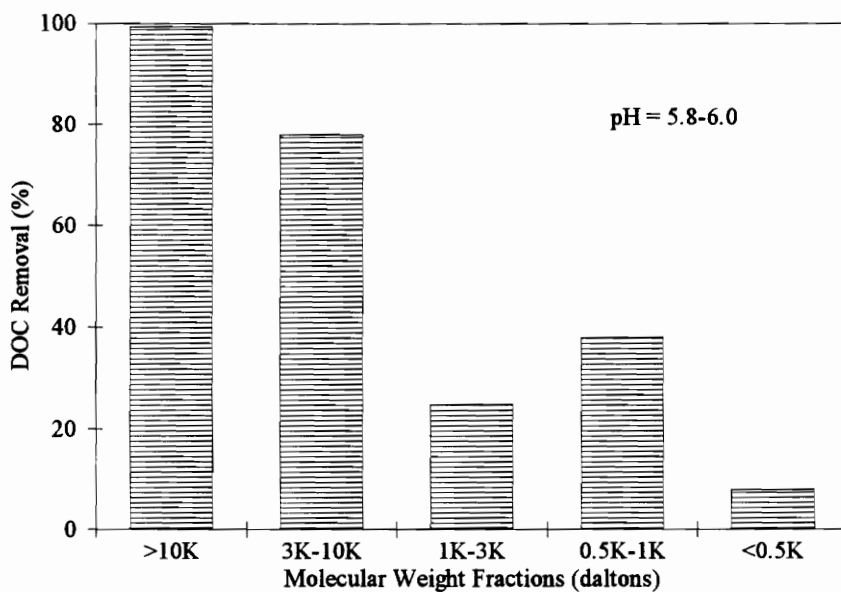


Figure 4.36. Percentage removals of DOC at alum enhanced dose for molecular weight fractions for Utility VT-1.

Table 4.19
DOX and THM Values for Utility VT-1

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	5.32 (TOC) 4.98 (DOC)	13.2	---	---	414	847
Std. Dev.	---	---	---	---	18	4.5
Baseline						
Avg.	2.53	5.96	81	242	212	558
Std. Dev.	---	---	7.2	7.1	6.9	142
Enhanced						
Avg.	2.25	4.83	70	224	175	343
Std. Dev.	---	---	4.7	41	4.5	19

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.20

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-1

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^- \cdot \text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^- \cdot \text{mg} \cdot \text{m}$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	96	41	103	3.0
Enhanced UFC	99	46	104	3.2
Raw FP	170	64	321	2.1
Baseline FP	221	94	238	2.6
Enhanced FP	152	71	160	2.0

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.21

Percentage Reduction of TOC, UV254, THMFP and DOXFP for Treated Samples for Utility VT-1

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	52	55	49	34
Enhanced	58	63	58	60

* TOC reduction is based on TOC of raw water and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

of TOC, UV254, THMFP, and NPDOXFP were all similar for baseline and for enhanced treatment for Utility VT-1.

Utility VT-6

The drinking water supply for Utility VT-6 is a reservoir with high alkalinity, low to moderate TOC, average turbidity of less than 5 NTU, and average hardness of approximately 60 mg/L as CaCO₃. For the bench-scale testing of Utility VT-6, both alum and ferric sulfate were examined. Also, for Utility VT-6, a DBP removal optimization was performed as previously described in the Methods and Materials section. This involved treating large batches of raw water at two additional alum doses other than enhanced and optimized. The complete set of analyses, except for the UFC test, was then performed on these two additional treated waters. The UFC test was conducted on the alum baseline, alum enhanced, and ferric enhanced samples only. The complete set of jar test and DBP results for Utility VT-6 is contained in Appendix G.

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-6 for both alum and ferric sulfate treatment are presented in Figure 4.37. The DOC results only are included in Figure 4.37. The UV254 results are contained in Appendix G. The pH optimization was performed at a coagulant dose of 30 mg/L for alum and 20 mg/L for ferric sulfate. Residual DOC values for alum coagulation decreased over the pH range of 5.3-6.7. An optimum pH value of 5.5-5.6 was chosen for alum coagulation. Residual DOC values for ferric sulfate coagulation were at a minimum at a pH range of approximately 5.0-5.2, which was chosen as the optimum pH range for ferric sulfate coagulation.

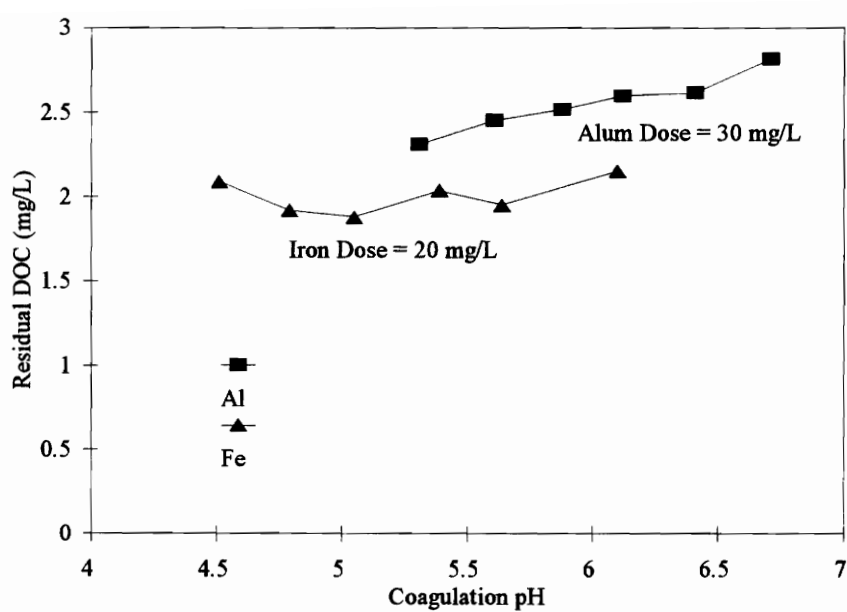


Figure 4.37. Residual DOC as a function of coagulation pH for Utility VT-6 alum and ferric sulfate treatment.

Dose Optimization

The dose optimization procedure for Utility VT-6 was performed at coagulant doses ranging from 0 to 110 mg/L in 10 mg/L increments for both alum and ferric sulfate at the previously determined optimum pH ranges. Both DOC and UV254 results are presented in Figure 4.38 for alum, and in Figure 4.39 for ferric sulfate. A slight increase in residual UV254 was seen at low ferric sulfate doses. The DOC curves approach a constant value at a coagulant dose of approximately 30 mg/L for both alum and ferric sulfate; therefore, these coagulant doses were chosen as the enhanced doses. The DOC curves reach a minimum value at a coagulant dose of approximately 110 mg/L for alum and 100 mg/L for ferric sulfate. These doses were chosen as the optimized doses. The additional large batch jar tests were performed at alum doses of 15 mg/L and 60 mg/L.

Specific UV absorbance as a function of both alum and ferric sulfate dose is presented in Figure 4.40. Different initial SUVA values were recorded for the alum and ferric sulfate dose optimization tests, with an average of approximately 1.7 L/mg-m. SUVA values remained fairly constant with treatment, although a spike was seen in SUVA values at low ferric sulfate doses due to the spike in residual UV254 at low ferric sulfate doses.

Residual Coagulant

The residual coagulant results for Utility VT-6 are presented in Figures 4.41 and 4.42. Figure 4.41 presents residual coagulant as a function of coagulation pH, while Figure 4.42 presents residual coagulant as a function of coagulant dose. Both residual iron and residual aluminum results are contained in Figures 4.41 and 4.42. Residual aluminum concentrations were at a minimum near pH 6.0, while residual iron concentrations were at a minimum near pH 5.4. These pH values were higher than the

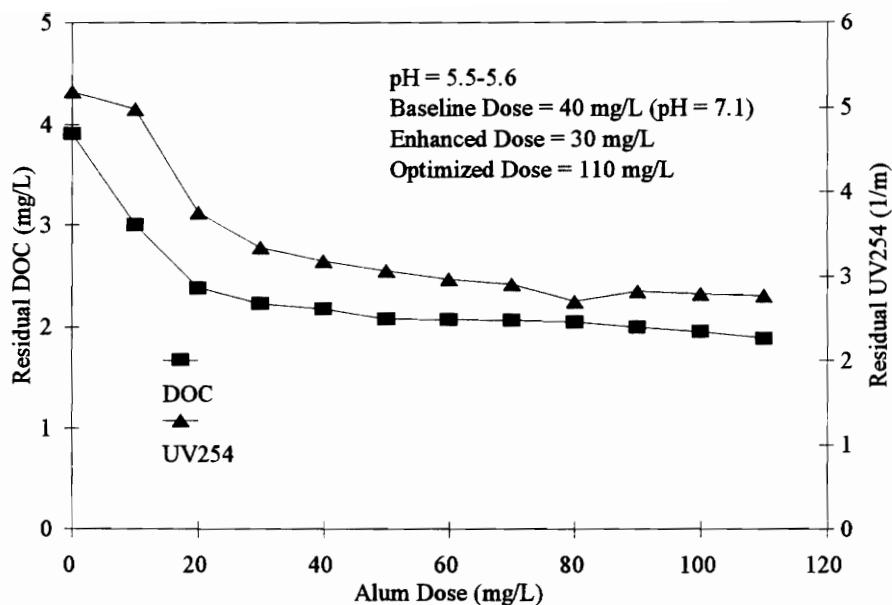


Figure 4.38. Residual DOC and UV254 as a function of alum dose for Utility VT-6 alum treatment.

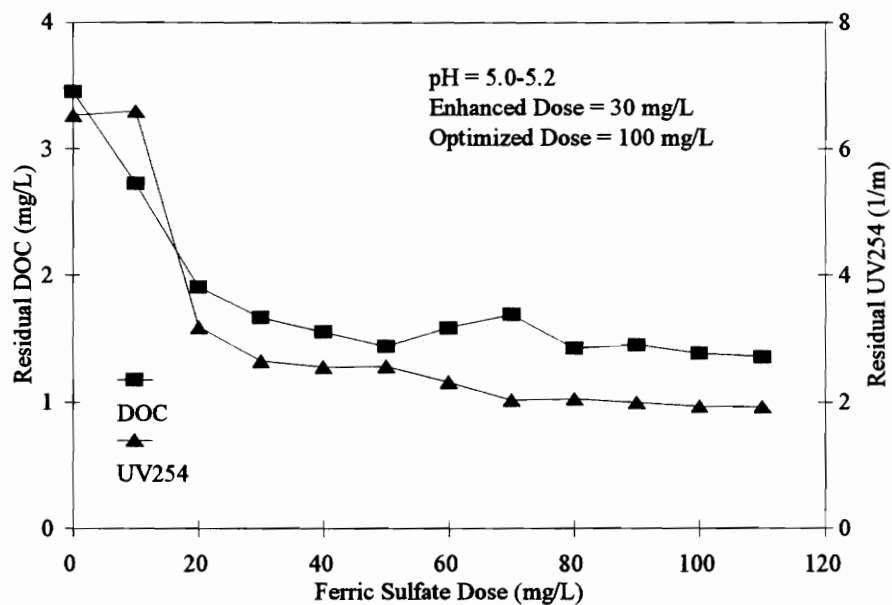


Figure 4.39. Residual DOC and UV254 as a function of ferric sulfate dose for Utility VT-6 ferric sulfate treatment.

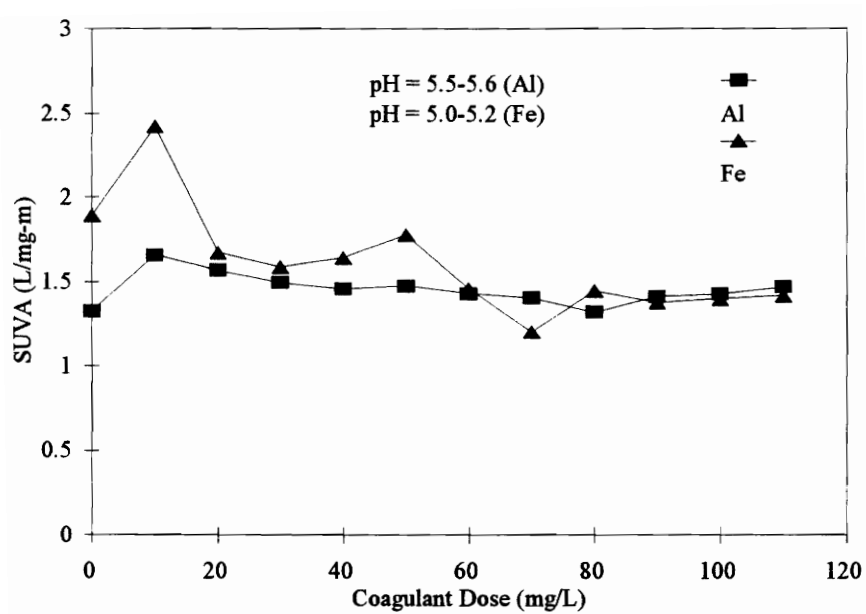


Figure 4.40. Specific UV absorbance as a function of coagulant dose for Utility VT-6 alum and ferric sulfate treatment.

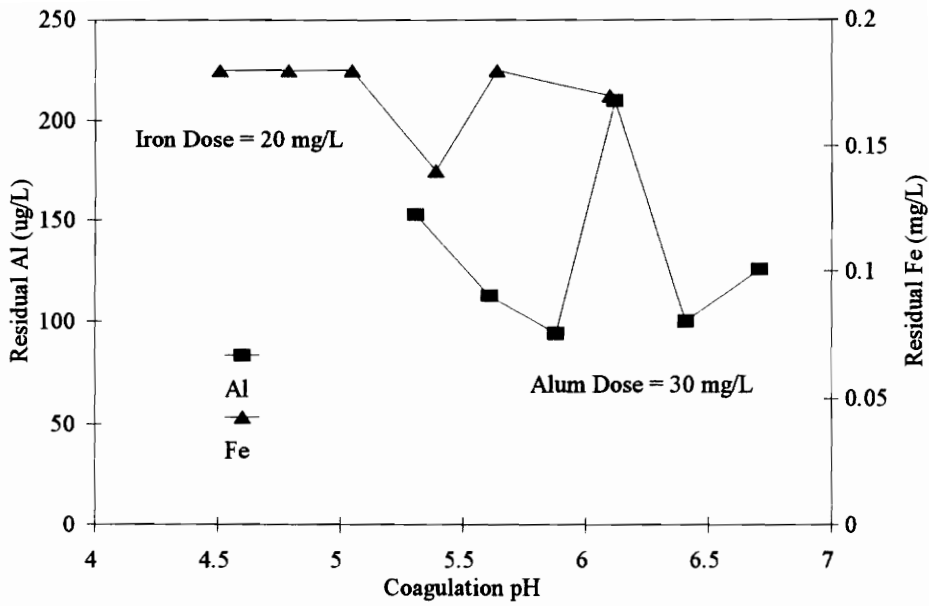


Figure 4.41. Residual coagulant as a function of coagulation pH for Utility VT-6 alum and ferric sulfate treatment.

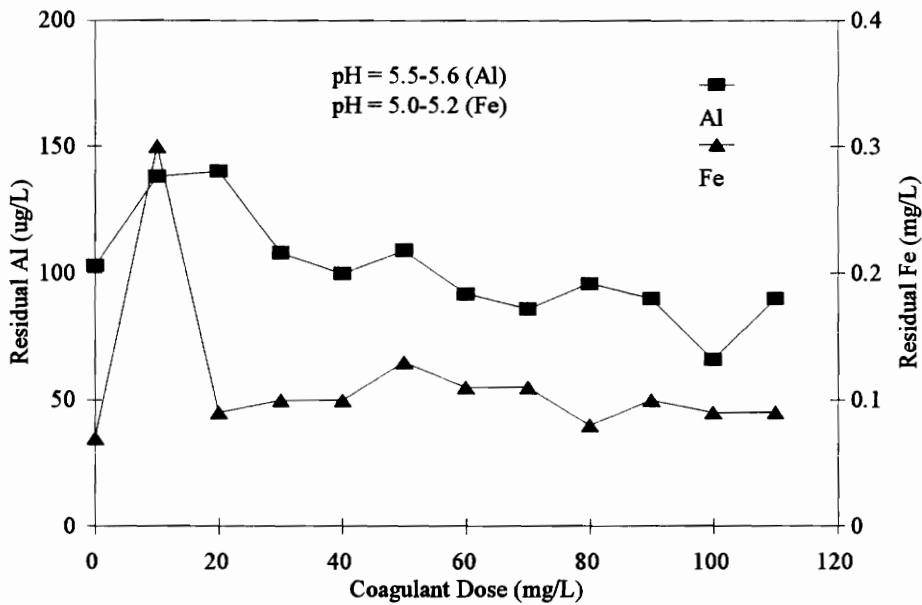


Figure 4.42. Residual coagulant as a function of coagulant dose for Utility VT-6 alum and ferric sulfate treatment.

optimum pH values chosen for organics removal. Aluminum and iron concentrations following coagulation were generally comparable to background concentrations. A spike in residual iron concentration was seen at low ferric sulfate doses.

Apparent Molecular Weight Distribution

The AMWD results for both coagulants for Utility VT-6 are presented in Figures 4.43 and 4.44. Figure 4.43 presents the DOC values for each of the molecular weight fractions for the raw and enhanced samples and for the samples treated at 15 mg/L and 60 mg/L alum. Figure 4.44 presents the percentage removal of each weight fraction of organic material. Almost no reduction was seen in the DOC fraction greater than 10,000 daltons. The largest percentage removals were seen in the DOC fraction between 3,000 and 10,000 daltons, and between 500 and 1,000 daltons.

Disinfection By-Product Formation

Table 4.22 includes the NPDOX and THM results for Utility VT-6 raw, baseline, enhanced, and optimized samples, as well as the results from the samples treated at the two additional alum doses of 15 mg/L and 60 mg/L. Table 4.23 correlates the NPDOX results with residual DOC, UV254, SUVA, and THMs. Table 4.24 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline, alum 15 mg/L, enhanced, alum 60 mg/L, and optimized treated samples. Results for both alum and ferric sulfate coagulation are included in each table. NPDOX and THM values generally decreased with decreasing organic content. NPDOX correlated well with DOC values for the UFC tests, with the NPDOX/DOC ratio ranging from 30-35 $\mu\text{g as Cl}^-/\text{mg TOC}$. The NPDOX yield based on DOC generally decreased with treatment, although two of the treated waters had higher yields than the raw water. The relative percentage reductions of the four parameters

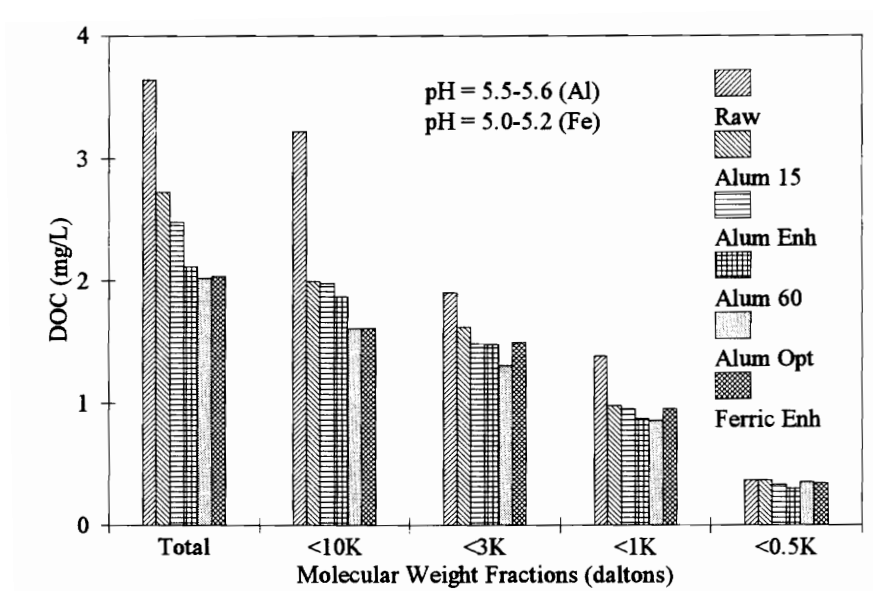


Figure 4.43. Apparent molecular weight distribution for raw, alum 15 mg/L, alum enhanced (30 mg/L), alum 60 mg/L, alum optimized (110 mg/L), and ferric enhanced (30 mg/L) samples for Utility VT-6.

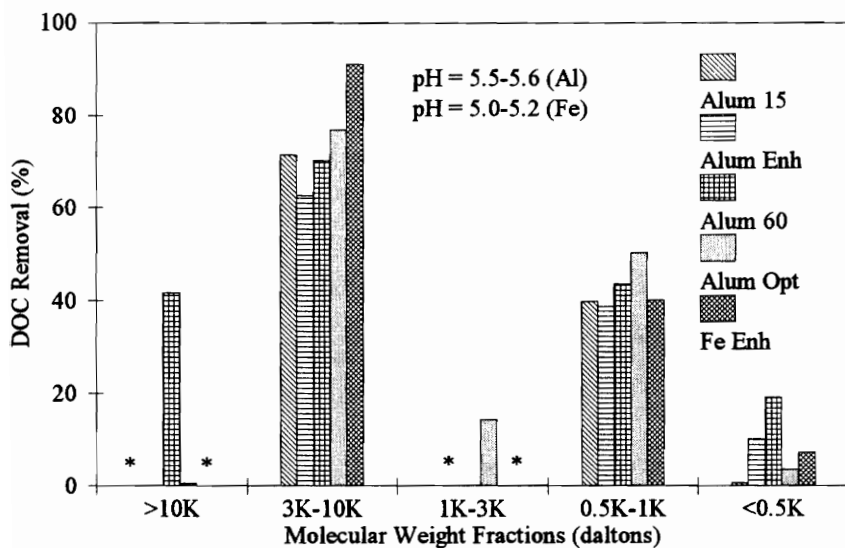


Figure 4.44. Percentage removals of DOC at alum 15 mg/L, alum enhanced (30 mg/L), alum 60 mg/L, alum optimized (110 mg/L), and ferric enhanced (30 mg/L) doses for molecular weight fractions for Utility VT-6. (Note: * indicates values which were negative and are not included in this figure.)

Table 4.22
DOX and THM Values for Utility VT-6

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	4.02 (TOC) 3.64 (DOC)	6.79	---	---	217	482
Std. Dev.	---	---	---	---	6.7	85
Baseline						
Avg.	3.07	4.70	118	106	209	397
Std. Dev.	---	---	5.7	33	0.71	7.8
Alum 15						
Avg.	2.73	4.29	---	---	230	301
Std. Dev.	---	---	---	---	5.7	11
Alum Enh						
Avg.	2.48	3.58	94	83	187	233
Std. Dev.	---	---	1.0	5.3	2.1	84
Alum 60						
Avg.	2.11	2.97	---	---	167	299
Std. Dev.	---	---	---	---	12	42
Alum Opt						
Avg.	2.02	2.80	---	---	163	211
Std. Dev.	---	---	---	---	13	44
Ferric Enh						
Avg.	2.03	2.16	99	61	119	237
Std. Dev.	---	---	40	8.1	7.8	37
Ferric Opt						
Avg.	1.55	1.49	---	---	109	208
Std. Dev.	---	---	---	---	7.1	5.3

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.23

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-6

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^-*\text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^-*$ $\text{mg}*m$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	35	23	69	0.90
Alum Enh UFC	33	23	57	0.88
Ferric Enh UFC	30	28	57	0.62
Raw FP	132	71	258	2.2
Baseline FP	129	84	259	1.9
Alum 15 FP	110	70	192	1.3
Alum Enh FP	94	65	161	1.2
Alum 60 FP	142	101	212	1.8
Alum Opt FP	104	75	152	1.3
Ferric Enh FP	117	110	223	2.0
Ferric Opt FP	134	140	216	1.9

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.24
Percentage Reduction of TOC, UV254, THMFP and DOXFP for
Treated Samples for Utility VT-6

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	24	31	4	18
Alum 15	32	37	(6)	38
Alum Enh	38	47	14	52
Alum 60	48	56	23	38
Alum Opt	50	59	25	56
Ferric Enh	50	68	45	51
Ferric Opt	61	78	50	57

* TOC reduction is based on TOC of raw water and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

generally corresponded to the following trend: $UV_{254} > NPDOXFP > TOC > THMFP$.

Utility VT-3

The drinking water supply for Utility VT-3 is a river with moderate alkalinity, high TOC, average turbidity of less than 1 NTU, and average hardness of approximately 130 mg/L as $CaCO_3$. For the bench-scale testing of Utility VT-3, both alum and ferric sulfate were examined. The ferric sulfate used for the bench-scale testing was a commercial ferric sulfate product obtained from Utility VT-3, which contained 12.4 % Fe by weight. The results of these jar tests are presented in Figures 4.45-4.50. All of the ferric sulfate doses listed in Figures 4.45-4.50 have been converted from the ferric sulfate product dose (12.4% Fe by weight) to an equivalent dose of $Fe_2(SO_4)_3 \cdot 5H_2O$, which is the iron coagulant used in the other jar tests. The complete set of jar test and DBP results for Utility VT-3 is contained in Appendix H.

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-3 for both alum and ferric sulfate treatment are presented in Figure 4.45. The DOC results only are included in Figure 4.45. The UV_{254} results are contained in Appendix H. The pH optimization was performed at a coagulant dose of 80 mg/L for alum and 76 mg/L for ferric sulfate. Minimum residual DOC values were seen at a solution pH range of approximately 5.5-5.6 for alum and 4.8-5.0 for ferric sulfate. These pH ranges were chosen as the optimum pH ranges.

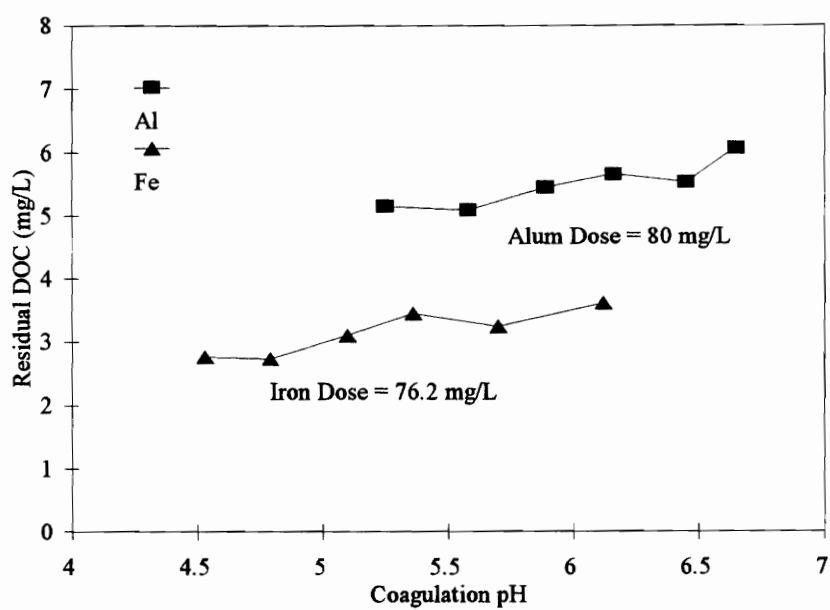


Figure 4.45. Residual DOC as a function of coagulation pH for Utility VT-3 alum and ferric sulfate treatment.

Dose Optimization

The dose optimization procedure for Utility VT-3 was performed at coagulant doses ranging from 0 to 170 mg/L for alum and from 0 to 125 mg/L for ferric sulfate, each at the respective optimum pH ranges. Both DOC and UV254 results are presented in Figure 4.46 for alum, and in Figure 4.47 for ferric sulfate. The DOC curves begin to approach a constant minimum value at an alum dose of approximately 100 mg/L and a ferric sulfate dose of approximately 65 mg/L; these coagulant doses were chosen as the enhanced doses. The DOC curves reach a minimum value at an alum dose of approximately 170 mg/L and a ferric sulfate dose of approximately 109 mg/L. These doses were chosen as the optimized doses. A spike in residual UV254 was present at low ferric sulfate doses.

Specific UV absorbance as a function of both alum and ferric sulfate dose is presented in Figure 4.48. The initial SUVA value was approximately 4 L/mg-m, with the value generally decreasing with increasing coagulant dose. A spike in SUVA was seen at low ferric sulfate doses due to the spike in residual UV254 at low ferric sulfate doses.

Residual Coagulant

The residual coagulant results for Utility VT-3 are presented in Figures 4.49 and 4.50. Figure 4.49 presents residual coagulant as a function of coagulation pH, while Figure 4.50 presents residual coagulant as a function of coagulant dose. Both residual iron and residual aluminum results are contained in Figures 4.49 and 4.50. Residual aluminum concentrations did not indicate a distinct minimum value, while residual iron concentrations were at a minimum near pH 5.7. Aluminum and iron concentrations were generally comparable to background concentrations, with spikes in both aluminum and iron concentrations seen at low coagulant doses.

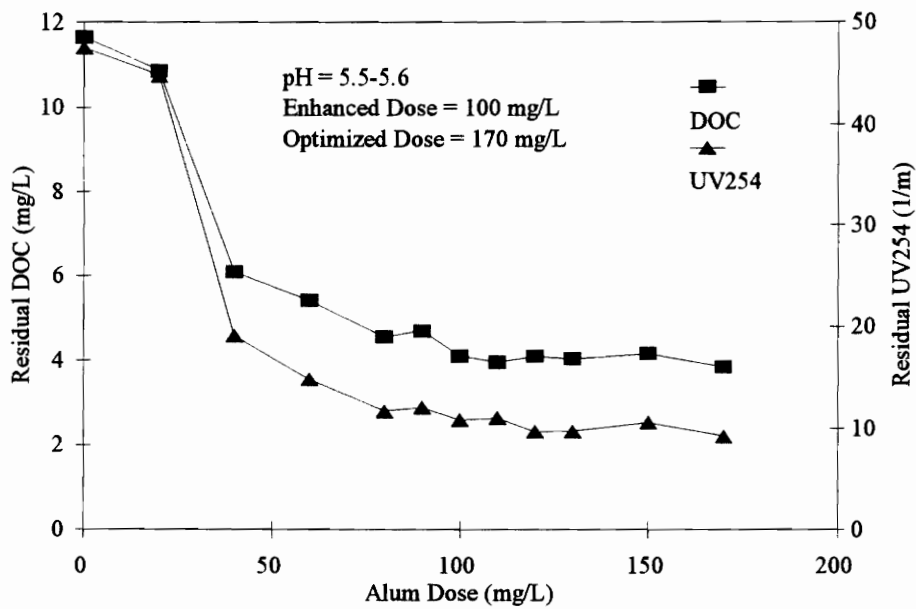


Figure 4.46. Residual DOC and UV254 as a function of alum dose for Utility VT-3 alum treatment.

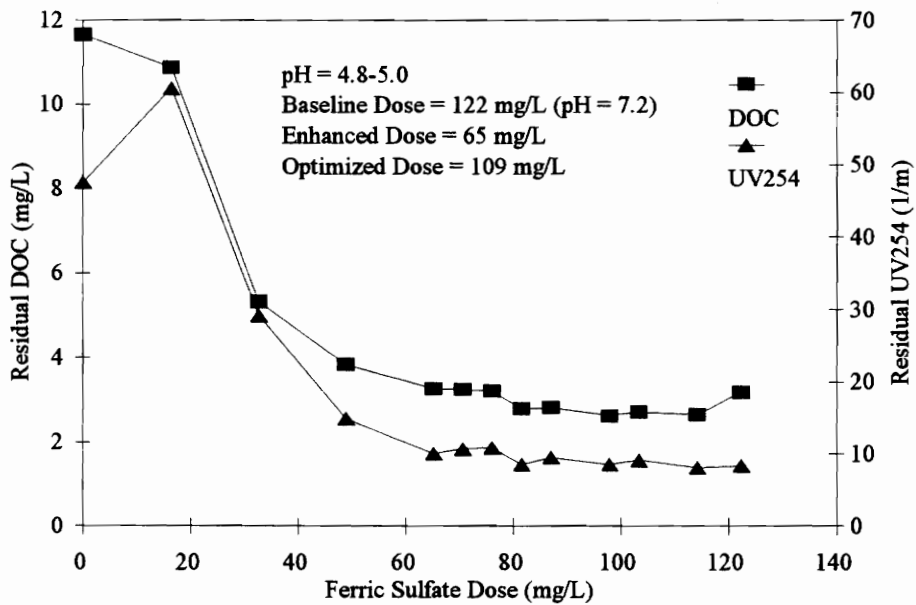


Figure 4.47. Residual DOC and UV254 as a function of ferric sulfate dose for Utility VT-3 ferric sulfate treatment.

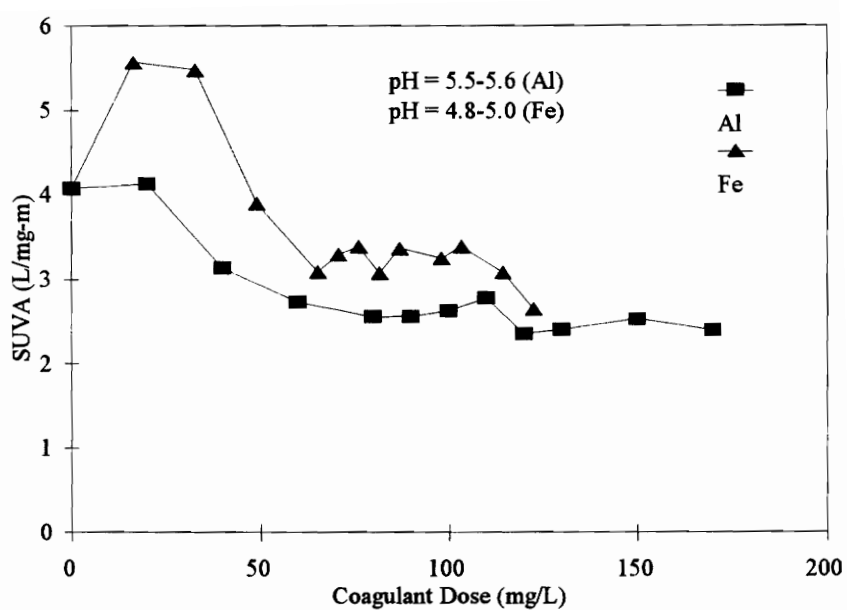


Figure 4.48. Specific UV absorbance as a function of coagulant dose for Utility VT-3 alum and ferric sulfate treatment.

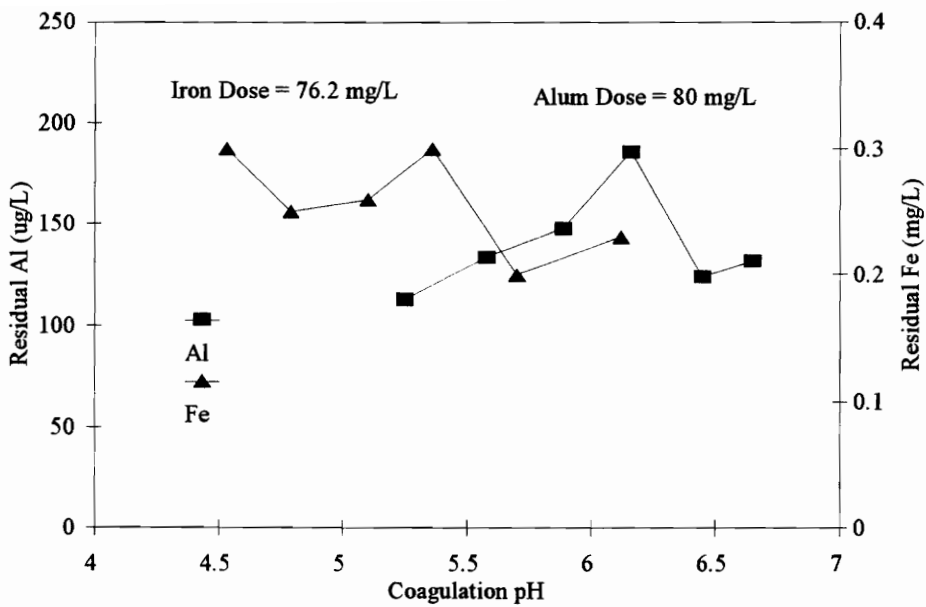


Figure 4.49. Residual coagulant as a function of coagulation pH for Utility VT-3 alum and ferric sulfate treatment.

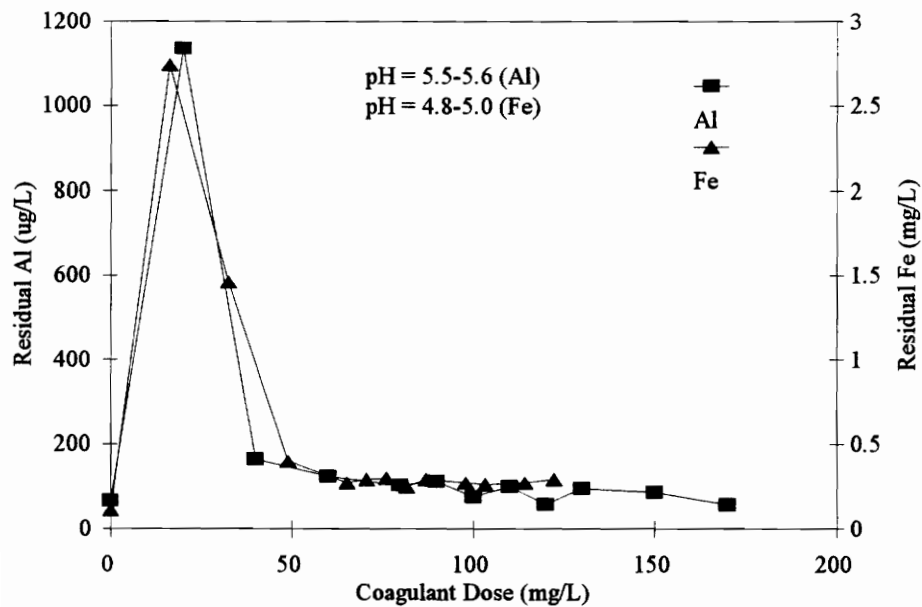


Figure 4.50. Residual coagulant as a function of coagulant dose for Utility VT-3 alum and ferric sulfate treatment.

Apparent Molecular Weight Distribution

The AMWD results for both coagulants for Utility VT-3 are presented in Figures 4.51 and 4.52. Figure 4.51 presents the DOC values for both raw and enhanced samples for each of the molecular weight fractions. Figure 4.52 presents the percentage removal of each weight fraction of organic material. Treatment generally decreased the amount of higher molecular weight fractions for both alum and ferric sulfate, with the greatest removal occurring in the DOC range of 3,000-10,000 daltons. The percentage removals of organics by ferric sulfate treatment was greater than or equal to the percentage removals of organics by alum treatment in each of the size ranges greater than 500 daltons.

Disinfection By-Product Formation

Table 4.25 includes the NPDOX and THM results for Utility VT-3 raw, baseline, enhanced, and optimized samples, while Table 4.26 correlates the NPDOX results with residual DOC, UV254, SUVA, and THMs. Table 4.27 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline, enhanced, and optimized treated samples. Results for both aluminum and iron coagulation are included in each table. NPDOX and THM values generally decreased with decreasing organic content. NPDOX correlated well with DOC values for the UFC tests, with the NPDOX/DOC ratio ranging from 84-90 $\mu\text{g as Cl}^-/\text{mg TOC}$. The NPDOX yield based on DOC generally decreased with treatment. The relative percentage reductions of the four parameters generally corresponded to the following trend: $\text{UV254} = \text{NPDOXFP} > \text{TOC} = \text{THMFP}$.

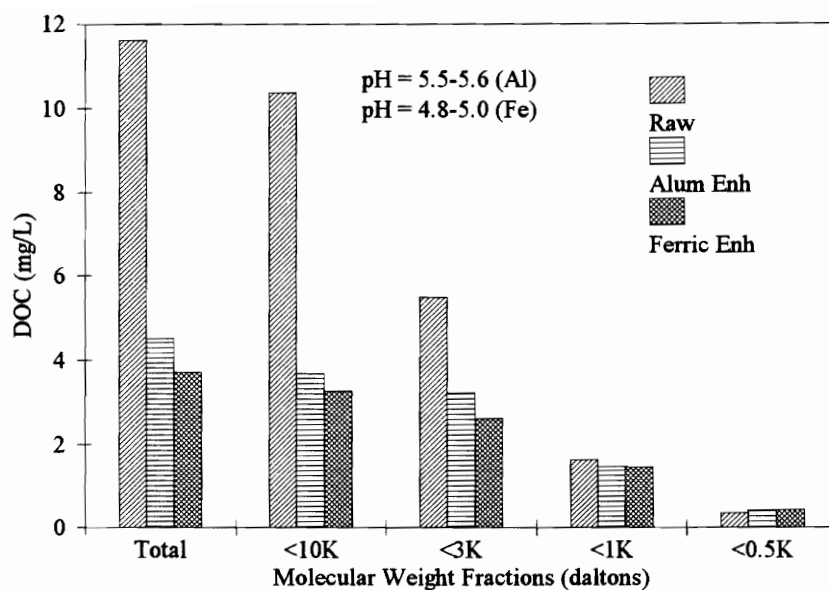


Figure 4.51. Apparent molecular weight distribution for raw, alum enhanced, and ferric enhanced samples for Utility VT-3.

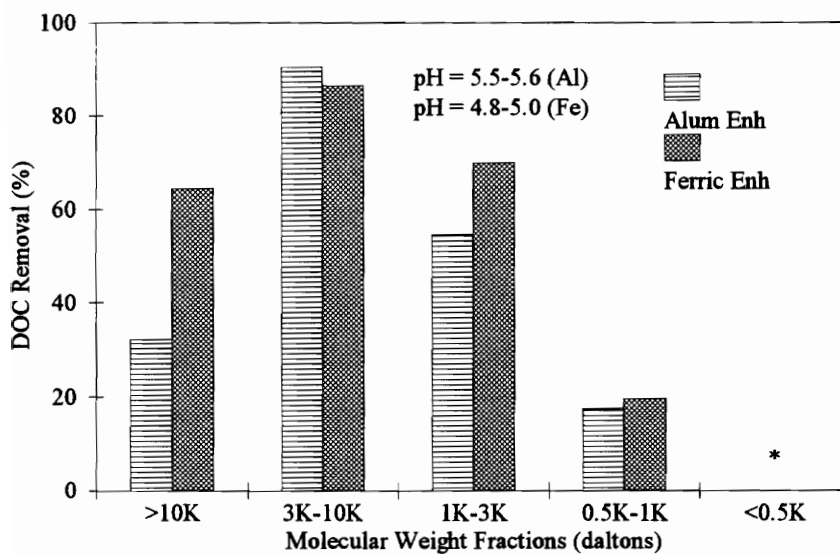


Figure 4.52. Percentage removals of DOC at alum enhanced and ferric enhanced doses for molecular weight fractions for Utility VT-3. (Note: * indicates values which were negative and are not included in this figure.)

Table 4.25
DOX and THM Values for Utility VT-3

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	11.8 (TOC) 11.6 (DOC)	47.5	---	---	732	2240
Std. Dev.	---	---	---	---	8.3	270
Baseline						
Avg.	2.87	7.52	131	262	158	437
Std. Dev.	---	---	7.1	33	6.5	51
Alum Enh						
Avg.	4.51	10.5	152	386	252	617
Std. Dev.	---	---	16	57	12	67
Ferric Enh						
Avg.	3.70	13.3	183	311	220	582
Std. Dev.	---	---	3.7	52	5.2	4.5
Alum Opt						
Avg.	3.64	8.69	---	---	244	472
Std. Dev.	---	---	---	---	9.7	11
Ferric Opt						
Avg.	3.00	9.97	---	---	183	310
Std. Dev.	---	---	---	---	3.7	66

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.26

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-3

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^- \cdot \text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^- \cdot \text{mg} \cdot \text{m}$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	90	35	101	2.0
Alum Enh UFC	86	37	165	2.5
Ferric Enh UFC	84	23	87	1.7
Raw FP	193	47	547	3.1
Baseline FP	151	58	169	2.8
Alum Enh FP	137	59	264	2.4
Ferric Enh FP	157	44	162	2.6
Alum Opt FP	131	54	195	1.9
Ferric Opt FP	103	31	93	1.7

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.27
Percentage Reduction of TOC, UV254, THMFP and DOXFP for
Treated Samples for Utility VT-3

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	75	84	78	80
Alum Enh	62	78	66	72
Ferric Enh	69	72	70	74
Alum Opt	69	82	67	79
Ferric Opt	75	79	75	86

* TOC reduction is based on TOC of raw water and DOC of finished waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Utility VT-8

The drinking water supply for Utility VT-8 is a river with high alkalinity, low TOC, average turbidity of 1-2 NTU, and average hardness of approximately 300 mg/L as CaCO_3 . For the bench-scale testing of Utility VT-8, both alum and ferric sulfate were examined. The complete set of jar test and DBP results for Utility VT-8 is contained in Appendix I.

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-8 for both alum and ferric sulfate treatment are presented in Figure 4.53. The DOC results only are included in Figure 4.53. The UV254 results are contained in Appendix I. The pH optimization was performed at a coagulant dose of 20 mg/L for alum and 15 mg/L for ferric sulfate. Minimum residual DOC values were seen at a solution pH range of approximately 5.8-5.9 for alum and 5.6-5.7 for ferric sulfate. These pH ranges were chosen as the optimum pH ranges.

Dose Optimization

The dose optimization procedure for Utility VT-8 was performed at coagulant doses ranging from 0 to 110 mg/L for alum. Due to a shortage of raw water, the ferric sulfate dose optimization was performed at doses ranging from 0 to 50 mg/L. The dose optimization jar tests were performed at the previously determined optimum pH ranges for aluminum and iron. Both DOC and UV254 results are presented in Figure 4.54 for alum and in Figure 4.55 for ferric sulfate. The DOC curves began to approach a constant minimum value at an alum dose of approximately 30 mg/L and a ferric sulfate dose of approximately 25 mg/L; therefore, these coagulant doses were

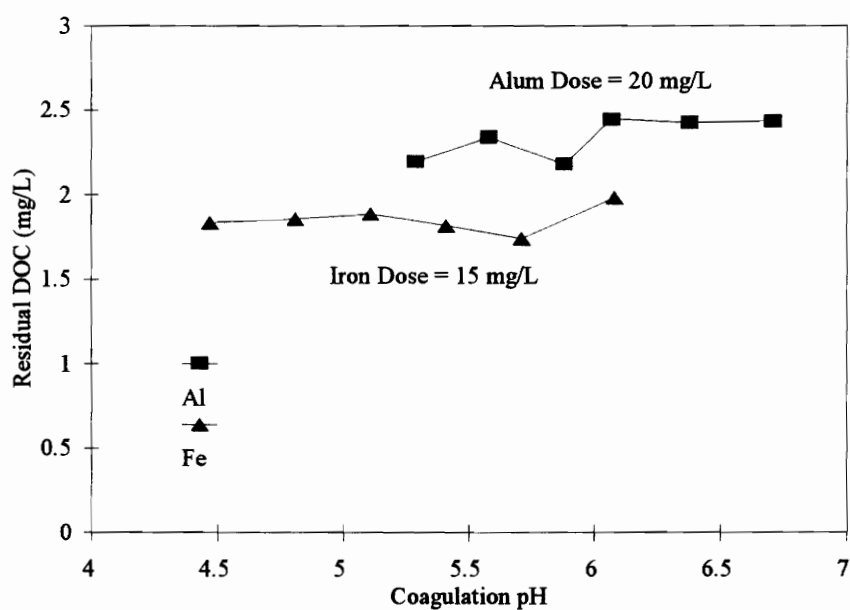


Figure 4.53. Residual DOC as a function of coagulation pH for Utility VT-8 alum and ferric sulfate treatment.

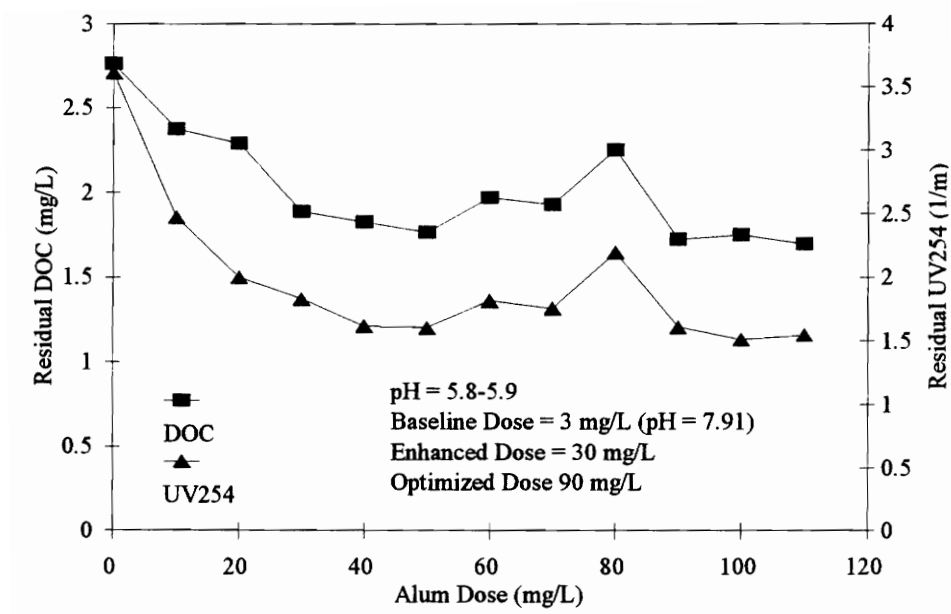


Figure 4.54. Residual DOC and UV254 as a function of alum dose for Utility VT-8 alum treatment.

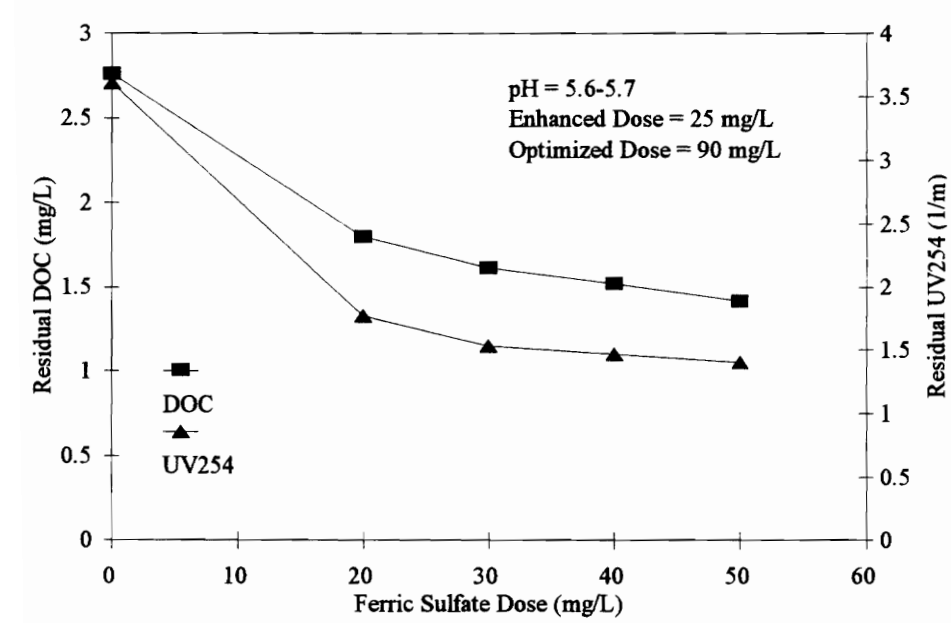


Figure 4.55. Residual DOC and UV254 as a function of ferric sulfate dose for Utility VT-8 ferric sulfate treatment.

chosen as the enhanced doses. The DOC curves reached a minimum value at an alum dose of approximately 90 mg/L. This was chosen as the optimized dose for alum treatment. An optimized dose of 90 mg/L was chosen for ferric sulfate based on prior jar test results for other utilities which indicated that the optimized doses for alum and ferric sulfate were similar.

Specific UV absorbance as a function of both alum and ferric sulfate dose is presented in Figure 4.56. The initial SUVA value was 1.3 L/mg-m. SUVA values decreased with treatment.

Residual Coagulant

The residual coagulant results for Utility VT-8 are presented in Figures 4.57 and 4.58. Figure 4.57 presents residual coagulant as a function of coagulation pH, while Figure 4.58 presents residual coagulant as a function of coagulant dose. Both residual iron and residual aluminum results are contained in Figures 4.57 and 4.58. Residual aluminum concentrations were at a minimum near pH 6.4, while residual iron concentrations were at a minimum near pH 6.1. Aluminum concentrations following coagulation were generally comparable to background concentrations, with a spike in residual aluminum at low coagulant doses. Iron concentrations increased with treatment, although the initial iron concentration measured was low (below the detection limit).

Apparent Molecular Weight Distribution

The AMWD results for both coagulants for Utility VT-8 are presented in Figures 4.59 and 4.60. Figure 4.59 presents the DOC values for both raw and enhanced samples for each of the molecular weight fractions. Figure 4.60 presents the percentage removal of each weight fraction of organic material. Treatment generally

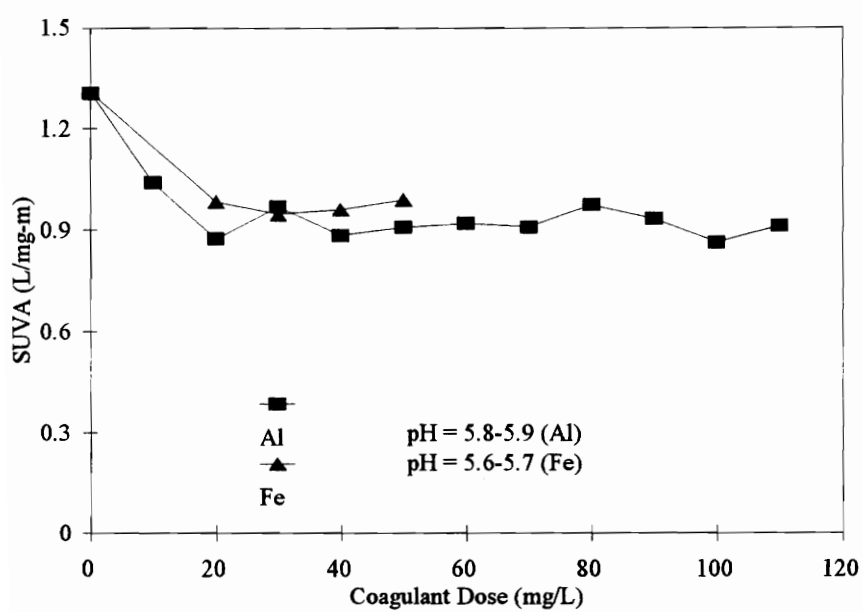


Figure 4.56. Specific UV absorbance as a function of coagulant dose for Utility VT-8 alum and ferric sulfate treatment.

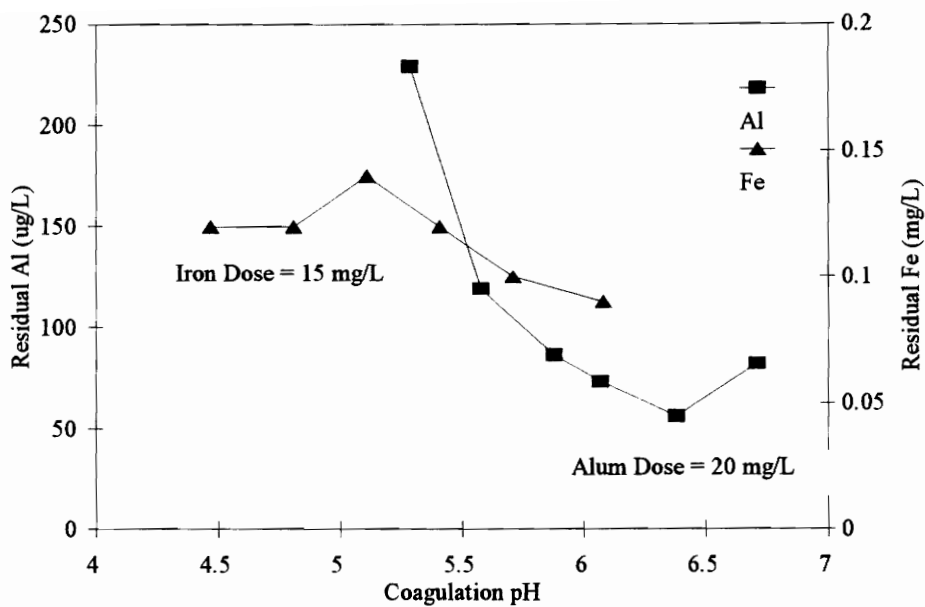


Figure 4.57. Residual coagulant as a function of coagulation pH for Utility VT-8 alum and ferric sulfate treatment.

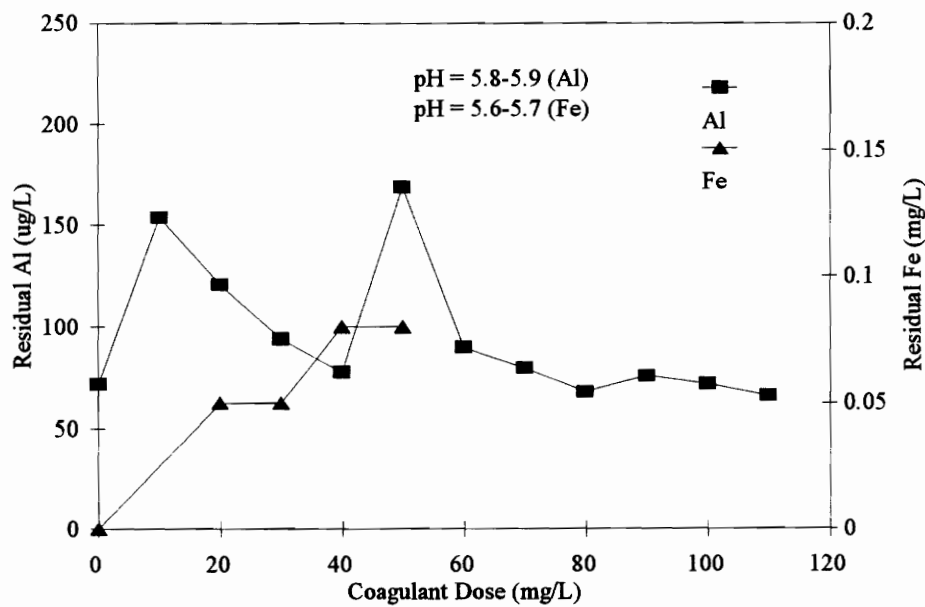


Figure 4.58. Residual coagulant as a function of coagulant dose for Utility VT-8 alum and ferric sulfate treatment.

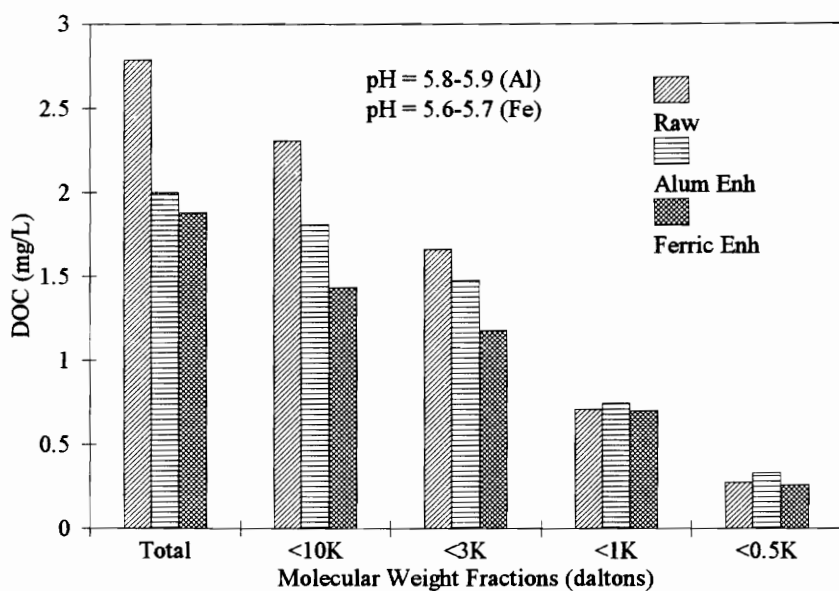


Figure 4.59. Apparent molecular weight distribution for raw, alum enhanced, and ferric enhanced samples for Utility VT-8.

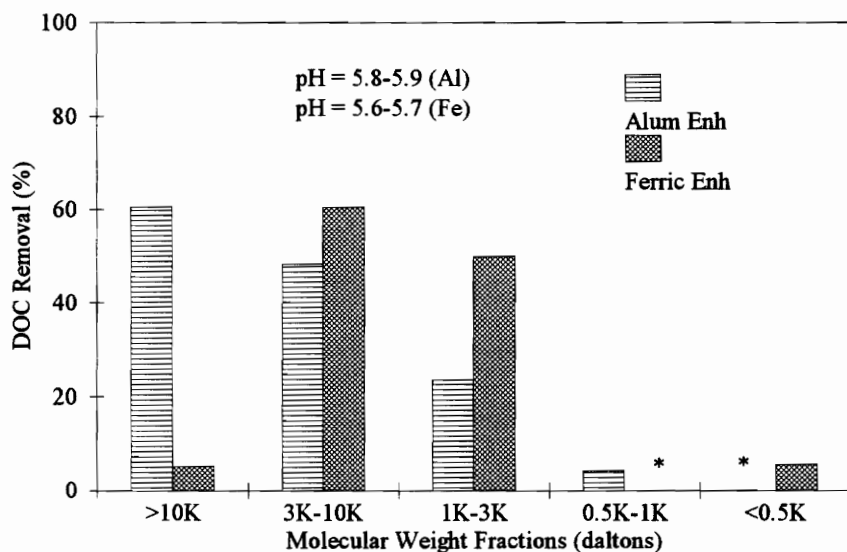


Figure 4.60. Percentage removals of DOC at alum enhanced and ferric enhanced doses for molecular weight fractions for Utility VT-8. (Note: * indicates values which were negative and are not included in this figure.)

decreased the amount of higher molecular weight fractions for both alum and ferric sulfate treatment. The majority of DOC removal occurred in the molecular weight fractions greater than 3,000 daltons.

Disinfection By-Product Formation

Table 4.28 includes the NPDOX and THM results for Utility VT-8 raw, baseline, enhanced, and optimized samples, while Table 4.29 correlates the NPDOX results with residual DOC, UV254, SUVA and THMs. Table 4.30 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline, enhanced, and optimized treated samples. Results for both aluminum and iron coagulation are included in each table. NPDOX and THM values generally correlated well with the organic content, and the NPDOXFP yield based on DOC was generally constant for both raw and treated waters. The relative percentage reductions of the four parameters generally corresponded to the following trend: UV254 > NPDOXFP > TOC > THMFP.

Utility VT-5

The drinking water supply for Utility VT-5 is a reservoir with high alkalinity, high TOC, average turbidity of approximately 20 NTU, and average hardness of approximately 90 mg/L as CaCO₃. For the bench-scale testing of Utility VT-5, alum was the only coagulant examined. The complete set of jar test and DBP results for Utility VT-5 is contained in Appendix J.

Table 4.28
DOX and THM Values for Utility VT-8

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	2.73 (TOC) 2.79 (DOC)	3.74	---	---	115	194
Std. Dev.	---	---	---	---	0.63	6.0
Baseline						
Avg.	2.87	3.11	144	127	178	203
Std. Dev.	---	---	35	2.4	3.1	4.4
Alum Enh						
Avg.	2.00	1.55	95	93	93	151
Std. Dev.	---	---	63	8.4	2.1	16
Ferric Enh						
Avg.	1.88	1.61	84	55	82	113
Std. Dev.	---	---	6.6	7.0	5.1	12
Alum Opt						
Avg.	2.03	1.09	---	---	84	109
Std. Dev.	---	---	---	---	6.7	13
Ferric Opt						
Avg.	1.43	1.10	---	---	80	109
Std. Dev.	---	---	---	---	2.8	2.1

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.29

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-8

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^-*\text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^-*$ $\text{mg}*m$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	44	41	117	0.86
Alum Enh UFC	47	60	120	0.98
Ferric Enh UFC	29	34	64	0.65
Raw FP	70	52	145	1.7
Baseline FP	71	65	187	1.1
Alum Enh FP	76	97	195	1.6
Ferric Enh FP	60	70	132	1.4
Alum Opt FP	54	100	203	1.3
Ferric Opt FP	76	99	142	1.4

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.30
Percentage Reduction of TOC, UV254, THMFP and DOXFP for
Treated Samples for Utility VT-8

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	(5.1)	17	(53)	(4.6)
Alum Enh	27	59	20	22
Ferric Enh	31	57	29	42
Alum Opt	26	71	28	44
Ferric Opt	48	71	31	44

* TOC reduction is based on TOC of raw water and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-5 are presented in Figure 4.61. The pH optimization was performed at an alum dose of 50 mg/L. Both DOC and UV254 results are included in Figure 4.61. A minimum residual DOC value was seen at a solution pH range of approximately 5.9-6.1, which was chosen as the optimum pH range.

Dose Optimization

The dose optimization procedure for Utility VT-5 was performed at coagulant doses ranging from 0 to 120 mg/L at the previously determined optimum pH range of 5.9-6.1. Both DOC and UV254 results are presented in Figure 4.62. The DOC curves began to approach a constant minimum value at an alum dose of approximately 50 mg/L. Residual DOC concentration was at its lowest value at an alum dose of approximately 100 mg/L. The residual UV254 values follow the same trend. Alum doses of 50 mg/L and 100 mg/L were selected for the enhanced and optimized doses, respectively.

Specific UV absorbance as a function of alum dose is presented in Figure 4.63. The initial SUVA value was approximately 4.1 L/mg-m. SUVA values decreased with treatment, and followed the same trend as the DOC and UV254 values.

Residual Aluminum

The residual aluminum results for Utility VT-5 are presented in Figures 4.64 and 4.65. Figure 4.64 presents residual aluminum as a function of coagulation pH, while Figure 4.65 presents residual aluminum as a function of coagulant dose. Residual aluminum concentrations were at a minimum near pH 5.9. Likewise, residual

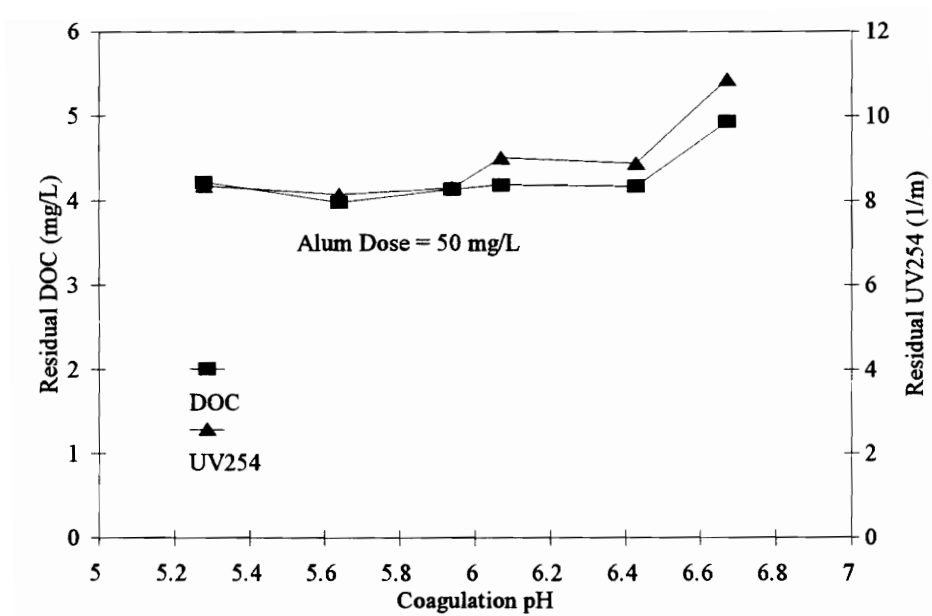


Figure 4.61. Residual DOC and UV254 as a function of coagulation pH for Utility VT-5 alum treatment.

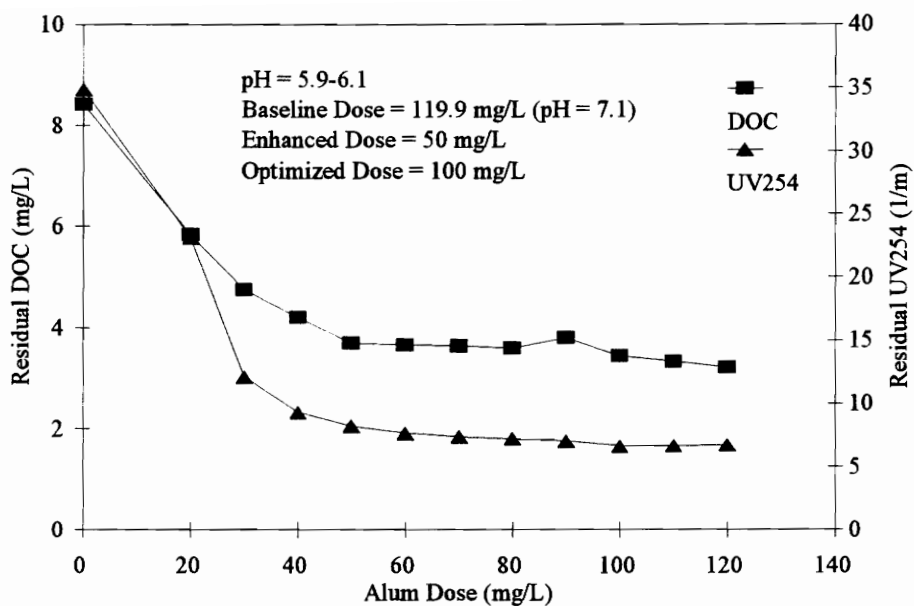


Figure 4.62. Residual DOC and UV254 as a function of alum dose for Utility VT-5 alum treatment.

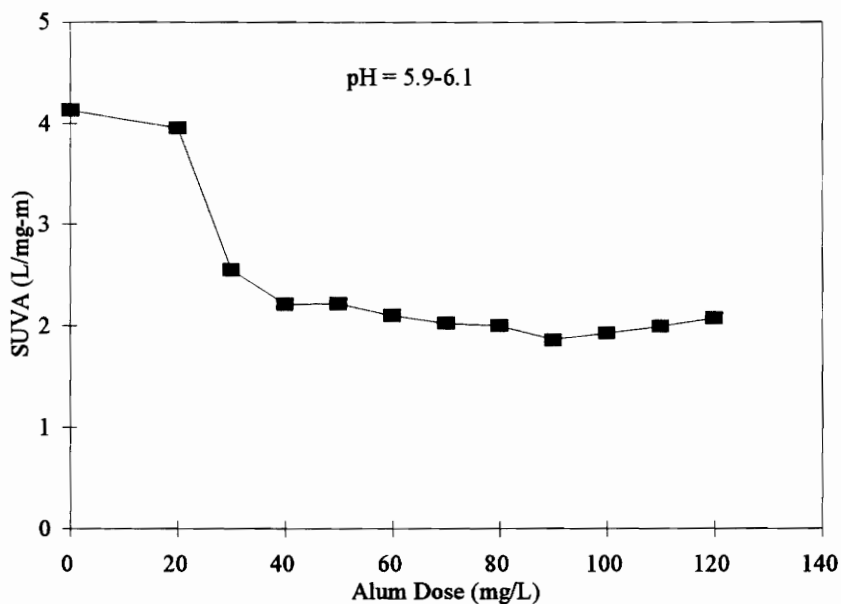


Figure 4.63. Specific UV absorbance as a function of alum dose for Utility VT-5 alum treatment.

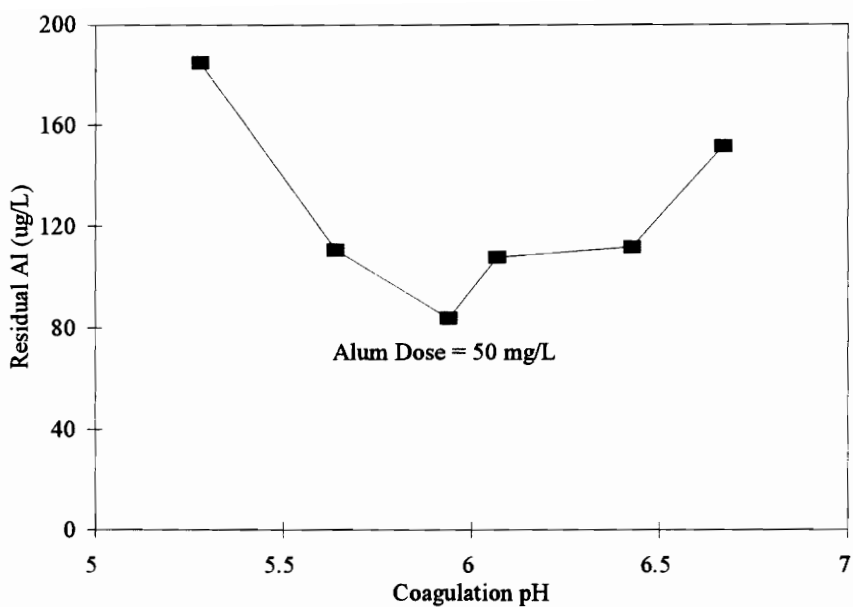


Figure 4.64. Residual aluminum as a function of coagulation pH for Utility VT-5 alum treatment.

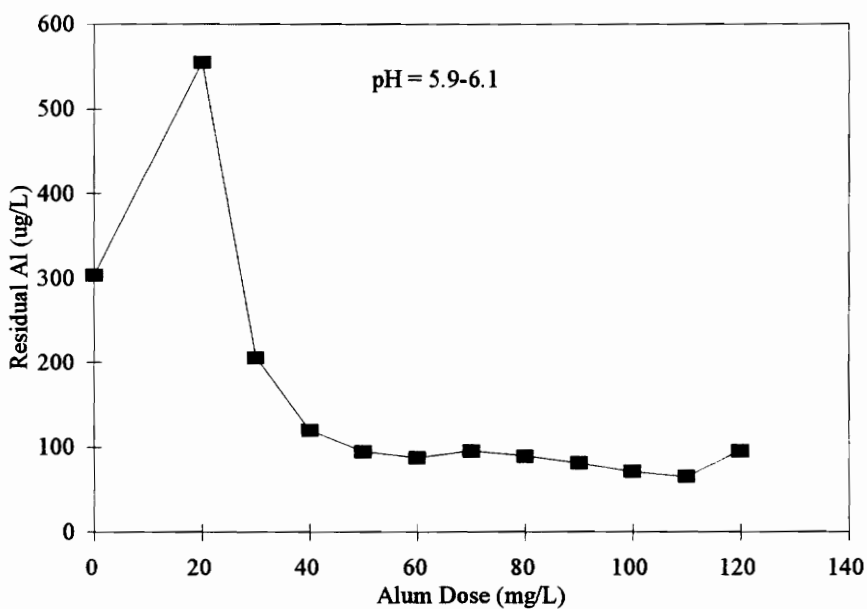


Figure 4.65. Residual aluminum as a function of coagulant dose for Utility VT-5 alum treatment.

aluminum concentrations decreased with treatment, with a spike in residual aluminum at low coagulant doses.

Apparent Molecular Weight Distribution

The AMWD results for Utility VT-5 are presented in Figures 4.66 and 4.67. Figure 4.66 presents the DOC values for both raw and enhanced samples for each of the molecular weight fractions. Figure 4.67 presents the percentage removal of each weight fraction of organic material. DOC values for the various molecular weight fractions decreased with treatment, with almost all of the DOC with molecular weight greater than 10,000 daltons, and over 60% of the DOC with molecular weight between 1,000 and 3,000 daltons, removed by treatment.

Disinfection By-Product Formation

Table 4.31 includes the NPDOX and THM results for Utility VT-5 raw, baseline, and enhanced samples, while Table 4.32 correlates the NPDOX results with residual DOC, UV254, SUVA, and THMs. Table 4.33 contains the percentage removals of TOC, UV254, THMFP, and NPDOXFP for baseline and enhanced treated samples. NPDOX and THM UFC and FP values decreased with increasing alum doses and corresponding decreasing DOC and UV254 values. NPDOX corresponded best with THM values, with the NPDOX/THM ratio ranging from 1.5-2.0 $\mu\text{g as Cl}^-/\mu\text{g}$ for the UFC tests, and ranging from 2.1-2.7 $\mu\text{g as Cl}^-/\mu\text{g}$ for the FP tests. NPDOX yield based on DOC decreased with treatment. The relative percentage reductions of the four parameters generally corresponded to the following trend: UV254 > NPDOXFP = TOC > THMFP.

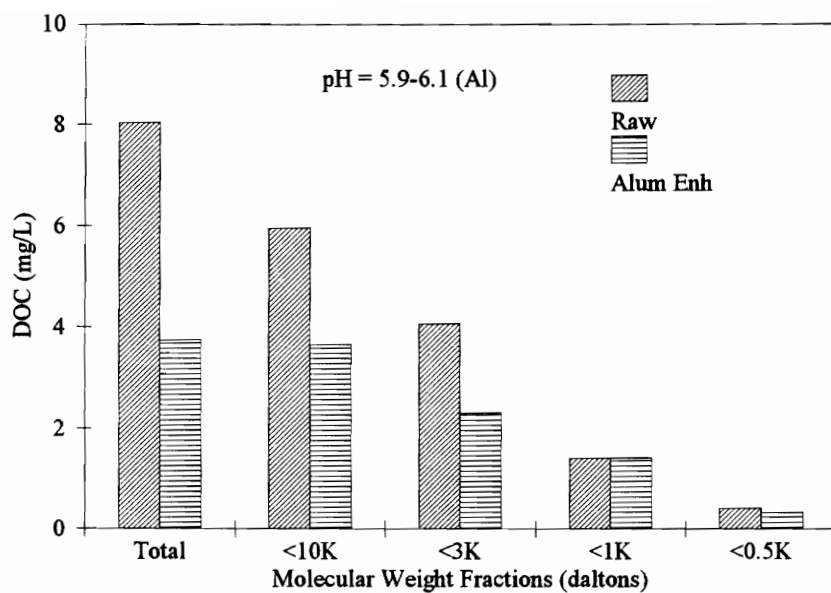


Figure 4.66. Apparent molecular weight distribution for raw and alum enhanced samples for Utility VT-5. (File: vt5doc.wb1:amwd)

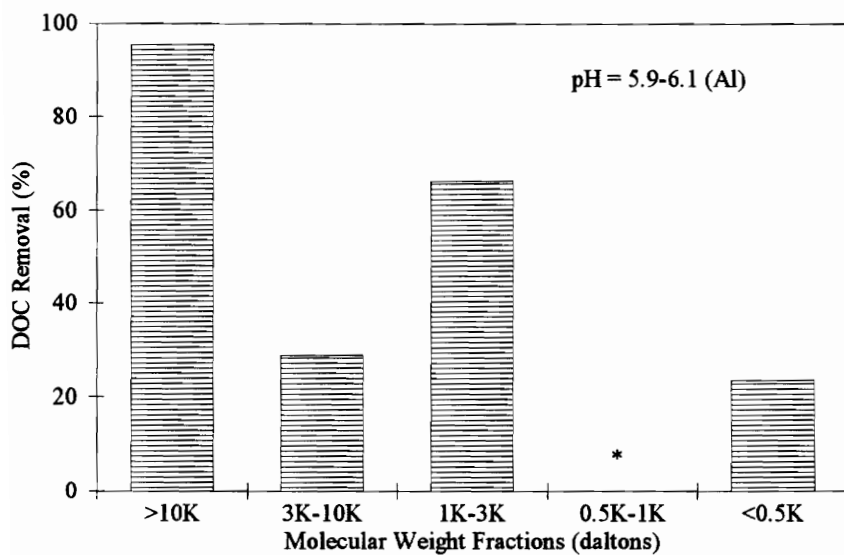


Figure 4.67. Percentage removals of DOC at alum enhanced dose for molecular weight fractions for Utility VT-5. (Note: * indicates values which were negative and are not included in this figure.) (File: vt5doc.wb1:amwd%rem)

Table 4.31
DOX and THM Values for Utility VT-5

Sample	DOC (mg/L)	UV254 (1/m)	UFC THM (µg/L)	UFC DOX* (µg/L as Cl ⁻)	THMFP (µg/L)	DOXFP* (µg/L as Cl ⁻)
Raw						
Avg.	9.41 (TOC) 8.04 (DOC)	24.5	---	---	517	1340
Std. Dev.	---	---	---	---	73	95
Baseline						
Avg.	4.84	8.73	195	285	338	739
Std. Dev.	---	---	12	38	16	109
Enhanced						
Avg.	3.75	7.87	126	251	207	549
Std. Dev.	---	---	11	41	30	34
Optimized						
Avg.	3.17	5.96	---	---	189	388
Std. Dev.	---	---	---	---	6.7	7.1

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.32

Correlation of DOX with Organic Carbon Measurements and THMs for Utility VT-5

Sample	DOX*/DOC ($\mu\text{g as Cl}^-/\text{mg}$)	DOX*/UV254 ($\mu\text{g as Cl}^- \cdot \text{m}$)	DOX**DOC/UV ($\mu\text{g as Cl}^- \cdot \text{mg} \cdot \text{m}$)	DOX*/THM ($\mu\text{g as Cl}^-/\mu\text{g}$)
Baseline UFC	59	33	158	1.5
Enhanced UFC	67	32	120	2.0
Raw FP	167	55	440	2.6
Baseline FP	153	85	410	2.2
Enhanced FP	146	70	262	2.7
Optimized FP	122	65	206	2.1

* All DOX values are for non-purgeable dissolved organic halides (NPDOX).

Table 4.33

Percentage Reduction of TOC, UV254, THMFP and DOXFP for Treated Samples for Utility VT-5

Sample	TOC* Reduction (%)	UV254 Reduction (%)	THMFP Reduction (%)	DOXFP† Reduction (%)
Baseline	49	64	34	45
Enhanced	60	68	60	59
Optimized	66	76	63	71

* TOC reduction is based on TOC of raw water and DOC of treated waters.

† All DOX values are for non-purgeable dissolved organic halides (NPDOX).

TEMPERATURE EFFECTS

For Utilities VT-9 and VT-6, the effects of temperature on pH optimization and dose optimization were examined. This involved performing a pH optimization jar test and a dose optimization jar test at 4°C. For the pH optimization at 4°C, the coagulant dose utilized was identical to that used at 25°C, but the pH range utilized was adjusted upward to account for the change in the ion product of water from 10^{-14} at 25°C to $10^{-14.78}$ at 4°C. The pH range utilized for alum at 4°C was approximately 5.7-7.6 as opposed to 5.3-6.7 at 25°C. For ferric sulfate, the pH range was adjusted from 4.5-6.1 at 25°C to 4.8-6.8 at 4°C.

The dose optimization jar test at 4°C was performed at the same coagulant doses as those used in the 25°C jar test, but at the optimum pH determined by the 4°C pH optimization testing. Additional detail concerning the temperature effects jar test procedures is contained in the Methods and Materials section.

Utility VT-9

For Utility VT-9, 4°C jar tests were performed using alum only as the coagulant. The data for these 4°C jar tests are contained in Appendix E.

Determination of Optimum pH for TOC Removal

The results from the pH optimization for Utility VT-9 for residual DOC are presented in Figure 4.68. Results from both the 25°C jar tests and the 4°C jar tests are included. The pH optimization was performed at a coagulant dose of 25 mg/L. The 4°C results indicate a minimum residual DOC concentration at a solution pH range of approximately 6.9-7.1, which was chosen as the optimum pH range at 4°C. As previously discussed, the optimum pH range at 25°C was 6.0-6.2 for alum. The

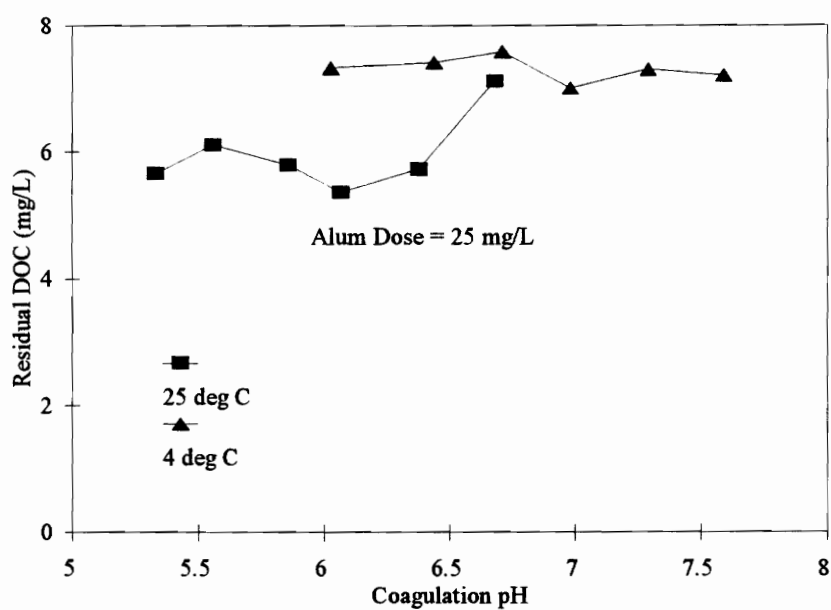


Figure 4.68. Residual DOC as a function of coagulation pH for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

UV254 results as a function of pH for both 4°C and 25°C are contained in Appendix E.

Dose Optimization

The dose optimization procedure at 4°C for Utility VT-9 alum treatment was performed at coagulant doses ranging from 0 to 150 mg/L at the previously determined optimum pH range. DOC results for alum at both 25°C and 4°C are presented in Figure 4.69. Residual UV254 results are contained in Appendix E. Figure 4.70 contains the SUVA values as a function of coagulant dose for Utility VT-9 for both 4°C and 25°C. The residual DOC values and SUVA values as a function of alum dose were almost identical at 4°C and 25°C.

Residual Aluminum

The residual aluminum results, at 4°C and 25°C, for Utility VT-9 as a function of coagulation pH are presented in Figures 4.71. Residual coagulant concentrations at 4°C were at a minimum at a pH range of approximately 7.2-7.4. The residual aluminum concentrations were greater at 4°C than at 25°C. Results of residual aluminum as a function of coagulant dose for 4°C are contained in Figure 4.72. The residual aluminum results as a function of alum dose were almost identical at 4°C and 25°C.

Utility VT-6

For Utility VT-6, 4°C jar tests were performed for both alum and ferric sulfate. The data for these tests is contained in Appendix G.

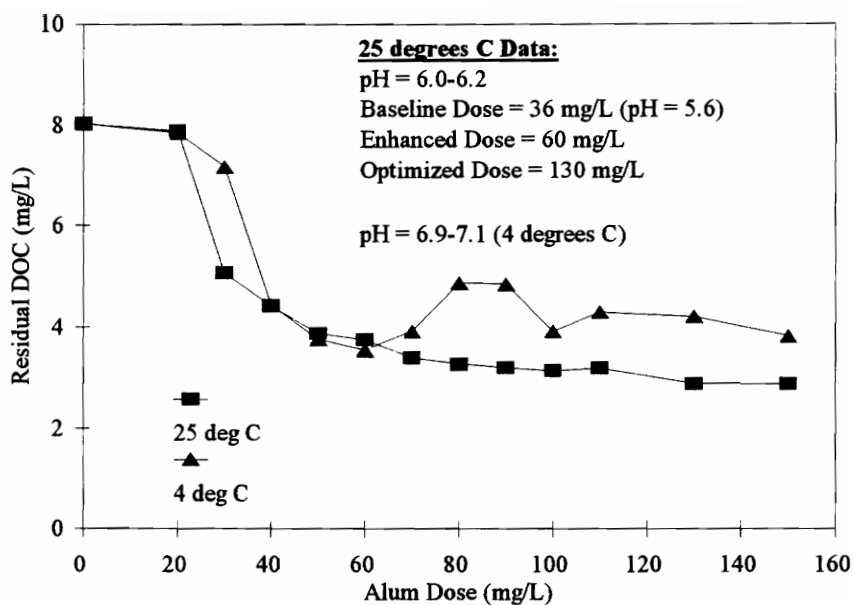


Figure 4.69. Residual DOC as a function of alum dose for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

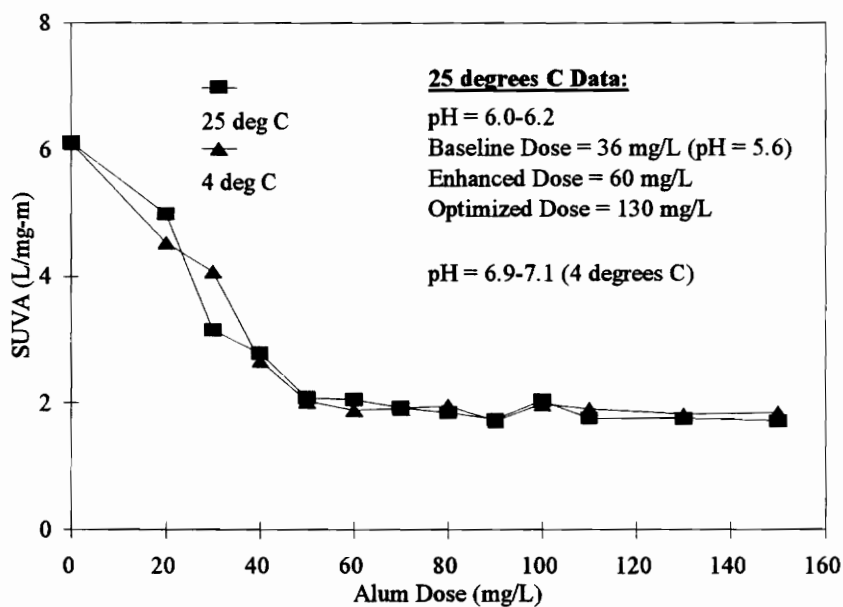


Figure 4.70. Specific UV absorbance as a function of alum dose for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

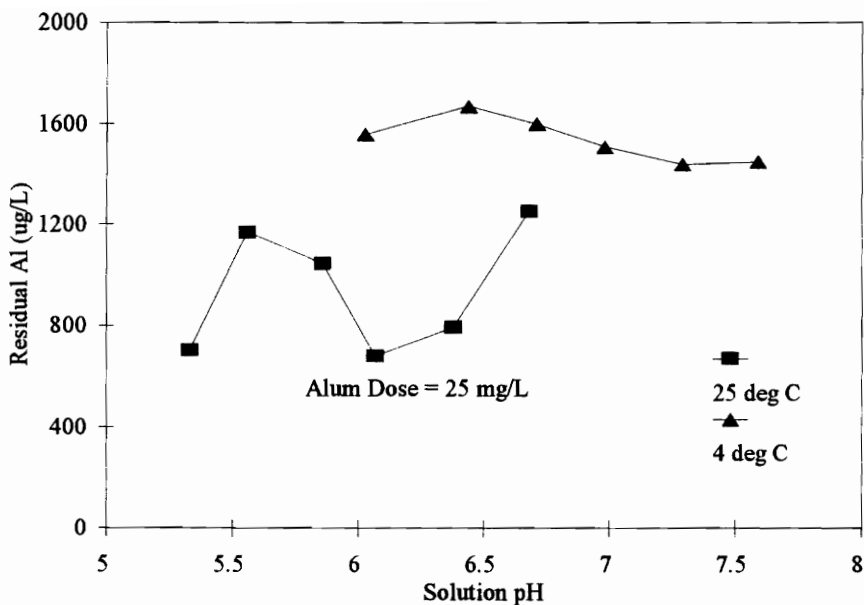


Figure 4.71. Residual aluminum as a function of coagulation pH for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

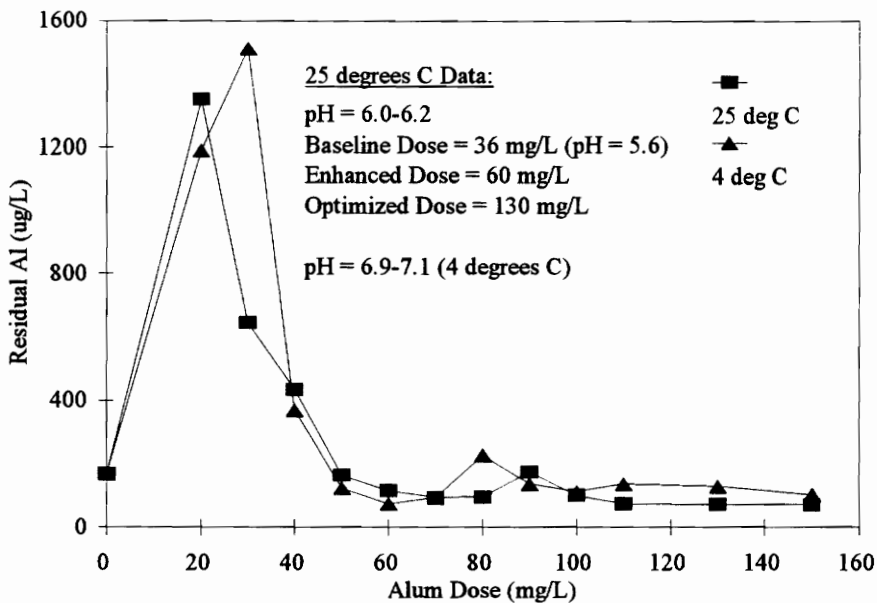


Figure 4.72. Residual aluminum as a function of alum dose for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

Determination of Optimum pH for TOC Removal

The results from the pH optimization test for Utility VT-6 for residual DOC are presented in Figure 4.73 for alum and Figure 4.74 for ferric sulfate. Results from both the 25°C jar tests and the 4°C jar tests are included in the figures. The pH optimization was performed at a coagulant dose of 30 mg/L for alum and 20 mg/L for ferric sulfate. Minimum residual DOC values at 4°C were seen at a solution pH range of approximately 5.9-6.1 for alum and 5.5-5.7 for ferric sulfate. These pH ranges were chosen as the optimum pH ranges at 4°C. As previously discussed, the optimum pH ranges at 25°C were 5.5-5.6 for alum, and 5.0-5.2 for ferric sulfate. The UV254 results as a function of coagulation pH are contained in Appendix G.

Dose Optimization

The dose optimization procedure at 4°C for Utility VT-6 alum and ferric sulfate treatment was performed at coagulant doses ranging from 0 to 110 mg/L at the previously determined optimum pH ranges. DOC results for alum and ferric sulfate at both 25°C and 4°C are presented in Figures 4.75 and 4.76, respectively. Residual DOC values were almost identical for 4°C and 25°C for both alum and ferric sulfate coagulation. The minimum residual DOC value observed was approximately the same at 4°C and 25°C. Residual UV254 results are contained in Appendix G.

Figures 4.77 and 4.78 contain the SUVA values as a function of coagulant dose, at 4°C and 25°C, for Utility VT-6 alum and ferric sulfate treatment, respectively. A spike was seen in SUVA at low coagulant doses at 4°C; similar to the spike seen at 25°C.

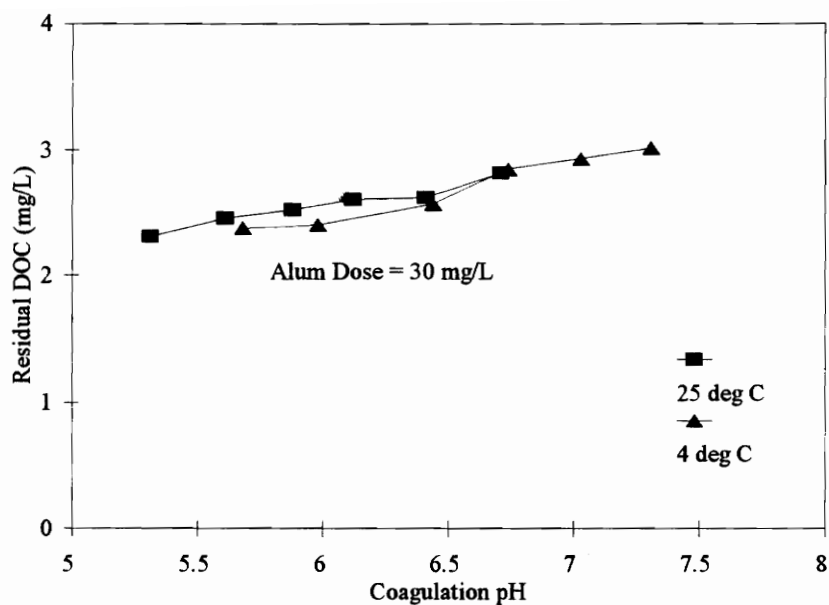


Figure 4.73. Residual DOC as a function of coagulation pH for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

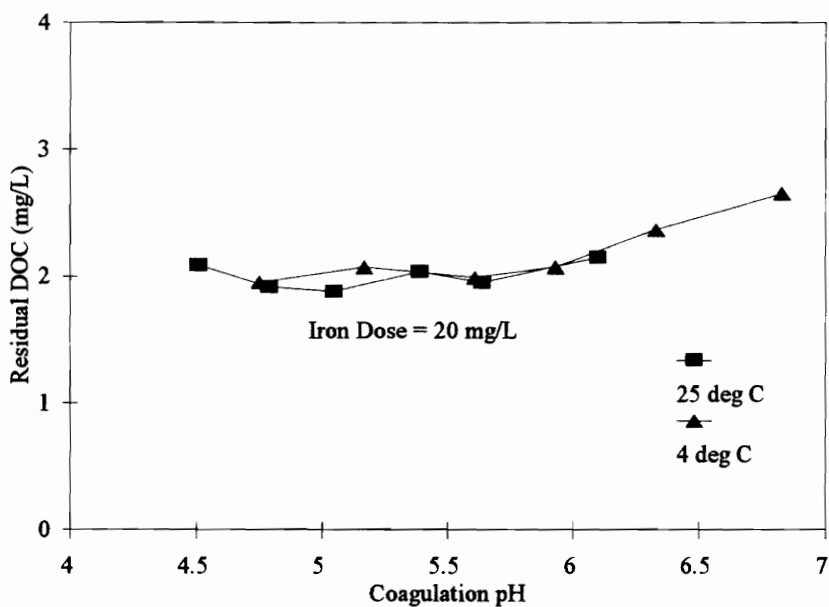


Figure 4.74. Residual DOC as a function of coagulation pH for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

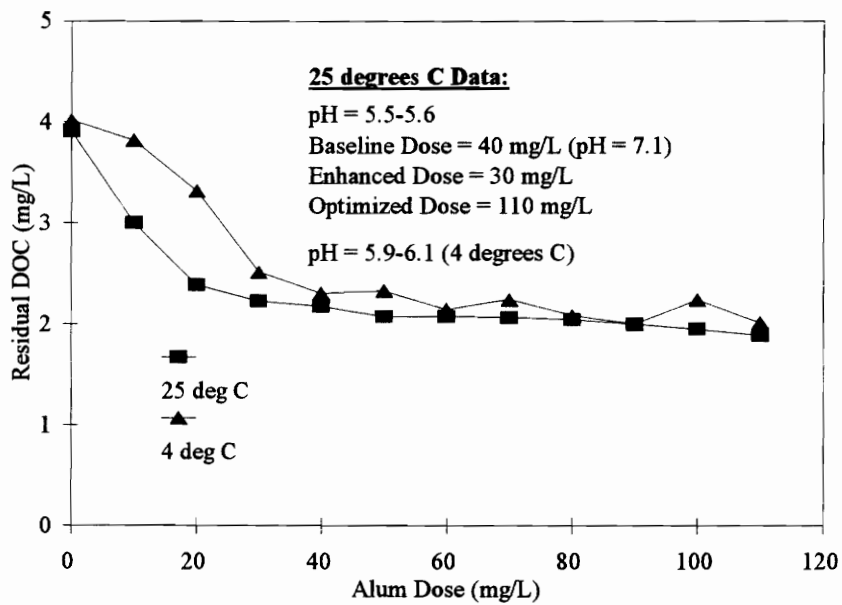


Figure 4.75. Residual DOC as a function of alum dose for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

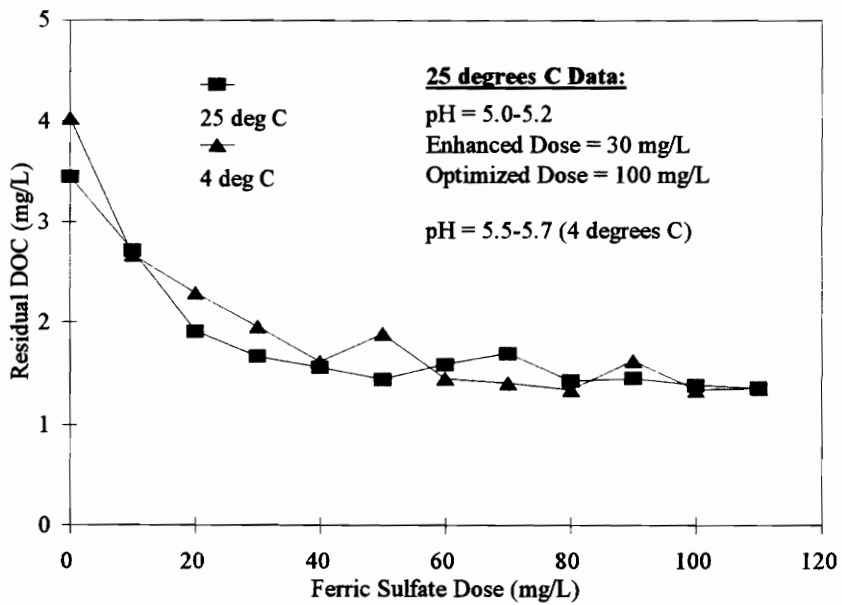


Figure 4.76. Residual DOC as a function of ferric sulfate dose for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

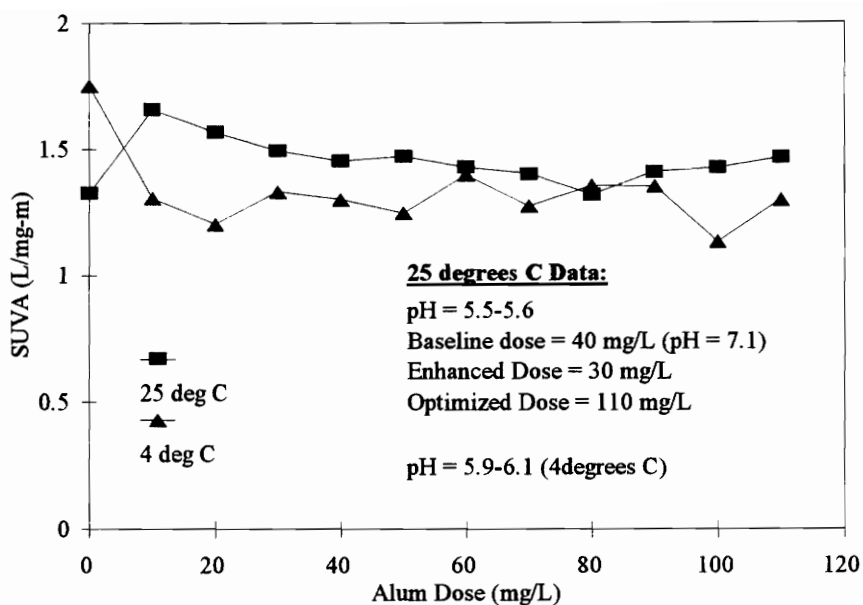


Figure 4.77. Specific UV absorbance as a function of alum dose for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

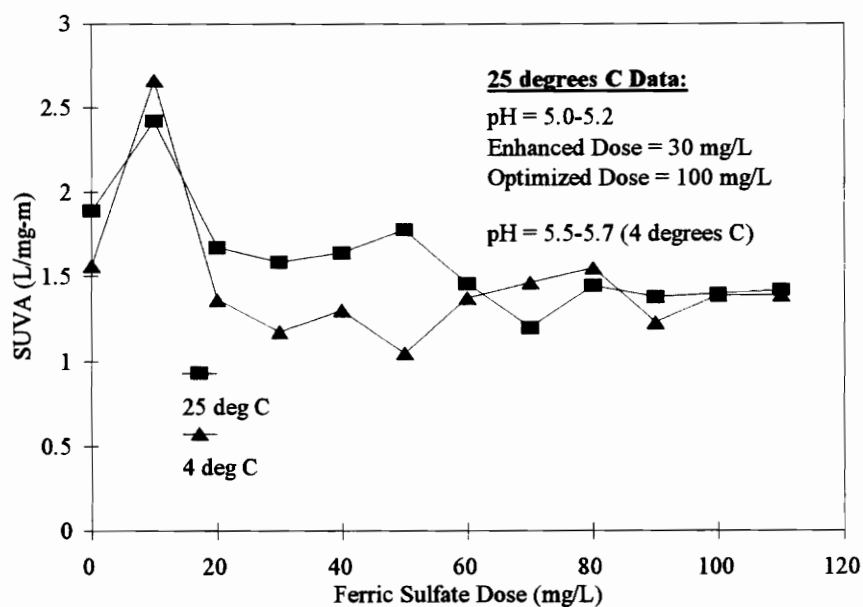


Figure 4.78. Specific UV absorbance as a function of ferric sulfate dose for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

Residual Coagulant

Figures 4.79 and 4.80 present residual coagulant as a function of pH for alum and ferric sulfate, respectively, at 4°C and at 25°C. Minimum residual coagulant levels at 4°C were seen at a pH value of approximately 6.4-6.6 for alum and approximately 5.6-5.8 for ferric sulfate. Results of residual aluminum and iron as a function of coagulant dose for 4°C are contained in Figure 4.81 and 4.82, respectively. The residual coagulant results as a function of coagulant dose were similar at 4°C and 25°C.

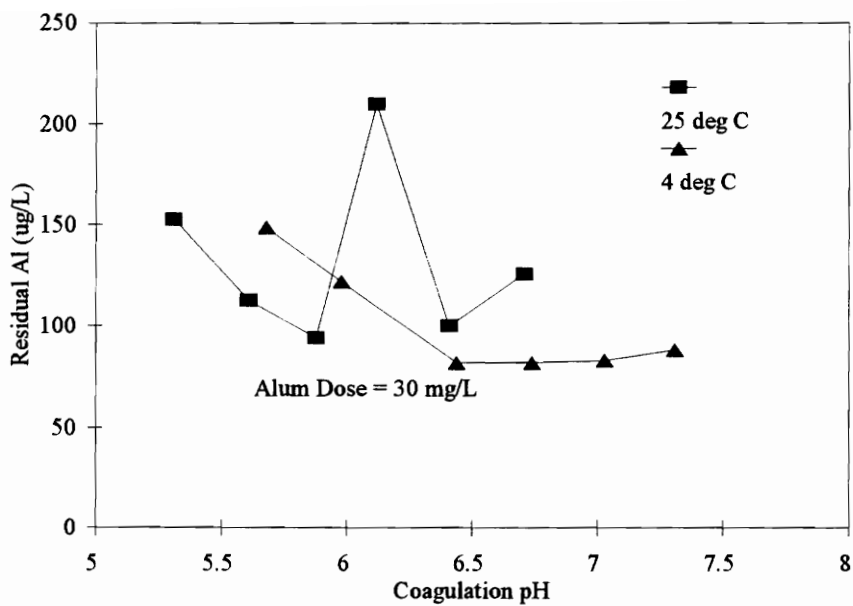


Figure 4.79. Residual aluminum as a function of coagulation pH for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

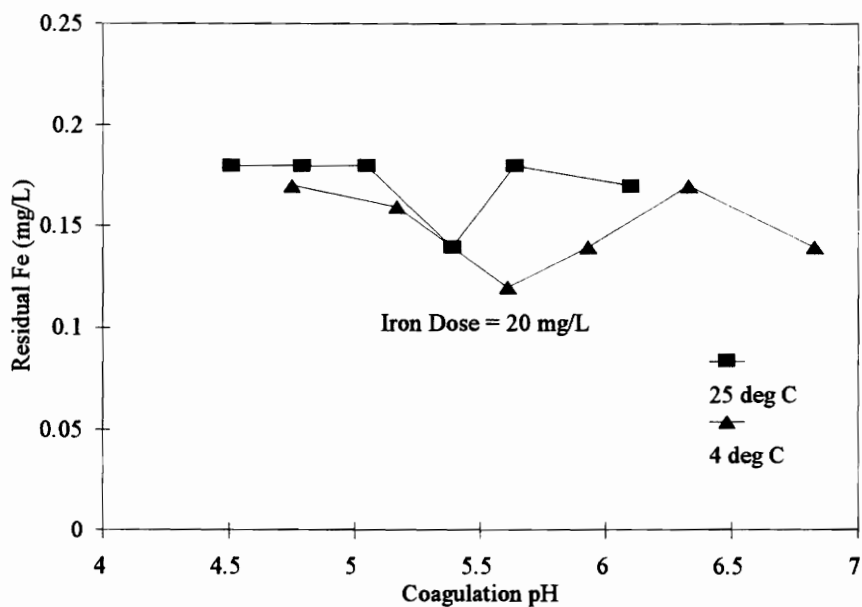


Figure 4.80. Residual iron as a function of coagulation pH for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

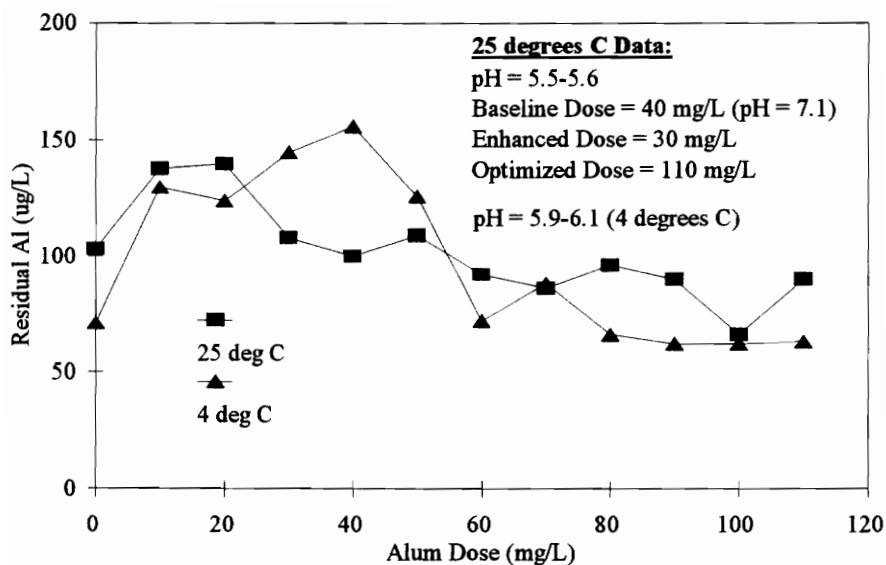


Figure 4.81. Residual aluminum as a function of alum dose for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

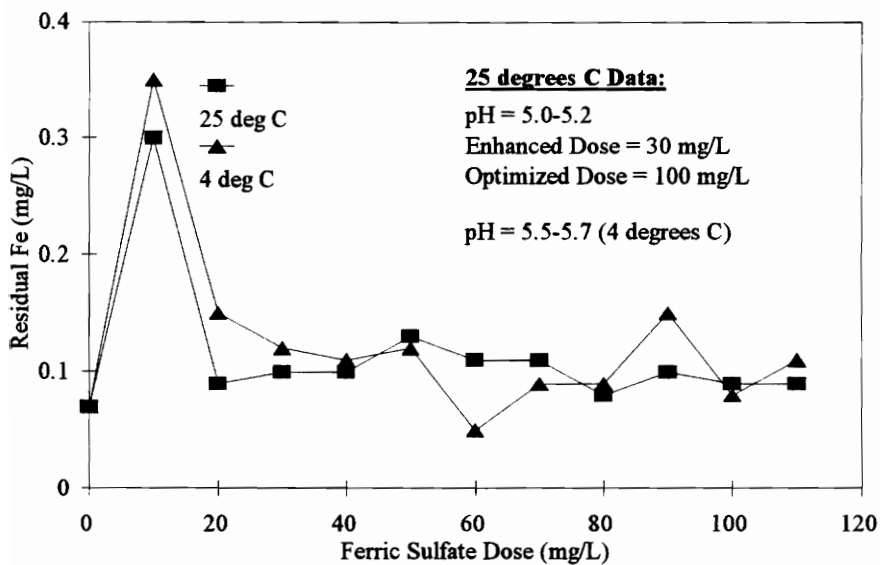


Figure 4.82. Residual iron as a function of ferric sulfate dose for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

Chapter V

DISCUSSION

In this chapter, a discussion of the information contained in the Results section will be presented. While the data contained in the Results section were organized by utility, this section is generally organized by subject, with the data from different utilities presented together. First, the reproducibility of replicate jar testing is discussed with respect to the proposed D/DBP rule. Next, pilot-scale and full-scale jar test results are compared with the bench-scale jar test results. The bench-scale jar test results are then discussed, including pH optimization for TOC removal, removal of TOC, reduction of UV254, specific UV absorbance, apparent molecular weight distribution, and residual coagulant, as well as the effects of low temperature on the optimum pH for TOC removal, removal of TOC, and residual coagulant. Next, the DBP results are discussed, including THMs and TOX. The last section of this chapter contains a comparison of the relative reductions of TOC, DOC, UV254, THMFP, and DOXFP by enhanced coagulation.

A glossary of the abbreviations used in this chapter is contained in Appendix P.

REPRODUCIBILITY OF JAR TEST DATA

The reproducibility of residual DOC results for the baseline and enhanced bench-scale jar testing for all utilities is contained in the previous chapter (Table 4.1). The D/DBP Rule (Step 2) defines enhanced coagulation as the coagulant dose where a 10 mg/L increase in coagulant dose does not produce greater than a 0.3 mg/L decrease in DOC or TOC over the previous dose (Federal Register 1994). Therefore, the standard deviation of replicate jar tests should be less than 0.3 mg/L, or a difference of 0.3 mg/L would not be a good indicator of differing levels of treatment. The standard deviations for the bench-scale residual DOC results for all of the utilities ranged from

0.039 mg/L to 0.327 mg/L. The average standard deviation was 0.136, less than half of the 0.3 mg/L amount. The median standard deviation was 0.115.

The percentage errors of the standard deviations with respect to the average residual DOC values ranged from 1.3 percent to 14.5 percent. The average and median percentage errors of the standard deviation were 5.5 percent and 4.8 percent, respectively. Figure 5.1 contains a graph of the percentage errors of the standard deviations with respect to the average residual DOC values for the baseline and enhanced jar tests for all of the utilities as a function of the average residual DOC. The r^2 value for this correlation based on linear regression analysis is 0.18. This does not indicate a strong linear relationship between the two variables; however, the highest percentage error values occurred at the lowest residual DOC values, an expected result.

These results seem to indicate that the D/DBP Rule requirement of defining enhanced coagulation based on a change in DOC of < 0.3 mg/L per 10 mg/L coagulant addition is reasonably estimated from jar test results. One should keep in mind that in evaluating data such as these, clear discontinuities in the data should be investigated closely prior to defining the enhanced coagulant dose.

COMPARISON OF PILOT-SCALE AND FULL-SCALE TREATMENT TO BENCH-SCALE TREATMENT

Pilot-Scale Treatment

As previously discussed, for Utilities VT-1, VT-6, and VT-8, pilot-scale treatment was performed to compare the removal of disinfection by-product precursors between pilot-scale and bench-scale treatment. The pilot-plant testing was performed at the enhanced coagulant dose determined by the bench-scale treatment, although at different coagulation pH values than the bench-scale testing.

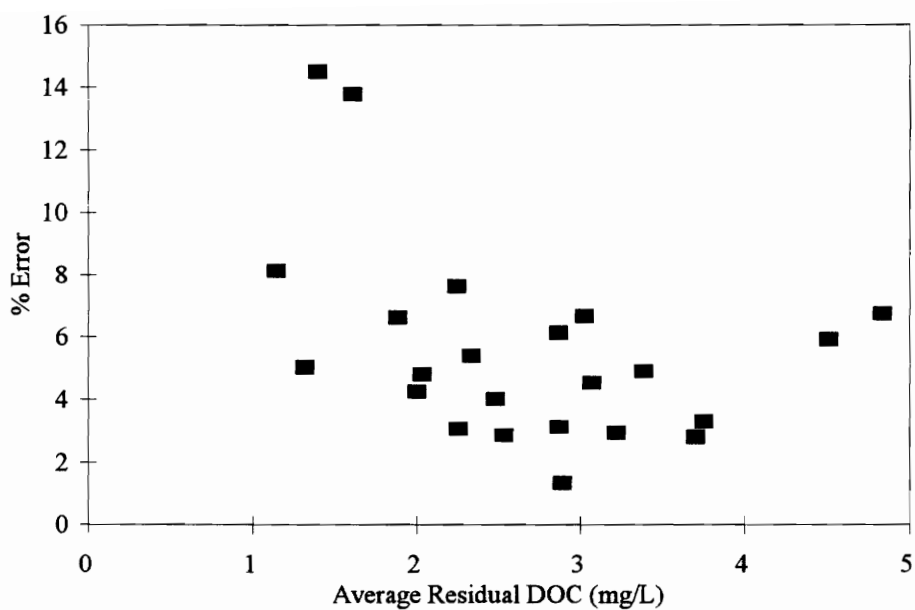


Figure 5.1. Percentage error of the standard deviations of DOC concentrations for replicate jar tests with respect to the average residual DOC concentrations as a function of the average residual DOC concentrations for baseline and enhanced treated samples.

Exact comparison of bench-scale to pilot-scale treatment is somewhat difficult due to the differing coagulation pH values (see Tables 4.2-4.5). In general, lower coagulation pH values were used for the bench-scale treatment and led to greater removals of TOC, THMFP, and NPDOXFP, an expected result. However, the difference in coagulation pH values typically had to be significant to affect DBP precursor removal results. For example, for Utility VT-6 alum treatment, the bench-scale enhanced treatment was conducted at a coagulation pH range of 5.5-5.6, and indicated greater removals than the pilot-scale baseline treatment which was conducted at the same coagulant dose, but at a coagulation pH value of 7.6. However, when comparing the bench-scale enhanced treatment (pH = 5.5-5.6) to the pilot-scale enhanced treatment (pH = 6.6) the removals of TOC, THMFP, and NPDOXFP were similar. This trend was also seen for Utility VT-6 and Utility VT-8 bench-scale and pilot-scale iron treatment.

Analysis of the Utility VT-6 and Utility VT-8 pilot-scale baseline removals versus the pilot-scale enhanced removals indicates that the lower pilot-scale enhanced treatment coagulation pH values of 6.6 for Utility VT-6 alum treatment, 5.8 for Utility VT-6 iron treatment, and 6.5 for Utility VT-8 iron treatment led to higher removals of TOC, THMFP, and NPDOXFP than the pilot-scale baseline treatment with coagulation pH values of 7.6 for Utility VT-6 alum treatment, 7.2 for Utility VT-6 iron treatment, and 7.6 for Utility VT-8 iron treatment.

Overall, these results indicate that lower coagulation pH values generally lead to greater removal of DOC by coagulation, an expected result. However, these results also seem to indicate that below a certain coagulation pH value, residual DOC is not highly sensitive to coagulation pH. This result was also seen for the bench-scale pH optimization jar tests, and will be discussed later in this chapter.

Full-Scale Treatment

A comparison of the bench-scale baseline treatment residual DOC results with the full-scale settled and finished water (clearwell) residual DOC results is contained in the previous chapter (Table 4.6). The percentage difference between the bench-scale residual DOC values and the full-scale finished residual DOC values (as a percentage of the full-scale values) ranged from -26 percent to +65 percent. The difference of 65 percent was for Utility VT-4, for which the full-scale treatment included a coagulant aid polymer which has been shown to improve liquid-solids separation thereby improving TOC removal (Jacangelo *et al.* 1995). This will be discussed further later in this chapter. When considering all the utilities except Utility VT-4, the percentage difference ranges from -26 percent to +16 percent. Also, the percentage difference was negative for three of the eight remaining utilities (bench-scale treatment removed more DOC than full-scale treatment), and was positive for five of the remaining eight utilities (bench-scale treatment removed less DOC than full-scale treatment). These results seem to indicate that bench-scale and full-scale results are comparable and neither type of treatment is consistently more effective than the other.

SOURCE WATER CHARACTERISTICS

Figure 5.2 contains a comparison of the TOC and DOC levels for the raw water for each of the nine utilities. The average and median values for the dissolved fraction of TOC as a percentage of the total TOC were 93.1 percent and 94.0 percent, respectively. The minimum value was 85 percent. These results clearly show that the vast majority of the TOC present was dissolved in nature, a result frequently observed in many surface water sources (Edzwald 1993).

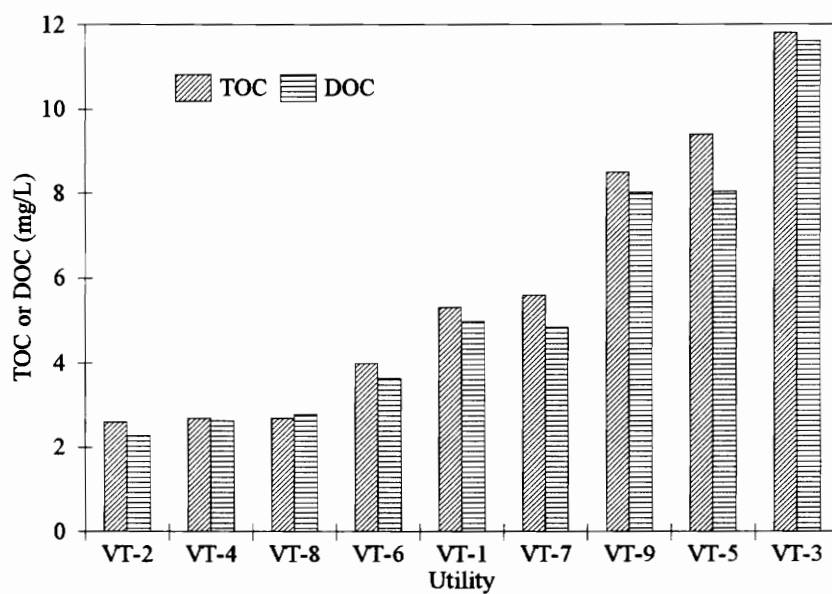


Figure 5.2. Comparison of raw water TOC and DOC concentrations for all utilities. (Utilities are ranked in order of increasing TOC value).

JAR TEST DATA

As previously discussed, the D/DBP Rule requires certain utilities to achieve specified levels of TOC removal prior to continuous disinfection for contact time (CT) credit (Crozes et al. 1995). Table 5.1 includes the D/DBP Rule revised Stage 1 TOC removal requirements by enhanced coagulation, and also indicates how each of the raw water samples analyzed in this study fit into this matrix. The location of the utilities in this table applies only to the specific raw water samples which were utilized in this study. The raw water TOC and/or alkalinity values for many of these utilities will vary during the year; therefore, the required TOC removals will also vary during the year as the raw water characteristics change.

Optimum pH for TOC Removal

Coagulation pH is an important parameter in TOC removal by coagulation with metal salts since the metal species present in the water, as well as the charge on DOM, are a function of the sample pH. The metal species present in the water and the charge on the DOM are two factors which affect the removal mechanism of TOC by coagulation. The optimum pH for organics removal for each of the utilities is included in Table 5.2. The optimum pH for alum coagulation ranged from 5.6 to 6.1. For ferric sulfate coagulation, the optimum pH varied from 4.9 to 5.7. This data corresponds well with previous research which indicated an optimum pH of 5-6 for organics removal with alum, and 4.5-5.5 for organics removal with iron salts (Vik et al. 1985; Edzwald 1987; Hubel and Edzwald 1987; Pontius 1990).

As previously discussed, the pH optimization curves (relating residual DOC to coagulation pH at a constant coagulant dose) were used to determine the optimum pH for organics removal for each utility. For a number of the utilities, these optimization curves did not exhibit a distinct minimum DOC value by which to pick the optimum

Table 5.1
Revised Stage 1 D/DBP Rule Required Removal of TOC
by Enhanced Coagulation for Each Utility

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L as CaCO ₃)					
	0-60		>60-120		>120	
0-2.0	NO ACTION		NO ACTION		NO ACTION	
>2.0-4.0	40%	VT-2 VT-4	30%		20%	VT-8
>4.0-8.0	45%	VT-7 VT-1	35%		25%	VT-6
>8.0	50%	VT-9	40%	VT-3	30%	VT-5

Source: Adapted from Federal Register 1994.

Table 5.2
Optimum pH for Organics Removal for Alum and
Ferric Sulfate Treatment for Each Utility

Coag	Utility								
	VT-1	VT-2	VT-3	VT-4	VT-5	VT-6	VT-7	VT-8	VT-9
Alum	5.9	6.0	5.6	5.9	6.0	5.6	6.0	5.9	6.1
Iron	---	---	4.9	5.1	---	5.1	5.0	5.7	5.6

(Optimum pH value selected based upon DOC removal considerations.)

pH value; instead, the optimization curves were either approximately flat or decreasing for all decreasing pH values. The utilities which exhibited a distinct minimum value were Utilities VT-2, VT-4, and VT-9 for alum coagulation, and Utilities VT-2, VT-4, and VT-6 for ferric sulfate coagulation. With the exception of Utility VT-9, these utilities had low initial TOC values, as well as low raw water specific UV absorbance (SUVA) values. The pH optimization curves for the utilities with higher initial TOC values and higher initial SUVA values were either flat or decreasing for all pH values. These data indicate that residual DOC is not highly sensitive to coagulation pH, in particular for utilities with higher initial TOC or higher initial SUVA values. Therefore, during full-scale plant operation, other factors (i.e. residual Al or Fe, solids settling behavior, etc.) would most likely play a significant role in determining the actual coagulation pH at which a plant would operate.

TOC Removal

As previously indicated, Step 1 of the Stage 1 D/DBP Rule includes required TOC removal percentages for certain utilities. The required removals vary from 20 percent to 50 percent depending on the raw water TOC and alkalinity values. Table 5.3 includes a comparison of the required TOC removals and the actual bench-scale and full-scale removals achieved at the baseline dose for each of the utilities. Figure 5.3 contains the percentage removals of TOC at the bench-scale and full-scale baseline doses for all nine utilities as a function of raw water TOC.

Utilities VT-1, VT-4, VT-6, and VT-8 did not meet the TOC removal requirements at one of the baseline doses, either bench-scale or full-scale. Some potential reasons for this occurrence could be coagulation pH, raw water supply characteristics, raw water TOC levels, and raw water SUVA values.

In terms of coagulation pH, these utilities have most likely optimized (at the time of this study) their treatment process for turbidity removal rather than organics

Table 5.3

Comparison of Required TOC Removals and Actual TOC Removals for Baseline Bench-Scale and Full-Scale Treatment for Each Utility (Utilities are Ranked in Order of Increasing Raw Water TOC)

Utility	Baseline Treatment	Alkalinity (mg/L as CaCO ₃)	Raw Water TOC (mg/L)	TOC (Full-Scale Plant Data)		TOC (Bench-Scale Data)		Required Removal† (percent)
				Finished* (mg/L)	Removal (percent)	Finished* (mg/L)	Removal (percent)	
VT-2	17 mg/L Alum	21	2.56	1.21	53	1.32	48	40
VT-4†	5.6 mg/L Fe ₂ (SO ₄) ₃	15	2.65	1.42	46	2.34	12	40
VT-8	3 mg/L Alum	135	2.73	2.50	8.4	2.87	(5.1)	20
VT-6	40 mg/L Alum	138	4.02	3.03	25	3.07	24	30
VT-1	40 mg/L Alum	60	5.32	3.18	40	2.53	52	45
VT-7	35 mg/L Alum	44	5.64	2.53	55	2.89	48	45
VT-9	36 mg/L Alum	9.8	8.54	2.78	67	3.22	62	50
VT-5	120 mg/L Alum	198	9.41	6.02	36	4.84	49	30
VT-3	122 mg/L Fe ₂ (SO ₄) ₃	112	11.8	3.88	67	2.87	75	40

* Full-scale and bench-scale finished water values are DOC values.

† Based on revised Stage 1 requirements (Step 1) of the D/DBP Rule (Federal Register 1994).

‡ Direct Filtration Plant (3.5 mg/L coagulant aid polymer utilized during full-scale treatment).

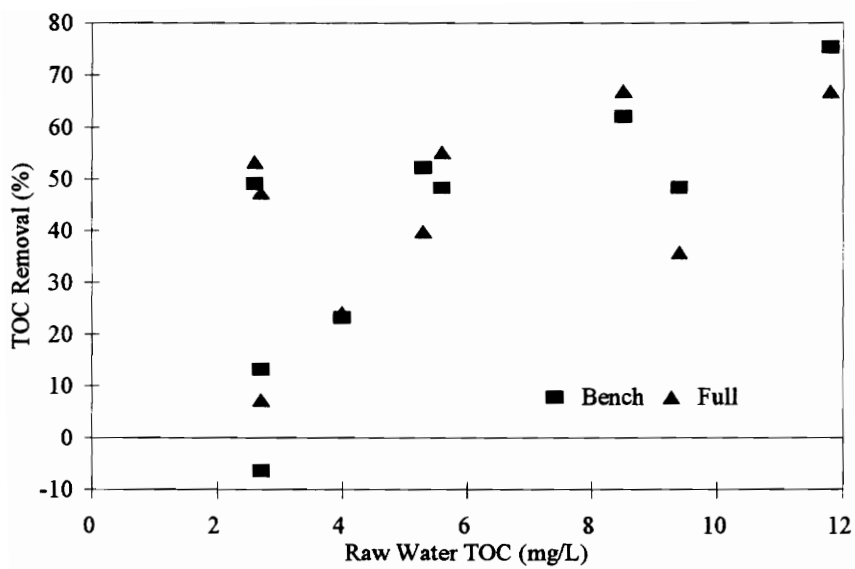


Figure 5.3. Percentage TOC removal for baseline bench-scale and full-scale treated samples as a function of raw water TOC concentration.

removal, often utilizing a higher coagulation pH value than the optimum required for TOC removal. In terms of water supply characteristics, each of these utilities utilize reservoirs as source waters. Some settling of particulate organic matter may occur in the reservoirs as indicated by the very small amount of particulate TOC seen in the raw water samples. This settling of particulate organic matter may improve overall raw water quality, but may make the TOC removal criteria required by the D/DBP Rule more difficult to achieve since no credit is given for the TOC removal in the reservoirs (Shorney *et al.* 1996).

These utilities (VT-1, VT-4, VT-6, and VT-8) have four of the five lowest raw water TOC values of the utilities tested, indicating that utilities with lower TOC values may have more difficulty in meeting the Step 1 D/DBP Rule requirements (Shorney *et al.* 1996). Figure 5.3 reinforces this conclusion in that the removal of TOC increased with increasing raw water TOC values. Also, these utilities had four of the five lowest raw water SUVA values, indicating that utilities with raw waters with low SUVA values may have more difficulty in removal of TOC by coagulation, a trend seen previously by other researchers (Edzwald *et al.* 1985, Edzwald 1994)

The largest discrepancy between bench-scale and full-scale treatment occurred for Utility VT-4. The full-scale treatment included 3.5 mg/L of coagulant aid polymer which was not included in the bench-scale treatment. The DOC removal for the bench-scale baseline treatment (without polymer addition) was 12 percent, while the DOC removal for the full-scale baseline treatment (with polymer addition) was 46 percent. One explanation of this occurrence is that coagulant addition alone did not create particles which were large enough to be filtered, while the addition of polymer increased the size of the particles, improving liquid-solid separation, thus allowing the particles to be filtered. This follows previous findings which have shown that, while polymers used alone have not been as effective at TOC removal as aluminum or iron salts, the use of polymers as a coagulant aid has improved TOC removal by improving liquid-solid separation (Jacangelo *et al.* 1995).

Table 5.4 includes a comparison of the required TOC removals and the actual bench-scale removals achieved at the enhanced alum and ferric sulfate doses for each of the utilities. All of the utilities except for Utility VT-4 (alum enhanced treatment) could meet the TOC removal requirements at the alum enhanced dose and/or the ferric sulfate enhanced dose. The bench-scale alum enhanced removal for Utility VT-4 was 39 percent, which is very close to the 40 percent requirement. Figure 5.4 contains the percentage removals of TOC at the alum enhanced and ferric enhanced doses for all nine utilities as a function of raw water TOC. The removal of TOC increased with increasing raw water TOC values, similar to the trend seen for the baseline treated samples.

UV254 Reduction

The two measurements of organic matter used in this study (DOC and UV254) are obviously related. Figure 5.5 contains the relationship between DOC and UV254 for the raw water samples. These measurements are not identical because not all TOC absorbs ultraviolet light at a wavelength of 254 nm (Van Benschoten and Edzwald 1990b). This is evident by the fact that the linear regression line in Figure 5.5 does not intersect the origin.

Utility VT-9, with a DOC value of 8.03 mg/L and a UV254 value of 49.1 m⁻¹ does not seem to follow the trend of the other utilities. The raw water for Utility VT-9 has headwaters in a swampy region. This could explain the apparent discrepancy in SUVA values for the raw water for Utility VT-9, since swampy regions often are predominant in high molecular weight humics and fulvics, often leading to high SUVA values (Edzwald 1993). As will be presented later, Utility VT-9 was, in fact, predominant in higher molecular weight organics. Due to the apparent differences in the raw water source for Utility VT-9, the linear regression line included in Figure 5.5 does not include the Utility VT-9 value.

Table 5.4

Comparison of Required TOC Removals and Actual TOC Removals
for Enhanced Bench-Scale Treatment for Each Utility

Utility	Enhanced Treatment	Coagulation pH	Alkalinity (mg/L as CaCO ₃)	TOC (Bench-Scale Data)		
				Raw (mg/L)	Enhanced* (mg/L)	Removal (percent)
VT-2	30 mg/L Alum	6.0	21	2.56	1.14	55
VT-4	20 mg/L Alum	5.9	15	2.65	1.61	39
	20 mg/L Fe ₂ (SO ₄) ₃	5.1			1.39	48
VT-8	30 mg/L Alum	5.9	135	2.73	2.00	27
	25 mg/L Fe ₂ (SO ₄) ₃	5.7			1.88	31
VT-6	30 mg/L Alum	5.6	138	4.02	2.48	38
	30 mg/L Fe ₂ (SO ₄) ₃	5.1			2.03	50
VT-1	40 mg/L Alum	5.9	60	5.32	2.25	58
VT-7	30 mg/L Alum	6.0	44	5.64	3.02	46
	40 mg/L Fe ₂ (SO ₄) ₃	5.0			2.24	60
VT-9	60 mg/L Alum	6.1	9.8	8.54	3.70	57
	60 mg/L Fe ₂ (SO ₄) ₃	5.6			3.39	60
VT-5	50 mg/L Alum	6.0	198	9.41	3.75	60
VT-3	100 mg/L Alum	5.6	112	11.8	4.51	62
	65 mg/L Fe ₂ (SO ₄) ₃	4.9			3.70	69

* Enhanced values are DOC values.

† Based on revised Stage 1 requirements (Step 1) of the D/DBP Rule (Federal Register 1994).

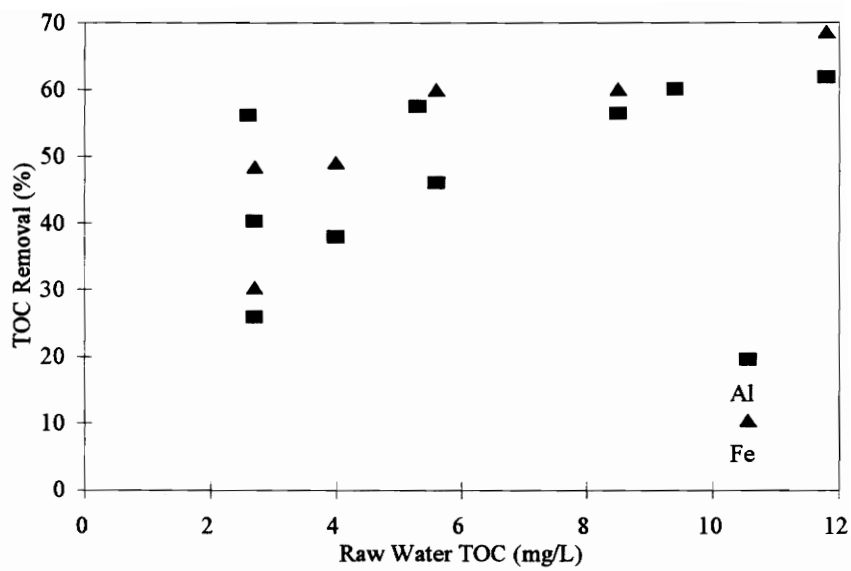


Figure 5.4. Percentage TOC removal for enhanced treated samples as a function of raw water TOC concentration.

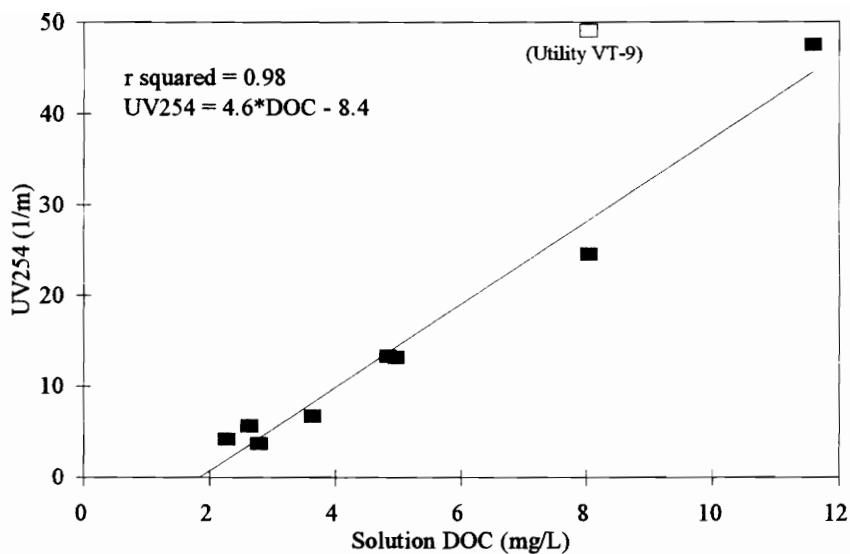


Figure 5.5. Relationship between DOC and UV254 for raw water samples for all utilities. (Note: Linear regression line does not include Utility VT-9 data due to the different nature of the organics present in the Utility VT-9 raw water.)

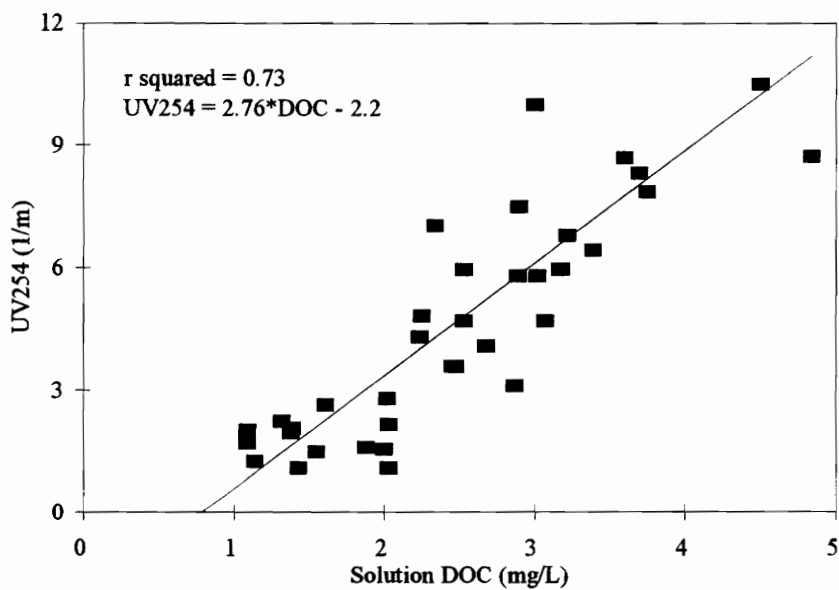


Figure 5.6. Relationship between DOC and UV254 for treated water samples for all utilities.

Figure 5.6 contains the relationship between DOC and UV254 for the treated water samples for all utilities. These data are not as closely related as those for the raw waters due to the varying levels of treatment they have undergone. The linear regression for this comparison does not go through the origin, indicating that a portion of the DOC present as residual DOC for the low DOC water samples has very little UV absorbance.

Specific UV Absorbance

As previously discussed, specific UV absorbance (SUVA) is defined as the ratio of ultraviolet absorbance at a wavelength of 254 nm (UV254) [1/m] to DOC concentration [mg/L]. Specific UV absorbance has been shown to be a good indicator of the expected removal of DOC from natural waters. Generally, if SUVA values are 4 to 5, the DOC consists largely of aquatic humics, and DOC removals of 50 percent to 70 percent can be expected. For SUVA values less than 3, the DOC is composed largely of non-humics, and 20 percent to 50 percent removals of DOC can be expected (Edzwald 1993). Table 5.5 includes the raw water SUVA values and the percentage DOC removals for both baseline and ferric enhanced treatment for the raw waters tested. These results do not exhibit a defined breakpoint of SUVA values of 3-4 which separate good and poor DOC removal. However, the general trend is that higher DOC removals are seen for waters with higher raw water SUVA values.

The pH optimization curves described previously indicate that raw waters with low SUVA values are potentially more sensitive to coagulation pH in terms of organics removal than raw waters with higher SUVA values. This seems logical in that the high SUVA waters contain organics which are more amenable to removal by coagulation than the low SUVA waters, and these organics may be removable over a wider range of coagulation pH values than the organics contained in the low SUVA waters.

Table 5.5

Raw Water SUVA Values and Percentage TOC Removals for Baseline
and Enhanced Treatment for Each Utility
(Utilities listed in order of decreasing SUVA value)

Utility	Raw Water TOC (mg/L)	Raw Water SUVA (L/mg-m)	Full-Scale		Bench-Scale	Alum Enhanced TOC Removal (%)	Ferric Enhanced TOC Removal (%)	Required Removal* (%)
			TOC Removal (%)	Baseline TOC Removal (%)				
VT-9	8.54	6.11	67	62	57	60	50	
VT-3	11.8	4.09	67	75	62	69	40	
VT-5	9.41	3.05	36	49	60	---	30	
VT-7	5.64	2.75	55	48	46	60	45	
VT-1	5.32	2.65	40	52	58	---	45	
VT-4	2.65	2.19	46	12	39	48	40	
VT-2	2.56	1.87	53	48	55	---	40	
VT-6	4.02	1.86	25	24	38	50	30	
VT-8	2.73	1.34	8.4	(5.1)	27	31	20	

* Based on revised Stage 1 requirements (Step 1) of the D/DBP Rule.

As previously discussed, Utilities VT-1, VT-4, VT-6, and VT-8 were the utilities which did not meet the revised Stage 1 D/DBP Rule required TOC removals at the baseline dose, either full-scale or bench-scale. Utility VT-4 was the only utility which did not meet these required TOC removals at one of the enhanced doses (alum enhanced). As can be seen from Table 5.5, these utilities have SUVA values less than approximately 2.5. Utility VT-2 appears to be an anomaly to this trend, with a low SUVA value (1.87 L/mg-m), but with high removals of TOC at both the baseline (53 percent full-scale and 48 percent bench-scale) and alum enhanced (55 percent) doses. These higher removals may be due to the fact that Utility VT-2 consists largely of higher molecular weight organics, with approximately 70 percent of the organics greater than 3,000 daltons in size. Also, the raw water SUVA value for Utility VT-2 may be falsely low because the SUVA value which was determined for the blank jar test (0 mg/L coagulant) was almost 2.5 L/mg-m, greater than the 1.87 L/mg-m value determined for the raw water.

Overall, raw water SUVA appears to be an excellent predictor of a utility's ability to satisfy the enhanced coagulation requirements of the D/DBP Rule. For the utilities analyzed in this study, utilities with raw water SUVA values greater than approximately 2.5-3.0 L/mg-m appear to more easily meet the D/DBP Rule TOC removal requirements than utilities with raw water SUVA values less than 2.5 L/mg-m.

Residual UV254 Spike

Analysis of the dose optimization jar test results for which ferric sulfate was used as the coagulant indicated a spike in residual UV254 at low coagulant doses. A corresponding spike in residual iron was also evident at these low coagulant doses (i.e. Utility VT-4; 5.6 mg/L and 10 mg/L $\text{Fe}_2(\text{SO}_4)_3$ in Figure 4.10 (residual UV254 spike) and in Figure 4.13 (residual Fe spike), Utility VT-7; 10 mg/L $\text{Fe}_2(\text{SO}_4)_3$ in Figure 4.18

(residual UV254 spike) and in Figure 4.21 (residual Fe spike)). In addition, the bench-scale baseline treatment for Utility VT-4 was performed at a low ferric sulfate dose (5.6 mg/L) and the residual UV254 value for the baseline treated water was 7.03 m^{-1} , while the raw water UV254 value was 5.75 m^{-1} . The Utility VT-4 bench-scale baseline treatment iron concentration was 0.49 mg/L, while the raw water iron concentration was 0.06 mg/L.

For the eight utilities for which residual aluminum samples were collected, a spike in residual aluminum concentrations at low alum doses was also seen, but no spike in residual UV254 was apparent.

One explanation of the spike in residual UV254 is that at low coagulant doses colloidal iron can become coated with organics. This colloidal iron would pass a $0.45 \mu\text{m}$ or $1.5 \mu\text{m}$ filter; therefore, it would be present in the filtered UV254 samples. The spikes in residual iron at low coagulant doses for these five utilities support this theory.

Since spikes in residual UV254 were not seen with alum coagulation, this could indicate that: (1) colloidal aluminum is not formed at low coagulant doses, or (2) the DOC present in the raw water samples does not have as great an affinity for colloidal aluminum as it does for colloidal iron. As previously mentioned, colloidal aluminum was formed at low coagulant doses as evidenced by the spike in residual aluminum concentrations at low coagulant doses for each of the eight utilities for which residual aluminum samples were collected. This would indicate that the first theory above is incorrect. Therefore, the most likely explanation is that the DOC present in the raw water samples does not have as great an affinity for colloidal aluminum as for colloidal iron. This theory is further substantiated by the fact that TOC removals by iron coagulation were greater than those for aluminum coagulation for all of the utilities in this study for which both coagulants were utilized.

A corresponding spike in residual organic carbon (dissolved and colloidal) concentration was not seen for any of the utilities which had a spike in UV254. This

would indicate that, if in fact the cause for the UV254 spike is colloidal iron coated with organics, then the organics which do adsorb to the colloidal iron is that portion which does absorb UV light. If this were true, one would expect that UV254 reduction by coagulation would be greater than TOC reduction by coagulation. Figure 5.7 contains a comparison between UV254 reduction and TOC reduction for all treated samples. A line with slope equal to one has been drawn to give an indication of whether TOC reduction or UV254 reduction was greater. Data points which fall above the line indicate that UV254 reduction was greater, while data points which fall below the line indicate that TOC reduction is greater. Reduction of UV254 was greater than reduction of TOC for a majority of the samples. This confirms that aluminum and iron species present in these pH ranges have a greater affinity for organic matter that absorbs ultraviolet light, than for organic matter that does not absorb ultraviolet light. This trend has been seen previously by other researchers (Chadik and Amy 1983; Edzwald *et al.* 1985; Knocke *et al.* 1986; Reckhow and Singer 1990).

Apparent Molecular Weight Distribution

The molecular weight of natural organic matter varies between sources. Previous research has indicated that, in general, a large majority of natural organics are less than 10,000 amu, with the distribution between smaller sizes varying between sources (Collins *et al.* 1986; Sinsabaugh *et al.* 1986a; El-Rehaili and Weber 1987). Table 5.6 gives the distribution of organics for each of the utilities tested. For this study, a number of the raw waters had a large amount of organics > 10,000 amu. The utilities in Table 5.6 are ranked in order of increasing TOC removal at the alum enhanced dose. Inspection of the percentage removals for each utility indicates that, in general, the utilities with the greater percentage of higher molecular weight organics tended to have a greater TOC removal percentage than the utilities which had a greater

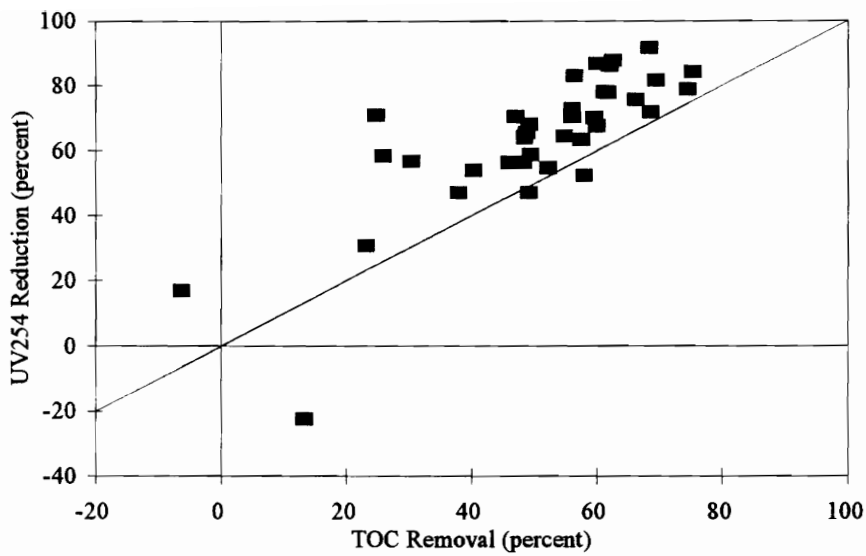


Figure 5.7. Comparison of TOC removal and UV254 reduction for all treated samples. (Note: Line shown is a line with 1:1 slope: data points located above the line indicate greater UV254 reduction, while data points located below the line indicate greater TOC removal.)

Table 5.6

AMWD Distribution for Raw Waters for Each Utility
(Utilities are Ranked in Order of Increasing TOC Removal at Alum Enhanced Dose)

Utility	Percentage of Total DOC				Alkalinity (mg/L as CaCO ₃)	Raw Water TOC (mg/L)	Baseline	Alum Enhanced	Ferric Enhanced
							TOC	TOC	TOC
	>10K (%)	3K-10K (%)	1K-3K (%)	0.5K-1K (%)			Removal (%)	Removal (%)	Removal (%)
VT-8	17.2	22.9	34.4	15.8	135	2.73	(5.1)	27	31
VT-6	11.5	36.3	14.3	27.7	138	4.02	24	38	50
VT-4	45.6	19.8	16.7	7.2	15	2.65	12	39	48
VT-7	30.2	29.3	21.9	12.2	44	5.64	48	46	60
VT-2	38.2	32.9	6.6	11.4	21	2.56	48	55	---
VT-9	61.3	13.1	15.1	5.9	9.8	8.54	62	57	60
VT-1	13.5	35.9	22.9	18.5	60	5.32	52	58	---
VT-5	25.7	23.8	33.1	12.3	198	9.41	49	60	---
VT-3	10.6	42.2	33.2	10.9	112	11.8	75	62	69

percentage of lower molecular weight organics, a trend seen by other researchers (Amy *et al.* 1992; Collins *et al.* 1986). Utilities VT-4 and VT-1 appear to be exceptions to this trend.

Figure 5.8 presents the percentage removals of DOC for each molecular weight fraction for alum enhanced treatment, while Figure 5.9 presents the same information for ferric enhanced treatment. The percentage removals for certain weight fractions for some utilities were negative, and these values were not included in compilation of the data for Figures 5.8 and 5.9. These figures indicate that the percentage removal of the organics increased with increasing AMW, a trend seen by other researchers (Collins *et al.* 1986; Amy *et al.* 1992). For the water sources utilized in this study, alum coagulation removed, on average, a greater percentage of the lower molecular weight organics (<0.5K - 1K) and the higher molecular weight organics (>10K), but ferric sulfate coagulation removed a greater percentage of the organics in the 1K-10K range.

Residual Coagulant

Based on the solubility diagrams for aluminum, the pH of minimum solubility of aluminum in equilibrium with gibbsite ($\text{Al}(\text{OH})_3$ (c)) is approximately 6.2. The minimum solubility of aluminum in equilibrium with amorphous $\text{Al}(\text{OH})_3$ occurs at a pH value of approximately 7. In water treatment plants, amorphous $\text{Al}(\text{OH})_3$ is most likely the solid present. Iron has a minimum solubility in equilibrium with either amorphous $\text{Fe}(\text{OH})_3$ or crystalline goethite (FeOOH) at a pH value of approximately 8 (Pontius 1990).

Based on these minimum solubility pH values, one concern of decreasing solution pH to optimize organics removal is that residual coagulant remaining in the finished water may increase. Increased aluminum levels have been hypothesized to have a possible link with neurological disorders, including Alzheimers disease (Letterman 1988 quoting Crapper *et al.* 1973; Davidson *et al.* 1982), while elevated

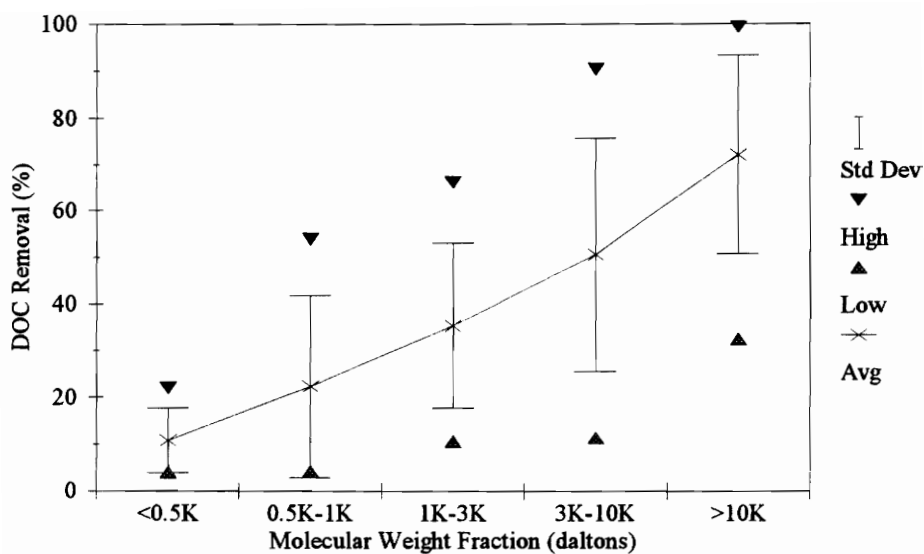


Figure 5.8. Percentage removals of DOC for each molecular weight fraction for alum enhanced treatment. (Note: % Removals which were less than 0 % were not included in these data).

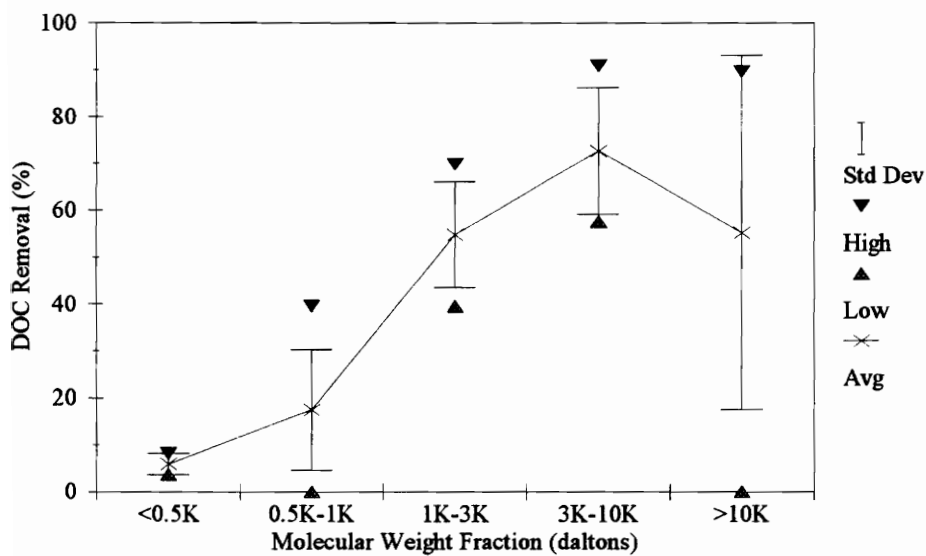


Figure 5.9. Percentage removals of DOC for each molecular weight fraction for ferric enhanced treatment. (Note: % Removals which were less than 0 % were not included in these data).

levels of iron are often associated with taste and/or fixture staining problems. The maximum contaminant level goal (MCLG) for aluminum is 0.050 mg/L. A secondary drinking water standard of 0.3 mg/L has been set for iron. Table 5.7 gives the total iron and aluminum concentrations for the raw and treated waters for each of the utilities.

All of the utilities had treated water aluminum concentrations at the baseline and enhanced doses of greater than 50 µg/L, with the exception of utilities VT-1 and VT-2. Utility VT-1 results are extremely low and do not seem reasonable compared to all the other utilities. The low Utility VT-1 results were most likely due to the fact that the residual aluminum samples were not preserved prior to analysis; therefore, the Utility VT-1 residual aluminum results are not included in Figure 5.10 or Figure 5.14. None of the utilities except VT-4 (baseline treatment) exceeded the secondary MCL of 0.3 mg/L for iron, although Utility VT-3 had a residual iron concentration equal to the MCL at the ferric enhanced dose. The elevated iron concentration for Utility VT-4 baseline treatment ($\text{Fe}_2(\text{SO}_4)_3$ dose = 5.6 mg/L) was most likely due to colloidal iron which is formed at low coagulant doses as previously discussed. For both iron and aluminum coagulation, there was not an apparent trend which indicated that treatment increased the residual coagulant concentrations.

Figures 5.10 and 5.11 contain plots of residual aluminum and residual iron, respectively, as a function of coagulation pH for the baseline, enhanced, and optimized treated samples. These curves appear to have similar shape to the solubility curves of aluminum in equilibrium with $\text{Al}(\text{OH})_3$ and iron in equilibrium with $\text{Fe}(\text{OH})_3$. The minimum residual coagulant concentrations for aluminum appear to be in the pH range of 5.8-6.5. The minimum residual coagulant concentrations for iron appear to be in the pH range of 5.0-5.5, although it is difficult to tell from the data collected due to the lack of data at coagulation pH values above 5.7.

One problem when considering Figures 5.10 and 5.11 is that the residual DOC values vary between the different samples; therefore it is difficult to determine whether

Table 5.7

Residual Coagulant Concentrations for Raw and Treated Waters for Each Utility

Utility	Raw			Baseline			Enhanced			Optimized		
	Al (µg/L)	Fe (mg/L)		DOC (mg/L)	Al (µg/L)	Fe (mg/L)	DOC (mg/L)	Al (µg/L)	Fe (mg/L)	DOC (mg/L)	Al (µg/L)	Fe (mg/L)
VT-1	7	---		2.53	2	---	2.25	1	---	---	---	---
VT-2	78	---		1.32	73	---	1.14	40	---	1.09	---	---
VT-3	66.5	0.11		2.87	---	0.25	4.51	120	3.70	3.64	158	0.23
VT-4	1.0	0.06		2.34	---	0.49	1.61	52	1.39	1.38	43	0.04
VT-5	76	---		4.84	149	---	3.75	58	---	3.17	59	---
VT-6	103	0.07		3.07	161	---	2.48	170	2.03	2.02	66	0.07
VT-7	112	0.20		2.89	67	---	3.02	92	2.24	2.51	58	0.09
VT-8	72	<0.03		2.87	242	---	2.00	52	1.88	2.03	87	0.07
VT-9	168	0.29		3.22	81	---	3.70	78	3.39	3.18	85	0.05

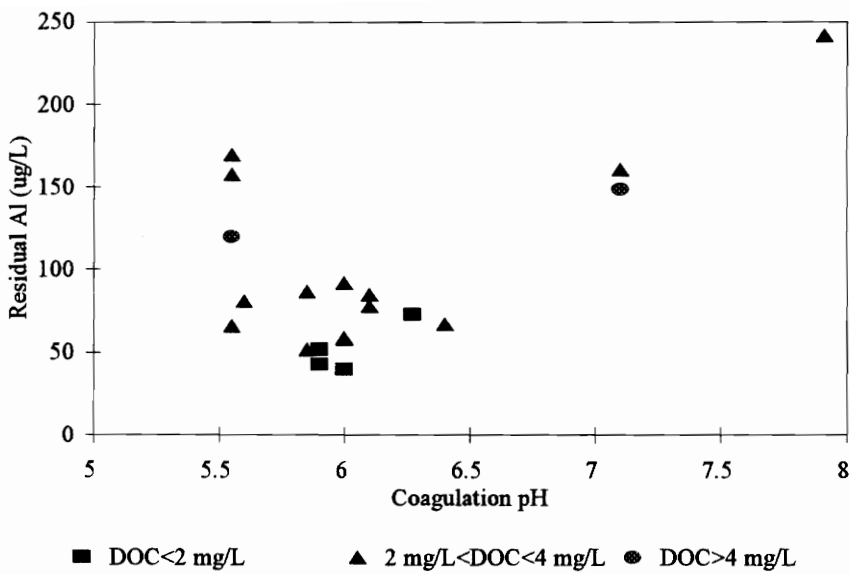


Figure 5.10. Residual aluminum concentrations as a function of coagulation pH for baseline, enhanced, and optimized treated waters for all utilities. (Utility VT-1 values were not included due to erroneous results.)

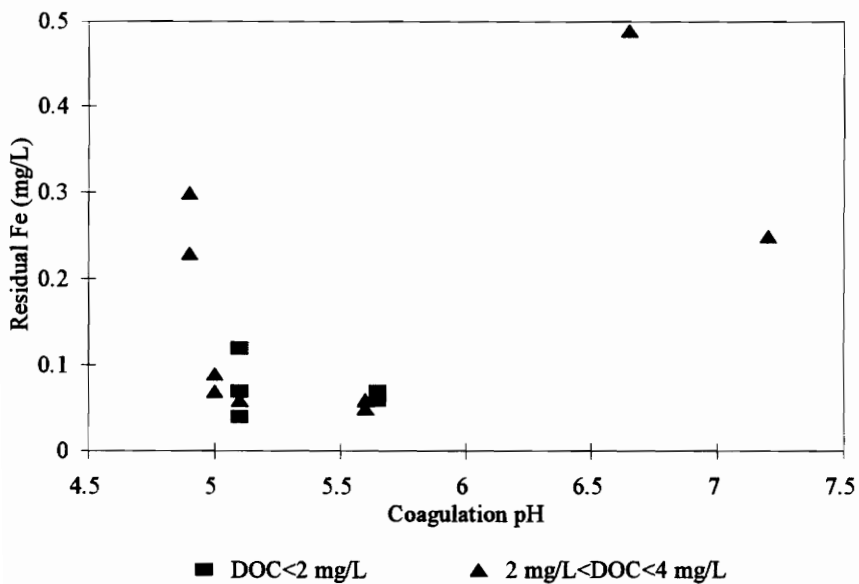


Figure 5.11. Residual iron concentrations as a function of coagulation pH for baseline, enhanced, and optimized treated waters for all utilities.

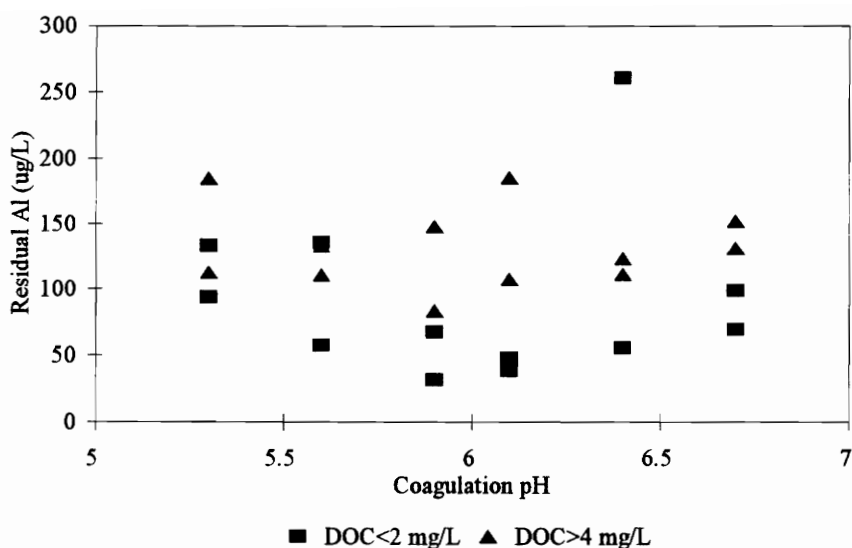


Figure 5.12. Data from pH optimization jar testing for four utilities showing residual aluminum concentrations as a function of coagulation pH. (Note: Two of the utilities have residual DOC concentrations < 2 mg/L and two have residual DOC concentrations > 4 mg/L.)

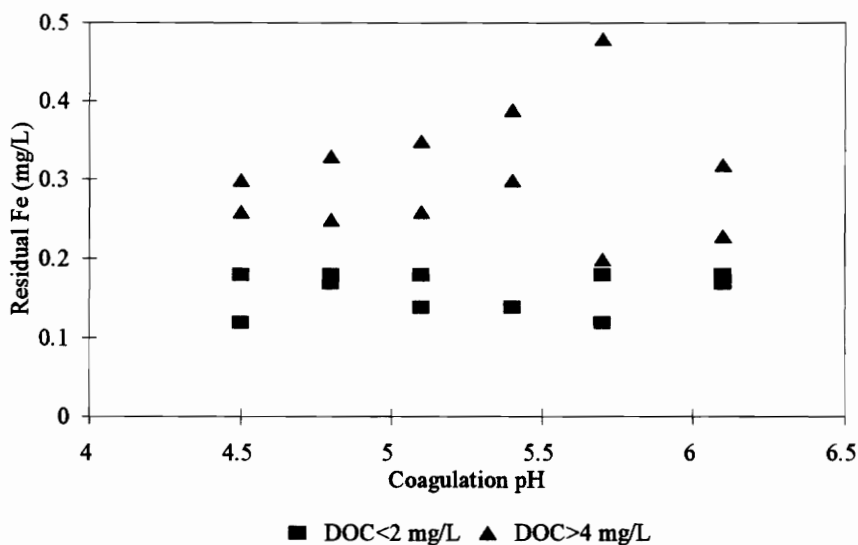


Figure 5.13. Data from pH optimization jar testing for four utilities showing residual iron concentrations as a function of coagulation pH. (Note: Two of the utilities have residual DOC concentrations < 2 mg/L and two have residual DOC concentrations > 4 mg/L.)

the increased residual coagulant concentrations are a result of lower pH values or of higher residual DOC values. Figures 5.12 and 5.13 present data from the pH optimization jar testing for four utilities showing residual coagulant concentrations as a function of coagulation pH. Figure 5.12 contains residual aluminum data, while Figure 5.13 contains residual iron data. In order to attempt to determine the combined effect of reduced coagulation pH values and residual DOC on residual aluminum concentrations, two of the utilities for each figure had residual DOC concentrations < 2 mg/L and two of the utilities had residual DOC concentrations > 4 mg/L. For both aluminum and iron, the samples with greater residual DOC concentrations had greater levels of residual coagulant remaining in the treated water, an expected result. Residual aluminum appears to have a minimum solubility pH value of approximately 5.7-6.2 for both low and high residual DOC waters. This corresponds well with the residual aluminum results for the baseline, enhanced and optimized treated samples (Figure 5.10). The residual iron results are fairly consistent over the pH range investigated, and lower pH values do not appear to lead to higher residual coagulant levels. Based on these results, it appears that it is a combination of solution pH and available organic matter which serves to complex aluminum or iron at a given pH value which may lead to higher residual coagulant levels.

The relationship of residual coagulant concentrations to residual DOC is presented in Figures 5.14 and 5.15. The data in these figures are separated based on utilities with low raw water SUVA values and those with high raw water SUVA values. As previously discussed, raw water SUVA values of approximately 3.0 L/mg-m have been shown to be the breakpoint between DOC which is composed largely of aquatic humics (SUVA > 3.0 L/mg-m) and DOC which is composed largely of non-humics (SUVA < 3.0 L/mg-m) (Edzwald 1993). The breakpoint used between low SUVA waters and high SUVA waters was approximately 3.0 L/mg-m. Utilities VT-1, VT-2, VT-4, VT-6, VT-7 and VT-8 had raw water SUVA values < 3.0 L/mg-m. The remaining utilities (Utilities VT-3, VT-5, and VT-9) had SUVA values > 3.0 L/mg-m.

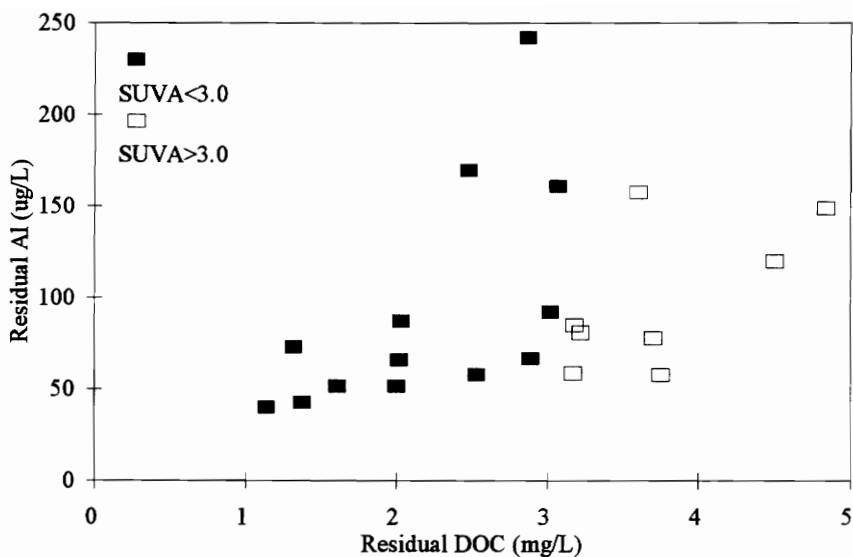


Figure 5.14. Residual aluminum concentrations as a function of residual DOC concentrations for treated waters. (Note: Data has been separated based on raw water SUVA values.)

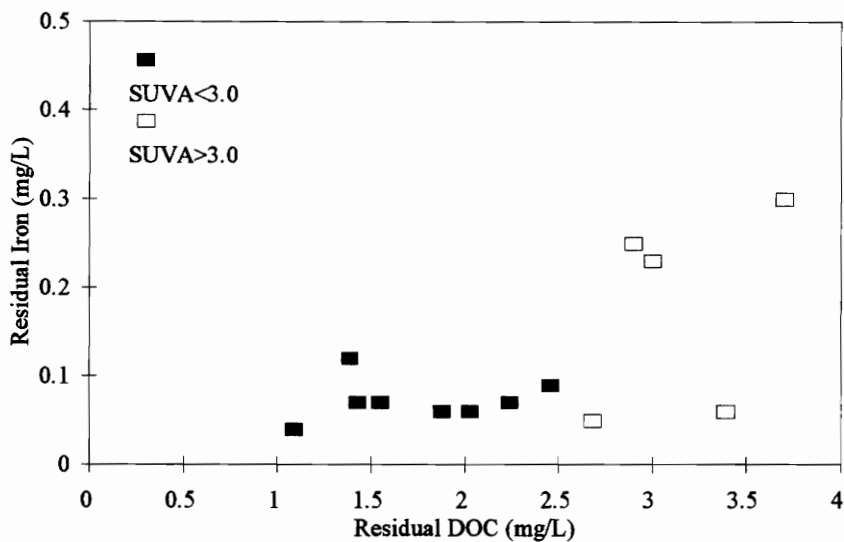


Figure 5.15. Residual iron concentrations as a function of residual DOC concentrations for treated waters. (Note: Utility VT-4 baseline data has not been included due to colloidal iron present at that dose. Also data has been separated based on raw water SUVA values.)

Figure 5.14 presents residual aluminum concentrations as a function of residual DOC concentration for all treated waters, while Figure 5.15 contains the same information for residual iron. In general, higher residual DOC concentrations corresponded to higher residual coagulant concentrations, particularly when considering residual aluminum concentrations.

As previously discussed, a residual UV254 spike was seen at low ferric sulfate doses along with a corresponding spike in residual iron. A spike in residual organic carbon was not seen at these low coagulant doses. For the alum coagulated waters, a spike in residual aluminum was also seen at low coagulant doses; however, a corresponding residual UV254 or organic carbon spike was not seen at low coagulant doses for the alum treated waters.

The spike in both residual iron and UV254 at low coagulant doses indicates that these spikes may be related. Figures 5.16-5.18 correlate the residual organic concentrations with the residual coagulant concentrations for the lowest coagulant doses utilized during the dose optimization studies (i.e. the doses where the spikes in residual coagulant occurred). Although no spike in residual organic carbon or residual UV254 was seen at low aluminum doses in conjunction with the spike in residual aluminum, residual organic carbon and residual aluminum at these low alum doses were related, as seen in Figure 5.16. The UV254 results are not presented, but had similar results. This was also the case for both residual organic carbon and residual UV254 and residual iron, as seen in Figures 5.17 and 5.18. As expected, residual UV254 and residual iron had the best correlation. The potential reasons for these relationships have been described previously. Note that the organic carbon present at these low coagulant doses should probably not be referred to as dissolved organic carbon, as this fraction represents most likely dissolved as well as colloidal organic matter.

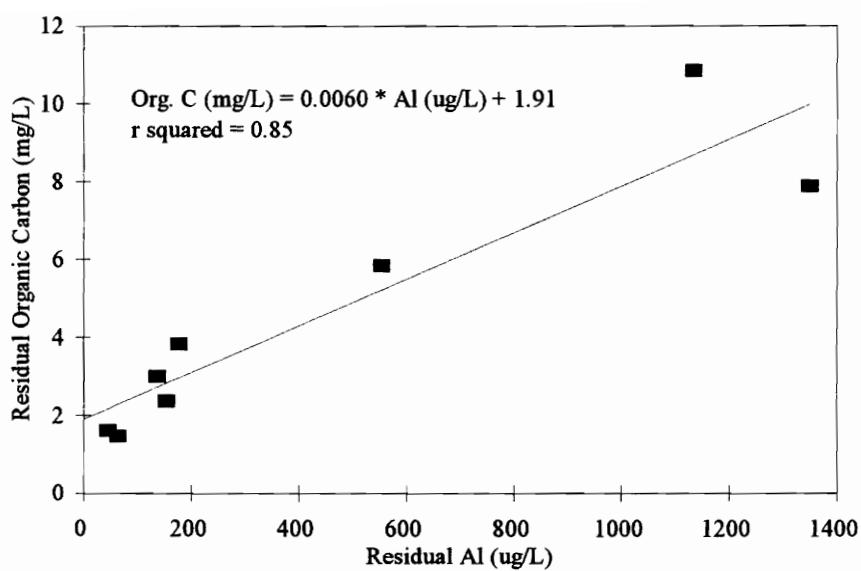


Figure 5.16. Comparison of residual organic carbon (colloidal + dissolved) and residual aluminum passing 1.5 um filter at lowest coagulant doses during dose optimization studies.

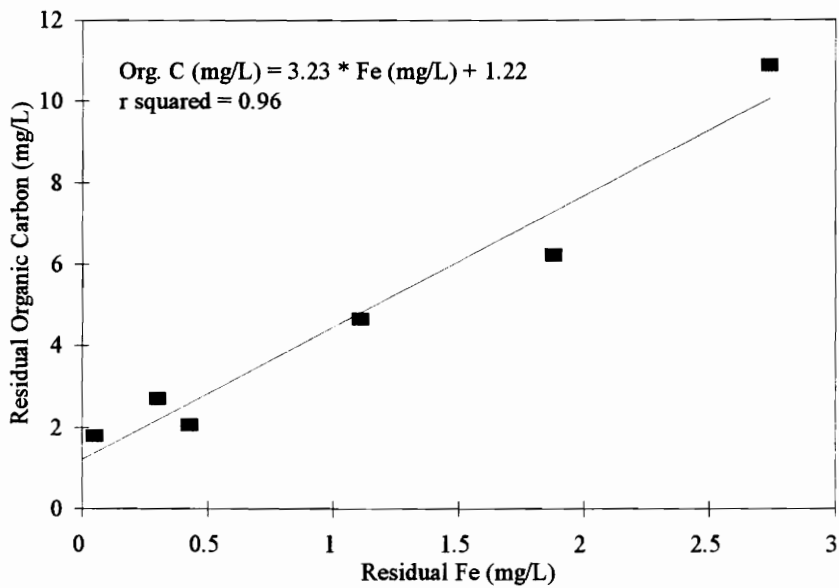


Figure 5.17. Comparison of residual organic carbon (colloidal + dissolved) and residual iron passing 1.5 um filter at lowest coagulant doses during dose optimization studies.

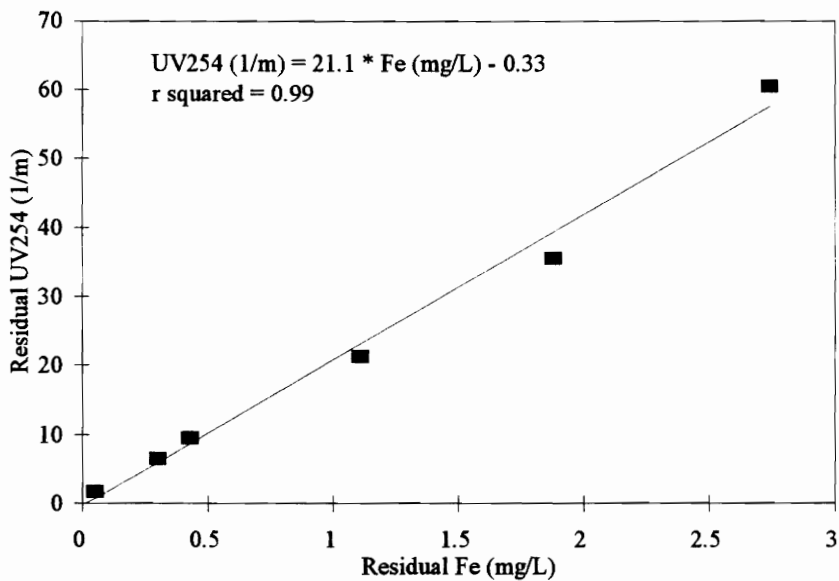


Figure 5.18. Comparison of residual UV254 and residual iron passing 1.5 um filter at lowest coagulant doses during dose optimization studies.

Comparison of Alum and Ferric Sulfate

Previous research has shown aluminum salts to be more effective at removal of organic material by coagulation in some cases while iron salts have been shown to be more effective in others (Randtke 1988). Figures 5.19 and 5.20 compare the DOC and UV254 reductions for alum and ferric sulfate baseline and enhanced treatment for all utilities. For each of the six utilities for which alum and ferric sulfate were compared in this study the DOC removal at the ferric sulfate enhanced dose was greater than that at the alum enhanced dose. Along with a greater reduction in DOC, typically a greater reduction in UV254, THMFP, and DOXFP was seen with ferric sulfate coagulation. These data are included in Table 5.8.

In comparing the results of organics removal by aluminum and iron salts, it is useful to compare the coagulant doses in molar units as the metal ion (either aluminum or iron) as opposed to concentration of alum or ferric sulfate. This comparison gives a more accurate view of the effectiveness of each coagulant in terms of the number of positive (+) charges added to the water. Figures 5.21-5.26 summarize the residual DOC results as a function of the molar concentration of metal ion added for the six utilities for which both alum and ferric sulfate were utilized. The residual UV254 results for each of these six utilities are included in the appropriate appendices for that utility. The trend and the amount of positive species required for each coagulant is very similar, and typically the curves begin to level out at approximately the same molar amount of metal species addition for each coagulant. However, the results do seem to indicate that on a mole per mole basis, iron addition generally worked slightly better than aluminum addition as evidenced by the fact that the Fe curve was generally lower than the Al curve at the same molar concentration. Also, the minimum residual DOC was typically lower with Fe than with Al. This is logical since for all the utilities the reduction in DOC was greater at the ferric sulfate enhanced dose than at the alum enhanced dose.

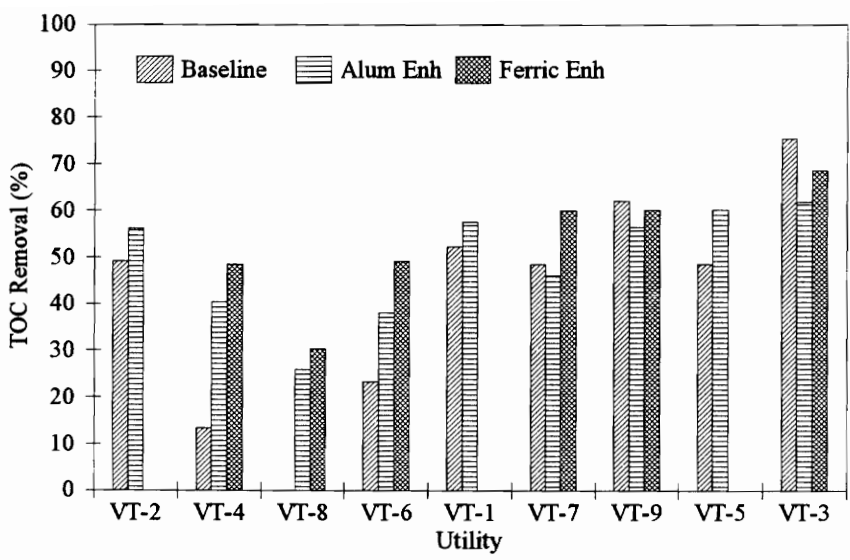


Figure 5.19. Percentage removals of TOC for all utilities for bench-scale baseline and enhanced treatment (Utilities are ranked in order of increasing raw water TOC value).

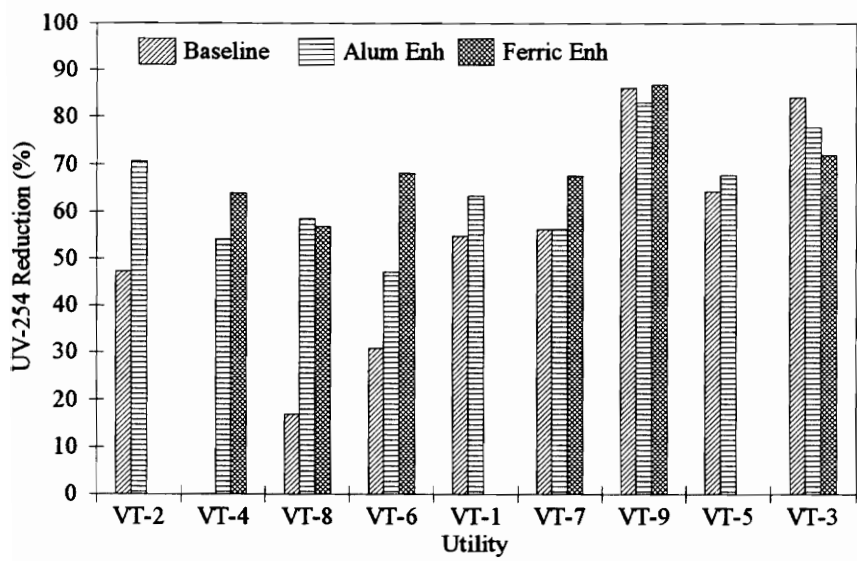


Figure 5.20. Percentage removals of UV254 for all utilities for bench-scale baseline and enhanced treatment (Utilities are ranked in order of increasing raw water TOC value).

Table 5.8

Comparison of Percentage Reduction of TOC, UV254, THMFP, and DOXFP
by Alum and Ferric Sulfate Enhanced and Optimized Coagulation
(Raw water TOC concentration in mg/L shown in parentheses beside each utility)

Utility	Enhanced Samples		Optimized Samples	
	Alum	Ferric Sulfate	Alum	Ferric Sulfate
VT-3 (11.8)				
TOC Red (%)	62	69	69	75
UV254 Red (%)	78	72	82	79
THMFP Red (%)	66	70	67	75
DOXFP Red (%)	72	74	79	86
VT-4 (2.65)				
TOC Red (%)	39	48	48	59
UV254 Red (%)	54	64	66	70
THMFP Red (%)	46	49	48	57
DOXFP Red (%)	25	39	37	48
VT-6 (4.02)				
TOC Red (%)	38	50	50	61
UV254 Red (%)	47	68	59	78
THMFP Red (%)	14	45	25	50
DOXFP Red (%)	52	51	56	57

(continued)

Table 5.8 (continued)

Utility	Enhanced Samples		Optimized Samples	
	Alum	Ferric Sulfate	Alum	Ferric Sulfate
VT-7 (5.64)				
TOC Red (%)	46	60	55	56
UV254 Red (%)	56	68	65	73
THMFP Red (%)	38	58	50	61
DOXFP Red (%)	50	67	58	70
VT-8 (2.73)				
TOC Red (%)	27	31	26	48
UV254 Red (%)	59	57	71	71
THMFP Red (%)	20	29	28	31
DOXFP Red (%)	22	42	44	44
VT-9 (8.54)				
TOC Red (%)	57	60	63	69
UV254 Red (%)	83	87	88	92
THMFP Red (%)	43	55	63	67
DOXFP Red (%)	67	73	73	82

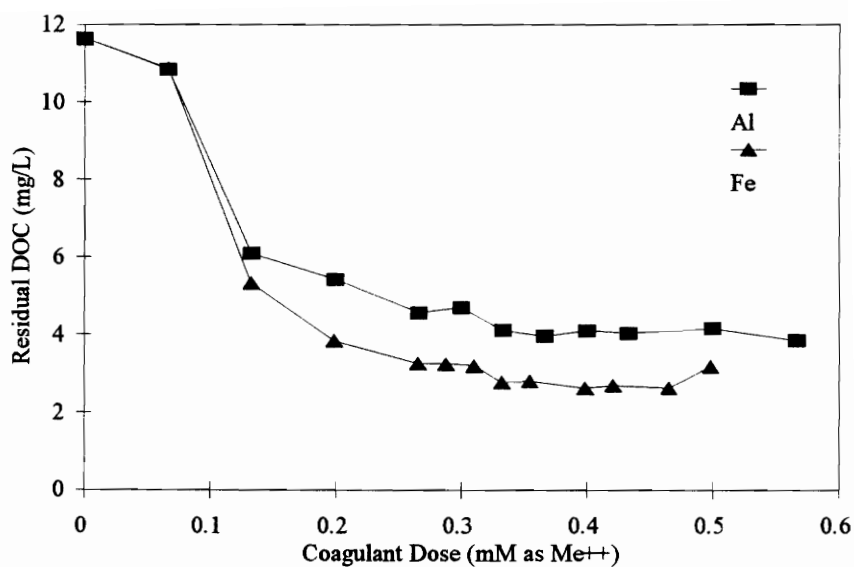


Figure 5.21. Residual DOC as a function of coagulant dose (millimolar as metal ion) for alum and ferric sulfate treatment for Utility VT-3.

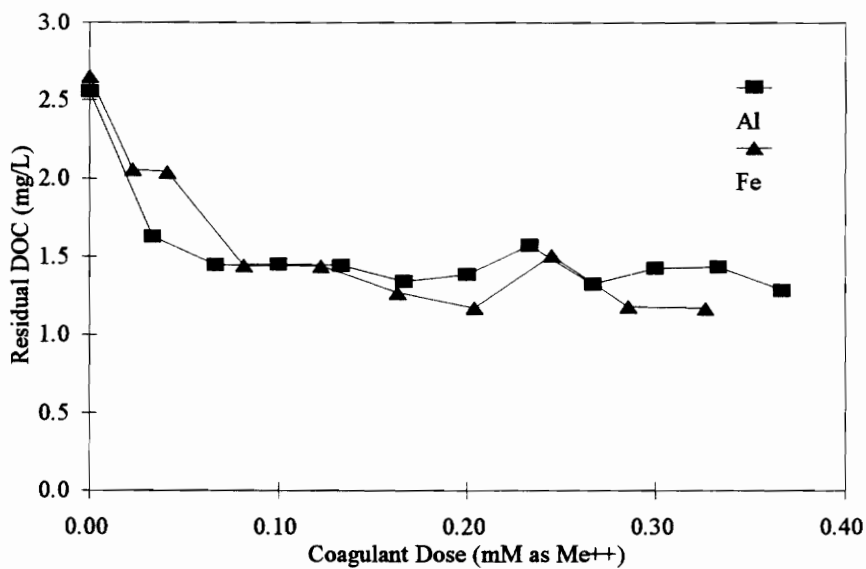


Figure 5.22. Residual DOC as a function of coagulant dose (millimolar as metal ion) for alum and ferric sulfate treatment for Utility VT-4.

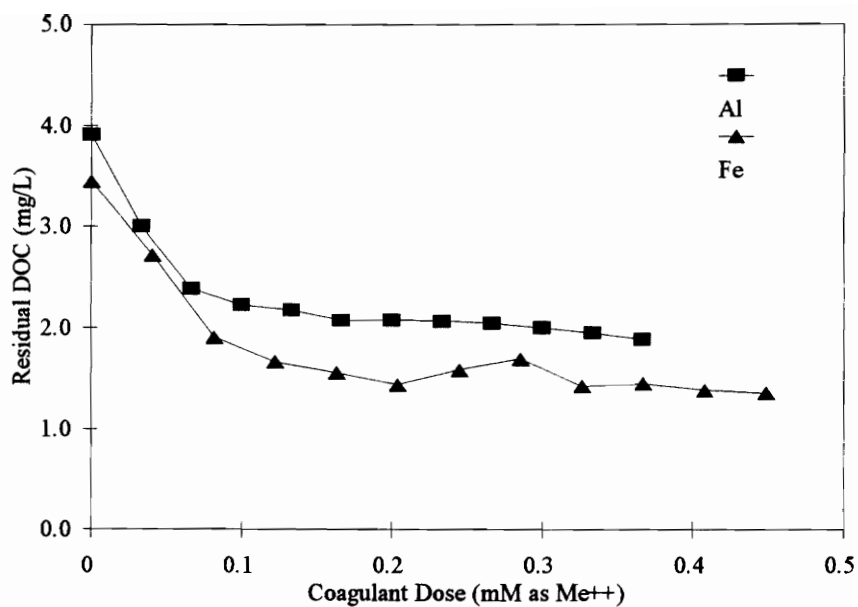


Figure 5.23. Residual DOC as a function of coagulant dose (millimolar as metal ion) for alum and ferric sulfate treatment for Utility VT-6.

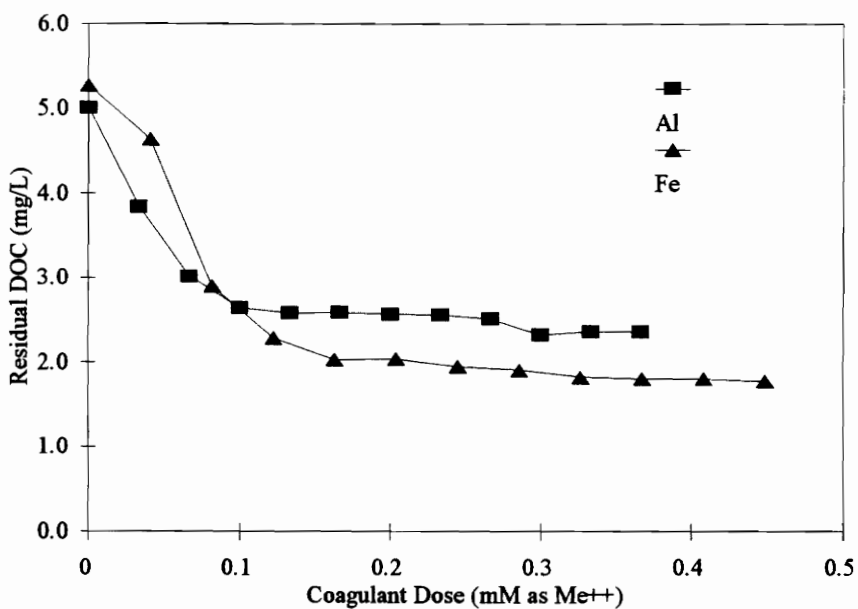


Figure 5.24. Residual DOC as a function of coagulant dose (millimolar as metal ion) for alum and ferric sulfate treatment for Utility VT-7.

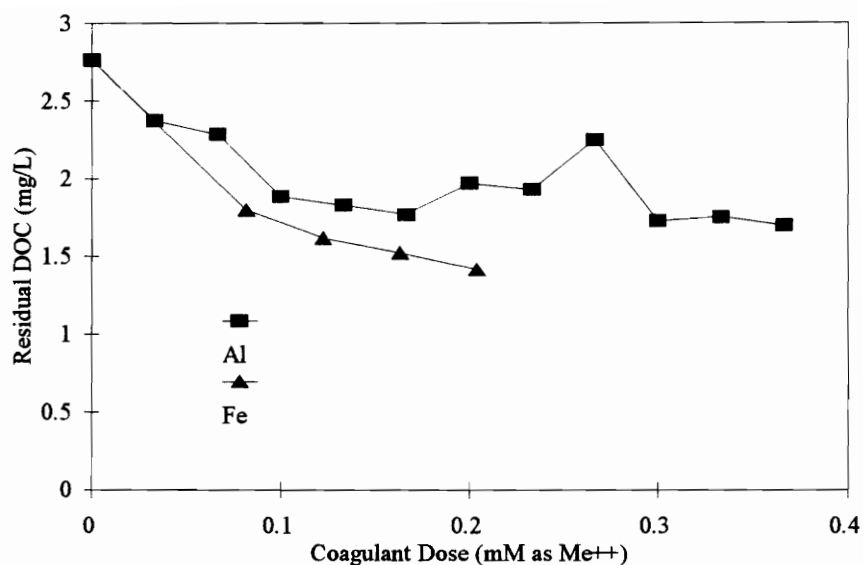


Figure 5.25. Residual DOC as a function of coagulant dose (millimolar as metal ion) for alum and ferric sulfate treatment for Utility VT-8.

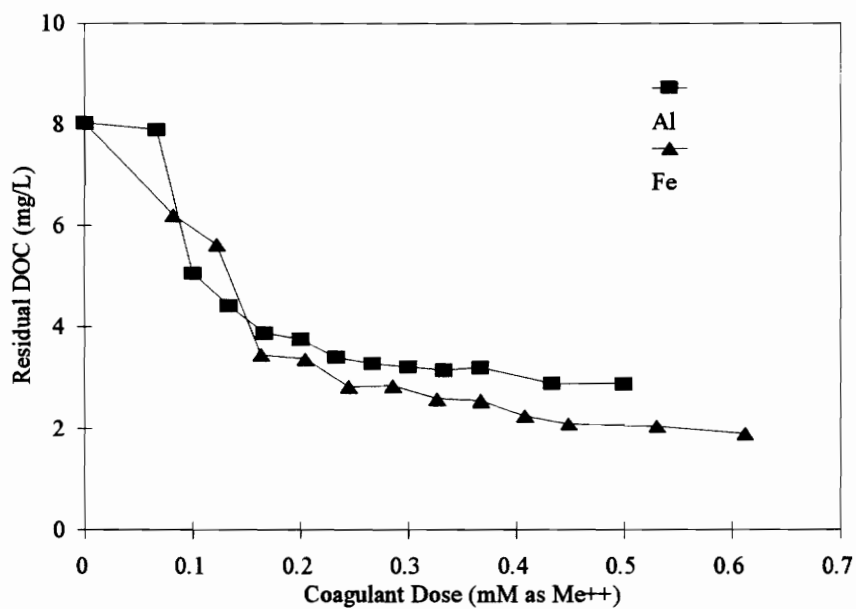


Figure 5.26. Residual DOC as a function of coagulant dose (millimolar as metal ion) for alum and ferric sulfate treatment for Utility VT-9.

TEMPERATURE EFFECTS

A summary of the optimum pH values for organics removal at 25°C and 4°C for Utilities VT-6 and VT-9 is contained in Table 5.9. As expected, since the minimum solubility of aluminum and iron occurs at a higher pH value at 4°C than at 25°C, therefore the optimum pH for organics removal is also higher at 4°C than at 25°C (Van Benschoten *et al.* 1994).

For Utility VT-6, the residual DOC concentrations were very similar at 4°C and at 25°C for the pH optimization jar testing. For the pH optimization jar testing for Utility VT-9, a greater amount of residual DOC was present at 4°C than at 25°C. For both utilities, lower temperatures did not greatly affect organics removal by coagulation (and filtration) during the dose optimization jar testing. Knocke *et al.* (1986) also found similar DOC removal at low temperatures and room temperature (2°C versus 22°C). Although specific enhanced coagulant doses were not picked at the time of the 4°C jar tests, a review of the data indicates that the enhanced dose at 4°C and 25°C would have been the same for both Utilities VT-6 and VT-9 (Figures 4.69, 4.75, and 4.76).

For Utility VT-6, lower coagulation temperatures did not have a significant effect on the residual coagulant remaining in the treated water either as a function of pH or as a function of coagulant dose. For Utility VT-9, the residual coagulant remaining in the treated water was greater at 4°C than at 25°C for the pH optimization jar tests, while the residual coagulant remaining in the treated water at 4°C and at 25°C were similar for the dose optimization jar testing. The increased residual coagulant levels for the pH optimization testing for Utility VT-9 at 4°C are most likely related to the increased residual DOC concentrations seen for Utility VT-9 at 4°C.

The relative magnitude of residual aluminum remaining in the treated waters for the pH optimization jar tests for Utility VT-9 was much greater than that for Utility VT-6. This is probably due to colloidal aluminum present at the alum dose of

Table 5.9
Optimum pH and pOH Values for Organics Removal by
Alum and Ferric Sulfate Coagulation

Utility	Coagulant	Optimum pH Range		Optimum pOH Range	
		25°C	4°C	25°C	4°C
VT-6	Alum	5.5-5.6	5.9-6.1	8.4-8.5	8.7-8.9
	Ferric Sulfate	5.0-5.2	5.5-5.7	8.8-9.2	9.2-9.3
VT-9	Alum	6.0-6.2	6.9-7.1	7.8-8.0	7.7-7.9

25 mg/L for Utility VT-9 (Figure 4.72), which was not present at the alum dose of 30 mg/L for Utility VT-6 (Figure 4.81).

Van Benschoten *et al.* (1994) recommended describing residual aluminum in terms of pOH instead of pH, because pOH is directly related to residual aluminum, but mostly independent of temperature. Therefore, in addition to plotting the 4°C results with pH as the independent variable, pOH was also plotted as the independent variable, with DOC, UV254, and residual coagulant as the dependent variables. The pH values were converted to pOH values by using the ion product (K_w) of water at the corresponding temperature. The K_w value for water at 25° C is 10^{-14} and at 4° C is $10^{-14.78}$.

Figures 5.27 and 5.28 present residual DOC as a function of pOH for Utility VT-6 for both 25° C and 4° C treatment for alum and ferric sulfate coagulation, respectively, while Figure 5.29 presents the same information for alum coagulation for Utility VT-9. The residual UV254 results as a function of pOH are included in Appendix G for Utility VT-6 and in Appendix E for Utility VT-9. The residual coagulant results as a function of pOH are presented in Figures 5.30-5.32. Figure 5.30 presents residual aluminum as a function of pOH for Utility VT-6, while Figure 5.31 presents residual iron as a function of pOH for Utility VT-6. Figure 5.32 contains the residual aluminum results as a function of pOH for Utility VT-9.

For Utility VT-6, residual DOC values as a function of pOH for 4°C and 25°C were almost identical for both alum and ferric sulfate coagulation. For Utility VT-9, the 4°C and 25°C results followed similar trends but the residual DOC at 4°C was greater than that at 25°C. Minimum residual DOC values occurred at pOH values of approximately 7.7-7.8 for both 4°C and 25°C for Utility VT-9.

For alum coagulation for Utility VT-6, pOH did better describe residual aluminum concentration data. The results for iron coagulation for Utility VT-6, and for alum coagulation for Utility VT-9 were inconclusive. Table 5.9 also includes the

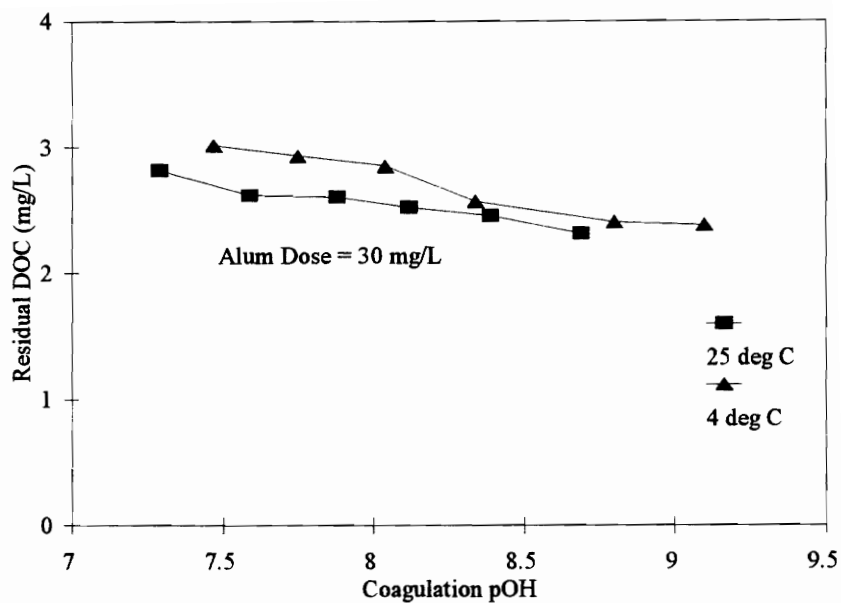


Figure 5.27. Residual DOC as a function of coagulation pOH for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

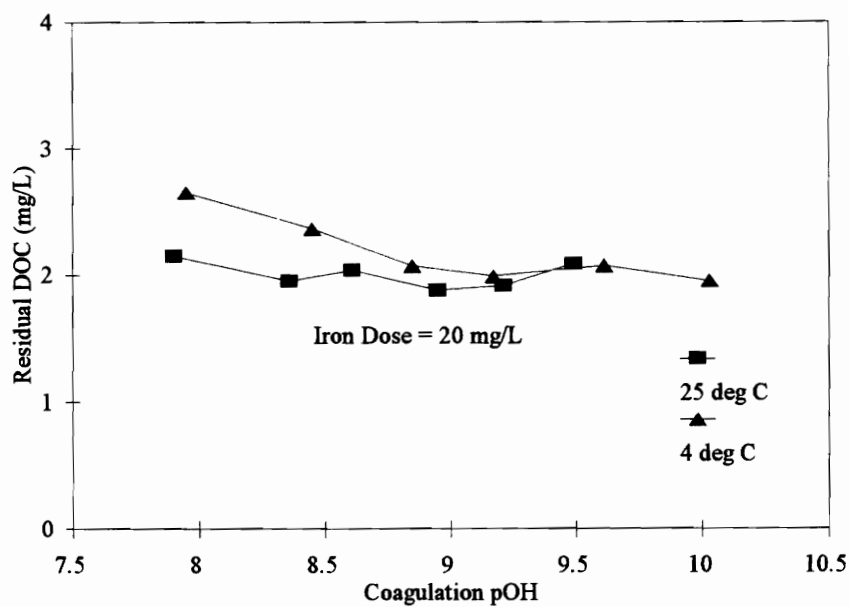


Figure 5.28. Residual DOC as a function of coagulation pOH for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

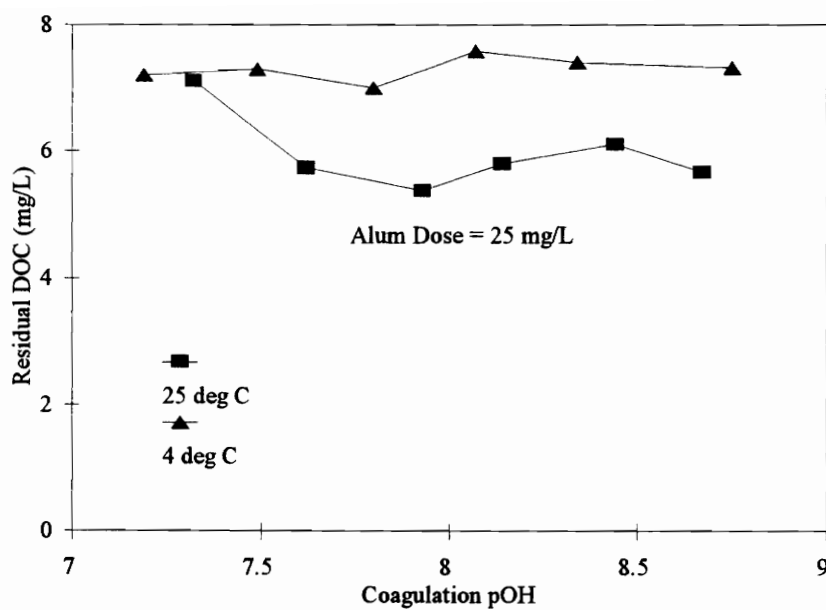


Figure 5.29. Residual DOC as a function of coagulation pOH for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

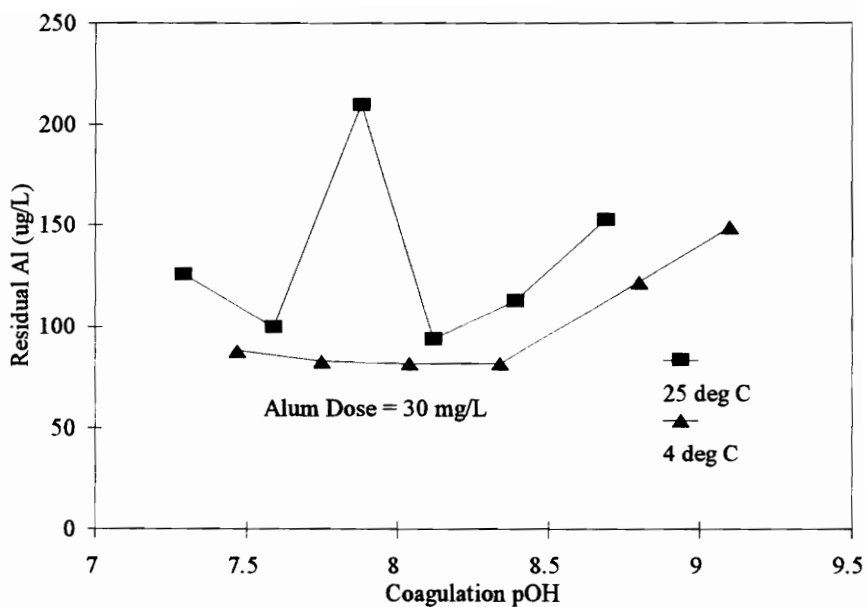


Figure 5.30. Residual aluminum as a function of coagulation pOH for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

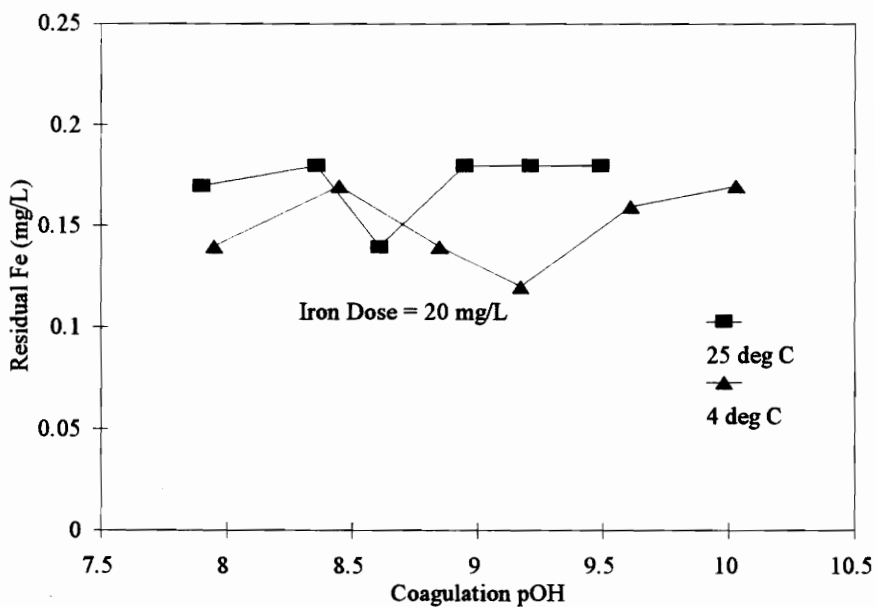


Figure 5.31. Residual iron as a function of coagulation pOH for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

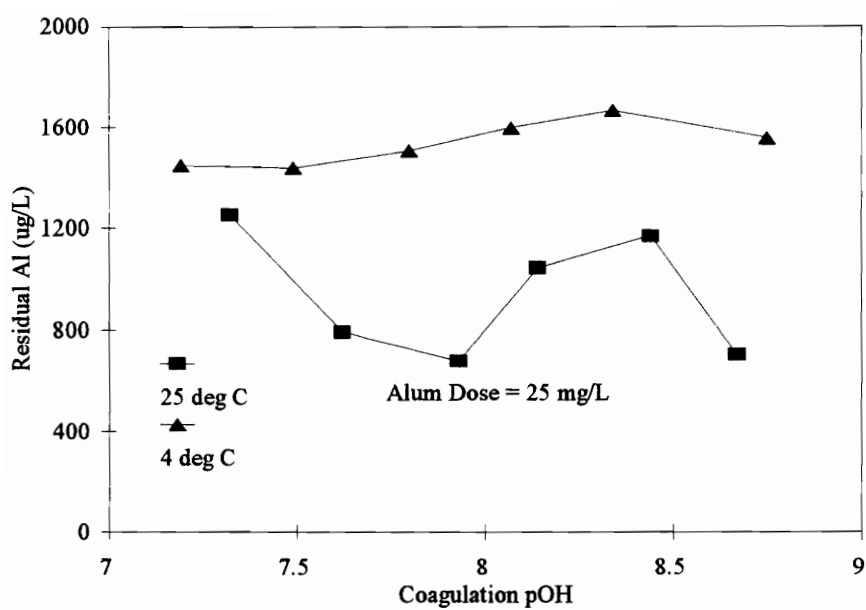


Figure 5.32. Residual aluminum as a function of coagulation pOH for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

optimum pOH values for 25°C and 4°C coagulation. The optimum pOH values for these two temperatures were similar.

DISINFECTION BY-PRODUCT FORMATION

Formation Potential Results

Disinfection by-products (DBPs) data are typically presented in terms of the standardized formation potential (FP) test (chlorination at 25°C for 7 days; chlorine residual of 2-5 mg/L). These tests are time-consuming and expensive and therefore the correlation of DOX and THM to other parameters such as TOC and ultraviolet absorbance is important. It is also important to develop relationships between different disinfection by-products such as DOX and THM.

Table 5.10 presents the non-purgeable DOXFP (NPDOXFP) yield based on DOC for all samples for each utility. The NPDOXFP yield varied from 54 µg as Cl⁻/mg DOC to 221 µg as Cl⁻/mg DOC with an overall mean value of 131 µg as Cl⁻/mg DOC. The average yield for the different treated samples is also included in Table 5.10. The yields decreased with improving treatment levels, indicating a preferential removal of DOX precursors to DOC.

Table 5.10 indicates that the NPDOXFP yields based on DOC for all utilities were within a similar range (94-221 µg as Cl⁻/mg DOC) except for Utility VT-8, for which the NPDOXFP yields based on DOC (range of 54-76 µg as Cl⁻/mg DOC) were much lower than for the other utilities. Utility VT-8 had a raw water SUVA value of 1.34 L/mg-m, the lowest of all the utilities. This is most likely the reason for the lower yields since waters with low SUVA values typically contain organics which are non-humic in nature, leading to a subsequent lower yield of disinfection by-products per unit of TOC than sources with a larger percentage of humic material (Krasner *et al.* 1996).

Table 5.10
DOXFP* Yield Based on DOC (DOXFP*/DOC) for Raw and
Treated Samples for Each Utility
(Utilities are listed in order of low to high raw water SUVA values.)

Utility	Raw Water SUVA (L/mg-m)	DOXFP* Yield (µg as Cl/mg DOC)					
		Raw	BL	AEN	AOP	FEN	FOP
VT-8	1.34	70	71	76	54	60	76
VT-2	1.86	179	158	126	192	---	---
VT-6	1.87	132	129	94	105	117	134
VT-4	2.19	99	100	121	120	115	124
VT-1	2.65	171	221	152	---	---	---
VT-7	2.75	189	130	150	152	135	113
VT-5	3.05	167	153	146	122	---	---
VT-3	4.09	193	151	137	131	157	103
VT-9	6.11	196	126	142	133	127	107
AVG	---	155	138	127	126	119	110

* All DOXFP values given are for non-purgeable dissolved organic halides.

Key: Raw = Raw Water Samples

BL = Baseline Treated Samples

AEN = Alum Enhanced Treated Samples

AOP = Alum Optimized Treated Samples

FEN = Ferric Enhanced Treated Samples

FOP = Ferric Optimized Treated Samples

Figures 5.33 and 5.34 present the linear regressions for NPDOXFP as a function of DOC. Figure 5.33 presents the results for the raw waters only, and Figure 5.34 presents the results for the treated waters only. Due to the dissimilar yields for Utility VT-8, the Utility VT-8 data is shown in Figures 5.33 and 5.34, but the linear regressions do not include the Utility VT-8 values. The treated water data in Figure 5.34 has been separated according to raw water SUVA values, with the data for the utilities with raw water SUVA values < 3.0 L/mg-m distinguished from the data for the utilities with raw water SUVA values > 3.0 L/mg-m. Separate linear regressions have been generated for these two data sets to determine if there is a difference in the relationship of DOC and NPDOXFP for sources with different SUVA values (i.e. sources which contain organic matter with differing characteristics). The resulting correlations are summarized below:

- $\text{NPDOXFP } [\mu\text{g/L as Cl}^-] = 207 \cdot \text{DOC } [\text{mg/L}] - 183$
 $r^2 = 0.98$ (Raw Water Samples)
- $\text{NPDOXFP } [\mu\text{g/L as Cl}^-] = 140 \cdot \text{DOC } [\text{mg/L}] - 12$
 $r^2 = 0.65$ (Treated Samples (for Utilities where raw water SUVA < 3.0 L/mg-m))
- $\text{NPDOXFP } [\mu\text{g/L as Cl}^-] = 193 \cdot \text{DOC } [\text{mg/L}] - 204$
 $r^2 = 0.89$ (Treated Samples (for Utilities where raw water SUVA > 3.0 L/mg-m))

Based on the varying linear regressions for the different SUVA values shown in Figure 5.34, it appears that the relationship between NPDOXFP and DOC for treated waters varies dependent upon the raw water SUVA value. In particular, for the treated waters from utilities with raw water SUVA values > 3.0 L/mg-m, there appears

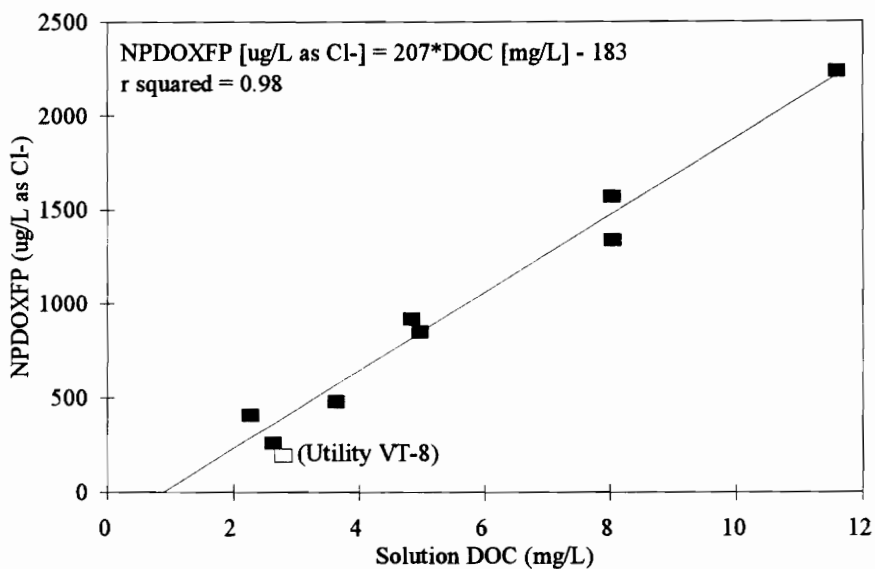


Figure 5.33. Relationship between DOC and NPDOXFP for raw water samples for all utilities. (Note: Linear regression line does not include Utility VT-8 data due to the different nature of the organics present in the Utility VT-8 raw water.)

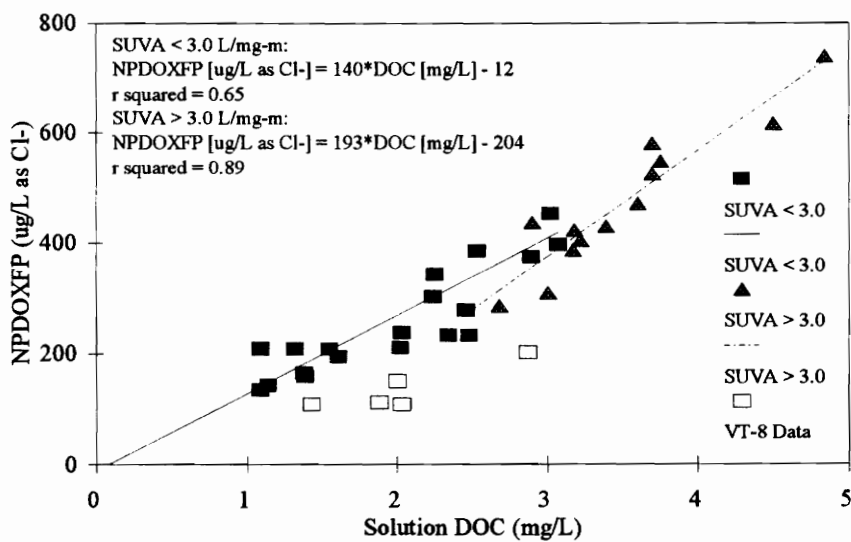


Figure 5.34. Relationship between DOC and NPDOXFP for treated samples for all utilities. (Note: Linear regression line does not include Utility VT-8 data due to the different nature of the organics present in the Utility VT-8 raw water. Also, regression lines have been separated based on raw water SUVA values.)

to be a greater portion of the residual DOC that forms very little dissolved organic halides upon chlorination than for the low raw water SUVA (< 3.0 L/mg-m) utilities.

Figure 5.35 presents the NPDOXFP results for the alum enhanced treated samples and for the ferric enhanced treated samples. The linear regression results are summarized below:

- $\text{NPDOXFP}^* [\mu\text{g/L as Cl}^-] = 151 * \text{DOC} [\text{mg/L}] - 40$
 $r^2 = 0.93$ (Alum Enhanced Samples)
- $\text{NPDOXFP}^* [\mu\text{g/L as Cl}^-] = 168 * \text{DOC} [\text{mg/L}] - 86$
 $r^2 = 0.95$ (Ferric Enhanced Samples)

As can be seen from the graphs, the slope of the regression lines increases from 151 $\mu\text{g as Cl}^-/\text{mg DOC}$ for the alum enhanced samples to 168 $\mu\text{g as Cl}^-/\text{mg DOC}$ for the ferric enhanced samples. Also, a slightly greater amount of the residual DOC remaining in the ferric enhanced treated samples appears to form little or no DOX than for the residual DOC in the alum enhanced treated samples. These items indicate some difference in the reaction with chlorine to produce dissolved organic halides between the DOC remaining in the alum treated samples versus the DOC remaining in the ferric treated samples, in particular at lower residual DOC concentrations (near 1 mg/L). However, at residual DOC values between approximately 2 mg/L and 5 mg/L, the range within which a majority of the residual DOC values were located, the predicted DOXFP values for the two different regression lines differed by less than 5 percent.

Table 5.11 presents the relationship between NPDOXFP and THMFP for the raw and treated samples for each utility. The ratio of NPDOXFP to THMFP for all samples varied from 1.1 $\mu\text{g as Cl}^-/\mu\text{g TTHM}$ to 3.6 $\mu\text{g as Cl}^-/\mu\text{g TTHM}$ with an overall mean value of 2.2 $\mu\text{g as Cl}^-/\mu\text{g TTHM}$. The average ratio for the different

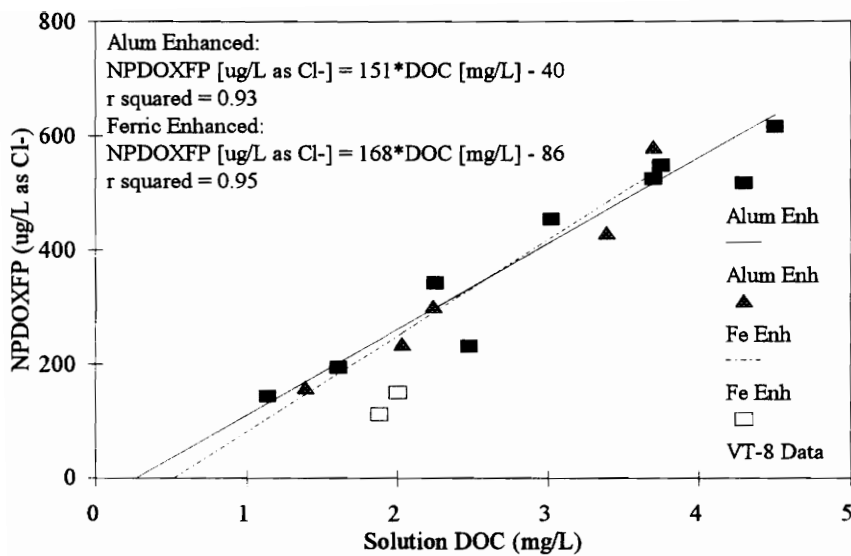


Figure 5.35. Relationship between DOC and NPDOXFP for alum enhanced and ferric enhanced samples for all utilities. (Note: Linear regression line does not include Utility VT-8 data due to the different nature of the organics present in the Utility VT-8 raw water.)

Table 5.11

DOXFP* Yield Based on THMFP (DOXFP*/THMFP) for Raw and Treated Samples for Each Utility
(Utilities are listed in order of low to high raw water SUVA values.)

Utility	Raw Water SUVA (L/mg-m)	DOXFP* Yield (μg as Cl/ μg TTHMs)					
		Raw	BL	AEN	AOP	FEN	FOP
VT-8	1.34	1.7	1.1	1.6	1.3	1.4	1.4
VT-2	1.86	2.0	3.3	2.7	3.6	---	---
VT-6	1.87	2.2	1.9	1.2	1.3	2.0	1.9
VT-4	2.19	1.9	1.8	2.6	2.3	2.3	2.3
VT-1	2.65	2.1	2.6	2.0	---	---	---
VT-7	2.75	2.8	1.9	2.2	2.3	2.2	2.2
VT-5	3.05	2.6	2.2	2.7	2.1	---	---
VT-3	4.09	3.1	2.8	2.4	1.9	2.6	1.7
VT-9	6.11	3.6	2.2	2.1	2.7	2.2	2.0
Avg	---	2.4	2.2	2.2	2.5	2.2	1.9

* All DOXFP values given are for non-purgeable dissolved organic halides.

Key: Raw = Raw Water Samples

BL = Baseline Treated Samples

AEN = Alum Enhanced Treated Samples

AOP = Alum Optimized Treated Samples

FEN = Ferric Enhanced Treated Samples

FOP = Ferric Optimized Treated Samples

treated samples is also included in Table 5.11. The ratio generally decreased slightly with improving treatment levels, indicating a preferential removal of DOX precursors to THM precursors. Also, the NPDOXFP:THMFP ratio generally increased with increasing SUVA value. This indicates that humic substances form a relatively higher percentage than non-humic substances of NPDOX in relation to the formation of THMs. This is particularly evident for Utility VT-8 which had the lowest SUVA value (indicating low humic content) and the lowest NPDOXFP/THMFP ratio.

Figures 5.36 and 5.37 present the NPDOXFP and THMFP data and the linear regression between the two variables for the raw waters and treated waters, respectively. The linear regression results are summarized below:

- $\text{NPDOXFP } [\mu\text{g/L as Cl}^-] = 3.3 * \text{THMFP } [\mu\text{g/L TTHMs}] - 232$
 $r^2 = 0.93$ (Raw Water Samples)
- $\text{NPDOXFP } [\mu\text{g/L as Cl}^-] = 2.2 * \text{THMFP } [\mu\text{g/L TTHMs}] - 15$
 $r^2 = 0.81$ (Treated Samples)

Another comparison which can be made is the relationship between THMFP concentrations and total DOXFP concentrations, as opposed to only the non-purgeable DOXFP concentrations. Approximate total DOXFP concentrations can be calculated by adding the THMFP concentrations in units of $\mu\text{g/L as Cl}^-$ (assumed to be the entire volatile fraction) to the non-purgeable DOXFP (assumed to be the non-volatile fraction). Table 5.12 contains the total DOXFP:THMFP ratios for all samples for each utility. The DOXFP:THMFP ratio decreased slightly with treatment, indicating preferential removal of DOX precursors to THM precursors. As with the NPDOXFP:THMFP ratio, the DOXFP:THMFP ratio tended to increase with increasing SUVA value.

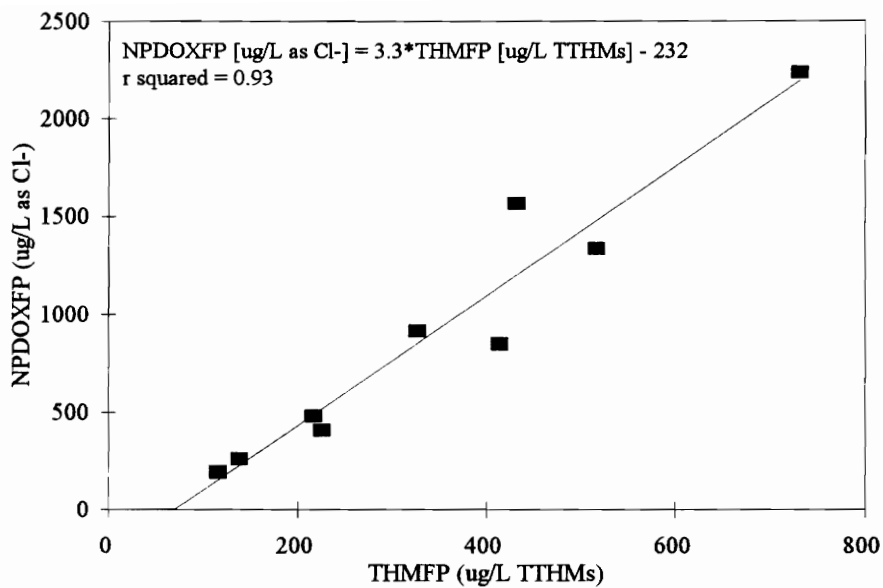


Figure 5.36. Relationship between THMFP and NPDOXFP for raw waters for all utilities.

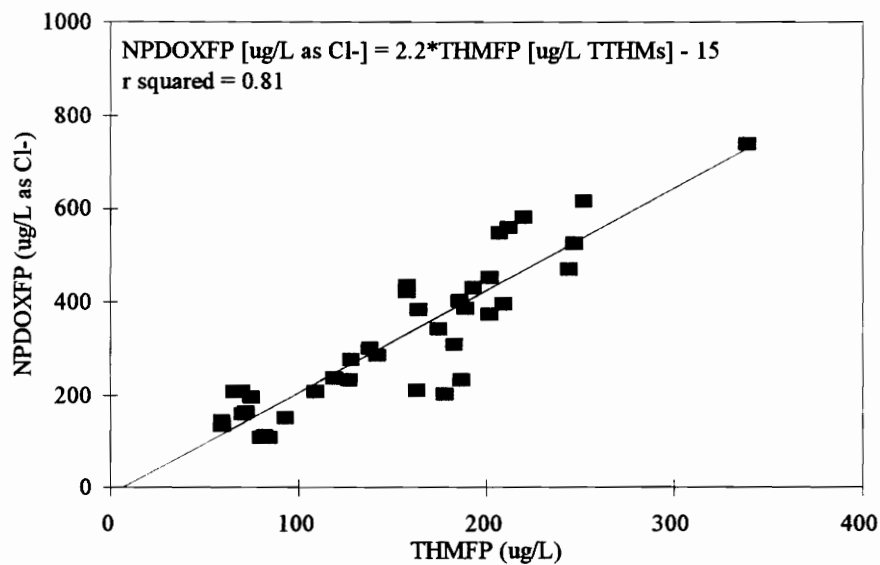


Figure 5.37. Relationship between THMFP and NPDOXFP for treated samples for all utilities.

Table 5.12
Total DOXFP Yield Based on THMFP (DOXFP/THMFP) for Raw and
Treated Samples for Each Utility
(Utilities are listed in order of low to high raw water SUVA values.)

Utility	Raw Water SUVA (L/mg-m)	DOXFP Yield ($\mu\text{g as Cl}^-/\mu\text{g as Cl}^-$)					
		Raw	BL	AEN	AOP	FEN	FOP
VT-8	1.34	3.2	2.5	3.3	2.8	3.0	3.0
VT-2	1.86	3.1	4.4	3.8	4.7	---	---
VT-6	1.87	3.6	3.3	2.5	2.6	3.4	3.3
VT-4	2.19	3.2	3.2	4.1	3.7	3.7	3.7
VT-1	2.65	3.3	4.0	3.3	---	---	---
VT-7	2.75	4.2	3.2	3.6	3.7	3.6	3.6
VT-5	3.05	4.0	3.5	4.1	3.4	---	---
VT-3	4.09	4.5	4.3	3.9	3.3	4.1	3.0
VT-9	6.11	5.1	3.5	3.5	4.1	3.6	3.4
Avg	---	3.8	3.6	3.5	3.5	3.6	3.3

Key: Raw = Raw Water Samples

BL = Baseline Treated Samples

AEN = Alum Enhanced Treated Samples

AOP = Alum Optimized Treated Samples

FEN = Ferric Enhanced Treated Samples

FOP = Ferric Optimized Treated Samples

Figures 5.38 and 5.39 present the relationship of total DOXFP to THMFP (in units of $\mu\text{g/L as Cl}^-$) for the raw waters and the treated waters, respectively. The linear regression lines for each of these figures has been forced through the origin based on the assumption that no portion of total DOX can be formed without also forming THMs. The linear regression results are summarized below:

- $\text{DOXFP } [\mu\text{g/L as Cl}^-] = 4.2 * \text{THMFP } [\mu\text{g/L as Cl}^-]$
 $r^2 = 0.94$ (Raw Water Samples)
- $\text{DOXFP } [\mu\text{g/L as Cl}^-] = 3.5 * \text{THMFP } [\mu\text{g/L as Cl}^-]$
 $r^2 = 0.92$ (Treated Samples)

The linear regression lines more closely fit the data for the relationship of total DOXFP to THMFP [$\mu\text{g/L as Cl}^-$] than for the relationship between NPDOXFP and THMFP [$\mu\text{g/L TTHMs}$] as evidenced by the improved r^2 values.

Uniform Formation Condition (UFC)

The Uniform Formation Condition (UFC) test for this study was conducted at a pH of 8, with a target chlorine residual of 0.7-1.3 mg/L after one day of chlorination. The UFC test is much less time-consuming than the FP tests and may give a good estimation of actual DBP concentrations in the water treatment distribution system since the chlorination conditions are somewhat similar to full-scale treatment conditions. Appendix O contains a complete summary of UFC THM and UFC DOX data along with the relationships of UFC THM, UFC DOX, THMFP, DOXFP, and DOC for the baseline and enhanced treated waters. These results are summarized in Tables 5.13 and 5.14.

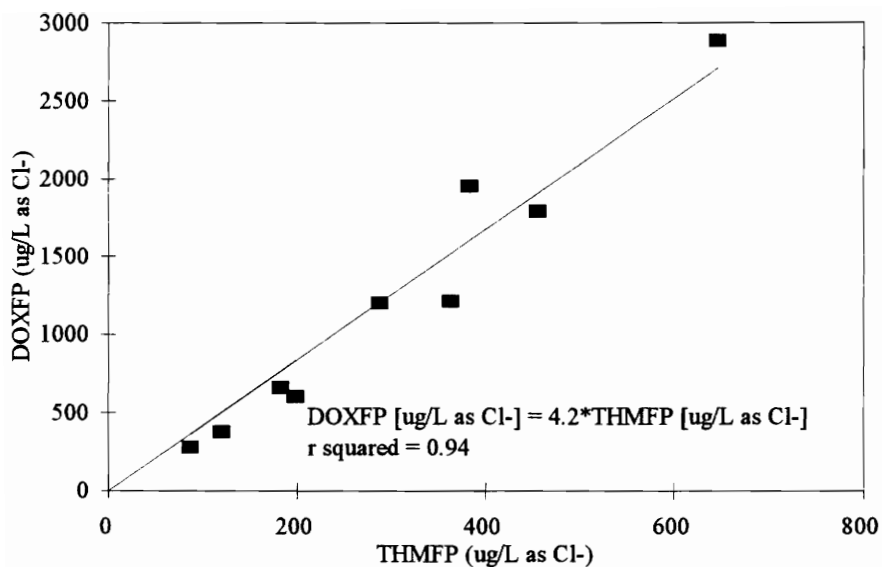


Figure 5.38. Relationship between THMFP [ug/L as Cl-] and DOXFP (Sum of NPDOXFP and THMFP) for raw waters for all utilities.

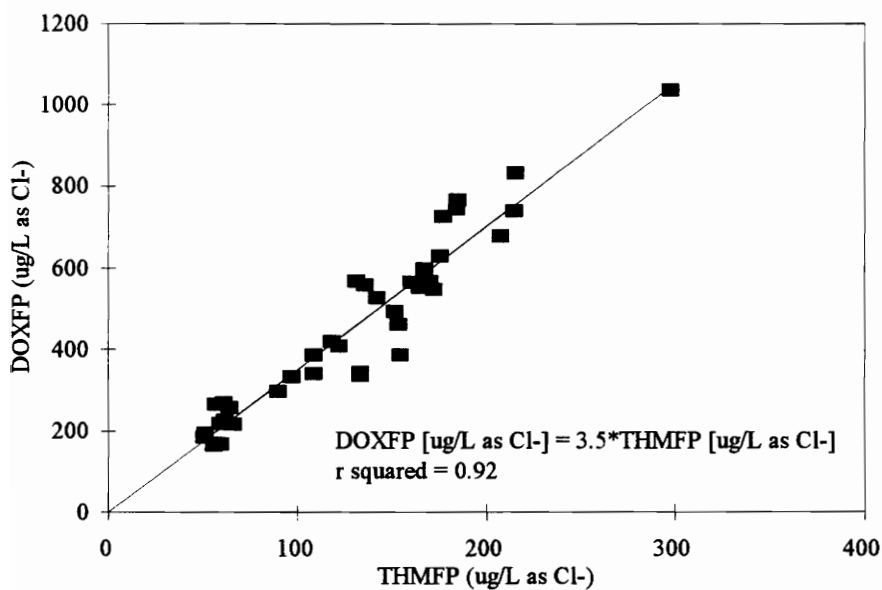


Figure 5.39. Relationship between THMFP [ug/L as Cl-] and DOXFP (Sum of NPDOXFP and THMFP) for treated samples for all utilities.

Table 5.13
UFC THM and DOX* Yields with Respect to DOC for All Treated Waters

	n	UFC DBP Yield	
		THMs (μg TTHMs/mg DOC)	DOX* (μg as Cl ⁻ /mg DOC)
Average \pm SD	24	34 \pm 10	69 \pm 25
Median	24	33	73

* All DOX values given are for non-purgeable dissolved organic halides.

Table 5.14
Summary of UFC THM and UFC DOX Data
with Respect to THMFP and DOXFP Data

	Ratio of UFC to 7-day FP		UFC DOX/UFC THM (μg / μg) (n = 24)	DOXFP/THMFP (μg / μg) (n = 38)
	THMs (μg / μg) (n = 24)	DOX (μg / μg) (n = 24)		
Average \pm SD	0.59 \pm 0.21	0.53 \pm 0.14	2.3 \pm 1.2	2.1 \pm 0.5
Median	0.57	0.55	2.2	2.2

* All DOX values given are for non-purgeable dissolved organic halides.

The specific yields for UFC DOX with respect to DOC ranged from 29 to 105 with an average of 69 and a median value of 73. The specific yields for UFC THMs with respect to DOC ranged from 19 to 50 $\mu\text{g TTHMs/mg DOC}$ with an average of 34 $\mu\text{g TTHMs/mg DOC}$ and a median value of 33 $\mu\text{g TTHMs/mg DOC}$. The UFC THM yield corresponds well with previous research which indicated a yield of 29 $\mu\text{g TTHMs/mg DOC}$ under UFC conditions (Summers *et al.* 1996).

The UFC DOX/DOXFP values ranged from 0.26 to 0.81 $\mu\text{g}/\mu\text{g}$, with an average value of 0.53 ± 0.14 $\mu\text{g}/\mu\text{g}$, and a median value of 0.55 $\mu\text{g}/\mu\text{g}$. The UFC THM/THMFP values ranged from 0.34 to 1.02 $\mu\text{g}/\mu\text{g}$, with an average value of 0.59 $\mu\text{g}/\mu\text{g} \pm 0.21$ and a median value of 0.57 $\mu\text{g}/\mu\text{g}$. Utility VT-8 had an average UFC THM/THMFP ratio of 0.95 $\mu\text{g}/\mu\text{g}$, almost 60 percent higher than the average. Utility VT-8 has the lowest raw water SUVA value, indicating that chlorination of non-humic material may form THMs more rapidly than chlorination of humic material. However, the UFC THM/THMFP ratios for the remaining utilities did not seem to validate this conclusion.

Figure 5.40 includes the linear regression of the UFC THM concentrations as a function of the DOC concentration. Horizontal lines have been included in Figure 5.40 at the D/DBP Rule Stage 1 THM MCL of 80 $\mu\text{g/L}$, and at the anticipated Stage 2 THM MCL of 40 $\mu\text{g/L}$. Assuming that these utilities utilized a chlorine dose which provided a free chlorine residual in the distribution system of 0.7-1.3 mg/L after 24 hours, less than half of the utilities could meet the proposed Stage 1 THM MCL of 80 $\mu\text{g/L}$ at the baseline or enhanced treatment conditions. Only two of the utilities (VT-2 and VT-4) could meet the anticipated Stage 2 THM MCL of 40 $\mu\text{g/L}$. These two utilities had treated water DOC concentrations of less than 1.6 mg/L .

Figure 5.41 contains a graph of UFC THM yield based on DOC as a function of chlorine residual following the 24-hour UFC chlorination period, while Figure 5.42 contains a graph of UFC DOX yield based on DOC as a function of chlorine residual. One concern with the UFC test is that the formation of DBPs may be "very sensitive

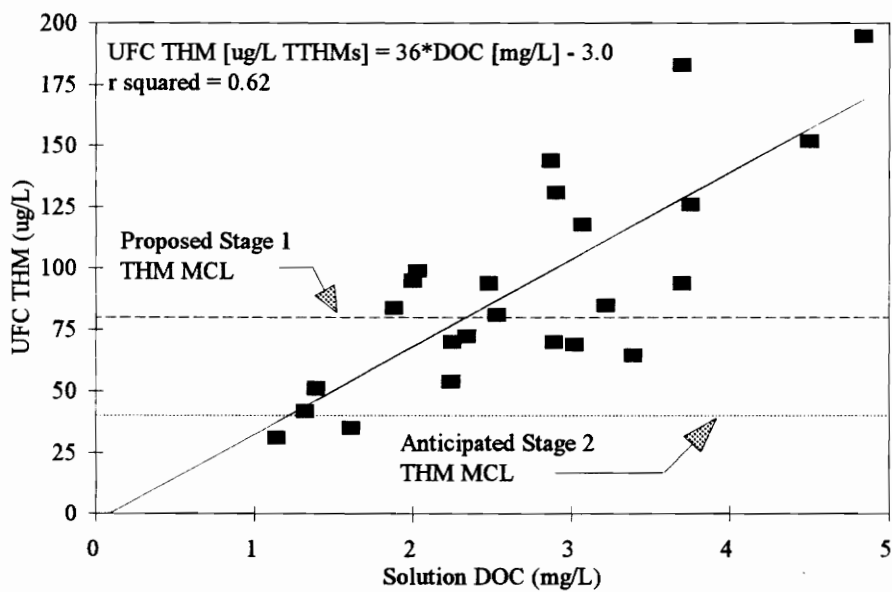


Figure 5.40. Relationship between DOC and UFC THM for baseline and enhanced treated samples for all utilities.

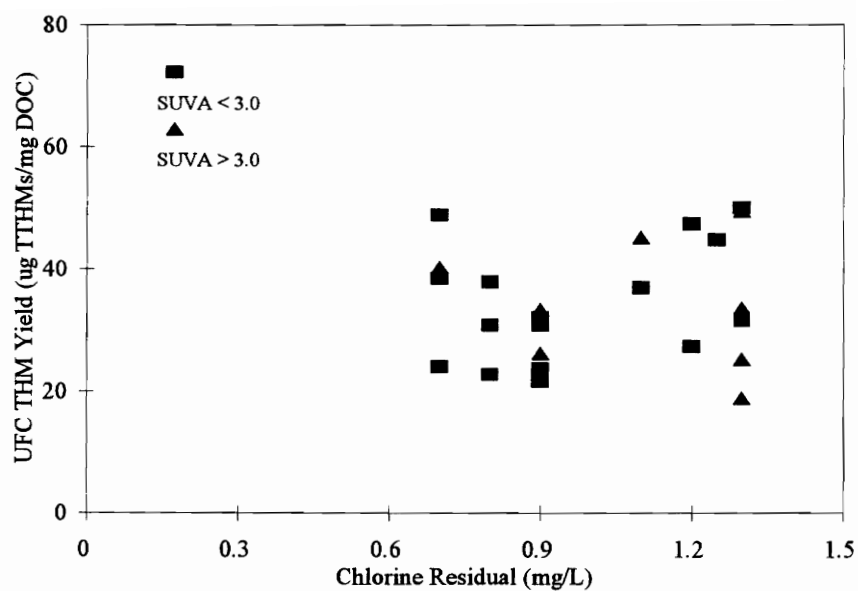


Figure 5.41. Relationship between UFC THM yield and UFC chlorine residual after 24 hour incubation period for baseline and enhanced treated samples. (Data has been separated based on raw water SUVA values.)

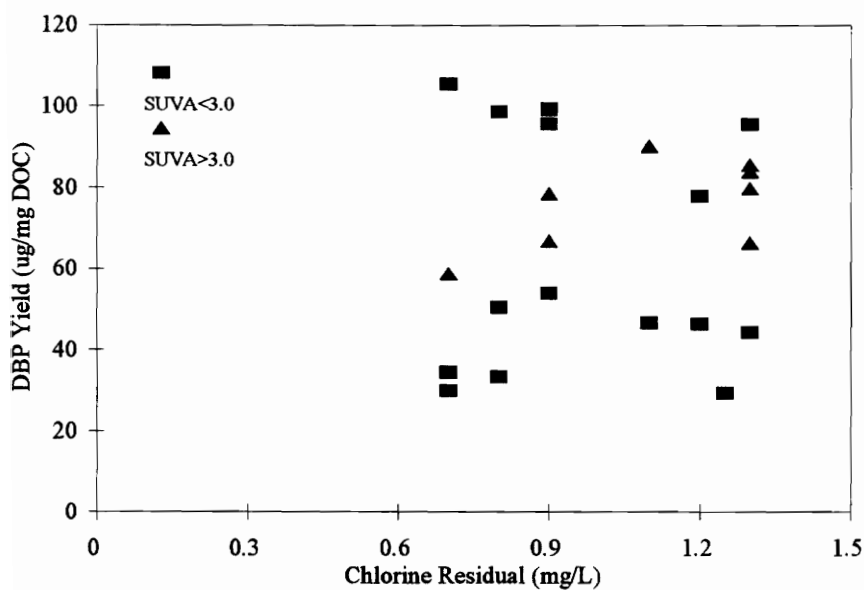


Figure 5.42. Relationship between UFC DOX yield and UFC chlorine residual after 24 hour incubation period for baseline and enhanced treated samples. (Data has been separated based on raw water SUVA values.)

to small changes in chlorine residual concentrations at the low chlorine residual concentrations utilized in the UFC test" (Summers *et al.* 1996). The data contained in Figures 5.41 and 5.42 do not seem to indicate a trend between chlorine residual and DBP yield, although it is difficult to make a definitive conclusion since the comparison is being made on different treated waters which may inherently have different yield characteristics independent of the chlorine residual. Summers *et al.* (1996) investigated this issue and found DBP yield differences for the UFC test of <5 percent to 20 percent over a chlorine residual range of 0.6-1.4 mg/L.

Utility VT-6 DBP Removal Optimization

As previously described in the Methods and Materials chapter, a DBP removal optimization was performed for Utility VT-6. This was performed by chlorinating water samples from two additional doses other than enhanced and optimized, and performing DBP analyses on these samples. The purpose of this was to determine how the removal of DBP precursors compared to the removal of organic material (DOC and UV254) over a wider range of coagulant doses. For Utility VT-6, the enhanced and optimized doses were 30 mg/L and 110 mg/L, respectively. Additional jar testing and subsequent chlorination and DBP analyses were performed at coagulant doses of 15 mg/L and 60 mg/L.

Figure 5.43 compares the reduction of TOC, UV254, THMFP, and NPDOXFP at each of the four coagulant doses. The data indicate that the incremental removals of the four parameters correlated reasonably well with alum dose, an expected result. For Figure 5.43, the DOXFP reduction at an alum dose of 60 mg/L was much lower than expected, and has not been included with the other DOXFP results. The DOXFP results at an alum dose of 60 mg/L had a high standard deviation, with the average DOXFP much higher than inspected, leading to a lower percentage removal than expected.

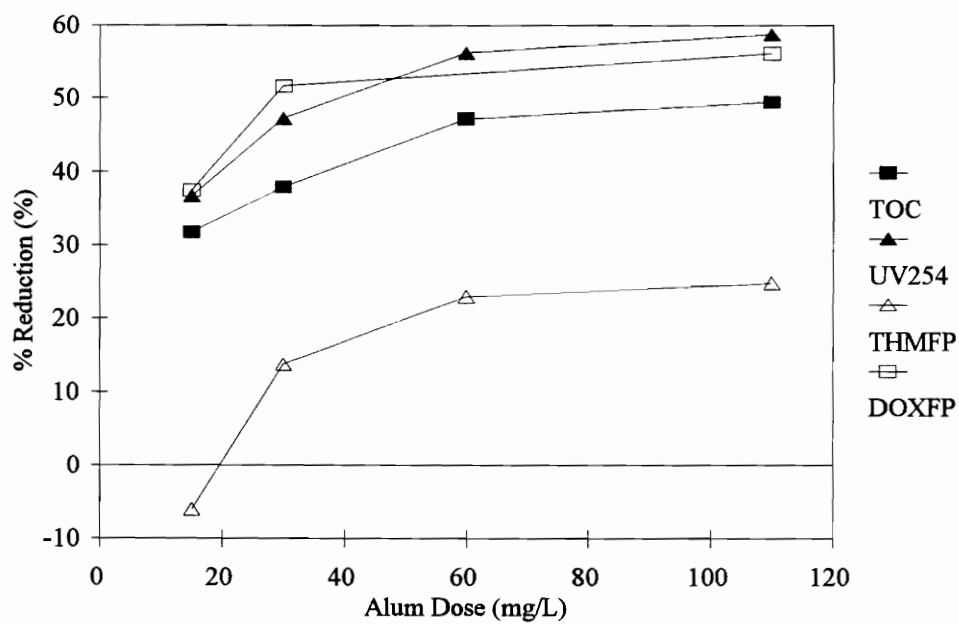


Figure 5.43. Percentage reduction of TOC, UV254, THMFP, and DOXFP for Utility VT-6. (Note: DOXFP reduction at an alum dose of 60 mg/L is not shown due to high standard deviation for DOXFP value at that dose.)

PERCENTAGE REMOVALS OF DOC, UV254, THMFP, AND DOXFP

Previous research has shown that the relative percentage reductions following coagulation with metal coagulants of DOC (or TOC), UV254, THMFP precursors, and DOXFP precursors generally corresponded to the following trend: $UV254 > DOXFP > THMFP > DOC$ (Reckhow and Singer 1990; Edzwald 1993; Owen *et al.* 1995).

Figures 5.44 through 5.47 include comparisons of TOC removal, DOC removal, UV254 reduction, THMFP precursor reduction, and DOXFP precursor reduction. For each of these figures a line with a slope equal to one has been drawn to indicate a line of equal reduction between the two parameters being compared. If a data point falls above the line, then the percentage reduction of the parameter contained on the y-axis is greater, while the opposite is true for data points which fall below the line.

Most of the data for this study contained in the previous chapters has been based on TOC reduction as opposed to DOC reduction. However, since much of the previous research has compared DOC reduction with the other parameters, both TOC and DOC reduction will be considered in this section. Earlier in this chapter, reduction of TOC was shown to be less than the reduction of UV254 (Figure 5.7). Figure 5.44 contains a comparison of TOC removal and THMFP reduction for all the treated waters. In general, TOC reduction was greater than THMFP reduction. Conversely, Figure 5.45 contains a comparison of DOC removal and THMFP reduction for these same waters. THMFP reduction was greater than DOC reduction. These two figures indicate that TOC removal is typically greater than THMFP reduction, which in turn is typically greater than DOC reduction.

Figure 5.46 contains a comparison of TOC removal and DOXFP reduction for all the treated waters. The reductions of these two parameters was very similar, with DOXFP reduction being slightly greater than TOC reduction.

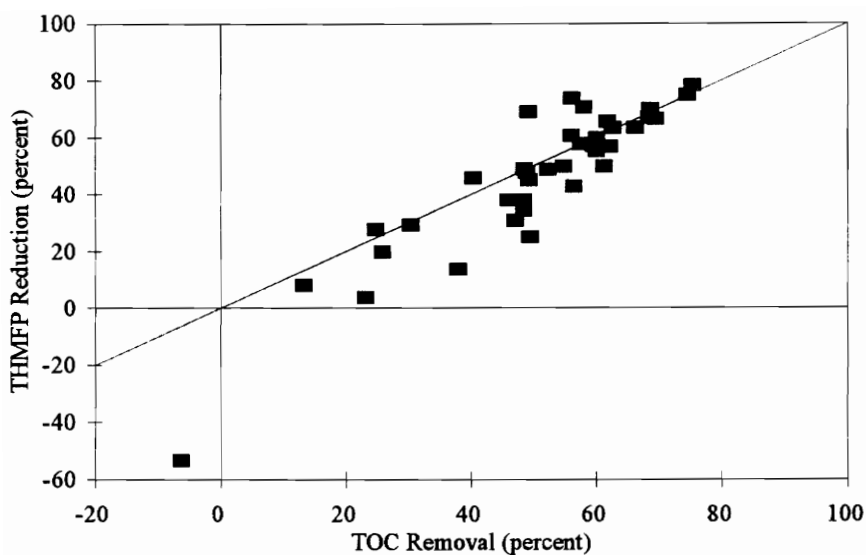


Figure 5.44. Comparison of TOC removal and THMFP reduction for all treated samples. (Note: Line shown is a line with 1:1 slope: data points located above the line indicated greater THMFP reduction, while data points located below the line indicate greater TOC removal.)

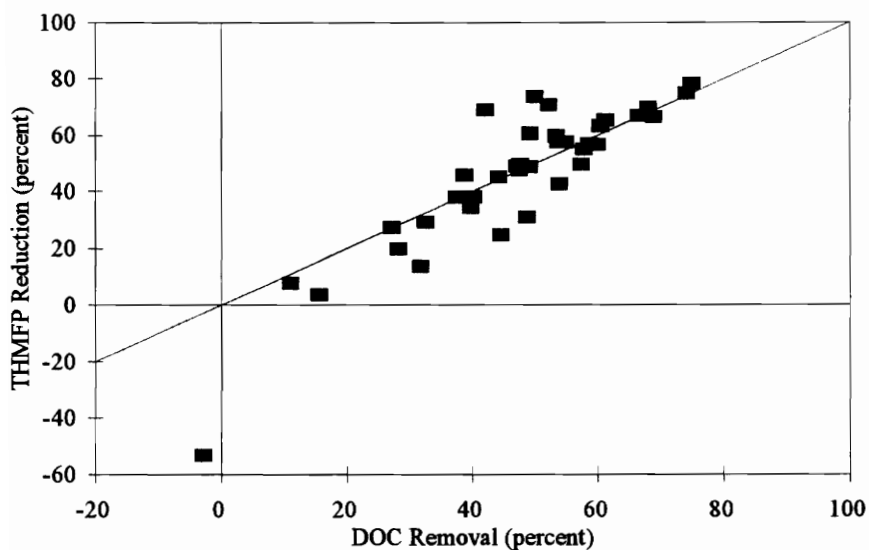


Figure 5.45. Comparison of DOC removal and THMFP reduction for all treated samples. (Note: Line shown is a line with 1:1 slope: data points located above the line indicate greater THMFP reduction, while data points located below the line indicate greater DOC removal.)

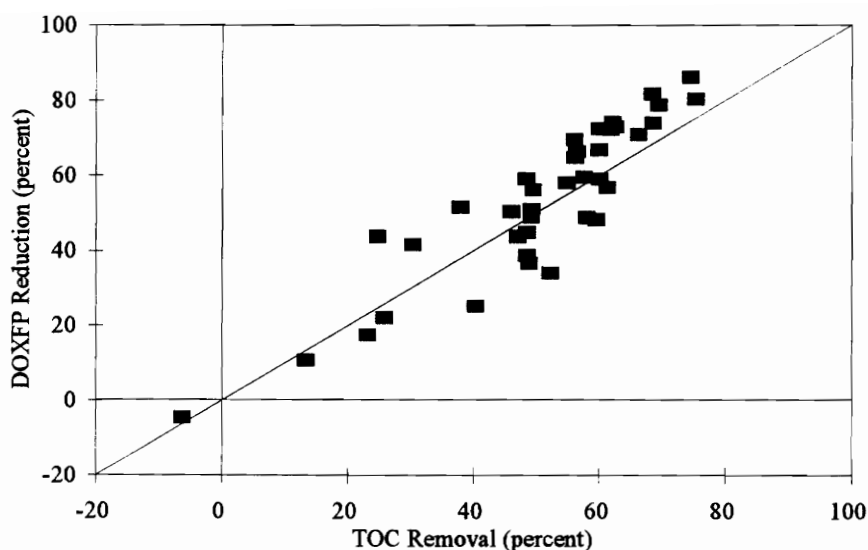


Figure 5.46. Comparison of TOC removal and DOXFP reduction for all treated samples. (Note: Line shown is a line with 1:1 slope: data points located above the line indicate greater DOXFP reduction, while data points located below the line indicate greater TOC removal.)

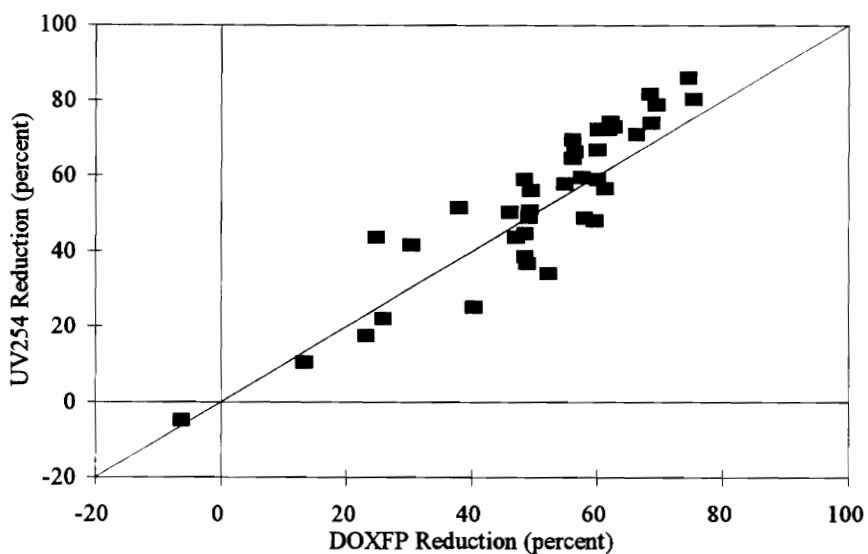


Figure 5.47. Comparison of UV254 reduction and DOXFP reduction for all treated samples. (Note: Line shown is a line with 1:1 slope: data points located above the line indicate greater UV254 reduction, while data points located below the line indicate greater DOXFP reduction.)

Figure 5.47 presents UV254 reduction in comparison to DOXFP reduction for the treated waters. These data indicate that UV254 reduction was greater than DOXFP reduction.

Based on these data, the trend seen for the five parameters was the following: $UV254 > DOXFP > TOC > THMFP > DOC$. This is the same trend seen by other researchers. This comparison is important when trying to utilize surrogate parameters to estimate DBP precursor removal. In particular, since DOC removal was generally the lowest percentage removal, it should serve as a conservative estimate of the removal of THM or DOX precursors.

Chapter VI

CONCLUSIONS

From the results of the research described in this thesis, the following conclusions were formulated:

1. The D/DBP Rule requirement of defining enhanced coagulation on a change in DOC of < 0.3 mg/L per 10 mg/L addition of coagulant is reasonably estimated from jar test results. Also, bench-scale testing was a good estimate of full-scale treatment in terms of removal of TOC and reduction of UV₂₅₄.
2. Enhanced coagulation was successful at achieving the TOC removals required by the D/DBP Rule. Specific UV absorbance (SUVA) appears to be the best indicator of the ability of coagulation to remove dissolved organic matter from natural waters, with greater TOC removal occurring for waters with higher SUVA values.
3. Increased residual coagulant concentrations in treated waters appear to be more a function of residual DOC remaining in the waters than a function of lower coagulation pH values.
4. Colder temperature did result in a slight worsening of TOC removal by coagulation and filtration treatment. Consideration of the data in terms of pOH was helpful when considering temperature effects, although decreases in TOC removal were still evident when considering the data on this basis.

5. Higher molecular weight organics were typically removed to a greater extent by coagulation than lower molecular weight organics.
6. The reduction of TOC, DOC, UV254, THMFP, and DOXFP generally followed the following trend: $UV254 > DOXFP > TOC > THMFP > DOC$. Removal of DOC was generally the lowest percentage removal, and therefore should serve as a conservative estimate of the removal of THM or DOX precursors.
7. The DOC concentration correlated well with DOXFP concentrations, in particular for the raw water samples. DOXFP concentrations also correlated well with THMFP concentrations.
8. Ferric sulfate generally worked slightly better than alum for removal of DOC, as well as for reduction of DBP precursors.

Chapter VII

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Chapter VIII

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APPENDIX A
DESCRIPTION OF WATER TREATMENT FACILITIES

Table A.1
Raw Water Characteristics for All Utilities

	Utility VT-1	Utility VT-2	Utility VT-3
Location	Newport News, VA	Fort Collins, CO	Tampa, FL
Date Sampled	6/21/93	7/21/93	8/16/93
pH	7.80	7.38	7.75
Alkalinity (mg/L as CaCO ₃)	60	21	112
Turbidity (NTU)	0.9	1.2	0.88
Color (PCU)	25	16	137
Anions (mg/L):			
Sulfate	7.2	4.2	23.5
Bromide	bd	bd	bd
Chloride	8.0	1.1	17.1
Hardness (mg/L as CaCO₃)			
Ca Hardness	64	15.5	118.5
Mg Hardness	5.3	4.3	14.3
Total Hardness	69.3	19.8	132.8
Organic Carbon:			
TOC (mg/L)	5.32	2.56	11.8
DOC (mg/L)	4.98	2.28	11.6
UV254 (1/m)	13.2	4.25	47.5
Residual Coagulant:			
Al (µg/L)	7	78	66.5
Fe (mg/L)	---	---	0.11

(continued)

Table A.1 (continued)

	Utility VT-4	Utility VT-5	Utility VT-6
Location	New Haven, CT	Muncie, IN	Buffalo Pound, Canada
Date Sampled	9/27/93	10/22/93	11/12/93
pH	7.00	7.98	8.05
Alkalinity (mg/L as CaCO ₃)	15	198	138
Turbidity (NTU)	1.1	20	3.5
Color (PCU)	15	84	12
Anions (mg/L):			
Sulfate	9.1	42.4	86.3
Bromide	bd	bd	bd
Chloride	13.2	22.2	8.35
Hardness (mg/L as CaCO₃)			
Ca Hardness	16.7	62.5	40.9
Mg Hardness	4.9	21.4	17.5
Total Hardness	21.7	83.9	58.4
Organic Carbon:			
TOC (mg/L)	2.65	9.41	4.02
DOC (mg/L)	2.63	8.04	3.64
UV254 (1/m)	5.75	24.5	6.79
Residual Coagulant:			
Al (µg/L)	1.0	76	103
Fe (mg/L)	0.06	---	0.07

(continued)

Table A.1 (con't)

	Utility VT-7	Utility VT-8	Utility VT-9
Location	New Castle, PA	MWD of Southern California	Grand Strand, SC
Date Sampled	12/3/93	1/21/94	2/21/94
pH	7.42	8.12	6.04
Alkalinity (mg/L as CaCO ₃)	44	135	9.8
Turbidity (NTU)	8.4	1.4	19
Color (PCU)	29	5.4	125
Anions (mg/L):			
Sulfate	30.9	275	12.4
Bromide	bd	bd	bd
Chloride	13.9	96	10.7
Hardness (mg/L as CaCO₃)			
Ca Hardness	57	186	11.9
Mg Hardness	20	121	7.98
Total Hardness	77	307	19.88
Organic Carbon:			
TOC (mg/L)	5.64	2.73	8.54
DOC (mg/L)	4.84	2.79	8.03
UV254 (1/m)	13.3	3.74	49.1
Residual Coagulant:			
Al (µg/L)	112	72	168
Fe (mg/L)	0.20	< 0.03	0.29

APPENDIX B
UTILITY VT-2

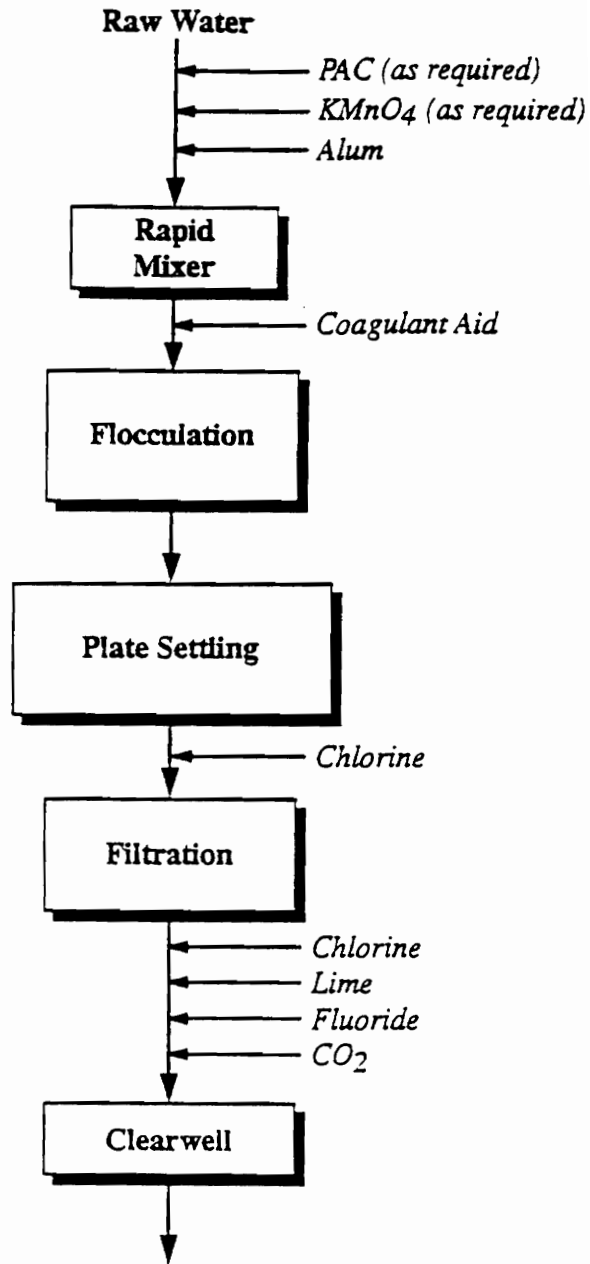


Figure B.1. Utility VT-2 Flow Diagram.

TABLE B.1
SUMMARY OF BENCH-SCALE AND FULL-SCALE RESULTS

Utility: VT-2
Location: Fort Collins, CO

Sample:	Bench-Scale				Full-Scale	
	Alum				Alum	
	Raw	Baseline	Enhanced	Optimized	Settled	Finished
Test:						
Date Received:	7/23/93	7/23/93	7/23/93	7/23/93	7/23/93	7/23/93
Date Sampled:	7/21/93	7/21/93	7/21/93	7/21/93	7/21/93	7/21/93
Coagulant Dose (mg/L)	---	17	30	80	17	17
pH	7.38	6.27	5.9-6.1	5.9-6.1	6.54	7.59
Alkalinity (mg/L as CaCO ₃)	21	13	---	---	---	28
Turbidity (NTU)	1.2	3.25	1.0	---	0.45	0.26
Color (PCU)	16	5.2	---	---	6.1	4.4
Organic Carbon:						
TOC (mg/L)	2.56	---	---	---	---	1.21
DOC (mg/L)	2.28	1.32	1.14	1.09	1.30	---
UV254 (1/m)	4.25	3.02	1.87	2.02	1.89	1.76
DOC Molecular Size Dist. (DOC Passing Filter - mg/L)						
10,000 Daltons	1.41	---	0.96	---	---	---
3,000 Daltons	0.66	---	0.69	---	---	---
1,000 Daltons	0.51	---	0.36	---	---	---
500 Daltons	0.25	---	0.24	---	---	---
Dissolved Al (ug/L)	78	73	40	---	---	---
Dissolved Fe (mg/L)	---	---	---	---	---	---
Anions: (mg/L)						
Sulfate	4.2	---	---	---	---	---
Bromide	< 0.5	---	---	---	---	---
Chloride	1.1	---	---	---	---	---
Hardness: (mg/L as CaCO₃)						
Ca Hardness	15.5	---	---	---	---	---
Mg Hardness	4.3	---	---	---	---	---
Total Hardness	19.8	---	---	---	---	---

TABLE B.1 (con't)

Utility:

VT-2

Location:

Fort Collins, CO

Sample:	Bench-Scale				Full-Scale	
	Alum					
	Raw	Baseline	Enhanced	Optimized	Settled	Finished
Test:						
Uniform Formation Condition (UFC), dissolved						
Initial Cl Dose (mg/L)	---	2.0	1.8	---	---	---
Free Cl Residual (mg/L)	---	1.3	1.2	---	---	---
THM, (ug/L):						
CHCl3	---	35.2	25.1	---	---	---
CHCl2Br	---	6.6	6.1	---	---	---
CHClBr2	---	bd	bd	---	---	---
CHBr3	---	bd	bd	---	---	---
Total THM's	---	41.8	31.2	---	---	---
DOX (ug/L as Cl)	---	126	89	---	---	---
7-day Formation Potentials, dissolved						
Initial Cl Dose (mg/L)	4.5	3.5	3.5	3.5	---	---
Free Cl Residual (mg/L)	2.0	1.9	2.0	2.5	---	---
THMFP (ug/L):						
CHCl3	215.9	63.0	52.9	58.2	---	---
CHCl2Br	10.1	7.0	6.2	7.8	---	---
CHClBr2	bd	bd	bd	bd	---	---
CHBr3	bd	bd	bd	bd	---	---
Total THM's	226.0	70.0	59.1	66.0	---	---
DOX (ug/L as Cl)	409	208	144	209	---	---

ADDITIONAL FP RESULTS

Sample:	Bench-Scale			
	Alum			
	Raw	Baseline	Enhanced	Optimized
Test:				
7-day Formation Potentials, dissolved				
Initial Cl Dose (mg/L)	7.5	6.5	6.5	6.5
Free Cl Residual (mg/L)	4.0	5.0	5.0	4.5
THMFP (ug/L):				
CHCl3	243.9	73.3	62.8	59.6
CHCl2Br	10.2	6.5	6.4	6.3
CHClBr2	bd	bd	bd	bd
CHBr3	bd	bd	bd	bd
Total THM's	254.1	79.8	69.2	65.9
DOX (ug/L as Cl)	---	---	---	---

TABLE B.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-2

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-2 (Fort Collins, CO)

Date Received: 7/23/93

Date Sampled: 7/21/93

Jar Test Conditions: Coag: Alum Dose: 30 mg/L

Target pH	5.3	5.6	5.9	6.1	6.4	6.7
Residual Al (ug/L)	134	136	32	48	261	99
DOC (mg/L)						
Mean	1.53	1.46	1.29	1.33	1.35	1.50
Std Dev	0.013	0.032	0.005	0.001	0.023	0.035
UV254 (1/m)						
Mean	2.98	2.46	2.30	2.61	2.28	2.42
Std Dev	0.029	0.007	0.015	0.012	0.000	0.007

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-2 (Fort Collins, CO)

Date Received: 7/23/93

Date Sampled: 7/21/93

Jar Test Conditions: Coag: Alum

Target pH range: 5.9-6.1

	COAGULANT DOSE (mg/L)					
	0	10	20	30	40	50
Turbidity (NTU)	0.88	0.42	0.26	0.27	0.18	0.34
Residual Al (ug/L)	52	64	61	46	62	38
DOC (mg/L)						
Mean	2.69	1.48	1.30	1.13	1.08	1.15
Std Dev	0.055	0.009	0.020	0.004	0.021	0.017
UV254 (1/m)						
Mean	6.50	3.16	2.72	2.75	2.10	1.91
Std Dev	0.015	0.015	0.007	0.000	0.000	0.015

	COAGULANT DOSE (mg/L)					
	60	70	80	90	100	110
Turbidity (NTU)	0.2	0.22	0.17	0.26	0.36	0.24
Residual Al (ug/L)	96	60	38	58	35	32
DOC (mg/L)						
Mean	1.22	1.14	1.11	1.30	1.25	1.23
Std Dev	0.035	0.042	0.017	0.010	0.028	0.028
UV254 (1/m)						
Mean	1.90	1.72	1.76	1.64	2.37	2.10
Std Dev	0.015	0.000	0.000	0.007	0.007	0.015

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

APPENDIX C
UTILITY VT-4

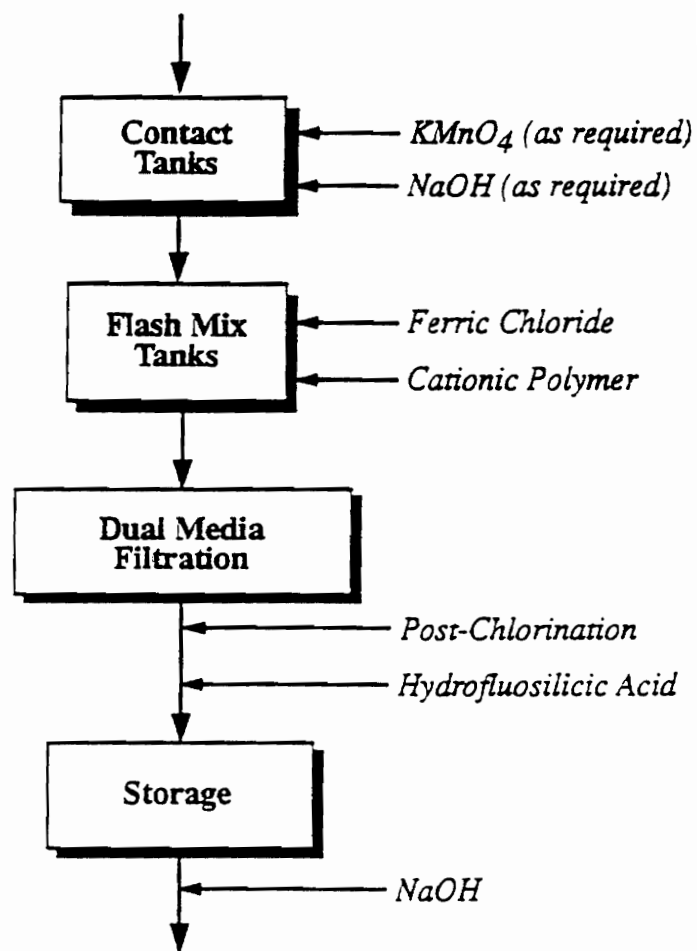


Figure C.1. Utility VT-4 Flow Diagram.

TABLE C.1
SUMMARY OF BENCH-SCALE AND FULL-SCALE RESULTS

Utility: VT-4
Location: New Haven, CT

Sample:	Bench-Scale						Full-Scale	
	Raw	Ferric			Alum		Ferric	
Test:		Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Date Received:	9/27/93	9/27/93	9/27/93	9/27/93	9/27/93	9/27/93	9/27/93	9/27/93
Date Sampled:	9/24/93	9/24/93	9/24/93	9/24/93	9/24/93	9/24/93	9/24/93	9/24/93
Coagulant Dose (mg/L)	---	5.6	20	50	20	50	5.6	5.6
pH	7.00	6.65	5.0-5.2	5.0-5.2	5.8-6.0	5.8-6.0	6.62	6.92
Alkalinity (mg/L as CaCO ₃)	15	16	---	---	---	---	---	31
Turbidity (NTU)	1.1	1.75	1.4	0.96	0.55	3.9	0.28	0.38
Color (PCU)	15	16	---	---	---	---	5.0	4.3
Organic Carbon:								
TOC (mg/L)	2.65	---	---	---	---	---	---	1.42
DOC (mg/L)	2.63	2.34	1.39	1.09	1.61	1.38	1.60	---
UV ₂₅₄ (1/m)	5.75	7.03	2.07	1.71	2.64	1.97	2.52	1.69
DOC Molecular Size Dist.								
(DOC Passing Filter - mg/L)								
10,000 Daltons	1.43	---	1.19	---	1.25	---	---	---
3,000 Daltons	0.91	---	0.97	---	0.83	---	---	---
1,000 Daltons	0.47	---	0.82	---	0.55	---	---	---
500 Daltons	0.28	---	0.51	---	0.34	---	---	---
Dissolved Al (ug/L)	1.0	---	---	---	52	43	---	---
Dissolved Fe (mg/L)	0.06	0.49	0.12	0.04	---	---	---	---
Anions: (mg/L)								
Sulfate	9.1	---	---	---	---	---	---	---
Bromide	< 0.5	---	---	---	---	---	---	---
Chloride	13.2	---	---	---	---	---	---	---
Hardness: (mg/L as CaCO₃)								
Ca Hardness	16.7	---	---	---	---	---	---	---
Mg Hardness	4.9	---	---	---	---	---	---	---
Total Hardness	21.7	---	---	---	---	---	---	---

TABLE C.1 (con't)

Utility:

VT-4

Location:

New Haven, CT

Sample:	Bench-Scale						Full-Scale	
		Ferric			Alum			
	Raw	Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Uniform Formation Condition (UFC), dissolved								
Initial Cl Dose (mg/L)	---	2.2	1.6	---	2.0	---	---	---
Free Cl Residual (mg/L)	---	0.8	1.1	---	0.9	---	---	---
THM, (ug/L):								
CHCl3	---	53.4	30.7	---	25.4	---	---	---
CHCl2Br	---	18.0	18.2	---	8.8	---	---	---
CHClBr2	---	0.9	2.5	---	0.9	---	---	---
CHBr3	---	bd	bd	---	bd	---	---	---
Total THM's	---	72.3	51.3	---	35.1	---	---	---
DOX (ug/L as Cl)	---	119	65	---	87	---	---	---
7-day Formation Potentials, dissolved								
Initial Cl Dose (mg/L)	8.0	7.0	7.0	7.0	7.0	7.0	---	---
Free Cl Residual (mg/L)	2.75	2.75	3.5	3.6	3.0	3.0	---	---
THMFP (ug/L):								
CHCl3	123.6	109.2	56.0	49.7	64.0	61.0	---	---
CHCl2Br	14.9	17.2	13.6	9.3	10.8	10.8	---	---
CHClBr2	bd	0.2	0.7	0.4	0.0	0.4	---	---
CHBr3	bd	bd	bd	bd	bd	bd	---	---
Total THM's	138.4	126.6	70.3	59.3	74.8	72.2	---	---
DOX (ug/L as Cl)	262	234	161	135	195	165	---	---

ADDITIONAL FP RESULTS

Sample:	Bench-Scale					
	Raw	Ferric			Alum	
		Baseline	Enhanced	Optimized	Enhanced	Optimized
Test:						
7-day Formation Potentials, dissolved						
Initial Cl Dose (mg/L)	---	10	---	---	10	10
Free Cl Residual (mg/L)	---	4.4	---	---	4	4
THMFP (ug/L):						
CHCl ₃	---	119.3	---	---	71.8	65.6
CHCl ₂ Br	---	18.7	---	---	13.2	10.7
CHClBr ₂	---	0.3	---	---	0.4	0.1
CHBr ₃	---	bd	---	---	bd	bd
Total THM's	---	138.3	---	---	85.4	76.4
DOX (ug/L as Cl)	---	---	---	---	---	---

TABLE C.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-4

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-4 (New Haven, CT)

Date Received: 9/27/93

Date Sampled: 9/24/93

Jar Test Conditions: Coag: Alum Dose: 20 mg/L

Target pH	5.3	5.6	5.9	6.1	6.4	6.7
Residual Al (ug/L)	94	58	68	39	56	70
DOC (mg/L)						
Mean	1.37	1.23	1.06	1.09	1.21	1.24
Std Dev	0.053	0.086	0.047	0.022	0.021	0.065
UV254 (1/m)						
Mean	2.32	2.19	2.23	2.28	2.62	2.64
Std Dev	0.007	0.029	0.029	0.007	0.015	0.007

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-4 (New Haven, CT)

Date Received: 9/27/93

Date Sampled: 9/24/93

Jar Test Conditions: Coag: Alum

Target pH range: 5.8-6.0

	COAGULANT DOSE (mg/L)					
	0	10	20	30	40	50
Coag Dose (mM as Al)	0	0.033	0.067	0.100	0.133	0.167
Turbidity (NTU)	1.5	0.89	1.2	0.75	0.7	0.57
Residual Al (ug/L)	41	46	41	41	36	39
DOC (mg/L)						
Mean	2.56	1.63	1.45	1.45	1.45	1.34
Std Dev	0.026	0.023	0.011	0.003	0.010	0.025
UV254 (1/m)						
Mean	5.80	3.18	2.48	2.11	2.09	2.00
Std Dev	0.007	0.007	0.007	0.015	0.007	0.015

	COAGULANT DOSE (mg/L)					
	60	70	80	90	100	110
Coag Dose (mM as Al)	0.200	0.233	0.267	0.300	0.333	0.367
Turbidity (NTU)	2	0.99	0.7	1	1	0.7
Residual Al (ug/L)	39	33	34	43	33	36
DOC (mg/L)						
Mean	1.39	1.58	1.33	1.43	1.44	1.29
Std Dev	0.015	0.017	0.013	0.008	0.005	0.044
UV254 (1/m)						
Mean	2.14	1.99	2.23	1.90	1.77	1.71
Std Dev	0.007	0.007	0.007	0.007	0.000	0.007

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE C.2 (con't)

JAR TEST DATA - pH OPTIMIZATION**FERRIC SULFATE**

Utility: VT-4 (New Haven, CT)

Date Received: 9/27/93

Date Sampled: 9/24/93

Jar Test Conditions: Coag: Ferric Sulfate Dose: 10 mg/L

Target pH	4.5	4.8	5.1	5.4	5.7	6.1
Residual Fe (mg/L)	0.12	0.17	0.14	0.14	0.12	0.18
DOC (mg/L)						
Mean	2.07	1.98	1.83	1.93	1.88	1.88
Std Dev	0.019	0.008	0.011	0.017	0.020	0.019
UV254 (1/m)						
Mean	4.24	4.18	4.11	4.78	4.12	4.93
Std Dev	0.012	0.012	0.000	0.016	0.012	0.000

JAR TEST DATA - DOC REMOVAL OPTIMIZATION**FERRIC SULFATE**

Utility: VT-4 (New Haven, CT)

Date Received: 9/27/93

Date Sampled: 9/24/93

Jar Test Conditions: Coag: Ferric Sulfate

Target pH range: 5.0-5.2

	COAGULANT DOSE (mg/L)					
	0	5.6	10	20	30	40
Coag Dose (mM as Fe)	0	0.023	0.041	0.082	0.122	0.163
Turbidity (NTU)		1.8	2	0.82	0.86	4.2
Residual Fe (mg/L)	0.14	0.43	0.5	0.06	0.04	0.04
DOC (mg/L)						
Mean	2.65	2.06	2.04	1.44	1.44	1.27
Std Dev	0.019	0.005	0.019	0.010	0.015	0.018
UV254 (1/m)						
Mean	5.56	9.57	9.41	2.14	1.89	1.77
Std Dev	0.015	0.007	0.000	0.007	0.007	0.007

	COAGULANT DOSE (mg/L)					
	50	60	70	80		
Coag Dose (mM as Fe)	0.204	0.245	0.286	0.327		
Turbidity (NTU)	1.5	1.7	1.2	1.35		
Residual Fe (mg/L)	0.04	0.05	0.05	0.05		
DOC (mg/L)						
Mean	1.17	1.51	1.18	1.17		
Std Dev	0.002	0.002	0.001	0.004		
UV254 (1/m)						
Mean	1.72	1.58	1.47	1.58		
Std Dev	0.007	0.007	0.007	0.000		

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

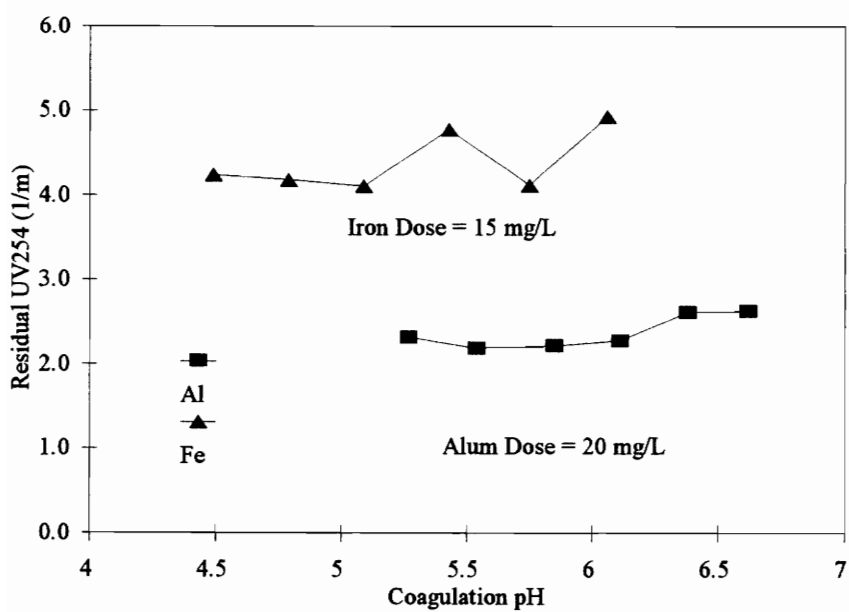


Figure C.2. Residual UV254 as a function of coagulation pH for Utility VT-4 alum and ferric sulfate treatment.

APPENDIX D
UTILITY VT-7

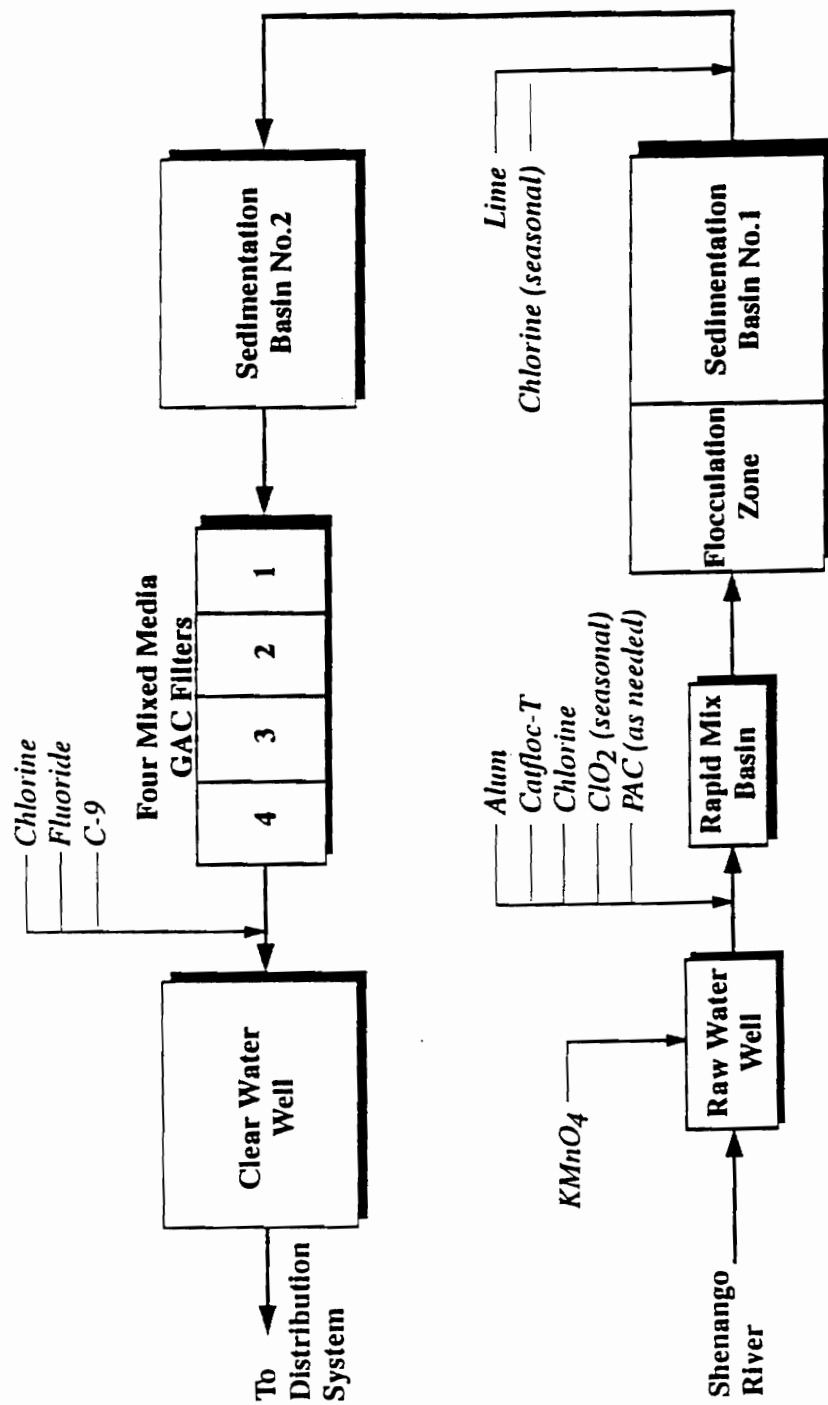


Figure D.1. Utility VT-7 Flow Diagram.

TABLE D.1
SUMMARY OF BENCH-SCALE AND FULL-SCALE RESULTS

Utility: VT-7
Location: New Castle, PA

Sample:	Bench-Scale						Full-Scale	
	Raw	Alum			Ferric		Alum	
		Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Date Received:	12/7/93	12/7/93	12/7/93	12/7/93	12/7/93	12/7/93	12/7/93	12/7/93
Date Sampled:	12/3/93	12/3/93	12/3/93	12/3/93	12/3/93	12/3/93	12/3/93	12/3/93
Coagulant Dose (mg/L)	---	35	30	90	40	80	35	35
pH	7.42	6.40	5.9-6.1	5.9-6.1	4.9-5.1	4.9-5.1	6.84	6.94
Alkalinity (mg/L as CaCO ₃)	44	31	---	---	---	---	---	40
Turbidity (NTU)	8.4	1.2	2.4	0.75	0.65	1.9	0.65	0.5
Color (PCU)	29	7.7	---	---	---	---	5.6	1.0
Organic Carbon:								
TOC (mg/L)	5.64	---	---	---	---	---	---	2.53
DOC (mg/L)	4.84	2.89	3.02	2.51	2.24	2.46	2.81	---
UV254 (1/m)	13.3	5.79	5.83	4.73	4.31	3.63	4.67	3.23
DOC Molecular Size Dist. (DOC Passing Filter - mg/L)								
10,000 Daltons	3.38	---	2.34	---	2.09	---	---	---
3,000 Daltons	1.96	---	1.67	---	1.63	---	---	---
1,000 Daltons	0.90	---	0.94	---	0.99	---	---	---
500 Daltons	0.31	---	0.35	---	0.49	---	---	---
Dissolved Al (ug/L)	112	67	92	58			---	---
Dissolved Fe (mg/L)	0.20	---	---	---	0.07	0.09	---	---
Anions: (mg/L)								
Sulfate	30.9	---	---	---	---	---	---	---
Bromide	< 0.5	---	---	---	---	---	---	---
Chloride	13.9	---	---	---	---	---	---	---
Hardness: (mg/L as CaCO₃)								
Ca Hardness	57	---	---	---	---	---	---	---
Mg Hardness	20	---	---	---	---	---	---	---
Total Hardness	77	---	---	---	---	---	---	---

TABLE D.1 (con't)

Utility: VT-7
 Location: New Castle, PA

Sample:	Bench-Scale						Full-Scale	
	Alum				Ferric		Alum	
	Raw	Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Uniform Formation Condition (UFC), dissolved								
Initial Cl Dose (mg/L)	---	4.9	5.5	---	4.5	---	---	---
Free Cl Residual (mg/L)	---	0.7	0.8	---	0.85	---	---	---
THM, (ug/L):								
CHCl ₃	---	52.23	57.23	---	39.88	---	---	---
CHCl ₂ Br	---	9.76	7.42	---	6.51	---	---	---
CHClBr ₂	---	7.68	4.52	---	6.88	---	---	---
CHBr ₃	---	bd	bd	---	bd	---	---	---
Total THM's	---	69.67	69.17	---	53.27	---	---	---
DOX (ug/L as Cl)	---	305	298	---	222	---	---	---
7-day Formation Potentials, dissolved								
Initial Cl Dose (mg/L)	22	14	17	15	12	12	---	---
Free Cl Residual (mg/L)	3.5	3.0	3.8	4.0	3.0	3.4	---	---
THMFP (ug/L):								
CHCl ₃	313.5	176.0	186.1	149.3	121.0	110.1	---	---
CHCl ₂ Br	12.7	16.2	11.4	10.4	10.2	10.1	---	---
CHClBr ₂	bd	10.1	5.0	5.0	7.5	7.9	---	---
CHBr ₃	bd	bd	bd	bd	bd	bd	---	---
Total THM's	326.3	202.4	202.5	164.7	138.6	128.1	---	---
DOX (ug/L as Cl)	916	375	454	385	302	278	---	---

TABLE D.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-7

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-7 (New Castle, PA)

Date Received: 12/7/93

Date Sampled: 12/3/93

Jar Test Conditions: Coag: Alum Dose: 25 mg/L

Target pH	5.3	5.6	5.9	6.1	6.4	6.7
Turbidity (NTU)	0.7	0.5	1.25	1.1	0.5	0.95
Residual Al (ug/L)	170	100	74	74	92	143
DOC (mg/L)						
Mean	2.91	2.86	3.04	3.06	3.24	3.67
Std Dev	0.013	0.007	0.037	0.020	0.001	0.025
UV254 (1/m)						
Mean	5.26	5.22	5.55	5.47	6.06	6.32
Std Dev	0.007	0.007	0.022	0.007	0.000	0.000

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-7 (New Castle, PA)

Date Received: 12/7/93

Date Sampled: 12/3/93

Jar Test Conditions: Coag: Alum

Target pH range: 5.9-6.1

	COAGULANT DOSE (mg/L)					
	0	10	20	30	40	50
Coag Dose (mM as Al)	0	0.033	0.067	0.100	0.133	0.167
Turbidity (NTU)	3.3	1.7	0.3	0.9	0.5	0.4
Residual Al (ug/L)	112	177	32	68	107	119
DOC (mg/L)						
Mean	5.01	3.85	3.02	2.65	2.59	2.59
Std Dev	0.002	0.017	0.081	0.008	0.007	0.042
UV254 (1/m)						
Mean	12.96	9.36	6.07	5.12	4.93	4.54
Std Dev	0.029	0.000	0.000	0.000	0.000	0.000

	COAGULANT DOSE (mg/L)					
	60	70	80	90	100	110
Coag Dose (mM as Al)	0.200	0.233	0.267	0.300	0.333	0.367
Turbidity (NTU)	3	0.4	0.3	0.3	0.2	0.2
Residual Al (ug/L)	60	50	47	47	65	94
DOC (mg/L)						
Mean	2.57	2.56	2.51	2.32	2.36	2.36
Std Dev	0.083	0.047	0.018	0.018	0.025	0.047
UV254 (1/m)						
Mean	4.60	4.48	4.38	4.20	4.22	4.14
Std Dev	0.000	0.022	0.007	0.015	0.007	0.000

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE D.2 (con't)

JAR TEST DATA - pH OPTIMIZATION

FERRIC SULFATE

Utility: VT-7 (New Castle, PA)

Date Received: 12/7/93

Date Sampled: 12/3/93

Jar Test Conditions: Coag: Ferric Sulfate Dose: 20 mg/L

Target pH	4.5	4.8	5.1	5.4	5.7	6.1
Turbidity (NTU)	0.7	1.2	1.55	1.4	1.8	0.95
Residual Fe (mg/L)	0.26	0.33	0.35	0.39	0.48	0.32
DOC (mg/L)						
Mean	2.69	2.80	2.88	2.90	3.08	3.21
Std Dev	0.063	0.043	0.049	0.001	0.027	0.012
UV254 (1/m)						
Mean	7.57	7.88	8.32	10.13	10.45	8.08
Std Dev	0.000	0.007	0.015	0.007	0.000	0.007

JAR TEST DATA - DOC REMOVAL OPTIMIZATION

FERRIC SULFATE

Utility: VT-7 (New Castle, PA)

Date Received: 12/7/93

Date Sampled: 12/3/93

Jar Test Conditions: Coag: Ferric Sulfate

Target pH range: 4.9-5.1

COAGULANT DOSE (mg/L)						
	0	10	20	30	40	50
Coag Dose (mM as Fe)	0.000	0.041	0.082	0.122	0.163	0.204
Turbidity (NTU)	3.5	3.6	1.25	0.85	1	2
Residual Fe (mg/L)	0.19	1.11	0.32	0.18	0.18	0.18
DOC (mg/L)						
Mean	5.27	4.65	2.90	2.29	2.03	2.04
Std Dev	0.059	0.078	0.021	0.004	0.016	0.018
UV254 (1/m)						
Mean	13.67	21.29	8.03	5.39	4.45	4.17
Std Dev	0.000	0.006	0.007	0.007	0.007	0.000

COAGULANT DOSE (mg/L)						
	60	70	80	90	100	110
Coag Dose (mM as Fe)	0.245	0.286	0.327	0.367	0.408	0.449
Turbidity (NTU)	0.7	1.5	0.75	0.5	0.5	0.5
Residual Fe (mg/L)	0.15	0.17	0.12	0.11	0.11	0.11
DOC (mg/L)						
Mean	1.95	1.91	1.82	1.85	1.81	1.78
Std Dev	0.017	0.025	0.013	0.006	0.007	0.016
UV254 (1/m)						
Mean	3.77	3.67	3.59	3.44	3.40	3.33
Std Dev	0.007	0.007	0.000	0.007	0.000	0.000

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

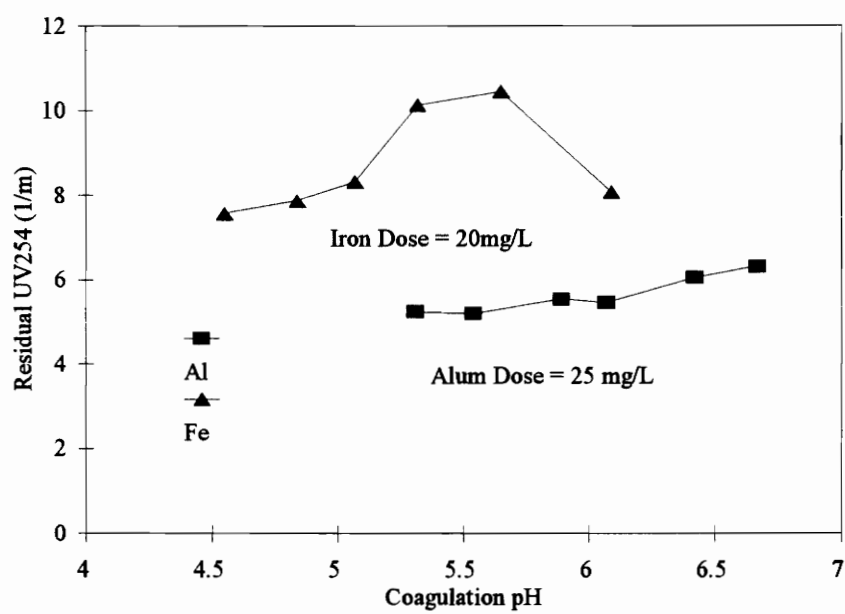


Figure D.2. Residual UV254 as a function of coagulation pH for Utility VT-7 alum and ferric sulfate treatment.

APPENDIX E
UTILITY VT-9

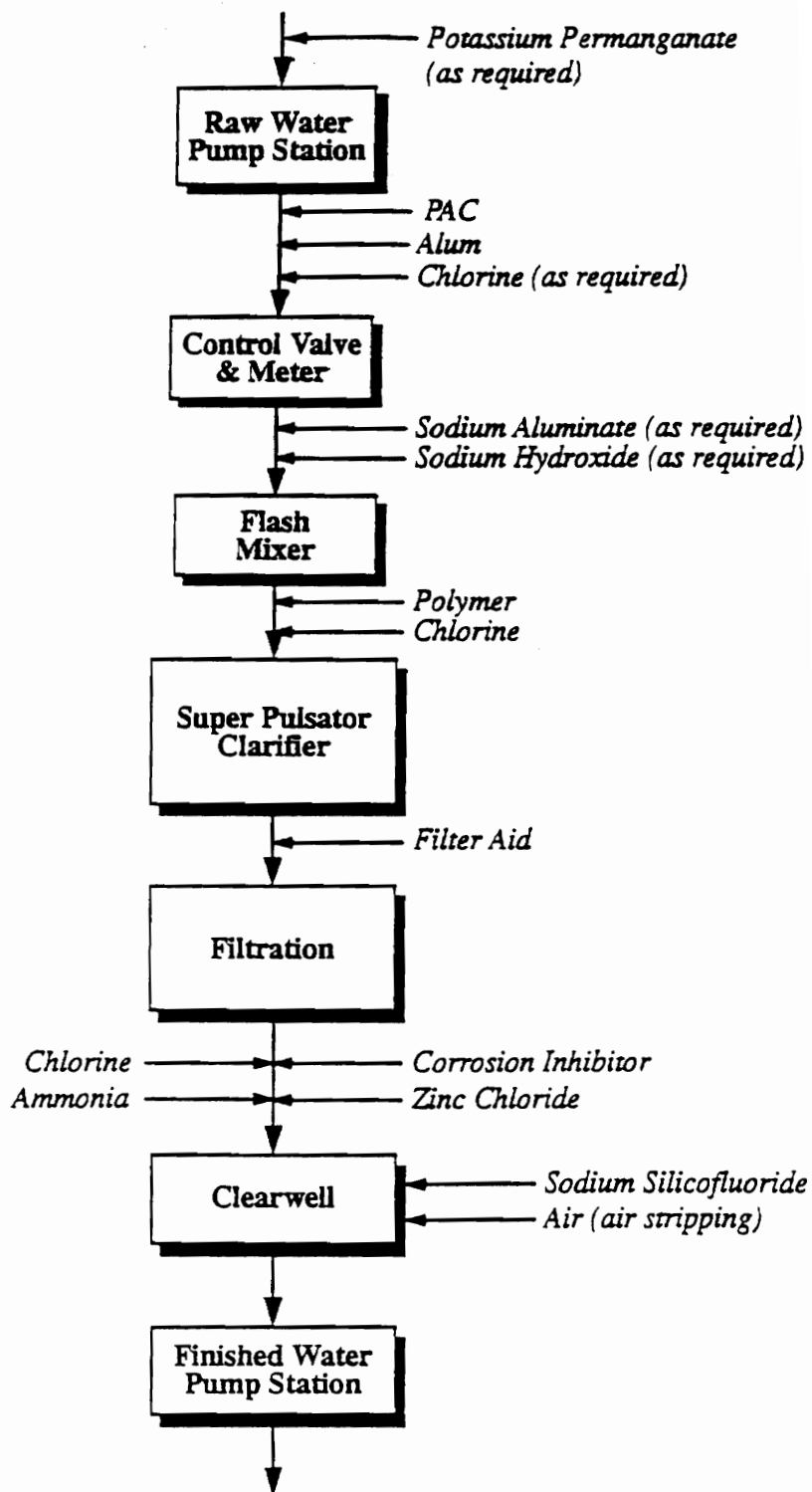


Figure E.1. Utility VT-9 Flow Diagram.

TABLE E.1
SUMMARY OF BENCH-SCALE AND FULL-SCALE RESULTS

Utility: VT-9
Location: Grand Strand, SC

Sample:	Bench-Scale						Full-Scale	
	Raw	Alum			Ferric		Alum	
Test:		Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Date Received:	2/22/94	2/22/94	2/22/94	2/22/94	2/22/94	2/22/94	2/22/94	2/22/94
Date Sampled:	2/21/94	2/21/94	2/21/94	2/21/94	2/21/94	2/21/94	2/21/94	2/21/94
Coagulant Dose (mg/L)	---	36	60	130	60	110	36	36
pH	6.04	5.60	6.0-6.2	6.0-6.2	5.5-5.7	5.5-5.7	4.85	7.21
Alkalinity (mg/L as CaCO ₃)	9.8	5.9	---	---	---	---	---	18
Turbidity (NTU)	19	2.1	1.3	0.7	1.6	3.5	1.5	1.0
Color (PCU)	125	9.7	---	---	---	---	6.8	9.2
Organic Carbon:								
TOC (mg/L)	8.54	---	---	---	---	---	---	2.78
DOC (mg/L)	8.03	3.22	3.70	3.18	3.39	2.68	2.59	---
UV ₂₅₄ (1/m)	49.1	6.80	8.32	5.97	6.44	4.09	4.56	5.83
DOC Molecular Size Dist.								
(DOC Passing Filter - mg/L)								
10,000 Daltons	3.11	---	3.04	---	2.77	---	---	---
3,000 Daltons	2.06	---	2.11	---	1.61	---	---	---
1,000 Daltons	0.85	---	1.03	---	0.99	---	---	---
500 Daltons	0.38	---	0.58	---	0.58	---	---	---
Dissolved Al (ug/L)	168	81	78	85			---	---
Dissolved Fe (mg/L)	0.29	---	---	---	0.06	0.05	---	---
Anions: (mg/L)								
Sulfate	12.4	---	---	---	---	---	---	---
Bromide	<0.5	---	---	---	---	---	---	---
Chloride	10.7	---	---	---	---	---	---	---
Hardness: (mg/L as CaCO₃)								
Ca Hardness	11.9	---	---	---	---	---	---	---
Mg Hardness	7.98	---	---	---	---	---	---	---
Total Hardness	19.88	---	---	---	---	---	---	---

TABLE E.1 (con't)

Utility:

VT-9

Location:

Grand Strand, SC

Sample:	Bench-Scale						Full-Scale	
	Raw	Alum			Ferric		Alum	
		Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Uniform Formation Condition (UFC), dissolved								
Initial Cl Dose (mg/L)	---	4.4	4.7	---	4.4	---	---	---
Free Cl Residual (mg/L)	---	0.9	1.3	---	1.3	---	---	---
THM ₁ (ug/L):								
CHCl ₃	---	69.5	77.5	---	51.6	---	---	---
CHCl ₂ Br	---	12.3	13.2	---	10.1	---	---	---
CHClBr ₂	---	3.2	3.2	---	2.8	---	---	---
CHBr ₃	---	bd	bd	---	bd	---	---	---
Total THM's	---	85.0	93.9	---	64.5	---	---	---
DOX (ug/L as Cl)	---	253	296	---	225	---	---	---
7-day Formation Potentials, dissolved								
Initial Cl Dose (mg/L)	30	12	15	12	12	12	---	---
Free Cl Residual (mg/L)	3.8	3.4	4	3	3	4	---	---
THMFP (ug/L):								
CHCl ₃	424.9	166.5	227.0	140.4	175.5	125.8	---	---
CHCl ₂ Br	6.7	16.1	17.2	14.9	14.7	13.4	---	---
CHClBr ₂	bd	3.5	3.2	2.3	2.8	3.0	---	---
CHBr ₃	bd	bd	bd	bd	bd	bd	---	---
Total THM's	431.6	186.1	247.3	157.6	193.0	142.1	---	---
DOX (ug/L as Cl)	1570	404	526	423	431	287	---	---

TABLE E.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-9

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-9 (Grand Strand, SC)

Date Received: 2/22/94

Date Sampled: 2/21/94

Jar Test Conditions: Coag: Alum

Dose: 25 mg/L

Target pH	5.3	5.6	5.9	6.1	6.4	6.7
Turbidity (NTU)	4.5	6.7	6.3	6.2	8.2	17
Residual Al (ug/L)	705	1170	1045	680	795	1255
DOC (mg/L)						
Mean	5.68	6.11	5.80	5.38	5.74	7.12
Std Dev	0.077	0.042	0.004	0.023	0.004	0.015
UV254 (1/m)						
Mean	20.53	25.73	20.55	18.73	22.85	33.58
Std Dev	0.007	0.022	0.000	0.015	0.015	0.007

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-9 (Grand Strand, SC)

Date Received: 2/22/94

Date Sampled: 2/21/94

Jar Test Conditions: Coag: Alum

Target pH range: 6.0-6.2

	COAGULANT DOSE (mg/L)					
	20	30	40	50	60	70
Coag Dose (mM as Al)	0.067	0.100	0.133	0.167	0.200	0.233
Turbidity (NTU)	18	4.4	2.3	1.3	1.2	1.4
Residual Al (ug/L)	1350	645	435	163	115	94
DOC (mg/L)						
Mean	7.89	5.07	4.42	3.88	3.76	3.40
Std Dev	0.004	0.037	0.017	0.005	0.035	0.050
UV254 (1/m)						
Mean	39.37	15.97	12.30	8.09	7.70	6.56
Std Dev	0.037	0.015	0.000	0.007	0.007	0.000

	COAGULANT DOSE (mg/L)					
	80	90	100	110	130	150
Coag Dose (mM as Al)	0.267	0.300	0.333	0.367	0.433	0.500
Turbidity (NTU)	1.25	1.7	1.1	1.2	1	1
Residual Al (ug/L)	96	174	100	74	72	71
DOC (mg/L)						
Mean	3.27	3.21	3.14	3.19	2.88	2.88
Std Dev	0.025	0.008	0.051	0.036	0.006	0.006
UV254 (1/m)						
Mean	6.06	5.61	6.42	5.62	5.06	4.94
Std Dev	0.007	0.000	0.000	0.007	0.000	0.015

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE E.2 (con't)

JAR TEST DATA - pH OPTIMIZATION

FERRIC SULFATE

Utility: VT-9 (Grand Strand, SC)

Date Received: 2/22/94

Date Sampled: 2/21/94

Jar Test Conditions: Coag: Ferric Sulfate Dose: 20 mg/L

Target pH	4.5	4.8	5.1	5.4	5.7	6.1
Turbidity (NTU)	8.5	7.8	8.9	7.4	12	18
Residual Fe (mg/L)	2.38	2.4	2.7	2.51	2.1	2.92
DOC (mg/L)						
Mean	6.09	6.06	6.37	6.37	6.29	7.19
Std Dev	0.022	0.023	0.029	0.001	0.018	0.045
UV254 (1/m)						
Mean	41.92	41.53	45.69	41.45	42.29	56.21
Std Dev	0.007	0.022	0.022	0.044	0.007	0.000

JAR TEST DATA - DOC REMOVAL OPTIMIZATION

FERRIC SULFATE

Utility: VT-9 (Grand Strand, SC)

Date Received: 2/22/94

Date Sampled: 2/21/94

Jar Test Conditions: Coag: Ferric Sulfate

Target pH range: 5.5-5.7

COAGULANT DOSE (mg/L)						
	20	30	40	50	60	70
Coag Dose (mM as Fe)	0.082	0.122	0.163	0.204	0.245	0.286
Turbidity (NTU)	5.2	4	1.7	0.9	1	1.1
Residual Fe (mg/L)	1.88	3.45	0.41	0.21	0.14	0.15
DOC (mg/L)						
Mean	6.22	5.63	3.46	3.37	2.82	2.84
Std Dev	0.056	0.078	0.030	0.004	0.035	0.019
UV254 (1/m)						
Mean	35.56	43.34	11.68	8.97	6.60	6.20
Std Dev	0.000	0.037	0.022	0.007	0.000	0.015

COAGULANT DOSE (mg/L)						
	80	90	100	110	130	150
Coag Dose (mM as Fe)	0.327	0.367	0.408	0.449	0.531	0.612
Turbidity (NTU)	1.5	1.6	1.6	1	1.4	2.2
Residual Fe (mg/L)	0.11	0.11	0.1	0.1	0.11	0.1
DOC (mg/L)						
Mean	2.59	2.55	2.25	2.09	2.04	1.88
Std Dev	0.013	0.064	0.023	0.006	0.016	0.004
UV254 (1/m)						
Mean	5.41	4.86	4.22	3.91	3.79	3.40
Std Dev	0.007	0.007	0.081	0.007	0.015	0.007

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE E.2 (con't)

TEMP EFFECTS JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-9 (Grand Strand, SC)

Date Received: 2/22/94

Date Sampled: 2/21/94

Jar Test Conditions: Coag: Alum (4 deg C) Dose: 25 mg/L

Target pH	6.0	6.4	6.7	7.0	7.3	7.6
Turbidity (NTU)	17	17	17	17	17	17
Residual Al (ug/L)	1560	1670	1600	1510	1440	1450
DOC (mg/L)						
Mean	7.33	7.42	7.58	7.01	7.31	7.21
Std Dev	0.013	0.062	0.069	0.006	0.016	0.046
UV254 (1/m)						
Mean	33.31	33.79	33.31	29.26	29.52	18.91
Std Dev	0.066	0.044	0.015	0.015	0.007	16.380

TEMP EFFECTS JAR TEST DATA - DOC REM. OPT.

ALUM (4 deg C)

Utility: VT-9 (Grand Strand, SC)

Date Received: 2/22/94

Date Sampled: 2/21/94

Jar Test Conditions: Coag: Alum (4 deg C)

Target pH range: 6.9-7.1

	COAGULANT DOSE (mg/L)					
	20	30	40	50	60	70
Coag Dose (mM as Al)	0.067	0.100	0.133	0.167	0.200	0.233
Turbidity (NTU)	17	16	2.3	2.5	3	1.5
Residual Al (ug/L)	1190	1510	370	124	75	94
DOC (mg/L)						
Mean	7.86	7.19	4.45	3.76	3.55	3.93
Std Dev	0.023	0.059	0.024	0.006	0.011	0.001
UV254 (1/m)						
Mean	35.64	29.33	11.84	7.64	6.70	7.54
Std Dev	0.022	0.000	0.007	0.007	0.007	0.000

	COAGULANT DOSE (mg/L)					
	80	90	100	110	130	150
Coag Dose (mM as Al)	0.267	0.300	0.333	0.367	0.433	0.500
Turbidity (NTU)	1.5	2.5	2	2.5	3	1.5
Residual Al (ug/L)	227	136	112	136	128	103
DOC (mg/L)						
Mean	4.86	4.85	3.91	4.30	4.21	3.82
Std Dev	0.011	0.058	0.036	0.006	0.001	0.009
UV254 (1/m)						
Mean	9.57	8.34	7.78	8.23	7.69	7.08
Std Dev	0.000	0.007	0.007	0.007	0.007	0.007

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

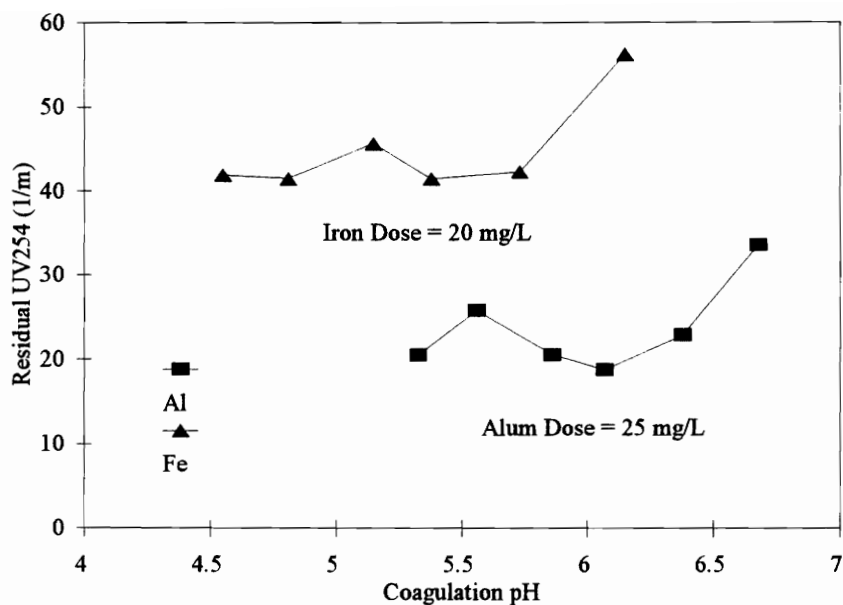


Figure E.2. Residual UV254 as a function of coagulation pH for Utility VT-9 alum and ferric sulfate treatment.

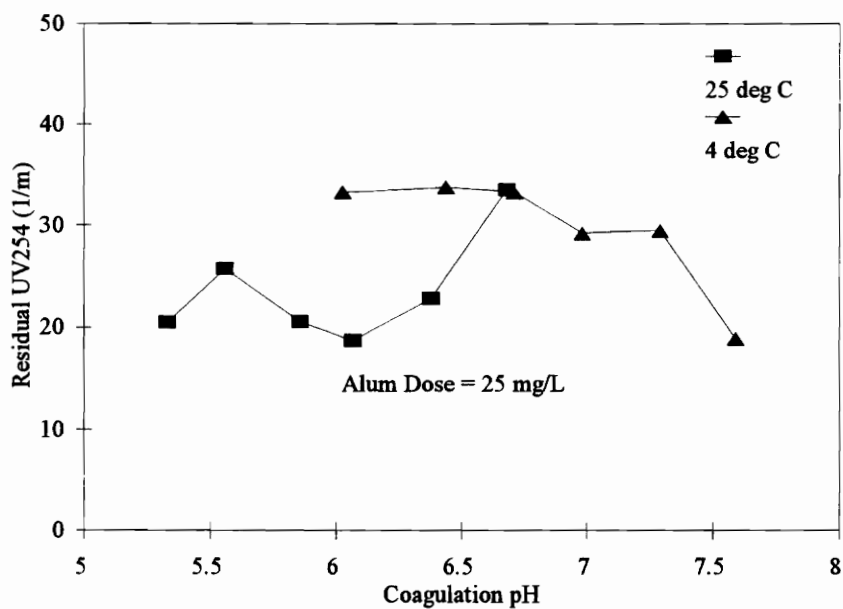


Figure E.3. Residual UV254 as a function of coagulation pH for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

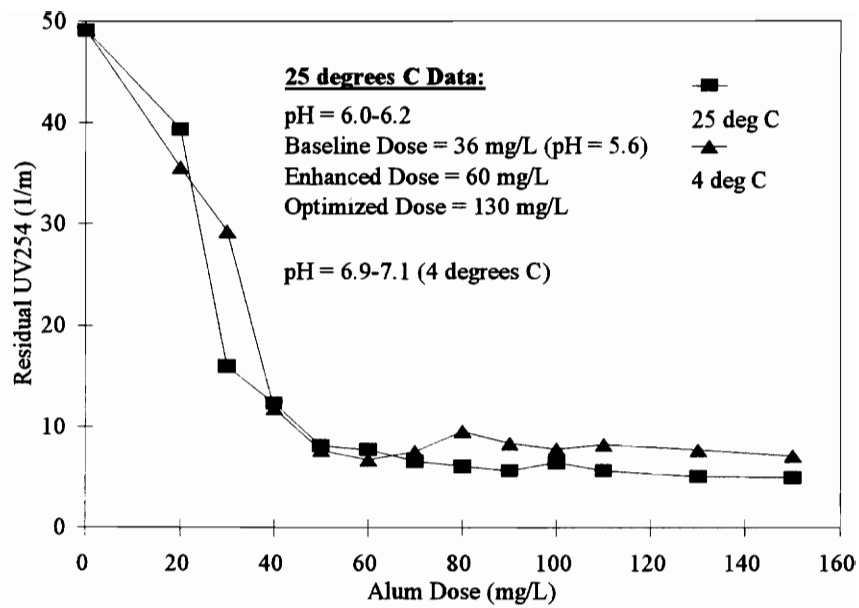


Figure E.4. Residual UV254 as a function of alum dose for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

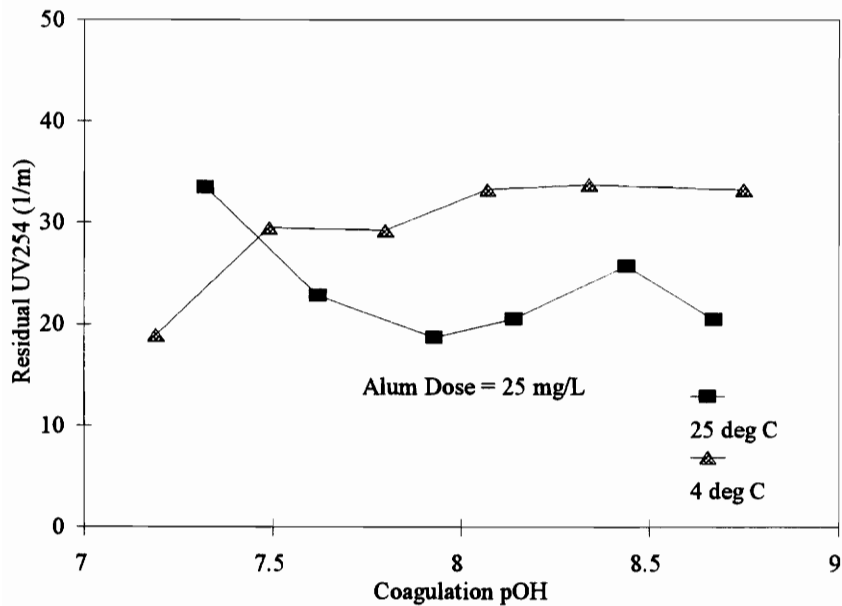


Figure E.5. Residual UV254 as a function of coagulation pOH for Utility VT-9 alum treatment at 25 degrees C and 4 degrees C.

APPENDIX F
UTILITY VT-1

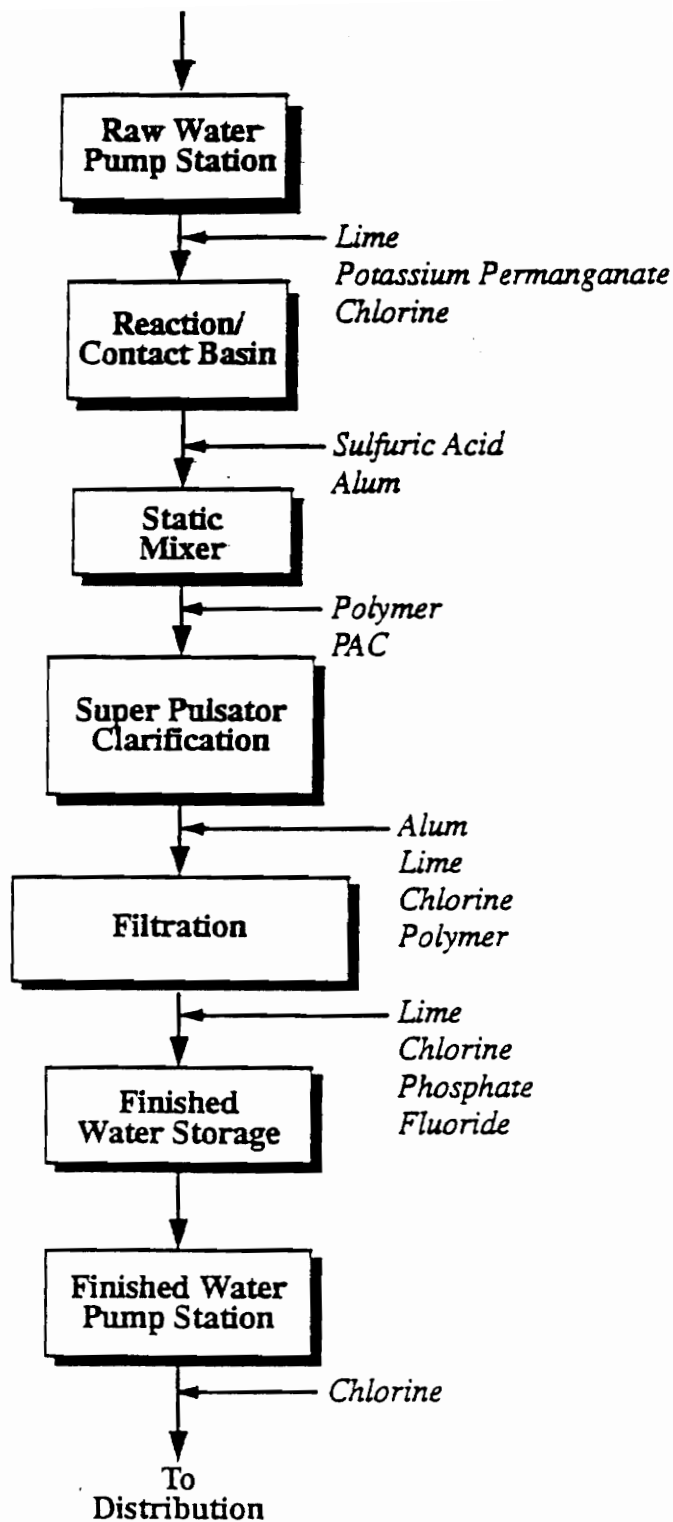


Figure F.1. Utility VT-1 Flow Diagram.

TABLE F.1
SUMMARY OF BENCH-SCALE, FULL-SCALE AND PILOT-SCALE RESULTS

Utility: VT-1
Location: Newport News, VA

Sample:	Bench-Scale			Full-Scale		Pilot-Scale	
	Raw	Alum		Alum		Alum	
		Baseline	Enhanced	Settled	Finished	Raw	Enhanced
Test:							
Date Received:	6/22/93	6/22/93	6/22/93	6/22/93	6/22/93	2/8/94	2/8/94
Date Sampled:	6/21/93	6/21/93	6/21/93	6/21/93	6/21/93	2/7/94	2/7/94
Coagulant Dose (mg/L)	---	40	40	40	40	---	40
pH	7.80	6.76	5.8-6.0	6.73	7.25	6.99	6.61
Alkalinity (mg/L as CaCO ₃)	60	41	---	---	56	43	---
Turbidity (NTU)	0.9	0.3	0.3	0.25	0.2	2.6	0.8
Color (PCU)	25	---	---	---	---	28	---
Organic Carbon:							
TOC (mg/L)	5.32	---	---	---	3.18	4.79	2.70
DOC (mg/L)	4.98	2.53	2.25	2.91	---	4.70	2.77
UV254 (1/m)	13.2	5.96	4.83	5.44	4.29	9.26	4.67
DOC Molecular Size Dist. (DOC Passing Filter - mg/L)							
10,000 Daltons	4.31	---	2.25	---	---	3.29	2.29
3,000 Daltons	2.52	---	1.86	---	---	1.93	1.79
1,000 Daltons	1.38	---	1.00	---	---	0.87	0.90
500 Daltons	0.46	---	0.43	---	---	0.43	0.43
Dissolved Al (ug/L)	7	2	1	---	---	58	44
Dissolved Fe (mg/L)	---	---	---	---	---	---	---
Anions: (mg/L)							
Sulfate	7.2	---	---	---	---	13.7	---
Bromide	< 0.5	---	---	---	---	< 0.5	---
Chloride	8.0	---	---	---	---	16.6	---
Hardness: (mg/L as CaCO₃)							
Ca Hardness	64	---	---	---	---	52.9	---
Mg Hardness	5.3	---	---	---	---	8.0	---
Total Hardness	69.3	---	---	---	---	60.9	---

TABLE F.1 (con't)

Utility:

VT-1

Location:

Newport News, VA

Sample:	Bench-Scale			Full-Scale		Pilot-Scale	
	Raw	Alum		Settled	Finished	Raw	Enhanced
		Baseline	Enhanced				
Uniform Formation Condition (UFC), dissolved							
Initial Cl Dose (mg/L)	—	3.25	3.0	—	—	—	—
Free Cl Residual (mg/L)	—	0.9	0.9	—	—	—	—
THM, (ug/L):							
CHCl3	—	68.8	57.9	—	—	—	—
CHCl2Br	—	12.4	11.6	—	—	—	—
CHClBr2	—	bd	bd	—	—	—	—
CHBr3	—	bd	bd	—	—	—	—
Total THM's	—	81.2	69.5	—	—	—	—
DOX (ug/L as Cl)	—	242	224	—	—	—	—
7-day Formation Potentials, dissolved							
Initial Cl Dose (mg/L)	15	10	7.0	—	—	14	8
Free Cl Residual (mg/L)	3.5	2.8	2.6	—	—	3.8	3.4
THMFP (ug/L):							
CHCl3	388.3	193.1	157.1	—	—	320.0	150.0
CHCl2Br	26.1	19.3	17.9	—	—	42.2	33.5
CHClBr2	bd	bd	bd	—	—	6.1	8.6
CHBr3	bd	bd	bd	—	—	6.0	10.3
Total THM's	414.4	212.4	175.0	—	—	374.4	202.4
DOX (ug/L as Cl)	847	558	343	—	—	593	299

ADDITIONAL UFC AND FP RESULTS

Sample:	Bench-Scale					
	Raw		Alum Baseline		Alum Enhanced	
Test:						
Uniform Formation Condition (UFC), dissolved						
Initial Cl Dose (mg/L)	—	—	2.75	3.5	2.5	3.3
Free Cl Residual (mg/L)	—	—	0.3	1.2	0.45	1.4
THM, (ug/L):						
CHCl3	—	—	62.8	68.4	54.7	55.5
CHCl2Br	—	—	12.4	11.3	10.7	11.2
CHClBr2	—	—	bd	—	bd	bd
CHBr3	—	—	bd	—	bd	bd
Total THM's	—	—	75.2	79.7	65.5	66.7
DOX (ug/L as Cl)	—	—	—	—	—	—
7-day Formation Potentials, dissolved						
Initial Cl Dose (mg/L)	12	18	13	—	10	13
Free Cl Residual (mg/L)	1.8	5.6	5.0	—	2.8	6.0
THMFP (ug/L):						
CHCl3	349.7	410.8	210.9	—	162.9	184.8
CHCl2Br	24.4	26.3	19.7	—	18.5	19.9
CHClBr2	bd	bd	bd	—	bd	bd
CHBr3	bd	bd	bd	—	bd	bd
Total THM's	374.1	437.2	230.6	—	181.4	204.7
DOX (ug/L as Cl)	—	—	—	—	—	—

TABLE F.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-1

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-1 (Newport News, VA)

Date Received: 6/22/93

Date Sampled: 6/21/93

Jar Test Conditions: Coag: Alum Dose: 30 mg/L

Target pH	5.3	5.6	5.8	6	6.2	6.5
DOC (mg/L)						
Mean	2.72	3.07	2.90	3.06	3.02	3.26
Std Dev	0.084	0.055	0.060	0.184	0.239	0.241
UV254 (1/m)						
Mean	6.23	6.10	6.25	6.24	6.59	7.29
Std Dev	0.027	0.026	0.006	0.010	0.006	0.016

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-1 (Newport News, VA)

Date Received: 6/22/93

Date Sampled: 6/21/93

Jar Test Conditions: Coag: Alum

Target pH range: 5.8-6.0

	COAGULANT DOSE (mg/L)					
	0	20	30	40	50	60
Turbidity (NTU)	0.95	0.75	0.4	0.3	0.2	0.35
DOC (mg/L)						
Mean	5.30	3.07	2.98	2.38	2.26	2.27
Std Dev	0.052	0.027	0.099	0.018	0.041	0.039
UV254 (1/m)						
Mean	13.33	8.80	5.25	5.51	5.96	4.87
Std Dev	0.016	0.000	0.036	0.006	0.016	0.006

	COAGULANT DOSE (mg/L)					
	70	80	90	100	120	140
Turbidity (NTU)	0.35	0.25	0.25	0.2	0.45	0.25
DOC (mg/L)						
Mean	2.24	2.13	2.16	2.18	2.22	2.05
Std Dev	0.072	0.040	0.005	0.017	0.068	0.053
UV254 (1/m)						
Mean	9.13	3.76	3.55	3.29	3.54	3.43
Std Dev	0.024	0.012	0.010	0.018	0.006	0.021

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

APPENDIX G
UTILITY VT-6

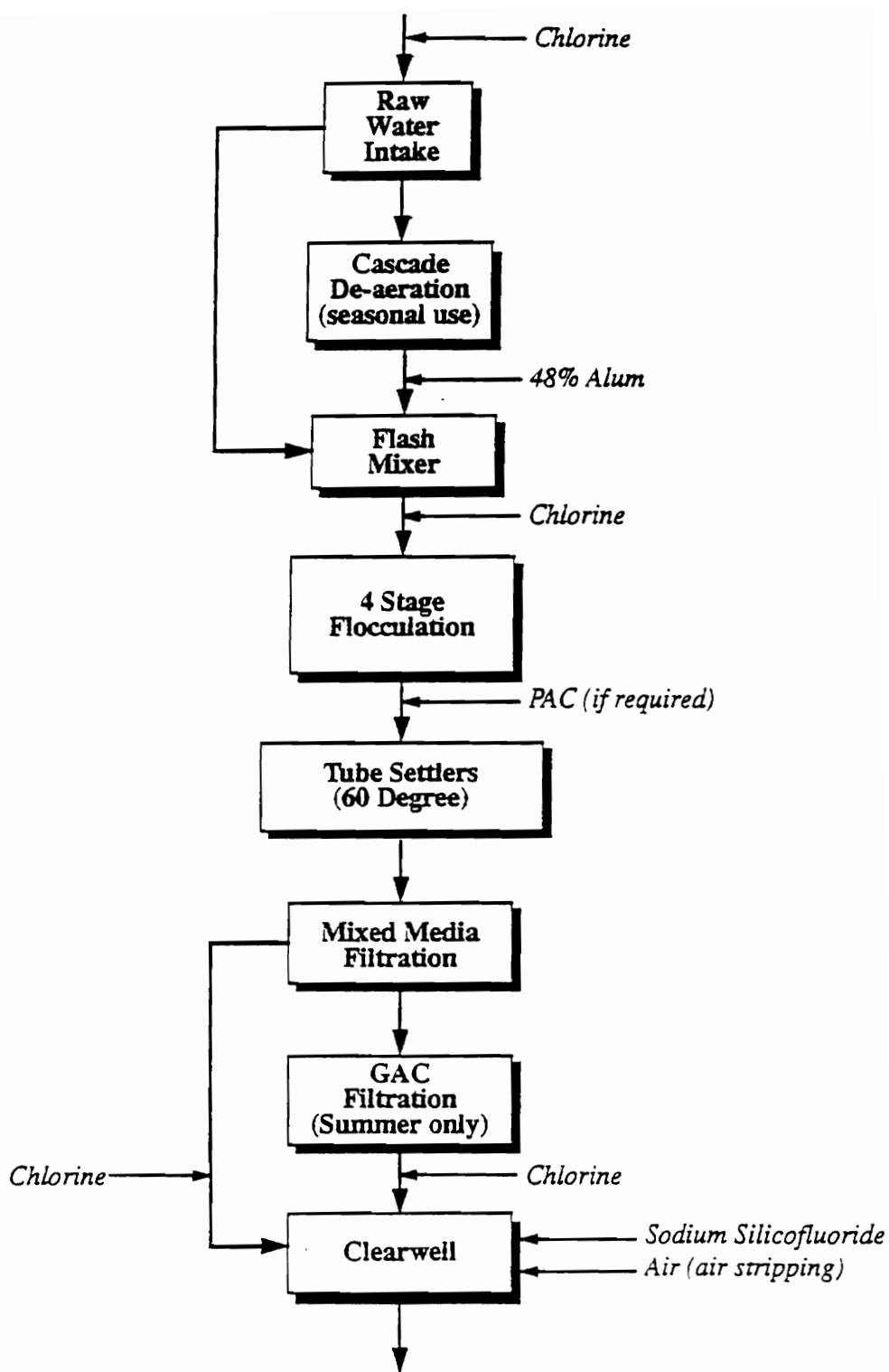


Figure G.1. Utility VT-6 Flow Diagram.

TABLE G.1
SUMMARY OF BENCH-SCALE, FULL-SCALE, AND PILOT-SCALE RESULTS

Utility: VT-6
Location: Buffalo Pound, Canada

Sample:	Bench-Scale						Full-Scale	
	Raw	Alum			Ferric		Alum	
Test:		Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Date Received:	11/16/93	11/16/93	11/16/93	11/16/93	11/19/93	11/19/93	11/16/93	11/16/93
Date Sampled:	11/12/93	11/12/93	11/12/93	11/12/93	11/12/93	11/12/93	11/12/93	11/12/93
Coagulant Dose (mg/L)	---	40	30	110	30	100	40	40
pH	8.05	7.10	5.5-5.6	5.5-5.6	5.0-5.2	5.0-5.2	7.23	7.40
Alkalinity (mg/L as CaCO ₃)	138	124	---	---	---	---	---	123
Turbidity (NTU)	3.5	0.35	0.3	0.6	1.4	3.0	0.7	0.45
Color (PCU)	12	6.7	---	---	---	---	4.3	2.3
Organic Carbon:								
TOC (mg/L)	4.02	---	---	---	---	---	---	3.03
DOC (mg/L)	3.64	3.07	2.48	2.02	2.03	1.55	2.92	---
UV254 (1/m)	6.79	4.70	3.58	2.8	2.16	1.49	4.88	3.53
DOC Molecular Size Dist.								
(DOC Passing Filter - mg/L)								
10,000 Daltons	3.22	---	1.98	1.61	1.61	---	---	---
3,000 Daltons	1.90	---	1.48	1.30	1.49	---	---	---
1,000 Daltons	1.38	---	0.95	0.86	0.95	---	---	---
500 Daltons	0.37	---	0.33	0.35	0.34	---	---	---
Dissolved Al (ug/L)	103	161	170	66	---	---	---	---
Dissolved Fe (mg/L)	0.07	---	---	---	0.06	0.07	---	---
Anions: (mg/L)								
Sulfate	86.3	---	---	---	---	---	---	---
Bromide	< 0.5	---	---	---	---	---	---	---
Chloride	8.35	---	---	---	---	---	---	---
Hardness: (mg/L as CaCO₃)								
Ca Hardness	40.9	---	---	---	---	---	---	---
Mg Hardness	17.5	---	---	---	---	---	---	---
Total Hardness	58.4	---	---	---	---	---	---	---

TABLE G.1 (con't)

Utility: VT-6
Location: Buffalo Pound, Canada

Sample:	Bench-Scale						Full-Scale	
	Alum				Ferric			
	Raw	Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Uniform Formation Condition (UFC), dissolved								
Initial Cl Dose (mg/L)	---	3.8	2.9	---	2.5	---	---	---
Free Cl Residual (mg/L)	---	0.7	0.8	---	0.7	---	---	---
THM, (ug/L):								
CHCl3	---	69.5	55.7	---	59.0	---	---	---
CHCl2Br	---	37.5	30.3	---	32.5	---	---	---
CHClBr2	---	10.0	8.0	---	7.5	---	---	---
CHBr3	---	1.0	bd	---	bd	---	---	---
Total THM's	---	118.0	94.0	---	99.0	---	---	---
DOX (ug/L as Cl)	---	106	83	---	61	---	---	---
7-day Formation Potentials, dissolved								
Initial Cl Dose (mg/L)	17	13	11	13	10	9.0	---	---
Free Cl Residual (mg/L)	4.0	3.0	2.75	3.5	2.75	3.2	---	---
THMFP (ug/L):								
CHCl3	176.3	153.0	143.0	120.0	86.0	81.5	---	---
CHCl2Br	36.0	43.5	35.5	36.0	27.0	22.0	---	---
CHClBr2	4.3	9.0	8.0	6.5	5.5	5.5	---	---
CHBr3	bd	3.0	bd	bd	bd	bd	---	---
Total THM's	216.7	208.5	186.5	162.5	118.5	109.0	---	---
DOX (ug/L as Cl)	482	397	233	211	237	208	---	---

ADDITIONAL JAR TEST AND FP RESULTS

Sample:	Bench-Scale		
	Alum		
	15 mg/L	Enhanced	60 mg/L
Test:			
Coagulant Dose (mg/L)	15	---	60
pH	5.5-5.6	---	5.5-5.6
Turbidity (NTU)	0.5	---	0.5
Organic Carbon:			
DOC (mg/L)	2.73	---	2.11
UV254 (1/m)	4.29	---	2.97
DOC Molecular Size Dist. (DOC Passing Filter - mg/L)			
10,000 Daltons	1.99	---	1.87
3,000 Daltons	1.62	---	1.47
1,000 Daltons	0.97	---	0.87
500 Daltons	0.37	---	0.30
Dissolved Al (ug/L)	184	---	74
7-day Formation Potentials, dissolved			
Initial Cl Dose (mg/L)	14	14	13
Free Cl Residual (mg/L)	3.5	5.0	3.8
THMFP (ug/L):			
CHCl3	176.5	174.0	128.5
CHCl2Br	44.5	39.5	32.0
CHClBr2	9.0	8.0	6.0
CHBr3	bd	bd	bd
Total THM's	230.0	221.5	166.5
DOX (ug/L as Cl)	301	---	299

TABLE G.1 (con't)

Utility: VT-6
 Location: Buffalo Pound, Canada

Sample:	Pilot-Scale						
	Alum		Alum		Ferric	Ferric	
	Baseline Raw	Baseline Treated	Enhanced Raw	Enhanced Treated	Baseline Treated	Enhanced Raw	Enhanced Treated
Test:							
Date Received:	12/15/93	12/15/93	12/15/93	12/15/93	12/20/93	12/20/93	12/20/93
Date Sampled:	12/6/93	12/6/93	12/7/93	12/7/93	12/8/93	12/8/93	12/8/93
Coagulant Dose (mg/L)	---	30	---	30	30	---	30
pH	8.00	7.57	7.94	6.64	7.17	7.86	5.82
Alkalinity (mg/L as CaCO ₃)	161	135	159	---	122	157	---
Turbidity (NTU)	2.5	0.7	1.0	0.9	0.7	1.0	0.85
Color (PCU)	7.4	3.8	7.9	---	2.4	7.4	---
Organic Carbon:							
TOC (mg/L)	3.95	---	4.63	---	---	2.89	---
DOC (mg/L)	3.77	2.89	4.53	2.47	1.68	2.53	1.09
UV254 (1/m)	6.36	4.37	6.81	3.71	3.73	6.61	2.25
DOC Molecular Size Dist. (DOC Passing Filter - mg/L)							
10,000 Daltons	---	---	2.05	1.93	---	1.68	0.96
3,000 Daltons	---	---	1.19	1.44	---	1.38	0.69
1,000 Daltons	---	---	0.61	0.82	---	0.55	0.36
500 Daltons	---	---	0.17	0.22	---	0.15	0.14
Dissolved Al (ug/L)	118	87	67	65	---		
Dissolved Fe (mg/L)	---	---	---	---	0.04	0.04	0.05
Anions: (mg/L)							
Sulfate	92.6	---	92.7	---	---	92.6	---
Bromide	< 0.5	---	< 0.5	---	---	< 0.5	---
Chloride	8.7	---	8.6	---	---	8.7	---
Hardness: (mg/L as CaCO₃)							
Ca Hardness	113	---	113.3	---	---	114.5	---
Mg Hardness	82.7	---	81.9	---	---	84	---
Total Hardness	195.7	---	195.2	---	---	198.5	---
7-day Formation Potentials, dissolved							
Initial Cl Dose (mg/L)	11	11	14	11	9.0	11	9.0
Free Cl Residual (mg/L)	2.75	3.0	4.0	3.6	4.0	4.5	4.5
THMFP (ug/L):							
CHCl ₃	165.4	143.8	196.7	137.3	107.7	188.2	76.8
CHCl ₂ Br	60.0	67.2	64.5	64.7	40.4	51.3	36.6
CHClBr ₂	31.8	38.9	29.7	36.4	27.1	25.7	32.8
CHBr ₃	bd	bd	bd	bd	bd	bd	bd
Total THM's	257.2	249.9	290.9	238.3	175.2	265.2	146.1
DOX (ug/L as Cl)	338	320	461	279	246	369	196

TABLE G.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-6

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-6 (Buffalo Pound WTP, Canada)

Date Received: 11/16/93

Date Sampled: 11/12/93

Jar Test Conditions: Coag: Alum

Dose: 30 mg/L

Target pH	5.3	5.6	5.9	6.1	6.4	6.7
Turbidity (NTU)	0.5	1	0.6	0.2	0.2	0.1
Residual Al (ug/L)	153	113	94	210	100	126
DOC (mg/L)						
Mean	2.315	2.455	2.521	2.602	2.618	2.819
Std Dev	0.002	0.011	0.004	0.039	0.009	0.008
UV254 (1/m)						
Mean	3.416	3.380	3.463	3.666	3.905	4.243
Std Dev	0.007	0.000	0.000	0.007	0.007	0.000

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-6 (Buffalo Pound WTP, Canada)

Date Received: 11/16/93

Date Sampled: 11/12/93

Jar Test Conditions: Coag: Alum

Target pH range: 5.5-5.6

	COAGULANT DOSE (mg/L)					
	0	10	20	30	40	50
Coag Dose (mM as Al)	0	0.033	0.067	0.100	0.133	0.167
Turbidity (NTU)	2.1	0.6	0.35	0.15	0.2	0
Residual Al (ug/L)	103	138	140	108	100	109
DOC (mg/L)						
Mean	3.912	3.005	2.389	2.233	2.184	2.082
Std Dev	0.021	0.021	0.004	0.005	0.024	0.004
UV254 (1/m)						
Mean	5.190	4.982	3.749	3.344	3.182	3.068
Std Dev	3.309	0.000	0.007	0.007	0.000	0.029

	COAGULANT DOSE (mg/L)					
	60	70	80	90	100	110
Coag Dose (mM as Al)	0.200	0.233	0.267	0.300	0.333	0.367
Turbidity (NTU)	0.2	0.35	0.15	0.2	0.5	0.2
Residual Al (ug/L)	92	86	96	90	66	90
DOC (mg/L)						
Mean	2.076	2.069	2.047	2.000	1.956	1.888
Std Dev	0.030	0.010	0.010	0.004	0.004	0.029
UV254 (1/m)						
Mean	2.969	2.907	2.704	2.824	2.792	2.772
Std Dev	0.007	0.007	0.000	0.007	0.007	0.022

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE G.2 (con't)

JAR TEST DATA - pH OPTIMIZATION

FERRIC SULFATE

Utility: VT-6 (Buffalo Pound WTP, Canada)

Date Received: 11/19/93

Date Sampled: 11/12/93

Jar Test Conditions: Coag: Ferric Dose: 20 mg/L

Target pH	4.5	4.8	5.1	5.4	5.7	6.1
Turbidity (NTU)	0.75	1.1	1.2	0.4	0.7	0.5
Residual Fe (mg/L)	0.18	0.18	0.18	0.14	0.18	0.17
DOC (mg/L)						
Mean	2.092	1.921	1.883	2.039	1.954	2.154
Std Dev	0.007	0.003	0.004	0.006	0.018	0.006
UV254 (1/m)						
Mean	3.562	3.780	3.468	3.474	3.645	3.921
Std Dev	0.007	0.007	0.007	0.000	0.007	0.000

JAR TEST DATA - DOC REMOVAL OPTIMIZATION

FERRIC SULFATE

Utility: VT-6 (Buffalo Pound WTP, Canada)

Date Received: 11/19/93

Date Sampled: 11/12/93

Jar Test Conditions: Coag: Ferric Sulfate

Target pH range: 5.0-5.2

	COAGULANT DOSE (mg/L)					
	0	10	20	30	40	50
Coag Dose (mM as Fe)	0	0.041	0.082	0.122	0.163	0.204
Turbidity (NTU)	1.75	1.7	0.7	2	0.85	1.6
Residual Fe (mg/L)	0.07	0.3	0.09	0.1	0.1	0.13
DOC (mg/L)						
Mean	3.452	2.723	1.909	1.667	1.557	1.442
Std Dev	0.013	0.008	0.013	0.013	0.024	0.007
UV254 (1/m)						
Mean	6.526	6.599	3.193	2.647	2.558	2.564
Std Dev	0.022	0.007	0.000	0.022	0.000	0.007

	COAGULANT DOSE (mg/L)					
	60	70	80	90	100	110
Coag Dose (mM as Fe)	0.245	0.286	0.327	0.367	0.408	0.449
Turbidity (NTU)	3.3	6.9	2.75	2.8	3.1	0.7
Residual Fe (mg/L)	0.11	0.11	0.08	0.1	0.09	0.09
DOC (mg/L)						
Mean	1.589	1.695	1.424	1.452	1.383	1.357
Std Dev	0.010	0.013	0.007	0.014	0.006	0.007
UV254 (1/m)						
Mean	2.319	2.038	2.059	2.002	1.934	1.924
Std Dev	0.000	0.015	0.000	0.007	0.000	0.015

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE G.2 (con't)

TEMP EFFECTS JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-6 (Buffalo Pound WTP, Canada)

Date Received: 11/16/93

Date Sampled: 11/12/93

Jar Test Conditions: Coag: Alum (4 deg C) Dose: 30 mg/L

Target pH	5.7	6.0	6.4	6.7	7.0	7.3
Turbidity (NTU)	1.1	0.6	0.55	1	0.4	0.65
Residual Al (ug/L)	149	122	82	82	83	88
DOC (mg/L)						
Mean	2.38	2.41	2.57	2.85	2.93	3.01
Std Dev	0.013	0.008	0.065	0.020	0.008	0.002
UV254 (1/m)						
Mean	3.27	3.29	3.49	4.14	4.50	4.95
Std Dev	0.022	0.000	0.059	0.118	0.029	0.115

TEMP EFFECTS JAR TEST DATA - DOC REMOVAL OPTIMIZATION

ALUM (4 deg C)

Utility: VT-6 (Buffalo Pound WTP, Canada)

Date Received: 11/16/93

Date Sampled: 11/12/93

Jar Test Conditions: Coag: Alum (4 deg C)

Target pH range: 5.9-6.1

	COAGULANT DOSE (mg/L)					
	0	10	20	30	40	50
Coag Dose (mM as Al)	0	0.033	0.067	0.100	0.133	0.167
Turbidity (NTU)	2.3	0.9	0.3	0.5	0.2	0.3
Residual Al (ug/L)	71	130	124	145	156	126
DOC (mg/L)						
Mean	4.02	3.83	3.32	2.52	2.31	2.33
Std Dev	0.038	0.033	0.017	0.011	0.028	0.006
UV254 (1/m)						
Mean	7.04	5.00	4.00	3.36	3.01	2.91
Std Dev	0.007	0.007	0.022	0.000	0.000	0.007

	COAGULANT DOSE (mg/L)					
	60	70	80	90	100	110
Coag Dose (mM as Al)	0.200	0.233	0.267	0.300	0.333	0.367
Turbidity (NTU)	1.35	0.4	0.2	0.75	0.25	0.4
Residual Al (ug/L)	72	88	66	62	62	63
DOC (mg/L)						
Mean	2.15	2.25	2.09	2.00	2.25	2.02
Std Dev	0.003	0.008	0.016	0.002	0.033	0.005
UV254 (1/m)						
Mean	3.01	2.87	2.83	2.71	2.55	2.62
Std Dev	0.007	0.000	0.007	0.022	0.000	0.015

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE G.2 (con't)

TEMP EFFECTS JAR TEST DATA - pH OPTIMIZATION

FERRIC SULFATE

Utility: VT-6 (Buffalo Pound WTP, Canada)

Date Received: 11/19/93

Date Sampled: 11/12/93

Jar Test Conditions: Coag: Ferric (4 deg C) Dose: 20 mg/L

Target pH	4.8	5.2	5.6	6.0	6.4	6.8
Turbidity (NTU)	1.1	2.5	2.75	1	1.25	---
Residual Fe (mg/L)	0.17	0.16	0.12	0.14	0.17	0.14
DOC (mg/L)						
Mean	1.96	2.07	1.99	2.07	2.37	2.65
Std Dev	0.033	0.011	0.036	0.004	0.004	0.012
UV254 (1/m)						
Mean	3.47	3.15	2.93	3.50	4.28	4.38
Std Dev	0.015	0.007	0.007	0.007	0.000	0.000

TEMP EFFECTS JAR TEST DATA - DOC REMOVAL OPTIMIZATION

FERRIC SULFATE (4 deg C)

Utility: VT-6 (Buffalo Pound WTP, Canada)

Date Received: 11/19/93

Date Sampled: 11/12/93

Jar Test Conditions: Coag: Ferric (4 deg C)

Target pH range: 5.5-5.7

	COAGULANT DOSE (mg/L)					
	0	10	20	30	40	50
Coag Dose (mM as Fe)	0	0.041	0.082	0.122	0.163	0.204
Turbidity (NTU)	2	1.7	0.75	0.5	0.3	0.65
Residual Fe (mg/L)	0.07	0.35	0.15	0.12	0.11	0.12
DOC (mg/L)						
Mean	4.03	2.68	2.30	1.96	1.62	1.89
Std Dev	0.024	0.032	0.013	0.002	0.002	0.012
UV254 (1/m)						
Mean	6.31	7.15	3.13	2.30	2.10	1.99
Std Dev	0.007	0.007	0.000	0.000	0.000	0.000

	COAGULANT DOSE (mg/L)					
	60	70	80	90	100	110
Coag Dose (mM as Fe)	0.245	0.286	0.327	0.367	0.408	0.449
Turbidity (NTU)	2	0.75	1	0.7	0.7	1.1
Residual Fe (mg/L)	0.05	0.09	0.09	0.15	0.08	0.11
DOC (mg/L)						
Mean	1.45	1.41	1.35	1.62	1.34	1.36
Std Dev	0.001	0.019	0.015	0.004	0.007	0.008
UV254 (1/m)						
Mean	1.99	2.06	2.09	2.00	1.86	1.88
Std Dev	0.007	0.015	0.000	0.000	0.000	0.015

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

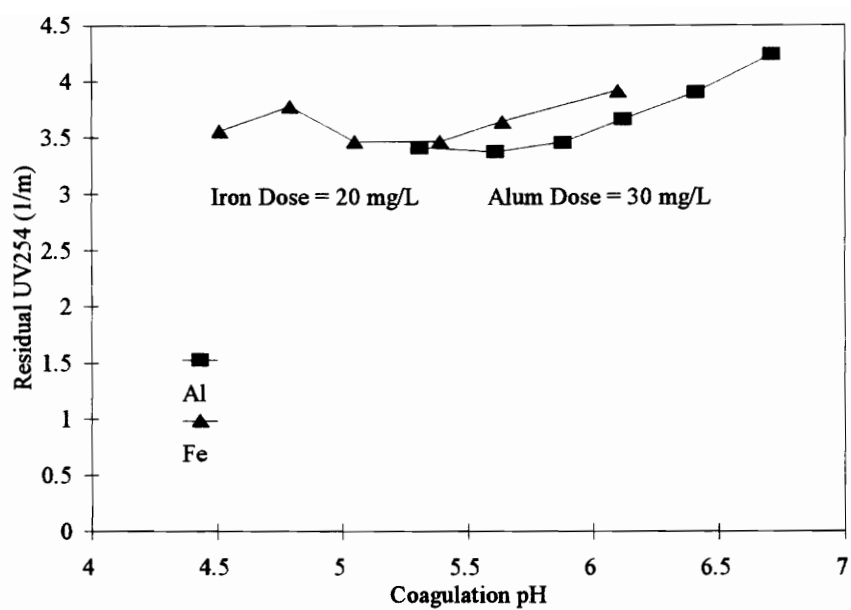


Figure G.2. Residual UV254 as a function of coagulation pH for Utility VT-6 alum and ferric sulfate treatment.

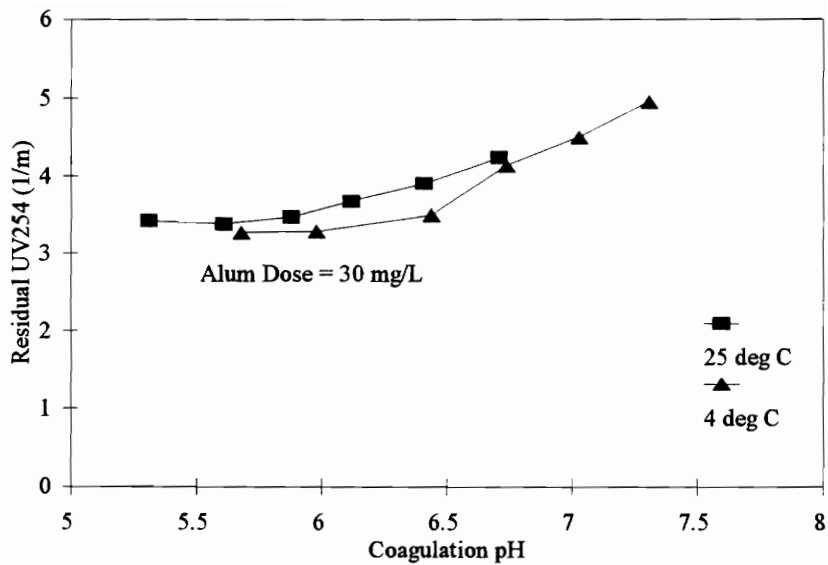


Figure G.3. Residual UV254 as a function of coagulation pH for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

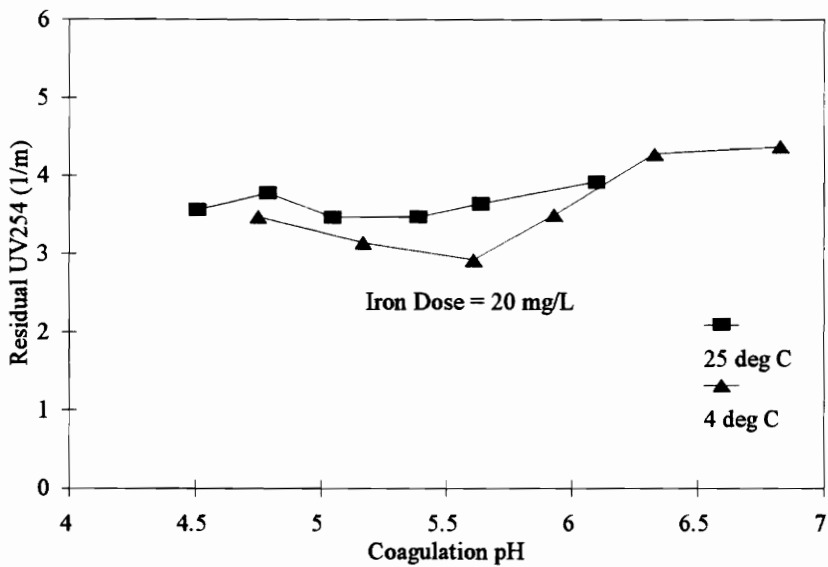


Figure G.4. Residual UV254 as a function of coagulation pH for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

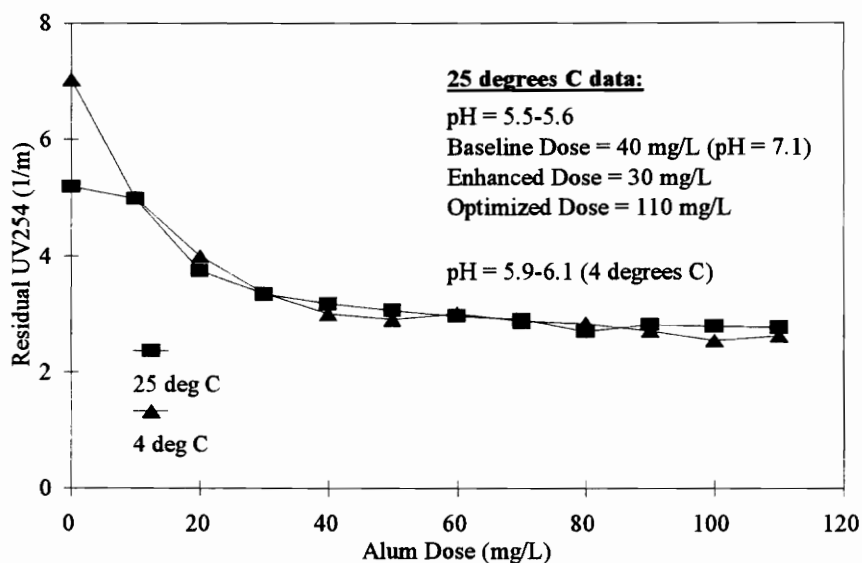


Figure G.5. Residual UV254 as a function of alum dose for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

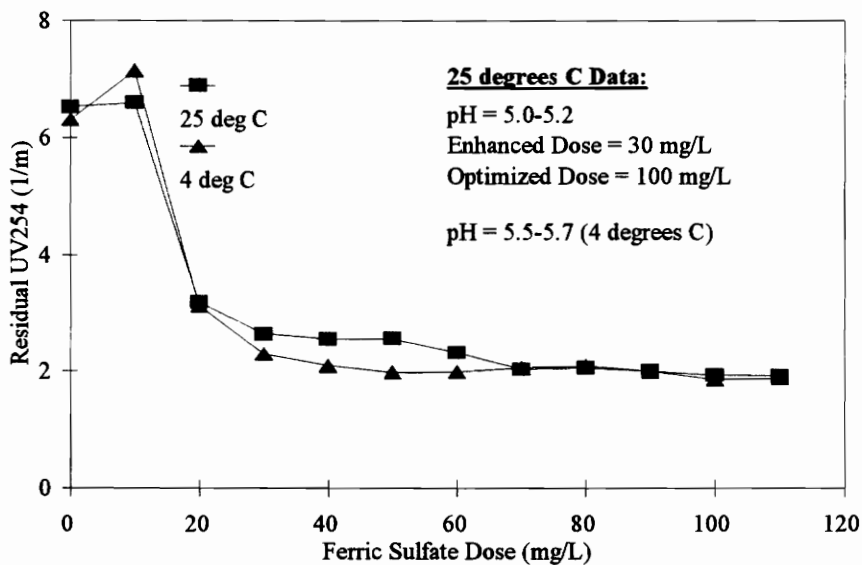


Figure G.6. Residual UV254 as a function of ferric sulfate dose for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

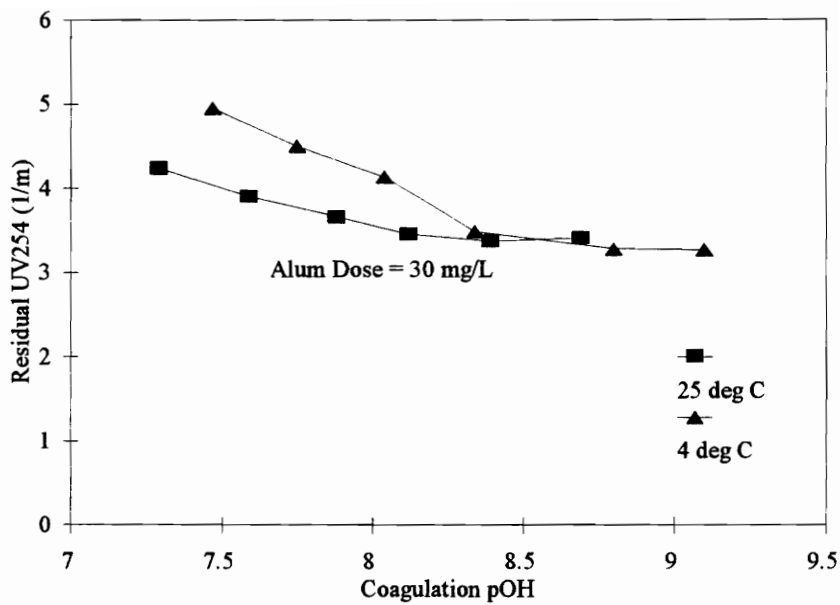


Figure G.7. Residual UV254 as a function of coagulation pOH for Utility VT-6 alum treatment at 25 degrees C and 4 degrees C.

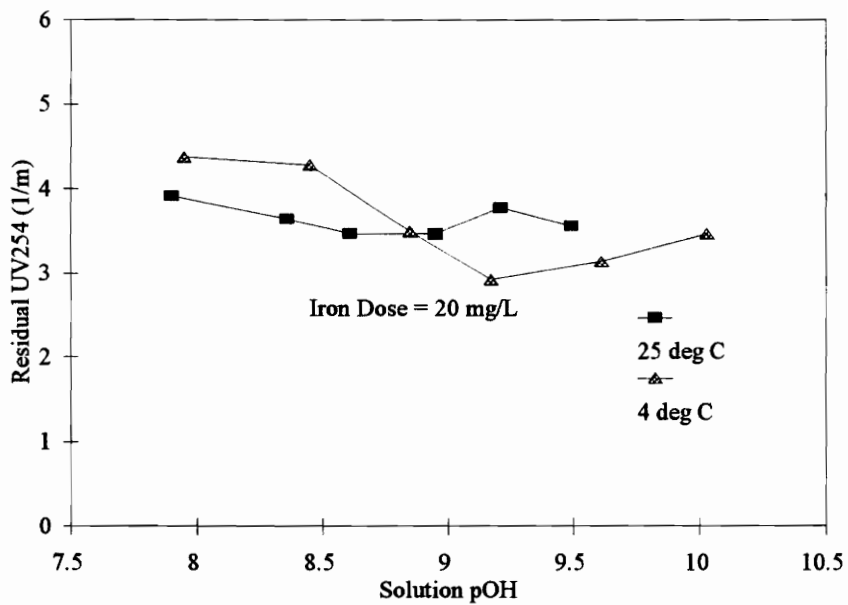


Figure G.8. Residual UV254 as a function of coagulation pOH for Utility VT-6 ferric sulfate treatment at 25 degrees C and 4 degrees C.

APPENDIX H
UTILITY VT-3

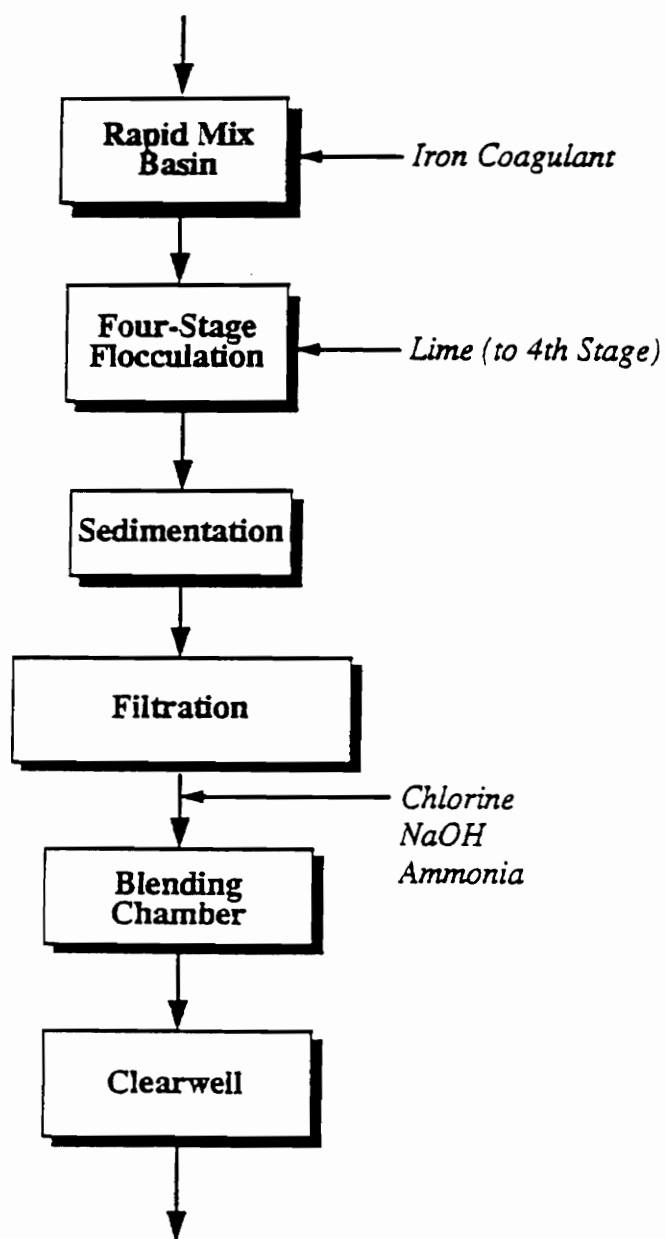


Figure H.1. Utility VT-3 Flow Diagram.

TABLE H.1
SUMMARY OF BENCH-SCALE AND FULL-SCALE RESULTS

Utility: VT-3
Location: Tampa, FL

Sample:	Bench-Scale						Full-Scale	
	Raw	Ferric			Alum		Ferric	
		Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Date Received:	8/18/93	8/18/93	8/18/93	8/18/93	8/18/93	8/18/93	8/18/93	8/18/93
Date Sampled:	8/16/93	8/16/93	8/16/93	8/16/93	8/16/93	8/16/93	8/16/93	8/16/93
Coagulant Dose (mg/L)	—	122	65	109	100	170	122	122
pH	7.75	7.22	4.8-5.0	4.8-5.0	5.5-5.6	5.5-5.6	5.88	7.52
Alkalinity (mg/L as CaCO ₃)	112	79	---	---	---	---	---	99
Turbidity (NTU)	0.88	1.1	1.75	1.6	0.65	1.2	2.4	0.4
Color (PCU)	137	9.1	---	---	---	---	14	12.5
Organic Carbon:								
TOC (mg/L)	11.8	---	---	---	---	---	---	3.88
DOC (mg/L)	11.6	2.87	3.70	3.00	4.51	3.64	4.33	---
UV ₂₅₄ (1/m)	47.5	7.52	13.3	9.97	10.5	8.69	10.7	8.36
DOC Molecular Size Dist. (DOC Passing Filter - mg/L)								
10,000 Daltons	10.4	---	3.27	---	3.68	---	---	---
3,000 Daltons	5.48	---	2.61	---	3.21	---	---	---
1,000 Daltons	1.63	---	1.45	---	1.47	---	---	---
500 Daltons	0.36	---	0.43	---	0.42	---	---	---
Dissolved Al (ug/L)	66.5	---	---	---	120	158	---	---
Dissolved Fe (mg/L)	0.11	0.25	0.30	0.23	---	---	---	---
Anions: (mg/L)								
Sulfate	23.5	---	---	---	---	---	---	---
Bromide	< 0.5	---	---	---	---	---	---	---
Chloride	17.1	---	---	---	---	---	---	---
Hardness: (mg/L as CaCO₃)								
Ca Hardness	118.5	---	---	---	---	---	---	---
Mg Hardness	14.3	---	---	---	---	---	---	---
Total Hardness	132.8	---	---	---	---	---	---	---

TABLE H.1 (con't)

Utility: VT-3
Location: Tampa, FL

Sample:	Bench-Scale						Full-Scale	
	Raw	Ferric			Alum		Ferric	
		Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Uniform Formation Condition (UFC), dissolved								
Initial Cl Dose (mg/L)	---	4.8	5.6	---	6.5	---	---	---
Free Cl Residual (mg/L)	---	1.3	1.3	---	1.1	---	---	---
THM, (ug/L):								
CHCl3	---	80.4	123.8	---	120.3	---	---	---
CHCl2Br	---	33.3	41.4	---	25.6	---	---	---
CHClBr2	---	12.2	11.4	---	5.8	---	---	---
CHBr3	---	5.5	6.5	---	bd	---	---	---
Total THM's	---	131.4	183.0	---	151.7	---	---	---
DOX (ug/L as Cl)	---	262	311	---	386	---	---	---
7-day Formation Potentials, dissolved								
Initial Cl Dose (mg/L)	42	14	17	14	17	17	---	---
Free Cl Residual (mg/L)	0.5	2.75	2.75	2.75	2.0	2.75	---	---
THMFP (ug/L):								
CHCl3	704.8	123.7	180.4	148.3	217.3	207.0	---	---
CHCl2Br	27.5	27.3	32.1	28.1	29.3	31.1	---	---
CHClBr2	bd	6.7	6.2	6.4	5.7	6.0	---	---
CHBr3	bd	bd	0.9	bd	bd	bd	---	---
Total THM's	732.3	157.7	219.6	182.8	252.3	244.0	---	---
DOX (ug/L as Cl)	2240	437	582	310	617	472	---	---

ADDITIONAL FP RESULTS

Sample:	Bench-Scale					
	Raw	Ferric			Alum	
		Baseline	Enhanced	Optimized	Enhanced	Optimized
Test:						
7-day Formation Potentials, dissolved						
Initial Cl Dose (mg/L)	---	17	---	17	---	---
Free Cl Residual (mg/L)	---	5.0	---	5.0	---	---
THMFP (ug/L):						
CHCl3	---	133.6	---	152.8	---	---
CHCl2Br	---	34.7	---	26.6	---	---
CHClBr2	---	6.9	---	6.0	---	---
CHBr3	---	bd	---	bd	---	---
Total THM's	---	175.3	---	185.4	---	---
DOX (ug/L as Cl)	---	425	---	269	---	---

TABLE H.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-3

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-3 (Tampa, FL)

Date Received: 8/18/93

Date Sampled: 8/16/93

Jar Test Conditions: Coag: Alum Dose: 80 mg/L

Target pH	5.3	5.6	5.9	6.1	6.4	6.7
Residual Al (ug/L)	113	134	148	186	124	132
DOC (mg/L)						
Mean	5.16	5.09	5.45	5.66	5.53	6.07
Std Dev	0.021	0.005	0.096	0.049	0.036	0.012
UV254 (1/m)						
Mean	11.40	12.00	12.39	14.15	15.26	16.39
Std Dev	0.000	0.022	0.016	0.024	0.012	0.016

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-3 (Tampa, FL)

Date Received: 8/18/93

Date Sampled: 8/16/93

Jar Test Conditions: Coag: Alum

Target pH range: 5.5-5.6

	COAGULANT DOSE (mg/L)					
	0	20	40	60	80	90
Coag Dose (mM as Al)	0	0.067	0.133	0.200	0.267	0.300
Turbidity (NTU)	0.9	3.7	1	0.9	1	1
Residual Al (ug/L)	66.5	1135	165	124	103	112
DOC (mg/L)						
Mean	11.65	10.85	6.09	5.42	4.56	4.69
Std Dev	0.042	0.110	0.018	0.025	0.002	0.013
UV254 (1/m)						
Mean	47.47	44.80	19.10	14.81	11.66	12.03
Std Dev	0.015	0.022	0.000	0.007	0.000	0.007

	COAGULANT DOSE (mg/L)					
	100	110	120	130	150	170
Coag Dose (mM as Al)	0.333	0.367	0.400	0.433	0.500	0.567
Turbidity (NTU)	0.85	1	0.65	0.85	0.92	0.64
Residual Al (ug/L)	75	100	57.5	95.5	85.5	57
DOC (mg/L)						
Mean	4.11	3.96	4.10	4.03	4.16	3.84
Std Dev	0.068	0.068	0.006	0.015	0.055	0.062
UV254 (1/m)						
Mean	10.80	11.01	9.66	9.69	10.54	9.20
Std Dev	0.015	0.007	0.007	0.000	0.000	0.007

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE H.2 (con't)

JAR TEST DATA - pH OPTIMIZATION

FERRIC SULFATE

Utility: VT-3 (Tampa, FL)

Date Received: 8/18/93

Date Sampled: 8/16/93

Jar Test Conditions: Coag: Ferric Sulfate Dose: 140 mg/L
Product (12.4% Fe)

Target pH	4.5	4.8	5.1	5.4	5.7	6.1
Residual Fe (mg/L)	0.3	0.25	0.26	0.3	0.2	0.23
DOC (mg/L)						
Mean	2.77	2.74	3.11	3.45	3.24	3.61
Std Dev	0.037	0.035	0.012	0.020	0.014	0.033
UV254 (1/m)						
Mean	8.03	8.08	8.49	10.95	9.57	14.14
Std Dev	0.010	0.006	0.010	0.006	0.006	3.339

JAR TEST DATA - DOC REMOVAL OPTIMIZATION

FERRIC SULFATE

Utility: VT-3 (Tampa, FL)

Date Received: 8/18/93

Date Sampled: 8/16/93

Jar Test Conditions: Coag: Ferric Sulfate Product (12.4% Fe)

Target pH range: 4.8-5.0

	COAGULANT DOSE (mg/L)					
	30	60	90	120	130	140
Coag Dose (mM as Fe)	0.066	0.133	0.199	0.266	0.288	0.310
Equiv. Fe ₂ (SO ₄) ₃ Dose	16.3	32.6	49.0	65.3	70.7	76.2
Turbidity (NTU)	2.75	3.6	1.2	1	1.6	1.65
Residual Fe (mg/L)	2.74	1.46	0.4	0.27	0.29	0.3
DOC (mg/L)						
Mean	10.88	5.32	3.85	3.27	3.26	3.22
Std Dev	0.093	0.030	0.022	0.066	0.099	0.009
UV254 (1/m)						
Mean	60.59	29.17	14.98	10.10	10.73	10.90
Std Dev	0.132	0.066	0.007	0.007	0.007	0.007

	COAGULANT DOSE (mg/L)					
	150	160	180	190	210	225
Coag Dose (mM as Fe)	0.332	0.354	0.399	0.421	0.465	0.498
Equiv. Fe ₂ (SO ₄) ₃ Dose	81.6	87.0	97.9	103.4	114.2	122.4
Turbidity (NTU)	0.9	1.1	0.9	1.1	1.6	1.1
Residual Fe (mg/L)	0.25	0.29	0.27	0.26	0.27	0.29
DOC (mg/L)						
Mean	2.79	2.83	2.64	2.71	2.65	3.18
Std Dev	0.028	0.073	0.023	0.036	0.112	0.178
UV254 (1/m)						
Mean	8.58	9.53	8.58	9.17	8.16	8.43
Std Dev	0.015	0.015	0.015	0.022	0.000	0.007

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

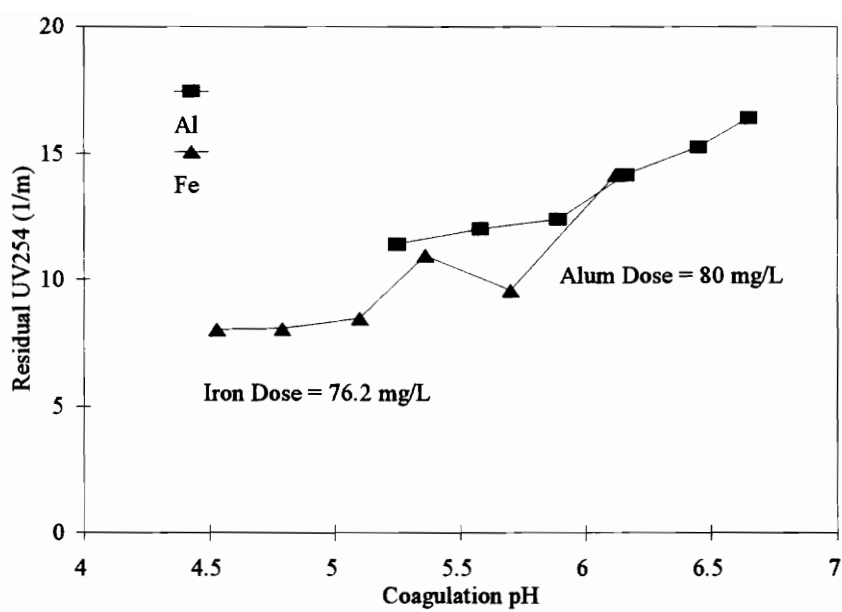


Figure H.2. Residual UV254 as a function of coagulation pH for Utility VT-3 alum and ferric sulfate treatment.

APPENDIX I
UTILITY VT-8

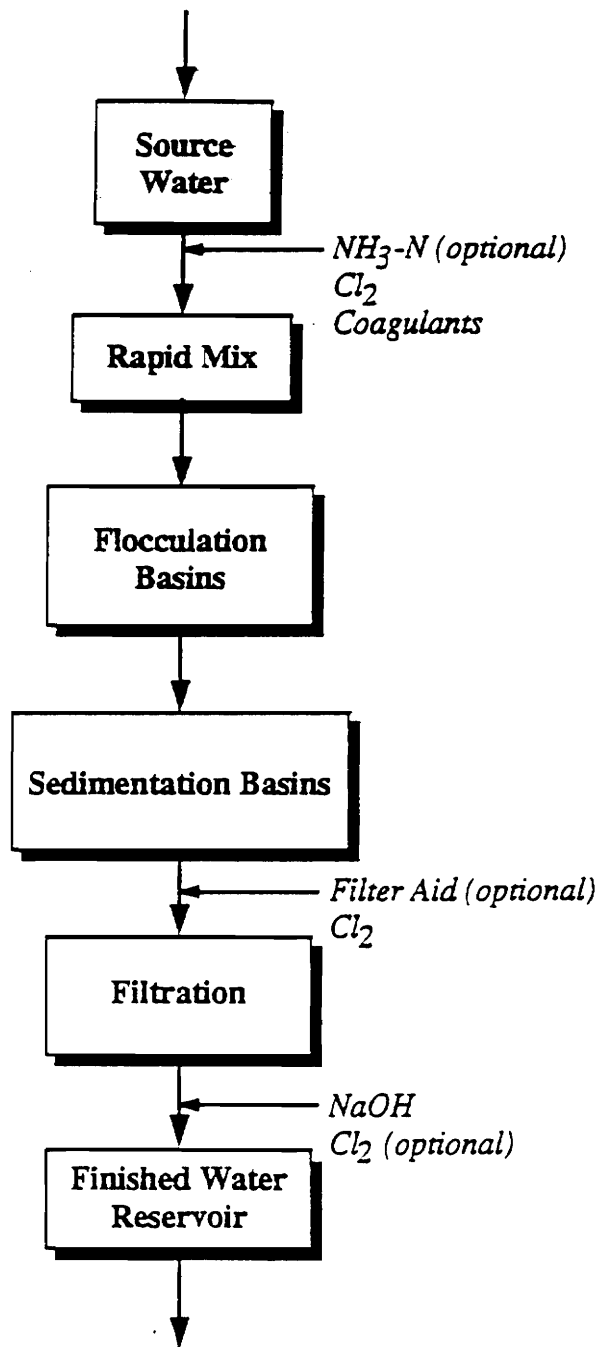


Figure I.1. Utility VT-8 Flow Diagram.

TABLE L1
SUMMARY OF BENCH-SCALE, FULL-SCALE, AND PILOT-SCALE RESULTS

Utility: VT-8
Location: Metropolitan Water District of Southern California

Sample:	Bench-Scale						Full-Scale	
	Raw	Alum			Ferric		Alum	
		Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Date Received:	1/24/94	1/24/94	1/24/94	1/24/94	1/24/94	1/24/94	1/24/94	1/24/94
Date Sampled:	1/21/94	1/21/94	1/21/94	1/21/94	1/21/94	1/21/94	1/21/94	1/21/94
Coagulant Dose (mg/L)	---	3	30	90	25	90	3	3
pH	8.12	7.91	5.8-5.9	5.8-5.9	5.6-5.7	5.6-5.7	---	---
Alkalinity (mg/L as CaCO ₃)	135	---	---	---	---	---	---	---
Turbidity (NTU)	1.4	1.65	1.0	---	1.5	6.0	0.6	0.54
Color (PCU)	5.4	5.6	---	---	---	---	2.9	1.2
Organic Carbon:								
TOC (mg/L)	2.73	---	---	---	---	---	---	2.50
DOC (mg/L)	2.79	2.87	2.00	2.03	1.88	1.43	2.66	---
UV254 (1/m)	3.74	3.11	1.55	1.09	1.61	1.10	2.62	2.19
DOC Molecular Size Dist. (DOC Passing Filter - mg/L)								
10,000 Daltons	2.31	---	1.81	---	1.43	---	---	---
3,000 Daltons	1.67	---	1.48	---	1.18	---	---	---
1,000 Daltons	0.71	---	0.75	---	0.70	---	---	---
500 Daltons	0.27	---	0.33	---	0.26	---	---	---
Dissolved Al (ug/L)	72	242	52	87			---	---
Dissolved Fe (mg/L)	< 0.03	---	---	---	0.06	0.07	---	---
Anions: (mg/L)								
Sulfate	275	---	---	---	---	---	---	---
Bromide	< 0.5	---	---	---	---	---	---	---
Chloride	96	---	---	---	---	---	---	---
Hardness: (mg/L as CaCO₃)								
Ca Hardness	186	---	---	---	---	---	---	---
Mg Hardness	121	---	---	---	---	---	---	---
Total Hardness	307	---	---	---	---	---	---	---

TABLE L1 (con't)

Utility:

VT-8

Location:

Metropolitan Water District of Southern California

Sample:	Bench-Scale						Full-Scale	
	Alum			Ferric			Alum	
	Raw	Baseline	Enhanced	Optimized	Enhanced	Optimized	Settled	Finished
Test:								
Uniform Formation Condition (UFC), dissolved								
Initial Cl Dose (mg/L)	---	4.0	3.2	---	2.75	---	---	---
Free Cl Residual (mg/L)	---	1.3	1.2	---	1.25	---	---	---
THM, (ug/L):								
CHCl3	---	21.7	33.8	---	30.0	---	---	---
CHCl2Br	---	30.0	25.3	---	21.5	---	---	---
CHClBr2	---	27.3	23.0	---	19.0	---	---	---
CHBr3	---	64.5	12.6	---	14.0	---	---	---
Total THM's	---	143.5	94.7	---	84.4	---	---	---
DOX (ug/L as Cl)	---	127	93	---	55	---	---	---
7-day Formation Potentials, dissolved								
Initial Cl Dose (mg/L)	11	11	8.0	8.0	8.0	8.0	---	---
Free Cl Residual (mg/L)	4.6	3.6	3.2	3.0	3.4	3.2	---	---
THMFP (ug/L):								
CHCl3	59.9	93.4	37.7	31.6	28.1	27.9	---	---
CHCl2Br	34.6	52.8	32.1	31.2	30.9	31.1	---	---
CHClBr2	21.0	28.3	22.9	21.3	22.8	20.8	---	---
CHBr3	bd	3.5	bd	bd	bd	bd	---	---
Total THM's	115.5	178.1	92.7	84.0	81.7	79.8	---	---
DOX (ug/L as Cl)	194	203	151	109	113	109	---	---

TABLE L1 (con't)

Utility: VT-8
 Location: Metropolitan Water District of Southern California

Sample:	Pilot-Scale		
	Ferric		
	Raw	Baseline	Enhanced
Test:			
Date Received:	2/8/94	2/8/94	2/8/94
Date Sampled:	2/4/94	2/3/94	2/4/94
Coagulant Dose (mg/L)	---	25	25
pH	7.86	7.6	6.52
Alkalinity (mg/L as CaCO ₃)	121	---	---
Turbidity (NTU)	0.8	2.5	2.3
Color (PCU)	5.6	3.58	---
Organic Carbon:			
TOC (mg/L)	3.22	2.90	1.51
DOC (mg/L)	2.60	2.33	1.30
UV254 (1/m)	3.66	2.23	1.38
DOC Molecular Size Dist. (DOC Passing Filter - mg/L)			
10,000 Daltons	2.33	---	1.15
3,000 Daltons	1.88	---	0.96
1,000 Daltons	0.85	---	0.53
500 Daltons	0.26	---	0.20
Dissolved Al (ug/L)	---	---	---
Dissolved Fe (mg/L)	0.05	0.04	0.06
Anions: (mg/L)			
Sulfate	275	---	---
Bromide	< 0.5	---	---
Chloride	101	---	---
Hardness: (mg/L as CaCO₃)			
Ca Hardness	192	---	---
Mg Hardness	130	---	---
Total Hardness	322	---	---
7-day Formation Potentials, dissolved			
Initial Cl Dose (mg/L)	8.0	8.0	5.0
Free Cl Residual (mg/L)	3.8	4.2	3.0
THMFP (ug/L):			
CHCl ₃	61.3	42.9	13.4
CHCl ₂ Br	35.8	34.9	24.6
CHClBr ₂	20.0	23.1	19.1
CHBr ₃	11.1	15.7	187.9
Total THM's	128.1	116.6	245.0
DOX (ug/L as Cl)	191	149	104

TABLE I.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-8

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-8

Date Received: 1/24/94

Date Sampled: 1/21/94

Jar Test Conditions: Coag: Alum Dose: 20 mg/L

Target pH	5.3	5.6	5.9	6.1	6.4	6.7
Turbidity (NTU)	0.92	0.95	0.8	0.8	0.7	0.8
Residual Al (ug/L)	229	119	86	73	56	82
DOC (mg/L)						
Mean	2.20	2.34	2.18	2.44	2.42	2.43
Std Dev	0.001	0.011	0.001	0.032	0.011	0.013
UV254 (1/m)						
Mean	1.98	2.37	2.28	2.93	2.78	2.62
Std Dev	0.044	0.068	0.029	0.029	0.075	0.071

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-8

Date Received: 1/24/94

Date Sampled: 1/21/94

Jar Test Conditions: Coag: Alum

Target pH range: 5.8-5.9

	COAGULANT DOSE (mg/L)					
	0	10	20	30	40	50
Coag Dose (mM as Al)	0	0.033	0.067	0.100	0.133	0.167
Turbidity (NTU)	2.5	1.5	1	1.2	0.9	0.8
Residual Al (ug/L)	72	154	121	94	78	169
DOC (mg/L)						
Mean	2.76	2.37	2.29	1.89	1.83	1.77
Std Dev	0.023	0.033	0.008	0.022	0.005	0.008
UV254 (1/m)						
Mean	3.61	2.47	2.00	1.83	1.62	1.61
Std Dev	0.044	0.067	0.007	0.015	0.022	0.007

	COAGULANT DOSE (mg/L)					
	60	70	80	90	100	110
Coag Dose (mM as Al)	0.2	0.233	0.267	0.300	0.333	0.367
Turbidity (NTU)	1.5	1.2	1.1	1.1	1.2	1.1
Residual Al (ug/L)	90	80	68	76	72	66
DOC (mg/L)						
Mean	1.97	1.93	2.25	1.73	1.75	1.70
Std Dev	0.036	0.004	0.023	0.009	0.005	0.005
UV254 (1/m)						
Mean	1.81	1.76	2.20	1.61	1.51	1.55
Std Dev	0.007	0.015	0.007	0.000	0.007	0.015

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

TABLE I.2 (con't)

JAR TEST DATA - pH OPTIMIZATION

FERRIC SULFATE

Utility: VT-8

Date Received: 1/24/94 Date Sampled: 1/21/94

Jar Test Conditions: Coag: Ferric Sulfate Dose: 15 mg/L

Target pH	4.5	4.8	5.1	5.4	5.7	6.1
Turbidity (NTU)	1.25	1.4	1.3	1.15	1.4	0.75
Residual Fe (mg/L)	0.12	0.12	0.14	0.12	0.1	0.09
DOC (mg/L)						
Mean	1.84	1.86	1.89	1.82	1.74	1.98
Std Dev	0.004	0.028	0.005	0.002	0.004	0.005
UV254 (1/m)						
Mean	2.79	2.67	2.24	2.25	2.59	2.46
Std Dev	0.073	0.037	0.007	0.007	0.044	0.022

JAR TEST DATA - DOC REMOVAL OPTIMIZATION

FERRIC SULFATE

Utility: VT-8

Date Received: 1/24/94 Date Sampled: 1/21/94

Jar Test Conditions: Coag: Ferric Sulfate

	COAGULANT DOSE (mg/L)				
	0	20	30	40	50
Coag Dose (mM as Fe)	0.000	0.082	0.122	0.163	0.204
Turbidity (NTU)	---	1	1.2	1.2	1.2
Residual Fe (mg/L)	<0.03	0.05	0.05	0.08	0.08
DOC (mg/L)					
Mean	2.76	1.80	1.62	1.52	1.42
Std Dev	0.023	0.006	0.005	0.008	0.004
UV254 (1/m)					
Mean	3.61	1.77	1.53	1.47	1.40
Std Dev	0.044	0.007	0.007	0.000	0.015

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

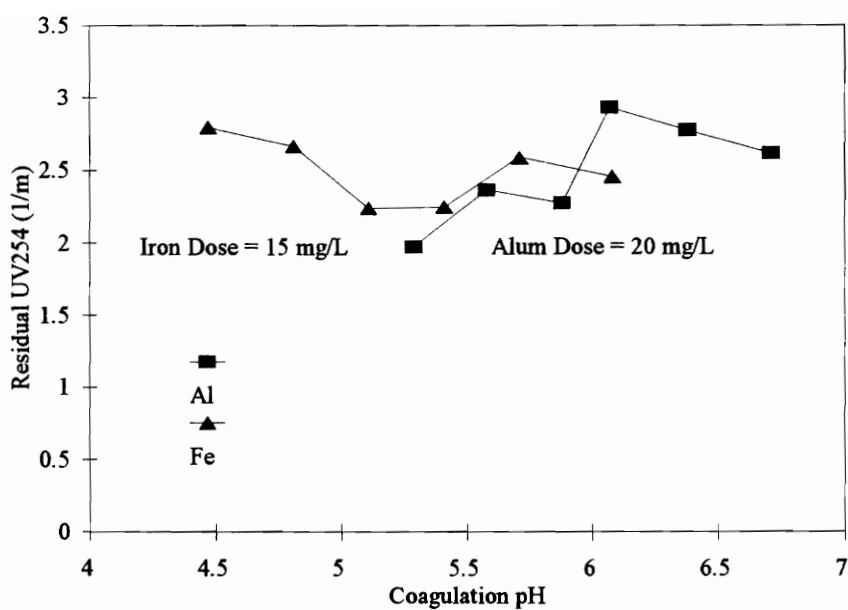


Figure I.2. Residual UV254 as a function of coagulation pH for Utility VT-8 alum and ferric sulfate treatment.

APPENDIX J
UTILITY VT-5

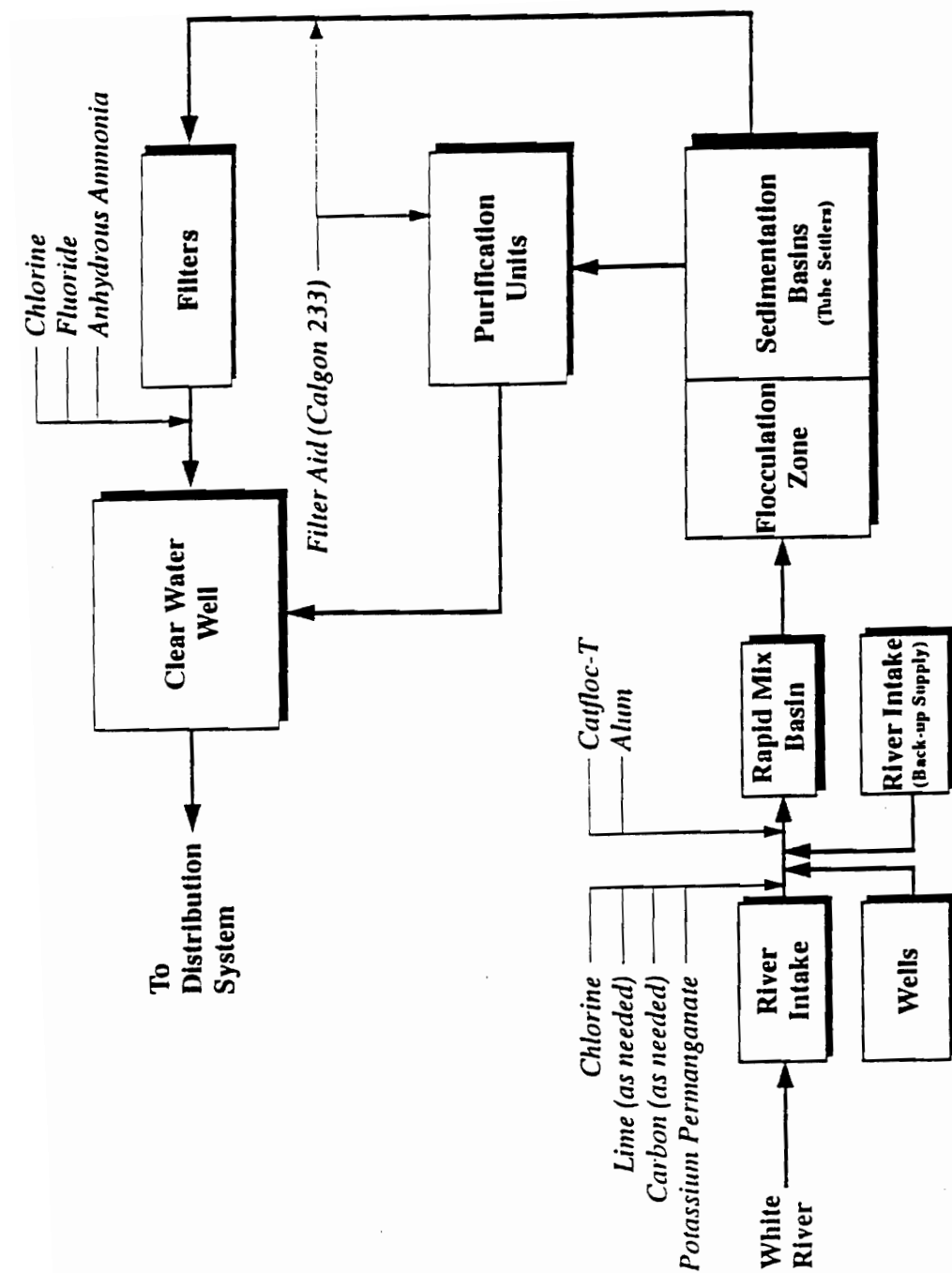


Figure J.1. Utility VT-5 Flow Diagram.

TABLE J.1
SUMMARY OF BENCH-SCALE AND FULL-SCALE RESULTS

Utility: VT-5
Location: Muncie, IN

Sample:	Bench-Scale				Full-Scale	
	Alum				Alum	
	Raw	Baseline	Enhanced	Optimized	Settled	Finished
Test:						
Date Received:	10/25/93	10/25/93	10/25/93	10/25/93	10/25/93	10/25/93
Date Sampled:	10/22/93	10/22/93	10/22/93	10/22/93	10/22/93	10/22/93
Coagulant Dose (mg/L)	---	120	50	100	120	120
pH	7.98	7.08	5.9-6.1	5.9-6.1	7.73	7.52
Alkalinity (mg/L as CaCO ₃)	198	178	---	---	---	204
Turbidity (NTU)	20	0.45	1.0	1.4	1.5	1.3
Color (PCU)	84	30	---	---	21	12
Organic Carbon:						
TOC (mg/L)	9.41	---	---	---	---	6.02
DOC (mg/L)	8.04	4.84	3.75	3.17	5.35	---
UV254 (1/m)	24.5	8.73	7.87	5.96	28.0	23.0
DOC Molecular Size Dist.						
(DOC Passing Filter - mg/L)						
10,000 Daltons	5.97	---	3.66	---	---	---
3,000 Daltons	4.06	---	2.30	---	---	---
1,000 Daltons	1.40	---	1.40	---	---	---
500 Daltons	0.41	---	0.32	---	---	---
Dissolved Al (ug/L)	76	149	58	59	---	---
Dissolved Fe (mg/L)	---	---	---	---	---	---
Anions: (mg/L)						
Sulfate	42.4	---	---	---	---	---
Bromide	< 0.5	---	---	---	---	---
Chloride	22.2	---	---	---	---	---
Hardness: (mg/L as CaCO₃)						
Ca Hardness	62.5	---	---	---	---	---
Mg Hardness	21.4	---	---	---	---	---
Total Hardness	83.9	---	---	---	---	---

TABLE J.1 (con't)

Utility: VT-5
 Location: Muncie, IN

Sample:	Bench-Scale				Full-Scale	
	Alum				Alum	
	Raw	Baseline	Enhanced	Optimized	Settled	Finished
Test:						
Uniform Formation Condition (UFC), dissolved						
Initial Cl Dose (mg/L)	---	5.1	4.4	---	---	---
Free Cl Residual (mg/L)	---	0.7	0.9	---	---	---
THM, (ug/L):						
CHCl3	---	168.1	108.3	---	---	---
CHCl2Br	---	26.6	17.5	---	---	---
CHClBr2	---	0.9	bd	---	---	---
CHBr3	---	bd	bd	---	---	---
Total THM's	---	195.5	125.7	---	---	---
DOX (ug/L as Cl)	---	285	251	---	---	---
7-day Formation Potentials, dissolved						
Initial Cl Dose (mg/L)	24	15	12	9	---	---
Free Cl Residual (mg/L)	3	3.1	2.8	2.3	---	---
THMFP (ug/L):						
CHCl3	497.2	322.8	177.7	176.3	---	---
CHCl2Br	19.5	15.7	28.5	12.4	---	---
CHClBr2	bd	bd	0.8	bd	---	---
CHBr3	bd	bd	0.3	bd	---	---
Total THM's	516.7	338.5	207.3	188.7	---	---
DOX (ug/L as Cl)	1340	739	549	388	---	---

ADDITIONAL FP RESULTS

Sample:	Bench-Scale				Full-Scale	
	Alum				Alum	
	Raw	Baseline	Enhanced	Optimized	Settled	Finished
Test:						
7-day Formation Potentials, dissolved						
Initial Cl Dose (mg/L)	21	---	---	12	---	---
Free Cl Residual (mg/L)	2.0	---	---	3.6	---	---
THMFP (ug/L):						
CHCl3	505.1	---	---	196.4	---	---
CHCl2Br	16.3	---	---	13.5	---	---
CHClBr2	bd	---	---	bd	---	---
CHBr3	bd	---	---	bd	---	---
Total THM's	521.4	---	---	209.8	---	---
DOX (ug/L as Cl)	1350	---	---	---	---	---

TABLE J.2
SUMMARY OF pH AND DOSE OPTIMIZATION JAR TESTING
FOR UTILITY VT-5

JAR TEST DATA - pH OPTIMIZATION - ALUM

Utility: VT-5 (Muncie, IN)

Date Received: 10/25/93

Date Sampled: 10/22/93

Jar Test Conditions: Coag: Alum

Dose: 50 mg/L

Target pH	5.3	5.6	5.9	6.1	6.4	6.7
Residual Al (ug/L)	185	111	84	108	112	152
DOC (mg/L)						
Mean	4.22	3.99	4.14	4.19	4.17	4.93
Std Dev	0.001	0.019	0.010	0.001	0.015	0.021
UV254 (1/m)						
Mean	8.35	8.17	8.31	9.03	8.89	10.87
Std Dev	0.006	0.012	0.016	0.010	0.006	0.010

JAR TEST DATA - DOC REMOVAL OPTIMIZATION - ALUM

Utility: VT-5 (Muncie, IN)

Date Received: 10/25/93

Date Sampled: 10/22/93

Jar Test Conditions: Coag: Alum

Target pH range: 5.9-6.1

	COAGULANT DOSE (mg/L)					
	0	20	30	40	50	60
Turbidity (NTU)	17	13	1.5	1.1	0.86	1
Residual Al (ug/L)	304	555	206	120	95	88
DOC (mg/L)						
Mean	8.43	5.84	4.75	4.20	3.69	3.66
Std Dev	0.058	0.030	0.008	0.011	0.004	0.036
UV254 (1/m)						
Mean	34.88	23.11	12.16	9.30	8.20	7.69
Std Dev	0.213	0.007	0.015	0.007	0.000	0.007

	COAGULANT DOSE (mg/L)					
	70	80	90	100	110	120
Turbidity (NTU)	1	0.81	0.76	0.84	1.4	0.7
Residual Al (ug/L)	96	90	82	72	66	96
DOC (mg/L)						
Mean	3.65	3.61	3.80	3.45	3.34	3.22
Std Dev	0.006	0.006	0.004	0.016	0.051	0.016
UV254 (1/m)						
Mean	7.40	7.23	7.06	6.65	6.68	6.71
Std Dev	0.007	0.015	0.007	0.007	0.000	0.000

Note: DOC and UV254 values are means of a minimum of two replicate analyses.

APPENDIX K
ULTRAFILTER DOC RESULTS

TABLE K.1
SUMMARY OF DOC DATA FROM THREE SAMPLES COLLECTED FROM ULTRAFILTERS
Notes: 1. Each number given below for the three samples is an average of at least two replicate samples analyzed using the DOC analyzer.
2. Samples were collected in parallel through each ultrafilter and were generally collected when the ultrafilter contained between 50 mL and 150 mL of 200 mL total sample.

Utility:		VT-1									
		DOC (mg/L) - RAW					DOC (mg/L) - ALUM ENH				
		10K	3K	1K	0.5K		10K	3K	1K	0.5K	
Sample 1		4.32	2.40	1.34	0.54		2.20	1.84	0.99	0.46	
Sample 2		4.30	2.47	1.12	0.48		2.26	1.88	0.98	0.39	
Sample 3		4.31	2.70	1.68	0.37		2.28	1.85	1.01	0.43	
Avg.		4.31	2.52	1.38	0.46		2.25	1.86	1.00	0.43	
Std. Dev.		0.01	0.15	0.28	0.08		0.04	0.02	0.02	0.04	

Utility:		VT-2									
		DOC (mg/L) - RAW					DOC (mg/L) - ALUM ENH				
		10K	3K	1K	0.5K		10K	3K	1K	0.5K	
Sample 1		1.23	0.65	0.52	0.26		0.94	0.68	0.33	0.22	
Sample 2		1.48	0.65	0.53	0.28		0.98	0.70	0.34	0.22	
Sample 3		1.53	0.70	0.47	0.21		0.98	0.70	0.40	0.29	
Avg.		1.41	0.66	0.51	0.25		0.96	0.69	0.36	0.24	
Std. Dev.		0.16	0.03	0.03	0.03		0.02	0.01	0.04	0.04	

TABLE K.1 (con't)

Utility:		VT3											
		DOC (mg/L) - RAW				DOC (mg/L) - FERRIC ENH				DOC (mg/L) - ALUM ENH			
		10K	3K	1K	0.5K	10K	3K	1K	0.5K	10K	3K	1K	0.5K
Sample 1		10.52	4.97	1.51	0.33	3.28	2.54	1.26	0.41	3.55	2.99	1.26	0.32
Sample 2		10.20	5.29	1.64	0.35	3.28	2.63	1.36	0.41	3.69	3.27	1.45	0.44
Sample 3		10.44	6.19	1.74	0.39	3.25	2.65	1.73	0.47	3.79	3.38	1.69	0.49
Avg.		10.38	5.48	1.63	0.36	3.27	2.61	1.45	0.43	3.68	3.21	1.47	0.42
Std. Dev.		0.17	0.63	0.11	0.03	0.02	0.05	0.25	0.03	0.12	0.20	0.21	0.09

Utility:		VT4		DOC (mg/L) - RAW				DOC (mg/L) - FERRIC ENH				DOC (mg/L) - ALUMENH			
				DOC (mg/L) - RAW				DOC (mg/L) - FERRIC ENH				DOC (mg/L) - ALUMENH			
				10K	3K	1K	0.5K	10K	3K	1K	0.5K	10K	3K	1K	0.5K
Sample 1		1.39	0.91	0.50	0.26	1.19	0.79	0.71	0.43	1.26	0.79	0.55	0.36		
	Sample 2	1.43	0.89	0.44	0.32	1.15	1.21	0.62	0.45	1.22	0.79	0.53	0.37		
		Sample 3	1.48	0.94	0.47	0.26	1.22	0.92	1.14	0.66	1.28	0.89	0.57	0.30	
Avg.		1.43	0.91	0.47	0.28	1.19	0.97	0.82	0.51	1.25	0.83	0.55	0.34		
Std. Dev.		0.05	0.03	0.03	0.03	0.04	0.21	0.28	0.13	0.03	0.06	0.02	0.04		

Utility:		VT5		DOC (mg/L) - RAW					DOC (mg/L) - ALUMENH			
		10K	3K	1K	0.5K	10K	3K	1K	0.5K			
Sample 1		8.20	3.39	1.21	0.32	4.54	2.11	1.20	0.30			
Sample 2		4.65	4.84	1.42	0.45	3.07	2.30	1.27	0.33			
Sample 3		5.05	3.96	1.57	0.47	3.36	2.49	1.73	0.33			
Avg.		5.97	4.06	1.40	0.41	3.66	2.30	1.40	0.32			
Std. Dev.		1.95	0.73	0.18	0.09	0.78	0.19	0.29	0.02			

TABLE K.1 (con't)

Utility:		VT6														
		DOC (mg/L) - RAW					DOC (mg/L) - ALUM ENH					DOC (mg/L) - FERRIC ENH				
		10K	3K	1K	0.5K		10K	3K	1K	0.5K		10K	3K	1K	0.5K	
Sample 1		3.32		1.71	1.00	0.34		1.91	1.40	0.85	0.36		1.54	1.17	0.75	0.28
Sample 2		3.78		1.83	1.56	0.43		1.98	1.45	0.87	0.30		1.68	1.43	0.98	0.28
Sample 3		2.57		2.15	1.58	0.34		2.04	1.60	1.13	0.33		1.60	1.86	1.10	0.46
Avg.		3.22		1.90	1.38	0.37		1.98	1.48	0.95	0.33		1.61	1.49	0.95	0.34
Std. Dev.		0.61		0.23	0.33	0.05		0.06	0.10	0.16	0.03		0.07	0.35	0.18	0.11

Utility:		VT6 (con't.)											
		DOC (mg/L) - ALUM 15 mg/L				DOC (mg/L) - ALUM 60 mg/L				DOC (mg/L) - ALUM OPT			
		10K	3K	1K	0.5K	10K	3K	1K	0.5K	10K	3K	1K	0.5K
Sample 1		1.92	1.55	0.90	0.43	1.89	1.43	0.80	0.29	1.56	1.26	0.81	0.25
Sample 2		1.91	1.56	0.95	0.33	1.85	1.44	0.88	0.31	1.59	1.29	0.82	0.54
Sample 3		2.14	1.73	1.07	0.33	1.87	1.55	0.93		1.67	1.34	0.94	0.27
Avg.		1.99	1.62	0.97	0.37	1.87	1.47	0.87	0.30	1.61	1.30	0.86	0.35
Std. Dev.		0.13	0.10	0.08	0.06	0.02	0.06	0.07	0.01	0.06	0.04	0.07	0.16

Utility:		VT7											
		DOC (mg/L) - RAW				DOC (mg/L) - ALUM ENH				DOC (mg/L) - FERRIC ENH			
		10K	3K	1K	0.5K	10K	3K	1K	0.5K	10K	3K	1K	0.5K
Sample 1		3.28	1.78	0.81	0.26	2.27	1.54	0.89	0.34	2.12	1.60	0.79	0.44
Sample 2		3.30	1.94	0.92	0.35	2.30	1.72	0.89	0.35	2.08	1.61	1.21	0.49
Sample 3		3.54	2.17	0.97	0.31	2.47	1.76	1.02	0.35	2.06	1.69	0.97	0.53
Avg.		3.38	1.96	0.90	0.31	2.34	1.67	0.94	0.35	2.09	1.63	0.99	0.49
Std. Dev.		0.15	0.19	0.09	0.05	0.11	0.11	0.08	0.01	0.03	0.05	0.21	0.04

TABLE K.1 (con't)

Utility:		VT8						DOC (mg/L) - ALUM ENH						DOC (mg/L) - FERRIC ENH					
		DOC (mg/L) - RAW																	
		10K	3K	1K	0.5K							10K	3K	1K	0.5K	10K	3K	1K	0.5K
Sample 1		2.26	1.55	0.65	0.24							1.79	1.36	0.69	0.31	1.40	1.15	0.63	0.25
Sample 2		2.22	1.68	0.72	0.27							1.76	1.51	0.73	0.33	1.46	1.15	0.65	0.24
Sample 3		2.45	1.77	0.75	0.31							1.88	1.57	0.81	0.35	1.44	1.23	0.82	0.29
Avg.		2.31	1.67	0.71	0.27							1.81	1.48	0.75	0.33	1.43	1.18	0.70	0.26
Std. Dev.		0.12	0.11	0.05	0.04							0.06	0.11	0.06	0.02	0.03	0.04	0.10	0.03

Utility:		VT9						DOC (mg/L) - ALUM ENH						DOC (mg/L) - FERRIC ENH					
		DOC (mg/L) - RAW																	
		10K	3K	1K	0.5K							10K	3K	1K	0.5K	10K	3K	1K	0.5K
Sample 1		2.73	1.83	0.74	0.33							2.98	1.92	0.92	0.49	2.75	1.50	0.80	0.53
Sample 2		3.16	2.01	0.86	0.37							2.98	2.05	1.01	0.62	2.75	1.62	0.97	0.57
Sample 3		3.46	2.33	0.97	0.43							3.16	2.37	1.17	0.64	2.83	1.72	1.20	0.64
Avg.		3.11	2.06	0.85	0.38							3.04	2.11	1.03	0.58	2.77	1.61	0.99	0.58
Std. Dev.		0.37	0.25	0.12	0.05							0.10	0.23	0.13	0.08	0.05	0.11	0.20	0.06

APPENDIX L
DOX STANDARD CURVES AND QA/QC

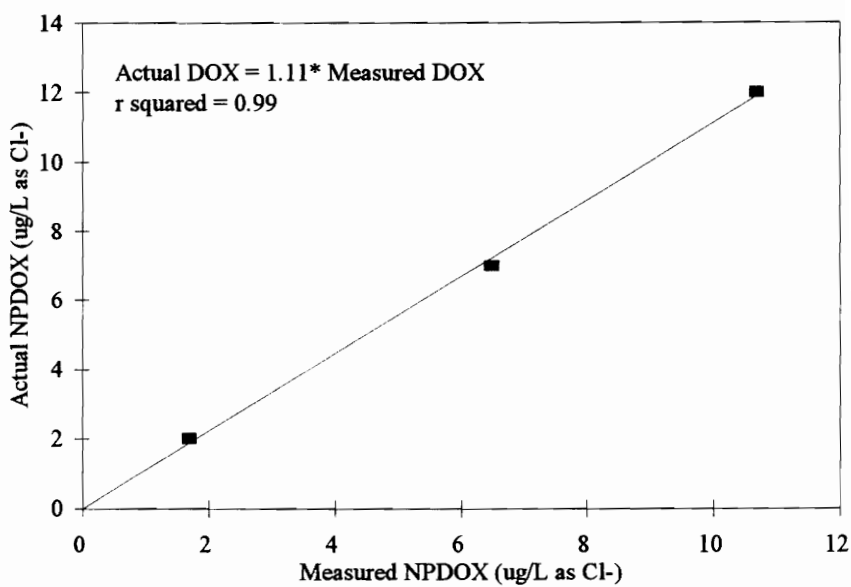


Figure L.1. Standard curve for Utility VT-5 samples.

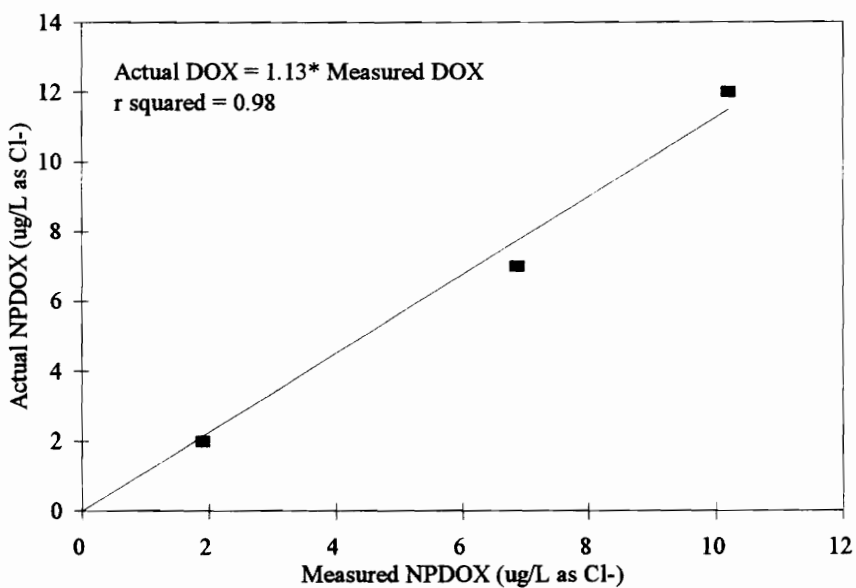


Figure L.2. Standard curve for Utility VT-6 samples.

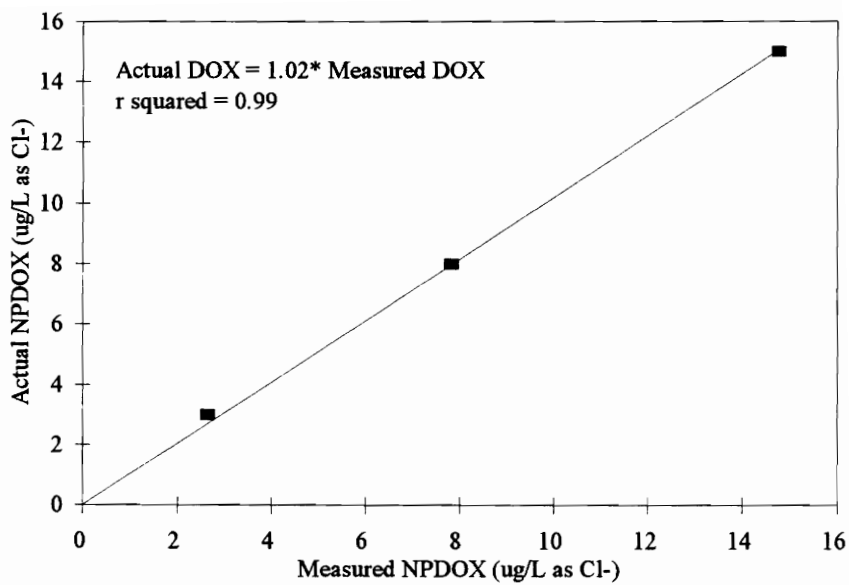


Figure L.3. Standard curve for Utility VT-6 pilot plant and Utility VT-7 samples.

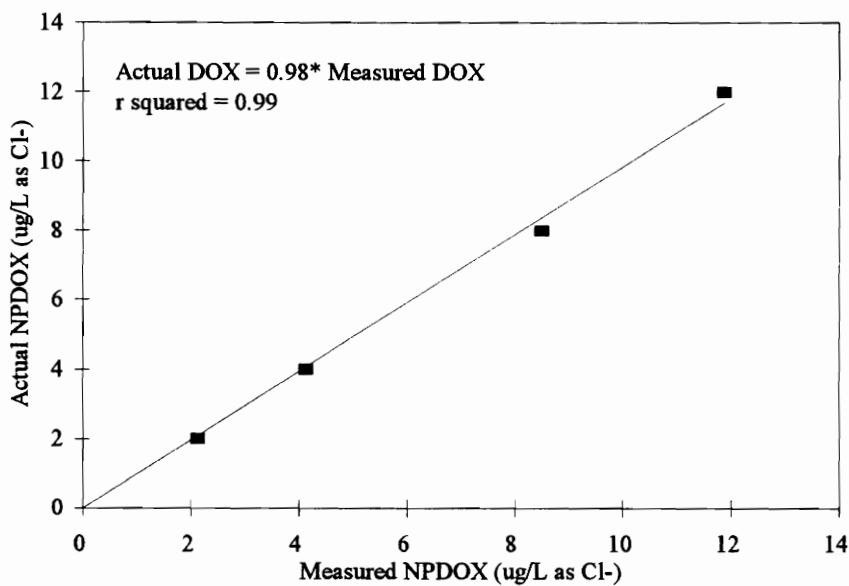


Figure L.4. Standard curve for Utility VT-6 pilot plant, VT-8 pilot plant, VT-8, and VT-9 samples.

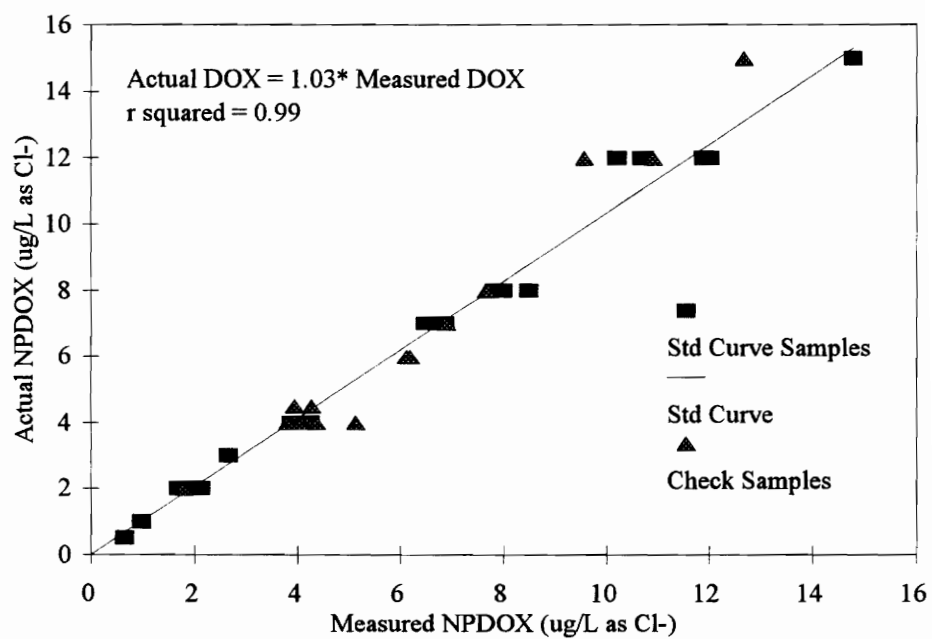


Figure L.5. Standard curve for all utilities combined. (Check samples for all utilities are also shown but were not included in the calculation of the linear regression line.)

TABLE L.1
QA/QC - TOX ANALYSES

Instrument: TOX

UTILITY DATE	VT-1 7/12/93	VT-1PP 3/11/94	VT-2 8/6/93	VT-3 9/17/93	VT-4 10/19/93	VT-5 11/18/93	VT-6 12/21/93	VT-6PP 1/26/94	VT-7 1/14/94	VT-8 3/7/94	VT-8PP 3/10/94	VT-9 3/12/94	3/14/94	3/15/94
BLANK	1.36	1.31	0.37	0.45	0.64	0.84	1.21	1.22	1.42	1.46	1.34	1.10	1.10	1.10

MATRIX SPIKE DUPLICATES: SAMPLE:	Fe										Alum									
	Eab					Eab					Eab					Eab				
	12.5	10	25	12.5	20	10	10	8	20	20	10	20	20	20	20	10	10	10	4	10
SAMPLE SIZE (mL):																				
Duplicate Col. A	6.71	10.28	5.45	6.19	6.42	7.83	5.55	5.35	8.33	8.33	6.57	8.6	8.6	8.6	8.6	8.85	11.03	6.62	8.85	6.62
Col. B	0.71	1.03	0.69	0.3	0.66	0.32	0.54	0.82	0.89	0.89	0.73	0.81	0.81	0.81	0.81	0.72	0.52	0.61	0.72	0.61
-Blank	-1.36	-1.31	-0.37	-0.45	-0.64	-0.84	-1.21	-1.22	-1.42	-1.42	-1.46	-1.46	-1.46	-1.46	-1.46	-1.10	-1.10	-1.10	-1.10	-1.10
Total	6.06	10.00	5.77	6.05	6.44	7.31	4.88	4.95	7.80	7.80	5.84	7.95	7.95	7.95	7.95	8.47	10.45	6.13	8.47	6.13
Duplicate Col. A	6.77	10.14	4.51	7.18	6.84	7.27	4.54	5.39	8.31	8.31	6.22	8.11	8.11	8.11	8.11	8.65	10.94	6.39	8.65	6.39
Col. B	0.48	0.82	0.51	0.85	0.43	0.45	0.56	0.97	1.21	1.21	0.8	0.85	0.85	0.85	0.8	0.69	0.54	0.54	0.69	0.54
-Blank	-1.36	-1.31	-0.37	-0.45	-0.64	-0.84	-1.21	-1.22	-1.42	-1.42	-1.46	-1.46	-1.46	-1.46	-1.46	-1.10	-1.10	-1.10	-1.10	-1.10
Total	5.89	9.65	4.65	7.59	6.63	6.88	3.89	5.14	8.10	8.10	5.56	7.50	7.50	7.50	8.11	8.37	10.38	5.83	8.37	5.83
Mean	5.97	9.83	5.21	6.82	6.54	7.10	4.39	5.04	7.95	7.95	5.70	7.73	7.73	7.73	8.42	10.42	5.98	8.42	10.42	5.98
Std Dev	0.120	0.247	0.792	1.089	0.134	0.304	0.700	0.134	0.212	0.212	0.198	0.318	0.318	0.318	1.068	0.071	0.049	0.212	0.071	0.049
% difference																				
100%(x1 - x2)/(mean x)	2.85	3.56	21.50	-22.60	-2.91	6.06	22.55	-3.77	-3.78	-3.78	4.91	5.82	5.82	5.82	-20.53	1.19	0.67	5.01	1.19	0.67
Initial concentration	4.28	5.93	3.6	3.36	3.91	5.49	2.37	2.95	6.05	6.05	1.94	3.88	3.88	3.88	3.82	4.04	6.29	4.23	4.04	6.29
Actual conc. added	2.5	4	2.5	2.5	2	2	2	2	2	2	4	4	4	4	4	4	4	2	4	4
Expected conc.	6.78	9.93	6.1	5.86	5.91	7.49	4.37	4.95	8.05	8.05	5.94	7.88	7.88	7.88	7.82	8.04	10.29	6.23	8.04	10.29
% difference																				
100%(measured-actual)/actual	-11.89	-1.02	-14.59	16.30	10.58	-5.23	0.45	1.85	-1.29	-1.29	-3.96	-1.91	-1.91	-1.91	-5.95	4.77	1.25	-3.96	4.77	1.25

DATE	7/12/93	3/11/94	9/3/93	10/19/93	11/21/93	12/17/93	12/18/93	12/21/93	1/21/94	1/26/94	1/13/94	1/14/94	3/7/94	3/8/94	3/9/94	3/10/94	3/11/94	3/12/94	3/14/94	3/15/94
CHECK SAMPLE																				
measured																				
Duplicate Col. A	14.79	4.79	1.78		4.33	10.06	2.81	9.6	11.48	4.84	5.47	4.75	4.4	4.55	4.93	8.43	8.51	4.94	4.79	6.73
Col. B	0.62	0.75	0.3		0.19	0.26	0.34	0.73	0.64	0.58	0.89	0.95	0.97	0.72	0.83	0.69	0.65	0.76	0.75	0.49
-2*MB	-1.36	-1.36	-0.37		-0.64	-0.84	-1.21	-1.21	-1.21	-1.21	-1.22	-1.22	-1.42	-1.46	-1.46	-1.46	-1.46	-1.34	-1.34	-1.10
Total	14.05	4.18	1.71		3.88	9.48	1.94	9.12	10.91	4.20	5.14	4.28	3.95	3.81	4.30	7.66	7.70	4.36	4.20	6.12
Duplicate Col. A	11.96	4.78	0.78		4.05	10.25	2.14	5.45												
Col. B	0.68	0.33	0.33		0.61	0.25	0.7	0.4												
-2*MB	-1.36	-0.37	-0.37		-0.64	-0.84	-1.21	-1.21												
Total	11.28	4.74	0.74		4.02	9.66	1.63	4.64												
Mean	12.66	1.23	3.95		3.95	9.57	1.79	6.88												
Std Dev	1.96	0.69	0.10		0.10	0.13	0.22	3.17												
actual concentration	15	4	2.5		4	12	2	7	12	4	4	4.5	4.5	4	4	8	8	4	4	6
% difference																				
100%(measured-actual)/actual	-15.57	4.48	-51.00		-1.25	-20.22	-10.51	-1.65	-9.04	4.92	28.42	-4.98	-12.31	-4.63	7.62	-4.19	-3.69	9.00	5.00	2.06
																				3.06

- Notes:
1. QC samples to be analyzed with every batch of <= 20 samples
 2. Check sample = spiked blank
 3. ** = Trouble getting check sample out of carbon column.
 4. Unless otherwise indicated, units for table above are micrograms of chloride ion.

TABLE L.2
MATRIX SPIKE DUPLICATES - TOX ANALYSES

Instrument: TOX

UTILITY	VT-1	VT-1	VT-2	VT-3	VT-4	VT-5	VT-6	VT-6PP	VT-7	VT-8	VT-8PP	VT-9	
DATE	7/12/93	3/11/94	8/6/93	9/17/93	10/19/93	11/18/93	12/21/93	1/26/94	1/14/94	3/7/94	3/10/94	3/12/94	3/14/94
SAMPLE:	Alum Enh	Raw	Alum Enh	Fe Opt (17 mg/L)	Alum Enh (7 mg/L)	Alum Enh	Fe Enh	Raw	Fe Enh	Raw	Raw	Alum BL	Raw Alum Opt
TOX Conc: (ug/L as Cl-)													
Duplicate 1	484.7	1000.3	230.8	483.6	322.0	731.3	488.5	618.3	389.8	584.5	330.0	847.3	2613.3
Duplicate 2	471.1	965.3	186.0	606.8	331.5	688.3	389.5	642.1	404.8	556.5	405.5	837.3	2595.8
Mean	477.92	982.83	208.40	545.20	326.75	709.83	438.98	630.21	397.29	570.47	367.75	842.33	2604.58
Std Dev	9.62	24.75	31.68	87.12	6.72	30.41	70.00	16.79	10.61	19.80	53.39	7.07	12.37
% difference													
100%(x1 - x2)/(mean x)	2.85	3.56	21.50	-22.60	-2.91	6.06	22.55	-3.77	-3.78	4.91	-20.53	1.19	0.67
Initial concentration	342.4	593	144	268.8	195.5	549	237	368.75	302.5	194	191	404	1572.5
Actual conc. added	200	400	100	200	100	200	200	250	100	400	200	400	1000
Expected conc.	542.4	993	244	468.8	295.5	749	437	618.75	402.5	594	394	804	2572.5
% difference													
100%(measured-actual)/actual	-11.89	-1.02	-14.59	16.30	10.58	-5.23	0.45	1.85	-1.29	-3.96	-5.95	4.77	1.25
													-3.96

APPENDIX M
REPRODUCIBILITY OF JAR TEST DATA

TABLE M.1

JAR TEST REPRODUCIBILITY OF DOC RESULTS - OPTIMIZED DOSES
(DETERMINED FROM PARALLEL TREATMENT IN DIFFERENT JAR TEST VESSELS)

Sample	Dose (mg/L)	Init. TO (mg/L)	Init. Alk. (mg/L as CaCO3)	DOC (mg/L)						Avg	Std Dev	% Error		
				DOC1	DOC2	DOC3	DOC4	DOC5	DOC6					
VT2AOP	80	2.6	21	1.03	1.18	1.05				1.09	0.082	7.54		
VT3AOP	170	11.8	112	3.59	3.69					3.64	0.065	1.80		
VT3FOP	109			2.84	3.15	3.01				3.00	0.157	5.24		
VT4AOP	50	2.7	15	1.39	1.37	1.38				1.38	0.012	0.87		
VT4FOP	50			1.03	1.05	1.18				1.09	0.083	7.67		
VT5AOP	100	9.4	198	3.13	3.18	3.19				3.17	0.035	1.10		
VT6AOP	110			1.94	2.14	1.95	1.99	1.98	2.13	2.02	0.090	4.44		
VT6FOP	100			1.62	1.49	1.52				1.55	0.068	4.42		
VT7AOP	90	5.6	44	2.53	2.49	2.52				2.51	0.019	0.76		
VT7FOP	80			3.10	2.30	1.99				2.46	0.571	23.16		
VT8AOP	90	2.7	135	2.26	1.81					2.03	0.319	15.70		
VT8FOP	90			1.43						1.43				
VT9AOP	130	8.5	10	3.40	3.07	3.08				3.18	0.190	5.96		
VT9FOP	110			2.68	2.78	2.59				2.68	0.095	3.54		
											Avg		0.137	6.32
											Median		0.083	4.43

TABLE M.2

JAR TEST REPRODUCIBILITY OF UV254 RESULTS - ALL TREATED SAMPLES
(DETERMINED FROM PARALLEL TREATMENT IN DIFFERENT JAR TEST VESSELS)

Sample	Dose (mg/L)	Init. TOC (mg/L)	Init. Alk. (mg/L as CaCO ₃)	UV1	UV2	UV3	UV4	UV5	UV6	Avg	Std Dev	% Error
VT1ABL	40	5.32	60	6.01	5.98	6.06	5.96	5.84	5.94	5.96	0.074	1.23
VT1AEN	40			5.40	4.90	4.65	4.75	4.52	4.73	4.83	0.310	6.42
VT2ABL	17	2.56	21	3.49	2.85	2.92	3.08	2.75		3.02	0.290	9.60
VT2AEN	30			1.83	1.93	1.89	1.74	1.91	1.92	1.87	0.072	3.84
VT2AOP	80			2.01	2.03	2.02				2.02	0.010	0.52
VT3AEN	100	11.8	112	11.11	10.39	10.77	10.60	10.34	9.99	10.53	0.388	3.68
VT3AOP	170			8.57	8.59	8.91				8.69	0.189	2.18
VT3FBL	122			7.30	8.00	7.59	7.44	7.30	7.47	7.52	0.260	3.46
VT3FEN	65			12.15	13.43	10.78	14.63	15.01	14.03	13.34	1.606	12.04
VT3FOP	109			10.46	9.21	10.23				9.97	0.662	6.65
VT4AEN	20	2.65	15	2.74	2.50	2.49	2.67	2.78	2.66	2.64	0.121	4.58
VT4AOP	50			1.90	1.90	2.12				1.97	0.128	6.46
VT4FBL	5.6			11.73	9.46	6.18	4.84	4.77	5.23	7.04	2.893	41.11
VT4FEN	20			2.15	1.87	2.11	1.93	2.26	2.13	2.07	0.146	7.04
VT4FOP	50			1.52	1.91	1.70				1.71	0.195	11.43
VT5ABL	119.9	9.41	198	8.64	8.95	8.66	8.72		8.67	8.73	0.127	1.46
VT5AEN	50			8.09	7.72	8.01	7.84	7.78	7.78	7.87	0.145	1.84
VT5AOP	100			6.02	6.00	5.88				5.96	0.073	1.22
VT6ABL	40	4.02	138	4.77	4.95	4.80	4.79	4.35	4.54	4.70	0.216	4.60
VT6AEN	30			3.66	3.72	3.40	3.52	3.60	3.57	3.58	0.112	3.12
VT6AOP	110			2.55	2.75	2.55	2.62	3.43	2.90	2.80	0.337	12.02
VT6FEN	30			2.17	2.20	2.19	2.13	2.15	2.15	2.16	0.026	1.19
VT6FOP	100			1.50	1.48	1.50				1.49	0.012	0.77
VT7ABL	35	5.64	44	5.52	5.62	5.76	5.79	5.88	6.18	5.79	0.227	3.93
VT7AEN	30			5.79	5.69	6.12	5.87	5.71	5.80	5.83	0.156	2.67
VT7AOP	90			4.48	5.06	4.64				4.73	0.301	6.36
VT7FEN	40			4.14	3.88	3.97	4.30	4.88	4.67	4.31	0.395	9.16
VT7FOP	80			3.63	3.72	3.55				3.63	0.088	2.43
VT8ABL	3	2.73	135	2.93	3.08	3.18	3.25			3.11	0.137	4.40
VT8AEN	30			1.47	1.47	1.54	1.82	1.50	1.51	1.55	0.134	8.63
VT8AOP	90			1.15	1.03					1.09	0.081	7.41
VT8FEN	25			1.52	1.64	1.55	1.79	1.56		1.61	0.110	6.83
VT8FOP	90			1.10						1.10		
VT9ABL	36	8.54	9.8	6.36	6.31	6.49	6.96	7.40	7.26	6.80	0.475	6.99
VT9AEN	60			8.14	8.46	8.38	8.37	8.10	8.50	8.32	0.165	1.99
VT9AOP	130				5.93	6.02				5.97	0.066	1.11
VT9FEN	60			6.54	6.34	6.29	6.34	6.69		6.44	0.169	2.63
VT9FOP	110			3.82	4.28	4.18				4.09	0.243	5.94
										Avg		5.86
										Median		4.16

APPENDIX N
FULL-SCALE AND BENCH-SCALE UV254 VALUES

Table N.1
Comparison of UV254 Values for Bench-Scale Baseline Treatment
and Full-Scale Treatment

Sample	Raw Water UV254 (1/m)	Bench-Scale	Full-Scale		% Difference [†] (%)
		Finished UV254 (1/m)	Settled UV254* (1/m)	Finished UV254* (1/m)	
VT-1	13.2	5.96	5.44	4.29	38.9
VT-2	4.25	3.02	1.89	1.76	71.6
VT-3	47.5	7.52	10.7	8.36	-10.1
VT-4	5.75	7.03	2.52	1.69	316.0
VT-5	24.5	8.73	28.0	23.0	-62.0
VT-6	6.79	4.70	4.88	3.53	33.1
VT-7	13.3	5.79	4.67	3.23	79.3
VT-8	3.74	3.11	2.62	2.19	42.0
VT-9	49.1	6.80	4.56	5.83	16.6

* Settled full-scale samples were filtered in laboratory through a 1.5 µm filter prior to UV254 analysis. Finished full-scale samples were not filtered in the laboratory prior to UV254 analysis.

† Percentage difference is the difference between the bench-scale and the full-scale finished water results as a percentage of the full-scale finished water results.

APPENDIX O
UNIFORM FORMATION CONDITION DATA

Table O.1
Summary of UFC THM Values for Baseline (BL)
and Enhanced (EN) Treatment for Each Utility

Utility	Coagulant	DOC (mg/L)			UFC THM (µg/L)	
		Initial	BL	EN	BL	EN
VT1	Al	4.98	2.53	2.25	81	70
VT2	Al	2.28	1.32	1.14	42	32
VT3	Al	11.6	---	4.51	---	152
	Fe	11.6	2.87	3.70	131	183
VT4	Al	2.63	---	1.61	---	35
	Fe	2.63	2.34	1.39	72	51
VT-5	Al	8.04	4.84	3.75	195	126
VT-6	Al	3.64	3.07	2.48	118	94
	Fe	3.64	---	2.03	---	99
VT-7	Al	4.84	2.89	3.02	70	69
	Fe	4.84	---	2.24	---	53
VT-8	Al	2.79	2.87	2.00	144	95
	Fe	2.79	---	1.88	---	84
VT-9	Al	8.03	3.22	3.70	85	94
	Fe	8.03	---	3.39	---	64

Table O.2
Summary of UFC DOX Values for Baseline (BL)
and Enhanced (EN) Treatment for Each Utility

Utility	Coagulant	DOC (mg/L)			UFC DOX (µg/L as Cl ⁻)	
		Initial	BL	EN	BL	EN
VT1	Al	4.98	2.53	2.25	242	224
VT2	Al	2.28	1.32	1.14	126	89
VT3	Al	11.6	---	4.51	---	386
	Fe	11.6	2.87	3.70	262	311
VT4	Al	2.63	---	1.61	---	87
	Fe	2.63	2.34	1.39	119	65
VT-5	Al	8.04	4.84	3.75	285	251
VT-6	Al	3.64	3.07	2.48	106	83
	Fe	3.64	---	2.03	---	61
VT-7	Al	4.84	2.89	3.02	305	298
	Fe	4.84	---	2.24	---	222
VT-8	Al	2.79	2.87	2.00	127	93
	Fe	2.79	---	1.88	---	55
VT-9	Al	8.03	3.22	3.70	253	296
	Fe	8.03	---	3.39	---	225

Table O.3
Relationship between UFC THM and THMFP for
Baseline (BL) and Enhanced (EN) Samples

Utility	DOC (mg/L)	THMFP (µg/L)	UFC THM (µg/L)	UFC/THMFP (µg/µg)
VT1				
Alum-BL	2.53	212	81	0.38
Alum-EN	2.25	175	70	0.40
VT2				
Alum-BL	1.32	70	42	0.60
Alum-EN	1.14	59	32	0.53
VT3				
Alum-EN	4.51	252	152	0.60
Ferric-BL	2.87	158	131	0.83
Ferric-EN	3.70	220	183	0.83
VT4				
Alum-EN	1.61	75	35	0.47
Ferric-BL	2.34	127	72	0.57
Ferric-EN	1.39	70	51	0.73
VT5				
Alum-BL	4.84	338	195	0.58
Alum-EN	3.75	207	126	0.61
VT6				
Alum-BL	3.07	209	118	0.56
Alum-EN	2.48	187	94	0.50
Ferric-EN	2.03	119	99	0.83

(continued)

Table O.3 (continued)

Utility	DOC (mg/L)	THMFP (µg/L)	UFC THM (µg/L)	UFC/THMFP (µg/µg)
VT7				
Alum-BL	2.89	202	70	0.35
Alum-EN	3.02	203	69	0.34
Ferric-EN	2.24	139	53	0.39
VT8				
Alum-BL	2.87	178	144	0.81
Alum-EN	2.00	93	95	1.02
Ferric-EN	1.88	82	84	1.02
VT9				
Alum-BL	3.22	186	85	0.46
Alum-EN	3.70	247	94	0.38
Ferric-EN	3.39	193	64	0.33

Table O.4
Relationship between UFC DOX and DOXFP for
Baseline (BL) and Enhanced (EN) Samples

Utility	DOC (mg/L)	DOXFP ($\mu\text{g/L as Cl}^-$)	UFC DOX ($\mu\text{g/L as Cl}^-$)	UFC/DOXFP ($\mu\text{g}/\mu\text{g}$)
VT1				
Alum-BL	2.53	558	242	0.43
Alum-EN	2.25	343	224	0.65
VT2				
Alum-BL	1.32	208	126	0.61
Alum-EN	1.14	144	89	0.62
VT3				
Alum-EN	4.51	617	386	0.63
Ferric-BL	2.87	437	262	0.60
Ferric-EN	3.70	582	311	0.53
VT4				
Alum-EN	1.61	195	87	0.45
Ferric-BL	2.34	234	119	0.51
Ferric-EN	1.39	161	65	0.41
VT5				
Alum-BL	4.84	739	285	0.39
Alum-EN	3.75	549	251	0.46
VT6				
Alum-BL	3.07	397	106	0.27
Alum-EN	2.48	233	83	0.36
Ferric-EN	2.03	237	61	0.26

(continued)

Table O.4 (continued)

Utility	DOC (mg/L)	DOXFP (µg/L as Cl ⁻)	UFC DOX (µg/L as Cl ⁻)	UFC/DOXFP (µg/µg)
VT7				
Alum-BL	2.89	375	305	0.81
Alum-EN	3.02	454	298	0.66
Ferric-EN	2.24	302	222	0.74
VT8				
Alum-BL	2.87	203	127	0.63
Alum-EN	2.00	151	93	0.62
Ferric-EN	1.88	113	55	0.49
VT9				
Alum-BL	3.22	404	253	0.63
Alum-EN	3.70	526	296	0.56
Ferric-EN	3.39	431	225	0.52

Table O.5

Comparison of Chlorine Residual and UFC DOX and UFC THM Yield
Based on DOC of Treated Waters

Utility	DOC (mg/L)	UFC Test Cl ⁻ Resid. (mg/L)	UFC THM (µg/L)	UFC DOX (µg/L as Cl ⁻)	UFC THM/ DOC (µg/mg)	UFC DOX/ DOC (µg/mg)
VT1						
Alum-BL	2.53	3.25/0.9	81	242	32	97
Alum-EN	2.25	3.0/0.9	70	224	32	102
VT2						
Alum-BL	1.32	2.0/1.3	42	126	32	97
Alum-EN	1.14	1.8/1.2	32	89	28	81
VT3						
Alum-EN	4.51	6.5/1.1	152	386	34	86
Ferric-BL	2.87	4.8/1.3	131	262	45	90
Ferric-EN	3.70	5.6/1.3	183	311	49	84
VT4						
Alum-EN	1.61	2.0/0.9	35	87	22	54
Ferric-BL	2.34	2.2/0.8	72	119	31	52
Ferric-EN	1.39	1.6/1.1	51	65	36	46
VT5						
Alum-BL	4.84	5.1/0.7	195	285	41	59
Alum-EN	3.75	4.4/0.9	126	251	33	66
VT6						
Alum-BL	3.07	3.8/0.7	118	106	38	34
Alum-EN	2.48	2.9/0.8	94	83	38	33
Ferric-EN	2.03	2.5/0.7	99	61	50	31

(continued)

Table O.5 (continued)

Utility	DOC (mg/L)	UFC Test Cl ⁻ Resid. (mg/L)	UFC THM (µg/L)	UFC DOX (µg/L as Cl ⁻)	UFC THM/ DOC (µg/mg)	UFC DOX/ DOC (µg/mg)
VT7						
Alum-BL	2.89	4.9/0.7	70	305	24	105
Alum-EN	3.02	5.5/0.8	69	298	23	99
Ferric-EN	2.24	4.5/0.85	53	222	25	101
VT8						
Alum-BL	2.87	4.0/1.3	144	127	50	44
Alum-EN	2.00	3.2/1.2	95	93	48	47
Ferric-EN	1.88	2.75/1.25	84	55	44	29
VT9						
Alum-BL	3.22	4.4/0.9	85	253	27	79
Alum-EN	3.70	4.7/1.3	94	296	25	80
Ferric-EN	3.39	4.4/1.3	64	225	19	66

APPENDIX P
GLOSSARY OF TERMS

GLOSSARY OF TERMS

ABL - Alum Baseline Treatment

AEN - Alum Enhanced Treatment

Al - Aluminum

AMW - Apparent Molecular Weight

AMWD - Apparent Molecular Weight Distribution

AOP - Alum Optimized Treatment

BL - Baseline Treatment

D/DBP Rule - Disinfectant/Disinfection By-Products Rule

DBPs - Disinfection By-Products

DOC - Dissolved Organic Carbon

DOM - Dissolved Organic Matter

DOX - Dissolved Organic Halides

DOXFP - Dissolved Organic Halide Formation Potential

DPD - N,N-Diethyl-p-Phenylendiamine

EN - Enhanced Treatment

FBL - Ferric Baseline Treatment

Fe - Iron

FEN - Ferric Enhanced Treatment

FOP - Ferric Optimized Treatment

FP - Formation Potential

HAA5 - Sum of Five Haloacetic Acids (mono-, di-, and trichloroacetic acids, and mono- and dibromoacetic acids)

HAA6 - Six of Six Haloacetic Acids (mono-, di-, and trichloroacetic acids, mono- and dibromoacetic acids, and bromochloroacetic acid)

HAAFP - Haloacetic Acid Formation Potential

HAAs - Haloacetic Acids

GLOSSARY OF TERMS (continued)

HANFP - Haloacetonitrile Formation Potential

HANs - Haloacetonitriles

HKFP - Haloketone Formation Potential

HKs - Haloketones

ICR - Information Collection Rule

MCL - Maximum Contaminant Level

MRDL - Maximum Residual Disinfectant Level

NOM - Natural Organic Matter

NPDOX - Non-purgeable Dissolved Organic Halides

NPDOXFP - Non-purgeable Dissolved Organic Halide Formation Potential

SDWA - Safe Drinking Water Act

SUVA - Specific Ultraviolet Absorbance (UV254/DOC)

THAAs - Total Haloacetic Acids

THMFP - Trihalomethane Formation Potential

THMs - Trihalomethanes

TOC - Total Organic Carbon

TOX - Total Organic Halides

TOXFP - Total Organic Halide Formation Potential

TTHMs - Total Trihalomethanes

UFC - Uniform Formation Condition

UV254 - Ultraviolet Absorbance at 254 nanometers

VITA

The author was born on January 11, 1967 in Waynesville, North Carolina to Rupert and Joy Hargette. He graduated from Tuscola High School in 1985. In 1989, he graduated from Virginia Polytechnic Institute and State University with a Bachelor of Science degree in Civil Engineering. He worked for Black & Veatch for three years prior to entering graduate school in 1992 in the Environmental Engineering Department at Virginia Polytechnic Institute and State University. The author is currently employed with Black & Veatch as a project engineer.

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