Advancing Ozone Optimization During Pre-Design, Design and Operation

Advancing Ozone Optimization During Pre-Design, Design and Operation

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REPORT SUMMARY

This report focuses on ways to optimize ozonation systems used to treat water and wastewater. Specifically, the study concentrates on minimizing operating and capital costs while maximizing benefits.

Background

Over the past two decades, the use of ozone in North America has increased by a factor of 25. Ozone is used in the treatment of water and wastewater to enhance disinfection, to improve the color, taste, and odor of drinking water, to reduce levels of disinfection byproducts, and to help with the oxidization or removal of organics, inorganic compounds, and particles. Many ozonation systems, however, are not operating as efficiently or as effectively as they could be.

Objective

The goal of this report is to help utility representatives and their water and wastewater customers understand some of the ways they can optimize their existing or future ozone water treatment systems.

Approach

This study was conducted in three stages. The first stage focused on the development of a standardized ozone evaluation protocol. The next stage examined nine existing ozone facilities in order to expand the database of information about such facilities. The second stage also looked at case study examples and strategies for achieving optimization. The final stage generalizes some of the findings from the second stage in order to produce a list of ideas for ozone system improvement.

Results

The study found potential for lowering capital cost through optimization during pre-design. Redundancy level and standby equipment were recognized as having significant impact. In addition, ozone demand and decay should influence generator and contact sizing decisions. Also, minor design modifications during the design stage can result in a 15% savings on average. The study suggests that plant administration make optimization a priority and that staff implement optimization strategies and monitor progress as well as keep meters in proper calibration and equipment in good working order.

EPRI Perspective

EPRI’s Municipal Water and Wastewater Program was created to help member utilities address the energy needs of the more than 60,000 water systems and 15,000 wastewater systems in the United States. These facilities are among the country’s largest energy consumers, requiring an estimated 75 billion kWh nationally, about 3% of the annual U.S. electricity use. Ozonation is an important electrotechnology for water and wastewater treatment and this report focuses on ways to optimize its implementation.

Key Words

Ozonation
Optimization
Benefit/Cost Ratio

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Project Advisory Committee

The following individuals participated on the Project Advisory Committee:

Charlie Bromley, Montgomery Watson; Ron Joost, Carollo Engineers; Ed Minchew, CH2M Hill; and Rip Rice, RICE International Consulting Enterprises.

Ozone Optimization Special Study Activities

The following agencies and persons participated in Phase 3 ozone optimization special study regarding ozone residual monitors:

TU Electric, Dallas, Texas: Paul Wolske. TU Electric is the electricity service provider for the cities of Arlington, Dallas and Fort Worth, Texas. TU Electric was a partial sponsor of the residual monitor special study.

AWWARF, Denver, Colorado: Elizabeth Kawczynski.

Texas Natural Resources Conservation Commission, Austin, Texas: Alicia Diehl and Jack Shultze.

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Metropolitan Water District of Southern California, Ontario, California: Brad Coffey.

City of Worcester, Worcester, Massachusetts: Bob Hoyt.

City of Newport News, Newport News, Virginia: Mike Hotaling graciously provided time for Randy Hawkins to conduct pilot-scale tests.

EXECUTIVE SUMMARY

Introduction

In 20 years a 25-fold increase in ozone use has occurred in North America (Rice, R.G. and M.A. Dimitriou, 1997). Ozone is installed to achieve multiple water quality benefits:

1. Enhanced disinfection.
2. Reduced levels of disinfection by-products.
3. Oxidation of color and taste and odor compounds.
4. Oxidation of trace organics such as solvents and pesticides.
5. Oxidation of inorganic compounds such as hydrogen sulfide, iron and manganese.
6. Improved particle removal via microflocculation.

Short-chained organic by-products formed upon ozonation are mineralized (converted to CO_2 and water) in biologically active filters (Huck et al., 1998). Operating at reduced pH lowers the amount of bromate ion formed when bromide is present (Amy et al., 1997) (Coffey et al., 1998).

Project Overview

Multiple water quality benefits are obtained with ozone at moderately high capital and operating cost. Ideas to improve the benefit/cost ratio were identified during the three-phase "Ozone Energy Optimization Project" sponsored by the American Water Works Association Research Foundation (AWWARF) and Electric Power Research Institute-Community Environmental Center (EPRI-CEC). A standardized ozone evaluation protocol was developed in Phase 1. The Phase 1 report is titled "Ozone System Energy Optimization Handbook" (DeMers et al., 1996). Nine ozone facilities of varying types and sizes were involved in Phase 2 to expand the database for optimization considerations. Case history examples and strategies for achieving optimization were presented in the Phase 2 report, titled "Ozone Facility Optimization Research Results and Case Studies" (Rakness and DeMers, 1998). Phase 3 research condenses ideas for ozone optimization during pre-design, design, and operation based on findings during Phases 1 and 2 and selected special studies during Phase 3.

- Potential exists for lowering capital cost through optimization during pre-design.
  - Level of redundancy and standby equipment is an important decision.
  - Ozone demand/decay greatly impacts generator and contactor sizing decisions.

- Potential exists to lower ozone operating cost during design.
  - An average 15 percent savings was projected with minor design modifications.
  - Plant automation generally is unused and was studied further during Phase 3.
- Potential exists to lower ozone operating cost with changes in process control practices.
  - Plant administration must make optimization a priority.
  - Plant staff must implement optimization strategies and monitor progress.
  - Plant staff must keep meters in proper calibration and equipment in good working order.
  - On-line residual analyzers for disinfection compliance generally were unused and were studied further during Phase 3.

Optimization During Pre-Design

Interpretation of Phases 1 and 2 results formed the basis for pre-design optimization ideas.

1. Unused ozone generation capacity was observed in several plants, and significant unused capacity occurred in three of twelve plants evaluated. Design dose might be high due to conservative design risk tolerance; however, pilot-study data might yield misleadingly high dosages depending on how the pilot plant was operated.

2. Operating ozone dose was greater than necessary at some plants due to non-optimized design criteria for ozone contactor size and shape.

Considerations for optimization during pre-design include:

1. Select a specific, measurable performance target and operating factor-of-safety. *Giardia* cyst inactivation credit is an example performance target. Example operating factors-of-safety might be 1.2, 1.5 or 2.0. The performance target and operating factor-of-safety should be established during pre-design and carried through into design and operation.

2. Develop design criteria for ozone generator and contactor size from ozone residual profile evaluations using a contactor operation model based on bench-scale or pilot-scale demand/decay test results.

3. Owner and engineer should jointly determine generator standby capacity, considering that ozone standby equipment might be proportionally more expensive than for other water treatment chemicals. Evaluate potential design production capacity for each month of the year at the expected water flow, ozone dose, and disinfection CT value for the subject month. Consider alternatives available to increase production capability of operating generators.

4. Ascertain number of times standby ozone contactors might be used. Ozone contactors have few mechanical equipment components. Catastrophic diffuser failure is rare. Annual diffuser preventive maintenance activities might be scheduled during periods of low water demand.

5. Consider developing a standby disinfection plan with chlorine.

Optimization During Design

Potential optimization areas of involvement during design are summarized on the following page.

1. Instrumentation for optimization-targeted monitoring and control. Instruments that give accurate determination of disinfection performance ratio (PR) and unit-volume cost of operation ($/MG) should be installed.

2. Process and equipment features that enhance controllability during manual or automatic operation. Process controllability might be improved through enhancements to gas flow control and more reliable automated control systems.

3. Basin and equipment arrangement for efficient operation at turndown flow.

Key instruments to monitor optimization are ozone residual analyzers, gas flow meters, gas-phase ozone concentration meters, and generator power meters. Location of meters and field-verification of their accuracy are critically important. Meters should be located strategically, with consideration as to how optimization might be documented. For example, continuously documenting optimization via SCADA might require more meters than routine (e.g., daily) documentation via a spreadsheet (see Chapter 3).

A design considerations checklist for ozone residual analyzers is shown in Table 3-2 (Chapter 3). Challenges include the influences of ozone decay, inherently fluctuating residuals, and sample flow consistency. A design considerations checklist for gas flow meters is shown in Table 3-3 (Chapter 3). All gas flow meters should be accurate, but correctness is essential when meters are used to monitor optimization status (i.e., determine unit-volume operating cost, $/MG). Gas flow measurement accuracy considerations are described in Appendix A, including use of an orifice plate to field-verify accuracy of mass flow and vortex type meters. Ozone concentration is commonly measured using an ultraviolet (UV) meter. A summary checklist of design-related considerations for ozone concentration meters is presented in Table 3-4 (Chapter 3). UV meter correctness depends on span adjustment for sample cell pressure and temperature, as discussed in Appendix B. Field-verification of meter accuracy is recommended at start-up to ensure proper meter functioning. A field-verification protocol is described in Appendix B. Power meters can be checked with portable calibrated meters.

Design-related considerations for optimizing process controllability involve emphasizing gas flow control and process automation.

1. Positive flow control at the contactor inlet will enhance disinfection performance optimization. Provide controllability at low flow conditions with a parallel, smaller-sized control valve and pressure regulating valve, if necessary.

2. The constant-flow automation control alternative discussed in Chapter 6 was patterned after successful manual control strategies that achieved steady-state disinfection performance. Constant-flow automation uses feed-forward control techniques to improve system responsiveness during major changes in process control, such as changes in water flow rate.

Process flexibility optimization involves ability to maintain optimum performance at low flow as well as design flow conditions. Specific ideas are listed below.

1. Maintain energy efficient operation at turndown flow for air-fed ozone systems and oxygen-fed ozone systems where oxygen is produced on-site.

2. Select number of ozone contactors in operation separately from number of water treatment trains in service.

3. Control gas flows to oxygen-fed ozone systems at low flow conditions.

Optimization During Operation

Optimized performance might be achieved by implementing the two-step process outlined below.

1. Develop a monitoring program that tracks optimization status.

    a. Performance optimization is measured by Performance Ratio (PR). The operational objective is to control PR at or above 1.0.

    b. Cost optimization is measured by unit-volume operating cost ($/MG). The goal is to maintain performance at the lowest possible operating cost.

2. Implement operating strategies that achieve optimized performance. A model program might include the following elements.

    a. Plant administration support and encouragement for optimization, including periodic review/update of optimization status.

    b. Design features and flexibility that support optimization criteria plus provide for steady-state operation with automated control.

    c. An optimization “champion” or teams to lead the project.

    d. Operations staff who monitor optimization status and achieve and maintain optimized performance.

    e. Operating staff who implement special studies to assess better ways of operating the ozone process. Special studies might include topics discussed in this report.

        (1) Compare residual analyzer readings with grab sample results to demonstrate meter adequacy for reporting disinfection compliance (see Chapter 4 and Chapter 7).

        (2) Perform quality control checks for gas flow (see Chapter 3 and Appendix A), ozone concentration (see Chapter 3 and Appendix B), and power meter readings (see Chapter 3).

(3) Utilize data monitoring program to assess performance and cost optimization improvements due to planned and implemented changes in process control strategies (see Case Histories in Phase 2 report for example operating strategies.

CONTENTS

1 INTRODUCTION 1-1
Ozone Background 1-1
Project Overview 1-1
Phase 1 1-1
Phase 2 1-2
Phase 3 1-2
Report Framework 1-3

2 OPTIMIZATION DURING PRE-DESIGN 2-1
Performance Target 2-1
Ozone Dose and Residual Profile 2-3
Generator Design Production Risk Tolerance 2-6
Contactor Design Risk Tolerance 2-7

3 OPTIMIZATION DURING DESIGN 3-1
Instrumentation for Monitoring Optimization 3-1
Ozone Residual Analyzers 3-2
Gas Flowmeters 3-2
Gas Phase Ozone Concentration Meters 3-5
Generator Power Meters 3-7
Process Controllability 3-8
Ozone Automation 3-8
Gas Flow Control 3-9
Process Flexibility 3-10

4 OPTIMIZATION DURING OPERATION 4-1
Ozone Optimization Criteria 4-1
Measuring Ozone Optimization Status 4-3

Model Program for Ozone Optimization 4-6

5 IMPACT OF DEMAND/DECAY ON OZONE OPTIMIZATION 5-1

Bench-Scale Testing 5-1

Data Collection 5-1

Data Development 5-4

Calculating CT Value 5-8

Comparing Predicted Versus Measured Dose 5-10

Assessing Pilot-Scale and Bench-Scale Data 5-18

Pilot-Scale Testing Method 1 5-18

Pilot-Scale Testing Method 2 5-20

6 OZONE OPTIMIZATION WITH IMPROVED AUTOMATION 6-1

Background 6-1

Overview of Ozone System Control Techniques 6-1

Manual Control 6-3

Description 6-3

Performance at Plant 11 6-4

Constant-Concentration Automated Control 6-6

Description 6-6

Performance at Plant 13 6-7

Performance at Plant 14 6-9

Constant Gas Flow Automated Control Alternative 6-10

Performance Illustration 6-10

Description 6-10

Example 6-15

7 ON-LINE OZONE RESIDUAL ANALYZERS FOR DISINFECTION COMPLIANCE 7-1

Research Approach 7-1

Fort Worth, Eagle Mountain WTP Testing 7-2

Dallas, Elm Fork WTP Testing 7-3

Disinfection Results - Eagle Mountain WTP 7-4

Residual Analyzer Standardization Protocol 7-4

Disinfection Compliance Results 7-10

Analyzer Results - Elm Fork WTP 7-14

Considerations for Obtaining Reliable Analyzer Readings 7-18
    Standardization Protocol 7-18
    Grab Sampling Considerations 7-18
    Frequency of Analyzer Standardization and Other Maintenance 7-20
    Sample Line Detention Time 7-20
    Continuous Ozone Residual Monitoring 7-22

***8* REFERENCES.. 8-1**

***A* GAS FLOW MEASUREMENT ACCURACY CONSIDERATIONS......................................A-1**
Importance of Field Verification..A-1
Theory of Orifice Plate Gas Flow Calculations A-2
Calculating Flow at Specified Reference Conditions A-8
Applying Correction Factors for Flowing Gas Conditions A-11
Measuring Ozone Production A-12
Quality Assurance Considerations for Accuracy of Flow A-13
    Gas Expansion Factor Considerations A-13
    Low Gas Flow Considerations...A-14

***B* GAS PHASE METER OZONE CONCENTRATION ACCURACY.......................................B-1**
Wet-Chemistry Test Procedure...B-1
Comparison of Wet-Chemistry and UV Meter Results B-7

LIST OF FIGURES

Figure 2-1 Required CT Value for Variable Water Temperature and *Giardia* Cyst Inactivation Credit Using Ozone (Based on Appendix O, USEPA 1991) 2-3

Figure 2-2 Bench-Test Projected Ozone Dose and Residual Profile Based on Bench-Scale Demand/Decay Tests 2-4

Figure 2-3 Ozone Concentration and Cooling Water Temperature Effect on Ozone Production 2-7

Figure 4-1 Unit-Volume Operating Cost at the Canal Road Water Treatment Plant, Somerset, New Jersey 4-3

Figure 4-2 Comparison of Cell 3 SINGLE-TEST Ozone Residuals 4-5

Figure 4-3 Comparison of Cell 3 AVERAGE Ozone Residual 4-5

Figure 4-4 Comparison of Performance Ratio for GRAB Versus METER 4-6

Figure 5-1 Bench-Scale Demand/Decay Test Setup 5-2

Figure 5-2 Indigo Stock Standardization Curve @ 5 cm 5-3

Figure 5-3 Ozone Residual Versus Sample Time Chart for Test 2 of Plant A Water Sample 5-4

Figure 5-4 Transferred Ozone Dose Versus 60-sec Residual and Ozone Half-Life 5-6

Figure 5-5 Plant A Ozone Residual Profile and CT Value Comparison 5-8

Figure 5-6 Predicted Dose for Equivalent CT Value at Plant A 5-11

Figure 5-7 Bench-Scale Predicted Versus Full-Scale Measured Dose to Achieve Similar CT Value 5-11

Figure 5-8 Predicted Dose and Residual Profile for Equivalent CT Value 5-12

Figure 5-9 Pilot-Scale Dose Versus Outlet Residual for HDT of 7.0 Min 5-18

Figure 5-10 Plant E Ozone Dose Versus 60-sec Residual and Ozone Half-Life 5-19

Figure 5-11 Plant E Bench-Scale Predicted Dose for CT Value of 4.1 mg/L•min 5-20

Figure 5-12 Bench- and Pilot-Scale Dose and Residual Profile Data for Equivalent CT Value 5-21

Figure 6-1 Simplified Liquid Oxygen-Fed Ozone Schematic 6-2

Figure 6-2 Unit-Mass Ozone Cost for LOX Oxygen-Fed Ozone System 6-2

Figure 6-3 Schematic for Manual Ozone Control 6-4

Figure 6-4 Plant 11 Percent Variation Chart for Generator Power, Gas Flow, and Ozone Concentration 6-5

Figure 6-5 Cell 1 Ozone Residual Variation Chart at Plant 11 6-5

Figure 6-6 Schematic for Constant-Concentration Automated Control 6-6

Figure 6-7 Illustration of Constant-Concentration Control Technique 6-7
Figure 6-8 Plant 13 Percent Variation Chart for Generator Power, Gas Flow, and Ozone Concentration 6-8
Figure 6-9 Cell 1 Ozone Residual Variation at Plant 13 6-8
Figure 6-10 Plant 14 Percent Variation Chart for Generator Power, Gas Flow, Ozone Concentration, and Water Flow 6-9
Figure 6-11 Plant 11 Percent Variation Chart for Generator Power, Gas Flow, Ozone Concentration, and Water Flow 6-11
Figure 6-12 Schematic for Constant Gas Flow Automated Control 6-12
Figure 6-13 Ozone Generator Specific Energy Versus Ozone Concentration Equation Chart 6-13
Figure 6-14 Example Optimized Ozone Concentration Range at Plant 7 6-14
Figure 6-15 Range of Concentration-Multiplier at Plant 11 to Control *Giardia* Cyst Inactivation Credit 6-15
Figure 7-1 Schematic of On-Line Analyzer Setup at Cell 3 of Contactor 3 at the Elm Fork Water Treatment Plant 7-4
Figure 7-2 Ozone Residual Variability From Cell 3, Train 2 at the Eagle Mountain Water Treatment Plant 7-5
Figure 7-3 Comparison of Simultaneous Grab Samples Using Hach Ampoules 7-6
Figure 7-4 Grab Sample Residual Acceptable Range Versus Average of Analyzer Readings 7-7
Figure 7-5 Standardization Trend for the Cell 1 Analyzer, Eagle Mountain WTP 7-8
Figure 7-6 Standardization Trend for the Cell 3 Analyzer, Eagle Mountain WTP 7-9
Figure 7-7 Calibration Trend for the Cell 5 Analyzer, Eagle Mountain WTP 7-10
Figure 7-8 Example Report From Ozone Disinfection Compliance Monitoring Program 7-11
Figure 7-9 Percent of Time Disinfection Compliance Was Achieved, May 1998, Eagle Mountain Water Treatment Plant 7-12
Figure 7-10 Percent of Time Disinfection Compliance Was Achieved, March 1998, Eagle Mountain Water Treatment Plant 7-13
Figure 7-11 Performance Ratio and Applied Ozone Dose Trend, Eagle Mountain WTP 7-14
Figure 7-12 Ozone Residual Variability From Cell 3, Contactor 3 - Elm Fork WTP 7-16
Figure 7-13 Rosemount Analyzer Standardization Data, Elm Fork WTP 7-16
Figure 7-14 Orbisphere Analyzer Standardization Data, Elm Fork WTP 7-17
Figure 7-15 IN-USA Analyzer Standardization Data, Elm Fork WTP 7-17
Figure 7-16 Reductions of Measured Ozone Residual Due to Ozone Decay and Sample Line HDT 7-21
Figure 7-17 Example Residual Smoothing for Computer Control Using 5-Min Average 7-22
Figure A-1 Gas Flow Inaccuracy for Two Factory-Calibrated Meters A-2
Figure A-2 Gas Flow Rate Was Within ±5 Percent for Three Factory-Calibrated Meters A-2
Figure A-3 Gas Flow Increases as Differential Pressure Increases A-13
Figure A-4 Gas Expansion Correction Impact Increases With Differential Pressure A-14

Figure B-1 Ozone Concentration Wet-Test Setup for Ozone Generator Product Gas............B-4
Figure B-2 Relationship Among Wet-Test Parameters for a Titration Volume of 20 mL..........B-4
Figure B-3 Relationship Among Wet-Test Parameters for a Titration Volume of 30 mL..........B-5

LIST OF TABLES

Table 2-1 Checklist for Ozone Generator/Contactor Sizing Optimization................................ 2-2
Table 3-1 Checklist of Process Design-Related Optimization Considerations......................... 3-2
Table 3-2 Checklist of Design Considerations for Ozone Residual Analyzers......................... 3-3
Table 3-3 Checklist of Design Considerations for Gas Flowmeters 3-4
Table 3-4 Checklist of Design Considerations for Ozone Concentration Meters...................... 3-6
Table 3-5 Checklist of Design Considerations for Process Controllability 3-8
Table 3-6 Checklist of Design Considerations for Process Flexibility.................................... 3-10
Table 4-1 Checklist of Operating Considerations for Ozone Optimization.............................. 4-2
Table 4-2 Checklist of Operating Considerations for Ozone Residual Analyzers 4-4
Table 4-3 Checklist of Ideas Regarding a Model Program for Ozone Optimization................. 4-7
Table B-1 Look-Up Table for Vapor Pressure..B-7

1

INTRODUCTION

Ozone Background

Ozone use for drinking water treatment is increasing in North America. In 1980 only ten plants used ozone. By 1997 over 250 plants operated ozone to achieve multiple water quality benefits systems (Rice and Dimitriou, 1997). Enhanced disinfection and reducing levels of disinfection by-products are the major reasons for installing ozonation. Other reasons include oxidation of color and taste and odor compounds; oxidation of trace organics such as solvents and pesticides; oxidation of inorganic compounds such as hydrogen sulfide, iron and manganese; and improved particle removal via microflocculation. Ozone disinfection by-products include short-chained organics (aldehydes and carboxylic acids) and can include bromate ion, when bromide is present. Short-chained organics are mineralized (oxidized to CO_2 and water) in biologically active filters (Huck and Coffey, 1997). Operating at reduced pH lowers the formation of bromate ion (Amy et al., 1997) (Coffey et. al., 1998).

Ozone system operation will increase the plant energy usage. Air-fed ozone system energy consumption might range from 50 to 400 kWh/MG or more, depending on water quality, system design, and process operation. Energy cost might range from $5/MG to $40/MG or more, depending on energy price, energy consumption and ozone usage. Liquid oxygen (LOX) oxygen-fed ozone systems have similar unit-volume operating costs but about 50 percent of the energy consumption. The cost of LOX may be about the same as the energy cost for LOX-fed ozone systems.

Project Overview

Ozone is generated on-site with electricity. Ozonation has multiple water quality benefits but moderate to high capital and operating cost. Ideas to improve the benefit/cost ratio were identified during the three-phase “Ozone Energy Optimization Project” sponsored by the American Water Works Association Research Foundation (AWWARF) and Electric Power Research Institute-Community Environmental Center (EPRI-CEC).

Phase 1

A standardized ozone evaluation protocol was developed in Phase 1, with involvement by three water utilities in the San Francisco Bay Area, including the Alameda County Water District in Fremont, California; East Bay Municipal Utility District in Oakland, California; and the City of Fairfield, California. The protocol’s evaluation component is called an Ozone Facility Evaluation (OFE), during which optimization strategies are identified and quantified. The follow-up component is called Ozone Facility Technical Assistance (OFTA), which focuses on implementation of optimization strategies identified during the OFE. The Phase 1 report is titled “Ozone System Energy Optimization Handbook” (DeMers et al., 1996).

Phase 2

Nine ozone facilities of varying types and sizes were involved in Phase 2 to expand the database for optimization considerations. Water utilities included Fort Worth, Texas; Dallas, Texas; Regional Municipality of Waterloo, Ontario, Canada; Central Lake County Joint Action Water Agency, Lake Bluff, Illinois; New Jersey American Water Company, Delran, New Jersey; Costa Mesa Consolidated Water, Costa Mesa, California; Sebago Lake Water Treatment Facility, Portland, Maine; Montréal, Québec, Canada; and Elizabethtown Water Company, Somerset, New Jersey. Phase 2 results indicated that potential exists for an average 16 percent cost savings with changes in O&M alone and another 15 percent savings with minor design modifications. Case history examples and strategies for achieving optimization were presented in the Phase 2 report titled “Ozone Facility Optimization Research Results and Case Studies” (Rakness and DeMers, 1997).

Phase 3

Phase 3 research condenses ideas for ozone optimization during pre-design, design, and operation based on findings during Phases 1 and 2. Special studies during Phase 3 were conducted to test potential optimization ideas. Water utilities involved in Phase 3 research included Arlington, Texas; Fort Worth, Texas; Dallas, Texas; Central Lake County Joint Action Water Agency, Lake Bluff, Illinois; Metropolitan Water District of Southern California, Los Angeles, California; Newport News, Virginia; and Sebago Lake Water Treatment Facility, Portland, Maine. Principal areas of involvement for optimization during pre-design, design and operation are listed below.

- Potential exists for lowering capital cost through optimization during pre-design.
    - – Six of twelve ozone facilities were operating at ozone production rates much below the installed capacity, and three facilities were operating at production rates significantly below the installed capacity.
    - – The level of redundancy and standby equipment is an important decision.
    - – Ozone demand and decay characteristics have significant impact on generator and contactor sizing decisions. A special study was conducted in Phase 3 to assess the ability of bench-scale testing to predict full-scale operation.
        - Bench-scale demand/decay test results are used to project and compare full-scale disinfection performance.
        - Comparisons were conducted at five facilities with variable water quality.
        - Bench-scale projections are used to explain by example how to evaluate and assess the level of risk that the ozone system will meet its design objectives.

  - Potential exists to lower ozone operating cost during design.
    - An average 15 percent savings was projected with minor design modifications.
    - Greater energy efficiency at turndown conditions.
    - Reliable and accurate metering at key locations.
    - Plant automation is generally unused and was studied further during Phase 3.
    - Automation was abandoned in 66 percent of the ozone facilities studied in Phases 1 and 2.
    - Manual ozone system control has been quite successful, but staff usually prefers a functional automation system to reduce operating safety factor and free up staff for other duties.
    - An alternative automatic control approach is presented based on the successes achieved with manual control.
- Potential exists to lower ozone operating cost with changes in process control practices.
  - Plant administration must make optimization a priority.
  - Plant staff must implement optimization strategies and monitor progress.
  - Plant staff must keep meters in proper calibration and equipment in good working order.
  - On-line residual analyzers for disinfection compliance generally were unused and were studied further during Phase 3.
    - Analyzer supplier’s installation and calibration suggestions were modified to accommodate special water quality needs for the Eagle Mountain and Elm Fork Water Treatment Plants located in Fort Worth and Dallas, Texas, respectively.
    - Testing was conducted to compare grab sample versus meter reading disinfection compliance at the Eagle Mountain Water Treatment Plant.
    - Testing was conducted to develop/report operating experiences for three different types of on-line residual monitors at the Elm Fork Water Treatment Plant.

Report Framework

Seven chapters are included in this report. Chapter 1 is the introduction. Chapters 2, 3, and 4 concern optimization during Pre-Design, Design, and Operation. Chapters 5, 6, and 7 discuss results for Phase 3 special studies concerning ozone demand/decay, automation, and on-line residual monitoring, respectively.

Chapters 2, 3, and 4 include an optimization idea checklist at the front-end of the chapter followed by a brief explanation of each idea. Detailed information about checklist ideas is contained in the Phase 2 report, titled “Ozone Facility Optimization Research Results and Case Studies” (Rakness and DeMers, 1997), or in the other chapters or the appendices of this report.

Chapters 5, 6, and 7 present the Phase 3 special study results. Chapter 5 presents ozone demand/decay results from five facilities and supports discussions in Chapter 2 regarding ozone generator and contactor sizing. Chapter 6 describes results from the automation special study and supports discussions in Chapter 3 regarding design flexibility for automation. Chapter 7 explains the results of the residual analyzer special study conducted during Phase 3. Information in Chapter 7 supports sampling system design considerations presented in Chapter 3 and analyzer calibration procedures discussed in Chapter 4.

2

OPTIMIZATION DURING PRE-DESIGN

Principal items for pre-design optimization were based on observations during Phases 1 and 2 of the Ozone Energy Efficiency Project:

1. Unused ozone generation capacity was observed in several plants, and significant unused capacity occurred in three of twelve plants evaluated. Design dose might be high due to conservative design risk tolerance; however, pilot study data might yield misleadingly high ozone dosages depending on how the pilot plant was operated.

2. Operating ozone dose was greater than necessary at some plants due to non-optimized design criteria for ozone contactor size and shape.

Several decisions are made during pre-design of an ozone system such as application point; type of feed-gas; generator number and size; and contactor number, size and shape. Decisions are based on site-specific needs including performance goal, plant layout, and raw water quality. A discussion of all pre-design issues and considerations is beyond the scope of this project. In this chapter optimization ideas are presented for consideration during pre-design. Ideas were based on Ozone Facility Evaluation and special study findings during Phases 1, 2, and 3 of the Ozone Energy Optimization Project. Considerations are listed in Table 2-1. Each is discussed further in this chapter.

Performance Target

Ozone performance goals observed were categorized as either: 1) General Treatment Objectives, 2) Operational-Related Objectives, or 3) Disinfection-Related Objectives (Rakness and DeMers, 1998) (Rakness et al., 1997). Plants operating to meet disinfection-related objectives could be optimized using the Performance Ratio (PR) concept. PR is the ratio of measured performance divided by required performance. The operating goal is to maintain PR slightly above 1.0. The operating factor of safety can be determined on a case-by-case basis. The performance target and operating factor of safety should be established during pre-design and carried through into design and operation.

Table 2-1
Checklist for Ozone Generator/Contactor Sizing Optimization

Consideration	Comment
1. What is the performance target and operating factor of safety?	A. Select a specific, measurable performance target. *Giardia* cyst inactivation credit is an example performance target. B. Select operating factor of safety such as 1.2, 1.5, or 2.0.
2. What is the expected ozone dose and residual profile when performance target is met?	A. Bench-scale or pilot-scale studies might be used to develop demand/decay data for the range of expected water quality and flow conditions. B. Results should be evaluated using contactor operation model to assess ozone dose, residual profile, and CT value for meeting the disinfection performance target.
3. What is the acceptable design risk tolerance for ozone generator back-up/standby capacity?	A. Ozone generator standby capacity not only delivers but also creates ozone on-site. B. Ozone standby equipment might be proportionally more expensive than for other chemicals. C. Generator standby capacity should be determined jointly by the owner, the engineer, and the regulatory agency based on site-specific considerations.
4. What is the acceptable design risk tolerance for ozone contactor back-up/standby capacity?	A. Most ozone contactor designs have few mechanical components. B. Ozone contactors might function satisfactorily without standby or back-up capability. C. Chlorine may be an acceptable standby primary disinfectant.

Common ozone disinfection objectives observed were 1-log and 3-logs *Giardia* cyst inactivation credit. “Appendix O” of the “Guidance Manual for Complying with the Requirements of the SWTR” (USEPA, 1991) describes the methodology for determining *Giardia* cyst inactivation credit for ozone contactors. Example CT values for variable water temperature are shown in Figure 2-1. Methods for calculating ozone CT values and *Giardia* cyst and virus inactivation credits are explained in the Phase 2 report (Rakness and DeMers, 1998). Operating factors-of-safety observed were 1.5 and 1.2 for 1-log and 3-logs *Giardia* cyst inactivation credit, respectively. Generator and contactor size optimization are contingent upon development of CT value design criteria for the expected range of water temperatures.

Some plants have implemented an enhanced disinfection target for ozone such as 1-log or 2-logs *Cryptosporidium* oocyst inactivation credit. Required CT values for *Cryptosporidium* oocyst inactivation credits currently are being developed by research studies. In the meantime, some utilities have designed ozone systems for enhanced disinfection using a *Giardia*:*Cryptosporidium* ratio of 5:1 to establish design CT values. This means that the design CT value for 1-log *Cryptosporidium* oocyst inactivation credit was five times the value for 1-log *Giardia* cyst inactivation credit. Other utilities have used a 10:1 ratio to establish design CT values. If enhanced disinfection is the performance target, then the most recent research results should be used to determine design CT values.

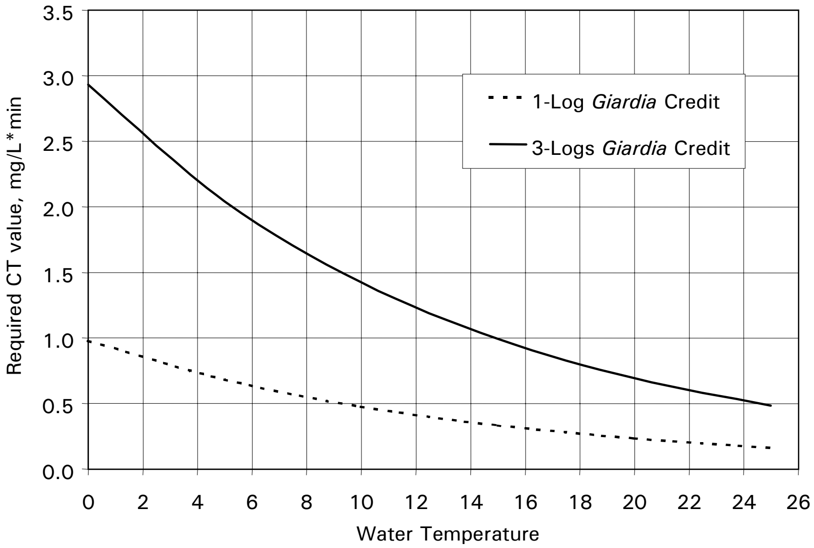


Figure 2-1
Required CT Value for Variable Water Temperature and *Giardia* Cyst Inactivation Credit Using Ozone (Based on Appendix O, USEPA 1991)

Ozone Dose and Residual Profile

Ozone residual follows a first order decay profile, as discussed in the Phase 2 report (Rakness and DeMers, 1998) and also in Chapter 5 of this report. The residual profile required to achieve a specific disinfection target depends on water quality, contactor shape, and contactor size. Evaluating ozone residual profile based on bench-scale or pilot-scale demand/decay tests might be used to develop design criteria for ozone generator and contactor size. Refer to Chapter 5 for additional information regarding bench- and pilot-scale testing.

Ozone residual profile illustrations are shown in Figure 2-2 for low, medium, and enhanced levels of disinfection to explain by example generator and contactor sizing considerations. The disinfection objectives are target CT values of 0.61-mg/L•min, 1.48-mg/L•min, and 4.11-mg/L•min to achieve, respectively, 1.5-logs *Giardia* cyst inactivation credit, 3.6-logs *Giardia* cyst inactivation credit, and enhanced disinfection for *Cryptosporidium* oocyst inactivation credit. The ozone dose and residual profile data were developed based on bench-scale studies on Plant E water conducted at the collected water temperature of 12°C.

These data represent water quality during the late fall. Bench-scale tests at different times of the year also should be conducted in order to evaluate design criteria for other operating conditions.

The illustrations in Figure 2-2 show ozone addition to cell 1 only, as is commonly practiced (Rakness and DeMers, 1998). Ozone contactor design criteria for the examples are ten equally-sized cells, a total hydraulic detention time of 10-min at design flow, a T_{10}/T ratio of 0.70, and a minimum residual of 0.05 mg/L for calculating CT value. The contactor operating model illustrated in Figure 2-2 could be used to assess different contactor design criteria (see Chapter 5 for explanation of model). The design team might investigate required ozone dose for variable design criteria for contactor size and shape. See also the Phase 2 report; page 3-13; Case Studies 2, 4, and 5 for additional discussion regarding ozone contactor sizing optimization considerations (Rakness and DeMers, 1998). The following optimization ideas might be considered for the example shown in Figure 2-2.

- The contactor might be smaller for the low CT value operating condition since the ozone residual is less than 0.05 mg/L after 8 minutes detention time (see also Phase 2 report, page 3-13, Case Study 1).
- The contactor seems appropriate for the medium disinfection target since the ozone residual at the outlet is less than 0.1 mg/L.
- The contactor might be larger for the high CT value operating condition since the outlet residual is greater than 0.4 mg/L.

Dose = 0.74 mg/L for CT value of 0.61 mg/Lxmin

Water Temperature	C	12
Predicted T. Dose	mg/L	0.74
Pred. Res. 1	mg/L	0.24
2	mg/L	0.19
3	mg/L	0.16
4	mg/L	0.13
5	mg/L	0.10
6	mg/L	0.08
7	mg/L	0.07
8	mg/L	0.06
9	mg/L	0.00
10	mg/L	0.00
T10/T Ratio	--	70%
Minimum Residual	--	0.05
Bench HL versus Dose		
Res. VS HL Slope	min/mg/L	5.990
Inter	min	-1.0646
Half-life	min	3.37
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	1.2018
Inter	mg/L	-0.6525
60-sec Ozone Residual	mg/L	0.24
CT value and *Giardia* Inactivation Credit		
Calculated CT	mg/Lxmin	0.61

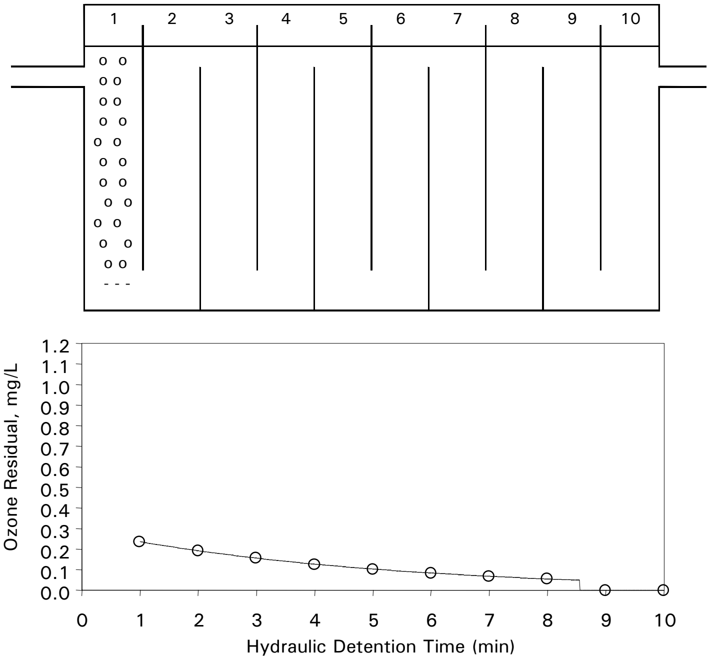
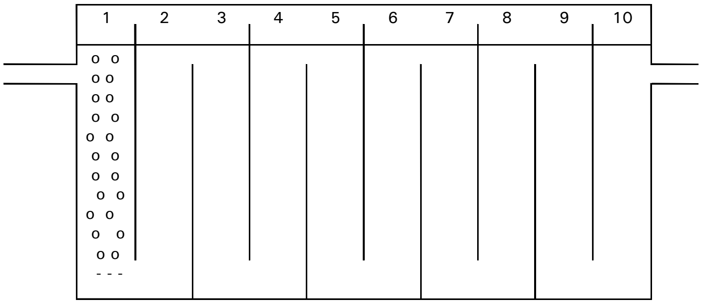
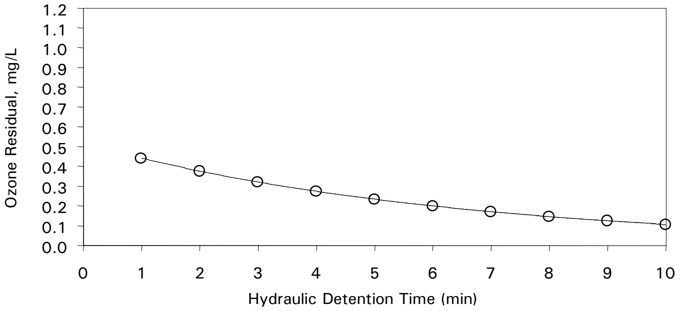


Figure 2-2
Bench-Test Projected Ozone Dose and Residual Profile Based on Bench-Scale Demand/Decay Tests

Dose = 0.91 mg/L for CT value of 1.48 mg/Lxmin

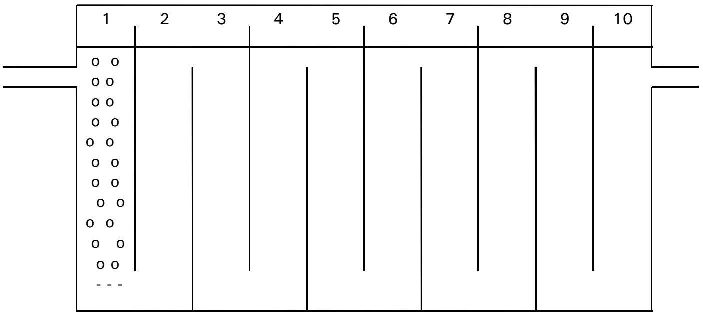
Water Temperature	C	12
Predicted T. Dose	mg/L	0.91
Pred. Res. 1	mg/L	0.44
2	mg/L	0.38
3	mg/L	0.32
4	mg/L	0.27
5	mg/L	0.23
6	mg/L	0.20
7	mg/L	0.17
8	mg/L	0.15
9	mg/L	0.12
10	mg/L	0.11
T10/T Ratio	--	70%
Minimum Residual	--	0.05
Bench HL versus Dose		
Res. VS HL Slope	min/mg/L	5.990
Inter	min	-1.0646
Half-life	min	4.39
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	1.2018
Inter	mg/L	-0.6525
60-sec Ozone Residual	mg/L	0.44
CT value and *Giardia* Inactivation Credit		
Calculated CT	mg/Lxmin	1.48





Dose = 1.36 mg/L for CT value of 4.11 mg/Lxmin

Water Temperature	C	12
Predicted T. Dose	mg/L	1.36
Pred. Res. 1	mg/L	0.98
2	mg/L	0.89
3	mg/L	0.81
4	mg/L	0.73
5	mg/L	0.66
6	mg/L	0.60
7	mg/L	0.55
8	mg/L	0.49
9	mg/L	0.45
10	mg/L	0.41
T10/T Ratio	--	70%
Minimum Residual	--	0.05
Bench HL versus Dose		
Res. VS HL Slope	min/mg/L	5.990
Inter	min	-1.0646
Half-life	min	7.08
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	1.2018
Inter	mg/L	-0.6525
60-sec Ozone Residual	mg/L	0.98
CT value and *Giardia* Inactivation Credit		
Calculated CT	mg/Lxmin	4.11



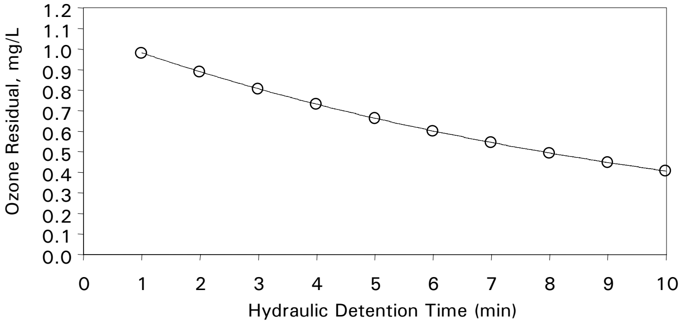


Figure 2-2
Bench-Test Projected Ozone Dose and Residual Profile Based on Bench-Scale Demand/Decay Tests (cont.)

Generator Design Production Risk Tolerance

Design risk tolerance includes criteria for design production capacity and criteria for standby capacity. Design production capacity might be based on maximum flow, maximum dose, and maximum CT value. However, this does not give consideration to the fact that maximum conditions might occur at different times of the year. For example, the maximum CT value might occur during the winter when maximum flow is unlikely. The design production capacity should be assessed for each month of the year, considering the expected operating conditions for the subject month. Bench-scale or pilot-plant data and a contactor simulation model, as shown in Figure 2-2, might be used to assess monthly design production requirement. The design production capacity might be required in the spring, summer, fall, or winter, depending on water quality and plant flow. Other alternatives, such as utilizing chlorine for short-term primary disinfection, could be considered when evaluating ozone standby production capacity needs.

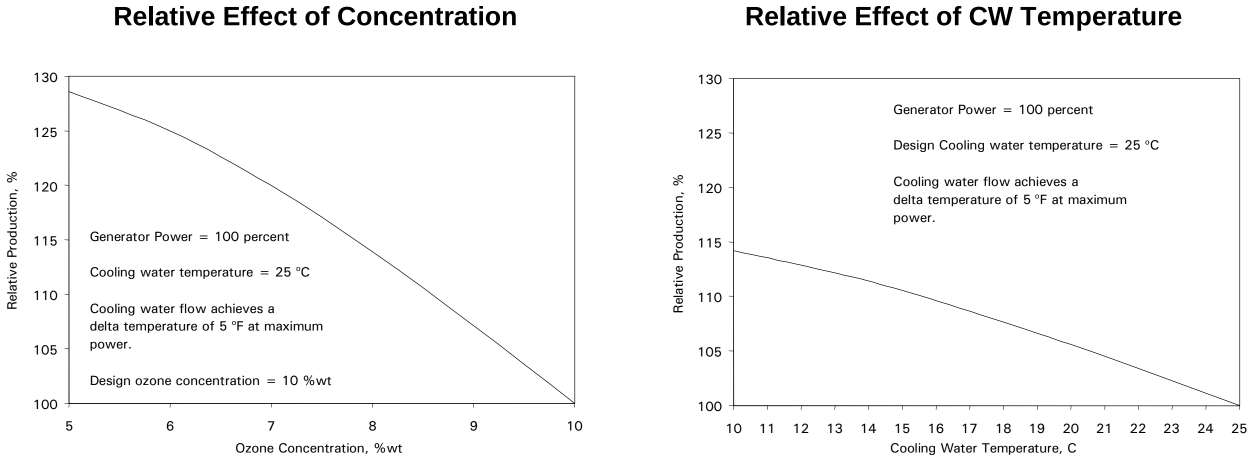
The extent of standby capacity for ozone should be assessed independently of standby criteria for other chemical feed equipment because ozone is unlike other chemicals. Most other chemicals used in water treatment (e.g., alum or chlorine) are manufactured off-site, are stored on-site, and are delivered to the process by chemical feed pumps. Installing a second chemical feed pump provides 100 percent standby capacity. Chemical cost is unaffected because the chemical is received from the same bulk storage vessel.

Ozone, on the other hand, is generated on-site. Standby ozone equipment not only delivers but also creates ozone. As such, ozone generation back-up and standby equipment might be proportionally more expensive than for other chemical feed equipment. Criteria for ozone back-up and standby should be assessed on a case-by-case basis.

Standby or back-up ozone production capacity might be provided in two ways: 1) install a back-up ozone generator, and 2) increase production capability of operating generators. Installing a back-up ozone generator is the most common method for obtaining standby capacity. The number of generators installed might be one plus one standby, two plus one standby, three plus one standby, etc, depending on plant size. Another consideration is equipment reliability. Should another back-up generator be installed in case one unit fails and a second unit is in maintenance? Most plants have had good success with generator reliability, but owner conservatism and design risk tolerance ultimately will influence the final design criterion for standby/back-up capacity.

Production rate from an ozone generator is controlled primarily by applied power (kW). The ozone supplier selects installed maximum power based on design criteria for ozone concentration (% wt), cooling water temperature, and cooling water maximum delta-temperature across the ozone generator. The maximum delta-temperature is generally 5 to 10°F (-15 to -12°C), with the lower number used in warm water situations (i.e., cooling water temperatures above 25°C). The design ozone concentration for LOX oxygen-fed ozone generators is generally 8 to 10% wt, sometimes up to 12% wt. Operating conditions that increase production capacity for a given design are operating at reduced ozone concentration and lower cooling water temperature.

A generic representation of relative effect on production of ozone concentration and cooling water temperature is shown in Figure 2-3. Individual equipment suppliers might have charts that are slightly different. The concentration chart indicates that generator production capacity can be enhanced by 25 percent by increasing gas flow so that the operating ozone concentration is 6% wt instead of the design concentration of 10% wt. Operating cost would increase by operating at a lower ozone concentration (see Phase 2 report, Chapter 3, page 36); however, increasing gas flow rate to enhance production might be a cost effective approach for providing standby capacity. The cooling water temperature chart indicates that ozone production rate might be enhanced by about 15 percent during the winter. If design-maximum production occurs in the winter (not usually the case, but could be the case), then the generator size might be reduced by 15 percent if the design criteria called for maximum production based on winter cooling water temperature.



Relative Effect of Concentration

Relative Effect of CW Temperature

Figure 2-3
Ozone Concentration and Cooling Water Temperature Effect on Ozone Production

Contactor Design Risk Tolerance

Standby ozone generators are typically installed more frequently than standby ozone contactors. Most ozone contactor designs have few mechanical equipment components. Ozone diffusers require maintenance periodically; catastrophic diffuser failure is rare. Diffusers generally are inspected/repaired/replaced once or possibly twice per year. Diffuser preventive maintenance activities might be scheduled during periods of low water demand.

Water flow rate through an ozone contactor might be limited physically by hydraulic design criteria or arbitrarily by process design criteria. Case Study 1, discussed on page 3-13 in the Phase 2 report (Rakness and DeMers, 1998), noted lower operating cost when the water flow rate was doubled. Fortunately, Case Study 1 plant hydraulics allowed doubling the water flow rate through the contactor. Contactor design detention time might be based on optimized criteria, as determined by a contactor operating model (see Chapter 5 for model explanation). Operating detention might be decreased during emergency situations as an alternative to installing standby/back-up ozone contactors, provided that increased water flow is allowed by the hydraulic design criteria.

3

OPTIMIZATION DURING DESIGN

Design areas of involvement for optimization were based on findings from Ozone Facility Evaluations conducted during Phases 1, 2, and 3 of the Ozone Energy Efficiency Project. Areas deserving attention during design include:

1. Instrumentation for optimization-targeted monitoring and control.

2. Process and equipment features that enhance controllability during manual or automatic operation.

3. Contactor and equipment arrangement for efficient operation at turndown flow.

Ozone system design involves subject areas beyond those affecting optimization. Other important design considerations involve disciplines such as electrical, mechanical, structural, architectural, hydraulics, corrosion control, etc. In this chapter process design-related optimization ideas are discussed. Considerations are presented elsewhere (Rakness, 1991) (Dimitriou, ed., 1990) for harmonics control, gas pipe size, materials of construction, ventilation, and other ozone design subjects. A checklist of process design optimization considerations is shown in Table 3-1. Each item listed is discussed further in this chapter.

Instrumentation for Monitoring Optimization

Ozone optimization is defined as achieving required performance at the lowest possible operating cost. Disinfection performance is measured by Performance Ratio (PR), which is the ratio of measured disinfection divided by target disinfection. Operating cost is measured by unit volume cost ($/MG). Calculating, monitoring and controlling ozone optimization are discussed further in Chapter 4. Key instruments to monitor ozone optimization are ozone residual analyzers, gas flowmeters, gas-phase ozone concentration meters, and generator power meters. Locations of meters and field verification of accuracy are discussed in this chapter.

Table 3-1
Checklist of Process Design-Related Optimization Considerations

Consideration	Comment
1. What instrumentation supports ozone optimization?	A. Instruments that give accurate determination of disinfection performance ratio (PR) and unit-volume cost of operation ($/MG) should be installed.
2. What process and equipment features are used to maintain optimized control manually and automatically?	A. Process controllability might be improved through enhancements to gas flow control and more reliable automated control systems.
3. What basin and equipment arrangements are utilized during optimized operation?	A. Process and equipment flexibility should be available to minimize operating cost at turndown flow.

Ozone Residual Analyzers

Residual analyzers were available at most plants evaluated during Phases 1 and 2 but were non-functional at several facilities. A special study was conducted during Phase 3; results are presented in Chapter 7 of this report. Design-related considerations for ozone analyzers are summarized in Table 3-2. Challenges include ozone decay, inherently fluctuating residuals, and sample flow consistency.

Gas Flowmeters

Gas flowmeters are installed on ozone systems for three main reasons:

1. Calculate ozone operating parameters such as ozone production, ozone dosage, and unit-volume operating cost.

2. Monitor and control ozone production and distribution to contactors, either manually or automatically.

3. Determine flow split between parallel units such as generators and contactors.

Table 3-2
Checklist of Design Considerations for Ozone Residual Analyzers

Consideration	Comment
1. What are key requirements for the sample lines? Where should the analyzer be located?	A. Minimize ozone loss due to decay in the sample line. Use criteria for design sample line diameter and length to minimize detention time in the sample line. If the sample line is too small, sample flow could be restricted and detention time increased. Typical sample line diameters that have worked well have been between ½ and ¾ inch (13 and 19 mm). Locating the analyzer as close as possible to the sample inlet point is generally advisable. Detention time should be short enough to ensure that the measured residual is at least 90 percent of the actual residual inside the contactor.
	B. Promote constant flow rate. Eliminate restrictions in sample piping if debris or particles can enter piping. Eliminate entry or development of bubbles in sample line that might cause loss of flow due to gas binding. Provide dedicated meters to each sample point. Provide means to physically verify sample flow rate.
	C. Promote representative sample. Locate sample inlet in the direct flow path of the cell outlet at a point that best represents residual from that cell.
	D. Provide means to back-flush and clean sample lines.
	E. Minimize ozone off-gassing from drain line. This may be accomplished with enclosed drain piping so that sample line discharge does not splash and flow in an open channel to a drain.
2. What are key requirements for obtaining a suitable grab sample?	A. Minimize detention time and avoid splashing. A workable arrangement is to use a tee on the main sample line and install a short, small diameter sample tube with shut-off valve.
	B. Locate points for grab samples strategically. A suitable location is immediately after the on-line analyzer. An alternative or supplemental location is where the sample line exits the contactor.
3. What are sampling system arrangements that will facilitate control of ozone system performance?	A. Consider using two on-line analyzers per contactor when ozone is added to the first cell only. Use analyzer 1 at cell 1 and analyzer 2 at a downstream sample point. Calculate decay rate using first-order reaction kinetics and CT value using log-integration methodology. When ozone is added to multiple cells, then an analyzer must be located at the outlet of each ozone addition cell.
	B. Monitor results with SCADA. Report ozone residuals using time-averaged results to minimize fluctuations. Calculate and display residuals, disinfection credit, and Performance Ratio (PR).

All gas flowmeters should be accurate, but correctness is essential when meters are used to monitor ozone optimization status (i.e., determine unit-volume operating cost, $/MG). Gas flow measurement accuracy considerations are described in Appendix A. A summary checklist of design-related considerations for gas flowmeters is presented in Table 3-3.

Table 3-3
Checklist of Design Considerations for Gas Flowmeters

Consideration	Comment
1. What about rotameters?	A. Rotameters usually are accurate if data are handled properly. For example, the indicated flow must be corrected for flowing gas pressure and temperature (see Appendix A). B. Rotameters usually provide local flow indication only and do not report flow to the SCADA system.
2. What about mass-flow and vortex meters?	A. Mass-flow and vortex meters have many advantages and are used often. Advantages include accurate readings without correction for variations in flowing gas temperature and pressure. B. SCADA display and use of accurate flow might be obtained with the signal from a single meter. Mass-flow and vortex meters have a better turndown range than an orifice plate. C. Mass-flow and vortex meters must be installed properly or gas flow readings **might be inaccurate**. D. Mass-flow and vortex meters cannot be field-calibrated independently. Accuracy of mass-flow and vortex meters must be field-verified with other meters, such as an orifice plate (see Appendix A) E A single orifice plate strategically located on the process flow piping might be used to field-verify meter accuracy.
3. What about an orifice plate?	A. Orifice plates have many advantages and are used often. The primary advantage is that accuracy can be field-verified. B. SCADA display and use of accurate flow cannot be obtained with the signal from a single meter. Orifice plate flow-correction involves adjustment for variable flowing gas temperature and pressure and also for ozone concentration when the orifice plate is located after the ozone generator (see Appendix A). C. Orifice plate accuracy is lost at turndown operating conditions (i.e. flow rates less than 33 percent of the maximum rated flow; see Appendix A). Flexibility should be provided to expand the flow range, as applicable, by replacement with a smaller-sized plate or by installing a parallel line that has a smaller-sized orifice plate. D. A single orifice plate strategically located on the process flow piping might be used to field-verify accuracy of other meters, such as mass-flow and vortex meters.
4. What about gas flowmeter location?	A. Provide accurate gas flowmetering on the common feed-gas line to all ozone generators, as a minimum. B. Provide accurate gas flowmetering on the gas inlet side of each ozone generator to determine generator specific energy correctly when multiple generators are in service. C. Provide meters to individual contactors that are in relative agreement; exactitude is unnecessary.

Indiscriminate application of precision gas-flowmeters is capital-intensive and should be avoided. Potential discriminatory situations are described below.

1. As a minimum, provide accurate gas flowmetering on the single feed-gas line to all ozone generators. Total gas flow and combined generator ozone concentration determines total ozone production. Total production, total power (kW), and price of energy and LOX determines unit-mass cost of operation ($/lb) which, combined with water flow rate, identifies unit-volume cost of operation ($/MG). Unit-volume cost of operation is one measure of optimization status (see Chapter 4). It should be noted that individual generator specific energy (kWh/lb) could only be evaluated when one generator is operating.

2. Provide accurate gas flowmetering for each ozone generator to correctly determine generator specific energy when multiple generators are in service. Generator specific energy trending might be used to establish preventive maintenance schedules (see Phase 2 report, Chapter 3, pg. 3-30). An accurate meter for each generator is unnecessary if a single precision meter (see No. 1 above) can be used periodically to determine individual generator specific energy (e.g., once per month).

3. Gas flow rate to ozone contactors is used to balance or control relative ozone dose. Meters to individual contactors must be in relative agreement, but exactitude is unnecessary.

Gas Phase Ozone Concentration Meters

The ultraviolet (UV) meter is commonly used for on-line measurement of ozone gas phase concentration. A summary checklist of design-related considerations for ozone concentration meters is presented in Table 3-4. The UV meter is self-calibrating and generally maintains accuracy. Some meters self-calibrate automatically and continually, and others self-calibrate when initiated by the operator. Installing piping for the reference gas (i.e., zero reference) is a design feature that supports self-calibration.

Ozone concentration meter reading correctness depends on span adjustment for sample cell pressure and temperature, as discussed in Appendix B. Field-verification of meter accuracy, using the KI wet-chemistry procedure, is recommended at start-up to ensure proper meter functioning. A field-verification protocol is described in Appendix B.

Table 3-4
Checklist of Design Considerations for Ozone Concentration Meters

Consideration	Comment
1. What about accuracy of UV ozone concentration meters?	A. Check accuracy at start-up to field-verify meter installation and operation. The UV ozone concentration meter is self-calibrated and is accurate if installed properly and operating correctly. B. Field-verification might be performed using KI wet-chemistry tests, as discussed in Appendix B.
2. How might ozone concentration meters be utilized?	A. Provide at least one meter on the common product-gas line from all generators. B. An enhancement to Item A is to provide a second meter to double-check the reading from the first meter continuously. The second meter also could be used periodically to check the ozone concentration from individual generators when two or more generators are on-line (i.e., sample lines could be directed to the second meter from individual ozone generators). C. The most expensive option is to provide an ozone concentration meter at the outlet of each ozone generator, and possibly on the common line as well. This approach will facilitate development of ozone generator performance trends using the SCADA system (see Chapter 4 for alternative methods of developing performance trends using spreadsheets).
3. What about delay time in registering changes in ozone concentration?	A. The delay time in updating ozone concentration depends on detention time in the ozone gas sample line, which is affected by meter location, sample line size, and sample flow rate. B. The delay time in updating ozone concentration might affect controllability of the ozone process when the meter is a major component in the automated control system (see Chapter 6).

Ozone concentration meters are fairly reliable but might fail unexpectedly and register a low ozone concentration (e.g., failure might occur due to electronics board malfunction or sample/zero-reference switching valve failure). If the meter is used to control generator power automatically (see Chapter 6), the generator power might increase significantly upon meter failure. Design features should be available to prevent unnecessary increases in generator power during automatic control. Example features include using an alternative approach for automation, as discussed in Chapter 6, providing a back-up ozone concentration meter, or providing alarms and stop-points for sudden and large changes in generator power.

Indiscriminant application of ozone concentration meters is capital-intensive and should be avoided. Several alternatives are described below.

1. As a minimum, provide one ozone concentration meter on the common ozone product-gas line from all ozone generators (see previous discussion above regarding gas flow instrumentation).

2. Consider providing parallel ozone concentration meters on the common ozone product-gas line from all ozone generators so that the second meter might double-check the first meter. This approach is most helpful when the ozone concentration meter is a critical instrument for process automation (see Chapter 6). Provide sample piping from individual ozone generators to the second meter to allow the plant staff to determine individual generator specific energy periodically when multiple generators are in service (see also discussion above regarding gas flow instrumentation).

3. Provide ozone concentration meters for each ozone generator if the SCADA system is to monitor performance (e.g., specific energy) continuously from individual ozone generators. This approach will increase the number of meters but supports an owner’s decision to utilize SCADA for documentation of ozone generator efficiency trending. An alternative approach to ozone generator efficiency trending is to manually collect individual generator flow, concentration, and power data periodically and assess efficiency using a spreadsheet program, as discussed in Appendix B of the Phase 2 report and Chapter 4 of this report. This alternative approach to ozone generator efficiency trending might allow installation of fewer ozone concentration meters.

The ozone concentration meters do not provide instantaneous updates of actual operating concentration. The delay time in concentration update depends on detention time in the ozone gas sample line. Meter location, sample line size, and sample flow rate are factors affecting gas sample detention time. The delay time for updating ozone concentration might affect controllability of the ozone process when operating in automatic control, as discussed in Chapter 6. The detention time should be minimized when the ozone concentration meter is a major component in the automated control system, such as for the constant concentration automation approach.

Generator Power Meters

Power demand information is required in order to assess optimization status with respect to unit-volume cost of operation ($/MG) and generator loss-of-efficiency trend. Gas flow and ozone concentration readings are also needed, as well as price of energy and liquid oxygen (LOX). For LOX oxygen-fed ozone systems, generator power is by far the biggest energy-consuming component. Other energy-consuming equipment includes the off-gas blower, off-gas destruct unit, instrumentation, controls, etc. Optimization of LOX oxygen-fed ozone systems is achieved by assessing and controlling generator power. As such, dedicated power meters are essential for monitoring ozone generator power demand and energy usage, but might not be necessary to assess power for other equipment.

Air-fed and on-site oxygen-fed ozone system energy consumption might be greater for equipment other than the ozone generator(s), depending on system design and operation (see Phase 2 report, Chapter 3, page 3-24). As such, power demand and energy consumption instrumentation for both the ozone generator and gas treatment equipment **would be utilized** during an optimization program for air-fed ozone systems. Refer to Chapter 4 for alternative methods of monitoring optimization status of ozone systems.

Process Controllability

Adjusting gas flow and generator power controls the ozone process. Control might be automated, but ozone automation is often abandoned. Most ozone systems are controlled manually. Phase 3 special study results regarding ozone automation are presented in Chapter 6. A checklist of design-related considerations for improving process controllability is presented in Table 3-5.

Table 3-5
Checklist of Design Considerations for Process Controllability

Consideration	Comment
1. What about ozone automation?	A. The constant flow automation control alternative discussed in Chapter 6 was patterned after successful manual control strategies that achieved steady-state disinfection performance. B. Constant flow automation uses feed-forward control techniques to improve system responsiveness during major changes in process control, such as changes in water flow rate.
2. Where should gas flow be controlled?	A. Gas flow rate to individual contactors likely will be different to maintain equivalent disinfection performance. B. Positive flow control at the contactor inlet will enhance disinfection performance optimization.
3. How should gas flow be controlled?	A. Install specially designed flow control valves that maintain steady flow. Provide controllability at low flow conditions with parallel, smaller-sized valves, if necessary. B. Install a pressure-regulating valve (PRV) that maintains unvarying pressure. Provide controllability at low flow conditions with a parallel, smaller-sized PRV, if necessary.

Ozone Automation

Automatic control was abandoned in several ozone facilities. Ozone systems might operate successfully in manual control mode, but plant staff prefer a functional automation system in order to reduce operating safety factor and free-up staff for other duties. Nearly steady-state disinfection performance has been documented during manual control by holding gas flow constant for set-point water flow rates (i.e., for several hours in the absence of significant water flow changes) and adjusting generator power slightly about once or twice per hour. The positive attributes of manual operation were used to develop the alternative automation strategy discussed further in Chapter 6, called constant flow automated control. Optimization is achieved using constant flow automated control because minimum operating cost is obtained over a fairly wide range of ozone concentration.

Gas Flow Control

Emphasizing gas flow control will greatly assist ozone optimization. Many options exist to control flow. Control options might be different for an air-fed ozone system of a certain design than for a differently designed air-fed system or an oxygen-fed ozone system. Workable options are described below, based on observations during Phases 1 and 2 of the research project. However, other options might achieve similar or possibly better results.

Air-fed ozone systems might have one or more constant speed, constant volume air compressors. With this design the air flow rate is dictated by number of compressors on-line. Gas flow control consists of balancing flow to multiple generators and distributing flow to multiple contactors. Achieving balanced flow to generators is a good idea but does not significantly affect optimized performance. Good control of flow distribution to ozone contactors is critically important. Ozone contactor gas flow control involves adjusting gas flow, as necessary, to achieve equivalent performance (e.g., ozone residual profile, CT value, and disinfection credits). Equal gas flow to operating contactors seldom is observed. Required gas flow rates to multiple contactors might vary by about 10 percent. Contactor gas flow distribution might be controlled effectively using high quality flow control valves and appropriate gas flowmetering (see discussion above regarding measurement of gas flow to individual contactors).

Some air-fed and all oxygen-fed ozone systems utilize variable-volume gas flow control. Air-fed ozone system air compressors might use variable speed operation to maintain controlled flow. Other air compressor arrangements and most oxygen-fed ozone system designs adjust flow rate through pressure control devices. For example, the gas flow rate for the LOX oxygen-fed ozone system is typically adjusted by a flow control valve at the contactor or generator. This causes a pressure change on the downstream side of the pressure-regulating valve (PRV) located between the liquid oxygen vaporizers and the ozone generators. The PRV adjusts the total oxygen gas flow rate from the LOX tank to maintain the set-point pressure. The type and size of PRV and flow control valves must be designed to provide steady-state operation at low flow as well as design flow conditions. A smaller-sized and design-sized PRV valve in parallel might be necessary if the expected flow range is too large for smooth functioning of a single PRV valve.

The location of gas flow control valves is an important decision for pressure regulation type flow control systems. Control point options include the ozone generator inlet, generator outlet, and contactor inlet. Good controllability has been observed when the flow control point is on the inlet piping to individual ozone contactors. Positive flow control at the contactor inlet using high quality flow control valves plus good flow measurement will facilitate disinfection performance optimization. Less sophisticated control valves might be acceptable at the ozone generators. Indeed, ozone generator flow might be balanced sufficiently even when inlet and outlet valves are fully open. Natural pressure drop across the ozone generators might perform well as a flow control device. If not, closing adjustments might be made using inlet or outlet valves on generators receiving too high flow. The valve on the generator with the lowest flow rate would be fully open.

Process Flexibility

Process flexibility involves equipment sizing and providing piping flexibility to maintain optimum performance at low flow as well as design flow conditions. Potential optimization areas of involvement identified during Phases 1 and 2 are listed below. A checklist of design-related considerations for improving process flexibility is presented in Table 3-6.

1. Maintaining energy efficient operation at turndown flow for air-fed ozone systems and oxygen-fed ozone systems where oxygen is produced on-site.
2. Selecting the number of ozone contactors in operation separately from number of water treatment trains in service.
3. Controlling gas flows to oxygen-fed ozone systems at low flow conditions.

Table 3-6
Checklist of Design Considerations for Process Flexibility

Consideration	Comment
1. What are ways to minimize air-fed ozone system specific energy at low flow conditions?	A. Provide flexibility in air treatment operation to reduce power demand in proportion to gas flow rate. B. See air treatment system Case Histories in Phase 2 report Chapter 3, page 3-24 and Phase 2 report Appendix D.
2. What are considerations for selecting the number of ozone contactors in operation?	A. Provide flexibility to select the number of ozone contactors on-line independently from the number of downstream treatment trains (e.g., sedimentation basins). B. This flexibility is helpful because optimization might be achieved by reducing hydraulic detention time in the ozone contactors (see Phase 2 report, Chapter 3, page 3-13) while at the same time operating all downstream treatment trains.
3. What about process flexibility for oxygen-fed ozone system optimization?	A. Provide flexibility in **on-site** oxygen generation equipment to reduce power demand in proportion to gas flow rate, as with air-fed ozone systems. B. LOX oxygen-fed ozone system efficiency generally is maintained at turndown operation. However, gas flow control might be an issue (see discussion in this chapter regarding Process Controllability).

4

OPTIMIZATION DURING OPERATION

Optimized performance might be achieved by implementing the two-step process outlined below. In this chapter the principal components of an optimization monitoring program are described. Also discussed are practical operating strategies that might lead to optimized performance. A checklist of operating considerations for ozone optimization is shown in Table 4-1.

1. Develop a monitoring program that tracks optimization status.

2. Implement operating strategies that achieve optimized performance.

Ozone Optimization Criteria

The goal of ozone operation is to achieve performance objectives at minimum operating cost. Optimization criteria are defined by Performance Ratio (PR) and unit-volume operating cost ($/MG). Calculating, monitoring, and trending these two parameters will document optimization status and will assist in quantifying improvement due to operational changes that might be made.

Performance ratio is measured disinfection credit divided by target credit. A PR of 1.0 means that measured disinfection credit is equal to target credit. A PR less than one means that required performance is not met and ozone dose should be increased. A PR of 10 or 20 (see Phase 2 report, Chapter 3) means that measured performance is much greater than necessary and that ozone dose and operating cost might be reduced. Methods to calculate CT value and disinfection credit are described in the Phase 2 report, Chapter 2. Data for an ozone system operating with an optimized PR is discussed in Appendix B of the Phase 2 report.

Table 4-1
Checklist of Operating Considerations for Ozone Optimization

Consideration	Comment
1. What are ozone optimization criteria?	A. Performance optimization is measured by Performance Ratio (PR). The operational objective is to control PR at or above 1.0. B. Cost optimization is measured by unit-volume operating cost ($/MG). The goal is to maintain required performance at the lowest possible operating cost.
2. What about monitoring optimization status?	A. Ozone residuals, water flow rates, and water temperature are used to calculate Performance Ratio. B. Gas flow rate, ozone concentration, generator and other power, and water flow rates are used to calculate unit-volume operating cost ($/MG). C. Continuous monitoring of optimization status on the SCADA system is nice, but might not be cost effective due to extra instrumentation required to support the effort. D. Periodic but routinely scheduled monitoring of optimization criteria using spreadsheets might provide good insight into optimization status.
3. What might be components of a model program for ozone optimization?	A. Plant administration support and encouragement for optimization, including periodic review/update of optimization status. B. Design features and flexibility that support optimization criteria and provide for steady-state operation with automated control. C. An optimization “champion” or teams to lead the project. D. Operations staff who monitor optimization status to achieve and maintain optimized performance.

Unit-volume operating cost ($/MG) is determined from unit-mass cost of ozone ($/lb) multiplied by ozone dose (lb/MG, which is ozone dose in mg/L • 8.34 lb/gal). Unit-mass cost of ozone includes specific energy (kWh/lb); price of energy ($/kWh); oxygen usage (lb O_2/lb O_3, which is the inverse of ozone concentration in % wt); and price of LOX ($/lb O_2). Implementing optimization strategies might lower unit-volume operating cost, as shown in Figure 4-1. The Canal Road Water Treatment Plant lowered unit-volume operating cost from $20/MG to $12/MG by modifying the operation of their ozone system, as discussed in Appendix D of the Phase 2 report.

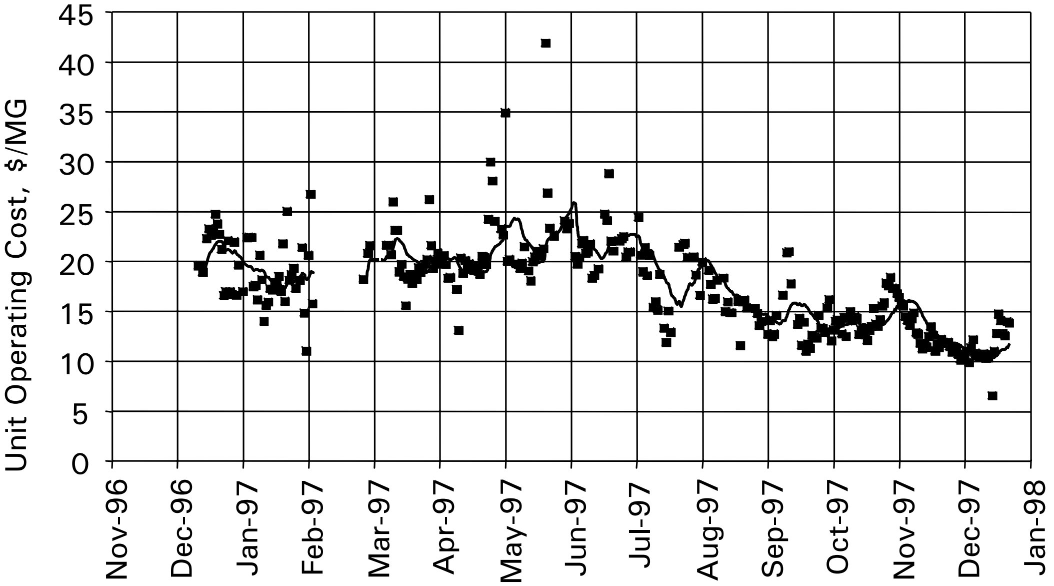


Figure 4-1
Unit-Volume Operating Cost at the Canal Road Water Treatment Plant, Somerset, New Jersey

Measuring Ozone Optimization Status

Instrumentation required for calculating optimization criteria was discussed in Chapter 3 of this report and includes gas flowmeters, ozone concentration meters, power demand or watt-hour meters, water flowmeters, and ozone residual analyzers. Developing and maintaining accurate meter readings are critically important for valid interpretation of optimization status. Incorrect readings have occurred mostly with ozone residual analyzers. Gas flowmeters were incorrect in a few plants. Ozone concentration meters and power demand and watt-hour meters have performed well, although they gave incorrect readings on occasion. Water flowmeters generally were accurate.

Ozone residual analyzers were studied during Phase 3; results are presented in Chapter 7. The most important operational considerations for ozone residual analyzers are summarized in Table 4-2. Most importantly, analyzer design and installation setup must be correct (see Chapter 3 and Chapter 7) and analyzer accuracy should be assessed routinely (e.g., once per week) using several grab sample laboratory tests (see Chapter 7 for discussion of analyzer calibration protocol).

Table 4-2
Checklist of Operating Considerations for Ozone Residual Analyzers

Consideration	Comment
1. What about ozone residual analyzer accuracy?	A. Ozone residual analyzers have demonstrated good performance when properly installed (see Chapter 3 and Chapter 7 for installation considerations). B. The average of several grab samples should be used to assess analyzer accuracy (see Chapter 7). Comparisons of a single reading versus a single grab sample might yield widely differing results.
2. What are ways to document acceptability of ozone residual analyzers for reporting disinfection compliance?	A. The analyzer should be standardized at least weekly using the protocol discussed in Chapter 7. B. Analyzer acceptability for reporting disinfection compliance should be judged by comparing: 1) CT value or PR in a percentage distribution chart (see Chapter 7) or 2) comparative ozone residual averages. Single-test ozone residual comparisons are unsatisfactory.

The residual analyzer is the one instrument in the ozone system that must be standardized routinely (e.g., weekly). The other meters generally maintain accuracy unless the installation is modified. However, their accuracy should be field-verified during start-up or at the beginning of an optimization program. Field-verification procedures for gas flow and ozone concentration meters are discussed in Appendices A and B, respectively, of this report (see also Chapter 3). Power demand or watt-hour meters may be field-verified using a calibrated portable power meter that might be available from the local electric utility, from another department within the water utility, or from a rental agency.

Acceptance of residual analyzer readings for reporting disinfection compliance is an objective at most water utilities. Operating managers are interested in comparing residual analyzer readings with grab sample results to demonstrate analyzer adequacy. A special study of this nature was conducted during Phase 3; results are reported in Chapter 7. The major finding of the study is that comparison of single test results is unsatisfactory. For example, the chart in Figure 4-2 might be interpreted as poor correlation between the analyzer reading and grab sample result. However, the variation shown in Figure 4-2 is due largely to actual fluctuation of residuals within the contactor, as discussed in Chapter 7. A better evaluation approach for assessing adequacy of analyzer readings is to compare averages of several grab samples and analyzer readings, as shown in Figure 4-3. Results in Figure 4-3 show that most data points are within ±10%. An even better approach might be to compare disinfection Performance Ratio (PR), as shown in Figure 4-4. The chart in Figure 4-4 shows that PR was alike, whether determined from analyzer readings or grab samples for the 186 tests during the month (i.e., six tests per day for 31 days). Based on the chart in Figure 4-4, it can be said that it might be acceptable to use either analyzer readings or grab sample laboratory tests to report disinfection compliance.

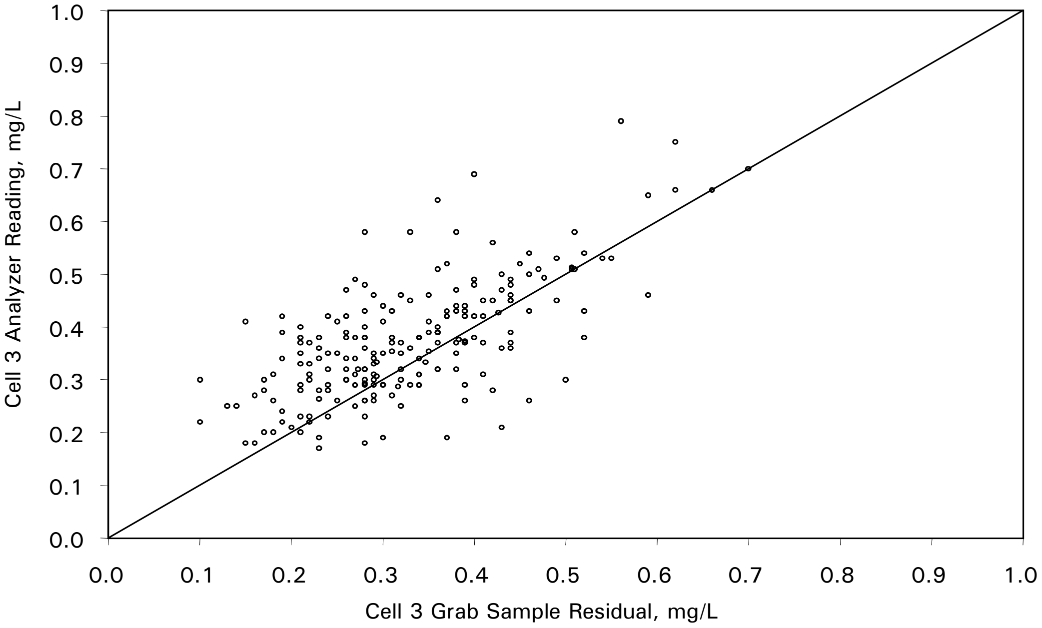


Figure 4-2
Comparison of Cell 3 SINGLE-TEST Ozone Residuals

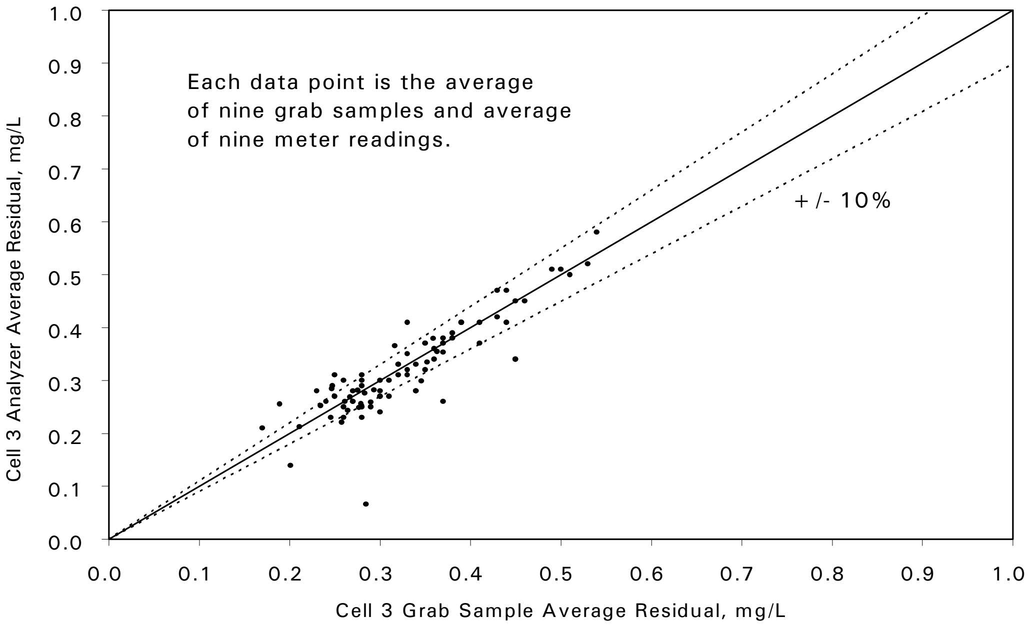


Figure 4-3
Comparison of Cell 3 AVERAGE Ozone Residual

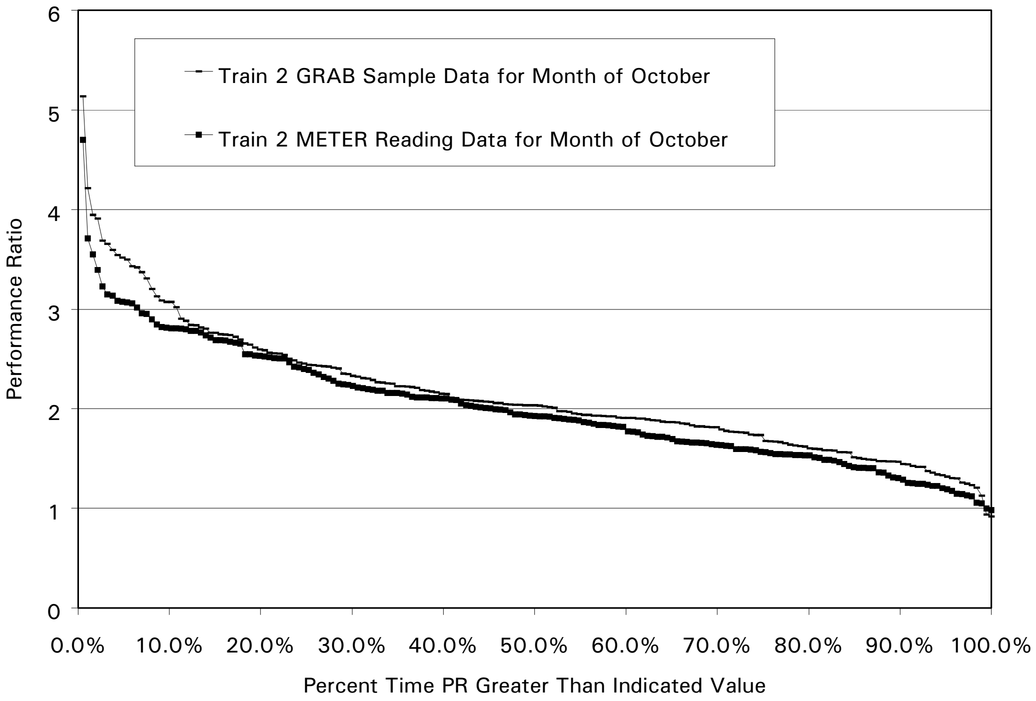


Figure 4-4
Comparison of Performance Ratio for GRAB Versus METER

Model Program for Ozone Optimization

A checklist of ideas regarding a model program for ozone optimization is outlined in Table 4-3. The ideas are based on observations during Phases 1 and 2 of the research project, Phase 3 special study results, and experience gained from optimization follow-up projects conducted outside of this research project. The ideas might represent a starting point in an optimization program. Individual projects might modify or expand upon these ideas to enhance results for site-specific situations.

Table 4-3
Checklist of Ideas Regarding a Model Program for Ozone Optimization

Consideration	Comment
1. Identify/select an optimization "champion" or optimization team.	A. The "champion" or team should lead the optimization effort. B. Plant administration and peer support should be solicited.
2. Identify a performance target that: (1) is related to water quality, (2) is easy to measure, and (3) provides instant feedback.	A. General and operations-related performance objectives are insufficient, as discussed in the Phase 2 report, Chapter 3, page 3-2. B. Disinfection performance criteria (e.g., 1-log or 3-logs *Giardia* cyst inactivation credit) meet the conditions for an optimization performance target, since CT tables are available for *Giardia* cyst inactivation credit. C. If enhanced disinfection for *Cryptosporidium* oocyst inactivation credit is an operating goal, then CT value targets might have to be developed based on current research.
3. Monitor performance using Performance Ratio and select an operating safety factor.	A. Performance Ratio is the ratio of measured disinfection versus target disinfection. B. PR must be greater than 1.0 at all times. C. An operating safety factor might be 1.2, 1.5, or another value to ensure the PR always is greater than 1.0. Safety factor will depend on PR fluctuations due to site-specific conditions (See Phase 2 report, Appendix B).
4. Develop reliable on-line residual analyzer performance and utilize analyzer readings to calculate CT value. See Chapter 7 for additional information regarding ozone residual analyzers.	A. Ensure analyzers are designed and installed correctly. B. Standardize analyzers routinely (e.g., weekly). C. Confirm validity of analyzer readings for determination of disinfection credit by comparing PR as opposed to comparing single-test residual readings. D. Strategically locate analyzers to calculate CT value using an acceptable minimum number of meters. For example, two analyzers per contactor might be used to calculate CT value using log-integration methodology, as discussed in Chapter 2 of the Phase 2 report and in Chapter 5 of this report.

Consideration	Comment
5. Verify accuracy of instrumentation used for determining unit-volume operating cost?	A. Gas flowmeter accuracy is discussed further in Appendix A. B. Ozone Concentration meter accuracy is discussed further in Appendix B. C. Power demand and watt-hour meter accuracy might be verified using calibrated portable units.
6. Monitor optimization status using a spreadsheet-based monitoring program. Report optimization status within the SCADA system at a later date, if necessary.	A. The monitoring program not only should calculate and report optimization status for the data point in question but also should provide flexibility to post individual data to a database from which trends in performance might be viewed. B. A monitoring program example is shown in Appendix B of the Phase 2 report.
7. Implement optimization techniques as needed. Obtain ideas from several sources.	A. Consider conducting a formal Ozone Facility Evaluation as discussed in the Phase 1 report. B. Review and evaluate ideas that are outlined in the Phase 2 and Phase 3 reports. C. Develop and discuss optimization ideas internally. D. Solicit ideas from other operating utilities, from plant-specific training programs, and from conferences and seminars.

5

IMPACT OF DEMAND/DECAY ON OZONE OPTIMIZATION

Some ozone systems operate at significant turndown conditions (Rakness and DeMers, 1998) because operating dose is much lower than design dose. Design dose might be high due to conservative design risk tolerance. However, pilot-study data also might yield misleadingly high dosages depending on how the pilot plant was operated. Ozone demand/decay reactions affect ozone system design criteria significantly. High demand and rapid decay will increase design dose. Rate of ozone decay should influence contactor size and shape. In this chapter demand/decay impacts are discussed relative to design criteria for optimizing ozone contactor and generator size.

Different methods have been used to conduct ozone demand/decay tests (Hoigné and Bader, 1994) (Roustan et al., 1998) (Richard, 1994) (Carlson et al., 1997). Each has merit and, if interpreted properly, might be used successfully to develop design ozone dose. The bench-scale testing method used for this study was based on procedures discussed initially by Hoigné and Bader (1994) and described further by Carlson (Carson et al., 1997). Comparing bench-scale methods is NOT the goal of this special study. The primary focus is on interpretation of bench-scale and pilot-scale data to establish optimized design criteria for ozone dose and contactor size/shape.

Bench-Scale Testing

Dean Gregory[1] conducted bench-scale ozone demand/decay tests at the City of Fort Collins, Colorado Water Treatment Plant laboratory. Waters from four full-scale and one pilot-scale ozone system were tested. Plant-scale CT value and operating ozone dose data were obtained when water samples were collected. Projected dose to achieve equivalent CT value was determined from bench-scale demand/decay data. Projected dose for all tests was within ±20 percent of plant-scale operating dose.

Data Collection

The bench-scale test apparatus is shown in Figure 5-1. Ozone stock solution was prepared at approximately 40-mg/L residual by bubbling high-concentration ozone (about 8-10% wt) into distilled water for about one hour. The stock residual began to decay at a slow rate after ozone bubbling was stopped. Decay rate was minimized because the container was immersed in an ice

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[1] Dean Gregory currently is a Ph.D. candidate at Colorado State University under the direction of Dr. Ken Carlson.

water bath. Stock solution ozone residual was determined just prior to delivering a specific volume of stock solution to a known volume of the temperature-controlled water sample. Using this approach, ozone dose was delivered at a controlled, accurate rate.

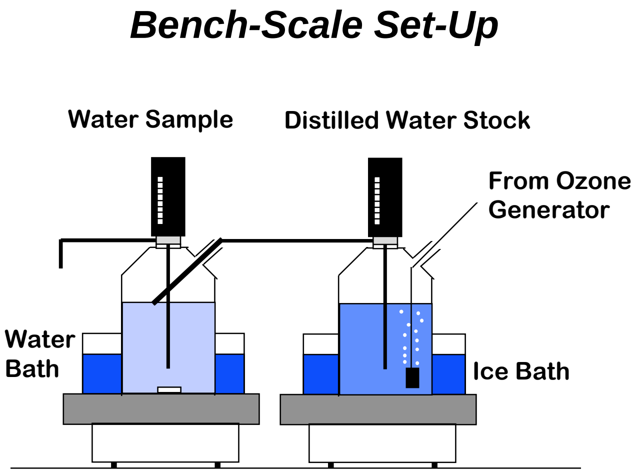


Figure 5-1
Bench-Scale Demand/Decay Test Setup

The stir-bar was shut off ten seconds after stock delivery. Twenty seconds after delivery the first aliquot of water sample was directed into a flask containing a pre-set volume of indigo trisulfonate (*Standard Methods for the Examination of Water and Wastewater*, 1998). Additional samples were collected at specified time intervals of twenty seconds up to one minute, and approximately every minute thereafter for several minutes until residual was less than 0.1 mg/L. Ozone residual was determined for each sample after all samples were collected. The following procedure was used for calculating residuals:

1. A standardization curve was developed for the indigo stock solution by adding a known volume of distilled water to a known volume of stock indigo. An example curve is shown in Figure 5-2.

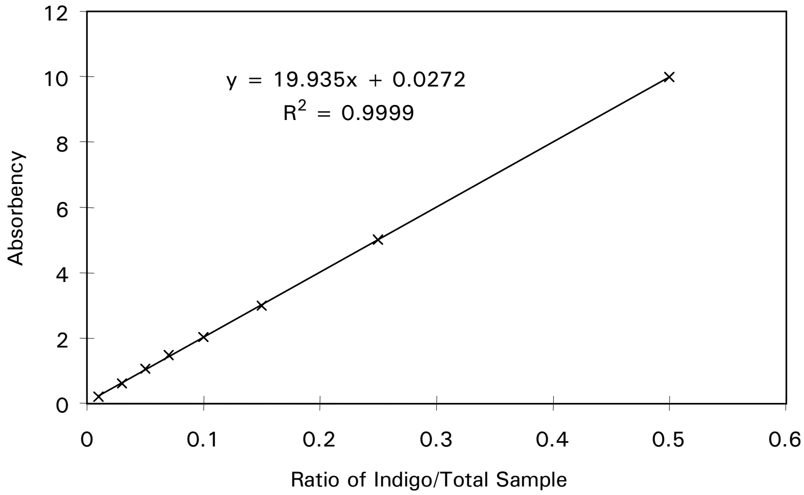


Figure 5-2
Indigo Stock Standardization Curve @ 5 cm

2. The stock solution ozone residual was determined. Example: Indigo sample volume is 45 mL, stock sample volume is 10 mL, and absorbency of mix is 0.785.

   A. Find fraction of indigo to total solution (45 mL ÷ 55 mL = 0.818).

   B. Find absorbency of blank using linear regression equation shown in Figure 5-2 ($19.935 \times 0.818 + 0.0272 = 16.33$).

   C. Find ozone residual of stock solution using Equation 5-1.

$$\text{mg / L} = \frac{(\text{ABS}_{\text{blank}} - \text{ABS}_{\text{sample}}) \times \text{TV}_{\text{sample + indigo}}}{0.42 \times \text{SV} \times \text{b}}$$ **Eq. 5-1**

$$40.7 \text{ mg / L} = \frac{(16.33 - 0.785) \times 55}{0.42 \times 10 \times 5}$$

Where:
b = path length of cell, cm
SV = sample volume, mL

3. Find ozone residual of sample.
   Example: Sample volume is 20 mL, indigo stock volume is 2 mL, and absorbency of sample is 0.805.

   A. Find fraction of indigo to total solution (2 mL ÷ 22 mL = is 0.0909).

   B. Find absorbency of blank using linear regression equation shown in Figure 5-2 ($19.935 \times 0.0909 + 0.0272 = 1.839$).

   C. Find ozone residual of collected sample using Equation 5-1.

$$0.54 \text{ mg/L} = \frac{(1.839 - 0.805) \times 22}{0.42 \times 20 \times 5}$$

Data Development

An ozone residual versus sample time relationship was developed for each test. An example residual versus time profile is shown in Figure 5-3. This profile is representative of other test data and shows that the rate of decay is faster within the first minute of reaction and slower and relatively consistent for the rest of the time. A fast, transitional decay rate within the first minute of reaction has been observed by other researchers (Hoigné and Bader, 1994) (Roustan et al., 1998) (Carlson et al., 1997) (Amy et al., 1997). After one minute, the reaction generally follows first-order kinetics.

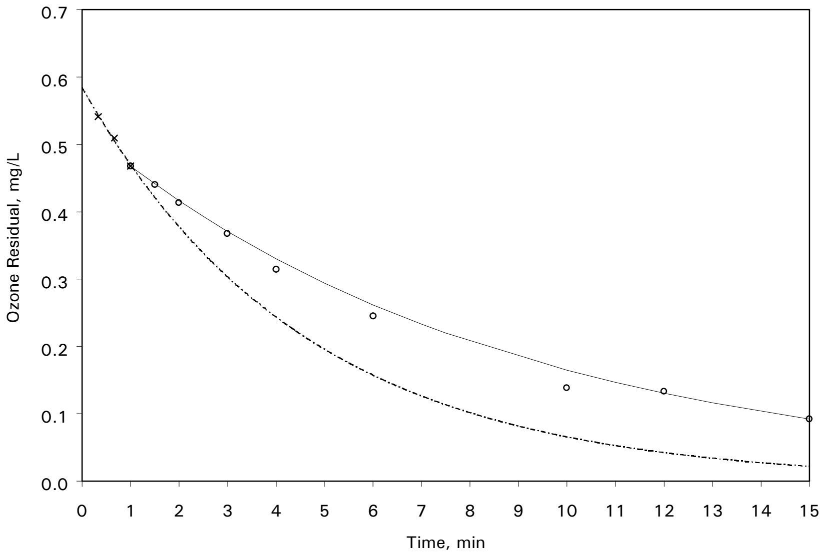


Figure 5-3
Ozone Residual Versus Sample Time Chart for Test 2 of Plant A Water Sample

Ozone dose and half-life were calculated for each test using the following procedure.

1. Find ozone half-life between 60-sec and the end of the test. Example: Residual at 60-sec is 0.47 mg/L and residual at 15-min is 0.09 mg/L.

   A. Find decay rate using Equation 5-2:

$$k = \frac{\mathrm{Ln}\left(\frac{C_T}{C_{start}}\right)}{T} \qquad \textbf{Eq. 5-2}$$

$$k = \frac{\mathrm{Ln}\left(\frac{0.09}{0.47}\right)}{(15 - 1)\ \mathrm{min}} = -0.118\ \mathrm{min}^{-1}$$

   B. Find ozone half-life using Equation 5-3:

$$T_{1/2} = \frac{\mathrm{Ln}(0.5)}{k}$$

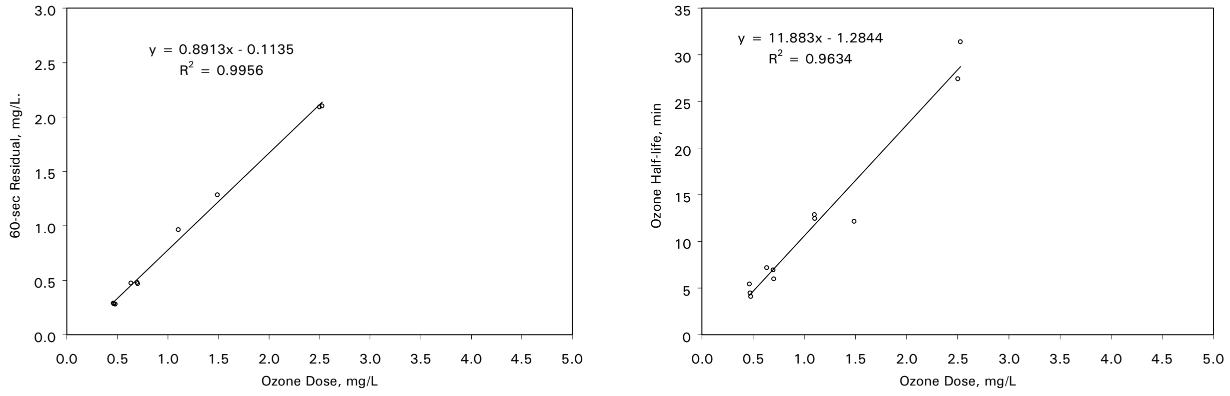
$$T_{1/2} = \frac{\mathrm{Ln}(0.5)}{-0.118\ \mathrm{min}^{-1}} = 5.9\ \mathrm{min} \qquad \textbf{Eq. 5-3}$$

2. Find ozone dose as the ratio of stock added divided by total volume (sample plus added stock) times ozone stock residual. Example: Sample volume is 950 mL, stock volume added is 17.5 mL, and stock ozone residual is 38.8 mg/L.

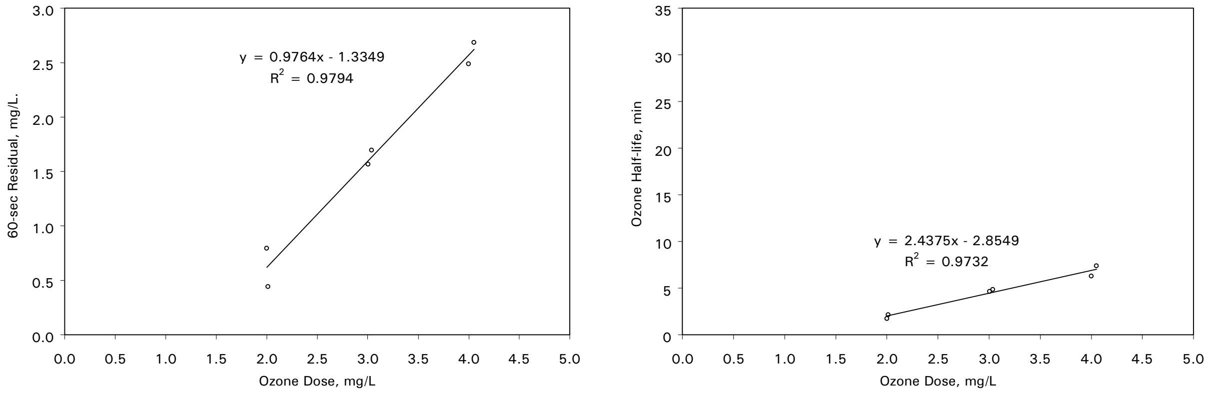
   0.70 mg/L = 38.8 mg/L × 17.5 mL ÷ (17.5 + 950 mL)

Several tests were conducted for each water sample over the range of ozone dose expected for the subject plant. The relationships between ozone dose versus ozone half-life and ozone dose versus 60-second residual were used in subsequent analyses. Results for each set of bench-scale tests are summarized in Figure 5-4. Charts on the left side show that the residual at a sample time of 60 seconds increases in proportion to the ozone dose. Charts on the right side show that the ozone half-life also increases in proportion to the ozone dosage. These relationships were used to project ozone residual profile and CT value for plant-scale ozone contactors, as discussed in the next section of this chapter. Charts are shown with the same scale in Figure 5-4 to illustrate differences in demand/decay profile. Water temperature and pH were recorded when samples were collected. Plant B was operated at ambient pH of 8.1 and also at controlled pH of 6.5.

Plant A - pH = 7.0 & Temp = 6.3°C **Plant A - pH = 7.0 & Temp = 6.3°C**



Plant B - pH = 8.1 & Temp = 11.7°C **Plant B - pH 8.1 & Temp = 11.7°C**



Plant B - pH 6.5 & Temp = 11.7°C **Plant B - pH 6.5 & Temp = 11.7°C**

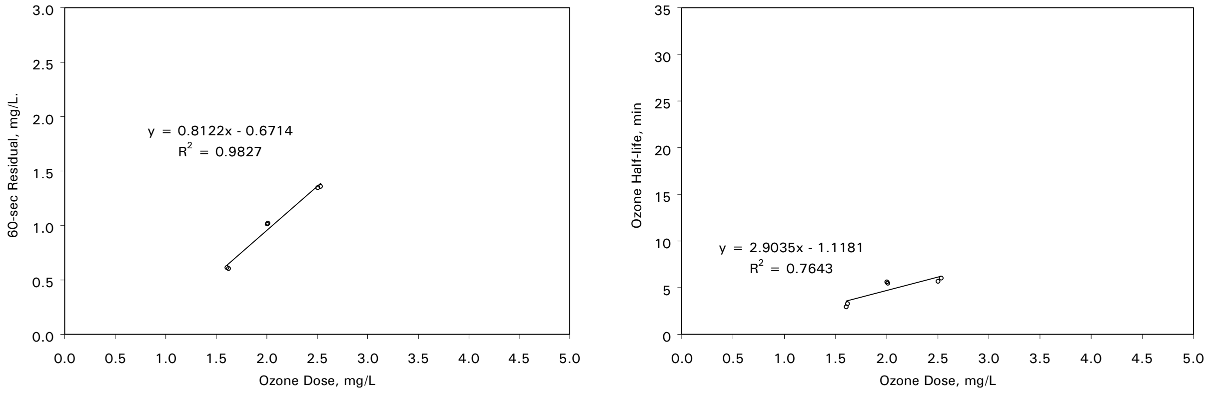


Figure 5-4
Transferred Ozone Dose Versus 60-sec Residual and Ozone Half-Life

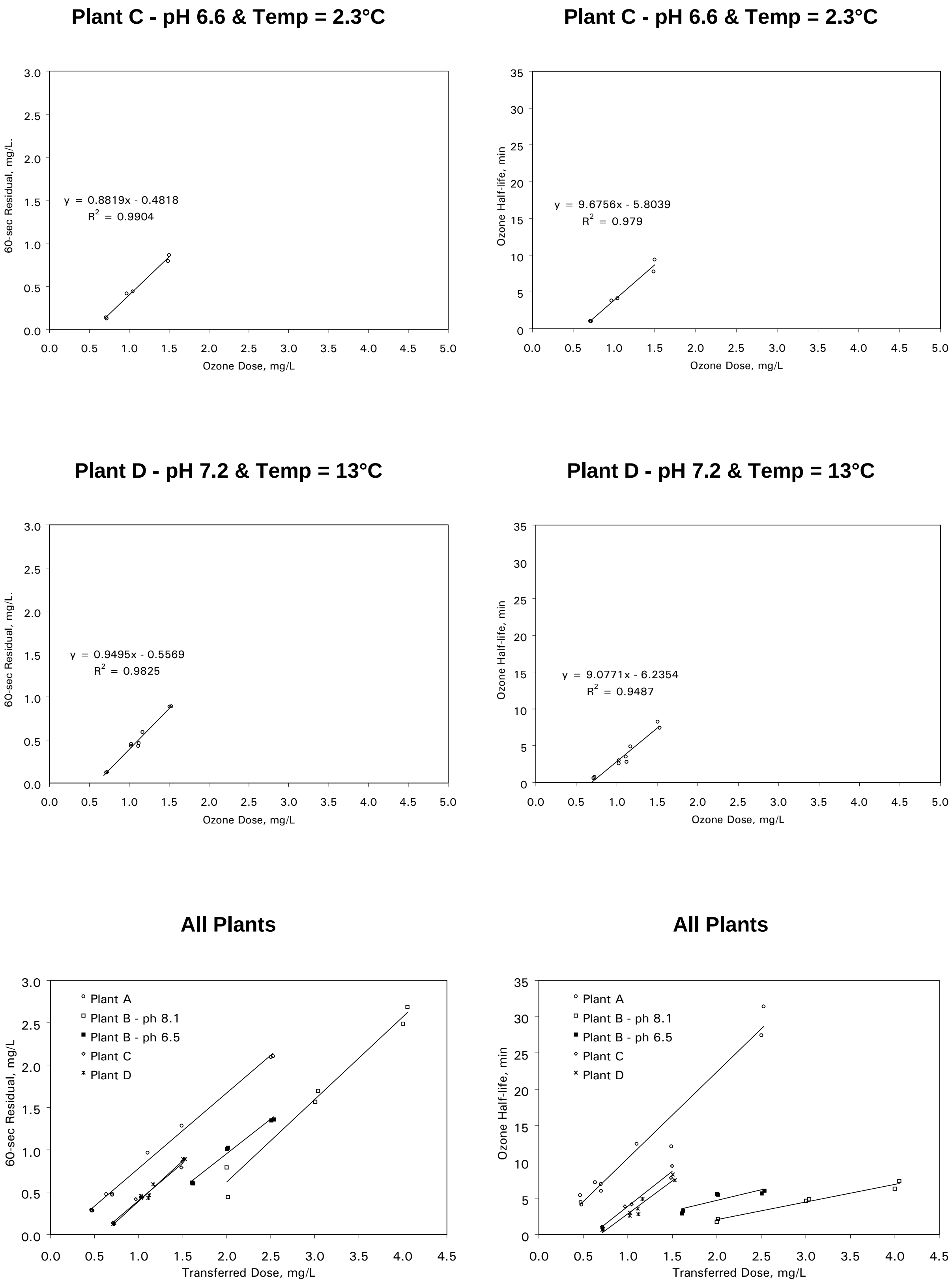


Figure 5-4
Transferred Ozone Dose Versus 60-sec Residual and Ozone Half-Life (cont.)

Calculating CT Value

Plant A applies ozone to a raw water supply. Three bubble diffuser ozone contactors were treating 16.3 MGD (714 L/s) total flow when the water sample was collected. The water temperature was 6.3°C, pH was 7.0, and applied ozone dose was 0.82 mg/L. The ozone transfer efficiency was 86 percent and transferred ozone dose was 0.71 mg/L. Ozone residual measurements were taken at the outlet of each cell of contactor 1. Measured data are shown in Figure 5-5, along with a residual versus time chart relative to side view of the ozone contactor. Measured residuals follow first order decay kinetics; the ozone half-life is 12.2 min. The CT value is 1.80 mg/L•min calculated using log integration methodology (Rakness and DeMers, 1998).

Plant A - pH 7.0, Temperature = 6.3 C and Measured T Dose = 0.71 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	16.3
Water Temperature	C	6.3
# Contactors On-line	#	3
Measured Dose	mg/L	0.82
Transferred Dose	mg/L	0.71
Residual 1	mg/L	0.24
2	mg/L	0.24
3	mg/L	0.16
4	mg/L	0.13
5	mg/L	0.1
6	mg/L	0.11
7	mg/L	0.08
8	mg/L	0.07
Ozone TE	%	86%
Measured Half-Life	min	12.23
Predicted From Bench-Scale Results		
Projected Dose	mg/L	0.82
Transferred Dose	mg/L	0.71
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	11.883
Intercept	min	-1.2844
Bench Half-Life	min	7.10
Bench 60-sec Residual VS Dose		
DoseVS 60-sec Slope	---	0.8913
Inter	mg/L	-0.1135
60-sec Ozone Res.	mg/L	0.515
Comparison of CT		
Measured CT	mg/Lxmin	1.80
Predicted CT	mg/Lxmin	1.99
Percent Difference	%	10.36%

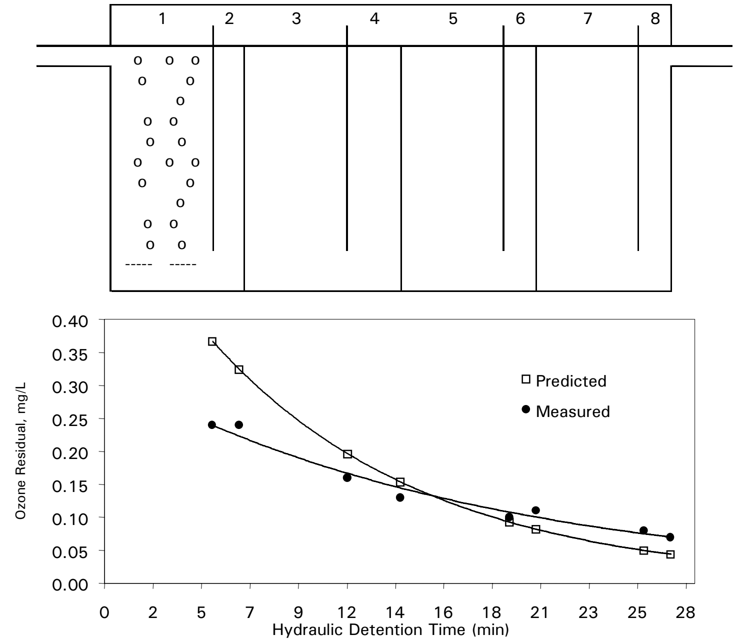


Figure 5-5
Plant A Ozone Residual Profile and CT Value Comparison

The projected ozone residual curve and CT value from bench-scale results were determined as follows:

1. The 60-sec residual was determined using the 60-sec residual versus ozone dose equation shown in Figure 5-4. The projected 60-sec residual is 0.52 mg/L at a transferred dose of 0.71 mg/L (0.52 mg/L = $0.8913 \times 0.71 - 0.1135$).

2. The ozone half-life was determined using the half-life versus ozone dose equation shown in Figure 5-4. The projected half-life is 7.1 min for the transferred dose of 0.71 mg/L (7.1 min = $11.88 \times 0.71 - 1.284$). The decay rate is determined using Equation 5-4.

$$k = \frac{\mathrm{Ln}(0.5)}{T_{1/2}} \qquad \textbf{Eq. 5-4}$$

$$k = \frac{\mathrm{Ln}(0.5)}{7.1\ \mathrm{min}} = -0.0976\ \mathrm{min}^{-1}$$

3. Ozone residual of 0.37 mg/L at the outlet of the ozone dissolution cell (i.e., first cell) was calculated using the mixed reactor decay Equation 5-5 (Roustan et al., 1998). The reaction time was the total detention time of cell 1 (5.1 min) minus one minute (i.e., 60-sec residual was used as the initial residual).

$$C_{\mathrm{outlet\ Cell\ 1}} = \frac{C_{60\text{-sec}}}{1 - kT} \qquad \textbf{Eq. 5-5}$$

$$0.37\ \mathrm{mg/L} = \frac{0.52}{\{1 - [-0.0976 \times (5.1 - 1)]\}}$$

4. Ozone residuals downstream of cell 1 were calculated using the batch reactor decay Equation 5-6.

$$C_T = C_{60\text{-sec}}\ \mathrm{x}\ e^{kT} \qquad \textbf{Eq. 5-6}$$

5. The projected CT value was 1.99 mg/L•min calculated using log integration methodology similarly used with full-scale-plant measured data.

Comparing Predicted Versus Measured Dose

The objective of bench- or pilot-scale testing is to determine required ozone dose to achieve target disinfection objectives. Comparing projected versus measured dose to achieve equivalent CT value assessed the usefulness of bench-scale results in projecting ozone dose. The dose comparison for Plant A is shown in Figure 5-6. The full-scale measured CT value was 1.80 mg/L•min when the transferred dose was 0.71 mg/L. Bench-scale predicted CT value was equivalent (1.81 mg/L•min) when the predicted dose was 0.68 mg/L. Similar comparisons for measured versus predicted dose were completed for other full-scale facility tests. Dose comparison data are summarized in Figure 5-7. Comparative results for individual plant tests are shown in Figure 5-8.

As shown in Figure 5-7, the predicted dose was within ±20 percent of the measured dose for all comparisons, despite wide ranges in operating conditions. Dose was under-predicted slightly, possibly due to a dilution effect that is inherent with the bench-scale test. However, bench-scale testing provides good estimation of full-scale dose requirements and might be used effectively to develop optimized contactor and generator design criteria for meeting target disinfection objectives.

Plant A - pH 7.0, Temperature = 6.3 C and Measured T Dose = 0.71 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	16.3
Water Temperature	C	6.3
# Contactors On-line	#	3
Measured Dose	mg/L	0.82
Transferred Dose	mg/L	0.71
Residual 1	mg/L	0.24
2	mg/L	0.24
3	mg/L	0.16
4	mg/L	0.13
5	mg/L	0.1
6	mg/L	0.11
7	mg/L	0.08
8	mg/L	0.07
Ozone TE	%	86%
Measured Half-Life	min	12.23
Predicted From Bench-Scale Results		
Projected Dose	mg/L	0.79
Transferred Dose	mg/L	0.68
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	11.883
Intercept	min	-1.2844
Bench Half-Life	min	6.79
Bench 60-sec Residual VS Dose		
DoseVS 60-sec Slope	---	0.8913
Inter	mg/L	-0.1135
60-sec Ozone Res.	mg/L	0.492
Comparison of CT		
Measured CT	mg/Lxmin	1.80
Predicted CT	mg/Lxmin	1.81
Percent Difference	%	0.82%

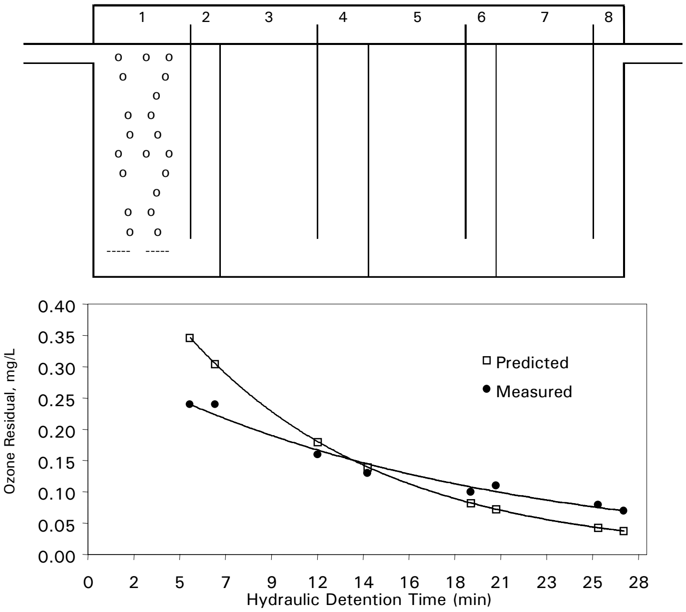


Figure 5-6
Predicted Dose for Equivalent CT Value at Plant A

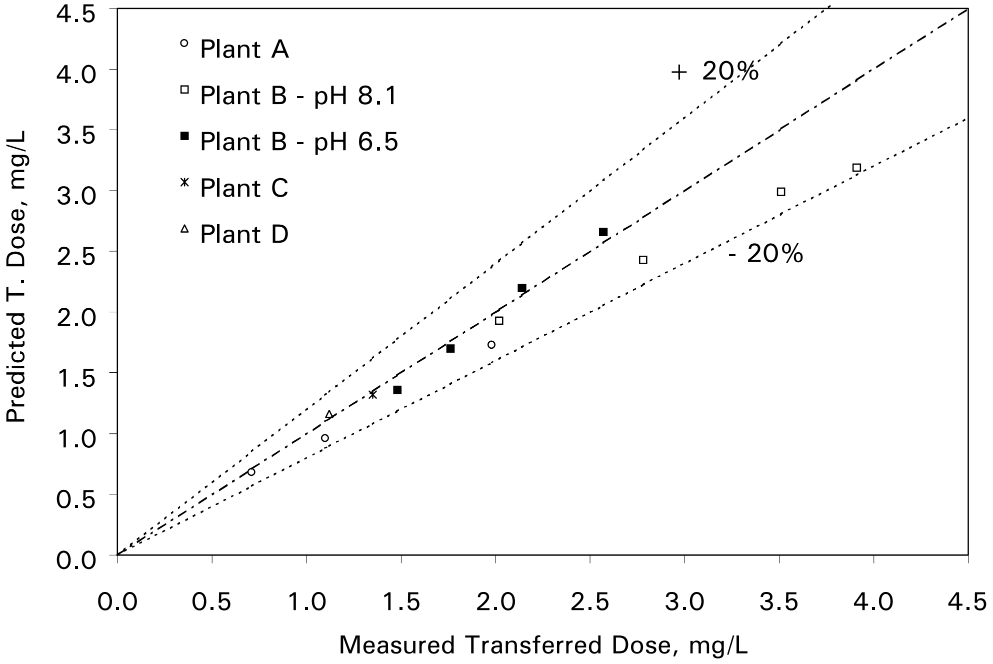
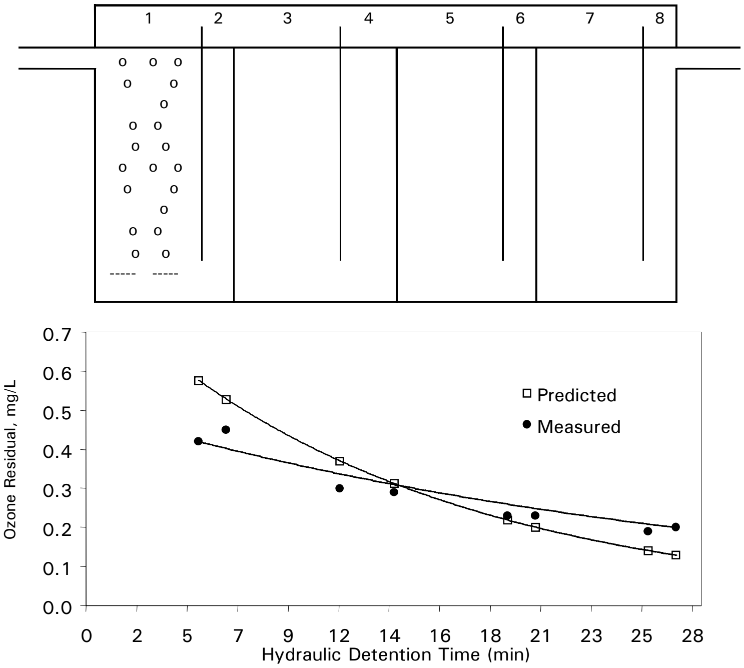


Figure 5-7
Bench-Scale Predicted Versus Full-Scale Measured Dose to Achieve Similar CT Value

Plant A - pH 7.0, Temperature = 6.5 C and Measured T Dose = 1.1 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	16.3
Water Temperature	C	6.5
# Contactors On-line	#	3
Measured Dose	mg/L	1.26
Transferred Dose	mg/L	1.10
Residual 1	mg/L	0.42
2	mg/L	0.45
3	mg/L	0.3
4	mg/L	0.29
5	mg/L	0.23
6	mg/L	0.23
7	mg/L	0.19
8	mg/L	0.2
Ozone TE	%	87%
Measured Half-Life	min	20.31
Predicted from Bench-Scale Results		
Projected Dose	mg/L	1.10
Transferred Dose	mg/L	0.96
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	11.883
Intercept	min	-1.2844
Bench Half-Life	min	10.09
Bench 60-sec Residual VS Dose		
DoseVS 60-sec Slope	---	0.8913
Inter	mg/L	-0.1135
60-sec Ozone Res.	mg/L	0.739
Comparison of CT		
Measured CT	mg/Lxmin	3.87
Predicted CT	mg/Lxmin	3.90
Percent Difference	%	0.83%



Plant A - pH 7.0, Temperature = 6.5 C and Measured T Dose = 1.98 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	16.3
Water Temperature	C	6.5
# Contactors On-line	#	3
Measured Dose	mg/L	2.44
Transferred Dose	mg/L	1.98
Residual 1	mg/L	1
2	mg/L	1.02
3	mg/L	0.835
4	mg/L	0.81
5	mg/L	0.68
6	mg/L	0.71
7	mg/L	0.67
8	mg/L	0.73
Ozone TE	%	81%
Measured Half-Life	min	47.88
Predicted from Bench-Scale Results		
Projected Dose	mg/L	2.13
Transferred Dose	mg/L	1.73
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	11.883
Intercept	min	-1.2844
Bench Half-Life	min	19.22
Bench 60-sec Residual VS Dose		
DoseVS 60-sec Slope	---	0.8913
Inter	mg/L	-0.1135
60-sec Ozone Res.	mg/L	1.424
Comparison of CT		
Measured CT	mg/Lxmin	11.19
Predicted CT	mg/Lxmin	11.21
Percent Difference	%	0.13%

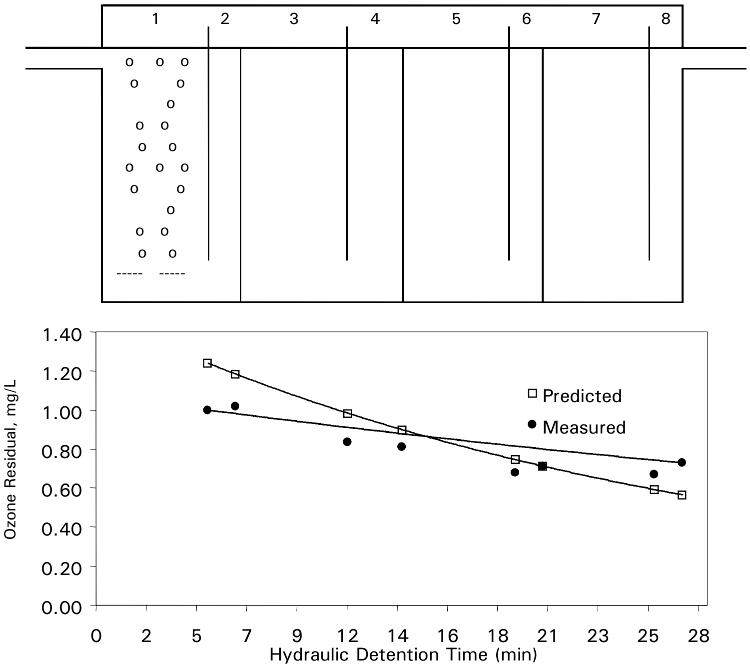
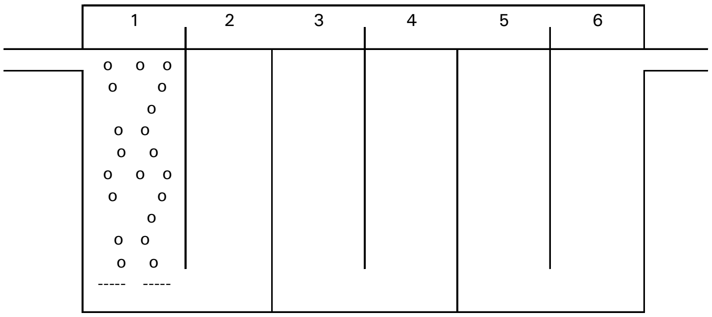


Figure 5-8
Predicted Dose and Residual Profile for Equivalent CT Value

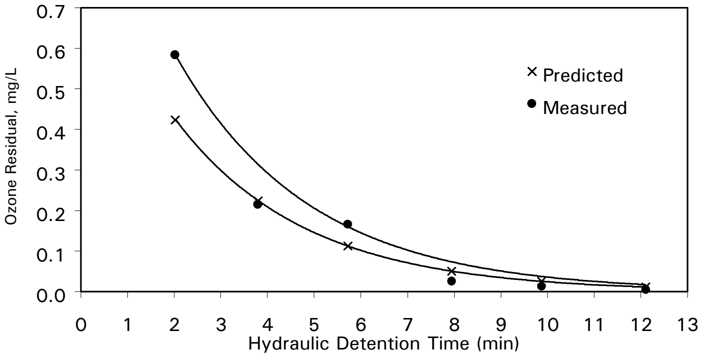
Plant B - pH 8.1, Temperature = 11.7 C and Measured T.Dose = 2.02 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	2.77
Water Temperature	F	53.1
	C	11.72
# Contactors On-line	#	1
Projected Dose	mg/L	2.07
Transferred Dose	mg/L	1.96
Measured Dose	mg/L	2.13
Transferred Dose	mg/L	2.02
Residual 1	mg/L	0.584
2	mg/L	0.214
3	mg/L	0.166
4	mg/L	0.025
5	mg/L	0.013
6	mg/L	0.005



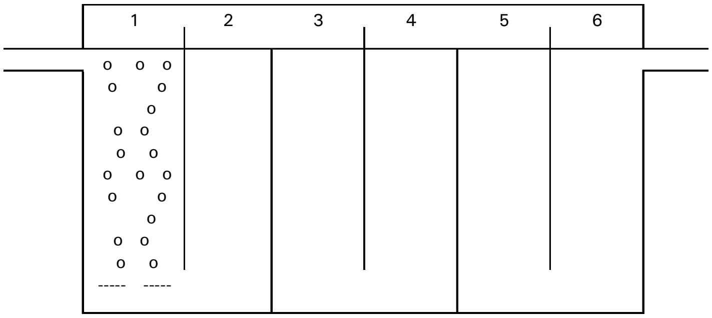
Ozone TE	%	95%
Calculated Full-Scale Data		
Ozone Half-life	min	1.98
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	2.4375
	min	-2.8549
Bench Half-Life	min	1.93
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.9764
	mg/L	-1.3349
60-sec Ozone Res.	mg/L	0.581

Comparison of CT		
Measured CT	mg/Lxmin	0.71
Predicted CT	mg/Lxmin	0.72
Percent Difference	%	2.02%



Plant B - pH 8.1, Temperature = 11.7 C and Measured T.Dose = 2.78 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	2.78
Water Temperature	F	53.1
	C	11.72
# Contactors On-line	#	1
Predicted Dose	mg/L	2.56
Transferred Dose	mg/L	2.43
Measured Dose	mg/L	2.93
Transferred Dose	mg/L	2.78
Residual 1	mg/L	0.773
2	mg/L	0.491
3	mg/L	0.393
4	mg/L	0.259
5	mg/L	0.184
6	mg/L	0.087



Ozone TE	%	95%
Calculated Full-Scale Data		
Ozone Half-life	min	3.22
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	2.438
Inter	min	-2.8549
Bench Half-Life	min	3.07
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.9764
	mg/L	-1.3349
60-sec Ozone Res.	mg/L	1.040

Comparison of CT		
Measured CT	mg/Lxmin	2.35
Predicted CT	mg/Lxmin	2.35
Percent Difference	%	-0.29%

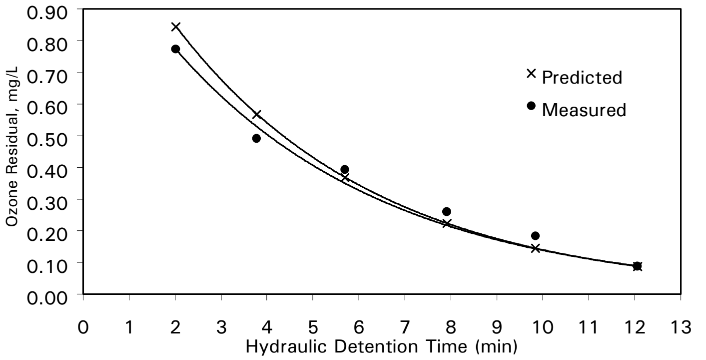
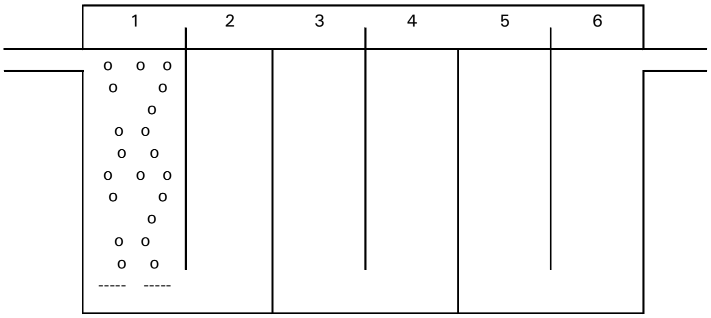


Figure 5-8
Predicted Dose and Residual Profile for Equivalent CT Value (cont.)

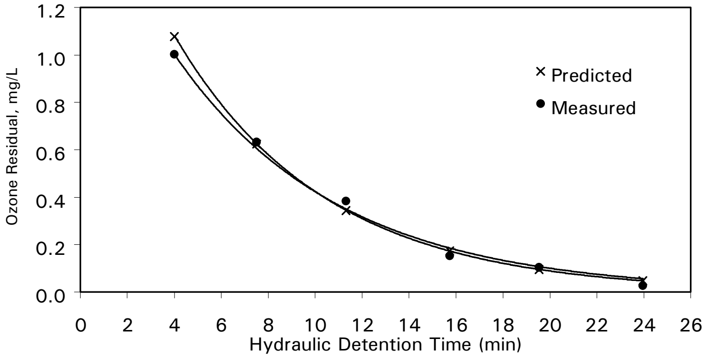
Plant B - pH 8.1, Temperature = 11.7 C and Measured T.Dose = 3.51 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	1.4
Water Temperature	F	53.1
	C	11.72
# Contactors On-line	#	1
Predicted Dose	mg/L	3.15
Transferred Dose	mg/L	2.99
Measured Dose	mg/L	3.69
Transferred Dose	mg/L	3.51
Residual 1	mg/L	1.002
2	mg/L	0.632
3	mg/L	0.383
4	mg/L	0.153
5	mg/L	0.103
6	mg/L	0.027



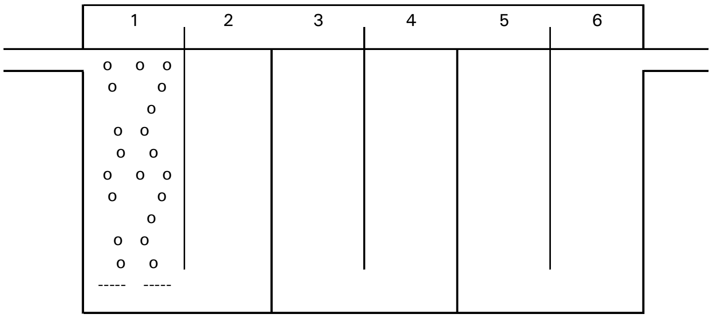
Ozone TE	%	95%
Calculated Full-Scale Data		
Ozone Half-life	min	4.82
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	2.438
Inter	min	-2.8549
Bench Half-Life	min	4.44
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.9764
	mg/L	-1.3349
60-sec Ozone Res.	mg/L	1.587

Comparison of CT		
Measured CT	mg/Lxmin	4.40
Predicted CT	mg/Lxmin	4.40
Percent Difference	%	-0.02%



Plant B - pH 8.1, Temperature = 11.8 C and Measured T.Dose = 3.91 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	1.39
Water Temperature	F	53.2
	C	11.78
# Contactors On-line	#	1
Predicted Dose	mg/L	3.36
Transferred	mg/L	3.19
Measured Dose	mg/L	4.12
Transferred	mg/L	3.91
Residual 1	mg/L	0.953
2	mg/L	0.69
3	mg/L	0.54
4	mg/L	0.254
5	mg/L	0.186
6	mg/L	0.09



Ozone TE	%	95%
Calculated Full-Scale Data		
Ozone Half-life	min	6.08
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	2.438
Inter	min	-2.8549
Bench Half-Life	min	4.93
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.9764
	mg/L	-1.3349
60-sec Ozone Res.	mg/L	1.782

Comparison of CT		
Measured CT	mg/Lxmin	5.83
Predicted CT	mg/Lxmin	5.83
Percent Difference	%	-0.03%

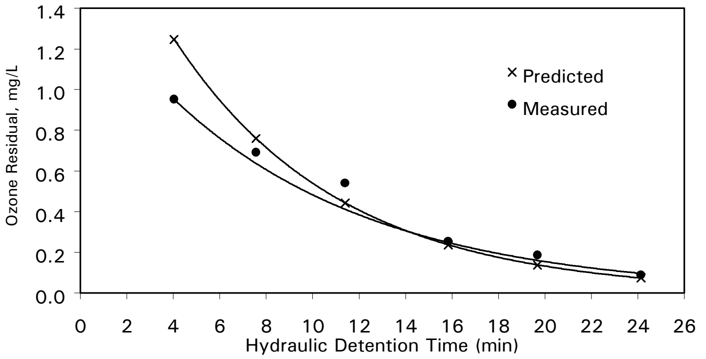
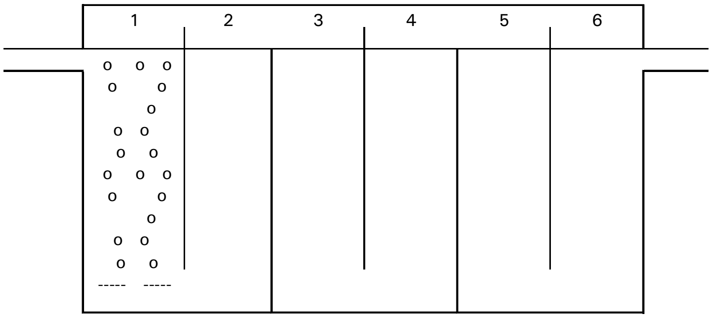


Figure 5-8
Predicted Dose and Residual Profile for Equivalent CT Value (cont.)

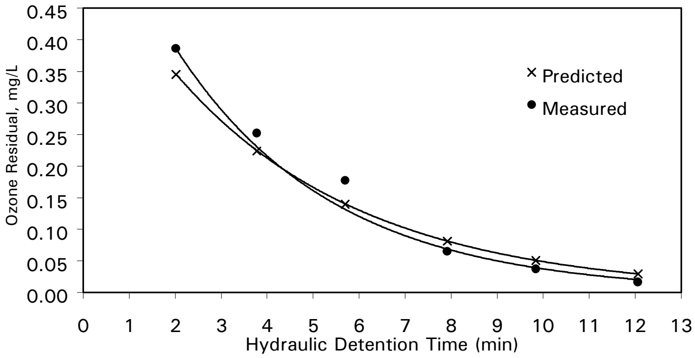
Plant B - pH 6.5, Temperature = 12 C and Measured T.Dose = 1.48 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	2.78
Water Temperature	F	53.6
	C	12.00
# Contactors On-line	#	1
Predicted Dose	mg/L	1.43
Transferred	mg/L	1.36
Measured Dose	mg/L	1.56
Transferred	mg/L	1.48
Residual 1	mg/L	0.386
2	mg/L	0.252
3	mg/L	0.177
4	mg/L	0.065
5	mg/L	0.037
6	mg/L	0.016



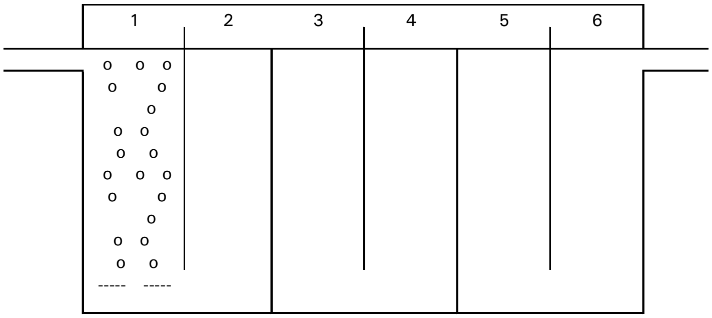
Ozone TE	%	95%
Calculated Full-Scale Data		
Ozone Half-life	min	2.37
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	2.904
	min	-1.1181
Bench Half-Life	min	2.83
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.8122
	mg/L	-0.6714
60-sec Ozone Res.	mg/L	0.432

Comparison of CT		
Measured CT	mg/Lxmin	0.85
Predicted CT	mg/Lxmin	0.84
Percent Difference	%	-0.77%



Plant B - pH 6.5, Temperature = 12 C and Measured T.Dose = 1.76 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	2.78
Water Temperature	F	53.6
	C	12.00
# Contactors On-line	#	1
Predicted Dose	mg/L	1.79
Transferred	mg/L	1.70
Measured Dose	mg/L	1.85
Transferred	mg/L	1.76
Residual 1	mg/L	0.603
2	mg/L	0.398
3	mg/L	0.322
4	mg/L	0.209
5	mg/L	0.141
6	mg/L	0.1



Ozone TE	%	95%
Calculated Full-Scale Data		
Ozone Half-life	min	3.85
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	2.904
	min	-1.1181
Bench Half-Life	min	3.82
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.8122
	mg/L	-0.6714
60-sec Ozone Res.	mg/L	0.710

Comparison of CT		
Measured CT	mg/Lxmin	1.91
Predicted CT	mg/Lxmin	1.93
Percent Difference	%	1.01%

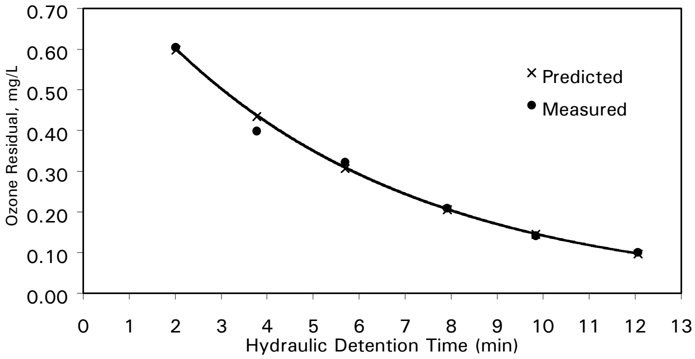


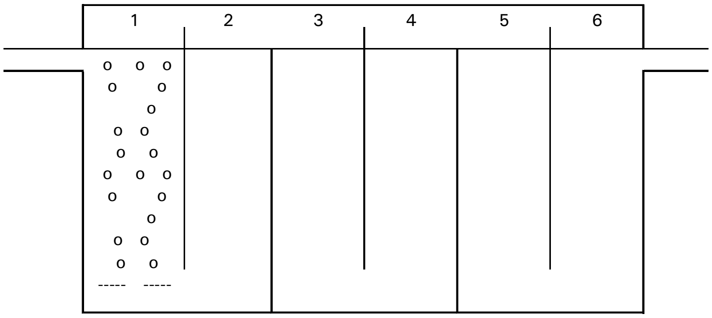
Figure 5-8
Predicted Dose and Residual Profile for Equivalent CT Value (cont.)

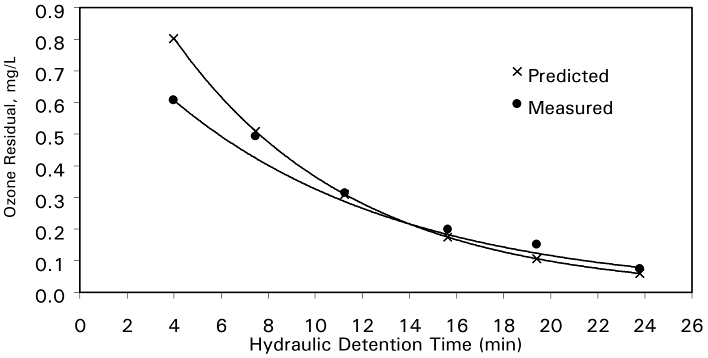
Plant B - pH 6.5, Temperature = 12 C and Measured T.Dose = 2.14 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	1.41
Water Temperature	F	53.6
	C	12.00
# Contactors On-line	#	1
Predicted Dose	mg/L	2.32
Transferred	mg/L	2.20
Measured Dose	mg/L	2.25
Transferred	mg/L	2.14
Residual 1	mg/L	0.608
2	mg/L	0.494
3	mg/L	0.315
4	mg/L	0.199
5	mg/L	0.152
6	mg/L	0.075

Ozone TE	%	95%
Calculated Full-Scale Data		
Ozone Half-life	min	6.72
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	2.904
Inter	min	-1.1181
Bench Half-Life	min	5.28
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.8122
	mg/L	-0.6714
60-sec Ozone Res.	mg/L	1.119

Comparison of CT		
Measured CT	mg/Lxmin	3.96
Predicted CT	mg/Lxmin	3.96
Percent Difference	%	0.06%



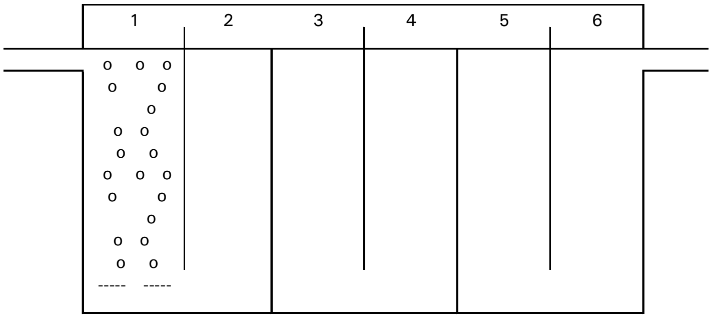


Plant B - pH 6.5, Temperature = 12.1 C and Measured T.Dose = 2.57 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	1.39
Water Temperature	F	53.7
	C	12.06
# Contactors On-line	#	1
Predicted Dose	mg/L	2.80
Transferred	mg/L	2.66
Measured Dose	mg/L	2.70
Transferred	mg/L	2.57
Residual 1	mg/L	0.721
2	mg/L	0.72
3	mg/L	0.5
4	mg/L	0.394
5	mg/L	0.323
6	mg/L	0.223

Ozone TE	%	95%
Calculated Full-Scale Data		
Ozone Half-life	min	12.20
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	2.904
Inter	min	-1.1181
Bench Half-Life	min	6.61
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.8122
	mg/L	-0.6714
60-sec Ozone Res.	mg/L	1.489

Comparison of CT		
Measured CT	mg/Lxmin	6.58
Predicted CT	mg/Lxmin	6.60
Percent Difference	%	0.35%



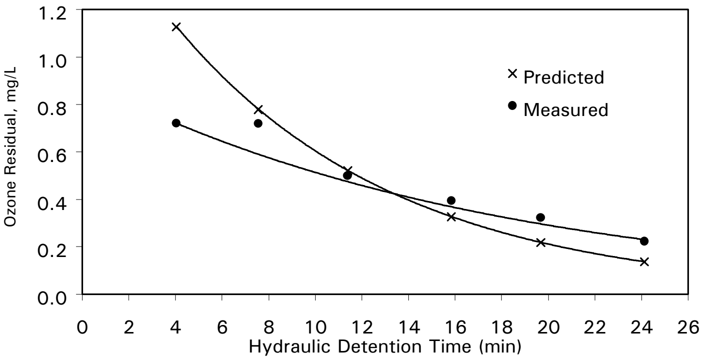
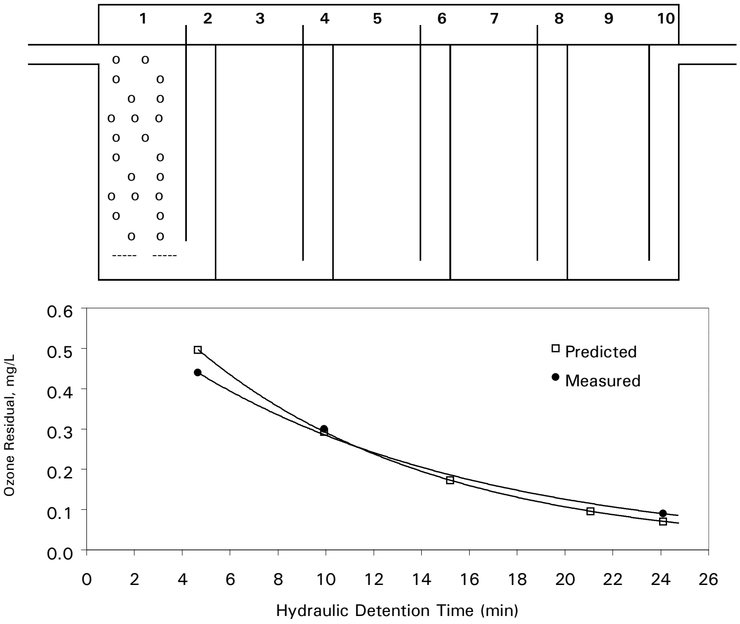


Figure 5-8
Predicted Dose and Residual Profile for Equivalent CT Value (cont.)

Plant C - pH 6.6, Temperature = 2.3 C and Measured T.Dose = 1.35 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	21.30
Water Temperature	C	2.30
# Contactors On-line	#	2
Predicted Dose	mg/L	1.40
Transferred Dose	mg/L	1.32
Measured Dose	mg/L	1.44
Transferred Dose	mg/L	1.35
Residual 1a	mg/L	
Residual 1b	mg/L	0.44
Residual 2a	mg/L	
Residual 2b	mg/L	0.30
Residual 3a	mg/L	
Residual 3b	mg/L	
Residual 4a	mg/L	
Residual 4b	mg/L	
Residual 5a	mg/L	
Residual 5b	mg/L	0.09
Ozone TE	%	94.0%
Calculated Full-Scale Data		
Measured HL	min	8.50
Bench HL versus Dose		
Dose VS HL Slope	min/mg/L	9.6756
Inter	min	-5.8039
Bench Half-Life	min	6.93
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.8819
Inter	mg/L	-0.4818
60-sec Ozone Res.	mg/L	0.68
Comparison of CT		
Measured CT	mg/Lxmin	2.90
Predicted CT	mg/Lxmin	2.91
Percent Difference	%	0.58%



Plant D - pH 7.2, Temperature = 13 C and Measured T.Dose = 0.99 mg/L

Measured Full-Scale Data		
Water Flow Rate	mgd	21.7
Water Temperature	C	13
# Contactors On-line	#	2
Projected Dose	mg/L	1.16
Transferred dose	mg/L	1.02
Measured Dose	mg/L	1.12
Transferred dose	mg/L	0.99
Residual 1	mg/L	
2	mg/L	0.245
3	mg/L	
4	mg/L	0.06
5	mg/L	
6	mg/L	0.009
Ozone TE	%	88%
Calculated Full-Scale Data		
Measured Half-life	min	2.78
Bench HL versus Dose		
Res. VS HL Slope	min/mg/L	9.077
	min	-6.2354
Bench Half-Life	min	2.99
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	0.9495
	mg/L	-0.5569
60-sec Ozone Res.	mg/L	0.408
Comparison of CT		
Measured CT	mg/Lxmin	0.82
Predicted CT	mg/Lxmin	0.82
Percent Difference	%	-0.84%

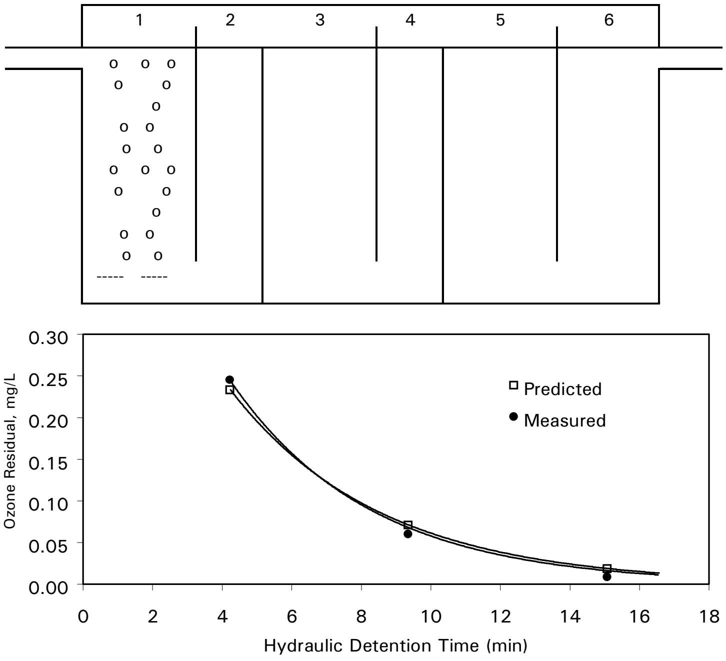


Figure 5-8
Predicted Dose and Residual Profile for Equivalent CT Value (cont.)

Assessing Pilot-Scale and Bench-Scale Data

Plant E was conducting pilot-scale tests prior to development of design criteria for their settled water ozone application. A standard 8-inch (20 cm) diameter bubble diffuser column was used for pilot plant tests at Plant E, similar to columns used in most other pilot-scale evaluations. Plant E's enhanced disinfection objective was to provide a treatment barrier for C*ryptosporidium* oocyst inactivation. An example design target CT value was 4.1-mg/L•min at 12°C. In this section of Chapter 5, two frequently used pilot-scale testing methods are discussed. Method 1 does not provide opportunity for developing optimized design criteria. Method 2 is the preferred pilot-scale testing protocol.

Pilot-Scale Testing Method 1

The objective of Method 1 is to determine required ozone dose for meeting target CT value. CT value is the product of pilot column hydraulic detention time (HDT) multiplied by outlet ozone residual. T_{10}/T ratio also might be incorporated into the analysis. At Plant E the contactor design HDT was 10 min. The design T_{10}/T ratio was 0.7.

The pilot-scale test was conducted at a detention time (volume/flow) of 7.0 min. Ozone residual was measured at the contactor outlet at variable ozone dose. Results are shown in Figure 5-9. Based on a target CT value of 4.1 mg/L•min and a T of 7.0 min, the necessary outlet residual is 0.59 mg/L (i.e., 4.1 mg/L•min ÷ 7.0 min). From Figure 5-9 the required transferred-dose is 2.8 mg/L.

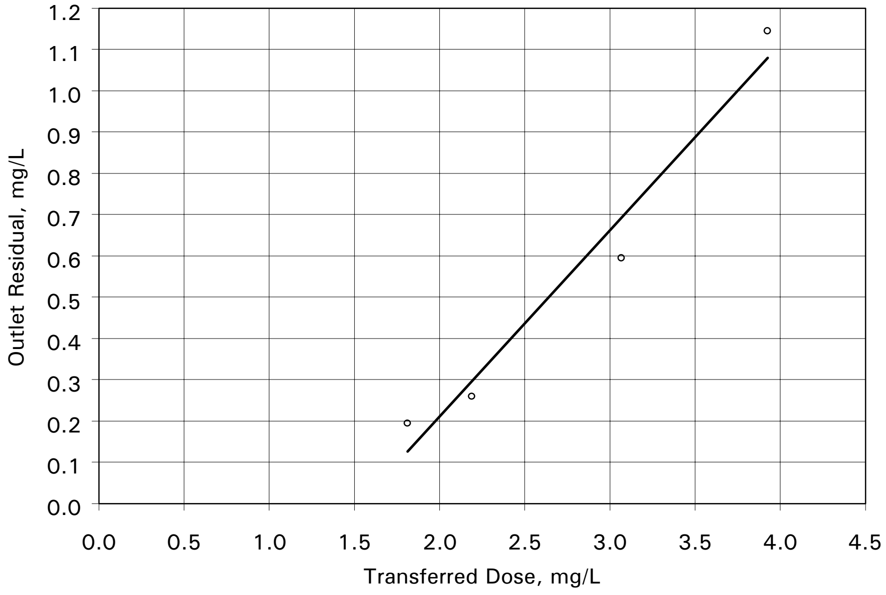


Figure 5-9
Pilot-Scale Dose Versus Outlet Residual for HDT of 7.0 Min

Bench-scale relationships for 60-second residual versus dose and ozone half-life versus dose were determined for Plant E water collected when pilot tests were conducted. Results are shown in Figure 5-10. These data were used to predict the ozone dose requirement to achieve a CT value of 4.1-mg/L•min. The predicted dose was 1.36 mg/L, as shown in Figure 5-11. The predicted dose from bench-scale testing, at 1.36 mg/L, is less than the projected dose based on pilot-scale data, at 2.8 mg/L. With a 20 percent factor-of-safety applied to the bench-scale results (see previous section of this chapter), the projected design dose is 1.65 mg/L, which is still less than the dose projected by pilot-scale tests. The Method 1 pilot-scale evaluation technique not only might overestimate required ozone dose, but also yields limited insight into contactor operation. Alternatively, the residual profile shown in Figure 5-11 might be used to develop design criteria for other contactor-related items, such as residual monitor sample location.

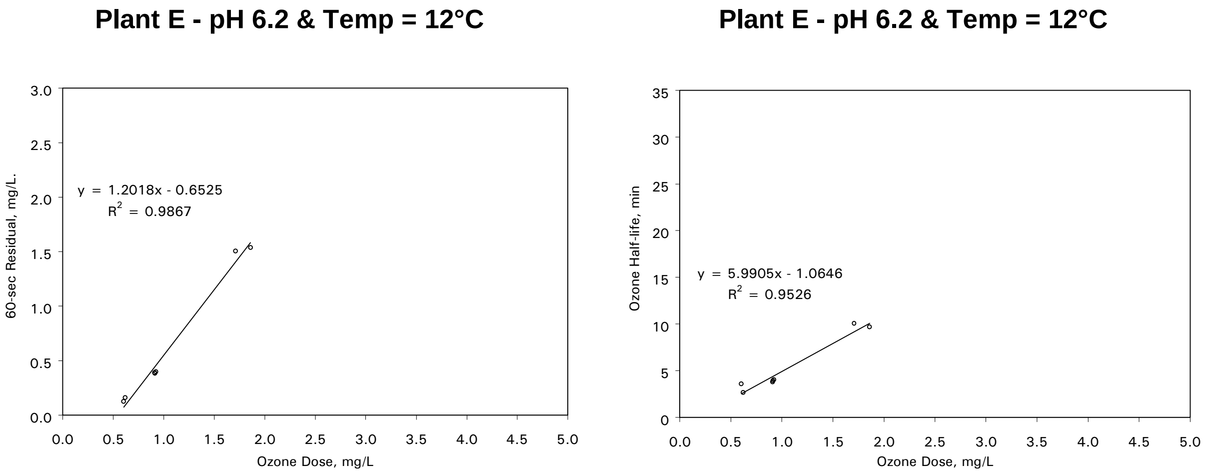


Figure 5-10
Plant E Ozone Dose Versus 60-sec Residual and Ozone Half-Life

Plant E - Bench-scale Predicted Dose and CT-value

Water Temperature	C	12
Predicted T. Dose	mg/L	1.36
Pred. Res. 1	mg/L	0.98
2	mg/L	0.89
3	mg/L	0.81
4	mg/L	0.73
5	mg/L	0.66
6	mg/L	0.60
7	mg/L	0.55
8	mg/L	0.49
9	mg/L	0.45
10	mg/L	0.41
T10/T Ratio	--	70%
Bench HL versus Dose		
Res. VS HL Slope	min/mg/L	5.990
Inter	min	-1.0646
Half-life	min	7.08
Bench 60-sec Residual VS Dose		
Dose VS Ini Res Slope	---	1.2018
Inter	mg/L	-0.6525
60-sec Ozone Residual	mg/L	0.98
CT-value		
Calculated CT	mg/Lxmin	4.11

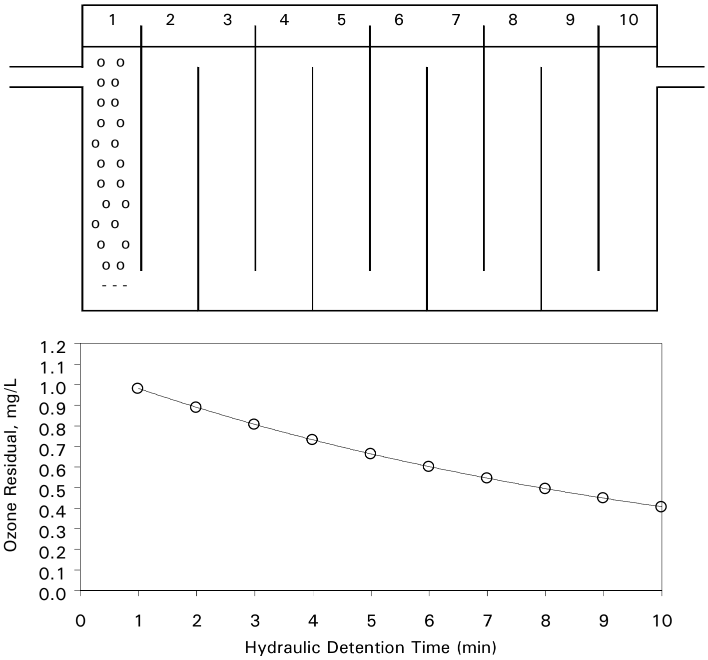


Figure 5-11
Plant E Bench-Scale Predicted Dose for CT Value of 4.1 mg/L•min

Pilot-Scale Testing Method 2

Method 2 pilot-scale testing was set up to provide data for: 1) outlet residual from the first cell of a multi-cell ozone contactor and 2) downstream residual profile using ozone decay rate information. The test protocol for Method 2 was to adjust water flow rate and column HDT to mimic HDT in the first cell of the full-scale ozone contactor. The pilot-column outlet residual then was taken as the residual at the outlet of the first cell of the multi-cell full-scale contactor. The ozone decay rate was determined by collecting a large water sample from the pilot-column outlet, holding the sample in a container with a floatable lid, and measuring residual at 30-second time intervals. The decay rate was used to project residuals downstream of the first cell of the multi-cell full-scale contactor.

Three pilot-scale tests were conducted at variable ozone dose and a controlled detention time of 1.72 minutes in the first cell. Pilot-scale ozone dose, cell 1 outlet residual, downstream residual profile, and CT value are shown in Figure 5-12. The projected dose from bench-scale data also is shown. Results are summarized below.

- Pilot-scale data using Method 2 test procedures might be used to project full-scale contactor operating conditions (e.g., ozone residual profile), as well as determine ozone dose versus CT value relationship.
- The Method 2 pilot-scale test protocol yielded design ozone doses that were more in line with bench-scale test results. The pilot-scale dose was 20 to 30 percent higher than the dose predicted by bench-scale results. Additional work in fine-tuning pilot-scale testing might reduce this apparent discrepancy.

- The ozone half-life from bench- and pilot-scale tests was similar; the residual profiles were comparable.

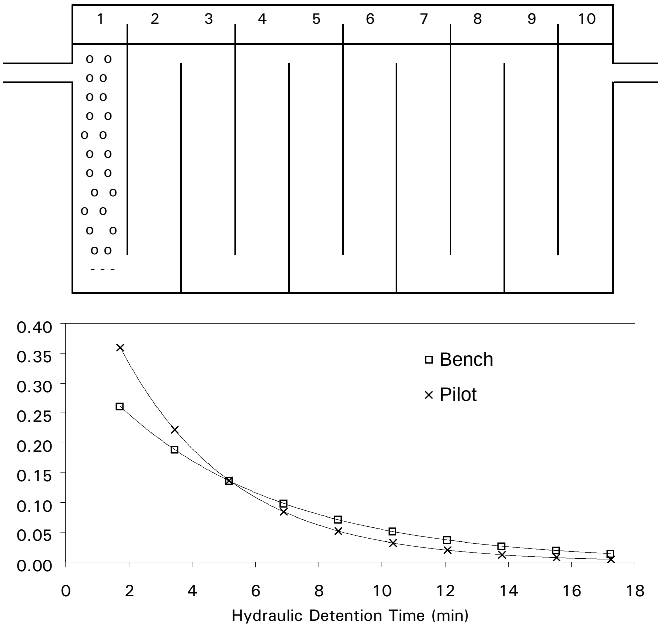
Plant E - First Cell HDT = 1.72 min; Pilot Dose = 1.00 mg/L min; Bench Dose = 0.79 mg/L

		Bench	Pilot
Water Temperature	C	12	
Bench Tran. O3 Dose	mg/L	0.79	
Pilot Tran. O3 Dose	mg/L		1.00
% Difference w/Bench	%	27%	

Residual 1	mg/L	0.26	0.36
2	mg/L	0.19	0.22
3	mg/L	0.14	0.14
4	mg/L	0.10	0.08
5	mg/L	0.07	0.05
6	mg/L	0.05	0.03
7	mg/L	0.04	0.02
8	mg/L	0.03	0.01
9	mg/L	0.02	0.01
10	mg/L	0.01	0.00

Bench HL versus Dose			
Dose VS HL Slope	min/mg/L	5.990	
Inter	min	-1.0646	
Half-life	min	3.67	2.47
Bench 60-sec Residual VS Dose			
Dose VS Ini Res Slope	---	1.2018	
Inter	mg/L	-0.6525	
60-sec Ozone Residual	mg/L	0.30	

CT and Giardia Inactivation Credit			
Calculated CT	mg/Lxmin	0.78	0.76
First Cell HDT	min	1.72	



Plant E - First Cell HDT = 1.72 min; Pilot Dose = 1.54 mg/L min; Bench Dose = 1.27 mg/L

		Bench	Pilot
Water Temperature	C	12	
Bench Tran. O3 Dose	mg/L	1.27	
Pilot Tran. O3 Dose	mg/L		1.54
% Difference w/Bench	%	21%	

Residual 1	mg/L	0.81	0.70
2	mg/L	0.68	0.61
3	mg/L	0.56	0.53
4	mg/L	0.47	0.46
5	mg/L	0.39	0.40
6	mg/L	0.33	0.35
7	mg/L	0.27	0.30
8	mg/L	0.23	0.26
9	mg/L	0.19	0.23
10	mg/L	0.16	0.20

Bench HL versus Dose			
Dose VS HL Slope	min/mg/L	5.990	
Inter	min	-1.0646	
Half-life	min	6.54	8.48
Bench 60-sec Residual VS Dose			
Dose VS Ini Res Slope	---	1.2018	
Inter	mg/L	-0.6525	
60-sec Ozone Residual	mg/L	0.87	

CT and Giardia Inactivation Credit			
Calculated CT	mg/Lxmin	3.71	3.69
First Cell HDT	min	1.72	

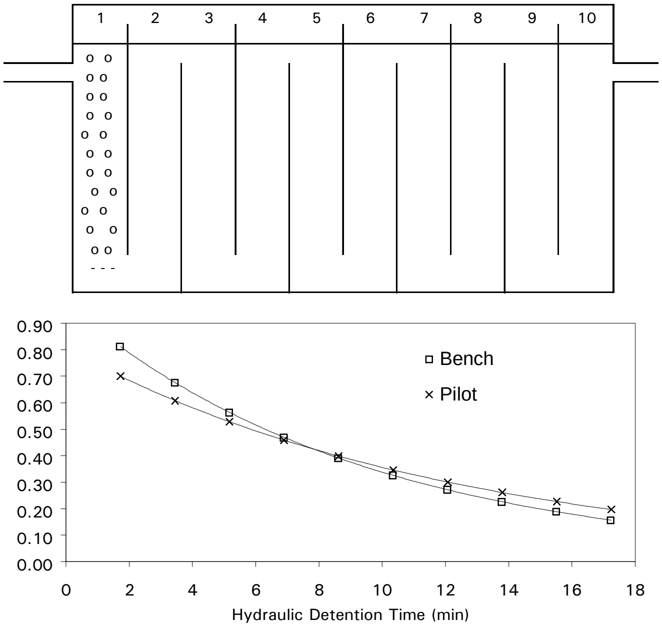


Figure 5-12
Bench- and Pilot-Scale Dose and Residual Profile Data for Equivalent CT Value

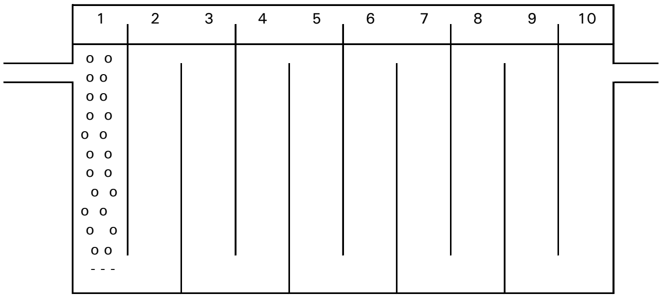
Plant E - First Cell HDT = 1.72 min; Pilot Dose = 1.75 mg/L min; Bench Dose = 1.36 mg/L

		Bench	Pilot
Water Temperature	C	12	
Bench Tran. O3 Dose	mg/L	1.36	
Pilot Tran. O3 Dose	mg/L		1.75
% Difference w/Bench	%	29%	

Residual 1	mg/L	0.92	0.84
2	mg/L	0.77	0.73
3	mg/L	0.65	0.63
4	mg/L	0.55	0.54
5	mg/L	0.47	0.47
6	mg/L	0.39	0.40
7	mg/L	0.33	0.35
8	mg/L	0.28	0.30
9	mg/L	0.24	0.26
10	mg/L	0.20	0.23

Bench HL versus Dose			
Dose VS HL Slope	min/mg/L	5.990	
Inter	min	-1.0646	
Half-life	min	7.08	8.19
Bench 60-sec Residual VS Dose			
Dose VS Ini Res Slope	---	1.2018	
Inter	mg/L	-0.6525	
60-sec Ozone Residual	mg/L	0.98	

CT and Giardia Inactivation Credit			
Calculated CT	mg/Lxmin	4.39	4.35
First Cell HDT	min	1.72	



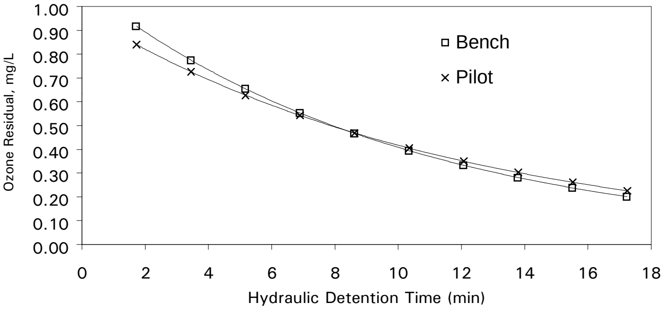


Figure 5-12
Bench- and Pilot-Scale Dose and Residual Profile Data for Equivalent CT Value (cont.)

6

OZONE OPTIMIZATION WITH IMPROVED AUTOMATION

Background

Automation control flexibility was installed in ten of twelve plants participating in Phases 1 and 2 of the Ozone Energy Optimization Project. Constant ozone concentration control was the most common automation technique. Constant-concentration control was fully functional in one facility. Automation was utilized partially at a second plant. Automation was replaced with manual control at eight plants for reasons listed below:

- Automation caused quite variable process operation or excessively long response time.
- Monitoring and control equipment were unreliable (i.e., SCADA systems, ozone residual meters, gas flowmeters, gas flow control valves, etc.)

Several ozone systems operate successfully in manual control mode. During manual control, gas flow adjustments are minimized and generator power adjustments are made periodically to meet performance objectives. Steady-state ozone residual performance has been documented with manual control that features constant gas flow. An alternative automation strategy called constant gas flow control is presented in this chapter based on the positive attributes of manual operation. Optimization is achieved because operating cost is minimized over a fairly wide range of ozone concentration.

Overview of Ozone System Control Techniques

Ozone systems normally operate to obtain a measurable ozone residual and sufficient CT value to meet *Giardia* cyst or virus inactivation credits. Ozone gas is generated on-site with electrical energy and is piped to the ozone contactor. The generator feed-gas may be dry air, gaseous oxygen, or dry air enriched with gaseous oxygen. Vaporized liquid oxygen (LOX) is becoming the most frequently used feed-gas. A simplified schematic of a LOX oxygen-fed ozone system is shown in Figure 6-1. Gas flow and generator power adjustments control ozone production.

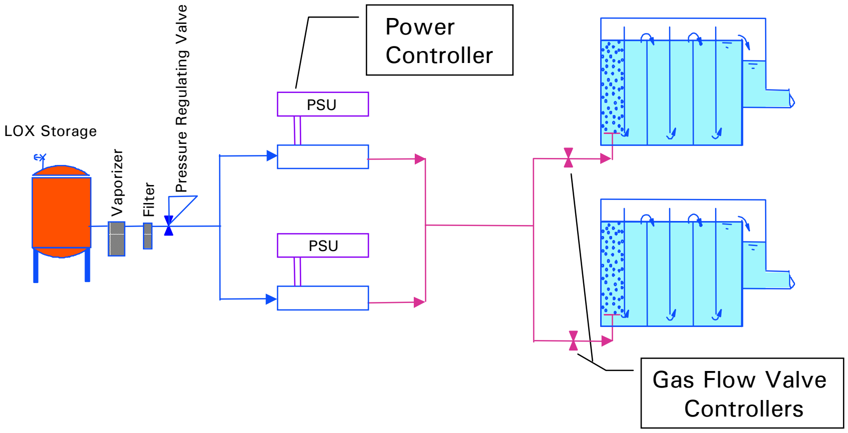


Figure 6-1
Simplified Liquid Oxygen-Fed Ozone Schematic

The cost of generating ozone includes both the cost of electricity and cost of LOX. The unit-mass cost (\$/lb O_3) of ozone is lowest at an optimum ozone concentration, as shown in Figure 6-2. Energy cost is too high above the optimum concentration, and LOX cost is too high below the optimum point. The optimum concentration point is unique to each installation, depending on price of energy, price of LOX, ozone generator efficiency, and cooling water temperature. The constant-concentration control strategy is based on operating continuously at the most efficient ozone concentration.

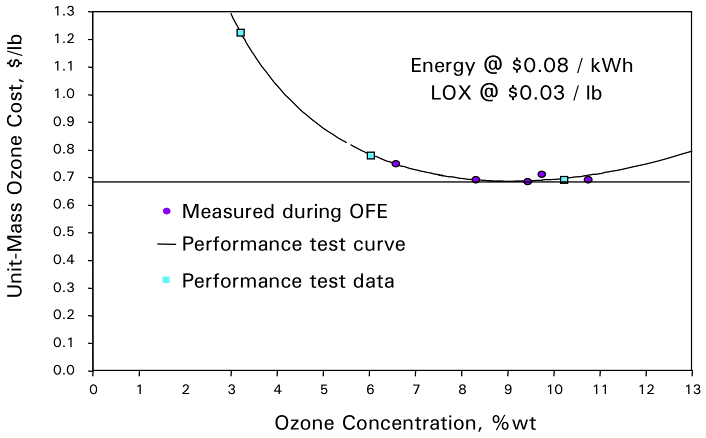


Figure 6-2
Unit-Mass Ozone Cost for LOX Oxygen-Fed Ozone System

Adjusting ozone generator power and/or feed-gas flow rate will affect the rate of ozone production. Controlling ozone production is necessary in order to meet performance objectives. Generator power is the primary control parameter that is used to modify operating ozone production rate. Feed-gas flow is a secondary control feature that is used to alter operating ozone concentration. If generator power is held constant, small changes in ozone production occur with large changes in feed-gas flow rate. If feed-gas flow rate is held constant, moderate changes in ozone production are possible by changing generator power. Changes to both generator power and feed-gas flow rate are made in order to effect large changes in ozone production rate.

In manual control mode the operator makes changes to generator power and feed-gas flow in the field or remotely at the computer. Ozone systems have been controlled effectively in manual mode, but staff attention is required continuously to maintain optimized performance, and operator time is necessary to make adjustments. Automated control might be semi-automated or fully automated. Semi-automation might consist of operator input of set-point applied ozone dose and target ozone concentration with the computer adjusting feed-gas flow rate and generator power to meet these set-points. Control is semi-automatic because the operator still must observe disinfection performance and change set-point dose accordingly. In fully automatic control, the computer will make adjustments based on disinfection performance.

During Phase 2 of the project it was observed that manual control provided steady-state performance. Also, it was noted that manual control was implemented differently than the control provided by automated programming. In this chapter, process and performance results are presented for both manual and semi-automatic operation to illustrate differences in steady-state operation. Ultimately, an alternative automated control approach is described based on operating successes observed during manual control.

Manual Control

Description

Figure 6-3 shows the relationship among ozone parameters for manual ozone control. The operator sets the water flow rate, selects the number of ozone generators and contactors, and controls the gas flow rate and generator power. Total generator power determines the operating ozone concentration in relation to the set-point gas flow rate. Ozone concentration and gas flow rate determine the ozone production rate. Water flow and ozone production determine applied ozone dose, which affects ozone residual profile, depending on ozone demand and decay. The number of contactors and water flow rate determines the hydraulic detention time (HDT) which, when combined with ozone residual profile and T_{10}/T ratio, determines ozone CT value. Ultimately, CT value, water temperature, and CT tables determine disinfection status, such as *Giardia* cyst inactivation credit. The operator adjusts generator power if measured disinfection credit is outside the desirable operating range.

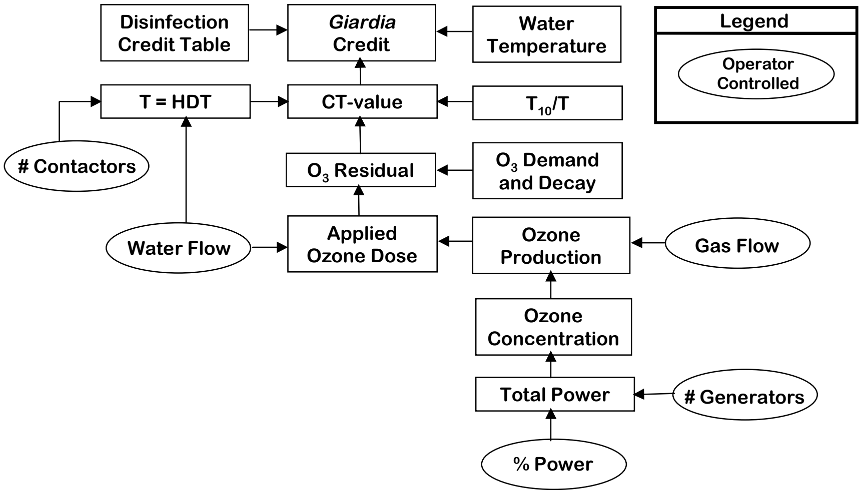


Figure 6-3
Schematic for Manual Ozone Control

Performance at Plant 11

Plant 11 is an air-fed ozone system that had been operating successfully for five years with manual control. Operators had abandoned their automated control system due to undesirable fluctuations in generator power, ozone concentration, and ozone residual. The water utility is making plans to re-design and implement automatic control sometime in the future.

Operating data were collected from the SCADA system at Plant 11 at five-minute intervals. Data were normalized to percent difference between each 5-minute reading and the average of all readings over a 150-minute time frame. Figure 6-4 shows small variation in water flow, generator power, gas flow, and ozone concentration. The variation observed might be due to inherent fluctuations in process parameters without control valve adjustments. Plant staff did not physically change water flow, generator power, or gas flow during the 150-minute time period.

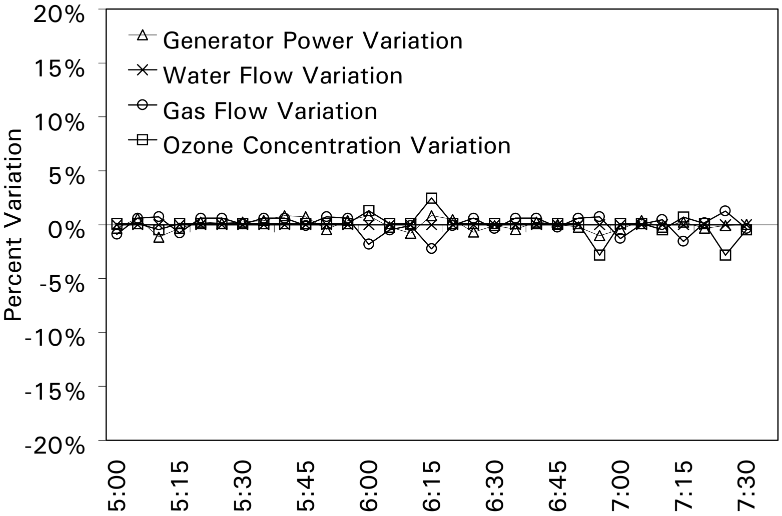


Figure 6-4
Plant 11 Percent Variation Chart for Generator Power, Gas Flow, and Ozone Concentration

The performance outcome at Plant 11 was consistent ozone residuals, as shown in Figure 6-5. Steady water flow, gas flow, and generator power achieved steady-state ozone residual performance. These favorable results are encouraging for development of an automated control system based on principles of manual control. A constant gas flow automated control alternative is discussed later in this chapter.

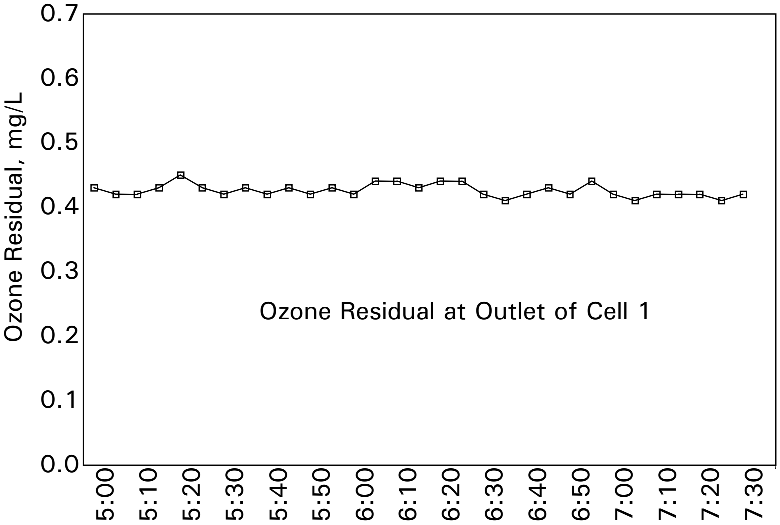


Figure 6-5
Cell 1 Ozone Residual Variation Chart at Plant 11

Constant-Concentration Automated Control

Description

Figure 6-6 shows the relationship among ozone parameters for constant-concentration automated control. Not all parameters are controlled automatically. The operator usually selects the number of ozone contactors. The operator also might select the number of generators, although generators-in-service sometimes is automated. In semi-automatic control, ozone dose and concentration are operator set-points that are used by the computer to control gas flow and generator power. Gas flow is adjusted based on measured water flow, set-point or trimmed ozone dose and set-point ozone concentration. Water flow and ozone dose determines required ozone production. Required production and set-point ozone concentration determine required gas flow rate. The computer makes gas flow valve adjustments so that measured gas flow equals required flow. Changes in ozone concentration occur when gas flow rate varies. Generator power is adjusted automatically so that measured ozone concentration is equal to set-point concentration.

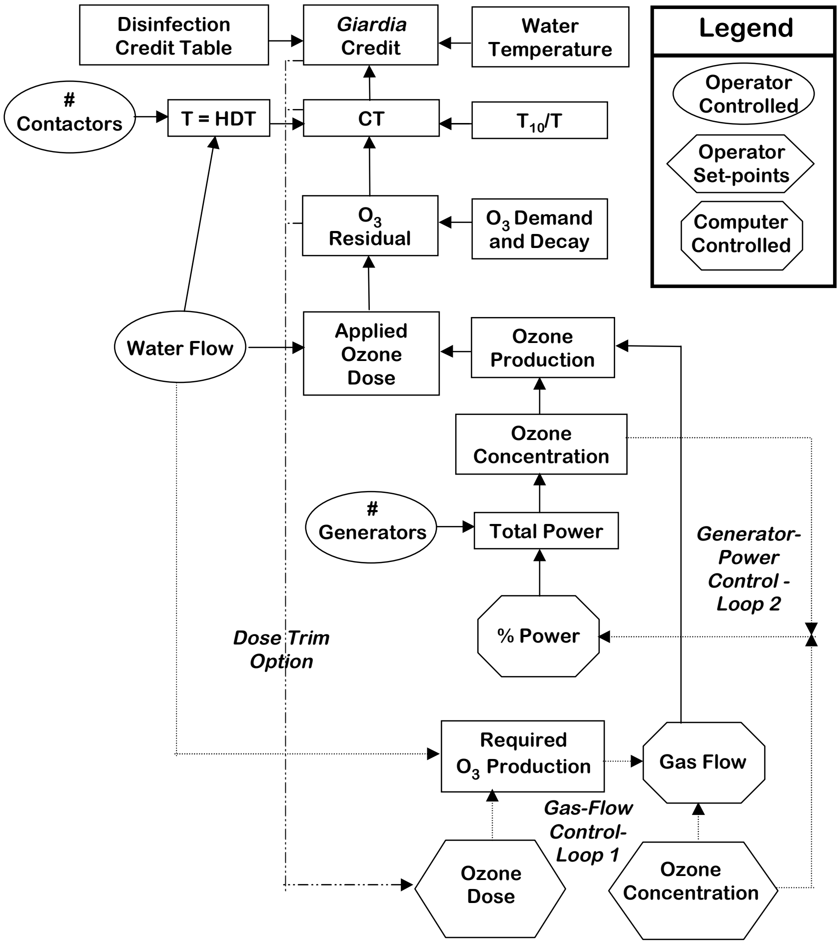


Figure 6-6
Schematic for Constant-Concentration Automated Control

Constant-concentration control might be termed integrated control because a change in process variables by one loop affects the control response of the other loop. Figure 6-7 illustrates that gas flow is adjusted in Loop 1 based on feedback signals from plant instrumentation, such as water flowmeters (and ozone residual analyzers in fully automated control). Ozone concentration is changed when gas flow is altered. Generator power is controlled in Loop 2 based on feedback signals from the ozone concentration meter. Achieving steady-state performance using feedback signals requires delay-time settings that are customized for the plant layout. Generator power adjustment that is based on the feedback signal from the ozone concentration meter is an example of a delay-time adjustment. If the delay times are too long, system response will be slow. The key to success with constant-concentration automated control is proper balance of the opposing ideals of steady-state operation and quick system responsiveness. Constant-concentration automated control was studied at two plants.

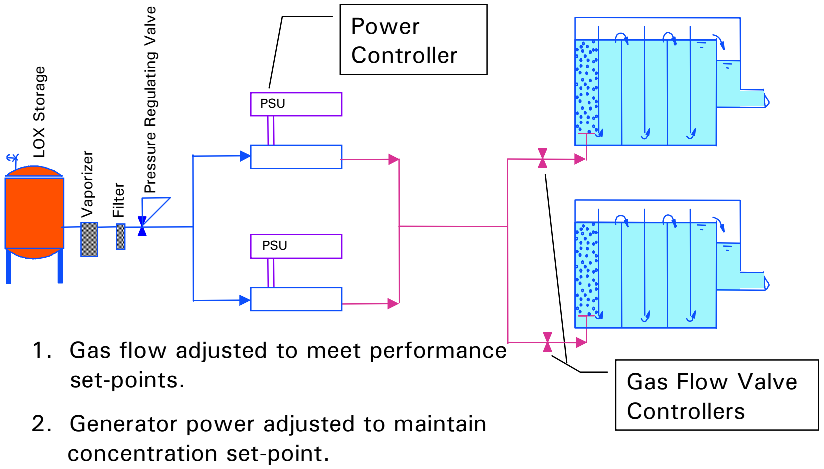


Figure 6-7
Illustration of Constant-Concentration Control Technique

Performance at Plant 13

Plant 13 is an oxygen-fed ozone system using liquid oxygen (LOX). The water flow rate was constant, and operator set-points for ozone dose and concentration were used to automatically control gas flow and generator power. The constant-concentration control mode was being used when operating data were collected from the SCADA system at 30-second intervals for 20 minutes. Data were normalized to percent difference between each 30-second reading and the average of all readings. Figure 6-8 shows that generator power and gas flow fluctuated by about 10 percent (i.e., ±5%) every five minutes. Ozone concentration varied about 6 percent (i.e., ±3%). These fluctuations caused variations in ozone production and dosage, and possibly in ozone residual. Figure 6-9 indicates cell 1 residual varied between 0.35 mg/L and 0.60 mg/L over the 20-minute time period. This variation might be dampened by time-averaging the residual, such as over a 5-minute time frame.

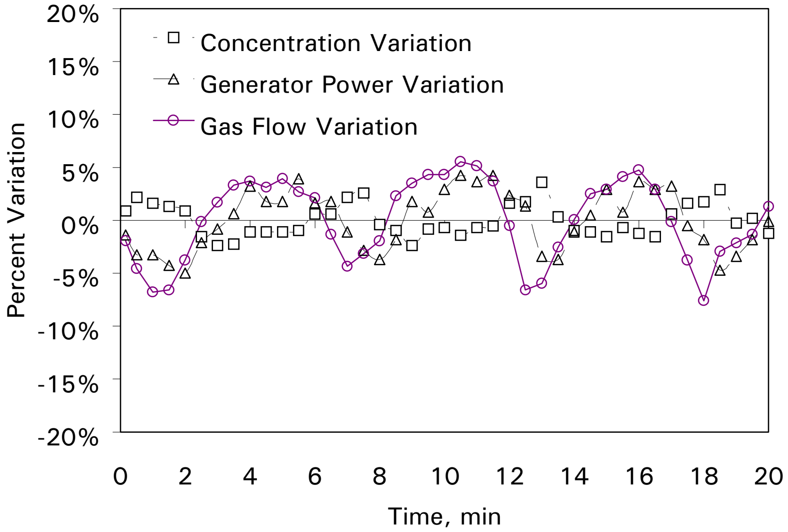


Figure 6-8
Plant 13 Percent Variation Chart for Generator Power, Gas Flow, and Ozone Concentration

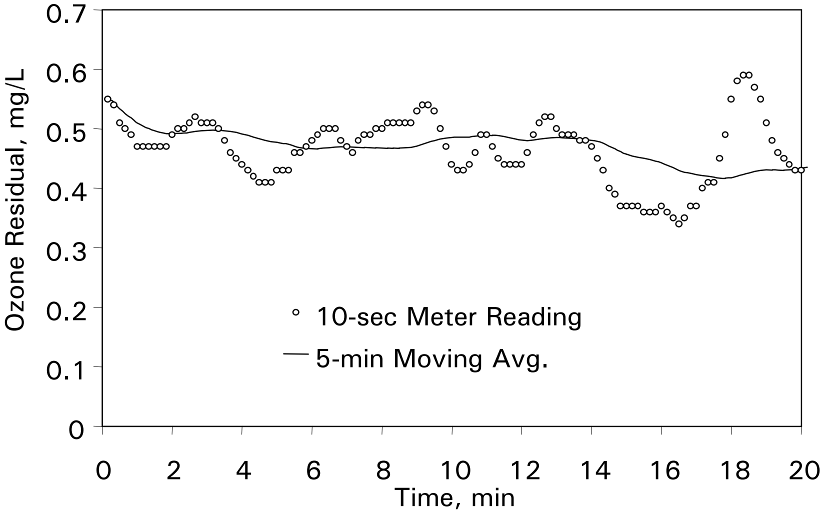


Figure 6-9
Cell 1 Ozone Residual Variation at Plant 13

The fluctuations in generator power and concentration might be acceptable at Plant 13, but possible reasons for the fluctuations were considered. It was believed that the primary cause was time delay in determination of ozone concentration. The instantaneous reading of the ultraviolet (UV) ozone concentration meter reflected actual concentration from about one minute preceding, due to ozone gas detention time in the sample line between the ozone generator and UV concentration meter. Generator power was adjusting faster than ozone concentration response was detected.

Performance at Plant 14

Plant 14 also is an oxygen-fed ozone system using LOX. Data were collected from field instruments at 60-second intervals for 30 minutes when the plant was operating using the constant-concentration control mode. Data were normalized to percent difference between each 60-second reading and the average of all readings. Figure 6-10 shows that gas flow and water flow variations were about 10 percent (i.e., ±5%). The plant set-point water flow rate was unchanged; variation in water flow was due to fluctuations caused by the water flow control valve. Gas flow variation matched water flow variation because set-points for ozone dose and concentration were used in conjunction with water flow rate to determine required gas flow rate.

Ozone concentration at Plant 14 was quite variable at about 30 percent (i.e., +10% and -20%), and generator power was extremely variable at about 80 percent (i.e., ±40%). The significant fluctuation in power at Plant 14 was due to delayed response by the UV ozone concentration meter, similar to Plant 13. Ozone sample-gas detention time was even longer at Plant 14 than at Plant 13, because Plant 14's UV meter was located on the other side of the room from the ozone generators.

Moving the ozone concentration meter closer to the generator at Plant 14 might reduce the fluctuation in generator power. The magnitude and frequency for generator power adjustments could be modified at both Plant 13 and Plant 14 to provide smother equipment operation. However, slowing down adjustment settings will decrease system responsiveness. Power adjustment settings must be able to achieve steady-state operation while at the same time preserve system responsiveness.

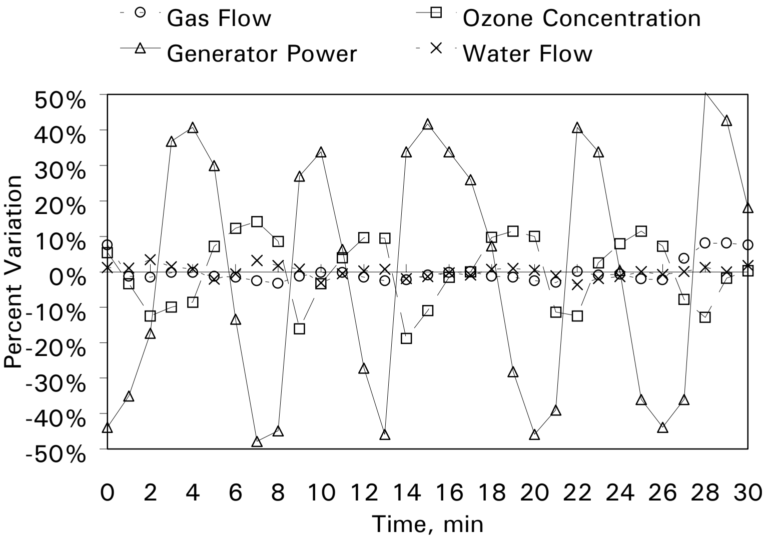


Figure 6-10
Plant 14 Percent Variation Chart for Generator Power, Gas Flow, Ozone Concentration, and Water Flow

Constant Gas Flow Automated Control Alternative

An alternative to constant-concentration control is needed because constant-concentration control is challenging to implement successfully. With constant-concentration control, selection of the magnitude and frequency of process adjustments are critically important. Constant-concentration-based automation was useable at one plant studied (Plant 7) when technicians slowed down adjustment settings to obtain steady operation. However, operators reported that system responsiveness was slow and that the constant-concentration automatic control operation is switched off when major changes to process operation are made, such as changes to plant water flow rate. Constant-concentration control is switched back on several minutes after manual adjustments are made to water flow, gas flow, and generator power settings. Several plants have abandoned constant-concentration control due to slow response time. Other plants have abandoned constant-concentration control due to extreme process fluctuations such as shown in Figure 6-10 for Plant 14.

The proposed constant gas flow automated control strategy is patterned after manual control successes. Manual control at Plant 11 demonstrated steady-state ozone residual performance when water flow, gas flow, and generator power were fixed. Despite success with manual control, Plant 11 staff wished for a functional automation system in order to free up staff for other duties and to possibly reduce the operating factor-of-safety to lower ozone generation cost.

Performance Illustration

Plant 11 data for a 24-hour time period are used to illustrate performance response for a control system based on constant gas flow. The operating target at Plant 11 is 3.6-logs *Giardia* cyst inactivation credit. The minimum requirement is 3.0-logs credit. Gas flow was basically constant for 24 hours, as shown in Figure 6-11; gas flow control valve settings were unchanged. Water flow was changed two times, and generator power was adjusted accordingly. Ozone concentration varied in response to changes in generator power. Small adjustments were made to generator power while water flow was constant. For example, power was decreased at 1700-hr when *Giardia* cyst inactivation credit approached 4.0-logs and was increased slightly at 0500-hr when inactivation credit approached 3.0-logs. The data illustrate that disinfection performance response can be controlled well using constant gas flow control techniques.

Description

Constant gas flow control is fundamentally different than constant-concentration control. Differences are explained in order to discuss benefits of the constant gas flow control alternative. Key benefits of constant gas flow control are steady-state performance during normal operation and instantaneous response when sudden changes are made, such as water flow rate.

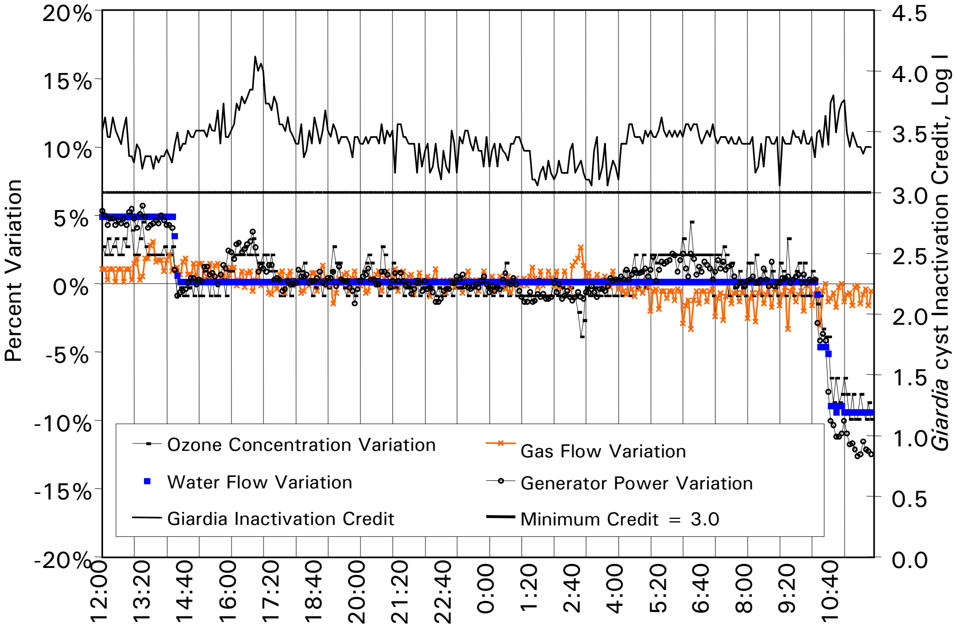


Figure 6-11
Plant 11 Percent Variation Chart for Generator Power, Gas Flow, Ozone Concentration, and Water Flow

Figure 6-12 shows the relationship among ozone parameters for constant gas flow automated control. The operator controls water flow rate, number of contactors, and number of generators. Operator set-points are water flow rate, ozone dose, ozone concentration, ozone concentration multiplier, and generator-specific energy curve offset factor. Ozone dose set-points for individual contactors might be used at multiple contactor ozone systems.

Gas flow rate to each contactor is fixed in the following three steps using set-point values for water flow, ozone dose, and ozone concentration.

1. Flow control ozone production target is calculated from set-point water flow and ozone dose.

2. Fixed gas flow rate is determined using the flow control production target and set-point ozone concentration.

3. Gas flow control valve adjustments are made until measured gas flow equals the fixed gas flow rate.

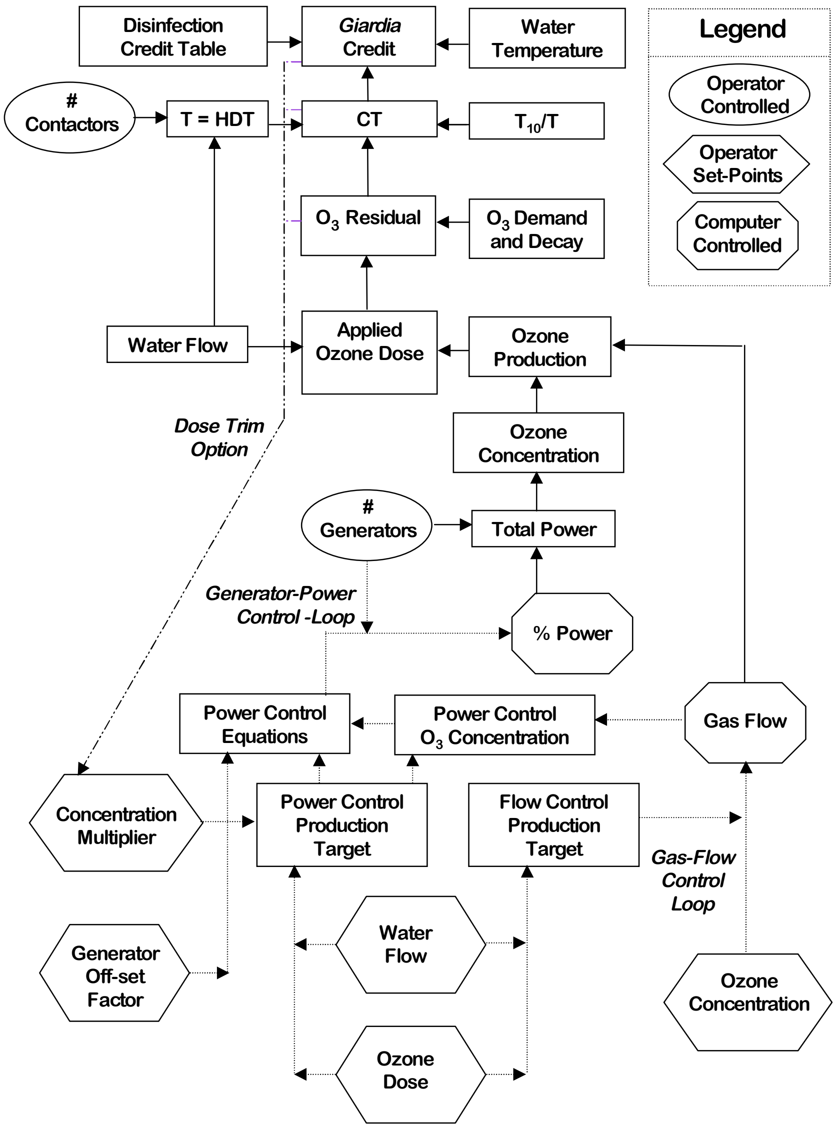


Figure 6-12
Schematic for Constant Gas Flow Automated Control

Establishing gas flow by set-point values achieves constant gas flow operation of the ozone process. It is important to note, however, that process response is enhanced when gas flow is highly controllable. For oxygen-fed ozone systems using LOX, the effectiveness of the pressure-regulating valve (PRV) and flow control valve is critically important. The PRV must be able to maintain consistent pressure over the entire flow range expected. Two high quality, differently-sized PRVs might be necessary to accomplish this task. The flow control valves must be high quality, specially designed flow control devices. The valves must be located on the inlet line to each ozone contactor because that is the point where gas flow is to be controlled precisely. Two differently-sized flow control valves might be necessary to accomplish this task. It is noted that other gas valves on the ozone system (e.g., generator inlet and outlet valves) are normally fully open or fully closed, and these valves can be conventional products.

Generator power is established, in a feed forward manner, with the following five steps using set-points for water flow, ozone dose, concentration-multiplier, and generator specific energy curve offset factor.

1. Power-control ozone production target is calculated using set-point water flow, set-point ozone dose, and concentration-multiplier values.
2. Power-control ozone concentration is determined using the power-control production target and fixed-gas flow rate from above.
3. Generator specific energy is calculated using power-control ozone concentration from step 2, an equation for the generator specific energy curve such as shown in Figure 6-13, and the set-point generator specific energy curve offset factor (see discussion below).
4. Generator power target is calculated using the specific energy value from step 3 and power control production target from step 1.
5. Generator power adjustments are made until measured power equals the calculated generator power target.

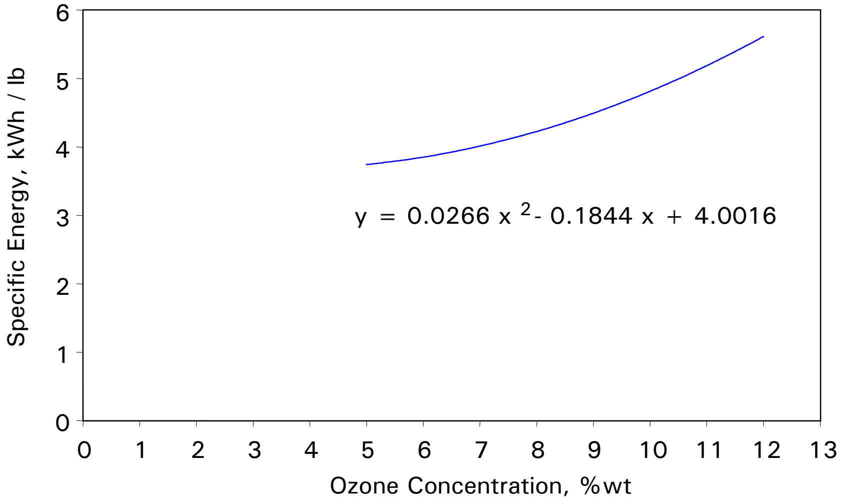


Figure 6-13
Ozone Generator Specific Energy Versus Ozone Concentration Equation Chart

Concentration-multiplier is set at 1.0 initially, but might be adjusted upward or downward based on assessment of performance parameters such as ozone residual or *Giardia* cyst inactivation credit. The operator executes the concentration-multiplier adjustment in semi-automatic operation. In fully automated control the concentration-multiplier adjustments are made automatically by the computer to maintain performance within limits pre-set by the software programmer. However, the plant staff should have access to these pre-set limits so that changes can be made based on system response.

The generator specific energy curve offset factor compensates for changes in generator performance due to dielectric cleanliness, water temperature, or other factors. The factor might change seasonally and range between 0.85 and 1.15. It is important to recognize, however, that disinfection controllability is independent of generator specific energy curve offset factor. The ozone dose and concentration-multiplier set-points are all that are needed to control disinfection performance. The purpose of the generator specific energy curve offset factor is to permit measured data to match computer-used values for ozone concentration and ozone dosage.

The constant gas flow automated control approach is an independent control system. Gas flow is modified only when major operational changes occur, such as plant water flow rate. Generator power adjustments are made in a feed-forward manner when gas flow is adjusted, but power adjustments also might be made without gas flow changes. While water flow is unchanged, the concentration-multiplier might be modified to make small changes in generator power and ozone production to elevate or decrease ozone residuals that might have changed due to variation in water quality. When multiple contactors are in service, the weakest performance signal would control the concentration-multiplier, which would affect performance in all contactors. If the operator notices large discrepancies in contactor performance, then individual contactor ozone dose set-points would be modified accordingly.

Concentration-multiplier changes will affect operating ozone concentration. A limited concentration change is tolerable with respect to optimized operation. Example concentration-range control limits are shown in Figure 6-14 for a LOX oxygen-fed ozone system that participated in Phase 2 of the research study. The chart indicates that the ideal optimized concentration range is 8-10% wt ozone. The unit-mass cost of ozone is essentially unchanged from \$0.69/lb O_3. In this plant the set-point ozone concentration would be 9% wt. The concentration-multiplier could range from 0.9 to 1.1 (i.e., ±10%) and optimization would occur because the ozone concentration would stay within the optimum range of 8-10% wt.

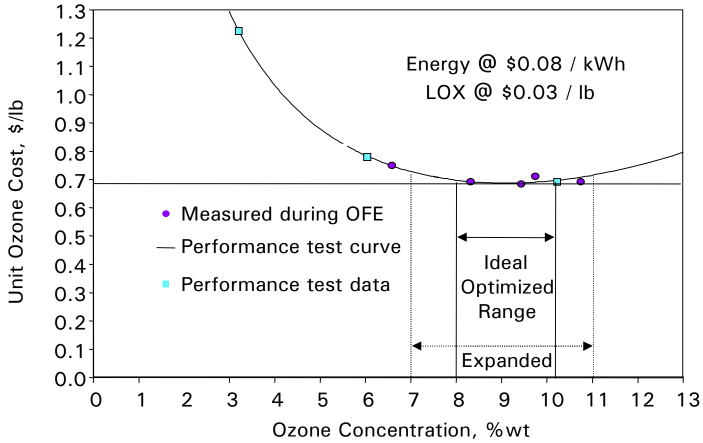


Figure 6-14
Example Optimized Ozone Concentration Range at Plant 7

An expanded concentration range limit (i.e., 7 to 11% wt at Plant 7) might be utilized if hourly changes in water quality are more extreme. This would permit a ±20 percent operating range for ozone dose (i.e., concentration-multiplier of 0.8 to 1.2) while still maintaining reasonably cost-effective operation (see Figure 6-14). It is recommended that alarm limits be placed at ±20 percent because concentration-multiplier values beyond ±20 percent might indicate problems with the ozone residual monitors. The alarm would notify the operator that a dramatic change in ozone dose has occurred. Gas flow and generator power might be unchanged during certain alarm situations in order to protect equipment, and the plant might be shut down at extreme alarm conditions. Operator involvement under alarm conditions ensures disinfection performance integrity and at the same time safeguards equipment operation.

Data charted in Figure 6-15 from Plant 11 indicates that a concentration-multiplier change of only 0.99 to 1.03 controlled the *Giardia* cyst credit. It is evident that small changes in concentration-multiplier will have significant impact on *Giardia* cyst inactivation credit for normal, minute-by-minute or hour-by-hour variations in plant water quality. As such, constant gas flow control can achieve cost-effective steady-state operation.

Benefits of constant gas flow automated control include:

- Gas flow and generator power change-response is immediate when significant adjustments are made in water flow or ozone dose.
- Ozone residual performance is steady because both gas flow and generator power are unchanged for long periods of time.
- Automated control parallels manual control strategies and enhances staff training regarding their automated control operation.

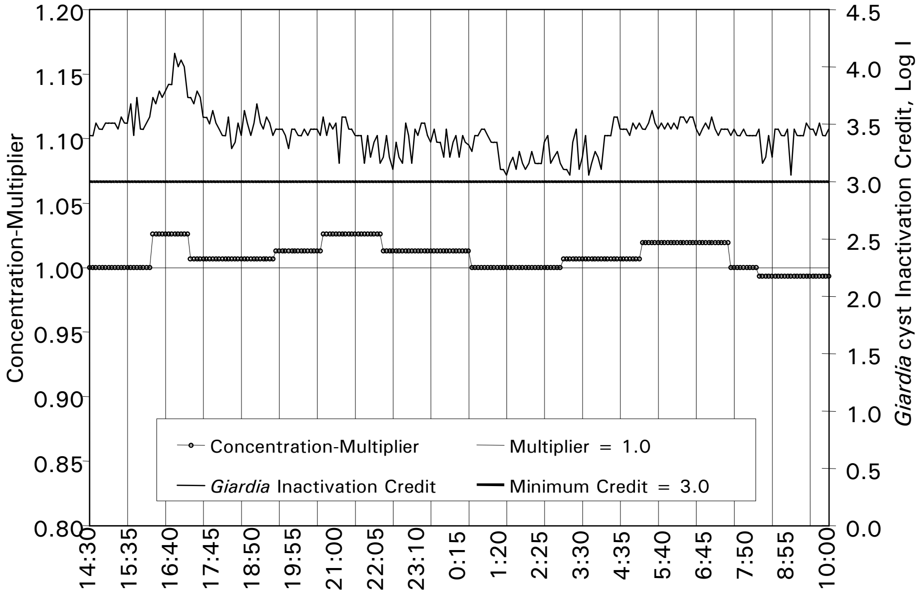


Figure 6-15
Range of Concentration-Multiplier at Plant 11 to Control *Giardia* Cyst Inactivation Credit

Example

The example outlined below assumes that multiple generators and contactors are manifold together and are operating fully automatically with constant gas flow control. It is also assumed that the operator manually changes the water flow rate set-point when plant water flow rate changes are made. An option can be added to the control system that will increase set-point water flow rate automatically if the measured water flow rate changes by, say, 15 percent. This feature would automate changes to gas flow rate, but on an incremental basis.

1. Operating characteristics.

    1.1. Constant gas flow to each contactor is established via set-point values for ozone concentration, total water flow rate, and ozone dose for each contactor. The operating gas flow will NOT change until the operator or computer changes the set-point values.

    1.2. The computer-control system calculates required total system generator power and adjusts power supply controllers for individual generators. The power might increase or decrease periodically based on a trimming signal for concentration-multiplier due to differential between set-point disinfection target versus measured target (e.g., set-point *Giardia* cyst inactivation credit versus measured credit).

2. Constant gas flow is implemented by the control system in the following way.

    2.1. The computer adjusts the gas flow control valve to each contactor until the measured gas flow rate to a contactor is equal (i.e., within a range such as ±3%) to the calculated flow for that contactor from Step 1.1.

    2.2. The following sequence of events occurs to establish constant gas flow (see Figure 6-7):

        2.2.1. The pressure decreases or increases in the piping upstream of the contactor when the gas inlet control valve opens or closes, respectively. The Pressure Regulating Valve (PRV) opens or closes to maintain set-point pressure downstream of the PRV (set by the ozone equipment manufacturer).

        2.2.2. The inlet/outlet motorized valves for all operating ozone generators are fully open. It is anticipated that balanced gas flow will occur. However, in case balanced flow does not exist, the operator can make a slight adjustment to the generator outlet isolation valve. An alarm may or may not be necessary as a warning of unbalanced generator flow.

3. Ozone generator power is controlled by the computer in the following way:

    3.1. The computer calculates total generator power using the following parameters:

        3.1.1. Set-point value for water flow.

        3.1.2. Average set-point ozone dose for all contactors.

        3.1.3. Concentration-multiplier trimmed value initially set at 1.0.

        3.1.4. Calculated gas flow rate from Step 1.1.

    - 3.1.5. Generator specific energy versus ozone concentration performance curve.
    - 3.1.6. The generator specific energy curve offset factor set-point.
  - 3.2. The computer adjusts individual generator power based on calculated total power from Step 3.1 and number of operating generators.
  - 3.3. Concentration-multiplier is trimmed if the measured *Giardia* inactivation credit drifts from the set-point credit. The contactor with the lowest calculated disinfection credit controls the trim adjustment. The concentration trimming procedure might be a step function with a time delay, such as 5 minutes between trimming adjustments. The magnitude and frequency of trimming adjustment should be adjustable. The trimming adjustment might utilize percentages or discrete values. An example percentage-based adjustment is to increase concentration-multiplier by 1 percent if measured disinfection credit is 5 percent below the set-point value. An example value-based adjustment is to increase the concentration-multiplier by 0.01 if measured disinfection credit is 0.2-log below the set-point value.

    NOTE: The displayed Giardia credit should be smoothed electronically, such as a 5-minute moving average residual used to calculate credit. The smoothing time should be adjustable.
  - 3.4. After the power adjustment is made, the computer waits for the delay time before determining if another dose trim is necessary. At that time if the delta between measured and set-point inactivation credit increases to, say, 0.5-log, then the concentration-multiplier adjustment increase might be a little greater, such as 0.02.

4. Automatic control failure/alarm considerations.
  - 4.1. The computer-control system will stop making adjustments to generator power when the concentration-multiplier reaches Level 2 alarm set-points, such as 0.8 and 1.2. A Level 1 alarm could be activated at lower set-point values, such as 0.85 and 1.15.
  - 4.2 The alarm point offers the following benefits.
    - 4.2.1. The ozone system maintains cost effective performance since the unit-mass ozone cost ($/lb) is unchanged within ±10 percent of the optimum ozone concentration and is changed only slightly with ±20 percent of the optimum concentration (see Figure 6-14).
    - 4.2.2. Protection from unsatisfactory disinfection performance is provided. The operator receives an alarm if the ozone demand increases dramatically and disinfection credit decreases. The operator assesses the situation and determines that the change is due to deterioration in water quality that calls for increase in set-point ozone dose.

4.2.3. Protection from ozone overdose is provided. If the residual monitor fails and drops to a low ozone reading, the operator is alarmed before the ozone system increases power unnecessarily.

4.3 Variations in water flow and transfer efficiency between contactors may cause the measured disinfection credit to vary significantly between contactors. If this occurs, the operator may adjust set-point dosage to individual contactors. This will result in slightly different gas flows to individual contactors.

7

ON-LINE OZONE RESIDUAL ANALYZERS FOR DISINFECTION COMPLIANCE

Ozone Facility Evaluations were conducted at ten (10) full-scale ozone facilities during Phase 2 of the ozone optimization research project. Results indicated that high potential exists for energy cost savings. One of many optimization opportunities involved ozone residual monitoring. Nine of ten facilities evaluated had on-line residual analyzers. Only one facility had reliable on-line analyzer performance. Eight facilities were trying to achieve reliable performance; some had given up. Improving on-line ozone residual analyzer reliability could lead to:

1. Less staff time to conduct manual sampling;
2. Lower cost of chemicals for conducting grab tests;
3. Improved public health protection because disinfection credit could be calculated continuously in the plant computer using analyzer data; and
4. Reduced operating cost by lowering applied ozone dose via automation, while maintaining performance.

In Phase 3 of the AWWARF/EPRI-CEC Ozone Energy Optimization Project, the cities of Arlington, Dallas, and Fort Worth, Texas joined with their electrical energy provider, TU Electric, in an effort to identify, implement, and document characteristics and attributes of a successful on-line ozone residual monitoring program. Issues addressed during the project and discussed in this chapter include:

1. Assessing analyzer accuracy.
2. Improving and maintaining analyzer reliability.
3. Detecting and protecting against sudden, unexpected analyzer malfunction when analyzers are utilized for automated process control.

Research Approach

The cities of Dallas and Fort Worth, Texas use ozone for disinfection compliance at the Elm Fork and Eagle Mountain Water Treatment Plants (WTPs), respectively. Compliance is achieved by maintaining a minimum 2-logs virus inactivation credit with ozone. Grab samples are collected at the required four-hour interval at both utilities. Unfortunately, the original on-line ozone residual monitoring systems were abandoned. The single analyzer for each contactor was installed on a common line that was connected to the individual cell sample lines. Sample flow from each cell was directed to the analyzer by a solenoid valve. Three main problems caused the on-line residual monitoring systems to be abandoned.

1. The measured residual was reduced significantly because of the long sample line hydraulic detention time (HDT) and rapid ozone decay.

2. The solenoid valves would partially plug, resulting in leakage when “closed” and causing mixing of sample water from other cells.

3. The analyzers proved to be inaccurate and unreliable. It should be noted that this analyzer no longer is marketed.

For this research project each plant emphasized a different aspect of ozone residual analyzer performance. The Fort Worth, Eagle Mountain WTP evaluated disinfection performance as determined by ozone residuals from the on-line analyzers and by grab samples. The Dallas, Elm Fork WTP assessed side-by-side performance characteristics of three different analyzers. The study approach at each plant is further described.

Fort Worth, Eagle Mountain WTP Testing

Ozone is applied to raw lake water in one pre-ozone contactor at the Eagle Mountain WTP. Disinfection credit for virus inactivation is determined based on direct credit (first cell) and CT value and water temperature, as described in Appendix O of Guidance Manual for Compliance With the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources (USEPA, 1990). Ozone residuals are measured using the Hach Accuvac[2] method in the first, third, and fifth cells of the ten-cell ozone contactor. Samples are collected quickly (i.e., with minimum detention time in the sample lines) because the ozone decay rate is very rapid. The ozone half-life ranges from 0.5 minutes to 2 minutes in the summer and winter, respectively.

The City of Fort Worth purchased one Orbisphere[3] probe-type analyzer prior to the research project. The probe was installed in the special probe-holder that came with the unit. The holder was designed for a relatively low flow rate past the probe. The holder was connected to the ¾-inch (19 mm) main sample line with ¼-inch (6 mm) tubing. To minimize detention time in the sample line, a larger volume of sample flow was directed through the ¾-inch (19 mm) line past the ¼-inch (6 mm) connection. The flow to the holder was controlled to the suggested 1 to 2 L/min rate using a control valve on the ¼-inch (6 mm) line. The operators reported that the analyzer was accurate as long as the flow rate past the probe was consistent. However, partial or full plugging of the ¼-inch (6 mm) line would occur due to debris in the raw water. The analyzer was useless when the sample flow was reduced.

An alternative probe installation technique was implemented based on success reported at another ozone facility (Anderson et al., 1995). Specifically, the probe was installed directly on

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[2] Hach Chemical Company, Loveland, CO

[3] Orbisphere Laboratories, Model 26506 (Analyzer), 31331.15 (Probe), 70 Kinderkamack Rd., Emerson, NJ 07630

the ¾-inch (19 mm) main sample line. A 1-½ inch (38 mm) stainless steel tee was fitted into the ¾-inch (19 mm) main sample line with two 1-½” × ¾” (38 × 19 mm) reducers. The 1-½ inch (38 mm) branch was threaded on the outside to allow the Orbisphere probe to be screwed directly into the tee. Control of the gravity sample flow rate was achieved using a ball valve that was installed after the modified tee and before the drain. For the research project, a similar probe installation set-up was used for two other Orbisphere probes that were loaned to the Project by the Portland, Maine Water District. With three analyzers at the Eagle Mountain WTP, disinfection Performance Ratio (PR) was measured using both the analyzer readings and grab sample results. Performance Ratio is defined as the actual, measured virus inactivation credit divided by the required 2-logs credit.

Dallas, Elm Fork WTP Testing

Ozone is applied to raw river water in four pre-ozone contactors at the Elm Fork WTP. Similar to the Eagle Mountain WTP, ozone residuals are measured in the first, third, and fifth cells of the ten-cell ozone contactors. Disinfection credit and Performance Ratios are determined similarly, and ozone decay rates are similar. One major difference is that the source water turbidity of the Elm Fork River is significantly higher than in the Eagle Mountain Reservoir water. The Elm Fork River turbidity ranges from 20 NTU to 50 NTU most of the time, and up to 3000 NTU during rain events.

The Elm Fork WTP staff had purchased an IN-USA[4] stripping-type analyzer prior to the research project. The analyzer provided good results, but would plug frequently. The frequency and time that were required for totally dismantling and cleaning the stripping column were unacceptable. To alleviate cleaning the unit, the supplier provided in-line filters to protect the stripping column. The filters are cleaned on a daily basis, and cleaning the stripping column has been virtually eliminated.

It is important to note that the turbid sample creates a very difficult situation for ozone residual monitoring at the Elm Fork WTP. On-line metering is highly susceptible to plugging. In addition, grab sample measurements must be performed in a special manner. Specifically, grab samples reacted with indigo are passed through a filter before absorbency is measured. Filtering eliminates interference caused by the turbidity.

Research activities at the Elm Fork WTP addressed on-line analyzer reading accuracy without excessive O&M for cleaning or standardization. Performance for three analyzers was examined. The existing IN-USA stripping-type analyzer was evaluated, as installed on the third cell of contactor 3. Two probe-type analyzers (Rosemount[5] and Orbisphere) were installed on the same sample line. The Portland, Maine Water District loaned an Orbisphere analyzer to the Project. The Rosemount analyzer was loaned to the project by the manufacturer. Figure 7-1 shows a diagram of the analyzer setup. The constant-head apparatus was designed to maintain a consistent, controlled flow to the analyzers and allow the quick collection of grab samples. Most importantly, the flow could be controlled without using a flow-restricting valve that might plug

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[4] IN-USA, Model W1 Dissolved Residual O3 Analyzer, 87 Crescent Rd., Needham, MA 02194

[5] Rosemount Analytical, Model 1054B OZ (Analyzer), 499A OZ (Probe), 4200 Barranca Parkway, Irvine, CA

in the high turbidity water sample. Under this arrangement, data for three analyzers was recorded for each grab sample measurement.

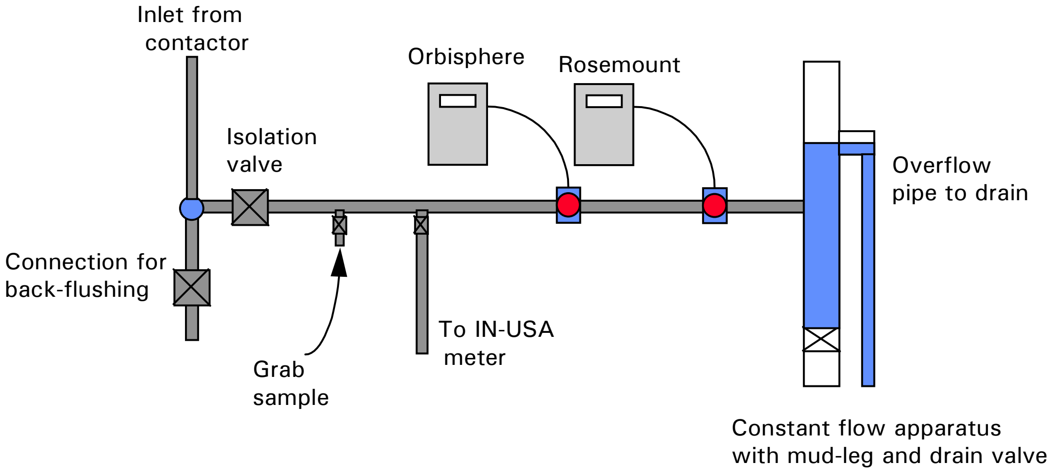

Figure 7-1
Schematic of On-Line Analyzer Setup at Cell 3 of Contactor 3 at the Elm Fork Water Treatment Plant

Disinfection Results - Eagle Mountain WTP

Research activities began at the Eagle Mountain WTP in February 1998. First, an analyzer standardization protocol was developed that addressed unique issues involved with ozone, such as variability in true residual. Second, the analyzer standardization protocol was conducted three times per week to assess analyzer accuracy and standardization frequency. Third, residual data for one grab sample and an associated analyzer reading were collected six times per day from each of the ozone contactor sampling points. Grab and analyzer data were used to calculate CT value and disinfection performance ratio.

Residual Analyzer Standardization Protocol

Ozone residuals within the bubble diffuser ozone contactor are naturally variable, especially for samples collected after bubble diffusion cells. The factors affecting residual variability include incomplete mixing, dispersed ozone bubbles from evenly spaced diffusers, and ozone decay rate. A high degree of variability at the outlet of diffusion cell 3 is shown in Figure 7-2. Analyzer readings collected at 5-second intervals over a 25-minute time frame varied from 0.20 to 0.33 mg/L. During that time, water flow, water quality, and applied ozone dose were unchanged. Variation was even more pronounced for grab samples collected at 15-second intervals, beginning at 5 minutes and ending at 15 minutes. Grab sample results shown in Figure 7-2 varied from 0.17 to 0.35 mg/L. The analyzer seemed to dampen the true variation in residual that was occurring inside the contactor. These data illustrate that the residual analyzer standardization protocol must take into account the variability in true ozone residual. One grab sample is insufficient to assess analyzer accuracy properly.

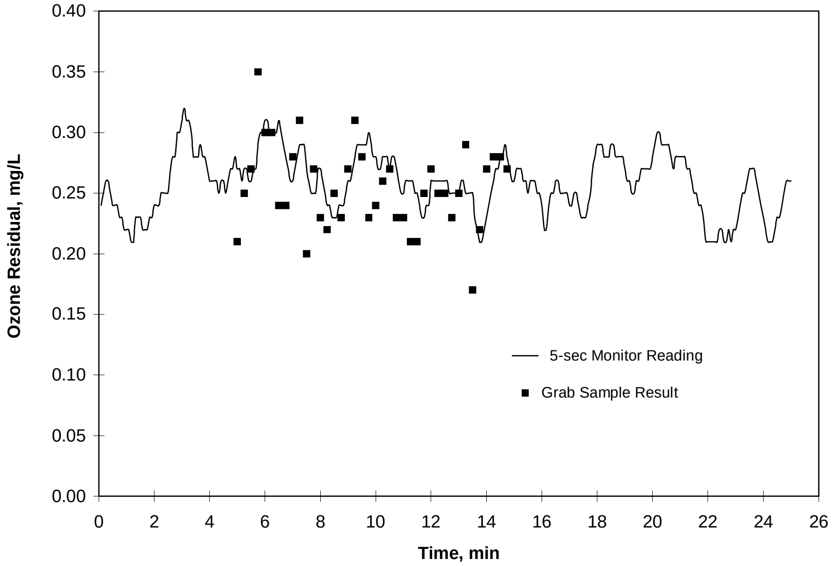

Figure 7-2
Ozone Residual Variability From Cell 3, Train 2 at the Eagle Mountain Water Treatment Plant

As a result of project team discussions, a special study was conducted to evaluate the repeatability of the grab samples taken with the Hach ampoules (mid-range). A total of 27 grab samples were collected, each with two ampoules simultaneously collecting a sample. Figure 7-3 shows that in most cases, comparative ampoule results were within 10 percent. Two comparative readings were significantly different. This discrepancy could have been a result of gas bubble interference or perhaps the ampoules were not broken at the exact same time in the beaker. These results show that multiple ampoules give similar results for a single grab sample. It was concluded that an individual ampoule provides a representative ozone residual value. Therefore, the high degree of fluctuation in grab sample results shown in Figure 7-2 is due to actual variation within the ozone contactor and not to improper sample collection or analysis protocols.

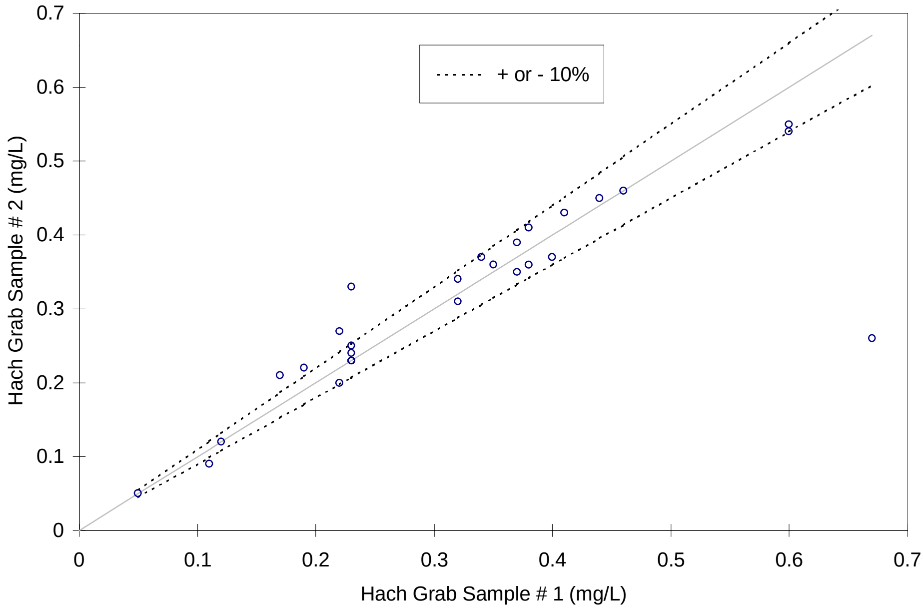

Figure 7-3
Comparison of Simultaneous Grab Samples Using Hach Ampoules

Figure 7-4 illustrates the principal aspects of the protocol for ozone residual analyzer standardization that was developed and implemented during the research project. Specifically, nine grab samples were collected at approximately 15-second intervals over the course of two minutes. The analyzer reading was recorded at the same time the grab sample was taken. The grab samples average, standard deviation, and standard deviation range (grab samples average plus/minus the standard deviation) were calculated, as well as the analyzer readings average. The analyzer was considered to be standardized when the average analyzer reading was within the grab sample standard deviation range. If the analyzer average was outside the range, then an adjustment was made to standardize the analyzer reading. The amount of adjustment was 50 percent of the difference between the grab sample average and analyzer reading average. The 50 percent adjustment convention was implemented after it was observed that a full 100 percent adjustment often caused an over-adjustment. Analyzer adjustments are somewhat sensitive.

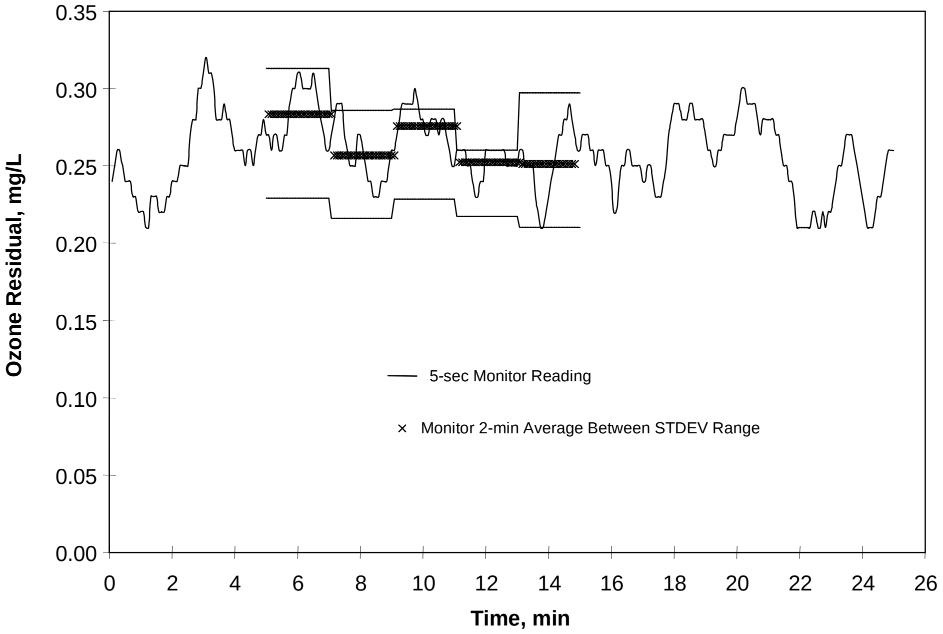

Figure 7-4
Grab Sample Residual Acceptable Range Versus Average of Analyzer Readings

From February 19, 1998 through February 10, 1999, Eagle Mountain WTP staff conducted formal analyzer standardization tests following this standardization protocol. Figure 7-5 shows the standardization test results for the cell 1 analyzer. From February 19, 1998 through June 19, 1998, standardization tests were conducted about three times per week. The analyzers were located on contactor 2 during the project. From June 19, 1998 through August 14, 1998 the analyzers were not in service because contactor 1 was in operation. Contactor 2 was put back in service in August, and standardization testing began again on August 14, 1998. From August 14 through the end of 1998, standardization tests were conducted less frequently because of the reliable performance demonstrated earlier in the project. Standardization testing frequency was increased to about three times per week beginning January 1, 1999 because on that date the City of Fort Worth began using residual analyzer readings to document disinfection compliance and chose to conduct the standardization protocol more frequently than the required weekly test. Figure 7-5 shows that the analyzer on cell 1 required an adjustment only seven times during about ten months of operation.

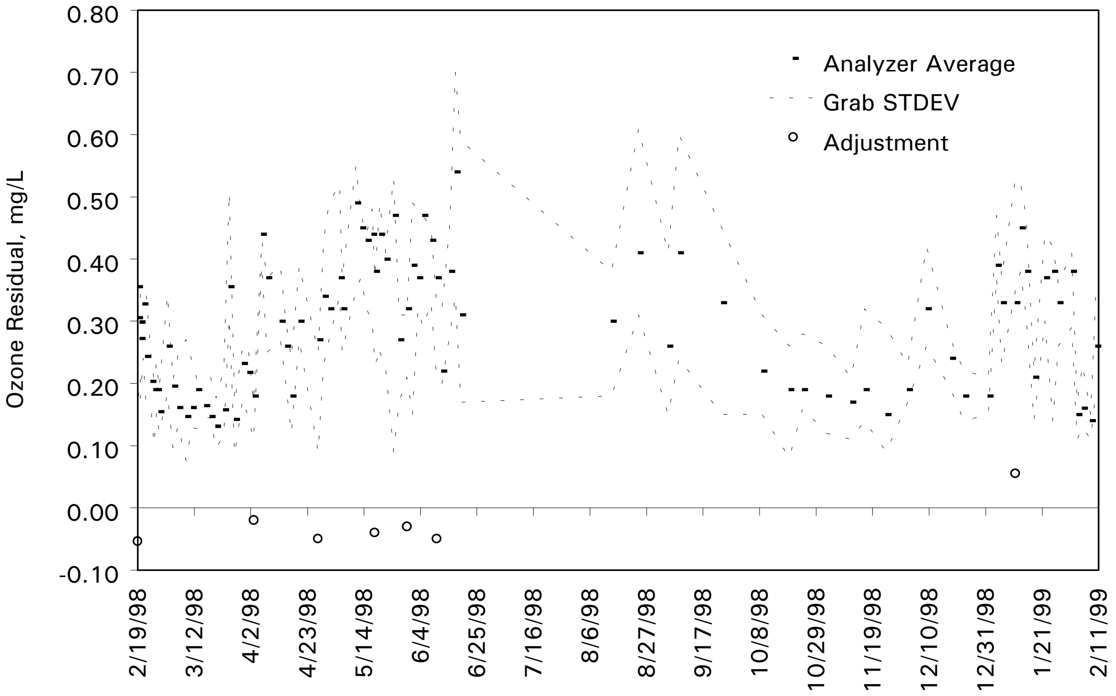

Figure 7-5
Standardization Trend for the Cell 1 Analyzer, Eagle Mountain WTP

The standardization test results for the Orbisphere analyzer on cell 3 indicate that an adjustment was needed about two weeks after the first adjustment was made on February 19 (see Figure 7-6). However, the analyzer adjustment knob had reached its limit, indicating that the probe required servicing. Unfortunately, electrolyte solution was unavailable and servicing was delayed a few days. After servicing and standardization, analyzer 3 maintained standardization for several weeks before the next adjustment was required. Over about ten months of operation, only six adjustments were required for the analyzer on cell 3.

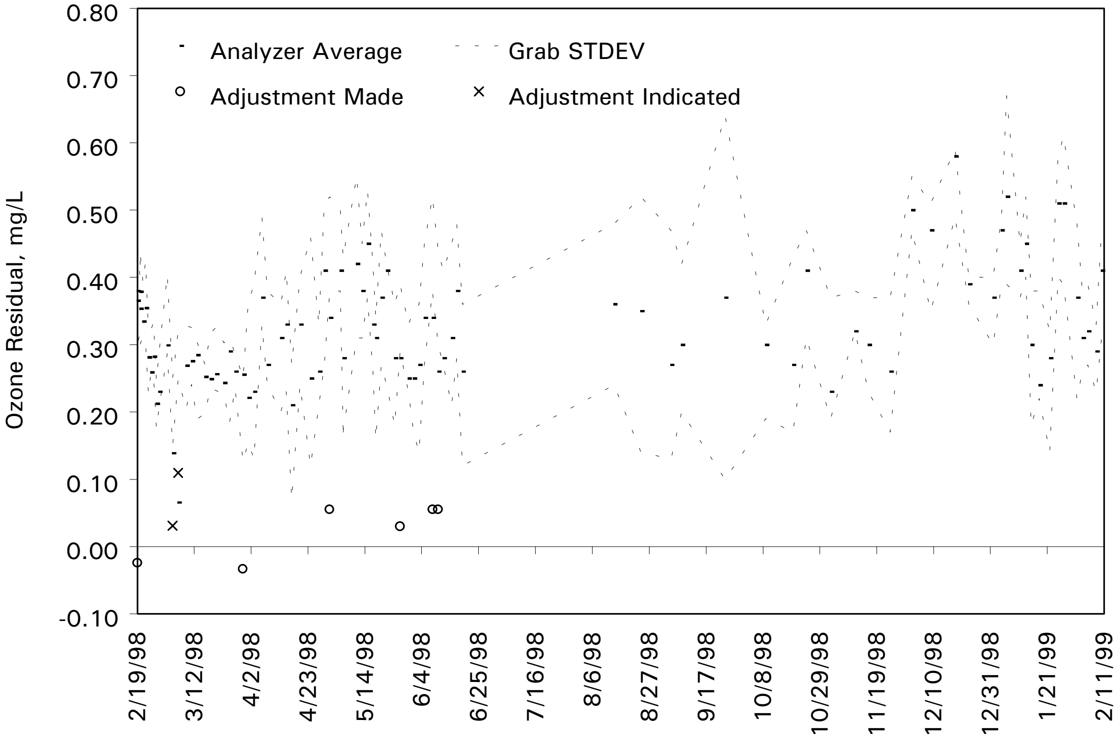

Figure 7-6
Standardization Trend for the Cell 3 Analyzer, Eagle Mountain WTP

As shown in Figure 7-7, the cell 5 analyzer indicated more calibration adjustments were necessary than for either analyzer 1 or analyzer 3. However, the ozone residual for cell 5 was much lower than for cells 1 and 3. Ozone was added to cells 1 and 3, but not to cell 5.

The indicated calibration adjustments for analyzer 5 often were very small (i.e., 0.02 mg/L or less) due to the low residuals. Data from cell 5 indicated that it would be appropriate to add a minimum adjustment to the protocol. The standardization protocol was modified to disregarded adjustments of 0.02 mg/L or less at the Eagle Mountain WTP. Following the modified protocol, eleven adjustments were made to the cell 5 analyzer during seven months of operation.

When contactor 2 was returned to service in August 1998, the analyzer on cell 5 was not providing accurate readings. The cell 5 analyzer was not returned to continuous service until November 11, 1998 because the cell 5 residuals were very low anyway and other plant activities were a higher priority than repairing the cell 5 analyzer.

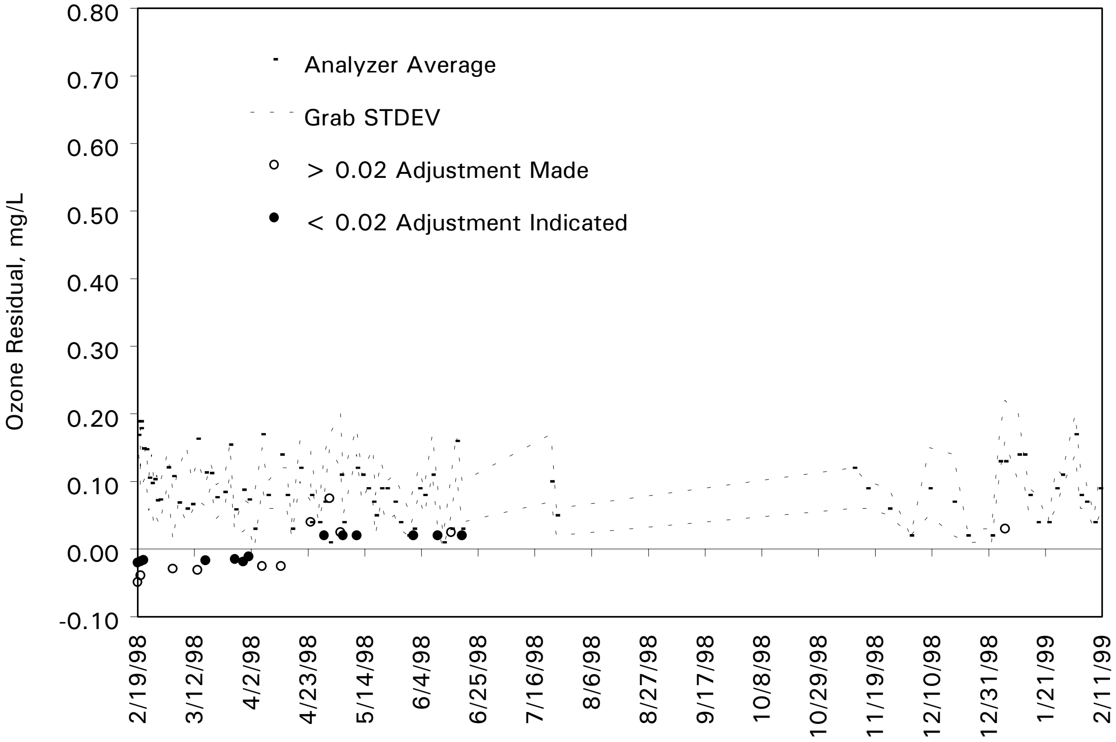

Figure 7-7
Calibration Trend for the Cell 5 Analyzer, Eagle Mountain WTP

Most of the analyzer adjustments for each cell occurred in the early part of the project as plant operations staff began using and testing the standardization protocol. On several occasions an analyzer adjustment was made a few days after a previous adjustment. The protocol was modified so that a second standardization test was conducted if the first test indicated that an adjustment was required. An adjustment was made only if both tests indicated an adjustment was necessary. This may have reduced the number of adjustments required later in the project.

Disinfection Compliance Results

A project goal was to obtain approval from the Texas Natural Resource Conservation Commission (TNRCC) to use on-line ozone residual analyzers for disinfection compliance purposes at the Eagle Mountain WTP. The TNRCC required proof that disinfection compliance calculated with analyzer readings or grab samples would provide similar results. A spreadsheet-based ozone system monitoring program was developed to provide the data required for accomplishing this goal.

The Eagle Mountain WTP staff collect ozone residual grab samples at four-hour intervals for disinfection compliance. Since February 20, 1998, the staff also has recorded analyzer readings and ozone system operating data that allowed determination of applied ozone dosage. Data for each test were input into the monitoring program. Results were summarized in a test report and data were posted to a database. An example report sheet is shown in Figure 7-8. Key data for the project included the applied ozone dose and disinfection performance ratio using both grab sample residuals and analyzer readings. Other data collected included operating cost, transfer efficiency, etc.

Eagle Mountain WTP Ozone System Performance Summary

Parameter	Units	Data	
Date	m/d/y	06/05/98	
Test Number	#	2	0800 Hr
# of Air Comp. on-line	(1,2)	1	
# of Ref. Dryers on-line	(0,1,2)	1	
# of Des. Dryers on-line	(1,2)	1	
# of Ozone Dest. on-line	(1,2)	1	
# of Cooling Pmps on-line	(1,2)	1	
	Genr No.	1	2
Generator Air Flow Rate	acfm	79.00	86.2
Pressure	psig	20.30	20.5
Temperature	F	70.20	70.2
DC Amperage	amps	225	223
O3 Concentration	%wt	3.231	
LOX Flow Rate	acfm	37.9	
Target Virus Inactivate Credi	Log I	2	

		Train 1		Train 2
Gas Flow to Train	scfm			160.75
to Cell	acfm			80.50
to Cell	acfm			99.20
Off-gas Ozone Conc.	%wt			0.434

AVERAGES		Train 1		Train 2	
O3 Residual Avg's.		Grab	Meter	Grab	Meter
Cell 1	mg/L			0.35	0.33
Cell 3	mg/L			0.39	0.38
Cell 5	mg/L			0.05	0.01
Meter Flow Rate		sec/L	L/min	sec/L	L/min
low Cell 1	sec/L			5	12.0
Cell 2	sec/L			5	12.0
Cell 3	sec/L			5	12.0

No. Trains In-Service	(1,2)	1
Barometric Pressure	in Hg	29.9
Plant Water Flow Rate	MGD	27
Water pH	units	8
Water Temperature	C	26.67

Ozone Generation System Performance

Parameter	Units	Total	Gen 1	Gen 2
Generator Air Flow Rate	scfm	161	76.76	83.99
Ozone Production	lb/day	574		
Generator Power Demand	kW	157.0	83.3	73.7
Measured SE	kWh/lb	6.56		
Air Comp. Power	kW	24.00	$/lb	0.86
RD and DD Power	kW	7.40	$/MG	18.30
OD Power	kW	3.30	$/day	494.20
Cooling Pump Power	kW	4.30		
TOTAL System Power	kW	196.0		
TOTAL System Specific Energ	kWh/lb	8.19		

Input Residual Data

	Train 1		Train 2	
	Grab	Meter	Grab	Meter
Cell 1-1			0.35	0.33
Cell 1-2				
Cell 1-3				
Cell 3-1			0.39	0.38
Cell 3-2				
Cell 3-3				
Cell 5-1			0.05	0.01
Cell 5-2				
Cell 5-3				

Ozone Contactor Train 2

No. Trains in Service	#	1	Cell1	Cell3	Cell5			
Percent Gas Flow to Train	%	100%	50%	50%				
Gas Flow to Train	scfm	161	80.50	80.25				
Diffuser Flow	scfm/diff		3.35	3.34				
Applied Ozone Dose	mg/L	2.55	1.28	1.27				
Hydraulic Detention Time	min	8.14	dn Flow	1.24	UpFlow	0.38		
Ozone Transfer Efficiency	%	87%	OG =	0.43	%wt			
Grab Residual for CT	mg/L		0.35	0.39	0.05			
Half-Life	min				0.55			
Calculated CT	mg/L*min	0.234		0.175	0.059			
Virus Inactivation Credits	Log I	3.94	T Log I=	2.94	Direct =	1.00	Train 2	
GRAB Sample PR	--	1.97	Virus Rate, K		12.595		***Grab PR***	**1.97**
Grab sample Ct basis PR	--			2.94			***Ct PR***	**2.94**
Meter Residual for CT	mg/L		0.33	0.38	0.01			
Half-Life	min				0.31			
Calculated CT	mg/L*min	0.182		0.171	0.012			
Virus Inactivation Credits	Log I	3.30	T Log I=	2.30	Direct =	1.00		
METER PR	--	1.65	Virus Rate, K		12.595		***Meter PR***	**1.65**
METER Ct basis PR	--			2.30			***Ct PR***	**2.30**

Figure 7-8
Example Report From Ozone Disinfection Compliance Monitoring Program

The TNRCC suggested using a percent-time distribution curve for comparing performance ratio calculated with both analyzer and grab sample data. Figure 7-9 shows the percent of time the PR was equal to or greater than the minimum target of 1.0 for the month of May 1998. The percent-time distribution curves for PR are similar for analyzer and grab sample data. Both methods of measuring residuals provided an equivalent report of disinfection compliance. The May 1998 data is typical of other months during the project except for March 1998. Figure 7-10 shows results for March 1998. Reported disinfection was above a PR value of 1.0 for 92 percent and 99 percent of the time for the analyzer readings and grab samples, respectively. The lower PR reported for analyzer readings occurred when the cell 3 analyzer was giving incorrect low readings for several days early in March 1998, as discussed previously. To protect against sudden inaccurate on-line residual readings that might develop, other ways of assessing performance on-line were evaluated.

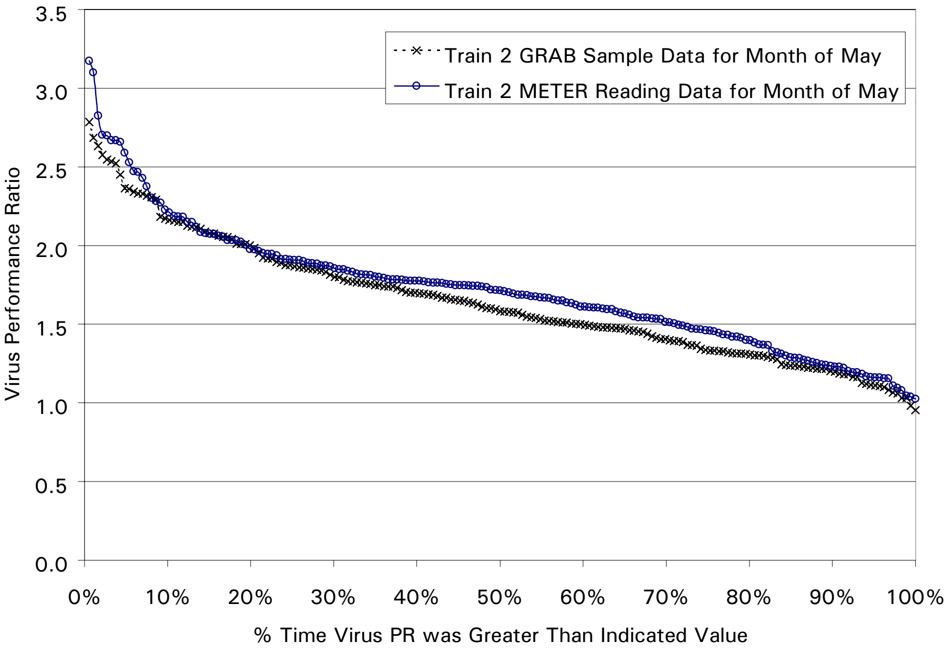

Figure 7-9
Percent of Time Disinfection Compliance Was Achieved, May 1998, Eagle Mountain Water Treatment Plant

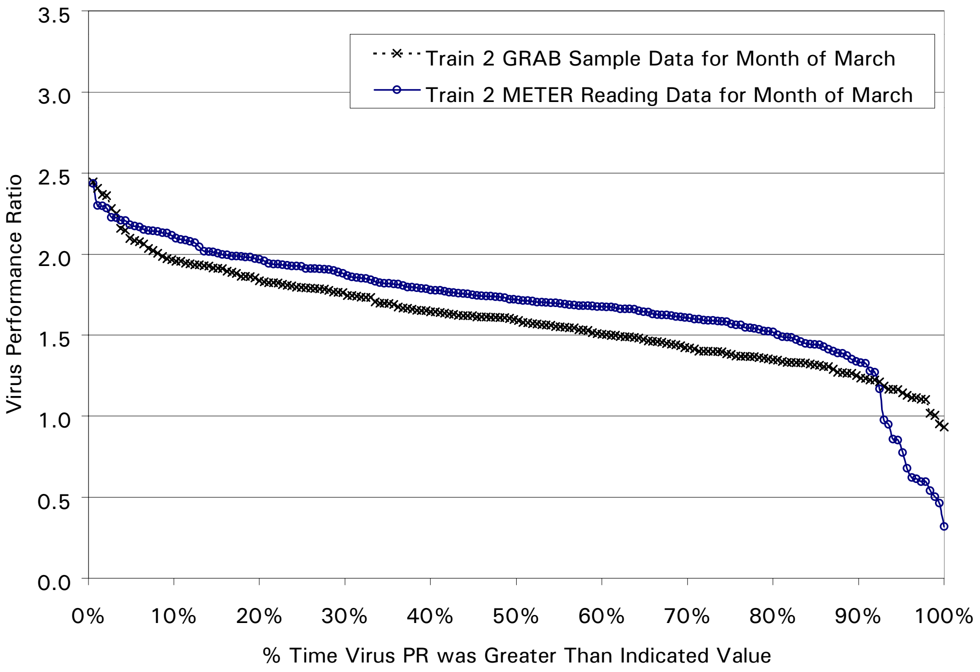

Figure 7-10
Percent of Time Disinfection Compliance Was Achieved, March 1998, Eagle Mountain Water Treatment Plant

Another indicator of process performance is the ozone dose. Ozone dose should remain relatively constant unless water quality changes occur. If one or more analyzers were to malfunction, ozone dose could be used for process control between grab sample readings. Two sudden changes in performance occurred in the Eagle Mountain PR and ozone dose data from March 1, 1998 through April 15, 1998, as shown in Figure 7-11. First, the analyzer PR dropped suddenly in early March. The operators determined that the analyzer was not standardized, but could not adjust the reading because electrolyte solution was not available. However, ozone dose remained constant and grab samples indicated that required disinfection performance was maintained.

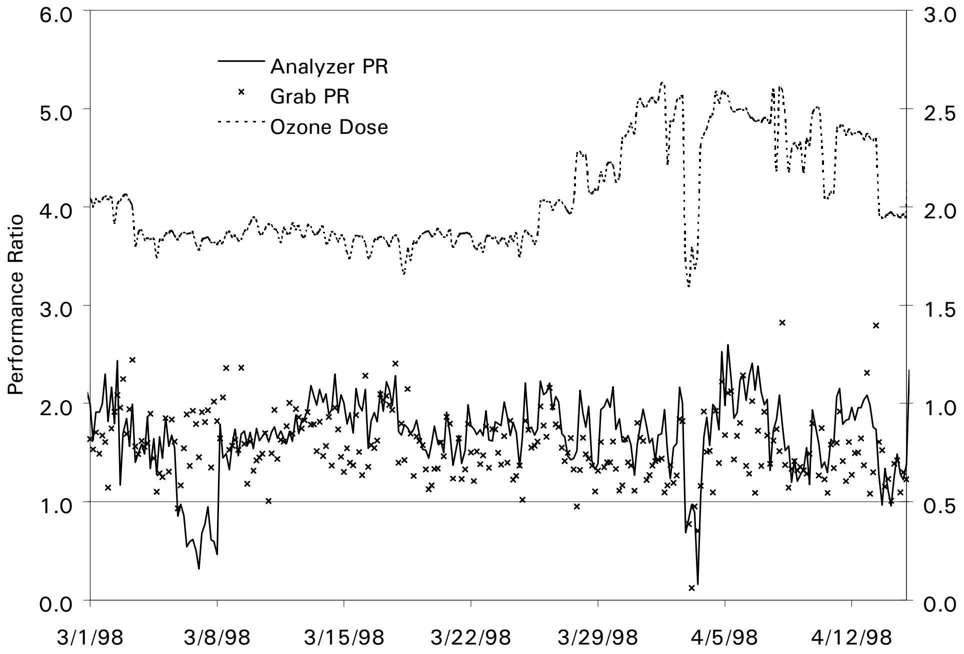

Figure 7-11
Performance Ratio and Applied Ozone Dose Trend, Eagle Mountain WTP

The second time PR dropped suddenly was early in April. In this case the PR dropped below 1.0 for both the grab samples and analyzer readings due to low applied ozone dose. (NOTE: At the Eagle Mountain WTP the ozone dose could not be increased at that time due to equipment maintenance. Required disinfection was achieved by increasing chlorine dose.) Based on these data, it was concluded that ozone dose might be a useful indicator for sounding an alarm if analyzer performance changes suddenly and the plant is operating automatically.

On December 22, 1998, the TNRCC authorized the Eagle Mountain Water Treatment Plant to use their on-line monitors for ozone residual readings of record, based in part on data such as shown in Figure 7-9 and Figure 7-10. On January 1, 1999 the Eagle Mountain Water Treatment Plant staff began using on-line ozone residual analyzer readings for reporting disinfection compliance.

Analyzer Results - Elm Fork WTP

Rosemount, Orbisphere, and IN-USA analyzers all were installed on the sample line from cell 3 of contactor 2 at the Elm Fork WTP, as described earlier in this chapter. This allowed data collection from the same sample for each analyzer. Grab samples also could be collected for comparison to the analyzer readings. This arrangement did not allow disinfection performance comparison between the analyzers and grab samples, as was done at the Eagle Mountain WTP, because more than one residual reading location is required to calculate ozone CT value. The goal of testing at the Elm Fork WTP was to observe analyzer performance and maintenance requirements.

A special study was conducted at Elm Fork to compare grab sample residuals with readings from the three analyzers. Readings from the analyzers were collected at 15-second intervals over a 68-minute time period. Nine grab samples were collected at 15-second intervals on four occasions during the same time period. Results are shown in Figure 7-12. Water flow, water quality, and applied ozone dose essentially were unchanged during data collection. Significant variation in residual readings occurred for all three analyzers, as well as for the grab samples. This shows that the actual residual inside the contactor is highly variable. The variation in true ozone residual likely was due to the effects of insufficient mixing, dispersed ozone bubbles from evenly spaced diffusers and ozone decay rate, similar to the Eagle Mountain WTP.

Grab sample residuals were used to check the standardization for each of the three on-line analyzers. The analyzers had not been standardized for two weeks prior to this special study. The Rosemount analyzer readings were within an acceptable standardization range all four times, as shown in Figure 7-13. The Orbisphere analyzer was within an acceptable standardization range for three of the four tests, as shown in Figure 7-14. It appears that the Orbisphere reading might be adjusted upward slightly. The IN-USA analyzer readings were much lower than grab sample results, as shown in Figure 7-15. It should be noted that the low readings for the IN-USA analyzer were believed to be due to ozone decay during the extra minute of detention time in the sample line and filters. The effect on ozone residual from sample line HDT is discussed further in the next section of this chapter.

The Elm Fork WTP staff has gained confidence with each type of analyzer. Both probe-type units maintain standardization similarly. The stripping-type unit is standardized successfully when ozone decay is lower (e.g., winter) and HDT in the sample line has less effect on the analyzer reading.

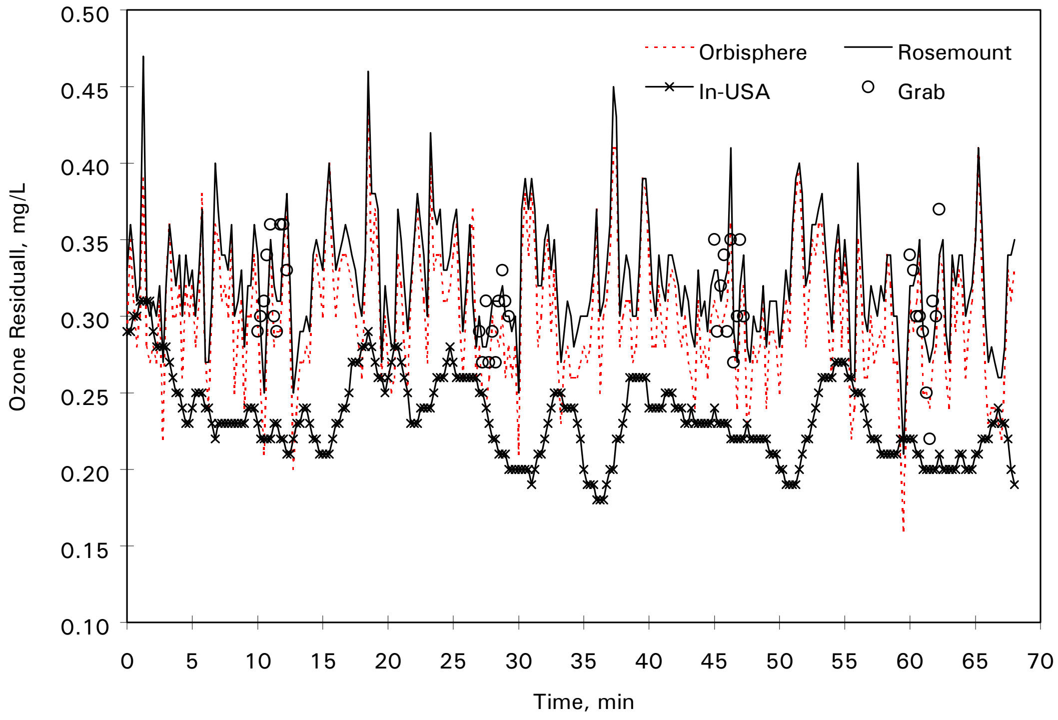

Figure 7-12
Ozone Residual Variability From Cell 3, Contactor 3 - Elm Fork WTP

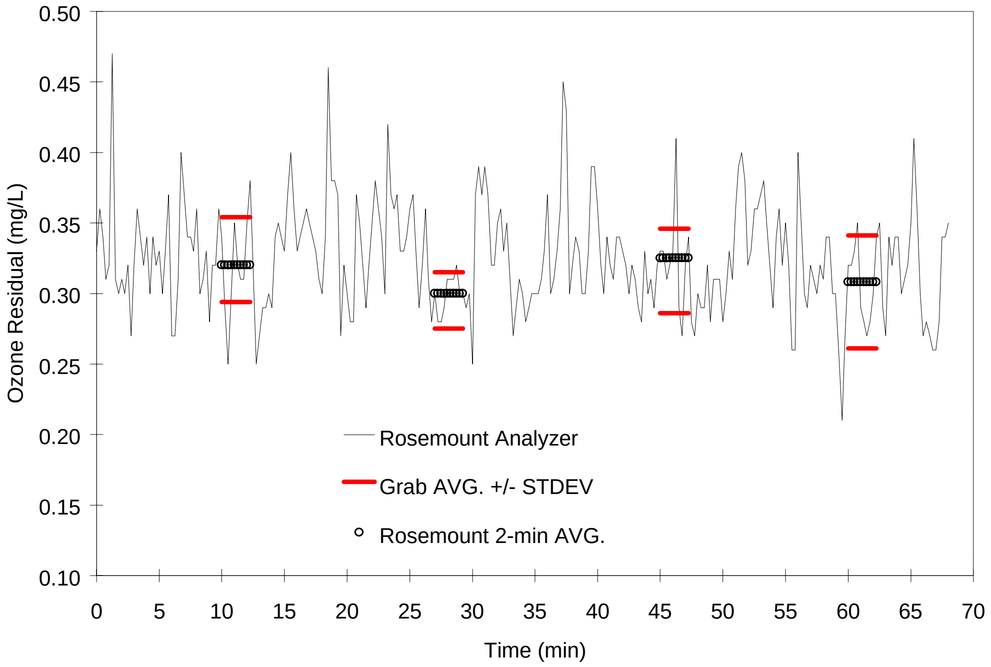

Figure 7-13
Rosemount Analyzer Standardization Data, Elm Fork WTP

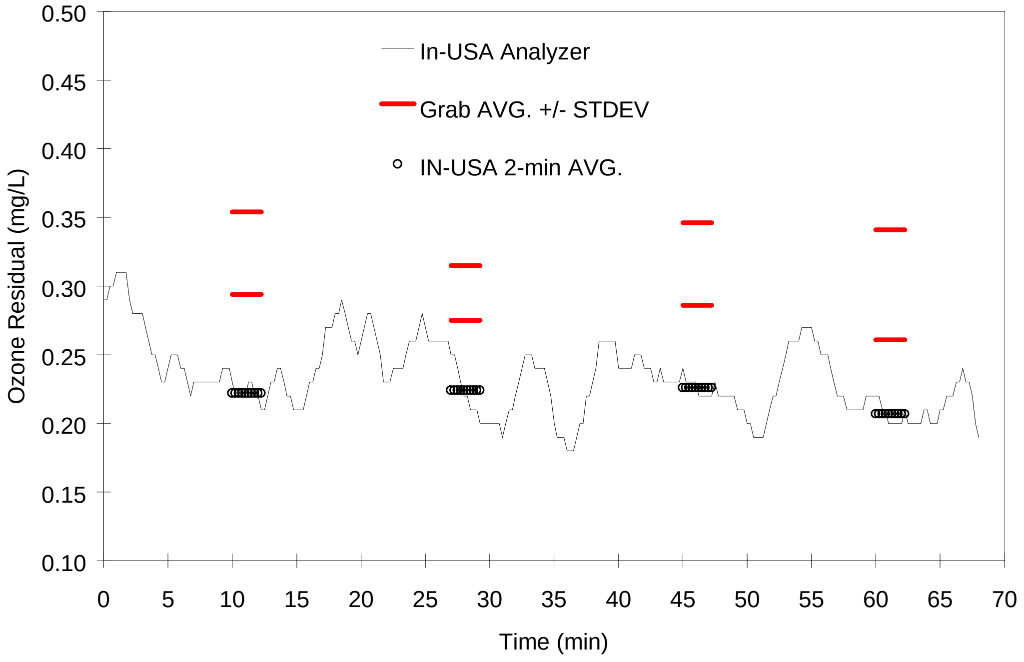

Figure 7-14
Orbisphere Analyzer Standardization Data, Elm Fork WTP

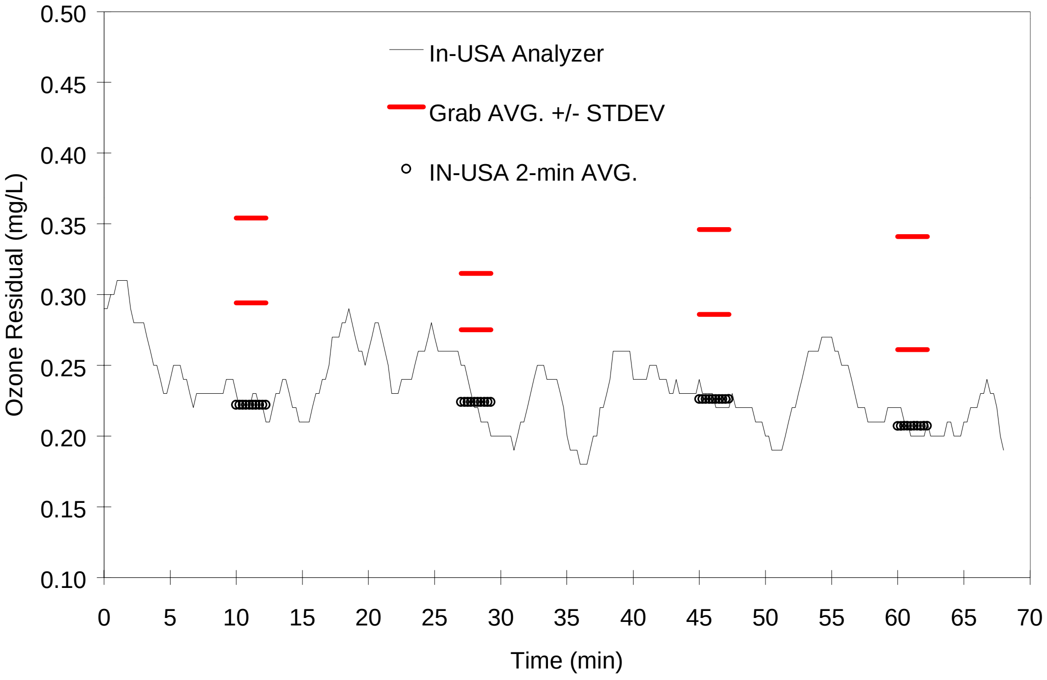

Figure 7-15
IN-USA Analyzer Standardization Data, Elm Fork WTP

Considerations for Obtaining Reliable Analyzer Readings

On-line ozone residual analyzers might be used with confidence for process control and compliance reporting if they are properly installed, maintained, and standardized. Important observations and considerations are discussed below.

Standardization Protocol

The ozone residuals at the outlet of the dissolution cells at the Eagle Mountain and Elm Fork plants were highly variable. As such, analyzer standardization could not be judged correctly with just one grab sample result. Instead, nine grab samples were collected and nine analyzer readings were taken simultaneously. Analyzer standardization was judged using the following protocol.

1. The average and standard deviation of the nine grab samples were calculated, as well as the standard deviation range defined as the grab sample average plus/minus the standard deviation.
2. The nine analyzer readings were averaged.
3. The analyzer was considered standardized if the analyzer average was within the grab sample standard deviation range.
4. If the analyzer average was outside the grab sample standard deviation range, the test might be repeated if the last standardization adjustment was recent (i.e., recent as defined by the analyzer's standardization history with respect to expected frequency for adjustment). The test might not be repeated if the standardization adjustment was some time ago.
5. When adjustments were made, the adjustment value was 50 percent of the difference between the grab samples average and analyzer readings average.

It should be noted that nine grab samples might not be the optimum number of samples. The optimum number may be less than nine, especially when the ozone half-life is longer. Nine is considered a conservative number of samples. The number of samples may be lowered at the Elm Fork and Eagle Mountain plants if follow-up special study results justify the change.

Grab Sampling Considerations

Several methods are available for collecting ozone residual grab samples. Detailed procedures for conducting the Indigo Colorimetric Method for determination of ozone residual in water may be found in Standard Methods (Standard Methods for the Examination of Water and Wastewater, 20th ed., 1998). Either the volumetric procedure or the gravimetric procedure may be used. Details for measuring ozone residual using Hach ampoules are available from the Hach Chemical Company, Loveland, Colorado. Each of these methods will provide good results if properly conducted. Detailed procedures for these tests are not covered in this report. Some tips for conducting these tests are presented below based on experience gained by the authors during this project and during start-up and optimization activities at other utilities.

Minimizing the **detention time** in the sample line is a priority regardless of what method is used for the grab samples. Once the sample is reacted with the indigo reagent the reacted solution can be set aside for a period of up to four hours. However, it is good practice to measure absorbency of the reacted sample as soon as possible. Collecting samples via a short, small diameter sample line (¼-inch) (6 mm), with valve, works well for each method. The grab sample location might be just after the analyzer or right after the sample line comes out of the contactor.

When using the volumetric procedure described in Standard Methods, care should be taken to avoid splashing sample on the narrow neck of the volumetric flask that is used to collect the grab sample. This will cause some of the ozone to be released from the sample before it reacts with the indigo at the bottom of the flask. A ¼-inch (6 mm) sample tube might be inserted into the narrow neck of the volumetric flask, allowing the sample to react directly with the indigo without splashing on the neck of the flask. Be sure to keep in mind that the sample must be collected quickly. This might be difficult with the volumetric procedure. The gravimetric procedure might be preferred.

A wide-mouth Erlenmeyer flask may be used to collect the grab sample when following the gravimetric indigo procedure. The wider neck of the Erlenmeyer flask facilitates sample collection quickly without losing ozone from splashing. The gravimetric method facilitates quick sample collection because a precise sample volume is not required. The authors prefer the gravimetric procedure over the volumetric procedure because it is easier and quicker. Sample is added to the Erlenmeyer flask until a light blue appearance is obtained (i.e., not completely bleached). The sample volume is obtained by weighing the flask after the sample has been collected and subtracting the tare weight of the flask and 10.0 mL indigo reagent.

A commercially available modification of the indigo colorimetric method is available from the Hach Chemical Company. Powdered indigo reagent is enclosed in a small glass ampoule under vacuum. When the tip of the ampoule is broken under water, a known volume of the sample water is drawn into the ampoule and mixed with a specific amount of indigo powder. When using this method, a small beaker is held under the sample flow and allowed to overflow continuously. The sample flow and beaker size should be such that the detention time in the beaker is negligible, thus minimizing ozone decay during sample collection. The ampoule is submerged in the beaker and the tip of the ampoule is broken against the side of the beaker close to the point where the sample enters the beaker. The vacuum inside the ampoule draws a controlled volume of sample into the ampoule to mix with the indigo powder. If there are too many bubbles in the sample flow, the ampoule may not fill with water completely. The sample flow and beaker position should be adjusted to minimize bubbles formed by turbulence. After sample reaction, the ampoule should be inverted several times to mix the sample completely. The time for mixing is increased when the water temperature is cold. The exterior of the ampoule should be wiped dry and clean before inserting it in a hand-held spectrophotometer.

High turbidity affects results of the indigo test. Once the sample is reacted with the indigo reagent, turbidity causing particles may be filtered out, if necessary, before measuring absorbency when using either the volumetric or gravimetric indigo procedure. Hach ampoules are not suitable for measuring ozone residual when there is significant interference from high turbidity conditions because it is not possible to filter the reacted sample inside the ampoule.

Frequency of Analyzer Standardization and Other Maintenance

The potential frequency for analyzer standardization adjustments may be judged partly by the ten-month experience at the Eagle Mountain WTP. The Eagle Mountain plant staff conducted standardization tests about three times per week from mid-February through mid-June 1998. From mid-August 1998 through February 1999, plant staff conducted standardization tests one to three times per week. The results for most tests indicated that standardization adjustments were not required. Adjustments to analyzer readings were required infrequently, as shown in Figures 7-5, 7-6, and 7-7 for analyzers 1, 3, and 5, respectively. Seven adjustments were required for analyzer 1 over ten months of operation. Eight adjustments were required for analyzer 3 over the same ten months of operation. Analyzer 5 required eleven adjustments over a seven-month period of operation, excluding the adjustments that were 0.02 mg/L or less. A standardization adjustment between 0.02 and 0.06 mg/L was required approximately every two weeks for each analyzer during the first four months of the project. Based on these data, the TNRCC requires that Eagle Mountain WTP staff conduct at least a weekly standardization check of each on-line analyzer as a condition for using them for disinfection compliance reporting.

It should be noted that a standardization test might be conducted if there is a mismatch between the expected analyzer residual reading and the operating dose. Two examples are illustrated in Figure 7-11, occurring in early March and early April 1998 at the Eagle Mountain WTP. The PR was less than 1.0 on both occasions. In March the ozone dosage was unchanged and a reduction in PR would be unexpected. In that case a standardization test would have shown that the analyzer was not reading accurately and needed servicing. In April the PR was low, but the ozone dose also was low. In this case the proper response would be to increase dose. The applied ozone dose is used as a back-up indicator for initiating non-routine analyzer standardization tests at the Eagle Mountain WTP. The plant staff also plans to service the probe on a quarterly basis as part of their preventive maintenance program.

Other maintenance activities associated with the on-line ozone residual analyzers might include cleaning of sample lines, dislodging debris from sample flow control valves, and cleaning in-line filters. At the Eagle Mountain WTP, lake water is ozonated and the turbidity normally is less than 5 NTU. Plugging problems occurred in the special probe holder and small ¼-inch (6 mm) sample line as originally installed. Plugging did not occur in the modified installation when the probe was installed directly on the ¾-inch (19 mm) main sample line. Highly turbid river water is ozonated at the Elm Fork WTP, and a constant-head sampling setup was installed (see Figure 7-1). Plugging and flow variability problems have not occurred for the probe-type analyzers using this setup. The IN-USA analyzer supplier has installed three filters in series to remove debris from sample water before it enters the stripping column. The filters are cleaned on a daily basis during normal operation. The filters are cleaned up to three times per day during extremely high turbidity events.

Sample Line Detention Time

Ozone residual will decay naturally, and long hydraulic detention time (HDT) in the sample line will decrease the measured residuals. In order to minimize the effect of rapid ozone decay, the sample line HDT should be as short as possible. Short HDT is critically important when the ozone decay rate is rapid, as at the Eagle Mountain and Elm Fork plants.

The impact on measured residual for variable ozone half-life and sample line HDT is shown in Figure 7-16. The measured ozone residual is 50 percent of the actual residual if the ozone half-life and sample line HDT are one minute. The sample flow rate was 10 L/min for the grab sample and the Orbisphere analyzer at the Eagle Mountain WTP. The corresponding HDT was four seconds. The flow rate was 30 L/min for the grab sample, the Orbisphere analyzer, and the Rosemount analyzer at the Elm Fork WTP—the corresponding HDT was less than two seconds. With this short HDT, the measured residual is believed to be within 90 percent of the actual residual inside the contactor cells at the Elm Fork and Eagle Mountain plants. From Figure 7-16 the measured residual is more than 90 percent of the actual residual when the ozone half-life is 0.5 minute and sample line HDT is less than five seconds. Figure 7-16 might be used during design to check the HDT of the sample line in conjunction with the expected ozone decay rate to ensure that the residual measured by the analyzer will be at least 90 percent of the actual residual in the contactor.

The HDT for the IN-USA analyzer was significantly longer, at about one minute. The longer HDT was due to the required sample flow rate of 4 L/min through the two filters and into the analyzer’s constant-head cell and flow rate of 1 L/min from the constant-head cell to the stripping column. The HDT would have been about 30 seconds without the filters. The additional one minute of sample HDT before the stripping column likely caused the lower residual readings for the IN-USA analyzer that were shown in Figure 7-12 and Figure 7-15. It should be noted that the negative effect of ozone decay in the sample line is reduced when the ozone half-life is longer, as depicted in Figure 7-16. Elm Fork staff indicate that the IN-USA analyzer readings are closer to the grab sample residuals when the ozone half-life is longer in the winter.

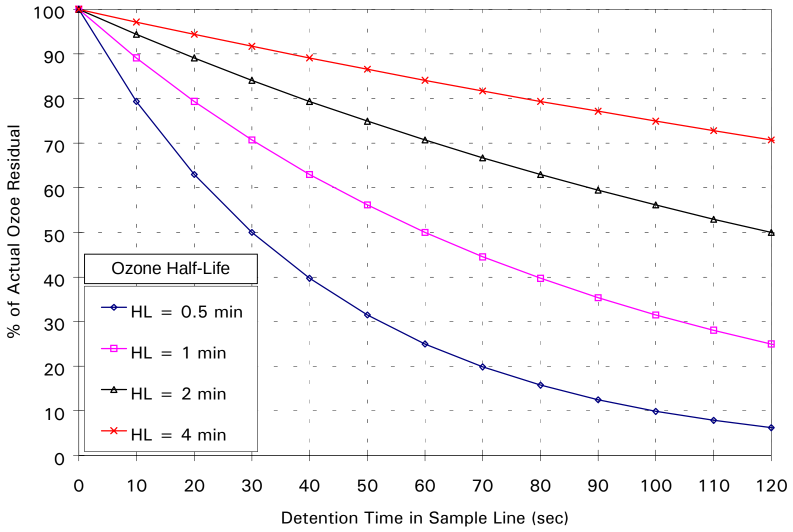

Figure 7-16
Reductions of Measured Ozone Residual Due to Ozone Decay and Sample Line HDT

Continuous Ozone Residual Monitoring

On-line residual analyzers may react quickly to actual changes in ozone residual, as shown in Figure 7-12. These instantaneous readings may be unusable for on-line computer monitoring and control. When the Eagle Mountain and Elm Fork plants incorporate the on-line ozone residual monitor information into their computer monitoring and control system, the analyzer readings will be averaged before they are utilized. An example smoothing trend line is shown in Figure 7-17 for the Rosemount analyzer data that was depicted in Figure 7-13. The length of time selected for trending is a balance between system responsiveness and achieving useable data. The example trend line used is a 5-minute moving average. The 5-minute trend might be a good starting point for system programming, and could be modified as necessary.

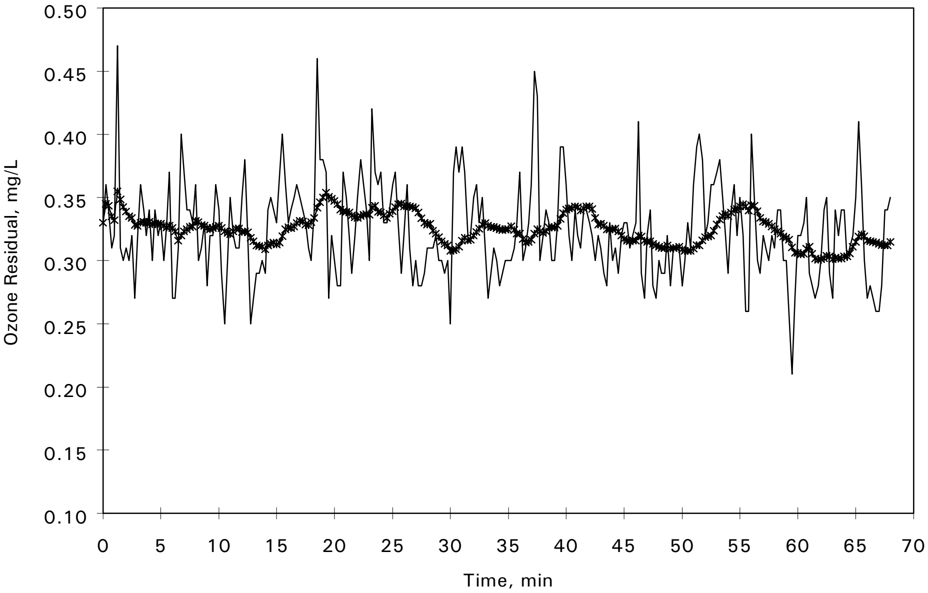

Figure 7-17
Example Residual Smoothing for Computer Control Using 5-Min Average

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A

GAS FLOW MEASUREMENT ACCURACY CONSIDERATIONS

Gas flowmeter types available and used in ozone systems include thermal mass flowmeters, Vortex meters, rotameters, and orifice plates (also flow-tubes and venturi meters). Rotameters usually are installed to provide local flow indication. Thermal mass flowmeters, Vortex meters, and orifice plates provide flow readings for computer monitoring/control. Thermal mass flowmeters and Vortex meters are favored for their simplistic installation and wide range of flow measurement. However, thermal mass and Vortex meter readings might be inaccurate. Orifice plates are favored because accuracy can be field-verified, but their turndown capability is limited. Some ozone installations have installed thermal mass flowmeters or Vortex meters for routine monitoring/control and an orifice plate that is located strategically to facilitate field-verification of the mass flowmeters. In this Appendix the importance of field-verification is discussed and orifice plate flow verification calculations are explained (Rakness et al., 1998) (Henry and Rakness, 1997).

Importance of Field Verification

Confidence exists in accuracy of gas flow when the flow rate is field-verified. Data from two full-scale plant tests illustrate the importance of field-verification. Figure A-1 shows comparative data for the field-verified orifice plate flow rate versus the reading from the Plant 1 thermal mass flowmeters that were installed in the field after being calibrated in the factory. As shown in Figure A-1, both thermal meters were inaccurate. On the other hand, Figure A-2 shows that the three Plant 2 factory-calibrated thermal mass flowmeters were accurate to within ±5 percent of the field-verified orifice plate flow rate. From these data it is concluded that correctly installed, factory-calibrated meters can provide accurate flow readings. However, the users are unsure if the meters are installed correctly unless the meters have been field-verified. Ozone systems that utilize factory-calibrated flowmeters should consider installing an orifice plate flowmeter (temporary or permanent) at some point in the process stream to verify correct installation of factory-calibrated meters.

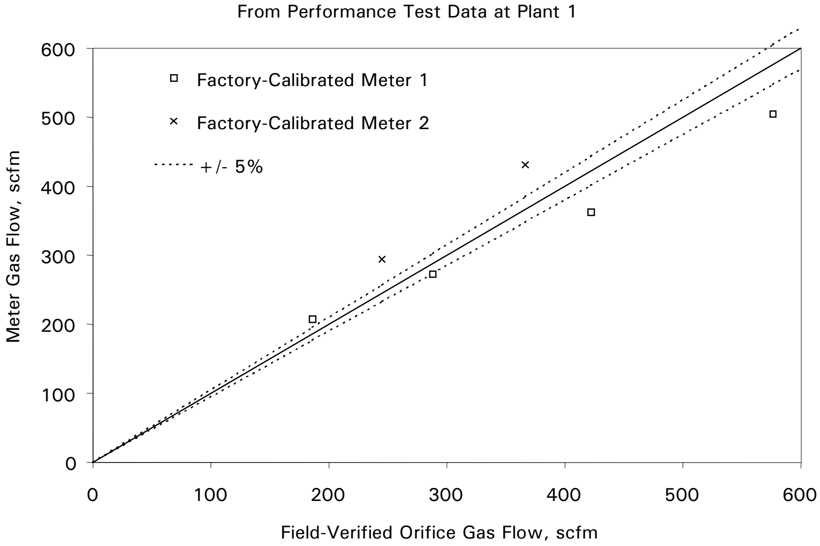

Figure A-1
Gas Flow Inaccuracy for Two Factory-Calibrated Meters

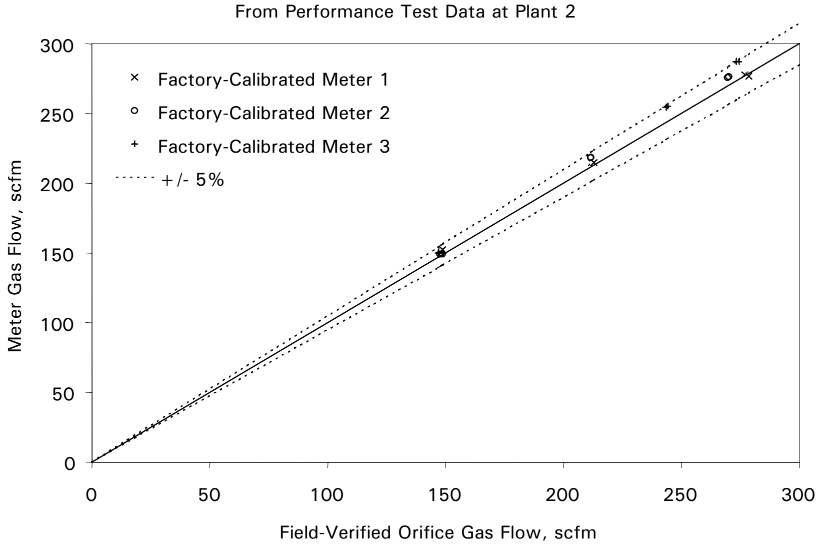

Figure A-2
Gas Flow Rate Was Within ±5 Percent for Three Factory-Calibrated Meters

Theory of Orifice Plate Gas Flow Calculations

The orifice plate has a bore, or throat, which is smaller in diameter than the pipe into which it is installed. The gas velocity increases as it passes through the bore. Bernoulli's equation without potential head variables (Equation A-1) is the basis of the flow equation for the orifice plate (Cusick, 1977) (Henry, and Rakness, 1997). Point 1 is upstream of the meter and point 2 is at the meter's throat. Equation A-1 assumes that the substance is an incompressible fluid and its density will not change as it transitions through the orifice. However, density will change slightly when the fluid is a gas. Corrections for slight changes in density and temperature are addressed by the gas expansion factor, Y, shown later in Equation A-12.

$$\frac{V_1^2}{2g} + \frac{P_1}{\rho} = \frac{V_2^2}{2g} + \frac{P_2}{\rho}$$ **Eq. A-1**

Where:

V_1 = Velocity in pipe upstream of meter, m/sec (ft/sec).

V_2 = Velocity at meter's throat, m/sec (ft/sec).

P_1 = Absolute pressure in pipe upstream of meter, kg/m^2 (lb/ft^2).

P_2 = Absolute pressure at meter's throat, kg/m^2 (lb/ft^2).

ρ = Density of the gas, kg/m^3 (lb/ft^3).

g = Gravitational constant, 9.807 m/sec^2 (32.174 ft/sec^2).

After rearranging, Equation A-1 becomes Equation A-2.

$$V_2^2 - V_1^2 = \frac{2g}{\rho} \bullet \left(P_1 - P_2\right)$$ **Eq. A-2**

A U-tube manometer filled with any liquid or a differential pressure-measuring device may be used to determine the pressure difference ($P_1 – P_2$) between point 1 and point 2. Equation A-3 shows the case when differential pressure (DP) is measured in meters (feet) of water pressure and converted to required units of kg/m^2 (lb/ft^2).

$$P_1 - P_2 = h \bullet \rho_w$$ **Eq. A-3**

Where:

h = Differential pressure across orifice, m of water (ft of water).

ρ_w = Density of water, 1,000 kg/m^3 (62.43 lb/ft^3).

Combining Equation A-2 and A-3 gives Equation A-4. Gas density (ρ_1) is measured upstream of the orifice plate. The gas expansion factor, Y, (Equation A-12) corrects for slight changes in density (and temperature) as the gas passes through the throat.

$$V_2^2 - V_1^2 = \frac{2g}{\rho_1} \bullet h \bullet \rho_w$$ **Eq. A-4**

Where:

ρ_1 = Density of flowing gas upstream of the orifice plate (see Equation A-15), kg/m^3 (lb/ft^3).

Since Q is constant and V=Q/A, Equation A-5 is obtained from Equation A-4.

$$\frac{Q^2}{A_2^2} - \frac{Q^2}{A_1^2} = \frac{2g}{\rho_1} \bullet h \bullet \rho_w$$ **Eq. A-5**

Where:

Q = Volumetric gas flow rate, m^3/sec (ft^3/sec).

A_1 = Area of pipe at point 1, m^2 (ft^2).

A_2 = Area of meter's throat, m^2 (ft^2).

Multiplying by A_2^2 gives Equation A-6.

$$Q^2\left(1 - \frac{A_2^2}{A_1^2}\right) = A_2^2 \bullet \frac{2g}{\rho_1} \bullet h \bullet \rho_w$$ **Eq. A-6**

With *beta* ratio defined as the ratio of diameters and after rearranging, Equation A-6 becomes Equation A-7.

$$Q = \frac{1}{\sqrt{(1 - \beta^4)}} \bullet A_2 \bullet \sqrt{\frac{2g}{\rho_1} \bullet h \bullet \rho_w}$$ **Eq. A-7**

Where:

β = Ratio of diameters, D_2 / D_1.

D_2 = Diameter of orifice throat, m (ft).

D_1 = Diameter (inside) of pipe, m (ft).

Equation A-7 is theoretical. In practice, the coefficient of discharge (C) is applied to Equation A-7, as shown in Equations A-8 and A-9. Coefficient of discharge, C, is determined experimentally and is a function of pipe size, orifice throat shape, type of orifice tap connections, and Reynolds number (Cusick, 1977). The orifice plate supplier establishes and reports the C-value for the meter.

$$Q = K \bullet A_2 \bullet \sqrt{\frac{2g}{\rho_1} \bullet h \bullet \rho_w} \qquad \textbf{Eq. A-8}$$

Where:

K = Meter factor (see Equation A-9).

$$K = \frac{C}{\sqrt{1 - \beta^4}} \qquad \textbf{Eq. A-9}$$

Where:

C = Coefficient of discharge specified by the flowmeter supplier.

It should be noted that, on occasion, the flowmeter supplier will specify a special orifice factor (S_o) instead of a coefficient of discharge. Given S_o, C may be found using Equation A-10.

$$C = S_o \bullet \frac{\sqrt{1 - \beta^4}}{\beta^2} \qquad \textbf{Eq. A-10}$$

Where:

S_o = Special orifice factor specified by the flowmeter supplier.

Two more correction factors, F_a and Y, are applied to Equation A-8 to achieve the volumetric gas flow equation shown in Equation A-11. The meter supplier may specify a minor (0.9995 to 1.0005) correction factor for orifice area, called F_a. The gas expansion factor, Y, is calculated using Equation A-12 and corrects for the effects of density and temperature changes through the meter.

$$Q = K \bullet A_2 \bullet Y \bullet F_a \bullet \sqrt{\frac{2g}{\rho_1} \bullet h \bullet \rho_w} \qquad \textbf{Eq. A-11}$$

Where:

F_a = Correction factor for orifice area specified by the flowmeter supplier.

Y = Gas expansion factor calculated by Equation A-12.
NOTE: The supplier often reports a singular value for Y on the meter's specification sheet. The potential error when using a singular Y-value is discussed later in this appendix.

$$Y = \left\{ \left(\frac{P_2}{P_1}\right)^{\frac{2}{s}} \left(\frac{s}{s-1}\right) \left(\frac{1-\left(\frac{P_2}{P_1}\right)^{\left(\frac{s-1}{s}\right)}}{1-\left(\frac{P_2}{P_1}\right)} \right) \left(\frac{1-\beta^4}{1-\beta^4\left(\frac{P_2}{P_1}\right)^{\frac{2}{s}}} \right) \right\}^{\frac{1}{2}}$$

Eq. A-12

Where:

P_1 = Absolute pressure upstream of the flowmeter, m of water (psia).

P_2 = Absolute pressure downstream of the flowmeter, m of water (psia).

s = Ratio of specific heats, 1.4 for O_2, N_2, O_3.

Equation A-11 is the basic equation for volumetric flow rate at upstream conditions for gas composition (i.e., molecular weight), pressure, and temperature. The flow is considered as actual volumetric flow because the value is relative to actual operating pressure and temperature conditions. Actual volumetric flow rate typically is not used for process reporting because the operating pressure and temperature conditions may be variable. Rather, volumetric flow should be reported relative to a standard temperature and pressure (STP). In metric units, STP is always Normal Temperature Pressure (NTP) at 0°C and one atmosphere pressure (1.013×10^5 Pa, or 10.34 m of water). In English units, STP usually is one atmosphere pressure; but the standard temperature may be 60°F, 68°F, 70°F, or other temperatures. The metric NTP standard is preferred to ensure uniformity in reporting. However, STP at other temperatures is discussed in this Appendix because flowmeter manufacturers may report flow at base (standard) temperatures other than 0°C. To facilitate conversion of flow to the prescribed STP, Equation A-11 is modified to calculate mass flow rate (*W*), as shown in Equation A-13, instead of volumetric flow rate (Q), as shown in Equation A-11. Combining Equation A-13 and Equation A-11 develops the mass flow equation shown in Equation A-14.

$$W = Q \bullet \rho_1$$

Eq. A-13

$$W = K \bullet A_2 \bullet Y \bullet F_a \bullet \sqrt{2 \bullet g \bullet \rho_1 \bullet h \bullet \rho_w}$$

Eq. A-14

Where:

W = Mass flow, kg/sec (lb/sec).

Density (ρ_1) of the flowing gas is calculated from pressure and temperature readings and gas composition information, as indicated in Equation A-15.

$$\rho_1 = \frac{MW_a}{V_{NTP}} \bullet \frac{P_a}{P_{NTP}} \bullet \frac{T_{NTP}}{T_a}$$

Eq. A-15

Where:

ρ_1 = Density of the gas upstream of the orifice plate, g/L or kg/m^3 (density in g/L may be converted to lb/ft^3 using the conversion factors of 453.6 g/lb and 28.32 L/ft^3).

MW_a = Actual molecular weight of the flowing gas, g/mol.
NOTE: The flowing gas MW usually is a constant number for the ozone generator feed-gas because the gas flow is either air or high purity oxygen. However, the MW for the generator product-gas is a variable number due to variable ozone concentration. The MW can be determined using Equation A-16.

$$MW = (V_{O2} \bullet MW_{O2}) + (V_{N2} \bullet MW_{N2}) + (V_{AR} \bullet MW_{AR}) + (V_{O3} \bullet MW_{O3}) \qquad \textbf{Eq. A-16}$$

Where:

V_{O2} = Oxygen concentration (20.94% vol for air).

V_{N2} = Nitrogen concentration (78.12% vol for air).

V_{AR} = Argon concentration (0.94% vol for air).

V_{O3} = Ozone concentration for generator product-gas, %vol.

MW_{N2} = Molecular weight of nitrogen, at 28.01 g/mol.

MW_{O2} = Molecular weight of oxygen, at 32.00 g/mol.

MW_{AR} = Molecular weight of argon, at 39.95 g/mol.

MW_{O3} = Molecular weight of ozone, at 48.00 g/mol.

V_{NTP} = Volume at normal temperature of 0°C (32°F), 22.41 L/mol.

P_a = Actual pressure of the flowing gas upstream of the orifice plate, m of water (psia).
NOTE: Measured gage pressure is added to measured barometric pressure to obtain actual, absolute pressure.

P_{NTP} = Normal pressure, 10.34 m of water (14.696 psia).

T_{NTP} = Normal temperature of 491.67 R (32°F + 459.67) or 273.15 K.

T_a = Actual temperature of the flowing gas, K (R).
NOTE: Add actual temperature to absolute zero to obtain actual temperature, absolute. Absolute zero is 273.15 K (459.67 R).

Equation A-14 yields mass flow in kg/sec (lb/sec). Mass flow can be converted to standard volumetric flow by dividing mass flow by standard density in kg/m^3 (lb/ft^3). Standard density (ρ_{STD}) is determined using Equation A-17.

$$\rho_{\mathrm{STD}} = \frac{\mathrm{MW}_{\mathrm{Ref}}}{\mathrm{V}_{\mathrm{NTP}}} \bullet \frac{\mathrm{T}_{\mathrm{NTP}}}{\mathrm{T}_{\mathrm{Standard}}}$$

Eq. A-17

Where:

ρ_{STD} = Standard density used to convert mass flow to standard volumetric flow, kg/m^3 (lb/ft^3).
NOTE: 1 kg/m^3 = 1 g/L.

$\mathrm{MW}_{\mathrm{Ref}}$ = Meter reference molecular weight, g/mol.
NOTE: The meter reference MW usually is 32 g/mol or 29 g/mol for high-purity oxygen-fed or air-fed ozone systems, respectively. Equation A-16 may be used to determine MW for other gas characteristics.

$\mathrm{V}_{\mathrm{NTP}}$ = Volume at normal temperature of 0°C (32°F), 22.41 L/mol.

$\mathrm{T}_{\mathrm{NTP}}$ = Normal temperature of 491.67 R (32°F + 459.67) or 273.15 K.

$\mathrm{T}_{\mathrm{Standard}}$ = Meter basis or standard temperature, K (R).

Some of the information needed to complete Equation A-14 may be obtained from the orifice plate supplier’s calibration sheet, including throat diameter, upstream pipe diameter, coefficient of discharge, and orifice area correction factor. Other information is measured in the field, including differential pressure, upstream pressure, and temperature and, if needed, gas composition. The specified flowmeter parameters and measured data may be used to calculate mass flow using Equations A-9, A-12, A-14, and A-15. Subsequently, mass flow may be converted to standard volumetric flow by determining flowmeter standard density from Equation A-17. These flow equations could be programmed into the on-line computer monitoring system, if desired.

Calculating Flow at Specified Reference Conditions

Common practice in the United States is to specify the volumetric flow rate for the flowmeter as well as the expected flowing gas composition, pressure, and temperature. For example, specifications for an air-fed ozone generator feed-gas flowmeter might be for a volumetric flow rate of 145 scfm at a standard temperature of 60°F, operating pressure of 10 psig, operating temperature of 80°F, and molecular weight of 29 g/mol. The flow rate displayed by the meter might be transmitted directly to the computer monitoring system based on the square root of the measured differential pressure reading. This displayed flow rate is correct as long as the operating pressure, temperature, and molecular weight are equal to the reference or specified conditions. Correction factors for non-reference operating conditions are discussed in the next section of this appendix.

In the example solution discussed below, the mass flow at flowmeter reference conditions is calculated. The calculations are based on a certain orifice plate with indicated meter specifications. Example calculations in both English and Metric units are completed. It is possible to utilize units of measurement other than those shown in the calculations. However, all units must be put to use correctly in the equations. Flowmeter specification criteria for the example problem are as follows:

C = Coefficient of discharge — 0.6042.

D_1 = Pipe diameter (inside) — 52.5 mm (2.067 in).

D_2 = Orifice throat diameter — 23.5 mm (0.9254 in).

Y = Gas expansion factor.
NOTE: Y-value is calculated for the example calculation. The Y-value that was denoted on the specification sheet was 0.9783. More discussion is presented in the next section of this publication regarding potential error using a singular Y-value.

F_a = Orifice area correction factor — 0.9999.

MW_{ref} = Specified reference molecular weight — 29 g/mol (Air).

P_{ref} = Specified reference pressure — 7.04 m of water gage pressure or 17.38 m of water absolute pressure (10 psig or 24.7 psia).

T_{ref} = Specified reference temperature for the flowing gas — 26.7°C or 299.85 K (80°F or 539.67 R).

h = Specified maximum differential pressure — 2.54 m of water (100 in. of water or 8.33 ft of water).

Calculation steps are as follows:

1. Find *beta* ratio (D_2 / D_1) — 0.4477 dimensionless.
2. Using Equation A-9, find meter factor, K — 0.6167, dimensionless.

$$K = \frac{0.6042}{\sqrt{1 - 0.4477^4}} = 0.6167$$

3. Find throat area of the orifice, A_2 — 0.0004337 m^2 (0.004671 ft^2).
4. Using Equation A-12 find gas expansion-factor, Y — 0.9145 dimensionless. For English units:

$$0.9145 = \left\{\left[\left(\frac{21.09}{24.7}\right)^{\frac{2}{1.4}}\left(\frac{1.4}{1.4-1}\right)\left(\frac{1-\left(\frac{21.09}{24.7}\right)^{\left(\frac{1.4\text{-}1}{1.4}\right)}}{1-\left(\frac{21.09}{24.7}\right)}\right)\left(\frac{1-0.4477^{4}}{1-0.4477^{4}\left(\frac{21.09}{24.7}\right)^{\frac{2}{1.4}}}\right)\right]\right\}^{\frac{1}{2}}$$

Where:

P_1 = Upstream pressure — 24.70 psia.

P_2 = Downstream pressure, P_1 - h — 21.09 psia.

s = Ratio of specific heats — 1.4 for O_2, N_2, O_3, dimensionless.

Or Metric Units:

$$0.9145 = \left\{\left[\left(\frac{14.84}{17.38}\right)^{\frac{2}{1.4}}\left(\frac{1.4}{1.4-1}\right)\left(\frac{1-\left(\frac{14.84}{17.38}\right)^{\left(\frac{1.4\text{-}1}{1.4}\right)}}{1-\left(\frac{14.84}{17.38}\right)}\right)\left(\frac{1-0.4477^{4}}{1-0.4477^{4}\left(\frac{14.84}{17.38}\right)^{\frac{2}{1.4}}}\right)\right]\right\}^{\frac{1}{2}}$$

Where:

P_1 = Upstream pressure — 17.38 m of water absolute pressure.

P_2 = Downstream pressure, P_1 - h — 14.84 m of water absolute pressure.

s = Ratio of specific heats — 1.4 for O_2, N_2, O_3, dimensionless.

5. Using Equation A-15 find density of the flowing gas at reference gas molecular weight, pressure, and temperature.

$$\rho_{\text{ref}} = \frac{29}{22.41}\bullet\frac{24.7}{14.7}\bullet\frac{491.67}{539.67}\bullet\frac{1\text{lb}}{453.6\text{g}}\bullet\frac{28.32\text{L}}{\text{ft}^3} = 0.1236\ \text{lb}/\text{ft}^3$$

or,

$$\rho_{\text{ref}} = \frac{29}{22.41}\bullet\frac{17.38}{10.34}\bullet\frac{273.15}{299.85} = 1.981\ \text{g}/\text{L or kg}/\text{m}^3$$

6. Calculate differential pressure ($h\bullet\rho_w$) in the required units of kg/m^2 (lb/ft^2). The density of water is 1 kg/L (62.43 lb/ft^3).
$8.33\ ft \bullet 62.43\ lb/ft^3 = 520.2\ lb/ft^2$
or,
$2.54\ m \bullet 1\ kg/L \bullet 1{,}000\ L/m^3 = 2{,}540\ kg/m^2$

7. Using Equation A-14 solve for mass flow at reference conditions.
English Units:

$$W = 0.6167\bullet 0.004671\bullet 0.9145\bullet 0.9999\bullet\sqrt{2\bullet 32.174\bullet 0.1236\bullet 520.2}$$

$W = 0.1694$ lb/sec

Metric Units:

$$W = 0.6167 \bullet 0.0004337 \bullet 0.9145 \bullet 0.9999 \bullet \sqrt{2 \bullet 9.807 \bullet 1.981 \bullet 2540}$$

$W = 0.07683$ kg/sec

The calculated mass gas flow rate of 0.1694 lb/sec may be converted to standard volumetric flow rate at flowmeter STP, which was defined as 60°F and one atmosphere pressure. The gas standard density at the meter's specified STP is 0.0764 lb/ft^3, as determined using Equation A-17.

$$\rho_{\text{meter STD}} = \frac{29}{22.41} \bullet \frac{491.67}{519.67} \bullet \frac{1\ \text{lb}}{453.6\ \text{g}} \bullet \frac{28.32\ \text{L}}{\text{ft}^3} = 0.0764\ \text{lb}/\text{ft}^3$$

The resulting standard volumetric flow rate is mass flow divided by standard density, or 133 scfm (i.e., standard cubic feet per minute). It should be noted that this gas flow rate is for flowmeter reference conditions for MW, P, and T. Correction factors for operating conditions other than reference conditions are discussed in the next section of this Appendix. Mass flow in metric units of 0.07683 kg/sec may be converted to standard volumetric flow, at NTP, in a similar manner.

Applying Correction Factors for Flowing Gas Conditions

Flowing gas operating conditions may exist that are different from reference conditions. In this section of the Appendix, the method to correct for non-reference conditions is discussed. It should be noted that non-reference operating conditions affect upstream gas density, ρ_1, relative to the design reference conditions for the flowmeter. Since upstream gas density (ρ_1) is contained in a square-root function in Equation A-14, the correction factor is a square-root function. The correction factor equation is shown in Equation A-18.

$$\text{CF} = \sqrt{\frac{\text{T}_{\text{ref}}}{\text{T}_{\text{a}}}} \bullet \sqrt{\frac{\text{P}_{\text{a}}}{\text{P}_{\text{ref}}}} \bullet \sqrt{\frac{\text{MW}_{\text{ref}}}{\text{MW}_{\text{a}}}} \qquad \textbf{Eq. A-1}$$

Where:

CF = Correction factor when actual gas composition, temperature, and pressure are different from reference conditions.

T_{ref} = Specified reference temperature for the flowing gas, K (R).

T_{a} = Actual temperature of the flowing gas, K (R).

P_a = Actual absolute pressure of the flowing gas upstream of the orifice plate, m of water (psia).

P_{ref} = Specified reference-absolute pressure for the flowing gas, m of water (psia).

MW_{ref} = Specified reference molecular weight for the flowing gas, g/mol.

MW_a = Actual molecular weight for the flowing gas, g/mol.

Measuring Ozone Production

Measuring gas flow before the ozone generator has been implemented in order to avoid correction for MW. Measuring gas flow before the generator is also practical in determining ozone production. Ozone generator feed-gas flow can be reported as mass flow (kg/hr or lb/day), and generator product-gas ozone concentration can be reported in percent weight units (% wt). Ozone production rate is the outcome of feed-gas mass flow multiplied by product-gas ozone concentration in % wt. Measuring mass flow before the generator is legitimate, because mass flow is unchanged through the generator. It should be noted that if ozone concentration is reported in weight/volume units, such as mg/L, then Equation A-19 might be used to convert ozone concentration from weight/volume to % wt units.

$$Y_1' = \frac{100\ Y_1}{\rho_{fg} \bullet \left(1000 + \dfrac{0.5\ Y_1 V_{NTP}}{48}\right)} \qquad \textbf{Eq. A-1}$$

Where:

Y_1' = Ozone concentration, percent by weight.

Y_1 = Ozone concentration, mg/L_{NTP}.

100 = Conversion of mass ratio to percent expression.

V_{NTP} = Molar volume at normal temperature and pressure (22.41 L_{NTP}/mol).

48 = Gram molecular weight of ozone, g/mol.

ρ_{fg} = Density of ozone generator feed-gas determined from Equation A-17, g/L_{NTP}.

Another option for calculating ozone production is to utilize ozone concentration readings reported in weight/volume units, such as mg/L or g/m^3, and volumetric flow rate of the ozone generator product-gas reported in m^3/hr. With this approach, the gas flow must be measured after the ozone generator and a correction factor must be applied for gas composition changes due to variable ozone concentration. Since most on-line ozone concentration meters can display readings in % wt, it might be convenient to measure gas flow before the ozone generator and avoid the gas-composition correction factor. Nevertheless, it is important to note that the use of % wt is ambiguous because, depending on type of feed-gas, the value of 1% wt does not mean the same ozone concentration in gas.

Quality Assurance Considerations for Accuracy of Flow

Gas flow increases as differential pressure increases in a square root relationship, as shown in Figure A-3. The chart denotes two issues with respect to quality assurance.

1. There is a potential for inaccuracy with misapplication of expansion factor, Y.
2. There is a potential for inaccuracy at low flow rates.

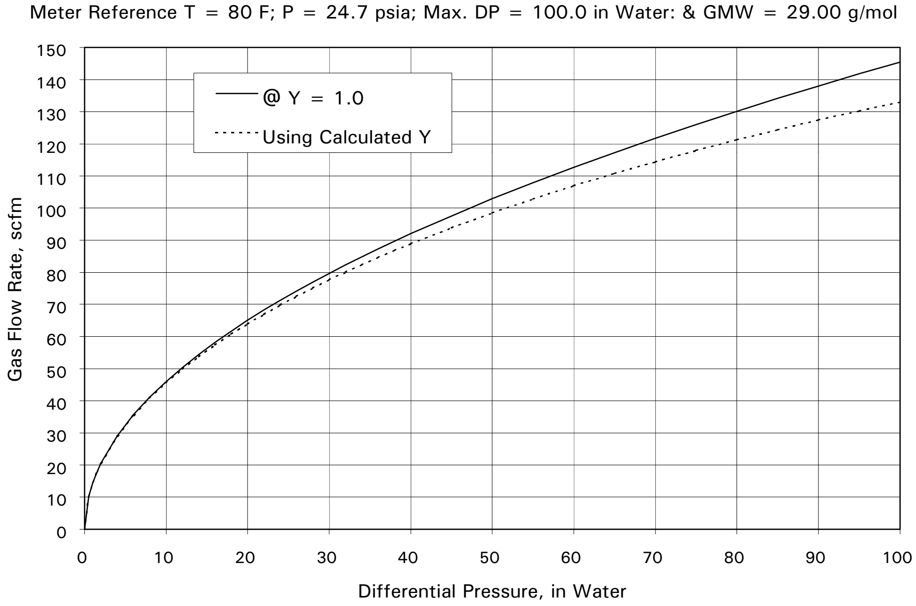

Figure A-1
Gas Flow Increases as Differential Pressure Increases

Gas Expansion Factor Considerations

The specification sheets for orifice plate flowmeters often report a single value for Y. The Y-value that was reported for the subject meter in the example calculations was 0.9783. The specified maximum flow rate for said meter was 145 scfm. However, per Equation A-12, the Y-value is a function of *beta* ratio, pressure, and differential pressure. Figure A-4 shows the calculated Y-value across the subject meter's specified range of differential pressure. The following key points are noted from Figures A-3 and A-4.

1. The specified maximum gas flow rate of 145 scfm was reported for a Y-value of 1.0.

2. The specified Y-value of 0.9783 occurred at a differential pressure of about 25-inches of water. The flow rate at a DP of 25-inches is 72.5 scfm, which is 50 percent of the specified maximum flow of the orifice plate.

   NOTE: It is common practice for suppliers to report Y-value for a flow rate other than the design flow, such as average flow.

3. For the subject meter with its large DP, a significant discrepancy in flow measurement could occur if the specified Y-value is used in the flow equation instead of the calculated Y-value. The calculated y-value should be used for accurate determination of gas flow.

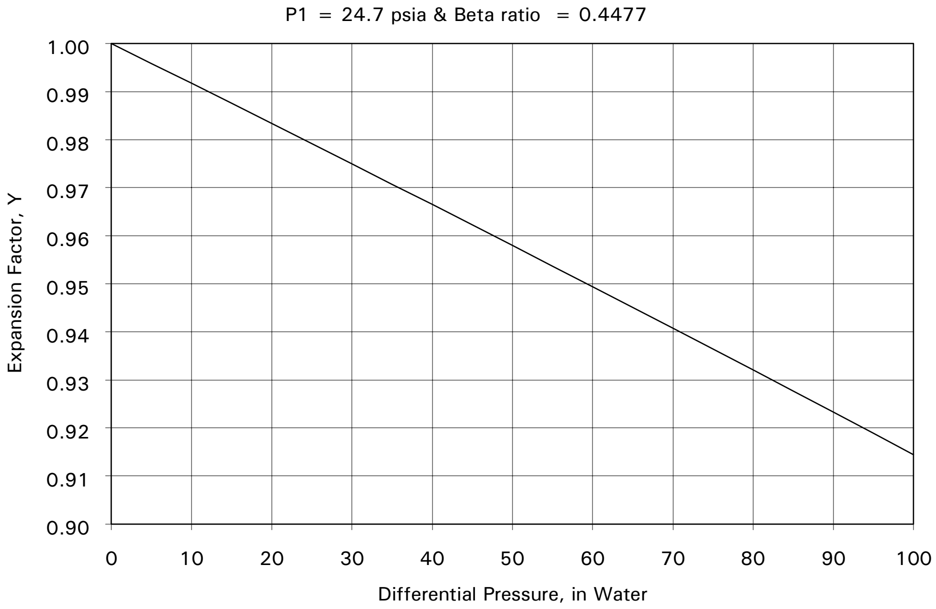

Figure A-1
Gas Expansion Correction Impact Increases With Differential Pressure

Low Gas Flow Considerations

Accurate flow measurement with an orifice plate is difficult to achieve at low-end gas flow rates, as illustrated in Figure A-3. In Figure A-3 the design flow is 133 scfm at the maximum DP of 100 inches of water. However, at 10 percent of maximum DP (10 inches of water) the flow is 45 scfm, or 33 percent of design. This relationship of flow versus DP is consistent for orifice plates and other differential pressure flowmeters as well. It is likely that the low-end readings for differential pressures might result in inaccurate flow readings. The key point to be made is that orifice plates have a limited accurate flow range. It is reasonable that flow rates between 33 and 100 percent of design are an acceptable range for accurate measurement using orifice plates with differential pressure readings between 10 and 100 percent of full-scale. However, if the potential operating flow rate is below 33 percent of design, then provisions should be made to insert another orifice plate with a smaller throat or install a by-pass line containing an orifice plate with a smaller throat.

B

GAS PHASE METER OZONE CONCENTRATION ACCURACY

Ozone concentration in the product-gas from an ozone generator is often measured with commercial, ultraviolet (UV) ozone concentration meters. Ozone concentration usually is reported as weight percent. Meter standards are given for temperature, pressure, and gram molecular weight (GMW). Adjustments to the meter span are necessary to correct for field-operating conditions that are different from meter standard conditions. The adjustments are made automatically with newer meters and manually with late-model units.

UV ozone concentration meters generally are accurate, provided they are installed correctly and the meter span is set properly, either manually or automatically. UV meter accuracy might be field-verified by conducting a potassium iodide (KI) wet-chemistry test (Birdsall et al., 1952) (Rakness et al., 1996a) (Rakness et al., 1996b). A UV meter field verification protocol is presented in this appendix.

Wet-Chemistry Test Procedure

The iodometric wet-chemistry method (otherwise known as the KI method) appears to have a standard deviation percentage of two percent when performed in a careful manner using a prescribed procedure (Rakness et al., 1996a) (Rakness et al., 1996b). Special precautions are necessary regarding normality of the titrant used to obtain mass of ozone reacted and accuracy of the volume of process gas that passes through the gas washing bottle(s).

The wet-chemistry test results are inherently variable due to the complex chemical reactions that occur during the test and due to its sensitivity to analytical procedures. A definitive procedure for conducting the wet-chemistry test is presented here to enable the reader to obtain reasonably consistent results with an approximate 1:1 stoichiometry.

1. Equipment

    1.1. One or two standard gas washing bottles, 500 mL capacity, WITHOUT a fritted diffuser. A fritted diffuser may destroy the ozone.

    1.2. One totalizer-type wet-test gas meter equipped with integral manometer and thermometer capable of reading water temperature within ± 0.2°C. It should be noted that the accuracy of the wet-test meter is critically important to the overall accuracy of the wet-test result (Rakness et al., 1996b). Toward this end, **the wet-test meter**

volumetric accuracy shall be within ±1 percent, as determined by an independent laboratory.

1.3. Tubing and connections of glass, stainless steel, aluminum, or Teflon. A small amount of Tygon tubing may be used to facilitate connections to glassware.

2. Reagents

2.1. Use either unbuffered KI or slightly buffered KI (called $NBKI_e$). No other buffering formulation for KI is acceptable.

2.1.1 **Unbuffered KI**. Potassium iodide stock reagent (2%): Dissolve 20 g KI in one liter of freshly boiled and cooled distilled water. Store in a brown bottle and refrigerate.

2.1.2 **Slightly buffered KI ($NBKI_e$)**. Potassium iodide stock reagent (2%): Dissolve 20 g KI in one liter of freshly boiled and cooled distilled water. Add 7.3 g/L of disodium hydrogenphosphate ($Na_2HPO_4 \cdot 2H_2O$) and 3.5 g/L of monopotassium dihydrogenphosphate (KH_2PO_4). Store in a brown bottle and refrigerate.

2.2. **Sulfuric acid (2 N)**: Add 56 mL concentrated sulfuric acid to 944 mL distilled water. Store in a reagent bottle.

2.3. **Sodium thiosulfate ($Na_2S_2O_3$) stock solution (1 N)**: Dissolve 250 g of sodium thiosulfate ($Na_2S_2O_3$) granules into one liter of freshly boiled distilled water. Store in a brown bottle and refrigerate.

2.4. Prepare the starch indicator solution by one of two methods listed below.

2.4.1. **Zinc chloride starch indicator**: To 4 g soluble starch add a little cold distilled water and grind to a thin paste. Disperse the paste into 100 mL of distilled water which contains 20 g of zinc chloride ($ZnCl_2$). Boil the solution until the volume has been reduced to 100 mL. Finally, dilute this solution to a total volume of 1 L and add 2 g of $ZnCl_2$. The indicator is stable for about one month when stored in the dark at room temperature.

2.4.2 **Starch indicator**: To 5 g soluble starch add a little cold distilled water and grind to a thin paste. Pour into one liter of boiling distilled water, stir, and let settle overnight. Decant and refrigerate the clear supernatant.

2.5. **Sodium thiosulfate ($Na_2S_2O_3$) titrant (0.1 N)**: Add 100 mL of 1 N $Na_2S_2O_3$ stock solution to 900 mL freshly boiled distilled water. Standardize this solution each day, as discussed in Steps 3.1.1 and 3.1.2 below. It should be noted that other normalities might be used, as discussed in Step 3.6 below.

2.6. **Potassium dichromate ($K_2Cr_2O_7$) (0.1000 N)**: Dissolve 4.904 g anhydrous $K_2Cr_2O_7$ (primary standard quality) in distilled water and dilute in a volumetric flask to one liter. Store in a reagent bottle.

2.7. **Potassium periodate (KIO_3)**.

2.8. **Distilled water**: Distilled water quality is critical to results. Conductivity shall be less than 10 micromhos/centimeter.

3. Methodology.

3.1 Standardize the 0.1 N sodium thiosulfate titrant using either method 3.1.1. or 3.1.2. below. This activity can be completed prior to the test, and shall be completed each day of the test.

3.1.1. To 150 mL distilled water in a 250 mL Erlenmeyer flask add, with constant stirring, 1.0 mL concentrated H_2SO_4, 20.0 mL of 0.1000 N $K_2Cr_2O_7$ and 2.0 g KI. Cover and let mixture stand six minutes in the dark. Titrate with the approximate 0.1 N $Na_2S_2O_3$ titrant until the yellow color is almost gone. Add 1.0 mL of starch indicator solution and continue titrating carefully until the blue color just disappears. The normality of $Na_2S_20_3$ titrant = 2.0 ÷ $Na_2S_20_3$ mL consumed.

3.1.2. To 50 mL of distilled water in a 250 mL Erlenmeyer flask add, with constant stirring, 0.05 g of potassium periodate (KIO_3) and 0.5 g of KI, followed by an additional 50 mL of distilled water. After mixing, add 10 mL of certified 0.1 N acid. The iodine formed is titrated with the approximate 0.1 N $Na_2S_2O_3$ titrant until the yellow color is almost gone. Add 1.0 mL of starch indicator solution and continue titrating carefully until the blue color just disappears. The normality of $Na_2S_20_3$ titrant = 2.0 ÷ $Na_2S_20_3$ mL consumed.

3.2. Fill a 50 mL Class A burette with the $Na_2S_20_3$ titrant that was standardized in Steps 3.1.1 and 3.1.2 above. Fill the burette just prior to adding ozone to the gas-washing bottle (see Step 3.6.). Maintain fresh titrant in the burette (e.g., refresh daily).

3.3. Add 400 mL of 2 percent KI or $NBKI_e$ solution to each gas washing bottle. Two bottles are suggested.

3.4. Level the wet-test meter.

3.5. Assemble the wet-test equipment for ozone product-gas measurements, as shown in Figure B-1 below. Bubble ozone through the KI solution and initiate recording the volume bubbled through the KI by using either Step 3.5.1 or 3.5.2 below:

3.5.1. Safely purge the tubing from the ozone piping source to the gas washing bottle with fresh ozone before connecting the tubing to the bottle (e.g., purge into an off-line gas washing bottle). Then, connect the tubing that has been purged with ozone to the gas washing bottles and immediately begin recording the wet-test meter volume.

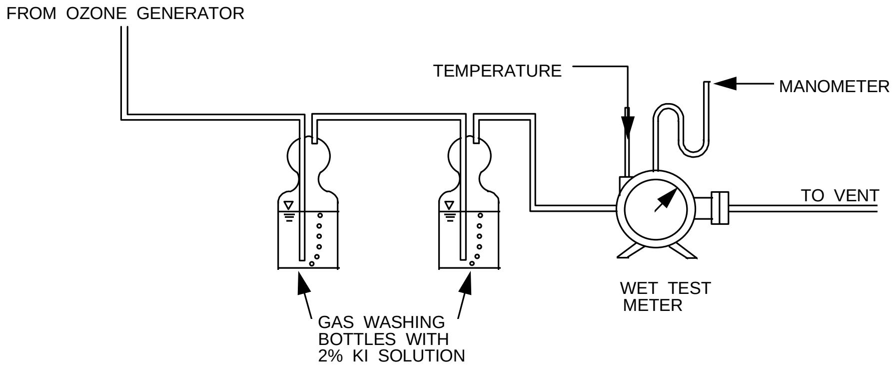

Figure B-1
Ozone Concentration Wet-Test Setup for Ozone Generator Product Gas

3.5.2. Allow the non-ozonated gas within the sample line to bubble through the test KI solution, in order to purge the sample line with sample ozone gas. Begin recording gas flow through the wet-test meter as soon as a yellow color is noticed at the point of entry in the gas-washing bottle.

3.6. Bubble 2 to 4 liters of ozone gas through the bottles at a rate of about 1 to 2 L/min, and record the exact gas volume flowed through the wet-test meter as the uncorrected volume on the data sheet. The recommended gas volume to be collected depends on ozone concentration, titration volume, and $Na_2S_2O_3$ normality (see Figures B-2 and B-3 below). Better accuracy is obtained when the titration volume is at least 20 mL and the gas volume is at least 2 L. Normality of the $Na_2S_2O_3$ titrant can be adjusted to achieve these conditions.

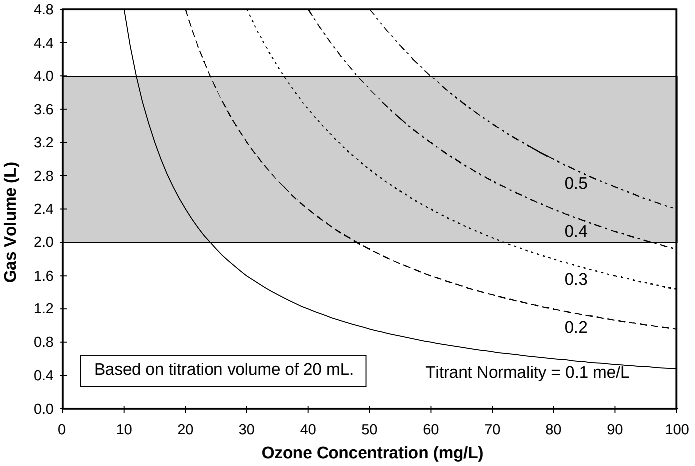

Figure B-2
Relationship Among Wet-Test Parameters for a Titration Volume of 20 mL

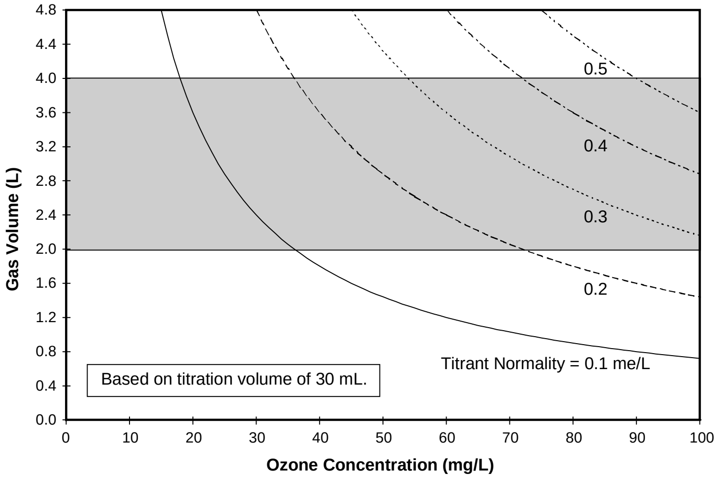

Figure B-3
Relationship Among Wet-Test Parameters for a Titration Volume of 30 mL

3.7. After bubbling has stopped, quickly add about 10 mL of 2 N H_2SO_4 to each gas washing bottle to lower the pH of the solution below pH = 2.

3.8. Transfer the liquid from each gas-washing bottle to a 1- or 2-liter Erlenmeyer flask (use 2-liter for two gas washing bottles). Thoroughly rinse the gas washing bottles three times with distilled water, retaining all rinse water in the Erlenmeyer flask. When transferring contents, minimize splashing and aeration.

3.9. Read the initial volume of $Na_2S_2O_3$ titrant in burette. **NOTE: The titrant should have been standardized recently, as described in Steps 3.1.1. and 3.1.2.** Titrate with $Na_2S_2O_3$ until the solution becomes a pale yellow color.

3.10. Add about 5 mL of starch solution to the flask. A bluish color will form. Carefully continue the titration, drop by drop, until the blue color just disappears and the solution is clear.

3.11. Record the final burette reading and determine the total volume of titrant used. Record the volume of titrant used and the exact normality of the titrant from Steps 3.1.1. or 3.1.2. above.

3.12. Complete the calculations described in Step 4. below.

4. Determination of ozone concentration from wet-chemistry test procedure discussed in Steps 3.1 through 3.12.

4.1. Find temperature/pressure corrected gas volume using Equation B-1.

$$V_{NTP} = V_a \times \frac{(P_a - P_v - P_m)}{P_{NTP}} \times \frac{T_{NTP}}{T_a} \qquad \text{Eq. B-1}$$

Where:

V_{NTP} = Gas volume in Liters (L_{NTP}) referenced to normal temperature and pressure conditions.

V_a = Uncorrected gas volume, in Liters, as measured by wet-test meter.

P_{NTP} = Normal, reference standard pressure (one atmosphere, which is 101.3 kPa or 760 mm Hg).

T_{NTP} = Normal, reference standard temperature (273.15 Kelvin = 0°C).

P_a = Barometric pressure in kPa or mm Hg.

P_v = Vapor pressure in kPa or mm Hg, based on wet-test meter temperature. (**See Table B-1, "Vapor Pressure Look-Up Table."**)

P_m = Wet-test meter manometer pressure in kPa or mm Hg. (**NOTE: May have to convert from inches of water, using 1.868 mm Hg per inch of water and 0.1333 kPa per mmHg. Typically, the wet-test manometer pressure is zero when testing the ozone generator product-gas.**)

T_a = Wet-test meter temperature in Kelvin, or 273.15 K plus wet-test meter temperature in °C.

4.2. Find mass of ozone trapped in KI or $NBKI_e$, using Equation B-2.

$$\text{Mass} = 24 \times V_t \times N_t \qquad \textbf{Eq. B-2}$$

Where:

Mass = Mass of ozone trapped in KI or $NBKI_e$, in mg.

24 = Conversion factor = 24,000 me/L per l000 mL/L.

V_t = Volume of sodium thiosulfate titrate used, in mL.

N_t = Normality of sodium thiosulfate, in mg/me.

4.3. Find concentration of ozone in mg/L_{NTP} (Y_1) using Equation B-3.

$$Y_1 = \frac{\text{Mass from Equation (B2)}}{V_{NTP}\,\text{from Equation (B1)}} \qquad \textbf{Eq. B-3}$$

4.4. End of wet-chemistry test procedure.

Table B-1
Look-Up Table for Vapor Pressure

Temp	V.P.	Temp	V.P.	Temp	V.P.	Temp	V.P.	Temp	V.P.
C	mm Hg	C	mm Hg	C	mm Hg	C	mm Hg	C	mm Hg
10.0	9.21	15.0	12.79	20.2	17.75	25.4	24.33	30.6	32.93
10.2	9.33	15.2	12.95	20.4	17.97	25.6	24.62	30.8	33.31
10.4	9.46	15.4	13.12	20.6	18.20	25.8	24.91	31.0	33.69
10.6	9.58	15.6	13.29	20.8	18.42	26.0	25.21	31.2	34.08
10.8	9.72	15.8	13.46	21.0	18.65	26.2	25.51	31.4	34.47
11.0	9.84	16.0	13.63	21.2	18.88	26.4	25.81	31.6	34.86
11.2	9.98	16.2	13.81	21.4	19.11	26.6	26.12	31.8	35.26
11.4	10.11	16.4	13.99	21.6	19.35	26.8	26.43	32.0	35.66
11.6	10.24	16.6	14.17	21.8	19.59	27.0	26.74	32.2	36.07
11.8	10.38	16.8	14.35	22.0	19.83	27.2	27.05	32.4	36.48
12.0	10.52	17.0	14.53	22.2	20.07	27.4	27.37	32.6	36.89
12.2	10.66	17.2	14.71	22.4	20.32	27.6	27.70	32.8	37.31
12.4	10.80	17.4	14.90	22.6	20.56	27.8	28.02	33.0	37.73
12.6	10.94	17.6	15.09	22.8	20.81	28.0	28.35	33.2	38.15
12.8	11.08	17.8	15.28	23.0	21.07	28.2	28.68	33.4	38.58
13.0	11.23	18.0	15.48	23.2	31.32	28.4	29.01	33.6	39.02
13.2	11.38	18.2	15.67	23.4	21.58	28.6	29.35	33.8	39.46
13.4	11.53	18.4	15.87	23.6	21.84	28.8	29.70	34.0	39.90
13.6	11.68	18.6	16.07	23.8	22.11	29.0	30.04	34.2	40.34
13.8	11.83	18.8	16.27	24.0	22.38	29.2	30.39	34.4	40.80
14.0	11.99	19.0	16.48	24.2	22.65	29.4	30.74	34.6	41.25
14.2	12.14	19.2	16.68	24.4	22.92	29.6	31.10	34.8	41.71
14.4	12.30	19.4	16.89	24.6	23.20	29.8	31.46		
14.6	12.46	19.6	17.10	24.8	23.48	30.0	31.82		
14.8	12.62	19.8	17.32	25.0	23.76	30.2	32.19		
15.0	12.79	20.0	17.53	25.2	24.04	30.4	32.56		

To convert from mm Hg to kPa, multiply by 0.1333 kPa/mm Hg.

Comparison of Wet-Chemistry and UV Meter Results

Ozone concentration may be determined by using the iodometric wet-chemistry method as a means of confirming the trustworthiness of the installed UV ozone monitors. ***It is important to note, however, that the UV monitor reading be established independent of the wet-chemistry result. Monitor temperature, pressure, and gas composition adjustments should be determined using manufacturer guidelines.*** The wet-chemistry test result should be utilized only as an independent comparison of UV monitor results. If the comparative ozone concentration exceeds ±2 percent then this provides a clue that something is wrong with the UV monitor installation, the wet-chemistry meter, or with the wet-chemistry test procedure. A second wet-chemistry meter may be used to verify results from the first wet-chemistry meter. Both the UV meter and wet-chemistry test procedures should then be re-evaluated to ensure correct operation of the UV meter and that the correct wet-chemistry test procedure has been used. The UV meter may be repaired or replaced if it is not functioning properly.

The procedure for completing a UV meter versus wet-chemistry test comparison is as follows.

1. Arrange the ozone product-gas sample flow to the UV meter and gas washing bottles, as described below, so that truly comparative ozone concentration readings are obtained.

    1.1. Provide a sample tap to the gas-washing bottle from the same sample line to the UV meter. If the UV meter reading **is not affected** when ozone is bubbled through the KI solution, simultaneously read the UV meter reading, or readings, while bubbling ozone. The UV meter reading **is not affected** when sufficient pressure exists to force the gas flow to both the gas washing bottles and the UV meter without affecting flow to the UV meter.

    1.2. If the UV meter reading **is affected** when ozone is bubbled through the KI solution, read the UV meter for a short period of time before and after bubbling ozone. However, it is important to confirm that the ozone generator production rate and associated ozone concentration do not change when switching from one test method to the other.

2. Establish that the UV meter is displaying an ozone concentration that properly takes into account the sample cell temperature and pressure and also feed-gas composition when the reading is displayed on a mass basis (i.e., % wt). Make calibration adjustments to the UV meter for sample cell temperature, pressure, and feed-gas composition, as necessary.

3. Independently perform the wet-chemistry test. If the UV meter reading changes during the course of bubbling ozone into the gas-washing bottle, collect several UV meter readings and average the results.

4. Using the equation that follows, determine the percent difference between the UV meter ozone concentration (average of several UV meter readings, if applicable) and wet-chemistry ozone concentration. Be sure that the ozone concentrations are properly determined, as discussed below.

$$\%\text{Difference} = \left\{ \frac{\text{UV Concentration}}{\text{Wet - Chemistry Concentration}} - 1 \right\} \times 100$$

    4.1. If the UV meter reading is displayed in mg/L, ensure that its reference temperature and pressure are the same as those used for determining the wet-chemistry ozone concentration (e.g., mg/L_{NTP}).

    4.2. If the UV meter reading is displayed in % wt, convert the mg/L wet-chemistry reading to mass basis, using Equation B-4. It should be noted that in Equation B-4, the term 0.5 Y_1 V_m / 48 effectively accounts for the fact that three oxygen molecules form two ozone molecules within the ozone generator and that the weight percent calculation must involve the determination of ozone generator product-gas density. It is incorrect to use feed-gas density in the denominator of Equation B-4.

$$Y_1' = \frac{100\ Y_1}{W_{fg}\left(1000 + \frac{0.5\ Y_1 V_m}{48}\right)}$$ **Eq. B-1**

Where:

Y_1' = Ozone concentration, percent by weight.

Y_1 = Ozone concentration, mg/L_{NTP}.

100 = Conversion of mass ratio to percent expression.

V_m = Molar volume (22.4 L_{NTP}/mol).

48 = Gram molecular weight of ozone, g/mol.

W_{fg} = Density of feed-gas, g/L_{NTP}, as shown in Equation B-5.

$$W_{fg} = \frac{(V_{O2} \times GMW_{O2}) + (V_{N2} \times GMW_{N2}) + (V_{ArR} \times GMW_{AR})}{V_m}$$ **Eq. B-2**

V_{O2} = Oxygen concentration in feed-gas (~20.94% vol for air).

V_{N2} = Nitrogen concentration in feed-gas (~78.12% vol for air).

V_{AR} = Argon concentration in feed-gas (~0.94% vol for air).

GMW_{O2} = Gram molecular weight of oxygen, at 32.00 g/mol.

GMW_{N2} = Gram molecular weight of nitrogen, at 28.01 g/mol.

GMW_{Ar} = Gram molecular weight of argon, at 39.95 g/mol.

NOTE: Other gases present in air or in the feed-gas may be included if desired, but typically would result in, at most, a minor adjustment.

Target:

Municipal Water and Wastewater

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