Tailored Collaboration

Biological Nitrate Removal Pretreatment for a Drinking Water Application

Subject Area: Water Quality
Biological Nitrate Removal Pretreatment for a Drinking Water Application
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Biological Nitrate Removal Pretreatment for a Drinking Water Application

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Published by:

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IDI Summary of Pilot Testing Activities

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FOREWORD

The Water Research Foundation (Foundation) is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The Foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry’s centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the Foundation’s staff and large cadre of volunteers who willingly contribute their time and expertise. The Foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the Foundation’s research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The Foundation’s trustees are pleased to offer this publication as a contribution toward that end.

Roy L. Wolfe, Ph.D. Robert C. Renner, P.E.
Chair, Board of Trustees Executive Director
Water Research Foundation Water Research Foundation
ACKNOWLEDGMENTS

Many people contributed to the success of this project. The authors wish to thank Jennifer Warner, Project Manager, Water Research Foundation and the following members of the Project Advisory Committee; JoAnn Silverstein, University of Colorado, Boulder, Colorado; Jess Brown, Carollo Engineers, PC; Rick Scott, City of Glendale Utilities Department; and David G. Wahman, U.S. Environmental Protection Agency, Cincinnati, Ohio; for their guidance and suggestions.

The authors of this report are indebted to the City of Thornton for its involvement and hosting of the pilot testing. From the City of Thornton, we thank Dennis Laurita for securing the City’s financial assistance for the project; Ron Ewig for his role as Pilot Coordinator which included data collection, troubleshooting and daily operation of the pilot systems; Vic Lucero for his efforts with the water quality sampling and analysis of over 16,000 samples; and Jason Pierce, for his role as project manager of the pilot program.

The authors sincerely thank each of the manufacturers and their staff for their participation in this study and for their assistance and dedication to the successful completion of this research.

The authors also wish to acknowledge the technical assistance of Angela Kana, Burns & McDonnell who contributed to the preparation and writing of reports, conducted data management/analysis, and was an immense help in the production of data graphs. In addition, technical review and assistance provided by Darin Brickman, Burns & McDonnell was invaluable, as was the insight and technical assistance from Professor Christopher Schmit, South Dakota State University, Brookings, South Dakota.
EXECUTIVE SUMMARY

BACKGROUND

Drinking water utilities are facing a universal concern: the need for water has begun to outpace high quality drinking water supplies and many water agencies are faced with problems related to high concentrations of nitrates. As a result, considering alternatives for nitrate removal has become necessary in the drinking water industry.

The City of Thornton’s (City) Wes Brown Water Treatment Plant (WTP) has a raw water source from the South Platte River via the Burlington Canal, which is heavily influenced by upstream municipal wastewater effluent discharges. The flow contribution from upstream wastewater discharges can be as high as 70 percent of the entire flow during the winter months, resulting in a nitrate concentration that is occasionally in excess of 10 mg/L NO₃-N. Although naturally occurring nitrogen reduction occurs within the City’s gravel lake storage complex prior to treatment, the City is still concerned about the high levels of nitrate present in the source water. The alternative identified as being the most efficient and cost effective method to remove this contaminant is to pretreat the water using a biological nitrate removal (BNR) process prior to the City’s new 50 million gallon per day (MGD) ultrafiltration plant. The water would enter the proposed BNR process from one gravel lake and be discharged to the next gravel lake in series.

The City conducted a pilot study from February 6, 2008 to August 28, 2008 to verify suitable biological nitrate removal options. The three biological treatment options that the City piloted have been primarily implemented in industrial and wastewater treatment applications to date. Their application in drinking water has been significantly less in Europe to almost none in the United States. One of the pilot processes was a moving bed biofilm reactor (MBBR™) and the other two pilot processes were packed bed biological reactors.

The goal of this research was to expand the current body of knowledge with respect to cold water denitrification in addition to optimizing the reaction conditions with respect to substrate and nutrient concentrations. During this pilot study, the effects of fluctuating dissolved oxygen (DO) concentrations and raw water pH were evaluated. This study helps to further characterize the limiting reaction conditions to determine if any one growth factor exerts an overriding influence on the rate of denitrification. Specific to this study is the removal of nitrates during cold temperatures. This study evaluates treatment of a water source that has increasing nitrate concentrations during the winter months when the cold water is limiting the bacterial processes. The represents the worst case scenario (i.e., highest nitrate during lowest temperatures) compared to many other source waters where nitrate levels decrease in cold temperature and increase during warm temperatures.

SPECIFIC OBJECTIVES

This research project involves the piloting of the following three biological processes for the removal of nitrate from a surface water source to a drinking water treatment plant:

- AnoxKaldnes Moving Bed™ (Moving Bed Biofilm Reactor /MBBR™)
- GE Water & Process Technologies ABMet® (Packed bed biological filter)
- Infilco Degremont Inc. (IDI) NITRAZUR DN® (Packed bed biological filter)
The overall goal of this research was to demonstrate the feasibility of utilizing biological processes to remove nitrate from a surface water supply to a drinking water treatment plant to less than 2 mg/L NO₃-N. This study provides the opportunity to develop new information on evolving and existing biological nitrate treatment technologies. Specific objectives included the following:

- Assess the performance of biological treatment processes for a nitrate contaminated surface water source for a drinking water application. This includes looking at various denitrification parameters under varying raw water conditions including water temperatures ranging from approximately 5°C to 27°C.
- Verify appropriate quantities of substrate (carbon source) addition.
- Evaluate and determine design and operational criteria.

**APPROACHES**

The research objectives were completed with the collection, evaluation and presentation of piloting results documenting the performance of the three biological units piloted for nitrate removal. The project team designed and oversaw the operation of a pilot-scale facility for the three biological processes, which were piloted simultaneously.

The following is an outline of the tasks completed during the study to evaluate the BNR systems:

- Task 1: BNR System Startup
  - Seeding and Acclimation Phase
- Task 2: Operation and Performance Testing
  - Carbon Dose Optimization Phase (Task 2a)
  - Steady State Phase (Task 2b)
  - Backwash Optimization Phase (Applicable for GE Water & Technologies ABMet® Only)
  - Solids Wasting Rate Optimization Phase (Applicable for AnoxKaldnes Only)
- Task 3: Monitoring and Sampling
  - Data Logging
  - Manual Data Collection
  - Water Quality Sampling and Analysis
- Task 4: Resiliency Test Phase
  - Incremental Nitrate Spiking (Task 4a)
  - Rapid Change Nitrate Spiking (Task 4b)
  - Influent Nitrate Spiking Shutdown (Task 4c)
  - Carbon Feed Pump Shutdown (Task 4d)
  - Raw Water Shutdown (Task 4e)
- Task 5: Column Testing (Applicable for GE Water & Technologies ABMet® Only)
- Task 6: Quality Assurance and Quality Control
- Task 7: Conclusions and Recommendations

The City intends to select a biological nitrate removal option for pretreating the surface water fed from their gravel lakes storage complex to their drinking water treatment facilities.
Selection of the BNR process for full-scale implementation will be based on a competitive analysis of cost, performance and suitability to the application.

RESULTS AND CONCLUSIONS

The results from this pilot study show that biological processes are a viable method for removing nitrate in drinking water applications. All piloted systems performed well with respect to the effluent water quality achieved from their units based on the established water quality goals of this research.

The following conclusions can be drawn from the pilot testing:

• **Nitrate Removal Performance:** All three biological processes exhibited the ability to exceed the pilot goal for nitrate removal from 10 mg/L NO₃-N to ≤ 2 mg/L NO₃-N during both cold and warm temperatures. The average nitrate removal percentages observed after optimization and during the Steady State Phase (average temperature of 23.8°C) ranged from 88 percent to 90 percent.

• **Seeding:** Seeding is an effective method of accelerating denitrification during start-up in cold temperatures. The systems that were seeded included GE and IDI, which were successfully denitrifying in one and seven weeks, respectively. The AnoxKaldnes system was not seeded and required eleven weeks to achieve the effluent nitrate concentration goal.

• **Carbon Dose Optimization:** For drinking water applications, carbon dose optimization is essential to avoid or minimize increases in TOC concentrations through the biological process. During the study, it became evident that carbon overdosing can result in a substantial increase in effluent TOC concentrations. In response to this observation, an extended carbon dose optimization phase was implemented. Following the optimization, the net increases in TOC were typically less than 1 mg/L in the effluent. While the goal of zero net increase in TOC was not achieved, the piloting results indicate that carbon dose can be optimized and controlled to provide acceptable levels of effluent TOC. A correlation between carbon dose and pH in the effluent was also observed. It is theorized that a reduction in carbon addition results in the bacteria producing less organic acid which in turn results in an increase in pH. Comparison of TOC and pH trends indicates that when excess carbon is dosed the pH decreases. However, in instances where an increase in pH was observed, no increase in effluent TOC was present.

• **Actual Carbon Dose vs. Calculated Carbon Dose:** During this study, it was noted that the actual required carbon dose did not necessarily correspond directly with the calculated dose based on stoichiometry. This is most likely due to the hydraulics within each system and potential variations in DO once the raw water was introduced to each pilot system. Carbon feed concentrations varied substantially among manufacturers. During the Steady State Phase, AnoxKaldnes dosed at a methanol to nitrate-nitrogen ratio of 5.04 g CH₃OH/g NO₃-N with GE and IDI’s ratios being 1.75 g CH₃OH/g NO₃-N and 1.17 g CH₃OH/g NO₃-N, respectively. The fact that the packed bed filters require a lower carbon dose than the moving bed bioreactor is attributed to the configuration as the filters most closely resemble plug flow. Based on discussions with
the manufacturers, the doses observed during this study are consistent with expected doses and those observed at operational denitrification facilities.

- **Selection of Carbon Source:** While this study did not involve testing and comparison of carbon sources, the research did provide some information that is useful in the selection of carbon sources. The GE pilot system was originally started using molasses as the carbon source based on experience at non-potable installations and recommendations from the manufacturer. While the molasses allowed the system to perform satisfactorily with regard to nitrate removal, the carbon source was changed to methanol after the City’s Laboratory staff discovered potential color and odor concerns. It is not known if the color and odor concerns are specific to the raw water tested or if this would be a concern at any drinking water facility. However, this observation highlights the need to carefully select (and potentially test) a carbon source prior to implementation in a drinking water application.

- **Sensitivity:** Based on the results documented during the Resiliency Test Phase, the GAC media used in the GE system was less sensitive to changes in carbon dose than other media tested. This is believed to be due to the adsorption capacity of the GAC. The data also indicates that after a carbon feed pump is shut-down and brought back online, all three systems responded quickly. Upon shutting down the pumps for four hours, the effluent nitrate concentration would increase above 2 mg/L NO₃-N for AnoxKaldnes and IDI, whereas effluent nitrate levels did not exceed 2 mg/L NO₃-N for GE due to the adsorption capacity of the GAC media. Once the carbon feed pumps were back online, AnoxKaldnes and IDI’s effluent nitrate-nitrogen concentration decreased below the pilot goal within 8.5 and 5.2 hours, respectively.

- **Phosphorus Addition:** Phosphorus may need to be added, if it is a limiting nutrient in the raw water supply. During the pilot study, raw water phosphorus concentrations were low and the addition of phosphorus improved the ability to denitrify. This confirmed that low levels of phosphorus can limit growth of the denitrifying bacteria and adversely affect the performance of the biological processes. The addition of phosphorus should be optimized to avoid an increase in the effluent concentration.

**RECOMMENDATIONS**

Results presented in this report are based on a seven-month pilot study with varying environmental and water quality conditions. For full-scale implementation of these biological processes as pretreatment in a drinking water application, it is recommended that:

- Process controls for carbon dose be based on real-time feedback of nitrate and TOC concentrations and be implemented to automatically adjust and optimize the carbon dose. As discussed in the conclusions, this optimization is essential to prevent net increases in TOC.

- Seeding be evaluated based on the need for intermittent operation or startup during cold temperatures. While seeding is an effective method in accelerating the startup of biological processes, it is most likely only necessary at colder temperatures. Designing a system for startup during warmer temperatures is preferred.
• Phosphorus levels in the raw water be evaluated to determine if it is a potential growth-limiting nutrient. A phosphoric acid feed system should be incorporated into the full-scale design in the event that low phosphorus concentrations occur.

While the objectives of this research were achieved, several areas of study were identified where more information would be beneficial in characterizing the use of biological denitrification processes for drinking water facilities:

• Conduct an additional extended-term pilot study over several cold and warm temperature seasons to allow for further investigation of the effects of temperature and other variables on the biological processes over a longer term. Specifically, conducting a Steady State Phase over a cold season would provide useful data relative to the long term operation at colder temperatures.
• Conduct a bench-scale analysis of different carbon sources and their applicability for drinking water applications. Specifically, investigation of any issues related to color and odor as was experienced with molasses in this study.
• Investigate biomass concentrations for the three biological processes. Since the hydraulic retention times (HRTs) and media are very different among the various processes, it would be useful as future research to measure biomass concentrations per unit volume of media for each of the biological processes.
• Conduct additional research to determine the variables contributing to the difference between the actual and calculated (stoichiometric) carbon dose as discussed in this report.
CHAPTER 1
INTRODUCTION

Nitrate contamination of drinking water sources is a serious and ever increasing problem in the United States and throughout the world. Drinking water utilities are facing a universal concern; the need for water has begun to outpace high quality drinking water supplies and many water agencies are faced with problems related to high concentration of nitrates. The City of Thornton, Colorado is an example of one utility facing this challenge.

The most common methods for removing nitrate from water sources are ion exchange, reverse osmosis (RO) and biological denitrification. While ion exchange and reverse osmosis have been widely used for nitrate removal in drinking water applications, the use of biological denitrification has been limited in this industry. Denitrification of drinking water is complicated by several factors. Potable water sources tend to be dilute with respect to the substrate and nutrients required for microbial growth. To sustain a denitrifying population, amending water with an energy source and phosphorus, as well as providing pH adjustment is often necessary. Following denitrification, additional treatment is required to remove excess substrate, microbial cells and extracellular products. Biological processes are also susceptible to fluctuating water conditions. Since the microorganisms may not respond favorably to fluctuating water conditions, the operation of these treatment processes can occasionally become more complex than physical and chemical processes.

The City previously intended to utilize RO membranes to treat a 15 MGD side stream at the City’s Wes Brown WTP to reduce nitrate and total dissolved solids (TDS) concentrations to acceptable levels. This capacity is based on treating one-third of the flow at the WTP to reduce the highest concentrations recorded in the City’s raw water storage gravel lakes to meet the Maximum Contaminant Level (MCL) of 10 mg/L NO₃⁻-N. While RO treatment would have provided many additional benefits including reduction in TDS, further removal of TOC and reductions in endocrine disrupting compounds (EDCs) and micropollutants, issues related to concentrate disposal have inhibited the implementation of the RO technology. Unlike biological nitrate removal processes, RO and ion exchange processes produce a concentrated brine that requires further treatment prior to disposal. Biological denitrification methods decompose the nitrate, whereas the conventional physical and chemical methods of nitrate removal simply displace and concentrate the constituent. Therefore, the City has decided to consider biological nitrate removal treatment processes for the removal of nitrate.

The proposed approach to using biological nitrate removal as pretreatment for the City of Thornton’s water treatment facilities is unique and provides an opportunity to offer valuable information to the industry on using these types of biological treatment processes on a drinking water source.

BACKGROUND

In Colorado and other arid western states, the availability of ambient water for dilution of storm water and wastewater discharges is limited. Ambient dilution water in streams has all but disappeared in many western urban watersheds due to urbanization and the competition for precious water sources. Without natural dilution water in rivers and streams, water treatment facilities are often required to treat poorer quality water that requires state of the art technologies.
The City’s primary water supply is influenced by upstream discharges and nitrate levels above the Environmental Protection Agency (EPA) MCL of 10 mg/L NO₃-N have occasionally been recorded. The City of Thornton has a unique gravel lake system which provides raw water diversion through the South Tani Reservoir as shown in Figure 1.1. This reservoir has a capacity of 7,000 acre-feet (AF) and will serve as the source water to the future BNR system.

The water flows from the South Tani Reservoir to the East Gravel Lake #4 (EGL4), which has a capacity of 3,000 AF and is where the BNR system will discharge. From EGL4, the water is pumped and serves as the main water supply to the City’s water treatment plant. These storage reservoirs provide a unique buffering of the water from fluctuations since they provide a long detention time and over four months of storage at the City’s maximum demands.

During the winter months, the total flow contribution from upstream wastewater discharges can be as high as 70 percent of the entire flow, resulting in elevated levels of ammonia, phosphorus, and nitrate. Although some naturally occurring nitrogen reduction occurs within the City’s gravel lakes, reducing nitrate levels below the MCL when high levels of nitrate are present is not always sufficient. Therefore, the City decided to evaluate the implementation of BNR processes for removing nitrate in their surface water upstream of their water treatment plant.

Since the initial design of the Wes Brown WTP, several biological processes have emerged as potential treatment options for nitrate removal in this application. These options have primarily been implemented in industrial applications to date and are similar to those used for post-denitification in wastewater applications. Their application in drinking water has been significantly less in Europe to almost none at all in the United States.

The City intends to select the most suitable BNR option for pretreating surface water fed to their drinking water treatment facilities from the East Gravel Lakes. To select this process, the available biological process options were narrowed down after an extensive evaluation conducted in 2007. The following three alternatives were piloted in 2008:

- AnoxKaldnes Moving Bed™ (Moving Bed Biofilm /MBBR™)
- GE Water & Process Technologies ABMet® (Packed bed biological filter)
- Infilco Degremont Inc. (IDI) NITRAZUR DN® (Packed bed biological filter)

This research addresses the performance of these systems and presents the data gathered and evaluated from the pilot study of these BNR treatment processes. The final phase of the City of Thornton's project, which this research does not address, will be full-scale implementation.
Chapter 1: Introduction

<table>
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(1) The City typically adds approximately 1–2 mg/L of potassium permanganate and less than 0.8 mg/L (typically 0.1–0.2 mg/L) of copper sulfate to the South Tani Reservoir for algae control.

(2) The influent design point for the BNR process is 10 mg/L NO₃-N.

WATER QUALITY DATA

EGL4 experiences seasonal variations in nitrate, pH, dissolved oxygen (DO) and temperature. Additionally, these values vary from the bottom of the lake to the surface. As this project utilizes influent water from near the middle of the lake through an existing intake, all design parameters are based on its respective data. Historical City data from 2004 to 2007 show that the typical water quality parameters in the raw (i.e., feed) water are as shown in Table 1.1.

The key constituent to be treated in this pilot test is nitrate. The data presented in Figure 1.2 shows that the peak nitrate-nitrogen level from 2004 to 2007 falls short of 4.5 mg/L after naturally occurring nitrate reduction occurs in the gravel lakes. However, additional historical data analysis shows that nitrate levels have been as high as 11 mg/L NO₃-N in both the South Tani and EGL4. The goal for this pilot study is to be able to treat influent levels of 10 mg/L NO₃-N to an effluent level of 2 mg/L NO₃-N. It is important to note that ammonia levels in the gravel lakes are low (<1 mg/L NH₃-N). Therefore, the BNR process for each of the three manufacturers piloted only included a denitrification step (i.e., nitrification is not required).

Biological treatment processes are dependent on influent pH, as the biological component’s ability to grow and metabolize nitrate has an optimum pH range of 6.5–8.0. Typically, the rate of treatment falls off outside of this range. The EGL4 pH data, presented in Figure 1.3, show that the average pH on the influent is approximately 8.6. This pH forces the piloted BNR treatment
Figure 1.2 2004–2007 East Gravel Lake 4 historical nitrate concentration data

Figure 1.3 2004–2007 East Gravel Lake 4 historical pH data
Figure 1.4  2004–2007 East Gravel Lake 4 historical temperature data

Figure 1.5  2004–2007 East Gravel Lake 4 historical DO data
processes outside of their optimum pH ranges. Therefore, the pilot study also evaluated whether pH adjustment was required upstream of a pilot unit. Additionally, the effluent stream of each pilot unit was monitored for any drastic changes in pH that may affect the properties of the East Gravel Lakes.

In addition to pH dependence, the biological metabolism is also dependent on temperature. As this pilot study was initiated during the coldest months of the year, the influent water was not at the optimum temperature for the biofilm. This tested the ruggedness of the biofilm, and its ability to metabolize nitrate at low temperatures.

The EGL4 temperature data, presented in Figure 1.4, show that the minimum design temperature for the pilot is 3°C. While the pilot systems were operated at warmer temperatures due to seasonal variations in temperature, the minimum temperature must be assumed as the design point for the full-scale design due to the slower microbial kinetics at lower temperatures.

DO was also an important parameter to monitor in this pilot test. Exceedingly high DO concentrations can force the anoxic process to become slightly aerobic, causing the bacteria to metabolize oxygen rather than nitrate. The DO concentrations in EGL4 experience high peaks in the spring when the gravel lakes are turning over, which could potentially cause what is known as oxygen poisoning in the pilot units. The EGL4 DO data, presented in Figure 1.5, show these spikes. DO levels were monitored on the main influent line as well as at the effluent lines of all three pilot units.

In addition to the conditions of the water in EGL4, the discharge water from each pilot unit was monitored in order to quantify the effects a full-scale unit would have on the gravel lakes.
The overall goal of this research is to demonstrate the feasibility of utilizing biological processes to remove nitrate from surface water drinking water supplies.

WATER QUALITY OBJECTIVES

The water quality goals for this pilot study were based on regulatory requirements. The EPA has established MCLs for both nitrate and nitrite. For the overall pilot performance, the City desired for the nitrate and nitrite levels to be well below these regulated limits. Each goal was established as 20 percent of the EPA MCL, so as to meet any future changes in the MCL, and to increase the quality of the water fed to the Wes Brown WTP. Table 2.1 displays the desired goals of nitrate and nitrite.

As shown in Table 2.1, the goal of the pilot study was to treat the nitrate present in the source surface water to a maximum acceptable effluent concentration of ≤2 mg/L NO$_3$-N by means of biological denitrification, when the influent nitrate concentration is at 10 mg/L NO$_3$-N or greater.

PILOT OPERATION OBJECTIVES

The specific objectives of the research include but are not limited to the following for each of the three pilot units:

- Determine process performance (specifically nitrate removal - % reduction) and preliminary design criteria at both cold and warm temperatures.
- Determine the hydraulic loading rate that will provide the basis for full-scale design and the range of acceptable loading rates.
- Determine the impact of fluctuations in raw water (feed) quality, specifically variations in nitrate concentrations, temperature, pH, DO, phosphorus, TOC, and alkalinity on performance.
- Determine the impact of raw water nitrate excursions.
- Determine optimal carbon source dose for sustaining the denitrification process.
- Determine backwashing, air scouring and mixing frequencies/conditioning requirements.
- Determine if any screening or other treatment process, chemical addition, etc. is required upstream of the process.
- Determine if any filtration/clarifications/polishing is required downstream of the process.
- Evaluate seeding and startup processes and determine the impact of both cold and warm temperatures on seeding.
- Assess operational difficulty and flexibility.
- Identify any potential operation and maintenance (O&M) issues or concerns.
Table 2.1
MCLs and water quality goals

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<th>Parameter</th>
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<td>Nitrite as nitrogen</td>
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CHAPTER 3
LITERATURE REVIEW

The goal of this research is to expand the current body of knowledge with respect to the way biological denitrification systems perform on nitrate-contaminated surface water for a drinking water application. This research is cutting edge since it is the first time biological denitrification pretreatment processes upstream of a drinking water treatment plant have been studied for removing nitrate from surface water in the United States. Denitrification has been used in drinking water applications in Europe, but the denitrification process has generally been incorporated as part of the filtration portion or as post treatment to drinking water treatment. In addition, the source water evaluated has typically been groundwater and not surface water. Pretreatment of surface water sources will continue to be more important in the water industry as more microfiltration and ultrafiltration membrane systems are implemented. This study is also unique in that it evaluates the denitrification process at cold water temperatures, which has not been studied extensively, especially in drinking water applications.

Prior to initiating this research, extensive literature and technology reviews were conducted. As a result of these reviews, it was determined that limited research has been conducted relative to biological processes for nitrate removal in drinking water facilities. However, since these biological processes are widely used in wastewater applications, the kinetics and potential limitations of biological processes are well understood. Fundamental information related to this research is provided below beginning with the implementation of denitrification in drinking water facilities and the basic process of denitrification. A list of references and suggested reading is provided at the end of this report.

DENITRIFICATION FACILITIES FOR DRINKING WATER

Several facilities currently provide denitrified drinking water to European communities. The first denitrification drinking water treatment facility in France was constructed in Eragny, France in 1983 and consisted of ethanol and phosphate addition, a biologically active clay filter, flocculation, dual media filtration (with activated carbon and sand), and disinfection (Gayle et al., 1989). Another facility was also constructed in 1983 in Chateau Landon, France. This facility consisted of acetic acid and phosphate addition, an up-flow fixed-bed reactor, flocculation, filtration (carbon media), and chlorination. In 1986, a biological denitrification facility using hydrogen as the carbon source went online in Monchengladbach, Germany. The facility unit processes included indirect hydrogen saturation, phosphate addition, four packed-bed reactors in series, post-aeration, flocculation, filtration, and UV disinfection.

Since the introduction of denitrification for drinking water facilities, several additional facilities have been brought online in Europe. While progress has been made in the area of biological nitrate removal for drinking water, it is still a relatively new field of study and much work remains. In fact, the United States does not have a specific biological nitrate removal system in operation as part of a municipal drinking water treatment facility.
DENITRIFICATION

Denitrification occurs when facultative heterotrophic bacteria are subjected to an environment that is absent of oxygen and contains nitrate and a carbon source (i.e., food). The facultative bacteria utilize nitrate as the terminal electron acceptor during energy formation resulting in the formation of nitrogen gas (with nitrite formation as an intermediate step) which is released to the atmosphere. All biological nitrogen (N) removal is based on the reduction of nitrate to nitrogen gas (N₂):

\[ \text{NO}_3^- + 6\text{H}^+ + 5\text{e}^- \rightarrow 0.5\text{N}_2 + 3\text{H}_2\text{O} \]

The nitrogen gas is poorly soluble in water and naturally evolves out of the water, affecting total-N removal. N₂ is completely harmless, constituting almost 70% of the earth’s atmosphere.

Bacteria carry out nitrate reduction when they are able to oxidize a bioavailable electron donor. Among the donors that can be delivered to bacteria for this purpose are hydrogen gas (H₂), elemental sulfur (S⁰) and simple organic elements such as ethanol (C₂H₆O). As the following reactions show, oxidation of each of the donors releases electrons (e⁻) that can fuel the nitrate reduction reaction.

- \( \text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^- \)
- \( \text{S}⁰ + 4\text{H}_2\text{O} \rightarrow \text{SO}_4^{2-} + 8\text{H}^+ + 6\text{e}^- \)
- \( \text{C}_2\text{H}_6\text{O} + 2\text{H}_2\text{O} \rightarrow 2\text{HCO}_3^- + 8\text{H}^+ + 6\text{e}^- \)

The key to successful and efficient denitrification is to provide the proper environment to facilitate the reaction. The requirements for biological nitrate reduction include an external carbon source (i.e., biochemical oxygen demand (BOD)/chemical oxygen demand (COD)/total nitrogen (TN), methanol, ethanol, acetate, etc.), a biological culture capable of denitrification, and an environment conducive to the growth and maintenance of the biological reaction.

Biological Processes

Biological processes used to reduce nitrate can be of the fixed-film (attached growth) or suspended growth type. In fixed-film approaches, bacteria attach themselves to media and form a biofilm, while in suspended growth applications, the bacteria are found in the liquid matrix.

With fixed-film denitrification, the organisms are attached to an inert support media and although various media can be used, the goal is to maximize the surface area available for the biofilm to develop. These include fluidized bed reactors, packed bed reactors, and biofilters comprised of sand, anthracite, activated carbon, calcium carbonate, or sulfur. The biofilm essentially allows a mature biological population to live without requiring a long hydraulic residence time/solids residence time for the influent raw water. Since the biological conversion of nitrate to gaseous nitrogen is almost instantaneous, a small basin size can be used. The three categories of treatment processes evaluated for this study are as follows:

- Moving Bed Bioreactor (MBBR™)
- Packed bed biological filters
- Fluidized bed biological filters.
The three treatment processes that were piloted fall into two of the three categories, MBBR™ and packed bed biological filters.

**Carbon Sources**

Organisms required for denitrification require a carbon substrate (food) to survive. In certain instances, including treatment of surface water, the quantity of biodegradable organic carbon available to serve as the substrate for the denitrification process is limited. In these applications, a carbonaceous substrate is added to the source water to augment the denitrification process. Suitable substrates include methanol, ethanol, acetate, glucose, or molasses. The form of the substrate is a key parameter related to the rate and efficiency of denitrification, specifically as it relates to the ease of biodegradation of that substance (Water Environment Federation, 2005).

The preferred material for denitrification is stable during storage, readily biodegradable, free of nutrients, and inexpensive. Methanol and ethanol meet these criteria and are commonly used. Methanol is typically one of the least expensive commercial sources of carbonaceous matter currently available and is capable of achieving high denitrification rates. Ethanol is typically the next least expensive source, with glucose typically being the third least expensive source. Methanol and ethanol are generally preferred over glucose because they are more completely oxidized and produce less sludge for disposal.

**Stoichiometry**

The stoichiometric relationship for denitrification using methanol is as follows (Water Environment Federation, 2005):

$$6\text{NO}_3^- + 5\text{CH}_3\text{OH} + \text{H}_2\text{CO}_3 \rightarrow 3\text{N}_2 + 8\text{H}_2\text{O} + 6\text{HCO}_3^-$$

Converting this to a mass basis and reducing the nitrogen species to ‘as-nitrogen’ results in the following:

$$84\text{g NO}_3^-\text{N} + 160\text{g CH}_3\text{OH} + 62\text{g H}_2\text{CO}_3 \rightarrow 84\text{g N}_2 + 144\text{g H}_2\text{O} + 366\text{g HCO}_3^-$$

One gram of methanol has the theoretical oxygen equivalent of 1.5g oxygen, which results in the following three key relationships related to denitrification:

- 1.91 grams of methanol is consumed per gram of NO$_3$-N reduced
- 2.86 grams of oxygen demand is consumed per gram of NO$_3$-N reduced
- 3.57 grams of CaCO$_3$ alkalinity is generated per gram of NO$_3$-N reduced.

Stoichiometric equations for methanol consumption using nitrate, nitrite, and oxygen are as follows (USEPA, 1975):

$$\text{Methanol Dose (mg/L)} = 2.47 \text{NO}_3^-\text{mg/L} + 1.53 \text{NO}_2^-\text{mg/L} + 0.87 \text{DO}$$
Kinetics of Denitrification

The rate of denitrification is a function of the growth of heterotrophic bacteria that use nitrate as their terminal electron acceptor and can be influenced by many factors. These factors include carbon source, DO concentrations, nitrate concentrations, temperature, and process configuration and operation. In addition, there must be adequate nutrients in the water to sustain bacterial growth.

As stated previously, denitrification is achieved through biological reduction of nitrate and/or nitrite to nitrogen gas in the absence of dissolved oxygen. The organisms used for denitrification are common and can use oxygen, nitrite, or nitrate as their terminal electron acceptor. They prefer to use oxygen as they are able to metabolize substrate more efficiently than when using nitrate and nitrite. The result is a greater amount of energy available to the bacteria and a greater volume of biomass produced per unit of substrate. Due to this preference for oxygen, DO in the source water will reduce the efficiency and capacity of the process. The City of Thornton experiences varying and often high DO levels in the gravel lakes, so proper sizing of the system to compensate for potentially high DO concentrations will be a critical consideration in the design. In addition to the reduction in efficiency and capacity, the higher DO concentrations result in increased chemical addition and sludge production.

The growth of microorganisms and the efficiency of denitrification processes are heavily influenced by temperature. The optimum temperature range for denitrification is generally from 28 to 35°C, and although denitrification does occur in temperatures ranges as low as 5 to 10°C, the process is very slow and requires substantial contact time. By increasing water temperature, the DO concentration decreases, thereby creating a more anoxic environment for denitrification to occur. More importantly, by increasing the temperature, the kinetics increase. As mentioned in the piloting objectives, the effects of temperature were studied and are presented in this report.

Finally, the growth of denitrifying bacteria must not be limited by low levels of specific essential nutrients. When an essential nutrient exists in low concentrations, it is used up first and becomes a ‘growth-limiting’ nutrient. This is often a concern in denitrification processes when low phosphorus levels exist, since phosphorus is an essential element for bacterial growth. As discussed in this report, this was a specific concern for the City of Thornton since phosphorus concentrations are historically low.
CHAPTER 4
METHODS AND MEASUREMENTS

PILOT STUDY

The City and Burns & McDonnell conducted a pilot study, from February 6, 2008 to August 28, 2008, to demonstrate the feasibility of utilizing biological processes to remove nitrate from the drinking water supplies and to determine full-scale operating conditions and design criteria for three biological processes. As previously stated, the following three biological processes were piloted:

- AnoxKaldnes Moving Bed™ (Moving Bed Biofilm or MBBR™)
- GE Water & Process Technologies ABMet® (Packed bed biological filter)
- Infilco Degremont Inc. (IDI) NITRAZUR DN® (Packed bed biological filter)

All three processes are of the fixed film (attached growth) type. However, each of the three technologies are different from one another. The MBBR™ uses inert engineered media within a moving bed, to maximize surface area for microbial growth whereas a packed bed biological reactor uses a packed bed of granular media. One of the main differences is that all three manufacturers had different proprietary media.

The AnoxKaldnes unit is a MBBR™ type which is a biological process that does not provide any filtering of the water, whereas the GE and IDI units are of the packed bed type that provide filtering. The AnoxKaldnes unit had three reactors, each filled with plastic media to allow more surface area for the media to grow. The first two reactors were mechanically mixed anoxic zones, and the third reactor was an aerated (aerobic) zone. There is no backwashing or waste stream for the AnoxKaldnes unit, unlike the GE and IDI units. The GE unit consisted of a reactor filled with granular activated carbon media. Influent water flows downward through the reactor, and the reactors are backwashed periodically to remove solids and degassed to release any air trapped within the media. The IDI unit is similar to a conventional media filter except water flows upward across the media. The unit is backwashed to remove solids and air scouring periodically. For the GE unit, the carbon provides the surface area for the media to grow and for the IDI unit, the proprietary sand media is used to provide the surface area.

During the pilot study, AnoxKaldnes and IDI used methanol as their preferred external carbon source, whereas GE used molasses and methanol during piloting. For approximately the first three months of piloting, the GE system used a proprietary molasses solution as the electron donor. Due to odor and color concerns associated with the molasses, the GE system was switched to methanol for the remainder of the pilot test. Methanol was primarily selected as the electron donor/carbon source for these systems since it is one of the least expensive commercial source of carbonaceous matter currently available and is capable of achieving high denitrification rates. Since the prices for external carbon sources fluctuates based on market conditions, the City of Thornton’s full-scale system will be designed to use either methanol or ethanol as the electron donor.

The City and Burns & McDonnell worked with the three manufacturers for the design and layout of the pilot plant. Each of the three pilot units were located directly southwest of the City’s...
South Tani Raw Water Pump Station and Storage Tank. A photo of the pilot location is shown in Figure 4.1.

The raw water to the pilot units was conveyed from a pipe installed on the existing suction line of the South Tani Raw Water Pump Station which pulls water directly from the South Tani Reservoir. Raw water was pulled approximately mid-level in the reservoir and was conveyed by a constant speed centrifugal pump through a common header that was routed through the City’s existing South Tani Reservoir Storage Tank to each of the pilot units. The City’s existing South Tani Reservoir Storage Tank is empty and no longer in operation so raw water equipment for the pilots could be stored inside the tank. In the City’s existing South Tani Storage Tank, a sodium nitrate mixing tank was installed with an injection point on the raw water common header for spiking of the influent nitrate-nitrogen. Downstream of this injection point, a sampling point and online analyzers were installed to sample for DO, pH, temperature, and nitrate-nitrogen.

A separate flush line for the GE unit, which was used for degassing and backwashing, was also installed on the existing suction line of the South Tani Raw Water Pump Station. The effluent from the pilot units and from the miscellaneous drains of each pilot unit was discharged to a manhole which conveyed water to EGL4. Figure 4.2 shows the site layout of the three pilot units, and Figure 4.3 shows a photo of all three pilot units.
Figure 4.2 Site layout of the three pilot units

Figure 4.3 Photo of the three pilot units
Following is a brief description of each of the three treatment technologies, followed by each manufacturer’s pilot plant design and operations. Key operational parameters for all of the piloting processes are defined below.

Definition of Key Operational Parameters

**Backwash Waste.** Water used in the backwash phase of both IDI’s and GE Water & Process Technologies’ process that is returned to the influent to be retreated in the process.

**Biocarrier.** A specialized polyethylene substrate with a high surface area for biological attachment of the denitrifying biofilm.

**Biofilm.** A complex aggregation of microorganisms protected by an adhesive matrix. Biofilms are often found attached on solid substrate submerged in an aqueous solution. Though often microscopic in scale, if given sufficient resources for growth, a biofilm can quickly grow to macroscopic sizes.

**Carbon Source.** The energy source for the biological component in the denitrification cycle of a BNR process. This is also commonly referred to as a Nutrient Source.

**Denitrifying Pathway.** The method by which nitrate is reduced to nitrogen gas in a biological nitrate removal treatment system:

\[
\text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2
\]

**Effect of Temperature on Kinetics.** Temperature has a significant effect on the growth rate of many denitrifying bacteria. It may be estimated by the following expression:

\[
P = 0.25T^2
\]

where \( P \) = Percent of denitrifying bacteria growth rate at 20°C

\( T \) = Temperature, °C

**Effluent.** Water produced by the BNR treatment system.

**Feed Water (Influent).** Water introduced into the BNR system for treatment.

**Head Loss.** The measure of the reduction of total head, which includes elevation head, velocity head, pressure head, and friction losses of a given fluid as it moves through a fluid system.

**Media.** The filtration and biological support material in a packed bed biological filter. The makeup of this substance varies from manufacturer to manufacturer. In this study, AnoxKaldnes used a plastic media, GE Water & Process Technologies utilized granulated activated carbon (GAC) and Infilco Degremont utilized their Biolite® media, which is an inert gravel-like substance.

**Nitrate Removal Efficiency.** One pilot study goal was that the maximum acceptable effluent nitrate concentration be 2 mg/L NO\(_3\)-N when the influent nitrate concentration is at 10 mg/L NO\(_3\)-N or greater. The nitrate removal efficiency of each pilot unit was calculated using the following.

\[
\eta = \frac{N_i - N_o}{N_i} \times 100\%
\]
where $\eta =$ Nitrate removal efficiency, percent

$N_i =$ Nitrate level in the influent, mg/L

$N_o =$ Nitrate level in the effluent, mg/L

**Terminal Electron Acceptor**

In anaerobic conditions, nitrate serves as the terminal electron acceptor and takes the place of oxygen to completely reduce nitrate ($\text{NO}_3^-$) to gaseous nitrogen ($\text{N}_2$). Carbon dioxide and sulfate can also be used if nitrate is not available.

**ANOXKALDNES PILOT SYSTEM**

AnoxKaldnes’ patented MBBR™ process is based on fixed-film principles and employs the benefits of activated sludge and biofilm systems in absence of their disadvantages. For example, this process requires no backwashing or return sludge like other typical fixed-film or conventional activated sludge processes. This system is based on specially designed plastic biofilm carriers, called biocarriers, in suspension, continually moving within a reactor. These biocarriers are made from polyethylene and have a density slightly less than that of water. As the mixers move the biocarriers throughout the anoxic reactor, the biofilm, which grows within the internal framework of the biocarriers, degrades the pollutants. The carbon source is the substrate for growth of the biofilm, and the nitrate serves as the terminal electron acceptor. In cases where there is excess biofilm, sloughing occurs naturally. In order to promote the growth of the biofilm in absence of internal available carbon in the raw water, an external carbon source is required. The biofilm fixed film thickness is controlled through both the mixing intensity and the sludge that is wasted from the reactor continuously. However, sludge wasting was not required for this pilot.

The AnoxKaldnes pilot system consisted of a 40-foot trailer, which had three reactors, each with a working volume of 180 gallons, operating in series. The pilot plant has a total of six reactors, three of which are usually operated as anoxic and three as post aerobic reactors. Figure 4.4 shows the layout of the trailer.

For the City of Thornton BNR pretreatment study, a single train of only three MBBR™ reactors was used. The remaining three vessels were not used during the pilot study. The first two reactors (Reactor 1 and 2) operated under anoxic conditions for denitrification of nitrates and contained media. Figure 4.5 shows an example of an anoxic reactor. These reactors contained vertically mounted propeller mechanical mixers to provide appropriate mixing of the water and to keep the media in suspension. In these reactors, methanol was used as the external carbon energy source for the denitrification process. Both phosphoric acid and methanol were dosed in the feed pipe to Reactor 1. From the start of piloting, methanol was added, however phosphoric acid was not added until April 15, 2008.

The third reactor (Reactor 3) was operated under aerobic conditions and helped to lower the amount of excess carbon in the process. This third reactor contained a small amount of media and air was supplied to the reactor through two 1-inch stainless steel pipes and a 25 standard cubic feet per minute (scfm) blower. The pipes had 4 mm holes to create a coarse bubble diffusion system located on the bottom of the reactor. Reactor 3 contained an individual valve for airflow control. Manual adjustment of the air flow was used to regulate the DO concentration in Reactor 3.

Treated water flowed from one reactor to the next through screen assemblies (grids or sieves) located in the reactor walls, which retained the K1 media (biocarriers) in the reactor.
AnoxKaldnes' K1 media provided the surface area for the growth of attached biomass during the denitrification process. Figure 4.6 shows photos of the AnoxKaldnes pilot unit, and Figure 4.7 shows the process flow diagram for the AnoxKaldnes MBBR™ pilot unit.

Reactor 1 and Reactor 2 were filled to 41 percent of their water volume with K1 type carrier elements (picture in Figure 4.8). This percent fill displaced approximately 15 percent of the water volume resulting in a liquid volume of approximately 152 gallons for each anoxic reactor. The effective surface area for biological growth of the K1 type media is 152.4 ft²/ft³ of media volume translating to 63.2 ft²/ft³ of anoxic tank volume for the 41 percent fill used. Reactor 3 was filled with 34 percent of its water volume with K1 type carrier elements. This reactor was acting as a carbon burn off reactor to lower any excess COD contained in the water.

**GE PILOT SYSTEM**

The ABMet® process consisted of reactors filled with granular activated carbon media. The biomass grows on the carbon media inside the reactor. Influent flows downward in the reactors, through the carbon media, contacting the microbial mixtures at a specified rate and specified HRT. The rate and HRT can be optimized to ensure maximum nitrate removal. Reduced contaminants are retained within the biomatrix until they are flushed out for recovery.

The reactors are backwashed periodically to remove solids and degassed to release any air trapped within the media. Two reactors were originally proposed for the pilot but due to hydraulics, a change was made during piloting to use only one reactor. Figure 4.9 shows a typical cross

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**Figure 4.4 AnoxKaldnes pilot unit diagram**

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section of an ABMet® bioreactor. The feed distribution piping at the top of the bioreactor is not shown for clarity.

The GE pilot system consisted of a 40-foot trailer, which had two, 600 US gallon bioreactors operating in series, both equipped with the carbon media, feed, and backwash distribution systems. Each bioreactor was 5 feet (60 inches) in diameter × 7.6 feet (91 inches) in height. The carbon media volume in each bioreactor was 65 ft³, the media depth was 3.3 feet and the approximate void volume of the proprietary carbon was 50 percent. At an influent flow of 2 gpm, the surface loading rate per reactor was 0.1 gpm/ft². The backwashing rate of the filters during piloting was approximately 7–14 gpm/ft² and the degassing rate was 10 gpm/ft². Figure 4.10 shows a 3-D rendering of the trailer pilot unit.

The feed water was delivered to a distribution system located at the top of the bioreactor cell and controlled by an operator-entered set point. Water flowed downward through the bioreactor cell and collected in a distribution system located at the bottom of the reactor. The feed and collection distribution systems ensured even flow across the cross sectional area of the bioreactor.
The distribution piping at the bottom of the bioreactor was located in a bed of graded gravel which retained the carbon bed and assisted in providing effective flow distribution. Treated water flowed from Bioreactor #1 to an effluent storage tank where it was pumped to Bioreactor #2. Similarly, the effluent from Bioreactor #2 flowed into an effluent storage tank where it was pumped back to the raw water reservoir.

Bioreactor flushing was performed periodically to allow the release of accumulated suspended solids that entered the cells from the influent water. Flushing was initiated based on the differential pressure across each bioreactor cell. Additionally, degassing of each bioreactor was performed to mitigate short-circuiting by releasing gas pockets that reduced residence time in the bioreactor.

Degassing was a process that utilized a pulse of flush water for bed expansion allowing any trapped gas pockets to escape from the carbon bed. Similar to backwashing, this was initiated based on the differential pressure across each bioreactor cell. If the differential pressure did not decrease to the baseline after degassing the reactor, a backflush was initiated. Figure 4.11 shows
The NITRAZUR DN® nitrate removal process is a submerged biological filter that utilizes a fixed-film biological treatment system. The NITRAZUR DN® system is similar to a conventional media filter. Water flows upward across the media. The unit is backwashed and air scoured periodically. The proprietary media, Biolite, is an expanded clay material with a high specific area to provide a surface for the biomass to attach to and filter suspended solids. As the influent water is pumped through the media, the nitrate is converted to nitrogen gas, which is then transported out through the media and to the atmosphere. Figure 4.13 shows a schematic of the NITRAZUR DN® process and Figure 4.14 shows bacterial growth on the clay media.

For the pilot study, a 1-foot diameter column, single stage unit was used. The media height in the filter column was 9.5 feet. The water depth above the media was 2.63 feet. The height for calculating the HRT of the unit would be the media height (9.5 feet) + the water depth above the media (2.63 feet) = 12.13 feet. HRT is typically not the design basis for filters, rather a hydraulic loading rate is given (i.e., gpm/ft²), since the media bed contains water only in interstitial void spaces. The pilot plant was designed for a process hydraulic loading rate of 4–12 gpm/ft², which

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Figure 4.9 GE ABMet® reactor cross section

Figure 4.10 GE ABMet® pilot trailer 3-D view

photos of the GE ABMet® pilot unit, and Figure 4.12 shows the process flow diagram for the GE ABMet® pilot unit.
corresponds to a flow of approximately 5.04–15.12 gpm. This flow range corresponds to a HRT of approximately 7–20 minutes. At startup, the flow rate was set at a low rate, and then progressively increased to ease the biomass installation and stabilization and to determine the optimal filtration rate that allows the desired removal efficiency.

This system requires a backwashing sequence to periodically clean the filter of sludge buildup and debris. The filter backwash was performed with a co-current upflow of water and air. The backwash water flow rate control valve was modulated to provide 11.5 gpm/ft². The water used for the backwash was treated water that was collected in the pilot clearwell. The pilot clearwell had a capacity of approximately 2130 gallons and was 8 feet in diameter × 5 feet 8 inches in height. The backwash sequence for the pilot plant was automated and required approximately 1 hour to operate.

Air scouring was conducted during the backwash sequence to expand the media and agitate the particles, which loosened the entrained material and excess bacteria on the Biolite media. Air scouring was also conducted to provide the necessary oxygen for aerobic biological activity. The air was introduced in the media through a network of diffusers located at the bottom of the reactor.
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Figure 4.13 Process diagram for IDI NITRAZUR DN® nitrate removal process

Figure 4.14 Denitrifying bacterial growth on clay media

Air scouring rates during piloting ranged from 7–10 scfm. Figure 4.15 shows the process flow diagram for the NITRAZUR DN® pilot unit, and Figure 4.16 shows photos of the NITRAZUR DN® pilot unit.

PILOT APPROACH

Pilot testing of the BNR treatment technology systems was designed to optimize the performance and operation of each system and obtain information that could be used to determine the design criteria for the full-scale plant and identify operation and maintenance issues. Piloting testing of the BNR systems was conducted at conditions similar to those expected in the full-scale plant to the fullest extent possible. Flow and loading rates were held fairly constant for each system, while the carbon feed rate, degassing/backwashing, and other operational parameters were adjusted to optimize operation and performance of each system.

Seven tasks were completed to evaluate the BNR systems. The tasks completed include the following:

• Task 1: System Start-up
Seeding and Acclimation Phase

- Task 2: Operation and Performance Testing
  - Carbon Dose Optimization Phase (Task 2a)
  - Steady State Phase (Task 2b)
  - Backwash Optimization Phase (Applicable for GE Water & Technologies ABMet® Only)
  - Solids Wasting Rate Optimization Phase (Applicable for AnoxKaldnes Only)

- Task 3: Monitoring and Sampling
  - Data Logging
  - Manual Data Collection
  - Water Quality Sampling and Analysis

- Task 4: Resiliency Test Phase
  - Incremental Nitrate Spiking (Task 4a)
  - Rapid Change Nitrate Spiking (Task 4b)
  - Influent Nitrate Spiking Shutdown (Task 4c)
  - Carbon Feed Pump Shutdown (Task 4d)
  - Raw Water Shutdown (Task 4e)

- Task 5: Column Testing (Applicable for GE Water & Technologies ABMet® Only)

- Task 6: Quality Assurance and Quality Control

- Task 7: Conclusions and Recommendations
The following sections describe the pilot test tasks and present results for all manufacturers. Detailed pilot results are presented in Chapter 5. Unless specifically noted, all tasks applied to all three pilot units.

**Task 1: System Start-up**

The goal of this task was to evaluate the performance of the system during seeding, startup, and subsequent initial steady state operation phases. Startup during cold temperature months was a key operational ability for the City of Thornton due to geographic location. Seeding each system was highly recommended as discussed in more detail below. The carbon dose required was determined by the manufacturer and was continuously monitored.

**Seeding and Acclimation Phase**

This task began immediately following the startup phase of the pilot test and continued for a maximum of three weeks. The startup was considered completed when the system began to denitrify and achieved effluent nitrate concentrations of $\leq 2 \text{ mg/L } \text{NO}_3^-\text{N}$ with $10 \text{ mg/L } \text{NO}_3^-\text{N}$ or greater of influent nitrate concentration. During this period, the manufacturer was permitted to optimize their system to the influent conditions once or twice per week. The duration of this pilot testing phase varied per manufacturer.

The manufacturer was allowed to use a seeding material from an outside source (such as microorganisms from a wastewater treatment plant (WWTP) anoxic basin) to expedite the seeding time, if they felt it was necessary. It was highly recommended that the manufacturer use a seeding material to accelerate the startup process in order to assure information is obtained on the pilot treatment process during the cold temperatures. The seeding material was required to be from a sensible source (i.e., compatible with the carbon source used) and to be capable of being used in a full-scale treatment process.

**Task 2: Operation and Performance Testing**

The goal of this task was to evaluate the performance of each system at maximum production under manufacturer’s recommended (typical) backwash frequency, if applicable for the
process. The performance of each system was determined by quantifying hydraulic loading rate, nitrate removal efficiency, nitrate loading rate, required backwash frequency, and/or solids wasting rate. Effluent nitrate concentrations of greater than 2 mg/L NO$_3$-N were considered unacceptable based on the water quality goals established prior to this study. The data collected during this phase was used to optimize and monitor each of the treatment systems and are presented in Chapter 5. Brief discussion of the settings and operational procedures for each BNR system are also discussed in more detail in Chapter 5 along with data and issues addressed during each phase.

**Carbon Optimization Phase**

Immediately following the acclimation phase, the intent was to originally operate each system without any further modification to process variables. This original timeline was made assuming a carbon dose optimization phase was not required since the stoichiometric amount of carbon is based on the influent nitrate, nitrite, and DO. However, once piloting began, TOC laboratory data showed the TOC levels were increasing across the pilot units. Typically, systems with lower HRTs, such as fixed-film systems, are most susceptible to methanol overdosing (Water Environment Federation, 2005). While different process configurations are more or less sensitive to the accurate control of methanol dosing, all three systems piloted experienced the elevated TOC levels. While stoichiometry provides a good approximation of actual required carbon dose, it is theorized that the DO levels may decrease within the pilot systems, resulting in a lower actual required dose. Since the effluent from the pilot units was discharged into a raw water basin (the City’s gravel lakes) upstream of a drinking water treatment plant, TOC was a concern. TOC is a precursor for disinfection byproducts so preventing the BNR treatment processes from increasing TOC concentrations is important. Therefore, a carbon dose optimization period was implemented and start date and duration varied per manufacturer. The goal was to optimize the carbon dose so there was no net increase in TOC from the raw water to the effluent. Once the acclimation period was completed, the carbon source dosing was modified by the manufacturers in order to maximize performance.

**Steady State Phase**

After the Carbon Optimization Phase ended, the systems were operated without any further modification to process variables as originally intended. The manufacturers were allowed to decide (with approval from the City of Thornton and Burns & McDonnell) how to operate their systems during the Steady State Phase. The criteria that were required to be fixed during the steady-state phase were hydraulic loading rate, backwashing/air scouring frequency (if applicable) and optimized carbon and phosphoric acid feed rate (if applicable). Once operational modifications were implemented, the treatment systems operated at constant influent loading, with no modifications allowed for a minimum of 30 days, unless a written request was received and approved by the City and Burns & McDonnell.

This period of piloting did not vary per manufacturer. All three manufacturers were required to have their pilot system optimized by June 11, 2008 to operate a minimum of 30 days without any adjustments. The Steady State Phase for all three systems began on June 11, 2008 and ended on August 3, 2008.
Task 3: Monitoring and Sampling

The City assigned a Pilot Coordinator to be responsible for the daily operation, monitoring, and sampling of the pilot systems. This task included data logging, manual data collection, and water quality sampling and analysis. The following section describes these activities in more detail.

Data Logging, Manual Collection, and Water Quality Sampling and Analysis

This section presents the water quality parameters data logged by the City and each manufacturer in addition to the parameters manually collected and measured by the City. Following these sections is a description of the water quality sampling and analysis procedures used during piloting.

**Data Logging.** To provide sufficient data for analysis and assist in troubleshooting, each BNR system was equipped with a data logger that automatically recorded operational parameters on a regular basis. Each BNR manufacturer was responsible for setup and testing of the data logging equipment prior to initiating the formal test plan. Software required for downloading was also provided to the City unless other arrangements were made. The data logging capabilities and requirements are listed in Table 4.1 and Table 4.2. At a minimum, this data was downloaded weekly.

Table 4.1

<table>
<thead>
<tr>
<th>Instrument</th>
<th>AnoxKaldnes</th>
<th>GE Water &amp; Process Technologies</th>
<th>Infilco Degremont</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>NO₃-N</td>
<td>(2) X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DO</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>ORP(3)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Carbon dosing rate</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

(2) Influent nitrate was measured using the nitrate analyzer on the raw water line common to all 3 pilot units. Only one unit, IDI, had a separate influent nitrate analyzer.
(3) ORP = Oxidation reduction potential.

Table 4.2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Location</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH (unitless)</td>
<td>Influent</td>
<td>Every 1 minute</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/L)</td>
<td>Influent</td>
<td>Every 1 minute</td>
</tr>
<tr>
<td>Nitrates (mg/L)</td>
<td>Influent</td>
<td>Every 5 minutes</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>Influent</td>
<td>Every 1 minute</td>
</tr>
</tbody>
</table>
Manual Data Collection. In addition to data logging, the City manually collected operational data on a routine basis for the parameters outlined in Table 4.1. This protected the City from the risk of losing data in the event of a data logging failure. The manually compiled data were compared to the data logged values as part of the quality assurance/quality control (QA/QC) program. Data collected varied based on the design of each BNR system.

City Lab Data—Water Quality Data Collection. In addition to data logging and manually measuring the parameters outlined in Table 4.1, the City also collected grab samples from each of the three pilot units. This also protected the City from the risk of losing data in the event of a data logging failure. The City’s lab data was compared to the data logged values as part of the QA/QC program. It should be noted that the City of Thornton’s laboratory is certified by the State of Colorado Department of Public Health and Environment as being in compliance with the criteria and procedures of the EPA Manual for the Certification of Laboratories Analyzing Drinking Water for nitrate, nitrite, fluoride, TOC, and DOC.

The data collected varied based on the design of each BNR system. Influent samples were collected upstream of carbon and phosphorus addition, and effluent sample locations are discussed in more detail for each system in Chapter 5. Table 4.3 shows the original parameters that grab samples were taken and analyzed for.

Throughout the pilot, the need to analyze additional parameters became apparent and as of March 18, 2008, true and apparent color were added along with daily TOC, turbidity and alkalinity. Dissolved organic carbon (DOC) samples were collected daily starting May 13, 2008 until then end of May. At the beginning of June 2008, DOC samples were collected weekly. During July 2008, no DOC samples were collected since the data from May and June 2008 indicated that the TOC and DOC were almost identical. For the Resiliency Test Phase in August 2008, DOC samples were collected weekly. Table 4.4 shows the revised collection schedule for the water sampling and

---

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sampling frequency</th>
<th>BNR system feed</th>
<th>BNR system effluent</th>
<th>BNR system backwash</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Daily</td>
<td>2 times/day</td>
<td>2 times/day</td>
<td>1 time/ backwash</td>
</tr>
<tr>
<td>Temperature</td>
<td>Daily</td>
<td>2 times/day</td>
<td>2 times/day</td>
<td>1 time/ backwash</td>
</tr>
<tr>
<td>Nitrate (NO₃-N)</td>
<td>Daily</td>
<td>2 times/day</td>
<td>2 times/day</td>
<td>1 time/ backwash</td>
</tr>
<tr>
<td>Nitrite (NO₂-N)</td>
<td>Weekly</td>
<td>1 time/week</td>
<td>1 time/week</td>
<td>—</td>
</tr>
<tr>
<td>Ammonia (NH₃-N)</td>
<td>Weekly</td>
<td>1 time/week</td>
<td>1 time/week</td>
<td>—</td>
</tr>
<tr>
<td>Total alkalinity (CaCO₃)</td>
<td>Weekly</td>
<td>1 time/week</td>
<td>1 time/week</td>
<td>1 time/ backwash</td>
</tr>
<tr>
<td>Total hardness (CaCO₃)</td>
<td>Weekly</td>
<td>1 time/week</td>
<td>1 time/week</td>
<td>—</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Weekly</td>
<td>1 time/week</td>
<td>1 time/week</td>
<td>1 time/ backwash</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>Weekly</td>
<td>3 times/week</td>
<td>3 times/week</td>
<td>1 time/ backwash</td>
</tr>
<tr>
<td>TDS</td>
<td>Weekly</td>
<td>3 times/week</td>
<td>3 times/week</td>
<td>1 time/ backwash</td>
</tr>
<tr>
<td>TSS</td>
<td>Weekly</td>
<td>3 times/week</td>
<td>3 times/week</td>
<td>1 time/ backwash</td>
</tr>
</tbody>
</table>

(1) For IDI and GE Water & Process Technologies which have backwash processes, at least four times during the pilot study, grab samples shall be taken once every minute for the IDI backwash cycle and once every 5 minutes for the GE Water & Process Technologies backwash cycle. These grab samples shall consist of nitrates and total suspended solids (TSS).
(2) Redundant grab samples and blanks shall be taken at least every two weeks for QA/QC.
(3) ‘—’ means no data recorded.
Any variations on this data collection schedule were determined to be necessary by the project team and are discussed with the piloting results in Chapter 5. The City of Thornton also sampled the raw water influent to the pilot units and the effluent from each of the three pilot units for disinfection byproduct formation potential. One sample to measure methanol was collected from the effluent of each pilot unit to try to detect if there was any residual. In addition, to simulate the effluent being discharged to the reservoir, the City collected bottles of the raw water and from the effluent of the three pilot systems and placed these bottles in the reservoir for approximately three weeks. After three weeks, the samples were measured for chlorophyll-a. These samples were sent to an outside laboratory.

Analytical Procedures. Most of the water quality parameters were measured following Standard Methods or EPA methods. A summary of analytical procedures used during the pilot is presented in Table 4.5.

Based on the listed Method Detection Limit (MDL) in Table 4.5, water quality averages presented and discussed in Chapter 5 for each piloted manufacturer include data points reported as below the MDL. When this occurs in water quality analysis, it is necessary to assign a value to each data point or exclude these from the analysis. Since data collected with values below the MDL appear to be accurate and statistically significant with regard to this study, the data was included in the averages. While there is no generally acceptable method for including these values, several methods are routinely used including replacing these data points with an arbitrary value such as zero, 0.5 MDL, or the MDL value. Each of these arbitrary values will introduce some bias
Typically, using zero or 0.5 MDL in an analysis will result in averages that are biased low, while using the MDL will result in averages that are biased high (MacBerthouex, 2002). Regardless of the method used, it is necessary to be consistent in the analysis and recognize when a bias may be affecting the results. The averages presented in this report were computed by assigning data points below the MDL a value of zero. Additional discussion has been included with certain parameters where it was believed that the averages were biased low.

### Task 4: Resiliency Test Phase

Beginning August 4, 2008 and ending August 28, 2008, all pilot systems underwent events that resulted in varying changes in influent nitrate levels and/or carbon dose. These tests were performed to observe each system’s response since events such as a carbon feed pump failure could occur during full-scale operation. It is critical to know how each system will respond. The following tasks were performed during the final stage of piloting and were applied equally to each pilot unit:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Facility</th>
<th>Standard methods(1) number or other method reference</th>
<th>EPA method(2)</th>
<th>MDL(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>City laboratory</td>
<td>4500 H</td>
<td>150.1 / 150.2</td>
<td>NA(4)</td>
</tr>
<tr>
<td>Temperature</td>
<td>City laboratory</td>
<td>2550 B</td>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>Turbidity – bench top</td>
<td>City laboratory</td>
<td>2130 B / Method 2</td>
<td>180.1</td>
<td>0.1 NTU</td>
</tr>
<tr>
<td>TOC/DOC</td>
<td>City laboratory</td>
<td>5310 C / Persulfate UV Method</td>
<td></td>
<td>0.5 mg/L</td>
</tr>
<tr>
<td>SUVA(5)</td>
<td>City laboratory</td>
<td>5910 B</td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Total dissolved solids</td>
<td>City laboratory</td>
<td>2540 C</td>
<td></td>
<td>10 mg/L</td>
</tr>
<tr>
<td>TSS</td>
<td>City laboratory</td>
<td>2540 D</td>
<td></td>
<td>2 mg/L</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>City laboratory</td>
<td>2320 B</td>
<td></td>
<td>10 mg/L</td>
</tr>
<tr>
<td>Total hardness</td>
<td>City laboratory</td>
<td>2340 C</td>
<td></td>
<td>10 mg/L</td>
</tr>
<tr>
<td>Major ion scan(6)</td>
<td>City laboratory</td>
<td></td>
<td>300.0(7)</td>
<td></td>
</tr>
<tr>
<td>Color (true)</td>
<td>City laboratory</td>
<td>2120C</td>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>Chlorophyll-a</td>
<td>City laboratory</td>
<td>10200H</td>
<td></td>
<td>1 μg/L</td>
</tr>
<tr>
<td>Methanol</td>
<td>MWH laboratory</td>
<td>Gas Chromatography - Flame Ionization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disinfection byproduct formation</td>
<td>MWH laboratory</td>
<td>5701B</td>
<td></td>
<td>0.5 μg/L</td>
</tr>
</tbody>
</table>

(2) EPA Methods Source: EPA Office of Ground Water and Drinking Water.
(3) MDL = Method Detection Limit.
(4) NA = Not applicable.
(5) SUVA = Specific Ultraviolet Adsorption at 254 nanometers.
(6) Includes F, Cl, Br, NO₂⁻, NO₃⁻, o-PO₄³⁻, SO₄²⁻, Ca, Mg, Fe, Mn, Na, NH₄⁺, K.
(7) Anions are done by EPA 300.0. Cations are not EPA approved on the ion chromatograph (IC) so there are no EPA/SM methods.
• Task 4a: Incremental Nitrate Spiking
• Task 4b: Rapid Change Nitrate Spiking
• Task 4c: Influent Nitrate Spiking Shutdown
• Task 4d: Carbon Feed Pump Shutdown
• Task 4e: Raw Water Shutdown

Each task is described in the following sections.

**Task 4a: Incremental Nitrate Spiking**

Throughout the Seeding and Acclimation, Carbon Optimization, and Steady State Phases, the raw water was spiked to maintain an influent concentration of 10 mg/L NO₃-N. Since the nitrate concentrations in the raw feed were relatively low, spiking the raw water continuously during piloting was necessary. The nitrate spiking also allowed evaluation of nitrate removal efficiency and product water quality under conditions of elevated nitrate in the feed water.

To spike nitrate, the use of an appropriate spiking solution and metering pump was employed to add approximately 5 mg/L NO₃-N to 20 mg/L NO₃-N (per direction of Burns & McDonnell) of nitrate to the feed water. Typically, a solution prepared from a monovalent nitrate salt is preferred (sodium nitrate or potassium nitrate). Use of nitric acid as a nitrate source is not recommended because it affects the pH. Therefore, sodium nitrate was used for nitrate spiking at the City of Thornton. The spiking solution was prepared using raw water from the South Tani Reservoir. The salt solution was injected into the feed water prior to the treatment processes. An inline static mixer in the raw water line was installed for mixing of the sodium nitrate. Since the raw water was pumped at a constant rate, the raw water flow rate did not change.

During the final stage of piloting, the influent nitrate to each of the pilots was increased in increments of 5 mg/L NO₃-N for the first task of this phase. The purpose of this task was to monitor each pilot unit’s response to small incremental changes in the raw water nitrate concentration. Starting on Monday, August 4, 2008, the raw water nitrate concentration was increased from 10 mg/L NO₃-N to 15 mg/L NO₃-N. On Friday, August 8, 2008, the raw water nitrate concentration was increased from 15 mg/L NO₃-N to 20 mg/L NO₃-N. The pilot units operated with a raw water concentration of 20 mg/L NO₃-N until Monday, August 11, 2008. Each pilot manufacturer provided the City with the required methanol dose required for 15 mg/L and 20 mg/L NO₃-N of influent nitrate by Thursday, July 31, 2008 allowing the City adequate time to prepare for fluctuating nitrate concentrations and carbon feed requirements.

The goal of this task was for each of the three pilot units to achieve the lowest effluent nitrate concentrations possible during this incremental nitrate spiking period. The City sampled the raw water to the pilot units and effluent from each pilot unit during this task for the following parameters: NO₂⁻, NO₃⁻, PO₄³⁻, SO₄²⁻, TOC, pH, and TSS. During this period, the manufacturer was permitted to optimize their system to the influent conditions during the first couple days of changing the influent nitrate concentration. If the manufacturers needed to make any additional adjustments, they required approval from the City and Burns & McDonnell prior to making any changes to their pilot units.
Task 4b and 4c: Rapid Change in Nitrate Spiking/Influent Nitrate Spiking Shutdown

The second task for the final month of piloting included abruptly changing the influent nitrate concentrations in order to observe each system’s response. On Tuesday, August 12, 2008, the influent nitrate concentration to the pilot units was decreased from 20 mg/L NO₃-N to 5 mg/L NO₃-N. The methanol dose to each of the pilot units was reduced per each manufacturer’s recommended amount for this event. On Saturday, August 16, 2008, the influent nitrate concentration was increased from 5 mg/L NO₃-N to 10 mg/L NO₃-N, and the system operated over the weekend for approximately 48 hours to reach steady state. On Monday, August 18, 2008, and again on Wednesday, August 20, 2008, spiking the influent with nitrate was stopped for four hours without any changes in carbon feed to each of the pilot units. Shutting off the nitrate spiking decreased the raw water nitrate concentration to approximately 1 mg/L NO₃-N to 2 mg/L NO₃-N. The goal of this task was to test how each process handles a major swing in influent nitrate concentration. Another goal was for each of the three pilot units to achieve the lowest effluent nitrate concentrations possible during this nitrate spiking period.

Each nitrate spiking shutdown lasted four hours and the influent nitrate concentration was brought back up to 10 mg/L NO₃-N after the shutdown. The City sampled the raw water to the pilot units and effluent from each pilot unit during this task for the following parameters: NO₂⁻, NO₃⁻, PO₄³⁻, SO₄²⁻, TOC, pH, and TSS. The manufacturer provided the City of Thornton with the required methanol dose required for 5 mg/L NO₃-N by Thursday, July 31, 2008, which allowed the City of Thornton adequate time to prepare any changes in the carbon feed to the systems. As with the previous task, the manufacturers were permitted to optimize their system to the influent conditions in the first day or two of changing the influent nitrate-nitrogen concentration. If more adjustments were needed by a manufacturer, these adjustments needed to be approved by the City and Burns & McDonnell prior to making any changes.

Task 4d: Carbon Feed Pump Shutdown

Task 4d began on August 21, 2008 when the first shutdown of the carbon feed pumps occurred for four hours. Again on August 22, the carbon feed pumps were shut down for another four hours. The influent nitrate concentration was kept at 10 mg/L NO₃-N. The goal of this task was to observe each system’s response to a sudden change in carbon feed source. The shutdown time of four hours was selected for this task because this time duration is likely the longest power outage the City of Thornton would experience during a full-scale application.

The City sampled the raw water to the pilot units and effluent from each pilot unit during this task for the following parameters: NO₂⁻, NO₃⁻, PO₄³⁻, SO₄²⁻, TOC, pH, and TSS. These samples were taken at the following times:

- Immediately before the carbon feed pump shutdown
- 2 hours after shutdown
- 4 hours after shutdown
- 8 hours after shutdown
- 24 hours after shutdown

This task was repeated both times the carbon feed pump was shut down.
Task 4e: Raw Water Shutdown

The last task of the Resiliency Test Phase consisted of a shutdown and startup of all pilot units to observe each system’s response to such an event. The purpose of shutting down the system completely was to simulate a total power failure that may occur during full-scale applications. Therefore, under this task, a total power failure included a shutdown of all equipment on the pilot units (i.e., carbon feed pumps, blowers, mixers, etc.). On Saturday, August 23, 2008, the raw water pump to the pilot units was turned off, and each unit was completely shut down for 72 hours and started back up again on Tuesday, August 26, 2008.

Immediately upon the raw water pump and pilot units turning back on, the City sampled two separate times each day for the remainder of the piloting period. Samples comprised the raw water to the pilot units and effluent from each unit for the following parameters: NO$_2^-$, NO$_3^-$, PO$_4^{3-}$, SO$_4^{2-}$, TOC, pH, and TSS.

Task 5: Column Testing

GE Water & Process Technologies ABMet® performed a column test to simulate field conditions (i.e., HRT and loading rate) to determine GAC breakthrough. GE submitted a method for their column testing for review and approval by the City and Burns & McDonnell prior to completing the pilot test. The results of the column test are presented in Chapter 5.

Task 6: Quality Assurance and Quality Control

The objective of this task was to maintain QA/QC throughout the pilot study. The City of Thornton’s laboratory is state-certified and maintains strict QA/QC in accordance with this certification. All parties involved in the project had responsibility within this task, which included the following activities:

- The City maintained an operational log describing all operational changes such as changes in carbon dose, backwashing interval, etc. This log was used during the data evaluation process to identify/clarify operational issues. The manufacturers were responsible for obtaining approval from the City’s Pilot Coordinator, prior to making any operational changes.
- Equipment, pipes, tubing, and instrumentation were visually inspected on a daily basis. Any issues or required repairs were noted on the operational log and repaired as soon as possible. When appropriate, the BNR manufacturer(s) were notified of the problem.
- Where possible, calibration of equipment was verified by laboratory methods (pH, temperature, turbidity, DO, and nitrate). This equipment was verified at a minimum of once per month or once per week, when possible.
- Data was collected manually and compared to data logged values to ensure accuracy of the data logging equipment. This was performed once per week.
- Data was compiled and analyzed in a timely manner to identify any potential QA/QC issues.
- Water quality samples were collected according to approved standard operating procedures (SOPs) or standard methods procedures. The City of Thornton maintained a
log of all samples collected which included date, time, sample location, and person collecting the sample.

- Laboratory analysis was conducted according to standard test methods and as outlined in the Standard Methods for the Examination of Water and Wastewater or approved Thornton SOPs.

**Task 7: Conclusions and Recommendations**

Based on the results of the pilot test study and evaluation of the data, conclusions and recommendations were developed and are presented in Chapter 6 and Chapter 7.
CHAPTER 5
RESULTS AND DISCUSSION

This chapter presents the piloting results for each manufacturer: AnoxKaldnes (AK), GE Water & Process Technologies and Infilco Degremont Inc (IDI). Each manufacturer’s section will also present their pilot testing activities during the following tasks:

- Task 1: Seeding and Acclimation Phase
- Task 2: Operation and Performance Testing
- Task 3: Monitoring and Sampling
- Task 4: Resiliency Test Phase
- Task 5: Column Testing (Applicable to GE Water Technologies ABMet® Only)
- Task 6: Quality Assurance and Quality Control
- Task 7: Conclusions and Recommendations

This chapter also presents the operational settings, issues/activities addressed during piloting, and data results (plots and tables) per manufacturer.

ANOXKALDNES SUMMARY OF PILOT TESTING ACTIVITIES

Startup of the AnoxKaldnes pilot system began on February 8, 2008. The actual start and completion dates for each task are provided in the Table 5.1.

In the following pages, data for each task are provided along with a brief narrative. Additionally, the events and pilot results will be discussed in this section.

TASK 1: STARTUP—SEEDING AND ACCLIMATION PHASE—ANOXKALDNES

The goal of this task was to evaluate the performance of the AnoxKaldnes pilot system during startup. Startup during cold temperature months was a key operational ability for this system’s geographic location. Although it was strongly suggested to seed, AnoxKaldnes decided not to seed their unit as described below.

The data collected during this task were used to monitor the MBBR™ system and are described below along with data tables and plots. A discussion of the settings and operational procedures for the MBBR™ system for this task is also presented in this section.

Seeding and Acclimation

February 8, 2008 was the startup date for the AnoxKaldnes MBBR™ pilot unit. Seeding this pilot unit was considered in order to speed up the projected five to six week cold-water seeding period. However, AnoxKaldnes ultimately decided not to seed their pilot for the following reasons:

- Concern of Erroneous Results: The pilot unit depended on a naturally developed, sustainable biofilm capable of nitrate reduction. AnoxKaldnes was concerned that introducing a foreign bioculture to the water could have potentially resulted in immediate
desirable denitrification, but the reduction of nitrate would be a result of the laboratory culture instead of the indigenous nitrate reducing organisms.

- **Non-wastewater Species Introduction:** As stated previously, the AnoxKaldnes pilot unit depended on a naturally grown bioculture, and the species typically found in the raw water may not have been similar to the species contained in the laboratory-created bioculture. Consequently, AnoxKaldnes was concerned that seeding the water may have resulted in unnatural denitrification in comparison to a standard startup. Another undesirable effect of seeding with a laboratory-created culture was the increase in time for bacteria to become larger in numbers. During this extended period, it would have been unknown what type of treatment could have been expected.

Although AnoxKaldnes did not seed their pilot unit, they continued to follow the operational procedure outlined for the Seeding and Acclimation Phase of testing. Startup was considered completed when AnoxKaldnes began denitrifying and achieving effluent nitrate concentrations \( \leq 2 \) mg/L NO\(_3\)-N with 10 mg/L NO\(_3\)-N or greater of influent nitrate concentrations. The effluent nitrate concentrations did not reach the pilot goal of \( \leq 2 \) mg/L NO\(_3\)-N until approximately 12 weeks into the pilot study. April 29, 2008 was the first City Laboratory and AnoxKaldnes data logger effluent nitrate reading below 2 mg/L NO\(_3\)-N. Thus, the Seeding and Acclimation Phase for AnoxKaldnes began February 8, 2008 and ended April 30, 2008. Operational procedures outlined in Chapter 4 were followed throughout this phase.

### Operational Settings

Operational settings during the Seeding and Acclimation Phase for the AnoxKaldnes pilot unit varied all through this phase. The operational parameters during the Seeding and Acclimation Phase are presented in Table 5.2. At a flow rate of 3.5 gpm, the HRT through each of the three

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**Table 5.1**

<table>
<thead>
<tr>
<th>Task description</th>
<th>Start date</th>
<th>Completion date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Startup: Seeding and Acclimation Phase</td>
<td>February 8, 2008</td>
<td>April 30, 2008</td>
</tr>
<tr>
<td>2. Operation and performance testing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Backwash Optimization Phase</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>3. Monitoring and sampling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Data logging</td>
<td>February 8, 2008</td>
<td>August 28, 2008</td>
</tr>
<tr>
<td>b. City manual data collection and analysis</td>
<td>February 20, 2008</td>
<td>August 28, 2008</td>
</tr>
<tr>
<td>4. Resiliency Test Phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Incremental nitrate spiking</td>
<td>August 4, 2008</td>
<td>August 11, 2008</td>
</tr>
<tr>
<td>b. Rapid change nitrate spiking</td>
<td>August 12, 2008</td>
<td>August 17, 2008</td>
</tr>
<tr>
<td>c. Influent nitrate shutdown</td>
<td>August 18, 2008</td>
<td>August 20, 2008</td>
</tr>
<tr>
<td>5. Column testing</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>6. QA/QC</td>
<td>February 8, 2008</td>
<td>August 28, 2008</td>
</tr>
</tbody>
</table>
reactors was approximately 50 minutes, for a total HRT through the process of 100 minutes (1.7 hours) for nitrate removal and 50 minutes for post aeration. The working volume of each reactor is 180 gallons including the displacement volume of the media.

**Issues and Activities Addressed**

Issues and activities addressed during AnoxKaldnes’ startup phase included phosphoric acid addition, nitrate analysis, trailer heating, and carbon feed pump installation difficulties. The following sections describe each issue/activity for the AnoxKaldnes pilot unit during their startup (Seeding and Acclimation Phase).

**Phosphoric Acid Addition**

Due to slow denitrification occurring in the reactors, the AnoxKaldnes process group decided to dose the system with phosphoric acid, since phosphorus could be a limiting nutrient for the denitrification process. AnoxKaldnes targeted their dose of phosphoric acid to increase the concentration by 0.5 mg/L as P. This chemical addition was highly monitored for its effects on treatment and was adjusted during the first few weeks to find the optimum dose. After dosing the system with phosphoric acid on April 11, 2008, the system began to show faster rates of denitrification and as stated previously, on April 29, 2008, AnoxKaldnes was denitrifying below the goal of 2 mg/L NO₃-N. AnoxKaldnes did not fully optimize their phosphoric dose during the Seeding and Acclimation Phase.

---

**Table 5.2**

<table>
<thead>
<tr>
<th>Date</th>
<th>Average raw water NO₃-N (mg/L)</th>
<th>Average influent DO (mg/L)</th>
<th>Average AK influent flow rate (gpm)</th>
<th>HRT Anoxic (hours)</th>
<th>Aeration (hours)</th>
<th>CH₃OH pump feed rate (mL/min)</th>
<th>CH₃OH/NO₃-N (g/g)</th>
<th>Average CH₃OH (99.9%) dose (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>02/08/08 to 02/11/08</td>
<td>—</td>
<td>11.88</td>
<td>2.00</td>
<td>3.0</td>
<td>1.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>02/12/08 to 03/12/08</td>
<td>10.54</td>
<td>—</td>
<td>0.60</td>
<td>10</td>
<td>5.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>03/13/08 to 03/25/08</td>
<td>9.8</td>
<td>9.42</td>
<td>3.50</td>
<td>1.7</td>
<td>0.9</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>03/26/08 to 04/03/08</td>
<td>9.6</td>
<td>9.57</td>
<td>3.57</td>
<td>1.7</td>
<td>0.9</td>
<td>9.0</td>
<td>11.0</td>
<td>105.2</td>
</tr>
<tr>
<td>04/04/08 to 04/07/08</td>
<td>10.2</td>
<td>9.83</td>
<td>3.54</td>
<td>1.7</td>
<td>0.9</td>
<td>4.5</td>
<td>5.2</td>
<td>53.0</td>
</tr>
<tr>
<td>04/08/08 to 04/29/08</td>
<td>10.2</td>
<td>8.96</td>
<td>3.59</td>
<td>1.7</td>
<td>0.9</td>
<td>5.0</td>
<td>5.5</td>
<td>56.7</td>
</tr>
</tbody>
</table>

(1) Effluent nitrate levels not given since all above pilot goal of ≤2 mg/L NO₃-N.
(2) Feed rate at 20% methanol dilution.
(3) ‘—’ indicates data not available and ‘– –’ indicates inconsistent methanol feed due to pump air binding issues.
Nitrate Analyzer and Laboratory Analysis

From February 8, 2008 to March 20, 2008, the AnoxKaldnes’ effluent nitrate analyzer was not communicating with the data logger. Hence, the nitrate analyzer data during this time was not used in the pilot results analysis. Furthermore, there were issues with the manually collected samples through March 28, 2008. Thus, the City Laboratory data for AnoxKaldnes’ effluent nitrate concentration from the beginning of startup to March 28, 2008 was not used in pilot results analysis.

System Heating

From February 8, 2008 to approximately March 13, 2008, the heater in the trailer was turned on which ultimately resulted in an increase in effluent water temperature. Since denitrification had not been observed to this point, it is not possible to determine if this increase in temperature resulted in a significant acceleration of biological growth.

Carbon Feed Pump Installation

When the AnoxKaldnes unit started, the carbon feed system experienced air binding issues on several occasions. The discharge flow was also low for the capacity of the peristaltic pump provided. To fix this problem, AnoxKaldnes diluted the methanol 1:1 on March 26, 2008 to create a flow the feed pump could handle better. Consequently, the problems with the methanol feed pump were minimized.

In April, the methanol feed pump had operational issues twice leading to increases in effluent nitrate around 11 mg/L NO$_3$-N. Not seeding, having inconsistent flow, and air binding issues with the carbon feed pump most likely led to the 12 week acclimation period that AnoxKaldnes had for their system to reach the pilot goal of 2 mg/L NO$_3$-N effluent concentration.

Data Results: Plots and Tables—AnoxKaldnes Task 1

Data plots for the AnoxKaldnes MBBR™ system are presented in Figure 5.1 through Figure 5.3 for the Acclimation Phase. Water quality parameters plotted include nitrate, TOC, and temperature. Discussions on the City Laboratory data for ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity, and pH are presented in Task 3.

Nitrate

Before adding phosphorus to the MBBR™, the effluent nitrate frequently fluctuated every 30 minutes. As shown in Figure 5.1, effluent nitrate-nitrogen concentrations gradually decreased from March 20, 2008 to April 8, 2008 despite the intermittent fluctuations every half hour. After adding phosphorus to the system on April 11, 2008, the denitrification rate increased, and AnoxKaldnes was able to denitrify below 2 mg/L NO$_3$-N on April 29, 2008.

During the Seeding and Acclimation Phase, AnoxKaldnes experienced difficulties with their methanol pump two times. The first instance occurred on April 10, 2008 and the other on April 20, 2008. Each event caused the effluent nitrate concentration to increase to approximately 11 mg/L NO$_3$-N, however, both times the system was able to recover and begin removing nitrate.
At this stage of the pilot, the goal of 2 mg/L NO$_3$-N had not yet been achieved. The influent nitrate concentration to the pilot unit was increased to 10 mg/L NO$_3$-N during this time.

**TOC**

The City began taking weekly TOC data on March 5, 2008 and daily as of March 18, 2008. Figure 5.2 shows that the effluent TOC concentration from the MBBR™ was on average 6.6 mg/L excluding the high TOC reading on March 18, 2008 and that the effluent TOC concentration increased on average by 2 mg/L relative to the raw water TOC concentration during AnoxKaldnes’ Seeding and Acclimation Phase. Taking into account the 42.8 mg/L reading on March 18, 2008, the average effluent TOC concentration from the MBBR™ was 7.6 mg/L resulting in a 3.0 mg/L increase in TOC across the MBBR™ system.

Samples were not collected during AnoxKaldnes’ Seeding and Acclimation Phase for DOC analysis. DOC measurements began May 13, 2008 during the Carbon Optimization Phase.

**Temperature**

One of the goals during this pilot study was to evaluate seeding and startup processes in cold temperatures. AnoxKaldnes’ MBBR™ pilot unit startup was at the beginning of February when the influent temperature of the water was approximately 5°C. The optimum temperature range for denitrification is generally from 28 to 35°C, and although denitrification does occur in
temperatures ranges as low as 5 to 10°C, the process is very slow and requires substantial contact time.

As shown in Figure 5.3, startup in cold temperatures for AnoxKaldnes was difficult to evaluate since they turned on a heater in the trailer from February 8, 2008 to March 13, 2008. The heater increased the effluent water temperature to approximately 9°C on February 8, 2008 and higher thereafter. However, for AnoxKaldnes, the effluent nitrate did not decrease during this period; possibly since they experienced difficulties with the methanol feed pump.

As shown in Figure 5.3, the temperature was approximately 10 °C when the effluent nitrate concentration from the MBBR™ achieved the effluent concentration goal of 2 mg/L NO₃⁻N on April 29, 2008.

**TASK 2: OPERATION AND PERFORMANCE TESTING—ANOXKALDNES**

The goal of this task was to evaluate the performance of the AnoxKaldnes system at maximum production under their recommended operational settings. The performance of the MBBR™ system was determined by quantifying nitrate removal efficiency, nitrate loading rate, carbon feed requirement, etc. Effluent nitrate concentrations of greater than 2 mg/L NO₃⁻N were considered unacceptable. The operation and maintenance testing included the Carbon Optimization and Steady State Phases.

The data collected during this task were used to optimize and monitor the MBBR™ system and are described below along with data tables and plots. Brief discussions of the settings and operational procedures for the MBBR™ system for each subtask listed above are contained in the following sections.
Task 2a: Carbon Optimization Phase—AnoxKaldnes

The Carbon Optimization Phase for AnoxKaldnes began April 30, 2008 and ended June 11, 2008. During this time, AnoxKaldnes was dosing excess methanol to account for the high DO concentrations, to help the growth of the biomass and to maintain an acceptable denitrification rate.

Operational Settings

The flow rate of 3.5 gpm from the end of AnoxKaldnes’ Seeding and Acclimation Phase continued through the beginning of the Carbon Optimization Phase until the first week of June. With the elevated DO concentrations observed, AnoxKaldnes had trouble estimating denitrification rates. In order to account for these elevated concentrations, they decided to increase the HRT by decreasing the flow from 3.5 gpm to 2.3 gpm on June 6, 2008.

The flow rate remained at 2.3 gpm for the remainder of AnoxKaldnes’ Carbon Optimization Phase ending June 11, 2008. At a flow rate of 2.3 gpm, the HRT through each of the three reactors was approximately 78 minutes, for a total HRT of 156 minutes (2.6 hours) for nitrate removal and 78 minutes (1.3 hours) for the post aeration.

Table 5.3 presents the operational parameters of the pilot system during the Carbon Optimization Phase. The dates are listed for when a change in the carbon dose was made.
Issues and Activities Addressed

Issues and activities addressed during AnoxKaldnes’ Carbon Optimization Phase included difficulties with their carbon feed pump and phosphorus optimization. The following sections describe each issue/activity for the AnoxKaldnes pilot unit during this phase.

**Methanol Pump.** On May 16, 2008, methanol was not being fed to the system due to clogging of the feed pump’s suction tubing. The tubing was changed and methanol was properly fed to the system. The clogging resulted in not meeting the effluent nitrate goal of 2 mg/L NO₃-N for a brief period.

**Phosphorus Optimization.** From May 9, 2008 to June 4, 2008, AnoxKaldnes’ effluent NO₃-N remained above 2 mg/L. During this period, they were optimizing the phosphoric acid and methanol in order to achieve acceptable denitrification. By June 5, 2008, AnoxKaldnes was denitrifying below 2 mg/L NO₃-N and continued to meet this goal until the end of the Carbon Optimization Phase.

**Data Results**

Data plots for the AnoxKaldnes MBBR™ system are presented in Figure 5.4 through Figure 5.8. Water quality parameters plotted include nitrate DOC, and TOC. Discussions on data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented in Task 3.

Shown in the following figures and tables, AK1 represents the effluent collected after Reactor 1 whereas AK2 represents the effluent sample collected after Reactor 2. AK3 represents the effluent sample collected after the Reactor 3 aeration tank.

**Nitrate.** Figure 5.4 shows the influent and effluent nitrate-nitrogen concentrations for AnoxKaldnes during the Carbon Optimization Phase. Also shown in Figure 5.4, effluent nitrate concentrations did not reach the goal of ≤2 mg/L NO₃-N throughout most of the Carbon Optimization Phase. On May 16, 2008 methanol was not

### Table 5.3
AnoxKaldnes operational parameters during the Carbon Optimization Phase

<table>
<thead>
<tr>
<th>Date</th>
<th>Average raw water NO₃-N (mg/L)</th>
<th>Average influent DO (mg/L)</th>
<th>Average effluent water NO₃-N (mg/L)</th>
<th>Average AK influent flow rate (gpm)</th>
<th>CH₃OH pump feed rate (1) (mL/min)</th>
<th>Average CH₃OH / NO₃-N (g/g)</th>
<th>Average CH₃OH (99.9%) dose (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/30/08 to 05/06/08</td>
<td>10.9</td>
<td>8.52</td>
<td>2.13</td>
<td>3.55</td>
<td>3.60</td>
<td>3.9</td>
<td>44.31</td>
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<tr>
<td>05/07/08 to 05/15/08</td>
<td>11.9</td>
<td>8.26</td>
<td>2.53</td>
<td>3.48</td>
<td>4.53</td>
<td>4.5</td>
<td>54.50</td>
</tr>
<tr>
<td>05/16/08 to 05/20/08</td>
<td>11.1</td>
<td>7.96</td>
<td>3.51</td>
<td>3.47</td>
<td>3.00</td>
<td>3.3</td>
<td>36.09</td>
</tr>
<tr>
<td>05/21/08 to 06/05/08</td>
<td>11.1</td>
<td>7.22</td>
<td>3.26</td>
<td>3.43</td>
<td>3.51</td>
<td>3.8</td>
<td>42.00</td>
</tr>
<tr>
<td>06/06/08 to 06/10/08</td>
<td>10.2</td>
<td>6.70</td>
<td>1.26</td>
<td>2.27</td>
<td>2.70</td>
<td>4.9</td>
<td>49.80</td>
</tr>
</tbody>
</table>

(1) Feed rate at 20% methanol dilution.
being fed to the system due to clogging of the feed pump’s suction tubing. The tubing was changed and methanol was properly fed to the system. Beginning June 5, 2008 the effluent nitrate concentration fell below 2 mg/L NO₃-N and continued to meet the goal for the remainder of the Carbon Optimization Phase. This drop in nitrate was most likely in result of the carbon and phosphorus being optimized by the end of this phase.

**TOC.** At the beginning of May, AnoxKaldnes started to optimize the carbon dose to see if zero net TOC increase could be obtained. The third reactor, the aerobic zone, helps to lower the amount of excess carbon in the process. However, a net increase in the TOC concentrations across the reactors remained during the Carbon Optimization Phase as shown in Figure 5.5.

The City began collecting TOC samples from Reactor 1 and 2 beginning May 14, 2008. The overall TOC concentrations decreased from each reactor since the carbon source was being used for energy during denitrification. Furthermore, aerobic Reactor 3 also oxidized some of the excess carbon. This same decrease in TOC was observed for the Steady State and Resiliency Test Phases.

As shown in Figure 5.5, the majority of Reactor 3 TOC effluent concentrations were higher than the feed water TOC concentrations. TOC effluent concentrations from Reactor 3 were approximately 0.5 to 1.0 mg/L higher than the incoming TOC concentrations during the Carbon Optimization Phase.

**DOC.** City Laboratory began collecting samples to measure DOC concentrations during AnoxKaldnes’ Carbon Optimization Phase on May 13, 2008. Samples were collected daily until May 28, 2008. Weekly sampling for DOC measurement began June 3, 2008 and ended June 10, 2008. **Table 5.4** shows the TOC and DOC data for AnoxKaldnes during the Carbon Optimization Phase.
As shown in Table 5.4, the difference between the TOC and DOC concentrations was not significant. Since the TOC and DOC concentrations were almost identical, DOC samples were not collected during the remainder of the piloting period. Similar TOC and DOC concentrations indicated that much of the organic matter existed in the dissolved form and not in the form of suspended organic matter.

**Temperature.** During AnoxKaldnes’ Carbon Optimization Phase, the influent temperature range was approximately between 11.5°C and 19.0°C with the temperature at the lower range in the beginning of the phase and increasing towards the end of the phase. The effluent temperature starting June 11, 2008 was approximately 11.0°C and by the end of the phase, the effluent temperature increased to approximately 16.0°C. Temperature data were collected by AnoxKaldnes’ data logger.

**Task 2b: Steady State Phase—AnoxKaldnes**

Immediately following the Carbon Optimization Phase, AnoxKaldnes was required to allow their system to operate without any further modification to process variables. AnoxKaldnes was allowed to indicate what set points (i.e., carbon feed rate, phosphoric acid feed rate, etc.) at which they wanted to operate their pilot unit during the Steady State Phase. Once operational modifications were implemented, the MBBR™ operated at constant influent loading, with no modifications allowed for a minimum of 30 days. However, AnoxKaldnes was allowed to make modifications if they had a justified reason for making the change and with the written approval of the City and Burns & McDonnell.
The Steady State Phase began June 11, 2008 and ended August 3, 2008. Operational procedures outlined in Chapter 4 were followed throughout this phase.

**Operational Settings**

The flow rate of 2.3 gpm from the end of AnoxKaldnes’ Carbon Optimization Phase continued through the beginning of the Steady State Phase until August 3, 2008. At a flow rate of 2.3 gpm, the HRT through each of the three reactors was approximately 78 minutes, for a total HRT of 156 minutes (2.6 hours) for nitrate removal and 78 minutes (1.3 hours) for the post aeration. Table 5.5 presents the operational parameters for AnoxKaldnes’ Steady State Phase.

As shown in Table 5.5, similar to the pilot influent flow rate, the carbon feed did not change throughout the Steady State Phase. The carbon feed pump was set at approximately 2.70 mL/min at the end of AnoxKaldnes’ Carbon Optimization Phase and remained at this rate until the end of the Steady State Phase on August 3, 2008.

**Issues and Activities Addressed**

No significant issues or activities were addressed during AnoxKaldnes’ Steady State Phase.

### Table 5.4

<table>
<thead>
<tr>
<th>Date</th>
<th>Feed water</th>
<th>AK1 effluent</th>
<th>AK2 effluent</th>
<th>AK3 effluent</th>
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<tbody>
<tr>
<td></td>
<td>TOC (mg/L)</td>
<td>DOC (gpm)</td>
<td>TOC (mg/L)</td>
<td>DOC (gpm)</td>
</tr>
<tr>
<td>Daily sampling</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>05/13/08</td>
<td>4.7</td>
<td>4.5</td>
<td>—(1)</td>
<td>—</td>
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<tr>
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<td>4.7</td>
<td>8.7</td>
<td>10.0</td>
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<td>5.2</td>
<td>—</td>
<td>—</td>
</tr>
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<td>4.3</td>
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<td>—</td>
</tr>
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<td>4.5</td>
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<td>—</td>
<td>—</td>
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</tbody>
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(1) ‘—’ means no data recorded.
Table 5.5
AnoxKaldnes operational parameters during the Steady State Phase

<table>
<thead>
<tr>
<th>Steady State Phase</th>
<th>Raw water NO₃-N (mg/L)</th>
<th>Raw water DO (mg/L)</th>
<th>Effluent water NO₃-N (mg/L)</th>
<th>AK influent flow rate (gpm)</th>
<th>CH₃OH pump feed rate (1) (mL/min)</th>
<th>CH₃OH/NO₃-N (g/g)</th>
<th>CH₃OH dose (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>9.87</td>
<td>4.37</td>
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<td>2.29</td>
<td>2.70</td>
<td>5.04</td>
<td>49.3</td>
</tr>
<tr>
<td>Maximum</td>
<td>12.32</td>
<td>7.00</td>
<td>10.09</td>
<td>2.33</td>
<td>2.70</td>
<td>7.51</td>
<td>49.9</td>
</tr>
<tr>
<td>Minimum</td>
<td>6.54</td>
<td>1.25</td>
<td>0.17</td>
<td>2.26</td>
<td>2.70</td>
<td>3.96</td>
<td>48.5</td>
</tr>
</tbody>
</table>

(1) Feed rate at 20% methanol dilution.

Figure 5.6 AnoxKaldnes NO₃-N concentration data during the Steady State Phase

Data Results

Data plots for the AnoxKaldnes MBBR™ system are presented in Figure 5.6 through Figure 5.14. Water quality parameters plotted include nitrate and TOC. Additionally, City Laboratory data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity, and pH are presented in Task 3.

Nitrate. As stated previously, beginning June 5, 2008 the effluent nitrate concentration fell below 2 mg/L NO₃-N. The effluent nitrate concentrations continued to meet the effluent goal until June 16, 2008 when the concentration increased above 2 mg/L NO₃-N. The increase was due to a carbon feed pump failure. The nitrate concentration fell below the goal starting June 27, 2008 and continued below 1 mg/L NO₃-N for the remainder of the Steady State Phase, as shown
The average effluent nitrate concentration during the Steady State Phase was 1.07 mg/L NO₃-N. 

**TOC.** After the carbon dosage was optimized, the net increase in TOC across the reactors was approximately 0.5 mg/L during the Steady State Phase, as shown in Figure 5.7. Even though the net increase in TOC decreased during the Steady State Phase, the effluent concentrations from Reactor 3 were still between 4 to 5 mg/L, which were similar to the effluent concentrations observed during the last half of AnoxKaldnes’ Carbon Optimization Phase.

**Temperature.** According to AnoxKaldnes’ data logger, the influent temperatures at the beginning and end of the Steady State Phase were approximately 17°C and 22°C, respectively.

**TASK 3: MONITORING AND SAMPLING—ANOXKALDNES**

Monitoring and sampling of the AnoxKaldnes pilot unit system was carried out in accordance with the methods described in Chapter 4. Discussions on the City Laboratory data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented below. Water quality parameters plotted include nitrite, alkalinity, and pH.

**Nitrite**

On May 1, 2008, the City Laboratory began collecting samples to measure the nitrite concentration in the raw water and effluent water for each pilot unit. Samples were collected on a daily basis until the end of pilot testing on August 28, 2008. Figure 5.8 and Table 5.6 show the effluent data.
Nitrite concentrations from AnoxKaldnes’ MBBR™ for Reactor 1, Reactor 2, and Reactor 3 during the Carbon Optimization Phase.

During AnoxKaldnes’ Carbon Optimization Phase, six samples out of all daily feed water samples had nitrite-nitrogen concentrations above the MDL of 0.05 resulting in an average influent nitrite-nitrogen concentration of 0.01 mg/L. However, as shown in Table 5.6, as the water was treated in the first two reactors, the average nitrite-nitrogen concentration increased from 0.01 to 0.30 mg/L. This increase was most likely due to the incomplete reduction of nitrate to nitrogen gas, which caused nitrite to accumulate in the process. The nitrite concentration decreased through Reactor 3 which aerated the treated water for TOC reduction. During aeration, the nitrite was most likely converted to nitrate, thereby decreasing the nitrite concentration from the Reactor 2 effluent to the Reactor 3 effluent.

The effluent nitrite concentrations from AnoxKaldnes’ MBBR™ for Reactor 1, Reactor 2, and Reactor 3 during the Steady State Phase are presented and shown in Figure 5.9 and Table 5.6. During the Steady State Phase, samples were collected on a daily basis. Similar to AnoxKaldnes’ nitrite concentrations during the Carbon Optimization Phase, average nitrite concentrations during the Steady State Phase increased from 0.08 mg/L NO$_2$-N in the feed water to 0.84 mg/L NO$_2$-N in Reactor 1 effluent.

This increase was most likely the result of nitrite accumulation due to incomplete reduction of nitrate. From Reactor 1 effluent to Reactor 3 effluent, the average nitrite concentration decreased from 0.84 to 0.10 mg/L NO$_2$-N. Nitrite was most likely reduced further in Reactor 2 and oxidized in Reactor 3, thereby lowering the amount of nitrite in AnoxKaldnes’ final effluent during the Steady State Phase.
Ammonia

During AnoxKaldnes’ Seeding and Acclimation Phase, the City Laboratory collected eight samples to measure the effluent concentration of ammonia-nitrogen. After May 6, 2008, the City Laboratory collected two to four samples weekly until June 17, 2008. From July 8, 2008 to July 29, 2008, three more samples were collected approximately every nine days.

Table 5.7 shows the average ammonia-nitrogen concentrations for the AnoxKaldnes MBBR™ during the Seeding and Acclimation Phase.

The maximum effluent concentration of ammonia was 0.30 mg/L NH$_3$-N, whereas the minimum effluent concentration was below the test method MDL of 0.10 mg/L NH$_3$-N. Moreover, three of the eight samples tested resulted in ammonia-nitrogen concentrations below the MDL. AnoxKaldnes averaged a 0.13 mg/L NH$_3$-N effluent concentration during the Seeding and Acclimation Phase while the average influent ammonia concentration was 0.52 mg/L NH$_3$-N. Therefore, on average, a decrease of approximately 0.4 mg/L NH$_3$-N from the influent to the effluent was observed with AnoxKaldnes’ MBBR™ process.

During AnoxKaldnes’ Carbon Optimization Phase, the City Laboratory collected one sample on May 6, 2008 and starting May 12, 2008, they collected three to four samples a week to measure the final effluent (AK3 effluent) concentration of ammonia until May 30, 2008. Two more samples were collected on June 3 and 6, 2008. For Reactors 1 and 2 effluents, the City collected a total of six samples per reactor. Table 5.7 also shows the average ammonia-nitrogen concentrations for the AnoxKaldnes MBBR™ during the Carbon Optimization Phase.

For Reactors 1 and 2, all samples collected during AnoxKaldnes Carbon Optimization were below the MDL of 0.10 mg/L NH$_3$-N. For Reactor 3, the maximum effluent concentration
Table 5.6
Average nitrite-nitrogen concentrations for AnoxKaldnes’ MBBR™ during Seeding and Acclimation, Carbon Optimization, and Steady State Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Average NO$_3$-N concentrations (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feed water</td>
</tr>
<tr>
<td>Seeding and Acclimation Phase</td>
<td></td>
</tr>
<tr>
<td>02/08/08 to 04/30/08</td>
<td>—</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td></td>
</tr>
<tr>
<td>04/30/08 to 06/11/08</td>
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<tr>
<td>Steady State Phase</td>
<td></td>
</tr>
<tr>
<td>06/11/08 to 08/03/08</td>
<td>0.08</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.

Table 5.7
Average ammonia-nitrogen concentrations for AnoxKaldnes’ MBBR™ during Seeding and Acclimation, Carbon Optimization, and Steady State Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Average NH$_3$-N concentrations (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feed water</td>
</tr>
<tr>
<td>Seeding and Acclimation Phase</td>
<td></td>
</tr>
<tr>
<td>02/08/08 to 04/30/08</td>
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</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td></td>
</tr>
<tr>
<td>04/30/08 to 06/11/08</td>
<td>0.20</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td></td>
</tr>
<tr>
<td>06/11/08 to 08/03/08</td>
<td>0.15</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.
(2) Test MDL of ammonia-nitrogen.

of ammonia was 0.72 mg/L NH$_3$-N whereas the average minimum effluent ammonia concentration was below the MDL. AnoxKaldnes averaged a 0.23 mg/L NH$_3$-N final effluent concentration during the Carbon Optimization Phase while the average influent ammonia concentration was 0.20 mg/L NH$_3$-N. Therefore, an increase of approximately of 0.03 mg/L NH$_3$-N from the influent to the effluent was observed with AnoxKaldnes’ MBBR™ process.

The City Laboratory collected a total of seven samples from each pilot system to measure the ammonia concentration throughout the Steady State Phase. For Reactors 1 and 2, the City collected only one sample to measure the ammonia concentration. Collected on June 13, 2008, these single samples had an ammonia concentration to be less than the MDL of 0.10 mg/L NH$_3$-N.

Table 5.7 also shows the average ammonia-nitrogen concentrations for the AnoxKaldnes MBBR™ during the Steady State Phase. During this phase for Reactor 3, the maximum effluent concentration of ammonia was 1.36 mg/L NH$_3$-N whereas the average minimum effluent ammonia concentration was below the MDL. AnoxKaldnes averaged a 0.60 mg/L NH$_3$-N final effluent concentration while the average influent ammonia concentration was 0.15 mg/L NH$_3$-N. Therefore, an increase of approximately of 0.45 mg/L NH$_3$-N from the influent to the effluent was observed with AnoxKaldnes’ MBBR™ process during the Steady State Phase.
Phosphate

For water to be biologically denitrified, it must contain an adequate amount of phosphorus (P) for nutrient uptake and bacterial growth. In the beginning of piloting, AnoxKaldnes did not add phosphorus to their system, however, they felt that since the influent nitrate was being enhanced, phosphorus limited the denitrification process. Therefore, AnoxKaldnes began adding phosphorus to their system on April 11, 2008. Phosphoric acid was added into the system at 0.5 mg/L as P and as previously shown in Figure 5.1, after AnoxKaldnes added phosphoric acid, the system showed faster rates of denitrification, which resulted in AnoxKaldnes reaching the effluent pilot goal of ≤2 mg/L NO$_3$-N on April 29, 2008.

Table 5.8 shows the average effluent phosphate concentrations from the AnoxKaldnes MBBR™ during the Seeding and Acclimation, Carbon Optimization, and Steady State Phases.

Although adding phosphorus enhanced the denitrification process, the City and Burns & McDonnell recommended that the effluent phosphorus concentration remain below 1 mg/L as P from the pilot unit since phosphorus increases the formation potential of algae blooms, which causes potential taste and odor issues and overall water quality concerns. During the Seeding and Acclimation Phase, AnoxKaldnes maintained an overall average effluent PO$_4$-P concentration below 0.5 mg/L as shown in Table 5.8. Excluding the City Laboratory measurements before April 11, 2008 (the start of phosphoric acid addition), the average effluent phosphate concentration from the MBBR™ was 0.51 mg/L PO$_4$-P, meeting the effluent concentration recommended by the City of Thornton. The maximum phosphate concentration during AnoxKaldnes’ Seeding and Acclimation Phase was 1.43 mg/L PO$_4$-P, and the minimum concentration was less than the MDL of 0.1 mg/L PO$_4$-P.

Since AnoxKaldnes was optimizing the phosphoric acid dose during the Carbon Optimization Phase, the phosphate concentrations in the effluent fluctuated during this phase from 0.1 to 1.2 mg/L PO$_4$-P, resulting in a final average effluent phosphate concentration not exceeding the recommended phosphorus concentration of 1 mg/L as P.

During AnoxKaldnes’ Carbon Optimization Phase, from the feed water to Reactor 1 effluent, the average phosphate concentration increased from 0.30 mg/L to 0.56 mg/L PO$_4$-P due to dosing the system with phosphoric acid. From Reactor 1 effluent to Reactor 2 effluent, the average phosphate increased to 0.62 mg/L PO$_4$-P. From Reactor 2 effluent to Reactor 3 effluent, the average phosphate concentration decreased. Therefore, the average increase from the feed water to the final effluent was 0.26 mg/L PO$_4$-P.

Table 5.8

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<th>Phase</th>
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(1) ‘—’ means not sampled.

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For the Steady State Phase, the City Laboratory collected daily samples to measure the final effluent phosphate concentrations for AnoxKaldnes’ MBBR\(^\text{TM}\), though for Reactors 1 and 2, samples were only collected every two days. During this phase, AnoxKaldnes’ average Reactor 3 effluent of 0\(^\text{.}052\) mg/L \(\text{PO}_4\)-P was less than the City’s recommended effluent phosphorus concentration of 1 mg/L as P. Additionally, from the feed water to Reactor 3 effluent, the average phosphate increased from 0\(^\text{.}32\) mg/L to 0\(^\text{.}52\) mg/L \(\text{PO}_4\)-P due to dosing the system with phosphoric acid.

**Color**

At the beginning of pilot testing, the City Laboratory was not measuring the color in the effluent from each pilot unit, but the City Laboratory staff observed a noticeable color in GE’s effluent, which was described as yellowish tint. The color in the effluent was most likely due to GE’s molasses nutrient. Therefore, on March 19, 2008, the City Laboratory began collecting samples to measure the color in the water from each pilot unit and as of March 26, 2008, turbidity concentrations were measured approximately three times per week.

Table 5.9 and Table 5.10 show the average color (true and apparent) for AnoxKaldnes’ MBBR\(^\text{TM}\) influent and effluent waters during the Seeding and Acclimation, Carbon Optimization, and Steady State Phases.

As shown in Table 5.9 and Table 5.10, the effluent true and apparent color increased from AnoxKaldnes’ Seeding and Acclimation Phase to the Carbon Optimization Phase. The increase in

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>AK1 effluent</th>
<th>AK2 effluent</th>
<th>AK3 effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td>02/08/08 to 04/30/08</td>
<td>23.2</td>
<td>—(^{(1)})</td>
<td>—</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td>04/30/08 to 06/11/08</td>
<td>34.7</td>
<td>122.4</td>
<td>162.0</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td>06/11/08 to 08/03/08</td>
<td>35.2</td>
<td>186.5</td>
<td>122.0</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>AK1 effluent</th>
<th>AK2 effluent</th>
<th>AK3 effluent</th>
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<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td>02/08/08 to 04/30/08</td>
<td>6.8</td>
<td>—(^{(1)})</td>
<td>—</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td>04/30/08 to 06/11/08</td>
<td>7.3</td>
<td>12.3</td>
<td>10.4</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td>06/11/08 to 08/03/08</td>
<td>18.6</td>
<td>17.5</td>
<td>12.5</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.
color was most likely the result of the carbon optimization dose fluctuations as well as the system removing more nitrate on a consistent basis thereby producing more biomass that is sloughed off into the effluent. Additionally, during these two phases (Seeding and Acclimation and Carbon Optimization), the average effluent true color was greater than the average influent true color.

During AnoxKaldnes’ Seeding and Acclimation Phase, the apparent color increased from an influent value of 23.2 Pt-Co units to 88.4 Pt-Co units from Reactor 3. The maximum and minimum apparent color measurements during AnoxKaldnes’ Seeding and Acclimation Phase were 200 and 12 Pt-Co units, respectively.

During AnoxKaldnes’ Carbon Optimization Phase, the average Reactor 3 effluent apparent color was 159.6 Pt-Co units with an average influent apparent color of 34.7 pt-Co units. Since more biomass was produced during the Carbon Optimization Phase, the average Reactor 3 effluent apparent color was approximately 71 Pt-Co units greater than the average Reactor 3 effluent apparent color from the Seeding and Acclimation Phase.

During the Steady State Phase for AnoxKaldnes, the average Reactor 3 apparent color was approximately 110 Pt-Co units greater than the average influent apparent color. The average influent apparent color during this phase was 35.20 Pt-Co units. Increase in apparent color was due to biomass growth in the reactor that increased the suspended solids in the water.

During AnoxKaldnes’ Seeding and Acclimation Phase, the true color increased from an influent value of 6.8 Pt-Co units to 11.5 Pt-Co units from Reactor 3. The maximum and minimum true color measurements were 40 and 12 Pt-Co units, respectively.

During AnoxKaldnes’ Carbon Optimization phase, the true color in Reactor 3 effluent was 19.3 Pt-Co units when influent true color was 7.3 Pt-Co units during AnoxKaldnes’ Carbon Optimization Phase. Similar to the trend in apparent color, the true color in Reactor 3 from AnoxKaldnes’ Carbon Optimization Phase was approximately 8 Pt-Co units greater than Reactor 3 effluent from the Seeding and Acclimation Phase.

The City Laboratory collected seven samples from AnoxKaldnes’ Reactor 3 effluent during the Steady State Phase. For Reactors 1 and 2, the City collected two samples per reactor. Shown in Table 5.10, during the Steady State Phase, the true color in Reactor 3 effluent was approximately 13.6 Pt-Co units with an average influent true color of 18.6 Pt-Co units. This decrease in average true color was the first average decrease observed for AnoxKaldnes.

Turbidity

Weekly turbidity measurements were taken by the City Laboratory for three weeks beginning February 21, 2008 and ending March 5, 2008. Starting on March 26, 2008, turbidity concentrations were measured approximately three times per week until the end of piloting. For AnoxKaldnes, the average effluent turbidity was greater than the average influent turbidity as shown in Table 5.11.

The average turbidity increase through AnoxKaldnes’ MBBR™ was approximately 4.8 NTU with the average influent turbidity of 2.0 NTU during the Seeding and Acclimation Phase. The maximum and minimum turbidity measurements during this phase were 34.6 and 0.8 NTU, respectively. Similar to the increase in apparent color, the increase in turbidity was most likely a result of AnoxKaldnes sloughing the biomass into the effluent water. Furthermore, the maximum turbidity occurred on the same sampling date as the maximum apparent color measurement.

The average turbidity increase through AnoxKaldnes’ MBBR™ during the Carbon Optimization Phase was approximately 10.5 NTU, which is greater than the increase observed in
the Seeding and Acclimation Phase. The average influent turbidity during this phase was 1.7 NTU. The maximum and minimum Reactor 3 effluent turbidity measurements were 46.5 and 4.7 NTU, respectively. The increase in turbidity through the MBBR™ was most likely due to the biomass produced in Reactors 1 and 2.

For all of AnoxKaldnes’ reactor effluents, the City Laboratory collected three to four samples a week to measure turbidity concentrations throughout the Steady State Phase. Similar to the Seeding and Acclimation and Carbon Optimization Phases, the average effluent turbidity was greater than the influent turbidity during the Steady State Phase.

The average turbidity increase through AnoxKaldnes’ MBBR™ during the Steady State Phase was approximately 17.5 NTU, which is greater than the increase observed in the Carbon Optimization Phase. The average influent turbidity for the Steady State Phase was 1.9 NTU. As stated previously, the increase in turbidity through the MBBR™ was most likely due to the biomass produced in Reactors 1 and 2.

### TSS

Beginning February 29, 2008, the City Laboratory collected samples to measure the TSS in the effluent from each pilot system. Samples were tested approximately weekly until May 19, 2008. **Table 5.12** shows AnoxKaldnes’ average influent and effluent TSS concentrations during AnoxKaldnes Seeding and Acclimation and Carbon Optimization Phases. AnoxKaldnes’ Seeding and Acclimation Phase, the average effluent TSS concentration was approximately 4 mg/L greater than the average feed water TSS concentration. Stated previously

---

**Table 5.11**

Average turbidity for AnoxKaldnes’ MBBR™ during Seeding and Acclimation, Carbon Optimization, and Steady State Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Average turbidity (NTU)</th>
<th>Feed water</th>
<th>AK1 effluent</th>
<th>AK2 effluent</th>
<th>AK3 effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02/08/08 to 04/30/08</td>
<td>2.0</td>
<td>—(1)</td>
<td>—</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td></td>
<td>1.7</td>
<td>10.8</td>
<td>12.0</td>
<td>12.3</td>
</tr>
<tr>
<td>04/30/08 to 06/11/08</td>
<td></td>
<td>1.9</td>
<td>12.9</td>
<td>16.6</td>
<td>19.7</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06/11/08 to 08/03/08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.

**Table 5.12**

Average TSS concentrations for AnoxKaldnes’ MBBR™ during Seeding and Acclimation, and Carbon Optimization Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Average TSS concentration (mg/L)</th>
<th>Feed water</th>
<th>AK1 effluent</th>
<th>AK2 effluent</th>
<th>AK3 effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.1</td>
</tr>
<tr>
<td>02/08/08 to 04/30/08</td>
<td>1.1</td>
<td>—(1)</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td></td>
<td>9.3</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>04/30/08 to 06/11/08</td>
<td></td>
<td>—(1)</td>
<td>—</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.
in regards to turbidity and color, AnoxKaldnes sloughs the biomass into their effluent whereby increasing the amount of suspended solids in the treated water and ultimately, increasing the turbidity and TSS concentration in their effluent. AnoxKaldnes is the only manufacturer piloted that discharges the biomass into the effluent by nature of their design.

Throughout AnoxKaldnes’ Carbon Optimization Phase, three samples to measure TSS concentrations were collected. All three samples were collected in the beginning of the phase on May 6, May 13, and May 20, 2008. Furthermore, the City Laboratory did not collect samples to measure the TSS concentration for Reactor 1 and 2 effluents.

During AnoxKaldnes’ Carbon Optimization Phase, the average effluent TSS concentration was approximately 6.5 mg/L greater than the average feed water TSS concentration. The average influent TSS during this phase was 9.3 mg/L. Both the average influent and effluent TSS concentrations increased in comparison to the concentrations during the Seeding and Acclimation Phase.

The increase in TSS concentrations from the Seeding and Acclimation Phase to the Carbon Optimization Phase was most likely due to more biomass produced since more nitrate was removed during the Carbon Optimization Phase.

For the Steady State Phase, the City Laboratory did not collect any samples to measure the TSS concentrations for AnoxKaldnes’ MBBR™ system.

### Alkalinity

Beginning February 21, 2008, the City Laboratory collected weekly samples to measure the alkalinity in the influent and effluent water for each pilot unit. On March 26, 2008, the City Laboratory began collecting three to four weekly samples to measure the alkalinity concentration through the end of piloting. As described in Chapter 3, nitrate is converted to nitrogen gas utilizing facultative heterotrophic bacteria during denitrification. This process generates alkalinity in the form of bicarbonate.

**Table 5.13** shows the average influent and effluent alkalinity concentrations for AnoxKaldnes’ MBBR™ system.

As shown in **Table 5.13** for AnoxKaldnes’ Seeding and Acclimation Phase, the average alkalinity increased by approximately 11 mg/L as CaCO$_3$ from the influent to the effluent of the reactors. The average influent alkalinity during this period was approximately 120 mg/L CaCO$_3$.

Similar to the trend during the Acclimation and Seeding Phase, the alkalinity increased across the reactors during AnoxKaldnes’ Carbon Optimization Phase. The increase during this
phase was approximately by 25 mg/L as CaCO₃, which is larger than the increase observed during the startup phase most likely because the system was removing more nitrate. Higher nitrate removal results in generating more alkalinity.

As shown in Table 5.13, during AnoxKaldnes’ Carbon Optimization Phase, the average alkalinity increased by 25 mg/L as CaCO₃ from the influent to the final effluent reactor. From the influent to Reactor 2 effluent, the alkalinity increased by approximately 23 mg/L as CaCO₃, which is approximately 90 percent of the increase in alkalinity throughout the entire process. The first two reactors removed nitrate while the aeration tank removed TOC. Hence, more alkalinity was created in Reactors 1 and 2 than in Reactor 3.

Similar to the trend during the Acclimation and Seeding and Carbon Optimization Phases, the alkalinity increased across the AnoxKaldnes MBBR™ reactors during the Steady State Phase. Furthermore, the increase during the Steady State Phase was similar to the increase during the Carbon Optimization Phase since in both phases, approximately 8 mg/L NO₃-N was removed. Specifically, as shown in Table 5.13, during the Steady State Phase, the average alkalinity increased by 25 mg/L as CaCO₃ from the influent to the final effluent reactor. From the influent to Reactor 2 effluent, the alkalinity increased by approximately 24 mg/L as CaCO₃.

Figure 5.10 shows the alkalinity concentrations for the MBBR™ during AnoxKaldnes’ Carbon Optimization Phase.

**pH**

The City Laboratory began collecting samples to measure the influent and effluent pH for each pilot unit on February 27, 2008 and continued to collect daily samples for the majority of piloting.
### Chapter 5: Results and Discussion

#### Table 5.14

**Average pH units for AnoxKaldnes’ MBBR™ during Seeding and Acclimation, Carbon Optimization, and Steady State Phases**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>AK1 effluent</th>
<th>AK2 effluent</th>
<th>AK3 effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td>8.6</td>
<td>—(1)</td>
<td>—</td>
<td>8.3</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td>8.4</td>
<td>7.8</td>
<td>7.7</td>
<td>7.9</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td>8.1</td>
<td>7.7</td>
<td>7.7</td>
<td>8.0</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.

**Table 5.14** shows the average pH during the Seeding and Acclimation, Carbon Optimization, and Steady State Phases for AnoxKaldnes.

A pH change from the influent to AnoxKaldnes’ Reactor 3 effluent was observed during the Seeding and Acclimation Phase. The average influent pH was 8.6, and the average effluent pH was 8.3. When denitrification occurs, the pH increases, because alkalinity is being produced. Since a decrease in pH was observed for AnoxKaldnes MBBR™ during the Seeding and Acclimation Phase, the change in alkalinity across the MBBR™ most likely was not significant enough to increase the pH. Additionally, nitrate reduction results in the production of H\(^+\), which most likely caused the drop in pH. In addition to H\(^+\) being produced during denitrification, the addition of phosphoric acid could have also cause a drop in pH across the system.

**Figure 5.11** shows AnoxKaldnes’ pH data during the Carbon Optimization Phase. Even though the alkalinity increased, the pH also decreased by 0.5 pH units. Similar to the Seeding and Acclimation Phase, this decrease in pH may be due to adding phosphoric acid to their pilot unit.

**Figure 5.12** and **Table 5.14** present AnoxKaldnes’ pH data and the average pH in the influent and in AnoxKaldnes final effluent for the Steady State Phase. As shown in this table and figure, the pH change from the influent to Reactor 3 effluent was negligible during the Steady State Phase. The average pH measurements during this phase were unlike the pH changes observed across the reactor during AnoxKaldnes’ Carbon Optimization Phase where the pH decreased by half a pH unit through the process.

**TASK 4: RESILIENCY TEST PHASE—ANOXKALDNES**

The Resiliency Test Phase was conducted by ‘shocking’ each system with varying influent nitrate concentrations and by shutting down equipment. This phase commenced on August 3, 2008 and ended August 28, 2008. Five main tasks were performed during this phase. These tasks include the following:

- Task 4a: Incremental Nitrate Spiking
- Task 4b: Rapid Change Nitrate Spiking
- Task 4c: Influent Nitrate Spiking Shutdown
- Task 4d: Carbon Feed Pump Shutdown
- Task 4e: Raw Water Shutdown
Figure 5.11 AnoxKaldnes pH data during the Carbon Optimization Phase

Figure 5.12 AnoxKaldnes pH data during the Steady State Phase
The following sections describe each task listed above for the AnoxKaldnes pilot unit along with plots and data from this phase.

**Task 4a: Incremental Nitrate Spiking—AnoxKaldnes**

Task 4a required AnoxKaldnes to adjust the carbon feed rate to account for the increase in influent nitrate-nitrogen. The first increase was up to 15 mg/L NO$_3$-N on August 4, 2008 and the second increase up to 20 mg/L on August 8, 2008. Once operational modifications (i.e., changes in carbon feed rate) were implemented for each increase in the raw water nitrate, the MBBR™ operated at constant influent loading for the remainder of each incremental nitrate spiking period.

Operational procedures for the Resiliency Test Phase outlined for AnoxKaldnes’ pilot unit continued throughout the phase in accordance to the methods outlined in Chapter 4.

**Operational Settings**

The flow rate of 2.3 gpm from the end of the Steady State Phase continued to the end of the Resiliency Test Phase on August 28, 2008 with the exception of when the pilot unit was shut down for Task 4e. At a flow rate of 2.3 gpm, the HRT through each of the three reactors #1 through #3 was approximately 78 minutes, for a total HRT of 156 minutes (2.6 hours) for nitrate removal and 78 minutes (1.3 hours) for the post aeration.

Since the influent nitrate concentrations fluctuated throughout this phase, AnoxKaldnes was required to adjust the carbon feed as necessary. Moving into the Resiliency Test Phase, AnoxKaldnes’ nutrient flow was approximately 48.4 mg/L 99.9% methanol (4.8 g CH$_3$OH/g NO$_3$-N) at an influent nitrate concentration of approximately 10 mg/L NO$_3$-N. Originally, AnoxKaldnes was going to increase the methanol dose to handle the increase in influent nitrate concentration from 10 to 15 mg/L NO$_3$-N. However, in the end, AnoxKaldnes made the decision to not adjust the feed rate of the methanol when the influent nitrate was increased to 15 mg/L NO$_3$-N to evaluate if the system would continue to denitrify to an acceptable level. Table 5.15 shows the operational settings during the incremental nitrate spiking.

**Task 4b: Rapid Change Nitrate Spiking—AnoxKaldnes**

Task 4b required AnoxKaldnes to adjust the carbon feed rate to account for a decrease in influent nitrate from 20 mg/L NO$_3$-N to 5 mg/L NO$_3$-N on August 12, 2008. Later on August 16, 2008, the influent nitrate was changed to 10 mg/L NO$_3$-N and again AnoxKaldnes was required to adjust the amount of carbon to their pilot unit.

### Table 5.15

<table>
<thead>
<tr>
<th>Date</th>
<th>Average raw water NO$_3$-N (mg/L)</th>
<th>Average AK influent flow rate (gpm)</th>
<th>Average CH$_3$OH/NO$_3$-N (g/g)</th>
<th>Average 99.9% CH$_3$OH (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/04/08 to 08/08/08</td>
<td>14.9</td>
<td>2.3</td>
<td>3.3</td>
<td>48.4</td>
</tr>
<tr>
<td>08/08/08 to 08/12/08</td>
<td>20.2</td>
<td>2.3</td>
<td>2.9</td>
<td>59.1</td>
</tr>
</tbody>
</table>
Operational Settings

The carbon feed rate was adjusted from 3.0 mL/min to 1.53 mL/min when the influent nitrate was decreased to 5 mg/L NO$_3$-N and increased to 2.70 mL/min when the nitrate increased to 10 mg/L NO$_3$-N, respectively. Table 5.16 shows the operational settings during the rapid change nitrate spiking.

Task 4c: Influent Nitrate Shutdown—AnoxKaldnes

Task 4c involved shutting down the influent nitrate on August 18, 2008 for four hours and again on August 20, 2008 for another four hours. During both of these shutdowns, the influent nitrate concentration decreased to approximately 1 to 2 mg/L NO$_3$-N.

Operational Settings

No operational changes were made to the MBBR™ during Task 4c.

Task 4d: Carbon Feed Pump Shutdown—AnoxKaldnes

During Task 4d, the carbon feed pump was shut down on two occasions. The first shutdown occurred on August 21, 2008 for four hours and the other on August 22, 2008 for another four hours.

Operational Settings

No operational changes were made to the MBBR™ during Task 4d.

Task 4e: Raw Water Shutdown—AnoxKaldnes

On August 23, 2008, the raw water pump was turned off for 72 hours, during which time the MBBR™ was completely shut down. The unit was started back up on August 26, 2008 and continued to operate until the end of the Resiliency Test Phase on August 28, 2008.

---

Table 5.16
AnoxKaldnes methanol dosing during rapid change nitrate spiking

<table>
<thead>
<tr>
<th>Date</th>
<th>Average raw water NO$_3$-N (mg/L)</th>
<th>Average AK influent flow rate (gpm)</th>
<th>Average CH$_3$OH / NO$_3$-N (g/g)</th>
<th>Average 99.9% CH$_3$OH (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/08/08 to 08/12/08</td>
<td>20.2</td>
<td>2.3</td>
<td>2.9</td>
<td>59.1</td>
</tr>
<tr>
<td>08/12/08 to 08/16/08</td>
<td>5.1</td>
<td>2.3</td>
<td>4.9</td>
<td>24.6</td>
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<tr>
<td>08/16/08</td>
<td>8.2</td>
<td>2.3</td>
<td>5.7</td>
<td>48.2</td>
</tr>
</tbody>
</table>

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Operational Settings

For the raw water shutdown, all MBBR™ equipment was shut off for a 72 hour period and started back up at the end of Task 4e.

Issues and Activities Addressed—AnoxKaldnes Task 4

Issues and activities addressed during AnoxKaldnes’ Resiliency Test Phase included only difficulties with their carbon feed pump. Starting August 8, 2008, the methanol feed pump was not operating properly and this issue was not remedied until August 11, 2008.

Data Results: Plots—AnoxKaldnes Task 4

Data plots for the AnoxKaldnes MBBR™ system are presented in Figure 5.13 and Figure 5.14 for the Resiliency Test Phase. Critical parameters plotted include nitrate and TOC. All other water quality parameters that were evaluated for the first three phases were not evaluated in detail for the Resiliency Test Phase since the pilot units underwent extreme operational changes.

Nitrate

For the final phase of piloting, influent nitrate concentrations were gradually or rapidly increased to monitor the response of each pilot unit. Figure 5.13 shows the performance of the AnoxKaldnes MBBR™ pilot unit for the last month of piloting. When the nitrate increased, the effluent nitrate concentration exceeded the goal limit of 2 mg/L NO₃-N but the system recovered from these shocks with effluent nitrate concentrations falling below the limit within a 26-hour period. When the carbon feed pump was shut down, the effluent nitrate concentrations rapidly increased but also rapidly decreased once the carbon feed pumps came back online.

A similar system response was observed when the raw water and all pilot unit equipment were shut down. Once the system was back online, the effluent nitrate was observed above 2 mg/L NO₃-N but within a few hours the system was denitrifying below the pilot goal. Therefore, based on the pilot testing results for this phase, the AnoxKaldnes unit was capable of recovering from each event within 26 hours with the exception of one event. This event was when the influent nitrate was spiked to 20 mg/L NO₃-N on Friday, August 8, 2008. The effluent nitrate concentrations increased above 2 mg/L NO₃-N and remained above this limit until the following Monday. Since the influent nitrate was spiked to 20 mg/L NO₃-N, an increase in effluent nitrate concentrations was most likely to be observed. However, the quick recovery of the pilot unit to denitrify below 2 mg/L was not observed due to a failure in the methanol pump. This pump problem was not discovered until Monday, August 11, 2008. Another unexpected increase in effluent nitrate concentrations occurred on August 19, 2008 after shutting down the influent nitrate spiking for four hours. Most likely the methanol pump was not dosing enough carbon to the system to keep the effluent nitrate concentrations to remain below the goal.

TOC

During Task 4 the influent nitrate concentration was spiked to 20 mg/L NO₃-N, which required an increase in the carbon dose. Figure 5.14 shows that even though the methanol dose
Figure 5.13 AnoxKaldnes NO$_3$-N concentration data during the Resiliency Test Phase
Figure 5.14 AnoxKaldnes TOC concentration data during the Resiliency Test Phase
increased, the final effluent TOC was still approximately 4 to 5 mg/L with minimal change in TOC between the influent and final effluent concentrations. During Task 4e, the effluent TOC increased to 9.0 mg/L immediately upon putting the pilot unit online after the equipment and raw water shutdown. However, within a day of turning on the MBBR™, the effluent TOC decreased to influent TOC concentrations.

**TASK 5: COLUMN TESTING (NOT APPLICABLE)—ANOXKALDNES**

**TASK 6: QUALITY ASSURANCE AND QUALITY CONTROL—ANOXKALDNES**

QA/QC procedures were conducted throughout the pilot study to ensure accuracy of data. The protocol outlined in Chapter 4 was strictly followed. No QC issues were identified relative to data for the AnoxKaldnes system.

**GE WATER & PROCESS TECHNOLOGIES SUMMARY OF PILOT TESTING ACTIVITIES**

Startup of the GE pilot system began on February 12, 2008. The start and completion dates for each task are provided in the Table 5.17.

In the following pages, data for each task are provided along with a brief narrative for each task. Additionally, the events and results will be discussed in this section.

**TASK 1: STARTUP—SEEDING AND ACCLIMATION PHASE—GE**

The goal of this task was to evaluate the performance of the system during startup and seeding activities. Startup during cold temperature months was a key operational ability for this system’s geographic location.

---

**Table 5.17**

<table>
<thead>
<tr>
<th>GE testing phases by task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task description</td>
</tr>
<tr>
<td>2. Operation and performance testing</td>
</tr>
<tr>
<td>c. Backwash Optimization Phase</td>
</tr>
<tr>
<td>3. Monitoring and sampling</td>
</tr>
<tr>
<td>a. Data logging</td>
</tr>
<tr>
<td>b. City manual data collection and analysis</td>
</tr>
<tr>
<td>4. Resiliency Test Phase</td>
</tr>
<tr>
<td>a. Incremental nitrate spiking</td>
</tr>
<tr>
<td>b. Rapid change nitrate spiking</td>
</tr>
<tr>
<td>c. Influent nitrate shutdown</td>
</tr>
<tr>
<td>5. Column testing</td>
</tr>
<tr>
<td>6. QA/QC</td>
</tr>
</tbody>
</table>
GE was allowed to use a seeding material from an outside source to expedite the acclimation time. The seeding material was required to be from a sensible source (i.e., compatible with the carbon source used) and to be capable of being used in a full-scale treatment process. GE decided to seed their pilot unit with their ABMet® culture.

The data collected from the beginning of this task to the beginning of GE’s Carbon Optimization Phase on April 3, 2008 was used to monitor the ABMet® system and are described below along with data tables and plots. Additionally, a discussion of the settings and operational procedures for the ABMet® system during this time period is presented in the following sections.

**Seeding and Acclimation**

February 12, 2008 was the startup date for the GE ABMet® pilot unit. Seeding this pilot unit was considered in order to speed up the projected five to six week cold-water seeding period. GE seeded their unit with 20 gallons of ABMet® culture. The seeding culture was a proprietary culture prepared by GE consisting of biomass which was acclimated to the proprietary molasses, which was the carbon source initially used.

GE followed the operational procedure outlined for the Seeding and Acclimation Phase of testing. Startup was considered completed when GE began denitrifying and achieving nitrate concentrations ≤2 mg/L NO₃-N with 10 mg/L NO₃-N or greater of influent nitrate concentrations. Even though GE’s data logger was not collecting correct effluent nitrate data until March 18, 2008, the City Laboratory measured GE’s effluent nitrate below 2 mg/L NO₃-N on February 21, 2008 resulting in GE achieving the pilot goal of ≤2 mg/L NO₃-N in approximately nine days after startup. Thus, the Seeding and Acclimation Phase for GE began February 12, 2008 and ended February 21, 2008.

The breakthrough and column tests showed that the removal of nitrate was not primarily due to adsorption, as shown in the results of GE’s column test in GE’s Task 5 section of this report. Operational procedures outlined in Chapter 4 were followed throughout this phase.

**Operational Settings**

On February 19, 2008, one week after pilot start-up, the system commenced at a flow rate of 2 gpm with a HRT of 1 hour for each bioreactor. Another week later on February 25, 2008 the flow rate was increased to 4 gpm with a HRT of 0.5 hour per bioreactor to maintain an overall HRT of 1 hour. GE’s system operated at this flow until the beginning of the Carbon Optimization Phase on April 3, 2008.

Initially, GE seeded the ABMet® unit with 20 gallons of ABMet® culture and thereafter dosed the system with approximately 0.92 gallons of nutrient per day. The 4 gpm system flow rate correlated to approximately 200 to 220 mg/L of nutrient. The nutrient used was a proprietary molasses which had phosphorus added.

Limited information was provided from GE on the proprietary molasses. According to GE, the molasses had a density of 10.9 lb/gallon and an assumed COD of 1,090 g/L. This compares to 99.9% methanol which has an assumed COD of 1,127 g/L. Table 5.18 shows GE’s nutrient dosing rate to their pilot unit from February 18, 2008 to April 3, 2008.

As shown, GE started to optimize the molasses dose as indicated by the decreasing trend in the dosing rate for Bioreactor 2. At the beginning of the pilot on February 18, 2008, GE was dosing molasses at 0.43 gpd, and on February 27, 2008, the dose rate had decreased to 0.20 gpd. GE
increased the dose rate to 0.40 gpd on March 4, 2008. However, at the beginning of GE’s Carbon Optimization Phase, the dose rate had decreased to 0.17 gpd since only Bioreactor 2 was online.

On February 28, 2008 total molasses concentration dosed was approximately 294 mg/L, and by decreased to 73 mg/L. However, as the molasses was being optimized, the concentration on March 19, 2008 was approximately 200 mg/L.

For Bioreactor 1, the molasses dose was not optimized since GE shut down this reactor on April 3, 2008. Reasons for the shutdown of Bioreactor 1 are described in the next section.

### Issues and Activities Addressed

No issues and activities were addressed during GE’s Seeding and Acclimation Phase except for the incorrect data analysis of GE’s effluent nitrate analyzer. However, from the end of the GE’s Seeding and Acclimation Phase to the beginning of the Carbon Optimization Phase, issues and activities addressed included bioreactor shutdown, backwashing, and degassing. The following sections describe each issue/activity for the GE pilot unit from the beginning of piloting (February 18, 2008) to the beginning of GE’s Carbon Optimization Phase (April 3, 2008).

### Nitrate Analyzer and Laboratory Analysis

From February 8, 2008 to March 18, 2008, both the influent and effluent nitrate analyzers originally provided on the GE unit were not measuring nitrate concentrations accurately. Hence, the nitrate analyzer data from the data logger during this time was not used in the water quality and pilot unit performance analysis. However, City Laboratory data during this period was collected and analyzed correctly and was used for the nitrate removal capability analysis of GE’s pilot unit. The City Laboratory also started collecting daily grab samples on February 21, 2008. However, by February 21, 2008, GE’s effluent nitrate concentration was already below the pilot goal of ≤2 mg/L NO₃-N resulting in an acclimation period of nine days.
Bioreactor Shutdown

After increasing the flow rate to 4 gpm, Bioreactor 1 experienced excessive head loss causing hydraulic difficulty with the underpiping system of the bioreactors. Due to the hydraulic problems, GE shut down Bioreactor 1 on April 3, 2008. Thus, the influent flow bypassed Bioreactor 1 to Bioreactor 2 with the flow rate being reduced to 2 gpm with a HRT of 1 hour. The pilot unit was not designed to handle a flow greater than 2 gpm which is most likely the reason the unit had problems at the larger flows.

Backwashing

GE’s ABMet® system required periodic backwashing to release accumulated suspended solids and excess bacteria. Backwashing was initiated when the differential pressure across the bioreactor reached a preset value of 10 inches of water column. The backwashing flow rate was approximately 90 times greater than the normal operating flow of the system. Table 5.19 shows the dates when GE backwashed the ABMet® system.

The initial full-scale plant design anticipated three to six flushes per year. However, as seen from the data above, backwashing occurred five times in approximately three months (from February 26, 2008 to April 2, 2008) for the pilot unit, thus, the required backwashing frequency for full-scale design was anticipated to be higher than initially proposed by GE. It was determined that this increase in backwashing frequency was a result of a high loading rate, as discussed later in this section.

Degassing

In addition to backwashing, GE’s pilot unit underwent periodic degassing to mitigate short-circuiting by releasing gas pockets that reduced residence time in the bioreactor. This process utilized a pulse of flush water for bed expansion, which allowed any trapped gas pockets to escape from the carbon bed. Table 5.20 shows the dates when GE degassed the ABMet® system.

As shown in Table 5.20, degassing of the bioreactors occurred approximately every three to four days. Though degassing the system this often was not expected by GE, this process did not produce any waste volume since the pulsed water was retained within the cell and treated. GE initially proposed that the frequency of degassing the bioreactors would be once every seven days. Although degassing occurred more often, after each degassing, the head loss in the reactors decreased, which improved the performance of the bioreactors. Moreover, dispersing the gas

<table>
<thead>
<tr>
<th>Date</th>
<th>Flow (gpm)</th>
<th>Duration (seconds)</th>
<th>Set point (gpm)</th>
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<tbody>
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<td>03/20/08</td>
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<tr>
<td>04/02/08</td>
<td>208</td>
<td>900</td>
<td>180</td>
</tr>
</tbody>
</table>
pockets in the bioreactor helped to prevent the water being treated from having a reduced residence time in the bioreactor. Reduced resident time occurs due to short circuiting via the channels remaining around the gas pockets.

The flow, duration, and set point of each degas for GE’s pilot unit remained nearly constant from the beginning of piloting to the beginning of the Carbon Optimization Phase on April 3, 2008. GE set the backwash flow at approximately 200 gpm, the duration at 90 seconds, and the set point at 180 gpm.

**Data Results**

Data plots for the GE ABMet® system are presented in Figure 5.15 and Figure 5.16. Water quality parameters plotted include nitrate and TOC. Discussions on the City Laboratory data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented in Task 3. For temperature data, the City data logger collected raw water temperature data.

**Nitrate**

The City’s data logger collected water quality data (influent nitrate, pH, temperature and DO) for GE’s pilot unit beginning February 12, 2008. GE’s data logger did not begin collecting data until February 22, 2008. Additionally, from this time to March 18, 2008, their nitrate analyzers were not measuring nitrate concentrations accurately. However, the City Laboratory’s grab sample analysis indicated that GE did meet the pilot effluent goal of ≤2 mg/L NO₃-N on February 21, 2008.

Figure 5.15 shows the City Laboratory’s effluent nitrate-nitrogen data for GE in comparison to the City’s data logger influent nitrate-nitrogen data. This figure presents data from February 20, 2008 to the beginning of GE’s Carbon Optimization Phase on April 3, 2008. During this time period, the average effluent nitrate concentration recorded by the City Laboratory for GE was 0.9 mg/L NO₃-N, as shown in Figure 5.15.

<table>
<thead>
<tr>
<th>Date</th>
<th>Flow (gpm)</th>
<th>Duration (seconds)</th>
<th>Set point (gpm)</th>
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</thead>
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<tr>
<td>04/01/08</td>
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<td>180</td>
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Table 5.20
GE degassing dates and operational settings through April 3, 2008
Figure 5.15 GE NO₃-N concentration data from February 12, 2008, to April 2, 2008

Figure 5.16 GE TOC concentration data from March 5, 2008, to March 29, 2008
Chapter 5: Results and Discussion

TOC

The City began taking weekly TOC data on March 5, 2008 and daily as of March 18, 2008 as shown in Figure 5.16. The last sample collected before GE’s Carbon Optimization Phase was on March 28, 2008. GE’s effluent TOC concentration increased from approximately 4.0 mg/L to 22.0 mg/L before GE began optimizing their molasses dose on April 3, 2008. The average influent TOC concentration during this period was approximately 4.0 mg/L. Thus, prior to GE’s Carbon Optimization Phase, the TOC in the treated water increased by approximately 18.0 mg/L across their pilot unit.

Samples were not collected during GE’s Seeding and Acclimation Phase for DOC analysis. DOC measurements began May 13, 2008 during GE’s Carbon Optimization Phase.

Temperature

During GE’s Seeding and Acclimation Phase, GE’s data logger did not collect influent and effluent temperature data. However, it is reasonable to assume that the influent temperatures measured on the other pilot systems are applicable. Since GE’s startup began February 12, 2008 and ended February 21, 2008, it was concluded that the cold water temperature did not limit the seeding and acclimation of the nitrate-removing bacteria.

TASK 2: OPERATION AND PERFORMANCE TESTING—GE

The goal of this task was to evaluate the performance of the GE system at maximum production under their recommended operational settings. The performance of the ABMet® system was determined by quantifying nitrate removal efficiency, nitrate loading rate, carbon feed requirement, etc. Effluent nitrate concentrations of greater than 2 mg/L NO₃-N were considered unacceptable. The operation and maintenance testing for GE was during the Carbon Optimization and Steady State Phases.

The data collected during this task was used to optimize and monitor the ABMet® system and are described below along with data tables and plots. A brief discussion of the settings and operational procedures for the ABMet® system are contained in the following sections.

Task 2a: Carbon Optimization Phase—GE

The Carbon Optimization Phase for GE began April 3, 2008 and ended June 11, 2008. Operational procedures outlined in Chapter 4 were followed throughout this phase. Also on April 3, 2008, Bioreactor 1 was shut down for the remainder of the pilot study as outlined above. Thus, the following discussions apply only to Bioreactor 2.

Operational Settings

As mentioned previously, on April 3, 2008, the flow to GE’s pilot system bypassed Bioreactor 1 to Bioreactor 2 with a reduced flow rate of 2 gpm and a 1-hour HRT. This flow rate was maintained until the end of the Carbon Optimization Phase on June 11, 2008.

The carbon concentration of molasses at the beginning of GE’s Carbon Optimization Phase was approximately 80 mg/L. As the molasses was optimized, the concentration decreased...
From May 20, 2008 to May 29, 2008, GE slowly switched to methanol (i.e., 50% molasses to 50% methanol and then 25% molasses to 75% methanol). On May 30, 2008, GE switched to methanol as the only external carbon source for denitrification.

Table 5.21 presents the operational parameters of the pilot system during GE’s Carbon Optimization Phase, when dosing methanol. The dates are given for when a change in the carbon dose was made.

### Issues and Activities Addressed

Issues and activities addressed during GE’s Carbon Optimization Phase included backwashing, degassing and switching of carbon sources. The following sections describe each issue/activity for the GE pilot unit during this phase.

**Backwashing.** As described previously, GE’s ABMet® system required periodic backwashing to release accumulated suspended solids and excess bacteria. Table 5.22 shows the dates when GE backwashed the ABMet® system.

As shown in Table 5.19, backwashing occurred five times in approximately three months (from February 26, 2008 to April 2, 2008) for the pilot unit, thus, the required backwashing frequency at full scale is anticipated to be much higher than initially proposed by GE. However, after Bioreactor 1 was shut down on April 3, 2008 and the flow was turned down to 2 gpm, a backwash was not needed for approximately four weeks until April 29, 2008. Three weeks later on May 21, 2008, the next backwash was performed.

For the full-scale proposal, GE had indicated that backwashing needed to be conducted approximately three to six times annually. Therefore, the backwashing frequency from April 3, 2008 to the end of the Carbon Optimization Phase more closely resembled the backwash recurrence that was originally proposed by GE in comparison to the backwashing frequency prior to April 3, 2008. Recall that the increased frequency of the pilot unit backwashes, especially during...
the high flow period at the beginning of this study, was due to mechanical hydraulic constraints of the pilot unit.

**Degassing.** Unlike the backwashing frequency during GE’s Carbon Optimization Phase, the degassing frequency from April 3, 2008 to April 22, 2008 did not change in comparison to the degassing frequency prior to April 3, 2008. However, after April 22, 2008, the degassing recurrence decreased and more closely resembled the degassing frequency that was originally proposed by GE. **Table 5.23** shows the dates when GE degassed the ABMet® system during the Carbon Optimization Phase.

As shown in **Table 5.23**, the GE’s degassing frequency during the Carbon Optimization Phase was approximately a degas every two days until April 22, 2008, after which time the next degas did not occur until approximately three weeks later on May 16, 2008. Again three weeks later, GE performed the next degas on June 6, 2008.

**Carbon Source Changes.** For GE’s process, a proprietary molasses mixture was used in the beginning of the pilot study. However, GE changed carbon sources because the molasses caused color and odor concerns in the effluent. During the first three months of piloting, the City Laboratory’s staff indicated that they observed the effluent from the GE pilot unit had a noticeable color, described as a yellowish tint. The effluent also had an odor which City Laboratory’s staff described as a sewage type smell. This odor was likely the result of using molasses as the external carbon source for denitrification.

GE began the switch over to methanol by first transitioning to a 50% methanol/50% molasses solution on May 21, 2008. On May 28, 2008, GE began using a 75% methanol/25% molasses solution, and on May 30, 2008, they used at 100% methanol. Once GE began dosing methanol, they did not add any phosphorus to the pilot unit. This is discussed in more detail in the Phosphate discussion under Task 3.

**Data Results**

Data plots for the GE ABMet® system are presented in **Figure 5.17, Figure 5.18, Figure 5.21, Figure 5.23** and **Figure 5.25** for the Carbon Optimization Phase. Water quality parameters plotted include nitrate, TOC, alkalinity, and pH. Additionally, DOC data is presented in this section. Discussions on the City Laboratory data for ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented in Task 3. For temperature data, the City collected raw water temperatures.

<table>
<thead>
<tr>
<th>GE’s degassing Dates</th>
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<tr>
<td>04/11/08</td>
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<tr>
<td>04/14/08</td>
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<td>04/16/08</td>
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<tr>
<td>04/18/08</td>
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<td>04/22/08</td>
</tr>
<tr>
<td>04/29/08</td>
</tr>
<tr>
<td>05/16/08</td>
</tr>
<tr>
<td>06/06/08</td>
</tr>
</tbody>
</table>

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Nitrate. During this period, the City collected daily grab samples on the raw water line for laboratory analysis. The laboratory influent results were used to as a comparison to GE’s effluent data to evaluate performance.

Abrupt increases in nitrate shown in Figure 5.17 correlate to either a degas or backwash. Additionally, the increase in nitrate from May 1, 2008 to May 16, 2008 can be attributed to the nutrient optimization. Nutrient optimization was performed during this period to balance TOC and nitrate concentrations. The pilot nutrient pump was replaced with two chemical metering pumps on April 30, 2008 to improve effluent TOC concentrations. The pumps dosed nutrient more accurately, but several attempts were made to balance low effluent TOC with sufficient nutrients for denitrification. The high nitrate concentrations in the effluent were the result of not enough nutrient. However, for the rest of the Carbon Optimization Phase, GE’s effluent nitrate was below 2 mg/L NO₃-N.

TOC. In the beginning of GE’s Carbon Optimization Phase, molasses was dosed to the pilot unit as the external carbon source. Around mid-April, the effluent TOC concentrations started to decrease while optimizing the molasses as shown in Figure 5.18.

GE optimized the molasses dose by May 19, 2008, at which time the carbon source was switched to methanol. Figure 5.18 shows the increase in TOC around the May 20, 2008 due to the switch in carbon source. However, methanol was optimized by June 11, 2008 and effluent TOC concentrations decreased to near the influent TOC concentrations before the Steady State Phase.

During GE’s Molasses Optimization Phase, the maximum and minimum effluent TOC concentrations were 44.3 and 4.7 mg/L, respectively. The average influent TOC concentration was 4.8 mg/L while the average effluent TOC concentration using molasses was 11.2 mg/L, resulting in an average increase in TOC concentration of approximately 9.0 mg/L. When GE dosed methanol
as the carbon source, the maximum and minimum effluent TOC concentrations were 46.6 and 4.3 mg/L, respectively. The average influent TOC concentration was 4.6 mg/L while the average effluent TOC concentration was 18.3 mg/L, resulting in an average increase in TOC concentration of 14.0 mg/L.

The average increase in TOC concentration was greater when GE dosed methanol than when GE dosed molasses. However, the effluent TOC concentrations using methanol decreased to as low as 4.3 mg/L and decreased even further moving into the Steady State Phase.

**DOC.** City Laboratory began collecting samples to measure DOC concentrations during GE’s Carbon Optimization Phase on May 13, 2008. Samples were collected daily until May 28, 2008. Weekly sampling for DOC measurements began June 3, 2008 and ended June 10, 2008. Table 5.24 shows the TOC and DOC data for GE during the Carbon Optimization Phase.

As shown in Table 5.24, the difference between the TOC and DOC concentrations was not significant. Since the TOC and DOC concentrations were almost identical, DOC samples were not collected during the remaining piloting period. Similar TOC and DOC concentrations indicated that much of the organic matter existed in the dissolved form and not in the form of suspended organic matter.

**Temperature.** Based on the City’s data logger, the raw water temperature at the beginning of GE’s Carbon Optimization Phase was approximately 14.5°C. By the end of this phase, the raw water temperature had increased to 23.5°C. No effluent temperature data was collected during this period.
Immediately following the Carbon Optimization Phase, GE was required to allow their system to operate without any further modification to process variables. GE was allowed to indicate what set points (i.e., carbon feed rate, phosphoric acid feed rate, etc.) they wanted to operate their pilot unit at during the Steady State Phase. Once operational modifications were implemented, the ABMet® system operated at constant influent loading, with no modifications allowed for a minimum of 30 days. However, GE was allowed to make modifications provided they had a justified reason for making the change and they received written approval by the Owner and Engineer. For GE, the Steady State Phase began on June 11, 2008 and ended August 3, 2008. Operational procedures outlined in Chapter 4 were followed throughout this phase.

### Operational Settings

Table 5.25 presents the operational parameters of the pilot system during the steady state phase. Dates are presented for when the carbon dose was changed. The average, maximum, and minimum values for the entire steady state period are also provided.

---

### Table 5.24

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<th>Feed water DOC (gpm)</th>
<th>GE effluent TOC (mg/L)</th>
<th>GE effluent DOC (gpm)</th>
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</table>

(1) ‘—’ means not sampled.
Issues and Activities Addressed

Issues and activities addressed during the Steady State Phase included backwashing and degassing. The following sections describe each issue/activity for the GE pilot unit during this phase.

**Backwashing.** As stated earlier, from the beginning of piloting to the beginning of GE’s Carbon Optimization Phase (April 3, 2008), GE backwashed their unit five times in approximately three months, which was more than originally proposed by GE. During the Carbon Optimization Phase from April 3, 2008 to June 11, 2008, GE backwashed their unit twice. During the Steady State Phase, GE performed a final backwash on August 3, 2008. For the full-scale proposal, GE had indicated that backwashing needed to be conducted approximately three to six times annually. Therefore, the backwashing frequency from April 3, 2008 to the end of piloting closely resembled the backwash recurrence that was originally proposed by GE.

**Degassing.** Similar to the backwashing frequency during the Steady State Phase, GE’s degassing frequency closely resembled the frequency originally proposed by GE. As shown in Table 5.26, GE’s degassing frequency during the Steady State Phase was approximately one degas every seven days.

**Data Results: Plots and Tables—GE Task 2b**

Data plots for the GE ABMet® system are presented in Figure 5.19, Figure 5.20, Figure 5.22, Figure 5.24, and Figure 5.26 for the Steady State Phase. Water quality parameters plotted include nitrate and TOC. Additionally, City Laboratory data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented in Task 3. For temperature data, the City collected raw water temperature data.

### Table 5.25
GE operational parameters during the Steady State Phase

<table>
<thead>
<tr>
<th>Dates</th>
<th>Raw water NO₃-N (mg/L)</th>
<th>Raw water DO (mg/L)</th>
<th>Effluent water NO₃-N (mg/L)</th>
<th>GE influent flow rate (gpm)</th>
<th>CH₃OH pump feed rate (mL/min)</th>
<th>CH₃OH / NO₃-N (g/g)</th>
<th>CH₃OH (99.9%) dose (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/11/08 to 06/13/08</td>
<td>10.00</td>
<td>6.83</td>
<td>3.04</td>
<td>1.72</td>
<td>0.37</td>
<td>2.12</td>
<td>21.27</td>
</tr>
<tr>
<td>06/13/08 to 06/17/08</td>
<td>9.91</td>
<td>6.51</td>
<td>2.34</td>
<td>1.59</td>
<td>0.30</td>
<td>1.99</td>
<td>19.73</td>
</tr>
<tr>
<td>06/18/08 to 07/09/08</td>
<td>10.16</td>
<td>4.93</td>
<td>0.47</td>
<td>1.53</td>
<td>0.26</td>
<td>1.77</td>
<td>17.96</td>
</tr>
<tr>
<td>07/10/08 to 07/15/08</td>
<td>8.41</td>
<td>4.88</td>
<td>1.54</td>
<td>1.43</td>
<td>0.23</td>
<td>2.46</td>
<td>20.26</td>
</tr>
<tr>
<td>07/16/08 to 08/03/08</td>
<td>9.96</td>
<td>2.71</td>
<td>1.27</td>
<td>1.97</td>
<td>0.23</td>
<td>1.40</td>
<td>13.87</td>
</tr>
<tr>
<td>Average</td>
<td>9.87</td>
<td>4.37</td>
<td>1.15</td>
<td>1.70</td>
<td>0.26</td>
<td>1.75</td>
<td>17.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>12.32</td>
<td>7.00</td>
<td>8.05</td>
<td>2.15</td>
<td>0.37</td>
<td>4.86</td>
<td>42.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>6.54</td>
<td>1.25</td>
<td>&lt;0.10</td>
<td>0.57</td>
<td>0.23</td>
<td>1.03</td>
<td>12.0</td>
</tr>
</tbody>
</table>

(1) Feed rate at 50% methanol dilution.
Nitrate. Based on GE’s data logger information as shown in Figure 5.19, the system performance during the Steady State Phase resulted in no events causing the effluent nitrate to exceed the nitrate goal. Around July 21, 2008, the City had inadvertently overdosed the influent nitrate concentration resulting in a high influent nitrate reading, however, GE’s effluent nitrate concentration remained below 2 mg/L NO₃-N. The average effluent nitrate concentration during the Steady State Phase was 0.26 mg/L NO₃-N.

TOC. GE had optimized the methanol dose before June 11, 2008. Consequently, during the Steady State Phase, the effluent TOC concentrations decreased to concentrations comparable to the influent TOC concentrations as shown in Figure 5.20.

On July 4, 2008, GE’s effluent TOC concentration increased to 18 mg/L when the raw water TOC concentration was at 4.2 mg/L. According to GE, the pilot unit had a shallow bed approximately 3.3 feet of media depth which is less than the proposed full-scale depth of approximately 24 feet, and that a gas bubble in a shallow bed was more likely to form potentially resulting in a channel of nutrient in the bed. When this gas is released from the bed, the nutrient levels can spike causing an increase in effluent TOC concentrations. Since no other parameters changed (i.e., carbon dose, influent nitrate-nitrogen concentrations, or DO concentrations), it was assumed that this was a likely explanation of the spike in effluent TOC concentration on July 4, 2008. After July 4, 2008, the effluent TOC concentration decreased below the influent TOC concentration for the remainder of the Steady State Phase.

As shown in Figure 5.20, the CH₃OH to NO₃-N ratio was approximately from 1.5 to 2 during the first half of the Steady State Phase. Excluding the spike around July 10, 2008, during the second half of the phase, the methanol to nitrate ratio remained approximately around 1.5. Furthermore, as the ratio stabilized around 1.5, the effluent TOC concentrations decreased below the influent TOC concentrations.

Temperature. Based on the City’s data logger temperature data, the raw water temperature at the beginning of this phase was approximately 23.5°C. By the end of this phase, the raw water temperature had increased to 27°C. No effluent temperature data was collected during this period.

**TASK 3: MONITORING AND SAMPLING—GE**

Monitoring and sampling of the GE pilot unit system was carried out in accordance with the protocol in Chapter 4. Discussions on the City Laboratory data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented below. Water quality parameters plotted include nitrite, alkalinity and pH.
Figure 5.19 GE NO₃-N concentration data during the Steady State Phase

Figure 5.20 GE TOC concentration data during the Steady State Phase
Nitrite

On May 1, 2008, the City Laboratory collected samples to measure the nitrite-nitrogen concentration in the influent and effluent water for each pilot unit. Samples were collected on a daily basis until the end of piloting on August 28, 2008. Figure 5.21 and Table 5.27 show influent and effluent nitrite-nitrogen concentrations for GE’s ABMet® during the Carbon Optimization Phase from April 30, 2008 to June 11, 2008.

During GE’s Carbon Optimization Phase, six of the daily influent samples had nitrite-nitrogen concentrations above the MDL of 0.05 resulting in an average influent nitrite-nitrogen concentration of 0.01 mg/L. However, as shown in Table 5.27, as the water was treated, the average nitrite-nitrogen concentration increased from 0.01 to 0.31 mg/L. This increase was most likely due to the incomplete reduction of nitrate to nitrogen gas, which causes nitrite to accumulate in the process and ultimately increase the nitrite concentration in the effluent. GE did not aerate their effluent water to reduce the effluent TOC concentration, and therefore, did not oxidize the nitrite.

During the Steady State Phase, nitrite samples were collected on a daily basis and as shown in Figure 5.22 and Table 5.27 the average nitrite-nitrogen concentration increased from 0.08 to 0.23 mg/L as the water was being treated.

Ammonia

Since the City Laboratory did not begin collecting samples to test for ammonia-nitrogen until March 5, 2008, no ammonia data exists for GE’s pilot unit during the Seeding and Acclimation Phase. However, from the end of this phase to the beginning of the Carbon Optimization Phase, the
City Laboratory collected four samples to measure the effluent concentration of ammonia-nitrogen. After May 6, 2008, the City Laboratory collected two to four samples weekly until June 17, 2008. From July 8, 2008 to July 29, 2008, three more samples were collected approximately every nine days. Table 5.28 shows the average ammonia-nitrogen concentrations for the GE ABMet® pilot unit during the beginning of piloting and the Carbon Optimization and Steady State Phases.

From the beginning of piloting to the start of GE’s Carbon Optimization Phase, four samples were collected to measure ammonia concentrations. Of the four samples collected, the City Laboratory measured the ammonia concentration to be below the test method MDL of 0.10 mg/L.
NH$_3$-N in three samples while the fourth sample had 0.8 mg/L NH$_3$-N. Thus, the average effluent ammonia concentration for GE’s ABMet® system was 0.20 mg/L NH$_3$-N. All influent samples collected during this period had ammonia concentrations below the MDL of 0.10 mg/L NH$_3$-N, which resulted in only one effluent sample having a greater ammonia-nitrogen concentration than the corresponding influent sample.

During GE’s Carbon Optimization Phase, sampling occurred from April 3, 2008 to May 6, 2008 on a weekly basis. From May 13, 2008 to May 30, 2008, sampling occurred three to four times a week. Two more samples were collected on June 3 and 6, 2008. The maximum effluent concentration of ammonia was 2.03 mg/L NH$_3$-N whereas the average minimum ammonia concentration was below the MDL. GE averaged a 0.39 mg/L NH$_3$-N influent ammonia concentration while the average effluent ammonia concentration was 1.46 mg/L NH$_3$-N. Therefore, an increase of approximately 1.07 mg/L NH$_3$-N from the influent to the effluent was observed with GE’s ABMet® process. The increase in ammonia was potentially due to the release of ammonia from cell lysis in the anoxic zone.

The City Laboratory collected a total of seven samples from each pilot system to measure the ammonia concentration throughout the Steady State Phase. During this phase, the maximum effluent concentration of ammonia for GE’s ABMet® was 2.43 mg/L NH$_3$-N whereas the average minimum ammonia concentration was below the MDL. GE averaged a 0.15 mg/L NH$_3$-N influent ammonia concentration while the average effluent ammonia concentration was 0.73 mg/L NH$_3$-N. Therefore, an increase of approximately 0.6 mg/L NH$_3$-N from the influent to the effluent was observed with GE’s ABMet® process.

**Phosphate**

As stated previously, for water to be biologically denitrified, it must contain a certain amount of phosphorus (P) for nutrient uptake and bacterial growth. GE’s molasses nutrient contained phosphorus, and therefore, GE did not add any additional phosphorus to their pilot unit. Table 5.29 shows the average effluent phosphate concentrations for the GE ABMet® system during the Seeding and Acclimation, Carbon Optimization and Steady State Phases.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>GE effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td>02/12/08 to 02/21/08</td>
<td>—(1)</td>
</tr>
<tr>
<td>Beginning of piloting to beginning of Carbon Optimization Phase</td>
<td>02/12/08 to 04/02/08</td>
<td>&lt; 0.10(2)</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td>04/03/08 to 06/11/08</td>
<td>0.39</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td>06/11/08 to 08/03/08</td>
<td>0.15</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.
(2) Test Method Maximum Detection Level of Ammonia-Nitrogen.

### Table 5.28

Average ammonia-nitrogen concentrations for GE’s ABMet® during Seeding and Acclimation, Carbon Optimization, and Steady State Phases

<table>
<thead>
<tr>
<th>Average NH$_3$-N concentrations (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>Seeding and Acclimation Phase</td>
</tr>
<tr>
<td>Beginning of piloting to beginning of Carbon Optimization Phase</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
</tr>
<tr>
<td>Steady State Phase</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.
(2) Test Method Maximum Detection Level of Ammonia-Nitrogen.
During GE’s Seeding and Acclimation Phase, the phosphate concentration increased by approximately 0.38 mg/L, however, the City Laboratory collected only one sample during this phase. Furthermore, from the beginning of piloting to the beginning of GE’s Carbon Optimization Phase, the average phosphate concentration decreased by 0.14 mg/L to 0.08 mg/L PO₄-P across the process which is less than the recommended effluent phosphorus concentration of 1 mg/L as P. The maximum phosphate concentration during GE’s Seeding and Acclimation Phase and up to the start of the Carbon Optimization Phase was 0.47 mg/L PO₄-P, and the minimum concentration was less than the MDL of 0.03 mg/L PO₄-P. The average influent phosphate concentration during this time was 0.22 mg/L PO₄-P.

During GE’s Carbon Optimization Phase, the average phosphate concentration decreased by 0.02 mg/L PO₄-P through the process. Furthermore, the average effluent phosphate concentration was below the recommended maximum effluent phosphorus concentration of 1 mg/L as P. The maximum effluent phosphate concentration during GE’s Carbon Optimization Phase was 0.98 mg/L PO₄-P with a minimum effluent phosphate concentration below the test MDL of 0.03 mg/L PO₄-P. During this phase, the average influent concentration was 0.30 mg/L PO₄-P. However, approximately 25 percent of the effluent samples were ≤0.16 mg/L PO₄-P, indicating that the phosphorus was used for biological growth.

For the Steady State Phase, the City Laboratory collected daily samples to measure the phosphate concentrations for GE’s ABMet®. During GE’s Steady State Phase, the average phosphate concentration decreased by 0.04 mg/L PO₄-P. Furthermore, the average effluent phosphate concentration was below the recommended maximum effluent phosphorus concentration of 1 mg/L as P. The maximum effluent phosphate concentration was 1.0 mg/L PO₄-P with a minimum effluent phosphate concentration below the test MDL of 0.03 mg/L PO₄-P.

**Color**

At the beginning of piloting, the City Laboratory was not measuring the color in the effluent from each pilot unit. However, once the City Laboratory’s staff observed a noticeable color in the effluent, the decision was made to begin sampling for color. Therefore, on March 19, 2008, the City Laboratory began collecting samples to measure the color in the water from each pilot unit and as of March 26, 2008, color concentrations were measured approximately three to four
times per week. For GE’s Seeding and Acclimation Phase, the City Laboratory did not collect any samples to measure for color, and from the beginning of piloting to the beginning of GE’s Carbon Optimization Phase, the City Laboratory collected only three samples. Table 5.30 and Table 5.31 show the average color (true and apparent) for GE’s ABMet® influent and effluent waters.

The average effluent apparent color increased from 65.0 Pt-Co from the beginning of GE’s piloting to 116.4 Pt-Co units during the Molasses Optimization Phase. While GE was optimizing the methanol dose, the average effluent apparent color decreased to 51.2 Pt-Co units and increased to 51.2 Pt-Co during the Steady State Phase.

The average effluent apparent color from the beginning of piloting to the beginning of the Carbon Optimization Phase was 65.0 Pt-Co units with an average influent of 12.0 Pt-Co units. For the true color during this same time, the average increase was approximately 36 Pt-Co units with an influent of 12 Pt-Co units.

During GE’s Carbon Optimization Phase, the average effluent apparent color was greater than the influent color for both carbon sources as shown in Table 5.30. As the molasses was optimized, the average effluent apparent color increased from 65 to 116 Pt-Co units when the average influent apparent color was approximately 32 Pt-Co units. However, once GE switched to methanol, the average effluent apparent color decreased from 116 to 51 Pt-Co units with an average influent apparent color of approximately 28 Pt-Co units.

The City Laboratory collected six samples from GE’s ABMet® effluent during the Steady State Phase. During the Steady State Phase, GE’s average effluent apparent color was 78.5 Pt-Co units with an average influent apparent color was 35.2 Pt-Co units, thus, the average effluent apparent color increased by 43.3 Pt-Co units.

Unlike the effluent apparent color, the effluent true color decreased from 47.7 pt-Co units from the beginning of GE’s piloting to 25.1 Pt-Co units during the Molasses Optimization Phase. However, the average effluent true color decreased more when GE switched their carbon source to methanol. The average effluent true color when dosing methanol was 15.7 Pt-Co units. During the Steady State Phase, the true color decreased even further to 10.0 Pt-Co units resulting in an overall average decrease in true color from the beginning of piloting to the Steady State Phase of 37.7 Pt-Co units. The increase in true color was most likely a result of GE’s molasses nutrient. The molasses degraded the aesthetic quality of the treated water and caused odor problems. GE mitigated these issues by optimizing the carbon dose and ultimately switching their carbon source to methanol.

For GE’s Molasses Optimization Phase, the average effluent true color was approximately 25.1 Pt-Co units with an average influent true color of 5.4 Pt-Co units. During the Methanol Optimization Phase, the average effluent true color was approximately 15.7 Pt-Co with an average influent true color of 9.4 Pt-Co units. When methanol was used as the external carbon source, the average effluent true color decreased by 9.4 Pt-Co units from when GE doses molasses.

The average effluent true color was approximately 9 Pt-Co units less than the average influent true color during the Steady State Phase for GE. Furthermore, the effluent true color decreased from 15.7 Pt-Co units from the Methanol Optimization Phase to 10.0 Pt-Co units during the Steady State Phase.

**Turbidity**

Weekly turbidity measurements were taken by the City Laboratory for three weeks beginning February 21, 2008 and ending March 5, 2008. On March 26, 2008, turbidity concentrations
were measured approximately three times per week until the end of piloting. For GE, the average effluent turbidity was greater than the average influent turbidity during the Seeding and Acclimation, Carbon Optimization, and Steady State Phases, as shown in Table 5.32.

The average turbidity increase during GE’s Seeding and Acclimation phase was approximately 15.7 NTU with an average influent turbidity of 0.7 NTU. The maximum and minimum turbidity measurements were 21.6 and 1.0 NTU, respectively. Similar to the increase in apparent and true color, the increase in turbidity was most likely the result of the addition of GE’s nutrient (molasses).

From the beginning of piloting to the beginning of GE’s Carbon Optimization Phase, the average turbidity increase was approximately 5.3 NTU with an average influent turbidity of

---

**Table 5.30**

Average apparent color for GE’s ABMet® during Seeding and Acclimation, Carbon Optimization, and Steady State Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>GE effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02/12/08 to 02/21/08</td>
<td>—(1)</td>
<td>—</td>
</tr>
<tr>
<td>Beginning of piloting to beginning of Carbon Optimization Phase</td>
<td>12.0</td>
<td>65.0</td>
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<tr>
<td>02/12/08 to 04/02/08</td>
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</tr>
<tr>
<td>Carbon Optimization Phase</td>
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<tr>
<td>Molasses Optimization Phase</td>
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<td></td>
</tr>
<tr>
<td>04/03/08 to 05/20/08</td>
<td>32.2</td>
<td>116.4</td>
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<td>Methanol Optimization Phase</td>
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</tr>
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<td>Steady State Phase</td>
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<tr>
<td>06/11/08 to 08/03/08</td>
<td>35.2</td>
<td>78.5</td>
</tr>
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</table>

(1) ‘—’ means not sampled.

**Table 5.31**

Average true color for GE’s ABMet® during Seeding and Acclimation, Carbon Optimization, and Steady State Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>GE effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
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<td></td>
</tr>
<tr>
<td>02/12/08 to 02/21/08</td>
<td>—(1)</td>
<td>—</td>
</tr>
<tr>
<td>Beginning of piloting to beginning of Carbon Optimization Phase</td>
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<tr>
<td>Carbon Optimization Phase</td>
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<tr>
<td>Molasses Optimization Phase</td>
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<td>04/03/08 to 05/20/08</td>
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<td>25.1</td>
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<tr>
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<td></td>
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<td>05/21/08 to 06/11/08</td>
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</tr>
<tr>
<td>06/11/08 to 08/03/08</td>
<td>18.6</td>
<td>10.0</td>
</tr>
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</table>

(1) ‘—’ means not sampled.

---
1.2 NTU. The maximum and minimum turbidity measurements during this time occurred during GE’s Seeding and Acclimation Phase (values mentioned previously).

When GE was optimizing their molasses dose, the average turbidity increase through their ABMet® system was approximately 6.5 NTU. The average influent turbidity during this period was 2.3 NTU, and the maximum and minimum turbidity measurements were 21.6 and 1.0 NTU, respectively. While optimizing the methanol dose, the average turbidity increase across GE’s pilot unit was 0.4 NTU. The average influent turbidity during this time was 1.5 NTU, and the maximum and minimum turbidity measurements were 4.9 and 0.8 NTU, respectively.

The average turbidity increase through GE’s pilot system during the Steady State Phase was approximately 6.0 NTU, which is greater than the increase observed during the optimization of methanol. Furthermore, from GE’s Carbon Optimization Phase to the Steady State Phase, the average effluent turbidity increased from 1.9 to 8.2 NTU. As mentioned earlier, the increase in turbidity through the ABMet® system was most likely due to the biomass produced during the denitrification process.

TSS

Beginning February 29, 2008, the City Laboratory collected samples to measure the TSS in the effluent from each pilot system. Samples were tested approximately weekly until May 20, 2008. Table 5.33 shows GE’s average effluent TSS concentration in comparison to the average influent TSS concentration during the Seeding and Acclimation, Carbon Optimization, and Steady State Phases.

From the beginning of piloting to the beginning of GE’s Carbon Optimization Phase, the average effluent TSS concentration was approximately 3.6 mg/L greater than the average feed water TSS concentration. The average feed water TSS concentration was 0.6 mg/L. As stated previously in regards to turbidity and color, GE’s dosed their molasses nutrient thereby they most likely increased the amount of suspended solids in their effluent and consequently increased the turbidity and TSS concentration.
The City Laboratory stopped collecting samples on May 20, 2008 during GE’s Carbon Optimization Phase. Therefore, samples were collected during the Molasses Optimization Phase only. As shown in Table 5.33, the average effluent TSS concentration during GE’s Carbon Optimization Phase was approximately 0.8 mg/L less than the average feed water TSS concentration. The average influent TSS was concentration was 6.6 mg/L. The decrease in TSS concentration was most likely due to GE optimizing their molasses dose by May 20, 2008.

The City Laboratory collected three samples of the GE ABMet® system backwash to measure the TSS concentrations. These samples were taken on July 1, 2008, during the Steady State Phase. The unit was backwashed for a total of 900 seconds (15 minutes). One sample was taken at the beginning of the backwash (within the first minute), one in the middle of the backwash (at approximately 7.5 minutes) and one at the end of the backwash (within the last minute). However, the City Laboratory did not collect any samples to measure the TSS concentrations in the feed water. The results of the backwash TSS concentration were 95 mg/L (beginning), 18 mg/L (middle) and 5 mg/L (end). Therefore, the average backwash TSS concentration for the GE unit was approximately 39 mg/L.

**Alkalinity**

Beginning February 21, 2008, the City Laboratory collected weekly samples to measure the alkalinity in the influent and effluent water for each pilot unit. On March 26, 2008, the City Laboratory began collecting three to four samples a week until the end of piloting. In the process of denitrification, nitrate is converted to nitrogen gas utilizing facultative heterotrophic bacteria and this process generates alkalinity in the form of bicarbonate.

Table 5.34 shows the average influent and effluent alkalinity concentrations for GE’s ABMet® during the Seeding and Acclimation, Carbon Optimization, and Steady State Phases and during the period from the beginning of piloting to the beginning of the Carbon Optimization Phase.

As shown in Table 5.34, during GE’s Seeding and Acclimation Phase, the average alkalinity increased by 26 mg/L as CaCO₃ from the influent to the effluent of the reactors. From the
beginning of piloting to the beginning of the Carbon Optimization Phase, GE’s average alkalinity increased by approximately 20 mg/L as CaCO$_3$. Average influent alkalinity concentrations for these periods were 123 and 112 mg/L as CaCO$_3$, respectively. These increases in alkalinity were the result of the denitrification process. When denitrification occurs, alkalinity is returned to the process at approximately 3.57 grams of CaCO$_3$ per gram of NO$_3$-N reduced.

Similar to the trend during the Seeding and Acclimation Phase, the alkalinity increased across the reactor during GE’s Carbon Optimization Phase. The increase during the Carbon Optimization Phase was approximately 37 mg/L as CaCO$_3$, which is larger than the increase observed during the startup phase. This is most likely due to the system removing more nitrate. Hence, higher nitrate removal results in generating more alkalinity. During this phase, the average influent alkalinity concentration was 126 mg/L CaCO$_3$ with an average effluent concentration of 163 mg/L CaCO$_3$. Figure 5.23 presents alkalinity concentrations from the feed water and in the reactor effluent during GE’s Carbon Optimization Phase.

Similar to the trend during the Seeding and Acclimation and Carbon Optimization Phases, the alkalinity increased across GE’s reactor during the Steady State Phase. As shown in Table 5.34, the increase during the Steady State Phase was by approximately 32 mg/L as CaCO$_3$, which was similar to the increase in alkalinity during the Carbon Optimization Phase. Similar increases in alkalinity were observed since approximately 8 mg/L NO$_3$-N was removed during both phases.

Figure 5.24 presents alkalinity concentrations for GE’s Steady State Phase. With the exception of the alkalinity concentration around July 8, 2008, the alkalinity remained consistent during this phase. The average influent alkalinity concentration was 123 mg/L CaCO$_3$ with the average effluent alkalinity concentration of 155 mg/L CaCO$_3$.

**pH**

The City Laboratory collected samples to measure the influent and effluent pH for each pilot unit starting February 27, 2008 and continued to collect daily samples for pH measurements for the majority of piloting. Table 5.35 shows the average pH measurements during GE’s Seeding and Acclimation, Carbon Optimization and Steady State Phases. Figure 5.25 and Figure 5.26 shows GE’s average pH data during the Carbon Optimization and Steady State Phases, respectively.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>GE effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td>02/12/08 to 02/21/08</td>
<td>123</td>
</tr>
<tr>
<td>Beginning of piloting to beginning of</td>
<td>02/12/08 to 04/02/08</td>
<td>112</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td>04/03/08 to 06/11/08</td>
<td>126</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td>06/11/08 to 08/03/08</td>
<td>123</td>
</tr>
</tbody>
</table>

Table 5.34
Average alkalinity for GE’s ABMet® during Seeding and Acclimation, Carbon Optimization, and Steady State Phases

Average alkalinity concentrations (mg/L CaCO$_3$)
Figure 5.23 GE alkalinity concentration data during the Carbon Optimization Phase

Figure 5.24 GE alkalinity concentration data during the Steady State Phase
As shown in Table 5.35, the average pH decreased across the reactor from the beginning of piloting to the beginning of GE’s Carbon Optimization and during the Carbon Optimization and Steady State Phases.

The average pH decreased by 1.5 pH units from the beginning of piloting to the beginning of GE’s Carbon Optimization Phase. During this period, the average influent pH was 8.6 with an average effluent pH of 7.1. While optimizing the carbon dose, the average pH decreased by only 0.6 pH units and decreased by only 0.1 pH units during the Steady State Phase. The average influent pH during GE’s Carbon Optimization Phase was 8.4 with an average effluent pH of 7.8.
and during the Steady State Phase, the average influent and effluent pH measurements were 8.1 and 8.0, respectively. Further investigation of the pH throughout this phase reveals a correlation between carbon dose and pH.

In Figure 5.26, the pH in the effluent suddenly spikes on July 13, 2009 to a level significantly greater than the influent. This spike corresponds with a reduction in carbon feed rate that was initiated due to an increase in TOC in the effluent. It is theorized that this reduction in carbon feed resulted in the bacteria producing less organic acid and resulted in an increase in pH. Comparison of TOC and pH results indicates that when excess carbon is dosed (resulting in an increase in TOC), the pH decreases. In instances where an increase in pH is observed, no increase in effluent TOC is present.

**TASK 4: RESILIENCY TEST PHASE—GE**

The Resiliency Test Phase was conducted by ‘shocking’ each system with varying influent nitrate concentrations and shutdown of equipment. For GE, this phase commenced on August 4, 2008 and ended August 28, 2008. Five main tasks were performed during this phase. These tasks include the following:

- Task 4a: Incremental Nitrate Spiking
- Task 4b: Rapid Change Nitrate Spiking
- Task 4c: Influent Nitrate Spiking Shutdown
- Task 4d: Carbon Feed Pump Shutdown
- Task 4e: Raw Water Shutdown
The following sections describe each task listed above for the GE pilot unit along with plots and data from this phase.

**Task 4a: Incremental Nitrate Spiking—GE**

Task 4a required GE to adjust the carbon feed rate to account for the increase in influent nitrate. The first increase was up to 15 mg/L $\text{NO}_3$-$\text{N}$ on August 4, 2008 and the second increase up to 20 mg/L $\text{NO}_3$-$\text{N}$ on August 8, 2008. Once operational modifications (i.e., changes to the carbon feed rate) were implemented for each increase in the influent nitrate-nitrogen, the ABMet® unit operated at constant influent loading for the remainder of each incremental nitrate spiking period.

**Operational Settings**

Moving into the Resiliency Test Phase, GE’s nutrient flow was approximately 16 mg/L 99.9% methanol (1.7 g CH$_3$OH/g $\text{NO}_3$-$\text{N}$) when the influent nitrate was approximately 10 mg/L $\text{NO}_3$-$\text{N}$. Table 5.36 shows the operational settings during the incremental nitrate spiking period.

**Task 4b: Rapid Change Nitrate Spiking—GE**

Task 4b required GE to adjust the carbon feed rate to account for a decrease in influent nitrate from 20 mg/L $\text{NO}_3$-$\text{N}$ to 5 mg/L $\text{NO}_3$-$\text{N}$ on August 12, 2008. On August 16, 2008, the influent nitrate was changed back to 10 mg/L $\text{NO}_3$-$\text{N}$ and again GE was required to adjust the carbon feed rate to their pilot unit.

**Operational Settings**

Table 5.37 shows the operational settings during the rapid change nitrate spiking.

**Task 4c: Influent Nitrate Shutdown—GE**

Task 4c involved shutting down the influent nitrate dosage pump on August 18, 2008 for 4 hours and again on August 20, 2008 for another 4 hours. During both of these shutdowns, the influent nitrate concentration decreased to approximately 1 to 2 mg/L $\text{NO}_3$-$\text{N}$.

**Operational Settings**

For Task 4c, no operational changes were made to the ABMet® system.

---

**Table 5.36**

GE methanol dosing during incremental nitrate spiking

<table>
<thead>
<tr>
<th>Date</th>
<th>Average raw water NO$_3$-$\text{N}$ (mg/L)</th>
<th>Average raw water DO (mg/L)</th>
<th>Average GE influent flow rate (gpm)</th>
<th>Average CH$_3$OH / NO$_3$-$\text{N}$ (g/g)</th>
<th>Average 99.9% CH$_3$OH (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/04/08 to 08/08/08</td>
<td>14.9</td>
<td>4.4</td>
<td>1.65</td>
<td>1.37</td>
<td>20.42</td>
</tr>
<tr>
<td>08/08/08 to 08/12/08</td>
<td>20.2</td>
<td>5.5</td>
<td>1.81</td>
<td>1.23</td>
<td>24.82</td>
</tr>
</tbody>
</table>
Table 5.37
GE methanol dosing during rapid change nitrate spiking

<table>
<thead>
<tr>
<th>Date</th>
<th>Average raw water NO₃⁻N (mg/L)</th>
<th>Average GE influent flow rate (gpm)</th>
<th>Average CH₃OH/NO₃⁻N (g/g)</th>
<th>Average 99.9% CH₃OH (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/08/08 to 8/12/08</td>
<td>20.2</td>
<td>1.81</td>
<td>1.23</td>
<td>24.82</td>
</tr>
<tr>
<td>08/12/08 to 08/16/08</td>
<td>5.1</td>
<td>1.80</td>
<td>1.23</td>
<td>6.24</td>
</tr>
<tr>
<td>08/16/08</td>
<td>8.2</td>
<td>1.71</td>
<td>1.89</td>
<td>15.89</td>
</tr>
</tbody>
</table>

Task 4d: Carbon Feed Pump Shutdown—GE

During Task 4d, the carbon feed pump was shut down on two occasions. The first shutdown occurred on August 21, 2008 for 4 hours and the other on August 22, 2008 for another 4 hours.

Operational Settings

For Task 4d, no operational changes were made to the ABMet® system.

Task 4e: Raw Water Shutdown—GE

On August 23, 2008, the raw water pump was turned off for 72 hours, during which time the ABMet® unit was completely shutdown. The unit was started back up on August 26, 2008 and continued to operate until the end of the Resiliency Test Phase and pilot study which ended August 28, 2008.

Operational Settings

Operational changes for Task 4e included a full shutdown of the ABMet® pilot unit for 72 hours, after which time the unit was put back online with all equipment in operation.

Issues and Activities Addressed—GE Task 4

Issues and activities addressed during GE’s Resiliency Test Phase only included degassing. During the Steady State Phase, GE was degassing approximately once every seven days. For the last month of piloting, only two degases were performed. The first degas was performed on August 8, 2008 and the other on August 25, 2008. Therefore, the frequency of degassing since the most recent backwash on July 25, 2008 for the Resiliency Test Phase was approximately one degas every 14 days.

Data Results: Plots—GE Task 4

Data plots for the GE ABMet® system are presented in Figure 5.27 and Figure 5.28 for the Resiliency Test Phase. Critical parameters plotted include nitrate and TOC. All other water quality parameters evaluated for the first three phases were not evaluated in detail for the Resiliency Test Phase since the pilot units underwent extreme operational changes.
Nitrate

On August 4, 2008, the final phase of piloting began when influent nitrate concentrations were gradually or rapidly increased to monitor the response of each pilot unit. During this phase, GE’s flow rate (EBCT) through their pilot unit did not change. Figure 5.27 shows the performance of the GE ABMet® pilot unit for this testing phase. GE’s pilot system performed well in response to the fluctuating influent nitrate concentrations.

When the influent nitrate concentration increased, the effluent nitrate increased slightly. However, when effluent concentrations increased above 2 mg/L NO₃-N, the system began denitrifying to under the pilot effluent goal within at most 17 hours. During the carbon feed pump shut off periods, the effluent nitrate concentrations increased but remained below the 2 mg/L NO₃-N limit. Furthermore, after the 72-hour raw water shutdown, the effluent nitrate was still below 2 mg/L NO₃-N.

Around August 12, 2008, the effluent nitrate concentration increased to approximately 4.5 mg/L NO₃-N. GE’s effluent nitrate concentration remained above the pilot goal of 2 mg/L NO₃-N for approximately 17 hours. On August 14, 2008, the effluent nitrate once again exceeded the pilot goal. However, the amount of increase in effluent nitrate concentration causing GE to not meet the pilot goal was unappreciable since the effluent concentration increased up to only 2.02 mg/L NO₃-N and this increase lasted for only 4 hours. Unlike this event, on August 16, 2008, the increase resulting in effluent nitrate concentrations above the pilot goal lasted for approximately 18.5 hours. From this time to the end of the Resiliency Test Phase, the effluent nitrate concentrations remained below 2 mg/L NO₃-N.

TOC

Moving into the last month of piloting, manufacturers adjusted their carbon feed based on the fluctuating influent nitrate concentrations. Figure 5.28 shows the TOC results for GE during the Resiliency Test Phase. The TOC effluent concentration increased to 8.4 mg/L when the influent nitrate concentrations were increased from 10 to 20 mg/L NO₃-N. However, this increase was likely attributed to the carbon dose being increased to account for the increased nitrate concentrations. The next day on August 9, 2008, the effluent TOC concentration decreased to 3.7 mg/L. Once the influent nitrate was decreased to 5 mg/L NO₃-N, the effluent TOC concentration was around 3.7 mg/L.

The data shows that the TOC decreased and was lower than the influent TOC concentration within two days of spiking of the influent nitrate. When the spiked nitrate on the influent stream was shut down for 4 hours and the influent nitrate concentration decreased from approximately 10 mg/L NO₃-N to approximately 1 to 2 mg/L NO₃-N on August 16, 2008 and August 18, 2008, the effluent TOC concentrations increased over 10 mg/L, as shown in Figure 5.28. These increases in TOC were most likely the result of the carbon feed not being adjusted to account for the change in influent nitrate concentration whereby excess carbon was fed during this time.

The effluent TOC concentration decreased below the influent TOC concentration when the carbon feed pump was shut down for 4 hours on August 22, 2008 and August 23, 2008 and was below the influent TOC concentration for the remainder of the Resiliency Test Phase. The TOC decreased to 3.1 mg/L shortly after the carbon feed pumps were shut down.
Figure 5.27 GE NO₃-N concentration data during the Resiliency Test Phase
Figure 5.28  GE TOC concentration data during the Resiliency Test Phase
 TASK 5: COLUMN TESTING—GE

GE performed a column test to simulate field conditions (i.e., HRT and loading rate) to determine nitrate breakthrough from a non-biological GAC bed. The column test determined the adsorption capacity of the activated carbon media and confirmed that the GE’s process removed nitrate through denitrification and not solely through adsorption of the carbon media. A bacterium was not added to the column since this test was to analyze nitrate removal by the media alone. Additionally, this test was conducted using a raw water solution with 20 mg/L NO₃-N. Raw water was fed through the column and monitored daily until breakthrough was observed (i.e., nitrate was measured in the effluent or through the back end of the column). The results indicated an approximate amount of nitrate removal that would be observed with the given adsorption capacity of the carbon media if the carbon feed source was shut down. The results of GE’s column test are shown in Figure 5.29.

GE performed two column tests, one utilizing virgin GAC and the other utilizing bioactive GAC seeded with denitrifying culture. The bioactive GAC was not fed a nutrient carbon source after seeding. Both columns were fed a nitrate solution of 20 mg/L NO₃-N. In both cases, nitrate values were observed. For the virgin GAC, nitrate was observed in 28 turnovers and for the bio-GAC, it was observed in 46 turnovers. Hence, these turnovers represent approximately one to two days breakthrough with a 1-hour HRT.
TASK 6: QUALITY ASSURANCE AND QUALITY CONTROL—GE

QA/QC procedures were conducted throughout the pilot study to ensure accuracy of data. The protocol outlined in Chapter 4 was strictly followed. No quality control issues were identified relative to data collected for the GE system.

IDI SUMMARY OF PILOT TESTING ACTIVITIES

Startup of the IDI pilot system began on February 6, 2008. The start and completion dates for each task are provided in the Table 5.38.

In the following pages, data for each task is provided along with a brief narrative for each task. Additionally, the events and results will be discussed in this section.

TASK 1: STARTUP—SEEDING AND ACCLIMATION PHASE—IDI

The goal of this task was to evaluate the performance of the system during startup and seeding activities. Startup during cold temperature months was a key operational ability for this system’s geographic location. IDI was allowed to use a seeding material from an outside source to expedite the acclimation time. The seeding material was required to be from a sensible source (i.e., compatible with the carbon source used) and to be capable of being used in a full-scale treatment process. IDI decided to seed their pilot unit with their MB17 bacteria.

The data collected from the beginning of this task to the beginning of IDI’s Carbon Optimization Phase on April 3, 2008 were used to monitor the NITRAZUR DN® system and are described below along with data tables and plots. A discussion of the settings and operational procedures for the NITRAZUR DN® system for this task is presented in the following sections.

Table 5.38
IDI testing phases by task

<table>
<thead>
<tr>
<th>Task description</th>
<th>Start date</th>
<th>Completion date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Startup: Seeding and Acclimation Phase</td>
<td>February 6, 2008</td>
<td>March 25, 2008</td>
</tr>
<tr>
<td>2. Operation and performance testing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Backwash Optimization Phase</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>3. Monitoring and sampling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Data logging</td>
<td>February 8, 2008</td>
<td>August 28, 2008</td>
</tr>
<tr>
<td>b. City manual data collection and analysis</td>
<td>February 20, 2008</td>
<td>August 28, 2008</td>
</tr>
<tr>
<td>4. Nitrate Spiking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Incremental nitrate spiking</td>
<td>August 4, 2008</td>
<td>August 11, 2008</td>
</tr>
<tr>
<td>b. Rapid change nitrate spiking</td>
<td>August 12, 2008</td>
<td>August 17, 2008</td>
</tr>
<tr>
<td>c. Influent nitrate shutdown</td>
<td>August 18, 2008</td>
<td>August 20, 2008</td>
</tr>
<tr>
<td>5. Column testing</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>6. QA/QC</td>
<td>February 6, 2008</td>
<td>August 28, 2008</td>
</tr>
</tbody>
</table>
Seeding and Acclimation

February 6, 2008 was the startup date for the IDI NITRAZUR DN® pilot unit. Seeding this pilot unit was considered in order to speed up the projected five to six week cold-water seeding period. On February 9, 2008, IDI seeded their unit with dry MB17 (bacteria). Manufactured by Maryland Biochemical, the bacteria was suspended on a wheat bran media, and packaged in 1-pound, water-soluble bags. Seeding was discontinued after March 14, 2008 since the IDI NITRAZUR DN® pilot unit showed consistent evidence of nitrate reduction. Table 5.39 shows the seeding schedule for IDI’s pilot unit.

IDI followed the operational procedure outlined for the Seeding and Acclimation Phase of testing. Startup was considered completed when IDI began denitrifying and achieving nitrate concentrations ≤2 mg/L NO₃-N with 10 mg/L NO₃-N or greater of influent nitrate concentration. The effluent nitrate concentrations did not reach the pilot goal of ≤2 mg/L NO₃-N until approximately seven weeks into the pilot study. March 25, 2008 was the first day the IDI pilot unit consistently removed nitrate and met the effluent nitrate goal of ≤2 mg/L NO₃-N for more than 24 hours. Thus, for IDI the Seeding and Acclimation phase for IDI began February 6, 2008 and ended March 25, 2008. Operational procedures outlined in Chapter 4 were followed throughout this phase.

Operational Settings

IDI’s pilot plant unit was designed for loading rates from 4 to 12 gpm/ft². However, operational settings during the Seeding and Acclimation Phase for the NITRAZUR DN® pilot unit varied and resulted in loading rates as low as 0.5 gpm/ft². Typically, the startup influent flow would be low and increase gradually over time to optimize the filtration rate that gives the desired nitrate removal efficiency. Starting February 8, 2008, IDI set the influent flow rate at an average of 5 gpm (6.3 gpm/ft²) and decreased the influent flow to as low as 0.4 gpm (0.5 gpm/ft²) on average.

Table 5.40 shows the changes in flow rate for the IDI pilot unit and other operating parameters during this phase. The raw water DO varied from approximately 12 mg/L in February 2008 down to 9 mg/L by the end of March 2008 with the average at approximately 10.2 mg/L.

During this phase, the average methanol pump feed rate and methanol to nitrate ratio decreased. Beginning February 8, 2008, the average methanol pump feed rate was 2 mL/min and decreased to 0.91 mL/min by April 3, 2008. The methanol to nitrate ratio at the beginning of this phase was 17.10 and decreased to 5.41 by the beginning of April.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Dose rate</th>
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</thead>
<tbody>
<tr>
<td>02/10/08 to 02/12/08</td>
<td>2 lbs/day</td>
</tr>
<tr>
<td>02/13/08 to 02/15/08</td>
<td>1 lb/day</td>
</tr>
<tr>
<td>02/16/08 to 02/18/08</td>
<td>None</td>
</tr>
<tr>
<td>02/19/08 to 02/25/08</td>
<td>2 lbs/day</td>
</tr>
<tr>
<td>02/26/08 to 02/29/08</td>
<td>3 lbs/day</td>
</tr>
<tr>
<td>03/01/08 to 03/04/08</td>
<td>None</td>
</tr>
<tr>
<td>03/05/08 to 03/14/08</td>
<td>3 lbs/day</td>
</tr>
</tbody>
</table>
Issues and Activities Addressed

Issues and activities addressed during IDI’s Seeding and Acclimation Phase included carbon feed in manual mode and backwashing. The following sections describe each issue/activity for the IDI pilot unit during the Seeding and Acclimation Phase.

Carbon Dosing in Manual Mode

From the beginning of piloting to April 5, 2008, IDI dosed carbon to their pilot in manual mode. Problems with the feed pump led to poor system performance and an unobservable decrease in effluent nitrate concentrations. Table 5.40 shows the approximate methanol dosage rates during the Seeding and Acclimation Phase. The carbon feed rate was changed with every flow change that was made.

Backwashing

Backwashing can be initiated in several ways: (1) manually, (2) set-time frequency, or (3) preset differential head loss. The water used for backwashing was effluent stored separately in

Table 5.40
IDI average operating parameters during the Seeding and Acclimation Phase

<table>
<thead>
<tr>
<th>Dates</th>
<th>Average raw water NO3-N (mg/L)</th>
<th>Average effluent NO3-N (mg/L)</th>
<th>Average IDI influent flow rate (gpm)</th>
<th>Filtration rate (gpm/ft²)</th>
<th>CH3OH pump feed rate (mL/min)</th>
<th>Average CH3OH/NO3-N (g/g)</th>
<th>Average CH3OH dose (mg/L)</th>
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<tbody>
<tr>
<td>02/08/08 to</td>
<td>— (2)</td>
<td>—</td>
<td>5.0</td>
<td>6.3</td>
<td>2.00</td>
<td>—</td>
<td>—</td>
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<td>02/13/08</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<td>02/14/08 to</td>
<td>5.8</td>
<td>5.8</td>
<td>4.2</td>
<td>5.3</td>
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<td>— (3)</td>
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<td>02/22/09 to</td>
<td>8.7</td>
<td>6.6</td>
<td>1.9</td>
<td>2.4</td>
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<td>6.92</td>
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<td>02/29/08</td>
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<td></td>
<td></td>
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<tr>
<td>03/04/08(4) to</td>
<td>8.3</td>
<td>6.8</td>
<td>1.1</td>
<td>1.4</td>
<td>0.37</td>
<td>8.66</td>
<td>71.5</td>
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<td>03/10/08</td>
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<td></td>
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<td>03/16/08 to</td>
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<td>03/19/08</td>
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</tr>
<tr>
<td>03/20/08 to</td>
<td>10.1</td>
<td>2.6</td>
<td>2.2</td>
<td>2.8</td>
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</tr>
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<td>03/30/08 to</td>
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<td>2.2</td>
<td>2.8</td>
<td>0.18</td>
<td>1.64</td>
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<td>03/31/08</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>04/02/08(4) to</td>
<td>9.7</td>
<td>0.2</td>
<td>3.6</td>
<td>4.6</td>
<td>0.91</td>
<td>5.41</td>
<td>52.5</td>
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<tr>
<td>4/03/08</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

(1) Feed rate at 100% methanol—no dilution.
(2) ‘—’ means not sampled.
(3) IDI data logger missing DO data.
(4) Missing IDI data from 03/01/08 through 03/03/08 and 03/10/08 through 03/16/08, and 04/01/08 due to data logger issues.
Figure 5.30  IDI NO$_3$-N concentration data during the Seeding and Acclimation Phase

a clean water tank. Backwash wastewater was stored in a separate holding tank and was pumped back to the head of the treatment process over time.

The IDI backwash sequence was automated and required approximately 1 hour of run time. Their sequence consisted primarily of a quick drain to backflush the influent distribution nozzles, an air scour, a series of simultaneous air/water washes, and a water rinse.

IDI originally expected to backwash their pilot unit once every 48 hours. However, during the Seeding and Acclimation Phase, IDI did not backwash their pilot unit. Instead, the backwash frequency was based on head loss, not a time interval. This was done primarily to try to operate the system based on head loss to potentially minimize the volume of backwash waste during full-scale.

Data Results: Plots and Tables—IDI Task 1

Data plots for the IDI NITRAZUR DN® are presented in Figure 5.30 and Figure 5.31. Water quality parameters plotted include nitrate and TOC. Discussions on the City Laboratory data for nitrite, ammonia, phosphate, temperature, color (true and apparent), turbidity, TSS, alkalinity and pH are presented in Task 3. For temperature data, the City collected raw water temperature data.

Nitrate

Figure 5.30 shows the nitrate-nitrogen concentrations for IDI’s pilot unit during the Seeding and Acclimation Phase. Prior to the period of missing data from February 18, 2008 to February 22, 2008, the effluent nitrate concentration had decreased below the pilot goal of ≤2 mg/L NO$_3$-N.
However, shutting down the pilot system increased the effluent nitrate concentration, and consequently, once the system was online February 22, 2008, the effluent nitrate was approximately 11 mg/L NO$_3$-N. IDI shut down their pilot unit for DO probe trouble shooting, screen box cleaning and data logger troubleshooting.

As shown in Figure 5.30, on February 23, 2008 and February 24, 2008, the effluent nitrate concentration fell below 2 mg/L NO$_3$-N due to the influent nitrate concentration decrease that resulted in the effluent nitrate concentration to decrease. Similarly, February 24, 2008 to February 27, 2008, the effluent concentration increased due to the influent concentration increase. The second system shut down was from February 29, 2008 to March 4, 2008. The system shut down for a third time from March 10, 2008 to March 16, 2008 causing the effluent nitrate concentration to increase from 5.5 mg/L NO$_3$-N on March 20, 2008 to approximately 9 mg/L NO$_3$-N by March 16, 2008. Shutting the system down most likely slowed or stopped the acclimation of bacteria to the nitrate in the raw water. The pilot unit was shut down for bacteria injection point installation and column differential pressure detector repair.

**TOC**

The City began taking weekly TOC data on March 5, 2008 and daily as of March 18, 2008. City Laboratory data, excluding the high reading on March 5, 2008, indicated that IDI ‘s effluent TOC concentration increased by as much as approximately 11.0 mg/L across IDI’s pilot unit before IDI began optimizing their methanol dose on April 3, 2008. On average and excluding the high reading on March 5, 2008, the effluent TOC concentration from the NITRAZUR DN$^\text{®}$ unit was 8.5 mg/L with an average influent TOC concentration of 4.2 mg/L during IDI’s Seeding and
Acclimation Phase. Taking into account the 54.7 mg/L TOC reading on March 5, 2008, the average effluent TOC from the NITRAZUR DN® unit was 7.8 mg/L, which resulted in a 2.6 mg/L increase in TOC concentration across the pilot unit.

Figure 5.31 shows the TOC concentrations for IDI’s pilot unit during the Seeding and Acclimation Phase. As shown in this figure, the effluent TOC concentration decreased from 54.7 mg/L to as low as 4.4 mg/L. Throughout this phase, IDI decreased their methanol feed rate as well as increase the influent flow to their pilot unit. Both of these changes most likely caused the effluent TOC concentrations to decrease.

Samples were not collected during IDI’s Seeding and Acclimation Phase for DOC analysis. DOC measurements began May 13, 2008 during IDI’s Carbon Optimization Phase.

**Temperature**

The cold water temperature effects on IDI’s NTIRAZUR DN® were difficult to assess since IDI’s pilot unit shut down three times from February 18, 2008 to March 16, 2008. The pilot unit shutdowns most likely caused the Seeding and Acclimation Phase to be extended to seven weeks. It should be noted that effluent temperatures were not logged during IDI’s Seeding and Acclimation Phase.

**TASK 2: OPERATION AND PERFORMANCE TESTING—IDI**

The goal of this task was to evaluate the performance of the IDI system at maximum production under their recommended operational settings. The performance of the NITRAZUR DN® system was evaluated by quantifying nitrate removal efficiency, nitrate loading rate, carbon feed requirement, etc. Effluent nitrate concentrations of greater than 2 mg/L NO₃-N were considered unacceptable. The operation and maintenance testing for IDI was during the Carbon Optimization and Steady State Phases.

The data collected during this task were used to optimize and monitor the NITRAZUR DN® system and are described below along with data tables and plots. Brief discussions of the settings and operational procedures for the NITRAZUR DN® system are contained in the following sections.

**Task 2a: Carbon Optimization Phase—IDI**

The Carbon Optimization Phase for IDI began April 3, 2008 and ended June 11, 2008. Operational procedures outlined in Chapter 4 were followed throughout this phase. IDI started dosing methanol at a rate of approximately 0.91 mL/min which corresponds to 52 mg/L of 99.9% methanol (5.41 g CH₃OH/g NO₃-N) and operated their system using the manual mode for the methanol feed pump. Hence, IDI dosed at an approximate concentration of 52 mg/L of 99.9% methanol until April 5, 2008 when the switch to the automatic mode was made.

In early April, IDI attempted to operate the methanol feed pump in automatic mode to gain more control of the carbon dose. The IDI automatic control system consisted of a combined feed forward and feed backward control loop that measured the NOₓ-N and DO concentrations in the influent and the NOₓ-N concentration in the effluent of the denitrification bioreactor. Additionally, their automatic system used the inlet water flow rate to calculate the necessary flow rate of the
methanol dosing pump. The system allowed the operator to input a set-point for the effluent nitrate (or NO₃-N) value and modify the range of the CH₃OH/NO₃-Nₑq ratio.

IDI had difficulty getting this control system to operate properly. Therefore, on May 1, 2008, they switched to the manual mode and on May 8, 2008 set the methanol flow rate to 0.4 mL/min. IDI continued to feed methanol at this rate until the end of the Carbon Optimization Phase.

**Operational Settings**

IDI’s average influent flow rate varied between 1.1 and 7.2 gpm (which corresponds to a hydraulic loading of 1.39 to 9.1 gpm/ft²), while IDI was working towards consistent and efficient nitrate removal in the pilot system during the Carbon Optimization Phase. At the beginning of the phase, the flow rate was set approximately at 2.2 gpm (2.77 gpm/ft²) and gradually increased to 7.2 gpm (9.1 gpm/ft²) by March 24, 2008. By the end of May, IDI decreased the flow to approximately 3.2 gpm and then increased the flow to 4.2 gpm at the start of the Steady State Phase.

As stated in the previous section and as shown in Table 5-40, IDI’s carbon feed rate at the beginning of the Carbon Optimization Phase was approximately 0.9 mL/min which corresponds to a methanol dosage rate of approximately 50 mg/L 99.9% methanol (~5.4 g CH₃OH/g NO₃-N). The carbon dose decreased as it was being optimized and by June 11, 2008, the carbon dose was approximately 0.45 mL/min or at a methanol dosage rate of approximately 15 mg/L of 99.9% methanol (~1.4 g CH₃OH/g NO₃-N).

**Issues and Activities Addressed**

Issues and activities addressed during IDI’s Carbon Optimization Phase included flow rate/carbon dose rate, backwashing, phosphorus addition, and aeration tank addition. The following sections describe each issue/activity for the IDI pilot unit during the Carbon Optimization Phase.

**Flow Rate and Carbon Dosing.** Beginning April 7, 2008, the flow increased to 4 gpm (5.1 gpm/ft²) and by May 8, 2008, it had increased to 6.3 gpm (8.0 gpm/ft²). After May 8, 2008, the flow rate changed on a daily basis. These flows remained between 1.8 to 5.0 gpm (or a hydraulic loading rate of 2.3 to 6.3 gpm/ft²). The influent flow rate and methanol-dosing rate continuously changed to find a flow rate that resulted in a consistent and efficient nitrate removal in the pilot system.

Throughout the beginning of May, IDI changed the flow rate frequently, increasing and decreasing the flow rate often when trying to stabilize their process. One of the problems that caused IDI to initially make changes in flow was that their automated carbon feed system did not operate correctly. When IDI switched to a manual feed pump, they experienced multiple failures with the pump resulting in a non-optimized carbon dose. Consequently, IDI’s effluent had high nitrate concentrations (above the pilot goal of ≤2 mg/L NO₃-N) and high TOC concentrations.

Due to the performance in the month of April and early May, the City of Thornton, IDI, and Burns & McDonnell held a conference call on May 13, 2008 to discuss having IDI provide recommendations on operating parameters to use for the Steady State Phase. In a second conference call on May 14, 2008, IDI indicated that the originally-recommended hydraulic loading rate of 4 -12 gpm/ft² was for better suited to wastewater and not drinking water applications. IDI’s staff indicated they had received feedback from their denitrification drinking water facility in France and that the recommended optimal design point for drinking water was closer to 4 gpm/ft². This loading rate was also recommended for the Steady State Phase. IDI indicated that operating the
unit at a higher loading rate (i.e., 8.0 gpm/ft$^2$) caused problems with the existing biomass in the filter column and the overall performance. On May 14, 2008, the hydraulic loading rate was changed to a set point of 4.0 gpm/ft$^2$. However, the influent flow in the pilot unit continued to vary until the beginning of the Steady State Phase on June 11, 2008.

**Backwashing.** Prior to IDI’s Carbon Optimization Phase, they did not backwash their pilot unit. However, from April 3, 2008 to May 14, 2008, they backwashed their unit approximately five times. From May 14, 2008 to the end of piloting, IDI backwashed their unit every 24 hours. The amount of backwashes before May 14, 2008, was less than IDI originally-projected frequency which was one backwash every 24 to 48 hours. However, after May 14, 2008, IDI began performing one backwash every 24 hours. Table 5.41 shows IDI’s backwashing schedule along with the backwashing flow rate and duration during the Carbon Optimization Phase.

**Phosphorus Addition.** In addition to changing the backwashing frequency and flow rate to optimize the pilot unit’s performance, IDI also started adding phosphorus on May 13, 2008. This was an effort to minimize any potential nutrient limiting issues associated with phosphate. The phosphoric pump minimum setting was 0.1 mL/min at a concentration of approximately 7 percent to achieve a phosphorus concentration of approximately 0.5 mg/L PO$_4^{3-}$-P.

**Aeration Tank Addition.** On May 28, 2008, IDI added an aeration tank after their filter unit to potentially minimize any increase in TOC concentrations across their pilot unit before the start of the Steady State Phase. IDI added the aeration tank since they were having difficulty optimizing their carbon dose. It was thought that the aeration tank could be used as an aerobic biological reactor, which may oxidize carbon residuals or act as a stripping tank, by which excess methanol could be potentially stripped from the water.

**Data Results: Plots and Tables—IDI Task 2a**

Data plots for the IDI NITRAZUR DN® system are presented in Figure 5.32, Figure 5.33, Figure 5.36, Figure 5.38 and Figure 5.40 for the Carbon Optimization Phase. Water quality parameters plotted include nitrate and TOC. Discussion regarding DOC has also been provided in this section. Discussions on the City Laboratory data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented in Task 3. For temperature data, the City collected raw water temperature data. Shown in the following figures and tables, IDI effluent represents the effluent sample collected after the filter whereas IDI2 effluent represents the effluent sample collected after the aeration tank.
**Nitrate.** Figure 5.32 shows the nitrate removal for IDI’s Carbon Optimization Phase from April 3, 2008 to June 11, 2008.

As IDI transitioned into the Carbon Optimization Phase, their unit operated below the pilot effluent of 2 mg/L NO₃-N. On April 5, 2008, the methanol feed pump had operational issues, and IDI attempted to remedy this issue. Due to these pump problems, the effluent nitrate concentrations did not decrease and stabilize below the pilot effluent goal of 2 mg/L NO₃-N until May 14, 2008. At the end of IDI’s Carbon Optimization Phase, the effluent nitrate-nitrogen concentrations were below the nitrate goal and remained under 2 mg/L NO₃-N into the Steady State Phase through June 21, 2008.

**TOC.** Results in Figure 5.33 show that IDI’s effluent TOC was greater than the influent TOC during most of the Carbon Optimization Phase. In early April, the feed pump was operated in manual mode. Due to carbon feed pump failure and biofilm clogging of the media triggering the unit to backwash four times on April 4, 2008, the TOC effluent concentrations were greater than the influent concentrations at which time IDI suggested changing to their automated system. Although the TOC concentrations decreased from approximately April 16, 2008 to April 22, 2008, a new pump was needed and on April 22, 2008, IDI switched the methanol feed pump to the automated mode.

From April 22, 2008, the effluent TOC concentrations exceeded the influent TOC, which was attributed to the automated system not operating correctly (i.e., the influent nitrate analyzer on the IDI pilot unit was reading low, therefore, the methanol feed pump was dosing low), and most likely not enough carbon was dosed to the system. The effluent nitrate concentrations were also high at this time. By May 26, 2008, after two conference calls with IDI (refer to the section “Issues and Activities Addressed” above) their system was optimized, and there was a minimal increase in TOC concentrations across the unit by the end of the Carbon Optimization Phase.

During IDI’s Carbon Optimization Phase, the maximum and minimum filter effluent TOC concentrations were 58.6 and 4.3 mg/L, respectively. The average influent TOC concentration was 4.8 mg/L while the average filter effluent TOC concentration was 13.3 mg/L. Although the average filter effluent TOC concentration was 8.5 mg/L greater than the influent, by the end of IDI’s Carbon Optimization Phase, the filter effluent TOC concentrations were approximately 5.0 mg/L with influent concentrations at approximately 4.5 mg/L.

For IDI’s aeration tank average effluent TOC concentrations, sampling did not begin until June 5, 2008. Hence, only seven samples were collected from this unit during IDI’s Carbon Optimization Phase. The average effluent TOC concentration from the aeration tank was 4.9 mg/L with a maximum and minimum TOC concentration of 5.2 and 4.6 mg/L, respectively.

**DOC.** The City Laboratory began collecting samples to measure DOC concentrations during IDI’s Carbon Optimization Phase on May 13, 2008. Samples were collected daily until May 28, 2008. Weekly sampling for DOC measurement began June 3, 2008 and ended June 10, 2008. Table 5.42 shows this data for IDI during the Carbon Optimization Phase.

As shown in Table 5.42, the difference between the TOC and DOC concentrations was not significant. Since the TOC and DOC concentrations were almost identical, DOC samples were not collected during the remaining piloting period. Similar TOC and DOC concentrations indicated that much of the organic matter existed in the dissolved form and not in the form of suspended organic matter.

**Temperature.** Based on the City’s data logger temperature data, the raw water temperature at the beginning of IDI’s Carbon Optimization Phase was approximately 14.5°C. By the end of this
Figure 5.32 IDI NO$_3$-N concentration data during the Carbon Optimization Phase

Figure 5.33 IDI TOC concentration data during the Carbon Optimization Phase
phase, the raw water temperature had increased to 23.5°C. The IDI datalogger did not log effluent temperature data.

**Task 2b: Steady State Phase—IDI**

Immediately following the Carbon Optimization Phase, IDI was required to allow their system to operate without any further modification to process variables. IDI was allowed to indicate what set points (i.e., carbon feed rate, phosphoric acid feed rate, etc.) they wanted to operate their pilot unit at during the Steady State Phase. Once operational modifications were implemented, the NITRAZUR DN® operated at constant influent loading, with no modifications allowed for a minimum of 30 days. However, IDI was allowed to make modifications provided they had a justified reason for making the change and they received written approval by the Owner and Engineer. For IDI, the Steady State Phase began on June 11, 2008 and ended August 3, 2008. Operational procedures outlined in Chapter 4 were followed throughout this phase.

**Operational Settings**

The carbon dose was changed frequently throughout the steady state phase. Table 5.43 presents the operational parameters of the pilot system during the steady state phase. The average, maximum and minimum values for the entire Steady State Phase are also provided.
Issues and Activities Addressed

Issues and activities addressed during IDI’s Steady State Phase included flow rate and backwashing. The following sections describe each issue/activity for the IDI during this phase.

**Flow Rate.** For the Carbon Optimization and Steady State Phases, IDI recommended a loading rate of 4.0 gpm/ft$^2$. Although the flow rate varied during the last month of the Carbon Optimization Phase, the flow rate stabilized approximately at 4.0 gpm/ft$^2$ moving into the Steady State Phase and remained at this rate for the remainder of the phase.

**Backwashing.** As part of IDI’s performance optimization recommendations and recommended operating parameter during the Steady State Phase, they indicated that the backwashing frequency should be adjusted to every 24 hours as previously discussed.

**Data Results**

Data plots for the IDI NITRAZUR DN® system are presented in Figure 5.34, Figure 5.35, Figure 5.37, Figure 5.39 and Figure 5.41 for the Steady State Phase. Water quality parameters plotted include nitrate and TOC. Additionally, City Laboratory data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented in Task 3. For temperature data, the City collected raw water temperature data.

**Nitrate.** Figure 5.34 shows the City Laboratory influent nitrate data and IDI’s data logger effluent nitrate concentrations during the Steady State Phase.

At the end of IDI’s Carbon Optimization Phase, the effluent nitrate concentrations were below the nitrate goal of 2 mg/L NO$_3$-N and remained under this goal into the Steady State Phase. However, after June 21, 2008, the effluent nitrate concentrations increased causing IDI to exceed the pilot goal. This increase was the result of the drifting tendency that was observed for the methanol dosing pump. Pump drawdown tests indicated that the actual methanol flow was in the range of 0.02–0.2 mL/min even if the pump indicated that it was feeding the 0.4 mL/min set value. This lower dosing caused the effluent nitrate concentrations to increase.

From mid July to the end of the Steady State Phase, the effluent nitrate concentrations remained under 2 mg/L NO$_3$-N, with the exception of the nitrate spikes around July 21 and 30, 2008. As explained earlier, the City inadvertently overdosed the influent nitrate causing a spike in the effluent nitrate around July 21, 2008. The nitrate spike on July 30, 2008 was due to worn tub-

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**Table 5.43**

<table>
<thead>
<tr>
<th>Raw water NO$_3$-N (mg/L)</th>
<th>Raw water DO (mg/L)</th>
<th>Effluent NO$_3$-N (mg/L)</th>
<th>IDI influent flow rate (gpm)</th>
<th>CH$_3$OH pump feed rate (mL/min)</th>
<th>CH$_3$OH / NO$_3$-N (g/g)</th>
<th>CH$_3$OH dose (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td>9.87</td>
<td>4.37</td>
<td>0.99</td>
<td>3.62</td>
<td>0.39</td>
<td>1.17</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>12.32</td>
<td>7.00</td>
<td>4.11</td>
<td>4.72</td>
<td>0.45</td>
<td>1.87</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>6.54</td>
<td>1.25</td>
<td>&lt;0.1</td>
<td>2.43</td>
<td>0.29</td>
<td>0.72</td>
</tr>
</tbody>
</table>

(1) Feed rate at 50% methanol dilution.
The average effluent nitrate concentration during the Steady State Phase was 1.76 mg/L NO$_3$-N. Figure 5.35 shows that the carbon dose was optimized before the beginning of the Steady State Phase since the effluent TOC concentration was comparable to the TOC concentration in the influent water. The influent TOC concentration during this phase was approximately 5.0 mg/L. Also shown in Figure 5.35 are two spikes in the effluent TOC concentration that occurred around July 5, 2008 and 11, 2008. Both these spikes were caused by carbon feed pump failures.

**Temperature.** Based on the City’s data logger temperature data, the raw water temperature at the beginning of this phase for IDI was approximately 23.5°C. By the end of this phase, the raw water temperature had increased to 27.0°C. Effluent temperature data was not logged by the IDI datalogger.

**TASK 3: MONITORING AND SAMPLING—IDI**

Monitoring and sampling of the IDI pilot unit system was carried out in accordance with the protocol outlined in Chapter 4. Discussions on the City Laboratory data for nitrite, ammonia, phosphate, color (true and apparent), turbidity, TSS, alkalinity and pH are presented below. Water quality parameters plotted include nitrite, alkalinity and pH.

**Nitrite**

The City Laboratory did not collect samples to measure nitrite concentrations until May 1, 2008. Thus, there is no nitrite discussion for IDI’s Seeding and Acclimation Phase. On May 1,
2008, nitrate samples were collected from the influent and effluent water on a daily basis until the end of piloting on August 28, 2008. However, IDI’s aeration tank was not added to their pilot system until May 28, 2008, and the City Laboratory did not collect samples to measure nitrite in the aeration tank effluent until June 5, 2008. Figure 5.36 shows the nitrite concentrations during IDI’s Carbon Optimization Phase and Table 5.44 shows the average influent and effluent nitrite concentrations for IDI’s Carbon Optimization and Steady State Phases.

As shown in Table 5.44, the average nitrite concentration increased from 0.01 to 0.05 mg/L NO₂-N through the filter during IDI’s Carbon Optimization Phase. This increase was most likely due to the incomplete reduction of nitrate to nitrogen gas that caused nitrite to accumulate in the process. From the filter effluent to the aeration tank effluent, the average nitrite-nitrogen concentration decreased from 0.05 to 0.02 mg/L. However, since limited data was collected from the aeration tank effluent during this time it is difficult to conclude that the nitrite decreased due to the oxidation of nitrite. Since the City Laboratory did not collect samples from the aeration tank effluent until June 5, 2008, the average nitrite concentrations shown in Table 5.44 during IDI’s Carbon Optimization Phase are based on a total of seven samples, four of which were below the nitrite-nitrogen MDL of 0.05 mg/L.

During the Steady State Phase, samples were collected on a daily basis. Figure 5.37 shows the nitrite concentrations for IDI’s pilot unit during the Steady State Phase. As shown in Table 5.44, the average nitrite concentrations across IDI’s pilot unit did not change in the Steady State Phase. Therefore, nitrite accumulation did not occur in IDI’s pilot unit or if nitrite did accumulate in the pilot system, it was most likely oxidized in the aeration tank or during the Steady State Phase.
Ammonia

During IDI’s Seeding and Acclimation Phase, the City Laboratory collected three samples to measure the effluent concentration of ammonia-nitrogen. Sampling began on March 5, 2008 and occurred approximately weekly thereafter until May 6, 2008. After May 6, 2008, the City Laboratory collected two to four samples weekly until June 17, 2008. From July 8, 2008 to July 29, 2008, three more samples were collected approximately every nine days. Table 5.45 shows the average ammonia-nitrogen concentrations for the IDI NITRAZUR DN® pilot unit during the Seeding and Acclimation Phase, Carbon Optimization and Steady State Phases.
Of the three samples collected, the City Laboratory measured the effluent ammonia concentration below the test MDL in two samples while the third sample had a 0.7 mg/L NH$_3$N concentration. Therefore, the average effluent ammonia concentration for during IDI’s Seeding and Acclimation Phase was 0.23 mg/L NH$_3$-N. Since all three influent samples had ammonia concentrations below the MDL of 0.10 mg/L NH$_3$-N, the average influent ammonia-nitrogen concentration during IDI’s Seeding and Acclimation Phase was also below the MDL, which resulted in only one effluent sample having a greater ammonia-nitrogen concentration than the corresponding influent sample.

During IDI’s Carbon Optimization Phase, sampling of the final effluent occurred from April 3, 2008 to May 6, 2008 on a weekly basis. From May 13, 2008 to May 30, 2008, sampling occurred three to four times a week, and two more samples were collected on June 3 and 6, 2008. IDI’s aeration tank was not added to their pilot system until May 28, 2008, and the City Laboratory did not collect samples to measure nitrite in the aeration tank effluent until June 6, 2008. This was the only aeration tank sample collected during this phase.

During IDI’s Carbon Optimization Phase, the maximum filter effluent concentration of ammonia for IDI’s NITRAZUR DN® was 4.8 mg/L NH$_3$-N with a minimum filter effluent concentration below the MDL. An average of 0.04 mg/L NH$_3$-N increase was observed from the feed water to the filter effluent. The average influent ammonia-nitrogen concentration was 0.39 mg/L. Although the ammonia concentration increased from the feed water to the filter effluent, the ammonia-nitrogen concentration decreased from the filter effluent to the aeration tank effluent to a concentration less than the MDL. Most likely, the ammonia was oxidized in the aeration tank.

The City Laboratory collected a total of seven samples from each pilot system to measure the ammonia concentration throughout the Steady State Phase. However, for the aeration tank effluent, only six samples were collected to measure the ammonia concentration.
During the Steady State Phase, the maximum filter effluent concentration of ammonia for IDI’s NITRAZUR DN® was 0.34 mg/L NH₃-N with a minimum filter effluent concentration below the MDL. Additionally, an average of 0.06 mg/L NH₃-N decrease was observed from the feed water to the filter effluent for this phase. From the filter effluent to the aeration tank effluent, the average ammonia concentration increased by 0.02 NH₃-N. The average influent ammonia concentration was 0.15 mg/L NH₃-N resulting in an overall decrease in ammonia concentration of 0.04 from the influent to the final effluent.

### Phosphate

For water to be biologically denitrified, it must contain a certain amount of phosphorus (P) for nutrient uptake and bacterial growth. However, IDI’s carbon source did not contain any phosphorus nor did IDI dose any additional phosphorus during the beginning of this pilot study. Table 5.46 shows the average effluent phosphate concentrations for the IDI NITRAZUR DN® system during the Seeding and Acclimation, Carbon Optimization and Steady State Phases.

Table 5.46 shows that during IDI’s Seeding and Acclimation Phase, the average effluent phosphate concentration was 0.12 mg/L PO₄-P with an average influent concentration of 0.22 mg/L PO₄-P. This decrease was most likely in result of phosphorus nutrient uptake by bacteria. The maximum effluent phosphate concentration during IDI’s Seeding and Acclimation Phase was 0.42 mg/L PO₄-P, and the minimum concentration was less than the MDL of 0.03 mg/L PO₄-P. During this phase, IDI’s effluent phosphate concentration of 0.12 mg/L PO₄-P was less than the City and Burns & McDonnell’s recommended maximum effluent phosphorus concentration of 1 mg/L as P.

On May 13, 2008, IDI began dosing phosphoric acid to their pilot unit. Table 5.46 shows that the phosphate concentration increased by approximately 0.23 mg/L PO₄-P from the feed water to the filter effluent during IDI’s Carbon Optimization Phase. However, the phosphate concentration decreased by 0.10 mg/L PO₄-P from the filter effluent to the aeration tank effluent. The overall increase in phosphate was a result of IDI adding phosphoric acid to their pilot unit. The average increase from the feed water to the final effluent was approximately 0.14 mg/L PO₄-P. During the Carbon Optimization, the average effluent phosphate concentration of 0.43 mg/L PO₄-P was less than the City’s recommended phosphorus concentration of 1 mg/L as P.
Throughout the Steady State Phase, the City Laboratory collected daily samples to measure the phosphate concentrations for IDI’s NITRAZUR DN®. For this phase, Table 5.46 shows that the average influent phosphate concentration was 0.32 PO$_4$-P and that the phosphorus increased by 0.05 mg/L PO$_4$-P from the feed water to the aeration tank effluent resulting in the final effluent phosphate concentration of 0.37 mg/L PO$_4$-P. The increase in phosphate was a result of IDI dosing phosphoric acid to their pilot unit. However, during the Steady State Phase, the average effluent phosphate concentration for IDI was still less than the City’s recommended phosphorus concentration of 1 mg/L.

**Color**

As mentioned previously, on March 19, 2008, the City Laboratory began collecting samples to measure the color in the water from each pilot unit and as of March 26, 2008, turbidity concentrations were measured approximately three times per week. Table 5.47 and Table 5.48 show the average color (true and apparent) for the IDI NITRAZUR DN® pilot unit influent and effluent waters.

For IDI’s Seeding and Acclimation Phase, the City Laboratory analyzed one sample for color. The true color measurement was 42.0 Pt-Co while the apparent color measurement was 5.0 Pt-Co. Hence, this data was not used to evaluate the decrease or increase in color through IDI’s NITRAZUR DN® pilot system.

From IDI’s Carbon Optimization Phase to the Steady State Phase, the final average effluent apparent color decreased from 59.2 to 39.2 Pt-Co units, resulting in a decrease of 20 Pt-Co units. Additionally, the final average effluent true color decreased from 12.3 to 9.0 Pt-Co units, resulting in a decrease of 3.3 Pt-Co units. Decrease in apparent and true color was most likely due to IDI optimizing their carbon feed dose.

As shown in Table 5.47, the average effluent apparent color from IDI’s filter was 59.2 Pt-Co units with an average influent apparent color of 31.2 Pt-Co units during the Carbon Optimization Phase. The maximum and minimum apparent color measurements during IDI’s Carbon Optimization Phase were 232 and 17 Pt-Co units, respectively.

The City Laboratory collected six samples from IDI’s filter effluent during the Steady State Phase. For their aeration tank, the City collected five samples during this time. During this phase, the average effluent apparent color from IDI’s filter was 44.2 Pt-Co units with an average influent apparent color of 35.2 Pt-Co units. However, from the filter effluent to the aeration tank effluent,
the average apparent color decreased to 39.2 Pt-Co units resulting in an overall increase in average apparent color of 4.0 Pt-Co units from the influent to final effluent.

For the true color, the average effluent was 12.3 Pt-Co units with an average influent of 6.5 Pt-Co units during IDI’s Carbon Optimization Phase. The maximum true color measurement during this phase was 48 Pt-Co units while the minimum true color measurement was less than 1 Pt-Co unit.

During IDI’s Steady State Phase, the average true color effluent was 9.0 Pt-Co units when the average influent was 18.6 Pt-Co units. Unlike the apparent color, the true color decrease through the pilot unit with an overall decrease in true color of 9.6 Pt-Co units.

Turbidity

Weekly turbidity measurements were taken by the City Laboratory for three weeks beginning February 21, 2008 and ending March 5, 2008. On March 26, 2008, turbidity concentrations were measured approximately three times per week until the end of piloting. Table 5.49 shows the average influent and effluent turbidity concentrations during IDI’s Seeding and Acclimation, Carbon Optimization, and Steady State Phases.

During IDI’s Seeding and Acclimation Phase, the average effluent turbidity was greater than the average influent turbidity as shown in Table 5.49. Although turbidity increased through
IDI’s NITRAZUR DN®, the average turbidity effluent increased by only 0.6 NTU from an average influent of 1.66 NTU. The NITRAZUR DN®, a dense granular bed filter, not only removes nitrate but removes TSS as well and therefore, keeps the effluent turbidity low.

For IDI, the average filter effluent turbidity was greater than the average influent turbidity during the Carbon Optimization Phase. However, the average aeration tank effluent turbidity was less than the average filter effluent turbidity as shown in Table 5.49. Although turbidity increased from the feed water to the filter effluent during IDI’s Carbon Optimization Phase, the increase was only approximately 0.7 NTU from an average influent turbidity of 2.1 NTU. The decrease from the filter effluent to the aeration tank effluent was from 2.8 to 1.0 NTU.

The City Laboratory collected three to four samples a week to measure turbidity concentrations throughout the Steady State Phase. Similar to the Seeding and Acclimation and Carbon Optimization Phases, the average filter effluent turbidity was greater than the influent turbidity during the Steady State Phase. Additionally during this phase, the average aeration tank effluent turbidity was less than the average filter effluent turbidity, as shown in Table 5.49. An overall increase of 1.0 NTU across IDI’s pilot system was observed during the Steady State Phase. In comparison to IDI’s Carbon Optimization Phase, the average aeration tank effluent increased from 1.0 NTU to 2.9 NTU.

**TSS**

Beginning February 29, 2008, the City Laboratory collected samples to measure the TSS in the effluent from each pilot system. Filter effluent samples were tested approximately weekly until May 19, 2008. However, during IDI’s Carbon Optimization and Steady State Phases, the City Laboratory did not collect samples to measure the effluent TSS concentration for the aeration tank. Table 5.50 shows IDI’s average filter effluent TSS concentration in comparison to the average feed water TSS concentration for the Seeding and Acclimation and Carbon Optimization Phases.

As shown in Table 5.50, the average filter effluent TSS concentration was 3.7 mg/L with an average influent TSS concentration of 0.40 mg/L during IDI’s Seeding and Acclimation Phase. The overall increase in turbidity across the process was 3.3 mg/L.

Also shown in Table 5.50 during IDI’s Carbon Optimization Phase, the average filter effluent TSS concentration was 9.0 mg/L with an average influent TSS concentration of 6.6 mg/L. The overall turbidity increase during this phase was 2.4 mg/L, which is less than the increase during the Seeding and Acclimation Phase.
For the Steady State Phase, the City Laboratory did not collect any samples to measure the TSS concentrations for IDI’s NITRAZUR DN® system.

Alkalinity

Beginning February 21, 2008, the City Laboratory collected weekly samples to measure the alkalinity in the influent and effluent water for each pilot unit. On March 26, 2008, the City Laboratory began collecting three to four samples a week until the end of piloting. In the process of denitrification, nitrate is converted to nitrogen gas utilizing facultative heterotrophic bacteria and this process generates alkalinity in the form of bicarbonate. Table 5.51 shows the average influent and effluent alkalinity concentrations for the NITRAZUR DN® during IDI’s Seeding and Acclimation, Carbon Optimization, and the Steady State Phases.

As shown in Table 5.51, during IDI’s Seeding and Acclimation Phase, the average alkalinity increased by approximately 12 mg/L as CaCO₃ from the influent to the effluent of the reactors. The average influent alkalinity for this phase was approximately 121 mg/L as CaCO₃. The increase in alkalinity was the result of the denitrification process. When denitrification occurs, alkalinity is returned to the process at approximately 3.57 grams of CaCO₃ per gram of NO₃-N reduced.

Similar to the trend during the Seeding and Acclimation Phase, the alkalinity increased across IDI’s pilot unit during the Carbon Optimization Phase. The increase during this phase was approximately by 20 mg/L as CaCO₃, which is larger than the increase observed during the startup phase most likely because the system was removing more nitrate. Hence, higher nitrate removal

### Table 5.50

Average TSS concentrations for IDI’s NITRAZUR DN® during Seeding and Acclimation, and Carbon Optimization Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>IDI effluent</th>
<th>IDI2 effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02/08/08 to 04/30/08</td>
<td>0.4</td>
<td>3.7</td>
<td>—(1)</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>04/03/08 to 06/11/08</td>
<td>6.6</td>
<td>9.0</td>
<td>—</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.

### Table 5.51

Average alkalinity for IDI’s NITRAZUR DN® during Seeding and Acclimation, Carbon Optimization, and the Steady State Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Feed water</th>
<th>IDI effluent</th>
<th>IDI2 effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02/08/08 to 04/30/08</td>
<td>121</td>
<td>133</td>
<td>—(1)</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>04/03/08 to 06/11/08</td>
<td>126</td>
<td>146</td>
<td>155</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06/11/08 to 08/03/08</td>
<td>123</td>
<td>150</td>
<td>148</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.
results in generating more alkalinity. Figure 5.38 shows the alkalinity concentrations for IDI’s pilot unit during the Carbon Optimization Phase.

As shown in Table 5.51, during IDI’s Carbon Optimization Phase, the average alkalinity increased by 29 mg/L as CaCO₃ from the influent to the final effluent. From the influent to the filter effluent, the alkalinity increased by approximately 20 mg/L as CaCO₃, which is approximately 70 percent of the alkalinity increase throughout the entire process. The biological filter removed nitrate while the aeration tank removed TOC. Hence, alkalinity increased more in the filter than in the aeration tank.

Also shown in Table 5.51, during the Steady State Phase, the average alkalinity increased by 25 mg/L as CaCO₃ from the influent to the final effluent, which was similar to the increase in alkalinity during IDI’s Carbon Optimization Phase. Similar increases in alkalinity were observed since approximately 8 mg/L NO₃-N was removed during both phases. Figure 5.39 shows IDI’s alkalinity concentrations during the Steady State Phase.

**pH**

The City Laboratory collected samples to measure the influent and effluent pH for each pilot unit starting February 27, 2008 and continued to collect daily samples for pH measurements for the majority of piloting. Table 5.52 shows the average pH measurements during the Seeding and Acclimation, Carbon Optimization and Steady State Phases for IDI’s pilot unit.

During IDI’s Seeding and Acclimation Phase, the average pH decreased by 0.8 pH units from the influent to the filter effluent. No effluent samples were collected from the aeration tank during this phase since the tank was not added to the pilot until May 2008.
The City Laboratory collected daily samples to measure the pH in IDI’s filter effluent during the Carbon Optimization Phase. However, pH samples were not collected until June 5, 2008 for IDI’s aeration tank effluent. Hence, only four samples were collected during this phase from the aeration tank effluent. Figure 5.40 and Figure 5.41 show IDI’s pH data during the Carbon Optimization Phase and Steady State Phase, respectively.

As shown in Table 5.52, the pH change from the influent to IDI’s reactor effluent was negligible during the Carbon Optimization Phase. Likewise, as shown in Figure 5.41 and Table 5.52, IDI’s pH data during the Steady State Phase for their pilot unit from the feed water to the aeration tank effluent was negligible. Furthermore, the average pH change during the Steady State Phase was unlike the pH change observed from the influent to filter effluent during IDI’s Seeding and Acclimation Phase where the pH decreased through process by more than half a pH unit.

**TASK 4: RESILIENCY TEST PHASE—IDI**

The resiliency test phase was conducted by ‘shocking’ each system with varying influent nitrate concentrations and shutdown of equipment. For IDI, this phase commenced on August 3, 2008 and ended August 28, 2008. There were five main tasks performed during this phase. These tasks include the following:

- Task 4a: Incremental Nitrate Spiking
- Task 4b: Rapid Change Nitrate Spiking
- Task 4c: Influent Nitrate Spiking Shutdown
- Task 4d: Carbon Feed Pump Shutdown
Task 4e: Raw Water Shutdown

The following sections describe each task listed above for the IDI pilot unit along with plots and data from this phase.

Task 4a: Incremental Nitrate Spiking—IDI

Task 4a required IDI to adjust the carbon feed rate to account for the increase in influent nitrate-nitrogen. The first increase was up to 15 mg/L NO₃-N on August 4, 2008 and the second increase up to 20 mg/L NO₃-N on August 8, 2008. Once operational modifications (i.e., changes

Table 5.52
Average pH for IDI’s NITRAZUR DN® during Seeding and Acclimation, Carbon Optimization, and Steady State Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Average pH</th>
<th>Feed water</th>
<th>IDI effluent</th>
<th>IDI2 effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeding and Acclimation Phase</td>
<td></td>
<td>8.6</td>
<td>7.8</td>
<td>___(1)</td>
</tr>
<tr>
<td>02/08/08 to 04/30/08</td>
<td></td>
<td>8.4</td>
<td>8.1</td>
<td>8.4</td>
</tr>
<tr>
<td>Carbon Optimization Phase</td>
<td></td>
<td>8.1</td>
<td>8.1</td>
<td>8.2</td>
</tr>
<tr>
<td>04/03/08 to 06/11/08</td>
<td></td>
<td>8.1</td>
<td>8.1</td>
<td>8.2</td>
</tr>
<tr>
<td>Steady State Phase</td>
<td></td>
<td>8.1</td>
<td>8.1</td>
<td>8.2</td>
</tr>
<tr>
<td>06/11/08 to 08/03/08</td>
<td></td>
<td>8.1</td>
<td>8.1</td>
<td>8.2</td>
</tr>
</tbody>
</table>

(1) ‘—’ means not sampled.

Figure 5.40  IDI pH data during the Carbon Optimization Phase

- Task 4e: Raw Water Shutdown

The following sections describe each task listed above for the IDI pilot unit along with plots and data from this phase.
to the carbon feed rate) were implemented for each increase in the feed water nitrate-nitrogen, the NITRAZUR DN® unit operated at constant influent loading for the remainder of each incremental nitrate spiking period. Operational procedures for the Resiliency Test Phase outlined for the IDI pilot unit continued throughout the phase in accordance with the methods outlined in Chapter 4.

Operational Settings

At the end of the Steady State Phase, IDI was dosing their system with carbon at a feed rate of approximately 0.40 mL/min at 50% methanol concentration which corresponded to a methanol dosage rate of approximately 11.5 mg/L 99.9% methanol (1.1 g CH₃OH/g NO₃-N). Since the influent nitrate-nitrogen concentrations fluctuated throughout this phase, IDI was required to adjust the carbon feed as necessary. The carbon feed rate was adjusted to 0.76 mL/min when the influent nitrate was increased to 15 mg/L NO₃-N and adjusted to 1.03 mL/min when the influent nitrate increased to 20 mg/L NO₃-N. Table 5.53 shows the operational settings during the incremental nitrate spiking.

Task 4b: Rapid Change Nitrate Spiking—IDI

Task 4b required IDI to adjust the carbon feed rate to account for a decrease in influent nitrate from 20 mg/L NO₃-N to 5 mg/L NO₃-N on August 12, 2008. Later on August 16, 2008, the influent nitrate concentration was changed back to 10 mg/L NO₃-N and again IDI was required to adjust the carbon feed rate to their pilot unit.
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Operational Settings

The carbon feed rate was adjusted from 1.03 mL/min to 0.27 mL/min when the influent nitrate was decreased to 5 mg/L NO₃-N and adjusted to 0.51 mL/min when the nitrate increased to 10 mg/L NO₃-N. Table 5.54 shows the corresponding methanol dosage rates during this task.

Task 4c: Influent Nitrate Shutdown—IDI

Task 4c involved shutting down the influent nitrate on August 18, 2008 for 4 hours and again on August 20, 2008 for another 4 hours. During both of these shutdowns, the influent nitrate concentration decreased to approximately 1 to 2 mg/L NO₃-N.

Operational Settings

For Task 4c, there were no operational changes to the NITRAZUR DN® system.

Task 4d: Carbon Feed Pump Shutdown—IDI

During Task 4d, the carbon feed pump was shut down on two occasions. The first shutdown occurred on August 21, 2008 for 4 hours and the other on August 22, 2008 for another 4 hours.

Operational Settings

For Task 4d, there were no operational changes to the NITRAZUR DN® system.

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Table 5.53
IDI methanol dosing during incremental nitrate spiking

<table>
<thead>
<tr>
<th>Date</th>
<th>Average raw water</th>
<th>Average IDI influent flow rate (gpm)</th>
<th>Average CH₃OH / NO₃-N (g/g)</th>
<th>Average 99.9% CH₃OH (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₃-N (mg/L)</td>
<td>DO (mg/L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08/04/08 to 08/08/08</td>
<td>14.9</td>
<td>3.87</td>
<td>1.40</td>
<td>20.9</td>
</tr>
<tr>
<td>08/08/08 to 08/12/08</td>
<td>20.2</td>
<td>3.51</td>
<td>1.57</td>
<td>31.6</td>
</tr>
</tbody>
</table>

Table 5.54
IDI methanol dosing during rapid change nitrate spiking

<table>
<thead>
<tr>
<th>Date</th>
<th>Average raw water</th>
<th>Average IDI influent flow rate (gpm)</th>
<th>Average CH₃OH / NO₃-N (g/g)</th>
<th>Average 99.9% CH₃OH (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₃-N (mg/L)</td>
<td>DO (mg/L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08/08/08 to 08/12/08</td>
<td>20.20</td>
<td>3.51</td>
<td>1.57</td>
<td>31.60</td>
</tr>
<tr>
<td>08/12/08 to 08/16/08</td>
<td>5.10</td>
<td>4.24</td>
<td>1.32</td>
<td>6.70</td>
</tr>
<tr>
<td>08/16/08</td>
<td>8.20</td>
<td>4.51</td>
<td>1.40</td>
<td>11.8</td>
</tr>
</tbody>
</table>
Task 4e: Raw Water Shutdown—IDI

On August 23, 2008, the raw water pump was turned off for 72 hours, during which time the NITRAZUR DN® unit was completely shut down. The unit was started back up on August 26, 2008 and continued to operate until the end of the Resiliency Test Phase and pilot study which ended on August 28, 2008.

Operational Settings

Operational changes for Task 4e included a full shut down of the NITRAZUR DN® pilot unit for 72 hours, after which time the unit was put back online with all equipment in operation.

Issues and Activities Addressed—IDI Task 4

Issues and activities addressed during the Resiliency Test Phase for IDI included only missing data logger information. From August 23, 2008 to August 28, 2008, IDI’s data logger did not collect water quality and hydraulic data. On Saturday, August 23, 2008 the system was shut down for Task 4e for 72 hours.

Data Results: Plots—IDI Task 4

Data plots for the IDI NITRAZUR DN® system are presented in Figure 5.42 and Figure 5.43 for the Resiliency Test Phase. Critical parameters plotted include nitrate and TOC. All other water quality parameters that were evaluated for the first three phases were not evaluated in detail for the Resiliency Test Phase since the pilot units underwent extreme operational changes.

Nitrate

Figure 5.42 shows the effluent nitrate-nitrogen concentrations for IDI during the Resiliency Test Phase where influent nitrate concentrations gradually or rapidly increased to monitor the response of each pilot unit. IDI provided methanol dosing concentrations to account for these changing nitrate concentrations. During this task, IDI’s pilot system performed well in response to the fluctuating influent nitrate concentrations.

When the influent nitrate concentration increased, the effluent nitrate increased above 2 mg/L NO₃-N, however, within 14 hours of the nitrate spike, effluent concentrations decreased and stabilized below 2 mg/L NO₃-N. More specifically, when the influent nitrate concentration was spiked to 15 mg/L NO₃-N, IDI’s effluent nitrate concentration increased above the pilot goal for approximately 4.8 hours, where the max effluent nitrate concentration was 4.8 mg/L NO₃-N during this time.

After the influent nitrate increased to 20 mg/L NO₃-N, the effluent nitrate concentration increased again above the pilot goal for approximately 8.6 hours, and the max effluent nitrate concentration during this spiking period was 3.0 mg/L NO₃-N.

Upon decreasing the influent nitrate concentration to 5 mg/L NO₃-N, IDI’s effluent nitrate concentration decreased below the pilot goal. However, once the influent was spiked back up to 10 mg/L NO₃-N, the effluent nitrate concentration increased to a max of 3.2 mg/L NO₃-N and exceeded the pilot goal for 1.3 hours.
Figure 5.42 IDI NO$_3$-N concentration data during the Resiliency Test Phase
Figure 5.43 IDI TOC concentration data during the Resiliency Test Phase
Once the influent nitrate spiking was shut down (influent nitrate concentrations of approximately 1 to 2 mg/L NO\textsubscript{3}-N), IDI’s effluent nitrate concentration remained below the pilot goal. However, during the carbon feed pump shut off periods, the effluent nitrate concentrations rapidly increased up to approximately 9.4 mg/L NO\textsubscript{3}-N during the first shut off and 9.8 mg/L NO\textsubscript{3}-N during the second pump shut off. Within five hours after the pumps were put back online, the effluent nitrate concentration decreased below the 2 mg/L NO\textsubscript{3}-N pilot goal limit.

**TOC**

Figure 5.43 shows the effluent TOC concentrations during the Resiliency Test Phase. The influent nitrate concentrations increased during this phase, first from 10 mg/L NO\textsubscript{3}-N to 15 mg/L NO\textsubscript{3}-N, 15 mg/L NO\textsubscript{3}-N to 20 mg/L NO\textsubscript{3}-N, and then decreased from 20 mg/L NO\textsubscript{3}-N to 5 mg/L NO\textsubscript{3}-N.

After increasing the influent nitrate to 15 mg/L NO\textsubscript{3}-N, IDI’s effluent TOC increased to approximately 8 mg/L, and when running at 20 mg/L NO\textsubscript{3}-N influent, the effluent TOC concentration increased above 24 mg/L. However, when the influent nitrate was decreased to 5 mg/L NO\textsubscript{3}-N, the TOC decreased to below 6 mg/L NO\textsubscript{3}-N. When the effluent TOC concentration increased to 24 mg/L, this reading could have been an outlier or a result of the carbon being overdosed.

When the influent nitrate was shut down and the carbon pump was still operating, the effluent TOC concentrations spiked, since without nitrate and changing the carbon feed rate, an overfeeding of carbon would occur. Aside from these events, the change in TOC concentration was negligible during the Resiliency Test Phase for IDI’s pilot unit since the effluent TOC concentration was similar to the influent TOC concentration.

**TASK 5: COLUMN TESTING (NOT APPLICABLE)—IDI**

**TASK 6: QUALITY ASSURANCE AND QUALITY CONTROL—IDI**

QA/QC procedures were conducted throughout the pilot study to ensure accuracy of data. The protocol outlined in Chapter 4 was strictly followed. No quality control issues were identified relative to the IDI system.

**ADDITIONAL TESTING**

As part of this study, additional testing was conducted on the raw water and the effluent from all three pilot processes. These additional tests include measuring the disinfection byproduct formation potential and chlorophyll-a concentrations. The test results are presented below.

**Disinfection Byproduct Formation Potential Test**

As part of this study, the City of Thornton sampled both raw water and pilot unit effluent for disinfection byproduct formation potential (on June 5, 2008). This test would check if the carbon source (i.e., methanol) that was added contributed to an increase in disinfection byproduct formation potential.

Disinfection byproduct formation potential sampling was limited but as presented in Table 5.55, samples taken and tested during the Carbon Optimization Phase showed that the total...
trihalomethane (TTHM) formation potential did not vary significantly between manufacturers and the raw water.

**Algal Biomass**

During the Resiliency Test Phase, the City of Thornton put both raw water and pilot unit effluent in bottles and submerged these bottles in the reservoir to simulate the effluent being discharged into the reservoir. This approach had been previously used by the City in studies to determine chlorophyll concentrations.

The bottles were submerged for a total duration of three weeks. The first two weeks, the bottles were submerged at approximately 4 feet below the water surface and at 1 foot below the water surface for the last week. At the end of this period, the bottles were collected and measured for chlorophyll-a. Chlorophyll-a was chosen since it is easier and more cost effective to measure than various other species of algae. Chlorophyll-a is a green pigment used by plants in photosynthesis and provides a reasonable estimate of algal biomass.

Table 5.56 presents the pilot results for chlorophyll-a testing for the raw water, feed water and each manufacturer.

Table 5.56 shows that all three manufacturers were below the BNR feed water chlorophyll-a concentrations. In addition, a sniff test for odor was conducted on these samples placed in the reservoir. The raw water had the highest odor over the three pilot effluent samples which indicated that no potential concerns existed regarding potential odor concerns related to biomass in the effluent.
SUMMARY

This chapter summarizes the piloting tasks and presents results for all manufacturers. Six major tasks were completed to evaluate the BNR systems. The tasks completed include the following:

- **Task 1: BNR System Startup**
  - Seeding and Acclimation Phase
- **Task 2: Operation and Performance Testing**
  - Carbon Dose Optimization Phase (Task 2a)
  - Steady State Phase (Task 2b)
  - Backwash Optimization Phase (Applicable for GE Water & Technologies ABMet® Only)
  - Solids Wasting Rate Optimization Phase (Applicable for AnoxKaldnes Only)
- **Task 3: Monitoring and Sampling**
  - Data Logging
  - Manual Data Collection
  - Water Quality Sampling and Analysis
- **Task 4: Resiliency Test Phase**
  - Incremental Nitrate Spiking (Task 4a)
  - Rapid Change Nitrate Spiking (Task 4b)
  - Influent Nitrate Spiking Shutdown (Task 4c)
  - Carbon Feed Pump Shutdown (Task 4d)
  - Raw Water Shutdown (Task 4e)
- **Task 5: Column Testing (Applicable for GE Water & Technologies ABMet® Only)**
- **Task 6: Quality Assurance and Quality Control**

**Task 1: System Start-up**

The goal of this task was to evaluate the performance of the three systems during seeding and startup. Startup during cold temperature months was a key operational ability for the systems’ geographic location.

For the entirety of the pilot study, both AnoxKaldnes and IDI used methanol as their external carbon source. For the GE Water & Process Technologies process, a proprietary molasses mixture was used in the beginning of the pilot study. Once the molasses mixture was optimized, methanol was used as the electron donor. On May 20, 2008, GE began the gradual switch to methanol as the carbon source, and by April 1, 2008, GE was using a only methanol.
Carbon Source

Both molasses (for the GE ABMet® pilot system only) and methanol (for all three pilot systems) were tested. Pilot results showed that for a drinking water application, careful selection of an appropriate carbon source is important. Molasses was problematic at the Wes Brown WTP, and most likely for use in any drinking water treatment application since the BNR effluent had a yellowish color and gave off an odor.

Seeding and Acclimation Phase

This task began immediately following the startup phase of this pilot test. The startup was considered completed when the system began to denitrify and achieved effluent nitrate concentrations of ≤ 2 mg/L NO₃-N with 10 mg/L NO₃-N or greater of influent nitrate concentration.

GE and IDI were the two manufacturers that seeded their pilot units. Although the project team strongly suggested that all manufacturers seed, AnoxKaldnes decided not to seed. Their rationale behind not seeding is described in their detailed results found in Chapter 5.

The acclimation period for AnoxKaldnes began on Friday, February 8, 2008. AnoxKaldnes reached the pilot effluent goal of 2 mg/L NO₃-N on April 29, 2008, resulting in an acclimation period of 11 weeks. During the Seeding and Acclimation Phase, AnoxKaldnes experienced difficulty with the methanol feed pump. These pump problems in addition to not seeding, most likely led to the 11-week acclimation period.

The Seeding and Acclimation Phase for GE started Tuesday, February 12, 2008. The pilot goal of 2 mg/L NO₃-N effluent was achieved in approximately nine days on February 21, 2008. GE seeded their pilot unit utilizing their proprietary culture consisting of biomass which was acclimated to the utilized carbon source (proprietary molasses). Seeding the pilot unit was the most likely cause for GE’s system to denitrify below the goal of 2 mg/L NO₃-N in little over a week.

On Wednesday, February 6, 2008, IDI began the startup of their pilot unit. IDI began dosing the system with methanol on Friday, February 8, 2008, and on Saturday, February 9, 2008, the pilot unit was seeded with dry MB17 bacteria. Their pilot unit did not show consistent evidence of nitrate reduction until March 25, 2008 which resulted in a seven-week Seeding and Acclimation Phase. Though IDI experienced three system shutdowns during this phase, only two of the shutdowns most likely contributed to the seeding and acclimation period lasting seven weeks.

Task 2: Operation and Performance Testing

The goal of this task was to evaluate the performance of each system at maximum production under manufacturer’s recommended backwash frequency (if applicable for the process). The performance of each system was determined by quantifying hydraulic loading rate, nitrate removal efficiency, nitrate loading rate, required backwash frequency, and/or solids wasting rate.

Effluent nitrate concentrations of greater than 2 mg/L NO₃-N were considered unacceptable. A brief discussion of the settings and operational procedures for each BNR system is presented in the following sections along with data and issues addressed during each phase.
Carbon Optimization Phase

The Carbon Optimization Phase was implemented and starting date and duration varied per manufacturer. The goal was to optimize the carbon dose so that a zero net increase in TOC from the raw water to the effluent was observed. Once the seeding and acclimation period was completed, the carbon source dosing was modified by the manufacturers in order to maximize performance. Since GE used a different carbon source (molasses) than the other two manufacturers in the initial months of this study, GE switched over to methanol once the molasses was optimized.

**TOC Optimization.** When implementing the three biological processes in a drinking water application, one of the key concerns is to not increase the TOC levels across the units since TOC is a precursor for disinfection byproducts. Figure 6.1 shows the effluent TOC before carbon feed optimization in relation to the raw water TOC concentration.

As seen in Figure 6.1, the effluent TOC concentrations from all three pilot units were significantly higher than the raw water reservoir influent TOC concentration. Due to these initial results, a carbon feed optimization phase was implemented during piloting for all three manufacturers. Figure 6.2 shows the effluent TOC concentrations for all three biological processes after carbon optimization in relation to the influent TOC concentration. Note that the effluent TOC concentrations from the pilot units closely follow the influent TOC levels, indicating minimal increases in TOC levels across the three units.

Immediately following their acclimation period, AnoxKaldnes optimized their carbon dose beginning April 30, 2008 and ending June 11, 2008. Throughout most of the Carbon Optimization Phase, AnoxKaldnes did not denitrify below the goal of 2 mg/L NO₃-N. As the carbon dose was optimized, their effluent nitrate concentrations decreased and stabilized below 2 mg/L NO₃-N beginning June 5, 2008. Additionally, during this phase, as the carbon dose was optimized, the effluent TOC concentrations were no more than 0.5 mg/L higher than the influent TOC levels.

GE optimized their molasses and methanol carbon dose from April 3, 2008 to June 11, 2008. During the majority of this phase, GE’s pilot unit denitrified below the pilot goal of 2 mg/L NO₃-N. Even though GE was denitrifying below the effluent goal, their effluent TOC concentrations were much greater than the influent TOC during most of April. GE began optimizing their molasses carbon source dose on April 3, 2008 and towards the end of April, the effluent TOC levels were only slightly higher than the influent TOC concentration. By May 19, 2008, they switched to dosing methanol to their pilot unit, and the effluent TOC concentration began to increase. However, GE’s methanol dose was optimized by June 11, 2008, and effluent TOC levels decreased near the influent TOC concentrations during the Steady State Phase.

Similar to GE, IDI optimized their carbon dose from April 3, 2008 to June 11, 2008. Prior to this phase, IDI was already denitrifying below 2 mg/L NO₃-N. However, the effluent nitrate levels exceeded the goal on April 5, 2008 due to carbon feed pump difficulties, and effluent nitrate levels did not fall below the piloting goal until May 14, 2008. IDI had two one-week intervals where no data logger information was available - one from April 29 to May 6, 2008 and another from May 8 to May 16, 2008. A week later, IDI collected incorrect data logger information from May 21 to May 30, 2008. However, City Laboratory data showed that their system was denitrifying to below the effluent goal on May 14, 2008.

AnoxKaldnes started the Carbon Optimization Period approximately four weeks later than GE and IDI. As previously discussed, the start-up period for AnoxKaldnes was longer than the start-up period for GE and IDI. AnoxKaldnes’ Seeding and Acclimation Phase lasted for 11 weeks.
Figure 6.1 TOC concentrations for all three manufacturers before carbon optimization

Figure 6.2 TOC concentrations for all three manufacturers after carbon optimization
Chapter 6: Summary and Conclusions

Steady State Phase

After each manufacturer’s Carbon Optimization Phase ended, the manufacturers were required to allow their systems to operate without any further modification to process variables. The manufacturers were allowed to indicate what set points (i.e., hydraulic loading rate, backwashing frequency, carbon feed rate, phosphoric acid feed rate, etc.) they wanted to operate their systems at during the Steady State Phase. This phase of piloting did not vary per manufacturer. All three manufacturers were required to have their pilot system optimized by June 11, 2008 in order to operate their unit for a minimum of 30 days without any adjustments. The Steady State Phase for all manufacturers formally began on June 11, 2008 and ended on August 3, 2008. A brief summary of each system’s performance is provided below.

Steady State Design Parameters. Table 6.1 shows a summary of the design parameters that were used during the Steady State Phase by each manufacturer. These parameters will likely be close to the design parameters used for full-scale design and include the influent nitrate concentration, influent DO concentration, influent temperature, methanol to nitrate ratio, loading rate, hydraulic retention time, concentration of methanol per liter of water treated, and effluent nitrate concentration. During the Steady State Phase, the average influent nitrate concentration was 9.87 mg/L NO₃-N, and the average DO concentration was 4.37 mg/L.

Nitrate Removal. On average, all three systems had nitrate removal efficiencies between 88 to 90 percent during the Steady State Phase. Overall, all three pilot manufacturers were successful in meeting the pilot goal for nitrate removal (≤ 2 mg/L NO₃-N) and study expectations. Figure 6.3 shows nitrate removal below the pilot goal of 2 mg/L NO₃-N for all three manufacturers during the Steady State Phase. Note that the City’s spiking of influent nitrate was increased for a short duration of time and that AnoxKaldnes and IDI units effluent nitrate concentrations increased above the pilot goal but was below this goal within 6 hours. GE’s pilot unit remained under 2 mg/L NO₃-N during the City influent nitrate spike.

For the majority of the Steady State Phase, AnoxKaldnes was denitrifying below 2 mg/L NO₃-N. Furthermore, the effluent TOC levels were no more than approximately 0.5 mg/L higher than the incoming TOC levels.

Table 6.1
Average Steady State Phase design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AnoxKaldnes</th>
<th>GE</th>
<th>IDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent nitrate NO₃-N (mg/L)</td>
<td>9.87</td>
<td>9.87</td>
<td>9.87</td>
</tr>
<tr>
<td>Influent DO (mg/L)</td>
<td>4.37</td>
<td>4.37</td>
<td>4.37</td>
</tr>
<tr>
<td>Influent temperature (°C)</td>
<td>23.8</td>
<td>23.8</td>
<td>23.8</td>
</tr>
<tr>
<td>HRT</td>
<td>~1.7 hr (anoxic)</td>
<td>~ 1 hr</td>
<td>~ 0.8 hr (aerobic)</td>
</tr>
<tr>
<td></td>
<td>~0.8 hr (aerobic)</td>
<td>~ 20 min(1)</td>
<td></td>
</tr>
<tr>
<td>Hydraulic loading rate (gpm/ft²)</td>
<td></td>
<td>-</td>
<td>~ 4.4</td>
</tr>
<tr>
<td>g CH₃OH/g NO₃-N</td>
<td>5.04</td>
<td>1.75</td>
<td>1.17</td>
</tr>
<tr>
<td>mg CH₃OH/L water treated</td>
<td>49.3</td>
<td>17.1</td>
<td>11.4</td>
</tr>
<tr>
<td>Effluent NO₃-N (mg/L)</td>
<td>1.07</td>
<td>1.15</td>
<td>0.99</td>
</tr>
<tr>
<td>% Nitrate removal</td>
<td>89</td>
<td>88</td>
<td>90</td>
</tr>
</tbody>
</table>

(1) Based on 1 foot diameter filter column and 12.13 foot water height with 9.5 feet media height.

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Figure 6.3  NO₃-N removal for all three manufacturers during the Steady State Phase
Based on their data logger information during the Steady State Phase, GE’s pilot system performed well resulting in no events causing the effluent nitrate to exceed the nitrate goal. Throughout this phase GE’s effluent TOC remained close to the influent TOC except on July 4, 2008, when a sudden extreme increase in TOC was observed. This increase was most likely due to gas bubbles being released and consequently spiking the nutrient levels.

For IDI, effluent nitrate levels remained under 2 mg/L NO₃-N for majority of the Steady State Phase. The times the effluent nitrate levels exceeded 2 mg/L NO₃-N were a result of mechanical equipment difficulties and the City inadvertently overdosing the influent nitrate concentration.

**Task 3: Monitoring and Sampling**

Water quality data collected throughout piloting can be found in more detail in Chapter 5.

**Task 4: Resiliency Test Phase**

Beginning August 4, 2008 and ending August 28, 2008, all pilot systems underwent varying changes in influent nitrate levels and/or carbon doses. These tests were performed to observe each system’s response. During full-scale operation, situations such as carbon feed pump failure could occur and knowing how these systems will respond is important. The following tasks were performed during the final stage of piloting and were applied equally to all pilot units:

- Task 4a: Incremental nitrate spiking
- Task 4b: Rapid change nitrate spiking
- Task 4c: Influent nitrate spiking shutdown
- Task 4d: Carbon feed pump shutdown
- Task 4e: Raw water shutdown

Each task is described in the following sections.

**Task 4a: Incremental Nitrate Spiking**

Starting on Monday, August 4, 2008, the influent nitrate concentration was increased from 10 mg/L NO₃-N to 15 mg/L NO₃-N and then on Friday, August 8, 2008, the raw water nitrate concentration increased from 15 mg/L NO₃-N to 20 mg/L NO₃-N. The pilot units operated with a raw water concentration of 20 mg/L NO₃-N until Monday, August 11, 2008.

The goal of this task was for each of the three pilot units to achieve the lowest effluent nitrate concentration possible during this incremental nitrate spiking period. All pilot units responded well to the incremental nitrate spikes during this task. Increases in effluent nitrate levels were observed immediately after spiking the raw water line. Shortly after the effluent nitrate levels exceeded the goal of 2 mg/L NO₃-N, the pilot systems began to denitrify below the limit within a few hours except for AnoxKaldnes’ pilot unit during the 20 mg/L nitrate-nitrogen spike.

When the raw influent nitrate levels were increased to 20 mg/L NO₃-N, the effluent concentration from AnoxKaldnes’ pilot unit exceeded the pilot goal of 2 mg/L and remained above 2 mg/L for approximately four days. This was due to a failure in their methanol feed pump. The effluent nitrate levels fell below the goal shortly after the pump was put back online. The influent nitrate was decreased to 5 mg/L NO₃-N at the beginning of the second task of the final stage of piloting.
Task 4b and 4c: Rapid Change in Nitrate Spiking/Influent Nitrate Spiking Shutdown

The goal of this task was to test how each process handles a major swing in influent nitrate concentration. Another goal was for each of the three pilot units to achieve the lowest effluent nitrate concentrations possible during this Resiliency Test Phase.

The manufacturer was permitted to optimize their system to the influent conditions during the two days after changing the influent nitrate concentration. If more adjustments were needed by the manufacturer, they must have been approved by the City and Burns & McDonnell prior to making any changes.

Task 4d: Carbon Feed Pump Shutdown

Task 4d began on August 21, 2008 with the first four-hour shutdown of the carbon feed pumps. On August 22, the carbon feed pumps were shut down for another four hours. During this task, the influent nitrate concentration was kept at 10 mg/L NO$_3$-N. The goal of this task was to observe each system’s response to a sudden change in carbon dosing. The shutdown time of four hours was selected because this time duration is likely the longest power outage the City of Thornton would experience during a full-scale application.

For AnoxKaldnes, the carbon feed shutdowns resulted in their effluent nitrate concentrations increasing to approximately 8 mg/L NO$_3$-N. After both shutdowns, the carbon feed pump was restarted, and within a few hours the system was denitrifying below 2 mg/L NO$_3$-N. The effluent TOC concentrations remained close to the influent TOC levels during this task.

Similar to AnoxKaldnes, the effluent nitrate levels from IDI’s pilot unit also exceeded the 2 mg/L NO$_3$-N limit after shutting down the pumps. Both times, the effluent nitrate concentration increased to approximately 9.5 mg/L NO$_3$-N. However, the system began denitrifying quickly after the carbon feed pump was put back online. The effluent TOC concentrations remained close to the influent TOC concentrations.

Unlike AnoxKaldnes and IDI, the effluent from GE’s pilot system did not increase above 2 mg/L NO$_3$-N when the carbon feed pump was shut down. Additionally, their effluent TOC levels were below the influent TOC concentrations during this task.

Task 4e: Raw Water Shutdown

The last task of the Resiliency Test Phase consisted of a shutdown and startup of all pilot units to observe each system’s response. The purpose of shutting down the system completely was to simulate a total power failure which may occur during full-scale operation. Therefore, under this task, a total shutdown of all equipment on the pilot units (i.e., carbon feed pumps, blowers, mixers, etc.) was necessary. On Saturday, August 23, 2008, the raw water pump to the pilot units was turned off, and each unit was completely shut down for 72 hours and started operation again on Tuesday, August 26, 2008.

Overall System Response. Figure 6.4 shows the nitrate concentrations for all three manufacturers during the Resiliency Test Phase. This figure also illustrates how well the systems responded during nitrate spikes. AnoxKaldnes had an unexpected methanol feed pump failure from approximately August 9, 2008 to August 14, 2008, which caused their nitrate concentrations to be above the pilot goal of ≤ 2 mg/L NO$_3$-N during this time. AnoxKaldnes and IDI’s effluent nitrate concentrations increased during the two carbon feed shutdowns, GE’s effluent nitrate concentrations did
Figure 6.4 NO₃-N concentrations for all three manufacturers during the Resiliency Test Phase
not increase rapidly but remained constant. One possible explanation may be that the GAC media in the GE system has a higher surface area and/or higher population of biomass.

**Task 5: Column Testing**

GE Water & Process Technologies ABMet® performed a column test to simulate field conditions (i.e., HRT and loading rate) to determine GAC breakthrough. The results of the column test are presented in Chapter 5.

**Task 6: Quality Assurance and Quality Control**

No significant quality assurance issues were identified throughout the pilot for each manufacturer. QA/QC was maintained throughout the pilot study as outlined below and any potential issues or concerns were resolved as outlined and addressed in Chapter 5 of this report.

- Operational logs were maintained for each pilot system to include all operational changes such as carbon dose, backwashing interval, etc.
- Equipment, pipes, tubing, and instrumentation were visually inspected on a daily basis. Any issues were immediately noted and all data/samples were evaluated accordingly and removed from the analysis where appropriate.
- Calibration of field and laboratory equipment was verified by appropriate laboratory methods (i.e., pH, temperature, turbidity, DO, and nitrate). All equipment was verified at a minimum of once per month or once per week, depending on the City Laboratory requirements. The only calibration issues occurred at the beginning of the pilot during startup as outlined in this report. These issues where quickly resolved and did not affect the results or analysis of the study.
- Data was collected manually and compared to data logged values on a weekly basis to ensure accuracy of the data logging equipment. Data was compiled and analyzed in a timely manner to identify any potential QA/QC issues.
- Water quality samples were collected and logged by the City of Thornton’s Laboratory staff. The City Laboratory is certified by the State of Colorado Department of Public Health and Environment as being in compliance with the criteria and procedures of the EPA Manual for the Certification of Laboratories Analyzing Drinking Water for nitrate, nitrite, fluoride, TOC, and DOC. The City Laboratory conducted all sampling and analysis in accordance with approved standard operating procedures (SOPs) or standard test methods. No QA/QC issues or concerns were identified.

**CONCLUSIONS**

The overall goal of this research was to demonstrate and evaluate the feasibility of utilizing biological processes to remove nitrate from a surface water supply to a drinking water treatment plant. This goal was achieved along with the specific objectives of the research including: (1) assessment the performance of biological treatment processes for a nitrate contaminated surface water for a drinking water application; (2) verification of the appropriate quantities of substrate addition; and (3) evaluation and determination of design and operational criteria required to achieve the desired performance.
The results from this pilot study show that biological processes are a viable method for removing nitrate in drinking water applications. All piloted systems performed well with respect to the effluent water quality achieved from their units based on the established water quality goals of this research.

The following conclusions can be drawn from the pilot testing:

- **Nitrate Removal Performance:** All three biological processes exhibited the ability to exceed the pilot goal for nitrate removal from 10 mg/L NO₃-N to ≤ 2 mg/L NO₃-N during both cold and warm temperatures. The average nitrate removal percentages observed after optimization and during the Steady State Phase (average temperature of 23.8°C) ranged from 88 percent to 90 percent.

- **Seeding:** Seeding is an effective method of accelerating denitrification during start-up in cold temperatures. The systems that were seeded included GE and IDI, which were successfully denitrifying in one and seven weeks, respectively. The AnoxKaldnes system was not seeded and required eleven weeks to achieve the effluent nitrate concentration goal.

- **Carbon Dose Optimization:** For drinking water applications, carbon dose optimization is essential to avoid or minimize increases in TOC concentrations through the biological process. During the study, it became evident that carbon overdosing can result in a substantial increase in effluent TOC concentrations. In response to this observation, an extended carbon dose optimization phase was implemented. Following the optimization, the net increases in TOC were typically less than 1 mg/L in the effluent. While the goal of zero net increase in TOC was not achieved, the piloting results indicate that carbon dose can be optimized and controlled to provide acceptable levels of effluent TOC. A correlation between carbon dose and pH in the effluent was also observed. It is theorized that a reduction in carbon addition results in the bacteria producing less organic acid which in turn results in an increase in pH. Comparison of TOC and pH trends indicates that when excess carbon is dosed the pH decreases. However, in instances where an increase in pH was observed, no increase in effluent TOC was present.

- **Actual Carbon Dose vs. Calculated Carbon Dose:** During this study, it was noted that the actual required carbon dose did not necessarily correspond directly with the calculated dose based on stoichiometry. This is most likely due to the hydraulics within each system and potential variations in DO once the raw water was introduced to each pilot system. Carbon feed concentrations varied substantially among manufacturers. During the Steady State Phase, AnoxKaldnes dosed at a methanol to nitrate-nitrogen ratio of 5.04 g CH₃OH/g NO₃-N with GE and IDI’s ratios being 1.75 g CH₃OH/g NO₃-N and 1.17 g CH₃OH/g NO₃-N, respectively. The fact that the packed bed filters require a lower carbon dose than the moving bed bioreactor is attributed to the configuration as the filters most closely resemble plug flow. Based on discussions with the manufacturers, the doses observed during this study are consistent with expected doses and those observed at operational denitrification facilities.

- **Selection of Carbon Source:** While this study did not involve testing and comparison of carbon sources, the research did provide some information that is useful in the selection of carbon sources. The GE pilot system was originally started using molasses as the carbon source based on experience at non-potable installations and
recommendations from the manufacturer. While the molasses allowed the system to perform satisfactorily with regard to nitrate removal, the carbon source was changed to methanol after the City’s Laboratory staff discovered potential color and odor concerns. It is not known if the color and odor concerns are specific to the raw water tested or if this would be a concern at any drinking water facility. However, this observation highlights the need to carefully select (and potentially test) a carbon source prior to implementation in a drinking water application.

- **Sensitivity:** Based on the results documented during the Resiliency Test Phase, the GAC media used in the GE system was less sensitive to changes in carbon dose than other media tested. This is believed to be due to the adsorption capacity of the GAC. The data also indicates that after a carbon feed pump is shut-down and brought back online, all three systems responded quickly. Upon shutting down the pumps for four hours, the effluent nitrate concentration would increase above 2 mg/L NO₃-N for AnoxKaldnes and IDI, whereas effluent nitrate levels did not exceed 2 mg/L NO₃-N for GE due to the adsorption capacity of the GAC media. Once the carbon feed pumps were back online, AnoxKaldnes and IDI’s effluent nitrate-nitrogen concentration decreased below the pilot goal within 8.5 and 5.2 hours, respectively.

- **Phosphorus Addition:** Phosphorus may need to be added, if it is a limiting nutrient in the raw water supply. During the pilot study, raw water phosphorus concentrations were low and the addition of phosphorus improved the ability to denitrify. This confirmed that low levels of phosphorus can limit growth of the denitrifying bacteria and adversely affect the performance of the biological processes. The addition of phosphorus should be optimized to avoid an increase in the effluent concentration.
CHAPTER 7
RECOMMENDATIONS

Results presented in this report are based on a seven-month pilot study with varying environmental and water quality conditions. For full-scale implementation of these biological processes as pretreatment in a drinking water application, it is recommended that:

• Process controls for carbon dose be based on real-time feedback of nitrate and TOC concentrations and be implemented to automatically adjust and optimize the carbon dose. As discussed in the conclusions, this optimization is essential to prevent net increases in TOC.
• Seeding be evaluated based on the need for intermittent operation or startup during cold temperatures. While seeding is an effective method in accelerating the startup of biological processes, it is most likely only necessary at colder temperatures. Designing a system for startup during warmer temperatures is preferred.
• Phosphorus levels in the raw water be evaluated to determine if it is a potential growth-limiting nutrient. A phosphoric acid feed system should be incorporated into the full-scale design in the event that low phosphorus concentrations occur.

While the objectives of this research were achieved, several areas of study were identified where more information would be beneficial in characterizing the use of biological denitrification processes for drinking water facilities:

• Conduct an additional extended-term pilot study over several cold and warm temperature seasons to allow for further investigation of the effects of temperature and other variables on the biological processes over a longer term. Specifically, conducting a Steady State Phase over a cold season would provide useful data relative to the long term operation at colder temperatures.
• Conduct a bench-scale analysis of different carbon sources and their applicability for drinking water applications. Specifically, investigation of any issues related to color and odor as was experienced with molasses in this study.
• Investigate biomass concentrations for the three biological processes. Since the hydraulic retention times (HRTs) and media are very different among the various processes, it would be useful as future research to measure biomass concentrations per unit volume of media for each of the biological processes.
• Conduct additional research to determine the variables contributing to the difference between the actual and calculated (stoichiometric) carbon dose as discussed in this report.
REFERENCES


SUGGESTED READING


ABBREVIATIONS

AF   acre-feet
BNR  biological nitrate removal
BOD  biochemical oxygen demand
°C   degrees Celsius
COD  chemical oxygen demand
DO   dissolved oxygen
DOC  dissolved organic carbon
EBCT empty bed contact time
ft²  square feet
ft³  cubic feet
GAC  granular activated carbon
g/L  grams per liter
gpd  gallons per day
gpm  gallons per minute
HLR  hydraulic loading rate
HRT  hydraulic retention time
MBBR™ moving bed biofilm reactor
MCL  method detection limit
MGD  million gallons per day
mg/L milligrams per liter
mL/min milliliters per minute
mm  millimeter
μg/L micrograms per liter
O&M  operation and maintenance
ORP  oxidation-reduction potential
QA/QC quality assurance/quality control
RO   reverse osmosis
<table>
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<tr>
<td>scfm</td>
<td>standard cubic feet per minute</td>
</tr>
<tr>
<td>SOP</td>
<td>standard operating procedure</td>
</tr>
<tr>
<td>SUVA</td>
<td>specific ultraviolet adsorption at 254 nanometers</td>
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<td>total nitrogen</td>
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<td>TOC</td>
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</tr>
<tr>
<td>WWTP</td>
<td>wastewater treatment plant</td>
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The following organization contributed financially to this Tailored Collaboration project:

- City of Thornton