

Environmental Technology Verification Report

On-Site Disinfectant Generation and
Inactivation of Pseudomonas in Raw
Drinking Water

OXI-2B
OXI Company, Inc.

Prepared by



NSF International

 Under a Cooperative Agreement with
U.S. Environmental Protection Agency

ET ✓ ET ✓ ET ✓

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM



U.S. Environmental Protection Agency



NSF International

ETV Joint Verification Statement

| | | | |
|------------------|---|------------------------------|--|
| TECHNOLOGY TYPE: | ON-SITE DISINFECTION UNIT USED IN DRINKING WATER TREATMENT SYSTEMS | | |
| APPLICATION: | ON-SITE DISINFECTANT GENERATION AND INACTIVATION OF PSEUDOMONAS | | |
| TECHNOLOGY NAME: | OXI-2B | | |
| COMPANY: | OXI COMPANY, INC. | | |
| ADDRESS: | 700 ORIOLE DRIVE, UNIT 111A | PHONE: (757) 422-0177 | |
| | VIRGINIA BEACH, VA 23451 | FAX: (757) 422-9716 | |
| WEB SITE: | n/a | | |
| EMAIL: | donald.e.meyers@worldnet.att.net | | |

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and permittees; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International (NSF) in cooperation with the EPA operates the Drinking Water Treatment Systems (DWTS) pilot, one of 12 technology areas under ETV. The DWTS pilot recently evaluated the performance of an on-site disinfectant generation system used in package drinking water treatment system applications. This verification statement provides a summary of the test results for the OXI Company's OXI-2B System. ARCADIS Geraghty & Miller, an NSF-qualified field testing organization (FTO), performed the verification testing.

ABSTRACT

Verification testing of OXI's on-site disinfectant generation system OXI-2B was conducted for 30 days between June 26 and August 17, 2000. The OXI-2B system is capable of producing at least 1 lb of chlorine in water using 2.7 lb of salt (NaCl) and 2.2 AC kilowatt hours (kWh) of power. In addition, the system was capable of producing a 4.2 log kill of *Pseudomonas aeruginosa* bacteria when chlorine is dosed to achieve a CT of 56 based on actual (field-confirmed) hydraulic retention time or a CT of 30 based on a T_{10} value in water with a pH between 7.0 and 8.0 and turbidity of 20 NTU or less, organic carbon concentrations between 1.8 and 2.6 mg/L and an alkalinity of less than 20 mg/L as CaCO_3 .

TECHNOLOGY DESCRIPTION

The OXI-2B disinfectant generation unit consists of two electrolytic cell halves, a brine tank and pump, and a stand with the power supply and piping attached. The OXI-2B unit uses sodium chloride (NaCl) brine to produce an oxidant gas, that is drawn into a side stream of the water by means of a venturi. The key part of the unit consists of an anode and cathode compartment separated by a proprietary membrane. When a direct current (DC) voltage is imposed across the cell, the (Cl) ions are attracted to the positively-charged anode and will combine to form chlorine (Cl_2) molecules, which will initially react with water from the brine solution. At a pH of about 2, an equilibrium is reached where free Cl_2 gas is released to the air in the upper part of the enclosed anode compartment. Gas is drawn into a side stream of water by means of a venturi.

VERIFICATION TESTING DESCRIPTION

Test Site

The host site for this demonstration is the SJWD Water District Drinking Water Treatment Plant in Lyman, South Carolina, which draws water from the Middle Tyger River. The water is generally of good quality with a turbidity of less than 10 nephelometric turbidity units (NTU), hardness under 10 g/L and TOC of approximately 2.5 mg/L. During storm events, the turbidity may rise significantly. Furthermore, the water is known to have coliforms with counts generally varying between 100 to 1,000 colony forming units (CFU) per 100 ml. Raw water was drawn at a rate of 23 gallons per minute (gpm) from a sump directly in contact with the Middle Tyger River.

Methods and Procedures

The test was divided into three tasks: 1) Equipment Disinfection Production Capabilities and Operation, 2) Microbiological Contaminant Inactivation (Challenge Test), and 3) Treated Water Quality.

The objectives of Task 1 included the generation of data that describe the operation of the OXI-2B, i.e., the concentration of disinfectant (as chlorine) produced, the electrical power consumption per pound of available chlorine, the sodium chloride consumption per pound of available chlorine, and the amount of potable water used. The combined waste flow rate from anode and cathode, pH, and temperature were recorded once per day and the waste composition was determined once during the test. The electric power consumption of the system was also monitored. The sodium chloride consumption was determined based on a comparison of the mass of sodium chloride added to the OXI-2B and the total disinfectant production (as chlorine).

The objective of this task was to verify OXI-2B's efficacy for inactivation of *P. aeruginosa* when disinfectant (as chlorine) is dosed to achieve a concentration time (CT) of 70 in water with a pH between

6.0 and 8.0 and turbidity of 20 NTU or less, organic carbon concentrations between 1.0 and 3.0 and an alkalinity less than 20 mg/L as CaCO₃. This microbe was spiked into the raw water flow for a period of time equivalent to three hydraulic retention times. Subsequent analyses revealed an average *P. aeruginosa* effluent concentration of 1.5×10^4 CFUs/100 ml. *P. aeruginosa* enumeration of the samples was done using Standard Methods 9213 E. Membrane Filter Technique for *P. aeruginosa*. During the challenge testing, the total and free chlorine concentrations were verified. *P. aeruginosa* was selected as the bacterial challenge test organism because the *Pseudomonas* species background in the raw water was expected to be minimal and selective culture methods exist such that *P. aeruginosa* can be reproducibly cultured in the disinfected water.

The objective of the treated water quality task was to assess the impact that treatment with disinfectant generated by the OXI-2B has on treated water quality. Water quality parameters that were monitored during the test period include: pH, temperature, turbidity, chlorine residual (free and total), hydrogen sulfide, alkalinity, TDS, ammonia nitrogen, total organic carbon (TOC), ultraviolet absorbance (UVA) at 254 nanometer (nm), true color, iron, manganese, chloride, chlorite, chlorate, sodium, total coliforms, and heterotrophic plate count (HPC) bacteria. Simulated Distribution System testing for disinfection by-product (DBP) formation was conducted as a one-time event.

VERIFICATION OF PERFORMANCE

Operation and Maintenance

The OXI-2B system was fully automated and capable of normal operation without manual intervention. During the ETV test the float switch in the brine tank got stuck and had to be operated manually on occasion. Other than periodically adding salt, no maintenance was required during the test period. However, ARCADIS found the Operation & Maintenance manual limited and suggests that OXI provides a (ring-)bound operations and maintenance manual with the unit that makes ample use of illustrations and schematics and includes comprehensive operational instructions.

Disinfectant Production Capabilities

The OXI-2B system produced and dosed oxidant (measured as chlorine) constantly and effectively during the test. All chlorine analyses were done onsite in the SJWD laboratory. The average finished free and total chlorine concentrations were 3.07 and 3.54 mg/L respectively. During the test the raw water flow rate was maintained at the set rate of 23 gpm. The free and total chlorine content of the disinfectant stream was 38 mg/L with a standard deviation of 9 mg/L and 42 mg/L with a standard deviation of 8 mg/L respectively. Because the total volume of the disinfectant stream was 510,407 L, the total chlorine produced during the ETV-test was 21 kg (46 lb).

A total of 240 lb of salt was used during the test. Most salt was added during the first part of the test: during the first 10 days, 120 lbs was added and during the last 10 days, only 40 lbs was added. The OXI-2B system was required to have a brine overflow, which was considerable during the first part of the test resulting in 5.2 lbs of salt expended for each pound of total chlorine produced. During the later part of testing, the brine overflow was significantly reduced. In the last 10 days of the test, 40 lbs of salt was needed to produce approximately 7 kg (15 lbs) of chlorine, resulting in a ratio of only 2.7 lbs salt/lb chlorine. OXI states that the newer models of the OXI disinfectant systems do not include a brine overflow, which they indicate was a cause of the higher salt consumption during verification testing.

Microbiological Contaminant Inactivation

Based on the results of an earlier tracer test, the hydraulic retention time was calculated to be 19 minutes. ARCADIS performed a challenge test to assess the disinfection capabilities of the OXI-2B system on *P. aeruginosa*. The concentration for *P. aeruginosa* in the broth culture was 1.6×10^{10} CFUs/100 ml. The results of the *P. aeruginosa* challenge test show that the OXI-2B system is capable of a 4.2-log kill of *P. aeruginosa* at a CT value of 56 based on actual hydraulic retention time or a CT of 30 based on a T_{10} value.

Finished Water Quality

In-line turbidity readings were taken twice daily for finished water and were verified by taking grab samples. The OXI-2B system has no apparent effect on turbidity: the average raw water turbidity was 11.45 NTU and the average finished water turbidity was 11.67 NTU for grab samples and 10.92 NTU for in-line samples.

The OXI-2B has no apparent effect on UVA, true color, TOC, manganese, and iron. Readings for chlorite and chlorate were always below the detection limit of 20 µg/L. The OXI-2B system produced some chloride (6.0 mg/L), which can probably be attributed to the use of brine. Ammonia nitrogen was not detected in raw nor finished water.

The OXI-2B system performed well in eliminating total coliforms. For all test days, total coliforms were reduced to zero cfu/100 ml. The OXI-2B system was very effective in reducing HPC during the first 20 days of the test, but for the remaining 10 days of the test, the HPC kill capacity diminished. Although ARCADIS has no complete explanation for this phenomenon, the concentration of heterotrophic bacteria in the raw water samples generally increased by an order of magnitude during this same interval.

Total trihalomethanes (TTHMs) and haloacetic acids (HAAs) were also analyzed as part of the ETV test. None of these analytes were detected in the raw water. The OXI-2B system generated some chloroform (10 µg/L) and small amounts of bromodichloromethane (2.8 µg/L) and dibromochloromethane (0.3 µg/L), whereas none of the other TTHMs were detected. Average dichloroacetic acid and trichloroacetic acid concentrations were 18 µg/L and 21 µg/L respectively. Small amounts of bromochloroacetic acid, monochloroacetic acid, and bromodichloroacetic acid were detected. No other HAAs were detected.

Simulated distribution system (SDS) testing was conducted to determine the extent to which disinfection byproducts would be formed when the OXI-2B was used as source for both primary and residual disinfection. Testing included analyses for TTHMs and HAAs. Significant amounts of chloroform (~ 85 µg/L), dichloroacetic acid (46-50 µg/L), trichloroacetic acid (78-91 µg/L) and relatively low levels of bromodichloromethane (9.9-11 µg/L), dibromochloromethane (0.7-0.8 µg/L), bromochloroacetic acid (4.1-4.2 µg/L), monochloroacetic acid (5.3-6.3 µg/L), and bromodichloroacetic acid (4.3-4.6 µg/L) were found. The support system for the verification of the OXI-2B during this project was not designed to remove dissolved organics from the raw water prior to chlorination. Thus, the formation of substantial quantities of DBPs during the verification interval is not a surprising result.

Waste Production

The OXI-2B produced a small continuous waste stream of 13.7 ml/min (5.2 gal. or 19.8 L per day). The waste stream had a high alkalinity, pH, and a high TDS content. The average alkalinity of the waste was 30,960 mg/L, the pH was 12.91, and the TDS was 13,800 mg/L. According to OXI documentation, the OXI-2B cathode generates 11.2 L of hydrogen for each 35.5 gram of total chlorine. Because 21 kg total

chlorine were generated, 6,625 L of hydrogen were produced over the duration of the verification test which was vented to the atmosphere.

Original Signed by
Frank Princiotta for
E. Timothy Oppelt

07/25/01

E. Timothy Oppelt
Director
National Risk Management Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original Signed by
Gordon Bellen

07/26/01

Gordon Bellen
Vice President
Federal Programs
NSF International

NOTICE: Verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and NSF make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of corporate names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products. This report is not a NSF Certification of the specific product mentioned herein.

Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing for Inactivation of Microbiological Contaminant* dated August 1999, the Verification Statement, and the Verification Report (NSF Report #01/28/EPADW395) are available from the following sources:

(NOTE: Appendices are not included in the Verification Report. Appendices are available from NSF upon request.)

1. Drinking Water Systems ETV Pilot Manager (order hard copy)
NSF International
P.O. Box 130140
Ann Arbor, Michigan 48113-0140
2. NSF web site: <http://www.nsf.org/etv> (electronic copy)
3. EPA web site: <http://www.epa.gov/etv> (electronic copy)

May 2001

Environmental Technology Verification Report

On-Site Disinfectant Generation and Inactivation of Pseudomonas in Raw Drinking Water

OXI Company, Inc. OXI Generator Model 2B

Prepared for:

NSF International
Ann Arbor, Michigan 48105

Prepared by:

ARCADIS G & M
4915 Prospectus Drive, Suite F
Durham, NC 27713

Under a cooperative agreement with the U.S. Environmental Protection Agency

Jeffrey Q. Adams, Project Officer
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development has financially supported and collaborated with NSF International (NSF) under Cooperative Agreement No. CR 824815. This verification effort was supported by Drinking Water Treatment Systems Pilot operating under the Environmental Technology Verification (ETV) Program. This document has been peer reviewed and reviewed by NSF and EPA and recommended for public release.

Foreword

The following is the final report on an Environmental Technology Verification (ETV) test performed for the NSF International (NSF) and the United States Environmental Protection Agency (EPA) by ARCADIS G & M (ARCADIS), in cooperation with OXI Company. The test was conducted during June, July, and August 2000 at the SJWD Drinking Water Plant in Lyman South Carolina.

Throughout its history, the EPA has evaluated the effectiveness of innovative technologies to protect human health and the environment. A new EPA program, the Environmental Technology Verification Program (ETV) has been instituted to verify the performance of innovative technical solutions to environmental pollution or human health threats. ETV was created to substantially accelerate the entrance of new environmental technologies into the domestic and international marketplace. Verifiable, high quality data on the performance of new technologies are made available to regulators, developers, consulting engineers, and those in the public health and environmental protection industries. This encourages more rapid availability of approaches to better protect the environment.

The EPA has partnered with NSF, an independent, not-for-profit testing and certification organization dedicated to public health, safety and protection of the environment, to verify performance of small package drinking water systems that serve small communities under the Drinking Water Treatment Systems (DWTS) ETV Pilot Project. A goal of verification testing is to enhance and facilitate the acceptance of small package drinking water treatment equipment by state drinking water regulatory officials and consulting engineers while reducing the need for testing of equipment at each location where the equipment's use is contemplated. NSF will meet this goal by working with manufacturers and NSF-qualified Field Testing Organizations (FTO), in this case ARCADIS, to conduct verification testing under the approved protocols.

The ETV DWTS is being conducted by NSF with participation of manufacturers, under the sponsorship of the EPA Office of Research and Development, National Risk Management Research Laboratory, Water Supply and Water Resources Division, Cincinnati, Ohio. It is important to note that verification of the equipment does not mean that the equipment is "certified" by NSF or "accepted" by EPA. Rather, it recognizes that the performance of the equipment has been determined and verified by these organizations for those conditions tested by the FTO.

Table of Contents

| <u>Section</u> | <u>Page</u> |
|---|-------------|
| Verification Statement | VS-i |
| Title Page | i |
| Notice | ii |
| Foreword | iii |
| Table of Contents | iv |
| Abbreviations and Acronyms | vi |
| Acknowledgements | viii |
| Chapter 1: Introduction | 1 |
| 1.1 ETV Purpose and Program Operation | 1 |
| 1.2 Testing Participants and Responsibilities | 1 |
| 1.2.1 NSF International | 2 |
| 1.2.2 Field Testing Organization | 2 |
| 1.2.3 Manufacturer | 3 |
| 1.2.4 Analytical Laboratories | 3 |
| 1.2.5 U.S. Environmental Protection Agency | 4 |
| 1.3 Verification Testing Site | 4 |
| 1.3.1 Source Water | 4 |
| 1.3.2 Pilot Effluent Discharge | 5 |
| Chapter 2: Equipment Description and Operating Processes | 6 |
| Chapter 3: Methods and Procedures | 11 |
| 3.1 Task 1: Equipment Disinfection Production Capabilities | 11 |
| 3.2 Task 2: Microbiological Contaminant Inactivation | 13 |
| 3.2.1 Hydrodynamic Tracer Test | 13 |
| 3.2.2 Protocol for Bacterial Challenge Test | 16 |
| 3.3 Task 3: Treated Water Quality | 17 |
| 3.4 Operation and Maintenance | 18 |
| Chapter 4: Results and Discussion | 19 |
| 4.1 Qualitative Operational and Maintenance Issues | 19 |
| 4.2 Disinfectant Production Capabilities (Task 1) | 20 |
| 4.3 Microbiological Contaminant Inactivation (Task 2) | 24 |
| 4.4 Finished Water Quality (Task 3) | 28 |
| 4.5 Waste Production | 33 |
| Chapter 5: Quality Assurance | 35 |
| 5.1 Calculation of DQI Goals | 35 |
| 5.2 Blanks, Duplicates and Hold Times | 37 |
| 5.3 Daily and Biweekly QA/QC Verifications | 38 |
| 5.4 Internal Audits | 39 |
| Chapter 6: References | 40 |

Table of Contents, continued

| <u>Tables</u> | <u>Page</u> |
|---|-------------|
| 1-1 Average Feed Water Quality During ETV Test Period | 5 |
| 3-1 Sampling and Analysis Summary..... | 12 |
| 3-2 Tracer Test Data..... | 14 |
| 4-1 Sodium Chloride Consumption..... | 21 |
| 4-2 Flow and Electrical Reading Summary | 21 |
| 4-3 Free and Total Chlorine Concentrations | 23 |
| 4-4 Bacterial Challenge Test Results | 25 |
| 4-5 Results of Total and Free Chlorine Testing during Bacterial Challenge Testing | 28 |
| 4-6 Summary of Daily pH, Temperature, and Turbidity Readings..... | 28 |
| 4-7 Miscellaneous Weekly and Biweekly Data | 30 |
| 4-8 Total Coliforms and Heterotrophic Plate Counts..... | 31 |
| 4-9 TTHMs and HAAs..... | 32 |
| 4-10 Simulated Distribution System Test Results..... | 33 |
| 4-11 Results of Heavy Metal Analysis on Water Softener Regeneration Waste Stream..... | 34 |
| 5-1 Data Quality Indicator Goals for Critical Measurements | 35 |
| 5-2 Calculated DQIs for Critical Measurements | 36 |
| 5-3 Trihalomethane Recoveries (70-130% criteria) | 36 |
| 5-4 Haloacetic Acid Recoveries for 20 µg/L Standard (70-130% criteria)..... | 37 |

Figures

| | |
|--|----|
| 2-1 Installation Drawing of OXI-2B | 6 |
| 2-2 Front View OXI-2B | 7 |
| 2-3 Rear View OXI-2B | 7 |
| 2-4 OXI-2B Verification Test Flow Diagram..... | 10 |
| 3-1 F-Curve for ClorTec T-12 ETV Tracer Test..... | 15 |
| 4-1 Bar Graph of Bacterial Challenge Test Positive Control Samples | 26 |
| 4-2 Mean Enumeration Values of Positive Control Samples..... | 26 |

Appendices

- A. Internal Audit Report
- B. Raw Data Tracer Test
- C. Daily Logbook Data Sheets
- D. Analytical Data, Laboratory Results
- E. OXI-2B Instruction Manual
- F. Bound Notebook
- G. Results of Raw Water Rotometer Verification
- H. Some Theoretical Aspects of Electrochemical Chlorine Production

Abbreviations and Acronyms

| | |
|--------|---|
| A | ampères |
| AC | alternating current |
| CT | concentration time |
| CFU | colony forming units |
| DBP | disinfection by-product |
| DC | direct current |
| DQA | data quality audit |
| DQI | data quality indicator |
| DWTS | drinking water treatment system |
| ETV | Environmental Technology Verification |
| FOD | field operations document |
| FRP | fiberglass reinforced plastic |
| ft | feet |
| FTO | field test organization |
| gpm | gallons per minute |
| HAAs | haloacetic acids |
| HPC | heterotrophic plate count |
| HRT | hydraulic retention time |
| Hz | Hertz |
| IC | ion chromatography |
| ICP | inductively coupled plasma |
| kg | kilogram |
| kWh | kilowatt-hour |
| l | liter |
| lb | pound |
| LCS | laboratory control spike |
| LSCD | laboratory control spike duplicate |
| mg/L | milligrams per liter |
| ml | milliliter |
| MS/MSD | matrix spike/matrix spike duplicate |
| NaCl | sodium chloride |
| NSF | NSF International, formerly known as the National Sanitation Foundation |
| NTU | nephelometric turbidity units |
| OIT | operator interface terminal |
| OSHA | Occupational Safety & Health Administration |
| pH | minus log hydrogen concentration |
| PEA | performance evaluation audit |
| PE(S) | performance evaluation (sample) |
| PLC | programmable logic controller |
| ppm | parts per million |
| psi | pounds per square inch |
| pt/Co | referring to the ratio of platinum to cobalt in a visual color standard |
| QAPP | quality assurance project plan |
| QA/QC | quality assurance, quality control |

| | |
|----------|---|
| RMP | risk management plan |
| RMS | Root Mean Square |
| RPD | relative percent difference |
| RSD | relative standard deviation |
| SDS | simulated distribution system |
| TDS | total dissolved solids |
| TOC | total organic carbon |
| TSA | technical system audit |
| TTHMs | total trihalomethanes |
| U.S. EPA | United States Environmental Protection Agency |
| UVA | ultraviolet absorbance |
| ZCS | zero current switching |

ACKNOWLEDGMENTS

The Field Testing Organization, ARCADIS, was responsible for all elements in the testing sequence, including collection of samples, calibration and verification of instruments, data collection and analysis, data management, data interpretation and the preparation of this report.

ARCADIS G & M
4915 Prospectus Drive, Suite F, Durham, NC 27713
Contact Person: Michiel Doorn

The laboratory selected for microbiological analysis and non-microbiological analytical work for this verification project was:

Environmental Health Laboratories
110 S. Hill Street, South Bend, IN 46617
Contact Person: Paul Bowers

The Manufacturer of the Equipment was:

OXI Company, Inc.
700 Oriole Drive, Unit 111A
Virginia Beach, VA 23451
Contact Person: Don Meyers

ARCADIS wishes to thank the staff of the SJWD Drinking Water Purification Plant in Lyman, South Carolina and Mr. Doug Waldrop for all their cooperation and practical advice received during the test.

Chapter 1 Introduction

1.1 ETV Purpose and Program Operation

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and permittees; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International (NSF) in cooperation with the EPA operates the Drinking Water Treatment Systems (DWTS) program, one of 12 technology areas under ETV. This ETV test under the DWTS program evaluated the operation of the OXI-2B System, which is an on-site disinfectant generation system used in drinking water treatment disinfection applications. The ETV test evaluated the OXI-2B system's ability to produce at least 1 lb of total chlorine in water using a maximum of 2 lb of salt (NaCl) and a maximum of 2.6 AC kilowatt hours of power. In addition, during a challenge test, the log kill of *P. aeruginosa* bacteria was determined as a result of dosing disinfectant to achieve a CT of 70.

1.2 Testing Participants and Responsibilities

The ETV testing of the OXI-2B System was a cooperative effort between the following participants:

- NSF International
- ARCADIS
- OXI Company, Inc.
- SJWD Drinking Water Purification Plant
- U.S. Environmental Protection Agency

The following is a brief description of each ETV participant and their roles and responsibilities.

1.2.1 NSF International

NSF is a not-for-profit testing and certification organization dedicated to public health safety and the protection of the environment. Founded in 1946 and located in Ann Arbor, Michigan, NSF has been instrumental in the development of consensus standards for the protection of public health and the environment. NSF also provides testing and certification services to ensure that products bearing the NSF Name, Logo and/or Mark meet those standards. The EPA partnered with the NSF to verify the performance of package drinking water treatment systems through the EPA's ETV Program.

NSF provided technical oversight of the verification testing. An audit of the field analytical and data gathering and recording procedures was conducted. NSF also provided review of the Field Operations Document (FOD) and this report.

Contact Information:

NSF International
789 N. Dixboro Rd., Ann Arbor, MI 48105
Contact Person: Bruce Bartley, Project Manager
Phone: (734) 769-8010
Fax: (734) 769-0109
Email: bartley@nsf.org

1.2.2 Field Testing Organization

ARCADIS, an infrastructure and environmental engineering consulting firm, conducted the verification testing of the OXI-2B System. ARCADIS is an NSF-qualified Field Testing Organization (FTO) for the ETV DWTS pilot project.

The FTO was responsible for conducting the verification testing for 30 calendar days. The FTO provided all needed logistical support, established a communications network, and scheduled and coordinated activities of all participants. The FTO was responsible for ensuring that the testing location and feed water conditions were such that the verification testing could meet its stated objectives. The FTO prepared the FOD, oversaw the pilot testing, managed, evaluated, interpreted and reported on the data generated by the testing, as well as evaluated and reported on the performance of the technology.

FTO employees conducted the onsite analyses and data recording during the testing. Oversight of the daily tests was provided by the FTO's Project Manager.

Contact Information:

ARCADIS G & M
4915 Prospectus Drive, Suite F, Durham, NC 27713
Contact Person: Michiel Doorn
Phone: (919) 544-4535
Fax: (919) 544-5690
Email: mdoorn@arcadis-us.com

1.2.3 Manufacturer

The treatment system is manufactured by OXI Company, Inc., manufacturer of on-site disinfectant generation systems for the drinking water industry.

The manufacturer was responsible for supplying a field-ready OXI Generator Model 2-B equipped with all necessary components including treatment equipment, instrumentation and controls and an operations and maintenance manual. The manufacturer was responsible for providing logistical and technical support as needed, as well as providing technical assistance to the FTO during operation and monitoring of the equipment undergoing field verification testing.

Contact Information:

OXI Company, Inc.
700 Oriole Drive, Unit 111A, Virginia Beach, VA 23451
Contact Person: Don Meyers
Phone: (757) 422-0177
Fax: (757) 422-9716
Email: donald.e.meyers@worldnet.att.net

1.2.4 Analytical Laboratories

Chlorine residual, pH, turbidity, alkalinity, hydrogen sulfide analyses, as well as Coliforms and HPC counts were conducted on-site in the laboratory of the SJWD drinking water plant:

SJWD Water District
161 Groce Road, Lyman, SC 29365
Contact Person: Mr. Doug Waldrop
Phone: (864) 949-2520

The SJWD on-site laboratory is certified by the state of South Carolina to perform selected drinking water analyses (Certificate No. 42012001).

Off-site analyses including *Pseudomonas aeruginosa*, were performed by:

Environmental Health Laboratories
110 Hill St., South Bend, IN 46617
Contact Person: Paul Bowers
Phone: (219) 233-4777
Fax: (219) 233-8207

EHL has been issued a certificate by the State of South Carolina to perform selected drinking water analyses (Certification No. 95005001).

1.2.5 U.S. Environmental Protection Agency

The EPA through its Office of Research and Development has financially supported and collaborated with NSF under Cooperative Agreement No. CR 824815. This verification effort was supported by Drinking Water Treatment Systems Pilot operating under the ETV Program. This document has been peer reviewed and reviewed by NSF and EPA and recommended for public release.

1.3 Verification Testing Site

The host site for this demonstration is the SJWD Water District Drinking Water Treatment Plant in Lyman, South Carolina. The SJWD Water District Drinking Water Treatment Plant draws water from the Middle Tyger River. The Middle Tyger River is identified as watershed 03050107-040 and is located in Greenville and Spartanburg Counties. The watershed occupies 64,948 acres of the Piedmont region of South Carolina. Land use/land cover in the watershed includes: 9.02 percent urban land, 23.85 percent agricultural land, 0.77 percent scrub/shrub land, 1.08 percent barren land, 64.32 percent forested land, and 0.95 percent water. There are several ponds and lakes (16-500 acres) in this watershed used for recreation, industrial, municipal and irrigation purposes. There are a total of 120.3 stream miles in the Middle Tyger River.

At the SJWD Drinking Water Treatment Plant, Middle Tyger River water is withdrawn into a flash mixer where caustic, alum and free chlorine are added. Next the water moves through 4-stage flocculators and into sedimentation basins. Following the sedimentation basins, the water being processed goes through dual media sand/antracite filters into a clear well where addition of caustic, phosphate, and occasionally free chlorine takes place. The clear well effluent goes into a storage reservoir prior to being distributed to the public. The SJWD plant has a capacity of 6 million gallons per day (mgd).

1.3.1 Source Water

Water for the verification test at the SJWD plant is raw water, drawn directly from the Middle Tyger River. Upstream of the plant is a reservoir that is used to regulate water levels in the river. During times of draught, the reservoir levels may fall significantly and in extreme cases the water may have high amounts of manganese and cadmium in it, which had been stored in the reservoir sediments. During storm events, the turbidity of the water goes up significantly. Typically, the turbidity is around 10 NTU or lower. A summary of average feed water quality is presented in Table 1-1 below.

Aquatic life uses are fully supported upstream based on the macroinvertebrate community, but may be threatened by a significantly increasing trend in turbidity, occurrences of zinc, and a very high concentration of cadmium measured in sediment. Aquatic life uses are fully supported midstream but may be threatened by a significantly decreasing trend in pH. Aquatic life uses are fully supported downstream based on physical, chemical and macroinvertebrate community data. Recreational uses are not supported at any site due to fecal coliform bacteria excursions and there is a significantly increasing trend in fecal coliform bacteria concentration.

Table 1-1. Average Feed Water Quality During ETV Test Period

| | Unit | Average | Standard Deviation | Minimum | Maximum | 95% Conf. Interval, Min | 95% Conf. Interval, Max |
|------------------|----------|---------|-----------------------|---------|---------|-------------------------------|-------------------------------|
| Chlorine, Free | mg/L | 0.02 | 0.02 | <0.01 | 0.10 | 0.01 | 0.02 |
| Chlorine, Total | mg/L | 0.03 | 0.02 | <0.01 | 0.15 | 0.03 | 0.04 |
| pH | | 7.20 | 0.12 | 6.97 | 7.98 | 7.15 | 7.24 |
| Temperature | C | 24.6 | 1.2 | 22.0 | 26.5 | 24.2 | 25.1 |
| Turb (grab) | NTU | 11.45 | 16.85 | 5.16 | 90.40 | 5.42 | 17.48 |
| Total Coliforms | #/100 ml | 532 | 381 | 0 | 1400 | 372 | 691 |
| HPC | #/ml | 892 | 1254 | 98 | >5200 | 356 | 1428 |
| H ₂ S | mg/L | <2 | 0 | <2 | <2 | n/a | n/a |
| Alkalinity | mg/L | 19 | 0.9 | 18 | 20 | 18 | 20 |
| TDS | mg/L | 68 | n/a | 60 | 76 | n/a | n/a |
| UVA (UV 254) | 1/cm | 0.19 | 0.06 | 0.14 | 0.27 | 0.13 | 0.25 |
| True Color | Pt/Co u. | 65 | 24 | 50 | 100 | 42 | 88 |
| Ammonia Nitrogen | mg/L | <0.3 | 0 | <0.3 | <0.3 | n/a | n/a |
| TOC | mg/L | 2.2 | 0.5 | 1.8 | 2.6 | 1.7 | 2.7 |
| Chloride | mg/L | 2.4 | 0.2 | 2.2 | 2.6 | 2.2 | 2.5 |
| Chlorate | µg/L | <20 | 0 | <20 | <20 | n/a | n/a |
| Chlorite | µg/L | <20 | 0 | <20 | <20 | n/a | n/a |
| Manganese | µg/L | 145 | n/a | 120 | 170 | n/a | n/a |
| Iron | µg/L | 1.7 | n/a | 1.4 | 2.0 | n/a | n/a |
| Sodium | mg/L | 15.2 | n/a | 3.3 | 27 | n/a | n/a |

n/a = Not applicable, because the sample size is too small, or values are below detection limit.

1.3.2 Pilot Effluent Discharge

The effluent of the pilot treatment unit was disposed through a two-inch pipe to a nearby man hole, that ultimately drained into the alum sludge holding pond of the plant. Because the effluent did not leave the jurisdiction of the SJWD plant, no discharge permit was required.

Chapter 2 Equipment Description and Operating Processes

The disinfectant generation unit supplied by OXI Co. for the verification program is the OXI-2B. The OXI system consists of two cell halves bolted together for shipment, a brine tank and pump, a stand with the power supply and piping attached, and a box of accessories. The cell is poly vinyl chloride (PVC) and is strapped to the pallet for shipping. The power supply is in a fiberglass enclosure mounted to an aluminum stand which is in turn mounted to the pallet. The brine pump is also mounted to the pallet and the plastic brine tank sits on the pallet. Where possible, all components are plastic.

The OXI-2B unit uses sodium chloride (NaCl) brine to produce oxidant gas. Because the gas can not be quantified directly, it is measured as free and/or total chlorine after it has been dissolved in water. According to the manufacturer and White (1992), the gas consists of chlorine and short-lived oxygen radicals. This gas is drawn into a side stream of the water by means of a venturi. Figure 2-1 is a simplified installation drawing provided by OXI and Figures 2-2 and 2-3 display the front and back of the unit.

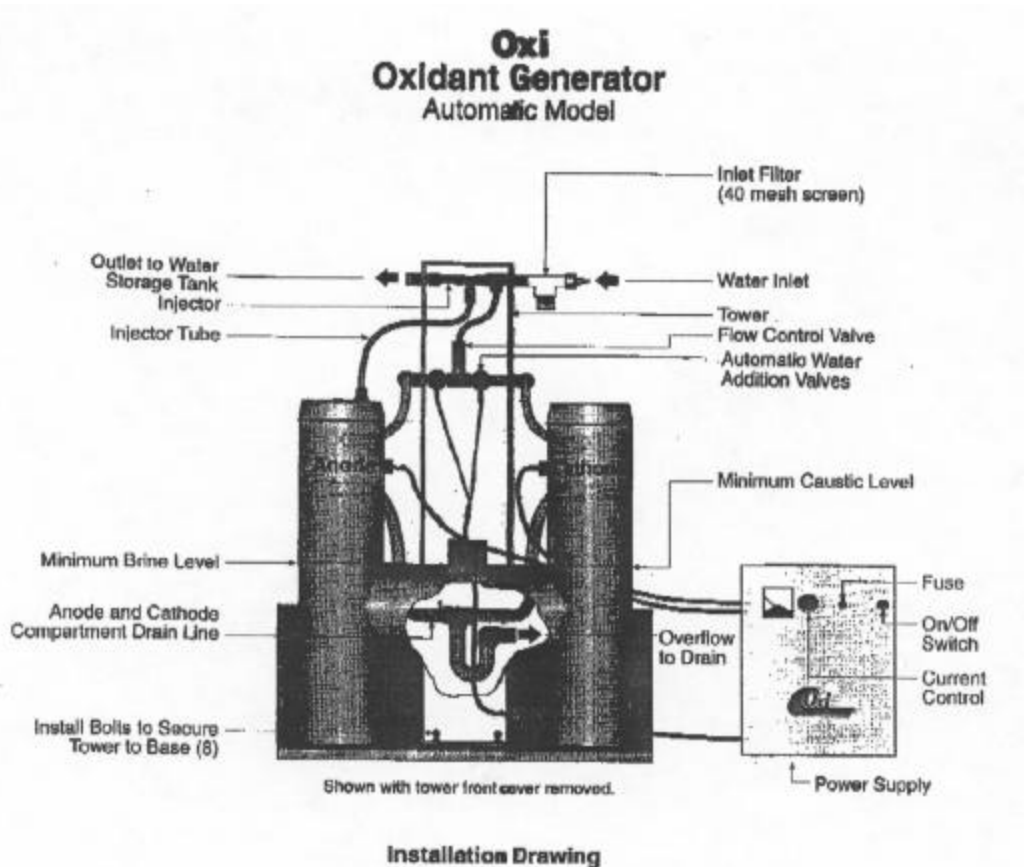


Figure 2-1 Installation Drawing of OXI-2B



Figure 2-2: Front View OXI-2B

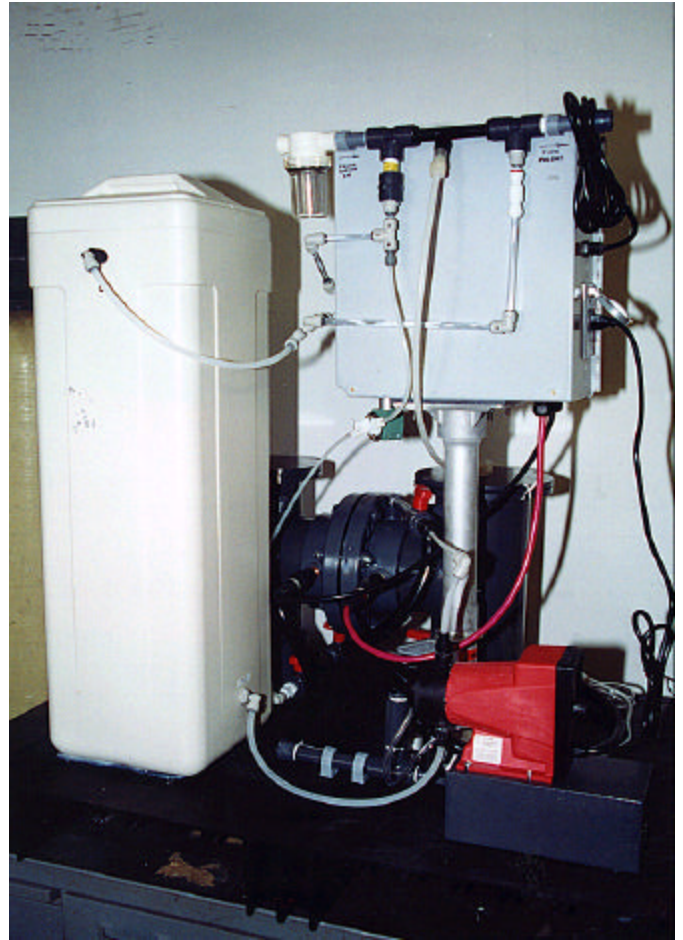
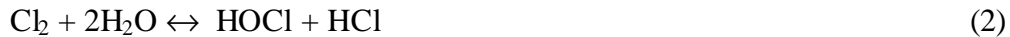


Figure 2-3: Rear View OXI-2B

The key part of the unit consists of an anode and cathode compartment separated by a proprietary membrane. The membrane will allow positively-charged ions to pass through but will block negatively-charged ions. When NaCl is dissolved in water it ionizes to (Cl⁻) and (Na⁺) ions and when a direct current (DC) voltage is imposed across the cell, the positively-charged ions (Na⁺) are attracted to the negatively-charged cathode and pass through the membrane. The (Cl⁻) ions are attracted to the positively-charged anode and stay in the anode compartment. Since an electrolyte is initially electrically neutral, an imbalance is created because the positive ions have passed through the membrane leaving the negatively-charged (Cl⁻) ions without a neutralizing positive charge. To compensate for this, (Cl⁻) ions combine to form Cl₂ molecules thereby releasing two electrons. The chlorine initially reacts with water, thereby creating hypochlorite and hydrochloric acid which will lower the pH in the anode compartment.

Reactions at anode:



At a pH of about 2, an equilibrium is reached where free Cl_2 gas does not react with water any more and is released to the air in the upper part of the anode compartment, where it reportedly reacts with air to form various oxidants (White, 1992). Next, the oxidant gas is drawn into the stream of water by means of a venturi. According to the manufacturer, the oxidant gas quickly forms products comparable to those from standard chlorine/hypochlorite dosage in water and these compounds can, therefore, be quantified as free or total chlorine. Gas speciation before the gas enters the water was beyond the scope of this field test.

At the cathode, sodium (Na^+) ions combine with OH^- ions to form NaOH (sodium hydroxide). The cathode side of the OXI unit produces 1.1 g of sodium hydroxide for each g of chlorine produced. A timer is factory preset to periodically add water to the cathode compartment keeping the sodium hydroxide concentration in the 5% - 10% range. During this water addition cycle, the diluted sodium hydroxide overflows into the drain manifold on the rear of the stand where it mixes with the (slightly) acidic overflow from the anode compartment. The result is a high pH solution with a total dissolved solids (TDS) content of about 120 mg/L that is piped to a drain or waste collector.

Reactions at cathode:



On a direct molar basis the cathode generates 11.2 liters of hydrogen for each 35.5 gram (g) of chlorine. A fitting and a tube on the cathode compartment lid are used to vent this small amount of hydrogen produced to a safe distance away from the generator.

In order to have sufficient salt to sustain operation it is necessary to continually flow brine through the anode compartment. Brine is continually pumped into the anode compartment by a diaphragm pump with an adjustable stroke, causing a slight overflow. This overflow enters the drain manifold on the rear of the stand, where it mixes with the sodium hydroxide from the cathode compartment.

The brine tank holds a large reserve of salt and brine, as well as a sequestering agent. A sequestering agent is used to inhibit chemical precipitation of calcium carbonate to avoid clogging the OXI membrane. The OXI sequestering agent is a proprietary product developed by the Mayo Chemical Company specifically for OXI. Salt must be added manually to the brine tank about every 15 days of actual operation. The brine tank is fed by a tap water hose and has a floater valve that controls the tap water supply.

The system operates in automatic mode, with the oxidant gas being injected (drawn) under a slight vacuum into a side stream of raw water. The side stream is then mixed with the main raw water flow. The combined flow then enters a contactor consisting of two baffled, 200-gallon

tanks in series to establish a minimum CT of 70. Finally the flow is discharged in the alum settling sludge holding pond.

The OXI system power supply uses a Zero Current Switching (ZCS) technology to convert 115 or 220 volt AC to 10 volt DC. ZCS offers reliable high power density with fast response, very low conducted and radiated noise, and requires minimal cooling. The advantages of using this technology as a DC supply for the OXI electrolytic cell are a significantly lower AC power requirement with less heat generation in the cell and the ability to mount the power supply components in a gas-tight box so that all power supply components are completely protected from corrosion. The control system for the OXI unit is preset at the factory on the internal control boards of the unit. Manual control of the current for the unit is performed at the door panel. Once adjusted, this amperage will be maintained until manually changed. The rate of oxidant generation can be manually controlled by the operator or automatically controlled by a chlorine residual or oxidation reduction potential controller.

To test the OXI-2B system without interfering with the existing operations of the SJWD facility, a parallel treatment system was established for the purposes of this verification program. The system begins with a pump that draws from an existing intake sump on the Middle Tyger River. This pump has a capacity larger than that needed for this demonstration and a throttling valve to regulate the flow to 23 gpm. A side stream of the raw water was established that served to inject the oxidant gas. This side stream is equipped with a rotometer, as is the main raw water stream. The water with disinfectant passes through two retention tanks of 795 liters each to reach the required retention time of 19 minutes. Chapter 3 includes a summary and results of a tracer test that was conducted to determine the hydraulic retention time of the pilot system. The verification system flow diagram is shown in Figure 2-4.

Under normal circumstances, for example in the disinfection of partially treated water, the OXI-2B does not require potable water to be consumed during treatment. However, at SJWD the OXI-2B was tested on raw water to provide a challenging environment. As a precautionary measure to prevent possible damage to the system, potable water was used to make brine. Before sampling, the disinfectant stream was flushed out with potable water for a few minutes, after which the chlorine samples were taken of the disinfectant dispersed in the potable water flow. This was done for sampling purposes only, because the components of the raw water would have interfered with the analysis. After sampling was completed, the original raw water flow through the disinfectant stream was established again.

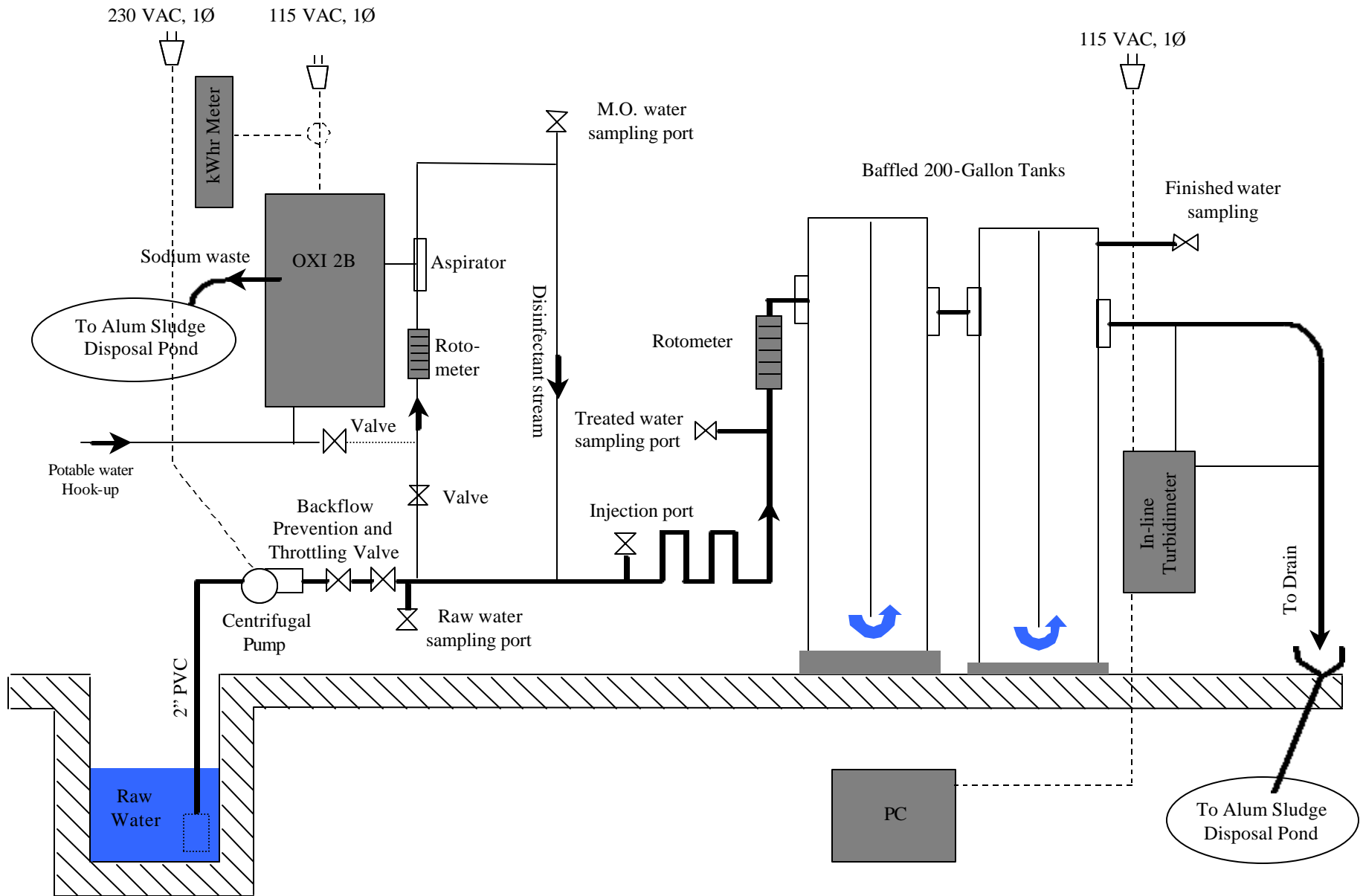


Figure 2-4. OXI-2B Verification Test Flow Diagram

Chapter 3

Methods and Procedures

The test was divided into three tasks, which are detailed below:

1. Equipment Disinfection Production Capabilities
2. Microbiological Contaminant Inactivation (Challenge test), and
3. Treated Water Quality

In addition, operation and maintenance aspects that arose during the test were evaluated during the ETV test period. Table 3-1 includes a sampling and analysis summary for parameters monitored under the three tasks. Also included is the sampling frequency, analytical method, analytical laboratory, reporting limit, hold time and the type of container/preservative that was used.

3.1 Task 1: Equipment Disinfection Production Capabilities

The objectives of Task 1 included the generation of data that describe the operation of the OXI-2B. The operation of the OXI-2B was verified in terms of:

- a) the concentration of disinfectant (as chlorine) produced,
- b) the electrical power consumption per pound of available chlorine,
- c) the sodium chloride consumption per pound of available chlorine, and
- d) the amount of potable water used.

The raw water flow rate was recorded twice daily. These recorded flow measurements were used to calculate the total number of gallons that the OXI-2B treated during the verification program. The total generated volume and concentration of disinfectant (as chlorine) was determined and recorded. This was done by determining the volume of the side stream (Disinfectant Stream) into which the oxidant gas was dispersed, and the concentration of disinfectant (as free and total chlorine in mg/L in water).

The electric power consumption of the system was monitored. The control panel of the OXI-2B has readouts for current and voltage at the cell, which were recorded once per day. The totalized AC power consumption going to the cell was also to be monitored. However, during the test it was noticed that this power meter was not functioning properly and voltage and current readings with a hand-held multi-meter were taken instead. Total power required for a given period of time in kWh was calculated and this number was compared with disinfectant concentration (as free and total chlorine) and volume consumption data to determine the amount of electricity required to produce a pound of available chlorine. The sodium chloride consumption was determined based on a comparison of the mass of sodium chloride added to the OXI-2B and the total disinfectant production (as chlorine). The data generated from tracking the consumption of these raw materials were used to verify operational performance of the OXI unit.

Table 3-1. Sampling and Analysis Summary

| Parameter | Sampling Frequency | Test Stream | Analytical Method | Analytical Laboratory | Reporting Limit | Hold Time | Container/Preservative |
|---------------------------|-----------------------------|--|-----------------------------|------------------------|-----------------------|----------------------|---|
| pH | 1/Day | Raw, Treated (first tank), Finished, Waste | 4500 H | SJWD | n/a ¹ | Analyze Immediately | |
| Temperature | 1/Day | Raw, Finished, Waste | 2550 B | SJWD | n/a | Analyze Immediately | |
| Raw Water Turbidity | 1/Day | Raw water | 2130 B | SJWD | 0.1 NTU | 48 hours | |
| Finished Water Turbidity | In-line | Finished water | Hach 1720D | SJWD | 0 – 100 NTU | n/a | n/a |
| Chlorine Residual | 2/Day | Raw, Disinfectant, Finished, Waste. (Weekly for potable water) | 4500-CI F | SJWD | 0.05 mg/L | Analyze Immediately | 250-ml poly |
| Hydrogen Sulfide | 1/Week | Raw water | SM 4500-S2-A4c | SJWD | 0.1 mg/L | Not specified | 100-ml glass 4 drops zinc acetate |
| Alkalinity | 1/Week | Raw, Finished, Waste | 2320 B | SJWD | 10 mg/L | 14 days | 250-ml poly/4 °C |
| TDS | 2/Verification Test | Raw, Finished, Waste | 2540 C | SJWD | 5 mg/L | 7 days | 250-ml poly/4 °C |
| Total Coliform Bacteria | 5/Week | Raw, Finished | 9221 B | SJWD | 2 MPN/100 ml | 24 hours | Sterile, 100-ml poly/4 °C |
| HPC Bacteria | 5/Week | Raw, Finished | 9215 B | SJWD | 1000 CFU/L | 8 hours | 0.008% Na ₂ S ₂ O ₃ Sterile, 100-ml poly/4 °C |
| Ammonia Nitrogen | 1/Week | Raw, Finished | 4500-NH ₃ G | Env. Health Labs (EHL) | 0.03 mg/L | 28 days | 100-ml poly/4 °C pH<2 W/ H ₂ SO ₄ |
| TOC | 4/Verification Test | Raw, Finished | 5310 C | EHL | 1 mg/L | 28 days | Glass/4 C |
| UVA | 1/Week | Raw, Finished | 5910 B | EHL | 0.01 cm ⁻¹ | Not to exceed 48 hrs | Glass/4 C |
| True Color | 1/Week | Raw, Finished | 2120 B | EHL | 5 PCU | 48 hours | 250-ml poly/4 °C |
| Iron | 2/Verification Test | Raw, Finished | 200.7 | EHL | 50 µg/L | Analyze Immediately | 250-ml poly/4 °C |
| Manganese | 2/Verification Test | Raw, Finished | 200.7 | EHL | 10 µg/L | 6 months | 2 ml HCL/100 ml 120 plastic, HNO ₃ < 2 |
| Chloride | 1/Week | Raw, Finished | 300.0 | EHL | 1 mg/L | 28 days | 100-ml poly |
| Chlorite, Chlorate | 1/Week | Raw, Finished | 300.0 B | EHL | 20 µg/L | 14 days, 28 days | 120 plastics bottles Chlorite EDA |
| Sodium | 2/Verification Test | Raw, Finished | 200.7 | EHL | 500 µg/ml | 24 hours | Acid washed/4 C |
| Heavy metals scan | 1/Verification Test | Waste | 200.8 | EHL | varies | varies | |
| TTHMs | 3/Verification Test | Raw, Finished | 524.2 | EHL | 1 µg/L | 14 days | 3- 40 VOA vials |
| HAAs | 2/Verification Test | Raw, Finished | 552.1 | EHL | 1 µg/L | 14 days | 3- 40 VOA vials |
| P. aeruginosa Enumeration | 25/Bacterial Challenge Test | 1/Day Raw, Balance Finished and Controls | See Challenge Test Protocol | EHL | 10/100 ml | 24 hours | Autoclaved 1 liter glass |

¹ n/a – not applicable

The waste flow rate from the OXI system was recorded once per day as was the pH and temperature of the waste stream. The waste composition was determined once during the 30-day test and analytes included sodium, alkalinity, free and total chlorine, TDS, and NaOH, as well as antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, and zinc.

During the verification interval, the OXI-2B was visually inspected by SJWD operators or ARCADIS staff once per 8-hour shift. These visits were documented on daily logbook data sheets (see Appendix A) and any additional comments were entered in a bound logbook (Appendix B). The logbook was also used by SJWD operators during daily documentation of qualitative equipment performance. Daily instrument calibrations and checks included calibrations regarding the pH meter, thermometer, in-line turbidimeter, bench-top turbidimeter, and the flow meter. As part of the test, operation and maintenance issues were also evaluated. This subtask was very limited because the OXI-2B and all its parts operate automatically. Also, no maintenance was required during the test period, with the exception of occasionally adding salt. However, ARCADIS did report on the effectiveness of the Operation & Maintenance manual whenever the operational progress required use of this manual.

3.2 Task 2: Microbiological Contaminant Inactivation

The objective of this task was to verify OXI-2B's efficacy for inactivation of *P. aeruginosa* when disinfectant (as chlorine) is dosed to achieve a concentration time (CT) of 70 in water with a pH between 6.0 and 8.0 and turbidity of 20 NTU or less, organic carbon concentrations between 1.0 and 3.0 and an alkalinity less than 20 mg/L as CaCO₃. *P. aeruginosa* was selected by ARCADIS as the bacterial challenge test organism because the *Pseudomonas* species background in the raw water was expected to be minimal and selective culture methods exist such that *P. aeruginosa* can be reproducibly cultured in the disinfected water. The laboratory that supplied the *P. aeruginosa* downstream enumeration was EHL.

3.2.1 Hydrodynamic Tracer Test

The OXI-2B set-up was similar to that of another ETV test that was performed in early spring 2000. The tracer test results from this earlier test (ClorTec T-12 ETV test report, NSF 01/21/EPADW395) are included below and the results were adjusted for the OXI-2B scheme. The only difference between the ClorTec T-12 system and the OXI system was that the OXI system utilized two disinfectant contact tanks while the ClorTec T-12 system used four.

The tracer test was performed on March 18, 2000 to provide a profile of the tracer concentration through the disinfection equipment as a function of time. The compound chosen to serve as the tracer was potassium chloride (KCl). In preparation for the tracer test, raw water background concentrations of potassium were determined. The concentrated KCl solution was added continuously through a dosing port for 190 minutes.

Chlorine contact chamber effluent samples were taken at 10-minute intervals throughout the 190-minute tracer test, with the first sample taken at 10 minutes after testing began. The target potassium concentration in the feed water to the unit (at 23 gpm) was 30 mg/L, which is greater

than 10 times the background concentration, measured to be 2.6 mg/L during the test (note that the 10-minute effluent sample yielded a potassium concentration of only 1.5 mg/L, implying that the actual feed water background potassium concentration is variable and often less than the 2.6 mg/L measured on the referenced grab sample). Grab samples of the feed background, stock solution and effluent (at 10-minute intervals) were sent to Savannah Laboratories for analysis. The raw data results are included in Appendix B and summarized in Table 3-2.

TABLE 3-2. TRACER TEST DATA

| Time (min) | Total K (mg/L) | F (%) |
|------------|----------------|--------|
| 0 | 0 | 0.0% |
| 10 | 1.5 | 5.2% |
| 20 | 3.9 | 13.4% |
| 30 | 11 | 37.9% |
| 40 | 21 | 72.4% |
| 50 | 24 | 82.8% |
| 60 | 27 | 93.1% |
| 70 | 29 | 100.0% |
| 80 | 29 | 100.0% |
| 90 | 29 | 100.0% |
| 100 | 28 | 96.6% |
| 110 | 28 | 96.6% |
| 120 | 28 | 96.6% |
| 130 | 28 | 96.6% |
| 140 | 29 | 100.0% |
| 150 | 28 | 96.6% |
| 160 | 30 | 103.4% |
| 170 | 29 | 100.0% |
| 180 | 30 | 103.4% |
| 190 | 27 | 93.1% |

The results were plotted in an F-curve, as described in many chemical engineering and reactor analysis texts (Levenspiel, 1972) and shown as Figure 3-1. The F-curve shows the percentage of tracer recovered at discrete points in time (i.e., not cumulative) in the effluent versus time after starting the continuous tracer feed. The actual hydraulic retention time was calculated as the area above the curve, per the equation below (DiGiano, Weber, 1996).

$$HRT = t_m = \int_0^{\infty} t \cdot dF(t)$$

The F-curve was plotted on grid paper with a relatively fine grid resolution and the number of grid squares above the curve (up to 100% recovery) were manually counted. The hydraulic residence time (HRT) was then calculated per the equation below.

$$HRT = 213 \text{ squares} \times \frac{0.04F}{\text{grid}} \times \frac{4 \text{ min}}{\text{grid}} = 34.1 \text{ min} .$$

ClorTec T-12 ETV Tracer Test Data

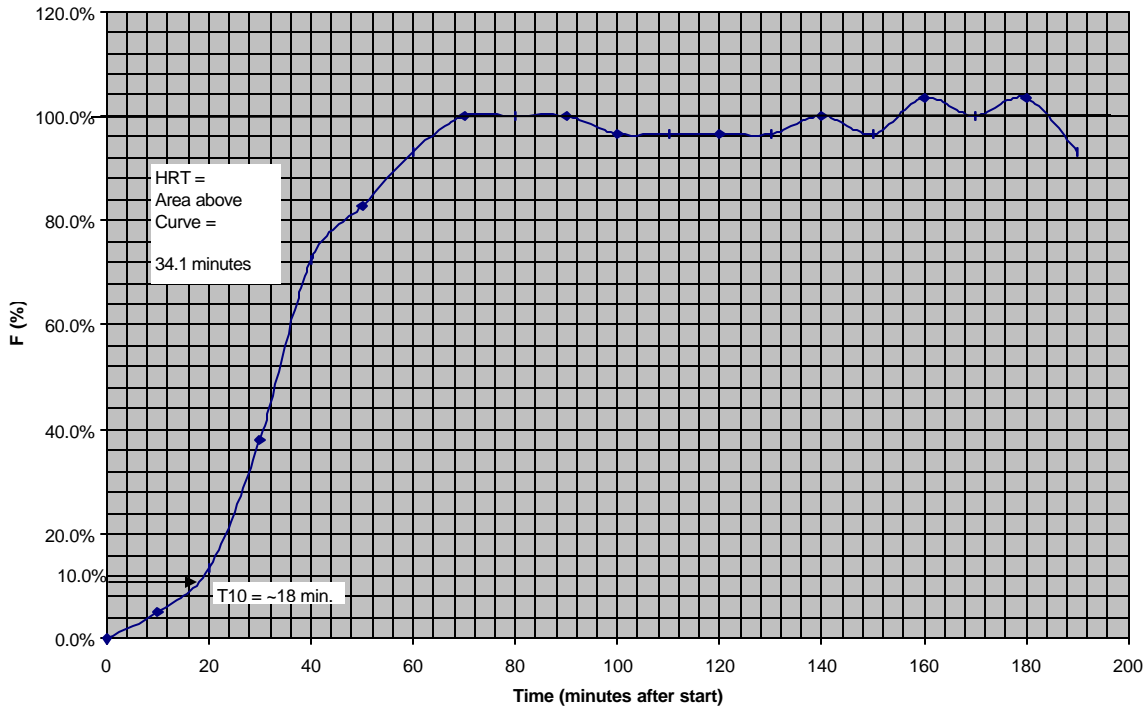


Figure 3-1. F-Curve for ClorTec T-12 ETV Tracer Test.

The chlorine contact chamber (CCC) for this system had a nominal capacity of 750 gallons. However, because of the location of the effluent overflow pipe and the head loss induced by piping between the three tanks employed, the actual volume of water contained in the CCC was approximately 850 gallons. At a volumetric capacity of 850 gallons and a measured flow rate of 23 gpm (87 l/min), the theoretical HRT for the CCC for the ClorTec T-12 system was 37 minutes. The actual experimentally measured HRT of 34.1 minutes indicates that while there was some short-circuiting, as expected, the overall performance of the experimental CCC was quite good (within 10% of theoretical).

Per EPA Guidelines (USEPA, 1989) for calculation of CT values, the T_{10} value was also determined graphically, as shown in Figure 3-1 above. T_{10} represents the elapsed time at which the tracer concentration in the effluent is equal to 10% of the feed. As shown, the T_{10} for the ClorTec system was determined to be approximately 18 minutes.

As mentioned, the only difference between the ClorTec T-12 system and the OXI-2B system is that the OXI system utilized two disinfectant contact tanks while the ClorTec T-12 system used four. Given this, considering that all of the contact tanks were of equal volume, and because the system volume from disinfectant injection point to the first tank was negligible in comparison to the contact chamber volumes, the HRTs (both theoretical and measured) and T_{10} values for the OXI system are one-half those for the ClorTec test system. As such, the theoretical HRT is $37 / 2$ or 18.5 minutes, the measured HRT is $34.1 / 2$ or about 17.1 minutes and the T_{10} value is $18 / 2$

or approximately 9 minutes. The theoretical HRT for the section of the system to the sampling port after the first tank can be calculated as 850 L / 87 liters per minute, or about 10 minutes.

3.2.2 Protocol for Bacterial Challenge Test

The protocol for the bacterial challenge is sequentially outlined below.

- 1) The broth was subsampled at the beginning of the challenge test to create a trip control that remained on ice during the bacterial challenge-testing interval and was shipped to the analytical laboratory with the samples. Disinfectant flow to the system was discontinued and a peristaltic pump and tubing was used to inject *P. aeruginosa* into the raw water line at a rate intended to maximize the *P. aeruginosa* concentration in the raw water while assuring that the volume of growth broth would not expire before the scheduled completion of the test. *P. aeruginosa* was spiked into the raw water flow for a period of time equivalent to three hydraulic retention times at 23-gallons/minute raw water flow (60 minutes). At the end of 60 minutes, ARCADIS collected three positive control samples, with the last sample being collected in duplicate (XPC-60, XPC-70, XPC-80A, and XPC-80B) with 10 minutes of elapsed time between sample collections.
- 2) After the collection of duplicate positive control samples at 80 minutes of elapsed time, ARCADIS began adding disinfectant from the OXI-2B into the system with the OXI-2B control settings being consistent with those previously used during the verification interval. After the elapse of 3 additional HRTs (60 more minutes for a total elapsed time of 140 minutes) ARCADIS collected three sets of three treated samples each at 140 minutes, 150 minutes and 160 minutes of elapsed time. The first set of samples was collected immediately after injection of *P. aeruginosa* and OXI-2B oxidant, prior to entry into Contact Tank 1. The second set of treated samples was collected at the effluent from Contact Tank 1. The third set of samples was collected at the effluent of Contact Tank 2. These samples were collected with 10 minutes of elapsed time between them such that the test concluded after the elapse of 160 total minutes. One sample at the effluent of Contact Tank 2 at 160 minutes of elapsed time was collected and analyzed in duplicate.
- 3) The broth was subsampled at the end of the challenge test to create a trip control that remained on ice during the bacterial challenge-testing interval and was shipped to the analytical laboratory with the samples. Following collection, the samples were shipped via overnight delivery to EHL's laboratory for *P. aeruginosa* enumeration using Standard Methods 9213 E. Membrane Filter Technique for *P. aeruginosa*.

During the challenge testing, the raw water flow rate was periodically verified at the rotometer. In addition, total and free chlorine concentrations were verified in the treated water from Contact Tank 1 and the finished water from Contact Tank 2 prior to and after the completion of the challenge test. Samples for the analysis of *P. aeruginosa* were collected in sterile, 1-liter sample bottles provided by EHL. Immediately after collection, one milliliter (ml) of a dechlorinating solution (sterile sodium thiosulfate solution 30 g/L per Standard Methods 9060 A. 2. Dechlorination) was added as a reducing agent to prevent prolonged exposure of the *P. aeruginosa* to the effects of residual chlorine. Samples were refrigerated at 4°C immediately after collection and shipped in a cooler maintained at or below that temperature during shipment.

3.3 Task 3: Treated Water Quality

The objective of this task was to assess the impact that treatment with disinfectant generated by the OXI-2B has on treated water quality.

Water quality parameters that were monitored during the test period include: pH, temperature, turbidity, chlorine residual (free and total), hydrogen sulfide, alkalinity, TDS, ammonia nitrogen, total organic carbon (TOC), ultraviolet absorbance (UVA) at 254 nanometer (nm), true color, iron, manganese, chloride, chlorite, chlorate, sodium, total coliforms, and heterotrophic plate count (HPC) bacteria. Table 3-1 includes the treated water quality sample analyses (denoted as “finished” water), the frequency with which individual analyses were performed, the analytical methodologies that were followed, the laboratory performing the analyses, the reporting limits, holding times and sampling containers that were required. Samples were preserved, stored, shipped and analyzed in accordance with appropriate procedures and hold times, as specified by the analytical methods.

Analytical samples were collected from various locations within the overall treatment system. A side stream of treated water was directed to a Hach Model 1720D in-line turbidimeter. Readings were taken twice per day. With the exception of the in-line turbidimeter, grab samples were collected to satisfy analytical needs. When collecting a grab sample from a sample tap, sample collection consisted of running a slow, steady stream from the sample tap, triple rinsing a dedicated sample beaker or sample container in this stream, and allowing the intended sample to flow down the side of the beaker or sample container to minimize bubble entrainment. When dipping a grab sample from a particular contact tank, sample collection consisted of triple rinsing a dedicated sample beaker with the tank water and then dipping the required sample.

Samples analyzed at SJWD included free and total chlorine, pH, temperature, bench-top turbidity, hydrogen sulfide (H₂S), alkalinity, TDS, total coliform and HPC. Also, some iron and manganese analyses were conducted at the plant. The free and total chlorine analysis was done at the SJWD plant laboratory immediately after sampling. The oxidant produced by the OXI-2B is a gas and its disinfectant capabilities are measured as free and total chlorine in water. If this had been done in raw water, uncertainties would have been introduced, because of unpredictable constituents in the raw water that would react with the disinfectant products. Therefore, prior to sampling, the raw water supply was directed away from the oxidant aspiration line to be replaced by SJWD potable water. Once the potable water flow had stabilized, samples of the aspirated oxidant (as free and total chlorine) were collected. The potable water layout is included in Figure 2-4. After sampling, the flow was switched back to raw water.

Simulated Distribution System testing for disinfection by-product (DBP) formation was conducted as a one-time event. Six raw water samples were collected in one-liter amber bottles with Teflon-lined caps. The samples were pH adjusted to 8.0 ± 0.2 using 1M hydrochloric acid (HCl) dosed with 0.8 ± 0.1 percent disinfectant solution to yield a target chlorine residual of 1.0 ± 0.4 mg/L after storage. The samples were capped with zero headspace and stored for 24 hours in the dark at 20 ± 1 °C. Following incubation, the six samples were reanalyzed for chlorine residual. The sample with chlorine residuals closest to the 1.0 ± 0.4 mg/L target was submitted for DBP testing.

3.4 Operation and Maintenance

As part of the test, operation and maintenance issues were evaluated. This subtask was very limited because the OXI-2B and all its parts operate automatically. Also, no maintenance was required during the test period, with the exception of occasionally adding salt. ARCADIS did report on the effectiveness of the Operation & Maintenance manual (Appendix E) when there was a need to consult it. Comments regarding operation and maintenance were recorded in the on-site logbook (Appendix F).

Chapter 4 Results and Discussion

The OXI-2B unit was brought on site in early May, 2000. Due to construction at the SJWD plant, however, installation and start-up was not completed until the end of June. Other equipment, including pump, sample ports and contact tanks, had been assembled in March 2000, prior to the OXI ETV test. The system was operated for a total of 725 hours for the during the 30-day test. The logbook notes and performance data sheets are included in Appendix C, D, and F. Initial test runs took place on June 23 and 24, and the actual ETV verification test started on June 26, 2000. The actual verification period lasted 30 days, but the system was shut down on July 13 due to construction activities at the host site. On July 31, the OXI was powered up again and the ETV test was completed. The last day of daily sampling was August 12. On August 8, a simulated distribution system test was performed.

The microbial challenge test was performed on August 16, 2000. Ms. Tina Beaugrand of NSF performed an audit during which the concentration of the *Ps. aeruginosa* broth, pump flow rate, and sampling procedures were checked. In the audit report it was further noted that no deviations were found from the submitted FOD during this challenge. The audit report is included in Appendix A.

4.1 Qualitative Operational and Maintenance Issues

The OXI-2B system was fully automated and capable of normal operation without manual intervention. ARCADIS found that there were two qualitative operational issues associated with the OXI-2B unit: the power supply unit and the float switch in the brine tank. During installation and initial test runs it was found that the power supply unit on the OXI had a defect. The power supply unit was returned and the manufacturer, Xantrex, provided a temporary unit (loaner unit). This loaner unit, however, had a lower humidity rating than the standard unit that OXI provides. When the OXI-2B was started up on July 28, after the down period, the power unit (loaner) tripped the breaker and the system could not be started. In discussion with OXI Company, it was determined that this was most likely caused by humidity in the power unit. The original power supply unit that had been repaired by Xantrex was shipped back to SJWD and was installed back on the OXI to replace the loaner unit. This installation was simple and lasted about 30 minutes. Once the right power unit was installed, the OXI system started up and operated without power-related problems. It should be emphasized that the standard power unit failed before the ETV test had started so further discussion of this failure is not considered to be part of the ETV test.

During the ETV test, the float switch in the brine tank did not operate well, because it got repeatedly stuck in the off position¹. Therefore, this valve was manually operated for the first part of the test. ARCADIS installed a pressure-reducing valve in the potable water line to the brine tank, which had a positive effect on the float valve operation. It did not get stuck anymore, but it continued to “chatter” on occasion, indicating it still did not move completely unhampered. The ARCADIS team further noticed that in the beginning of the test this brine overflow was

¹ According to the manufacturer it is likely that problems with the brine tank float switch were caused because the unit was not completely level.

considerable and proceeded to decrease the output of the brine pump several times until the overflow was significantly less. This had obvious consequences for the salt and the potable water intake which will be discussed in Section 4.1.3.

Non-OXI-specific maintenance consisted of replacing a burst potable water hose, cleaning of the rotometers, main valve and water intake, and cleaning and recalibrating the in-line turbidimeter. OXI-specific maintenance consisted of periodically adding sodium chloride to the brine tank and cleaning a small wire mesh filter in the water line leading to the brine tank. Because potable water was used for making brine during the ETV test, this filter did not accumulate any debris. However, on one occasion it was inspected because ARCADIS believed that air or debris had accumulated in it. This turned out to be air. The inspection and cleaning procedure lasted about five minutes.

It should be noted that the ARCADIS team spent considerable time during the first two days of the ETV test fine tuning the system, i.e. finding the right electrical current setting to produce the required oxidant output. ARCADIS personnel referred to the OXI manual several times during the fine tuning of the system, but found only generic information that described the linear relationship between current and output. ARCADIS suggests that OXI assures adequate OXI operator assistance during start-up and also provides instructions in the Instruction Manual (see Appendix E).

It was noted that the OXI-2B Instruction Manual had adequate installation instructions, background information and safety warnings, but contained no illustrations or schematics. As mentioned above, operational instructions were absent or very limited. Also, there was no section in the manual regarding the power supply or its connections or troubleshooting. However, instructions on the power supply unit were received from Xantrex with the replacement unit. These instructions were somewhat helpful in troubleshooting later problems. The index of the manual reflected erroneous page numbers. Furthermore, there are six or seven appendices listed in the index of the Manual which were not provided. ARCADIS suggests that OXI provides a (ring-)bound operations and maintenance manual with the unit that makes ample use of illustrations and schematics and includes comprehensive operational instructions.

4.2 Disinfectant Production Capabilities (Task 1)

Sodium chloride was added to the OXI-2B unit by the operator as required. Table 4-1 provides an overview of the frequency and amount of salt added to the system. A total of 240 lb of salt was used during the test. It should be noted that most salt was added during the first part of the test. During the first 10 days, 120 lbs was added and during the last 10 days, only 40 lbs was added. Because potable water was used to dissolve the salt, a similar observation regarding usage can be made for the potable water use (see below). The OXI 2B system is required to have a slight brine overflow (see page 14) and during the first part of the test this brine overflow was considerable. ARCADIS continued to decrease the output of the brine pump until the overflow was significantly less.

Table 4-1. Sodium Chloride Consumption

| Day of test | Date | Amount of salt added |
|-------------------|------|---------------------------------|
| 1 | 6/26 | 80 |
| 10 | 7/5 | 40 |
| 12 | 7/7 | 40 |
| 17 | 7/12 | 40 |
| 27 | 8/9 | 20 |
| 29 | 8/11 | 20 |
| 30 | 8/12 | Verified that all salt was used |
| Total salt added: | | 240 lbs. |

Typically the OXI-2B unit will be marketed for use to disinfect partially or fully treated water. During this ETV test however, the unit was connected to raw water, because raw water provides a more challenging environment for the ETV-test. Potable water was used for making brine and during sampling of the disinfectant stream. Raw water, potable water and power consumption data are included in Table 4-2. Comprehensive daily sampling results can be found in Tables C-1 and C-2 in Appendix C.

Table 4-2. Flow and Electrical Reading Summary

| | Potable water consumption (gal/day) | Raw water flow (gal/min) | Disinfectant Stream flow (gal/min) | Waste-water flow (ml/min) | AC Volt (Line) ² (V) | AC Amp (Line) ² (A) | DC Volt to cell ³ (V) | DC Amp to cell ³ (A) |
|----------------------------------|--|-----------------------------|---------------------------------------|------------------------------|------------------------------------|-----------------------------------|-------------------------------------|------------------------------------|
| Average | 335 ¹ | 23 | 2.9 | 14.1 | 118.2 | 1.2 | 4.2 | 18.1 |
| Standard Deviation | n/a | 1 | 0.1 | 10.8 | 2.5 | 0.0 | 0.2 | 0.4 |
| Sample size | n/a | 52 | 30 | 38 | 12 | 12 | 29 | 29 |
| Minimum | n/a | 20 | 2.7 | 3 | 114.4 | 1.1 | 3.8 | 17.8 |
| Maximum | n/a | 25 | 3.0 | 54 | 121.2 | 1.2 | 4.5 | 20 |
| 95% Conf. Int. ⁴ Min. | n/a | 23 | 2.8 | 10.6 | 116.8 | 1.1 | 4.1 | 17.9 |
| 95% Conf. Int. ⁴ Max. | n/a | 23 | 2.9 | 17.5 | 119.6 | 1.2 | 4.3 | 18.2 |

¹ Calculated from cumulative reading.

² incoming current, collected daily from day 19 to day 30 with hand held meter.

³ Reading of DC current to electrolytic cell on Xantrex display.

⁴ Confidence Interval

During the test the raw water flow rate was maintained at the set rate of 23 gpm. The flow rate was checked three times per 24 hours and adjusted, if necessary. Because the verification test lasted 725 hours, 1.00 million gallons (3.79 million L) of raw water were treated. Based on the recordings of the totalizer, the amount of water consumed during the 30-day (725 hour) test was 10,040 gallons (or 335 gal/day or 0.23 gal/min). During the first 10 days of the test 7,519

gallons were used and during the last 10 days of the test 1,379 gallons were used, because the brine overflow was continuously adjusted downward until minimum overflow was reached.

The disinfectant stream, which is the side stream of the raw water into which the oxidant was aspirated, was 2.8 gal/min with a standard deviation of 0.3 gal/min or a cumulative total of 121,800 gal with a standard deviation of 13,050 gal (461,061 L with a standard deviation of 49,399 L) for the duration of the ETV test. There was a significant variation in this flow because the valve leading into this line was very touchy and drew occasional air bubbles, which caused turbulence into the stream just before the rotometer. Hence, the high variability in this value may be attributed in part or completely to inaccurate rotometer readings. This condition did not affect the disinfectant capabilities of the OXI, however, as can be seen in the Section 4.1.3. ARCADIS recommends that OXI Company considers providing engineering support that includes ancillary equipment selection and testing when an OXI unit is placed in the field.

Unfortunately, the Xantrex power totalizing meter that had been installed on the OXI ingoing AC electricity line did not function properly. As soon as this was noticed, on day 18, ARCADIS decided to start taking manual volt and current measurements. Average voltage was 118.2 V and average current was 1.2 A, translating into a power consumption of 139 Watt. As can be seen in summary Table 4-2, both values showed very little variability, therefore it is acceptable to assume that during the time that no readings were taken, the power consumption also was 139 Watt. Because the ETV test lasted 725 hours, the energy consumption is estimated at 101 kWhr. Because the total amount of water treated was 1.00 million gallons, 0.101 Whr was required to treat one gallon of water. The OXI unit also displays the DC voltage and current that is used in the electrolytic cell. Average voltage was 4.2 V and average current was 18 A, which is equivalent to a DC power consumption of 76 Watt.

The OXI-2B system produced and dosed oxidant (measured as chlorine) constantly and effectively during the test. Table 4-3 includes summarized residual free and total chlorine data for raw and finished water, as well as for the concentrated disinfectant stream. Comprehensive daily data are included in Appendix F. All chlorine analyses were done onsite in the SJWD laboratory.

Table 4-3. Free and Total Chlorine Concentrations

| | Raw Water, Free Cl (mg/L) | Raw Water, Total Cl (mg/L) | Potable Water, Free Cl (mg/L) | Potable Water, Total Cl (mg/L) | Disinfectant Stream, Free Cl (mg/L) | Disinfectant Stream, Total Cl (mg/L) | Finished Water, Free Cl (mg/L) | Finished Water, Total Cl (mg/L) |
|------------------------|---------------------------|----------------------------|-------------------------------|--------------------------------|-------------------------------------|--------------------------------------|--------------------------------|---------------------------------|
| Average | 0.02 | 0.03 | 0.98 | 1.18 | 38 | 42 | 3.07 | 3.54 |
| Standard Deviation | 0.02 | 0.02 | 0.27 | 0.15 | 9 | 8 | 0.92 | 0.93 |
| Sample size | 53 | 52 | 3 | 4 | 59 | 59 | 59 | 59 |
| Minimum | <0.01 | <0.01 | 0.67 | 0.98 | 13 | 20 | 1.10 | 1.40 |
| Maximum | 0.1 | 0.15 | 1.15 | 1.35 | 60 | 62 | 5.80 | 6.90 |
| 95% Conf. Int. Minimum | 0.00 | 0.03 | 0.68 | 1.03 | 36 | 40 | 2.83 | 3.31 |
| 95% Conf. Int. Maximum | 0.02 | 0.04 | 1.28 | 1.32 | 41 | 43 | 3.30 | 3.78 |

The raw water had an average free chlorine concentration of 0.02 mg/L, whereas the total chlorine concentration was 0.03 mg/L. Due to the nature of raw water, minimum and maximum values varied significantly and the standard deviation was in the same range as the average value. The average finished free and total chlorine concentrations were 3.07 and 3.54 mg/L respectively. Standard deviations are included in the table but are not believed to be meaningful in the case of raw and finished water, because there are constituents in the raw water that will affect residual chlorine.

The average total chlorine concentration for the concentrated disinfectant stream was 42 mg/L with a standard deviation of 8 mg/L, and consisted of mainly free chlorine (38 mg/L with a standard deviation of 9 mg/L). There was significant fluctuation in the free chlorine of the disinfectant stream with minimum and maximum values being 13 and 60 mg/L. In order to obtain an accurate measurement, the oxidant gas was aspirated into SJWD potable water and not into raw river water. The potable water free and total chlorine concentrations were 0.98 mg/L with a standard deviation of 0.27 mg/L and 1.18 mg/L with a standard deviation of 0.15 mg/L respectively. Therefore the true free and total chlorine content of the disinfectant stream was 37 mg/L with a standard deviation of 9 mg/L and 41 mg/L with a standard deviation of 8 mg/L respectively. Because the total volume of the disinfectant stream generated was 510,407 L, the total chlorine produced during the ETV-test was 21 kg (46 lb). The amount of salt used was 240 lbs, so for each pound of total chlorine 5.2 lbs of salt were needed. However, if we only take the last 10 days of the test into account, 40 lb of salt was needed to produce approximately 7 kg (15 lb) of chlorine. In this case, the ratio of chlorine to salt is 2.7. Based on Faraday's Law (see Appendix H), it is possible that during prolonged adjustments or with sufficient OXI-operator help, the salt consumption can be further reduced, but this was not shown during this ETV test. OXI informs NSF that they will undergo additional field data collection to substantiate this further reduction. OXI also reports that the newer models of the OXI disinfectant systems do not include a brine overflow, which they indicate was a cause of the higher salt consumption during verification testing.

4.3 Microbiological Contaminant Inactivation (Task 2)

The results of a tracer test on a previously assembled, 4-tank system revealed an HRT of 34 minutes. All tanks in the 4-tanks system were of equal size. Two of the tanks in the 4-tank system were used in the OXI-2B 2-tank system. Dividing the 34-minute HRT of the 4-tank system in half results in an HRT for the 2-tank system of 17 minutes. For the purposes of this challenge test, ARCADIS conservatively assumed the HRT of the 2-tank system to be 20 minutes.

ARCADIS performed a challenge test to assess the disinfection capabilities of the OXI-2B system on *P. aeruginosa*. The challenge test was conducted on August 16, 2000. The field notes on the challenge testing are included in Appendix C. The results of the August 16 challenge test are found in Table 4-5. The target concentration for *P. aeruginosa* in the broth culture was 5.0×10^{10} CFUs/100 ml. Magellan Laboratories, who supplied the *P. aeruginosa*, quantified it in the whole broth at 1.6×10^{10} CFUs/100 ml. The difference in the delivered broth concentration and the target is not considered to be significant. Approximately one gallon of this cell suspension was shipped to the SJWD Water Treatment Plant on ice.

The broth was subsampled at the beginning and end of the challenge test to create two trip controls that remained on ice during the bacterial challenge-testing interval and were shipped to the analytical laboratory with the post-treatment samples. The results of analysis on these two trip controls can be found in Table 4-4 identified as XBC-1 (collected at challenge test initiation) and XBC-2 (collected at challenge test completion). These values compare favorably with the *P. aeruginosa* concentration provided by Magellan Laboratories for the broth suggesting that the microorganisms remained viable during the challenge test interval.

The raw river water was sampled at the beginning and completion of the challenge test to establish the background concentration of native *P. aeruginosa*. The analytical results for these samples identified as XRW pre and XRW post can be found in Table 4-4. XRW pre was below the detection limit (< 1 viable *P. aeruginosa* cells/100 ml) and the analysis performed on XRW post by EHL resulted in filters with colonies too numerous to count. Using the most dilute sample tested by EHL, ARCADIS determined that *P. Aeruginosa* in this sample that was reported as too numerous to count exceeded 800 CFU/100 ml. XRW post was collected from the same sample port that was used for *P. aeruginosa* injection. Despite what seemed like adequate flushing, it is believed that the organisms present in XRW post resulted from the use of the same injection/sampling port.

Three separate positive control samples were collected from the effluent of Contact Tank 2 after spiking *P. aeruginosa* into the raw water stream for three hydraulic residence times (60 minutes). The third positive control sample was collected in duplicate. The positive control samples are identified in Table 4-4 as XPC-60, XPC-70, XPC-80A, and XPC-80B with XPC-80A and XPC-80B being duplicate samples.

Table 4-4. Bacterial Challenge Test Results

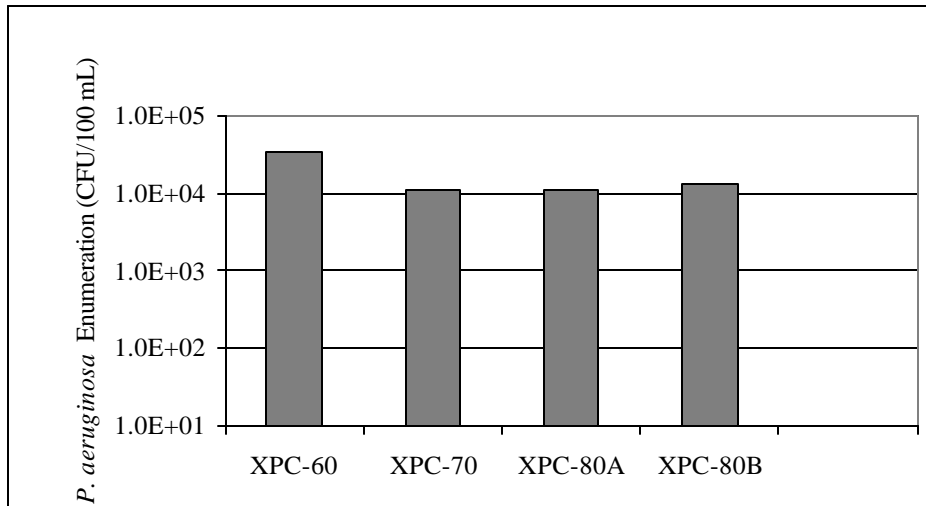
| ARCADIS Sample I.D. | EHL Laboratory Sample I.D. | Sample Description | Collection Date | <i>P. aeruginosa</i> Concentration (CFU/100 mL) |
|---------------------|----------------------------|--|-----------------|---|
| XBC-1 | 524071 | <i>P. aeruginosa</i> spiking broth prior to challenge test | 8/16/00 | 1.5E+10* |
| XRW Pre | 524061 | <i>P. aerug.</i> background in raw water prior to challenge test | 8/16/00 | < 1 |
| XPC-60 | 524018 | Positive Control - Contact Tank 2 Effluent @ 60 min. | 8/16/00 | 3.3E+04 |
| XPC-70 | 524020 | Positive Control - Contact Tank 2 Effluent @ 70 min. | 8/16/00 | 1.1E+04 |
| XPC-80A | 524023 | Duplicate Pos. Control - Contact Tank 2 Effl. @ 80 min. | 8/16/00 | 1.1E+04 |
| XPC-80B | 524026 | Duplicate Pos. Control - Contact Tank 2 Effl. @ 80 min. | 8/16/00 | 1.3E+04 |
| XPC-90 ¹ | 524068 | Additional Sample-Contact Tank 2 Effl. @ 90 min. | 8/16/00 | <1 |
| XPC-95 ¹ | 524065 | Additional Sample-Contact Tank 1 Effl. @ 95 min. | 8/16/00 | <1 |
| XT1-140 | 524029 | Treated Sample - Contact Tank 1 Influent @ 140 min. | 8/16/00 | 3.1E+02 |
| XBT-140 | 524032 | Treated Sample - Between Contact Tanks @ 140 min. | 8/16/00 | 7.9E+02 |
| XT2-140 | 524037 | Treated Sample - Contact Tank 2 Effluent @ 140 min. | 8/16/00 | < 1 |
| XT1-150 | 524038 | Treated Sample - Contact Tank 1 Influent @ 150 min. | 8/16/00 | 2.8E+02 |
| XBT-150 | 524041 | Treated Sample - Between Contact Tanks @ 150 min. | 8/16/00 | 1.0E+01 |
| XT2-150 | 524046 | Treated Sample - Contact Tank 2 Effluent @ 150 min. | 8/16/00 | < 1 |
| XT1-160 | 524048 | Treated Sample - Contact Tank 1 Influent @ 160 min. | 8/16/00 | 1.3E+02 |
| XBT-160 | 524052 | Treated Sample - Between Contact Tanks @ 160 min. | 8/16/00 | < 1 |
| XT2-160A | 524055 | Duplicate Treated Sample – Cont. Tank 2 Effl. @ 160 min. | 8/16/00 | <1 |
| XT2-160B | 524058 | Duplicate Treated Sample – Cont. Tank 2 Effl @ 160 min. | 8/16/00 | <1 |
| XBC-2 | 524074 | <i>P. aeruginosa</i> spiking broth post challenge test | 8/16/00 | 2.2E+10* |
| XRW post | 524062 | <i>P. aeruginosa</i> background in raw water post challenge test | 8/16/00 | > 800 |

* concentration generated using SM9215 B
¹ samples taken after initiation of oxidant gas injection/not included in statistical calculations. (These samples were in addition to those required in the FOD protocol)

During the challenge test, treated and finished water samples were collected simultaneously from three individual sample points within the system at sequential, 10-minute intervals. The first sample point was in the raw water feed supply pipe following the dosage points for both *P. aeruginosa* and oxidant gas and in-line mixing (contact time with disinfectant ~ 20 seconds). The second sample point was installed in the pipe transferring water from Contact Tank 1 to Contact Tank 2 (contact time with disinfectant = 10 minutes). The third and final sample point was at the effluent of Contact Tank 2 (contact time with disinfectant = 20 minutes). Treated samples were collected at 140 minutes, 150 minutes, and 160 minutes into the challenge test. All samples collected from the raw water pipe feeding Contact Tank 1 can be distinguished by the ARCADIS sample prefix “XT1”. All samples collected from the piping between Contact Tank 1 and Contact Tank 2 can be distinguished by the ARCADIS sample prefix “XBT”. All samples collected at the effluent of Contact Tank 2 can be distinguished by the ARCADIS sample prefix “XT2”. The sample collected at the Contact Tank 2 effluent at 160 minutes of elapsed time was collected in duplicate leading to the designations XT2-160A and XT2-160B.

The *P. aeruginosa* enumeration of the positive control samples ranged from 1.1 x 10⁴ CFUs/100 ml to 3.3 x 10⁴ CFUs/100 ml with a log average of 1.5 x 10⁴ CFUs/100 ml. The control samples were sequentially collected at ten-minute intervals from the finished water leaving Contact Tank 2 after spiking the raw water with *P. aeruginosa* for three hydraulic retention times. The 95

percent confidence interval bounding positive control enumeration is 6.5×10^3 CFUs/100 ml to 3.5×10^4 CFUs/100 ml with three degrees of freedom. Figure 4-1 is a graphic portrayal of the positive control sample enumerations. Figure 4-2 shows the mean of the positive control enumerations. Additionally, the statistically calculated 95 percent confidence interval is displayed on Figure 4-2.



XPC-60 = positive control @ 60 minutes
 XPC-70 = positive control @ 70 minutes
 XPC-80A = duplicate positive control @ 80 minutes
 XPC-80B = duplicate positive control @ 80 minutes

Figure 4-1. Bar Graph of Bacterial Challenge Test Positive Control Samples

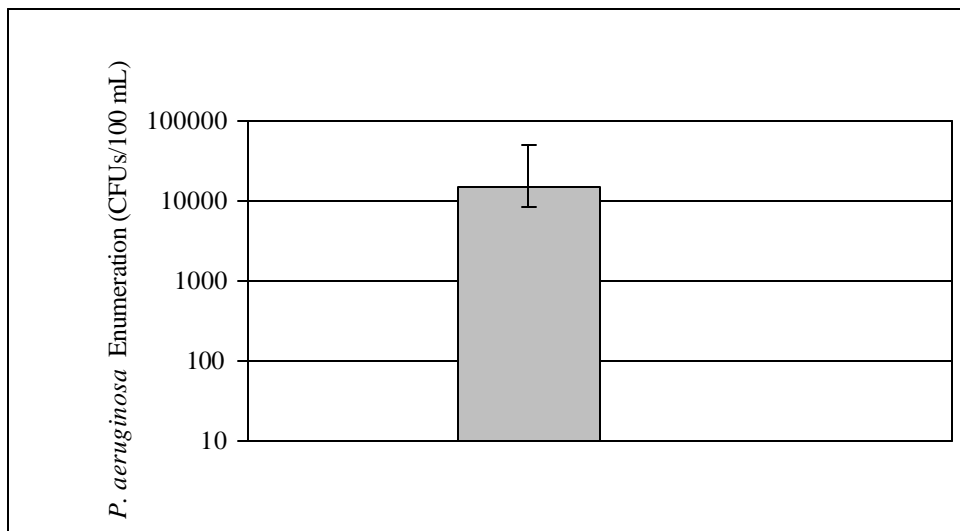


Figure 4-2. Mean Enumeration Values of Positive Control Samples

Though OXI-2B treated samples were collected at three different sampling points during the challenge test, only data from the Contact Tank 2 effluent need be statistically analyzed to evaluate the 4-log reduction performance claim. It can be visually determined that data from the other two sampling points does not approach a 4-log reduction. The *P. aeruginosa* enumeration of the effluent samples collected from Contact Tank 2 were all below the detection limit of the filtered sample volumes or < 1 CFU/100ml. In order for errors to be considered conservative, samples reported as being less than the detection limit were treated as if they contained 1 CFUs/100 ml. Because these treated samples all resulted in enumeration results that were below the detection limit, ARCADIS did not prepare graphical representations of the data or the mean of the treated effluent samples.

Enumerations for the four positive control samples (XPC-60, XPC-70, XPC-80A, and XPC-80B) demonstrate that a *P. aeruginosa* was recovered at a log-average concentration of 1.5×10^4 CFUs/100 ml. Enumeration for the four treated samples recovered from Contact Tank 2 effluent indicate a survival of 1 CFUs/100 ml using worst-case approximations. The log removal of *P. aeruginosa* is calculated below.

$$\text{log removal of } P. \text{ aeruginosa} = \log_{10} \left[\frac{\left(\text{CFU/ml} \right)_{\text{feedwater}}}{\left(\text{CFU/ml} \right)_{\text{effluent}}} \right]$$

$$\text{log removal of } P. \text{ aeruginosa} = \log_{10} \left[\frac{1.5 \times 10^4 \text{ CFU/ml}}{1.0 \times 10^0 \text{ CFU/ml}} \right]$$

$$\text{log removal of } P. \text{ aeruginosa} = 4.2$$

The results of the *P. aeruginosa* challenge test show that the OXI-2B system is capable of a 4-log kill of *P. aeruginosa* at a CT value of 56 based on calculated hydraulic retention time (17 minutes) or a CT of 30 based on a T_{10} value (9 minutes).

Using the free chlorine concentrations found in Table 4-5 and actual hydraulic retention time (17 minutes), the CT value calculated prior to the commencement of bacterial injection is 56. The calculated CT value using a sample collected near the completion of the challenge test (using 0.20 mg/L and 17 minutes as a HRT) is 3.4. ARCADIS contends that this CT value is artificially depressed by the inadvertent injection of the organic material associated with the *P. aeruginosa* growth broth along with the microorganism. ARCADIS believes that the nonbiological organic compounds present in the growth broth consumed substantial oxidant leading to the free and total chlorine results presented in Table 4-5. Despite the resultant, depressed CT values calculated for the challenge test, the OXI-2B challenge test data support a 4-log reduction in *P. aeruginosa* during the test.

Table 4-5. Results of Total and Free Chlorine Testing During Bacterial Challenge Testing

| Sample Description | Prior to Bacterial Injection | | During Bacterial Injection (near challenge test conclusion) | |
|---------------------------------|------------------------------|-----------------------|--|-----------------------|
| | Free Chlorine (mg/L) | Total Chlorine (mg/L) | Free Chlorine (mg/L) | Total Chlorine (mg/L) |
| Treated Water (Contact Tank 1) | 2.70 | 3.50 | 0.70 | 3.10 |
| Finished Water (Contact Tank 2) | 3.30 | 3.10 | 0.20 | 1.70 |

See Appendix C, daily log sheet, dd. 8/16

4.4 Finished Water Quality (Task 3)

This section presents results for water quality data that were collected during the test. Daily raw water and finished water levels of pH, temperature and turbidity are reflected in Table 4-6. The average raw water pH was 7.27 with a standard deviation of 0.39. The average pH for finished water was 6.63. The OXI unit had a slight decreasing effect on pH, because the pH of the disinfectant side stream was acidic (3.75). On the other hand, the waste stream was very basic with a pH of 12.91. None of the pH values for treated, finished, or disinfectant stream showed much variability, which indicates that the disinfectant output of the OXI was stable as far as pH.

Table 4-6. Summary of Daily pH, Temperature, and Turbidity Readings

| | pH, Raw | pH, Disinfectant Stream | pH, Treat. | pH, Fin. | pH, Waste | Temp, Raw °C | Temp, Fin. °C | Temp, Waste °C | Turb (grab), Raw NTU | Turb (grab), Fin. NTU | Turb (in-line), Fin. NTU |
|------------------------|---------|-------------------------|------------|----------|-----------|--------------|---------------|----------------|----------------------|-----------------------|--------------------------|
| Average | 7.20 | 3.76 | 6.63 | 6.63 | 12.91 | 24.6 | 24.8 | 27.4 | 11.45 | 11.67 | 10.92 |
| St. Dev. | 0.12 | 0.141 | 0.15 | 0.15 | 0.244 | 1.2 | 1.3 | 2.4 | 16.85 | 17.68 | 18.79 |
| Minimum | 6.97 | 3.49 | 6.14 | 6.10 | 12.27 | 22.0 | 22.0 | 23.8 | 5.16 | 4.26 | 0.47 |
| Maximum | 7.98 | 3.93 | 7.89 | 7.86 | 13.37 | 26.5 | 27 | 34.5 | 90.40 | 94.00 | 96.83 |
| 95% Conf. Int. Minimum | 7.15 | 3.69 | 6.58 | 6.57 | 12.82 | 24.2 | 24.3 | 26.4 | 5.42 | 5.35 | 3.84 |
| 95% Conf. Int. Maximum | 7.24 | 3.83 | 6.69 | 6.68 | 13.01 | 25.1 | 25.2 | 28.4 | 17.48 | 18.00 | 18.01 |

Temperature readings were taken twice daily for raw², finished, and wastewater. The OXI-2B system had no effect on the finished water temperature. The temperature of the waste stream was higher than that of the water stream. Most likely, this increase was governed by exposure to ambient temperature. In-line turbidity readings were taken twice daily for finished water and

² As of day 19, the Treated water temperature readings were used as a surrogate for Raw water temperature readings. It was expected that the Raw water temperature readings were inaccurate, because the Raw water had to be sampled with a beaker, whereas the Treated water could be sampled in the top of the first tank. This sampling location was very close to the Raw water sampling port, so it is expected that the Treated water reading accurately reflects the Raw water reading.

were verified by taking grab samples. Also, raw water grab samples were analyzed for turbidity. The OXI-2B system has no apparent effect on turbidity: the average raw water turbidity was 11.45 NTU and the average finished water turbidity was 11.67 NTU for grab samples and 10.92 NTU for in-line samples. A turbidity spike occurred on day 22 as a result of a storm, when the turbidity rose to over 90 NTU. This event caused the standard deviation to be higher than the average.

Table 4-7 includes results of additional weekly and biweekly sampling. Hydrogen sulfide, alkalinity and TDS were analyzed on-site by SJWD, whereas all other samples were sent off to be analyzed by EHL. The OXI-2B waste stream has very high TDS and alkalinity as well as a corresponding high pH. The OXI-2B has no apparent effect on either UVA, true color, TOC, manganese, and iron. (One TOC finished water reading was 29 mg/L, whereas the three other readings were between 1.9 and 2.8 mg/L. The high reading is believed to be recorded erroneously. See Summary Table D-1, Appendix D). Readings³ for chlorite and chlorate were always below the detection limit of 20 µg/L. The OXI-2B system produced some chloride (6.0 mg/L), which can probably be attributed to the use of brine. The sodium went down in the finished water, indicating that sodium is removed by the membrane. Ammonia nitrogen was not detected in raw nor finished water.

Table 4-8 includes data for coliforms and HPC. The OXI-2B system performed well in eliminating total coliforms. For all test days, total coliforms were reduced to zero cfu/100 ml and therefore, the log inactivation was not calculated (see Table 4-9). The OXI-2B system was very effective in reducing HPC during the first 20 days of the test, but for the remaining 10 days of the test, the HPC kill capacity may have diminished. Although ARCADIS has no complete explanation for this phenomenon, the concentration of heterotrophic bacteria in the raw water samples generally increased by an order of magnitude during this same interval. Although the disinfectant (as chlorine) output remained stable during the same interval, the higher concentrations of heterotrophic microorganisms may be indicative of other changes in raw water characteristics which may account for decreased disinfectant performance such as an increase in total organic carbon. Because total organic carbon was not a daily analyte in this verification program, such an increase may go undetected. Other changes in raw water characteristics that might affect the disinfection capabilities of the OXI-2B such as turbidity were not noted during this interval. Also, during this time, the coliform inactivation remained maximal. It is unlikely that possible decrease in performance is a sampling induced phenomenon. Finished water samples were dipped from contact tank 2. Because the samples were not removed from a sampling port in the effluent discharge pipe, there was not opportunity for the samples to be contaminated by microorganisms potentially growing in the effluent discharge pipe or sample port itself.

³ Chloride = Cl⁻; chlorate = ClO₃⁻; chlorite = ClO₂⁻.

Table 4-7. Miscellaneous Weekly and Biweekly Data

| | Unit | Lab | Average | St Dev | Min. | Max. | 95% Conf. Int. Min | 95% Conf. Int. Max |
|----------------------------|-------------|------|---------|--------|--------|--------|--------------------|--------------------|
| H ₂ S, Raw | µg/L | SJWD | <2 | n/a | <2 | <2 | n/a | n/a |
| Alkalinity, Raw | mg/L | SJWD | 19 | 0.9 | 18 | 20 | 18 | 20 |
| Alkalinity, Finished | mg/L | SJWD | 16.2 | 2.9 | 13 | 21 | 14 | 19 |
| Alkalinity, Waste | mg/L | SJWD | 30,960 | 10,585 | 24,960 | 41,280 | 25,023 | 44,737 |
| TDS, Raw | mg/L | SJWD | 68 | 11 | 60 | 76 | 52 | 84 |
| TDS, Finished | mg/L | SJWD | 16 | 0 | 16 | 16 | 16 | 16 |
| TDS, Waste | mg/L | SJWD | 13,800 | n/a | 7,480 | 20,120 | n/a | n/a |
| UVA (UV 254), Raw | 1/cm | EHL | 0.19 | 0.06 | 0.14 | 0.27 | 0.13 | 0.25 |
| UVA (UV 254), Finished | 1/cm | EHL | 0.19 | 0.08 | 0.13 | 0.3 | 0.11 | 0.27 |
| True Color, Raw | Pt/Co units | EHL | 65 | 24 | 50 | 100 | 42 | 88 |
| True Color, Finished | Pt/Co units | EHL | 70 | 22 | 50 | 100 | 49 | 91 |
| Ammonia Nitrogen, Raw | mg/L | EHL | <0.3 | n/a | <0.3 | <0.3 | n/a | n/a |
| Ammonia Nitrogen, finished | mg/L | EHL | <0.3 | n/a | <0.3 | <0.3 | n/a | n/a |
| TOC, Raw | mg/L | EHL | 2.2 | 0.5 | 1.8 | 2.6 | 1.8 | 2.7 |
| TOC, Finished | mg/L | EHL | 2.4 | 13.3 | 1.9 | 29 | 2.0 | 2.9 |
| Chloride, Raw | mg/L | EHL | 2.4 | 0.2 | 2.2 | 2.6 | 2.2 | 2.5 |
| Chloride, Finished | mg/L | EHL | 6.0 | 0.5 | 5.5 | 6.6 | 5.5 | 6.5 |
| Chlorate, Raw | µg/L | EHL | <20 | n/a | <20 | <20 | n/a | n/a |
| Chlorate, Finished | µg/L | EHL | <20 | n/a | <20 | <20 | n/a | n/a |
| Chlorite, Raw | µg/L | EHL | <20 | n/a | <20 | <20 | n/a | n/a |
| Chlorite, Finished | µg/L | EHL | <20 | n/a | <20 | <20 | n/a | n/a |
| Manganese, Raw | µg/L | EHL | 145 | n/a | 120 | 170 | n/a | n/a |
| Manganese, Finished | µg/L | EHL | 130 | n/a | 100 | 160 | n/a | n/a |
| Iron, Raw | µg/L | EHL | 1.7 | n/a | 1.4 | 2.0 | n/a | n/a |
| Iron, Finished | µg/L | EHL | 1.6 | n/a | 1.2 | 2.0 | n/a | n/a |
| Sodium, Raw | mg/L | EHL | 15.2 | n/a | 3.3 | 27.0 | n/a | n/a |
| Sodium, Finished | mg/L | EHL | 5.4 | n/a | 3.3 | 7.4 | n/a | n/a |

n/a: standard deviation not applicable because values were below detection limit or sample size is too small.

Table 4-8. Total Coliforms and Heterotrophic Plate Counts

| Day | Total Coliforms, Raw #/100 ml | Total Coliforms, Finished #/100 ml | Log Inactivation Coliforms | HPC, Raw CFU/ml | HPC, Finished CFU/ml | Log Inactivation HPC |
|-----|----------------------------------|---------------------------------------|----------------------------|--------------------|-------------------------|----------------------|
| 1 | 144 | < 20 | >0.9 | 300 | 1 | 2.5 |
| 2 | 500 | < 20 | >1.4 | 114 | < 1 | >2.1 |
| 3 | 800 | < 20 | >1.6 | 416 | 1 | 2.6 |
| 4 | 200 | < 20 | >1.0 | 208 | 2 | 2.0 |
| 5 | 350 | < 20 | >1.2 | 237 | 2 | 2.1 |
| 6 | ** | ** | ** | ** | ** | ** |
| 7 | ** | ** | ** | ** | ** | ** |
| 8 | 250 | < 20 | >1.1 | 244 | < 1 | >2.4 |
| 9 | 400 | < 20 | >1.3 | 108 | 2 | 1.7 |
| 10 | ** | ** | ** | ** | ** | ** |
| 11 | < 1000 | < 20 | ** | 192 | < 1 | >2.3 |
| 12 | 350 | < 20 | >1.2 | 182 | 1 | 2.3 |
| 13 | ** | ** | ** | ** | ** | ** |
| 14 | ** | ** | ** | ** | ** | ** |
| 15 | 250 | < 20 | >1.1 | 150 | 1 | 2.2 |
| 16 | 300 | < 20 | >1.2 | 192 | < 1 | 2.3 |
| 17 | 1400 | < 20 | >1.8 | 1820 | 5 | 2.6 |
| 18 | 300 | < 20 | >1.2 | ** | ** | ** |
| 19 | 50 | < 20 | >0.4 | 2756 | 4 | 2.8 |
| 20 | 700 | < 20 | >1.5 | 1560 | 1 | 3.2 |
| 21 | 150 | < 20 | >0.9 | 1664 | 77 | 1.3 |
| 22 | 1400 | < 20 | >1.8 | 1820 | 214 | 0.9 |
| 23 | ** | ** | ** | ** | ** | ** |
| 24 | ** | ** | ** | ** | ** | ** |
| 25 | 900 | < 20 | >1.7 | >5200 | 416 | >1.1 |
| 26 | 1000 | < 20 | >1.7 | 988 | 832 | 0.1 |
| 27 | 600 | < 20 | >1.5 | 98 | 39 | 0.4 |
| 28 | 700 | < 20 | >1.5 | 316 | 18 | 1.2 |
| 29 | 650 | < 20 | >1.5 | 168 | 216 | -0.1 |
| 30 | ** | ** | ** | ** | ** | ** |

** = no data collected

Total trihalomethanes (TTHMs) and haloacetic acids (HAAs) were also analyzed as part of the ETV verification project and the results are included in Table 4-9. None of the analytes were detected in the raw water. The OXI-2B system generated some chloroform (10 µg/L) and small amounts of bromodichloromethane (2.8 µg/L) and dibromochloromethane (0.3 µg/L), whereas none of the other TTHMs were detected. As far as HAAs, average dichloroacetic acid and trichloroacetic acid concentrations were 18 µg/L and 21 µg/L respectively. Small amounts of bromochloroacetic acid, monochloroacetic acid, and bromodichloroacetic acid were detected. No other HAAs were detected.

Table 4-9. TTHMs and HAAs

| Parameter | Unit | Jul 7 | Aug 8 | Aug 16 | Average |
|------------------------------------|------|-------|-------|--------|---------|
| <u>TTHMs</u> | | | | | |
| Bromodichloromethane, Raw | µg/L | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Bromodichloromethane, Finished | µg/L | 2.0 | 3.6 | < 0.1 | 1.9 |
| Chloroform, Raw | µg/L | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Chloroform, Finished | µg/L | 5.6 | 15 | < 0.1 | 6.9 |
| Bromoform, Raw | µg/L | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Bromoform, Finished | µg/L | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Dibromochloromethane, Raw | µg/L | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Dibromochloromethane, Finished | µg/L | 0.3 | 0.4 | < 0.1 | 0.3 |
| <u>HAAs</u> | | | | | |
| Bromochloroacetic acid, Raw | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Bromochloroacetic acid, Finished | µg/L | XX | 2.5 | 2.3 | 2.4 |
| Dibromoacetic acid, Raw | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Dibromoacetic acid, Finished | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Dichloroacetic acid, Raw | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Dichloroacetic acid, Finished | µg/L | XX | 20 | 15 | 18 |
| Monobromoacetic acid, Raw | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Monobromoacetic acid, Finished | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Monochloroacetic acid, Raw | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Monochloroacetic acid, Finished | µg/L | XX | < 0.1 | 4.0 | 2.1 |
| Trichloroacetic acid, Raw | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Trichloroacetic acid, Finished | µg/L | XX | 26 | 16 | 21 |
| Bromodichloroacetic acid, Raw | µg/L | XX | < 0.1 | < 0.1 | < 0.1 |
| Bromodichloroacetic acid, Finished | µg/L | XX | 2.5 | 2.0 | 2.3 |

XX = not required

Note: If one or more samples were below the detection limit, the detection limit was used to calculate averages.

Furthermore, ARCADIS conducted simulated distribution system (SDS) testing to determine the extent to which disinfection byproducts would be formed using effluent from the OXI-2B system while dosing it with additional OXI disinfectant stream. This test was performed because the OXI system can be used for both primary and residual disinfection. Five 1-liter effluent samples were collected, pH-adjusted to approximately 8.2, spiked with effluent from the disinfectant stream (at 25, 50, 75, 100, and 150 ml dosing rates) and incubated for 24 hours at 20 °C. In addition, a deionized water sample was collected, spiked, and incubated to which 100 ml water from the disinfectant stream was added. Lastly, a sample of OXI finished water was incubated with no additional water from the disinfectant added. After incubation, the five OXI samples were analyzed for residual chlorine. The 50 ml-dosed sample contained 2.32 mg/L residual chlorine and was shipped to the analytical laboratory along with the deionized water and SJWD finished water sample and the unamended OXI finished water sample. The results of the SDS testing are presented in Table 4-10.

Table 4-10. Simulated Distribution System Test Results

| | Unit | LTB | DI Water + 100 ml | SJWD-OXI Finished | SJWD-OXI + 50 ml |
|-----------------------------|------|-------|----------------------|----------------------|---------------------|
| <u>TTHM Analytes</u> | | | | | |
| Bromodichloromethane | µg/L | < 0.1 | 0.8 | 11 | 9.9 |
| Bromoform | µg/L | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Chloroform | µg/L | < 0.1 | 12 | 86 | 85 |
| Dibromochloromethane | µg/L | < 0.1 | < 0.1 | 0.8 | 0.7 |
| <u>HAA Analytes</u> | | | | | |
| Bromochloroacetic acid | µg/L | ** | < 1.0 | 4.2 | 4.1 |
| Dibromoacetic acid | µg/L | ** | < 1.0 | < 1.0 | < 1.0 |
| Dichloroacetic acid | µg/L | ** | 6.8 | 46 | 50 |
| Monobromoacetic acid | µg/L | ** | < 1.0 | < 1.0 | < 1.0 |
| Monochloroacetic acid | µg/L | ** | 2.1 | 5.3 | 6.3 |
| Trichloroacetic acid | µg/L | ** | 9.3 | 78 | 91 |
| Bromodichloroacetic acid | µg/L | ** | < 1.0 | 4.3 | 4.6 |
| LTB = laboratory trip blank | | | | | |
| ** = no data collected | | | | | |

Testing included analyses for TTHMs and HAAs. DBPs were below the detection limits in the laboratory trip blank (LTB). The deionized water blank with OXI-2B disinfectant added was found to contain 0.8 µg/L bromodichloromethane, 12 µg/L chloroform, 6.8 µg/L dichloroacetic acid, 2.1 µg/L monochloroacetic acid and 9.3 µg/L trichloroacetic acid. The OXI finished water and the OXI “finished + 50 ml” sample had comparable amounts of DBPs. Both had significant amounts of chloroform (~ 85 µg/L), dichloroacetic acid (46-50 µg/L), and trichloroacetic acid (78-91 µg/L) and relatively low levels of bromodichloromethane (9.9-11 µg/L), dibromochloromethane (0.7-0.8 µg/L), bromochloroacetic acid (4.1-4.2 µg/L), monochloroacetic acid (5.3-6.3 µg/L), and bromodichloroacetic acid (4.3-4.6 µg/L).

In a typical drinking water treatment plant, it is customary to remove dissolved organics from the raw water prior to treatment with chlorine. Removal of dissolved organics prior to chlorination can minimize DBP formation. The support system designed for the verification of the OXI-2B during this project was not designed to remove dissolved organics from the raw water prior to chlorination. Thus, the formation of substantial quantities of DBPs during the verification interval is not a surprising result. It should be noted that ARCADIS believes that the potential for formation of DBPs is specific to the raw water source and to the degree of dissolved organic pre-treatment applied prior to chlorination. The results shown in Table 4-10 illustrate how the OXI-2B performed with regard to DBP formation in the setting established for the verification testing and using raw water from the Middle Tyger River.

4.5 Waste Production

The OXI produced a small continuous waste stream of 13.7 ml/min, so for the duration of the test (725 hours) 596 liters (157 gal) of waste was produced (Table 4-2). On a daily basis, 5.2 gal

(19.8 L) of waste was produced. A heavy metals analysis on the waste stream was performed as a one-time event (see Table 4-11). As was indicated in Tables 4-6 and 4-7, the waste stream had a high alkalinity, pH, and a high TDS content. The average alkalinity of the waste was 30,960 mg/L, the pH was 12.91, and the TDS was 13,800 mg/L. No sodium or sodium hydroxide samples were taken from the waste stream. The concentration of sodium in the waste stream may be estimated based on the sodium chloride consumption, which was 4 lbs (or 1.82 kg or 31 moles) per day during the last ten days of the test. As mentioned, during the last ten days of the test the salt dosage had been adjusted more effectively compared to the first 20 days of the test. Because the average daily wastewater generation was 19.8 L, the sodium concentration in the waste stream can be estimated at 1.57 mol/L or 36 g/L.

According to OXI documentation, the OXI-2B cathode generates 11.2 L of hydrogen for each 35.5 gram of total chlorine. Because 21 kg total chlorine were generated, 6,625 L of hydrogen were produced over the duration of the verification test. A fitting and a tube on the cathode compartment lid are used to vent this small amount of hydrogen produced to a safe distance away from the generator.

Table 4-11. Results of Heavy Metal Analysis on Water Softener Regeneration Waste Stream

| Analyte | Analytical Method | Concentration (µg/L) |
|-----------|-------------------|----------------------|
| Antimony | USEPA 200.8 | < 42.2 |
| Arsenic | USEPA 200.8 | < 105.5 |
| Beryllium | USEPA 200.8 | < 42.2 |
| Cadmium | USEPA 200.8 | < 42.2 |
| Chromium | USEPA 200.8 | < 42.2 |
| Copper | USEPA 200.8 | < 105.5 |
| Lead | USEPA 200.8 | < 105.5 |
| Mercury | USEPA 200.8 | < 105.5 |
| Nickel | USEPA 200.8 | < 105.5 |
| Selenium | USEPA 200.8 | < 422.0 |
| Silver | USEPA 200.8 | < 42.2 |
| Zinc | USEPA 200.8 | 170 |

Chapter 5 Quality Assurance

5.1 Calculation of DQI Goals

Table 5-1 shows the data quality indicator (DQI) goals established for accuracy and precision presented in the OXI FOD. The calculated DQIs for the majority of the parameters listed in Table 5-1 are presented in Table 5-2. These DQIs were calculated using data from replicate analysis of laboratory or field QA/QC checks for each parameter. Obtained values represent the average of all replicate measurements. The number of replicates for each parameter is shown in parentheses. Accuracy was assessed by calculating recovery of spikes or surrogates or by calculating the bias from an obtained value compared to a known standard. Precision is expressed as percent relative standard deviation (RSD) and is calculated by dividing the standard deviation of replicate measurements by the mean. The 95 percent confidence intervals have also been calculated for data sets that contained at least three replicate measurements. It can be seen in Table 5-2 that DQI goals were met for chlorate/chlorite, iron, ammonia-nitrogen, sodium, TDS, total organic carbon, manganese, pH, free chlorine, and turbidity measurements.

Table 5-1. Data Quality Indicator Goals for Critical Measurements

| Parameter | Method | Accuracy | Precision (%RSD) |
|-------------------------|------------------|----------------|------------------|
| Flow Rates | Rotometers | ± 2 gal/minute | N/A |
| PH | SM 4500 H | ± 0.1 pH unit | Not listed |
| Temperature | SM 2550B | N/A | 10 |
| MO Stream concentration | 4500-CI F | N/A | 40 |
| Raw Water Turbidity | SM 2130B | 80-120% Rec. | 25 |
| Bacteria Dose Rate | Peristaltic Pump | ±4 ml/min | 20 |
| Chlorine Residual | SM 4500-CI F | N/A | 40 |
| Hydrogen sulfide | SM 4500-S2-A4c | 90-110% Rec. | 40 |
| Alkalinity | SM 2320B | 75-120% Rec. | 30 |
| Total dissolved solids | SM 2540C | 80-120% Rec. | 25 |
| Ammonia-N | SM 4500-NH3 G | 80-120% Rec. | 25 |
| Total organic carbon | SM 5310C | 80-120% Rec. | 25 |
| Color | SM 2120B | N/A | 40 |
| UVA | SM 5910B | 85-120% Rec. | 20 |
| Iron | EPA Method 200.7 | 85-115% Rec. | 20 |
| Manganese | EPA Method 200.7 | 85-115% Rec. | 20 |
| Chloride | EPA Method 300 | 90-110% Rec. | 30 |
| Sodium | EPA Method 200.7 | 85-115% Rec. | 20 |
| Potassium | EPA Method 200.7 | 85-115% Rec. | 20 |
| Total coliform | SM 9222B | N/A | 200 |
| TTHMs | EPA Method 524.2 | 70-130% Rec. | 40 |
| HAAs | EPA Method 552.1 | 70-130% | 40 |
| Chlorite/Chlorate | EPA Method 300 B | 90-110% Rec. | 30 |

Table 5-2. Calculated DQIs for Critical Measurements

| Analyte | Actual Conc. | Avg. Obtained (# points) | Recovery/Bias* (Average %) | Precision (%RSD) |
|------------------------|--------------|--------------------------|----------------------------|------------------|
| Chloride | 25 µg/L | 26.2 (4) | 105.2 | 3.1 |
| Chlorate/Chlorite | 100 µg/L | 96.9 (9) | 94.7 | 2.2 |
| Iron | 1 mg/L | 99.6 (2) | 99.6 | 3.0 |
| Ammonia-N | 5 mg/L | 4.59 (11) | 91.8 | 4.1 |
| Sodium | 1 mg/L | 0.93 (2) | 93 | 0 |
| Total Dissolved Solids | 451 mg/L | (1) | | |
| | 467.5 mg/L | (2) | | |
| Total Organic Carbon | 10 mg/L | 10.09 (12) | 100.9 | N/A |
| Manganese | 50 µg/L | (2) | | |
| Free Chlorine | 1.0 mg/L | 0.92 (18) | 8.0* | 4.6 |
| | 2.0 mg/L | 1.81 (7) | 9.5* | 2.0 |
| Turbidity | 1.43 NTU | 1.42 (4) | 0.7* | |
| | 17.2 NTU | 17.2 (23) | 0* | 0.3 |

* - indicates that the result is presented as % bias from a known value

Parameters not addressed in Table 5-2 include flow rate, pH, temperature, alkalinity, TDS, TOC, color, and UVA. Daily flow rate accuracy was assessed by examining daily flow measurements and determining whether or not they were within the established 21-25 gal/min range (23 g/min target, ± 2 gal/min). There were 53 measurements of flow rate and only one measurement (Day 22 @ 20 g/min) was outside of the acceptable range. The accuracy of rotameter used to determine raw water flow is discussed in Section 5.3. The pH meter was checked daily with buffer solution at 2 points. Actual pH values were not recorded by the operator unless the calibration check was not within the acceptable range. Daily data sheets indicate that the pH meter adequately measured daily buffer checks on all test days. Temperature measurements were made with factory calibrated thermocouples. Analyses for alkalinity, TDS, TOC, color and UVA were performed by EHL. Laboratory reports from EHL indicate that all measurements were within method specific acceptance criteria.

Table 5-3 presents the TTHM recovery results from surrogates spiked by EHL prior to sample analysis by EPA Method 524.2. The surrogate standards are purchased by EHL from AccuStandard, Inc. Representative Certificates of Analysis for the surrogate standards have been provided by EHL and are included in Appendix C. Acceptance criteria established in the method is 70-130 percent. It can be seen that all compounds met the acceptance criteria.

Table 5-3. Trihalomethane Recoveries (70-130% criteria)

| Date | Spiked Conc. (µg/L) | Bromodichloromethane | | Bromoform | | Chloroform | | Dibromochloromethane | |
|------|---------------------|----------------------|-------|-----------|-------|------------|-------|----------------------|-------|
| | | Obtained | %Rec | Obtained | %Rec | Obtained | %Rec | Obtained | %Rec |
| 7/10 | 2 | 2.26 | 113 | 2.29 | 114.7 | 2.15 | 107.3 | 2.44 | 121.9 |
| | 10 | 10.98 | 109.8 | 11.36 | 113.6 | 10.26 | 102.6 | 10.69 | 106.9 |
| 9/1 | 10 | 9.88 | 98.8 | 9.55 | 95.5 | 10.90 | 109 | 10.92 | 109.2 |
| | | 9.64 | 96.4 | 8.76 | 87.6 | 9.53 | 95.3 | 9.66 | 96.6 |

Table 5-4 shows the HAA recoveries of a 20 µg/L standard analyzed by EPA Method 552.2. Acceptance criteria are established as 70-130 percent. All compounds fell within the acceptance criteria for this analysis.

Table 5-4. Haloacetic Acid Recoveries for 20 mg/L Standard (70-130% criteria)

| Analysis Date | Bromochloro Acetic Acid | | Dibromo Acetic Acid | | Dichloro Acetic Acid | |
|---------------|-------------------------|-------|---------------------|-------|----------------------|-------|
| | Obtained | %Rec | Obtained | %Rec | Obtained | %Rec |
| 8/17 | 21.8 | 109 | 19.9 | 99.7 | 19.1 | 95.7 |
| 8/18 | 20.1 | 100.6 | 20.3 | 101.3 | 19.1 | 95.7 |
| 8/22 | 24.2 | 124.8 | 24.7 | 123.7 | 22.2 | 111 |
| | 23.6 | 117.8 | 22.0 | 109.9 | 21.0 | 104.8 |

| Analysis Date | Monobromo Acetic Acid | | Monochloro Acetic Acid | | Trichloro Acetic Acid | |
|---------------|-----------------------|-------|------------------------|-------|-----------------------|-------|
| | Obtained | %Rec | Obtained | %Rec | Obtained | %Rec |
| 8/17 | 21.5 | 107.5 | 21.3 | 106.6 | 21.9 | 109.7 |
| 8/18 | 18.7 | 93.2 | 19.4 | 97.1 | 19.7 | 98.7 |
| 8/22 | 21.0 | 105.1 | 20.2 | 101.1 | 24.9 | 124.5 |
| | 23.0 | 114.9 | 20.9 | 104.3 | 24.2 | 121.1 |

5.2 Blanks, Duplicates and Hold Times

Blank samples were routinely sent to the laboratories with each set of samples for analysis. Each laboratory also ran internal laboratory and reagent blanks as a part of their daily QA/QC procedures. Results from analysis of field and laboratory blanks did not indicate contamination problems for any analyte of interest in this study.

During the conduct of total chlorine analyses at SJWD, 10 deionized water blanks were analyzed. The blank analysis resulted in a range of values from 0.00 to 0.03 mg/L total chlorine. During the conduct of free chlorine analyses at SJWD, 31 deionized water blanks were analyzed. The blank analysis resulted in a range of values from - 0.01 to 0.01 mg/L free chlorine. The deionized water blanks for the verification interval are shown in the OXI-2B Field Data File.

A total of 20 duplicate total chlorine samples were conducted at SJWD during the verification interval. ARCADIS has evaluated the relative percent difference (RPD) for each pair of duplicates. The entire data set of 20 duplicates cannot be evaluated using an RSD calculation because it is legitimate and expected that the chlorine dosing vary subtly over time. RPD is calculated by dividing the difference between the two duplicate analytical results by the mean for the two analytical results. The range of RPD values for the set of total chlorine analytical duplicates was 0 percent to 15 percent for disinfectant and finished water analyses. The calculations for % RPD are shown in the OXI-2B Field Data File.

A total of 29 duplicate free chlorine samples were conducted at SJWD during the verification interval. ARCADIS has evaluated the relative percent difference (RPD) for each pair of duplicates. The entire data set of 29 duplicates cannot be evaluated using an RSD calculation because it is legitimate and expected that the chlorine dosing vary subtly over time. RPD is calculated by dividing the difference between the two duplicate analytical results by the mean for

the two analytical results. The range of RPD values for the set of total chlorine analytical duplicates was 0 percent to 25 percent for disinfectant and finished water analyses. The calculations for % RPD are shown in the OXI-2B Field Data File. A total of 90 pH measurements were taken over the 30-day test period. In addition, 8 duplicate pH measurements were taken and recorded on daily data sheets by SJWD staff. Relative percent differences ranged from 0-4.4% for the duplicate measurements.

For total coliform samples routinely taken by SJWD were used as duplicates. SJWD samples were taken from the same raw water intake where water for the ETV test was taken. During the test, Coliform samples for both SJWD and ETV were collected by the same person around the same time of day. ARCADIS chose three dates randomly and compared the counts. Total Coliform counts for the SJWD routine samples (“duplicates”) for these dates were 7/6/00 (Test Day 11) – 300 coliforms/100 ml, 7/12/00 (Test Day 17) – 1,600 coliforms/100 ml, and 8/3/00 (Test Day 21) – 150 coliforms/100 ml. The raw water sample for the OXI-2B verification test for 7/6/00 was below the detection limits for coliforms (< 20 CFU/100 ml). The raw water sample for the OXI-2B for 7/6/00 (Test Day 11) contained 1,400 coliforms/100 ml for a relative percent difference of 13.3 percent. The raw water sample for the OXI-2B for 8/3/00 (Test Day 21) contained 150 CFU/100 ml, which was equal to the coliform concentration detected in the SJWD routine sample for 8/3/00.

EHL conducted negative controls on the agar and sterile filters used for *P. aeruginosa* enumeration. In addition, positive controls were conducted for the *Pseudomonas* isolation agar used for incubation.

Hold times specified in the methods were met for all samples with the following exception: samples submitted on 07/07/00 for color and UV 254 analysis exceeded the 48-hour hold time specified in the method. The laboratory informed the Project Manager that the hold times had been exceeded and was instructed to analyze the sample as soon as possible. In addition, the reanalysis of sample number 524315 for mercury was analyzed outside of the 28-day hold time. Also, for a number of the samples submitted for Method 524.2 analysis, the pH on receipt exceeded the method requirement of a pH<2. These deviations were noted on the EHL laboratory reports. Hold times for *P. aeruginosa* samples exceeded the 24-hour holding time by 6 to 15 minutes. The results from these samples were not used in the calculation of log inactivation of *P. aeruginosa*.

5.3 Daily and Bi-Weekly QA/QC Verifications

As indicated in the FOD, certain parameters associated with verification testing required daily or bi-weekly verification. The raw water flow rate and the disinfectant stream flow were recorded using existing rotameters. The performance of the raw water flow rotameter was verified as a function of its involvement in a previous ETV verification program. The results of this rotameter performance evaluation are found in Appendix G. The raw water rotameter’s accuracy was confirmed with a total of twenty timed sequential events both before and during the OXI-2B verification interval while filling the volumetrically calibrated vessels that served as contact tanks within the system. With 23 gpm as the set point, the range in flow rates was 85 percent to 104 percent of the target flow. Finished water flow to the turbidimeter was verified daily using a

timed, volumetric collection method. A minimum of 200 ml/min flow to the turbidimeter is considered critical to assure accurate readings. The flow to the turbidimeter was verified on 29 out of 30 test days using a graduated cylinder and a stopwatch. On 7/10/00, the flow to the turbidimeter was found to be below 200 ml/min. In this instance the turbidimeter suction tubing was cleaned and the flow rate increases subsequently to 420 ml/min. All other turbidimeter flow measurements exceeded 200 ml/min. A summary of this data can be found in Appendix G. The summary was created using the actual readings recorded on daily log sheets found in Appendix C. In-line turbidimeter readings were compared on a daily basis to readings from a calibrated bench-top turbidimeter and recorded on the data sheets in Appendix C. Turbidity comparison data exists for twenty-six of the thirty test days. It is known within industry that agreement between in-line and bench-top turbidimeters is problematic (personal communication with Doug Waldrop). The RPDs have been calculated for the twenty-six comparable data points. The RPDs range from 0 percent to 173 percent and are summarized in Appendix G. References to in-line rotameter maintenance and flow verification and in-line turbidimeter maintenance can be found in the bound project notebook presented as Appendix F. Tubing and piping were visually inspected on a daily basis. On 6/27/00, visual inspection revealed a stuck brine tank fill valve and a ruptured potable water make-up hose. On 7/3/00, visual inspection found a stuck potable water valve. On 7/5/00, visual inspection revealed a need to replace a 2-inch PVC union on the discharge side of the raw water supply pump. On 8/5/00, visual inspection revealed a stuck brine tank float switch.

5.4 Internal Audits

Dr. Jane McLamarrah of ARCADIS performed an internal technical systems audit at the demonstration site on August 17, 2000. Results from the audit were reported to the ARCADIS Project Manager in an audit report, which is included in Appendix B. An internal data quality assessment was done on the raw field and laboratory data. QA/QC data supplied by the field crew and contract laboratories was reviewed and data quality indicators including accuracy and precision were calculated. Calibration curves were reviewed and calculation verified for at least 10 percent of all the analytical data. Laura Beach, ARCADIS QA Manager/Durham Office, performed this assessment.

Chapter 6 References

Berthouex, P. M. and L. C. Brown. 1994. *Statistics for Environmental Engineers*. CRC Press, Lewis Publishers p. 129.

DiGiano, F.A., W.J. Weber, Jr. 1996. *Process Dynamics in Environmental Systems*. First Edition. John Wiley & Sons, Inc.

Levenspiel, O. 1972. *Chemical Reaction Engineering*. Second Edition. John Wiley & Sons, Inc.

NSF International. 1999. Protocol for Equipment Verification Testing for Inactivation of Microbiological Contaminants. August 1999.

NSF International. 2001. Environmental Technology Verification Report, ClorTec T-12.

NSF International. 2000. Field Operations Document. EPA/NSF Environmental Technology Verification Test of the OXI-2B On-site Hypochlorite Generator at SJWD Water District Drinking Water Plant, Lyman, South Carolina.

APHA, AWWA and WPCF (1999). *Standard Methods for the Evaluation of Water and Wastewater*, 20th Edition, Washington, D.C.

USEPA. 1989. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements of the Surface Water Treatment Rule for Public Water Systems using Surface Water Sources*. Appendix C. Science and Technology Branch.

White, Geo. Clifford. 1992. *Handbook of Chlorination*, 3rd edition. Van Nostrand Reinhold, New York, NY.