DISINFECTION BYPRODUCT CONTROL – BENCH TEST RESULTS FOR MCL COMPLIANCE

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ABSTRACT

The Disinfection Byproduct (DBP) results from recent sampling of the distribution system in Rock Hill, South Carolina, included several sites where the Total Trihalomethane (TTHM) concentrations were above 80 micrograms per liter (ug/L), while the TTHM results at the water treatment plant (WTP) were consistently below 80 ug/L. DBP precursors were passing through the WTP and reacting with residual chlorine in the distribution system. Raw water was treated in bench tests with enhanced coagulation, powered activated carbon and ozone; and the removal of precursors was compared using measurements of TTHM and Haloacetic Acids (HAA5) in Simulated Distribution Samples. The DBP data showed an increase in TTHM and to a lesser extent an increase in HAA5 versus storage time. The Simulated Distribution Samples were stored with a normal residual chlorine concentration for six days before sampling for TTHM and HAA5. Six days equals the maximum water age at the monitoring sites in the distribution system. Removal of TTHM and HAA5 precursors was greater with powdered activated carbon than with enhanced coagulation or ozone treatment.

INTRODUCTION

In 2008 the City of Rock Hill measured disinfection by-products (DBPs) at sixteen locations in the City's water distribution system. This monitoring was part of the Stage 2 Disinfection Byproducts Rule (DBPR) monitoring program. The maximum contaminant levels (MCL) for the DBPs were not changed by the Stage 2 DBPR. The MCLs are:

- Total Trihalomethanes (TTHM) [1] 80 micrograms/liter (ug/L)
- Haloacetic Acids (HAA5)[2] 60 ug/L

However, when the Stage 2 DBPR takes effect (1) the MCL must be achieved based on the running annual averages at each site[3] rather than the running annual average of all the sites[4] and (2) compliance monitoring must be performed at the monitoring sites that have the highest TTHM and HAA5 averages.

The TTHM concentrations in some of the recent samples were higher than the MCL and indicate that the City may have compliance problems when the Stage 2 DBPR requirements take effect unless treatment process changes are made at their WTP. Thus far HAA5 concentrations do not appear to be a future compliance issue (**Table 1 and Figure 1**).

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[1] TTHM is the sum of the concentrations four trihalomethanes: Chloroform, Bromoform, Bromodichloromethane and Dibromochloromethane

[2] HAA5 is the sum of the concentrations of five Haloacetic acids: Dibromoacetic acid, Dichloroacetic acid, Monobromoacetic acid, Monochloroacetic acid, and Trichloroacetic acid

[3] A Locational Running Annual Average (LRAA) is the average of four most recent quarterly samples at each site and computed every quarter.

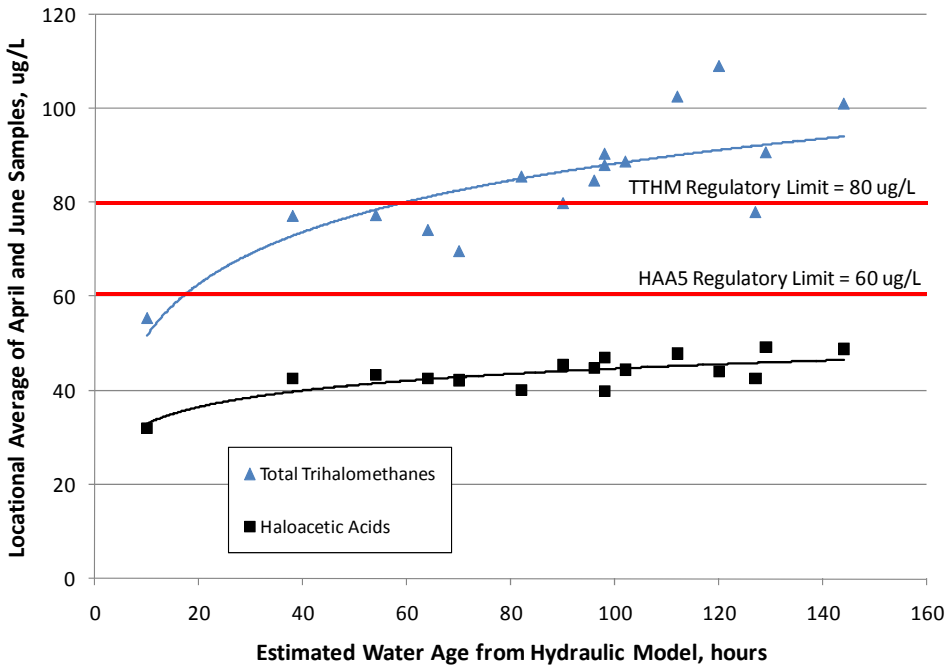
[4] A Running Annual Average (RAA) is the average of four most recent quarterly samples from all the sites and computed every quarter.

Table 1
Average DBPs at the Sixteen Monitoring Sites from April and June, 2008

Site ID	Water Age, hours	Average TTHM, ug/L	Average HAA5, ug/L
1	10	55.5	32.2
2	38	77.2	42.7
3	54	77.3	43.4
4	64	74.2	42.6
5	70	69.7	42.2
6	82	85.5	40.1
7	90	79.9	45.5
8	96	84.7	44.9
9	98	90.4	39.9
10	98	88.0	47.0
11	102	88.7	44.5
12	112	102.5	47.9
13	120	109.0	44.0
14	127	78.0	42.7
15	129	90.7	49.2
16	144	101.0	48.8

Free chlorine reacts with precursors to form disinfection by-products (DBPs). Moving the first application point of free chlorine downstream in the water treatment plant (e.g., after sedimentation) allows the treatment processes to remove some of the precursors before chlorine is introduced and this has been an effective method to reduce DBPs at many WTPs.

Figure 1
Disinfection Byproducts in Distribution System through June 2008



Precursors, which are not removed via treatment, will pass through the WTP and react with free chlorine (and free bromine) in the distribution system to form more DBPs. In the literature, the time of travel in the distribution system is often called "water age." Distribution system locations with longer water ages have longer chlorine contact times, which result in higher DBP concentrations. Since precursors can pass through many of the processes at a conventional WTP, simply delaying the application of free chlorine alone may not be sufficient without the removal of more precursors as part of an improved treatment system.

The average water age at each monitoring site in Rock Hill was estimated from a hydraulic model of the distribution system, which was developed previously by Wiedeman and Singleton, Inc. The locational averages of the first two sets of samples in 2008 and the computed water ages are shown in **Table 1** and **Figure 1**. As illustrated in **Figure 1**, the TTHM concentrations and to a lesser extent the HAA5 concentrations increase with contact time. The Site 1 is the Rock Hill Water Treatment Plant and has the shortest water age and the lowest DBP concentrations. Under the Stage 2 DBPR, the sites with the highest DBP averages will be used for future compliance monitoring. Please note that the MCL for TTHM is exceeded by the averages at nine sites and the MCL for HAA5 is not exceeded at any sites.

EXPERIMENTAL APPROACH

In February, 2009, a set of experiments were conducted to investigate potential methods to reduce the DBP precursors and to further reduce DBPs in the City's distribution system. The treatment methods investigated were:

- Enhanced Coagulation
- Powdered Activated Carbon (PAC)
- Ozone

Preliminary jar tests and batch tests were conducted for each treatment method investigated. Direct measurements of the various compounds that make up the DBP precursors are not practical for this type of study. However, the precursors can be characterized by surrogate analyses that include Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), Ultraviolet (UV) absorbance, Specific UV Absorbance (SUVA) and DBP formation potentials (THMFP and HAAFP).

In these experiments, the definitive measurement of the precursors was the formation of TTHM and HAA5 in simulated distribution system samples[5] (SDS-TTHM and SDS-HAA5). The formation of TTHM and HAA5 are strongly affected by reaction time, chlorine dose, temperature and pH. In the SDS samples these variables were controlled in a consistent manner with conditions that are expected to exist in the City's distribution system rather than the conditions listed in the method for formation potentials in ***Standard Methods***. Samples of finished water were incubated for six days, which is the longest water age in **Table 1**. The pH was controlled by addition of a phosphate buffer; however, the pH of the buffer was adjusted to match the WTP goal of pH 7.7 in the finished water rather than pH 7.0. Control of the free chlorine residual after the incubation period was provided by incubation of a series of bottles for each sample with a series chlorine doses. After the incubation period (six days), the bottles with

[5] APHA, 2005. ***Standard Methods for Examination of Water and Wastewater***, 21st Edition, Washington, D.C., Method SM 5710C, pp 5-68 & 5-69.

a final free chlorine residual between 0.7 and 1.5 mg/L were sampled for TTHM and HAA5 while the other bottles were discarded without sampling (versus 3 to 5 mg/L free chlorine in ***Standard Methods*** for formation potentials). The bottles were incubated at room temperature in cardboard boxes; hence the temperature was closer to worst case conditions in the summer.

Although TTHM, HAA5, SDS-THM and SDS-HAA5 could not be measured in a timely manner (i.e., independent laboratory testing required), the City has recently purchased and installed a TOC Analyzer in the lab at the WTP.[6] As such, the removal of DBP precursors and chemical dosages were evaluated by TOC removal in preliminary jar tests prior to SDS-TTHM and SDS-HAA5 testing.

The bench tests simulated the processes and chemical addition as illustrated in **Figure 2.** Full-scale operations samples were also taken concurrently from the existing plant so that results for "current operation" could be compared with the process modifications that were under consideration. (Please note that "current operation" includes the addition of free chlorine at the rapid mix tank due to start-up delays with the chlorine dioxide generator recently installed at the WTP). However, the WTP chlorine dioxide generator is expected to be operational and in continual service in the near future. In all bench tests, chlorine dioxide was added at the rapid mix instead of chlorine.

For enhanced coagulation, an optimal dosage of the current coagulant (DelPAC[7]) was selected using TOC removal results in the jar tests. Two "enhanced coagulation" bench tests were conducted with 30 liter samples (Runs 3B and 3C) and the same "enhanced coagulation" DelPAC dosage was used in all bench tests. After flocculation and settling, the settled sample was filtered through a 2 inch diameter glass column with 24 inches of filter media (sand and anthracite) from the plant filters at a rate of 4 gallons per minute per square foot. A chlorine dose of 2 milligrams per liter (mg/L) was added in all bench tests and the only difference between Runs 3B and 3C was that half of the 2 mg/L chlorine was added after settling and before the filtration in Run 3C, while 2 mg/L of free chlorine was added after filtration and no chlorine was added before filtration in Run 3B. It is important to note that Run 3C was the only bench test in which chlorine was added before filtration.

The bench tests with Powdered Activated Carbon (PAC) were conducted with "lake water" from the raw water pump station at Lake Wylie before chlorine dioxide addition (**Figure 2**). The City's existing pump station at Lake Wylie includes a pre-oxidation facility and the water from the pump station is currently dosed with approximately 0.5 mg/L chlorine dioxide before the "raw water" is transported through the 4.5 mile pipeline to the WTP. Powdered activated carbon is a reducing agent and will react with oxidants (e.g., chlorine, chlorine dioxide and ozone) and thereby increase the demand for these chemicals and decrease the effectiveness of the activated carbon;[8] therefore, "lake water" was used in the PAC bench tests instead of "raw water" at the WTP. The only difference between the bench tests in Runs 4A and 4B was that a higher PAC dose was used in bench test 4B.

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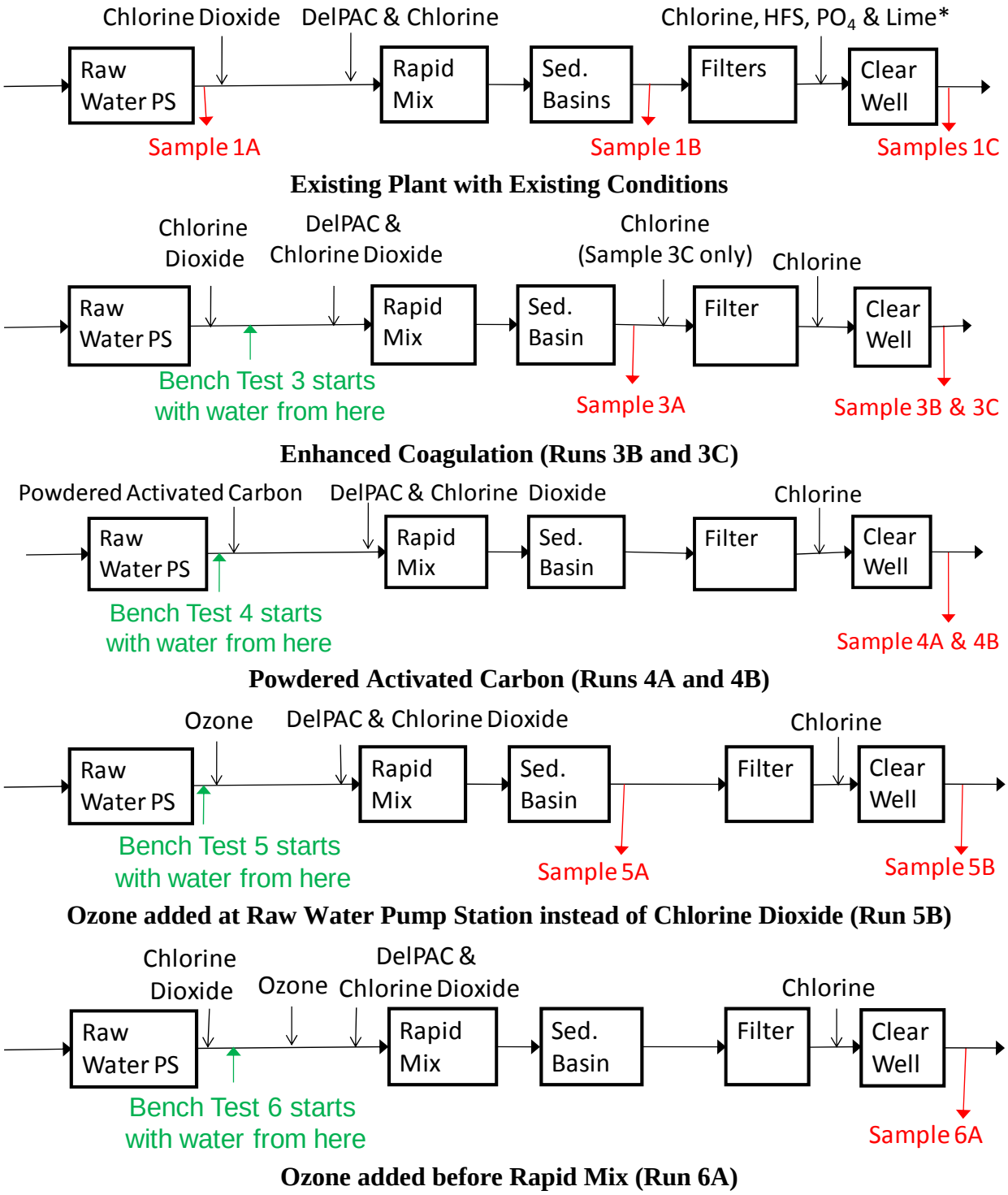
[6] Model Phoenix 8000 UV-Persulfate TOC Analyzer from Teledyne Tekmar.

[7] DelPAC 2500, Aluminum chloride hydroxide sulfate (polyaluminum chloride), from Delta Chemical Corporation, Baltimore, MD.

[8] AWWA, 1999. ***Water Quality & Treatment,*** 5th Edition, McGraw-Hill, New York, page 13.65.

Figure 2 - Diagram of Tested Processes and Sample Locations



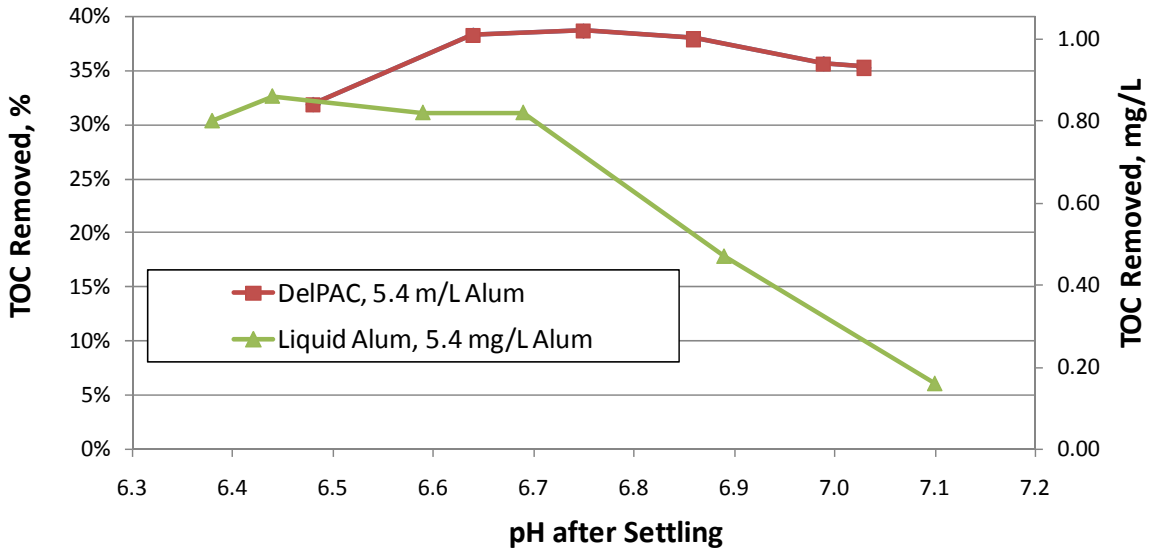
Two bench tests were conducted with ozone (Runs 5B and 6A). The difference between these tests was the ozone application point. In Run 5B, the ozone was added to the "lake water" before the chlorine dioxide addition; hence, Run 5B was intended to simulate the process with an ozone generator at the raw water pump station at the lake and no chlorine dioxide addition at the raw

water pump station. In Run 6A, the ozone was added to "raw water" after treatment with chlorine dioxide and was intended to simulate the process with the ozone generator at the WTP with ozone applied after the long raw water pipeline and immediately before the existing rapid mix. The ozone dose was 4.5 mg/L in both bench tests 5B and 6A.

JAR TEST RESULTS

Some preliminary jars tests were conducted before the bench tests to compare doses, pH, etc. prior to SDS-TTHM and SDS-HAA5 testing. DelPAC was diluted to a 1% solution (v/v)[9] and 5 mL of the 1% dosing solution was then added to six 2-liter beakers containing 1.5 liters of raw water. Varying amounts of sodium hydroxide was added to five of the test beakers to adjust the pH. The settled water TOC was similar throughout the pH range from 6.5 to 7.1 with slightly higher removals in the pH range of 6.65 to 6.85 (**Figure 3**).

Figure 3
Comparison of TOC Removal with Liquid Alum and DelPAC



Liquid Alum, which was formerly used at the City's WTP, was also compared to DelPAC's performance as shown in **Figure 3**. Liquid Alum was diluted to form a dosing solution with the same alum concentration as the DelPAC dosing solution.[10] 5 mL of the dosing solution was added to 1.5 liters of raw water in six beakers. TOC removal was greater between pH 6.4 and 6.7 than at pH 6.9 and 7.1. Both sets of beakers had an alum dose of 5.4 mg/L as Al_2O_3 or 31 mg/L as $Al_{2(}SO_4)_3$-$14H_2O$. The jar tests with DelPAC had higher TOC removals and were less sensitive to pH. It was concluded that further tests should be conducted with DelPAC and not liquid alum.

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[9] (v/v) = volume/volume. 10 mL of DelPAC was diluted to 1.000 liter with deionized water. DelPAC 2500 has a concentration of 12.5% Al_2O_3 (Aluminum Oxide) and a density of 1.29 grams per milliliter.

[10] 14.6 mL of liquid alum was diluted to 1.000 liter with deionized water. The liquid alum has a concentration of 8.3% Al_2O_3 and a density of the 1.33 grams per milliliter. The concentrations of DelPAC and liquid alum dosing solutions were 1,610 mg/L alum as Al_2O_3.

The DelPAC dose was varied in another jar test (**Figure 4** and **Table 2**). At the time of the tests, the DelPAC dose in full-scale WTP operation was 4.6 mg/L as Al_2O_3. The dosage was varied in six beakers and the TOC was compared to the TOC before treatment. The 10.8 mg/L dose appeared to be near the point of diminishing returns and was selected as the dose in the bench tests. This DelPAC dose is 2.3 times the current dose at the Rock Hill WTP.

Figure 4
TOC Removal by Enhanced Coagulation Dose

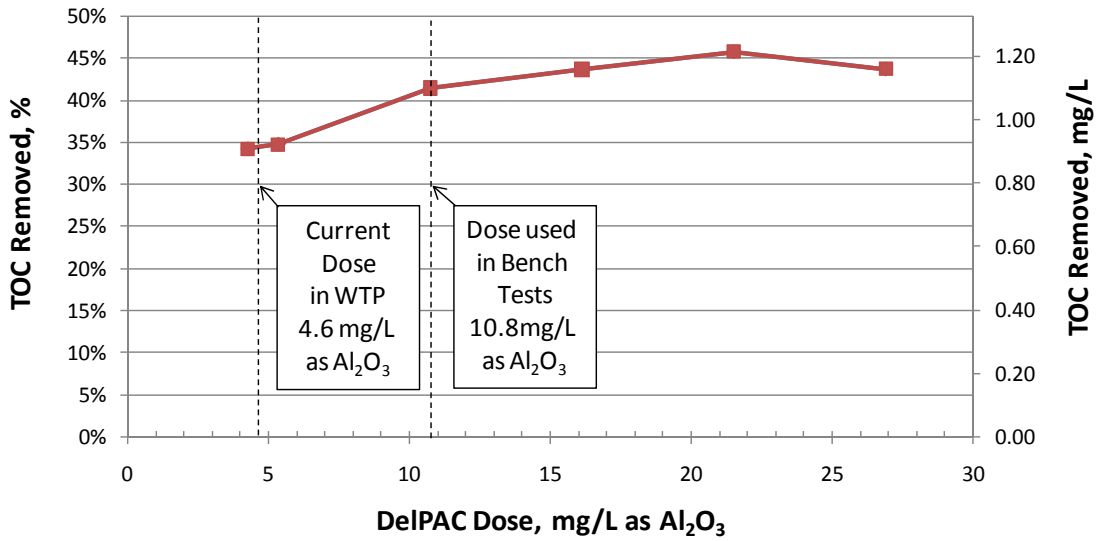


Table 2 – TOC Removed in DelPAC Jar Test

Jar	Sample Volume, L	PACl Dose, mL	PACl Dose, mg/L as Al_2O_3	Final pH	TOC, mg/L	TOC Removal, mg/L	TOC Removal, %
		0	0		2.656		
1	1.5	4	4.3	7.01	1.748	0.909	34.2%
2	1.5	5	5.4	6.90	1.734	0.923	34.7%
3	1.5	10	10.8	6.87	1.556	1.100	41.4%
4	1.5	15	16.1	6.75	1.498	1.158	43.6%
5	1.5	20	21.5	6.60	1.442	1.214	45.7%
6	1.5	25	26.9	6.53	1.497	1.160	43.7%

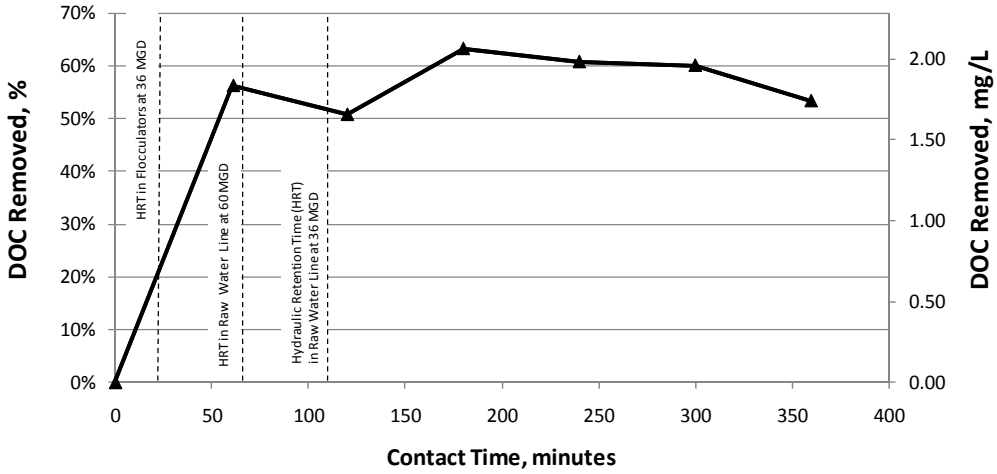
Activated carbon is manufactured from carbonaceous sources such as lignite, peat, wood and coal. The surface of the carbon absorbs organic molecules (e.g., DBP precursors). High absorption capacity is obtained by creating a large surface area per gram, which means a large number of pores. The finished material is honeycombed with pores and is used in WTPs in two forms: powdered activated carbon (PAC) and granular activated carbon (GAC). Different manufactured carbons have higher capacities and slightly different selectivity. A bench study or full scale process using GAC would likely require a separate treatment vessel. One promising powdered activated carbon was selected for study in this project. [11]

[11] Calgon Carbon Corporation indicated that type WPH had the best performance but may require more contact time.

A carbon slurry was made using 15 grams of PAC and diluted to 1.0 liter with deionized water. The slurry was stirred on a magnetic stirrer to keep the carbon in suspension while portions were removed and added to six beakers. The beakers were started at the same time and mixed on a jar test apparatus. After one hour of mixing, DelPAC was added to one beaker for coagulation, flocculation and settling before filtration with a membrane filter and measurement of Dissolved Organic Carbon (DOC).[12] After each hour another beaker was coagulated, flocculated and settled (**Figure 5**). The data indicate that a contact time of one hour is sufficient for significant DOC removal and that additional contact did not have a large effect on the DOC removal. The PAC bench tests were mixed for one hour before coagulation with DelPAC. The DelPAC dose in the PAC tests was 10.8 mg/L as Al_2O_3.

The samples from the jar tests with PAC were filtered before analysis in the TOC Analyzer because some of the carbon did not coagulate and remained in suspension. It was speculated that if the PAC entered the TOC Analyzer it would be measured as TOC/DOC and might absorb to some of the tubing in the analyzer's tubing and contaminate future samples when the PAC desorbed from the tubing. It was also noted that black carbon could be seen visually on the membrane filters when the PAC samples were filtered.

Figure 5
DOC Removal by PAC with Increased Contact Time



The membrane filters were 4.7 centimeter discs and were held in a glass filter holder. Although there were many potential sources of contamination by trace amounts of organic carbon during testing, the membrane filters appeared to consistently add TOC to the samples. Several filter blanks were filtered after rinses with increasing amounts of deionized water and are summarized in **Table 3**. All filter blanks increased the measured TOC; however, the glass fiber filters resulted in less TOC than the membrane filters and were used in the last jar test instead of the membrane filters. The bench scale filtration apparatus, which included contact with several

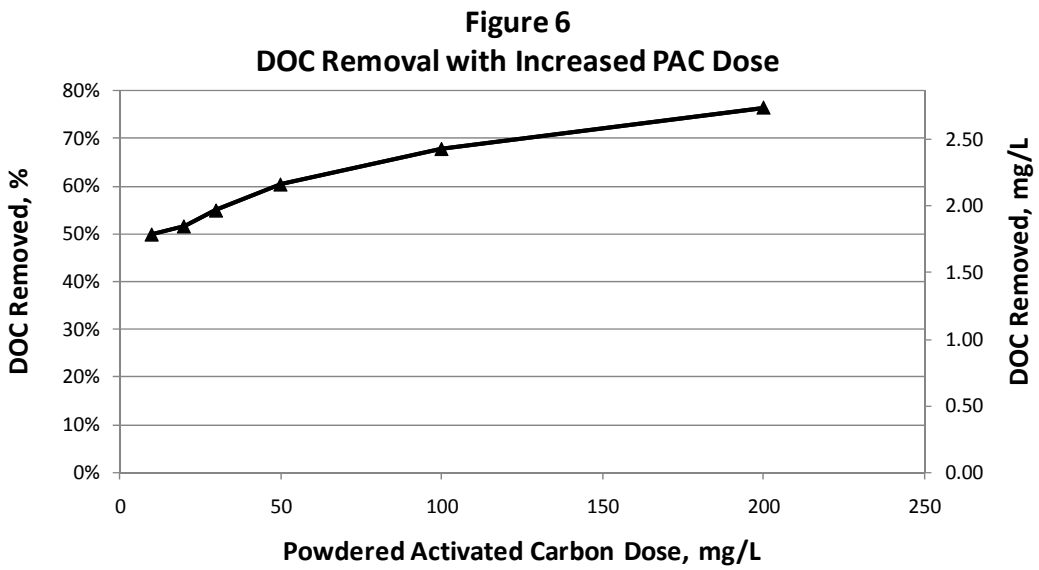
[12] If the sample was filtered by membrane or glass fiber filters prior to measurement of TOC, then the results are reported as Dissolved Organic Carbon (DOC) instead of TOC.

plastic parts, did not increase the TOC in the deionized water more than the other filtration methods.

Table 3 - Summary of Filtration Blanks

Sample ID	Description	Filter Material	Volume of Water used in Rinse	Measured TOC/DOC, mg/L
C1	Deionized Water Prior to Filtration	none	n/a	0.278
C2	Filter Blank with no rinse	Nylon Membrane	0 mL	2.117
C3	Filter Blank	Nylon Membrane	100 mL	0.431
FB0	Deionized Water Prior to Filtration	none	n/a	0.2124
FB1	Filter Blank with no rinse	Nylon Membrane	0 mL	1.0175
FB2	Filter Blank	Nylon Membrane	1 liter	0.2971
FB3	Filter Blank	Nylon Membrane	2 liters	0.2752
FB4	Filter Blank	Nylon Membrane	3 liters	0.4700
FB5	Deionized Water Prior to Filtration	none	n/a	0.2018
FB6	Filter Apparatus without filter	none	1 liter	0.2351
FB7	Filter Blank	Glass Fiber	100 mL	0.3231
FB8	Filter Blank	Glass Fiber	1 liter	0.2707
FB9	Deionized Water Prior to Filtration	none	n/a	0.1929
FB10	Deionized Water after pumping to top of filtration column	none	n/a	0.2249
FB11	Filter Blank in Filtration Column	Anthracite & Sand	10 liters	0.3062
FB12	Filter Blank in Filtration Column	Anthracite & Sand	20 liters	0.3144

The last jar test was conducted with varying doses of PAC. The dose response curve for PAC was expected to flatten out at a higher dosage, but the removal of DOC continues to increase as the dosage increases (**Figure 6**). Doses of 10 mg/L and 20 mg/L PAC were used in the PAC bench tests based on the practical limitations of PAC addition into the full scale plant.



OZONE TREATMENT

Ozone is generated as a gas and is a gas at room temperatures. Ozone is more soluble in water than oxygen and less soluble than chlorine. Ozone is the most powerful oxidant used in water treatment and will oxidize bromide to bromine and bromate; and chloride to chlorine. For several reasons, ozone is unstable and must be generated at the point of use. An ozone treatment system must generate ozone and then inject the ozone gas into the water with enough efficiency to reduce the loss of ozone gas that does not dissolve. Ozone can only be used as a primary disinfectant since it does not produce a residual.

Two small ozone generators were purchased to conduct the tests. The first generator did not produce any ozone and the second generator did not work reliably. A preliminary test was conducted with the second ozone generator in which deionized water was treated with ozone gas through a diffuser for 15 hours. The ozone concentration in the deionized water increased for several hours to a maximum of 0.68 mg/L, but thereafter the ozone concentration decreased. After 15 hours of continuous operation the ozone measured only 0.28 mg/L in the deionized water.

A manufacturer of full scale ozone generators for WTPs offered assistance.[13] Subsequently, "lake water" and "raw water" were taken to a local facility where ozone was added to the samples. This generator produced a stock ozone stock solution with a concentration of 45 mg/L ozone in about one hour. One liter of the stock solution was used to treat ten liter samples for a dose of 4.5 mg/L ozone based on the original volume of sample. According to an EPA Guidance Manual, THMFPs have been reduced by 3% to 20% with ozone doses from 0.2 mg/L to 1.6 mg Ozone per mg TOC.[14] The dosage in Run 5B was 1.25 mg Ozone per mg TOC. The DBP

[13] ITT Industries, Wedeco, Inc., 14125 South Bridge Circle, Charlotte, NC, 28273, contact: Ronnie Bemus, 704-409-9704.

[14] USEPA, 1999. ***Alternate Disinfectants and Oxidants Guidance Manual,*** EPA 815-R-99-014, Office of Water, April, 1999, page 3-17.

results for the ozone bench tests were corrected for dilution of the ten liter samples by one liter of stock solution. Deionized water at the manufacturer's facility measured 0.30 mg/L TOC. TOC results were also corrected for the dilution by one liter of deionized water.

Bromide in raw water sources at WTPs utilizing ozone can be converted to bromate and bromine; and contribute to higher concentrations of brominated organics (i.e., disinfection byproducts) in the finished water; therefore, bromide analysis was conducted in the raw water that was used from Lake Wylie. No bromide was detected above the detection limit of 0.5 mg/L.

CHANGE IN DBPS OVER TIME

The samples collected from the full scale plant included a series of finished water samples that were incubated for time periods other than the period used in the SDS formation potential tests (**Table 4**). These samples were taken from the first tap after the clear well. After a predetermined period, each bottle was opened and sampled with volatile organic compound (VOC) sample vials that had compounds to stop the formation of additional DBPs.[15] Data in **Figure 7** confirms that the TTHMs increase significantly with the length of the incubation period (water age). Although the typical water age in Rock Hill's distribution system is expected to be 6 days or less, the water age in surrounding water distribution systems purchasing wholesale water from the City may be longer than 6 days.

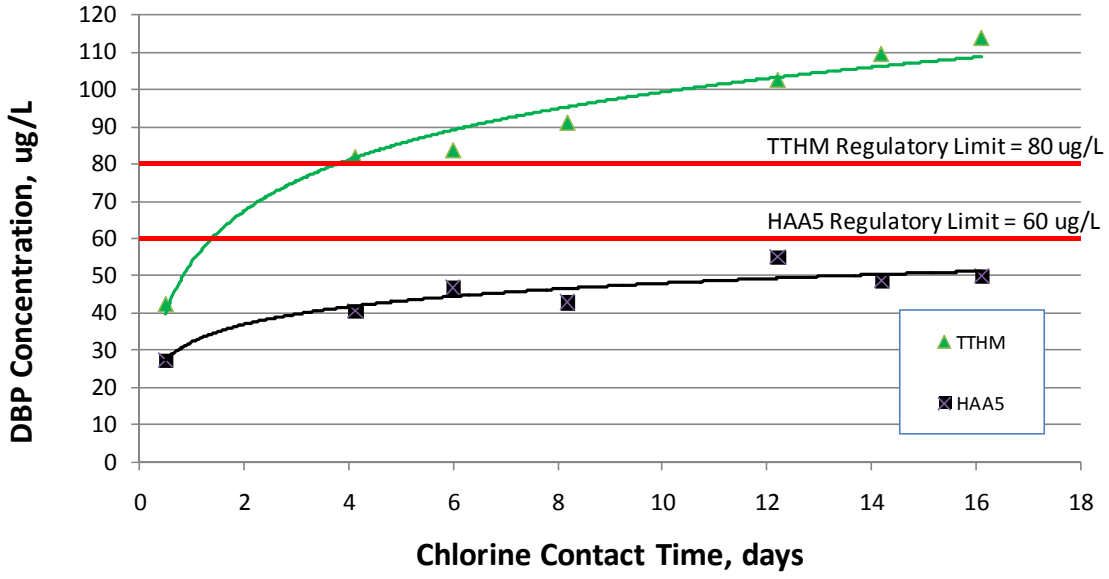
Table 4 - Change in DBPs over Time

Sample ID	Incubation Period, days	Final Free Chlorine, mg/L	Final Total Chlorine, mg/L	Measured TTHM, ug/L	Measured HAA5, ug/L
1C	0.5	1.83	2.04	42.1	27.3
2A	4.1	1.36	1.47	81.6	40.6
1CFP[16]	6.0	1.21	1.37	83.5	46.7
2B	8.2	1.23	1.28	90.9	42.8
2C	12.2	0.72	0.88	102.4	54.9
2D	14.2	0.91	1.03	109.4	48.7
2E	16.1	0.78	0.87	113.7	49.8

[15] Sodium thiosulfite was used to preserve THMs and ammonium chloride was used to preserve HAAs.

[16] The six day sample (1CFP) was treated the same as the other "FP" samples and had a phosphate buffer to maintain the pH, but needed no additional chlorine to maintain a free chlorine residual of 1.2 mg/L after six days.

Figure 7
Increase in DBPs with Water Age



BENCH TEST RESULTS

All of the finished water DBPs from the existing WTP and the alternatives were below the MCLs (**Table 5**). These finished water samples were intended to simulate the finished water from the full scale plant under alternate conditions; however, the low DBP results during the bench testing were the result of the short retention time in the clear well (2 hours). In addition, no chlorine was added before coagulation and in most cases no free chlorine was added before filtration (i.e., travel time in distribution system was simulated by the SDS-TTHM and SDS-HAA5 samples). The bench tests with ozone had the lowest concentrations of DBPs. Since the DBPs in the samples from the existing WTP and all the alternatives were within the MCL limits, the removal of the precursors (TOC and SUVA removals) should be considered when reviewing the DBP data.

Table 5
Summary of the DBP Data from the Bench Tests

Description	TTHM, ug/L	HAA5, ug/L	TTHM Reduction	HAA5 Reduction
Existing WTP (1C)	42.1	27.3	na	na
Enhanced Coagulation (3B)	10.2	7.4	76%	73%
Enhanced Coagulation (3C)	15.3	14.6	64%	47%
Powdered Activated Carbon 10 mg/L (4A)	9.2	6.2	78%	77%
Powdered Activated Carbon 20 mg/L (4B)	9.3	6.2	78%	77%
Ozone Addition at Lake (5B)	5.6	4.0	87%	85%
Ozone Addition at WTP (6A)	6.9	8.1	84%	70%

The removal of the DBP precursors is summarized in **Table 6**. The existing WTP removed 46% of the TOC on the day of the tests. TOC removal in all of the treatment alternatives was higher than 46%. Powdered activated carbon provided the highest TOC removal (54%). Although the ozone bench tests had the same coagulant dose as the enhanced coagulation bench tests, the ozone tests did not remove more TOC. The Ozone alternatives removed more SUVA (73-80%) than the other alternatives.[17]

As expected, however, the formation of DBPs after six days gave a different picture of the precursor removals. Activated carbon had the lowest formation of TTHM and HAA5 after six days. Enhanced coagulation was also very effective. Ozone as tested in this study reduced the DBPs after six days, but not as much as the other alternatives. SCDHEC's optimization goals for DBPs are 60 ug/L for TTHM and 40 ug/L for HAA5 concentrations, which were achieved in the simulated distribution system (SDS) samples for Runs 3B, 3C, 4A and 4B.

Table 6
Summary of Precursor Removal Data

[17] The TOC data instead of DOC was used to calculate the SUVA since the filtered TOC was higher in most cases (**Table A2**).

Description	TOC Removal	SUVA Removal	SDS-TTHM ug/L	SDS-HAA5 ug/L	SDS-TTHM Reduction	SDS-HAA5 Reduction
Existing WTP (1C)	46%	65%	83.5	46.7	na	na
Enhanced Coagulation (3B)	50%	63%	56.1	21.2	33%	55%
Enhanced Coagulation (3C)	49%	60%	59.4	31.3	29%	33%
Powdered Activated Carbon 10 mg/L (4A)	53%	63%	46.2	17.1	45%	63%
Powdered Activated Carbon 20 mg/L (4B)	55%	63%	45.3	16.7	46%	64%
Ozone Addition at Lake (5B)	48%	83%	74.8	31.0	10%	34%
Ozone Addition at WTP (6A)	49%	76%	73.5	36.0	12%	23%

CONCLUSIONS

1. **Ozone Treatment:** Precursor removal rates with ozone were not as favorable as other treatment methods; however, it is hypothesized that ozone oxidized larger organic molecules into smaller organic molecules without reducing the TOC. The smaller molecules are most likely degradable and are Assimilable Organic Carbon (AOC), which may be removed biologically in biologically active filters. If treatment with ozone is pursued further, a pilot study is needed. However, based on our bench scale results and the full-scale facilities required to feed ozone, we recommend the City consider other treatment methods to remove DBP precursors.

2. **Application of free chlorine to the filter influent:** Comparison of the results in Bench Tests 3B and 3C indicate that addition of chlorine to the top of the filter results in higher DBPs in the finished water and higher DBPs after six days in the distribution system. The use of free chlorine ahead of the filters will generate more DBPs than no free chlorine before the clear well; however, we recommend the use of chlorine in the filters to retain manganese on the filter media using the "naturally occurring greensand effect."[18] This recommendation is based on bench scale results which demonstrate that DBP concentrations can be maintained below MCL target limits if the addition of free chlorine is delayed until after the sedimentation process.

3. **Enhanced Coagulation:** Bench scale results show that utilizing higher DelPAC doses (i.e., enhanced coagulation) will significantly reduce the DBPs in the City's distribution system. As such, we recommend testing enhanced coagulation on a full scale basis by increasing the

[18] Knocke, et al. 1990. ***Removal of Soluble Manganese from Water by Oxide Coated Filter Media,*** AWWARF Research Foundation, AWWA, Denver.

DelPAC dose to at least 10 mg/L as Al_2O3 and taking a set of sixteen sample pairs two weeks after the change is made. Simultaneously, lime should be added as needed at the rapid mix to maintain a settled water pH in the range of 6.6 to 6.9, while monitoring settled water turbidity to make sure the DelPAC dose is appropriate.

4. **Powdered Activated Carbon (PAC):** PAC was the most effective treatment process utilized during bench testing to remove DBP precursors, with simulated distribution system (SDS) results for DBP concentrations being well below SCDHEC's optimization goals of 60 ug/L for TTHMs and 40 ug/L for HAA5s. Additionally, the data indicate that utilizing a combination of PAC and enhanced coagulation will significantly reduce DBP concentrations in the distribution system. Due to the available contact time in the City's 54" raw water main and the ability of PAC to help control taste and odor compounds, we recommend that a PAC feed system be installed at the City's Raw Water Pump Station. The capital costs for installing a PAC feed system are minor compared to other alternatives (e.g., ozone) and the PAC feed rates can be minimized (or eliminated) if enhanced coagulation provides adequate precursor removal.