

SECTION 51 45 15
PHASE 2 BENCH SCALE REPORT

PART 1 GENERAL

BUREAU OF RECLAMATION
TECHNICAL SERVICE CENTER



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CUTTER RESERVOIR WATER TREATMENT
PHASE 2 BENCH-SCALE TESTING

FINAL

BENCH-SCALE TEST RESULTS
REPORT

January 23, 2014

HDR-CDM Joint Venture

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- Appendix A Test Plan
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List of Acronyms

ANSI	American National Standards Institute
AOC	assimilable organic carbon
APHA	American Public Health Association
AWWA	American Water Works Association
BAF	biologically active filtration
BCAA	bromochloroacetic acid
BDCM	bromodichloromethane
BDOC	biodegradable organic carbon
°C	degrees Celsius
CaCO ₃	calcium carbonate
CBXA	carboxylic acid
DBAA	dibromoacetic acid
DBCM	dibromochloromethane
DBM	dibromomethane
DBP	disinfection byproduct
DCAA	dichloroacetic acid
DCM	tribromomethane
DI	deionized
DOC	dissolved organic carbon
EBCT	empty-bed contact time
EPA	Environmental Protection Agency
FCCO	Reclamation Four Corners Construction Office
FeCl ₃	ferric chloride
ft ²	square feet
<i>G</i>	velocity gradient
GAC	granular activated carbon
g/hr	grams/hour
gpm	gallons per minute
gpm/ft ²	gallons per minute per square foot
H ₂ SO ₄	sulfuric acid
HAA	haloacetic acid
HAA5	five regulated haloacetic acids
HAAFP	haloacetic acid formation potential
HCl	hydrochloric acid
hrs	hours
JV	joint venture
k*	ozone decay constant
L/mg/m	liters per milligram per meter
LOX	liquid oxygen
LRAA	locational running annual average
MBAA	monobromoacetic acid
MCAA	monochloroacetic acid
MCL	maximum contaminant level

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mg	milligrams
mgd	million gallons per day
mg/L	milligrams per liter
mL	milliliters
mL/min	milliliters per minute
mm	millimeters
N	nitrogen
Na ₃ PO ₄	sodium phosphate
NGWSP	Navajo Gallup Water Supply Project
NH ₄ Cl	ammonium chloride
NOM	natural organic matter
NSF	NSF International
NTU	nephelometric turbidity units
O ₃	ozone
PAC	powdered activated carbon
PCU	platinum-cobalt units
PTFE	polytetrafluoroethylene
R ²	coefficient of determination
Reclamation	Bureau of Reclamation
scfm/ft ²	standard cubic feet per minute per square foot
SDS	simulated distribution system study
SDS-HAA	simulated distribution system study of haloacetic acids
SDS-THM	simulated distribution system study of trihalomethanes
sec ⁻¹	inverse seconds
SM	Standard Methods
SOR	surface overflow rate
s.u.	standard units
SUVA	specific UV absorbance
TBM	tribromomethane
TCCA	trichloroacetic acid
TCM	trichloromethane
THMFP	trihalomethane formation potential
TOC	total organic carbon
TSC	Reclamation Technical Services Center
TTHM	total trihalomethanes
µg/L	micrograms per liter
UNM	University of New Mexico
UV	ultraviolet
UV ₂₅₄	ultraviolet light at a wavelength of 254 nanometers
WTP	water treatment plant
l/cm	inverse centimeters

Executive Summary

The Cutter Lateral of the Navajo Gallup Water Supply Project will deliver treated, potable water from the Cutter Reservoir to users in the Jicarilla Apache and Navajo Nations. The Cutter Lateral, when completed, will consist of a lengthy network of pipelines and pump stations along the eastern portion of the NGWSP and will include a new 5.4 million gallon per day (mgd) water treatment plant (WTP) that will provide treated water from the Cutter Reservoir. The Bureau of Reclamation has retained the HDR-CDM Smith Joint Venture (JV) Team to assist with investigating water treatment processes for the Cutter Reservoir water treatment plant. The proposed Reclamation water treatment system includes enhanced coagulation, flocculation, sedimentation, ozonation, and biologically active filtration (BAF), followed by disinfection with ultraviolet (UV) irradiation and possibly free chlorine to meet Federal and State drinking water standards.

The investigation consisted of collecting a water sample from the Cutter Reservoir, which was completed on August 24, 2014, and shipping the water to the JV Team's laboratory in Bellevue, Washington for bench-scale testing. The objective of the testing was to optimize the coagulation, ozonation, and BAF processes to meet Safe Drinking Water Act Disinfection By-Products (DBPs) standards. The treated waters were analyzed for several physical and water quality parameters to determine the effectiveness of varying coagulant and ozone dosages as well as BAF contact times. The principal parameters included dissolved organic carbon (DOC), total trihalomethanes (TTHM), the five regulated haloacetic acids (HAA5), carboxylic acids (CBXAs), and assimilable organic carbon (AOC). Reclamation established the following treatment criteria during previous bench-scale testing completed by the JV team, which was also used for this optimization testing:

- DOC of ≤ 1.5 mg/L.
- AOC of ≤ 100 $\mu\text{g/L}$.
- Trihalomethane formation potential (THMFP) of ≤ 64 $\mu\text{g/L}$ (80 percent of the maximum contaminant level [MCL]).
- Trihalomethane simulated distribution study (SDS-TTHM) of ≤ 64 $\mu\text{g/L}$.
- Haloacetic acid formation potential (HAAFP) of ≤ 48 $\mu\text{g/L}$ (80 percent of the MCL).
- Haloacetic acid simulated distribution study (SDS-HAA) of ≤ 48 $\mu\text{g/L}$.

The pre-treatment testing consisted of evaluating ferric chloride coagulant dosages ranging from 20 to 45 mg/L and pH levels ranging from 7.5 to 6.0. Pre-oxidation with 0.5 mg/l ozone was also evaluated as part of the pre-treatment testing. The pre-treatment testing determined that depressing the pH from the ambient 7.6 to as low as 6.0 and adding 20 to 30 mg/L of ferric chloride was optimal in terms of the lowest TTHM and HAA5 formation. The benefit of depressing pH was greater than increasing coagulant dosages. Pre-treating the water at a lower pH 6.0 and 20 mg/L ferric chloride resulted in lower THMFP and HAAFP results than water treated at pH 7.5 and 30 mg/L ferric chloride. The testing also determined that pre-oxidizing the water with 0.5 mg/L ozone had no significant benefit in treating the water. Ferric chloride pre-treatment only at a dosage up to 45 mg/L was not capable of meeting the treatment criteria; therefore, ozone and BAF would be required.

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Based on the pre-treatment results, Reclamation staff and the JV Team agreed to advance the testing using waters that were pre-treated with 20 mg/L ferric chloride at pH 6.0 (designated as Settled Water A) and with 30 mg/L ferric chloride at pH 6.6, which was the resulting pH after ferric coagulation, (designated as Settled Water B). The DOC was reduced from 2.4 - 2.6 mg/L in the untreated water sample to 1.5 - 1.6 mg/L in the treated water under these conditions.

The two waters (Settled Water A and B) were ozonated at ozone:DOC ratios of 0.5:1.0, 1.0:1.0, and 1.5:1.0 and then passed through bench-scale BAF columns. DOC removal was greater at all ozone:DOC ratios for Settled Water A when compared to Settled Water B, whereas there was minimal difference observed for DOC removal when BAF empty bed contact times (EBCT) varied between 5.0 minutes to 12.5 minutes. Based on the results of the ozone/BAF testing, Reclamation and the JV agreed to conduct subsequent THMFP, SDS-THM, HAAFP, SDS-HAA, AOC, and CBXA testing for the following samples:

1. Settled Water A, ozone:DOC of 0.5:1.0, and 5 minute EBCT
2. Settled Water A, ozone:DOC of 1.0:1.0, and 5 minute EBCT
3. Settled Water A, ozone:DOC of 1.0:1.0, and 10 minute EBCT
4. Settled Water B, ozone:DOC of 1.0:1.0, and 5 minute EBCT

The analysis determined that only the Settled Water A at an ozone:DOC ratio of 0.5:1.0 and 5 minute EBCT had THMFP results below the treatment criteria of 64 µg/L; the other three analyzed waters had THMFP results exceeding the treatment criteria but were below the TTHM MCL. The sample with the highest THMFP result was Settled Water B (30 mg/L ferric chloride at pH 6.6). Correspondingly, the waters with the lowest THMFP also had the lowest SDS-THM results. In comparison, all four water samples analyzed for HAAFP and SDS-HAA had HAA5 concentrations below the test criteria.

The AOC analysis was determined to be inconclusive. The analysis found that the water treatment process that produced the lowest TTHM, HAA5, and DOC had the highest AOC concentrations (1,400 µg/L), and that there were no understandable trends with regards to ferric chloride dosages, pH, ozone:DOC ratios, or EBCT. The lowest detected AOC concentration was still approximately twice the 100 µg/L AOC treatment criteria.

In comparison, analysis of CBXAs indicated that oxalic acid provided the clearest explanation of ozone/BAF performance and was a good surrogate for this test for disinfection byproduct precursors. Consistent correlations between increasing EBCT and decreasing oxalic acid concentrations were established. The other CBXAs examined (acetic acid, formic acid, and pyruvic acid) were detected but the correlation between their concentrations and EBCT was not as strong as with oxalic acid. The testing found that 7.5 minutes EBCT was required for complete oxalic acid removal.

The testing results were used to establish design criteria for the 5.4 mgd Cutter WTP using ferric coagulation, pH depression, ozonation, BAF, free chlorination, and corrosion control chemical adjustment. Based on the bench-scale SDS testing, it is anticipated that the full-scale WTP will reach a TTHM concentration of 64 µg/L by 11 to 12 days of water age during the summer and longer water ages can likely occur during other seasons when cooler water temperatures are expected.

1.0 Introduction

The Cutter Lateral of the Navajo Gallup Water Supply Project (NGWSP) will deliver treated, potable water from the Cutter Reservoir to users in the Jicarilla Apache and Navajo Nations. The Cutter Lateral, when completed, will consist of a lengthy network of pipelines and pump stations along the eastern portion of the NGWSP and will include a new 5.4 million gallon per day (mgd) water treatment plant (WTP) that will provide treated water from the Cutter Reservoir. The treated water may experience a water age of up to 10 days. The Bureau of Reclamation (Reclamation) is investigating water treatment processes for the Cutter Reservoir WTP that include enhanced coagulation, flocculation, sedimentation, ozonation, and biological active filtration (BAF), followed by disinfection with ultraviolet (UV) irradiation and possibly free chlorine to meet Federal and State drinking water standards.

The HDR-CDM Smith Joint Venture (JV) Team previously conducted bench-scale testing for Reclamation on the ozone and BAF treatment processes with Cutter Reservoir water samples, which is considered Phase 1 testing. The bench-scale test results determined that using the ozone/BAF treatment process to remove natural organic matter (NOM) was a feasible treatment process. The Phase 1 test results are documented in the January 2014 “Cutter Reservoir Water Treatment Bench-Scale Testing: Final Bench-Scale Test Results Report”. The Phase 1 testing showed that ferric coagulation/flocculation followed by sedimentation was an effective pre-treatment technique to remove a significant portion of the NOM and the addition of biologically active filtration subsequent to the sedimentation process removed much of the remaining NOM. This removal resulted in reduced concentrations of dissolved organic carbon (DOC), greater finished water stability, lower disinfection byproducts (DBP) formation potential, and high water quality compared to the raw water. Table 1 lists the Phase 1 testing criteria and associated results. The testing for the simulated treatment process was based on the following conditions specified by Reclamation:

- 20 milligrams/liter (mg/L) ferric chloride (FeCl_3) coagulant
- No pH adjustment
- 1.5:1 ozone:TOC ratio
- Disinfection with free chlorine

An empty bed contact time (EBCT) of 10 minutes was selected in collaboration with Reclamation based on JV experience with the ozone/BAF treatment process. The results of the testing showed that the treatment process was able to meet the DOC treatment criteria but did not meet the assimilable organic carbon (AOC) objective and slightly exceeded the total trihalomethanes (TTHM) and five regulated haloacetic acids (HAA5) criteria.

Table 1. Phase 1 Testing Criteria and Results

Finished Water Parameters	Phase 1 Testing Criteria	Was Phase 1 Criteria Met in Testing?	Will Phase 1 Criteria be Met with Optimization?
Dissolved Organic Carbon (DOC)	≤1.5 mg/L	Yes, 1.5 mg/L	Yes
Assimilable Organic Carbon (AOC)	≤100 µg/L	No, 300 µg/L	Not Likely
Trihalomethanes Formation Potential (THMFP)	≤64 µg/L*	No, 82 µg/L	Yes
Five Regulated Haloacetic Acids Formation Potential (HAAFP)	≤48 µg/L*	No, 65 µg/L	Yes
Note: * - 80% of the locational running annual average maximum contaminant level. Source: Modified from Reclamation report “Cutter Reservoir Water Treatment Bench-Scale Testing: Final Bench-Scale Test Results Report”, January 2014.			

Table 1 was included in the final Phase 1 report and also shows a column indicating the JV Team’s qualitative assessment for treatment optimization to meet Phase 1 objectives. Reclamation contracted with the JV Team to conduct enhanced bench scale testing by varying the specified test conditions from Phase 1 and provide design criteria for the full scale treatment facility. The objective of the Enhanced/Phase 2 testing was to build upon the initial Phase 1 feasibility results and optimize elements of the coagulation, ozone, and BAF processes for DBP reduction, such that secondary disinfection with free chlorine will meet Stages 1 and 2 of the Disinfection/Disinfectants Byproducts Rule of the Safe Drinking Water Act.

Table 1 states that the AOC assay will not likely meet the Phase 1 criterion with optimization. The reason for this opinion is based on the JV Team’s experience with the reliability of the AOC test as noted in our proposal and the recommendation to use CBXAs as an alternative to AOC. The AOC test and the threshold value of 100 µg/L is not considered to be a reliable indicator of biological stability for several reasons. First, LeChevallier et al. (1996) indicated that while coliform regrowth was generally greater in distributions systems having greater AOC concentrations, one of the systems with the lowest AOC concentration had the greatest rate of coliform occurrence. The researchers concluded that low AOC concentrations alone did not ensure coliform-free water. Secondly, in Water Research Foundation project 4312 (An Operational Definition of Biological Stability in Drinking Water) (Water Research Foundation, 2015), the JV Team demonstrated that chlorine concentration, temperature, DOC concentration, biofilm formation rate, and corrosion rate were primary factors controlling stability, and that AOC was not observed to be a controlling factor. Part of the reason for this apparent lack of a controlling role for AOC may be associated with inter-laboratory quality control for the AOC assay. The luminescent AOC assay was developed by LeChevallier et al. (1993) and Weinrich et al. (2009). Commercially, the analysis is conducted by Eaton-Eurofins Laboratory. It has been the JV Team’s experience that results from split samples analyzed by Weinrich and by Eaton-Eurofins are not similar. The reasons for this dissimilarity may be associated with uncharacterized interferences, sensitivities of the pure strains, and evolving laboratory methodologies. These factors have produced inconsistent results and limited cross-facility/cross-source comparisons.

2.0 Methodology for Sample Collection and Testing

The following tasks were completed in collaboration with Reclamation for the Phase 2 bench-scale testing:

1. Test Planning
2. Sample Collection
3. Process Testing
 - a. Jar Testing
 - b. Ozone Demand and Decay Testing
 - c. Ozone/BAF Testing
4. Engineering Design Parameter Evaluation
5. Reporting

The Task 1 DRAFT Enhanced Bench Scale Study Test Plan was submitted in August after coordination with Reclamation for the sample collection efforts. The plan is considered an amendment to the Phase 1 Test Plan. The Phase 2 plan was treated as a working document based on continued collaboration and coordination with Reclamation after each process test to determine the final test conditions for subsequent treatment steps. A copy of the Final Phase 2 Test Plan is included as an appendix to this report. Tasks 2 (Water Collection), 3 (Process Testing) and 4 (Engineering Design Parameter Evaluation) are discussed in this report. This report is the work product for Task 5.

The following section describes the JV Team’s methodology in completing Tasks 2 and 3.

2.1 Task 2 - Sample Collection and Test Preparation

The JV Team collected a water sample from Cutter Reservoir and BAF media for the Phase 2 testing. This section describes how each sample type was collected and shipped to the JV laboratory in Bellevue, Washington. Description of how the media was placed in columns and acclimated to the Cutter sample water is also included in this section.

2.1.1 Water Sample

Water sampling consisted of onsite collection of 420 gallons of Cutter Reservoir water using a portable, electric-powered pump to transfer reservoir water into twenty-one 20-gallon barrels. The water sample was collected by the JV Team and Reclamation Four Corners Construction Office (FCCO) staff members on August 28, 2014. Based on coordination with FCCO and Reclamation Technical Services Center (TSC), the sample was collected where the water enters the outlet canal. Figure 1 is an aerial photo of the Cutter Reservoir and Dam showing the sampling location. The samples were transported by truck to the Gallegos Pumping Plant, located south of the Reclamation's Farmington Construction Office, where equipment was available to palletize and load the samples onto the contracted refrigerated truck. The refrigerated truck arrived for sample pick-up and the water was delivered to an offsite temperature-controlled warehouse in Kent, Washington, approximately 18 miles south of Bellevue. Sample collection took two days with one day to test the pumping equipment and one day to collect the sample and transport sample containers to the Gallegos Pumping Plant.

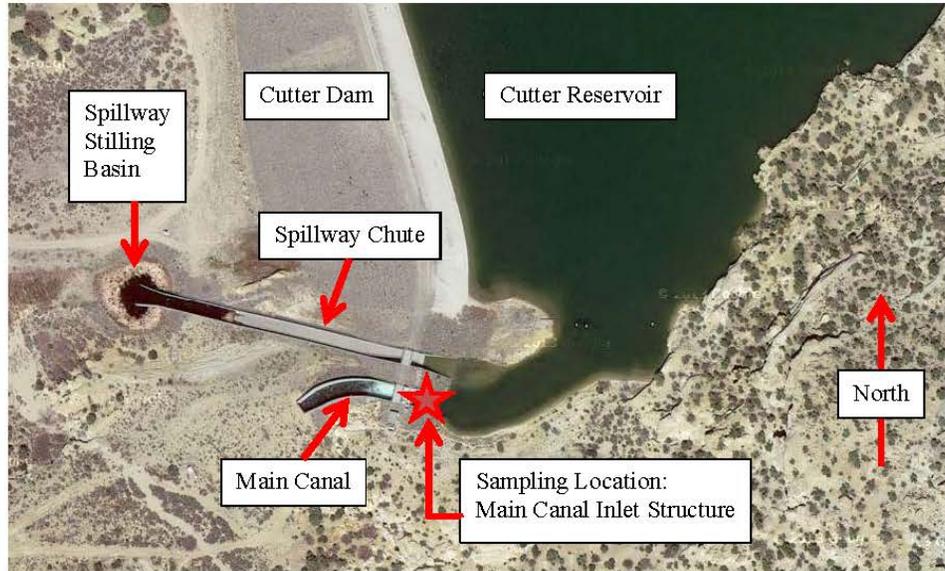


Figure 1. Sampling Location at Cutter Reservoir

The Cutter reservoir water sample was inspected upon arrival at the warehouse in Kent, Washington and at the JV laboratory to confirm sample integrity and acceptability for analysis. The inspection indicated that none of the collected sample barrels had leaked or been compromised. The sample was stored at the Kent warehouse until they were needed. The required volume of water was collected from the warehouse on a daily basis and transported to the JV laboratory. The water was stored in a dark area of the JV laboratory to allow gradual equilibration to room temperature. The sample barrels were homogenized by gently rolling the barrels on the floor before any use.

2.1.2 Media Acquisition and Acclimation

Three liters of biomass-established anthracite BAF media was acquired from the Rolling Hills WTP in Fort Worth, Texas. This plant supplied the media used in the Phase 1 testing and had been selected for media acquisition because of the media's high adenosine triphosphate content, an indicator of biological activity (Lauderdale et al. 2011; Evans et al. 2013) and success with the Phase 1 testing. Table 2 provides a summary of the media characteristics.

Table 2. Characteristics of Anthracite Media Used for Testing

Characteristic	Value
Material	Anthracite
Uniformity coefficient	1.40
Effective size	1.29 mm
Specific gravity	1.62
Moh's hardness	3.0

The process of media collection consisted of scraping and discarding the top 0.5-inch of the media layer in the BAF because this may contain undesirable captured solids. Media below the scraping was then collected from the next six inches of the BAF, where the most extensive biological activity is expected. Media was collected in three one-liter polyethylene bottles, unchlorinated BAF influent water was added to the bottle to keep the biofilm moist, and then shipped on ice by overnight delivery to the JV laboratory.

2.1.3 Biological Active Filtration (BAF) Column

The shipped media was placed into one-inch diameter BAF columns, each with a bed depth of 30 inches. Figure 2 is a schematic of one of the columns and Figure 3 shows photographs of the installed system. Sample ports are located at the influent, 12, 18, and 24 inches from the bottom, and at the filter effluent. The associated EBCTs at the test flow rate of 30 milliliters per minute (mL/min) for the three intermediate sample ports and the effluent are 5.0, 7.5, 10, and 12.5 minutes.

A plastic perforated disk with approximately one-inch of glass wool was placed on each end of the column to support and restrain the BAF media inside the column. Each column was packed with 375 mL of media and then operated in recirculation mode with Cutter Reservoir sample water for approximately one week to acclimate the BAF biology to the Cutter water quality prior to initiation of the bench-scale testing.

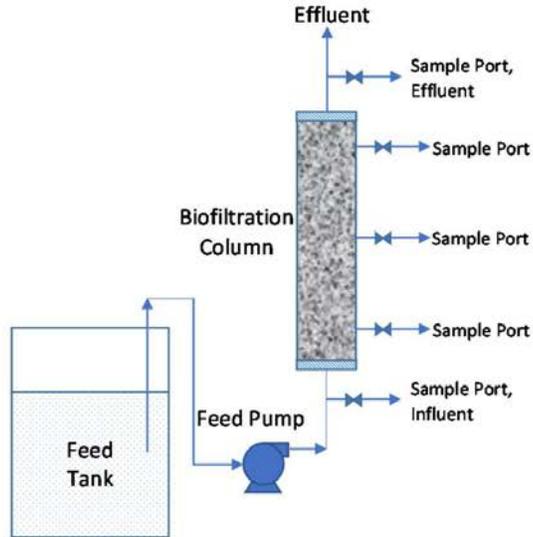


Figure 2. BAF Column Schematic



Figure 3. Installed BAF Columns (left) and Close-up of Sampling Ports (right)

2.2 Task 3 - Process Testing

Task 3 was conducted in three subtasks in collaboration and coordination with Reclamation to determine specific parameters for the subsequent WTP design. Jar testing (Subtask 3a) was conducted to optimize the coagulation process by testing various levels of FeCl₃, pH, and pre-oxidation. Subtask 3b was conducted to optimize the ozone oxidation process and characterize ozone demand and decay kinetics for the Cutter Reservoir water. Subtask 3c evaluated water quality improvements resulting from variations of BAF EBCT and ozone:DOC ratios.

This section provides a detailed description for each subtask along with a description of the BAF and analytical methods used. Based on the defined scope of work, the process testing did not include the use of coagulant aid polymers, filter aid polymers, alternate coagulants, or alternate pre-oxidants.

2.2.1 Subtask 3a – Jar Testing

A series of 13 jar tests were conducted to evaluate various pre-treatment parameters, six for Run 1 and seven for Run 2. The conducted tests and conditions are shown in Table 3. The JV Team completed Run 1 using the test plan in Appendix A, with FeCl₃ dose, pre-oxidation, and pH systematically varied to identify improved coagulation and flocculation performance for turbidity and NOM removal. The parameters for Run 2 were established after a review of most of the Run 1 data by both TSC staff and the JV Team on September 18, 2014. Run 1 THMFP and HAAFP results were not available at the time of the coordination. The test conditions for Run 2, Tests 1 through 6, are based on JV collaboration with Reclamation to further refine the process ranges for optimized organics pre-treatment. The refinements concentrated on a narrower coagulant dose and more investigation of pre-treatment enhancement at lower pHs.

Based on discussions with Reclamation, Run 2, Tests 7 and 8 were added by the JV Team to explore performance at higher pHs, with the concept that pre-treatment performance might degrade slightly but the reduction would be offset by an overall reduction in treatment costs as little to no post-filtration pH adjustment would be required. Tests 7 and 8 were added at no cost to Reclamation.

Table 3. Jar Testing Parameters (Subtask 3a)

Run	Test	Ferric Dose (mg/L)	Settled water pH (to be obtained by adjusting alkalinity)	Pre-oxidation with 0.5 mg/L O ₃	Temperature (°C)	Sub-objective
1	1	20	Ambient after coagulation	No	19 - 21	Determine whether pre-oxidation is beneficial and optimize ferric dose
1	2	30	Ambient after coagulation	No	19 - 21	
1	3	45	Ambient after coagulation	No	19 - 21	
1	4	20	Ambient after coagulation	Yes	19 - 21	
1	5	30	Ambient after coagulation	Yes	19 - 21	
1	6	45	Ambient after coagulation	Yes	19 - 21	
2	1	20	6.0	Yes	19 - 21	Optimize pH at two best ferric doses
2	2	20	6.0	No	19 - 21	Optimize pH at two best ferric doses
2	3	30	Ambient after coagulation	Yes	19 - 21	Optimize pH at two best ferric doses
2	4	30	Ambient after coagulation	No	19 - 21	Optimize pH at two best ferric doses
2	5	30	6.0	Yes	19 - 21	Optimize pH at two best ferric doses
2	6	30	6.0	No	19 - 21	Optimize pH at two best ferric doses
2	7	20	7.5	Yes	19 - 21	Optimize pH at two best ferric doses
2	8	20	7.5	No	19 - 21	Optimize pH at two best ferric doses

Jar testing was conducted using a six-gang programmable Phipps and Bird jar tester with 2-L jars. Rapid mix was conducted at a velocity gradient (G value) of approximately 950 sec^{-1} for 30 seconds. During the rapid mix stage, pH was adjusted to 7.0 with 0.1 N sodium hydroxide or 0.1 N hydrochloric acid (HCl). Afterwards, flocculation was initiated by slowing down the jar tester mixers to achieve a G of 40 sec^{-1} for 20 minutes. The water was then settled for 60 minutes and samples collected for analysis. The settled water was analyzed for the parameters listed in Table 4. The conditions that provide the best turbidity removal and light absorbance reduction at the ultraviolet wavelength of 254 nanometers (UV_{254}) were considered optimal.

Table 4. Jar Testing Analyses (Subtask 3a)

Parameter	Method	Raw Water	Run 1	Run 2
pH	Standard Method (SM) 4500-H B	√	√	√
Color	SM 2120/ EPA 110.2	√	√	√
Alkalinity	SM 2320 / EPA 310.1	√	√	√
Turbidity	SM 2130 / 2130B	√	√	√
UV ₂₅₄	SM 5910	√	√	√
DOC	SM 5310B	√	√	√
AOC	Weinrich et al., 2009	No	No	No
Carboxylic Acid (CBXA)	Environmental Protection Agency (EPA) 300.1, modified	No	No	No
THMFP	SM 5710B, EPA 524.2	No	√	√
HAAFP	SM 5710B,D, EPA 552.3	No	√	√
SDS-THM	SM 5710C, EPA 524.2	No	No	No
SDS-HAA	SM 5710C,D, EPA 552.3	No	No	No
Ozone Residual	SM 4500	No	Ozonated tests only	Ozonated tests only

THMFP and HAAFP tests were conducted at a water distribution system pH of 8.0 and a temperature of 20 °C, using chlorine as the residual disinfectant. Simulated distribution system (SDS) testing, which was completed for subsequent subtasks, was conducted at a temperature of 20 °C, a pH of 8.0, and a chlorine dose of 2 mg/L based on discussions with Reclamation. Sampling and analysis for TTHM and HAA5 was conducted at 1, 3, 5, 7 and 10 days after disinfectant addition as specified in the Solicitation. Total and free chlorine content were only measured during THMFP and HAAFP testing. TTHM analysis consisted of measurement of:

- Trichloromethane (TCM, also known as chloroform),
- Tribromomethane (TBM, also known as bromoform),
- Dibromochloromethane (DBCM), and
- Bromodichloromethane (BDCM)

HAA5 analysis consisted of:

- Trichloroacetic acid (TCAA),
- Dichloroacetic acid (DCAA),
- Monochloroacetic acid (MCAA),
- Dibromoacetic acid (DBAA), and
- Monobromoacetic acid (MBAA).

Run 1 THMFP and HAAFP results and all of the Run 2 results were reviewed by TSC staff and the JV Team on October 14, 2014 to establish the two optimal process chemistries for providing optimal turbidity removal and UV₂₅₄ absorbance reduction. These chemistries, identified as “Settled Water A” and Settled Water B”, are listed below and were evaluated for the following Subtask 3b.

- A. 20 mg/L FeCl₃ adjusted to pH 6.0, and no pre-ozonation
- B. 30 mg/L FeCl₃ at the ambient pH following coagulant addition, and no pre-ozonation

Discussion on how these chemistries were identified for Settled Waters A and B is included in the subsequent testing results section.

2.2.2 Subtask 3b – Ozone Demand and Decay Testing

Ozone demand and decay tests were conducted to provide ozone decay rate constants for Settled Water A and B as shown in Table 5. The tests were conducted at the anticipated minimum and maximum Cutter Reservoir water temperatures based on input from TSC staff from historical temperature monitoring completed by Reclamation. Fresh batches of Settled Waters A and B were prepared immediately before this test using the jar testing equipment. Samples were placed in glass reaction bottles in a temperate controlled water bath, augmented with recirculating water chillers and heaters, to reach and maintain the desired temperature.

Table 5. Ozone Demand and Decay Testing (Subtask 3b)

Run	Test	Settled Water	FeCl ₃ Dosage	pH	Ozone: DOC Ratio	Temperature (°C)
3	1	A	20 mg/L	6.0	1.5:1.0	4.0 – min. observed
3	2	A	20 mg/L	6.0	1.5:1.0	20.0 – max. observed
3	3	B	30 mg/L	Ambient after coagulation	1.5:1.0	4.0 – min. observed
3	4	B	30 mg/L	Ambient after coagulation	1.5:1.0	20.0 – max. observed

Ozone was then applied to the water at a constant concentration ratio of 1.5:1.0 ozone-to-DOC. Ozone was generated by a Clearwater Tech CD 12 ozonator with a maximum capacity of 8 grams per hour (g/hr) ozone generation (using ultra-high purity oxygen) and introduced into the sample bottles through stainless steel diffusers. Subsamples were collected at various times after dosing and analyzed to prepare ozone decay curves and to calculate the first-order rate constants. Following complete ozone decay, the remaining samples were analyzed as summarized in Table 6.

Table 6. Ozone Demand and Decay Testing Analyses (Subtask 3b)

Parameter	Method	Settled Water	Ozonated Water
pH	SM 4500-H B	√	√
Ozone Residual	SM 4500	No	√

2.2.3 Subtask 3c – Ozone/BAF Testing

The same Settled Waters A and B identified in Subtask 3a were used in this subtask using ozone/BAF column tests. This testing consumed 340 gallons of the 420 gallons of water collected. The following section describes how the JV Team processed this large volume of water and then pumped the water into six BAF columns for six continuous days.

Coagulation/Flocculation

All of the remaining source water barrels were removed from the Kent warehouse and brought to the JV laboratory for processing. After warming up to room temperature (19 to 21 °C at the JV laboratory), the barrel lids were removed one at a time and an impeller mounted to a variable speed rotary drill was inserted. The impeller was operated to rapidly mix the barrel contents. Rapid mixing, flocculation, and sedimentation *G* values and times were the same as the jar testing. The water was first mixed at a *G* value of approximately 950 sec⁻¹ for 60 seconds. Calculated amounts of FeCl₃ and HCl (if needed) were added to the barrel to achieve the required coagulant dose for Settled Water A or B. Mixing continued at 950 sec⁻¹ for 30 seconds before the drill speed was reduced to achieve flocculation with a *G* value of approximately 30 sec⁻¹ for 20 minutes.

The flocculated source water settled for 60 minutes. Visual inspection found that the vast majority of the flocs in each barrel had settled to the bottom at the end of the settling period. No visible flocs were observed as being suspended in the water prior to decanting but there were some very minor amounts of floating flocs at the water surface. The flocs observed at the surface were estimated to cover approximately ten percent of the barrel water surface area and were confined to the very top of the water. Decanting the water involved submergence of a clean plastic suction tubing into each barrel and pumping the water into clean 5-gallon polyethylene buckets. The end of the suction tubing was placed several inches below the water surface to avoid sucking up the floating flocs and was carefully lowered further down in the barrel as the water surface lowered. The transfer pumping stopped before the settled sludge blanket was

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disturbed. The result was that no floc carryover was visually observed in the settled water buckets.

The rapid mixing/flocculation/sedimentation/decanting process was repeated for each source water barrel until the entire 340 gallons were processed. Approximately 300 gallons of the source water were recovered as settled water while the remaining 40 gallons were laden with settled coagulant and discharged. The batches of prepared Settled Waters A and B were stored at 4°C in a walk-in cooler until use.

Ozonation

Barrels of Settled Waters A and B were removed from the cooler daily when needed and allowed to naturally warm to room temperature (19 – 21°C), and then ozonated in approximately 12 gallon batches at varying ozone dosages to achieve dosage ratios of 0.5, 1.0, and 1.5 milligrams (mg) ozone (O₃) to 1 mg TOC. The collected settled water was pumped through an in-line Mazzei venturi injector to transfer ozone into the water. Figure 4 is a schematic of the ozonation system while Figure 5 is a photograph of the same system. The Mazzei injector and the associated rotameters and control valves were tested and calibrated using distilled water to verify the required ozone dosage was being transferred prior to being used with settled water.

The ozonated water was allowed to off-gas under a fume hood for 30 minutes. The water was checked after this time to verify that the water had fully off-gassed and contained no ozone residual.

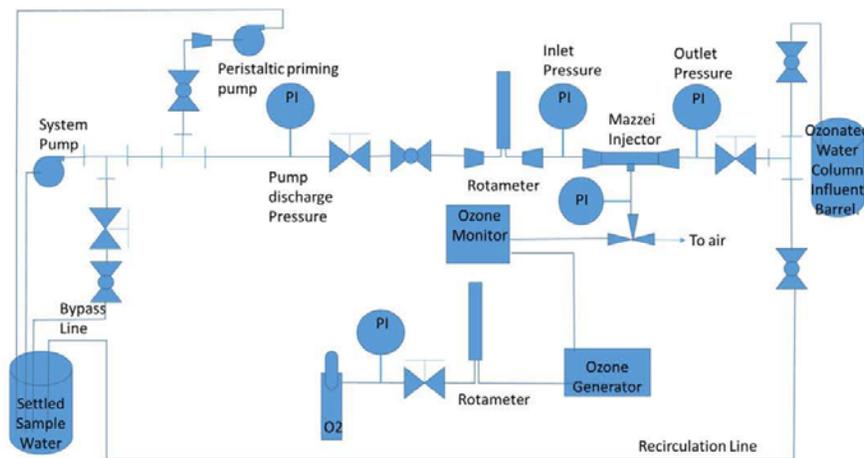


Figure 4. Subtask 3c Ozonation Schematic

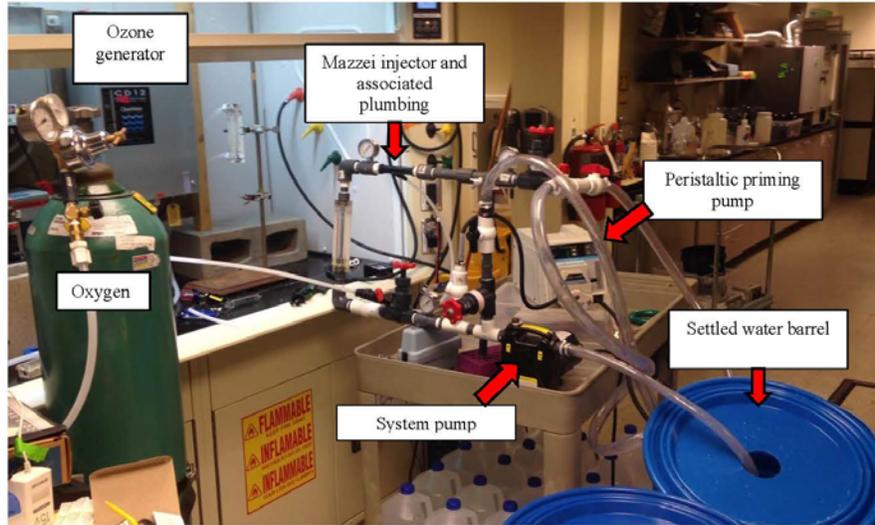


Figure 5. Subtask 3c Ozonation Set-up

Ozone/BAF

Six parallel columns (labeled I through VI) were built for this test. Each batch of room-temperature, ozonated water was pumped through the columns at a constant rate of 30 mL/minute per column for seven consecutive days. The water supply to each column and the sampled EBCT is listed in Table 7.

Samples were collected and analyzed as indicated in Table 8. Turbidity, UV_{254} , and DOC were analyzed daily to quantify BAF performance and assess when steady state conditions were achieved. Other parameters were determined when steady state was achieved. SDS testing was conducted on final samples and testing results for each test condition were evaluated to determine the maximum water age that would allow compliance with each DBP's respective locational running annual average (LRAA) maximum contaminant levels (MCLs).

The values in Table 8 indicate the number of analyses that were conducted. Daily samples were analyzed for turbidity, DOC, and UV_{254} over the five-day period to demonstrate steady state conditions. Other analytes were measured as single time points. AOC, THMFP, HAAFP, and SDS testing were conducted on four of the best performing of the 18 conditions. These conditions were selected in consultation with Reclamation and will be discussed in the following section.

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Table 7. Ozone/BAF Optimization (Subtask 3c)

Test	Settled Water	Ozone: DOC	EBCT (minutes)	Column
1	A	0.5:1.0	5.0	I
2	A	0.5:1.0	7.5	I
3	A	0.5:1.0	10.0	I
4	A	0.5:1.0	12.5	I
5	A	1.0:1.0	5.0	II
6	A	1.0:1.0	7.5	II
7	A	1.0:1.0	10.0	II
8	A	1.0:1.0	12.5	II
9	A	1.5:1.0	5.0	III
10	A	1.5:1.0	7.5	III
11	A	1.5:1.0	10.0	III
12	A	1.5:1.0	12.5	III
13	B	0.5:1.0	5.0	IV
14	B	0.5:1.0	7.5	IV
15	B	0.5:1.0	10.0	IV
16	B	0.5:1.0	12.5	IV
17	B	1.0:1.0	5.0	V
18	B	1.0:1.0	7.5	V
19	B	1.0:1.0	10.0	V
20	B	1.0:1.0	12.5	V
21	B	1.5:1.0	5.0	VI
22	B	1.5:1.0	7.5	VI
23	B	1.5:1.0	10.0	VI
24	B	1.5:1.0	12.5	VI

Table 8. Ozone/BAF Optimization Analyses (Subtask 3c)

Parameter	Method	BAF effluent
pH	SM 4500-H B	24 tests x 1 sample/test = 24
Color	SM 2120/ EPA 110.2	24 tests x 1 sample/test = 24
Alkalinity	SM 2320 / EPA 310.1	24 tests x 1 sample/test = 24
Turbidity	SM 2130 /2130B	24 tests x 5 samples/week = 120
UV ₂₅₄	SM 5910	24 tests x 5 samples/week = 120
DOC	SM 5310B	24 tests x 5 samples/week = 120
AOC	Weinrich et al., 2009	4 tests
CBXA	EPA 300.1, modified	24 tests x 1 sample/test = 24
THMFP	SM 5710B, EPA 524.2	4 tests x 1 sample/test = 4
HAAFP	SM 5710B,D, EPA 552.3	4 tests x 1 sample/test = 4
SDS-THM	SM 5710C, EPA 524.2	4 tests x 1 sample/test = 4
SDS-HAA	SM 5710C,D, EPA 552.3	4 tests x 1 sample/test = 4

3.0 Testing Results

This section provides a summary of the bench-scale testing that was conducted for this contract. To maintain consistency with prior testing, the Phase 2 results were compared to the original Phase 1 criteria and a variation of the DBP criteria using SDS testing. The test criteria is shown in Section 1 of this report and also provided below:

Original Phase 1 criteria:

- DOC of ≤ 1.5 mg/L
- AOC of ≤ 100 μ g/L
- THMFP of ≤ 64 μ g/L
- HAAFP of ≤ 48 μ g/L

Modified Phase 1 criteria:

- SDS-THM of ≤ 64 μ g/L
- SDS-HAA of ≤ 48 μ g/L

The raw data collected for each of the tests is included in tabular format as Appendix B of this report.

3.1 Subtask 3a - Jar Testing

The collected water sample was measured at the JV Laboratory twice at the start of jar testing to determine the initial water quality. The measurements were conducted by the JV Team on the two batches of water used for Runs 1 and 2 testing. Table 9 provides a summary of the measured water quality. There was little variability between the two measurements for the raw water analytes. In addition to these two analyses by the JV Team, Reclamation staff also obtained a field water sample at the Cutter Reservoir during the August 28, 2014 sample collection for an independent analyses of DOC. The Reclamation sample was taken from one of the sample barrels prior to sealing and shipment. This sample was analyzed by Reclamation to quantify changes to DOC, if any, that might have occurred during the shipment of the Cutter water sample to the JV Laboratory. The Reclamation sample was determined to contain 10 to 16 percent more DOC than what was measured at the JV Laboratory, which is a minor difference, and indicates that no major changes in organic material occurred during sample transport.

Table 9. Raw Water Quality

Analyte	Units	JV Team Measurements Prior to:		Reclamation Measurement
		Run 1 Jar Testing	Run 2 Jar Testing	
pH	s.u.	7.60	7.60	(not taken)
Color	PCU	10	11	(not taken)
Alkalinity	mg/L as CaCO ₃	76.75	75.40	(not taken)
Turbidity	NTU	0.81	0.46	(not taken)
Dissolved organic carbon	mg/L	2.44	2.59	2.84
UV ₂₅₄ absorbance	l/cm	0.077	0.076	(not taken)
SUVA	L/mg/m	3.138	2.938	(not taken)

Figure 6 through Figure 12 graphically depict the Run 1 jar testing results used to identify the performance of FeCl₃ across the specified range of coagulant dosages. Where available, the graphs also show the comparative results from the JV Team’s Phase 1 testing and from the Reclamation report “Analysis Results for Coagulation Jar Testing and Disinfection By-Product Formation for the USBR Navajo/Gallup Water Supply Project (September 2011 – Cutter Reservoir)” prepared by the University of New Mexico (UNM) (Kerry, 2011).

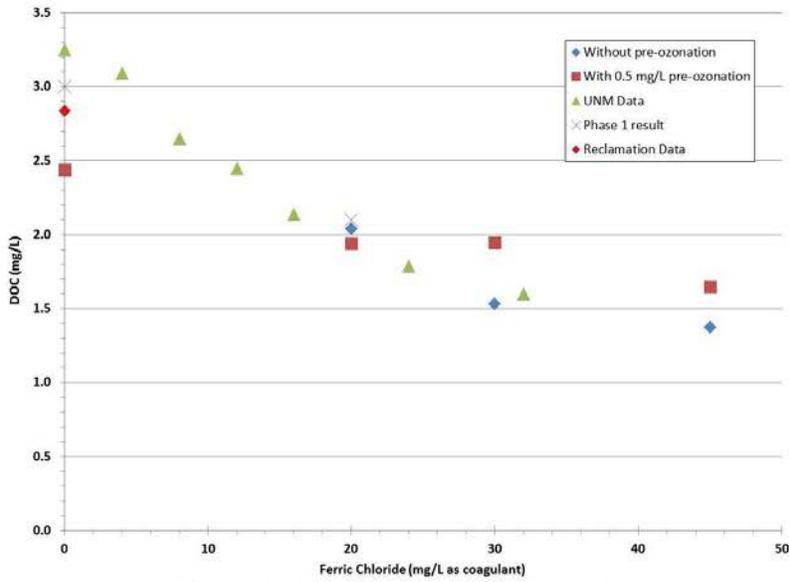


Figure 6. Subtask 3a, Run 1 DOC Results

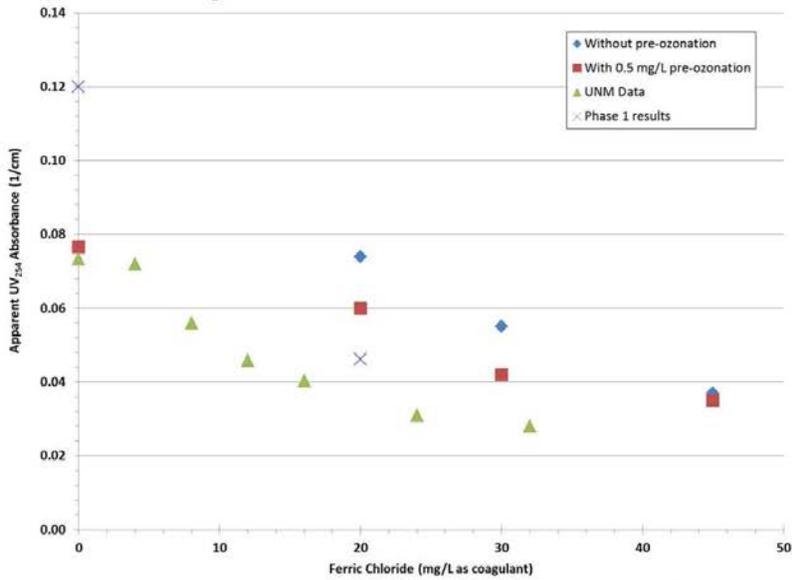


Figure 7. Subtask 3a, Run 1 UV₂₅₄ Absorbance Results

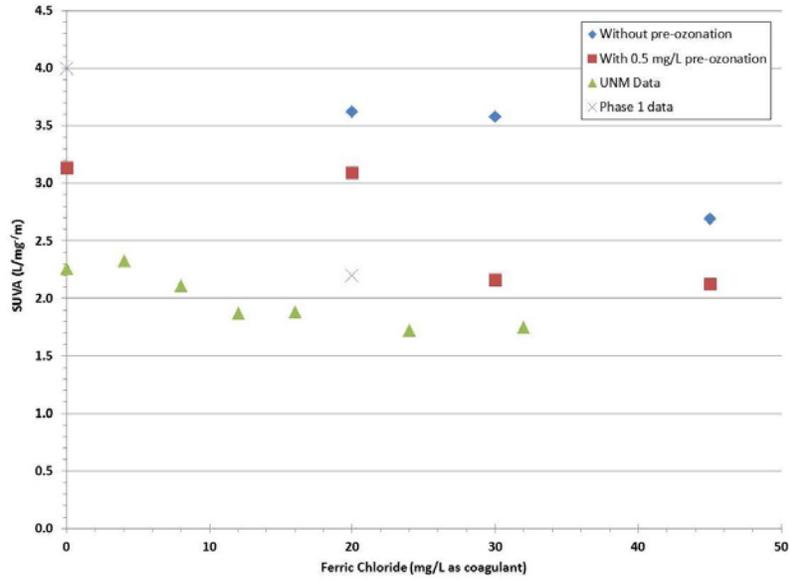


Figure 8. Subtask 3a, Run 1 SUVA Results

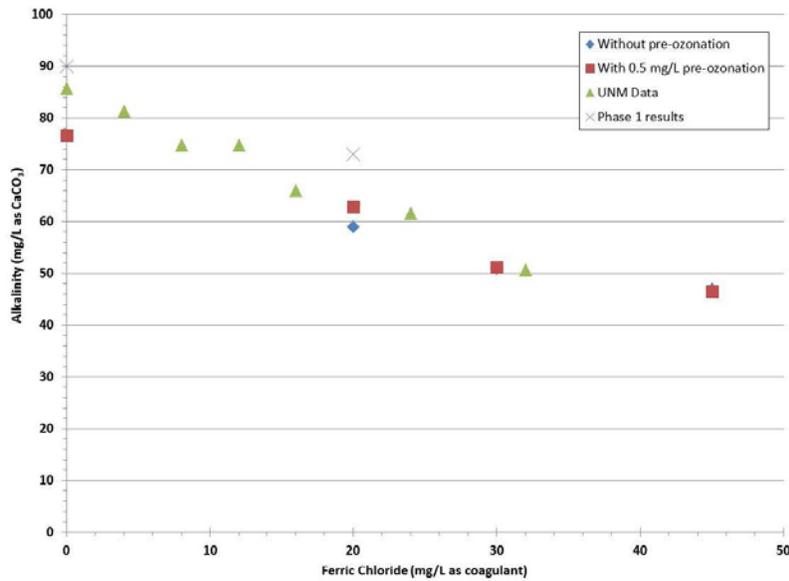


Figure 9. Subtask 3a, Run 1 Alkalinity Results

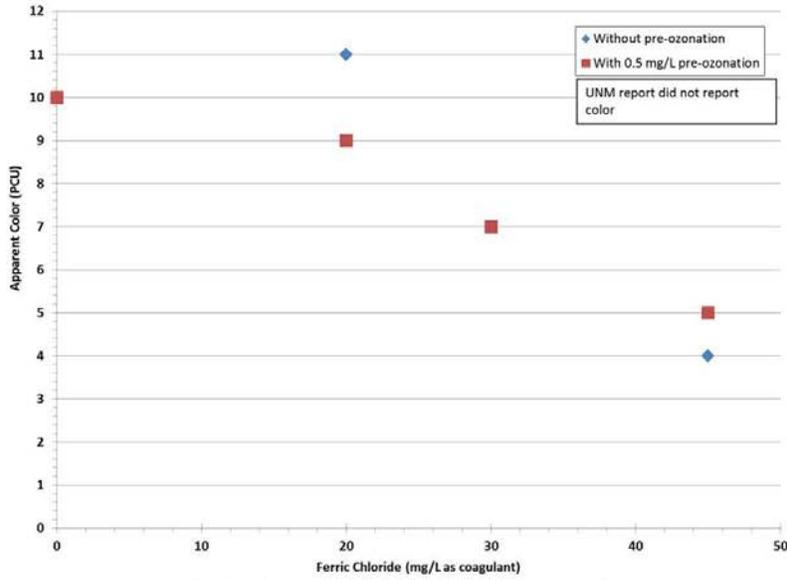


Figure 10. Subtask 3a, Run 1 Color Results

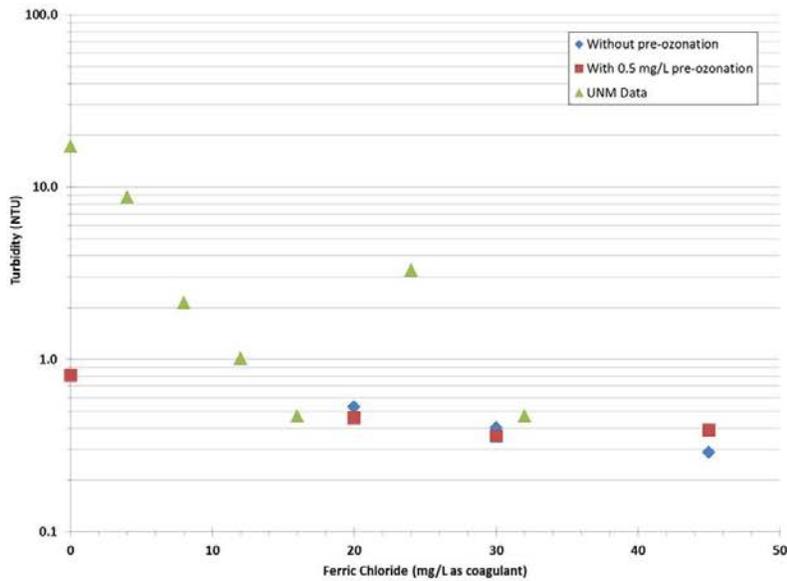


Figure 11. Subtask 3a, Run 1 Turbidity Results (in log scale)

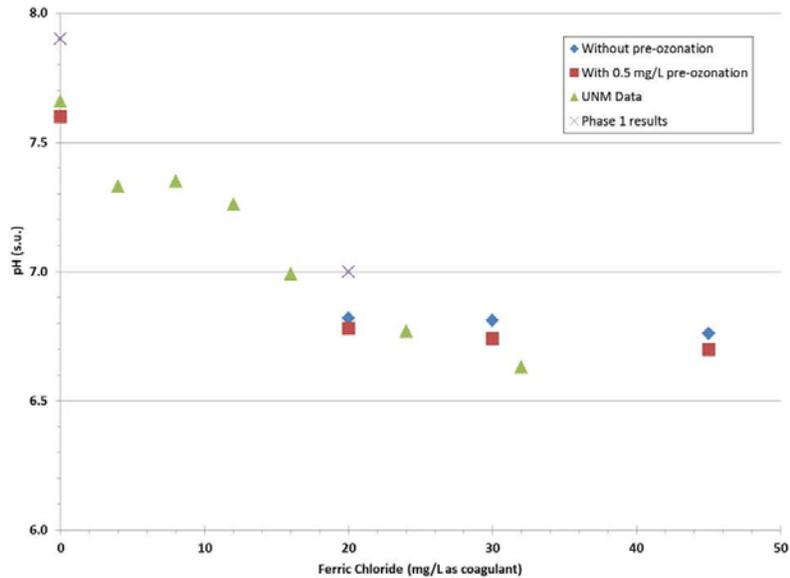


Figure 12. Subtask 3a, Run 1 pH Results

The raw water that was collected and used for this Phase 2 testing was found to be somewhat different from both the 2011 UNM water and the 2013 Phase 1 water. Specifically, the uncoagulated Phase 2 water contained slightly less organic material based on DOC (Figure 6) and the organic material that was present had less aromatic carbon rings content based on lower specific UV₂₅₄ absorbance (SUVA) (Figure 8) that are DBP precursors. The water also had a lower pH (Figure 12) and was less buffered (i.e. lower alkalinity – Figure 9) than previously collected water. The detected differences are well within the JV Team’s experience with naturally occurring seasonal and annual variability of surface waters.

The Run 1 testing found the following broad trends:

1. Increasing FeCl₃ dosages for the entire range of dosages tested resulted in lower DOC concentrations, UV₂₅₄ absorbance, alkalinity, color, turbidity, and pH.
2. Using 0.5 mg/L pre-ozonation appeared to result in higher DOC and lower UV₂₅₄ absorbance. The higher DOC could be the result of particulate organic carbon transforming into DOC, while the lower UV₂₅₄ absorbance meant that more of the aromatic DBP precursors were being destroyed by the pre-ozonation.
3. The lower UV₂₅₄ absorbance for pre-ozonation, when divided by the corresponding higher DOC, resulted in higher SUVA results compared to testing without pre-ozonation. The mathematically-derived SUVA is the only parameter which is reduced by pre-ozonation.

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As mentioned in the prior methodology section, the TSC staff and JV Team discussed the results on September 18 prior to the receipt of the THMFP and HAAFP results. The discussion centered on testing the lower FeCl₃ dosages of 20 mg/L and 30 mg/L. The higher 45 mg/L FeCl₃ was removed from further consideration. The higher dosage did result in improved organics removal but the higher dosage would also result in greater post-filtration water chemistry adjustment for corrosion control purposes and greater coagulated solids handling and disposal.

The benefit of further pH depression to 6.0 versus ambient pH depression associated with FeCl₃ addition was evaluated in Run 2. Pre-ozonation was carried forward to Run 2 as the available Run 1 data was not conclusive on benefits. As was mentioned in the earlier methodology section, the JV Team also evaluated the potential treatment performance of FeCl₃ coagulation at a higher pH of 7.5.

Graphs of the Run 2 results start on Figure 13 and end on Figure 18. The following trends were concluded from the testing results:

1. DOC removal improved with higher FeCl₃ dosage and lower pHs. Pre-ozonation had no discernable impact.
2. UV₂₅₄ absorbance removal also improved with higher FeCl₃ dosages and lower pHs. However, unlike DOC removal, pre-ozonation appears to have a minor benefit.
3. Pre-ozonation appears to be the only treatment process that reduced SUVA₂₅₄, which is a direct function of the changes in UV₂₅₄ absorbance.
4. Alkalinities again decreased with pH depression. Pre-ozonation had no impact.
5. The Cutter water color improved when dosed with more FeCl₃. Water pH and pre-ozonation had no impact.
6. The settled water turbidity was better with more FeCl₃. Water pH and pre-ozonation again had no impact.

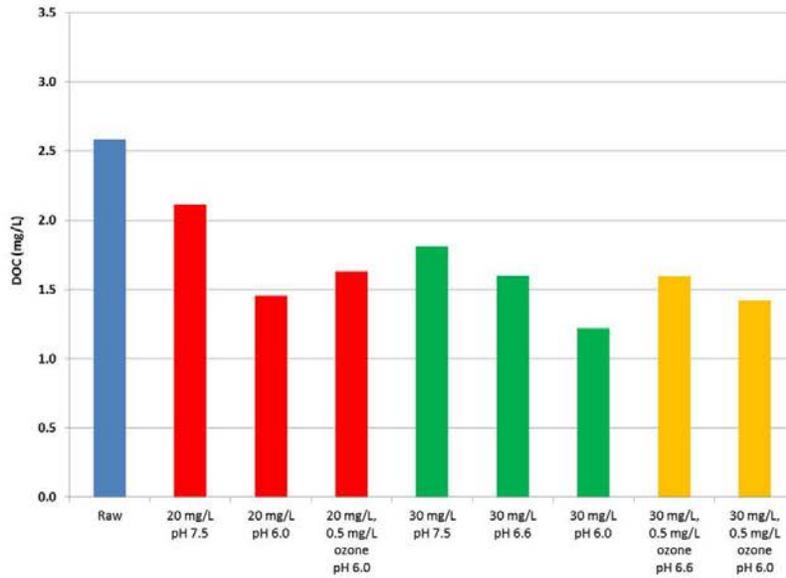


Figure 13. Subtask 3a, Run 2 DOC Results

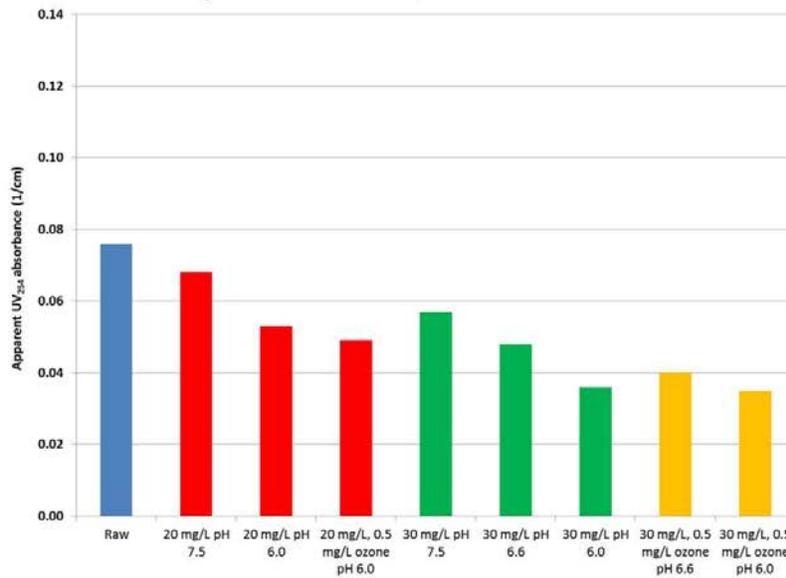


Figure 14. Subtask 3a, Run 2 UV₂₅₄ Absorbance Results

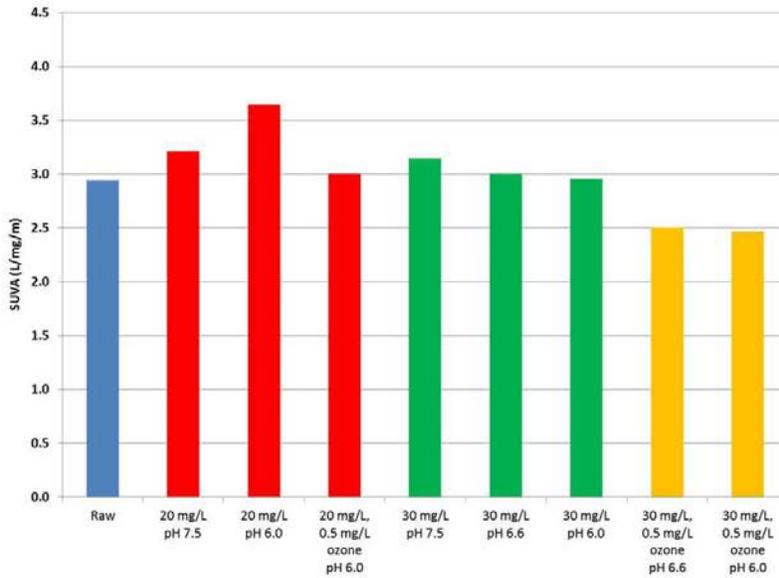


Figure 15. Subtask 3a, Run 2 SUVA Results

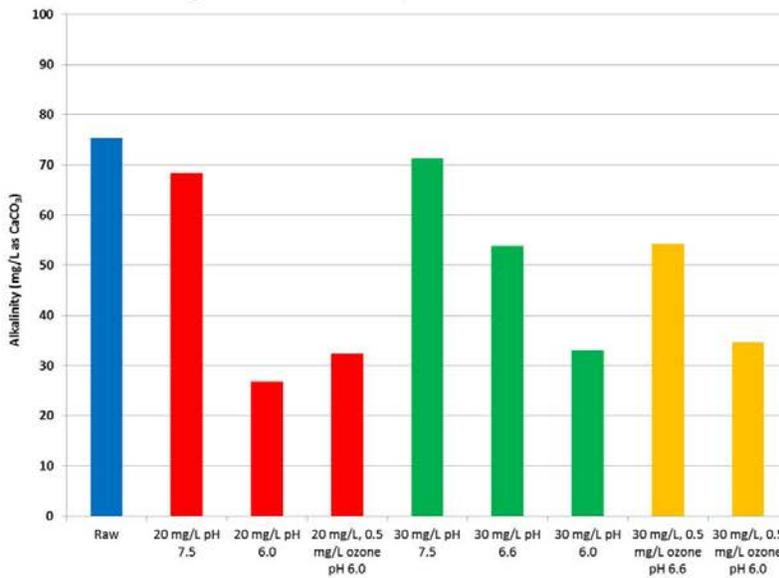


Figure 16. Subtask 3a, Run 2 Alkalinity Results

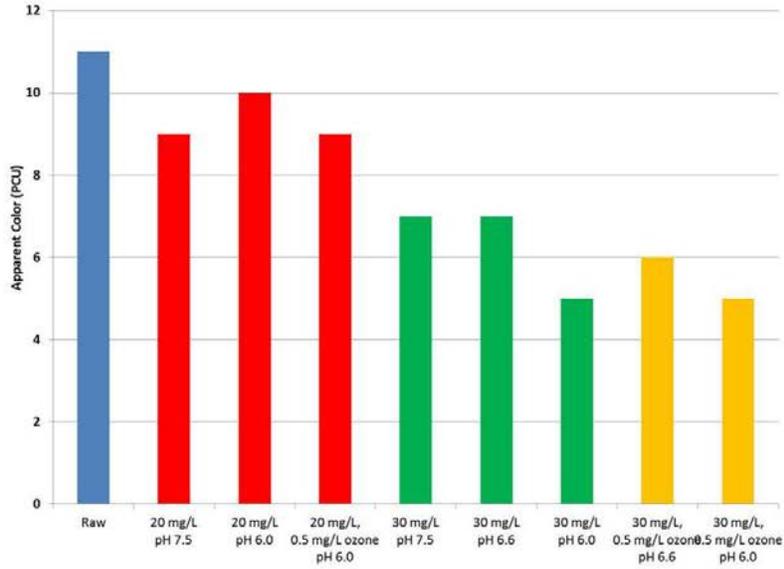


Figure 17. Subtask 3a, Run 2 Color Results

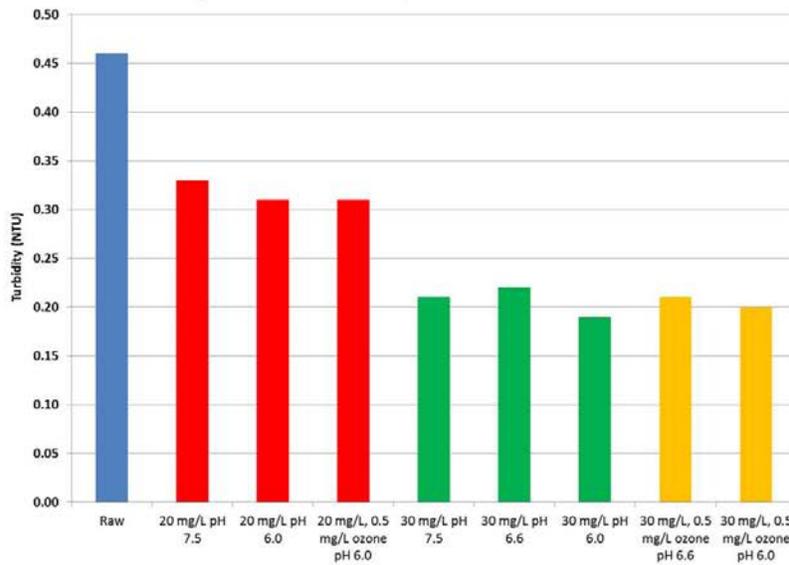


Figure 18. Subtask 3a, Run 2 Turbidity Results

The THMFP results from both Runs 1 and 2 were received upon the conclusion of Run 2 testing. Figure 19 shows the Run 1 results while the Run 2 results are shown in Figure 20. No raw water THMFP was collected for Phase 2, but the Phase 1 testing determined the untreated Cutter Reservoir water had a THMFP of 178 µg/L at that time. Ferric coagulation alone removed 28 to 58 percent of the TTHM precursors. However, the testing also determined that FeCl₃ pre-treatment alone, including the higher FeCl₃ dose of 45 mg/L, was not able to reach the TTHM criteria of 64 µg/L. The results show that a combination of FeCl₃ pre-treatment followed by ozone/BAF is required to treat this water and meet DPB treatment goals.

Further review of the Runs 1 and 2 data indicated that FeCl₃ was determined to have a significant impact with increasing coagulant dosages showing consistently better performance resulting in lower THMFP results. There was no discernable improvement with pre-ozonation. However, the second round of testing also showed that adjusting pH for a given FeCl₃ dosage also had a big effect on THMFP. TTHM results from testing at 20 mg/L FeCl₃ dropped by nearly half when the pH was decreased from pH 7.5 to 6.0, while THMFP decreased by a third across the same pH values when dosed at 30 mg/L. The analysis also found that the TCM accounted for 84 to 91 percent of the formed TTHM, with a minor (8 to 14 percent) contribution from BDCM. DBCM and TBM were present at negligible concentrations.

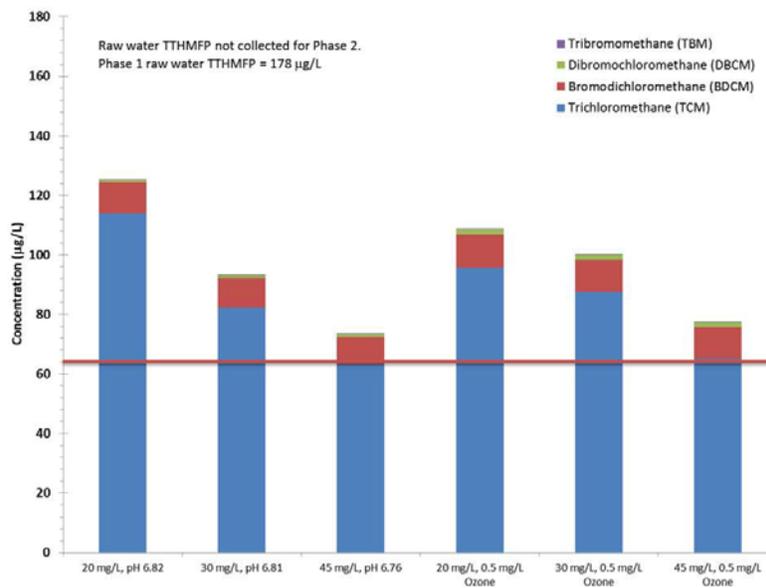


Figure 19. Subtask 3a, Run 1 THMFP Results

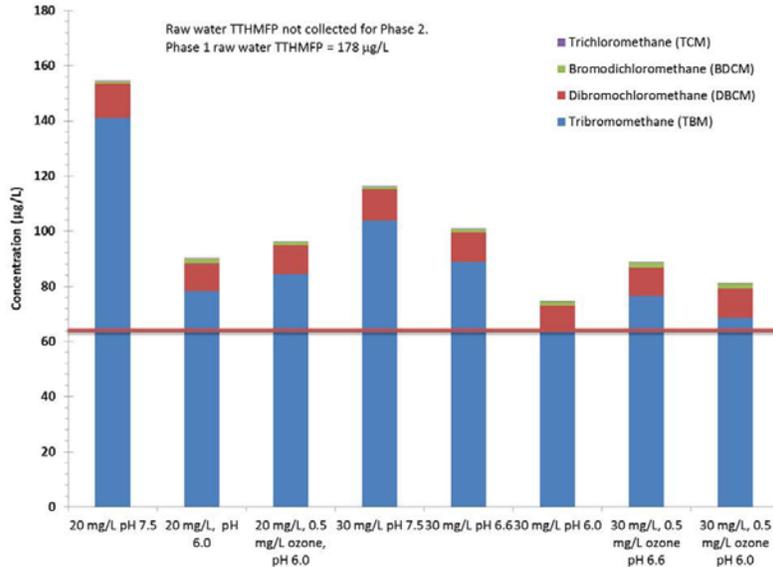


Figure 20. Subtask 3a, Run 2 THMFP Results

The corresponding HAAFP results are shown in Figure 21 for Run 1 and Figure 22 for Run 2. As with the THMFP, there is no Phase 2 HAAFP data for the raw water but the Phase 1 (untreated Cutter Reservoir water) HAAFP was 240 µg/L. The HAAFP results indicated that:

1. FeCl₃ pre-treatment is removing 50 percent to 79 percent of the HAA5 precursors.
2. Ozone/BAF needs to be used in conjunction with FeCl₃ pre-treatment to meet the Phase 1 criteria.
3. Increasing FeCl₃ dosages and lower pHs reduced HAAFP results.
4. Pre-ozonation had no meaningful impact.

TCAA and DCAA accounted for most of the HAA5 results, with each compound in approximately equal concentrations. MCAA was detected in several of the results but always at low concentrations. MBAA and DBAA were never detected.

A review of the Run 2 results and the Run 1 and 2 THMFP/HAAFP results by the TSC staff and the JV Team occurred on October 14, 2014. The JV Team recommended, and the TSC staff concurred, that the following water qualities be advanced for subsequent subtask testing:

- A. 20 mg/L FeCl₃ at pH 6.0 and no pre-ozonation, and
- B. 30 mg/L FeCl₃ at the ambient pH (~6.6), and no pre-ozonation.

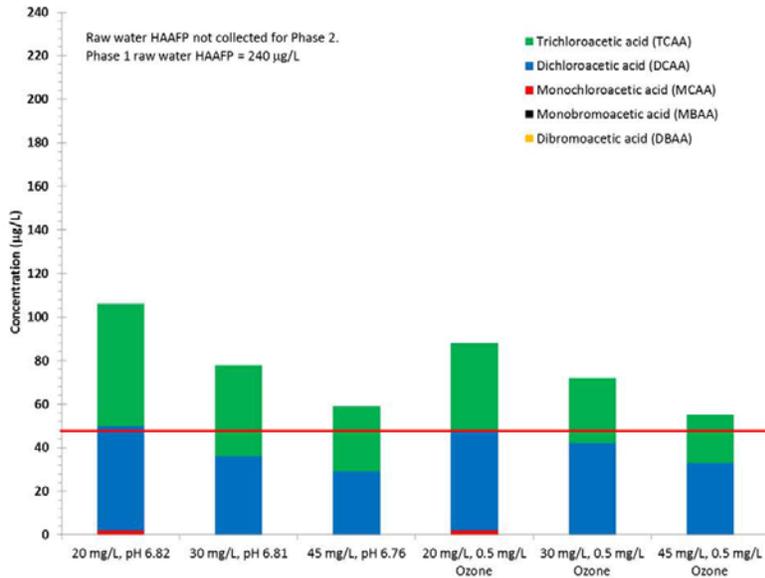


Figure 21. Subtask 3a, Run 1 HAAFP Results

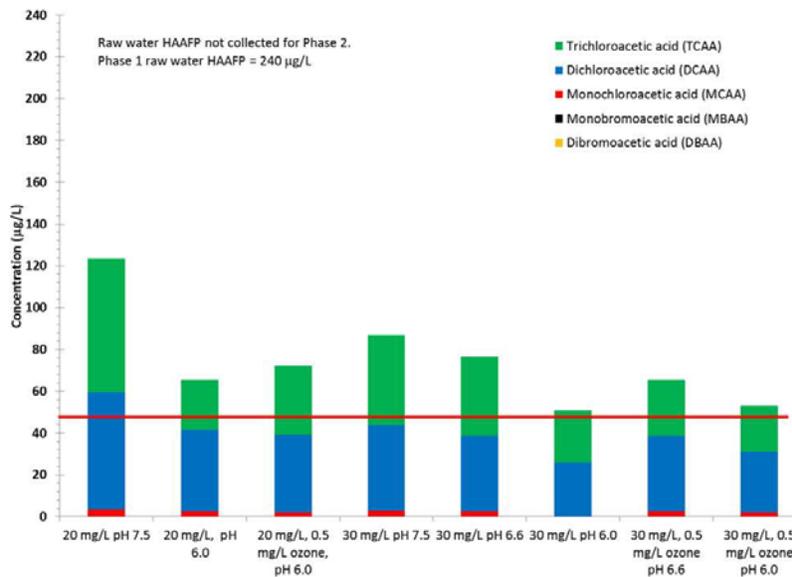


Figure 22. Subtask 3a, Run 2 HAAFP Results

3.2 Subtask 3b - Ozone Demand and Decay Testing

Table 10 shows the Run 3 test conditions. Settled Water A was found to have 1.5 mg/L DOC so it was dosed with 2.2 mg/L ozone to achieve the 1.5:1.0 ozone-to-DOC ratio. Similarly, 2.4 mg/L ozone was added to Settled Water B as it was determined to have 1.6 mg/L DOC. Figure 23 presents the ozone residual decaying over time after the applied ozone dosage was reached and ozonation was then terminated. Settled Water A clearly showed that ozone decay was faster when the water temperature was higher.

Table 10. Subtask 3b Applied Ozone Dosage

Run	Test	Settled Water	Detected DOC (mg/L)	Applied Ozone Dosage (mg/L)	Temperature (°C)
3	1	A – 20 mg/L FeCl ₃ , pH 6.0	1.5	2.2	4.0
3	2	A – 20 mg/L FeCl ₃ , pH 6.0	1.5	2.2	20.0
3	3	B – 30 mg/L FeCl ₃ , pH 6.6	1.6	2.4	4.0
3	4	B – 30 mg/L FeCl ₃ , pH 6.6	1.6	2.4	20.0

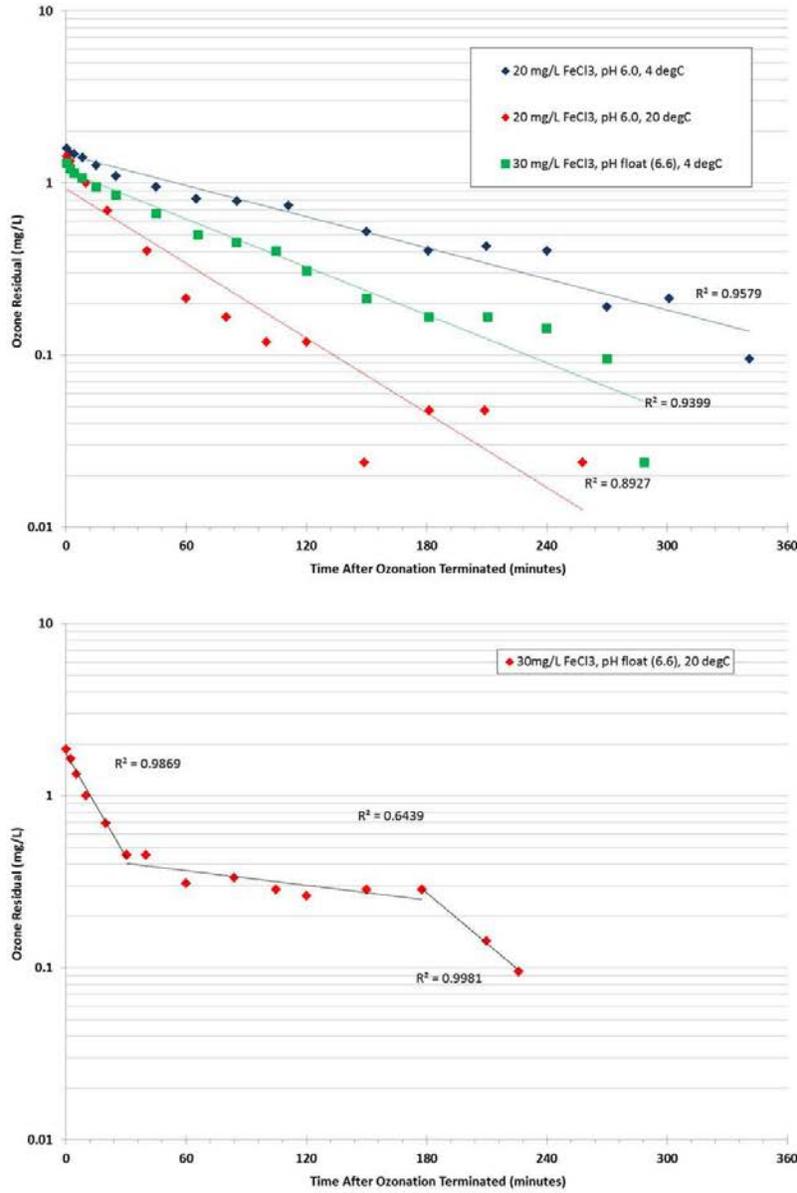


Figure 23. Subtask 3b Ozone Decay Testing

Settled Water B at 4 °C also had a first-order ozone decay rate. However, the testing results for this water at 20 °C had a different trend. The ozone decay rate was rapid for the first 30 minutes but slowed down considerably from 30 minutes to 180 minutes and increased again for the final 45 minutes. The ozone decay data was fitted with exponential trend lines to calculate the first-order ozone decay constant, k^* , of each settled water. Table 11 lists decay constants with the coefficient of determination, R^2 . The exponential trend line fitted very well (i.e. high R^2) for both Settled Water A tests and for Settled Water at 4 °C. The k^* value for Settled Water B at 20 °C is for only the first 30 minutes, the time before the unknown decay slowdown.

Table 11. Subtask 3c Ozone Decay Constants and Correlation of Determination

Temperature (°C)	Settled Water	
	A (20 mg/L FeCl ₃ , pH 6.0)	B (30 mg/L Fe Cl ₃ , pH 6.6)
4	$k^* = 0.0069$ $R^2 = 0.96$	$k^* = 0.0107$ $R^2 = 0.94$
20	$k^* = 0.0167$ $R^2 = 0.89$	$k^* = 0.0462$ for first 30 mins. $R^2 = 0.99$

Decay constants (k^*) in units of min^{-1} .
 Coefficient of determination (R^2) is dimensionless.

3.3 Subtask 3c - Ozone/BAF Testing

The data collected from the six BAF columns is shown in a series of figures following this paragraph, organized by water chemistry parameter. The parameters and figures are:

- DOC – Figures 22 through 25.
- UV₂₅₄ absorbance – Figures 26 to 29.
- SUVA – Figures 30 to 33.
- Turbidity – Figures 34 to 37.

Each group of figures is shown from shortest EBCT (5.0 minutes) to longest EBCT (12.5 minutes). In addition, each figure legend was written with the following codes to shorten the legend to allow everything to be shown:

{x} Fe, {pH 6}, {y} O₃, {z}

Where:

- {x} = FeCl₃ (not iron [Fe]) dosage of 20 or 30 mg/L.
- {pH 6} = pH was adjusted to 6.0 if required. If this value is missing, then the pH was allowed to float and ended at ~6.6, which is considered the ambient pH after coagulation.
- {y} = applied ozone:DOC ratio of 0.5, 1.0, or 1.5
- {z} = EBCT of 5.0, 7.5, 10.0, or 12.5 minutes.

The applied ozone dosages for these tests are summarized in Table 12.

Table 12. Applied Ozone Dosages for Subtask 3c

Ozone:DOC ratio	Applied Ozone Dose (mg/L) after Pre-treatment with:	
	20 mg/L FeCl₃	30 mg/L FeCl₃
0.5	0.8	0.8
1.0	1.6	1.5
1.5	2.4	2.3

The graphs show that the BAF columns reached steady state operating conditions by approximately 14 hours of run time and stayed at this condition for the remainder of the experiment. The following overall trends could be identified once the columns reached steady state:

1. The BAF columns removed more DOC and UV₂₅₄ absorbance when the water was pre-treated with 20 mg/L FeCl₃ at pH 6.0 compared to pre-treating the water with 30 mg/L FeCl₃ at the ambient pH (6.6).
2. There were minor discernable DOC and UV₂₅₄ absorbance differences between ozonating the water at ozone:DOC ratios of 0.5:1.0, 1.0:1.0, and 1.5:1.0, with greater ozone:DOC ratios resulting in slightly better DOC removal and UV₂₅₄ absorbance reduction.
3. There were no discernable differences in the BAF-treated water SUVA.
4. EBCT had little observable effect on performance.

In addition, the detected turbidity was always high in all samples, with many samples over 0.1 NTU, the Surface Water Treatment Rule (SWTR) limit that has to be met 95 percent of the time each month, and 0.3 NTU, the maximum allowed per the SWTR. However, these turbidity values are likely experimental artifacts associated with the short settling time and using very small 1-inch diameter and short (2-feet) columns. These turbidity results would not occur in full-scale filters. There are no issues with turbidity on the other analytical results as the samples were filtered to obtain DOC and UV₂₅₄ absorbance.

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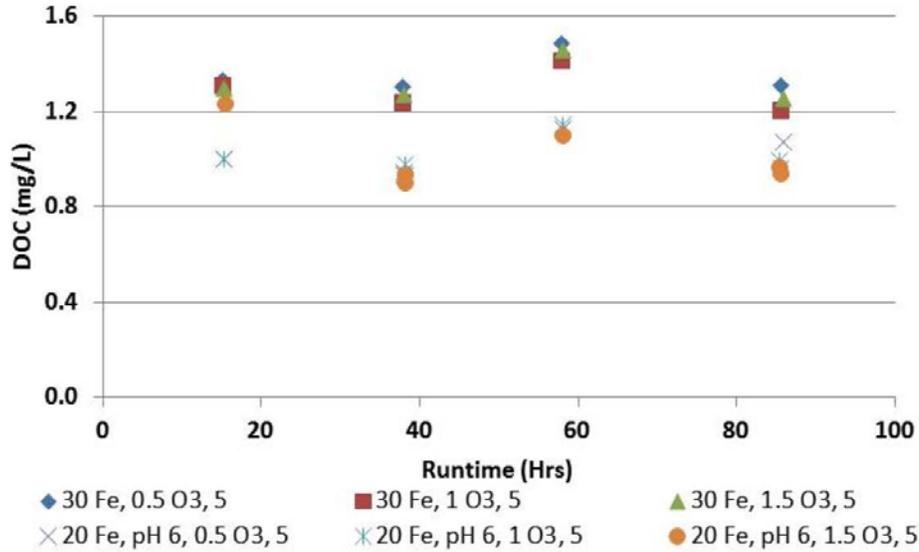


Figure 24. Subtask 3c BAF Results, Effluent DOC at 5.0 minute EBCT

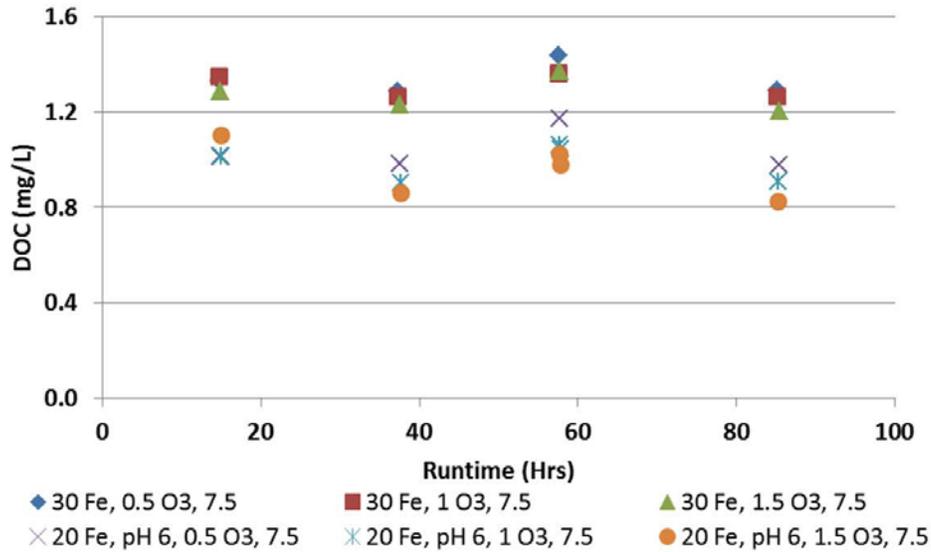


Figure 25. Subtask 3c BAF Results, Effluent DOC at 7.5 minute EBCT

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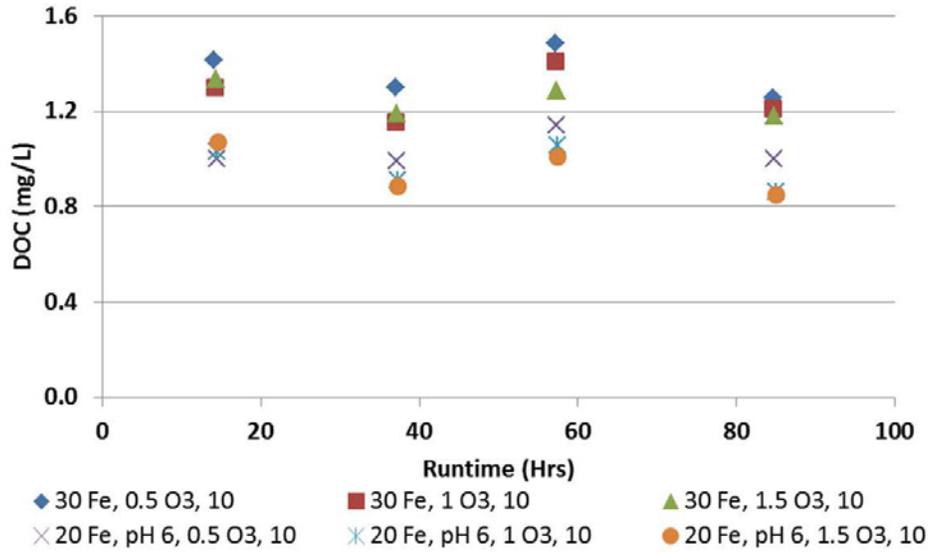


Figure 26. Subtask 3c BAF Results, Effluent DOC at 10.0 minute EBCT

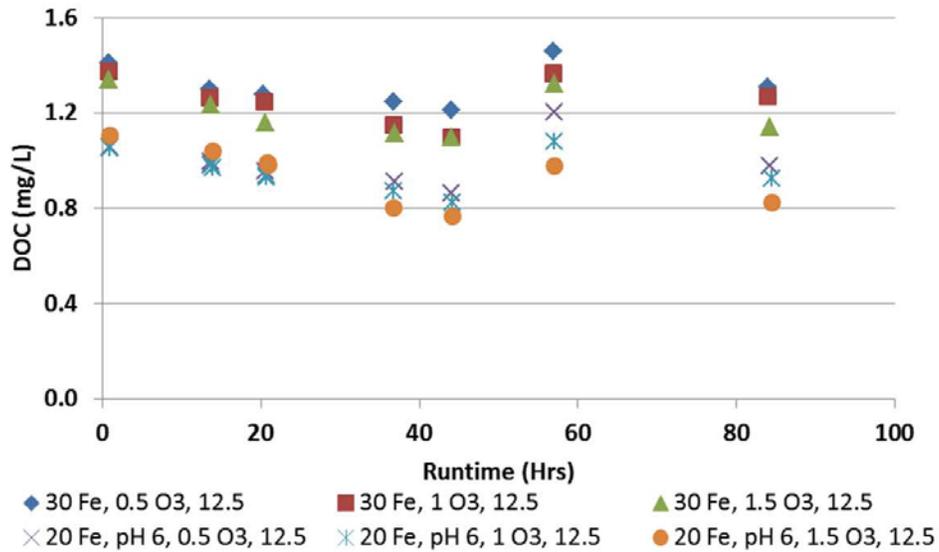


Figure 27. Subtask 3c BAF Results, Effluent DOC at 12.5 minute EBCT

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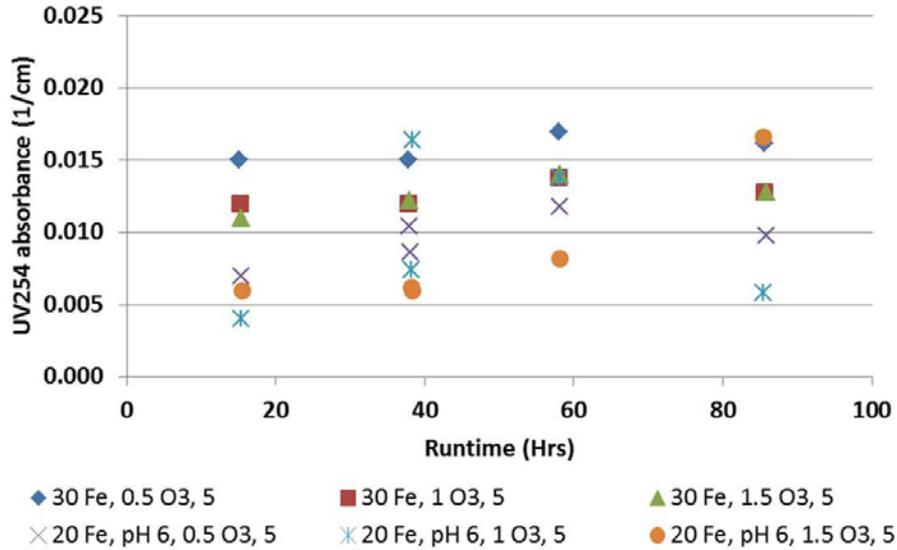


Figure 28. Subtask 3c BAF Results, Effluent UV₂₅₄ Absorbance at 5.0 minute EBCT

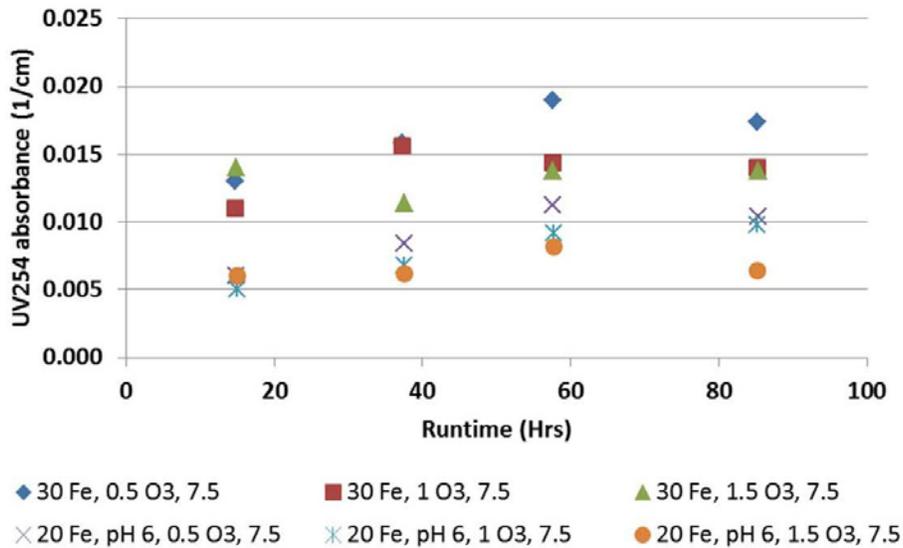


Figure 29. Subtask 3c BAF Results, Effluent UV₂₅₄ Absorbance at 7.5 minute EBCT

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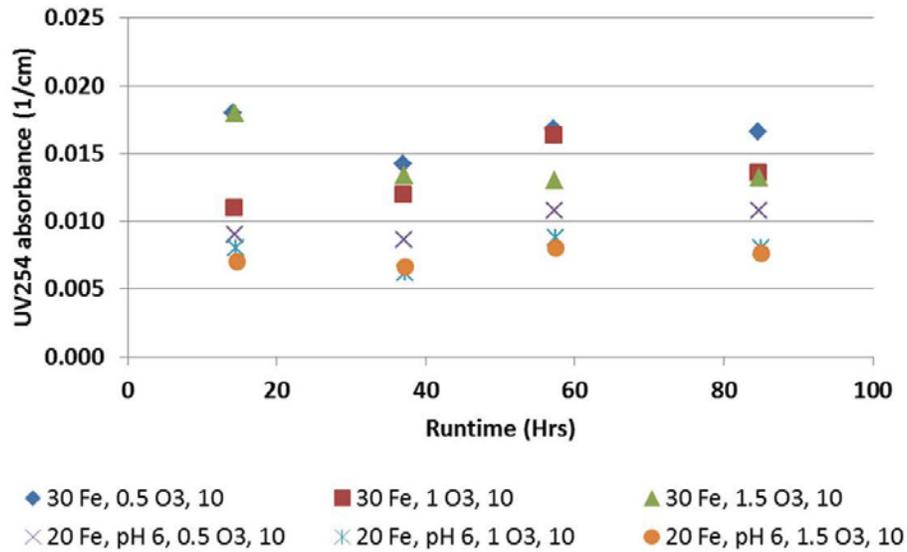


Figure 30. Subtask 3c BAF Results, Effluent UV₂₅₄ Absorbance at 10.0 minute EBCT

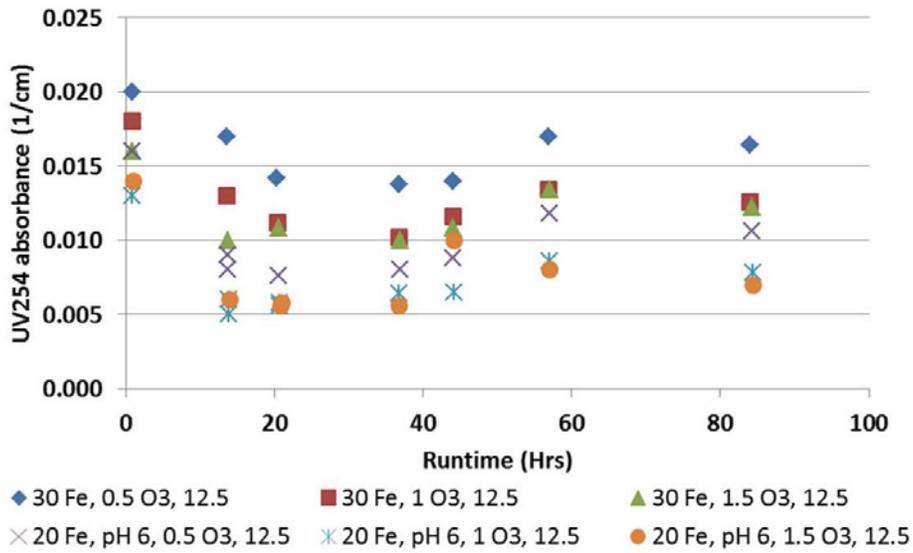


Figure 31. Subtask 3c BAF Results, Effluent UV₂₅₄ Absorbance at 12.5 minute EBCT

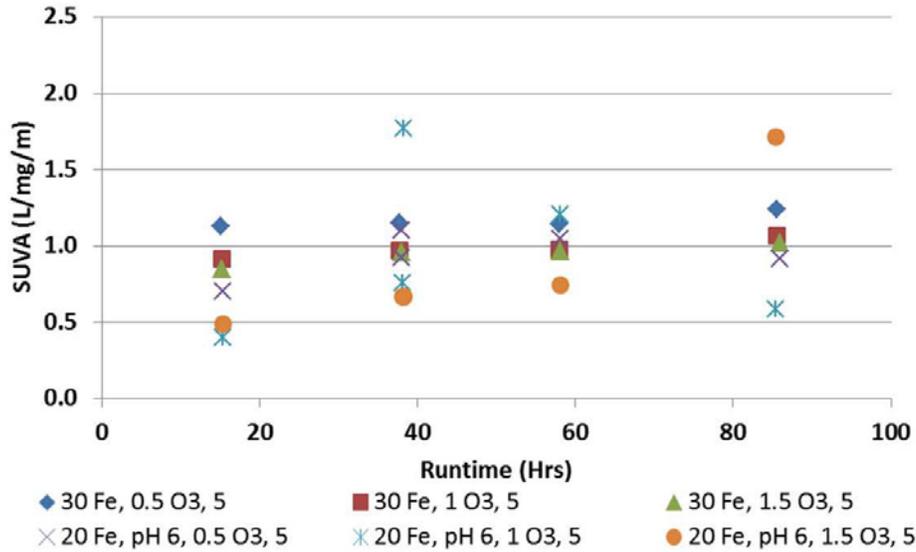


Figure 32. Subtask 3c BAF Results, Effluent SUVA at 5.0 minute EBCT

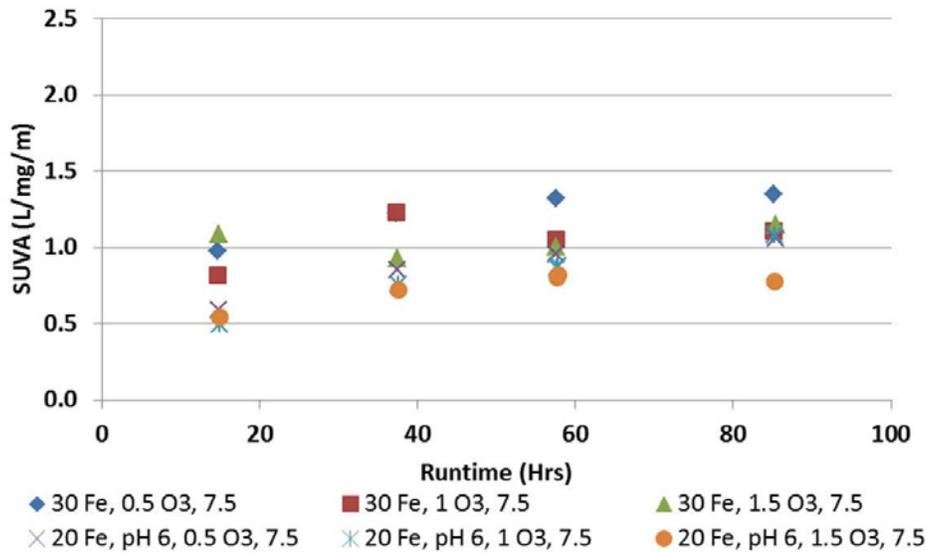


Figure 33. Subtask 3c BAF Results, Effluent SUVA at 7.5 minute EBCT

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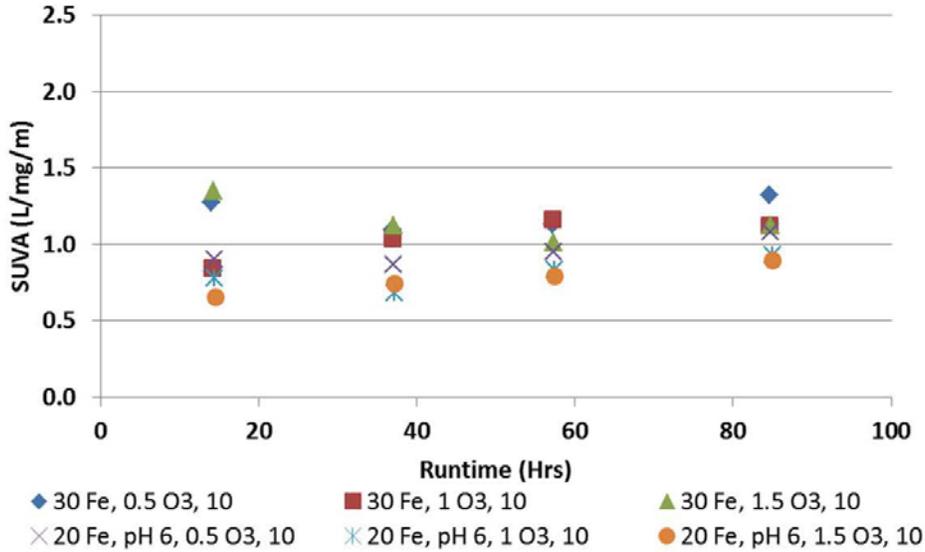


Figure 34. Subtask 3c BAF Results, Effluent SUVA at 10.0 minute EBCT

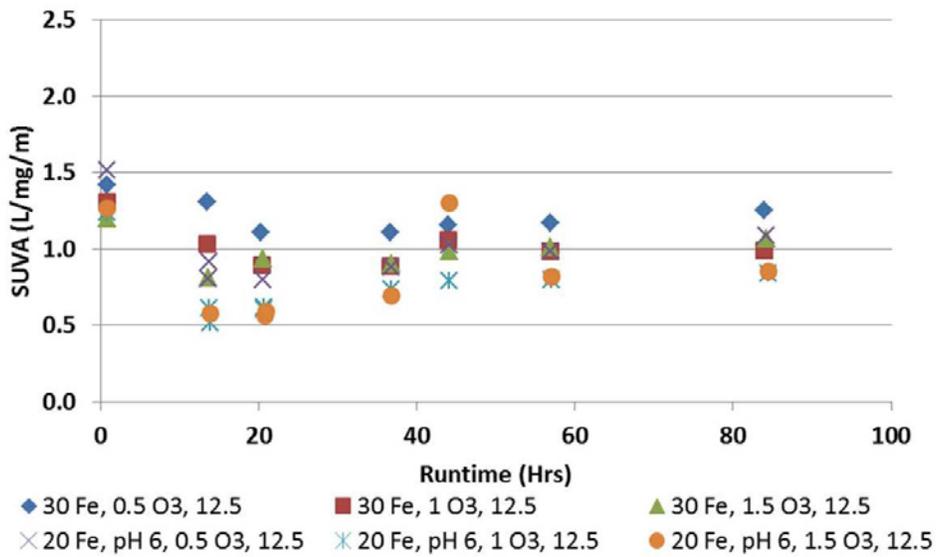


Figure 35. Subtask 3c BAF Results, Effluent SUVA at 12.5 minute EBCT

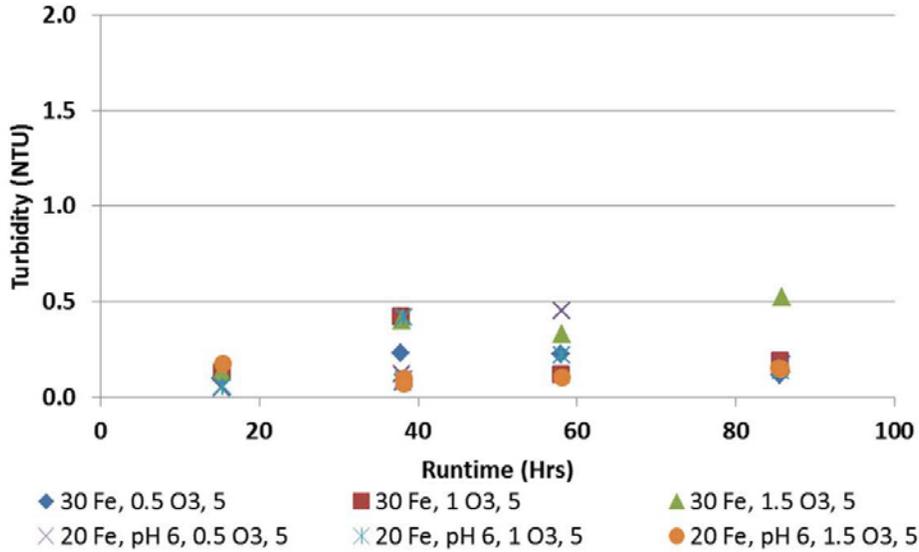


Figure 36. Subtask 3c BAF Results, Effluent Turbidity at 5.0 minute EBCT

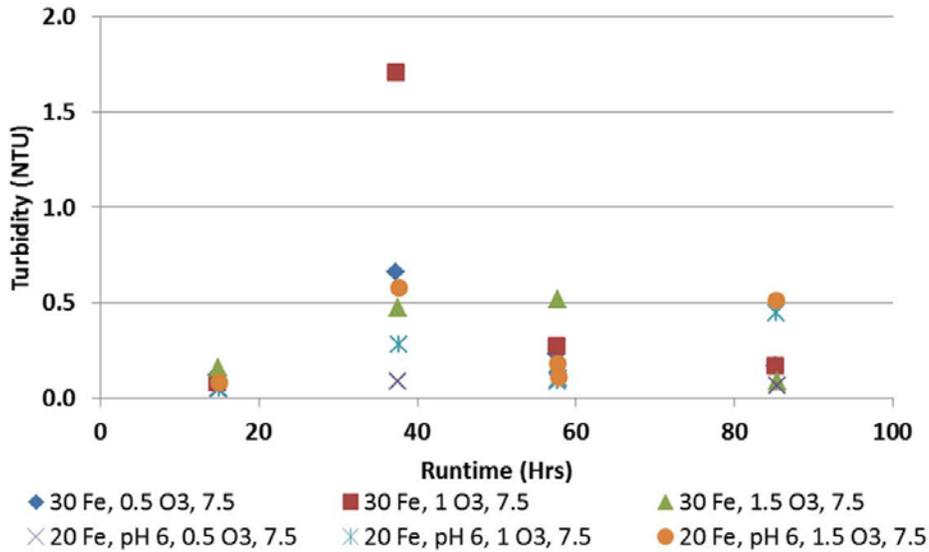


Figure 37. Subtask 3c BAF Results, Effluent Turbidity at 7.5 minute EBCT

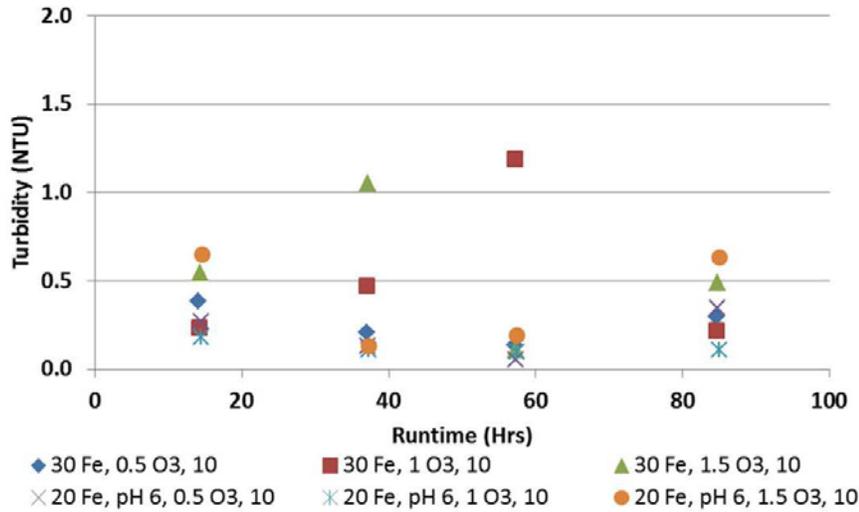


Figure 38. Subtask 3c BAF Results, Effluent Turbidity at 10.0 minute EBCT

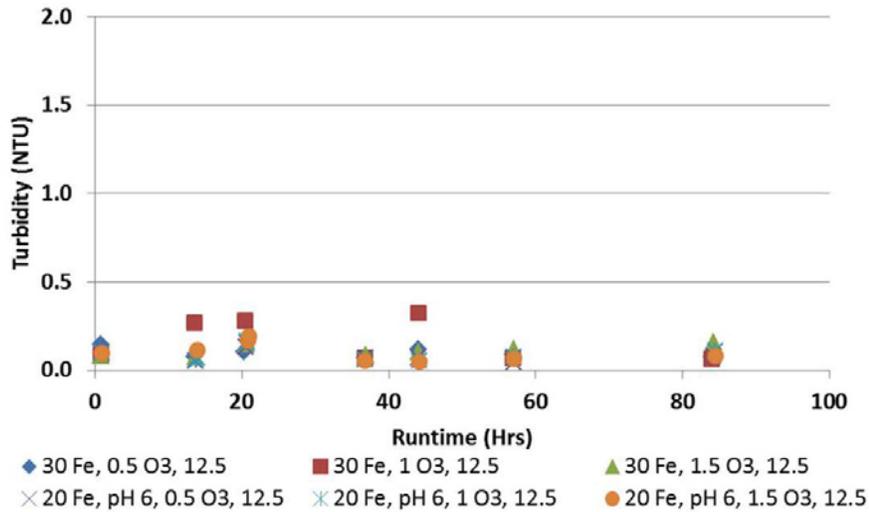


Figure 39. Subtask 3c BAF Results, Effluent Turbidity at 12.5 minute EBCT

Figure 40 shows the DOC data for just the 30 mg/L FeCl₃ coagulated, 1.5 mg/L ozonated pre-treated water by EBCT. This graph shows that there was no DOC removal difference as the EBCT increased from 5.0 minutes to 12.5 minutes. This lack of EBCT differences was repeated

for nearly all the other water quality parameters for this column, and across all the columns. The only performance difference was turbidity, where the variability and maximum turbidities decreased as EBCT increased. The decrease in turbidity is a function of greater test column depth, allowing for increased particulate capacity. Again, the improved turbidity removal by EBCT determined in this test is not meaningful for the full-scale WTP design as the results are artifacts of the experimental set-up. In addition, the experimental bench-scale reactors were designed to emulate the biological activity of a BAF and not filtration performance, which would have required larger-scaled units or customized medias.

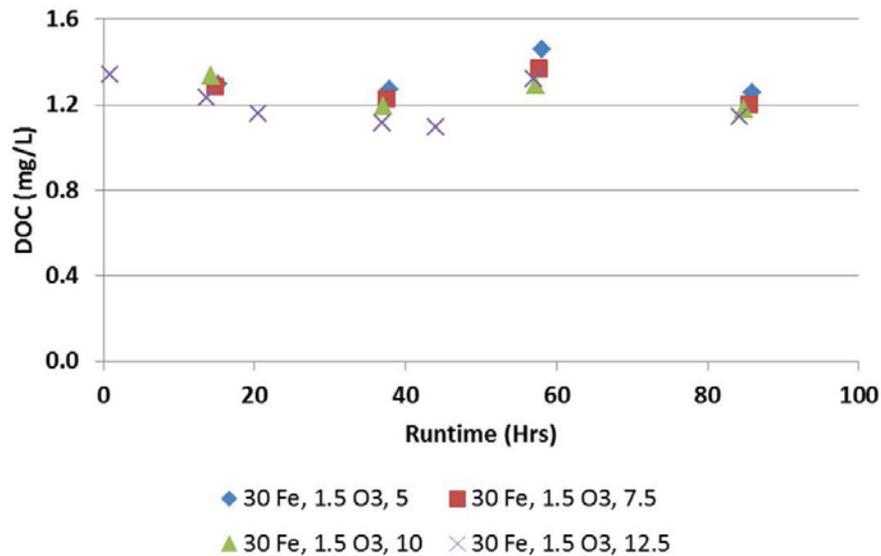


Figure 40. Subtask 3c BAF DOC Results by EBCT

As indicated in the test plan, a total of four samples collected during this time would be analyzed for AOC, THMFP, SDS-THM, HAAFP, and SDS-HAA. The JV Team recommended and the TSC staff concurred that the samples listed in Table 13 would be analyzed. The rationale for the recommendation and selection was that the pre-treatment with 20 mg/L FeCl₃ resulted in better water quality than pre-treatment with 30 mg/L FeCl₃. Therefore, three of four analyses would be on samples treated with the lower FeCl₃ dose but one analysis would be done on the higher ferric dosage for comparison. The same rationale was used for EBCT where three of the four analyses would be on samples with 5.0 minute EBCT and one sample at 10 minute EBCT for comparison. Finally, emphasis would be placed on analyzing the samples treated with 1:0:1:0 ozone-to-DOC ratios as ozonating at greater ratios appeared to provide little additional treatment.

Table 13. Subtask 3c Samples for AOC, CBXA, TTHM and HAA Analysis

EBCT (minutes)	20 mg/L FeCl ₃ , pH 6.0			30 mg/L FeCl ₃ , pH Float		
	0.5:1.0 O ₃ :DOC	1.0:1.0 O ₃ :DOC	1.5:1.0 O ₃ :DOC	0.5:1.0 O ₃ :DOC	1.0:1.0 O ₃ :DOC	1.5:1.0 O ₃ :DOC
5.0	X	X			X	
7.5						
10.0		X				
12.5						

The SDS-TTHM results are shown in Figure 41. As expected, longer reaction times in the SDS-TTHM test resulted in greater TTHM formation. TTHM concentrations did not exceed the Phase 1 test criteria of 64 µg/L after ten days for the water treated with 20 mg/L FeCl₃ at pH 6.0, and with either 0.5:1.0 ozone:DOC and 5 minute EBCT or 1.0:1.0 ozone:DOC and 10 minute EBCT, with the generally best (i.e. lowest TTHM) water coming after 0.5:1.0 ozone:DOC and 5 minute EBCT. However, the 0.5:1.0 ozone:DOC, 5-minute EBCT data had some variability from 7 to 10 minutes of reaction time. The 1.0:1.0 ozone:DOC, 10-minute EBCT condition appeared to be more consistent with respect to maintenance of low TTHM formation under varying SDS conditions.

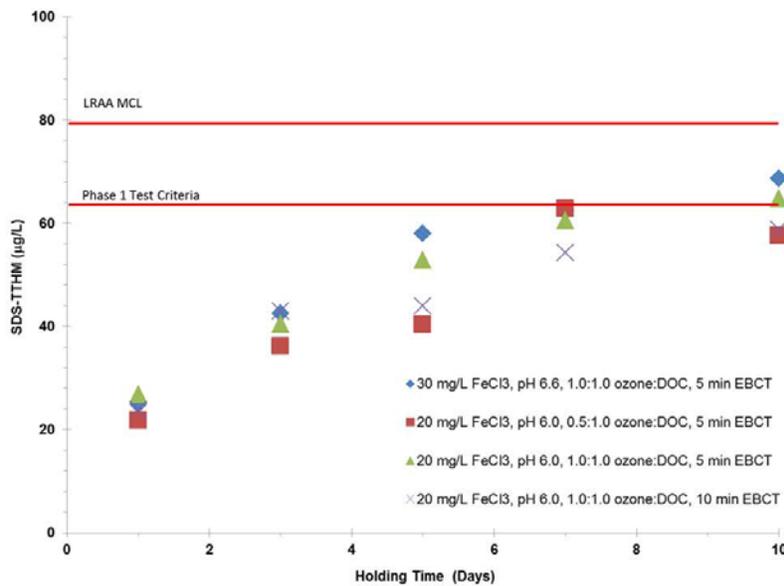


Figure 41. Subtask 3c SDS-TTHM Results

The THMFP results show a similar trend. As shown in Figure 42, treating the water with 20 mg/L FeCl₃, pH 6.0, 0.5:1.0 ozone:DOC, and 5 minute EBCT was the only treatment

combination with the resultant TTHM concentrations not exceeding the Phase 1 criteria. Treatment with 1.0:1.0 ozone:DOC and 10 minute EBCT slightly exceeded the criteria. For both SDS-TTHM and THMFP, treatment with 30 mg/L at the higher pH 6.6 and 20 mg/L at pH 6.0 with 1.0:1.0 ozone:DOC and 5 minute EBCT resulted in TTHM concentrations that exceeded 64 µg/L. The relatively reduced treatment performance at higher ferric dosages and higher pH matches the trends discussed earlier in this report. The 1.0:1.0 ozone:DOC, 5 minute EBCT for the 20 mg/L FeCl₃ water had higher TTHM concentrations compared to the other two combinations of ozone:DOC and EBCT (0.5:1.0, 5-minute and 1.0:1.0, 10 minute). It is possible that the greater ozone dose produced more biodegradable organic carbon that would require longer EBCT for removal. This hypothesis appears to be reasonable based on CBXA data presented below. Oxalic acid concentrations were much greater in the 1.0:1.0 ozone:DOC, 5-minute EBCT sample compared to the 1.0:1.0 ozone:DOC, 10-minute EBCT sample. CBXA results and their relationship to DBP formation potential are described further below.

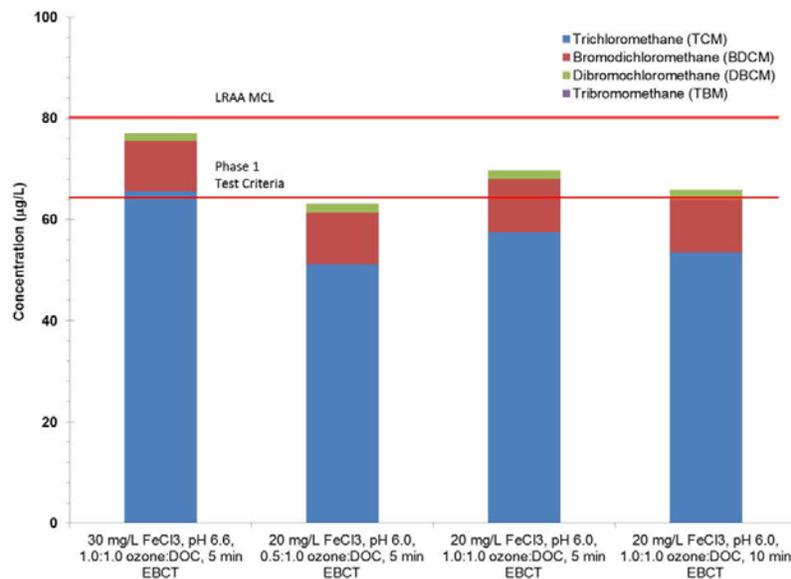


Figure 42. Subtask 3c THMFP Results

The HAA5 analysis determined that this particular set of DBPs was very well removed by ozone/BAF. Figure 43 shows the SDS-HAA data and Figure 44 displays HAAFP results. Both sets of analyses show that HAA5 concentrations were well below the Phase 1 testing criteria. The general trend is that 20 mg/L FeCl₃ at pH 6.0 followed by ozonation at a dose of 0.5:1:0 ozone:DOC and 5 minute EBCT produced water with the lowest HAA5.

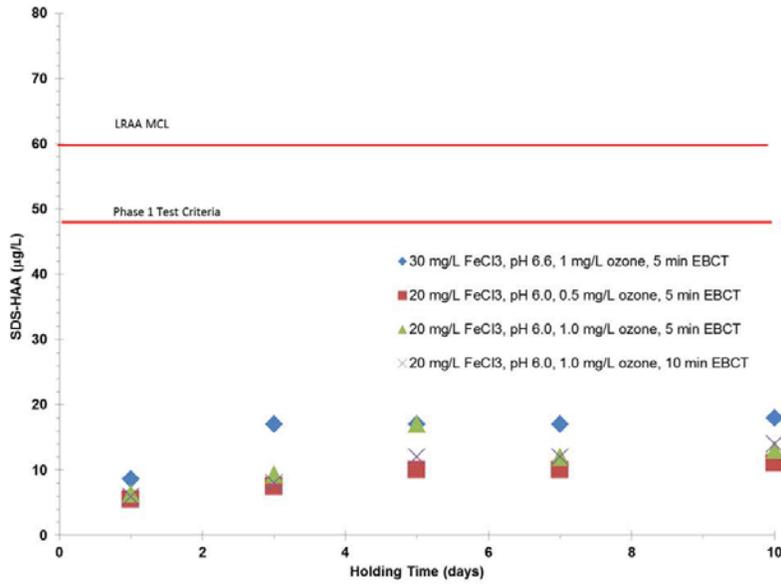


Figure 43. Subtask 3c SDS-HAA Results by Time

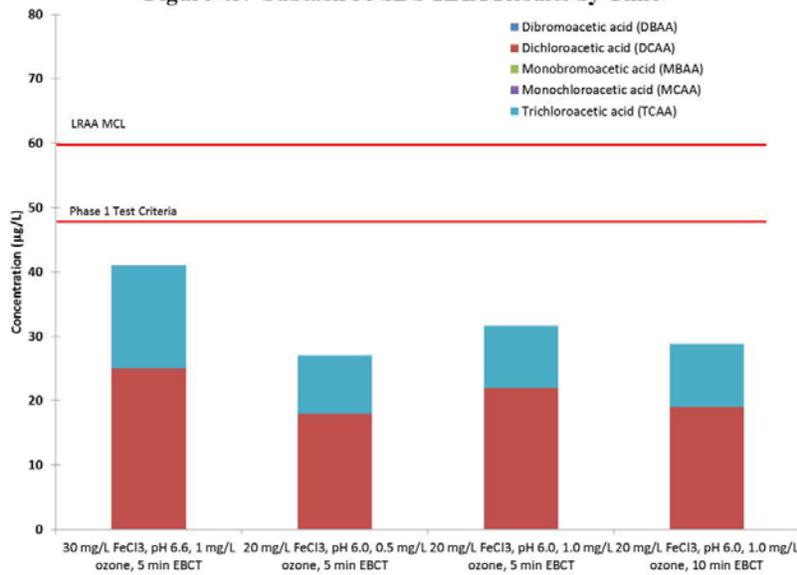


Figure 44. Subtask 3c HAAFP Results

Table 14 compares the results from the Subtask 3a pre-treatment evaluation and this ozone/BAF evaluation for common treatment steps. The data shows that though a higher FeCl₃ dosage at pH 6.6 (after coagulation) had lower DBP concentrations than a lower ferric dosage at pH 6.0 (after coagulation), the ozone/BAF treatment step provided no further THMFP reduction and little HAAFP reduction for the higher FeCl₃ dosage and pH water. In comparison, ozone/BAF treatment worked synergistically with the lower pH water to result in a filtered water with the lowest DBPs.

Table 14. Comparison of Subtask 3a and 3c THMFP and HAAFP Results

Treatment Step	THMFP	HAAFP
After 20 mg/L at pH 6.0	90 µg/L	66 µg/L
After ozonation, 5 minutes EBCT	63 µg/L	27 µg/L
Change due to ozone/BAF	-27 µg/L, -30%	-39 µg/L, -59%
After 30 mg/L at pH 6.6	75 µg/L	51 µg/L
After ozonation, 5 minutes EBCT	77 µg/L	41 µg/L
Change due to ozone/BAF	+2 µg/L, +3%	-10 µg/L, -20%

Figure 45 presents the CBXA concentrations for the collected samples. While various amounts of acetic acid, formic acid, and pyruvic acid were detected, oxalic acid concentrations provided the clearest explanation of ozone/BAF performance. For each water type (30 mg/L FeCl₃, pH 6.6 and 20 mg/L FeCl₃, pH 6.0), increasing ozone:DOC ratios resulted in greater concentrations of oxalic acid after 5 minutes EBCT. In general, more oxalic acid was generated in the 20 mg/L FeCl₃, pH 6.0 water relative to the 30 mg/L FeCl₃ water. This result is likely associated with ozone reactivity dependence on pH (see Figure 23). For all conditions, increased EBCT led to decreased oxalic acid concentrations. This result illustrates that the oxalic acid was biodegraded in the BAF columns and at least 7.5 minutes EBCT was required for complete removal in this study. These results help to explain the TTHM formation results discussed previously. TTHM are not formed directly from oxalic acid; however, oxalic acid is a component of biodegradable organic carbon which, in general, can contribute to TTHM formation. Therefore, oxalic acid is a good surrogate or indicator compound for DBP precursors. TTHM concentrations in the SDS-TTHM and THMFP tests were greater in the 20 mg/L FeCl₃ water under the 1.0:1.0 ozone:DOC, 5 minute EBCT condition relative to the 0.5:1.0 ozone:DOC, 5 minute EBCT and 1.0:1.0 ozone:DOC, 10 minute EBCT conditions. These results directly parallel the oxalic acid concentrations shown in Figure 45, where greater ozone:DOC ratios led to more TTHM and oxalic acid but the oxalic acid and TTHM precursors could be reduced provided there was longer EBCT. Therefore, a minimum EBCT of 7.5 minutes is recommended.

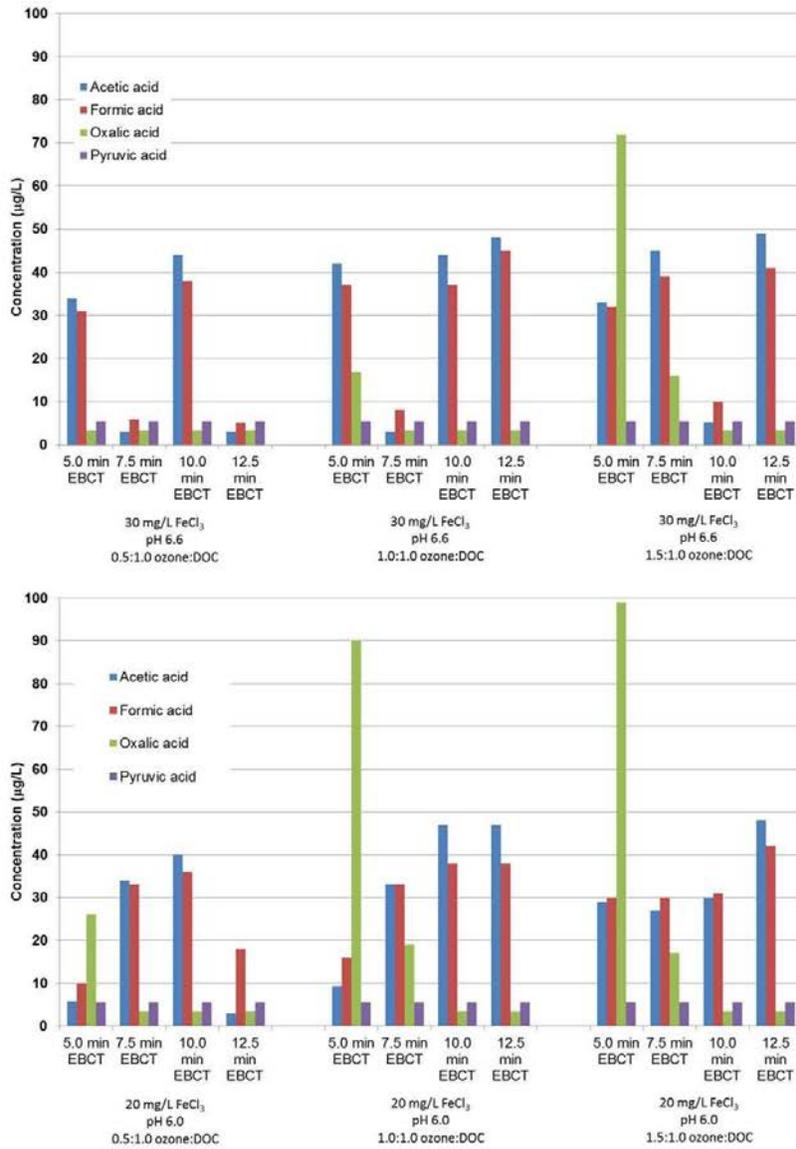


Figure 45. Subtask 3c CBXA Results

Uncertainty associated with the AOC test results possibly led to a lack of correlation with other variables. Figure 46 shows that the water treatment process that produced the lowest DBPs had the highest AOC concentrations, and that there were no understandable trends with regards to FeCl₃ dosages, pH, ozone:DOC ratios, or EBCT. An unidentified interference may have contributed to the poor quality of the data. As noted in the test plan (See Appendix A), the AOC test is an indirect measurement of biologically available organic carbon. The growth of the pure strains (i.e. *Pseudomonas fluorescens* strain P17 and the *Spirillum* species strain NOX) genetically modified with the *lux* gene on the tested aqueous sample are assayed by luminescence, then converted to concentration of AOC through an empirical formula (Weinrich et al., 2009). This method is dependent on the number and metabolic activity of the pure strains tested and estimates only the easily biodegradable organic material. Slowly degradable organics and/or organics that are not degradable to the pure strains will not be characterized in an AOC test. In addition, uncharacterized interferences, sensitivities of the pure strains, and evolving laboratory methodologies have produced inconsistent results and limited cross-facility/cross-source comparisons. Thus, despite being commonplace in the industry, the AOC test may have limited effectiveness to determine true water stability and long-term process optimization benchmarking. The lack of confidence in the AOC test leads the JV Team to not use this parameter for any subsequent design guidance and recommendations.

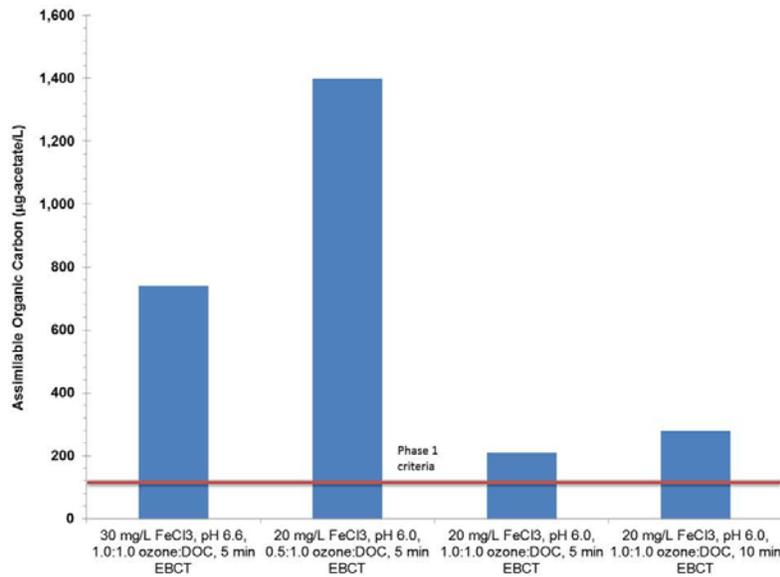


Figure 46. Subtask 3c AOC Results

4.0 Engineering Design Parameter Evaluation

The obtained bench-scale test data was used as a basis to provide guidance for key design parameters identified in the project scope. This section identifies the values for these design parameters. When required, the JV Team used industry design guidance literature and its experience to establish the design parameters for the full-scale Cutter WTP. This section describes each of the design parameters, followed by a summary table of the identified parameters.

4.1 Pre-oxidation

The testing conducted in this report indicates that pre-oxidation is not required for the full-scale system because it did not show any additional benefit in removing DBP precursors or reduction in DBPs.

4.2 Coagulation

Coagulation for the future full-scale Cutter WTP will be conducted using FeCl_3 . The FeCl_3 needs to be compliant with American Water Works Association (AWWA) Standard B407-12 (Liquid Ferric Chloride) and have NSF International (NSF)/American National Standards Institute (ANSI) Standard 60 certification (Drinking Water Treatment Chemicals – Health Effects). The identified coagulant dosage prior ozone/BAF was 20 mg/L FeCl_3 for the Cutter water sample tested. A design maximum coagulant dosage of 40 mg/L is appropriate to account for the known variability in the Cutter Reservoir water quality.

Testing described in this report indicates that the coagulation step needs to be augmented with pH depression to achieve the best overall DBP reduction. The testing was conducted with HCl due to its simplicity in laboratory analyses. However, NSF/ANSI-60 certified sulfuric acid (H_2SO_4) is more commonly used for full scale drinking water treatment due to its lower cost and greater availability. This testing determined that a HCl dosage of 24 mg/L was required to depress the water pH to 6.0. An equivalent H_2SO_4 dosage would be 32.4 mg/L. As with the coagulant, design maximum acid dosages of 48 mg/L HCl or 66 mg/L H_2SO_4 would be appropriate to account for raw water variability.

The coagulant and acid should be added at the same time or slightly before the rapid mix step in the full-scale Cutter WTP. The recommended rapid mix G would be 700 to 1,000 sec^{-1} , the same used for the testing conducted. This range of velocity gradients is noted in both HDR (2002) and Hand and Howe (2012) as typical values for mechanical mixers.

4.3 Flocculation and Sedimentation

The JV Team recommends that flocculation be conducted in two stages to maximize floc formation. Each stage would have a hydraulic retention time of 15 minutes for a total flocculation time of 30 minutes. The first stage would have a mixer providing a velocity gradient of $G = 60 \text{ sec}^{-1}$ while the second stage mixer would provide a gentler $G = 20 \text{ sec}^{-1}$.

The recommendations for longer overall duration and tapered mixing improve upon the approach used in the jar testing as the recommendations improve the floc size and strength, parameters that are less crucial in the small-scale testing conducted. The Ten States Standards (2012) indicates

that the detention time for floc formation should be 30 minutes and be tapered, while Hand and Howe (2012) noted that 20 to 30 minutes is often used for conventional (i.e. coagulation, flocculation, sedimentation, filtration) treatment plants and the typical number of flocculation stages varies between two to six. The flocculation used in jar testing (single stage, $G = 40 \text{ sec}^{-1}$, 20 minutes) was selected to optimize bench-scale testing logistics and results. This condition would work in a full-scale system but is not an ideal set-up.

The 60-minute settling time used by the JV Team was selected to quickly process all the water in a laboratory setting. The needed time for the full-scale Cutter WTP will depend on the selected sedimentation process. Conventional gravity sedimentation should last four hours per the Ten States Standards to maximize solids removal and minimize floc carryover. At 0.5 gallon per minute per square feet (gpm/ft^2) surface overflow rate (SOR) and 5.4 MGD, the duty sedimentation basins would have a total surface area of 7,500 ft^2 and have an average wetted depth of 16 feet. The JV Team recommends installing steeply inclined plate settlers to reduce the overall size of the sedimentation basins. A conservative SOR of 2.0 gpm/ft^2 results in the duty basins shrinking to a surface area of 1,875 ft^2 , an average wetted basin depth of 21 feet, and a hydraulic residence time of 1.3 hours. Sludge removal will be accomplished using a moving vacuum sludge collector mounted on the bottom of the basin floor.

The Phase 2 laboratory testing found formed flocs that were still floating after 60 minutes of quiescent settling time. Formation of floating flocs in a full-scale system would be minimized as settling times are extended. In addition, these floating flocs will be readily prevented from being carried over to the downstream ozonation step by installing scum weirs across the sedimentation basins.

4.4 Ozonation

The Phase 2 test results indicate that an ozone dosage of 0.8 mg/L to the settled water will be adequate for the Cutter water sample tested. A maximum design dosage for the future Cutter WTP should be 1.6 mg/L. There are three general types of ozone generation systems: ambient air, pressure swing adsorption, and liquid oxygen (LOX). Table 15 is a high-level summary of the ozone generation systems. The JV Team recommends that a LOX system be installed if a cost-effective and dependable LOX supply is available. If LOX is unavailable, or very expensive, a pressure swing adsorption system should be considered instead.

The ozone contactor geometry for the 5.4 MGD facility would be a two-train (one duty and one standby) horizontally-baffled serpentine contact chamber. Each train will be sized to provide 10 minute contact time. The width of the serpentine path through the chamber will be 3 feet to allow of access for inspection and cleanings. The ozone contacting portion of the serpentine path length will be 120 feet, a length-to-width ratio of 40:1 to achieve plug-flow conditions and minimize hydraulic short-circuiting. Achieving 10 minutes contact time using these dimensions results in a wetted basin depth of 14 feet. The chamber has an air-tight roof. The headspace of the basin will be under slight vacuum to prevent ozone gas from entering the atmosphere. The captured gas from the basin headspace will be routed to thermal destruction units to destroy the residual ozone prior discharging into the atmosphere.

Table 15. High-Level Summary of Ozone Generation Systems

Parameter	Ambient Air System	Pressure Swing Adsorption System	Liquid Oxygen System
Oxygen supply	Ambient air.	Ambient air.	Liquid oxygen (LOX).
Ozone generation	Electrical corona discharge through ambient air.	Electrical corona discharge through ambient air that has been processed to have enriched oxygen content.	Electrical corona discharge through evaporated liquid oxygen.
Main advantages	Least mechanically complex. Simplest operations Lowest capital cost per gram/hour capacity. Lowest capital and operational costs.	Does not require LOX. Can be used at high elevations.	Compact. Generates very high ozone concentration gas.
Main constraints	Generates low ozone concentration gas – larger equipment required. Very difficult to operate at high elevations due to low atmospheric oxygen partial pressure.	Highest capital and operational cost per gram/hour capacity. Complex operations.	Requires LOX delivery, which may be costly if WTP location is remote. Operational cost highly dependent on LOX cost. Requires cryogenic liquid storage and handling.

The narrow pathway through the contact chamber makes installation and maintenance of diffusers inside the chamber very difficult. In addition, the Ten States Standards (2012) state that the depth of water over the diffusers should be 18 feet at a minimum while Hand and Howe (2012) state that depths of 15 to 20 feet are typical for in-basin diffuser high transfer efficiency, whereas the recommended basin depth is only 14 feet. As a result, ozone addition into the water will occur as a side stream injection in the pipe leading into ozone contact chamber. The side stream will draw 10 to 15 percent of the settled water to push through a venturi eductor. The eductor will draw ozone gas into the water and mix it prior to injecting the ozone-enriched water back to the main process flow stream. An example eductor will be the Mazzei injector, of which a smaller version was used for the Subtask 3c testing. A simplified schematic of the system is shown in Figure 47.

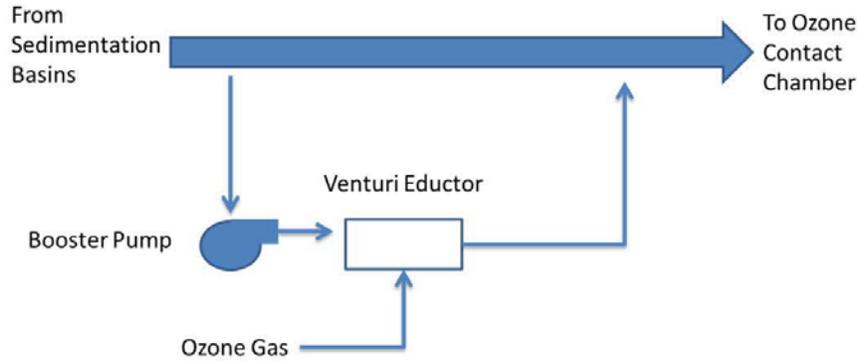


Figure 47. Ozone Side stream Injection Schematic

The calculated cold water ozone decay rate of $k^* = 0.0069$ determined in Subtask 3b indicates that only 14 percent of the ozone would have decayed in the 10 minutes the ozonated water is in the contactor. Nearly the entire applied ozone dosage would need to be quenched to prevent residual ozone from going onto and disinfecting the downstream BAF. Quenching is the process of adding a reducing chemical (typically calcium thiosulfate) to destroy (quench) the remaining dissolved ozone residual. To be conservative, the JV Team assumes that no ozone decay occurs and the quenching dose is 2:1 thiosulfate-to-dissolved ozone. The calculated design calcium thiosulfate dose is then 3.2 mg/L. The quenching chemical will be added in the last 12 feet of the ozone contact chamber to provide 1 minute of quenching reaction time. The total ozone contact chamber length then becomes 120 feet ozone contacting + 12 feet quenching reaction = 132 feet. The quenching chemical should be added with carrier water through a multiple-port injection rod to provide maximum dispersion at the point of injection.

4.5 Biologically Active Filtration

The test results indicated that a 7.5-minute EBCT provided the best treatment performance, and the JV Team recommends using this EBCT for the full-scale system. The surface loading rate is dependent on media type and size. The JV Team recommends using dual media BAFs with slightly larger 1.4 to 1.5 mm GAC over 0.70 to 0.75 mm silica sand allows for increased bed capacity for particulates and biological growth, which result in extending filter run times and higher uniform filter run volumes. Such a media profile can be operated for filter run times of 100 hours and higher at surface loading rates of 5 – 8 gpm/ft². The JV Team recommends a conservative design of 72 hour filter run times at 5 gpm/ft². Table 16 lists dual media filter configuration based on the recommended EBCT and hydraulic loading rate. Operational study and optimization needs to be conducted as part of the plant commissioning process, after the filters become fully biologically active, to determine how much longer filter run times can be extended and how much higher filter loading rates can increase without compromising treatment performance.

Table 16. Recommended Dual Media Filter Configuration

Parameter	Recommended Value
Media top layer	
Media type	Granular activated carbon
Media depth	60 inches
Media characteristics	1.4 – 1.5 mm effective size 1.9 uniformity coefficient (max.)
Media standard	Compliant with AWWA B604-12, Granular Activated Carbon
Media bottom layer	
Media type	Silica sand
Media depth	12 inches
Media characteristics	0.70 – 0.75 mm effective size 1.3 – 1.7 uniformity coefficient
Media standard	Compliant with AWWA B100-09, Granular Filter Material

The testing indicated that BAF columns reached steady state very quickly using just untreated Cutter Reservoir water. As a result, ancillary processes, such as supplemental nutrient addition, may not be required once the filter media becomes fully biologically active. However, provisions for supplemental sodium phosphate addition are recommended in the event of unforeseen water quality or operational changes that severely disrupt or destroy the BAF biota. The sodium phosphate addition would augment BAF growth to counteract any ongoing water quality inhibitions and/or allow the BAF to re-establish itself quicker in the event of a complete process restart (Lauderdale et al., 2011). Alternatively, the phosphate addition can be used seasonally in the future if further TTHM precursor removal is required. The optimal sodium phosphate dosage is such that the dosed settled water would have a nutrient ratio of 100:10:1 carbon:nitrogen:phosphate on a molar basis. The Subtask 3b results indicated that the settled water would have 1.5 mg/L DOC, so the requisite sodium phosphate dosage (as Na₃PO₄) would be 0.15 mg/L. A design maximum dosage is recommended to be 0.30 mg/L sodium phosphate. This recommendation assumes that there is no phosphate in the water, which is highly likely as coagulating water with a metal salt, such as FeCl₃, is very effective at removing phosphate.

Continuous phosphate addition is practiced and a ratio of 100:10:1 carbon:nitrogen:phosphate is maintained will result in optimized biological activity in the BAF. Lauderdale et al. (2011) indicated that optimized biological activity was found to result in the following treatment benefits:

1. Reduced filter headloss development resulting in 15 percent longer filter run times, compared to a non-biologically optimized BAF, reduced backwashing frequency, and greater water efficiency.
2. Over 75 percent improved DOC removal, again compared to a non-biologically optimized BAF.

The selection of sodium phosphate is because the coagulation process causes most BAFs to be phosphate-limited. Coagulation and ozonation has no impacts on nitrogen compounds and most surface waters have trace nitrogen compounds in it. However, analysis of nitrogen species (ammonia, nitrate, and nitrite) was not conducted in this project, nor in the JV Team’s earlier

Phase 1 testing. The 2011 UNM report also does not indicate what nitrogen species are present in the water. The JV Team recommends that both nitrogen and phosphate monitoring be a regular activity when the full-scale plant is commissioned to track how optimized the BAF biota is and when sodium phosphate should be added.

The backwashing scheme for the Cutter WTP BAF would use both air scour and water to clean the filters. The recommended steps, as summarized from Lauderdale et al. (2011) are:

1. Air scour only at up to 3 scfm/ft² for five minutes
2. Air scouring at 3 scfm/ft² while also water backwashing at a low rate of 6 to 7 gpm/ft². This step lasts one to two minutes.
3. High rate backwashing at 20 gpm/ft² for up to twenty minutes.
4. Low rate backwashing at 6 to 7 gpm/ft² for up to five minutes.
5. Quiescent settling for two minutes.
6. Filter-to-waste.

As with the filter run times, operational study and optimization can be conducted after the plant is commissioned to optimize these rates to shorten the overall duration and minimize backwash/filter-to-waste water generation.

4.6 Disinfection

The testing results indicates that a full-scale Cutter WTP operating with the coagulation, ozonation, and BAF parameters described in this section would be expected to be in compliance with both TTHM and HAA5 LRAA MCLs when free chlorination is practiced. The testing data indicates that TTHM and HAA5 formed from free chlorination should be approximately 60 µg/L and 10 µg/L, respectively, when water ages have reached ten days, as long as a chlorine residual is still present. Extrapolating the SDS testing data would seem to indicate that TTHM would reach the testing/design criteria of 80 percent of the MCL (64 µg/L) by eleven to twelve days and the 80 µg/L LRAA MCL by approximately 14 days. Therefore, eleven to twelve days should be the summer-time maximum design water age for the transmission and distribution system. Longer water ages can occur during other seasons without exceeding the testing/design criteria or the LRAA MCL as cooler water temperatures reduces DBP formation kinetics.

The design recommendations for the Cutter WTP are fairly conservative. The first margin of safety is that the DBP design criteria is 80 percent of the MCL. Secondly, the recommendations establish design dosages twice that of the dosages used during testing in order to account for raw water quality variations. In addition, the testing was conducted at the warmer temperature. As noted earlier in this section, cooler water temperatures reduce DBP formation kinetics, which in turn reduces TTHM concentrations when all other factors are equal. Finally, the DBP MCLs are LRAA and allows for occasional TTHM concentrations exceeding the MCL as long as all other subsequent samples are below the MCL. The combination of conservative TTHM design criteria, chemical system design criteria, warmer water temperatures, and the use of LRAA means that the likelihood that the Cutter WTP becomes out of compliance for TTHM should be low.

In the event that summertime water ages exceed eleven to twelve days, the following operational changes can be made to reduce TTHM in the distribution system:

1. If possible, reduce the free chlorine concentration while still maintaining a measureable residual throughout the distribution system.
2. Temporarily add powdered activated carbon to the rapid mix chamber.
3. Conduct phosphate and nitrogen analysis of settled water to determine if the BAF is nutrient-constrained. If constrained, begin supplemental nutrient addition.
4. Conduct spot and unidirectional flushing on the portions of the distribution systems with the longest water ages.
5. Evaluate reducing the volume of stored water in the distribution system without compromising pressure or fire flow requirements.

The focus of DPB compliance is TTHM because HAA5 compliance is not expected to be an issue for the future distribution system since the concentrations would be considerably lower than the 80 percent of MCL criteria based on the bench-scale testing results.

4.7 Corrosion Control

As noted earlier, the water passing through the coagulation and ozone/BAF treatment steps had to be lowered to pH 6.0 to reach the TTHM treatment criteria. The bench-scale testing found that treatment at pH 6.6 would result in filtered waters with TTHM concentrations over the treatment criteria and very close to the TTHM MCL. However, filtered water at pH 6.0 is very corrosive to most metal distribution system piping and appurtenances, and to customer plumbing and fixtures. Therefore, the filtered water pH will need to be adjusted to increase the pH level. The JV Team recommends an initial finished water quality of pH 7.5 or greater, an alkalinity of 50 mg/L (as CaCO₃) or greater, and a Langlier Index greater than zero. An initial water quality model was conducted using corrosion control modeling program Rothberg, Tamburini and Winsor (RTW) Model (version 4.0). The model indicated that a pH of 7.7, 80 mg/L alkalinity, and a Langlier Index of 0.1 can be achieved with the addition of 35 mg/L slaked lime and 4 mg/L caustic soda. This analysis assumes that liquid sodium hypochlorite is used as the chlorination chemical. Based on this analysis, the JV Team recommends that the Cutter WTP have the capacity to feed up to 70 mg/L slaked lime and 8 mg/L caustic soda.

Once the Cutter WTP has been operational for two to three years, the JV Team recommends operations staff conduct an evaluation to determine if lower treated water pHs, and therefore lower lime and caustic soda usage, can be achieved without causing distribution system corrosion issues. The relatively long period between plant commissioning and conducting the evaluation is because a change in the distribution system corrosion rates is a very slow process and the distribution system needs to reach equilibrium with the Cutter treated water quality before pH/alkalinity changes should be made.

4.8 Summary of Design Parameters

Table 17 provides a summary of the recommended design parameters presented in previous sections.

Table 17. Design Parameters Summary

Design Parameter	Value/Comment
Pre-oxidation	
Type and dosage	None.
Coagulation	
Number of trains	Two (one duty and one standby), each sized for 5.4 MGD
Type and design dosage	FeCl ₃ at 20 mg/L (as coagulant), average, and 40 mg/L maximum.
pH adjustment	Depress pH to 6.0 after coagulation using up to 24 mg/L HCl or 32.4 mg/L H ₂ SO ₄ , on average. Design maximum acid dosages of 48 mg/L HCl or 66 mg/L H ₂ SO ₄ . Acid selection will be based on chemical availability and costs,
Coagulant mixing	Mechanical mixers operating at <i>G</i> values of 700 to 1,000 sec ⁻¹ .
Flocculation	
Number of trains	Two (one duty and one standby), each sized for 5.4 MGD
Stages per train	Two
Detention times	15 minutes per stage
<i>G</i> values	Stage 1: 60 sec ⁻¹ Stage 2: 20 sec ⁻¹
Sedimentation	
Number of trains	Two (one duty and one standby), each sized for 5.4 MGD
Configuration	Gravity settling with steeply inclined plate settlers
Surface overflow rate	2.0 gpm/ft ²
Surface area	1,875 ft ² per train. Length by width dimensions dependent on selected plate settler vendor.
Basin depth	24 feet total: 3 feet freeboard, 16 feet deep plate settlers, and 5 feet underneath plate settlers for access and sludge removal mechanism
Sludge removal mechanism	Moving vacuum sludge collector mounted on the bottom of the basin floor.
Ozonation	
Number of ozone generation trains	Two (one duty and one standby), each sized for 5.4 MGD
Ozone generation	Liquid oxygen if LOX supply is available and cost-effective. Otherwise, pressure swing adsorption.
Design dosage	0.8 mg/L average, 1.6 mg/L maximum
Ozone contactor configuration	Horizontally baffled chamber with air-tight roof
Ozone contactor hydraulic residence time	10 minutes at 5.4 MGD

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Design Parameter	Value/Comment
Contact dimensions	3.0 wide serpentine path, total length of 132 feet, wetted basin depth of 14 feet.
Residual ozone gas handling	Capture in ozone contact chamber and route to thermal destruction units.
Residual dissolved ozone handling	Quench at a rate of 2:1 calcium thiosulfate-to-ozone. Design maximum dosage of 3.2 mg/L calcium thiosulfate.
Biologically Active Filtration	
Empty bed contact time	7.5 minutes
Loading rate	5 gpm/ft ² at 5.4 MGD
Media configuration	Dual media: Top media: 60 inches of GAC, 1.4 – 1.5 mm effective size Bottom media: 12 inches of silica sand, 0.70 – 0.75 mm effective size.
Backwash frequency and rate	Every 72 hours using up to 3 scfm/ft ² of air and up to 20 gpm/ft ² of water. distribution Total backwash duration is up to 34 minutes.
Ancillary processes	Sodium phosphate addition at up to 0.30 mg/L.
Disinfection	
Maximum water age	11 to 12 days during summer. Longer duration during other, colder water periods.
Disinfection products formation	Reaching 64 µg/L TTHM by 11 to 12 days during summer. Reaching 12 µg/L HAA5 during the same period. Lower TTHM and HAA5 concentrations at 11 to 12 days when the water is colder.
Corrosion control	
Finished water pH	7.5 or higher
Finished water alkalinity	50 mg/L (as CaCO ₃) or greater
Chemical type and design dose	70 mg/L slaked lime and 8 mg/L caustic soda

5.0 Conclusions

The Phase 2 testing of the Cutter Reservoir water determined the following conclusions:

Pre-treatment

1. Water pH had the strongest effect on DOC removal and DBP formation, with pH 6.0 providing significantly better results than pH 6.6 or 7.5.
2. The second strongest parameter for DBP reduction was FeCl₃ dosage. Higher dosages removed more organic material than lower dosages. However, a lower dosage at pH 6.0 resulted in waters with lower DBP formation potentials than a higher FeCl₃ dosage at pH 6.6 (ambient pH after coagulant addition).
3. Pre-treatment alone using up to 45 mg/L FeCl₃ was insufficient to remove enough organic material to reduce THMFP and HAAFP to below the testing criteria. Pre-

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treatment would remove most of the material but that the ozone/BAF process is required to reach the testing criteria.

4. Pre-ozonation at 0.5 mg/L provided no benefits for DOC removal, UV₂₅₄ absorbance, or DBP reduction.

Ozone/BAF

1. Ozonating the water up to a ozone:DOC ratio of 1.0:1.0 provided significant treatment benefits for removing DOC and UV₂₅₄ absorbance. Ozonating to a higher 1.5:1.0 ratio provided very little additional removal.
2. An EBCT of 7.5 minutes was adequate. Longer EBCTs had little effect on oxalic acid removal which is an indicator of biological stability. DOC concentrations and UV₂₅₄ absorbance were relatively insensitive to EBCT.

DBP Formation

1. The treatment combinations that met or just slightly exceeded the Phase 1 criteria of 64 µg/L TTHM for both THMFP and SDS-THM were pre-treatment at 20 mg/L FeCl₃ at pH 6.0 followed by either ozonating to 0.5:1.0 ozone:DOC ratio and BAF to 5.0 minutes EBCT or ozonating to a ratio of 1.0:1.0 ozone:DOC and BAF to 10 minutes EBCT.
2. Ozone/BAF provided no THMFP reduction and little HAAFP reduction at the higher pH 6.6.
3. Ozone/BAF effectively removed the organic precursors that generate HAA5. Both HAAFP and SDS-HAA were well below the Phase 1 criteria.

AOC/CBXA Reduction

1. The generated AOC data is questionable and did not match any of the other water treatment or quality variables observed and evaluated in this report. In addition, none of the final optimized testing conditions resulted in AOC concentrations below 100 µg/L. As a result, the AOC data produced in this report should not be used for any subsequent biostability study or designs.
2. Of the four CBXAs analyzed, oxalic acid appears to be a good indicator for biostability and its removal for waters treated with 20 mg/L FeCl₃.
3. An EBCT of 10 minutes shows nearly complete removal of oxalic acid while 5 minutes results in significant remaining oxalic acid concentrations.
4. A BAF EBCT of 7.5 minutes would be a good balance between minimizing TTHM formation, maximizing biostability, and controlling filter sizes and costs.
5. The oxalic acid reduction would indicate that the water has high biostability, and result in higher and more consistent chlorine residuals in the distribution system, less likely potential for nitrification to develop or for coliform growth to occur.

6.0 References

- American Public Health Association (APHA). 2005. *Standard Methods of Water and Wastewater*. 21st ed. American Public Health Association, American Water Works Association, Water Environment Federation publication. APHA, Washington D.C.
- Evans, P.J. 2010. "Nature works: Biological treatment methods yield high quality water." *Opflow* July: 12-15.
- Evans, P.J., J.L. Smith, M.W. LeChevallier, O.D. Schneider, L.A. Weinrich, and P.K. Jjemba. 2013. "Monitoring and Control Tool Box for Assessing and Enhancing Biological Filtration." *Water Research Foundation Project 4231 Report* Water Research Foundation, Denver, CO.
- Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. 2012. *Recommended Standards for Water Works (Ten States Standards)*, 2012 ed.. Health Research Inc, Albany, NY.
- Hand, D.W. and K.J. Howe. 2012. *MWH's Water Treatment: Principles and Design*. 3rd ed. John Wiley & Sons.
- HDR Engineering. 2002. *Handbook of Public Water Systems*. 2nd ed. John Wiley & Sons.
- Kerry, K. 2012. "Analysis Results for Coagulation Jar Testing and Disinfection By-Product Formation for the USBR Navajo/Gallup Water Supply Project (September 2011 – Cutter Reservoir)". Report for Bureau of Reclamation, January 2012.
- Lauderdale, C.V., J.C. Brown, P.A. Chadik, and M.J. Kirisits. 2011. "Engineered Biofiltration for Enhanced Hydraulic and Water Treatment Performance." *Water Research Foundation Project 4215 Report*, Water Research Foundation, Denver, CO.
- LeChevallier, M. W.; Shaw, N. E.; Kaplan, L. A.; Bott, T. L. 1993. Development of a Rapid Assimilable Organic Carbon Method for Water. *Applied Environmental Microbiology*. 59(5):1526-1531.
- LeChevallier, M. W.; Welch, N. J.; Smith, D. B. 1996. "Full-Scale Studies of Factors Related to Coliform Regrowth in Drinking Water. *Applied Environmental Microbiology*. 62(7):2201-2211.
- Water Research Foundation. 2015 "An Operational Definition of Biostability for Drinking Water" *Water Research Foundation Project 4312 Report*, Water Research Foundation, Denver, CO (in progress).
- Weinrich, L.A., E. Giraldo, and M.W. LeChevallier. 2009. Development and Application of a Bioluminescence-Based Test for Assimilable Organic Carbon in Reclaimed Waters. *Applied Environmental Microbiology*. 75(23):7385-7390.

Appendix A

Test Plan

**BUREAU OF RECLAMATION
TECHNICAL SERVICE CENTER**



**CONTRACT: R12PC80235
TASK ORDER: R14PS00331**

**CUTTER RESERVOIR WATER TREATMENT
BENCH SCALE TESTING**

**ENHANCED BENCH SCALE STUDY
TEST PLAN AMENDMENT**

FINAL

December 23, 2014

HDR-CDM Joint Venture

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APPENDIX

- September 2013 Phase 1 Test Plan

ACRONYMS

AOC	Assimilable Organic Carbon
APHA	American Public Health Association
ATP	Adenosine Triphosphate
BAF	Biologically Active Filtration
BDOC	biodegradable dissolved organic carbon
CFU/g	colony forming units per gram
DBP	Disinfection Byproduct
DBPFP	Disinfection Byproduct Formation Potential
DI	de-ionized
DOC	Dissolved Organic Carbon
EBCT	Empty Bed Contact Time
g/hr	grams per hour
GC-MS	Gas Chromatograph - Mass Spectrometer
H ₂ SO ₄	Sulfuric Acid
HAA6	Haloacetic Acids 6
HASP	Health and Safety Plan
HCl	Hydrochloric Acid
JV	Joint Venture
MCL	Maximum Contaminant Level
mg/L	milligrams per liter
mgd	million gallons per day
mL	milliliter
mL/min	milliliters per minute
Na ₂ S ₂ O ₃	Sodium Thiosulfate
NaOH	Sodium Hydroxide
NGWSP	Navajo/Gallup Water Supply Project
NH ₄ Cl	Ammonium Chloride
NOM	Natural Organic Matter
PBRWS	Pojoaque Basin Regional Water System
pg/g	picograms per gram
PWS	Project Work Statement
QA/QC	Quality Assurance/Quality Control
scfh	standard cubic feet per hour
SDS	Simulated Distribution System
SDWA	Safe Drinking Water Act
DBPSDS	Disinfection Byproduct Simulated Distribution System
SWTR	Surface Water Treatment Rule
TOC	Total Organic Carbon
TSC	Technical Service Center
TTHM	Total Trihalomethanes
US EPA	United States Environmental Protection Agency
UV	Ultra-Violet
Water RF	Water Research Foundation
WTP	Water Treatment Plant
°C	degrees Centigrade
µg/L	micrograms per liter

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Cutter Reservoir Water Treatment Bench Scale Testing
Enhanced Bench Testing- Part 2 Test Plan/Part 1 Amendment

1.0 INTRODUCTION

The Cutter Lateral of the Navajo Gallup Water Supply Project (NGWSP) will deliver treated, potable water from the Cutter Reservoir to users in the Jicarilla Apache and Navajo Nations. The Cutter Lateral when completed will consist of a lengthy network of pipelines and pump stations along the eastern portion of the Navajo/Gallup Water Supply Project (NGWSP) and will include a new 5.4 million gallon per day (mgd) water treatment plant (WTP) that will provide treated water from the Cutter Reservoir. The treated water may experience a water age of up to 10 days. Reclamation is investigating water treatment processes for the Cutter Reservoir water treatment plant that include enhanced coagulation, flocculation, sedimentation, ozonation and biological active filtration (BAF or biofiltration), followed by disinfection with ultraviolet (UV) irradiation and possibly free chlorine.

The HDR-CDM Smith Joint Venture (JV) previously conducted bench-scale testing for Reclamation on the ozone and BAF treatment processes with Cutter Reservoir water samples as a proof of concept for the ozone/BAF treatment process. The bench-scale test results determined that using the ozone/BAF treatment process to remove natural organic matter (NOM) was a feasible treatment process. The Phase 1 test results are summarized in the January 2014 report “Cutter Reservoir Water Treatment Bench-Scale Testing: Final Bench-Scale Test Results Report”.

2.0 PROBLEM STATEMENT

Based on the Project Work Statement (PWS), Reclamation is contracting with the JV Team to conduct the testing necessary to provide design criteria for the treatment facility. The objective of this Phase 2 bench scale testing is build upon the initial Phase 1 feasibility results to optimize parts of the coagulation, ozone, and BAF processes for the reduction of Disinfection By-Products (DBPs), such that secondary disinfection with free chlorine will meet Stages 1 and 2 of the Disinfection/ Disinfectants Byproducts Rule of the Safe Drinking Water Act.

The JV Team will complete a three-part test to meet the project objectives noted in the Reclamation PWS and the JV proposal, which supplements and modifies the original PWS. The goal of Part 1 testing will be to optimize the coagulation process by testing various levels of ferric chloride, pH, and pre-oxidation. Parts 2 and 3 will test varying ozone dose and empty bed contact time (EBCT) in an effort to optimize the Ozone and BAF processes. This test plan describes proposed bench scale testing to be conducted at the JV Laboratory in Bellevue Washington. The JV Team will systematically apply our laboratory bench scale expertise with the goal of determining if the proposed treatment scheme can meet the water quality goals.

The JV Team will summarize the Phase 2 results and provide optimized design parameters that can be used for final design of the treatment plant after testing is completed. The JV will work collaboratively with Reclamation throughout the testing program by conducting regular coordination conference calls. A summary of the design parameters is shown in Table 1.

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US Bureau of Reclamation
Cutter Reservoir Water Treatment Bench Scale Testing
Enhanced Bench Testing- Part 2 Test Plan/Part 1 Amendment

Table 1. Design Parameters

Process	Design Parameters
Pre-oxidation	Type and dosage
Coagulation	Type, dosage, pH and G-value
Flocculation	Stages, detention time, and G-value
Ozonation	Dosage, contact time, and contactor geometry
Biofiltration	EBCT, surface loading rate, filter run times, backwash rate and frequency, ancillary processes (type and dosage)
Disinfection	SDS DBP formation and maximum water age

3.0 TEST PLAN AMENDMENT

This test plan builds upon the Phase 1 Cutter Reservoir Ozone/BAF Test Plan submitted by the JV Team in September 2013 (See Appendix) and will be considered an amendment to that test plan. The JV Team repeats the Phase 1 test plan methodology for the following items in this particular test plan:

- Section 4.1 – Media acquisition and acclimation, modified to use obtained Cutter Reservoir water instead Lake Washington water;
- Section 5 – Specific testing methods for coagulation/filtration, ozonation, and DBPSDS testing using chlorine; and
- Section 9 – Project staffing, with the replacement of Michael Zafer with Christopher Schultz for Quality Assurance/ Quality Control.

This test plan amendment modifies the September 2013 test plan with the method of Cutter water sample collection and associated quantity and also consists of varying the following test variables:

- Coagulant (ferric chloride) dose
- pH
- pre-oxidation
- Ozone dose
- Empty bed contact time (EBCT)

4.0 TESTING ACTIVITIES

Phase 2 testing will consist of the following tasks:

1. Test Planning
2. Water Collection
3. Process Testing
 - a. Jar Testing
 - b. Ozone Demand and Decay Testing
 - c. Ozone/BAF Testing
4. Engineering Design Parameter Evaluation
5. Reporting

This test plan document constitutes the summation of the test planning activities for Task 1 (Test Planning). Tasks 2 (Water Collection) and 3 (Process Testing [including all subtasks]) are described in greater detail in this document. Task 4 is outside the scope of this test plan as it is a literature- and design-based review with no sampling, monitoring, or analytical component. Task 5 (Reporting), as it pertains to this test plan, is described in Section 9.0 of this document.

4.1 Task 2 – Water Collection

Water sampling consists of onsite sample collection of 420 gallons of Cutter Reservoir water using a portable, gas-powered pump to transfer reservoir water into 20-gallon barrels. A battery powered pump will also be available as a back-up. Approximately 20-25 barrels will be transported by truck to the Reclamation Four Corners Construction Office (FCCO), located in Farmington, NM, for temporary storage until the JV Team's contracted refrigerated truck arrives for sample pick-up and delivery to an offsite temperature-controlled warehouse in Kent, Washington, just outside Seattle. The sample will be collected by one field person from the JV Team and one Reclamation representative from the FCCO. It is anticipated that the Cutter water sample collection will require one day for testing of pump equipment and one day to collect the sample and transport to the FCCO.

The JV Team has completed initial coordination with Reclamation staff from the FCCO and Technical Services Center (TSC) and determined that the sample will be collected from the location where Cutter Reservoir water enters the outlet canal. The water will be pumped into sample bottles that will be located in the initial transport trucks and/or trailers. Prior to the start of the field collection, the onsite JV staff person will meet with the FCCO representative to review the proposed sampling area, identify potential health and safety hazards associated with the sampling activities, and develop a plan to address the hazards. Both the JV and FCCO onsite staff will need to agree that the sampling procedure is safe before proceeding.

Cutter reservoir water samples will be inspected upon arrival at the warehouse in Kent, Washington and at the JV laboratory to confirm the integrity of the sample and that the sample is acceptable for analysis. Samples leaked during transportation will be discarded. The samples will be stored at the Kent warehouse until they are needed, at which time the JV Team will remove the required daily volume from the warehouse and drive the water to the

JV laboratory. Upon receipt at the JV laboratory, the water will be stored in a dark area of the laboratory to allow gradual equilibration with room temperature. Before any use, the source water samples will be homogenized by rolling the containers on the floor.

4.2 Task 3 – Process Testing

Task 3 will be conducted to determine specific parameters for the subsequent WTP design. Jar testing (Subtask 3a) will be conducted to optimize the coagulation process by testing various levels of ferric chloride, pH, and pre-oxidation. Subtask 3b will be conducted to optimize the ozone oxidation process and characterize ozone demand and decay kinetics for the Cutter Reservoir water. Subtask 3c will evaluate water quality improvements resulting from variations of BAF EBCT and ozone:TOC ratios.

This process testing will not include the use of coagulant aid polymers, filter aid polymers, alternate coagulants, or alternate pre-oxidants.

4.2.1 Subtask 3a – Jar Testing

A series of 12 jar tests will be conducted to evaluate ferric chloride dose, pre-oxidation, and pH. The number of jar tests corresponds to two test runs each with six jar conditions, which is equal to the number of jars in the tester that will be used. These parameters will be systematically varied in order to optimize the coagulation and flocculation processes for turbidity and NOM removal. The planned tests and conditions are shown in Table 1.

Run 1 will be conducted to optimize coagulant dose at a constant pH and to also evaluate the potential benefit of pre-oxidation. The Reclamation report “Analysis Results for Coagulation Jar Testing and Disinfection By-Product Formation for the USBR Navajo/Gallup Water Supply Project (September 2011 – Cutter Reservoir)” prepared by the University of New Mexico (UNM) (2012) indicated that coagulating the Cutter Reservoir water with a 16 mg/L FeCl_3 (0.1 mM Fe) and then chlorinating it with sodium hypochlorite resulted in DBP concentrations of 135 $\mu\text{g/L}$ TTHM and 103 $\mu\text{g/L}$ HAA5, which exceeds the respective maximum contaminant limits (MCLs) 80 $\mu\text{g/L}$ and 60 $\mu\text{g/L}$ for both contaminants. A dosage of 32 mg/L FeCl_3 (0.2 mM Fe) resulted in 103 $\mu\text{g/L}$ TTHM and 79 $\mu\text{g/L}$ HAA5, lower but still in excess of the MCLs. The JV Team is using a range of coagulant dosages of 20 mg/L, 30 mg/L and 40 mg/L FeCl_3 . The low dosage of 20 mg/L matches the Phase 1 testing for data comparison and is also higher than the 2012 UNM dosage of 16 mg/L. The upper dosage of 40 mg/L was selected as a balance between enhanced DBP removal, pH depression and neutralization, chemical costs, and coagulant sludge formation. The 30 mg/L FeCl_3 dosage is the midpoint between the low and high dosages. Raw water ozone pre-oxidation and coagulation jar testing will be conducted immediately thereafter in Run 2.

Jar testing will be conducted using a six-gang programmable Phipps and Bird jar tester with 2-L jars. Rapid mix will be conducted based on a single set of mixing stages, proposed G values, and mixing durations that the JV team identifies as most appropriate for this type of water and coagulant. During the rapid mix stage, pH will be adjusted to 7.0 with 0.1 N sodium hydroxide or 0.1 N hydrochloric acid. The water will then be allowed to settle for 60 minutes and samples will be collected for analysis. Settled water will be analyzed for the

parameters listed in Table 3. The conditions that provide the best turbidity removal and UV₂₅₄ absorbance reduction will be considered optimal. The results will be evaluated to answer two questions:

1. Should pre-oxidation be used for subsequent testing?
2. What are the two best coagulant doses to be used for subsequent testing?

The JV Team will summarize the Run 1 results and present the information to Reclamation in a conference call to answer these questions. At the end of the call, the JV Team and Reclamation will select the two optimal conditions for testing in Run 2.

Table 2. Jar Testing (Subtask 3a)

Run	Test	Ferric Dose (mg/L)	Settled water pH (to be obtained by adjusting alkalinity)	Preoxidation with 0.5 mg/L O ₃	Temperature (deg C)	Sub-objective
1	1	20	Ambient after coagulation	No	Room (~20)	Determine whether pre-oxidation is beneficial and optimize ferric dose
1	2	30	Ambient after coagulation	No	Room (~20)	Determine whether pre-oxidation is beneficial and optimize ferric dose
1	3	45	Ambient after coagulation	No	Room (~20)	Determine whether pre-oxidation is beneficial and optimize ferric dose
1	4	20	Ambient after coagulation	Yes	Room (~20)	Determine whether pre-oxidation is beneficial and optimize ferric dose
1	5	30	Ambient after coagulation	Yes	Room (~20)	Determine whether pre-oxidation is beneficial and optimize ferric dose
1	6	45	Ambient after coagulation	Yes	Room (~20)	Determine whether pre-oxidation is beneficial and optimize ferric dose
2	1	20	6.0	Yes	Room (~20)	Optimize pH at two best ferric doses
2	2	20	6.0	No	Room (~20)	Optimize pH at two best ferric doses
2	3	30	Ambient after coagulation	Yes	Room (~20)	Optimize pH at two best ferric doses
2	4	30	Ambient after coagulation	No	Room (~20)	Optimize pH at two best ferric doses
2	5	30	6.0	Yes	Room (~20)	Optimize pH at two best ferric doses
2	6	30	6.0	No	Room (~20)	Optimize pH at two best ferric doses

The six tests for Run 2 will be conducted as shown in Table 2. The water pH will be adjusted using either 0.1 N sodium hydroxide or 0.1 N hydrochloric acid. Sample analyses will be conducted as described in Table 3. The results will be evaluated with respect to optimal

treatment, again based on the best settled water turbidity and UV₂₅₄ absorbance. The outcome of Test 2 will be two process chemistry design recommendations providing optimal turbidity removal and UV₂₅₄ absorbance reduction. These two process chemistries will be defined by ozone pre-oxidation (i.e., presence/absence), ferric chloride dose, and pH. The two optimal process chemistries are designated “Settled Water A” and Settled Water B” and will be evaluated further in Subtask 3b described below.

Table 3. Jar Testing Analyses (Subtask 3a)

Parameter	Method	Raw Water	Run 1	Run 2
pH	SM 4500-H B	1	6	6
Color	SM 2120/ EPA 110.2	1	6	6
Alkalinity	SM 2320 / EPA 310.1	1	6	6
Turbidity	SM 2130 /2130B	1	6	6
UV ₂₅₄	SM 5910	1	6	6
DOC	SM 5310B	1	6	6
AOC	Weinrich et al., 2009	0	0	0
Carboxylic Acid	EPA 300.1, modified	0	0	0
THMFP	SM 5710B, EPA 524.2	0	6	6
HAAFP	SM 5710B,D, EPA 552.3	0	6	6
SDS-THM	SM 5710C, EPA 524.2	0	0	0
SDS-HAA	SM 5710C,D, EPA 552.3	0	0	0
Ozone Residual	SM 4500	0	3	Up to 6

Note – The numbers indicate the number of analyses that will be conducted.

4.2.2 Subtask 3b – Ozone Demand and Decay Testing

Ozone demand and decay tests will be conducted to provide rate constants for ozone decay as a function of pH for Settled Water A and B as shown in Table 4. The tests will be conducted at two water temperatures using recirculating water chillers and heaters to maintain constant water temperatures for the duration of these tests. Refer to the September 2013 test plan for equipment, ozone flowrates, and ozonation process. Fresh batches of Settled Waters A and B will be prepared immediately before initiation of this test. Samples will be placed in glass reaction bottles in a temperate controlled water bath and allowed to reach the desired temperature (Table 3). Ozone will then be dosed to the water at a constant weight ratio of

1.5:1.0 ozone-to-TOC. Subsamples will be collected immediately upon dosing and analyzed for ozone residual so that an ozone decay curve can be prepared. First-order rate constants will be calculated for ozone decay. Following complete decay of ozone, the remaining samples will be analyzed as described in Table 5. The results of this test will provide engineering data for use by Reclamation in designing the ozone system.

Table 4. Ozone Demand and Decay Testing (Subtask 3b)

Run	Test	Settled Water	Ferric Chloride Dosage	pH	Ozone: TOC Ratio	Temperature (deg C)
4	1	A	20 mg/L	6.0	1.5:1.0	4.0 – min. observed
4	2	A	20 mg/L	6.0	1.5:1.0	20.0 – max. observed
4	3	B	30 mg/L	Ambient after coagulation	1.5:1.0	4.0 – min. observed
4	4	B	30 mg/L	Ambient after coagulation	1.5:1.0	20.0 – max. observed

Table 5. Ozone Demand and Decay Testing Analyses (Subtask 3b)

Parameter	Method	Settled Water	Ozonated Water
pH	SM 4500-H B	2	4
Ozone Residual	SM 4500	0	Up to 40 (4 tests x 10 samples/test)

Note – The numbers indicate the number of analyses that will be conducted.

4.2.3 Subtask 3c – Ozone/BAF Testing

Ozone/BAF of Settled Waters A and B will be evaluated in this subtask using column tests as outlined in Table 5. Six columns (I through VI) will be built as illustrated in Figure 1 and will be equipped with multiple sample ports along the column length. The column will be 1-inch in diameter and the length will be 30 inches to provide a maximum EBCT of 12.5 minutes. Sample ports will be located at the influent, effluent, and at 12, 18, and 24 inches from the bottom to vary the EBCT. The associated EBCTs for a flow rate of 30 milliliters per minute (mL/min) for the three intermediate sample ports and the effluent are 5.0, 7.5, 10, and 12.5 minutes. Assuming operation of 6 columns for 5 days at 30 mL/min, a minimum volume of 340 gallons is required. Refer to the September 2013 test plan (See Appendix) for how the water will be coagulated, settled, and ozonated prior to being pumped into the columns.

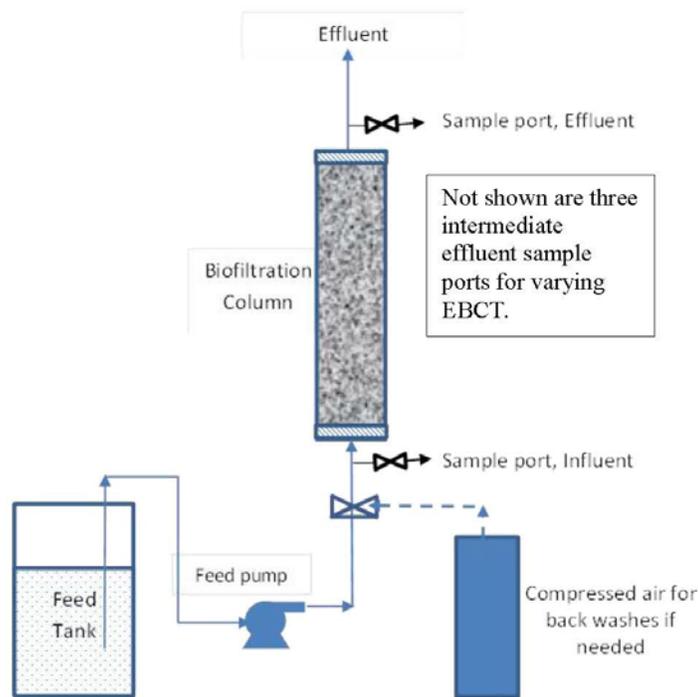


Figure 1. BAF Column Schematic

Three liters of anthracite BAF media will be acquired from the Fort Worth, Texas Rolling Hills WTP. This WTP is where the media for the previous Phase 1 study was acquired. Each column will be packed with 390 mL of media and then operated in recirculation mode with water from Cutter Reservoir for approximately one week prior to initiation of the experiment. Each of the columns will then be transitioned to pretreated Cutter Reservoir water as

specified in Table 6. The columns will be operated for one week and samples (described further below) will be collected daily for five consecutive days.

Table 6. Ozone/BAF Optimization (Subtask 3c)

Test	Settled Water	Ozone: TOC	EBCT (min)	Column
1	A	0.5:1.0	5.0	I
2	A	0.5:1.0	7.5	I
3	A	0.5:1.0	10.0	I
4	A	0.5:1.0	12.5	I
5	A	1.0:1.0	5.0	II
6	A	1.0:1.0	7.5	II
7	A	1.0:1.0	10.0	II
8	A	1.0:1.0	12.5	II
9	A	1.5:1.0	5.0	III
10	A	1.5:1.0	7.5	III
11	A	1.5:1.0	10.0	III
12	A	1.5:1.0	12.5	III
13	B	0.5:1.0	5.0	IV
14	B	0.5:1.0	7.5	IV
15	B	0.5:1.0	10.0	IV
16	B	0.5:1.0	12.5	IV
17	B	1.0:1.0	5.0	V
18	B	1.0:1.0	7.5	V
19	B	1.0:1.0	10.0	V
20	B	1.0:1.0	12.5	V
21	B	1.5:1.0	5.0	VI
22	B	1.5:1.0	7.5	VI
23	B	1.5:1.0	10.0	VI
24	B	1.5:1.0	12.5	VI

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Coagulation, pH adjustment (if needed), flocculation, and settling will be conducted in 25-gallon batches to obtain the same level of treatment as the previously identified Settled Waters A and B. The large batches of prepared Settled Waters A and B will be stored in 5-gallon polyethylene jugs at 4°C in a walk-in cooler until use. When needed, the jugs of Settled Waters A and B will be removed from the cooler daily, allowed to naturally warm up to room temperature (~20 deg C), and then ozonated in ~12 gallon batches. Ozonation will achieve dosage ratios of 0.5, 1.0, and 1.5 mg O₃/mg TOC. Each batch of water will then be pumped through the six columns at a constant rate of 30 mL/min.

Samples will be collected as indicated in Table 7. Turbidity, UV₂₅₄, and DOC will be analyzed daily to quantify BAF performance and assess when steady state conditions has been achieved. Other parameters will be determined after 5 days or when steady state is achieved, whichever comes first. SDS testing will be conducted on final samples. SDS testing results will be evaluated to determine, for each test condition, the maximum water age that will allow compliance with MCLs.

Table 7. Ozone/BAF Optimization Analyses (Subtask 3c)

Parameter	Method	BAF effluent
pH	SM 4500-H B	24 tests x 1 samples/test = 24
Color	SM 2120/ EPA 110.2	24 tests x 1 samples/test = 24
Alkalinity	SM 2320 / EPA 310.1	24 tests x 1 samples/test = 24
Turbidity	SM 2130 /2130B	24 tests x 5 samples/week = 120
UV ₂₅₄	SM 5910	24 tests x 5 samples/week = 120
DOC	SM 5310B	24 tests x 5 samples/week = 120
AOC	Weinrich et al., 2009	4 tests
Carboxylic Acid	EPA 300.1, modified	24 tests x 1 samples/test = 24
THMFP	SM 5710B, EPA 524.2	4 tests x 1 samples/test = 4
HAAFP	SM 5710B,D, EPA 552.3	4 tests x 1 samples/test = 4
SDS-THM	SM 5710C, EPA 524.2	4 tests x 1 samples/test = 4
SDS-HAA	SM 5710C,D, EPA 552.3	4 tests x 1 samples/test = 4
Ozone Residual	SM 4500	0

The numbers in Table 7 indicate the number of analyses that will be conducted. Daily samples will analyzed for turbidity, DOC, and UV₂₅₄ over the period of up to 5 days to demonstrate steady state conditions. If steady state is attained earlier, the test may be terminated before five days in consultation with Reclamation. Other analytes will be measured at single time points. AOC, DBPFP and SDS testing will be conducted on 4 of the best performing of the 18 conditions. These conditions will be selected in consultation with Reclamation. THMFP and HAAFP tests will be conducted at a water distribution system pH of 8.0 and a temperature of 20 C, using chlorine as the disinfectant. SDS testing will be conducted at a temperature of 20 C, a pH of 8.0, and a chlorine dose of 2 mg/L based on discussions with Reclamation. Sampling and analysis for TTHM and HAA5 will be conducted 1, 3, 5, 7 and 10 days after disinfectant addition as specified in the Solicitation.

5.0 MONITORING, SAMPLING, AND ANALYTICAL TESTING

Water samples will be collected and analyzed for different water quality parameters. Table 8 lists the analytical methods and equipment necessary to evaluate the treatment options.

Table 8: Analytical methods and instrumentation for bench testing

Parameter	Analytical Method	Method Detection Limit	Bottle type	Preservative	Holding Time	JV Lab Equipment/Vendor
pH	SM 4500-H B	±0.1 SU	15 mL polypropylene centrifuge tube	None	Analyze immediately	Multiple calibrated digital pH meters
Color	SM 2120/ EPA 110.2	1 PCU	15 mL polypropylene centrifuge tube	None	14 days	Hach DR 6000 and Hach DR 4000 UV-spectrophotometers
Alkalinity	SM 2320 / EPA 310.1	1 mg/L	250 mL glass jar	None	14 days	Hach digital titrator
Turbidity	SM 2130/2130B	0.01 NTU	15 mL polypropylene centrifuge tube	None	14 days	Hach turbidimeter
UV ₂₅₄	SM 5910	0.01 cm ⁻¹	15 mL polypropylene centrifuge tube	None	14 days	Hach DR 6000 and Hach DR 4000 UV-spectrophotometers
Free chlorine	Hach Method 10069	0.1 mg/L	15 mL polypropylene centrifuge tube	None	Analyze immediately	Hach test kit
Total chlorine	Hach Method 10070	0.1 mg/L	15 mL polypropylene centrifuge tube	None	Analyze immediately	Hach test kit
Ozone residual	SM 4500- O ₃	0.01 mg/L	15 mL polypropylene centrifuge tube	None	Analyze immediately	Hach DR 6000 and Hach DR 4000 UV-spectrophotometers
Carboxylic Acid	Peldszus et al. 1996, Peldszus and Huck 1996	4.5 µg/L	50 mL polypropylene centrifuge tube	Frozen or 4°C	24 hours unless frozen	East Bay Municipal Water District
TOC	SM 5310 B	0.1 mg/L	40 mL pre-cleaned glass TOC vial	H ₂ SO ₄ (sample pH<2)	28 days	Shimadzu TOC analyzer
DOC	SM 5310 B	0.1 mg/L	40 mL pre-cleaned glass TOC vial	H ₂ SO ₄ (sample pH<2)	28 days	Shimadzu TOC analyzer
AOC	SM 9217 B	10 µg/L	40 mL pre-cleaned glass TOC vials	4°C and Na ₂ S ₂ O ₃	3 days	Eurofins Eaton Laboratories
THMFP	SM 5710B, EPA 524.2	0.5 µg/L	40 mL VOA vials	4°C	14 days	Gas chromatograph-mass spectrometer (GC-MS) with purge & trap
THM-SDS	SM 5710C, EPA 524.2	0.5 µg/L	40 mL VOA vials	4°C	14 days	Gas chromatograph-mass spectrometer (GC-MS) with purge & trap
HAAFP	SM 5710B,C, EPA 552.3	1.0 µg/L	60mL vials with PTFE lined cap	100 mg/L NH ₄ Cl	14 days	Eurofins Eaton Laboratories
HAA5 – SDS	SM 5710B,C, EPA 552.3	1.0 µg/L	60mL vials with PTFE lined cap	100 mg/L NH ₄ Cl	14 days	Eurofins Eaton Laboratories

H₂SO₄ = Sulfuric Acid; PTFE = Polytetrafluoroethylene; NH₄Cl= Ammonium Chloride; Na₂S₂O₃ = Sodium Thiosulfate; N/A = Not applicable

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6.0 DESCRIPTION OF TESTING EQUIPMENT

Table 9: Description of testing equipment for bench testing

Equipment	Quantity	Make and Model
Water Storage and Preparation		
▪ Water heaters and chillers	1	Sheldon Manufacturing, Inc. 1213
▪ Walk-in coolers (cold room) and refrigerators	2	Piedmont Air PR12-1AS, Marvel Scientific
Experimental equipment		
▪ Fume hoods	1	Jamestown Metal Products MHC0
▪ Bench-scale ozone generators	1	Clearwater Tech CD12
▪ Vacuum filtration systems	1	Gast Aerojet Vacuum Pump, AO3
▪ Biofiltration columns	1	Plastic column with end caps
▪ Pumps, piping and tubing for bench-scale columns	1	Cole-Parmer Tygon Tubing
Analytical Equipment		
▪ UV visible spectrophotometers	1	HACH DR6000
▪ Imhoff sludge settling columns	1	Wheaton W990800
▪ TOC analyzer	1	Shimadzu TOC-V CSH
▪ Ion chromatograph with auto sampler	1	Dionex LC 20
▪ GC-MS	2	Agilent 6890 w/ 5973N
▪ pH/DO meters	1	Orion

7.0 QUALITY ASSURANCE/QUALITY CONTROL

Quality assurance/quality control (QA/QC) for the water quality testing will include chain-of-custody procedures, instrument calibration requirements, bench testing protocols, data recording and data collections spreadsheets. All sample collection, preservation and analysis will be performed in accordance with the appropriate EPA or Standard Methods requirements. Sample collection and analysis will be performed by laboratory staff that has been trained in the appropriate laboratory methods including sample collection, preservation, analysis, data entry and the appropriate QA/QC procedures.

Chain of custody forms will be generated and accompany all samples that are sent to outside laboratories (East Bay Municipal Water District [EBMUD] and Eurofins Eaton Analytical [EEA]) for analysis. Copies of the chain of custody forms will be received from the outside laboratories once analyses are completed. Upon receipt of the results, sample quality control will be reviewed and, if acceptable, the sample data will be added to the project database. All data and submittals performed by outside analytical laboratories will be reviewed and approved by the JV Team prior to their submittal to Reclamation. If requested, data will be made available to the project participants and/or the Navajo Nation regulatory agents.

7.1 Accuracy

The JV Team, EEA, and EBMUD will conduct the analytical methods indicated in the proposal to generate data that are of acceptable quality. Laboratory instruments will be calibrated in accordance with EPA, standard methods, laboratory standard operating procedures (SOPs), and manufacturer’s recommendations. Equipment will also be examined to determine whether it is functioning properly. Calibrations will be performed at the start of each pH, turbidity, DOC, AOC, carboxylic acid, THM, and HAA sampling event. Light sources in the spectrophotometers for color, alkalinity, UV₂₅₄, and ozone residual analyses are calibrated annually based on the manufacturer’s recommendations. Reagents used in the preparation of standard solutions will be of analytical quality (typically ≥99% purity). The accuracy of instrument calibration will be verified in accordance with laboratory SOPs. In addition to calibrations, method blank samples will be used to assess carryover and contamination of laboratory equipment at the frequencies noted in Table 10 below. Check standards will be used to check the calibration accuracy throughout test runs outlined below.

Table 10. Plan Procedures for Accuracy

Phase	Analyte	Laboratory	Calibration	Method Blanks	Check Standards
Jar Testing, Ozone Demand and Decay Testing, Ozone/BAF Testing	pH	JV Team	2 point, prior to each sample event	N/A	1 per sample event
Jar Testing, Ozone Demand and Decay Testing, Ozone/BAF Testing	Color	JV Team	Annual	N/A (Deionized water [DI] used to zero)	N/A
Jar Testing, Ozone Demand and Decay Testing, Ozone/BAF Testing	Alkalinity	JV Team	Annual	1 per sample event	1 per sample event
Jar Testing, Ozone Demand and Decay Testing, Ozone/BAF Testing	Turbidity	JV Team	2 point, prior to each sample event	1 per sample event	1 per sample event

Table 10. Plan Procedures for Accuracy

Phase	Analyte	Laboratory	Calibration	Method Blanks	Check Standards
Jar Testing, Ozone Demand and Decay Testing, Ozone/BAF Testing	UV ₂₅₄	JV Team	Annual	N/A (Deionized water [DI] used to zero)	N/A
Jar Testing, Ozone Demand and Decay Testing, Ozone/BAF Testing	DOC	JV Team	3 point (minimum), prior to each sample event	3 per sample event	10%
Ozone Demand and Decay Testing, Ozone/BAF Testing	AOC	EEA	Prior to each sample event, performed per method and lab SOP specifications	Performed per method and lab SOP specifications	
Ozone/BAF Testing	Carboxylic acids	EBMUD	Prior to each sample event, performed per method and lab SOP specifications	Performed per method and lab SOP specifications	
Jar Testing, Ozone/BAF Testing	THMs ¹	JV Team	4 point, prior to each sample event	3 per sample event	10%
Jar Testing, Ozone/BAF Testing	HAA ²	EEA	Prior to each sample event, performed per method and lab SOP specifications	Performed per method and lab SOP specifications	
Jar Testing, Ozone Demand and Decay Testing	Ozone Residual	JV Team	Annual	N/A (Ozone free water used to zero)	N/A

Notes

¹ As assessed for THMFP and SDS-THM

² As assessed for HAAFP and SDS-HAA

7.2 Precision

Analytical duplicates will be used to assess precision. Table 11 notes the frequency at which duplicates will be performed. Parameters that are dependent on rapid kinetic changes during the ozone demand/decay testing make duplicate analysis infeasible, and will therefore not be performed. Analytical duplicates provided to EEA and EBMUD will be blind duplicates, in addition to any laboratory control duplicates.

Table 11. Precision Sample Frequency

Analyte	Laboratory	Jar Testing	Ozone Demand/Decay	BAF Testing
pH	JV Team	10%	N/A	10%
Color	JV Team	10%	-	10%
Alkalinity	JV Team	10%	-	10%
Turbidity	JV Team	10%	-	10%
UV ₂₅₄	JV Team	10%	-	10%
DOC	JV Team	10%	-	10%
AOC	EEA	-	-	10%
Carboxylic acids	EBMUD	-	-	10%
THMs ¹	JV Team	10%	-	10%
HAA ²	EEA	10%	-	10%
Ozone Residual	JV Team	N/A	N/A	N/A

Notes

¹ As assessed for THMFP and SDS-THM

² As assessed for HAAFP and SDS-HAA

- = Not tested in this phase

N/A = Analytical duplicates not feasible

7.3 QA/QC Calculations

Accuracy and precision of quality control samples will be calculated with the following calculations and methods.

7.3.1 Method Blanks

Method blanks will be assessed against the method reporting limits, values greater than the reporting limit, and the associated results, will be flagged.

7.3.2 Percent Recovery

The percent recovery of laboratory check standards will be calculated using the following equation:

$$\%R = \frac{A}{B} \times 100$$

Where: A = Analyte concentration determined experimentally in control sample
B = Analyte concentration of the control sample

The accuracy goal for the method defined control samples are defined by the laboratories' SOPs. If no laboratory recovery is specified, acceptance criteria will be defined as $\pm 40\%$ of the analyte concentration.

7.3.3 Analytical Duplicates

Precision will be assessed by calculating the relative percent difference (RPD) between the sample and laboratory duplicate sample per the following equation:

$$\%RPD = \frac{S-D}{(S+D)/2} \times 100$$

Where: S = Sample value
D = Analytical duplicate sample value

Precision goals will be assessed on sample pairs where the values are at least 10 times higher than the reporting limit. Precision goals are defined by the laboratories in their standard operating procedures. If no laboratory recovery is specified, acceptance criteria will be defined as less than 40% difference between samples.

7.4 Quality Review and Corrective Actions

Data will be promptly evaluated to determine if QA objectives are being met so that corrective actions may be taken immediately, if necessary. Examples of possible corrective actions include recalibration, checking equipment for possible malfunctions, checking mathematical calculations, modifying sample methods, adjusting experimental techniques, and/or re-analyzing samples, where feasible.

All results released prior to the final report will be flagged as preliminary screening results. At project completion, The JV Team will perform an independent quality review of the project results, calculations, and quality data generated. Quality results and any deviations from the proposal or work plan will be documented in the final project report. The draft report will be reviewed by a senior technical staff member responsible for quality assurance and quality control.

7.5 Data Storage, Reporting, and Statistics

The data management system used for the bench scale testing program will involve the use of computer spreadsheets and/or a project database. As much as possible, data collection will be done electronically with data entry to the project spreadsheet or database after validation. All data will be stored electronically with backup copies made routinely. If appropriate, original data will be included as a part of the appendices for the final report.

8.0 HEALTH AND SAFETY

Laboratory health and safety plan (HASP) will be developed and implemented prior to starting any testing. An addendum to the plan will be written to address additional hazards posed by the use of oxidants, including ozone and sodium hypochlorite. This addendum will address storage and signage requirements for these oxidants to protect laboratory personnel from associated hazards.

9.0 DATA REVIEW AND REPORTING

Throughout the bench-scale testing period, the Project Team will review and interpret all of the laboratory performance and water quality data and extract useful information through data analysis techniques. A draft report will be prepared after the completion of the Tasks 2 and 3 bench scale testing activities summarized in this test, and completion of the Task 4 (Engineering Design Parameter Evaluation), for Reclamation review/comments. Reclamation comments will be incorporated and a final project report will be prepared and submitted to Reclamation. The final report will summarize the results of the testing and will also discuss recommendations for future optimization testing of the pre-treatment and BAF processes if needed.

10.0 PROJECT SCHEDULE

Table 12: Project Schedule

Activity Number	Activity Description	Completion Date
1	Bench Scale Test Plan – Draft	Friday, Aug. 22, 2014
	TSC Comments to JV Team	Friday, Aug. 29, 2014
	Bench Scale Test Plan – Final	Friday, Sept. 12, 2014
2	Sample Collection and Shipment	Wednesday, Sept. 10, 2014
3a	Jar Testing	Friday, Oct. 10, 2014
3b	Ozone Demand and Decay Testing	Friday, Sept. 26, 2014
3c	Ozone/BAF Testing – Column Tests	Tuesday, Oct. 21, 2014
	Ozone/BAF Testing – SDS/FP Analytical Testing	Friday, Oct. 31, 2014
5	Process Test Results Report – Draft	Friday, Dec. 5, 2014
	TSC Comments to JV Team	Friday, Dec. 12, 2014
	Process Test Results Report – Final	Wednesday, Dec. 31, 2014
	Note – Task 4 (Engineering Design Parameter Evaluation) to be completed prior to Task draft report.	

APPENDIX

SEPTEMBER 2013 PHASE 1 TEST PLAN

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Cutter Reservoir Water Treatment Bench Scale Testing
Enhanced Bench Testing- Part 2 Test Plan/Part 1 Amendment

**US BUREAU OF RECLAMATION
TECHNICAL SERVICE CENTER**



**CONTRACT: R12PC80235
TASK ORDER: R13PD80243**

**CUTTER RESERVOIR WATER TREATMENT
BENCH SCALE TESTING**

**BENCH SCALE STUDY
TEST PLAN**

September 2013

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ACRONYMS

AOC	Assimilable Organic Carbon
APHA	American Public Health Association
ATP	Adenosine Triphosphate
BAF	Biologically Active Filtration
BDOC	biodegradable dissolved organic carbon
CFU/g	colony forming units per gram
DBP	Disinfection Byproduct
DBPFP	Disinfection Byproduct Formation Potential
DI	de-ionized
DOC	Dissolved Organic Carbon
EBCT	Empty Bed Contact Time
g/hr	grams per hour
GC-MS	Gas Chromatograph - Mass Spectrometer
H ₂ SO ₄	Sulfuric Acid
HAA6	Haloacetic Acids 6
HASP	Health and Safety Plan
HCl	Hydrochloric Acid
JV	Joint Venture
MCL	Maximum Contaminant Level
mg/L	milligrams per liter
mgd	million gallons per day
mL	milliliter
mL/min	milliliters per minute
Na ₂ S ₂ O ₃	Sodium Thiosulfate
NaOH	Sodium Hydroxide
NGWSP	Navajo/Gallup Water Supply Project
NH ₄ Cl	Ammonium Chloride
NOM	Natural Organic Matter
PBRWS	Pojoaque Basin Regional Water System
pg/g	picograms per gram
PWS	Project Work Statement
QA/QC	Quality Assurance/Quality Control
scfh	standard cubic feet per hour
SDS	Simulated Distribution System
SDWA	Safe Drinking Water Act
DBPSDS	Disinfection Byproduct Simulated Distribution System
SWTR	Surface Water Treatment Rule
TOC	Total Organic Carbon
TSC	Technical Service Center
TTHM	Total Trihalomethanes
US EPA	United States Environmental Protection Agency
UV	Ultra-Violet
Water RF	Water Research Foundation
WTP	Water Treatment Plant
°C	degrees Centigrade
µg/L	micrograms per liter

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1.0 INTRODUCTION

Cutter Lateral is a 100-mile network of pipelines and pump stations at the eastern portion of the Navajo/Gallup Water Supply Project (NGWSP) and will include a new 5.4 million gallons per day (mgd) water treatment plant (WTP) that will treat water from the Cutter Reservoir. The new Cutter WTP will supply treated water to the Cutter Lateral and deliver water to the eastern Navajo Nation and Jicaralla Apache Nation. The United States Bureau of Reclamation (Reclamation) is conducting studies to evaluate the treatability of the Cutter Reservoir water in San Juan County in northwest New Mexico to meet Federal and state drinking water standards.

2.0 PROBLEM STATEMENT

Based on the Project Work Statement (PWS), Reclamation has been investigating several water treatment processes for the Cutter WTP. Reclamation wants to verify the acceptability of the currently preferred WTP process of enhanced coagulation-flocculation sedimentation, ozone coupled with biologically active filtration (BAF), followed by disinfection with ultra-violet (UV) and free chlorine to meet turbidity, disinfection and disinfection byproduct (DBP) goals of the U.S. Environmental Protection Agency (U.S. EPA), Navajo Nation EPA, and applicable regulations such as the Safe Drinking Water Act (SDWA) and Surface Water Treatment Rule (SWTR). Bench scale testing has been requested by Reclamation to determine if the ozone/BAF process will remove sufficient natural organic matter (NOM) to reduce DBP formation with the use of free chlorine.

The CDM Smith and HDR joint venture (JV) team will conduct a bench scale study to evaluate the feasibility of ozone/BAF as a potential treatment process to reduce the NOM levels in Cutter reservoir water. This test plan describes proposed bench scale testing to be conducted at the JV Laboratory in Bellevue Washington. The JV team will systematically apply our laboratory bench scale expertise with the goal of determining if the proposed treatment scheme can meet the water quality goals.

The primary objective of the bench scale study is to evaluate the feasibility of ozone/BAF for reducing disinfection byproduct formation potential (DBPFP), assimilable organic carbon (AOC), and dissolved organic carbon (DOC). The study will evaluate if these constituents can be reduced to levels that meet the treatment goals summarized in Table 1 without process optimization.

Table 1: Treatment goals for the finished water

	Regulatory requirement
Dissolved Organic Carbon (DOC)	≤ 1.5 mg/L
Assimilable Organic Carbon (AOC)	≤ 100 µg/L
Disinfection Byproduct Formation Potential (DBPFP)	
Total Trihalomethanes (TTHM)	80% of the maximum contaminant level (MCL) (≤ 64 µg/L)
Haloacetic Acids 6 (HAA6)	80% of the MCL (≤ 48 µg/L)

3.0 GENERAL APPROACH - OZONE/BIOLOGICALLY ACTIVE FILTRATION

Previous bench and pilot studies conducted by our team recognize the key to minimizing DBP formation is maximizing natural organic matter (NOM) removal. Therefore, our approach is based on removal or conversion of NOM to a form that can be more easily removed by biological filtration. Coagulation followed by oxidation with ozone and biofiltration is an effective process (Evans 2010). Coagulation removes the bulk of the NOM and ozonation converts a sufficient amount of the residual NOM to a form that can be removed in a biological filter. Pre-oxidation increases the biodegradability of complex NOM that is present in surface water and typically results in generation of biodegradable dissolved organic carbon (BDOC) and smaller organic compounds including carboxylic acids and aldehydes. BAF downstream of oxidation is capable of oxidizing these biodegradable compounds to carbon dioxide leading to decreased DBP formation potential upon chlorination and increased water stability in the distribution system.

4.0 DETERMINING ACCEPTABILITY OF OZONE/BAF PROCESS

The primary goal of this bench scale study is to determine if the ozone/BAF treatment process can reduce Cutter Reservoir water (source water) NOM to acceptable levels and reduce DBP formation potential. The study will also evaluate if the proposed treatment process can meet the treatment goals summarized in Table 1. For this purpose, bench scale testing is divided into two phases. Phase 1 will involve collection of source water, Lake Washington water (Lake water), and anthracite media (media) from a bioactive filter. Phase 2 will consist of conducting bench scale treatability testing involving pretreatment followed BAF. Details of these activities are provided in the following sections.

4.1 Phase 1 - Sample Collection

Lake Washington water samples - Grab water samples from Lake Washington (lake water) will be collected in sixteen 5-gallon plastic containers. A total of 80 gallons of lake water will be collected and transported to the JV laboratory where this water will be stored at 4°C for preservation. Lake water will be filtered by using a high flow rate filtration system to remove solids before using in the anthracite acclimation process. This activity is an in-kind contribution from the JV team and is currently in progress.

Cutter reservoir water samples - Reclamation will collect 100 gallons of source water from Cutter Reservoir and ship to the JV laboratory at the following address:

CDM Smith
Attn: Tony Singh
14432 SE Eastgate Way
Suite #100
Bellevue, WA 98007

For easy handling during transportation and storage, five-gallon plastic cubitainers are preferred for sample collection. Source water samples will be shipped on ice via overnight delivery to the JV laboratory. The JV laboratory will send a sample shipment memo to the Reclamation prior to source water sample shipment. This memo is used to identify any

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hazards associated with the samples. For test planning purposes, the source water sample is anticipated to be received on October 1, 2013. Cutter reservoir water samples will be inspected upon arrival in the laboratory to confirm the integrity of the sample and that the sample is acceptable for analysis. Samples leaked during transportation will be discarded.

Upon receipt at the JV laboratory, the source water will be pre-treated as discussed in Section 5.0 and stored at 4°C. Prior to any testing, water will be taken out of the cold room and placed in a dark area in the laboratory to allow equilibration with room temperature. Before any testing, the source water samples will be homogenized by rolling the cubitainer on the countertop.

Media Acquisition and Acclimation - The JV team is in the process of acquiring 1000 milliliters (mL) of biomass-established anthracite BAF media from the Rolling Hills Water Treatment Plant in Fort Worth, Texas. This plant was selected for media collection because of the high adenosine triphosphate (ATP) (5.04×10^4 picograms per gram (pg/g) media dry weight and heterotrophic plate counts (3.15×10^8 colony forming units per gram (CFU/g) media dry weight) observed during a previous WaterRF 4231 project (Evans et al. 2013). For media collection, the top 0.5-inch of media layer in the biofilter will be scraped and discarded as this may contain solids. Media will then be collected from the top six inches of the BAF, where the most extensive biological activity is expected. Media will be collected in a one-liter polyethylene bottle. To keep the biofilm moist during shipping/transportation, biofilter influent water (unchlorinated) will be added to the polyethylene bottle containing media. Media will be shipped on ice via overnight delivery to the JV laboratory.

The media will be loaded into a one-inch diameter, 24-inch (bed height) long BAF column at the JV laboratory. A plastic perforated disk with approximately one-inch of glass wool on each end of the column will be used for supporting anthracite media. Lake water will be recirculated through the column at a flow rate of 30 milliliters per minute (mL/min) (10 minutes empty-bed contact time [EBCT]) to start the media acclimation process. Lake water will be changed twice a week for two weeks. The goal is to have the BAF system ready when the shipment of source water arrives. Use of Lake water for acclimation will acclimate the BAF media column prior to operation with Cutter Reservoir water.

4.2 Phase 2 – Bench Scale Testing

Pretreatment Process Train – In accordance with the PWS the pretreatment process train will consist of coagulation/flocculation/sedimentation and ozonation. Ferric chloride will be used as coagulant at dose of 20 milligrams per liter (mg/L), as indicated by Reclamation in the PWS, followed by flocculation and sedimentation. An additional pretreatment process step of filtering the water after sedimentation will be employed to remove solids or floc. Filtered source water will be ozonated in separate batches of 13 gallons each day and this will be used as the feed water to the BAF column. Detailed test procedures on the pretreatment testing are given in Section 5.0.

Bench Scale BAF Column testing - Biofiltration column tests will be conducted on the ozonated source water that have been pre-treated using coagulation/flocculation/sedimentation and filtration. The objective of the column testing is to evaluate the feasibility of BAF in combination with pre-oxidation for reducing NOM, and thus DBPFP. A one-inch diameter 24-inch bed height column containing acclimated anthracite media will be operated in single pass flow through mode. Ozonated source water will be introduced to the column using a peristaltic pump at a flow rate of 30 mL/minute to achieve an EBCT of 10 minutes.

5.0 SPECIFIC TESTING METHODS

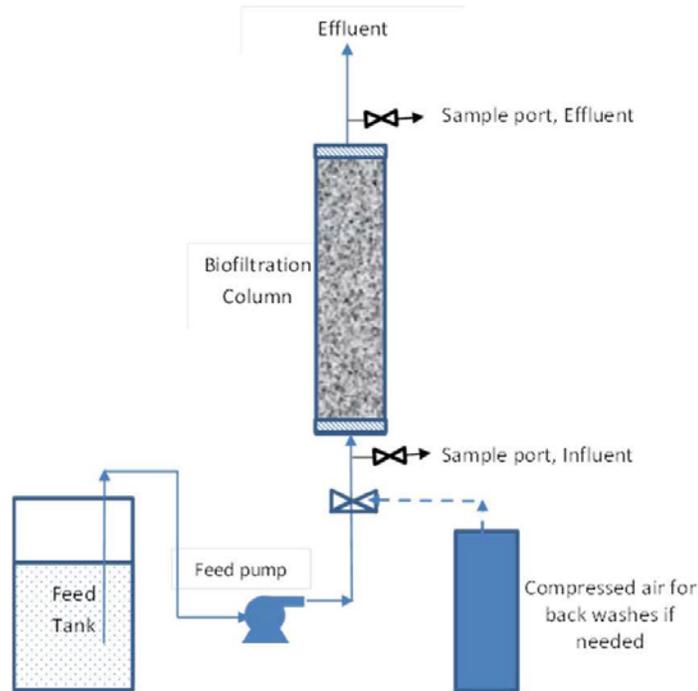
Coagulation/Flocculation - The 100-gallon source water sample will be divided and treated in three batches at the JV laboratory upon arrival. Each batch will be coagulated, settled, and filtered prior to storage at 4°C in a cold room. Approximately 34 gallons of sample will be transferred to a clean unused 55-gallon drum. 20 mg/L of ferric chloride (NSF certified) will be added to the sample followed by a rapid mixing with a velocity gradient (G value) between 700 – 1,000 sec⁻¹ for 30 seconds and then a slow mixing (flocculation) with a G value between 25 and 50 sec⁻¹ for 20 minutes. A variable speed mixer will be used in conjunction with a mixing paddle to provide appropriate mixing energy for coagulation and flocculation. The flocculated water will be settled for 60 minutes before the supernatant is carefully decanted and filtered through a high flow rate filtration system using a pump. Filtered water pH will be measured and recorded. If the pH is considered too low for optimal biological filtration (6.5 – 8.5), pH will be adjusted using diluted NaOH or HCl.

Ozonation - A 1.5 ozone/total organic carbon (TOC) dose ratio will be used in this study to provide adequate pre-oxidation for BAF. The TOC of the pretreated water sample will be analyzed using an in-house TOC analyzer. An ozone generator (Clearwater Tech CD 12) that has a capacity of 8 grams/hour (8 standard cubic feet per hour ((scfh)) with oxygen source (3 grams per hour [g/hr] with air) will be used to generate ozone needed. Thirteen gallons of pretreated water sample (the quantity needed for one day of BAF operation is approximately 12 gallons) will be ozonated in a vertical ozone reactor (equipped with a ceramic fine bubble diffuser) in semi batch mode. At 8 scfh oxygen and full power setting, ozone will be generated and passed through one gallon of deionized (DI) water in a semi batch mode (continuous gas flow through a batch of water). Aqueous samples will be withdrawn at different time intervals (5, 10, 15, 30, 45, and 60 minutes) and analyzed for residual aqueous phase ozone content using standard method 4500 O₃ B (APHA, 2005). An ozone dose calibration graph of aqueous ozone content versus time will be developed. Assuming the same ozone mass transfer efficiency in source water, this calibrated ozone dose curve will be used as the operation guidance for appropriate ozone dosing throughout the study.

Biological active filtration (BAF) Column Testing – A schematic of the BAF column setup is shown in Figure 1. An EBCT of 10 minutes is selected based on the JV team's experience in achieving appropriate filter column hydraulics, optimal BAF performance, and the quantity of water sample available (100 gallons). Ozonated source water will be pumped to the BAF column through a peristaltic pump at 30 mL/min flow rate that corresponds to a

column run of 8 days (using 100 gallons of water). Influent and effluent samples will be taken at a minimum of once per day and measured for analytes listed in Table 2. Exact sampling frequency will be determined based on the DOC reduction observed at each sampling point. Sample analysis is described in Section 7.0.

Figure 1: Schematic of single pass flow through BAF column setup



DBPSDS Testing using Chlorine – Standard 5-day Simulated Distribution System (SDS) testing will be performed using the standard method 5710 (APHA, 2005). SDS testing will be conducted with chlorine. Free chlorine, TTHM, and HAA6 will be analyzed during SDS testing. To determine an appropriate chlorine dose for the SDS testing, a preliminary 24-hour chlorine demand test will be conducted. For this, 5 mg/L of sodium hypochlorite will be added to a water sample (100 mL), and left to react for 24 hours in the dark at room temperature. Phosphate buffer will be added for pH adjustment. An initial water sample will be collected and analyzed for free chlorine dose (Initial). After 24 hours, residual free chlorine of the sample will be determined. The 24-hour chlorine demand value will be calculated by subtracting the final chlorine dose from the initial applied chlorine dose. Chlorine dose for the actual SDS testing will be calculated by adding 1 mg/L to the 24-hour chlorine demand value.

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6.0 DESCRIPTION OF THE EXPECTED RESULTS

NOM is a key surface water quality parameter that affects the disinfection process and formation of DBPFP. Coagulation/flocculation is an effective technique to remove NOM. With an optimized oxidation step (ozonation), it is expected that NOM will be converted to smaller and more easily biodegradable organic compounds (carboxylic acids and aldehydes). These smaller organic compounds can be effectively removed by the BAF process. This removal is anticipated to translate into reduced DOC, AOC, and DBPSDS. The actual reductions will be determined by the testing.

7.0 MONITORING, SAMPLING, AND ANALYTICAL TESTING

Water samples will be collected and analyzed for different water quality parameters at four stages during bench testing (Table 2). Sample pH, TOC and DOC will be measured in all four stages. Table 2 lists the analytical methods and equipment necessary to evaluate the treatment options.

Raw source water will be characterized for all the analytes mentioned in Table 2 except AOC and ozone residuals. Total and free chlorine content will be measured during DBPSDS testing only. Current BAF column influent and effluent will be sampled every day but this sampling frequency may be altered during column testing based on effluent DOC, and TOC reduction observed. AOC and DBPSDS analysis on the post biofiltration will be conducted for the sample at the end of the column run. The BAF column will be operated for a maximum of 8 days based on the 100 gallons source water.

Table 2: Analytical methods and instrumentation for bench testing

Parameter	Sampling Points					Analytical Method	Method Detection Limit	Bottle type	Preservative	Holding Time	JV Lab Equipment
	Raw Water	Post Sedimentation	Post Ozonation	Post Biofiltration (Column study)	Post Biofiltration (SDS testing)						
pH	1X	1X	Daily	Daily	Daily	SM 4500-H B	±0.1 SU	15 ml polypropylene centrifuge tube	4°C	Analyze immediately	Multiple calibrated digital pH meters
Free chlorine	1X	1X	-	-	Daily	Hach Method 10069	0.1 mg/L	15 ml polypropylene centrifuge tube	none	Analyze immediately	Hach test kit
Total chlorine	1X	1X	-	-	Daily	Hach Method 10070	0.1mg/L	15 ml polypropylene centrifuge tube	none	Analyze immediately	Hach test kit
Ozone residual	-	-	Daily	-	-	SM 4500- O ₃	0.01mg/L	15 ml polypropylene centrifuge tube	none	Analyze immediately	Hach DR 6000 and Hach DR 4000 UV-spectrophotometers
TOC	1X	1X	Daily	Daily	-	SM 5310 B	0.1 mg/L	40 ml pre-cleaned glass TOC vial	H ₂ SO ₄ (sample pH<2)	28 days	Shimadzu TOC analyzer
DOC	1X	1X	Daily	Daily	-	SM 5310 B	0.1 mg/L	40 ml pre-cleaned glass TOC vial	H ₂ SO ₄ (sample pH<2)	28 days	Shimadzu TOC analyzer
DBPSDS – TTHM	1X	1X	-	-	1x	EPA Method 501.1	0.5µg/L	40 ml VOA vials	4°C	14 days	Gas chromatograph-mass spectrometer (GC-MS) with purge & trap
DBPSDS – HAA6	1X	1X	-	-	1x	EPA Method 552.2	1.0µg/L	3 x60mL vials with PTFE lined cap	100 mg/L NH ₄ Cl	14 days	Eurofins Eaton Laboratories
AOC		1X	-	1X	-	SM 9217 B	10 µg/L	40 ml pre-cleaned glass TOC vials (10 per sample)	4°C and Na ₂ S ₂ O ₃	3 days	Eurofins Eaton Laboratories
SDS Testing	1X	1X		-	1X	SM 5710	N/A	N/A	4°C	N/A	JV Laboratory

1X: One time per day
 H₂SO₄ = Sulfuric Acid
 PTFE = Polytetrafluoroethylene
 NH₄Cl= Ammonium Chloride
 Na₂S₂O₃ = Sodium Thiosulfate
 N/A: Not applicable

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8.0 DESCRIPTION OF TESTING EQUIPMENT

Table 3: Description of testing equipment for bench testing

	Quantity	Make and Model
Water Storage and Preparation		
▪ Water heaters and chillers	1	Sheldon Manufacturing, Inc. 1213
▪ Walk-in coolers (cold room) and refrigerators	2	Piedmont Air PR12-1AS, Marvel Scientific
Experimental equipment		
▪ Fume hoods	1	Jamestown Metal Products MHC0
▪ Bench-scale ozone generators	1	Clearwater Tech CD12
▪ Vacuum filtration systems	1	Gast Aerojet Vacuum Pump, AO3
▪ Biofiltration columns	1	Plastic column with end caps
▪ Pumps, piping and tubing for bench-scale columns	1	Cole-Parmer Tygon Tubing
Analytical Equipment		
▪ UV visible spectrophotometers	1	HACH DR6000
▪ Imhoff sludge settling columns	1	Wheaton W990800
▪ TOC analyzer	1	Shimadzu TOC-V CSH
▪ Ion chromatograph with auto sampler	1	Dionex LC 20
▪ GC-MS	2	Agilent 6890 w/ 5973N
▪ pH/DO meters	1	Orion

9.0 KEY PERSONNEL PERFORMING THE BENCH WORK WITH QUALIFICATIONS

The following paragraphs provide more detail about the key project team members’ roles and responsibilities as well as the benefits they provide to Reclamation on the Cutter Bench Scale testing.

Task Order Manager | Chris Rodriguez, PE. The task order contract administration for Cutter Bench Scale testing project will be led by Chris Rodriguez. Mr. Rodriguez has over 19 years of experience with a variety of water and wastewater related projects and will oversee and manage all day-to-day project activities and will coordinate communication between team members to keep the project on schedule and within budget. Mr. Rodriguez has been regularly attending the NGWSP Pre-Construction Committee meetings, which has allowed him and the team to gain first-hand knowledge regarding some of the challenges and issues associated with the NGWSP as well as establish positive relationships with the Navajo Nation, City of Gallup, Indian Health Service and Reclamation staff in the Four Corners Construction Office. His previous project experience including on-going work for the Reclamation Pojoaque Basin Regional Water System (PBRWS) water treatment pilot study project in Northern New Mexico will enable him to work effectively on this project.

Technical Lead | Dr. Pat Evans, PhD. Dr. Evans will serve as the Technical Lead for the project and will oversee the development of the bench-scale testing program including protocols and procedures as well as analysis and interpretation of the testing results. Dr. Evans is considered an industry expert in water treatment and ozone/BAF treatment and has

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completed several recent studies for the Water Research Foundation (WaterRF) that included bench-scale testing. Dr. Evans's knowledge and experience will be valuable for developing and implementing the testing program as well as assessing the overall technical feasibility of the treatment processes, specifically BAF.

Technical Advisor | Scott Summers, PhD. As Technical Advisor to the JV team, Dr. Summers will provide guidance for the overall program and insight regarding the most current research and development pertaining to BAF. Scott also participated in previous bench-scale testing for the NGWSP San Juan WTP which included evaluation of ozone/BAF unit treatment processes and source water with similarities to this project.

Test Planning and Analysis | YuJung Chang, PhD. Dr. Chang is a nationally recognized expert in the water treatment industry and will primarily be responsible for the pre-treatment testing prior to the BAF testing. He will work closely and collaboratively with Dr. Evans to provide guidance on the overall planning and implementation of the testing program and assist with the analysis of the testing results of the pre-treatment and BAF processes.

Test Planning, Analysis and Reporting | Jennifer Smith, PE. Ms. Smith will be Responsible for preparation of the bench scale test plan, data analysis, and final bench scale testing report. Ms. Smith has worked closely with Dr. Evans on many of the BAF research projects and will be responsible for the BAF column testing elements.

Bench Scale Laboratory Process and Analytical Testing | Tony Singh, PhD and Al Vetrovs. Dr. Singh and Mr. Vetrovs have a combined experience of more than 40 years with water treatability studies at both the bench and pilot-scale. Dr. Singh and Mr. Vetrovs will be responsible for the day-to-day process and analytical testing required to complete the bench-scale testing program. Dr. Singh will be primarily responsible for the BAF testing and analytical testing, with Mr. Vetrovs primarily responsible for the pre-treatment bench-scale testing.

Quality Assurance/ Quality Control | Michael Zafer, PE. Mr. Zafer has extensive experience with the completion of bench-scale and pilot-scale studies for numerous water treatment plants across the U.S. Mr. Zafer will be responsible for the QA/QC for the bench-scale testing program and will provide independent review of both the bench-scale test plan and report documentation.

10.0 QUALITY ASSURANCE/QUALITY CONTROL

Quality assurance/quality control (QA/QC) for the water quality testing will include chain-of-custody procedures, instrument calibration requirements, bench testing protocols, data recording and data collections spreadsheets. All sample collection, preservation and analysis will be performed in accordance with the appropriate EPA or Standard Methods requirements. Sample collection and analysis will be performed by laboratory staff that has been trained in the appropriate laboratory methods including sample collection, preservation, analysis, data entry and the appropriate QA/QC procedures.

Detection limits have been or will be determined for each of the analytical parameters and the use of blanks, replicate samples, spiked samples, and method recovery samples will be employed as per the applicable analytical method. Replicate samples will be collected at a frequency of 10% to assess the precision of laboratory results. Applicable precision and accuracy goals for the bench scale testing are provided in Table 4.

Table 4: Project data precision and accuracy goals

Parameter	Accuracy	Precision
pH	92-102%	-
Free chlorine	± 1 mg/L	-
Total chlorine	± 1 mg/L	-
Ozone residual	-	-
TOC	85%-115%	70%-130% RPD
DOC	85%-115%	70%-130% RPD
DBPFP – TTHM	60-140%	60-140% RPD
DBPFP – HAA6	60-140%	60-140% RPD
AOC	60-140%	60-140% RPD

RPD: Relative Percent Difference

Chain of custody forms will be generated and accompany all samples that are sent to outside laboratories for analysis (HAA6 and AOC). Copies of the chain of custody forms will be received from the outside laboratories once analyses are completed. Upon receipt of the results, sample quality control will be reviewed and, if acceptable, the sample data will be added to the project database. All data and submittals performed by outside analytical laboratories will be reviewed and approved by the JV team prior to their submittal to Reclamation. If requested, data will be made available to the project participants and/or the Navajo Nation regulatory agents.

Data Storage, Reporting, and Statistics - The data management system used for the bench scale testing program will involve the use of computer spreadsheets and/or a project database. As much as possible, data collection will be done electronically with data entry to the project spreadsheet or database after validation. All data will be stored electronically with backup copies made routinely. If appropriate, original data will be included as a part of the appendices for the final report.

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11.0 HEALTH AND SAFETY

Laboratory health and safety plan (HASP) will be developed and implemented prior to starting any testing. An addendum to the plan will be written to address additional hazards posed by the use of oxidants including ozone, and sodium hypochlorite. This addendum will address storage and signage requirements for these oxidants to protect laboratory personnel from associated hazards.

12.0 DATA REVIEW AND REPORTING

Throughout the bench-scale testing period, the Project Team will review and interpret all of the laboratory performance and water quality data and extract useful information through data analysis techniques. A draft report will be prepared after the completion of bench scale testing for Reclamation review/comments. Reclamation comments will be incorporated and a final project report will be prepared and submitted to Reclamation. The final report will summarize the results of the testing and will also discuss recommendations for future optimization testing of the pre-treatment and BAF processes if needed.

13.0 PROJECT SCHEDULE

Table 5: Deliverables/reviews for bench scale testing project

Deliverable	Due date
Bench Scale Test Plan	09/26/2013
TSC Comments to Contractor	10/03/2013
Start of Bench Tests	10/04/2013
Bench Scale Test Report – Draft	10/18/2013
TSC Comments to contractor and conference call	10/30/2013
Bench Scale Test Report – Final	11/19/2013

14.0 REFERENCES

- American Public Health Association (APHA). 2005. *Standard Methods of Water and Wastewater*. 21st ed. American Public Health Association, American Water Works Association, Water Environment Federation publication. APHA, Washington D.C.
- Evans, P.J. 2010. "Nature works: Biological treatment methods yield high quality water." *Opflow* July: 12-15.
- Evans, P.J., J.L. Smith, M.W. LeChevallier, O.D. Schneider, L.A. Weinrich, and P.K. Jjemba. 2013. "Monitoring and Control Tool Box for Assessing and Enhancing Biological Filtration." *Water Research Foundation Project 4231 Report* Water Research Foundation.

Rodriguez, Chris

From: Jurenka, Robert <rjurenka@usbr.gov>
Sent: Monday, November 04, 2013 2:58 PM
To: Rodriguez, Chris
Cc: Judith Chamberlin; Ronald LeBlanc
Subject: Comments on Ozone/BAF Test Plan, Cutter Reservoir, T.O. R13PD80423
Attachments: Cutter Bench Test Plan - BOR Review Comments 11.4.13.pdf

Thank you for the subject Test Plan.

Ron and I are ready to discuss these comments with you and your team as soon as possible. We found out today that sample coolers are in and reservoir water samples will be collected and shipped this week.

Please share these comments with your team and let me know when we can discuss these comments. A re-submittal of the Test Plan is not required.

Thanks again!

Robert Jurenka, P.E.
Environmental Engineer
Bureau of Reclamation
Technical Services Center
Water Treatment Group
303 445-2254 work
303 947-8013 cell

Contract # R12PC80235, Task Order R13PD80243
Cutter Reservoir Water Treatment Bench Scale Testing
Reclamation Review Comments on Bench Scale Study Test Plan
November 4, 2013

Conference call requested to discuss our comments. A resubmittal of the Test Plan is NOT necessary.

1. Re: Page 5: Has the memo described at the bottom of the page been sent? If not, let's discuss.
2. Re: Page 6:
 - a. The date of October 1 for sample receipt has slipped. Samples are to be shipped the week of November 4th. Can a new schedule (not a new Test Plan) be provided?
 - b. 3rd paragraph, describes water being added to the media to keep it moist. What is the source of this "bio-filter influent water" and how was it selected?
 - c. Section 4.2 and 5.0 discusses using a high rate filter after sedimentation. Our preference was to ozonate clarifier effluent with the only filter in the process being the biofilter. What are the details of your clarifier? What is the justification or rationale of using a pre-ozone filter (POF)?
 - d. We question the need, description and type of filter requested. We are concerned that using a filter will not accurately simulate the full-scale treatment process proposed by Reclamation. Also, it may remove some potential food source for biomass on the BAF.
3. Page 7:
 - a. A description of specification for the material of the 55-gallon drums proposed for sample holding is requested.
 - b. For ozone, confirm the ozone: TOC ratio is 1.5:1
4. Page 8: Our PWS called for Disinfectant Formation Potential Tests, not SDS tests.
5. Page 9: What kind of graphical results will be used in the Results Report to show the expected performance of the BAF over the 8 day test?
6. Page 10:
 - a. Is Column 1's "Raw Water" collected before or after coagulation?
 - b. Is "Holding Time, column 11, a maximum that is not to be exceeded?"

Appendix B

Tabular Data

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Appendix B: Tabular Data

Table B-1. Data for Figures 6 through 12

Parameter/Analyte	Units	Raw	Jan 1	Jan 2	Jan 3	Jan 4	Jan 5	Jan 6
Ferric Chloride Dose	mg/L	0	20	30	45	20	30	45
Ozone Dose	mg/L	0	0	0	0	0.5	0.5	0.5
pH	s.u.	7.60	6.82	6.81	6.76	6.78	6.74	6.70
Color	PCU	10	11	7	4	9	7	5
Alkalinity	mg/L as CaCO3	76.75	59.00	50.90	46.95	62.85	51.25	46.50
Turbidity	NTU	0.81	0.53	0.40	0.29	0.46	0.36	0.39
Dissolved Organic C	mg/L	2.44	2.04	1.54	1.37	1.94	1.94	1.65
UV 254 abs	1/cm	0.077	0.074	0.055	0.037	0.060	0.042	0.035
SUVA	L/mg/m	3.138	3.624	3.583	2.695	3.093	2.160	2.125

Comparative 2012 UNM Data

Parameter/Analyte	mg/L	0	4	8	12	16	24	32
Ferric Chloride Dose	mg/L	0	4	8	12	16	24	32
pH	s.u.	7.66	7.33	7.35	7.26	6.99	6.77	6.63
Color	PCU	Not recorded						
Alkalinity	mg/L as CaCO3	85.80	81.40	74.80	74.80	66.00	61.60	50.60
Turbidity	NTU	17.30	8.73	2.14	1.02	0.47	3.30	0.47
Dissolved Organic C	mg/L	3.25	3.09	2.65	2.45	2.14	1.79	1.60
UV 254 abs	1/cm	0.073	0.072	0.056	0.046	0.040	0.031	0.028
SUVA	L/mg/m	2.258	2.330	2.113	1.873	1.883	1.726	1.750

Comparative 2013 Phase 1 Data

Parameter/Analyte	mg/L	0	20
Ferric Chloride Dose	mg/L	0	20
Ozone Dose	mg/L	0	0
pH	s.u.	7.90	7.00
Color	PCU	Not recorded	
Alkalinity	mg/L as CaCO3	90.00	73.00
Turbidity	NTU	Not recorded	
Dissolved Organic C	mg/L	3.00	2.10
UV 254 abs	1/cm	0.120	0.046
SUVA	L/mg/m	4.000	2.200

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Appendix B: Tabular Data

Table B-2. Data for Figures 13 through 18

Parameter/ Analyte	Units	Raw	20 mg/L pH 7.5	20 mg/L pH 6.0	20 mg/L, 0.5 mg/L ozone pH 6.0	30 mg/L pH 7.5	30 mg/L pH 6.6	30 mg/L pH 6.0	30 mg/L, 0.5 mg/L ozone pH 6.6	30 mg/L, 0.5 mg/L ozone pH 6.0
Jar	(none)	-	1	2	3	4	5	6	7	8
Ferric Chloride Dose	mg/L	0	20	20	20	30	30	30	30	30
Ferric Chloride Dose	mL per 2-L jar	0	0.069	0.069	0.069	0.104	0.104	0.104	0.104	0.104
Ozone Dose	mg/L	0	0	0	5	0	0	0	5	5
pH	s.u.	7.60	7.51	6.02	6.01	7.52	6.58	6.00	6.59	6.03
Color	PCU	11	9	10	9	7	7	5	6	5
Alkalinity	mg/L as CaCO ₃	75.40	68.40	26.90	32.40	71.30	53.80	33.10	54.30	34.70
Turbidity	NTU	0.46	0.33	0.31	0.31	0.21	0.22	0.19	0.21	0.20
Dissolved Organic C	mg/L	2.59	2.12	1.45	1.63	1.81	1.60	1.22	1.60	1.42
UV 254 abs	1/cm	0.076	0.068	0.053	0.049	0.057	0.048	0.036	0.040	0.035
SUVA	L/mg/m	2.938	3.215	3.645	3.006	3.147	3.002	2.958	2.505	2.465

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Appendix B: Tabular Data

Table B-3. Data for Figures 19 and 20

Jar Test No. Test Parameters		A	B	C	D	A+B+C+ D
		Trichloromet hane	Bromodichlor omethane	Dibromochlo romethane	Tribromomet hane	TTHM
1-1	20 mg/L, pH 6.82	113.90	10.49	0.82	0.04	125.25
1-2	30 mg/L, pH 6.81	82.40	9.89	1.03	0.05	93.37
1-3	45 mg/L, pH 6.76	63.20	9.04	1.14	0.05	73.43
1-4	20 mg/L, 0.5 mg/L Ozone	95.70	11.27	1.71	0.07	108.75
1-5	30 mg/L, 0.5 mg/L Ozone	87.62	10.83	1.61	0.08	100.14
1-6	45 mg/L, 0.5 mg/L Ozone	65.11	10.53	1.90	0.10	77.64
2-7	20 mg/L pH 7.5	141.07	12.41	0.89	0.03	154.40
2-1	20 mg/L, pH 6.0	78.12	10.21	1.68	0.08	90.09
2-2	20 mg/L, 0.5 mg/L ozone, pH 6.0	84.35	10.56	1.16	0.05	96.12
2-8	30 mg/L pH 7.5	103.85	11.21	1.04	0.04	116.14
2-4	30 mg/L pH 6.6	88.82	10.77	1.18	0.05	100.82
2-6	30 mg/L pH 6.0	63.39	9.70	1.33	0.06	74.48
2-3	30 mg/L, 0.5 mg/L ozone pH 6.6	76.57	10.27	1.82	0.09	88.75
2-5	30 mg/L, 0.5 mg/L ozone pH 6.0	68.59	10.59	1.90	0.09	81.17

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Appendix B: Tabular Data

Table B-4. Data for Figures 21 and 22

Jar Test No.	Test Parameters	E Trichloroacetic acid	F Dichloroacetic acid	G Monochloroacetic acid	H Dibromoacetic acid	J Monobromoacetic acid	K = E+F+G+J HAA5	L Bromochloroacetic Acid	K+L HAA6
1-1	20 mg/L, pH 6.82	56	48	2.0	0	0	106	4.4	110
1-2	30 mg/L, pH 6.81	42	36	0.0	0	0	78	4.2	82
1-3	45 mg/L, pH 6.76	30	29	0.0	0	0	59	3.7	63
1-4	20 mg/L, 0.5 mg/L Ozone	40	46	2.0	0	0	88	5.0	93
1-5	30 mg/L, 0.5 mg/L Ozone	30	42	0.0	0	0	72	4.9	77
1-6	45 mg/L, 0.5 mg/L Ozone	22	33	0.0	0	0	55	4.4	59
2-7	20 mg/L pH 7.5	64	56	3.6	0	0	124	5.2	129
2-1	20 mg/L, pH 6.0	24	39	2.6	0	0	66	5.1	71
2-2	20 mg/L, 0.5 mg/L ozone, pH 6.0	33	37	2.2	0	0	72	4.7	77
2-8	30 mg/L pH 7.5	43	41	2.9	0	0	87	4.8	92
2-4	30 mg/L pH 6.6	38	36	2.6	0	0	77	4.4	81
2-6	30 mg/L pH 6.0	25	26	0.0	0	0	51	4.0	55
2-3	30 mg/L, 0.5 mg/L ozone pH 6.6	27	36	2.6	0	0	66	5.1	71
2-5	30 mg/L, 0.5 mg/L ozone pH 6.0	22	29	2.2	0	0	53	4.6	58

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Appendix B: Tabular Data

Table B-5. Data for Figure 23

Run 1: 20 mg/L FeCl₃, pH 6.0, 4 degC

Time (min)	O3 (mg/L)	LN(Normalized Ozone Residual)
0	0	
0.57	1.60	0.000
2.00	1.50	-0.062
4.08	1.48	-0.078
8.28	1.40	-0.127
15.00	1.26	-0.234
25.00	1.10	-0.376
45.03	0.95	-0.516
65.00	0.81	-0.678
85.50	0.79	-0.708
111.00	0.74	-0.771
150.17	0.52	-1.114
180.90	0.40	-1.371
210.00	0.43	-1.314
240.00	0.40	-1.371
270.00	0.19	-2.125
301.00	0.21	-2.007
341.00	0.10	-2.818

Run 2: 30 mg/L FeCl₃, pH float (6.6), 4 degC

Time (min)	O3 conc. (mg/L)	LN(Normalized Ozone Residual)
0	0	
0.38	1.31	0.000
2.07	1.21	-0.076
4.03	1.14	-0.136
8.17	1.07	-0.201
15.05	0.95	-0.318
25.07	0.86	-0.424
45.00	0.67	-0.675
66.00	0.50	-0.963
85.07	0.45	-1.063
105.00	0.40	-1.174
120.00	0.31	-1.442
150.08	0.21	-1.810
181.00	0.17	-2.061
210.50	0.17	-2.061
239.75	0.14	-2.216
270.00	0.10	-2.621
288.67	0.02	-4.007

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Appendix B: Tabular Data

Table B-5. Data for Figure 23

Run 3: 20 mg/L FeCl₃, pH 6.0, 20 degC

Time (min)	O3 conc. (mg/L)	LN(Normalized Ozone Residual)
0	0	
0.37	1.43	0.000
2.07	1.33	-0.069
4.08	1.17	-0.203
10.00	1.00	-0.357
20.83	0.69	-0.727
40.67	0.40	-1.261
60.03	0.21	-1.897
80.10	0.17	-2.148
100.07	0.12	-2.485
120.00	0.12	-2.485
149.00	0.02	-4.094
181.48	0.05	-3.401
209.00	0.05	-3.401
258.00	0.02	-4.094

Run 4: 30mg/L FeCl₃, pH float (6.6), 20 degC

Time (min)	O3 Measured Residual reading (mg/L)	LN(Normalized Ozone Residual)
0	0	
0.30	1.86	0.000
2.37	1.64	-0.123
5.17	1.33	-0.331
10.12	1.00	-0.619
20.07	0.69	-0.989
30.33	0.45	-1.412
40.07	0.45	-1.412
59.92	0.31	-1.792
84.00	0.33	-1.718
105.00	0.29	-1.872
120.00	0.26	-1.959
150.00	0.29	-1.872
177.58	0.29	-1.872
210.00	0.14	-2.565
226.00	0.10	-2.970

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Appendix B: Tabular Data

Table B-6. DOC (mg/L) Data for Figures 24 through 40

Column:	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III		
Runtime (Hrs)	30 Fe, 0.5 O3, 12.5	30 Fe, 1 O3, 12.5	30 Fe, 1.5 O3, 12.5	20 Fe, pH 6, 0.5 O3, 12.5	20 Fe, pH 6, 1 O3, 12.5	20 Fe, pH 6, 1.5 O3, 12.5	30 Fe, 0.5 O3, 10	30 Fe, 1 O3, 10	30 Fe, 1.5 O3, 10	20 Fe, pH 6, 0.5 O3, 10	20 Fe, pH 6, 1 O3, 10	20 Fe, pH 6, 1.5 O3, 10	30 Fe, 0.5 O3, 7.5	30 Fe, 1 O3, 7.5	30 Fe, 1.5 O3, 7.5	20 Fe, pH 6, 0.5 O3, 7.5	20 Fe, pH 6, 1 O3, 7.5	20 Fe, pH 6, 1.5 O3, 7.5	30 Fe, 0.5 O3, 5	30 Fe, 1 O3, 5	30 Fe, 1.5 O3, 5	20 Fe, pH 6, 0.5 O3, 5	20 Fe, pH 6, 1 O3, 5	20 Fe, pH 6, 1.5 O3, 5	20 Fe, pH 6, 1.5 O3, 5	
84.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
84.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.257	1.213	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
84.8	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.179	0.9998	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.8627	0.85	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.293	1.263	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.201	0.9799	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.9068	0.8246	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.311	1.203	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.257	1.071	#N/A	#N/A	#N/A	#N/A	
85.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.9948	0.9667	#N/A	
85.7	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.9603	0.9408	#N/A

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Appendix B: Tabular Data

Table 7. UV₂₅₄ Absorbance (1/cm) Data for Figures 24 through 40

Column:	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	
Runtime (Hrs)	30 Fe, 0.5 O3, 12.5	30 Fe, 1 O3, 12.5	30 Fe, 1.5 O3, 12.5	20 Fe, pH 6, 0.5 O3, 12.5	20 Fe, pH 6, 1 O3, 12.5	20 Fe, pH 6, 1.5 O3, 12.5	30 Fe, 0.5 O3, 10	30 Fe, 1 O3, 10	30 Fe, 1.5 O3, 10	20 Fe, pH 6, 0.5 O3, 10	20 Fe, pH 6, 1 O3, 10	20 Fe, pH 6, 1.5 O3, 10	30 Fe, 0.5 O3, 7.5	30 Fe, 1 O3, 7.5	30 Fe, 1.5 O3, 7.5	20 Fe, pH 6, 0.5 O3, 7.5	20 Fe, pH 6, 1 O3, 7.5	20 Fe, pH 6, 1.5 O3, 7.5	30 Fe, 0.5 O3, 5	30 Fe, 1 O3, 5	30 Fe, 1.5 O3, 5	20 Fe, pH 6, 0.5 O3, 5	20 Fe, pH 6, 1 O3, 5	20 Fe, pH 6, 1.5 O3, 5	
0.8	0.02	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.8	#N/A	0.018	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.9	#N/A	#N/A	0.016	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.9	#N/A	#N/A	#N/A	0.016	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.9	#N/A	#N/A	#N/A	#N/A	0.013	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.9	#N/A	#N/A	#N/A	#N/A	#N/A	0.014	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.5	0.017	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.6	#N/A	0.013	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.6	#N/A	#N/A	0.01	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.7	#N/A	#N/A	#N/A	0.008	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.8	#N/A	#N/A	#N/A	#N/A	0.006	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.9	#N/A	#N/A	#N/A	#N/A	#N/A	0.006	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.1	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.018	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.011	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.018	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.009	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.5	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.008	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.007	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.7	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.013	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.7	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.011	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.8	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.014	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.006	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.005	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.006	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.1	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.015	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.012	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.011	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.007	#N/A	#N/A	#N/A	#N/A	#N/A
15.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.004	#N/A	#N/A
15.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.006	#N/A
13.7	#N/A	#N/A	#N/A	0.009	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.9	#N/A	#N/A	#N/A	#N/A	0.005	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.3	0.0142	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.4	#N/A	0.0112	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.5	#N/A	0.0108	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.6	#N/A	#N/A	#N/A	0.0076	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

B-12

HDR-CDM Joint Venture

Appendix B: Tabular Data

Table 7. UV₂₅₄ Absorbance (1/cm) Data for Figures 24 through 40

Column:	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	
Runtime (Hrs)	30 Fe, 0.5 O3, 12.5	30 Fe, 1 O3, 12.5	30 Fe, 1.5 O3, 12.5	20 Fe, pH 6, 0.5 O3, 12.5	20 Fe, pH 6, 1 O3, 12.5	20 Fe, pH 6, 1.5 O3, 12.5	30 Fe, 0.5 O3, 10	30 Fe, 1 O3, 10	30 Fe, 1.5 O3, 10	20 Fe, pH 6, 0.5 O3, 10	20 Fe, pH 6, 1 O3, 10	20 Fe, pH 6, 1.5 O3, 10	30 Fe, 0.5 O3, 7.5	30 Fe, 1 O3, 7.5	30 Fe, 1.5 O3, 7.5	20 Fe, pH 6, 0.5 O3, 7.5	20 Fe, pH 6, 1 O3, 7.5	20 Fe, pH 6, 1.5 O3, 7.5	30 Fe, 0.5 O3, 5	30 Fe, 1 O3, 5	30 Fe, 1.5 O3, 5	20 Fe, pH 6, 0.5 O3, 5	20 Fe, pH 6, 1 O3, 5	20 Fe, pH 6, 1.5 O3, 5	30 Fe, 0.5 O3, 5
20.7	#N/A	#N/A	#N/A	#N/A	#N/A	0.0058	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.8	#N/A	#N/A	#N/A	#N/A	#N/A	0.0056	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.7	#N/A	#N/A	#N/A	#N/A	#N/A	0.0056	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.9	#N/A	#N/A	#N/A	#N/A	#N/A	0.0058	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
36.7	0.0138	0.0102	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
36.9	#N/A	#N/A	0.01	0.008	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
36.8	#N/A	#N/A	#N/A	0.0064	0.0056	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
37.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0142	0.012	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
37.1	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0134	0.0086	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
37.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0062	0.0056	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
37.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0158	0.0156	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
37.5	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0114	0.0084	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
37.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0068	0.0062	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
37.8	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.015	0.012	#N/A	#N/A	#N/A	#N/A	#N/A
37.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0122	0.0104	#N/A	#N/A	#N/A
38.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0074	0.0062	#N/A
38.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0086	#N/A	#N/A
38.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0164	0.006	#N/A
44.0	0.014	0.0116	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
44.1	#N/A	#N/A	0.0108	0.0088	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
44.2	#N/A	#N/A	#N/A	0.0065	0.01	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
56.9	0.017	0.0134	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.0	#N/A	#N/A	0.0134	0.0118	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.1	#N/A	#N/A	#N/A	#N/A	0.0086	0.008	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0168	0.0164	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.013	0.0108	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0088	0.008	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.5	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.019	0.0144	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0138	0.0112	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.8	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0092	0.0082	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
57.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.017	0.0138	#N/A	#N/A	#N/A	#N/A	#N/A
58.1	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.014	0.0118	#N/A	#N/A	#N/A
58.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0138	0.0082	#N/A
84.0	0.0164	0.0126	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
84.3	#N/A	#N/A	0.0122	0.0106	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
84.4	#N/A	#N/A	#N/A	#N/A	0.0078	0.007	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

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HDR-CDM Joint Venture

Appendix B: Tabular Data

Table 7. UV₂₅₄ Absorbance (1/cm) Data for Figures 24 through 40

Column:	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	
Runtime (Hrs)	30 Fe, 0.5 O3, 12.5	30 Fe, 1 O3, 12.5	30 Fe, 1.5 O3, 12.5	20 Fe, pH 6, 0.5 O3, 12.5	20 Fe, pH 6, 1 O3, 12.5	20 Fe, pH 6, 1.5 O3, 12.5	30 Fe, 0.5 O3, 10	30 Fe, 1 O3, 10	30 Fe, 1.5 O3, 10	20 Fe, pH 6, 0.5 O3, 10	20 Fe, pH 6, 1 O3, 10	20 Fe, pH 6, 1.5 O3, 10	30 Fe, 0.5 O3, 7.5	30 Fe, 1 O3, 7.5	30 Fe, 1.5 O3, 7.5	20 Fe, pH 6, 0.5 O3, 7.5	20 Fe, pH 6, 1 O3, 7.5	20 Fe, pH 6, 1.5 O3, 7.5	30 Fe, 0.5 O3, 5	30 Fe, 1 O3, 5	30 Fe, 1.5 O3, 5	20 Fe, pH 6, 0.5 O3, 5	20 Fe, pH 6, 1 O3, 5	20 Fe, pH 6, 1.5 O3, 5	
84.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0166	0.0136	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
84.8	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0132	0.0108	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.008	0.0076	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0174	0.014	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0138	0.0104	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0098	0.0064	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0162	0.0128	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0128	0.0098	#N/A	#N/A
85.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0058	0.0166	#N/A
85.7	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

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HDR-CDM Joint Venture

Appendix B: Tabular Data

Table 8. Specific UV₂₅₄ Absorbance (L/mg/m) Data for Figures 24 through 40

Column:	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	
Runtime (Hrs)	30 Fe, 0.5 O3, 12.5	30 Fe, 1 O3, 12.5	30 Fe, 1.5 O3, 12.5	20 Fe, pH 6, 0.5 O3, 12.5	20 Fe, pH 6, 1 O3, 12.5	20 Fe, pH 6, 1.5 O3, 12.5	30 Fe, 0.5 O3, 10	30 Fe, 1 O3, 10	30 Fe, 1.5 O3, 10	20 Fe, pH 6, 0.5 O3, 10	20 Fe, pH 6, 1 O3, 10	20 Fe, pH 6, 1.5 O3, 10	30 Fe, 0.5 O3, 7.5	30 Fe, 1 O3, 7.5	30 Fe, 1.5 O3, 7.5	20 Fe, pH 6, 0.5 O3, 7.5	20 Fe, pH 6, 1 O3, 7.5	20 Fe, pH 6, 1.5 O3, 7.5	30 Fe, 0.5 O3, 5	30 Fe, 1 O3, 5	30 Fe, 1.5 O3, 5	20 Fe, pH 6, 0.5 O3, 5	20 Fe, pH 6, 1 O3, 5	20 Fe, pH 6, 1.5 O3, 5	20 Fe, pH 6, 1.5 O3, 5
84.4	#N/A	#N/A	#N/A	#N/A	#N/A	0.841	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
84.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.321	1.121	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
84.8	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.120	1.080	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.927	0.894	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.346	1.108	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.149	1.061	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.081	0.776	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.236	1.064	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
85.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.018	0.915	#N/A	#N/A	#N/A	#N/A	#N/A
85.4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.583	1.717	#N/A	#N/A	#N/A
85.7	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

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HDR-CDM Joint Venture

Appendix B: Tabular Data

Table 9. Turbidity (NTU) Data for Figures 24 through 40

Column:	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	
Runtime (Hrs)	30 Fe, 0.5 O3, 12.5	30 Fe, 1 O3, 12.5	30 Fe, 1.5 O3, 12.5	20 Fe, pH 6, 0.5 O3, 12.5	20 Fe, pH 6, 1 O3, 12.5	20 Fe, pH 6, 1.5 O3, 12.5	30 Fe, 0.5 O3, 10	30 Fe, 1 O3, 10	30 Fe, 1.5 O3, 10	20 Fe, pH 6, 0.5 O3, 10	20 Fe, pH 6, 1 O3, 10	20 Fe, pH 6, 1.5 O3, 10	30 Fe, 0.5 O3, 7.5	30 Fe, 1 O3, 7.5	30 Fe, 1.5 O3, 7.5	20 Fe, pH 6, 0.5 O3, 7.5	20 Fe, pH 6, 1 O3, 7.5	20 Fe, pH 6, 1.5 O3, 7.5	30 Fe, 0.5 O3, 5	30 Fe, 1 O3, 5	30 Fe, 1.5 O3, 5	20 Fe, pH 6, 0.5 O3, 5	20 Fe, pH 6, 1 O3, 5	20 Fe, pH 6, 1.5 O3, 5	
0.83	0.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.85	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.87	#N/A	#N/A	0.08	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.88	#N/A	#N/A	#N/A	0.10	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.90	#N/A	#N/A	#N/A	#N/A	0.10	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.92	#N/A	#N/A	#N/A	#N/A	#N/A	0.10	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.50	0.08	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.57	#N/A	0.27	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.63	#N/A	#N/A	0.08	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.68	#N/A	#N/A	#N/A	0.05	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.83	#N/A	#N/A	#N/A	#N/A	0.05	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.93	#N/A	#N/A	#N/A	#N/A	0.11	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.07	#N/A	#N/A	#N/A	#N/A	#N/A	0.39	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.23	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.23	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.32	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.54	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.40	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.37	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.50	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.38	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.58	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.55	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.67	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.12	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.75	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.08	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.82	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.16	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.88	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.05	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
14.95	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.05	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.03	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.08	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.12	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.10	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.20	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.13	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.28	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.13	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15.32	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.05	#N/A	#N/A	#N/A	#N/A
15.38	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.05	#N/A	#N/A
15.43	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.17	#N/A
13.73	#N/A	#N/A	#N/A	0.05	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
13.90	#N/A	#N/A	#N/A	#N/A	0.07	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.32	0.10	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.40	#N/A	0.28	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.52	#N/A	#N/A	0.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
20.58	#N/A	#N/A	#N/A	0.13	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

HDR-CDM Joint Venture

Appendix B: Tabular Data

Table 9. Turbidity (NTU) Data for Figures 24 through 40

Column:	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	
Runtime (Hrs)	30 Fe, 0.5 O3, 12.5	30 Fe, 1 O3, 12.5	30 Fe, 1.5 O3, 12.5	20 Fe, pH 6, 0.5 O3, 12.5	20 Fe, pH 6, 1 O3, 12.5	20 Fe, pH 6, 1.5 O3, 12.5	30 Fe, 0.5 O3, 10	30 Fe, 1 O3, 10	30 Fe, 1.5 O3, 10	20 Fe, pH 6, 0.5 O3, 10	20 Fe, pH 6, 1 O3, 10	20 Fe, pH 6, 1.5 O3, 10	30 Fe, 0.5 O3, 7.5	30 Fe, 1 O3, 7.5	30 Fe, 1.5 O3, 7.5	20 Fe, pH 6, 0.5 O3, 7.5	20 Fe, pH 6, 1 O3, 7.5	20 Fe, pH 6, 1.5 O3, 7.5	30 Fe, 0.5 O3, 5	30 Fe, 1 O3, 5	30 Fe, 1.5 O3, 5	30 Fe, 1 O3, 5	20 Fe, pH 6, 0.5 O3, 5	20 Fe, pH 6, 1 O3, 5	20 Fe, pH 6, 1.5 O3, 5
20.67	#N/A	#N/A	#N/A	#N/A	#N/A	0.15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
20.83	#N/A	#N/A	#N/A	#N/A	#N/A	0.17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
20.73	#N/A	#N/A	#N/A	#N/A	#N/A	0.17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
20.90	#N/A	#N/A	#N/A	#N/A	#N/A	0.19	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
36.72	0.07	0.07	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
36.87	#N/A	#N/A	0.08	0.07	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
36.77	#N/A	#N/A	#N/A	#N/A	0.06	0.05	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
36.97	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.21	0.48	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
37.10	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.05	0.13	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
37.23	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.21	0.13	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
37.32	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.66	1.71	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
37.50	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.47	0.09	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
37.62	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.28	0.58	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
37.78	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.23	0.43	#N/A	#N/A	#N/A	#N/A	#N/A	
37.95	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.40	0.12	#N/A	#N/A	#N/A	
38.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.09	0.10	0.10	
38.03	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.08	#N/A	#N/A	
38.27	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.42	0.07	
44.00	0.12	0.33	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
44.08	#N/A	#N/A	0.10	0.07	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
44.18	#N/A	#N/A	#N/A	#N/A	0.05	0.05	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
56.90	0.09	0.07	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
56.98	#N/A	#N/A	0.12	0.04	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
57.08	#N/A	#N/A	#N/A	#N/A	0.07	0.06	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
57.20	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.14	1.19	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
57.30	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.11	0.05	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
57.42	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.10	0.19	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
57.53	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.23	0.27	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
57.65	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.51	0.09	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
57.75	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.09	0.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
57.95	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.23	0.12	#N/A	#N/A	#N/A	#N/A	#N/A	
58.07	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.33	0.45	#N/A	#N/A	
58.17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.22	0.10	
57.85	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.10	0.11	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
84.02	0.08	0.06	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
84.27	#N/A	#N/A	0.16	0.08	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	

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HDR-CDM Joint Venture

Appendix B: Tabular Data

Table 9. Turbidity (NTU) Data for Figures 24 through 40

Column:	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	
Runtime (Hrs)	30 Fe, 0.5 O3, 12.5	30 Fe, 1 O3, 12.5	30 Fe, 1.5 O3, 12.5	20 Fe, pH 6, 0.5 O3, 12.5	20 Fe, pH 6, 1 O3, 12.5	20 Fe, pH 6, 1.5 O3, 12.5	30 Fe, 0.5 O3, 10	30 Fe, 1 O3, 10	30 Fe, 1.5 O3, 10	20 Fe, pH 6, 0.5 O3, 10	20 Fe, pH 6, 1 O3, 10	20 Fe, pH 6, 1.5 O3, 10	30 Fe, 0.5 O3, 7.5	30 Fe, 1 O3, 7.5	30 Fe, 1.5 O3, 7.5	20 Fe, pH 6, 0.5 O3, 7.5	20 Fe, pH 6, 1 O3, 7.5	20 Fe, pH 6, 1.5 O3, 7.5	30 Fe, 0.5 O3, 5	30 Fe, 1 O3, 5	30 Fe, 1.5 O3, 5	30 Fe, 1 O3, 5	20 Fe, pH 6, 0.5 O3, 5	20 Fe, pH 6, 1 O3, 5	20 Fe, pH 6, 1.5 O3, 5
84.45	#N/A	#N/A	#N/A	#N/A	0.11	0.08	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
84.63	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.30	0.22	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
84.80	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.69	0.35	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
84.98	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.11	0.63	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.17	0.17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.42	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.09	0.07	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.27	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.45	0.51	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	
85.60	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.11	0.19	#N/A	#N/A	#N/A	#N/A	#N/A	
85.88	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.52	0.17	#N/A	#N/A	
85.45	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	3.50	0.15	
85.67	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.14	0.15	

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HDR-CDM Joint Venture

Appendix B: Tabular Data

Table B-10. Data for Figures 41 and 42 (units of µg/L)

Description	Day	Trichloro methane	Bromodichloromethane	Dibromochloromethane	Tribromomethane	TTHM
20 mg/L FeCl ₃ , pH 6.0, 0.5:1.0 ozone:DOC, 5 min EBCT	1	13.2	5.9	2.7	ND	21.8
	3	24.4	8.3	3.5	ND	36.2
	5	27.8	9.0	3.6	ND	40.4
	7	47.0	11.7	4.2	ND	62.9
	10	42.4	11.3	4.0	ND	57.6
20 mg/L FeCl ₃ , pH 6.0, 1.0:1.0 ozone:DOC, 10 min EBCT	1	14.8	6.3	2.9	ND	23.9
	3	30.1	9.2	3.7	ND	43.0
	5	31.1	9.2	3.7	ND	44.0
	7	39.7	10.6	3.9	ND	54.3
	10	43.8	11.1	3.9	ND	58.8
20 mg/L FeCl ₃ , pH 6.0, 1.0:1.0 ozone:DOC, 5 min EBCT	1	17.3	6.6	3.0	ND	26.9
	3	28.0	9.0	3.6	ND	40.5
	5	38.8	10.3	3.8	ND	52.8
	7	45.4	11.2	4.0	ND	60.6
	10	49.3	11.6	3.9	ND	64.8
30 mg/L FeCl ₃ , pH 6.6, 1.0:1.0 ozone:DOC, 5 min EBCT	1	16.2	6.2	2.4	ND	24.9
	3	31.0	8.6	3.0	ND	42.6
	5	44.1	10.5	3.4	ND	58.0
	7	48.0	10.9	3.4	ND	62.3
	10	53.8	11.4	3.5	ND	68.7
30 mg/L FeCl ₃ , pH 6.6, 1.0:1.0 ozone:DOC, 5 min EBCT	THMFP	65.5	10.0	1.5	Non-detect	77.0
20 mg/L FeCl ₃ , pH 6.0, 0.5:1.0 ozone:DOC, 5 min EBCT	THMFP	51.1	10.2	1.7	Non-detect	63.1
20 mg/L FeCl ₃ , pH 6.0, 1.0:1.0 ozone:DOC, 5 min EBCT	THMFP	57.5	10.6	1.6	Non-detect	69.7
20 mg/L FeCl ₃ , pH 6.0, 1.0:1.0 ozone:DOC, 10 min EBCT	THMFP	53.5	10.5	1.8	Non-detect	65.8

HDR-CDM Joint Venture

Appendix B: Tabular Data

Table B-11. Data for Figures 43 and 44 (units of µg/L)

Parameter	Day	Trichloro acetic acid	Dichloroacetic acid	Monochloroacetic acid	Monobromoacetic acid	Dibromoacetic acid	HAAS	Bromochloroacetic acid	HAAG
30 mg/L FeCl ₃ , pH 6.6, 1 mg/L ozone, 5 min EBCT	1	3.8	4.8	ND	ND	ND	8.6	2.2	10.8
	3	5.8	11.0	ND	ND	ND	16.8	2.7	19.5
	5	5.8	11.0	ND	ND	ND	16.8	2.7	19.5
	7	5.8	11.0	ND	ND	ND	16.8	2.4	19.2
	10	6.2	12.0	ND	ND	ND	18.2	2.8	21.0
20 mg/L FeCl ₃ , pH 6.0, 0.5 mg/L ozone, 5 min EBCT	1	1.7	3.8	ND	ND	ND	5.5	2.0	7.5
	3	2.1	5.4	ND	ND	ND	7.5	1.8	9.3
	5	3.4	7.0	ND	ND	ND	10.4	2.7	13.1
	7	1.9	8.2	ND	ND	ND	10.1	2.4	12.5
	10	2.9	8.5	ND	ND	ND	11.4	2.6	14.0
20 mg/L FeCl ₃ , pH 6.0, 1.0 mg/L ozone, 5 min EBCT	1	1.8	4.5	ND	ND	ND	6.3	2.0	8.3
	3	2.5	6.8	ND	ND	ND	9.3	2.1	11.4
	5	5.8	11.0	ND	ND	ND	16.8	2.7	19.5
	7	2.6	9.0	ND	ND	ND	11.6	2.5	14.1
	10	3.3	10.0	ND	ND	ND	13.3	2.8	16.1
20 mg/L FeCl ₃ , pH 6.0, 1.0 mg/L ozone, 10 min EBCT	1	2.1	3.8	ND	ND	ND	5.9	2.0	7.9
	3	1.9	6.1	ND	ND	ND	8.0	1.8	9.8
	5	4.4	7.7	ND	ND	ND	12.1	2.7	14.8
	7	3.3	8.7	ND	ND	ND	12.0	2.6	14.6
	10	4.0	9.6	ND	ND	ND	13.6	2.6	16.2

30 mg/L FeCl ₃ , pH 6.6, 1 mg/L ozone, 5 min EBCT	HAAFP	16.0	25.0	ND	ND	ND	41.0	3.4	44.4
20 mg/L FeCl ₃ , pH 6.0, 0.5 mg/L ozone, 5 min EBCT	HAAFP	9.0	18.0	ND	ND	ND	27.0	3.4	30.4
20 mg/L FeCl ₃ , pH 6.0, 1.0 mg/L ozone, 5 min EBCT	HAAFP	9.6	22.0	ND	ND	ND	31.6	3.5	35.1
20 mg/L FeCl ₃ , pH 6.0, 1.0 mg/L ozone, 10 min EBCT	HAAFP	9.8	19.0	ND	ND	ND	28.8	3.4	32.2

HDR-CDM Joint Venture

Appendix B: Tabular Data

Table B-12. Data for Figure 45

Ferric Chloride Dose (mg/L)	pH	Ozone:DOC	EBCT (min)	CBXA Concentration (ug-C/L)			
				Acetic acid	Formic acid	Oxalic acid	Pyruvic acid
30	6.6	0.5	5.0	34	31	3.4	5.5
			7.5	3	5.9	3.4	5.5
			10.0	44	38	3.4	5.5
			12.5	3	5.1	3.4	5.5
		1	5.0	42	37	17	5.5
			7.5	3	8.2	3.4	5.5
			10.0	44	37	3.4	5.5
			12.5	48	45	3.4	5.5
		1.5	5.0	33	32	72	5.5
			7.5	45	39	16	5.5
			10.0	5.2	10	3.4	5.5
			12.5	49	41	3.4	5.5
20	6.0	0.5	5.0	5.8	10	26	5.5
			7.5	34	33	3.4	5.5
			10.0	40	36	3.4	5.5
			12.5	3	18	3.4	5.5
		1	5.0	9.3	16	90	5.5
			7.5	33	33	19	5.5
			10.0	47	38	3.4	5.5
			12.5	47	38	3.4	5.5
		1.5	5.0	29	30	99	5.5
			7.5	27	30	17	5.5
			10.0	30	31	3.4	5.5
			12.5	48	42	3.4	5.5

Table B-13. Data for Figure 46

Parameter	AOC (ug/L)
30 mg/L FeCl ₃ , pH 6.6, 1.0:1.0 ozone:DOC, 5 min EBCT	740
20 mg/L FeCl ₃ , pH 6.0, 0.5:1.0 ozone:DOC, 5 min EBCT	1400
20 mg/L FeCl ₃ , pH 6.0, 1.0:1.0 ozone:DOC, 5 min EBCT	210
20 mg/L FeCl ₃ , pH 6.0, 1.0:1.0 ozone:DOC, 10 min EBCT	280

PART 2 PRODUCTS

Not Used

PART 3 EXECUTION

Not Used

END OF SECTION

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SECTION 51 45 16 TOC SAMPLING RESULTS

PART 1 GENERAL



ARIZONA STATE UNIVERSITY

Date: February 7, 2012
To: Ron LeBlanc/USBR
From: Paul Westerhoff / ASU
Chao-An Chiu / ASU
Subject: Results of sampling for USBR_Updated with 2nd SEC-TOC

This memo summarizes results of one sample received on October 4, 2011 from the USBR. The sample was characterized by several organic matter measurements. Because this is just a single sample the data is somewhat isolated, but will be interpreted relative to our experience on organic matter in other southwestern water supplies. Table 1 summarizes the numerical values of the measurements, with methods and graphical data in subsequent sections. The interpretation of the sample is as follows:

- 1) The dissolved organic carbon (DOC) concentration is 2.9 mg/L. This is value for surface water is slightly lower than others in the southwestern USA. For reference, the Colorado, Salt and Verde Rivers in Arizona have DOC levels are 3.5 to 5.5 mg/L.
- 2) The Total dissolved nitrogen (TDN) is a combination of inorganic and organic nitrogen. We usually observe low levels of inorganic nitrogen during summers in lakes, as algae take up this nutrient, whereas roughly 60% is inorganic during the winter when productivity levels and cell counts are lower.
- 3) The SUVA value of 2.6 L/mg-m is a measure of the saturated carbon-carbon bonds, and on a relative scale across the USA is on the lower side indicator a low humic-acid content water. However, the value is higher than typically observed in very hard water reservoirs with long residence times where coagulation of DOC can occur naturally. Examples of these are the reservoirs on the Colorado River and Salt River in Arizona which have SUVA values of 1.7 and 2.2 L/mg-m, respectively. However, the USBR sample SUVA value is more typical of short-retention time reservoirs such as Bartlett Lake on the Verde River which is more heavily sporadically influenced by snowmelt and monsoon rains and has SUVA values which range from 2 L/mg-m during dry periods to > 4 L/mg-m after major runoff events which bring soil organic matter into the lake.
- 4) The fluorescence analysis and specifically the fluorescence index (FI) is an indicator of likely sources of the organic matter. FI values of 1.6 are tending towards being microbially derived organics, rather than soil derived. This FI value is consistent with the low SUVA value, suggesting autochthonous sources of organic matter.
- 5) The molecular weight distribution based upon SEC-TOC measurements indicates that most of the DOC is in the size range of 1000 to 10,000 dalton. There is a relatively low fraction (11% of colloidal organics), which are usually the byproduct of algae and bacterial decay processes.

Overall, the available data for this single sample suggest a water with low DOC of relatively low humic acid content. If such a water was subjected to common water treatment processes (coagulation and chlorination) it would not be easy to remove a significant fraction of the DOC,

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SCHOOL OF SUSTAINABLE ENGINEERING AND THE BUILT ENVIRONMENT
CIVIL, ENVIRONMENTAL AND SUSTAINABLE ENGINEERING PROGRAM
DEL E. WEBB CONSTRUCTION PROGRAM

PO Box 875306, TEMPE, AZ 85287-5306
480.965.3589 FAX: 480.965.0057

because low SUVA organics don't sorb particularly well to aluminum hydroxide floc, yet would react with chlorine. Using a simple model we have for water treatment and trihalomethane (THM) formation, and assuming pH (7.5), bromide (0.1 mg/L), temperature (20 C) a 3 mg/L chlorine dose to maintain a chlorine residual after a 24 hour contact time would lead to roughly 49 µg/L of THM formation (final DOC of 1.9 mg/L after 25 mg/L alum and 5 mg/L sulfuric acid doses).

Table 1 – Numerical summary of data

					Percentage TOC response in each region	TOC (mg/L) concentration in each region
Dissolved Organic Carbon	DOC	mg-C/L	2.9	(Calculated from SEC-DOC)		
Dissolved Organic Nitrogen	TDN	mg-N/L	0.2	Molecular weight Range		
UV absorbance at 254 nm	UV254	1/cm	0.0745	10,000 to 100,000	11%	0.3
Specific UV absorbance	SUVA	L/mg-m	2.60	1,000 to 10,000	53%	1.5
Fluorescence Index	FI		1.6	100 to 1,000	37%	1.1

ANALYTICAL METHODS & DESCRIPTION OF MEASUREMENTS

UV-VIS, UV₂₅₄ and SUVA:

UV/Vis Absorbance spectroscopy (UV/VIS from 200 to 700 nm) is measured using Shimadzu UV-1601 variable wavelength spectrophotometer and a 1-cm path length quartz cuvette. This is conducted on filtered samples (0.7 µm, GF/F, Whatman). Blank sample prepared from Nanopure water is run for each experimental set as quality control sample.

Specific ultraviolet absorbance at 254 nm (SUVA), calculated by normalizing the UV absorbance measurement at 254 nm to DOC concentration:

$$SUVA = 100 \times UVA_{254} / DOC$$

SUVA value allows classification according to humic (> 4L/mg-m) versus non-humic NOM (< 2 L/mg-m) (Van Benschoten and Edzwald, 1990). Increasing SUVA values indicate a higher density of sp²-hybridized carbon-carbon double bonds and a larger degree of humification (Chin et al., 1994; Westerhoff et al., 1999).

Size Exclusion Chromatography with in-line TOC analysis (SEC-TOC):

High performance size exclusion chromatography (HP-SEC) to obtain molecular weight distributions is determined on select samples (at least 30%) to determine colloidal organic content of the waters. This is conducted on filtered samples (0.7 µm, GF/F, Whatman). HP-SEC is performed using a high performance liquid chromatography (Waters 2695 Separation Module) followed by a UV detector (Waters 2996 photodiode Array Detector) at 254 nm and a total organic carbon (TOC) detector (Modified Sievers Total Organic Carbon Analyzer 800 Turbo). This system employs a TSK 50S column (Tosho Toyopearl HW-50S resin, Japan) with a phosphate buffer eluent (2.4 mM NaH₂PO₄ and 1.6 mM Na₂HPO₄, pH= 6.8) containing 25 mM Na₂SO₄ to produce an ionic strength of 0.1 M or a conductivity of 4.57 mS Krasner et al. (2009). Before analysis, the sample is filtered with a glass-fiber filter (0.7 µm), and the conductivity of each sample is adjusted to approximately the conductivity of the mobile phase using 40-times

concentrated eluent. To reduce the interference of the inorganic carbon and dissolved oxygen with the stationary phase, nitrogen gas is sparged into the eluent reservoir. The flow rate is 1 ml min⁻¹, and the injection volume is 1 ml. DOC data is collected every 2 sec using the Empower chromatography software package. The system is calibrated with prepared 10 mg/L-C polyethylene glycol standards (Sigma Aldrich) with MWs of 200, 600, 1000, 1450, 3350, 4600, 8000 and 10000 Da. Suwannee River Humic Acid Standard (IHSS) stock solution (2.5 mg/L-C) and nanopure water samples are run for each sample set as quality control samples.

Dissolved Organic Carbon (DOC) and Total Dissolved Nitrogen (TDN):

Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) were measured using a Shimadzu TOC-V_{CSH} analyzer (high temperature combustion at 720°C non-dispersive infrared detection with TNM-1 unit chemiluminescence detection) (Shimadzu Corp., Tokyo, Japan). This is conducted on filtered samples (0.7 µm, GF/F, Whatman). Before analysis, water samples are acidified with HCl to adjust pH to 2~3 to remove inorganic carbon during purging by nitrogen gas. Standards for calibration curve are prepared by potassium hydrogen phthalate (ACS grade, EMD chemicals Inc.) and potassium nitrate (Wako Pure Chemical Industries, Ltd.) for DOC and TDN concentration calculation. The concentrations of calibration curve are 0.5~10 mg/L of carbon and 0.1~5 mg/L of nitrogen. Blank samples (prepared from Nanopure water) and quality control (QC) samples (prepared from the same chemicals described above) are inserted between every 10 samples for quality control. QC samples are made as 5 mg/L of carbon and 3 mg/L of nitrogen.

Fluorescence Index (FI):

The fluorescence index (FI) corresponds to the fluorescence intensity ratio of the emission at 450 nm to the emission at 500 nm, both at an excitation of 370 nm. Fluorescence index was used to distinguish the microbially derived DOC sources from terrestrially derived DOC sources (McKnight, et al., 2001, Battin, 1998, Donahue et al., 1998). The higher FI value indicates a higher content of autochthonous DOM. For terrestrially derived fluorophores, the fluorescence index ranged from 1.3 to 1.4, whereas for microbially derived organic matter the index was suggested to be 1.7 to 2.0 (McKnight et al., 2001).

Fluorescence Excitation-Emission Matrix (EEM)

Fluorescence excitation-emission matrix (EEM) is presented by a 3-Dimensional spectrum showing fluorescence intensity as a function of excitation wavelength and emission wavelength. The “mountain” location(s) of contour plots indicates NOM composition and can be used to assess differentiate biological (algae and bacteria) organic matter from humic and fulvic acids. Fluorescence EEM measurements are conducted using a Perkin-Elmer LS-50B luminescence spectrometer. The spectrometer displays a maximum emission intensity of 1000 A.U. The spectrometer uses a xenon excitation source, and excitation and emission slits are set to 10 nm. To obtain fluorescence EEMs, excitation wavelengths are incremented from 200 to 400 nm at 5-nm steps; for each excitation wavelength, the emission is detected from 290 to 550 nm at 0.5-nm steps. To account for Rayleigh scattering, the fluorometer instrument response of a blank solution is subtracted from the fluorescence spectra recorded for samples containing DOC. The blank solution is prepared from Nanopure water, and contained a DOC < 0.2 mg/L.

Instruments: TOC analyzer (TOC-Vcsh, Shimadzu) with ASI-V autosampler and TNM-I (total nitrogen measuring unit). UV-vis spectrophotometer (Shimadzu MultiSpec-1501). Waters Alliance (Separation Module Waters 2695, UV detector and Sievers 800 Portable Total Organic Carbon Analyzer).

DATA ANALYSIS

Data Summary for USBR sample

Fluorescence EEM

Organic matter will absorb light and fluorescence depending upon carbon bonding. Higher intensities equate to more conjugated bonding and fluorescence at shorter emission wavelengths generally indicate more biological activity. This sample has low overall fluorescence with 2 characteristic fulvic-acid like regions responding.

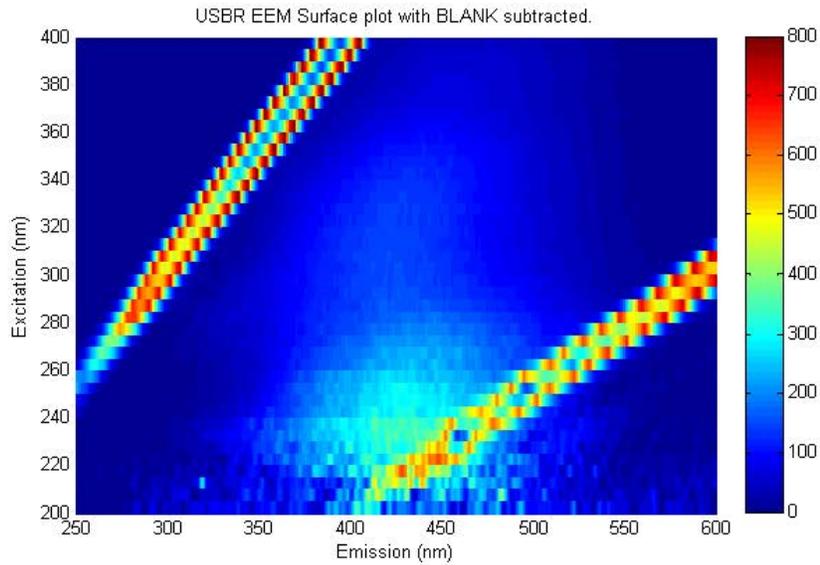


Figure 1 – EEM sample

UV-VIS spectra is typical. At 254 nm carbon double bonds are measured, and a small peak is observed.

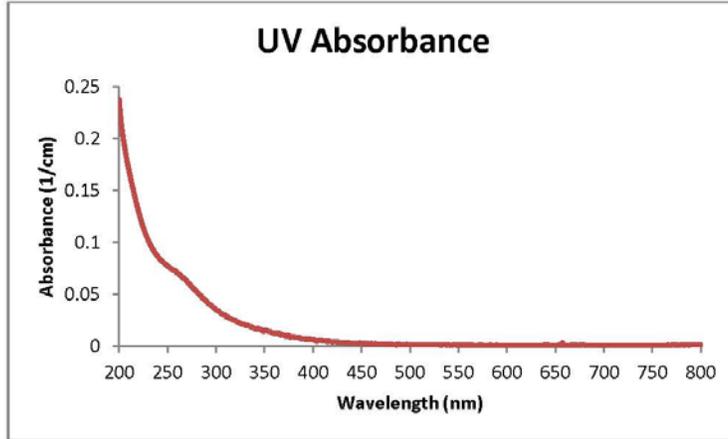


Figure 2 – UV spectra

SEC-TOC data shown below is of good quality. The response (area under the curve) correlates with DOC concentration generally for samples run on the same day. While distinct low molecular weight organics are present, it is also clear that higher molecular weight organics are also present. These background bulk organics would likely not be detected in typical GC screening of priority pollutants, yet are known to have a significant and usually detrimental impact on TCE or other trace organic pollutant removal by GAC.

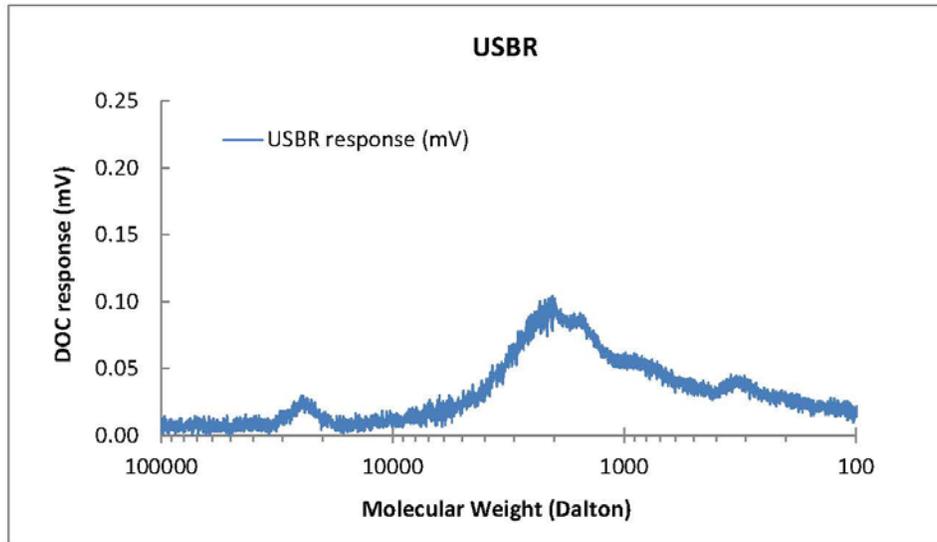
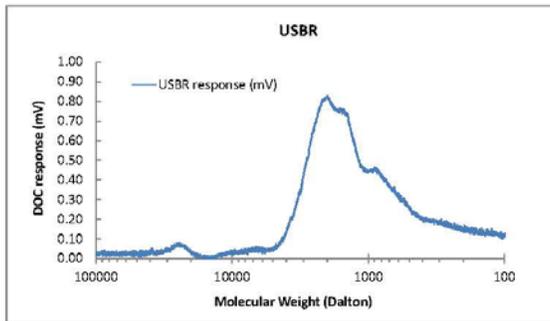


Figure 3 – Molecular weight (MW) distribution of organic carbon of Molecular weight range of 10,000-100,000 Daltons is indicative of colloids and large MW organics; 1,000-10,000 fulvic and humic acids; and 100-1,000 of low molecular weight organics. Percent of TOC in each of these molecular weight ranges are provided in Table 1.

The SEC-TOC sample was rerun in February 2012 after an improved detector system was installed. The distribution of DOC into each molecular weight range was consistent with the earlier run, but the signal to noise is improved.

(Calculated from SEC-DOC)	Percentage TOC response in each region	TOC (mg/L) concentration in each region
Molecular weight Range		
10,000 to 100,000	5%	0.1
1,000 to 10,000	58%	1.7
100 to 1,000	37%	1.1



PART 2 PRODUCTS

Not Used

PART 3 EXECUTION

Not Used

END OF SECTION

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SECTION 51 45 17

DISTRIBUTION SYSTEM CHLORINE DISINFECTION MODELING

PART 1 GENERAL

CUTTER LATERAL CHLORINE DISINFECTION MODELING ANALYSIS

TO: Bob Jurenka, P.E. – Bureau of Reclamation – TSC – Water Treatment Group
Linda Bowles, P.E. – Bureau of Reclamation – TSC – Water Conveyance Group
Ken Yokoyama, P.E. – Bureau of Reclamation – TSC – Water Conveyance Group
FROM: Matt Hirschbeck, P.E. – Bureau of Reclamation – TSC – Water Treatment Group
DATE: March 31, 2015
WOID: NG015
SUBJECT: Navajo-Gallup Water Supply Project
Cutter Lateral – Chlorine Decay Analysis

BACKGROUND

The Cutter Lateral of the Navajo-Gallup Water Supply Project (NGWSP) will provide the Navajo and Jicarilla Apache Nations with treated surface water from the Cutter Reservoir. This project includes a new surface water treatment plant (WTP), several miles of transmission piping, multiple booster pump stations, and millions of gallons of water storage. The capacity of the Cutter WTP will be 5.4 million gallons per day (mgd).

In 2014, the joint venture team of HDR and CDM (HDR-CDM) completed bench-scale testing to evaluate the water treatment process for the Cutter WTP. The proposed treatment process includes enhanced coagulation, flocculation, sedimentation, ozonation, biologically active filtration (BAF), ultraviolet (UV) primary disinfection and secondary free chlorine disinfection. The purpose of the bench-scale testing was to further optimize the design for the coagulation/ozonation/BAF processes in order to meet the Safe Drinking Water Act's Disinfection Byproducts (DBPs) standards. The testing evaluated key process parameters at various setpoints. Simulated distribution system (SDS) analyses were completed after treating site water at the specified process parameters to determine maximum anticipated levels of total trihalomethanes (TTHM) and haloacetic acids (HAA5) in the distribution system. Results of the bench-scale testing yielded the following design recommendations:

1. *Coagulant Dose and pH Adjustment* – 20 mg/L of Ferric Chloride fed at a pH of 6.0
2. *Ozone to Dissolved Organic Carbon (DOC) Ratio* – 0.5:1.0
3. *Empty Bed Contact Time (EBCT)* – 5 minutes

Based on results of the HDR-CDM study, it is anticipated that the secondary disinfection strategy of ozone/BAF treatment with secondary chlorine disinfection and strategic chlorine boosting is the preferred means of maintaining water quality through the transmission system to the end-users.

PURPOSE

The purpose of this analysis is to further evaluate and document any chlorine boosting requirements for the Cutter Lateral transmission line. Figure 1 (attached) shows the proposed Cutter Lateral transmission system, including approximate turnout locations, proposed tank volumes, and pipe reach diameters and lengths. Chlorine decay modeling was performed from the WTP to the farthest reaches of the transmission system: (1) Pueblo Pintado Turnout, and (2) Ojo Encino-East/Torreón Distribution Loop. The goal of the chlorine decay modeling is to determine where chlorine boosting stations would be

required in order to maintain a chlorine residual of at least 0.2 mg/L through the transmission system to these two locations. It is assumed that a minimum residual of 0.2 mg/L (4.0 mg/L maximum) shall be maintained along the Cutter Lateral (and within any “inline” water storage tanks), upstream of any turnout distribution piping or distribution tanks, as directed by TSC’s Water Conveyance Group (8140). Any chlorine boosting on the distribution side will be assessed at a later date, with the knowledge that chlorine boosting may be required upstream of the distribution tanks.

This report is used to document the chlorine decay modeling assumptions, limitations, results, recommendations and conclusions. The chlorine decay modeling calculations are attached at the end of this analysis.

EQUATIONS & VARIABLES

The following is a summary of equations and definitions of variables that were used in preparation of the chlorine decay model calculations for the Cutter Lateral.

(Equation 1A): $C_t = C_0 e^{-Kt}$	[First-order reaction - Batch Reactor for Bulk Decay Rate]
(Equation 1B): $C_t = C_0 e^{-Kt}$	[First-order reaction - Plug Flow for Pipes]
(Equation 1C): $C_t = C_0 / (1 + Kt)$	[First-order reaction - Continuous-stirred Tank Reactor (CSTR) for Tanks]
(Equation 2): $K = k_b + k_w/R$	[Total chlorine decay coefficient]
(Equation 3): $R = A/P_w$	[Pipe hydraulic radius]

C_t = Chlorine residual at a specified time (mg/L)

C_0 = Chlorine dose at time zero (mg/L)

t = Time (days)

K = Total chlorine decay coefficient

k_b = Bulk water chlorine decay coefficient

k_w = Pipe wall chlorine decay coefficient (ft/day)

R = Pipe hydraulic radius (ft)

A = Pipe cross-sectional area (ft²)

P_w = Pipe wetted perimeter (ft)

ASSUMPTIONS & LIMITATIONS

It is well-documented that a water distribution system's free chlorine residual can decay over time through reactions with the bulk water and the pipe wall (Li Xin et al, 2003). The rate of chlorine decay can vary significantly from system to system based on water quality, pipe material, water temperature, pH, and several other key factors. The following is a list of assumptions and limitations that were made for the Cutter Lateral chlorine decay model:

1. The bulk water chlorine decay rate coefficient (k_b) is estimated based on bench-scale chlorine decay modeling completed by HDR-CDM, as presented in the "Chlorine Decay Measures Associated with SDS-THM and SDS-HAA Measurements" table in the "Navajo Gallup Water Supply Project – Cutter Reservoir Enhanced Bench Scale Testing Summary," as provided to Reclamation via email from HDR on March 10, 2015. The "Recommended Treatment Scheme" data was utilized, as it represents raw water that is treated with the proposed treatment scheme (i.e. ferric dose of 20 mg/L, pH of 6.0, Ozone:DOC ratio of 0.5:1.0, and Empty Bed Contact Time (EBCT) of 5 minutes). The bulk water decay results indicated a good fit for a first order reaction (which is typical for chlorine decay). The batch reactor equations were utilized for estimation of the bulk chlorine decay coefficient (Equation 1A).
2. It is noted that chlorine undergoes three reactions in water: oxidation, substitution and addition. Approximately 80-90+% of these reactions are oxidation, and elemental chloride is the reduction product as water constituents are oxidized. When chlorine is applied to potable waters, the oxidation of inorganic constituents such as ammonia, hydrogen sulfide, iron and to a lesser extent, manganese, generally occur rapidly. This initial chlorine decay is influenced by fast reacting humic and fulvic acids that also oxidize rapidly. Once compounds that induce rapid decay rates have been oxidized, chlorine residual decays at a slower rate, which is governed by slowly oxidizing organic matter. In general the fast reacting compounds have been fully oxidized by a 4-8 hour time frame, and slow reacting organic compounds become the constituents causing chlorine decay past this reaction time. When predicting longer chlorine decay (or residual), it is best practice to consider data past the fast reaction threshold. For this reason, the initial chlorine dose (at time $t = 0$) in the bulk chlorine decay data from the HDR-CDM study was not included in the estimation of the bulk chlorine decay rate.
3. It is assumed that all pipes will operate as plug flow reactors. A first-order reaction is assumed based on the HDR-CDM bench test results (Equation 1B).
4. The pipe wall chlorine decay coefficient (k_w) is assumed to be a first order reaction. The pipe wall chlorine decay coefficient can vary significantly based on site specific conditions, such as pipe material, biofilm formation, temperature, pipe roughness, corrosion, etc. Newer PVC pipe would typically have a lower k_w than older ductile iron pipe (DIP); however, it is difficult to accurately estimate the k_w value without field calibration/data collection, or without knowing the actual piping material. A **0.25 to 0.50 ft/day** range is utilized for this study, given the selection of HDPE and PVC piping for all reaches of the Cutter Lateral. Pipe material selection and field testing would be required for a more accurate estimation of k_w . If any piping is proposed to be modified to ductile or steel, the pipe wall chlorine decay coefficient requires further assessment.
5. It is assumed that the water storage tank operation will most closely resemble a continuous-stirred tank reactor (CSTR) (AWWARF, 2000). A first-order reaction is assumed based on the HDR-CDM bench results (Equation 1C). Tank wall chlorine decay was calculated to be negligible.
6. For modeling purposes, the chlorine decay model was prepared using the highest, average, and lowest estimated chlorine decay coefficients. The highest decay rate (i.e. the largest loss of

residual over time) includes the estimated bulk water chlorine decay coefficient and the maximum estimated pipe wall decay coefficient. Similarly, the average and lowest decay rates are based on the estimated bulk water and average and minimum pipe wall decay coefficient, respectively. The “worst case scenario” (largest loss of residual) is based on the highest estimated chlorine decay rate. It should be noted that the “worst case” bulk water decay rate would occur during monsoon conditions; however, the bulk decay rate for this analysis is based on a representative water sample used by HDR-CDM for their bench tests.

- Turnout water demands are based on the “Navajo Gallup Water Supply Project – Project Issue Notice No. 27,” which is currently marked “draft”, with a date of 2013. The chlorine decay model was prepared based on minimum, average and maximum turnout flows in calendar years (CY’s) 2020 and 2040. Phasing of construction is not anticipated; thus the “worst case scenario” (longest water age) is based on the CY 2020 minimum flow conditions presented in the Project Issue Notice.

Two chlorine decay simulations are presented using the previously mentioned chlorine decay model calculations: (1) Cutter WTP to Pueblo Pintado, and (2) Cutter WTP to the Ojo Encino-East/Torreon Distribution Loop. Tables 1 and 2 summarize the pipe reach and tank attributes of each model.

Table 1 – Cutter WTP to Pueblo Pintado – Pipe Reach and Tank Summary

Reach	From	To	Pipe Diameter (inches)	Pipe Length (feet)	Tank Volume per Tank (gallons)	No. of Tanks Online (2020/2040) ¹
22B.3	Cutter WTP	Reg Tank #3	19.03	13,530	--	--
<i>Regulating Tank #3</i>			--	--	508,000	1/2
22B.3	Regulating Tank #3	Huerfano TO	19.03	1,667	--	--
Phase 3	Huerfano TO	Nageezi Tanks #2	19.05	86,950	--	--
<i>Nageezi Tanks #2</i>			--	--	101,500	1/1
Phase 2	Nageezi Tanks #2	Counselor TO & Tanks	18.12	67,030	--	--
<i>Counselor Tanks</i>			--	--	102,000	1/1
24.1	Counselor TO & Tanks	Jicarillo TO	13.6	14,567	--	--
25A	Jicarillo TO	Reach 25 Pump Station	13.6	7,482	--	--
25B	Reach 25 Pump Station	Ojo Encino - North TO & Tanks	13.6	34,683	--	--
<i>Ojo Encino - North Tanks</i>			--	--	109,000	1/1
26.1	Ojo Encino - North TO & Tanks	Ojo Encino – East/ Torreon TO	11.73	14,283	--	--
26.2	Ojo Encino – East/ Torreon TO	Pueblo Pintado TO	9.6	81,127	--	--

Table 2 – Cutter WTP to Ojo Encino-East/Torreon Distribution Loop – Pipe Reach and Tank Summary

Reach	From	To	Pipe Diameter (inches)	Pipe Length (feet)	Tank Volume per Tank (gallons) ¹	No. of Tanks Online (2020/2040) ²
22B.3	Cutter WTP	Reg Tank #3	19.03	13,530	--	--
<i>Regulating Tank #3</i>			--	--	508,000	1/2
22B.3	Regulating Tank #3	Huerfano TO	19.03	1,667	--	--
Phase 3	Huerfano TO	Nageezi Tanks #2	19.05	86,950	--	--
<i>Nageezi Tanks #2</i>			--	--	101,500	1/1
Phase 2	Nageezi Tanks #2	Counselor TO & Tanks	18.12	67,030	--	--
<i>Counselor Tanks</i>			--	--	102,000	1/1
24.1	Counselor TO & Tanks	Jicarillo TO	13.6	14,567	--	--
25A	Jicarillo TO	Reach 25 Pump Station	13.6	7,482	--	--
25B	Reach 25 Pump Station	Ojo Encino - North TO & Tanks	13.6	34,683	--	--
<i>Ojo Encino - North Tanks</i>			--	--	109,000	1/1
26.1	Ojo Encino - North TO & Tanks	Ojo Encino – East/ Torreon TO	11.73	14,283	--	--
26.3A	Ojo Encino – East/ Torreon TO	Ojo-Torreon Tanks	9.87	16,205	--	--
<i>Ojo-Torreon Tanks</i>			--	--	250,000	2/2
26.3B	Ojo-Torreon Tanks	Ojo Encino – East/ Torreon Distribution Loop	11.73	29,507	--	--

Notes:

1. Tank volumes are taken from various sources, and were confirmed to be current anticipated volumes with the project team, including SMA representatives (see confirmation email dated 03/13/2015); only those tanks considered to be "in-line" storage are used for water age along the transmission main, with the exception of Pueblo Pintado, where no tanks are included as chlorine boosting is included in the SMA design; See Appendix B.
2. Number of tanks online shown for the year 2020 and the year 2040 (e.g. 1/2 represents one tank in 2020, two tanks in 2040.)

It should be noted that per Souder Miller & Associates (SMA), chlorine boosting capabilities are currently included in the design of the inline Ojo-Torreon Tanks (two @ 250,000-gallon tanks). There are currently no additional chlorine boosting stations included in the Cutter Lateral transmission system.

KEY RESULTS

Several iterations of the chlorine decay models were run in order to estimate chlorine residuals through the transmission system for varying operating conditions. Complete results and calculations for the decay models are attached at the end of this technical memorandum. The following provides a summary of key results for each of the models. It should be noted that for this analysis, the “worst case scenario” for the chlorine decay modeling occurs at the lowest flow rates (CY 2020 minimum flows) and highest combined ($k_b + k_w$) chlorine decay rate (K_{high}).

1. Cutter WTP to Pueblo Pintado Modeling Results

- a. The maximum water age of water reaching Pueblo Pintado is approximately 3.4 days at the “worst case scenario” (CY 2020) flow rates, upstream of all Pueblo Pintado tanks. The maximum water age of water reaching the Ojo Encino-East/Torreon Turnout (intersection of Reaches 26.1 and 26.3) is approximately 2.3 days.
- b. Without chlorine boosting, a chlorine residual of over 10 mg/L leaving the WTP would be required to maintain a chlorine residual of 0.2 mg/L at Pueblo Pintado, assuming the average chlorine decay rate, which is well above the maximum allowable residual of 4.0 mg/L.
- c. Without chlorine boosting and assuming the maximum chlorine decay rate, a chlorine residual of 4.0 mg/L (maximum allowable) leaving the WTP would result in a 0.01 mg/L residual at Pueblo Pintado. This residual is below the required minimum residual of 0.2 mg/L, again indicating that chlorine boosting may be required.
- d. A chlorine residual of 3.4 mg/L leaving the WTP would result in minimum residual of 0.2 mg/L at the Ojo Encino-East/Torreon Turnout (assuming the maximum decay rate). A subsequent chlorine boost at the Ojo Encino-East/Torreon Turnout up to 3.3 mg/L would result in a minimum residual of 0.2 mg/L at Pueblo Pintado, upstream of all Pueblo Pintado tanks.
- e. It should be noted that chlorine boosting at the Reach 25 Booster Station and the Ojo Encino-North Turnout/Tanks was also investigated. It was determined that if chlorine boosting is provided at either of these locations, subsequent boosting at the Ojo Encino-East/Torreon Turnout would also be needed to maintain a 0.2 mg/L residual at Pueblo Pintado without exceeding the maximum residual of 4.0 mg/L in the transmission line. For this reason, a single chlorine boosting point at the Ojo Encino-East/Torreon Turnout is recommended.

2. Cutter WTP to Ojo Encino-East/Torreon Distribution Loop Modeling Results

- a. The maximum water age reaching the Ojo Encino-East/Torreon Distribution Loop is approximately 4.1 days at the “worst case scenario” (CY 2020) flow rates. The water age in this same scenario at the Ojo Encino-East/Torreon Turnout (intersection of Reaches 26.1 and 26.3) is approximately 2.3 days, which is approximately the “mid-point” of transmission system detention time.
- b. As previously noted, the current design of Reach 26.3 includes chlorine boosting capabilities at the Ojo-Torreon Tanks. Without additional chlorine boosting upstream of this location, a chlorine residual of approximately 4.9 mg/L leaving the WTP would be required to maintain a chlorine residual of 0.2 mg/L upstream of the Ojo-Torreon Tanks, assuming the maximum chlorine decay rate, which is above the maximum allowable residual of 4.0 mg/L.

- c. Without chlorine boosting and assuming the maximum chlorine decay rate, a chlorine residual of 4.0 mg/L (maximum allowable) leaving the WTP would result in a 0.16 mg/L residual upstream of the Ojo-Torreon Tanks. This residual is below the required minimum residual of 0.2 mg/L, again indicating that chlorine boosting may be required.
- d. A chlorine residual of 3.4 mg/L leaving the WTP would result in minimum residual of 0.2 mg/L at the Ojo Encino-East/Torreon Turnout (assuming the maximum decay rate). A subsequent chlorine boost at the Ojo Encino-East/Torreon Turnout up to 0.3 mg/L would result in a minimum residual of 0.2 mg/L at the Ojo-Torreon Tanks. Subsequent boosting at the Ojo-Torreon Tanks up to 0.5 mg/L would result in a minimum residual of 0.2 mg/L at the Ojo Encino-East/Torreon Distribution Loop.

RECOMMENDATIONS & CONCLUSIONS

The following recommendations and conclusions are made as a result of the chlorine decay modeling that was completed for the Cutter Lateral:

1. In addition to the already planned chlorine boosting at the Ojo-Torreon Tanks, chlorine boosting capabilities should be provided at the Ojo Encino-East/Torreon Turnout (intersection of Reaches 26.1, 26.2 and 26.3). Based on the “worst case scenarios” that were utilized in the chlorine decay modeling, chlorine boosting may be required at these strategic locations in order to maintain a minimum chlorine residual of 0.2 mg/L throughout the transmission system without exceeding a maximum residual of 4.0 mg/L. Operations of the chlorine boosting systems could vary significantly seasonally based on water quality, water temperature, flow rates, etc. Chlorine boosting may not be required continuously throughout the year, but providing chlorine boosting equipment and chlorine residual monitoring equipment at these locations would provide operational flexibility to maintain water quality to the end-users. The use of intermediate chlorine boosting also allows lower chlorine residuals to be maintained, which can help minimize the DBP formation in the transmission system.
2. It is noted that the maximum water age at Pueblo Pintado is estimated to be 3.4 days, compared to 4.1 days at the Ojo Encino-East/Torreon Distribution Loop. However, there is significantly more piping in Reach 26.2 (~81,000 ft to Pueblo Pintado) than in Reach 26.3 (~46,000 ft to Ojo Encino-East/Torreon Distribution Loop). Given the significantly longer length of piping in Reach 26.2 and the effects of the pipe wall chlorine decay coefficient, the results show that maintaining a chlorine residual from the WTP to Pueblo Pintado may be more difficult than maintaining a chlorine residual from the WTP to the Ojo Encino-East/Torreon Distribution Loop.
3. Further analysis is required to determine chlorine boosting requirements for the distribution systems (including tanks) for each turnout.
4. If feasible, it would be beneficial to complete field testing/calibration of the chlorine decay model. Field testing would determine the actual pipe wall decay rate coefficients for the Cutter Lateral, which would allow for calibration of chlorine decay models.
5. Table 3 provides a summary of estimated chlorine dose requirements and chlorine usage at each of the recommended chlorine dosing locations for the 2020 minimum flow conditions at varying chlorine decay rates.

Table 3 – Chlorine Dosing Location & Estimated Dose/Usage at 2020 Minimum Flows

Chlorine Dosing Location	2020 Minimum Flow at Dosing Location (cfs)	K _{low} ³		K _{mid}		K _{high}	
		Chlorine Dose Required ¹ (mg/L)	Chlorine Usage ² (lbs/day)	Chlorine Dose Required ¹ (mg/L)	Chlorine Usage ² (lbs/day)	Chlorine Dose Required ¹ (mg/L)	Chlorine Usage ² (lbs/day)
Cutter WTP	3.33	0.86	15.4	1.49	26.7	3.35	60.1
Ojo Encino-East/Torreón TO - Booster to Pueblo Pintado	0.43	0.63	1.5	1.24	2.9	3.07	7.1
Ojo Encino-East/Torreón TO - Booster to Ojo Encino-East/Torreón Distribution Loop	0.69	0.04	0.1	0.06	0.2	0.09	0.3
TOTAL		–	17.0	–	29.8	–	67.6

Notes:

1. For chlorine boosting locations, the "chlorine dose" is equal to the required residual leaving the facility minus the residual entering the facility.
2. The chlorine usage is the estimated chlorine usage at 2020 minimum flows at the specified chlorine dose. Usage should not be used for equipment sizing or O&M estimates.
3. It is noted that for the K_{low} scenario, a dose of 3.58 mg/L at the WTP results in a minimum residual of 0.2 mg/L at all locations; however, the total chlorine usage for this dose is approximately 64.3 lb/day. It is more efficient to maintain the lower dose leaving the WTP, then boost at the proposed location.
4. Chlorine doses are approximate based on the chlorine decay modeling; actual dose can vary significantly seasonally based on flow rates, water quality, water temperature, and several other factors that can affect the chlorine decay rate.

REFERENCES

AWWA Research Foundation (AWWARF), March 2000. "Water Quality Modeling of Distribution System Storage Facilities," Table 2.1.

Bureau of Reclamation, Draft, 2013. "Project Issue Notice No. 27 – Design Criteria Element, Cutter Lateral Turnout Flows."

Li Xin et al, 2003. "Modeling of Residual Chlorine in Water Distribution System," *Journal of Environmental Sciences*, Volume 15, No. 1, pp. 136-144, 2003.

HDR-CDM, January 23, 2014. "Cutter Reservoir Water Treatment Phase 2 Bench-Scale Testing – Final Bench-Scale Test Results Report."

Attachments

Attachment A: Figure 1 – Cutter Lateral Map

Attachment B: Cutter Water Age – Tank Schematic

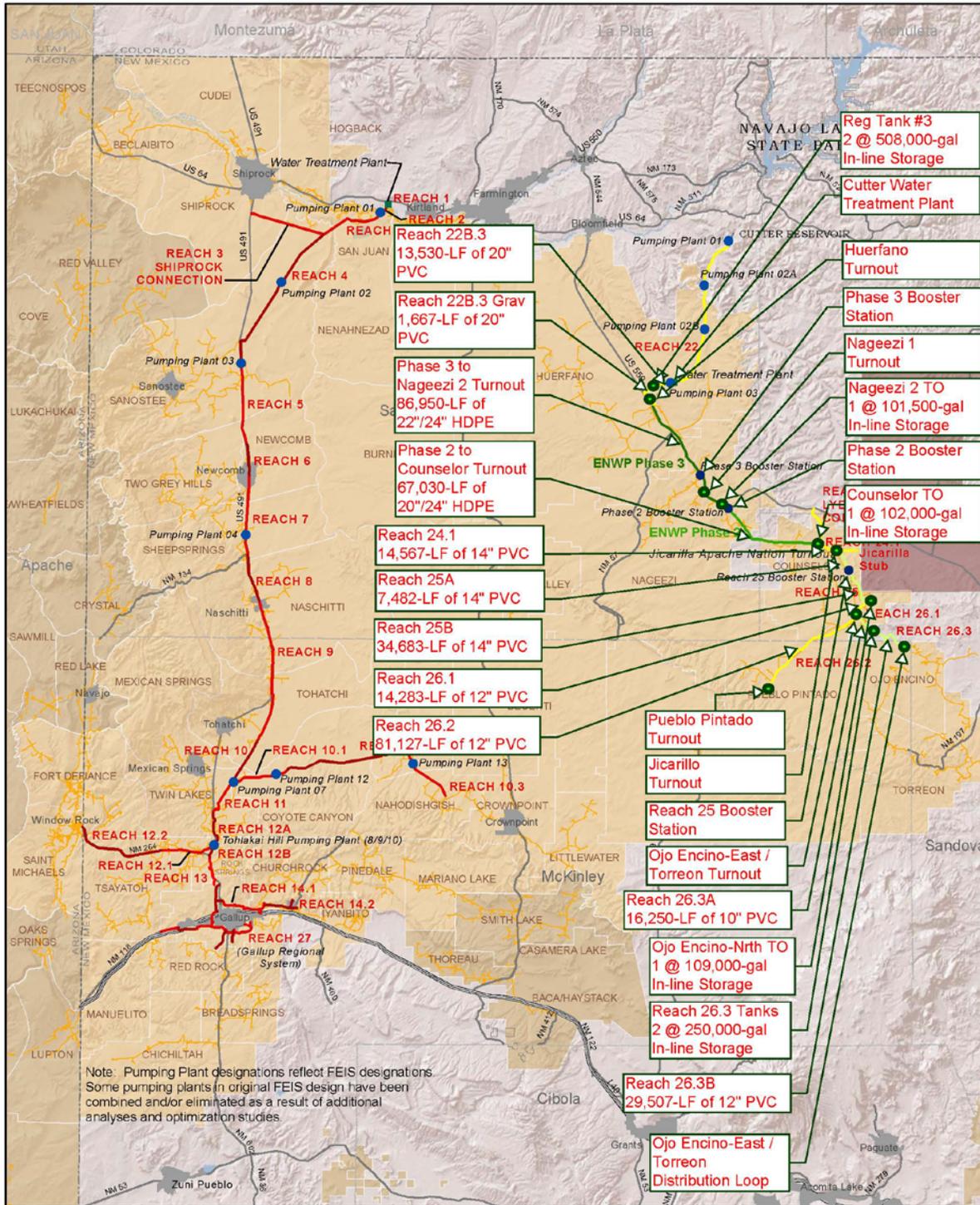
Attachment C: Chlorine Decay Calculations

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ATTACHMENT A

FIGURE 1 – CUTTER LATERAL MAP



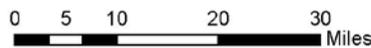
Legend

- Pumping Plants
- Water Treatment Plant
- San Juan Lateral
- Cutter Lateral
- Eastern Navajo Water Pipeline (ENWP) Phase 3
- Eastern Navajo Water Pipeline (ENWP) Phase 2
- Interstate
- State Highway
- US Highway
- NTUA Line
- Navajo Nation Non-Serviced Chapters
- Navajo Nation Serviced Chapters
- Jicarilla Apache Nation
- Turnout or Beginning/End of Reach

Navajo Gallup Water Supply Project

RECLAMATION
Managing Water for the West

**FIGURE 1
 CUTTER LATERAL MAP**



ATTACHMENT B

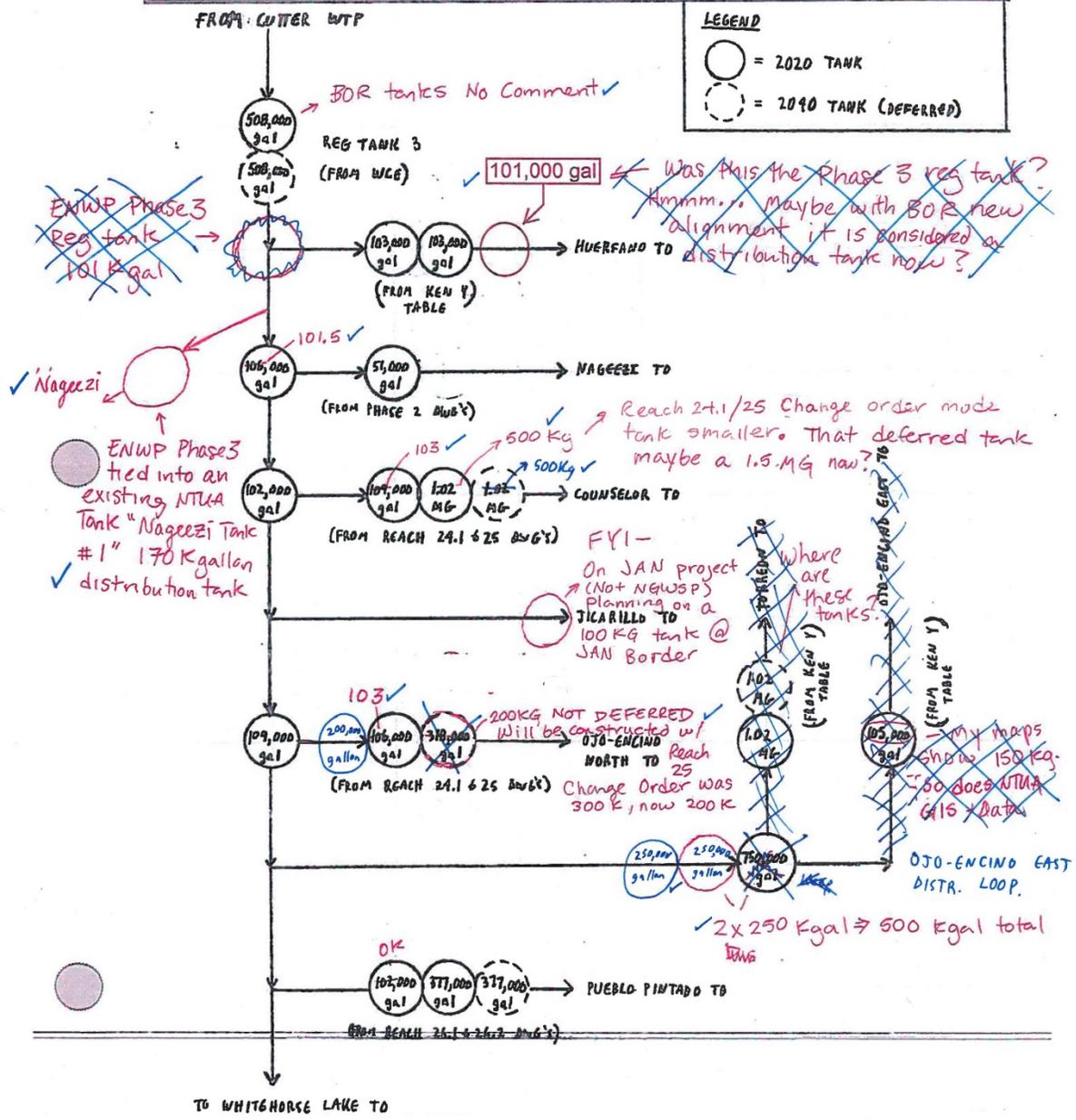
CUTTER WATER AGE – TANK SCHEMATIC

UPDATED - 03/13/15 - HIRSCHBECK
 WITH INPUT FROM
 TORY & ANDREW

7-1654 (11-94)
 Bureau of Reclamation

COMPUTATION SHEET

BY HIRSCHBECK	DATE 02/13/15	PROJECT NAVAJO-GALLUP	SHEET 1 OF 1
CHKD BY	DATE	FEATURE CUTTER WATER AGE - TANK SCHEMATIC	
DETAILS			



ATTACHMENT C

CHLORINE DECAY CALCULATIONS

Navajo-Gallup Water Supply Project
Cutter Lateral Disinfection Study
Chlorine Decay Analysis
WQOD: NG2015

Bureau of Reclamation
Technical Services Center - Denver
REV March 30, 2015
Hirschback

NAVAJO-GALLUP - CUTTER LATERAL - DISINFECTION STUDY
CHLORINE DECAY ANALYSIS - CUTTER WTP TO PUEBLO PINTADO TANKS

EQUATIONS & VARIABLES:

- (Equation 1A) $C_t = C_0 - Kt$ [Zero-order reaction - Batch Reactor for Bulk Decay Rate]
 - (Equation 1B) $C_t = C_0 - K_p t$ [Zero-order reaction - Plug Flow for Pipes]
 - (Equation 1C) $C_t = C_0 - Kt$ [Zero-order reaction - CSTR for Tanks]
 - (Equation 2A) $C_t = C_0 e^{-Kt}$ [First-order reaction - Batch Reactor for Bulk Decay Rate]
 - (Equation 2B) $C_t = C_0 e^{-K_p t}$ [First-order reaction - Plug Flow for Pipes]
 - (Equation 2C) $C_t = C_0 / (1 + Kt)$ [First-order reaction - CSTR for Tanks]
 - (Equation 3A) $C_t = C_0 / (1 + K_p t)$ [Second-order reaction - Batch Reactor for Bulk Decay Rate]
 - (Equation 3B) $C_t = C_0 / (1 + K_p t)$ [Second-order reaction - Plug Flow for Pipes]
 - (Equation 3C) $C_t = C_0 / (1 + K_p t)$ [Second-order reaction - CSTR for Tanks]
 - (Equation 4) $C_t = C_0 e^{-K_p t}$
 - (Equation 5) $C_t = C_0 e^{-K_p t}$
- C_t = Chlorine residual at a specified time (mg/L)
 C_0 = Chlorine dose at time zero (mg/L) - Assume measured at exit from the WTP
 t = Time (days)
 K = Total chlorine decay coefficient
 K_p = Bulk water chlorine decay coefficient - Typical first order chlorine decay values = 0.34 to 0.51 /day - See Tables 1A, 1B & 1C for Site Specific Analysis and Results.
 K_w = Pipe wall chlorine decay coefficient (1/Day) - Typical first order chlorine decay values = 0.25 to 1.0 1/Day - Not used in Tank Chlorine Decay Calculations.
 A = Pipe hydraulic radius (ft)
 A_p = Pipe cross-sectional area (ft²)
 P_w = Pipe wetted perimeter (ft) - Equal to pipe circumference for pressure pipe

USER INPUTS:

Cl ₂ Dose @ Old Reservoir	3.55 mg/L	Chlorine Dose Leaving the WTP - USER INPUT
Reservoir T0?	Yes (Yes or No?)	Chlorine Boosting upstream of Old Reservoir - East/Terrace T0? - USER INPUT
Boost Dose	3.77 mg/L	Minimum Pipe Wall Chlorine Decay Coefficient - USER INPUT
K _w	0.25 1/Day	Average Pipe Wall Chlorine Decay Coefficient - USER INPUT
K _{min}	0.15 1/Day	Maximum Pipe Wall Chlorine Decay Coefficient - USER INPUT
K _{max}	0.50 1/Day	Maximum Pipe Wall Chlorine Decay Coefficient - USER INPUT

2020 MINIMUM FLOW RESULTS (FROM TABLE 3 BELOW)

Residual Measurement Location	Chlorine Residual (mg/L)		
	C_{min}	C_{avg}	C_{max}
Old Reservoir - East/Terrace Turnout	0.78	0.45	0.30
Upstream of All Pueblo Pintado Tanks	0.79	0.46	0.30

TABLE 1A - ZERO ORDER BULK WATER CHLORINE DECAY RATE COEFFICIENT CALCULATIONS¹

Time (Days)	Chlorine Residual (mg/L)
0.00	3.55
1.00	2.00
3.00	1.11
5.00	0.79
7.00	0.65
10.00	0.50

- Notes:
 1. Chlorine data from HDR (Chris Rodriguez), Enhanced Bench Scale Testing (DS5-TM3 & DS5-HA4) - received on March 10, 2015.
 2. Per Equation 1A, (t) is plotted versus time; the slope of the trend line is equal to the zero order decay coefficient (K)
 3. Not used, zero order not typical for chlorine decay, and R2 values are lower than first order.
 4. Initial chlorine dose at t=0 not utilized; explanation provided in report.

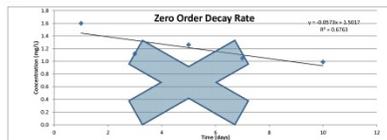
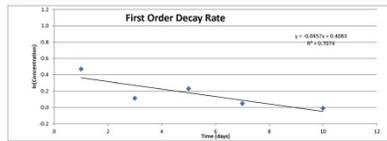


TABLE 1B - FIRST ORDER BULK WATER CHLORINE DECAY RATE COEFFICIENT CALCULATIONS¹

Time (Days)	Chlorine Residual (mg/L)
0.00	3.55
1.00	2.00
3.00	1.11
5.00	0.79
7.00	0.65
10.00	0.50

- Notes:
 1. Chlorine data from HDR (Chris Rodriguez), Enhanced Bench Scale Testing (DS5-TM3 & DS5-HA4) - received on March 10, 2015.
 2. Per Equation 2A, LN(C) is plotted versus time; the slope of the trend line is equal to the first order decay coefficient (K)
 3. First order reaction selected as it's typical for chlorine decay, and R2 value is reasonable.
 4. Initial chlorine dose at t=0 not utilized; explanation provided in report.



Navajo-Gallup Water Supply Project
Cutter Lateral Disinfection Study
Chlorine Decay Analysis
WQOD: NG2015

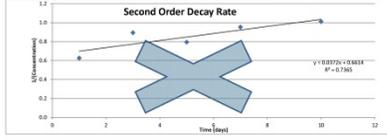
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NAVAJO-GALLUP - CUTTER LATERAL - DISINFECTION STUDY
CHLORINE DECAY ANALYSIS - CUTTER WTP TO PUEBLO PINTADO TANKS

TABLE 1C - SECOND ORDER BULK WATER CHLORINE DECAY RATE COEFFICIENT CALCULATIONS¹

Time (Days)	Chlorine Residual (mg/L)
0.00	3.55
1.00	2.00
3.00	1.11
5.00	0.79
7.00	0.65
10.00	0.50

- Notes:
 1. Chlorine data from HDR (Chris Rodriguez), Enhanced Bench Scale Testing (DS5-TM3 & DS5-HA4) - received on March 10, 2015.
 2. Per Equation 3A, 1/C(t) is plotted versus time; the slope of the trend line is equal to the second order decay coefficient (K)
 3. Not used, second order not typical for chlorine decay.
 4. Initial chlorine dose at t=0 not utilized; explanation provided in report.



From Table 1B - First Order Reaction Rate Coefficient

K _{min}	0.0407 1/Day
------------------	--------------

TABLE 2 - TURNOUT FLOWS¹

Reach	Turnout	2020 Flows (MGD)			2040 Flows (MGD)		
		Q _{min}	Q _{avg}	Q _{max}	Q _{min}	Q _{avg}	Q _{max}
Phase 1	Mountain	0.16	0.20	0.26	0.31	0.39	0.50
Phase 2	Compressor	0.38	0.48	0.62	0.44	0.55	0.70
Phase 3	Compressor	0.54	0.70	0.92	0.62	0.79	1.00
26.1	Old Reservoir - North	0.09	1.36	1.77	1.33	1.66	2.15
26.1/26.2	Pueblo Pintado	0.20	0.24	0.31	0.32	0.40	0.52
26.2	Whitehouse Lake	0.21	0.29	0.38	0.38	0.47	0.61
26.3A	Terrace	0.48	0.60	0.78	0.65	0.80	1.00
26.3B	Old Reservoir - East	0.18	0.22	0.29	0.30	0.37	0.48
TOTALS		3.33	6.15	8.43	5.45	6.42	8.34

- Table 2 Notes:
 1. From Navajo-Gallup Water Supply Project - Project Issue Notice No. 27, Dated XXXXX, XX 2013 (DIRM7).

Navajo-Gallup Water Supply Project
Cutter Lateral Disinfection Study
Chlorine Decay Analysis
WQOD, NG2015

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NAVAJO-GALLUP - CUTTER LATERAL - DISINFECTION STUDY
CHLORINE DECAY ANALYSIS - CUTTER WTP TO PUEBLO PINTADO TANKS

TABLE 3 - PUEBLO PINTADO CHLORINE RESIDUAL CALCULATIONS - 2000 FLOW RATES

Reach	From	To	Pipe Diameter (inches)	Pipe Length (feet)	Tank Volume per Tank (gallons)	No. of Tanks	Total Residual Tank Volume (MG)	2000 Minimum Flow			2000 Average Flow			2000 Maximum Flow											
								Segment Flow (MG)	Segment Water Age (days)	Cumulative Water Age (days)	Chlorine Residual (mg/L) (C @ end of segment)	Segment Flow (MG)	Segment Water Age (days)	Cumulative Water Age (days)	Chlorine Residual (mg/L) (C @ end of segment)	Segment Flow (MG)	Segment Water Age (days)	Cumulative Water Age (days)	Chlorine Residual (mg/L) (C @ end of segment)						
228.3	Cutter WTP	Regulating Tank #3	18.03	13,330	308,000	1	0.31	3.34	0.29	0.31	0.09	0.31	0.09	0.31	0.09	0.31	0.09	0.31	0.09						
228.3	Regulating Tank #3	Heurterco TO	18.03	1,667	—	—	0.31	3.33	0.01	0.30	3.01	2.88	4.75	0.01	0.27	3.15	3.08	2.88	5.41	0.01	0.21	3.05	3.05		
Phase 1	Heurterco TO	Regulating Tank #1	18.03	86,950	—	—	1.29	3.17	0.53	0.87	2.02	1.69	1.27	3.95	0.50	0.79	2.23	1.93	1.54	5.15	0.50	0.60	2.46	2.18	1.85
Phase 2	Regulating Tank #2	Cowenboro TO & Tanks	18.12	47,030	181,000	1	0.30	2.79	0.50	1.52	1.42	1.03	0.64	3.47	0.40	1.22	1.88	1.50	0.89	4.53	0.31	0.43	1.83	1.62	1.23
24.1	Cowenboro TO & Tanks	Javelito TO	13.6	14,547	—	—	0.11	2.23	2.08	1.05	1.32	0.93	0.56	2.27	0.06	1.52	1.58	1.20	0.79	3.01	0.20	1.02	1.88	1.53	1.13
25A	Javelito TO	Reach 25 Pump Station	13.6	7,482	—	—	0.06	1.34	0.28	1.15	1.20	0.90	0.49	1.61	0.09	1.39	1.40	1.11	0.71	1.84	0.20	1.04	1.83	1.44	1.02
25B	Reach 25 Pump Station	Op Inflow - North TO & Tanks	13.6	34,883	—	—	0.26	1.34	0.36	2.08	0.88	0.54	0.26	1.41	0.29	1.67	1.15	0.77	0.42	1.84	0.22	1.28	1.67	1.08	0.88
26.1	Op Inflow - North TO & Tanks	Op Inflow - East/Torreon TO	11.73	14,283	—	—	0.09	1.09	0.11	2.34	0.78	0.48	0.20	1.35	0.09	1.89	1.03	0.63	0.30	1.76	0.07	1.45	1.38	0.92	0.90
26.2	Op Inflow - East/Torreon TO	Pueblo Pintado TO & Tanks	9.6	91,837	—	—	0.31	0.43	0.13	3.44	0.75	0.48	0.20	0.53	0.89	3.78	1.00	0.64	0.34	0.69	0.68	2.13	1.00	0.64	0.30

TABLE 4 - PUEBLO PINTADO CHLORINE RESIDUAL CALCULATIONS - 2500 FLOW RATES

Reach	From	To	Pipe Diameter (inches)	Pipe Length (feet)	Tank Volume per Tank (gallons)	No. of Tanks	Total Residual Tank Volume (MG)	2500 Minimum Flow			2500 Average Flow			2500 Maximum Flow												
								Segment Flow (MG)	Segment Water Age (days)	Cumulative Water Age (days)	Chlorine Residual (mg/L) (C @ end of segment)	Segment Flow (MG)	Segment Water Age (days)	Cumulative Water Age (days)	Chlorine Residual (mg/L) (C @ end of segment)	Segment Flow (MG)	Segment Water Age (days)	Cumulative Water Age (days)	Chlorine Residual (mg/L) (C @ end of segment)							
228.3	Cutter WTP	Regulating Tank #3	18.03	13,330	308,000	1	0.31	3.16	0.05	0.16	0.27	1.17	1.01	0.20	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
228.3	Regulating Tank #3	Heurterco TO	18.03	1,667	—	—	0.29	3.34	0.01	0.37	3.16	3.14	1.53	0.42	0.01	0.30	3.10	3.10	3.10	0.34	0.01	0.29	3.09	3.05	3.05	
Phase 1	Heurterco TO	Regulating Tank #1	18.03	86,950	—	—	1.29	3.03	0.83	0.41	0.78	2.31	1.07	0.20	0.33	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Phase 2	Regulating Tank #2	Cowenboro TO & Tanks	18.12	47,030	181,000	1	0.30	2.82	0.88	0.62	2.88	2.24	1.36	0.93	0.60	0.60	2.00	2.00	2.00	2.86	0.60	0.60	2.00	2.00	2.00	
24.1	Cowenboro TO & Tanks	Javelito TO	13.6	14,547	—	—	0.11	2.12	0.94	1.18	1.48	1.33	1.22	0.27	0.09	0.95	1.11	1.29	1.29	0.78	0.09	0.78	0.60	0.78	0.60	
25A	Javelito TO	Reach 25 Pump Station	13.6	7,482	—	—	0.06	1.84	0.25	1.38	1.29	1.05	0.64	2.43	0.04	1.03	1.87	1.63	1.21	3.14	0.05	0.78	2.22	1.81	1.53	
25B	Reach 25 Pump Station	Op Inflow - North TO & Tanks	13.6	34,883	—	—	0.26	1.84	0.31	1.49	1.42	1.03	0.64	2.43	0.17	1.03	1.80	1.50	0.89	3.14	0.17	0.80	1.97	1.62	1.23	
26.1	Op Inflow - North TO & Tanks	Op Inflow - East/Torreon TO	11.73	14,283	—	—	0.09	1.85	0.07	1.65	1.31	0.93	0.36	2.30	0.05	1.32	1.58	1.20	0.75	3.00	0.04	1.02	1.86	1.52	1.11	
26.2	Op Inflow - East/Torreon TO	Pueblo Pintado TO & Tanks	9.6	91,837	—	—	0.31	0.70	0.67	2.32	1.36	0.87	0.08	0.47	0.54	1.86	1.82	1.23	0.40	1.11	0.42	1.43	1.08	0.64	0.30	

Notes 1 & 2 below

1. $C_{min} = C_0 - k_{app}t$
2. $C_{min} = C_0 - k_{app}t$

3. Assume First Order Plug Flow for Pipes (Equation 26) and First Order CSTR for Tanks (Equation 23)
4. Pipe and tank flow assumed to be equal for tanks
5. Segment flows are calculated from Table 2 based on tank demands
6. Tank volumes are taken from various sources, and are considered to be current anticipated volumes with the project team, including MA (see confirmation of final 02/13/2015); only tanks considered to be "in use" are used for water age along the transmission main, with the exception of Pueblo Pintado, where no tanks are included, as chlorine dosing is included in the MA design.

Filename: Navajo-Gallup - NG2015 - Cutter Lateral Chlorine Decay - REV 03 30 15.xlsx
Worksheet: 02 Decay - WTP to Pueblo Pintado

Navajo-Gallup Water Supply Project
Cutter Lateral Disinfection Study
Chlorine Decay Analysis
WQOD, NG2015

Bureau of Reclamation
Technical Services Center - Denver
REV March 30, 2015
Hirschbach

NAVAJO-GALLUP - CUTTER LATERAL - DISINFECTION STUDY
CHLORINE DECAY ANALYSIS - CUTTER WTP TO OJO ENCINO - EAST/TORREON DISTRIBUTION LOOP

EQUATIONS & VARIABLES:

- (Equation 16) $C = C_0 - kt$ (Zero-order reaction - Batch Reactor for Bulk Decay Rate)
- (Equation 18) $C = C_0 - kt$ (Zero-order reaction - Plug Flow for Pipe)
- (Equation 19) $C = C_0 - kt$ (Zero-order reaction - CSTR for Tank)
- (Equation 20) $C = C_0 e^{-kt}$ (First-order reaction - Batch Reactor for Bulk Decay Rate)
- (Equation 21) $C = C_0 e^{-kt}$ (First-order reaction - Plug Flow for Pipe)
- (Equation 22) $C = C_0 (1 - kt)^{-1}$ (First-order reaction - CSTR for Tank)
- (Equation 23) $C = C_0 (1 - kt)^{-1}$ (Second-order reaction - Batch Reactor for Bulk Decay Rate)
- (Equation 24) $C = C_0 (1 - kt)^{-1}$ (Second-order reaction - Plug Flow for Pipe)
- (Equation 25) $C = C_0 (1 - kt)^{-1}$ (Second-order reaction - CSTR for Tank)

- C_0 = Chlorine residual at a specified time (mg/L)
- C_t = Chlorine dose at time zero (mg/L) - Assume measured at exit from the WTP
- t = Time (days)
- k = First-order chlorine decay coefficient
- k_{app} = Bulk water chlorine decay coefficient - Typical first order chlorine decay values = 0.04 to 1.0/day - See Tables JA, JB & JC for Site Specific Analysis and Results.
- k_p = Pipe wall chlorine decay coefficient (D/Day) - Typical first order chlorine decay values = 0.25 to 1.0/Day - Not used in Tank Chlorine Decay Calculations.
- R = Pipe hydraulic radius (ft)
- A = Pipe cross-sectional area (ft²)
- d_p = Pipe outside diameter (ft) - Equal to pipe circumference for pressure pipe

USER INPUTS:	Value	Description
C_0 Boost @ Ojo Encino	0.35 mg/L	Chlorine Dose Leaving the WTP - USER INPUT
Boosted @ Torreon TO?	Yes (Yes or No)	Chlorine Boosting upstream of Ojo Encino - East/Torreon TO? - USER INPUT
Boost @ Ojo Torreon Tanks?	Yes (Yes or No)	Chlorine Boosting upstream of Ojo Torreon Tanks - USER INPUT
k_{app}	0.47 /day	Minimum Pipe Wall Chlorine Decay Coefficient - USER INPUT
k_{app}	0.5 /day	Average Pipe Wall Chlorine Decay Coefficient - USER INPUT
k_{app}	0.50 /day	Maximum Pipe Wall Chlorine Decay Coefficient - USER INPUT

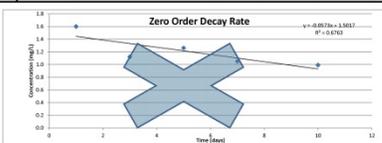
2000 MINIMUM FLOW RESULTS (FROM TABLE 3) BELOW

Residual Measurement Location	Chlorine Residual (mg/L)		
	C_{min}	C_{avg}	C_{max}
Op Encino - East/Torreon Tank	0.38	0.43	0.38
Upstream of Ojo Torreon Tanks	0.24	0.22	0.20
Op Encino - East/Torreon Distribution Loop	0.30	0.25	0.20

TABLE 1A - ZERO ORDER BULK WATER CHLORINE DECAY RATE COEFFICIENT CALCULATIONS¹

Time (days)	Chlorine Residual (mg/L)
0.00	0.35
1.00	0.30
2.00	0.25
3.00	0.20
4.00	0.15
5.00	0.10
6.00	0.05
7.00	0.00

1. Chlorine data from HCR (Chlorine Residual) and Enhanced Bench Scale Testing (DS5-PHM & DS5-WA) - retrieved on March 30, 2015.
2. Per Equation 1A, Cl₀ is plotted versus time (the slope of the line is equal to the zero order decay coefficient (k)) for each series in the units of mg/L/day.
3. Not used, zero-order not typical for chlorine decay, and R² values are lower than first order.
4. Initial chlorine dose at 0.00, chlorine residual plotted at 0.00.



Filename: Navajo-Gallup - NG2015 - Cutter Lateral Chlorine Decay - REV 03 30 15.xlsx
Worksheet: 02 Decay - WTP to Ojo Enc - C-Tor

Navajo-Gallup Water Supply Project
Cutter Lateral Disinfection Study
Chlorine Decay Analysis
WQID: NG215

Bureau of Reclamation
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REV March 30, 2015
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NAVAJO-GALLUP - CUTTER LATERAL - DISINFECTION STUDY
CHLORINE DECAY ANALYSIS - CUTTER WTP TO OJO ENCINO - EAST/TORREON DISTRIBUTION LOOP

TABLE 1B - FIRST ORDER BULK WATER CHLORINE DECAY RATE COEFFICIENT CALCULATIONS¹

Time (days)	Chlorine Residual (mg/L)
0.00	0.60
1.00	0.47
3.00	0.31
5.00	0.23
7.00	0.05
10.00	0.21

Notes:
1. Chlorine data from WQID (WQID - Red Spots), Enhanced Bench Scale Testing (DSS-TM4 & DSS-MA4) - reviewed on March 10, 2015.
2. Per Equation 3A, LN(C) is plotted versus time; the slope of the trend line is equal to the first order decay coefficient (k).
For each series in the units of 1/day.
3. First order reaction estimated as R² typical for chlorine decay and the R² value is reasonable.
4. Initial chlorine dose at t=0 not utilized; explanation provided in report.

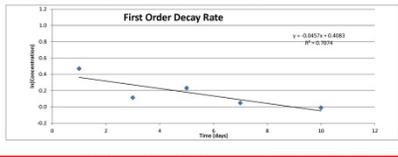
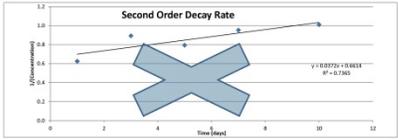


TABLE 1C - SECOND ORDER BULK WATER CHLORINE DECAY RATE COEFFICIENT CALCULATIONS¹

Time (days)	ln(Concentration)
0.00	0.60
1.00	0.47
3.00	0.31
5.00	0.23
7.00	0.05
10.00	0.21

Notes:
1. Chlorine data from WQID (WQID - Red Spots), Enhanced Bench Scale Testing (DSS-TM4 & DSS-MA4) - reviewed on March 10, 2015.
2. Per Equation 3A, LN(C) is plotted versus time; the slope of the trend line is equal to the second order decay coefficient (k).
For each series in the units of 1/day.
3. Not used; second order not typical for chlorine decay.
4. Initial chlorine dose at t=0 not utilized; explanation provided in report.



From Table 1B - First Order Reaction Rate Coefficient
k_{avg} = 0.0457 1/day

TABLE 2 - TURNOUT FLOWS¹

Phase	Segment	2020 Flow (MGD)	Flow	2040 Flow (MGD)	Flow
22B.3	Acquirer WTP	0.16	0.26	0.33	0.50
Phase 2	Regulating Tank #1	0.38	0.48	0.62	0.84
24.1	Regulating Tank #2	0.10	1.36	1.77	1.93
25.0	Regulating Tank #3	0.02	0.30	0.50	0.87
26.1/26.2	26.1/26.2	0.39	0.24	0.33	0.32
26.3A	26.3A	0.23	0.29	0.38	0.47
26.3B	26.3B	0.44	0.60	0.78	1.06
26.3C	26.3C	0.11	0.22	0.30	0.37
TOTAL	TOTAL	3.33	4.18	5.41	6.28

Table 2 Notes:
1. From Navajo-Gallup Water Supply Project - Project Issue Notice No. 27, Dated XXXX, XX 2013 (20M47).

Filename: Navajo-Gallup - NG215 - Cutter Lateral Chlorine Decay - REV 03 30 15.xlsx
Worksheet: Cl2 Decay - WTP to Ojo Enc 4 For

Navajo-Gallup Water Supply Project
Cutter Lateral Disinfection Study
Chlorine Decay Analysis
WQID: NG215

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NAVAJO-GALLUP - CUTTER LATERAL - DISINFECTION STUDY
CHLORINE DECAY ANALYSIS - CUTTER WTP TO OJO ENCINO - EAST/TORREON DISTRIBUTION LOOP

TABLE 3 - OJO ENCINO - EAST/TORREON DISTRIBUTION LOOP CHLORINE RESIDUAL CALCULATIONS - 2020 FLOW RATES

Reach	From	To	Pipe Segment (ft)	Pipe Diameter (in)	Tank Volume (per Reach Gallons)	No. of Tanks	Total Reach Volume (MG)	2020 Minimum Flows			2020 Average Flows			2020 Maximum Flows										
								Segment Flow (MGD)	Segment Water Age (days)	Cumulative Water Age (days)	Segment Flow (MGD)	Segment Water Age (days)	Cumulative Water Age (days)	Segment Flow (MGD)	Segment Water Age (days)	Cumulative Water Age (days)								
22B.3	Acquirer WTP	Regulating Tank #1	10.03	13.50	568,000	1	0.20	0.33	0.24	0.10	3.31	1.38	1.37	4.30	0.07	8.19	0.13	1.38	5.41	0.08	3.29	1.92	3.18	
22B.3	Regulating Tank #1	Regulating Tank #2	10.03	13.50	568,000	1	0.20	0.33	0.57	0.30	3.09	3.01	3.99	4.35	0.01	0.27	3.16	3.08	2.98	5.41	0.05	0.21	3.19	3.16
Phase 2	Regulating Tank #2	Regulating Tank #3	10.03	13.50	568,000	1	0.20	0.33	0.63	0.37	2.02	1.68	1.77	3.95	0.50	0.78	2.70	1.93	1.54	5.41	0.38	0.60	2.80	1.80
Phase 2	Regulating Tank #3	Coumboir Tank & Tanks	18.12	47,000	392,000	1	0.20	0.29	0.66	0.62	2.60	2.68	2.77	3.95	0.66	0.82	2.33	1.90	1.42	5.41	0.88	0.83	2.49	2.39
24.1	Coumboir Tank & Tanks	Jicorillo TD	13.6	14,567	180,000	1	0.20	0.28	0.68	1.05	1.52	1.51	0.54	1.47	0.50	0.22	1.68	1.50	0.89	4.53	0.31	0.59	1.97	1.92
25A	Jicorillo TD	Reach 25 Pump Station	13.6	7,482	0	0	0.06	1.84	0.08	1.73	1.23	0.85	0.48	1.41	0.06	1.39	1.49	1.11	0.71	1.84	0.05	1.06	1.81	1.62
25B	Reach 25 Pump Station	Ojo Inflow - North 10 A Tanks	13.6	34,883	0	0	0.26	1.36	0.36	2.08	0.88	0.54	0.36	1.41	0.29	1.67	1.15	0.77	0.42	1.86	0.22	1.28	1.49	1.08
26.1	Ojo Inflow - North 10 A Tanks	Ojo Inflow - East/Torreon 10 A Tanks	11.73	14,393	0	0	0.08	1.06	0.14	2.34	0.26	0.46	0.20	1.36	0.58	1.89	1.01	0.67	0.36	1.76	0.07	1.49	1.36	0.97
26.3A	Ojo Inflow - East/Torreon 10 A Tanks	Ojo Torreon Tanks	8.87	16,205	0	0	0.06	0.66	0.15	2.48	0.24	0.22	0.20	0.43	0.12	2.01	0.26	0.34	0.22	1.07	0.08	1.54	0.26	0.33
26.3B	Ojo Torreon Tanks	Ojo Inflow - East/Torreon Distribution Loop	0	0	293,000	2	0.40	0.66	0.17	3.67	0.43	0.44	0.43	0.82	0.94	2.89	0.46	0.46	0.46	1.87	0.24	1.48	0.46	0.46
26.3C	Ojo Torreon Tanks	Ojo Inflow - East/Torreon Distribution Loop	11.73	29,507	0	0	0.17	0.66	0.38	4.05	0.38	0.25	0.20	0.81	0.38	3.33	0.29	0.24	1.07	0.24	1.50	0.36	0.32	0.38

TABLE 4 - OJO ENCINO - EAST/TORREON DISTRIBUTION LOOP CHLORINE RESIDUAL CALCULATIONS - 2040 FLOW RATES

Reach	From	To	Pipe Segment (ft)	Pipe Diameter (in)	Tank Volume (per Reach Gallons)	No. of Tanks	Total Reach Volume (MG)	2020 Minimum Flows			2020 Average Flows			2020 Maximum Flows										
								Segment Flow (MGD)	Segment Water Age (days)	Cumulative Water Age (days)	Segment Flow (MGD)	Segment Water Age (days)	Cumulative Water Age (days)	Segment Flow (MGD)	Segment Water Age (days)	Cumulative Water Age (days)								
22B.3	Acquirer WTP	Regulating Tank #1	10.03	13.50	568,000	2	0.40	0.54	0.28	0.26	3.27	3.17	1.32	6.47	0.20	0.20	3.20	3.20	0.34	8.34	0.04	0.04	3.27	3.34
22B.3	Regulating Tank #1	Regulating Tank #2	10.03	13.50	568,000	1	0.20	0.34	0.51	0.37	3.16	3.11	3.03	6.42	0.01	0.30	3.20	3.15	3.28	8.34	0.00	0.23	3.20	3.10
Phase 2	Regulating Tank #2	Regulating Tank #3	10.03	13.50	568,000	1	0.20	0.41	0.41	0.78	2.38	2.11	1.77	6.20	0.33	0.56	3.02	2.71	2.01	7.61	0.29	0.48	2.71	2.56
Phase 2	Regulating Tank #3	Coumboir Tank & Tanks	18.12	47,000	392,000	1	0.20	0.49	0.69	0.82	2.49	2.21	1.76	6.93	0.69	0.66	2.35	2.32	2.20	7.99	0.60	0.30	2.32	2.26
24.1	Coumboir Tank & Tanks	Jicorillo TD	13.6	14,567	180,000	1	0.20	0.29	0.66	1.19	1.68	1.62	1.22	3.22	0.60	0.89	2.11	1.79	1.29	6.29	0.60	0.19	2.10	2.07
25A	Jicorillo TD	Reach 25 Pump Station	13.6	7,482	0	0	0.06	1.84	0.05	1.28	1.72	1.30	0.84	2.41	0.04	1.03	1.87	1.62	1.21	3.14	0.03	0.79	2.22	1.81
25B	Reach 25 Pump Station	Ojo Inflow - North 10 A Tanks	13.6	34,883	0	0	0.26	1.36	0.31	1.48	1.42	1.03	0.61	0.57	1.08	1.30	1.08	0.89	3.14	0.13	0.82	1.30	1.02	
26.1	Ojo Inflow - North 10 A Tanks	Ojo Inflow - East/Torreon 10 A Tanks	11.73	14,393	0	0	0.08	1.06	0.27	1.85	0.30	0.50	0.26	1.52	0.58	1.58	1.39	0.71	3.00	0.09	1.02	1.48	1.02	
26.3A	Ojo Inflow - East/Torreon 10 A Tanks	Ojo Torreon Tanks	8.87	16,205	0	0	0.06	0.66	0.15	1.73	0.30	0.29	0.20	1.43	0.07	1.39	0.27	0.34	0.20	1.87	0.09	1.07	0.30	0.30
26.3B	Ojo Torreon Tanks	Ojo Inflow - East/Torreon Distribution Loop	0	0	293,000	2	0.40	1.12	0.27	2.41	0.46	0.46	0.46	1.43	0.94	1.82	0.46	0.46	0.46	1.87	0.46	1.48	0.47	0.47
26.3C	Ojo Torreon Tanks	Ojo Inflow - East/Torreon Distribution Loop	11.73	29,507	0	0	0.17	1.05	0.42	2.63	0.36	0.25	0.20	1.43	0.18	2.11	0.34	0.34	0.32	1.87	0.14	1.02	0.40	0.34

Table 3 & 4 Notes:
1. k_{avg} = 0.0457 1/day
2. k_{avg} = 0.0457 1/day
3. k_{avg} = 0.0457 1/day
4. A non-Fickian Plug Flow for Phases 2B, 3A, and First Order CDR for Tanks Coumboir, 25, 26.1, 26.2, 26.3A, 26.3B, 26.3C.
5. Pipe wall decay rate assumed to be zero for tanks.
6. Segment flows are calculated from Table 2 based on normal demands.
7. Tank volumes are taken from various sources, and were confirmed to the current anticipated volumes with the project team, including IMA (see confirmation email of 05/13/2015); only tanks considered to be "in-line" are used for water age along the transmission main, with the exception of Pueblo Prietas, where no tanks are included as chlorine bleeding is included in the IMA design.

Filename: Navajo-Gallup - NG215 - Cutter Lateral Chlorine Decay - REV 03 30 15.xlsx
Worksheet: Cl2 Decay - WTP to Ojo Enc 4 For

PART 2 PRODUCTS

Not Used

PART 3 EXECUTION

Not Used

END OF SECTION

SECTION 51 45 18

BASIS OF DESIGN FOR START UP AND FUTURE FLOW DETERMINATION

PART 1 GENERAL

Cutter Lateral - Water Treatment Plant and Reach 21

Basis of Design: Startup and Future Flow Determination

January 13, 2016

Author: Anthony Kennedy, Ph.D.

Check: Bob Jurenka, P.E.

Peer Review: Steve Dundorf, P.E.

Summary of Recommendations

Recommendation

Startup Flow

Flow (MGD)	
Minimum	0.51
Average	0.87
Maximum	1.23

Timing of Phases

Phase	Year
Phase 1	2034
Phase 2	2050

Assumptions

- Jicarilla Apache Nation power generation demand of 750 AFY or 0.67 MGD will be online before Phase 1.
- Actual population growth from 1990 to 2010 was included, but future population growth will be the EIS growth rate of 2.48%.
- Per capita water use will increase from the estimated 73 gpcd based on existing water use data to the EIS value of 160 gpcd over a period of 20 years.

Risks

- If historic population growth for each community continues, the aggregate population and water demand curves will be significantly different than current estimates for water demand (will be higher) and timing of water demand (will occur sooner).
- Historic water use by community varies widely. Applying the same water use to each community may average out in the end, especially after they receive the same source water, but could introduce some significant errors.

Purpose

The primary purpose of this Basis of Design document (BOD) is to re-evaluate the anticipated population growth and subsequent water demands for the area serviced by the future Cutter Lateral Water Treatment Plant (CLWTP) as part of the Navajo-Gallup Water Supply Project (NGWSP). A re-evaluation was prompted by recently acquired well withdrawal data for some of the communities in the anticipated service area. Additionally, original projections for population growth from the Bureau of Reclamation (USBR) NGWSP Planning Report and Final Environmental Impact Statement (USBR, 2009) were in question due to declining populations in several of the service areas. This document outlines the original population projections and water demands and then provides new projections based on well data and more recent census data. A basis for startup flows and timeline corresponding to expected treatment capacities for Phase 1 (2020) and Phase 2 (2040) will be established.

Original Population and Water Demand Projections

The CLWTP is the eastern drinking water treatment plant (WTP) in the NGWSP. A map showing the anticipated location of the WTP and the areas it will serve is shown in **Figure 1**. All of the service areas are in New Mexico serving both the Navajo Nation (NN) and the Jicarilla Apache Nation (JAN). Communities in the NN within the anticipated CLWTP service area are:

- Counselor
- Huerfano
- Nageezi
- Ojo Encino
- Pueblo Pintado
- Torreon
- Whitehorse Lake

Original population projections for the seven NN communities and JAN from USBR (2009) are shown in **Table 1**. Population projections for the NN were based on 1990 census data and extrapolated to 2040 assuming a growth rate of 2.48% per year. JAN population projections were made at a later date and therefore include data from the 2000 census. Extrapolations for JAN to 2040 assume a varying growth rate near 1% (0.91-1.19%). According to these projections, the population within the CLWTP service area was expected to reach about 26,000 people by 2040.

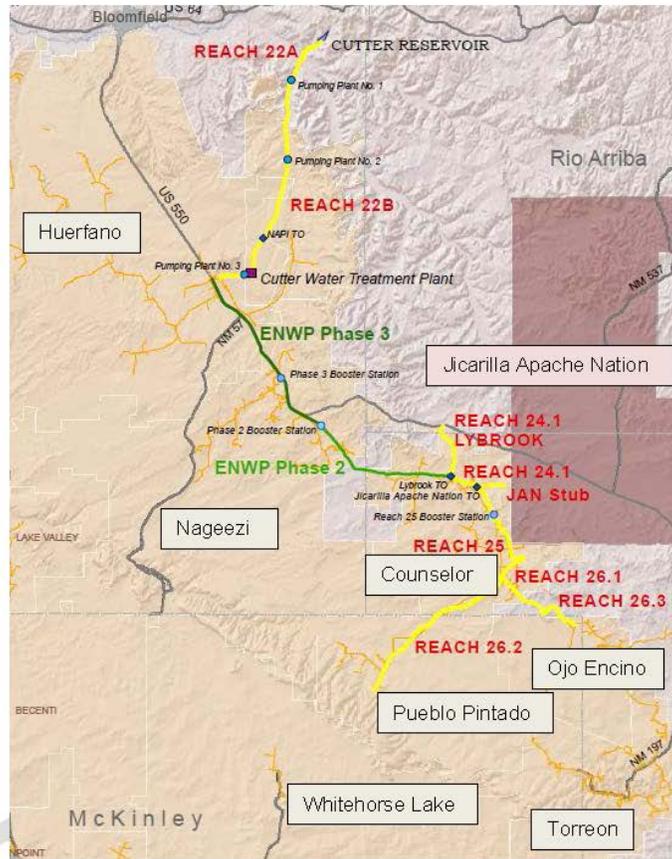


Figure 1. CLWTP location and service area communities (USBR, 2009).

Water demand for the seven NN communities and the JAN is planned to be met by groundwater production, the Animas-La Plata Project (ALP), and water from the San Juan River. Collectively, these sources are expected to meet an anticipated average water demand of 160 gallons per capita per day (gpcd) for the NN communities (USBR, 2009). Anticipated water demands for JAN are based on a casino/travel center, power generation, housing, and other uses (USBR, 2009). The water demand will mostly be met by the CLWTP, which will treat water from Cutter Reservoir. San Juan River water is fed to Cutter Reservoir from Navajo Reservoir. Expected withdrawals and therefore demands on the San Juan River to be treated by the CLWTP are shown in **Table 2**. These values were taken directly from the NGWSP Project Issue Notice Number 27 (USBR, 2015). From **Table 2** it can be seen the CLWTP should be capable of treating a minimum flow of 2.15 million gallons per day (MGD) in 2020 and peak flows of 3.50 and 5.40 MGD in 2020 and 2040, respectively.

Table 1. Population projections based on a 2.48% growth rate for NN communities and a varying growth rate near 1% for the JAN (USBR, 2009). Asterisk denotes census data.

Service Area	1990	2000	2010	2020	2030	2040
Counselor	1,365*	1,744	2,228	2,846	3,637	4,646
Huerfano	511*	653	834	1,066	1,361	1,739
Jicarilla Apache Nation	3,155*	3,977*	4,411	4,829	5,436	6,045
Nageezi	981*	1,253	1,601	2,046	2,614	3,339
Ojo Encino	596*	761	973	1,243	1,588	2,029
Pueblo Pintado	472*	603	770	984	1,257	1,607
Torreon	1,364*	1,743	2,226	2,844	3,634	4,643
Whitehorse Lake	610*	779	996	1,272	1,625	2,076
Total	9,054	11,513	14,039	17,130	21,152	26,124

Table 2. 2020 and 2040 CLWTP demands from the San Juan River (USBR, 2009; 2015).

Service Area	Projections for 2020						
	2020	Minimum Flow ¹		Base Flow ²		Peak Flow ³	
	Population	Gpm	MGD	gpm	MGD	gpm	MGD
Counselor	2,846	252	0.36	314	0.45	413	0.59
Huerfano	1,066	73	0.11	91	0.13	118	0.17
Jicarilla Apache Nation	4,829	489	0.70	611	0.88	794	1.14
Nageezi	2,046	170	0.24	213	0.31	277	0.40
Ojo Encino	1,243	101	0.15	127	0.18	166	0.24
Pueblo Pintado	984	87	0.13	109	0.16	142	0.20
Torreon	2,844	215	0.31	268	0.39	349	0.50
Whitehorse Lake	1,272	104	0.15	130	0.19	169	0.24
Total	17,130	1,491	2.15	1,863	2.68	2,428	3.50
Service Area	Projections for 2040						
	2040	Minimum Flow ¹		Base Flow ²		Peak Flow ³	
	Population	Gpm	MGD	gpm	MGD	gpm	MGD
Counselor	4,646	418	0.60	520	0.75	673	0.97
Huerfano	1,739	139	0.20	174	0.25	226	0.33
Jicarilla Apache Nation	6,045	595	0.86	744	1.07	967	1.39
Nageezi	3,339	289	0.42	361	0.52	470	0.68
Ojo Encino	2,029	174	0.25	217	0.31	283	0.41
Pueblo Pintado	1,607	143	0.21	179	0.26	232	0.33
Torreon	4,643	382	0.55	478	0.69	621	0.89
Whitehorse Lake	2,076	169	0.24	211	0.30	275	0.40
Total	26,124	2,309	3.33	2,884	4.15	3,747	5.40

¹80% of base flow from USBR (2015). ²Assumes 160 gpcd, from average depletion flows from the San Juan River from USBR (2009, 2015). ³1.3 times the base flow from USBR (2015).

Updated Population and Water Demand Projections

The following sections detail updated population projections based on more recent census data as well as updated water demand projections based on recently reviewed groundwater use. Two population scenarios, high and low, and corresponding water demand projections are presented.

Establishing Per Capita Water Use for Navajo Nation Communities

In December 2015, pump station/groundwater well data for several of the NN communities was provided to the USBR Technical Service Center Water Treatment Group. The original PDF well data from the Navajo Tribal Utility Authority (NTUA) was summarized by the USBR Four Corners Construction Office and are shown in the Appendix **Table A1** for 2013, 2014, and 2015. The well data are limited and quite irregular. Averaging was used to interpolate water use for missing months, shown in Appendix **Table A2**, which is followed by an explanation of the interpolations.

In order to get a more relevant and current per capita water use rate, the well data in **Table A2** was used to derive maximum and minimum daily flows in the NN communities of Nageezi, Ojo Encino, Torreon, and Whitehorse Lake. These communities were the only ones with well data, but water use in those four communities was extended to all other NN communities for this BOD. Maximum and minimum flows in gallons per day (gpd) for each of the four communities are shown in **Table 3**. These values were divided by the estimated 2014 population to determine per capita water use. As seen in **Table 3**, per capita water use for the four communities ranged from 5 to 214 gpcd. All of the minimum and maximum per capita use rates were averaged to produce more representative values. Therefore, per capita use rates were established at 34, 73, and 111 gpcd as a minimum, average, and maximum, respectively. These values agree well the New Mexico average values of 85 gpcd for self-supplied domestic water use and 91 gpcd for public supply domestic water use (Maupin et al., 2014). However, due to the very wide range of water use in the 4 communities shown, there is high chance of some error. This wide range also demonstrates that applying one value for water use to all communities has its own associated error. This variation may be reduced once each community receives the same water.

Table 3. Per capita water use estimations based on well data in Table A2.

Service Area	Well Flow (gpd)		2014 Population ¹	Water Use (gpcd)	
	Max	Min		Max	Min
Nageezi	47,624	25,543	1,119	43	23
Ojo Encino	151,297	58,769	708	214	83
Torreon	182,687	43,394	1,667	110	26
Whitehorse Lake	29,035	1,803	374	78	5
Average:				111	34
Overall Average:				73	

¹Population for 2014 was extrapolated from 2010 based on the 1990 to 2010 individual growth rates shown in **Table 4**.

Under high and low population scenarios, the three per capita values of 34, 73, and 111 gpcd were used to estimate minimum, average, and maximum (peak) daily demands. For each case, the per capita use rates were linearly increased to 128, 160, and 208 gpcd by 2038, 20 years after expected WTP startup in 2018. The values of 128, 160, and 208 gpcd originate from USBR (2009, 2015), where 160 gpcd is the base case, 208 is the peak at 1.3 times the base case, and 128 gpcd is the minimum at 0.8 times the base case. These values were then held constant from 2038 through 2068 assuming a 50 year WTP life. Changing per capita water use only changed the demand for the NN communities. JAN demands were held constant based on the values in USBR (2009, 2015) because no specific water use data was available at the time of this BOD.

High Population and Demand Scenario

Original (USBR, 2009) population projections were based on 1990 census data and an expected growth rate of 2.48%. However, population from the most recent census, 2010, should be considered when making population projections in the CLWTP service areas. NN 2010 census data was taken from a report by the Navajo Epidemiology Center (NEC, 2013). JAN 2010 census data was taken directly from the US Census Bureau under the category American Indian and Alaska Native Tribes in the United States and Puerto Rico (USCB, 2010). A comparison between 1990 to 2010 census data in **Table 4** shows growth rates ranging from -2.23% to 8.54%. Growth rates in **Table 4** illustrate there is not consistent growth and even population decline in some of the CLWTP service areas. Extrapolating these growth rates to 2040 results in a population of approximately 43,000, which is almost twice as large as the population of 26,000 in **Table 1**. This large population projection is skewed by the 8.54% growth rate of the Huerfano community. Although 8.54% is the census growth rate from 1990 to 2010, maintaining such a high growth rate is unlikely considering the lower growth rates of the neighboring NN communities.

Table 4. High population projections based on individual growth rates from 1990 to 2010.

Service Area	Census Data		1990-2010 Growth Rate	Projections		
	1990	2010		2020	2030	2040
Counselor	1,365	870	-2.23%	695	555	443
Huerfano	511	2,633	8.54%	5,977	13,567	30,796
Jicarilla Apache Nation	3,155	4,228	1.47%	4,894	5,666	6,559
Nageezi	981	1,095	0.55%	1,157	1,222	1,291
Ojo Encino	596	688	0.72%	739	794	853
Pueblo Pintado	472	419	-0.59%	395	372	350
Torreon	1,364	1,612	0.84%	1,752	1,905	2,071
Whitehorse Lake	610	406	-2.01%	331	270	220
Total	9,054	11,951		15,940	24,351	42,583

Population projections from **Table 1** and **Table 4** are compared in **Figure 2** (blue and orange lines, respectively). The time axis has been extended to 2068 assuming the life of the CLWTP

will be 50 years. Population projections in **Figure 2** further illustrate the influence of the 8.54% growth rate for Huerfano by projecting a population near 325,000 in 2068 as opposed to a projection of 50,000 assuming a 2.48% growth rate. Two average water demand curves are also shown in **Figure 2**, one (solid red line) assuming a 0.67 MGD demand for JAN power generation (USBR, 2009) and the other (dashed red line) assuming no JAN power generation demand. They are difficult to distinguish in **Figure 2** because of the water demand scale. Again, to further illustrate the improbable growth of the high population scenario, the 2068 demand in **Figure 2** is 50 MGD, nearly ten times greater than the original 2040 peak demand estimate of 5.40 MGD.

Comparisons of minimum, average, and maximum daily water demands with and without JAN power generation are shown in **Figure 3** and **Figure 4**, respectively. These curves provide an envelope of water demands over the life of the WTP, which is useful for initial WTP sizing and future expansion. Assuming a maximum demand of 111 gpcd in 2018 increasing linearly to 208 gpcd in 2038, the original 2020 peak demand of 3.50 MGD from USBR (2009, 2015) will be reached by 2028 with JAN power generation and 2031 without JAN power generation. The original 2040 peak demand of 5.40 MGD from USBR (2009, 2015) will be reached by 2034 with JAN power generation and 2036 without power generation.

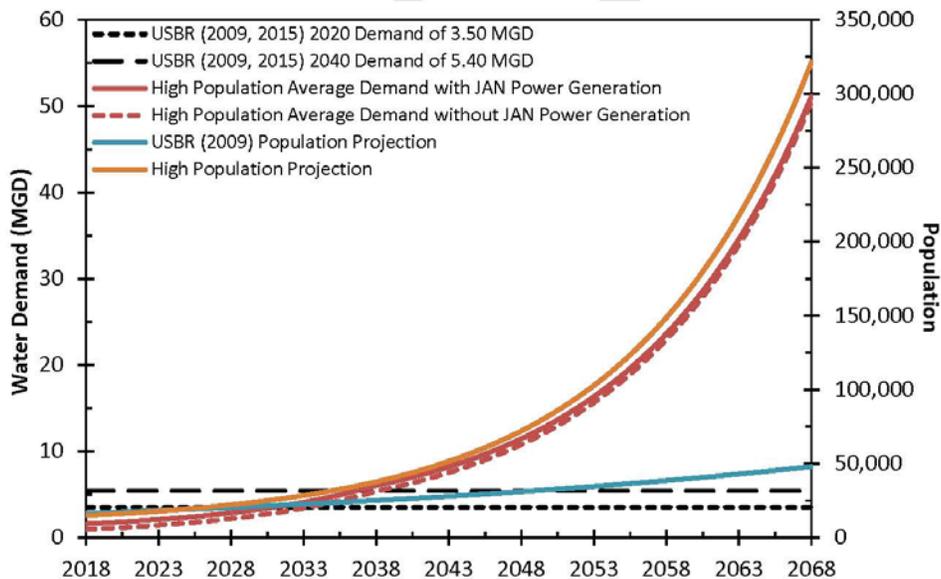


Figure 2. High population and water demand projection assuming 73 gpcd increased linearly to 160 gpcd in 2038 through 2068.

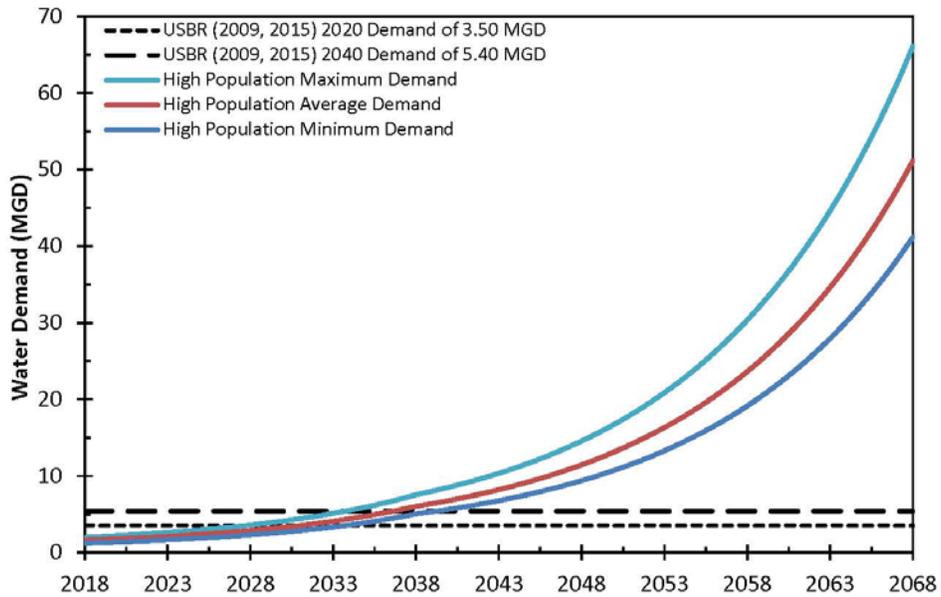


Figure 3. High population and water demand projection assuming a constant JAN power generation demand of 0.67 MGD. Minimum: 34 gpcd in 2018 increased linearly to 128 gpcd in 2038 through 2068; Average: 73 gpcd in 2018 increased linearly to 160 gpcd in 2038 through 2068; Maximum: 111 gpcd in 2018 increased linearly to 208 gpcd in 2038 through 2068.

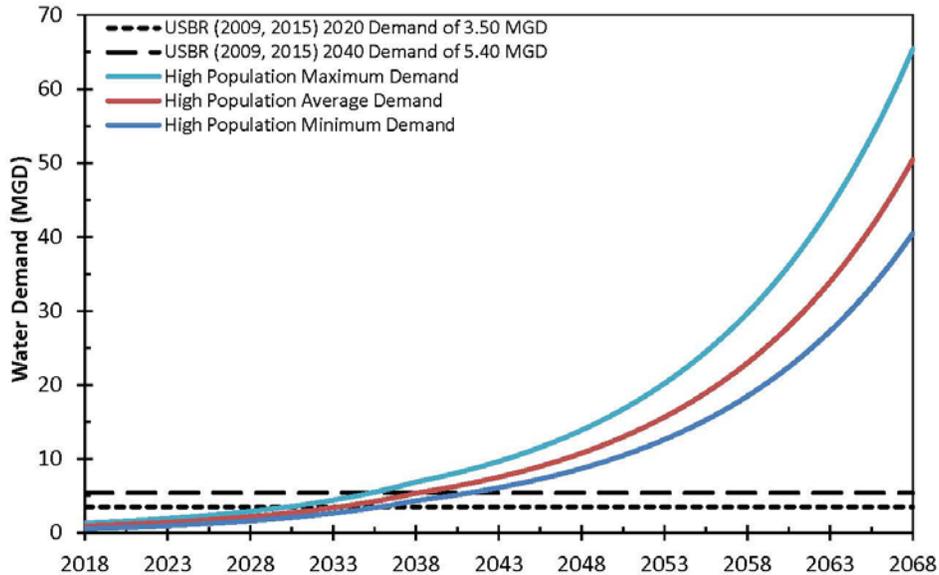


Figure 4. High population and water demand projection assuming no JAN power generation demand. Minimum: 34 gpcd in 2018 increased linearly to 128 gpcd in 2038 through 2068; Average: 73 gpcd in 2018 increased linearly to 160 gpcd in 2038 through 2068; Maximum: 111 gpcd in 2018 increased linearly to 208 gpcd in 2038 through 2068.

Low Population and Demand Scenario

Under the low population scenario, a constant 2.48% growth rate was implemented following 2010 instead of 1990 as was used in USBR (2009) for NN communities. A growth rate of 1.05% following 2010 was used for JAN per the original projections in USBR (2009). Therefore the projections fall close to the original projections but take into account more current census data. Low population projections are shown in **Table 5** and are more comparable to the USBR (2009) projections in **Table 1** with both 2040 projected populations in the 20,000’s. Population projections from **Table 1** and **Table 5** are compared in **Figure 5** (blue and orange lines, respectively).

Water demand assumptions were the same as under the high population scenario following **Table 3** and increased in the same manner from 2018 to 2038 through 2068. Comparisons of minimum, average, and maximum with and without JAN power generation are shown in **Figure 6** and **Figure 7**, respectively. Assuming a maximum demand of 111 gpcd in 2018 increasing linearly to 208 gpcd in 2038, the original 2020 peak demand of 3.50 MGD from USBR (2009, 2015) will be reached by 2034 with JAN power generation and 2038 without JAN power generation. The original 2040 peak demand of 5.40 MGD from USBR (2009, 2015) will be reached by 2050 with JAN power generation and 2056 without power generation.

Table 5. Low population projections based on individual growth rates from 1990 to 2010 followed by 2.48% and 1.05% growth rates for NN communities and JAN, respectively, from 2011 to 2040.

Service Area	Census Data		1990-2010 Growth Rate	Projections			2011-2040 Growth Rate
	1990	2010		2020	2030	2040	
Counselor	1,365	870	-2.23%	1,112	1,420	1,814	2.48%
Huerfano	511	2,633	8.54%	3,364	4,298	5,491	2.48%
Jicarilla Apache Nation	3,155	4,228	1.47%	4,694	5,210	5,784	1.05%
Nageezi	981	1,095	0.55%	1,399	1,787	2,283	2.48%
Ojo Encino	596	688	0.72%	879	1,123	1,435	2.48%
Pueblo Pintado	472	419	-0.59%	535	684	874	2.48%
Torreon	1,364	1,612	0.84%	2,059	2,631	3,362	2.48%
Whitehorse Lake	610	406	-2.01%	519	663	847	2.48%
Total	9,054	11,951	-	14,561	17,816	21,890	-

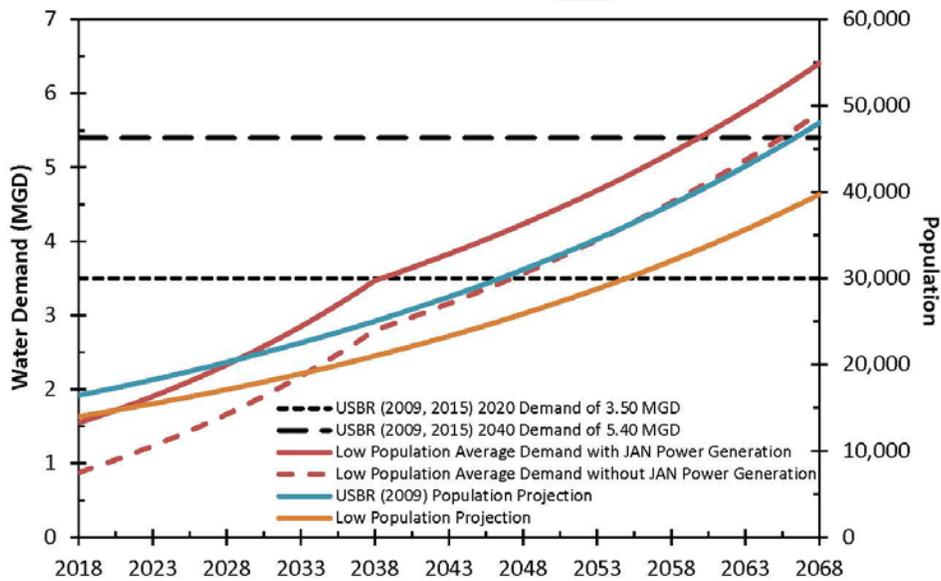


Figure 5. Low population and water demand projection assuming 73 gpcd increased linearly to 160 gpcd in 2038 through 2068.

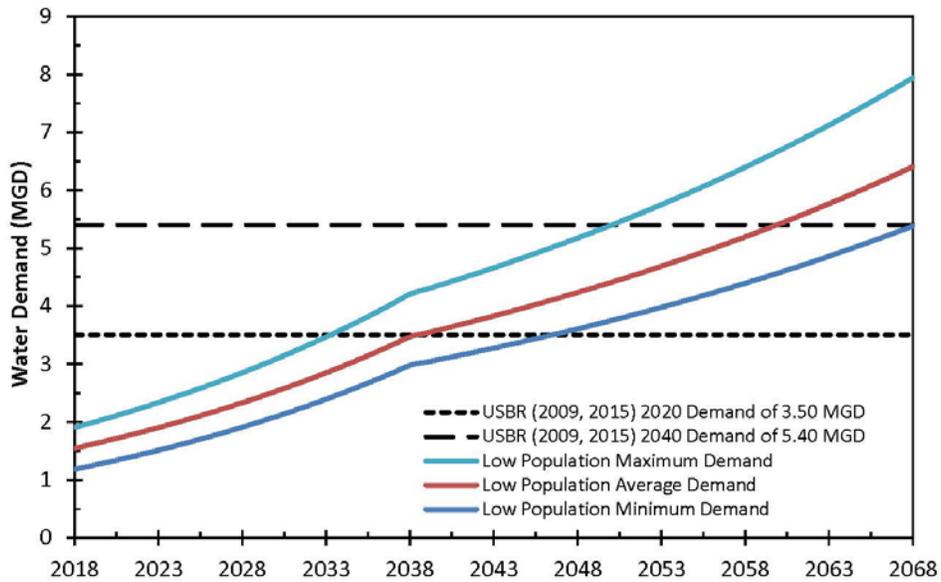


Figure 6. Low population and water demand projection assuming a constant JAN power generation demand of 0.67 MGD. Minimum: 34 gpcd in 2018 increased linearly to 128 gpcd in 2038 through 2068; Average: 73 gpcd in 2018 increased linearly to 160 gpcd in 2038 through 2068; Maximum: 111 gpcd in 2018 increased linearly to 208 gpcd in 2038 through 2068.

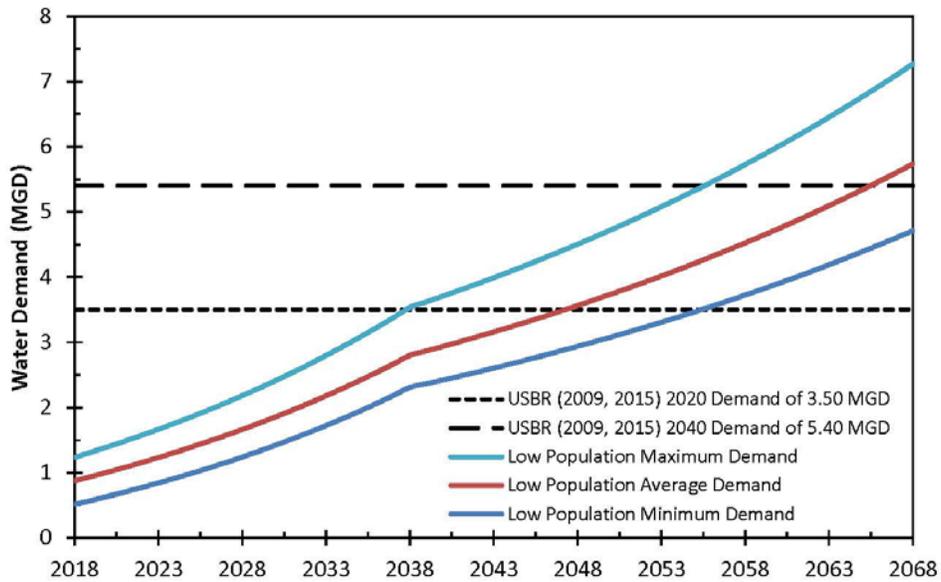


Figure 7. Low population and water demand projection assuming no JAN power generation demand. Minimum: 34 gpcd in 2018 increased linearly to 128 gpcd in 2038 through 2068; Average: 73 gpcd in 2018 increased linearly to 160 gpcd in 2038 through 2068; Maximum: 111 gpcd in 2018 increased linearly to 208 gpcd in 2038 through 2068.

Summary of Potential Startup Demands and Conclusions

Although water use and population growth data is limited, expected water demand for the CLWTP at startup is crucial for WTP sizing. From the data and assumptions presented in this BOD, constructing a WTP to initially treat 3.50 MGD (original peak for 2020) may vastly overestimate the true water demand, resulting in underutilized infrastructure. Therefore a range of potential startup demands is shown in **Table 6**, which directly shows the importance of the 0.67 MGD of estimated water use from JAN power generation.

Table 6. Summary of potential startup water demands for CLWTP in MGD.

Scenario	Minimum	Average	Maximum
With JAN Power Generation			
High Population	1.21	1.60	1.99
Low Population	1.18	1.54	1.90
Without JAN Power Generation			
High Population	0.54	0.93	1.32
Low Population	0.51	0.87	1.23

Startup demands in **Table 6** also show there is not a large difference between the two population scenarios. So although the high population projection is unlikely, it still may be relevant for choosing an initial WTP startup capacity. A summary of the years when the CLWTP is expected to reach the demands of 3.50 and 5.40 MGD is shown in **Table 7**. Unlike the startup flows in **Table 6**, the two population scenarios result in significantly different dates for reaching the two treatment capacities. Assuming the low population scenario with JAN power generation is the most likely, expected water demands will fall behind 2020 and 2040 by 14 and 10 years, respectively.

Table 7. Summary of future demand years for CLWTP.

Scenario	3.50 MGD	5.40 MGD
With JAN Power Generation		
High Population	2028	2034
Low Population	2034	2050
Without JAN Power Generation		
High Population	2031	2036
Low Population	2038	2056

Assumptions

- Jicarilla Apache Nation power generation demand of 750 AFY or 0.67 MGD will be online before Phase 1.
- Actual population growth from 1990 to 2010 was included, but future population growth will be the EIS growth rate of 2.48%.
- Per capita water use will increase from the estimated 73 gpcd based on existing water use data to the EIS value of 160 gpcd over a period of 20 years.

Risks

- If historic population growth for each community continues, the aggregate population and water demand curves will be significantly different than current estimates for water demand (will be higher) and timing of water demand (will occur sooner).
- Historic water use by community varies widely. Applying the same water use to each community may average out in the end, especially after they receive the same source water, but could introduce some significant errors.

References

Navajo Division of Health Navajo Epidemiology Center (NEC). 2013. Navajo Population Profile, 2010 U.S. Census. <http://www.nec.navajo-nsn.gov/Portals/0/Reports/NN2010PopulationProfile.pdf>. Accessed December 29, 2015.

US Bureau of Reclamation (USBR). 2009. Navajo-Gallup Water Supply Project Planning Report and Final Environmental Impact Statement, Chapter 2 – Need for Action. <http://www.usbr.gov/uc/envdocs/eis/navgallup/FEIS/vol1/ch2.pdf>. Accessed December 29, 2015.

US Bureau of Reclamation (USBR). 2015. Navajo-Gallup Water Supply Project – PIN 027, Design Criteria Element, Cutter Lateral Turnout Flows. Q:\Navajo Gallup Water Supply Project\General\PINs\PIN 027 Cutter Lateral Turnout Flows.

US Census Bureau (USCB). 2010. 2010 Census CPH-T-6. American Indian and Alaska Native Tribes in the United States and Puerto Rico. [https://www.census.gov/population/www/cen2010/cph-t-6tables/TABLE%20\(1\).pdf](https://www.census.gov/population/www/cen2010/cph-t-6tables/TABLE%20(1).pdf). Accessed December 29, 2015.

Maupin, MA, Kenny, JF, Hutson, SS, Lovelace, JK, Barber, NL, and Linsey, KS. 2014. Estimated Use of Water in the United States in 2010: US Geological Survey Circular 1405. <http://dx.doi.org/10.3133/cir1405>. Accessed December 29, 2015.

Original Spreadsheet

Year Pump Station	JAN		FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC	
	Daily Gal	Total Gal	Daily Gal	Total Gal	Daily Gal	Total Gal	Daily Gal	Total Gal	Daily Gal	Total Gal	Daily Gal	Total Gal												
DZ-Otis																								
DZ																								
Nageezi																								
Ojo Enchino N1																								
Ojo Enchino N2																								
2013 Torreon 1																	1,204,055	34,402						
Torreon 2																								
Torreon 3																								
Torreon 5																								
Whitehorse Lake 1																								
Whitehorse Lake 2																								
DZ-Otis		901	33	4,035	139	241,575	6,902	142,304	4,066	95,066	2,881	2,474,955	85,743	2,573,625	77,989	2,703,090	90,102	2,133,595	62,753	2,267,820	83,993	2,258,845	77,891	
DZ		1,990,119	73,708	1,722,151	59,385	1,737,021	51,088	1,691,539	54,566	2,354,551	69,252	77,574	2,502	CONTROL OFF	41,730	738,430	27,349	808,330	22,952	565,038	21,732	994,050	32,066	
Nageezi		739,678	36,983	1,035,297	33,397	1,170,408	35,467	1,017,008	36,322	1,423,145	41,857	1,933,128	64,438	1,377,075	41,730	738,430	27,349	808,330	22,952	565,038	21,732	994,050	32,066	
Ojo Enchino 1		3,041,227	92,158	2,620,092	84,519	1,987,264	70,974	2,890,550	90,330	1,617,100	57,754	3,176,800	128,390	2,525,416	109,801	4,174,924	97,091							
Ojo Enchino 1		31,6762	13,198	199,822	6,446	137,732	3,625	342,298	10,068	204,725	6,398	215,121	11,951	186,430	4,336	75,302	4,183	363,987	8,465					
2014 Torreon 1		762,755	42,375	DATA	UCLEA	2,822,218	91,039	1,609,040	39,594	14,885	1,240	1,976,635	61,770	3,281,268	64,339	1,347,292	46,458	3,103,030	96,970					
Torreon 2		867,055	21,148	52,770	1,649	610,510	15,654	355,209	11,458	297,126	27,011	284,290	8,884	999,605	17,537	277,131	9,556	228,053	7,127					
Torreon 3		1,680,264	54,202	711,556	24,536	1,124,238	62,459	499,027	8,755	802,210	89,134	266,240	24,204	878,685	19,102	1,010,085	28,058	990,330	29,073					
Torreon 5										231,007	7,452	261,835	6,890	503,745	10,281	497,698	17,162	239,020	8,833					
Whitehorse 1		571,023	22,841	690	20							103,813	6,488	20,438	454	109,307	3,769							
Whitehorse 1		329,076	11,733	246,104	9,115	389,724	12,991	432,879	11,392	0	0	682,498	22,016	35,468	1,419	67,436	6,131	170,475	5,878	319,940	6,035	71,132	2,295	
DZ-Otis		2,557,585	85,233	2,450,749	90,768	2,189,860	78,209	3,102,461	88,642	2,157,605	74,400	2,522,140	74,180	2,452,705	87,577	2,888,000	82,514	2,632,682	82,271	2,888,000	82,514	2,632,682	82,271	
DZ		163,455	5,449	2,559	95	1,672	60	929	66	1,490	30	242,700	7,138	136,700	4,882	2,600	74	1,100	40	2,600	74	1,100	40	
Nageezi		874,462	32,388	690,715	26,566	778,524	21,625	1,171,236	41,830	700,693	24,162	1,104,594	32,488	1,019,548	36,412	1,453,000	41,514	1,024,500	35,328	1,453,000	41,514	1,024,500	35,328	
Ojo Enchino N1																								
Ojo Enchino N2																								
2015 Torreon 1																								
Torreon 2																								
Torreon 3																								
Torreon 5																								
Whitehorse Lake 1																								
Whitehorse Lake 2																								

Table A2. Interpolated values based on well data in **Table A1**. Interpolated values are highlighted in yellow. Values different than the original spreadsheet data are highlighted in green, originating from discrepancies in the PDF well files.

Month	January		February		March		April		May		June	
	Total (gal)	Daily (gal)										
DZ-Otis	2,557,585	82,503	1,225,825	43,779	1,096,948	35,385	1,672,018	55,734	1,149,955	37,095	1,308,603	43,620
DZ	163,455	5,273	996,339	35,584	861,912	27,804	868,975	28,966	846,525	27,307	1,298,626	43,288
Nageezi	874,462	28,208	715,197	25,543	906,911	29,255	1,170,822	39,027	858,851	27,705	1,263,870	42,129
Ojo Encino N1	3,041,227	98,104	2,620,092	93,575	1,987,264	64,105	2,890,550	96,352	1,817,100	52,165	3,176,800	105,693
Ojo Encino N2	316,762	10,218	199,822	7,137	137,732	4,443	342,298	11,410	204,725	6,604	215,121	7,171
Torroon 1	762,755	24,605	1,792,487	64,017	2,822,218	91,039	1,609,040	53,635	14,885	480	1,976,635	65,888
Torroon 2	867,055	27,970	52,770	1,885	610,510	19,694	355,209	11,840	297,126	9,585	284,290	9,476
Torroon 3	1,890,264	17,485	711,556	25,413	1,124,258	36,256	499,027	16,634	802,210	25,878	266,240	8,875
Torroon 5	239,020	7,710	239,020	8,536	239,020	7,710	239,020	7,967	231,000	7,452	261,835	8,728
Whitehorse Lake 1	571,023	18,420	690	25	70,000	2,258	80,000	2,667	90,000	2,903	103,813	3,460
Whitehorse Lake 2	329,078	10,615	246,104	8,789	389,724	12,572	432,879	14,429	557,889	17,990	682,498	22,750
Total	11,042,684	367,829	8,799,901	314,282	10,246,496	330,532	10,159,838	338,661	6,870,071	215,164	10,836,330	361,278
Month	July		August		September		October		November		December	
	Total (gal)	Daily (gal)										
DZ-Otis	2,463,830	79,478	2,730,813	88,091	2,667,866	88,930	2,510,798	80,593	2,450,251	81,675	2,258,845	72,866
DZ	107,137	3,456	2,600	84	1,100	37	2,600	84	2,267	76	2,327	75
Nageezi	1,476,338	47,624	1,415,038	45,646	881,465	29,382	1,128,165	35,392	794,769	28,492	994,050	32,086
Ojo Encino N1	3,851,680	124,248	2,525,416	81,465	4,174,924	139,164	2,876,117	92,778	2,876,117	95,871	2,876,117	92,778
Ojo Encino N2	186,430	6,014	75,302	2,429	363,987	12,133	228,909	7,320	226,909	7,564	226,909	7,320
Torroon 1	3,281,266	105,847	1,347,292	43,461	2,153,543	71,785	1,458,149	47,037	1,458,149	48,605	1,458,149	47,037
Torroon 2	995,605	32,245	277,131	8,940	228,053	7,802	441,305	14,238	441,305	14,710	441,305	14,236
Torroon 3	878,685	28,345	1,010,085	32,583	930,330	31,011	1,305,297	42,106	1,305,297	43,510	1,305,297	42,106
Torroon 5	503,745	16,250	497,898	16,055	239,020	7,967	239,020	7,710	239,020	7,967	239,020	7,710
Whitehorse Lake 1	20,438	659	109,307	3,526	100,000	3,333	90,000	2,903	80,000	2,667	70,000	2,258
Whitehorse Lake 2	35,468	1,144	67,436	2,175	170,475	5,583	319,840	10,317	71,132	2,371	200,104	6,455
Total	13,804,624	445,310	10,058,117	324,455	11,910,783	397,026	10,598,199	341,877	9,945,215	331,507	10,072,123	324,907

Explanation for interpolations in **Table A2**:

- For Ojo Encino 1, the average monthly flow for the months of January through September 2014 (2, 876,117 gallons per month) was used for the months of October, November, and December.
- For Ojo Encino 2, the average monthly flow for the months of January through September 2014 (226,909 gallons per month) was used for the months of October, November, and December.
- For Torreon 1, the February value of 1,792,487 is the average of flows from the month before and after February. Also for Torreon 1, estimates for the months of October, November, and December, were made based on the average of flows from the months of January and September 2014 of 1,458,149. This value was selected after comparing it to the average 2014 monthly flow of 1,745,954 since these 3 months occur in the winter when demand is lower than the yearly average.
- For Torreon 2, the average monthly flow for the months of January through September 2014 (441,305 gallons per month) was used for the months of October, November, and December.
- For Torreon 3, estimates for the months of October, November, and December, were made based on the average of flows from the months of January and September 2014. This value, 1,305,297 was selected after comparing it to the average 2014 monthly flow of 878,073 since these 3 months occur in the winter when demand is lower than the yearly average.
- For Torreon 5, the value of 239,020, the most recent flow received September 2014, was used for missing months (Oct. Nov. Dec. Jan. Feb. Mar. and April) because the month of September falls between typically high (summer) and low (winter) demand.
- For Whitehorse Lake 1, estimates for the months of March, April, and May, were made based on the June 2014 value of 103, 813 gallons per month. Ramping up to that value and rounding, values of 70,000, 80,000, and 90,000 gallons per month were used respectively. Similarly, estimates for the months of September, October, November, and December, were made based on the August 2014 value of 109,307 gallons per month. Ramping down from that value and rounding, values of 100,000, 90,000, 80,000 and 70,000 gallons per month were used respectively.
- For Whitehorse Lake 2, May's estimate is the average of flows from the month before and after May. Also for Whitehorse Lake 2, the December estimate of 200,104 gallons per month is the average flow from January 2014 and November 2014. This value was selected after comparing it to the average 2014 monthly flow of 274,463 since December is in the winter when demand is lower than the yearly average.

PART 2 PRODUCTS

Not Used

PART 3 EXECUTION

Not Used

END OF SECTION