PILOT-SCALE TESTING OF CHLORITE TO CONTROL NITRIFICATION IN DRINKING WATER DISTRIBUTION SYSTEMS

By

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CHAPTER I

INTRODUCTION

Background

The City of Tulsa (COT) was founded in 1898 and at the time utilized the Arkansas River as its source of drinking water. However, the Arkansas River posed many issues for its customers including high salinity, high sediment loading, and prominent tastes and odors unsuitable for drinking water. In 1922, the COT undertook a massive construction project to store and deliver high quality drinking water from Spavinaw Creek in Northeastern Oklahoma to the citizens of Tulsa. Lake Spavinaw, Lake Yahola, and Mohawk Water Treatment Plant (Mohawk WTP) were built during this time. As the population of Tulsa increased, the COT increased the capacity of the Spavinaw-Mohawk system by building Lake Eucha, a second raw water flowline, and doing several upgrades to Mohawk WTP and Lake Yahola in the 1950's. To meet the demands of growth in the eastern and southern portions of Tulsa, the COT built a new water treatment plant at the far eastern corner of Tulsa County. The A.B. Jewell Water Treatment Plant (ABJ WTP) began treating and delivering Lake Oologah water in 1972. ABJ WTP received an upgrade in 1994 to bring its capacity to 120 million gallons per day (MGD), and Mohawk WTP received a major upgrade in 1998 to modernize the plant and increase capacity to 125 MGD.

Due to the geology and relatively low development in both the Oologah and Spavinaw/Eucha Watersheds, the COT has enjoyed drinking water with microbial and chemical contaminants that have been below detection or easily treated to the requirements of the 1986 Surface Water Treatment Rule and its amendments. However, the Stage 2 Disinfectant by Product Rule (DBPR) that was promulgated in 2006 targets contaminants that could possibly cause concern for the COT.

The contaminants causing the greatest concern for the COT are trihalomethanes. Studies have shown a link between trihalomethanes in drinking water and certain forms of cancer (USEPA 1999). The Stage 2 DBPR regulates total trihalomethanes (TTHM), which are the sum of the four most prominent trihalomethanes: chloroform, dichlorobromomethane, dibromochloromethane, and bromoform. These contaminants are created by reactions of free chlorine and natural organic matter (NOM) in the drinking water treatment process and in the distribution system. For a utility with a population greater than 100,000, Stage 1 DBPR required a maximum running annual average (RAA) of 0.08 mg/l TTHM for all the combined sampling points in the distribution system.

However, Stage 2 DBPR requires the RAA to be below 0.08 mg/l at each individual sampling point. This change is referred to as the locational running annual average (LRAA). While the COT has historically had no problems complying with the system-wide RAA, the City may have some sampling points that exceed the 0.08 mg/l TTHM level set by the Stage 2 DBPR regulations. The COT has studied various technologies that will ensure compliance with the Stage 2 DBPR. The most promising of these technologies is the use of chloramines as a secondary disinfectant in place of chlorine.

Chloramines have a lower oxidation potential than free chlorine, which is currently used by the COT for disinfection. This is advantageous in that chloramines are less reactive with organic matter and create significantly low levels of TTHM's (Kirmeyer 2004). A 2007 bench scale study (Gipson 2007) demonstrated that chloramines can lower TTHM's (Appendix A). After 30 days of reaction time, the chloraminated test water only created 0.010 mg/l additional TTHM's whereas chlorinated water from the same time created 0.099 mg/l of TTHM's. However, the lower oxidation potential is also a disadvantage because chloramines are not as strong of a disinfectant as free chlorine.

Research Objective

The COT will likely convert to chloramines as a secondary disinfectant by 2012 to meet the Stage 2 DBPR deadline. The COT has shown a strong desire to understand the positive and negative changes to water quality that may result from a switch to chloramines. Bench-scale testing has been completed to study TTHM formation and a pilot study has been completed for lead and copper release from a switch to chloramines (Gipson 2008). Another major water quality change that the COT is concerned with is nitrification. Many utilities in the United

States have reported nitrification episodes that have caused bacterial issues and corrosion in the distribution system while using chloramines.

The primary objective of this research is a nitrification study to test chlorite addition for nitrification control. The COT has reviewed research indicating that chlorite may aid in controlling nitrification, and would like to test various levels of chlorite and observe whether or not these levels control nitrification on a pilot scale. The pilot scale nitrification test units need to be multi-functional so that the COT can use the test units for other future distribution system tests. In addition, the COT requested the design and construction of the test units be formally documented, so other utilities could have a guide of how to build these test units.

The following two hypotheses will define the objectives of what this study hopes to produce:

- Null hypothesis 1: With the addition of chloramines and ammonia-oxidizing bacteria, nitrification will not occur in the pilot test units. A nitrification occurrence is based on a test unit effluent nitrite-nitrogen level of 0.05 mg/l or greater.

- Alternate hypothesis 1: With the addition of chloramines and ammonia-oxidizing bacteria, nitrification will occur in the pilot test units. A nitrification occurrence is based on a test unit effluent nitrite-nitrogen level of 0.05 mg/l or greater.

- Null hypothesis 2: In a test unit with established nitrification, chlorite residuals will have no affect on limiting or stopping nitrification. Nitrite-nitrogen levels will stay above 0.05 mg/l.

- Alternate hypothesis 2: In a test unit with established nitrification, chlorite residuals will limit or stop nitrification from occurring. Nitrite-nitrogen levels will drop below 0.05 mg/l.

CHAPTER II

REVIEW OF LITERATURE

Chloramines as a Secondary Disinfectant

There are three chloramine molecules that can occur in a drinking water system. The most basic and most desired chloramine molecule is monochloramine. Monochloramine is created through the chemical combination of free chlorine and free ammonia, as shown in Equation 1. This combination is optimum at a stoichiometric ratio of 5.1 mg/l free chlorine to 1 mg/l liter ammonia-nitrogen. If this ratio increases, the monochloramine molecule will begin to transform into dichloramine and trichloramine, as shown in Equations 2 and 3(Connell 1996).

$$NH_3 + HOCL \rightarrow NH_2Cl + H_2O \qquad \text{Equation 1}$$

$$NH_2Cl + HOCL \rightarrow NHCl_2 + H_2O \qquad \text{Equation 2}$$

$$NHCl_2 + HOCL \rightarrow NCl_3 + H_2O \qquad \text{Equation 3}$$

According to a 2004 survey by the American Water Works Association, chloramines are currently used in 29% of the nation's utilities as a secondary disinfectant (Seidel 2005). The two major advantages of using chloramines is that chloramines do not create the levels of regulated disinfection byproducts that free chlorine creates and the chloramine molecule can last longer in the distribution system. These two advantages are the result of chloramines' lower oxidation potential when compared to free chlorine. Table 1 compares the electrode potentials of chloramines to other disinfectants.

Table 1: Standard electrode potentials of various drinking water disinfectants

Disinfectant	Chemical Formula	Standard Electrode Potential (Volts)
Ozone	O_3	2.07
Chlorine Dioxide	ClO_2	1.71
Hypochlorous Acid*	HOCl	1.49
Hypochlorite*	OCl^-	0.90
Dichloramine	$NHCl_2$	0.79
Monochloramine	NH_2Cl	0.75

Adapted from Kirmeyer (2004)

*Hypochlorous acid and hypochlorite are the two forms of free chlorine. The COT's finished water is approximately 75% hypochlorite and 25% hypochlorous acid.

The disadvantage of the lower oxidation potential is that chloramines are not as effective of a disinfectant as free chlorine. Table 2 compares the necessary contact time in minutes to achieve 99.9% inactivation of Giardia cysts at pH 7 and 20 degree Celsius. The contact times in Table 2 are similar to the inactivation time of the various disinfectants with other pathogens such as bacteria, viruses, and Cryptosporidium (AWWA 1991).

Table 2: Contact time required for 99.9% inactivation of Giardia cysts (AWWA, 1991)

Disinfectant	**Contact Time (minutes)**
Free chlorine	62
Chlorine Dioxide	15
Ozone	0.72
Chloramine	1100

Breakpoint Chlorination

Chloramines are created through a phenomenon known as breakpoint chlorination. When chlorine reacts with ammonia at low levels, monochloramine is the primary molecule formed. However, once the chlorine to ammonia-nitrogen ratio exceeds 5.1:1, then di- and trichloramines are formed and the total chloramine residual is being destroyed. The chloramine residual is destroyed until the next significant ratio, 7.6:1, is achieved. This ratio is referred to as the “breakpoint” because all additional chlorine added to the system will be free chlorine and the ammonia will be oxidized to nitrogen gas and other oxidized nitrogen products (nitrate, nitrous oxide, nitric oxide) that will no longer create a chloramine residual (Kirmeyer 2004). It is important during the formation of chloramines that this 5.1:1 ratio is not exceeded. This reaction is displayed graphically in Figure 1.

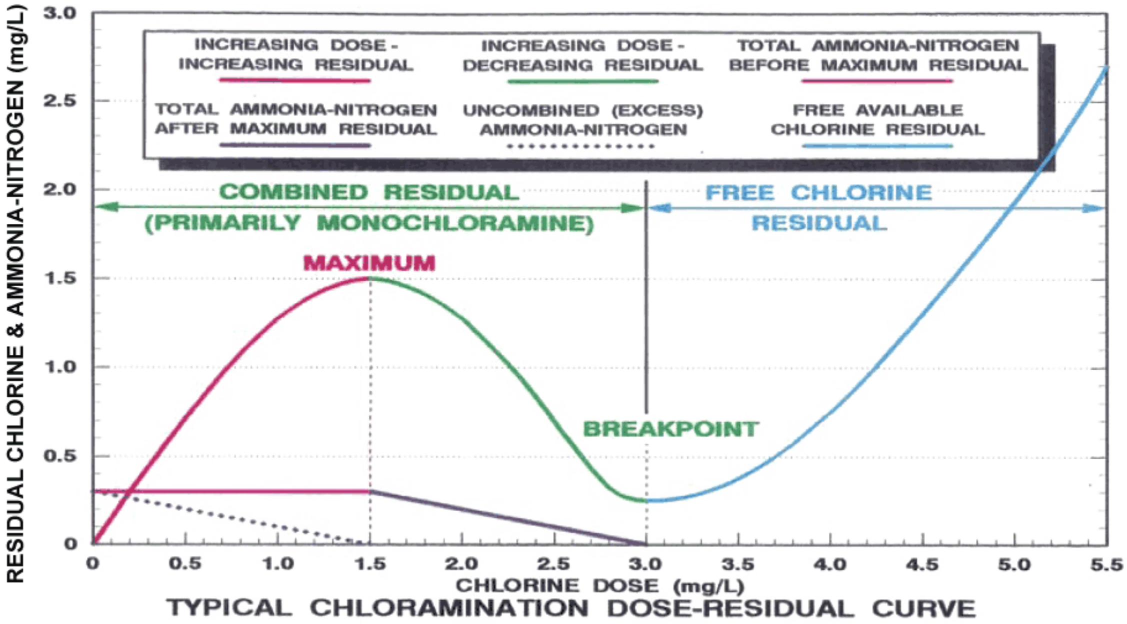

Figure 1: Breakpoint chlorination curve for varying chlorine to ammonia ratios in drinking water (Hach 2008)

Chloramine Decomposition Pathways

The nitrification process cannot occur in the water distribution system if the chlorine and ammonia molecular bond does not break. There are several pathways that are responsible for the breakdown of the chlorine/ammonia bond. These pathways are listed in Equations 4-7 (Woolschlager 2001).

Auto-catalytic decay reaction

$3NH_2Cl \rightarrow N_2 + NH_3 + 3Cl^- + 3H^+$ Equation 4

Oxidation reaction (organic)

$$\frac{1}{10}C_5H_7O_2N + NH_2Cl + \frac{9}{10}H_2O \rightarrow \frac{4}{10}CO_2 + \frac{1}{10}HCO_3^- + \frac{11}{10}NH_4^+ + Cl^-$$

Equation 5

Oxidation reaction (inorganic)

$$\frac{1}{2}NH_2Cl + H^+ + Fe^{2+} \rightarrow Fe^{3+} + \frac{1}{2}NH_4^+ + \frac{1}{2}Cl^{\overset{-}{-}}$$

Equation 6

Biologically assisted reaction

$$NH_2Cl + NO_2 + H_2O \rightarrow NH_3 + HCl$$

Equation 7

Equation 7, the oxidation of nitrite by chloramine, is the least likely pathway of chloramine decomposition. If enough ammonia oxidizing bacteria (AOB) are present to create elevated levels of nitrite, then the chloramine will decompose by Equation 5 before Equation 7. The inorganic oxidation reaction can occur with dissolved inorganic molecules and at the internal surface of metallic distribution pipe.

Nitrification in Drinking Water

Nitrification is a microbiological process by which ammonia is oxidized to nitrite and nitrate (AWWA 2006). The approximate reactions of nitrification are shown in Equations 8 and 9 (AWWA 2006).

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$$

Equation 8

$NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$ Equation 9

AOB are responsible for the reaction in Equation 8 while nitrite oxidizing bacteria (NOB) are responsible for the reaction in Equation 9.

Nitrification can negatively affect water quality in several ways. The most prevalent and threatening effect is the loss of chloramine residual. As nitrifying bacteria grow and establish themselves in the distribution system, they will consume more of the chloramine residual. When the chloramine residual decreases, the opportunity increases for other potentially harmful bacteria to flourish in the distribution system without the threat of a disinfectant. Another threat of nitrification is the drop in pH. As shown in Equations 8 and 9, hydrogen ions are released during the nitrification process. The hydrogen ions can decrease the pH of the distribution system and cause the water to become corrosive to the metallic and cement piping. The last major threat of nitrification is the production of nitrite and nitrate. Nitrite and nitrate are regulated by the U.S. Environmental Protection Agency (USEPA) at maximum contaminant level’s (MCL) of 1 mg/l nitrite-nitrogen and 10 mg/l nitrate-nitrogen. The COT historically has had low background levels of both nitrite-nitrogen and nitrate-nitrogen, and will not add enough ammonia-nitrogen to exceed either MCL in the event of nitrification.

Bacteria Responsible for Nitrification

AOB and NOB are Gram-negative, aerobic chemolithotrophic bacteria that are members of the *Proteobacteria* division (AWWA 2006). NOB are more sensitive to environmental conditions than AOB, which explains why nitrite is often used to indicate nitrification in a water distribution system than nitrate (AWWA 2006). AOB are ubiquitous in chloraminated distribution systems, and *Nitrosomonas oligothropha* has been identified as the dominant AOB in drinking water systems (AWWA 2006). AOB grow best in drinking water systems with a pH of 7.5 to 8.0 and a temperature of 20-30 degrees C (AWWA 2006).

The quantification of AOB and NOB is severely hindered by their slow growth. Surrogate measurements such as nitrite-nitrogen are the most useful indicators of nitrification due to the long incubation time and complexity of microbiological methods.

Control Strategies

A comprehensive monitoring program is the first step in controlling nitrification. Tables 3 and 4 contain the suggested order of importance of analytical parameters in monitoring for nitrification both at the treatment plant and in the distribution system.

Table 3: Analytical parameters for a nitrification monitoring program at the water treatment plant “point-of-entry” to the distribution system

Very Useful	**Useful**	**Limited Usefulness**
Free chlorine	TOC	Hardness
Total chlorine	Chloramine decay	Alkalinity
Free Ammonia-N		Nitrite-nitrogen
pH		Nitrate-nitrogen
Temperature		Total ammonia-N

Table 4: Analytical parameters for monitoring nitrification or likelihood of nitrification in the distribution system

Very Useful	**Useful**	**Limited Usefulness**
Total chlorine	Nitrate-nitrogen	Dissolved oxygen
Nitrite-nitrogen	Total ammonia-N	TOC
Free ammonia-N	Heterotrophic plate count (HPC)	Hardness
Temperature	pH	Alkalinity
Free chlorine		AOB

(Adapted from AWWA 2006)

The parameters in the “Very Useful” column can alert the utility to the presence and severity of a nitrification episode in the distribution system. An increasing concentration of nitrite-nitrogen is the most useful indicator of the presence of nitrification. Decreasing levels of total chlorine and free ammonia-nitrogen are a signal of bacterial growth that will indicate the severity of the nitrification episode.

When a monitoring program reveals a distribution system nitrification problem, the utility has several options for controlling the outbreak of nitrifying bacteria. As stated earlier, AOB and NOB are slow growing and proliferate best in warm, stagnant distribution systems where there is adequate substrate (free ammonia-nitrogen). To both prevent and control a nitrification episode, these optimum growth conditions should be controlled.

The first way to control a nitrification outbreak is to manage the free ammonia-nitrogen levels. As the chloramine is added at the treatment plant, it is important for free ammonia-nitrogen levels to be as low as possible. Free ammonia-nitrogen levels greater than 0.1 mg/l will create a healthy environment for AOB to grow. If the free ammonia-nitrogen level can be kept to less than 0.05 mg/l, then the AOB will depend on chloramine decomposition to release free ammonia.

A second way to control a nitrification problem is to decrease distribution system residence time, especially in reservoirs and dead-end areas. A flushing program may help prolong the onset of a nitrification episode by allowing less time for the mechanisms of chloramine decomposition to occur. A flushing program can also help remove sediment and biofilm that may be harboring nitrifying bacteria. Storage reservoirs can be a potential environment for nitrification if short-circuiting is increasing the residence time of the corners of each tank. Thorough mixing will ensure that the entire tank contents have experienced approximately the same residence time in the tank.

If controlling free ammonia and decreasing distribution residence time do not help prevent a nitrification episode, then a free chlorine burnout may be necessary. A free chlorine burnout is simply a change of disinfectant from chloramines to free chorine. Free chlorine is a stronger oxidant that will inactivate nitrifying bacteria better than chloramines while also starving the bacteria of their free ammonia substrate. A utility survey done by the AWWA Research Foundation found that 35% of utilities using chloramines performed a free chlorine burnout at least once per year (Kirmeyer 2004). Free chlorine burnout has several issues which include swimming pool tastes and odors and public notification to dialysis units and other critical facilities (Kirmeyer 2004).

Nitrification Control by Chlorite

A fairly new and promising technology for controlling nitrification episodes is the use of chlorite residual in the distribution system. Chlorite (ClO_2^-) is a byproduct of chlorine dioxide (Equation 10) but can also be added to drinking water systems in the form of sodium chlorite (Equation 11).

$$ClO_{2(aq)} + e^- \rightarrow ClO_2^- \qquad \text{Equation 10}$$

$$NaClO_2 \rightarrow Na^+ + ClO_2^- \qquad \text{Equation 11}$$

The first documented case of nitrification control by chlorite was at Gulf Coast Water Authority (GCWA) in May 1995 (McGuire 1999). GCWA had prime conditions for nitrification including chloraminated water, warm water temperatures, and long residence time in distribution. However, GCWA never had a documented nitrification episode (McGuire 1999). This absence of nitrification peaked the interest of drinking water researchers, and an in-depth study of GCWA and other utilities revealed that utilities using chlorine dioxide, which produces chlorite residual, were experiencing little to no nitrification episodes. These researchers hypothesized that the chlorite ion was generating intracellular chlorine dioxide by combining with hydrogen ions released by AOB during the nitrification process (Equation 12). Chlorine dioxide is a powerful disinfectant that is very toxic to AOB.

$$2ClO_2^- + 2H^+ \rightarrow ClO_2 + 2H_2O \qquad \text{Equation 12}$$

(Adapted from McGuire 1999)

In 2003, Dr. Michael McGuire pilot tested chlorite in Tucson, Arizona to identify optimum levels of chlorite to both prevent and control nitrification (McGuire 2006). Tucson was considering a switch from free chlorine to chloramines and knew that their distribution system was a prime environment for nitrification due to warm temperatures and long distribution residence time. Dr. McGuire used a unique pilot setup that included a carboy to slowly feed chloraminated water, a bacterial reactor to add AOB to the water from the carboy, and a distribution system made of irrigation tubing that could simulate five days of distribution residence time. Dr. McGuire’s study revealed that chlorite residual concentrations as low as 0.1 mg/l could prevent nitrification and chlorite residual concentrations of 0.2 mg/l could control a nitrification episode already underway.

CHAPTER III

METHODOLOGY

The COT typically conducts water treatment testing by bench top jar tests and/or pilot scale tests.   Pilot scale tests were chosen for this study because the pilot test units were a better simulation of the actual distribution system than a static jar.

Test Unit Design

In collaboration with the COT, the following design criteria and rational for the nitrification test units were developed.

- **Number of test units** - The COT desired to know what continuous concentration of chlorite could control a nitrification episode and prevent a reoccurrence. Dr. McGuire's Tucson study tested continuous concentrations of chlorite with four test units and two controls (McGuire 2006). The COT decided to use six test units and two controls to bring the total number of test units to eight. Table 5 shows the chlorite concentration that the COT desired to feed to each test unit.

Table 5: Chlorite dose to each pilot test unit during the 2008 nitrification study

Test Unit #	Chlorite (mg/l)
1	0 (control)
2	0.05
3	0.1
4	0.2
5	0 (control)
6	0.4
7	0.6
8	0.8

The test objectives could probably be accomplished with one control unit and three test units. However, due to the sensitive nature of the nitrifying bacteria, the additional control and tests units were added in case any operational issues were to arise. This redundancy could help improve the reliability of the test results and possibly save the test if one or more of the test units were to have operational issues. The EPA's maximum contaminant level goal (MCLG) for chlorite is 0.8 mg/l (USEPA 1998), and that is why no test units have a higher concentration than test unit number eight.

- **Residence time**- Typical bench scale and laboratory tests mix the test water and input chemicals in a jar or other container and allow them to sit for the prescribed time of the experiment. While this method is appropriate for some testing, the nitrification testing needs a better simulation for the vast surface area of interior piping that the water will flow through in a distribution system. Dr. McGuire'study used 400 feet of irrigation tubing wound around a PVC tubing support that was controlled by an effluent needle valve. The effluent needle valve could be adjusted to obtain a range of residence times in the irrigation tubing. The Tucson study used a residence time of five days.

In 2006, the COT ran a citywide tracer test to find the residence time of the entire distribution system at summertime flows. This test revealed that 95% of the COT's 200 sampling sites had a residence time of less than seven days. However, the COT sells water to approximately twenty outlying cities and rural water districts which may have residence times considerably beyond seven days. The COT decided that the nitrification test units should have a target residence time of seven days.

Appendix B contains the design calculations used to size the length of the irrigation tubing, the volume of the carboy, and the diameter of the PVC tubing support.

- **Bacterial injection**- The COT chose to dose the test units with AOB to prevent an excessively long acclimation period. Dr. McGuire's study used a bacterial glass-bead reactor that was dosed with a slug of AOB twice during the study. However, the COT chose to use a syringe pump for a more continuous injection of AOB. The COT found a low-cost syringe pump manufactured by Razel, Incorporated. Razel had a model with a feed rate of 0.01 ml/min from a 60 ml syringe. This feed rate would make up 0.5% of the total flow of the system at a test unit flow rate of 2 ml/min.

The bacteria for the nitrification study were grown from a culture that Oral Roberts University was using for testing. The culture was slowly acclimated to chloramines at the ABJ WTP pilot plant lab.

- **Timeline of events**- The plan for the test units was to startup the units and establish nitrification. Once nitrification had been established in the test units, then chlorite feed would begin in the units that were to receive chlorite. This allowed the test to show that chlorite could control a nitrification outbreak already underway.

Site Requirements

The nitrification test units for the COT study were located at ABJ WTP. The test units needed a location with an ultraviolet light source, a water tap, electricity, and a drain. ABJ WTP had ample space in a corner of the filter gallery basement where all the necessary equipment was available. Scaffolding was installed in the basement to support the carboys and keep the system gravity-flow. The metal halide bulbs in the basement light fixtures had partial ultraviolet filtration, but the bulbs still emitted enough UV light to suppress AOB growth in the carboys. Unfortunately, the tap water from ABJ WTP was unsuitable for the trial because ABJ WTP uses chlorine dioxide and therefore has a chlorite residual in the finished tap water. Therefore, each time the carboys needed to be refilled, the pilot plant at ABJ WTP had to be started up and operated without chlorine dioxide addition ensure that no chlorite would enter the test units except the chlorite that was added during the study.

Building the Test Units

The test units were constructed by COT personnel using input from COT management, Oklahoma State University, and Dr. Michael McGuire and his associates. The test units are divided into three parts: the carboy, the AOB injection point, and the distribution system. The COT produced a manual with step-by-step instructions and pictures for constructing a test unit. This manual is in Appendix C.

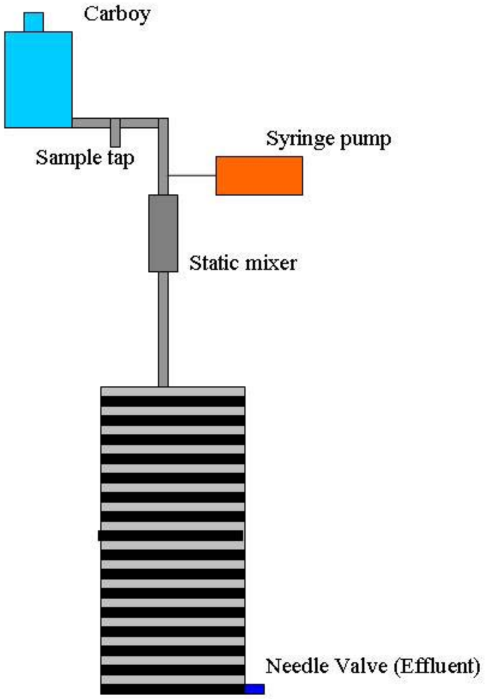

Figure 2: Schematic of pilot test unit for 2008 City of Tulsa nitrification study

Carboy

The purpose of the carboy was to store the test water before it flowed into the AOB injection point and the distribution system. The elevated position of the carboy also allowed the test units to operate with gravity flow which saved the time, cost, and operational oversight of running a pump.

The carboys chosen for this system were 20 liter Nalgene Clearboys. The COT chose clear carboys to allow for the penetration of UV light. As mentioned earlier, UV light inhibits AOB growth and would delay the occurrence of nitrification until the test water reached the distribution system. Also, the necessary calculated size of the carboys (Appendix B) was 26 liters. Nalgene's carboys came in a standard size of 20 liters which, at 7 days of residence time meant that the carboys would only need to be refilled every 6 days.

The initial operation of the test units was hindered by air-locking issues with the spigot supplied by Nalgene. These spigots were removed and replaced with a length of the PEX tubing fitted to a ½" true union ball valve. This new setup no longer encountered the air-locking issues, and all the carboy spigots were replaced with the PEX-ball valve setup.

AOB injection point

The AOB injection point served as the connection between the carboy and the distribution system where the AOB can be introduced and mixed into the test water. The first component of the AOB injection point was the carboy sample valve. It was important in the study to analyze the water in the carboy for chlorine residual and nitrite-nitrogen to ensure that bacterial activity was not occurring in the carboy. After the carboy sample valve, the piping made a 90 degree turn downward. It is at this turn that the AOB were injected from the syringe pump. The syringe pumps in this study were housed in modified toolboxes that were mounted on the PVC tubing support. The toolboxes kept the UV light out of the syringes as the AOB were injected.

Directly after the AOB injection was a static mixer. The purpose of the static mixer was to provide a short stretch of serpentine flow to promote mixing of the injected AOB and the test water. Each static mixer was 12 inches long with six mixing blades.

Distribution system

The distribution system simulated the actual conditions and residence time of a real distribution system. Irrigation tubing was chosen for its availability in long lengths and its price. At the end of the 500-foot length of irrigation tubing was an effluent needle valve that could be adjusted at very precise increments to control flow out of the test units. The particular needle valves in this study were custom made by Don Roth, an engineer in Oregon who was involved in the Tucson study with Dr. McGuire.

PVC pipe was chosen to provide a sturdy support for the irrigation tubing to be coiled. The COT used 24 inch Schedule 20 PVC in five foot lengths. These lengths were calculated in Appendix B, but in future projects a free board of one foot should be used instead of six inches to allow more room to aid in mounting the syringe pump housing on top and placement of the sampling container on bottom.

Equipment costs

Appendix D contains a comprehensive list of the equipment needed to build the test units. The total cost for each test unit was $1,310, and the estimated time to construct a test unit was 25 man-hours per unit.

Analytical Parameters

The nitrification testing was dependent on analytical parameters as an indicator of the success or failure of the project. After reviewing factors (costs, prior experience, etc) involved in the analysis of the parameters, the COT decided to analyze the parameters in Table 6 with the corresponding methods and frequency.

Table 6: 2008 City of Tulsa nitrification study measured analytical parameters, frequency, and method

Analyte Name	Frequency of Analysis	Location	Method
Nitrite-nitrogen	Weekly	Effluent, Carboy	Hach Method 8507
Free ammonia-nitrogen	Weekly	Effluent, Carboy	Hach Method 10200
Monochloramine	Weekly	Effluent, Carboy	Hach Method 10200
Chlorite	Weekly	Carboy	Amperometric titration
Total chlorine	Weekly	Carboy	Amperometric titration
pH	Weekly	Effluent, Carboy	Standard Methods 4500H+
Temperature	Weekly	Carboy	Mercury thermometer
Heterotrophic plate count (HPC)	Once or more as needed	Effluent	Standard Methods 9215

Below is an explanation and rational for each analyte:

Nitrite-nitrogen- Nitrite is the product of the first step of nitrification. The nitrite-nitrogen field test can be done in less than 20 minutes for less than $1.00 per test and have reliable results.

Free ammonia-nitrogen- Free ammonia-nitrogen is a vital parameter for the nitrification testing because it tells how much substrate the AOB have available and how much has been utilized. Free ammonia-nitrogen testing is done in conjunction with the monochloramine test, and both together take less than 20 minutes and cost less than $1.00 per test.

Monochloramine- Monochloramine is the only disinfectant in the test units. The carboy concentration of monochloramine can be compared to the total chlorine measurement to determine if the chlorine to ammonia-nitrogen ratios are correct. Also, the monochloramine will decompose in the distribution system and release free ammonia. Monochloramine is measured in conjunction with free ammonia-nitrogen and takes less than 20 minutes and costs less than $1.00 per test.

Chlorite- It was necessary to analyze the carboy levels of chlorite to ensure that what was measured equaled what was added. It would also be desirable to know the chlorite level of the effluent, but nitrite is a strong interference to the chlorite test and caused erroneous values. The chlorite test takes less than 15 minutes and was done in conjunction with the total chlorine test.

Total Chlorine- Total chlorine is the measure of all free and combined chlorine in the test water. Total chlorine is useful as a process control when the results are compared to the monochloramine test. If the total chlorine is consistently higher than the monochloramine, it could be an indication of incorrect chlorine to ammonia-nitrogen ratio. The total chlorine test was done in conjunction with the chlorite test on the amperometric titrator.

pH- AOB grow best at a pH of 7.5 to 8.0, so it is important to check that the pH is within or near that range. The test water pH can be affected by a variety of chemical and biological reactions, so pH is not necessarily an indicator of nitrification. The pH test was conducted using an Orion pH meter.

Temperature- The optimum temperature for AOB growth is 20-30 degrees Celsius. Temperature was monitored during the study by a simple mercury thermometer.

Heterotrophic plate count (HPC)- HPC indicates the degree of bacterial growth in the distribution system. Most drinking water AOB are autotrophic and do not show up on an HPC test (AWWA 2006). HPC is a useful parameter in nitrification testing because it quantifies the negative effect of a nitrification episode.

Creating the Test Water

Ideally, any pilot testing should be done using actual water from the main drinking water plant. However, ABJ WTP has a chlorite residual of approximately 0.3 mg/l in the finished water which would prevent the test from having a zero and low-dose chlorite test water. Therefore, the personnel at ABJ WTP started the pilot plant each time test water was needed. The process for operating the pilot plant to create test water is outlined in Table 7. Care was taken to ensure that chlorite was never accidentally introduced to the system from the main plant's finished water.

Table 7: A.B. Jewell WTP pilot plant operational parameters for creating the test water to be added to each pilot test unit during the 2008 nitrification study

Process	**Comments**
Pre-oxidation	The pre-oxidation processes of chlorine, chlorine dioxide, and potassium permanganate were shut off while the nitrification test water was produced.
Coagulation/ Flocculation/ Sedimentation	45 mg/l of aluminum sulfate and 2.5 mg/l of cationic polymer were added to the raw water from Lake Oologah which was then flocculated and settled in plate settlers.
Filtration	The settled water was pumped through four feet of granular activated carbon and one foot of sand at a filter loading rate of approximately six gpm per square foot. The filtered water was collected in carboys for chemical addition and transfer to the nitrification test units.
Disinfection	0.6-1.0 ml of 10% Sodium hypochlorite (industrial bleach) was added and allowed to react for 10 minutes to remove most of the inorganic chlorine demand. The target chlorine concentration at the end of this 10 minute period was 2.0 mg/l free chlorine.
Chloramination	After the reaction period, 10 ml of 1,000ppm ammonia-nitrogen solution was added to the test water to obtain a chlorine to ammonia nitrogen ratio of 4:1.
Transfer	The carboys containing the chloraminated test water were then carried to the nitrification test units and dumped into

	each of the eight test units.
Chlorite Addition	Chlorite was added to each test unit according to the amounts called for in the test protocol.

Bacterial Startup

The COT worked in conjunction with Dr. Joel Gaikwad from Oral Roberts University Department of Biology to do lab scale tests of pH, temperature, and chloramine concentration effects on AOB. The COT took a sample of one of the AOB cultures to ABJ WTP and began acclimating the culture to chloramine concentrations that the AOB would see in the test units. Dr. Ying Wu from Malcolm Pirnie supplied the COT with instructions on this acclimation process; those instructions are included in Appendix E.

The COT began the bacterial injection once the carboys started up. Fifty milliliters of bacteria and 10 milliliters of air (AOB are aerobic) were pulled into 60 milliliters syringes. This 60 milliliter mixture was then infused into the test units over a 4.2 day period through the syringe pump.

CHAPTER IV

FINDINGS

Nitrification Test Timeline

The test began on May 12th, 2008 with the first bacterial injection on May 19th. No chlorite was added to the system until June 2nd to allow for nitrification to be established in all eight test units. The first samples were recorded on June 2nd. Because of suspected overfeed, the bacterial injections were halted on June 25th. The COT needed 6-7 weeks of data (1-2 samples per week) to make a decision on whether or not the chlorite was effective in controlling bacteria. The last samples were taken on August 19th, giving a total of 11 weeks of data.

Table 8: Adjusted Timeline for 2008 nitrification study at A.B. Jewell WTP

Date	Event
May 12, 2008	Filled up test units with chloraminated water. Set effluent flow to 2 ml/min.
May 19, 2008	Turned on syringe pumps. Began injecting bacteria at 0.01 ml/min.
June 2, 2008	Collected first round of samples and began adding chlorite to the system.
June 25, 2008	Bacterial injection turned off.
August 19, 2008	Test units turned off. Last sample analyzed and recorded.

Test Unit Flow Rates

Each week the operational data from each test unit was recorded on the Operational Data Sheet, given in Appendix F. The total volume of test water added to each carboy could then be divided by the total time of the test to establish the average flowrate over the entire study period. The overall flow rate for each nitrification test unit can be found in Table 9.

Table 9: Total volume of flow and average residence time of each pilot test unit during the 2008 nitrification study

Carboy #	Total Volume Added (liters)	Average flow rate (ml/min)	Average residence time (days)
1	240	1.5	11.8
2	253	1.6	11.2
3	210	1.3	13.5
4	208	1.3	13.6
5	249	1.6	11.4
6	241	1.5	11.8
7	291	1.9	9.7
8	185	1.2	15.3

Issues With Test Unit Five

Shortly after startup, test unit five experienced a leak around the 90 degree elbow of the AOB injection point. This unit was taken off-line and the fitting was removed and replaced with a new fitting. The new fitting was a slip fitting that was installed using purple primer and PVC glue.

Once the test started, test unit five showed different nitrite-nitrogen and free ammonia-nitrogen data than the other units. Test unit five was a control unit that should have experienced high levels of nitrification similar to test unit one, but test unit five never experienced a nitrite-nitrogen level higher than 0.17 mg/l. For the last two samples in June, no test unit experienced a nitrite-nitrogen level lower than 0.26 mg/l except for test unit five, which experienced levels of 0.01 and 0.03 mg/l of nitrite-nitrogen.

It was suspected that the chemical residue from the purple primer and the PVC glue may have been responsible for the inhibition of nitrification. Purple primer and PVC glue contain methyl ethyl ketone, acetone, tetrahydrofuran, cyclohexanone, PVC resin and amorphous fumed silica. Many organic and inorganic compounds have been identified as inhibitory substances for the nitrification including acetone (USEPA 1993). Because of these issues, test unit five was removed from the analysis.

Nitrite-Nitrogen

On June 2nd (after three weeks of operation), effluent nitrite-nitrogen levels were elevated in all carboys. That same day marked the beginning of chlorite addition to the test units in the amount shown in Table 5 in Chapter III. By July 16th (week 9), nitrification had ceased in test units 3, 4, 6, and 7. After the bacterial injection was turned off July 25th, nitrite-nitrogen levels dropped to non-detect after three weeks in test unit 2, and nitrite-nitrogen concentrations were still dropping in test unit 8 at the completion of the test. Effluent nitrite-nitrogen results are displayed in Table 10 and graphically in Figure 3-10.

The following seven graphs contain the nitrite-nitrogen levels in the effluent during the study. Due to the lack of occurrence, carboy nitrite-nitrogen levels were not graphed.

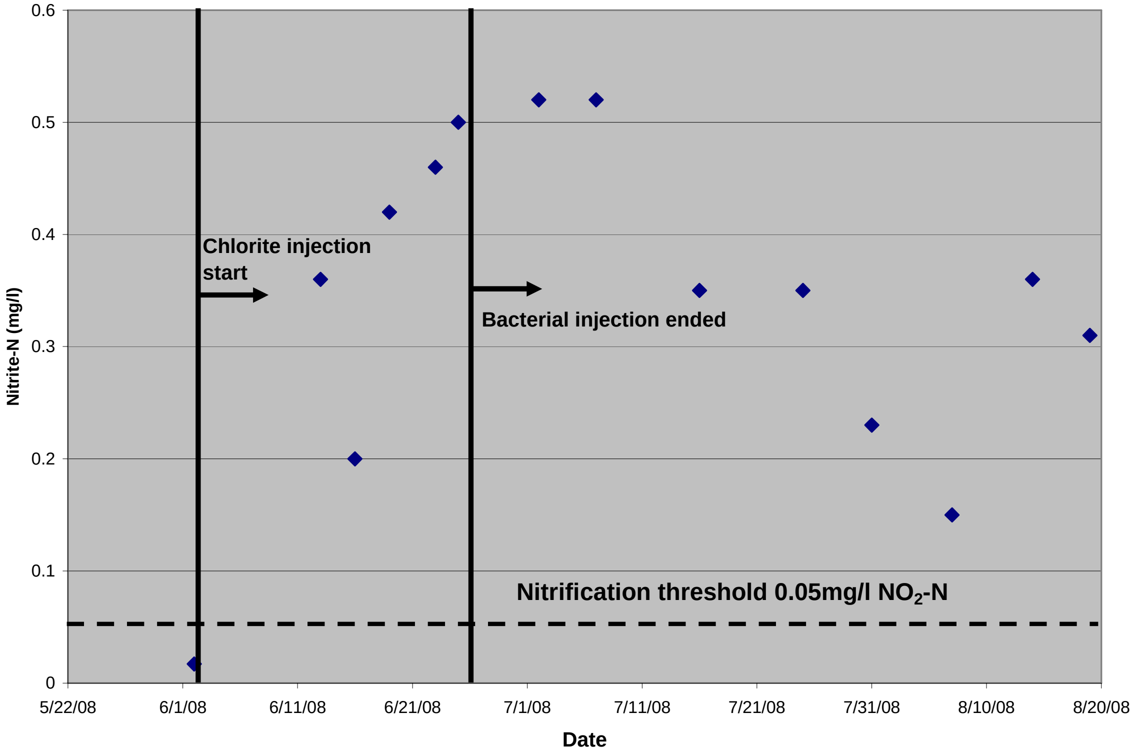

Figure 3: Pilot test unit #1 effluent nitrite-nitrogen during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

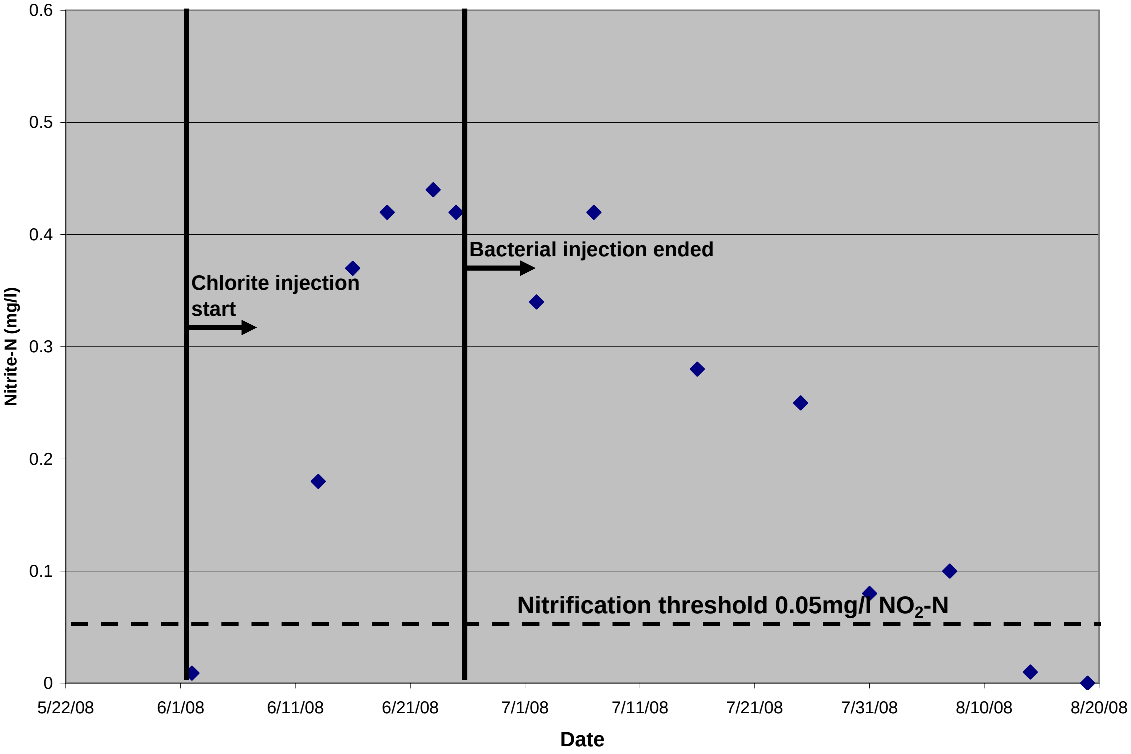

Figure 4: Pilot test unit #2 effluent nitrite-nitrogen during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

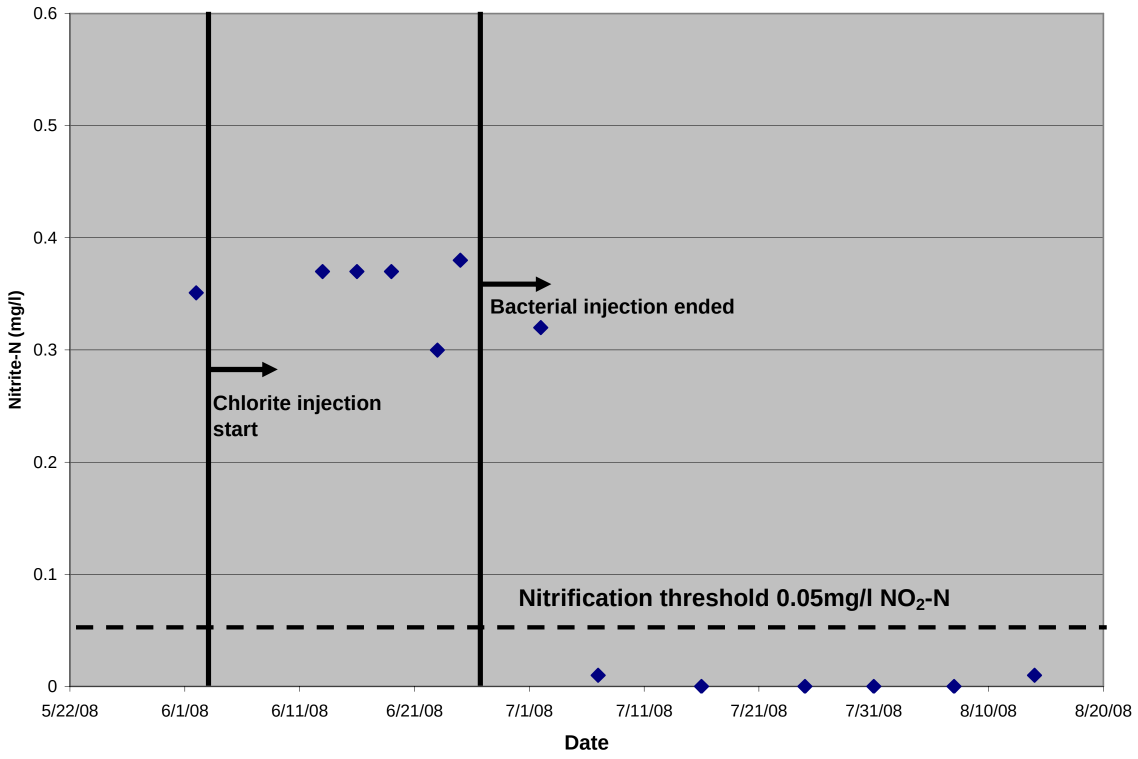

Figure 5: Pilot test unit #3 effluent nitrite-nitrogen during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

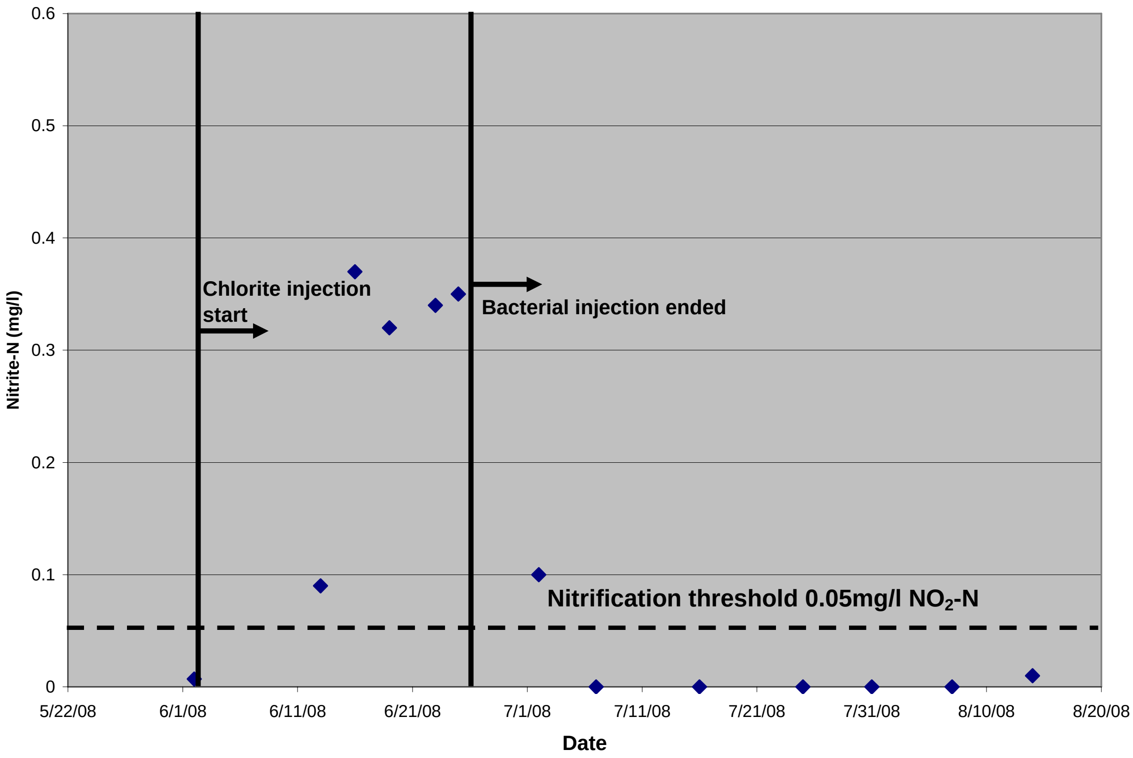

Figure 6: Pilot test unit #4 effluent nitrite-nitrogen during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

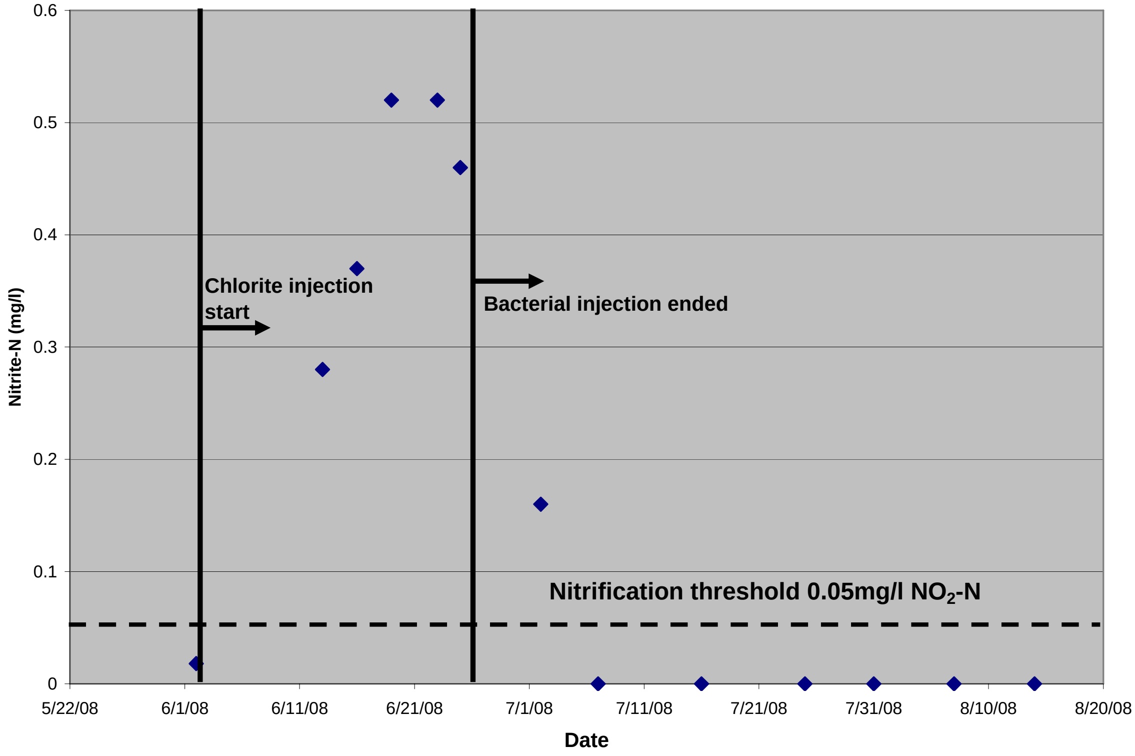

Figure 7: Pilot test unit #6 effluent nitrite-nitrogen during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

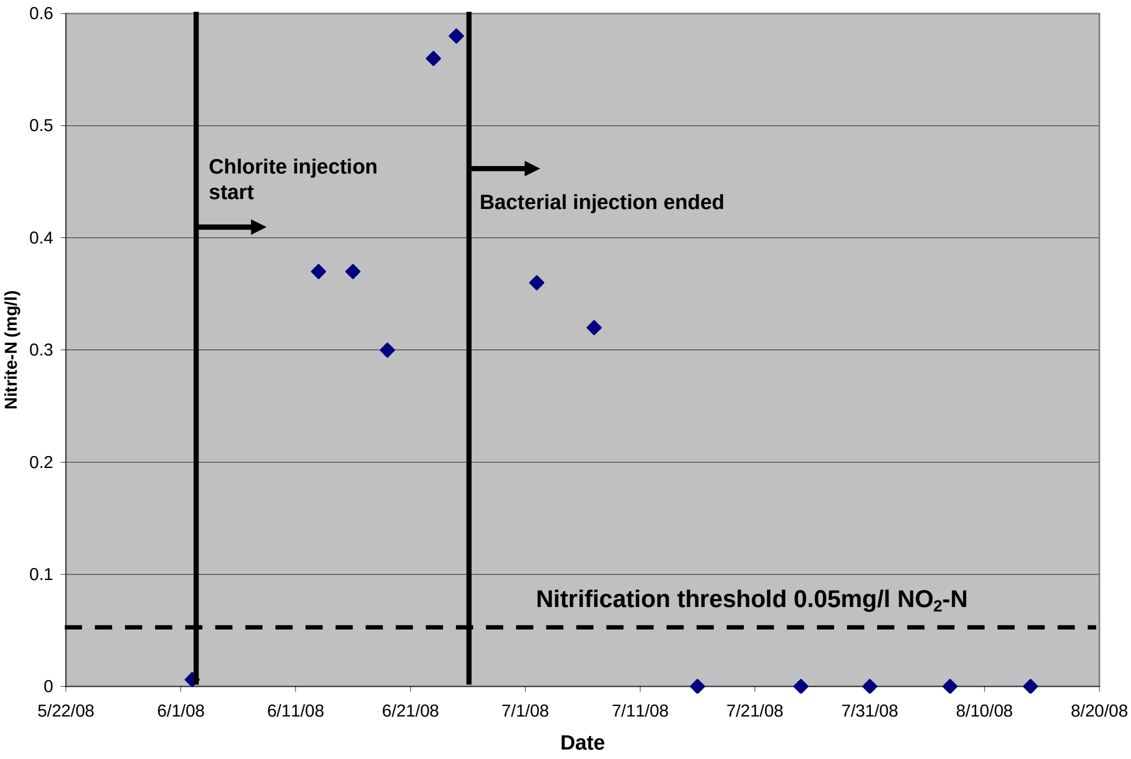

Figure 8: Pilot test unit #7 effluent nitrite-nitrogen during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

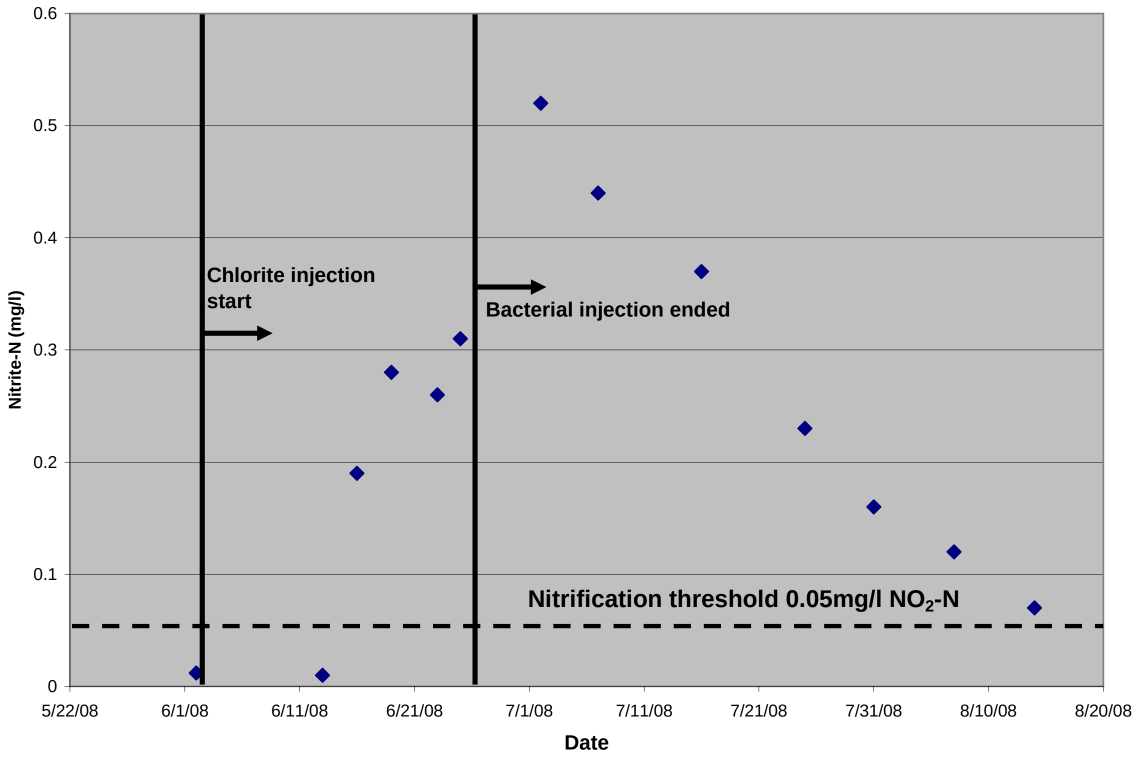

Figure 9: Pilot test unit #8 effluent nitrite-nitrogen during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

Table 10: Effluent nitrite-nitrogen results for pilot test units during 2008 nitrification study. Nine samples were taken after the bacterial injection was stopped.

Test Unit #	Chlorite Dose (mg/l)	Time (days) for nitrite-N to drop below 0.05 mg/l after bacterial injection stopped	Final Concentration nitrite-N (mg/l)
1	0	Did not drop below	0.31
2	0.05	43	0
3	0.1	14	0
4	0.2	14	0
6	0.4	14	0
7	0.6	23	0
8	0.8	Did not drop below	0.09

Monochloramine and Free Ammonia-Nitrogen

Monochloramine and free ammonia-nitrogen were regularly monitored in the carboy and effluent. Although the target monochloramine level in the carboy was 2 mg/l, the measured carboy monochloramine levels were significantly lower during the study. The target free ammonia-nitrogen level for the carboy was less than 0.1 mg/l of ammonia-nitrogen. However, free ammonia-nitrogen levels were much higher in the carboys for the duration of the study.

Monochloramine was extremely low or non-detect in the effluent for the entire study. Free ammonia-nitrogen levels in the effluent were low but detected in the beginning of the study, but all free ammonia-nitrogen levels fell to non-detect by the end of the study. The graphical results of the monochloramine and free ammonia-nitrogen concentrations are contained in Appendix H.

Temperature and pH

The temperature of the test units matched the ambient conditions of the basement throughout the study. This temperature range was from 26 to 28 degrees Celsius.

The carboy pH ranged from 8.2 to 7.7 for the duration of the test. Until early July, most of the effluent pH values were near the carboy values. However, by July 16th, all effluent values were showing a lower pH than the carboy values, and through the rest of July and all of August, effluent pH values ranged from 7.5 to

7.7 standard units. The differences in carboy and effluent pH are displayed in Appendix I.

Chlorite and Total Chlorine

Chlorite and total chlorine measurements were only taken on the test water in the carboys due to the strong interference of nitrite in the amperometric chlorite test. For the most part, the analyzed chlorite levels were close to the theoretical dosages of chlorite.

The total chlorine was taken as a check of the monochloramine test to ensure that the di- and trichloramines were not being created excessively as well as any other chlorinated species. Twenty of the corresponding monochloramine and total chlorine values from carboys one through four were analyzed, and 11 of the values had higher total chlorine than monochloramine and nine of the values had a higher monochloramine than total chlorine. This suggests that di- and trichloramines were not being formed. Detailed results of this comparison are in Appendix J.

Heterotrophic Plate Count (HPC)

HPC's were only sampled on one date during the test. This one HPC test was done on the effluent on August 8th. The HPC results are in Table 11.

Table 11: Pilot test unit effluent HPC's on August 8, 2008

Carboy #	Heterotrophic Plate Count (Most Probable Number)
1	510
2	360
3	260
4	>740
6	>740
7	>740
8	>740

CHAPTER V

DISCUSSION AND CONCLUSIONS

Discussion

Test Unit Operation

The needle valves on the test units proved to be very difficult to control at such low flows. While the desired residence time of the distribution system was 7 days, the actual residence time ranged from 9.7 to 15.3 days. This was not a major problem for the testing, but it did create an environment that was more amenable for nitrification to occur than what most of the COT would experience.

One very cumbersome component of the test was the formation of the test water. The more desirable operation of this test would have been to have finished water available from the water treatment plant. However, since the finished water from A.B. Jewell contained chlorite, this option was not available. Ideally, the finished water from the plant would be directly added to the carboys, and ammonia and chlorite would be mixed into the carboys after the water was added. Because the water in this nitrification test came from a pilot plant, the operation of the pilot plant became an additional variable during the test. Also, the addition of chlorine and its reaction with inorganic and organic constituents was a variable that a full-scale plant finished water would have already experienced through its pre-oxidation and disinfection processes.

Although the light source was necessary to inhibit AOB growth in the carboys, it had a very troublesome byproduct effect of algal growth in the carboys. At several occasions during the test, small amounts of green algae were spotted growing along the submerged lower edges of the carboys. To counter this, the lights were turned off and a temporary black plastic cover was wrapped around the carboys. This solution efficiently controlled the algal growth, but unfortunately allowed several small nitrification episodes to occur in carboys one and three.

Nitrite-Nitrogen

The primary indicator of nitrification is the presence of nitrite-nitrogen. By the time chlorite was added to the test units on June 2nd, elevated levels of nitrite-nitrogen (indicating nitrification) were observed in all seven of the test units. Even with the chlorite addition, nitrite-nitrogen values continued to climb in test units two and eight because the injection of nitrifying bacteria was apparently overpowering the inactivation abilities of the chlorite. Once the AOB injection pump was turned off, test unit two took 43 days to get below 0.05 mg/l of nitrite-nitrogen probably due to the lower level of 0.05 mg/l of chlorite. Test unit eight gave unexpected results. Even though test unit eight received the highest dose of chlorite (0.8 mg/l), it took the longest for the nitrite-nitrogen level to drop, and the nitrite-nitrogen level never actually dropped below the threshold of 0.05 mg/l nitrite-nitrogen. Several factors could have caused this. The most likely factor was the residence time in test unit eight was 15.3 days. This residence time was much longer than the other test units (average residence time of 11.9 days) and was due to a defect in the needle valve that restricted flow over time.

The nitrite-nitrogen results suggest that a chlorite residual of 0.1 mg/l can aid in controlling a nitrification episode. However, chlorite addition alone may not control nitrification as exhibited in test unit eight. Chlorite should be used along with other nitrification control methods in the COT's water system.

Monochloramine and Free Ammonia-nitrogen

The lower monochloramine values in the carboys were most likely due to additional organic and inorganic chloramine demand in the pilot plant test water. The demand caused by the organic and inorganic contaminants results in chloramine decomposition by Equations 5 and 6 from Chapter II. If the test had been able to use finished water from a full-scale plant, then the majority of the chloramine demand would have already be quenched in the plant pre-oxidation and disinfection processes. The lower monochloramine values are probably to blame for the high HPC's from the August 8th test.

The high free ammonia-nitrogen levels in the carboys are likely a result of the chloramine decomposition from the reactions with inorganic and organic compounds. The high free ammonia-nitrogen makes a perfect condition for nitrification to occur because of the available substrate for the AOB. What was unusual in the testing were the low levels of free ammonia-nitrogen in the effluent. The test units that were not experiencing nitrification should have had free ammonia-nitrogen in the effluent. It is possible that other microbes were synthesizing the free ammonia back to organic-nitrogen by absorbing the ammonia into their cellular mass.

Temperature and pH

For the duration of the study the temperature stayed in the optimum range for nitrification to occur. The temperature in May when the testing started was 26 degrees Celsius, and the temperature in August at the end of the testing was 28 degrees Celsius. These numbers are at the upper end of the optimum range of 20-30 degree Celsius.

At the beginning of the test, there was only a slight drop (0.1 or less) in pH from the carboy to the effluent. However, as the test progressed, the pH began to drop as much as 0.6 standard units in the carboys. Nitrification can cause a pH depression, but the pH drop was no more pronounced in the carboys experiencing nitrification than the ones not experiencing nitrification. Other processes such as heterotrophic bacterial growth and auto-decomposition most likely were responsible for the lowering of the pH.

Significance of the High HPC

The high HPC values of August 8th can explain several issues with the system. The first issue would be the disappearance of the monochloramine residual from carboy to effluent. An outbreak of HPC could easily consume the monochloramine; once the monochloramine residual was gone, then HPC growth could continue without threat of a disinfectant. Another side effect of the high HPC is the uptake of ammonia. The rapidly growing HPC could uptake the free ammonia into their cellular mass. Further nitrification tests should include more regular HPC sampling to find the relationship between HPC and monochloramine residual and to see how nitrification is affected by HPC.

Hypothesis Discussion

- Null hypothesis 1: With the addition of chloramines and ammonia-oxidizing bacteria, nitrification will not occur in the pilot test units. A nitrification occurrence is based on a test unit effluent nitrite-nitrogen level of 0.05 mg/l or greater.

- Alternate hypothesis 1: With the addition of chloramines and ammonia-oxidizing bacteria, nitrification will occur in the pilot test units. A nitrification occurrence is based on a test unit effluent nitrite-nitrogen level of 0.05 mg/l or greater.

The null hypothesis 1 will be rejected and alternate hypothesis accepted based on the nitrite-nitrogen levels of all 7 carboys being above 0.05 mg/l. Because this was the identified threshold level of nitrite-nitrogen, it can be confirmed that nitrification was established.

- Null hypothesis 2: In a test unit with established nitrification, chlorite residuals will have no affect on limiting or stopping nitrification. Nitrite-nitrogen levels will stay above 0.05 mg/l.

- Alternate hypothesis 2: In a test unit with established nitrification, chlorite residuals will limit or stop nitrification from occurring. Nitrite-nitrogen levels will drop below 0.05 mg/l.

The null hypothesis 2 can be rejected in five of the six test units that received a chlorite residual. However, test unit 8 received the highest dose of chlorite but did not experience a nitrite-nitrogen concentration below the threshold of 0.05 mg/l. This is most likely due to the abnormally long residence time that test unit 8 experienced. A slight malfunction in the needle valve on test unit 8 caused it to have longer residence times than the other units. It can be hypothesized that this contributed to the ineffectiveness of the chlorite to control the nitrification.

Conclusions

Recommendation for the City of Tulsa

The COT is geographically far enough south that nitrification could become a problem in the summer months due to the water temperature entering the optimum range for nitrification. If the COT decides to switch to chloramines as the secondary disinfectant, then the city should take preventative measures to control nitrification. These include but are not limited to:

- Shorten distribution system residence time by flushing and/or rerouting water flow
- Keep the free ammonia-nitrogen concentration of finished water below 0.1 mg/l
- Maintain a finished water chlorite residual of 0.1 mg/l or higher.

The results of this study indicate that the 0.1 mg/l chlorite concentration controlled the nitrification outbreak as quickly as 0.2, 0.4, and 0.6 mg/l. The fact that nitrification was more difficult to control at the highest level of chlorite, 0.8 mg/l, indicates that even high levels of chlorite will not alone control nitrification if the nitrification is well-established in optimum growth conditions. However, the decreasing concentration of nitrite-nitrogen in test unit 8 may indicate that chlorite was slowly working to limit nitrification in that test unit as well, but not as effective as in the other test units with shorter residence times.

One possible component of nitrification that this study did not test was the stagnant areas in COT distribution storage tanks. This study assumed complete mixing of water as it uniformly flowed through distribution piping. However, the COT uses 17 tanks of various sizes throughout the distribution system for storage. There are no mixing equipment in these tanks, and thus stagnation zones in these tanks could become an environment for nitrification due to the increased residence time. Due to potential stagnation zones, the COT should install mixing equipment in each of these 17 tanks to ensure that the residence time in the tanks does not create conditions for nitrification.

The addition of chlorine dioxide at ABJ WTP and its corresponding residual of 0.2-0.3 mg/l of chlorite should be enough to aid the control of nitrification in the distribution system. However, Mohawk WTP does not add chlorine dioxide and therefore has no chlorite residual in its finished water. Mohawk could choose one of two scenarios to ensure that the finished water would have a chlorite residual. These scenarios are detailed in Appendix K. ABJ WTP should also consider these scenarios when deciding whether or not to continue chlorine dioxide addition.

The first scenario would be the conversion of Mohawk's pre-oxidant from chlorine to chlorine dioxide. This would also give Mohawk the advantages of a stronger disinfectant and lower in-plant TTHM's. However, the cost of chlorine dioxide would be tremendously more than chlorine. As of August 2008, the chemical cost to add one pound of chlorine to the water was $0.28. The chemical cost to add one pound of chlorine dioxide to the water was $1.82. The additional annual cost to switch Mohawk's pre-oxidant from chlorine to chlorine dioxide would be $234,396. The major disadvantage of using chlorine dioxide to create a chlorite residual is that new granular activated carbon (GAC) filters can absorb chlorite. For the first 6-9 months of service, the filters with new GAC will absorb the chlorite and lower the chlorite residual of the finished water.

The second scenario would be to directly add sodium chlorite to Mohawk's finished water. This scenario would add greater control of the residual, easier application, and much lower cost. The estimated chemical cost per pound of chlorite added would be $0.30. This would yield a yearly cost of $18,264 to keep a residual of 0.1 mg/l of chlorite in the finished water. Also, this cost could be even lower if Mohawk chose to only apply chlorite during the warmer temperatures from March to October. The major disadvantage of this scenario is the public perception and regulatory implications of adding a regulated contaminant directly to the drinking water. Before this scenario is chosen, the COT needs to meet with the ODEQ and Tulsa Metropolitan Utility Authority to discuss this option.

Table 12: Treatment technique for adding chlorite to Mohawk's finished water and associated yearly cost

Treatment Technique	Estimated Yearly Cost (2008 dollars)
Add sodium chlorite at 0.1 mg/l to the finished water	$18,264
Use chlorine dioxide on the raw water which will leave a chlorite residual of 0.2-0.7 mg/l on the finished water	$234,396

However, before a decision is made regarding chlorite in Mohawk's finished water, this same nitrification study should be conducted at Mohawk.

Suggested Improvements for Future Nitrification Studies

For future nitrification studies at the COT and elsewhere, there are several improvements that could aid to the quality of data and usefulness of the study to drinking water utilities.

The first improvement would be a nitrogen balance. The COT study analyzed free ammonia-nitrogen, monochloramine, and nitrite-nitrogen, but nitrate-nitrogen and organic-nitrogen were not analyzed. With nitrate-nitrogen and organic-nitrogen concentrations, all the nitrogen would be accounted for with the exception of nitrogen gases. Since most drinking water distribution systems are aerobic, it would be unlikely to find denitrification and the resulting nitrogen gases. If a utility chooses to analyze the extra parameters to obtain a nitrogen balance, then extra money should be budgeted for analysis. Field nitrate-nitrogen analysis is very unreliable and must be done in a lab by EPA method 353.2. The COT attempted the field nitrate-nitrogen testing, but the detection limit was 0.23 mg/l which was too high to produce useful results. Also, organic-nitrogen testing should also be done by the method that can produce the greatest accuracy at the lowest range.

In addition to a nitrogen balance, future studies could be improved by analyzing for nitrifying bacteria. Current AOB and NOB analysis methods are plagued by excessive incubation times (three to four weeks) and inability to isolate species of bacteria responsible for nitrification due to the diverse groups that can nitrify. Researchers are continuing to develop faster and more accurate methods to analyze nitrifying bacteria, and utilities with microbiology capabilities may want to try some of these methods.

Future testing should include HPC testing at weekly intervals from both the carboy and the effluent. Only one HPC test point was taken in this study, and four of the seven values came back over the HPC test range. More regular testing of HPC will allow the utility to see the relationship between nitrification, chloramine residual, and HPC.

One variable of the COT nitrification study is the AOB injection. Utilities would get a more realistic nitrification episode if AOB were allowed to naturally grow in the test units instead of being injected. This would be very arduous and time consuming, but the results would be more representative of what may happen in an actual distribution system.

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APPENDICES

Appendix A: Chloramine Jar Test at A.B. Jewell

Background

To better understand how the chloramine molecule will break down and how trihalomethanes will be produced in chloraminated water, the COT ran a jar test with chloraminated water in January 2007.

Methods

Eight one-gallon jars were filled with chloraminated water and then analyzed every five days (the first jar was analyzed immediately after filling). The jars were made of amber glass and stored in a temperature-controlled (~15 degree Celsius) dark room.

Results

Chloramine break-down and free ammonia-nitrogen concentrations are in Figure 10.

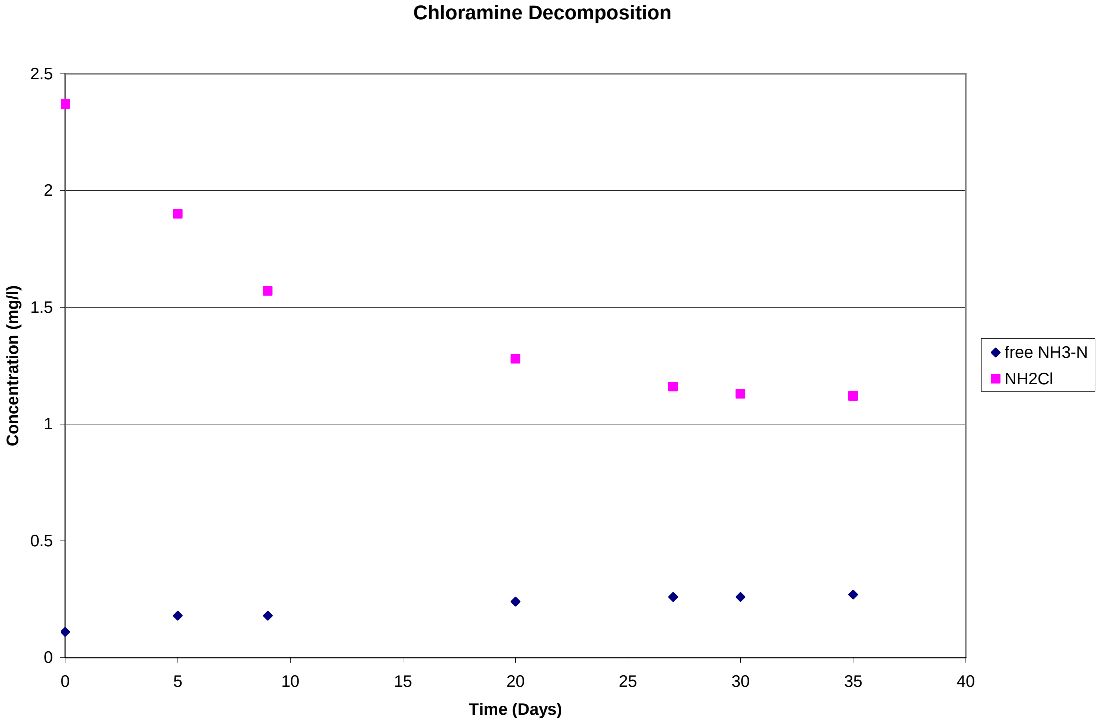

Figure 10: Monochloramine decomposition and free-ammonia increase over time during 2007 chloramine jar test at A.B. Jewell WTP.

The monochloramine residual decreased from 2.4 to 1.1 mg/l over the 35 day period of this study. The free ammonia-nitrogen concentration increased from 0.1 to 0.3 mg/l over the 35 day period.

Trihalomethane concentrations are contained in Figure 11.

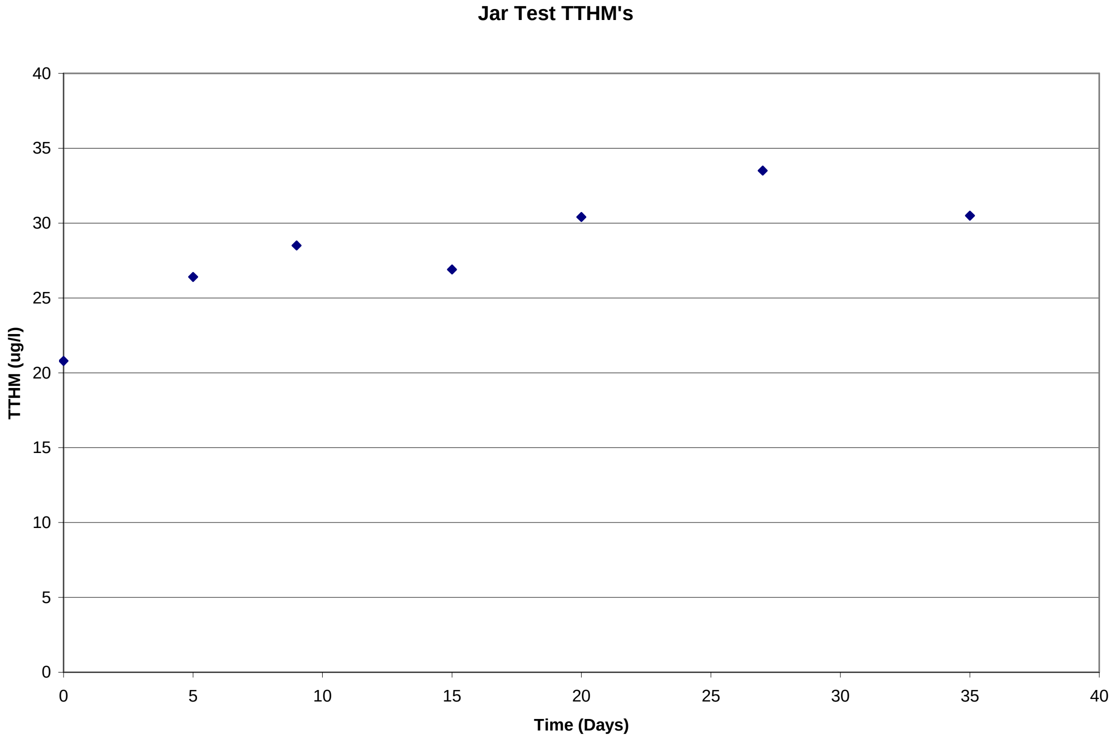

Figure 11: TTHM concentrations over time during 2007 chloramine jar test at A.B. Jewell WTP.

For January 2007, the finished water had a TTHM max formation potential of 99 ug/l.

Discussion

By Day 25 both the free ammonia-nitrogen increase and chloramine decomposition had leveled off. The monochloramine residual hovered slightly above 1.1 mg/l. This is important because ODEQ requires a distribution residual chloramine concentration of 1.0 mg/l. The COT may desire to dose chloramine above the 2.4 mg/l initial concentration used in this test.

The free ammonia-nitrogen levels climbed to almost 0.3 mg/l by the end of the test. This amount of free ammonia-nitrogen could provide substrate for nitrifying bacteria.

The TTHM concentrations increased approximately 10 ug/l during the 35 days of the testing. From this data, it appears that chloramines would be effective in reducing TTHM's to well below Stage 2 Disinfection By-Product Rule levels.

Appendix B- Designing the Test Unit Components

The first equation used in sizing the test unit components is the residence time equation:

Residence Time = Volume / Flowrate

The desired residence time and flowrate are already known. The COT identified seven days as the desired residence time based on the 2006 fluoride tracer study. Based on Dr. McGuire’s 2003 study, the COT chose to use a minimum target flowrate of 2 ml/min.

The following step-by-step calculation procedure was used to size the irrigation tubing and adjust the flowrate (if necessary):

1. Find the total volume of the AOB injection point
2. Based on residence time and a flowrate of 2ml/min, find the theoretical volume of the distribution system
3. Using a standard irrigation tubing diameter to find the length of tubing necessary to equal the theoretical volume
4. Find the actual volume of the distribution system using the actual length of irrigation tubing used in construction
5. Find the new flowrate necessary to keep the residence time near 7 days

1. AOB injection point

The volume of the AOB injection point should be calculated first. This small amount of volume will most likely be negligible, but it should still be known.

COT study numbers:

13 inches of 1 inch PVC pipe

25 inches of ½ inch PVC pipe

$$Volume(liter) = Length\ (feet) * \pi * \left[\frac{InsideDiameter^2 (inch)^2}{4} \right] * \frac{feet^2}{144\ inch^2} * \frac{28.3\ liter}{feet^3}$$

$$Volume = \left[13\ in * \left(\frac{1^2 in^2}{4} \right) + 25\ in * \left(\frac{0.5^2 in^2}{4} \right) \right] * \pi * \frac{1\ foot}{12 inch} * \frac{feet^2}{144\ inch^2} * \frac{28.3\ liter}{feet^3}$$

$$Volume = 0.248\ liters$$

The AOB injection point contributes 248 milliliters of volume.

2. Distribution System Irrigation Tubing

The equation for volume of irrigation tubing is below:

Volume = Residence Time * Flowrate

COT study numbers:

Residence time 7 days

Desired flowrate 2 ml/min

$$Volume = 7\ days * \frac{2ml}{\min} * \frac{1440\min}{day} * \frac{liter}{1000ml}$$

$$Volume = 20.2\ liters$$

3. Find the length of irrigation tubing

Divide the volume by the cross sectional area to find length. Rainbird manufactures an irrigation tubing with and inside diameter (I.D.) of 0.58 inch.

$$Length = \frac{Volume}{Area}$$

$$Length = \frac{20.2\ liters}{\pi * \frac{0.58^2}{4} in^2} * \frac{144 in^2}{ft^2} * \frac{ft^3}{28.3 liters}$$

Length = 389 feet of 0.58 ID irrigation tubing

For ease of construction, the COT chose to purchase the irrigation tubing in the standard 0.58 inch ID and 500 foot lengths. The volume should now be re-calculated with the 500 foot length and the addition of the AOB injection point volume.

4. Find the actual volume with the chosen irrigation tubing

$$Volume(liter) = Length\ (feet) * \pi * \left[\frac{InsideDiameter^2 (inch)^2}{4} \right] * \frac{feet^2}{144\, inch^2} * \frac{28.3\, liter}{feet^3}$$

$$Volume = 500\, feet * \pi * \left[\frac{0.58^2\, in^2}{4} \right] * \frac{feet^2}{144\, inch^2} * \frac{28.3\, liter}{feet^3}$$

Distribution system volume = 26.0 liters

Now add the AOB injection point volume to the distribution system volume to find total volume.

Total Volume = Distribution system volume + AOB injection point volume

Total Volume = 26.0 liters + 0.248 liters

Total Volume = 26.2 liters

5. Find the new flowrate

Flowrate = Volume / Residence Time

$$Flowrate = \frac{26.2\ liters}{7\ days} * \frac{1000 ml}{liter} * \frac{day}{1440 \min}$$

Flowrate = 2.6 ml/min

Sizing the PVC tubing support

Once the diameter and length of the irrigation tubing are known, one can get an idea of the size of PVC tubing support. The circumference of the PVC tubing support must be calculated first to know how many times the irrigation tubing will need to be wrapped around the PVC support. The number of wraps can then be multiplied by the outside diameter of the irrigation tubing to find the height of PVC tubing support necessary for each test unit.

COT study numbers:

Irrigation tubing length	500 feet
Irrigation tubing OD	0.70 inch
Desired PVC diameter	24 inch

Find circumference of the PVC tubing support

$$\begin{aligned} 2*\pi*\mathit{pipe\ radius} &= \mathit{Circumference} \\ 2*\pi*12\ \mathit{inch} &= 75.4\ \mathit{inch} \\ &= 6.28\ \mathit{feet} \end{aligned}$$

Divide the feet of irrigation tubing by the circumference of the pipe to find the number of times the tubing will be wrapped around the PVC support.

$$\frac{Calculated\ length\ of\ tubing}{PVC\ pipe\ circumference} = number\ of\ wraps$$

$$\frac{500\ feet}{6.28\ feet\ per\ wrap} = 79.6\ wraps$$

The tubing will have to be wrapped around a 24 inch PVC tubing support 79.6 times. Now, multiply the number of wraps times the outside diameter of the irrigation tubing to find the length of PVC support needed.

$$\begin{aligned} &number\ of\ wraps * outside\ diameter\ of\ irrigation\ tubing = height\ of\ PVC\ pipe \\ &79.6\ wraps * 0.70 inch = 55.7\ inches \\ &\qquad\qquad\qquad\qquad\quad = 4.64\ feet \end{aligned}$$

It is a good idea to leave 6 inches of free board on the top of the PVC support. That will add 0.5 feet of length to the calculated length above, so the total length of 24” PVC tubing support will need to be 5.1 feet.

Both Tucson and COT used 24” PVC pipe for the tubing support.

Sizing the carboy

For operational ease, it is best to only refill the carboy once a week. The carboy needs to be able to hold approximately a week’s worth of test water. Previously the total test unit volume was calculated to be 26.2 liters. The carboy should be as close to this size as possible.

Nalgene Clearboys standard size is 10 and 20 liters. The 20 liter size will need to be filled every 5.3 days, which is slightly more often than the COT would like, but it will be satisfactory.

Appendix C: Construction Manual

(Note: The manual is a stand-alone document that contains figures, tables, and appendices that do not correspond to the main thesis document.)

Manual for the Design and Construction of Distribution Test Units

City of Tulsa Department of Public Works
Tyler Gipson

September 2008

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I. Foreword

This manual is intended to assist drinking water engineers, operators, and maintenance personnel in the design and construction of distribution simulation test units. The specific test units described in this manual were built at the City of Tulsa, Oklahoma and used for simulating nitrification in a distribution system.

The design and construction ideas contained in this manual are based on a 2003 nitrification study in Tuscon, AZ. This study was performed by Dr. Michael McGuire, Katie Arnold, Don Roth, and Dr. Nicole Blute and was published in the January 2006 issue of the Journal of the American Water Works Association.

Please feel free to contact the author with any questions or comments about this manual.

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II. Background

Many of the nation's water utilities use chloramines as the secondary disinfectant in their distribution system. Chloramines are created by mixing free chlorine with free ammonia.

Free ammonia is a concern in chloraminated distribution systems. Free ammonia can be a result of ammonia over-feed at the water treatment plant or chloramine decomposition in the distribution system. The concern of having free ammonia is that it may cause nitrification in the distribution system. Nitrification is the biological process by which ammonia is oxidized to nitrite and nitrate. The bacteria that convert ammonia to nitrite are named ammonia oxidizing bacteria (AOB), and the bacteria that convert nitrite to nitrate are named nitrite oxidizing bacteria (NOB). Both of the bacteria are present in chloraminated drinking water systems.

Nitrification can cause several high priority issues in a distribution system. The first issue is pH depression. As the AOB oxidize the ammonia, hydrogen ions are released which can cause the pH to drop. This pH drop can promote corrosion of distribution system piping, which could possibly lead to violations of the Lead and Copper Rule.

Nitrification can also cause issues with the chloramine residual in the distribution system. As the AOB proliferate, it takes more chloramine residual to inactivate them. Unfortunately, as the chloramine molecule attacks the bacteria, it also releases ammonia. This free ammonia then feeds the growth of additional AOB which in turn requires more chloramine. Once this cycle begins, it is very difficult to return the distribution system to pre-nitrification conditions.

As the problems of nitrification came to light through the 1980's and early 1990's, drinking water scientists and engineers noticed that one Texas utility, Gulf Coast Water Authority (GCWA), was not experiencing nitrification. GCWA used chlorine dioxide as a disinfectant, which left a residual of chlorite in the distribution system. Further research revealed that several other Texas utilities that used chlorine dioxide were not experiencing nitrification. This finding led to bench and pilot scale research that showed that chlorite residuals as low as 0.1 mg/l could prevent nitrification.

A 2003 pilot study in Tucson, AZ is the basis for the test units in this manual. This study used pilot scale distribution units which were each dosed with different levels of chlorite in the test water. The test water then spent 5 days flowing through 400 feet of irrigation tubing that gave a much better simulation of time in distribution that a jar test. Further information on this study can be obtained in the January 2006 Journal AWWA article which contains the results of this study.

The City of Tulsa (COT) is considering a switch to chloramines to meet Stage 2 DBPR TTHM levels. After learning of the chlorite studies, the COT desired to conduct in-house studies to see if similar results could be achieved. This manual contains a step-by-step guide of how the COT constructed its nitrification test units.

III. Pre-Construction Considerations and Equipment

When selecting a location for the test units, be sure to address the following site considerations.

- Elevated Carboy Placement
  Since the system is completely gravity flow, the carboys must be elevated above the rest of the test unit. For the COT tests, scaffolding was used to place the carboys approximately 7 feet off the ground at the AB Jewell WTP. In the next section, "Preconstruction Design Parameters," there is a place to calculate the height of the PVC tubing support. The scaffolding should be at least 2.5 feet taller than this calculated height.

- Step ladders
  Because of the elevation of the carboys, stepladders will be necessary for constructing and operating the test units. Rolling stepladders are the best due to their sturdy construction and ease of movement.

- Light Source
  Ammonia oxidizing bacteria (AOB) are sensitive to UV light, so be sure to place the carboys in an area that will receive ample sunlight or UV light from a metal halide bulb. Place the carboys far enough from the light to keep the carboy temperature from rising.

- Power source
  Be sure that the carboys have an uninterrupted power supply available for powering the syringe pumps.

- Water source
  A water source will be necessary for cleaning, flushing, and filling the carboys. A simple hose connection will suffice.

- Drain
  When all the test units are operating, there will be a small but steady flow of water draining from the needle valves. Be sure that the area is well drained.

Preconstruction Design Parameters

It is important to know what parameters will be tested before constructing the test units. The most important parameter for these test units is detention time. Decide on the desired distribution detention time before buying equipment for the test units.

From the testing experience at the COT, it is cumbersome to set needle valve flowrates below 1 ml per min. The higher the flowrate used, the easier the system will be to operate. However, operating at a higher flowrate will greatly increase the volume of the test unit and increase construction equipment and labor costs.

Sizing the Test Unit tubing

The first and most important equation for the system is the detention time equation:

Detention Time = Volume / Flowrate

The user should already have an idea of the detention time they want to use to best model their distribution system. The COT identified 7 days as the desired detention time based on a 2006 fluoride tracer study. During the tracer study, greater than 90% of the COT's test sites had a detention time of less than 7 days. The 2003 study in Tucson used a detention time of 5 days.

Once the detention time and flowrate are chosen, the volume can now be calculated and test unit equipment can be sized.

The equation for volume in tubing is below:

$$Volume(liter) = Length\ (feet) * \pi * \left[\frac{InsideDiameter^2 (inch)^2}{4} \right] * \frac{feet^2}{144\ inch^2} * \frac{28.3\ liter}{feet^3}$$

Example:

A utility wants to test for nitrification using a detention time of 6 days. Based on the Tucson study and the COT study, a flowrate of 2 ml/min is chosen. A local irrigation tubing dealer has a popular tubing with an inside diameter of 0.58 inch. What length of this irrigation tubing should be purchased?

(First find the total volume)

Volume = Detention Time * Flowrate

$$Volume = 6\ days * \frac{2ml}{\min} * \frac{1440 \min}{day} * \frac{liter}{1000ml}$$

$$Volume = 17.28\ liters$$

(Next divide the volume by the cross sectional area to find length)

$$Length = \frac{Volume}{Area}$$

$$Length = \frac{17.28 liters}{\pi * \frac{0.58^2}{4} in^2} * \frac{144 in^2}{ft^2} * \frac{ft^3}{28.3 liters}$$

Answer:
Length = 333 feet of 0.58 ID irrigation tubing

Sizing the PVC tubing support
Once the diameter and length of the irrigation tubing are known, one can get an idea of the size of PVC tubing support. The circumference of the PVC tubing support must be calculated first to know how many times the irrigation tubing will need to be wrapped around the PVC support. The number of wraps can then be multiplied by the outside diameter of the irrigation tubing to find the height of PVC tubing support necessary for each test unit.

Example:
The previous example concluded that 333 feet (round up to 350 feet) of 0.58 I.D. irrigation tubing would be sufficient for the test units. A local plumbing warehouse has PVC pipe available in 12 inch, 18 inch, 24 inch, and 36 inch diameters. The outside diameter of the irrigation tubing is 0.70 inches. Find how tall each the PVC pipe will have to be to support all the irrigation tubing on each test unit.

Using 12” PVC:
Find circumference of the PVC tubing support

$$\begin{aligned} 2*\pi*pipe\ radius &= Circumference \\ 2*\pi*6\ inch &= 37.7\ inch \\ &= 3.14\ feet \end{aligned}$$

Divide the feet of irrigation tubing by the circumference of the pipe to find the number of times the tubing will be wrapped around the PVC support.

$$\frac{Calculated\ length\ of\ tubing}{PVC\ pipe\ circumference} = number\ of\ wraps$$

$$\frac{350\ feet}{3.14\ feet\ per\ wrap} = 112\ wraps$$

The tubing will have to be wrapped around a 12 inch PVC support 112 times. Now, multiply the number of wraps times the outside diameter of the irrigation tubing to find the length of PVC support needed.

$$number\ of\ wraps * outside\ diameter\ of\ irrigation\ tubing = height\ of\ PVC\ pipe$$

$$\begin{aligned} 112\ wraps * 0.70 inch &= 78.4\ inches \\ &= 6.5\ feet \end{aligned}$$

It is a good idea to leave 6 inches of free board on the top and bottom of the PVC support. That will add 1 foot of length to the calculated length above, so the total length of 12” PVC tubing support will need to be 7.5 feet.

The shorter the PVC support, the easier it will be to handle in both construction and operation. Tucson and COT used 24” PVC pipe for the tubing support.

Sizing the carboy

For operational ease, it is best to only refill the carboy once a week. Be sure to purchase a carboy with a capacity greater than the volume that was identified in the above section “Sizing the Test Unit Tubing.”

IV. The Nitrification Test Unit

For simplicity, the nitrification test unit will be explained in three sections: the distribution system, the carboy, and the AOB injection point. Each section will contain the purpose, choosing the equipment, and installation of each component.

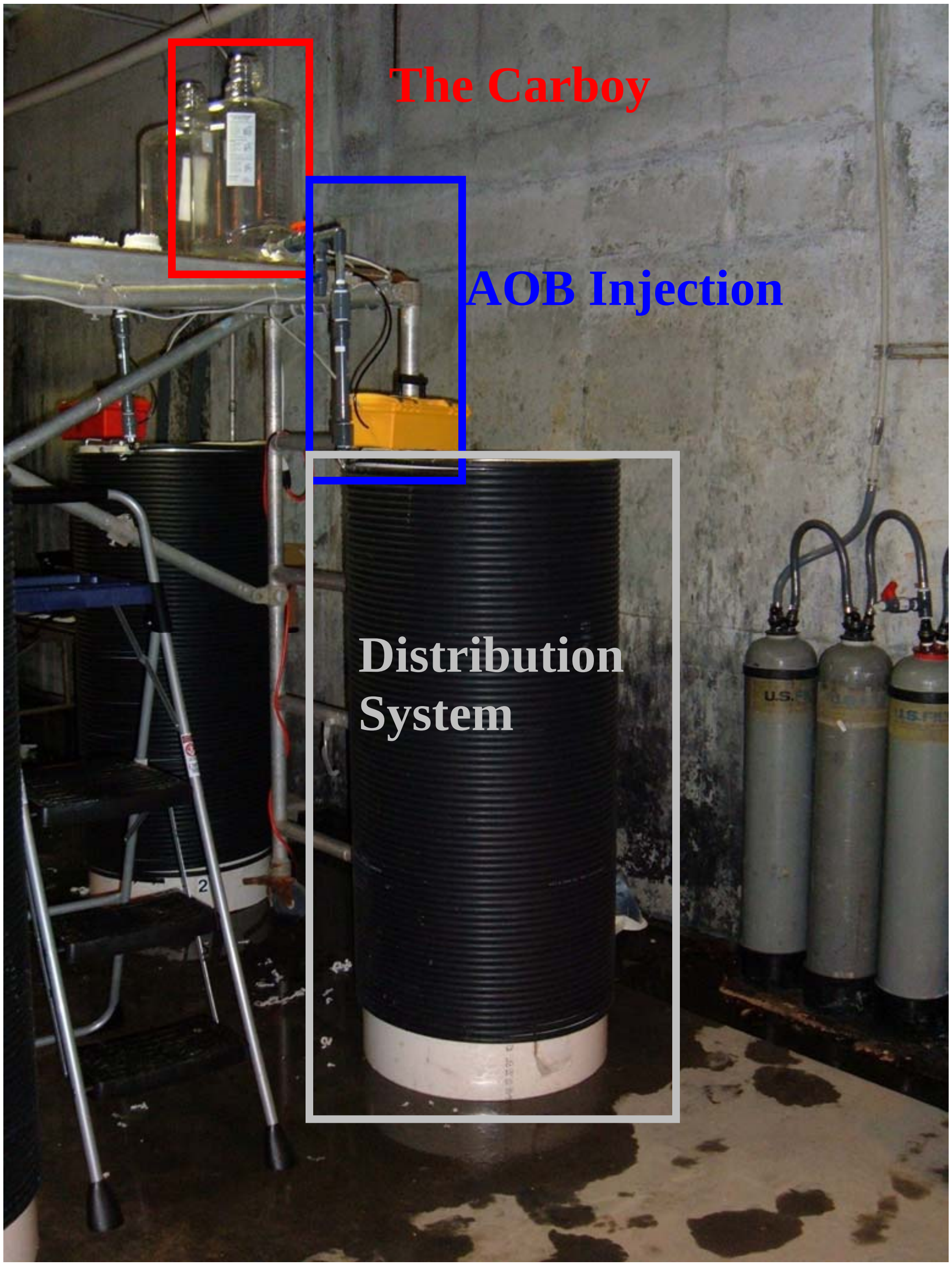


Figure 1: Nitrification test unit overview

a. The Distribution System

Purpose

The purpose of the distribution system is to dynamically model detention time of a full-scale distribution system. The test unit distribution system is advantageous in that it is a better simulation of water movement during a test period that a jar test would be.

Choosing the equipment

The COT used basically the same equipment from the Tucson study. Irrigation tubing works well for the distribution system because it is readily available in very long, continuous lengths.

The PVC tubing support provides a rigid structure for the irrigation tubing to be wrapped around. The COT looked at several other options (i.e. corrugated pipe, rolled aluminum), but none offered the smooth outer surface and support of PVC.

The needle valve is the only flow controller on the entire test unit. It is essential that the needle valve be high quality and easily adjustable to the desired flow rate. Be sure to choose a needle valve that can be fitted to the inside diameter of the irrigation tubing.

Installing the equipment

1. Place the PVC tubing support on a moving dolly or other object with wheels that can spin in a circle.
2. Stretch out the entire length of irrigation tubing.
3. Drill four holes in the PVC tubing support 6 inches from the bottom.
4. Insert zip ties into the holes and use the zip ties to clamp the irrigation tubing against the PVC tubing support.
5. Begin slowly winding the irrigation tubing onto the PVC support by spinning the dolly in a circle.
6. Be sure to keep the irrigation tubing tight against the PVC support as it is wound.
7. When there is only a few feet left to wind, drill four more holes near the top of the PVC support.


Figure 2: Zip tie attached to irrigation tubing at top of PVC support

8. Wind the last few feet of the irrigation tubing and then use zip ties to clamp the irrigation tubing against the PVC support.
9. Designate one end of the PVC support as the bottom and slide a worm gear clamp over that end.
10. Insert the needle valve into the irrigation tubing and tighten the worm gear clamp around the needle valve.
11. Move the completed distribution system next to the scaffolding.


Figure 3: Needle valve at the bottom of the irrigation tubing

b. The Carboy

Purpose

The purpose of the carboy is to be a holding tank for the test water while the test water slowly feeds into the system.

Choosing the equipment

As stated earlier, the carboy will need to be clear. The size of the carboy should be based on the preconstruction design parameters in Section III. The COT chose to use 20 liter clear carboys with spigot.

The spigot fitting on the carboy is an unusual threading and size, so the COT decided to use 4-5 inches of 1 inch diameter PEX tubing to make the connection.

A 1 inch slip male X ½ inch thread male reducer bushing was chosen to connect the PEX to the carboy isolation valve. This setup is shown in Figure 4.

Figure 4: Carboy connection to isolation valve

COT used true union ½ inch valves for the carboy isolation valve. One may question why the COT did not use the supplied spigot connection for the carboys as the carboy isolation valve. During initial testing, the COT had issues with air locking in the line that was preventing test water in the carboy from flowing into the AOB injection point and the distribution system. There are ways to use the supplied spigot as the isolation valve, but the COT chose this connection.

Equipment Installation

1. Identify where the test units will be located.
2. Setup the scaffolding high enough to place the carboys above the rest of the test unit.

Figure 5: Scaffolding with carboys on top

3. If using PEX tubing to connect the isolation valve, be sure to have the expander tool.
4. After wrapping the carboy fitting with Teflon tape, use the expander tool to place the PEX tubing around the carboy fitting.
5. Use the expander to place the other end of the PEX over a 1 inch slip male X 1/2 inch threaded male reducer bushing.
6. Now connect the threaded female end of the isolation valve to the threaded male end of the reducer bushing.
7. Close the isolation valve and fill the carboy to the top.
8. Place the lid on top of the carboy, but do not tighten the lid. If the lid is tightened, the test water will not flow out of the carboy.
9. Check and fix any leaks.

Figure 6: Carboy connected and operating

c. The AOB Injection Point

Purpose

The purpose of the AOB injection point is to have a place where AOB can be added to the system as needed to speed up the testing of nitrification. If the AOB were grown in the distribution system with no seeding, then it could take months before nitrification could occur. With the AOB injection, one will see nitrification almost immediately if an acclimated culture of AOB is injected.

Dr. McGuire's Tucson study used a closed bacterial reactor that consisted of piping full of glass beads. The seed bacteria were added at the beginning of the study before the test started and again halfway through the study.

COT suggests using a syringe pump for greater control on the injection of the bacteria. The syringe pumps add extra cost to the project, but they also add a greater degree of nitrification control. Dr. McGuire's method worked well for his study and may be a cheaper option for utilities with a budget constraint.

Choosing the equipment

The components of the AOB injection point are the sample valve, syringe pump, pump housing, injection tap, and static mixer.

Figure 7: AOB injection point

The sample valve needs only to be a simple valve or stopcock that allows the collection of water from the carboy. COT chose to use a ½ inch threaded ball valve.

Figure 8: Syringe pump

COT used single speed syringe pumps fitted with 60ml plastic syringes. These syringes injected the AOB at a rate of ~0.01 ml/min. The full-time injection of this volume of AOB proved to be too high to simulate a distribution system. Future tests should use a smaller (5-10ml) syringe or use the larger syringe in 3-4 week intervals.

Due to the sensitivity of AOB to ultraviolet radiation, the syringes cannot have direct UV light. COT found that basic plastic toolboxes worked perfectly. Each toolbox had to be drilled in one spot for the syringe pump power cord and another spot for the syringe outflow tubing.

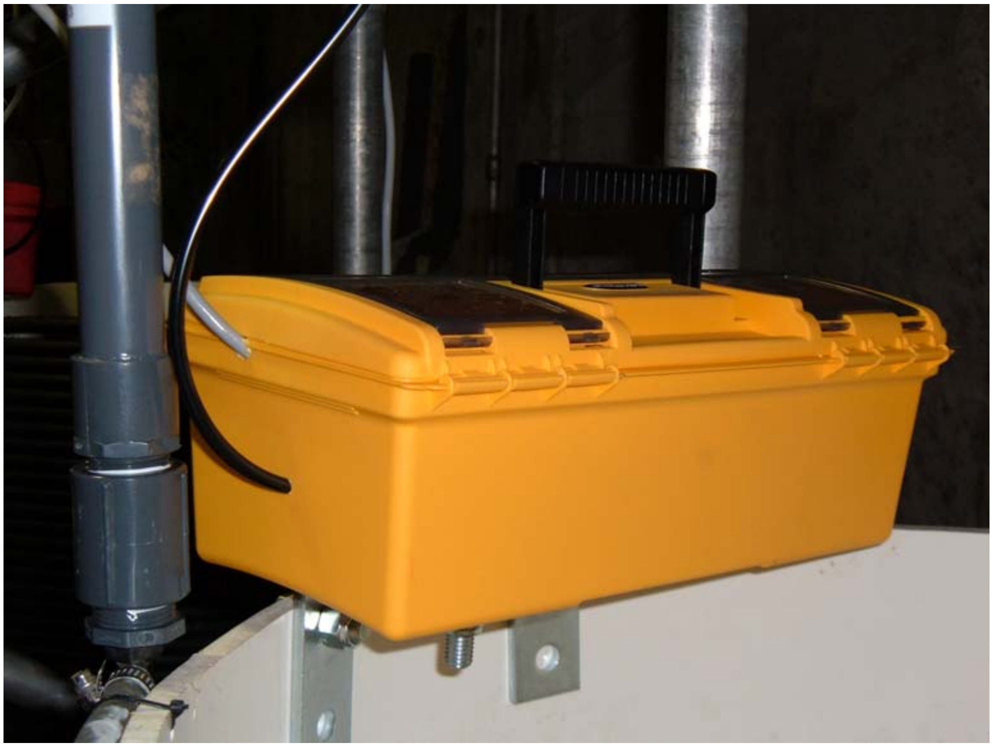


Figure 9: Toolbox used to house syringe pump

The injection tap was simply a threaded connection into the 1/2” PVC pipe that was carrying the test water. It is very important to attach tubing clamps to the tubing from the syringe pump to the tap. As the syringe pumps is taken off line and filled, there will need to be a way to stop the test water from flowing out of the injection tap.

Figure 10: Tubing clamps

To facilitate mixing of the test water with the injected AOB, COT used static inline mixers. These 1” mixers have 6 blades on the inside that maximize the integration of the AOB into the test water.

Installing the equipment

Sample valve, test water delivery line, and static mixer

1. Slide a ½ inch worm gear clamp over the irrigation tubing at the top of the distribution system.
2. Insert a ½ inch 90 degree barb-thread fitting into the irrigation tubing.
3. Slide the worm gear clamp over the barb end of the fitting and tighten.

Figure 11: Static mixer connection to irrigation tubing

4. Connect the thread end of the barb-thread fitting to the female end of a 1 inch male-½ inch female reducer.
5. Connect the 1 inch male end of the reducer and the 1 inch male end of the static mixer to a 1 inch threaded coupling.

(Note: There is probably an easier way to make this connection.)

6. Connect the upper 1 inch male end of the static mixer into another 1 inch threaded coupling.
7. Connect another 1 inch male-1/2 inch female reducer to the coupling.
8. Measure the vertical distance between the top of the static mixer and the centerline of the carboy spigot where the carboy sits on the scaffolding.
9. Cut a piece of ½ inch PVC pipe to the length measured in step 8.
10. Thread one end of the pipe.
11. Complete all 9 steps of the following section titled “Syringe pump, housing, and injection tap”
12. Insert the threaded end of the pipe into the female end of the 1 inch male X 1/2 inch female reducer.
13. Glue the other end of the pipe into a 90 degree slip fitting.
14. Cut a small piece of ½ inch PVC to serve as a nipple between the 90 degree fitting and a ½ inch PVC slip T fitting.
15. Glue the nipple to the 90 degree fitting and one of the straight ends of the T.
16. Install the sample valve out of the perpendicular end of the T fitting.
17. Install the final straight end of the T to the carboy isolation valve.

Figure 12: Connection of isolation valve to sample valve and static mixer

Syringe pump, housing, and injection tap

1. Place two L-brackets against the side of the PVC tubing support and the toolbox to determine where holes will need to be drilled.
2. Drill two holes in the side of the PVC tubing support and drill two more holes in the bottom of the toolbox.
3. Using nuts and bolts mount the L-brackets to the tubing support and then mount the toolbox to the L- brackets.

Figure 13: L-brackets mounted to toolbox and PVC tubing support

4. Place the syringe pump in the toolbox and mark the drill hole locations of where the syringe tubing and the syringe pump power cord will exit the toolbox.

Figure 14: Top view of syringe pump mounted and operating in the toolbox

5. Cut enough length of tubing to reach the test water line from the syringe.
6. Install a tubing clamp on the syringe tubing line.

7. Drill and tap the ½ inch PVC pipe from step 9 in the above section “*Sample valve, test water delivery line, and static mixer*” to accept the fitting for the tubing. COT used a 1/8 inch barb X 3/16 inch thread fitting.

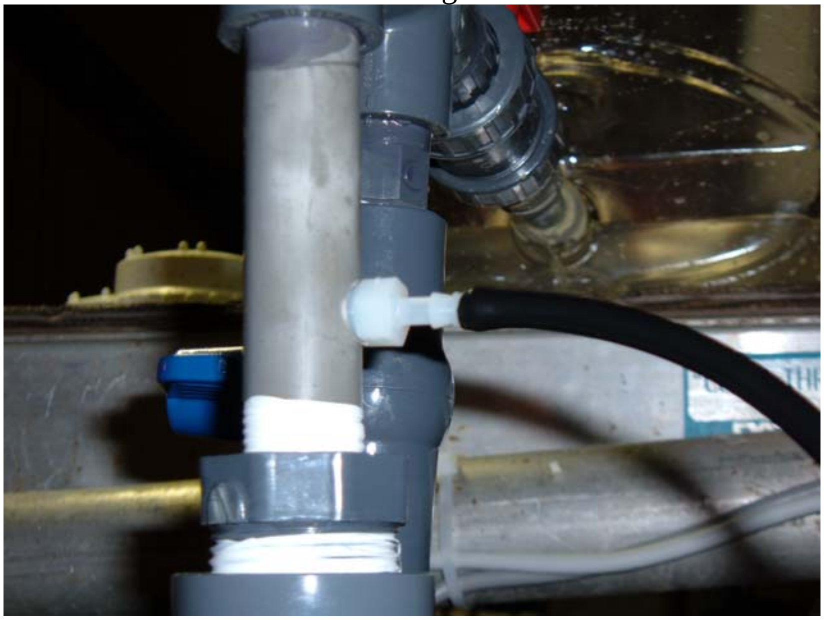


Figure 15: Injection tap into test water delivery line

8. Do not connect the syringe tubing to the injection tap until the entire test water line is complete.
9. Return to step 12 in the “*Sample valve, test water delivery line, and static mixer*” section.

V. **Suggested Improvements**

Although these units performed well during the nitrification study, there is always room for improvement. Below are some suggestions to pursue the next time these units are built.

- The carboy fitting-There has to be a way to get the spigot that is supplied with the carboy to work. The COT’s air locking issue may have just been a random occurrence or the result of some other component within the system.
- The static mixer- The static mixer and its inlet and outlet connections can be simplified. The static mixers used in the study were more specifically designed for higher flows and more complex systems. Also, some kind of 1 inch female X 1/2 inch female reducer could have made the inlet/outlet connections easier.
- The syringe pumps- If the test units are close enough together, it may be possible to use one central multi-syringe pump. The COT’s syringe pump vendor has several models that can hold between 1-12 syringes on one pump. If the distance is not too great, one pump could hold enough syringes to feed all of the carboys in the test. This would save money and simplify the construction and operation.

It is of the utmost importance that this manual be updated and improved. Please contact the author with any suggested improvements or modifications that could be included in this manual.

VI. Equipment List

Note: The manufacturer and location of purchase information are for convenience only. The COT does not endorse any of the products or vendors on this list. Most of the products listed as “na” are general products that can be purchased from various locations.

a. Distribution system

Quantity	Item description	Manufacturer	Location of purchase
1	24 inch PVC Schedule 40 pipe	na	Ferguson Plumbing
1	500 feet 0.58 inch ID irrigation tubing	Rainbird	The Water Store
4	7.5 inch zip ties	na	Lowes
2	Worm gear clamps	na	Lowes
1	Needle valve	na	na

b. The carboys

Quantity	Item description	Manufacturer	Location of purchase
1	Clearboy Carboys	Nalgene	VWR.com
1	PEX tubing	Zurn	Ferguson Plumbing
1	Reducer bushing 1 inch slip male X ½ inch thread male	na	Ferguson Plumbing
1	½ true union ball valve	Dura	Ferguson Plumbing

c. AOB injection point

Quantity	Item description	Manufacturer	Location of purchase
1	½ inch barb X ½ inch thread 90 degree PVC fitting	na	Lowes
2	½ inch thread female X 1 inch thread male PVC reducer bushing	na	Ferguson Plumbing
1	Static mixer PVC 1 inch	Koflo	BigBrandWater.com
2	1 inch threaded PVC coupling	na	Ferguson Plumbing
1	Measured length of ½ inch PVC pipe, one end threaded	na	Ferguson Plumbing
1	½ inch slip PVC 90 degree fitting	na	Ferguson Plumbing
3	3-4 inch long, ½ inch PVC pipe pieces	na	Ferguson Plumbing
1	½ inch PVC slip tee	na	Ferguson Plumbing
1	½ inch PVC slip ball valve	Nibco	Grainger
1	1/8 inch thread male X 3/16 inch barb	US Plastic	US Plastic.com

	PVC fitting		
1	Measured length of 3/16 inch ID black tubing	na	Lowes
1	Clamp for up to ¼ inch tubing	US Plastic	US Plastic.com
1	Syringe 60 ml	National Scientific	Fishersci.com
1	Single speed syringe pump	Razel	Braintree Scientific.com
1	Plastic toolbox	Task Force	Lowes
4	Nuts and bolts	na	na
2	L brackets	na	na

VII. Operational Considerations

The operation of the nitrification test units will be dependent upon the goals of the pilot test program. Each utility will run a different test with different operational parameters. Below are some possible test parameters:

- Chlorite for nitrification control
- Varying detention times for finding chloramine decomposition
- Varying detention times for nitrification control
- Comparison of chlorine to ammonia ratio for nitrification control
- Length and intensity of free chlorine burn for nitrification control

This is definitely a short list of possibilities. Basically any jar test with the variable of distribution system detention time can be better modeled using these test units.

For the nitrification testing, the following analytical parameters were tested or considered for testing:

- Free ammonia
- Monochloramine
- Free chlorine
- Total chlorine
- pH
- Alkalinity
- Temperature
- Nitrite
- Nitrate
- Chlorite
- Heterotrophic Plate Count (HPC)
- Total coliforms
- AOB counts
- Total trihalomethanes (TTHM)
- Haloacetic Acids (HAA5)
- Total Organic Carbon (TOC)

During this testing, the City of Tulsa encountered several operational issues that should be mentioned. This is not a comprehensive list, but it does point out some of the major problems that could be avoided.

- Carboy lighting-While a source of ultraviolet light is necessary to control AOB growth in the carboy, the light source can also cause an algae growth issue. The algae will consume the monochloramine residual in the carboy and cause high levels of bacterial growth within the distribution system. A balance of light/dark may be necessary if algae growth becomes an issue.
- Chlorite/nitrite/nitrate analysis- On field testing kits, the chemical nature of chlorite, nitrite, and nitrate tend to cause them interference with each other. If those parameters are the cornerstone of a study, then extra money and time should be budgeted to prepare/ analyze the samples with methods that will eliminate the interference.
- Overfeed of AOB- During the beginning of the COT study, AOB were grossly overfed into the test units. Nitrite was detected in all the test units effluents-even the test units with chlorite addition. Only feed enough AOB to gently start and maintain the nitrification episode.
- Regular adjustment of the needle valves- The test units were flowing such small amounts of water that it was necessary to constantly adjust/calibrate the needle valves. A minute drift in 2ml/min flow can really be amplified over a 7 day period if not adjusted.
- Clamps on the syringe tubing- The syringes were originally installed without clamps on the syringe tubing. Every time the syringes were taken out to be refilled, test water flowed out of the syringe tubing. Make sure to have the clamps installed when the testing begins.

Appendix D- Equipment List with Cost

For simplicity, every item that cost less than $1.00 was given a cost of a $1.00.

a. Distribution system

Quantity	Item description	Cost
1	24 inch PVC Schedule 40 pipe-5 feet	$204
1	500 feet 0.58 inch ID irrigation tubing	$79
4	7.5 inch zip ties	$1
2	Worm gear clamps	$1
1	Needle valve	$250
	Total	**$535**

b. The carboys

Quantity	Item description	Cost
1	Clearboy Carboys	$210
1	PEX tubing	$1
1	Reducer bushing 1 inch slip male X ½ inch thread male	$2
1	½ true union ball valve	$19
	Total	**$232**

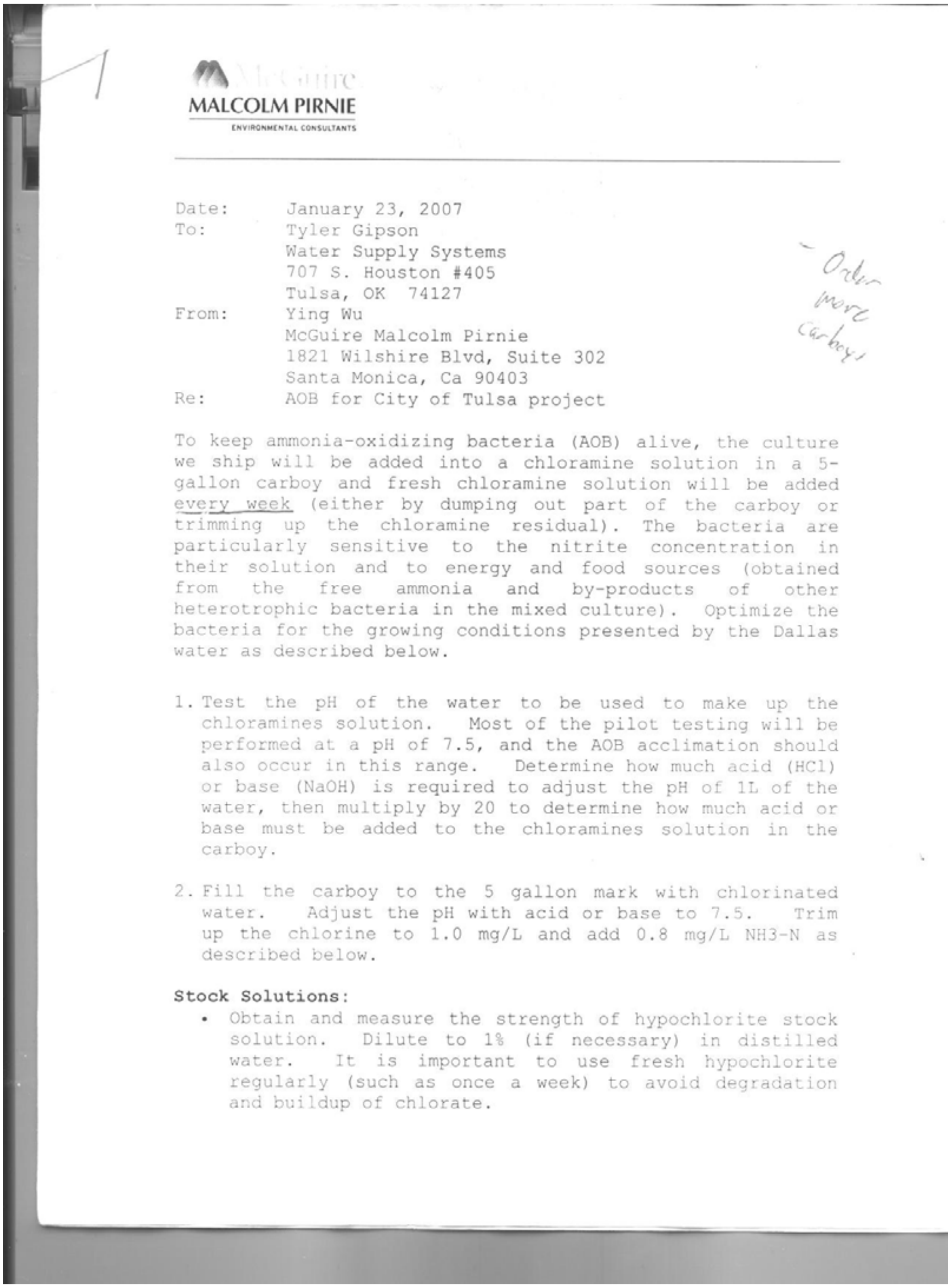
c. AOB injection point

Quantity	Item description	Cost
1	½ inch barb X ½ inch thread 90 degree PVC fitting	$1
2	½ inch thread female X 1 inch thread male PVC reducer bushing	$2
1	Static mixer PVC 1 inch	$99
2	1 inch threaded PVC coupling	$2
1	Measured length of ½ inch PVC pipe, one end threaded	$1
1	½ inch slip PVC 90 degree fitting	$2
3	3-4 inch long, ½ inch PVC pipe pieces	$1
1	½ inch PVC slip tee	$2
1	½ inch PVC slip ball valve	$5
1	1/8 inch thread male X 3/16 inch barb PVC fitting	$1
1	Measured length of 3/16 inch ID black tubing	$1
1	Clamp for up to ¼ inch tubing	$1
1	Syringe 60 ml	$3
1	Single speed syringe pump	$400

Quantity	**Item description**	**Cost**
1	Plastic toolbox	$15
4	Nuts and bolts	$2
2	L brackets	$5
	Total	**$543**

Total equipment cost to construct each test unit	**$1,310**
Total for 8 test units	**$10,480**

Appendix E: AOB Growth Instructions from Malcolm Pirnie



McGuire
MALCOLM PIRNIE
ENVIRONMENTAL CONSULTANTS

Date: January 23, 2007
To: Tyler Gipson
Water Supply Systems
707 S. Houston #405
Tulsa, OK 74127
From: Ying Wu
McGuire Malcolm Pirnie
1821 Wilshire Blvd, Suite 302
Santa Monica, Ca 90403
Re: AOB for City of Tulsa project

– Order more carboys

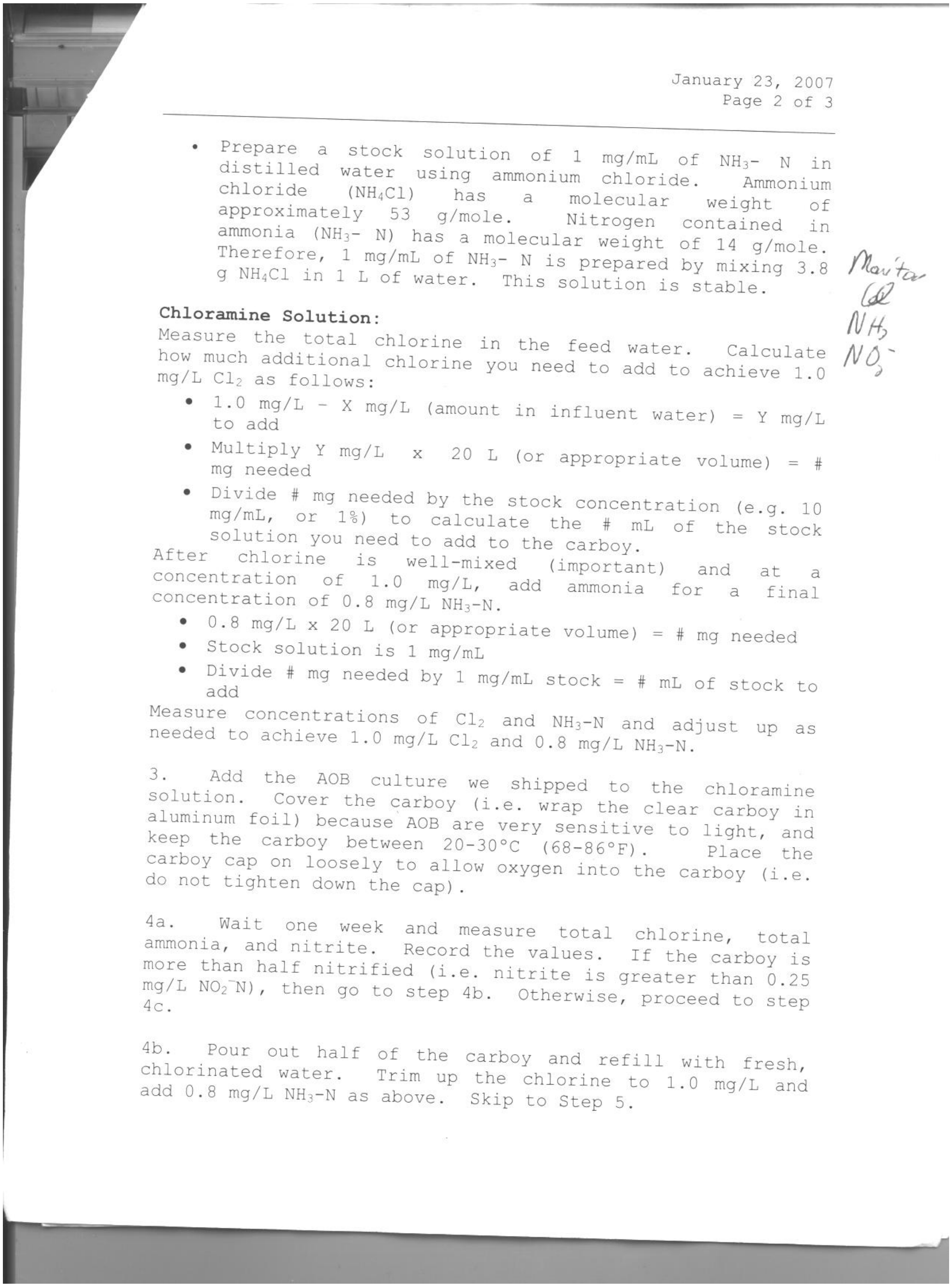
To keep ammonia-oxidizing bacteria (AOB) alive, the culture we ship will be added into a chloramine solution in a 5-gallon carboy and fresh chloramine solution will be added every week (either by dumping out part of the carboy or trimming up the chloramine residual). The bacteria are particularly sensitive to the nitrite concentration in their solution and to energy and food sources (obtained from the free ammonia and by-products of other heterotrophic bacteria in the mixed culture). Optimize the bacteria for the growing conditions presented by the Dallas water as described below.

1. Test the pH of the water to be used to make up the chloramines solution. Most of the pilot testing will be performed at a pH of 7.5, and the AOB acclimation should also occur in this range. Determine how much acid (HCl) or base (NaOH) is required to adjust the pH of 1L of the water, then multiply by 20 to determine how much acid or base must be added to the chloramines solution in the carboy.

2. Fill the carboy to the 5 gallon mark with chlorinated water. Adjust the pH with acid or base to 7.5. Trim up the chlorine to 1.0 mg/L and add 0.8 mg/L NH3-N as described below.

Stock Solutions:

- Obtain and measure the strength of hypochlorite stock solution. Dilute to 1% (if necessary) in distilled water. It is important to use fresh hypochlorite regularly (such as once a week) to avoid degradation and buildup of chlorate.



- Prepare a stock solution of 1 mg/mL of NH_3- N in distilled water using ammonium chloride. Ammonium chloride (NH_4Cl) has a molecular weight of approximately 53 g/mole. Nitrogen contained in ammonia (NH_3- N) has a molecular weight of 14 g/mole. Therefore, 1 mg/mL of NH_3- N is prepared by mixing 3.8 g NH_4Cl in 1 L of water. This solution is stable.

Monitor
Cl
NH_3
NO_2^-

Chloramine Solution:
Measure the total chlorine in the feed water. Calculate how much additional chlorine you need to add to achieve 1.0 mg/L Cl_2 as follows:

- 1.0 mg/L - X mg/L (amount in influent water) = Y mg/L to add
- Multiply Y mg/L x 20 L (or appropriate volume) = # mg needed
- Divide # mg needed by the stock concentration (e.g. 10 mg/mL, or 1%) to calculate the # mL of the stock solution you need to add to the carboy.

After chlorine is well-mixed (important) and at a concentration of 1.0 mg/L, add ammonia for a final concentration of 0.8 mg/L NH_3-N.

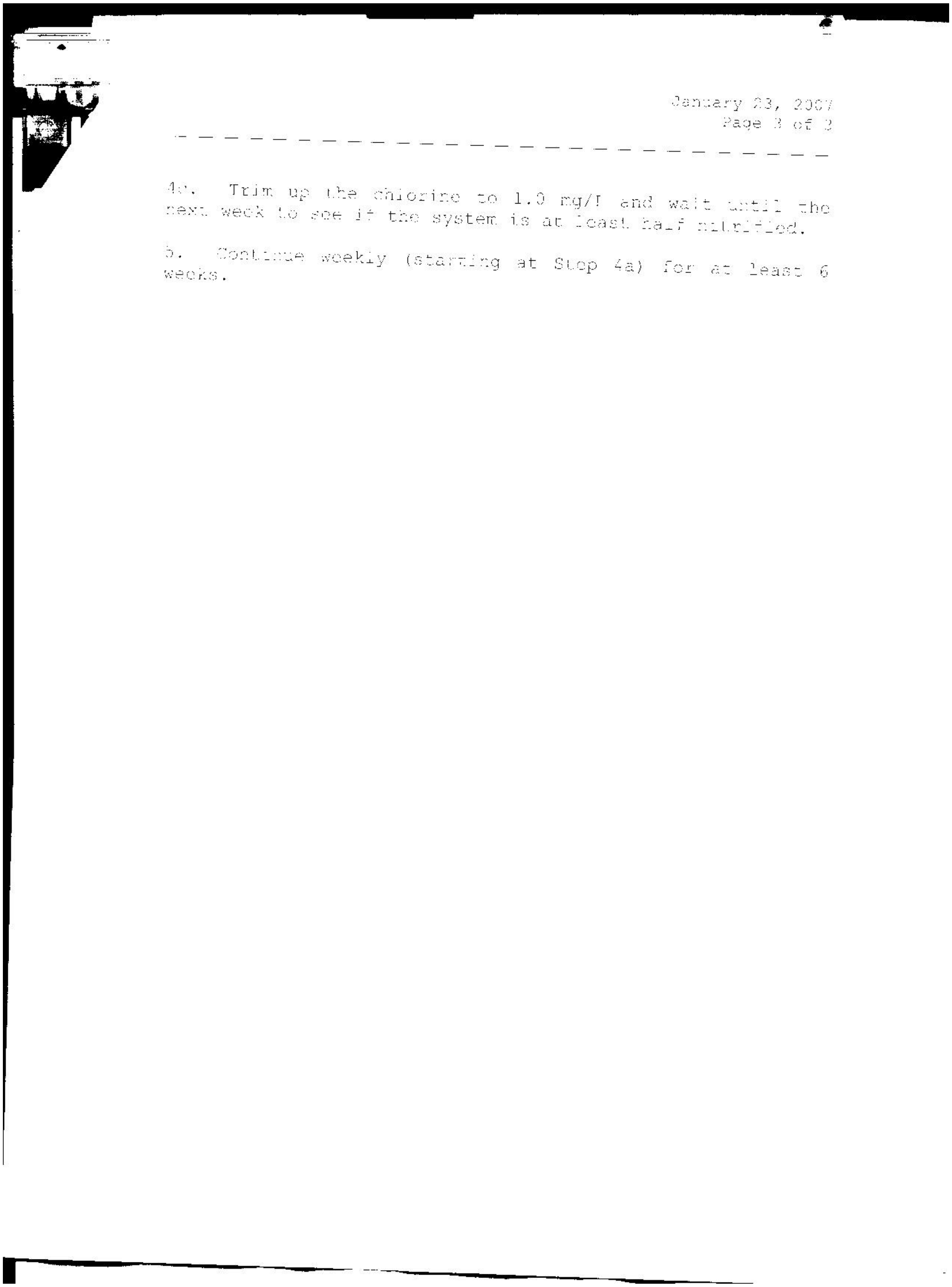
- 0.8 mg/L x 20 L (or appropriate volume) = # mg needed
- Stock solution is 1 mg/mL
- Divide # mg needed by 1 mg/mL stock = # mL of stock to add

Measure concentrations of Cl_2 and NH_3-N and adjust up as needed to achieve 1.0 mg/L Cl_2 and 0.8 mg/L NH_3-N.

3. Add the AOB culture we shipped to the chloramine solution. Cover the carboy (i.e. wrap the clear carboy in aluminum foil) because AOB are very sensitive to light, and keep the carboy between 20-30°C (68-86°F). Place the carboy cap on loosely to allow oxygen into the carboy (i.e. do not tighten down the cap).

4a. Wait one week and measure total chlorine, total ammonia, and nitrite. Record the values. If the carboy is more than half nitrified (i.e. nitrite is greater than 0.25 mg/L NO_2^-N), then go to step 4b. Otherwise, proceed to step 4c.

4b. Pour out half of the carboy and refill with fresh, chlorinated water. Trim up the chlorine to 1.0 mg/L and add 0.8 mg/L NH_3-N as above. Skip to Step 5.



January 23, 2007
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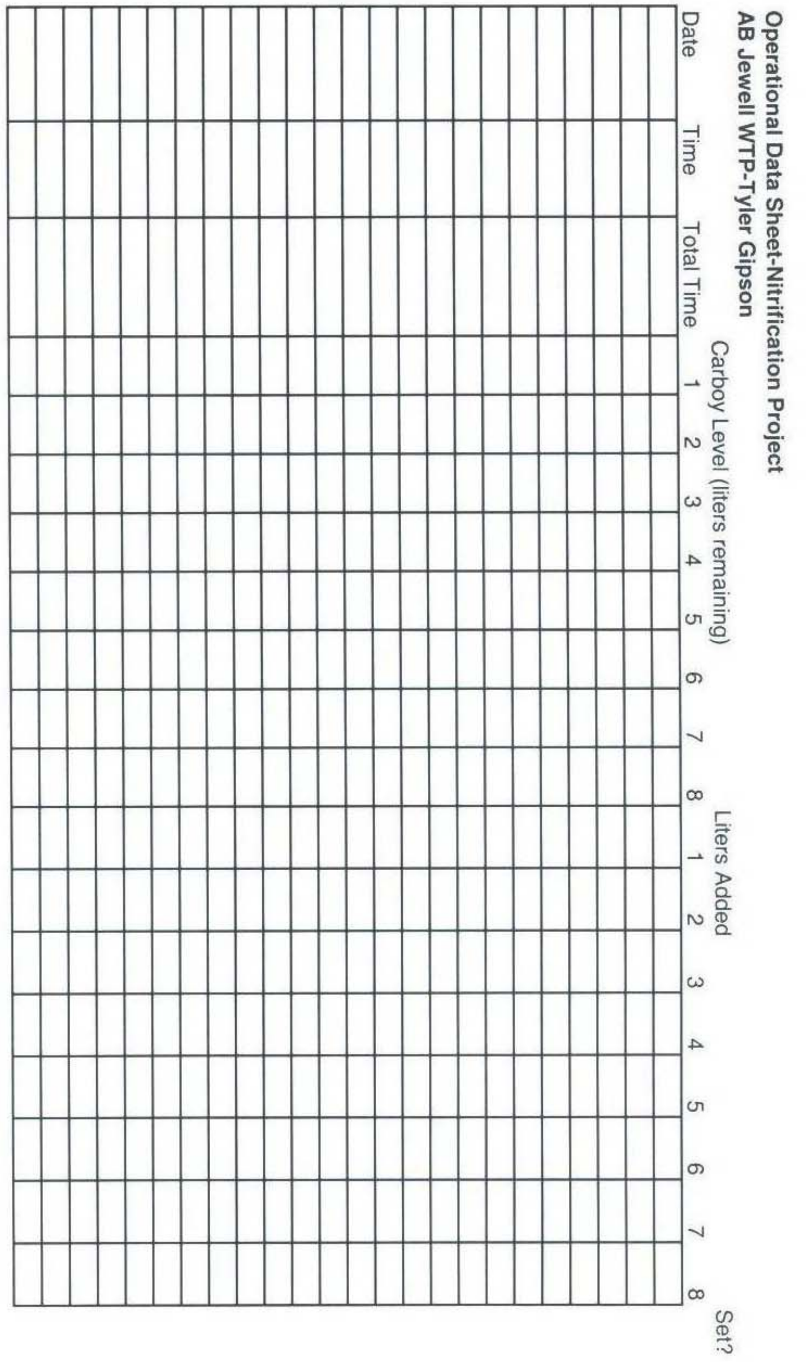
4c. Trim up the chlorine to 1.0 mg/l and wait until the next week to see if the system is at least half nitrified.

5. Continue weekly (starting at Step 4a) for at least 6 weeks.

Appendix F: Operational Data Sheet



Operational Data Sheet-Nitrification Project
AB Jewell WTP-Tyler Gipson

			Carboy Level (liters remaining)								Liters Added							Set?
Date	Time	Total Time	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8

Appendix G: Nitrite-Nitrogen Raw Data

Table 13: Effluent nitrite-nitrogen raw data from the pilot test units during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

	Date		All results in Nitrite-nitrogen (mg/l)											
Carboy	2-Jun	13-Jun	16-Jun	19-Jun	23-Jun	25-Jun	2-Jul	7-Jul	16-Jul	25-Jul	31-Jul	7-Aug	14-Aug	19-Aug
1	0.017	0.36	0.2	0.42	0.46	0.5	0.52	0.52	0.35	0.35	0.23	0.15	0.36	0.31
2	0.009	0.18	0.37	0.42	0.44	0.42	0.34	0.42	0.28	0.25	0.08	0.1	0.01	0
3	0.351	0.37	0.37	0.37	0.3	0.38	0.32	0.01	0	0	0	0	0.01	0
4	0.007	0.09	0.37	0.32	0.34	0.35	0.1	0	0	0	0	0	0.01	0
6	0.018	0.28	0.37	0.52	0.52	0.46	0.16	0	0	0	0	0	0	0
7	0.006	0.37	0.37	0.3	0.56	0.58	0.36	0.32	0	0	0	0	0	0
8	0.012	0.01	0.19	0.28	0.26	0.31	0.52	0.44	0.37	0.23	0.16	0.12	0.07	0.09

Table 14: Carboy nitrite-nitrogen results from the pilot test units during the 2008 nitrification study at A.B. Jewell WTP. Chlorite injection began on 6/2/08, and bacterial injection ended on 6/25/08.

	Date	All results in nitrite-nitrogen (mg/l)						
Carboy	6/16	6/26	7/2	7/8	7/15	7/21	8/4	8/14
1	0.01	0	0.01	0	0.01	0	0.1	0.01
2	0.01	0.01	0.01	0	0	0	0.02	0
3	0.01	0.01	0.03	0.15	0.03	0.02	0.09	0.06
4	0.01	0.01	0.01	0	0	0	0	0
6	0.01	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	na	0.01	0.01	0	0	0	0	0.01

Appendix H: Monochloramine and Free Ammonia Results

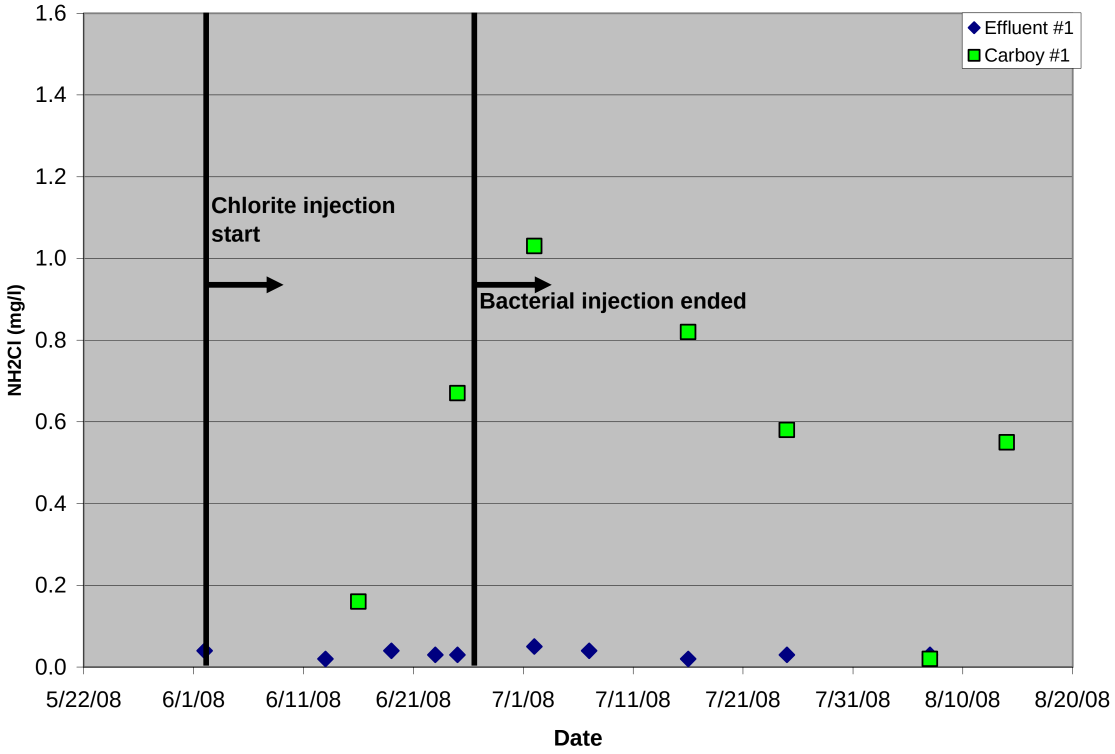


Figure 12: Pilot test unit #1 monochloramine effluent and carboy values during 2008 nitrification study at A.B. Jewell WTP.

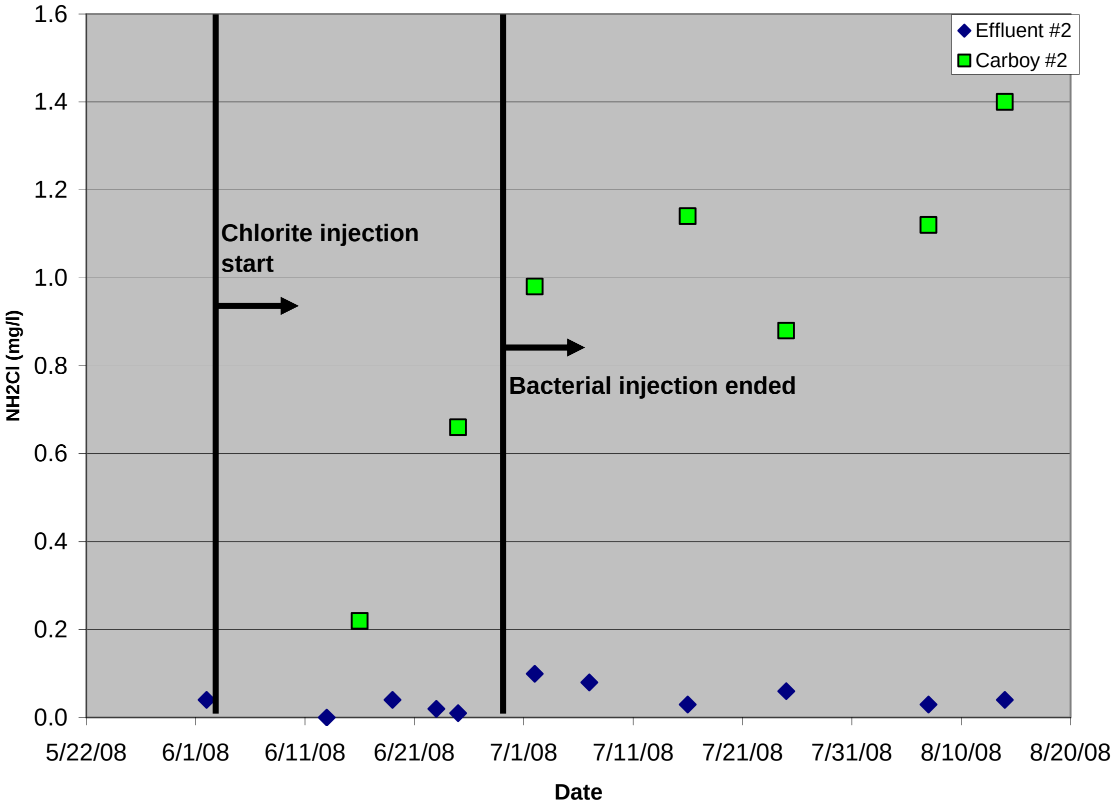


Figure 13: Pilot test unit #2 monochloramine effluent and carboy values during 2008 nitrification study at A.B. Jewell WTP.

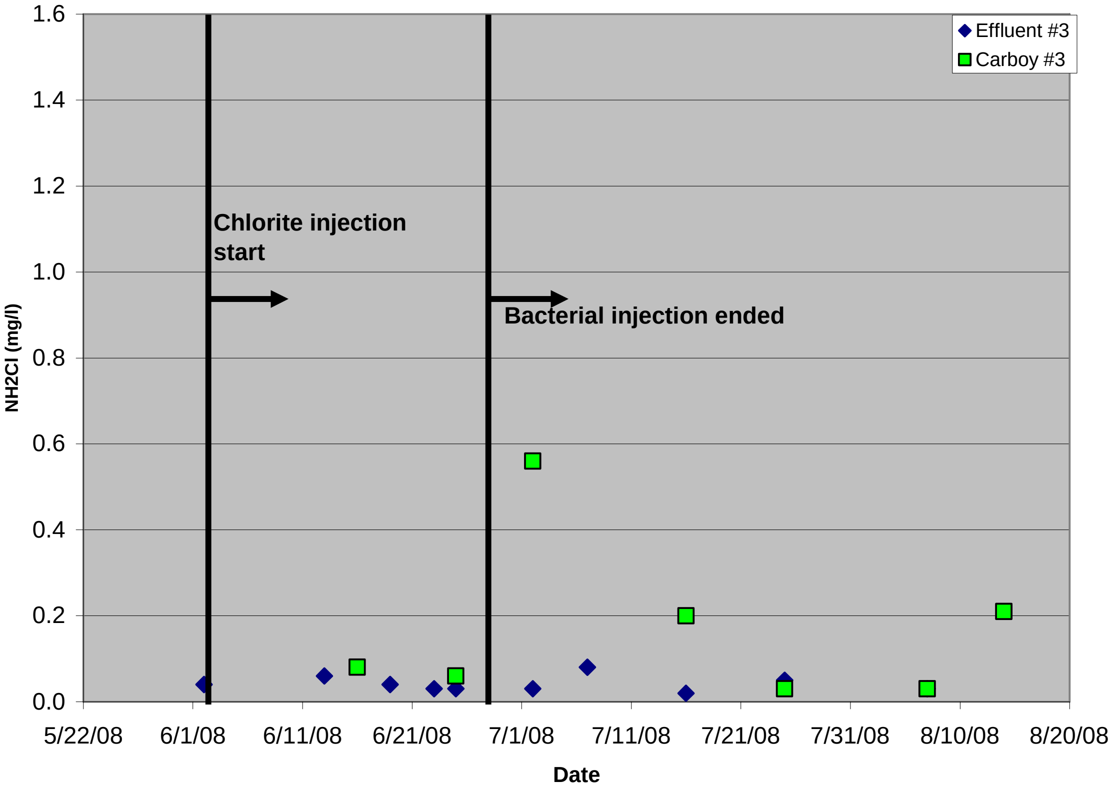


Figure 14: Pilot test unit #3 monochloramine effluent and carboy values during 2008 nitrification study at A.B. Jewell WTP.

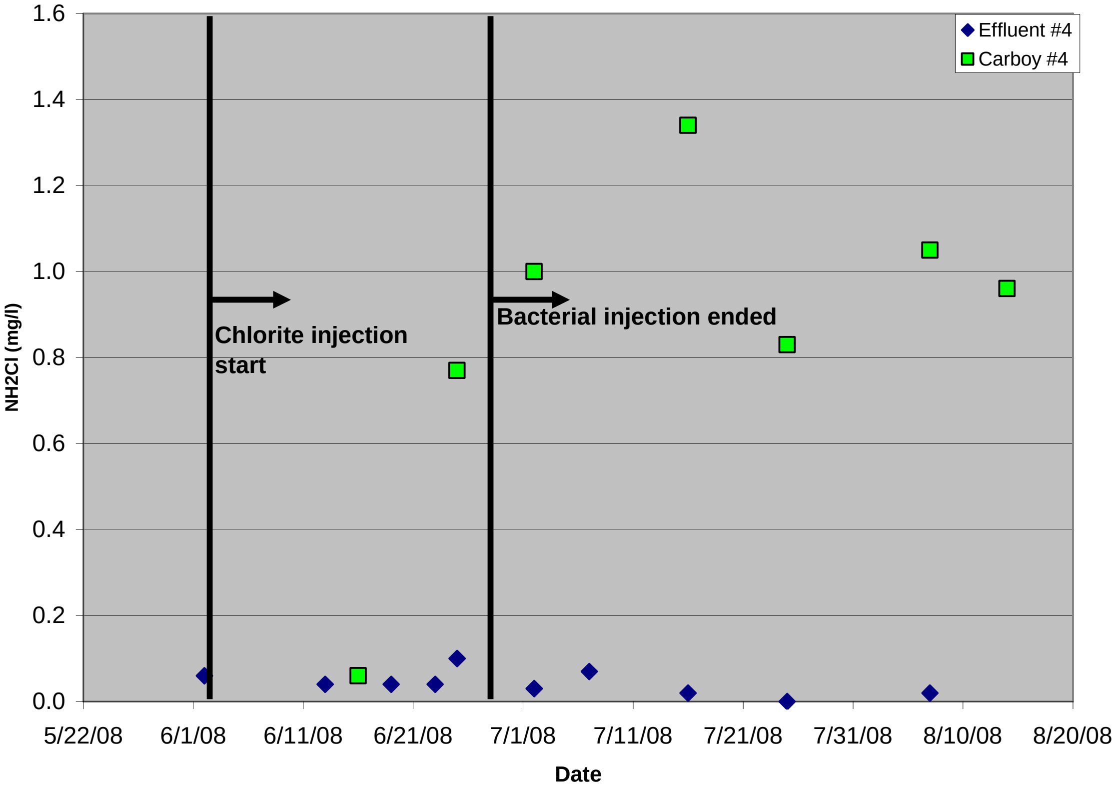


Figure 15: Pilot test unit #4 monochloramine effluent and carboy values during 2008 nitrification study at A.B. Jewell WTP.

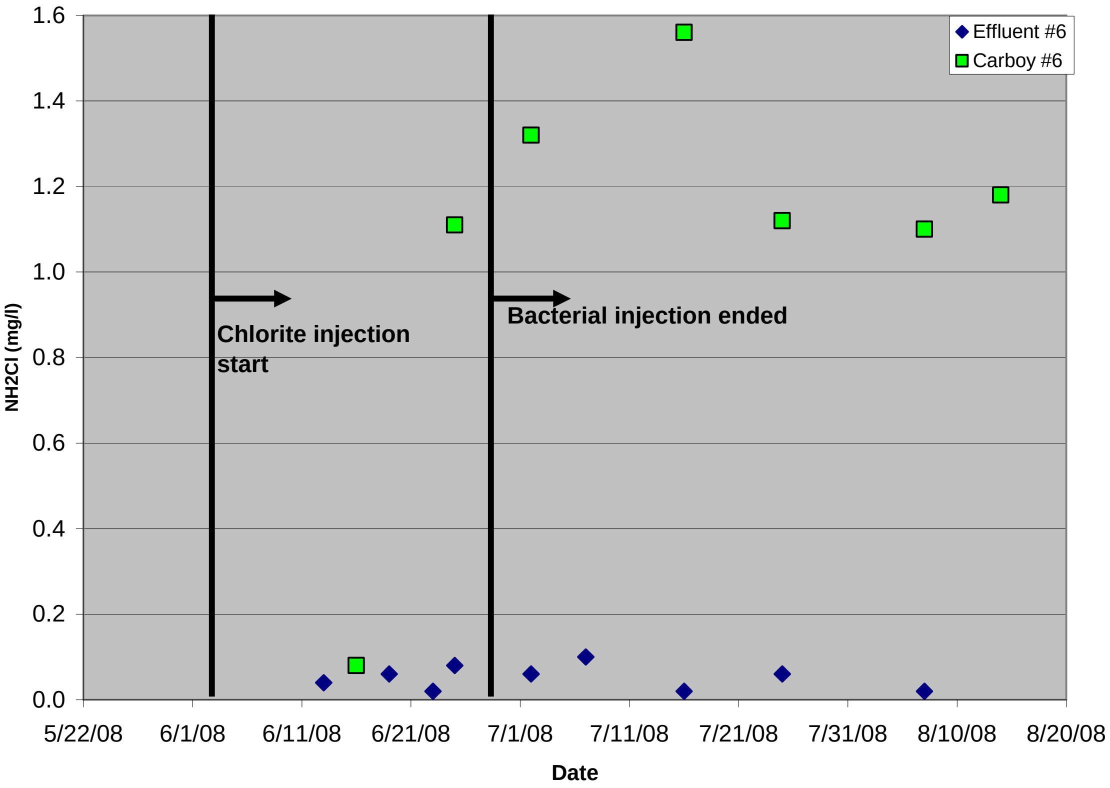


Figure 16: Pilot test unit #6 monochloramine effluent and carboy values during 2008 nitrification study at A.B. Jewell WTP.

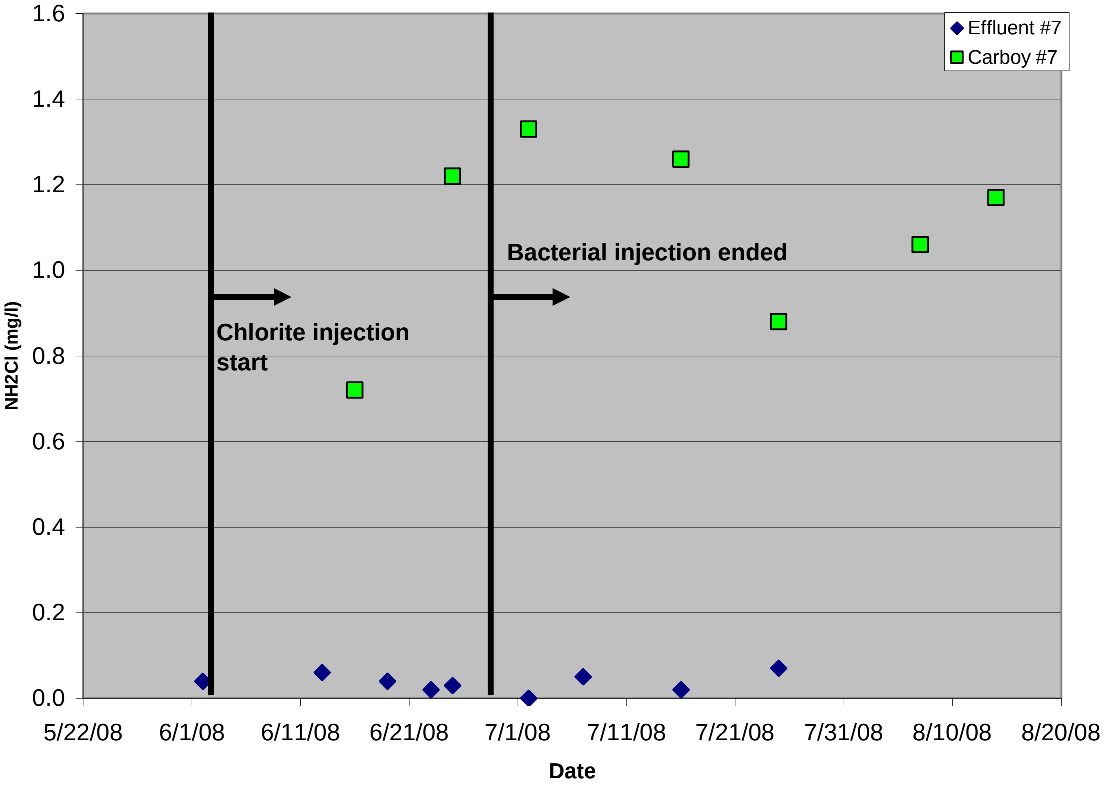


Figure 17: Pilot test unit #7 monochloramine effluent and carboy values during 2008 nitrification study at A.B. Jewell WTP.

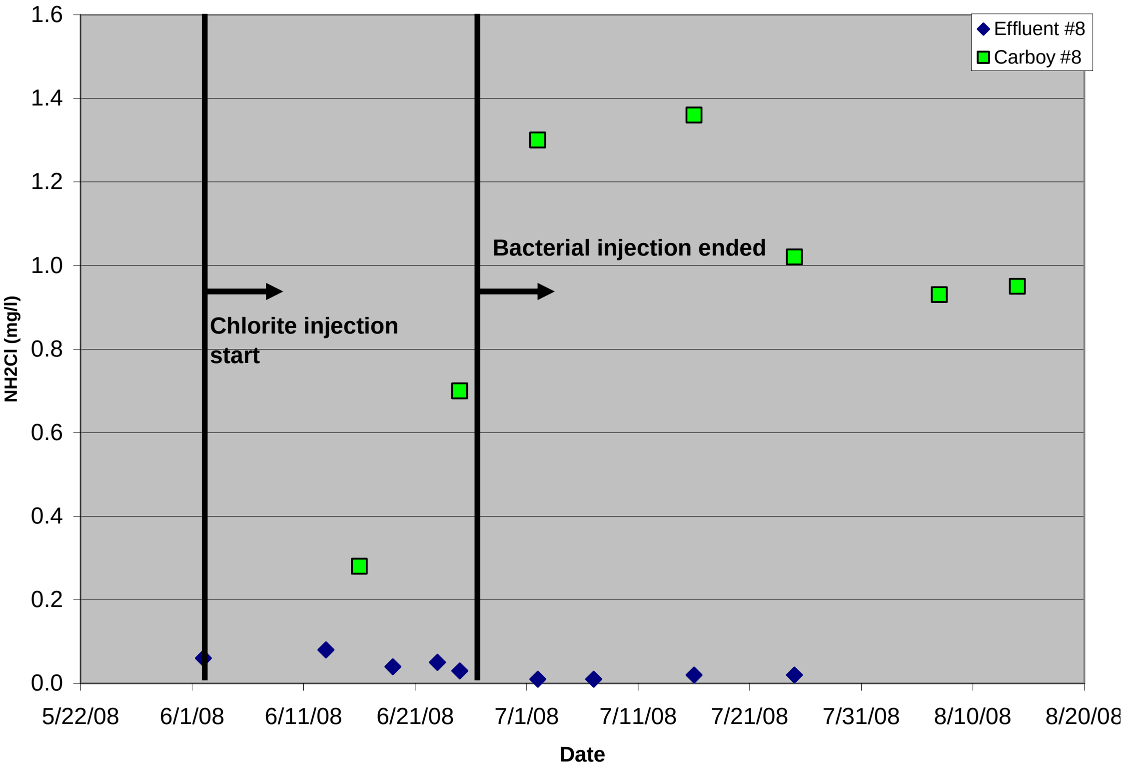


Figure 18: Pilot test unit #8 monochloramine effluent and carboy values during 2008 nitrification study at A.B. Jewell WTP.

Table 15: Monochloramine results from the pilot test units during the 2008 nitrification study at A.B. Jewell WTP.

Date

All results are monochloramine (mg/l)

	2-Jun	13-Jun	16-Jun	19-Jun	23-Jun	25-Jun	2-Jul	7-Jul	16-Jul	25-Jul	7-Aug	14-Aug
Effluent #1	0.04	0.02		0.04	0.03	0.03	0.05	0.04	0.02	0.03	0.03	
Carboy #1			0.16			0.67	1.03		0.82	0.58	0.02	0.55
Effluent #2	0.04	0		0.04	0.02	0.01	0.1	0.08	0.03	0.06	0.03	0.04
Carboy #2			0.22			0.66	0.98		1.14	0.88	1.12	1.4
Effluent #3	0.04	0.06		0.04	0.03	0.03	0.03	0.08	0.02	0.05	0.03	
Carboy #3			0.08			0.06	0.56		0.2	0.03	0.03	0.21
Effluent #4	0.06	0.04		0.04	0.04	0.1	0.03	0.07	0.02	0	0.02	
Carboy #4			0.06			0.77	1		1.34	0.83	1.05	0.96
Effluent #6		0.04		0.06	0.02	0.08	0.06	0.1	0.02	0.06	0.02	
Carboy #6			0.08			1.11	1.32		1.56	1.12	1.1	1.18
Effluent #7	0.04	0.06		0.04	0.02	0.03	0	0.05	0.02	0.07		
Carboy #7			0.72			1.22	1.33		1.26	0.88	1.06	1.17
Effluent #8	0.06	0.08		0.04	0.05	0.03	0.01	0.01	0.02	0.02		
Carboy #8			0.28			0.7	1.3		1.36	1.02	0.93	0.95

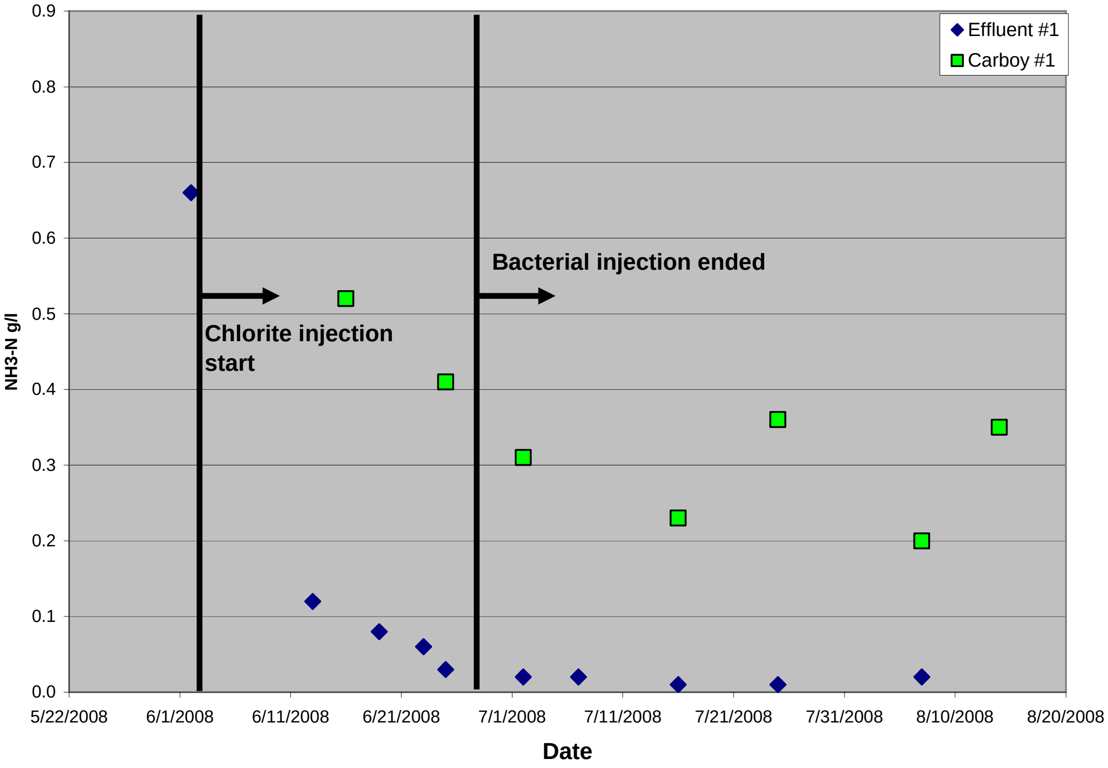


Figure 19: Pilot test unit #1 free ammonia-nitrogen during the 2008 nitrification study at A.B. Jewell WTP.

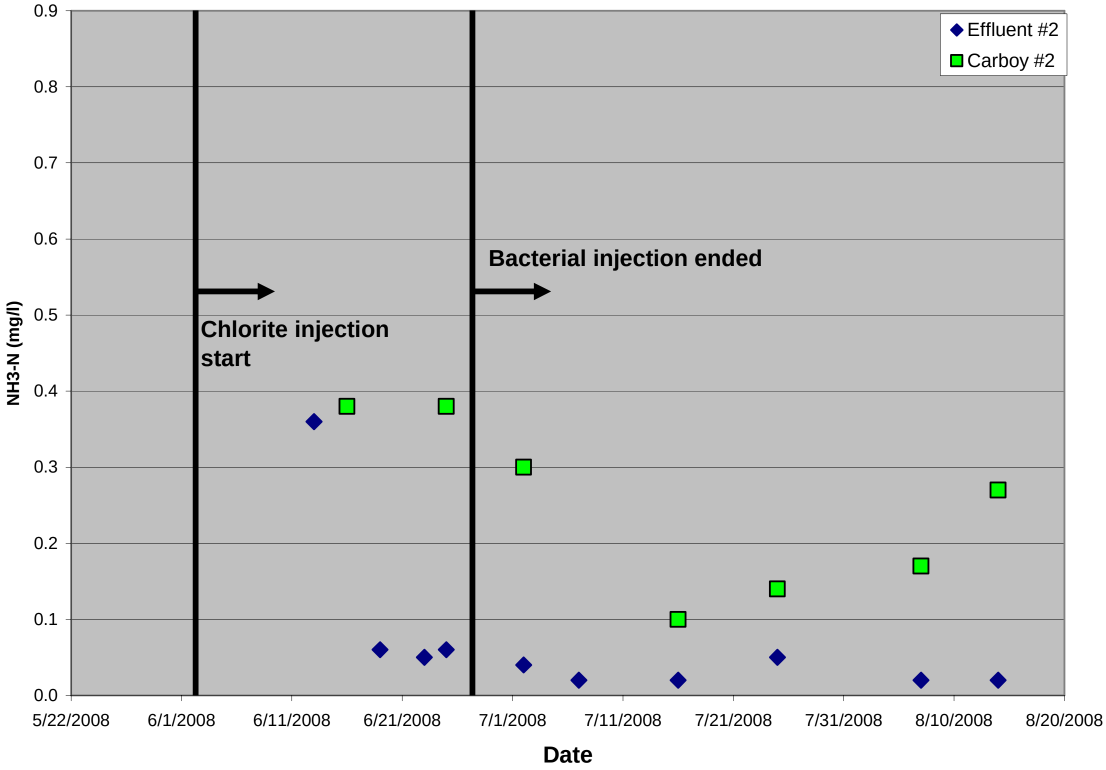


Figure 20: Pilot test unit #2 free ammonia-nitrogen during the 2008 nitrification study at A.B. Jewell WTP.

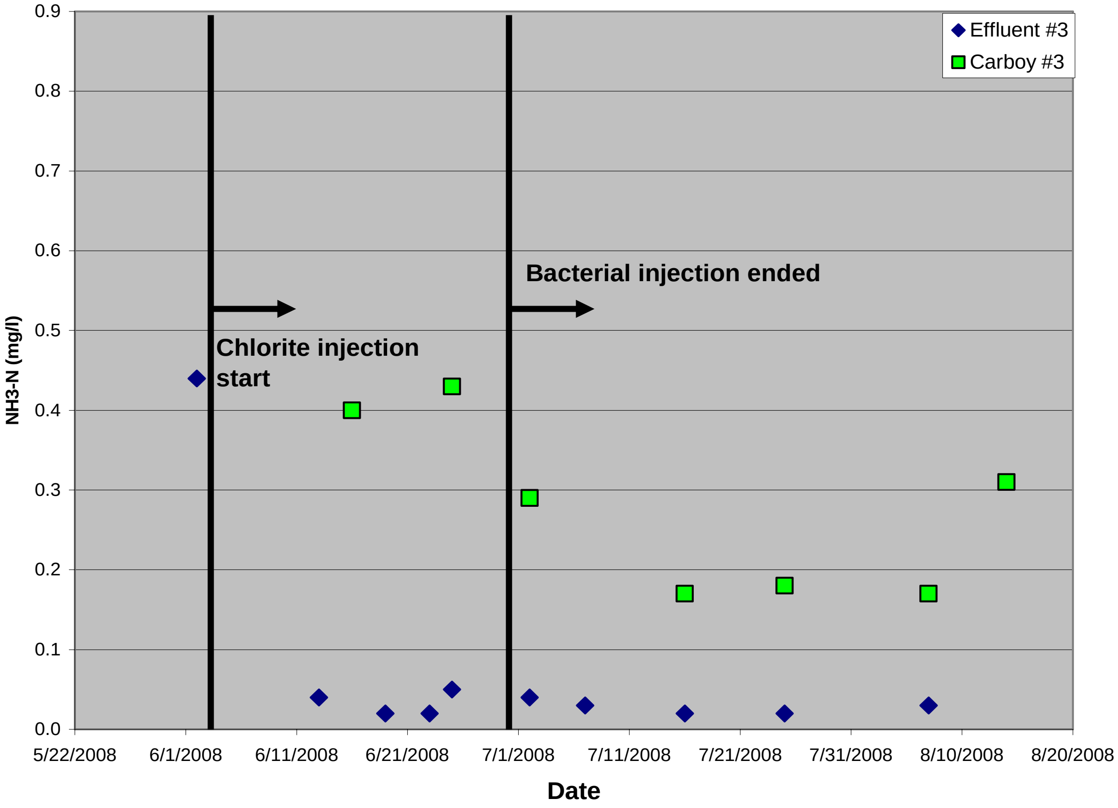


Figure 21: Pilot test unit #3 free ammonia-nitrogen during the 2008 nitrification study at A.B. Jewell WTP.

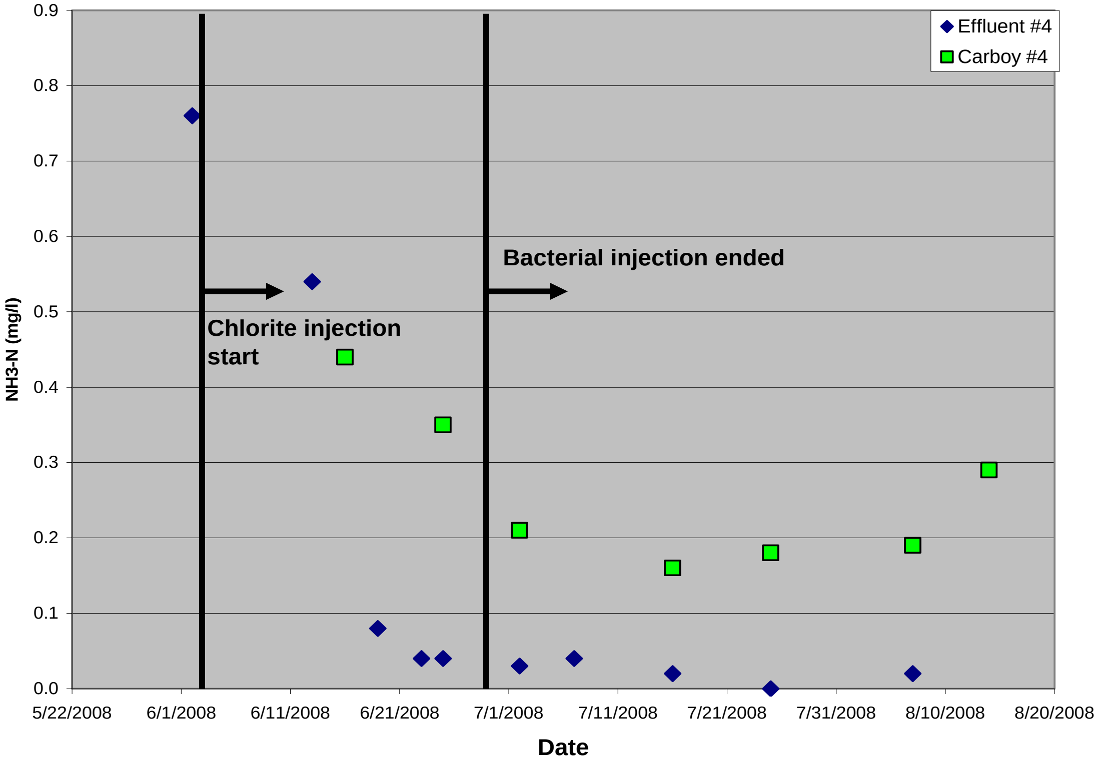


Figure 22: Pilot test unit #4 free ammonia-nitrogen during the 2008 nitrification study at A.B. Jewell WTP.

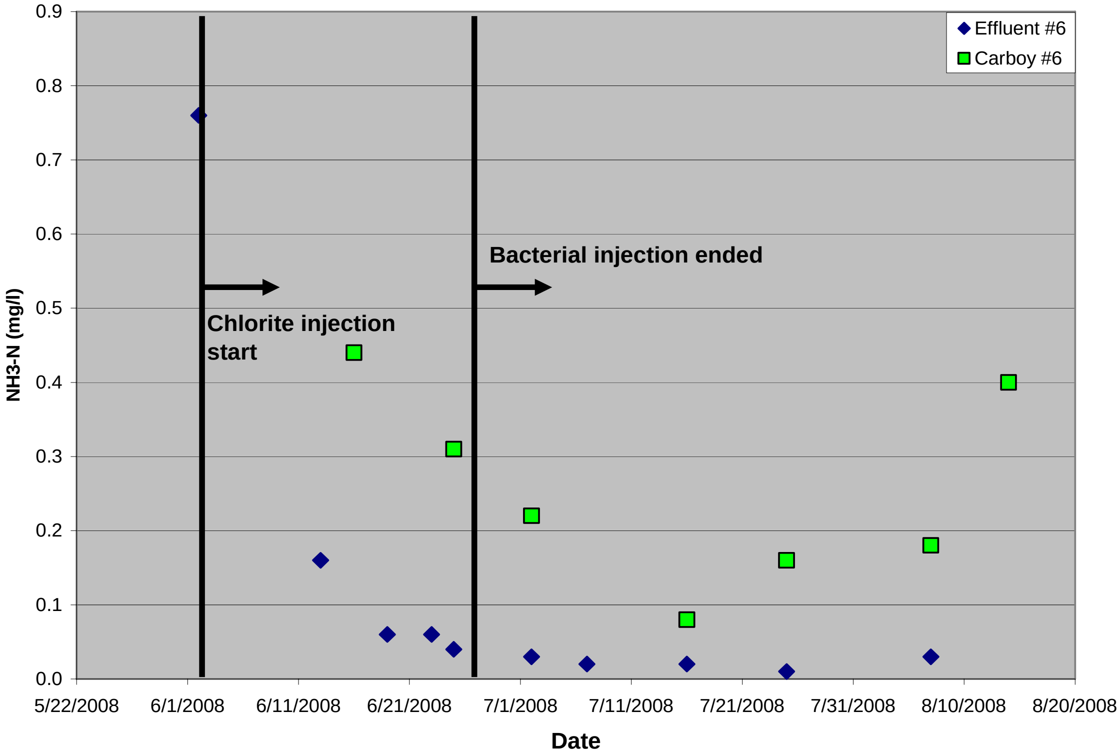


Figure 23: Pilot test unit #6 free ammonia-nitrogen during the 2008 nitrification study at A.B. Jewell WTP.

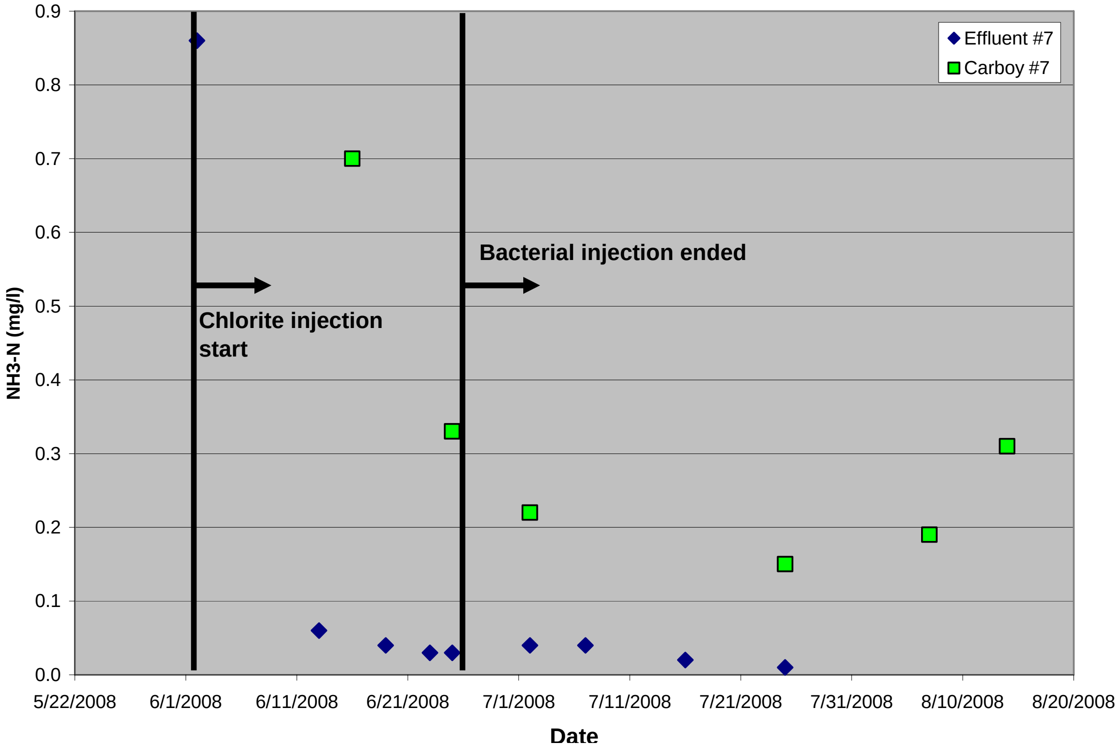


Figure 24: Pilot test unit #7 free ammonia-nitrogen during the 2008 nitrification study at A.B. Jewell WTP.

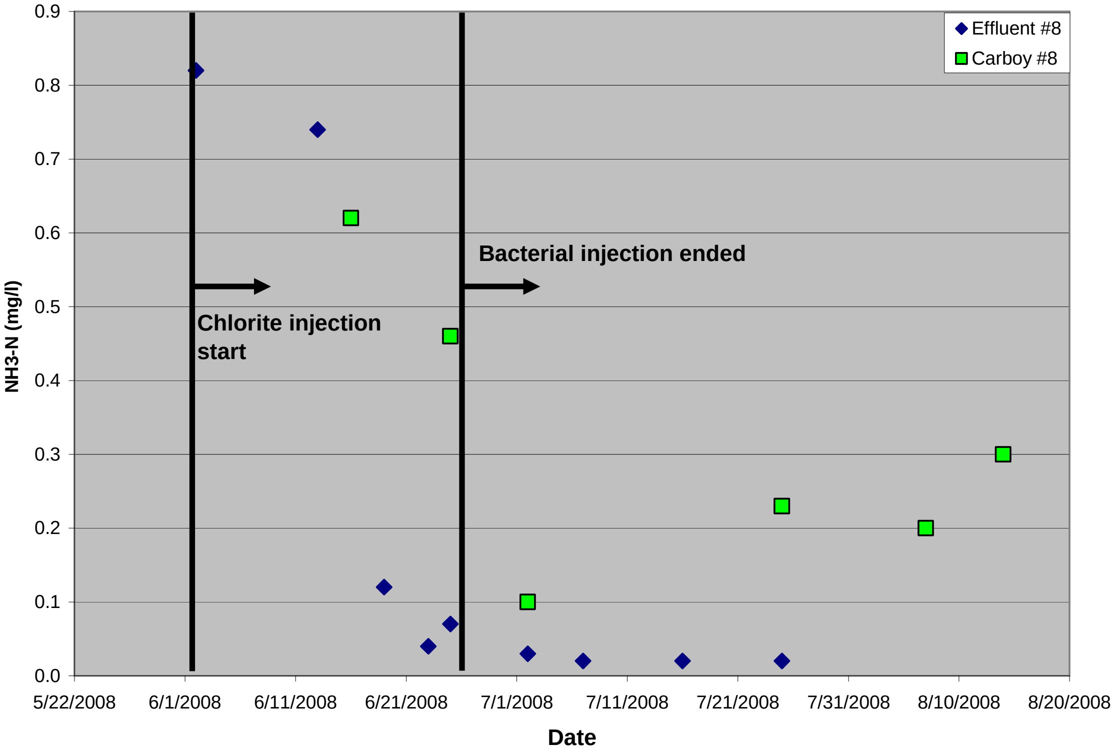


Figure 25: Pilot test unit #8 free ammonia-nitrogen during the 2008 nitrification study at A.B. Jewell WTP.

Table 16: Carboy and effluent free ammonia-nitrogen results from the pilot test units during the 2008 nitrification study at A.B. Jewell WTP.

	Date		All results in free ammonia-nitrogen (mg/l)									
	2-Jun	13-Jun	16-Jun	19-Jun	23-Jun	25-Jun	2-Jul	7-Jul	16-Jul	25-Jul	7-Aug	14-Aug
Effluent #1	0.66	0.12		0.08	0.06	0.03	0.02	0.02	0.01	0.01	0.02	
Carboy #1			0.52			0.41	0.31		0.23	0.36	0.2	0.35
Effluent #2	0.92	0.36		0.06	0.05	0.06	0.04	0.02	0.02	0.05	0.02	0.02
Carboy #2			0.38			0.38	0.3		0.1	0.14	0.17	0.27
Effluent #3	0.44	0.04		0.02	0.02	0.05	0.04	0.03	0.02	0.02	0.03	
Carboy #3			0.4			0.43	0.29		0.17	0.18	0.17	0.31
Effluent #4	0.76	0.54		0.08	0.04	0.04	0.03	0.04	0.02	0	0.02	
Carboy #4			0.44			0.35	0.21		0.16	0.18	0.19	0.29
Effluent #6	0.76	0.16		0.06	0.06	0.04	0.03	0.02	0.02	0.01	0.03	
Carboy #6			0.44			0.31	0.22		0.08	0.16	0.18	0.4
Effluent #7	0.86	0.06		0.04	0.03	0.03	0.04	0.04	0.02	0.01		
Carboy #7			0.7			0.33	0.22			0.15	0.19	0.31
Effluent #8	0.82	0.74		0.12	0.04	0.07	0.03	0.02	0.02	0.02		
Carboy #8			0.62			0.46	0.1			0.23	0.2	0.3

Appendix I: pH Results

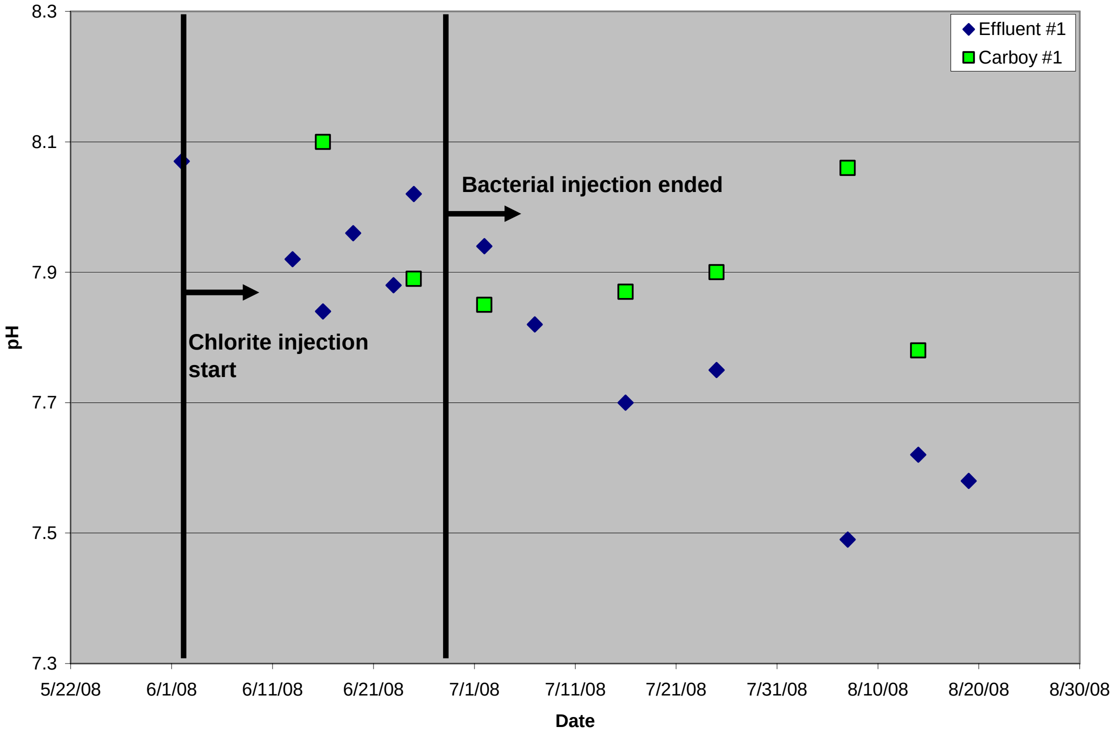


Figure 26: Pilot test unit #1 effluent and carboy pH during the 2008 nitrification study at A. B. Jewell WTP.

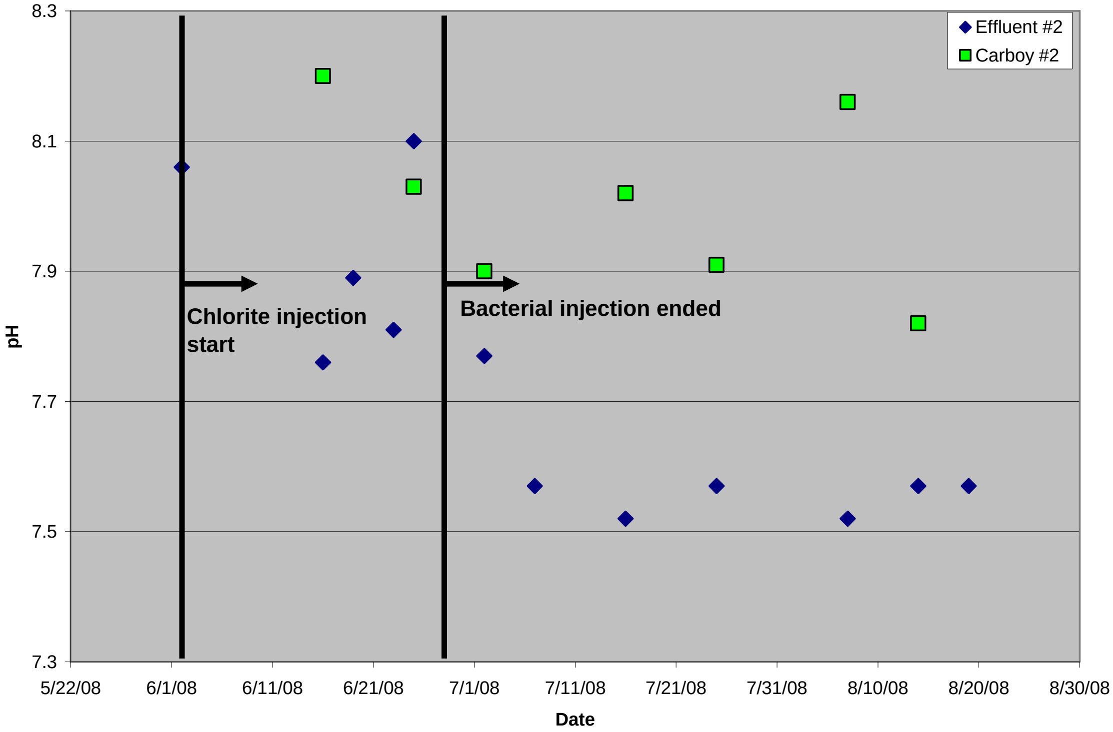


Figure 27: Pilot test unit #2 effluent and carboy pH during the 2008 nitrification study at A. B. Jewell WTP.

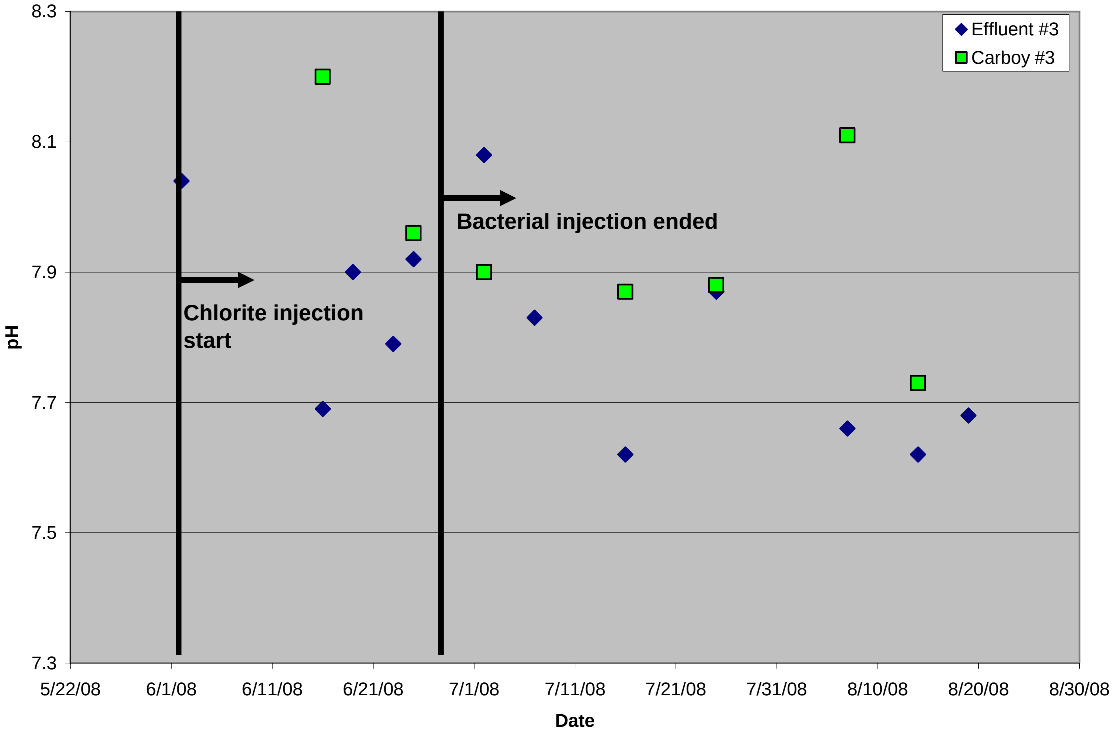


Figure 28: Pilot test unit #3 effluent and carboy pH during the 2008 nitrification study at A. B. Jewell WTP.

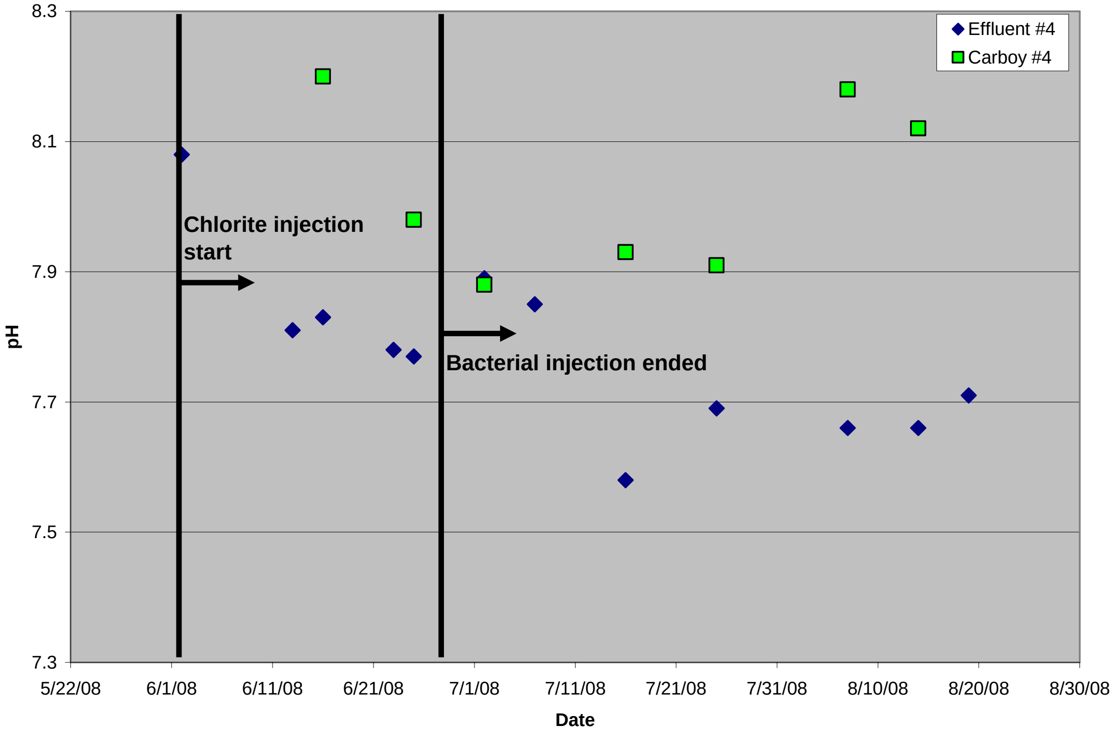


Figure 29: Pilot test unit #4 effluent and carboy pH during the 2008 nitrification study at A. B. Jewell WTP.

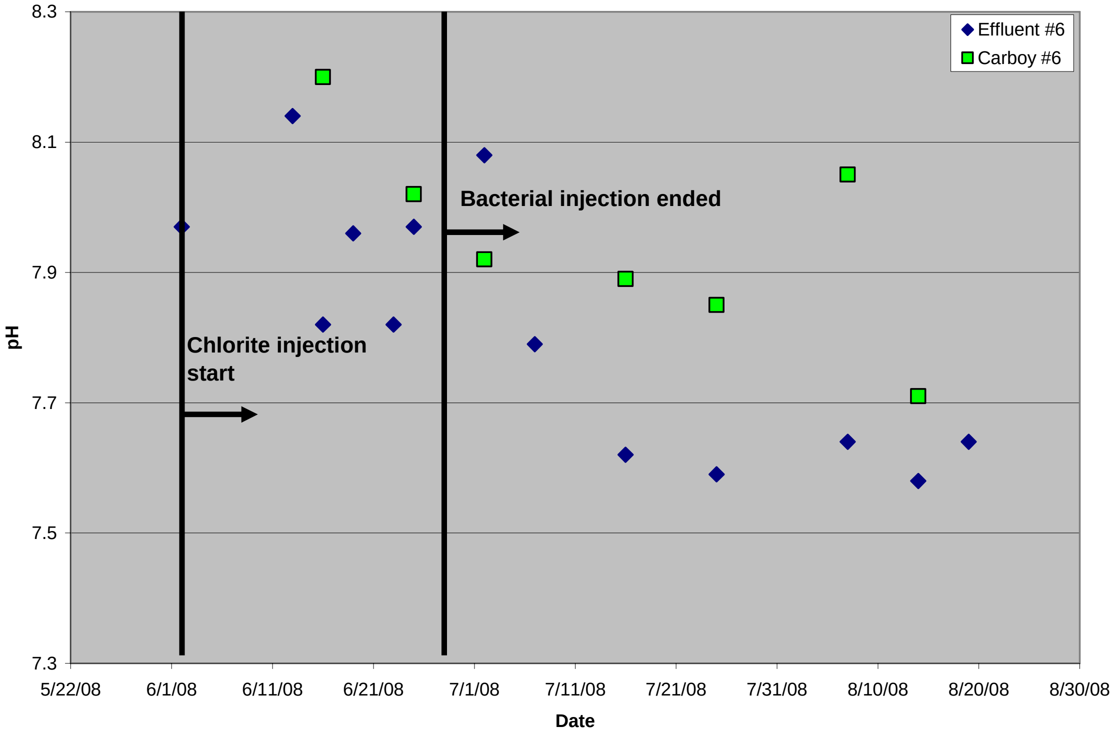


Figure 30: Pilot test unit #6 effluent and carboy pH during the 2008 nitrification study at A. B. Jewell WTP.

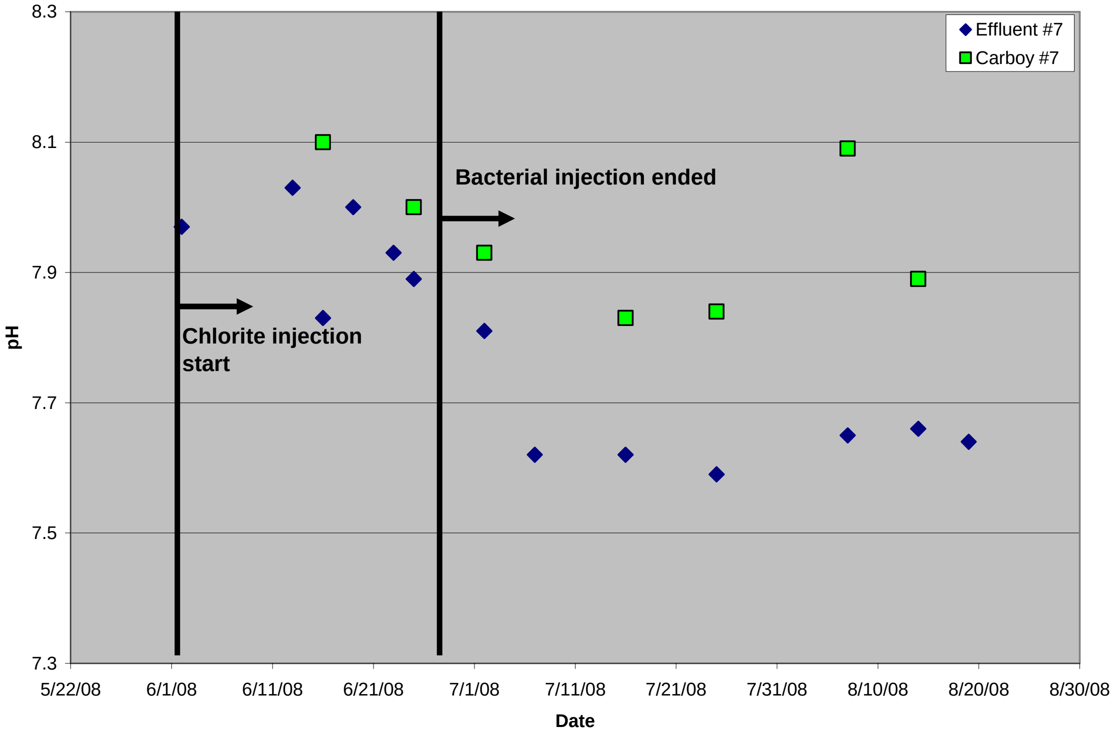


Figure 31: Pilot test unit #7 effluent and carboy pH during the 2008 nitrification study at A. B. Jewell WTP.

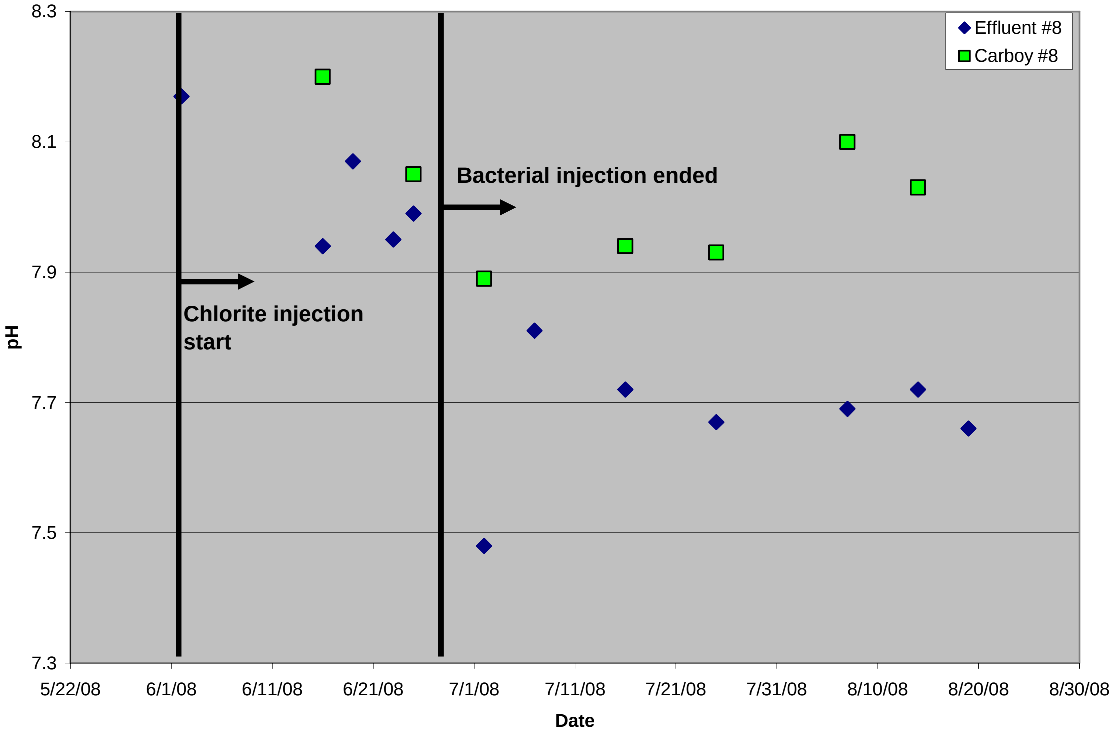


Figure 32: Pilot test unit #8 effluent and carboy pH during the 2008 nitrification study at A. B. Jewell WTP.

Table 17: Carboy and Effluent pH results from the pilot test units during the 2008 nitrification study at A.B. Jewell WTP.

	Date												
	2-Jun	13-Jun	16-Jun	19-Jun	23-Jun	25-Jun	2-Jul	7-Jul	16-Jul	25-Jul	7-Aug	14-Aug	19-Aug
Effluent #1	8.07	7.92	7.84	7.96	7.88	8.02	7.94	7.82	7.7	7.75	7.49	7.62	7.58
Carboy #1			8.1			7.89	7.85		7.87	7.9	8.06	7.78	
Effluent #2	8.06		7.76	7.89	7.81	8.1	7.77	7.57	7.52	7.57	7.52	7.57	7.57
Carboy #2			8.2			8.03	7.9		8.02	7.91	8.16	7.82	
Effluent #3	8.04		7.69	7.9	7.79	7.92	8.08	7.83	7.62	7.87	7.66	7.62	7.68
Carboy #3			8.2			7.96	7.9		7.87	7.88	8.11	7.73	
Effluent #4	8.08	7.81	7.83		7.78	7.77	7.89	7.85	7.58	7.69	7.66	7.66	7.71
Carboy #4			8.2			7.98	7.88		7.93	7.91	8.18	8.12	
Effluent #6	7.97	8.14	7.82	7.96	7.82	7.97	8.08	7.79	7.62	7.59	7.64	7.58	7.64
Carboy #6			8.2			8.02	7.92		7.89	7.85	8.05	7.71	
Effluent #7	7.97	8.03	7.83	8	7.93	7.89	7.81	7.62	7.62	7.59	7.65	7.66	7.64
Carboy #7			8.1			8	7.93		7.83	7.84	8.09	7.89	
Effluent #8	8.17		7.94	8.07	7.95	7.99	7.48	7.81	7.72	7.67	7.69	7.72	7.66
Carboy #8			8.2			8.05	7.89		7.94	7.93	8.1	8.03	

Appendix J: Monochloramine/Total Chlorine Comparison

Carboy	1		
Date	NH2Cl	Total Chlorine	Difference
6/16	0.16	0.3	0.14
6/26	0.67	0.9	0.23
7/21	0.58	0.6	0.02
8/4	0.02	0	-0.02
8/14	0.55	1.3	0.75

Carboy	2		
Date	NH2Cl	Total Chlorine	Difference
6/16	0.22	0.2	-0.02
6/26	0.66	0.7	0.04
7/21	0.88	0.9	0.02
8/4	1.12	1.1	-0.02
8/14	1.4	1.5	0.1

Carboy	3		
Date	NH2Cl	Total Chlorine	Difference
6/16	0.08	0.1	0.02
6/26	0.06	0.1	0.04
7/21	0.03	0	-0.03
8/4	0.03	0	-0.03
8/14	0.21	0.9	0.69

Carboy	4		
Date	NH2Cl	Total Chlorine	Difference
6/16	0.06	0	-0.06
6/26	0.77	0.7	-0.07
7/21	0.83	0.8	-0.03
8/4	1.05	0.9	-0.15
8/14	0.96	1	0.04

These five dates were the only dates that total chlorine and monochloramine were ran simultaneously. There were other dates when total chlorine and monochloramine were analyzed, but there were the only time they were ran together.

15 of the 20 samples had a difference of <0.1 mg/l. This suggests that there was no significant difference of total chlorine and monochloramine during the test.

Appendix K: Cost Calculations for Chlorite Addition

Currently:

Pre-oxidant feed of chlorine	1 mg/l
Cost of chlorine	$0.28 per pound
% Strength	~100%
Mohawk average annual daily flow	50 MGD
Yearly cost for pre-oxidation with chlorine	**$42,617**

Scenario 1: Mohawk changes pre-oxidant from chlorine to chlorine dioxide

Change to chlorine dioxide:

Pre-oxidant feed of chlorine dioxide	1 mg/l (should yield chlorite residual of 0.2-0.5 mg/l)
Cost of chlorine dioxide	
Sodium Chlorite (leased price includes equipment costs)	$0.42 per pound
Chlorine (must be mixed with sodium chlorite on a ~1:2 ratio to make chlorine dioxide)	$0.28 per pound
Total cost	$1.82 per pound
% Strength of sodium chlorite	25%
% Strength of chlorine	~100%
Mohawk average annual daily flow	50 MGD
Total yearly cost for pre-oxidation with chlorine dioxide	$277,013
Savings for replacing pre-chlorination	-$42,617
Additional yearly cost for pre-oxidation with chlorine dioxide	**$234,396**

Scenario 2: Directly add sodium chlorite to finished water and keep chlorine as pre-oxidant)

Target chlorite residual	0.1 mg/l
Cost of sodium chlorite (25%)	$0.30 (estimate)
Mohawk average annual daily flow	50 MGD
Additional yearly cost to add sodium chlorite to finished water	**$18,264**

VITA

Tyler Garrick Gipson

Candidate for the Degree of

Master of Science

Thesis: TYLER GARRICK GIPSON

Major Field: Biosystems Engineering

Biographical:

Personal: Born in Tulsa, Oklahoma on September 10th, 1980

Education: Graduated from Broken Arrow Senior High School, Broken Arrow, Oklahoma in May 1999; received the Bachelor of Science in Biological Engineering from the University of Arkansas, Fayetteville, Arkansas in May 2004; completed the requirements for the Master of Science in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in July 2009.

Experience: Worked for Dr. Tom Costello and Dr. Marty Matlock with the University of Arkansas Department of Biological and Agricultural Engineering, Fayetteville, Arkansas in 2001 and 2003; Interned with MRV Technologies, Georgetown, Texas in 2002; Employed by Pure Process Systems, Houston, Texas from 2004-2005; Employed by Oklahoma State University Department of Biosystems Engineering, Stillwater, Oklahoma in 2005; Employed by the City of Tulsa Department of Public Works, Tulsa, Oklahoma from 2005 to present.

Professional Memberships: American Water Works Association

Name: Tyler Garrick Gipson Date of Degree: July 2009

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: PILOT-SCALE TESTING OF CHLORITE TO CONTROL
NITRIFICATION IN DRINKING WATER DISTRIBUTION SYSTEMS

Pages in Study: 124 Candidate for the Degree of Master of Science

Major Field: Biosystems Engineering

Scope and Method of Study:

The study used pilot test units to simulate a drinking water distribution system. Each test unit was dosed with chloraminated test water and ammonia-oxidizing bacteria to see if nitrification would become established in the test units. Once nitrification was established, the test units were dosed with chlorite at concentrations of 0.05, 0.1, 0.2, 0.4, 0.6, and 0.8 mg/l. Nitrite-nitrogen levels of 0.05 mg/l and higher signified a nitrification event.

Findings and Conclusions:

Nitrification did become established in all the test units. The chlorite feed stopped nitrification within 23 days in the test units with doses of 0.1, 0.2, 0.4, and 0.6 mg/l of nitrite-nitrogen. It took 43 days for nitrification to stop in the test unit with 0.05mg/l of nitrite-nitrogen. The test unit with 0.8 mg/l of chlorite never reached the nitrification threshold of 0.05 mg/l nitrite-nitrogen even though nitrite-nitrogen levels had fallen to levels of 0.09 mg/l nitrite-nitrogen by the end of the test. This test unit had a malfunctioning effluent needle valve that caused the residence time of the test water to be over 15 days whereas the other test units averaged 11 days of residence time.

It can be concluded that chlorite, when used with other nitrification control strategies, can control nitrification in the City of Tulsa's drinking water distribution system. Chlorite can either be directly added to the drinking water in the form of sodium chlorite, or it can be the residual of chlorine dioxide use. It is significantly more cost effective to directly add chlorite as sodium chlorite.

ADVISER'S APPROVAL: Dr. Dan Storm