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Environmental Technology Verification Report

Removal of Chemical and Microbial Contaminants in Drinking Water

Watts Premier, Inc.
M-2400 Point-of-Entry Reverse Osmosis Drinking Water Treatment System

Prepared by

NSF International

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

ETV ETV ETV

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THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**POINT-OF-ENTRY DRINKING WATER TREATMENT SYSTEM**
APPLICATION:	**REMOVAL OF CHEMICAL AND MICROBIAL CONTAMINANTS IN DRINKING WATER**
PRODUCT NAME:	**M-2400 REVERSE OSMOSIS SYSTEM**
VENDOR:	**WATTS PREMIER, INC.**
ADDRESS:	**1725 WEST WILLIAMS DRIVE, SUITE C-20 PHOENIX, AZ 85027**
PHONE:	**800-752-5582**
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NSF International (NSF) manages the Drinking Water Systems (DWS) Center under the U.S. Environmental Protection Agency's (EPA) Environmental Technology Verification (ETV) Program. The DWS Center recently evaluated the performance of the Watts Premier, Inc. M-2400 Point-of-Entry (POE) Reverse Osmosis (RO) Drinking Water Treatment System. NSF performed all of the testing activities and also authored the verification report and this verification statement. The verification report contains a comprehensive description of the testing activities.

The EPA created the 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 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, stakeholder groups (consisting of buyers, vendor organizations, and permitters), 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.

ABSTRACT

The Watts Premier M-2400 POE RO Drinking Water Treatment System was tested at the NSF Drinking Water Treatment Systems Laboratory for removal of the viruses fr and MS2, the bacteria *Brevundimonas diminuta*, and chemicals aldicarb, benzene, cadmium, carbofuran, cesium, chloroform, dichlorvos, mercury, methomyl, mevinphos, oxamyl, paraquat, sodium fluoroacetate, strontium, and strychnine. The microorganisms used in this study served as surrogates for pathogenic bacteria and viruses that may be introduced into drinking water through accidental or intentional contamination. The target chemical challenge concentration was 1 milligram per liter (mg/L). The target microorganism challenge concentrations were $1x10^6$ colony forming units per 100 milliliters (CFU/100 mL) for *B. diminuta*, and $1x10^4$ plaque forming units per milliliter (PFU/mL) for the viruses. NSF also separately tested an optional post-membrane activated carbon filter that Watts Premier offers, the Flowmatic MAXVOC FF-975. This filter was only tested with the chemicals not removed to 20 micrograms per liter (μg/L) or lower by the RO membrane. One M-2400 system and one MAXVOC FF-975 carbon filter were tested. Each challenge was 30 minutes in length. The M-2400 removed a minimum of 2.9 $\log_{10}$ of the viruses, and 2.5 $\log_{10}$ of *B. diminuta*. The M-2400 removed all of the chemicals by 96% or more, except for mercury, which was only removed by 38%. Based on the M-2400 chemical challenge results, the MAXVOC FF-975 filter was challenged with chloroform, dichlorvos, mercury, and methomyl. The MAXVOC FF-975 removed 96% or more of the four chemicals. The M-2400 and MAXVOC FF-975 together removed 99% or more of all chemicals but sodium flouroacetate, whose percent reduction was limited by its high detection limit of 20 μg/L.

TECHNOLOGY DESCRIPTION

The following technology description was provided by the manufacturer and has not been verified.

The M-2400 is a skid-mounted RO system that utilizes one 4" x 40" RO membrane with a surface area of 82 square feet (ft^2). The membrane is fed by a 330 gallons-per-hour booster pump. The system also includes a pre-membrane sediment or activated carbon filter, an optional post-membrane activated carbon filter, and an optional product water storage tank. The M-2400 has a control panel with pressure gauges and flow meters to calibrate the system and monitor performance. The skid measures 27" wide, 32" deep, and 57" high. The system as tested did not include any pre-membrane filters or a storage tank, but did include a post-membrane carbon filter. Watts Premier uses the Flowmatic MAXVOC-FF975 activated carbon filter as an optional post-membrane treatment step for organic chemical removal. The MAXVOC FF-975 is a 4.625" x 9.75" block filter with a rated service flow rate of 2 gallons per minute (gpm).

Under normal operation, raw water entering the system first passes through the sediment or carbon pre-filter to remove large particles. The pre-membrane filter effluent is then sent through the booster pump and then on to the RO membrane. Water passing through the membrane is collected in a permeate line that can be plumbed to a storage tank. A portion of the concentrate water from the membrane module can be recycled back into the feed water line depending on the desired recovery for the system. The remainder of the concentrate is sent to the drain. The recycle rate can be manually adjusted with a needle control valve.

VERIFICATION TESTING DESCRIPTION

Test Site

The testing site was the Drinking Water Treatment Systems Laboratory at NSF in Ann Arbor, Michigan. A description of the test apparatus can be found in the verification report. The testing was conducted in January through April of 2006.

Methods and Procedures

The testing methods and procedures are detailed in the *Test/QA Plan for Verification Testing of the Watts Premier M-2400 Point-of-Entry Reverse Osmosis Drinking Water Treatment System for Removal of Microbial and Chemical Contaminants*. One M-2400 system and one MAXVOC FF-975 filter were tested separately. The M-2400 was challenged with the chemicals, bacteria, and viruses listed in Table VS-1. The MAXVOC filter was only challenged with the chemicals that the RO membrane did not remove to 20 μg/L or below.

The challenge chemicals were chosen from a list of chemicals of interest supplied by the EPA. The challenge bacteria and viruses were recommended by an advisory panel because they are smaller than most other viruses and bacteria, and so provide a conservative estimate of performance. In addition to using *B. diminuta* strain 19146 as obtained from American Type Culture Collection (ATCC), NSF also used a genetically engineered strain of the organism. The NSF Microbiology Laboratory inserted into a culture of *B. diminuta* a gene conferring resistance to the antibiotic kanamycin (KanR *B. diminuta*). This allowed the Microbiology Laboratory to use a growth media amended with 50 μg/L of kanamycin to prohibit heterotrophic plate count (HPC) bacteria in the treated water samples from growing along with the kanamycin resistant *B. diminuta*.

Table VS-1. Challenge Chemicals and Microorganisms

Chemicals	Bacteria	Viruses
Aldicarb	*Brevundimonas diminuta*	fr
Benzene		MS2
Cadmium Chloride		
Carbofuran		
Cesium Chloride (nonradioactive isotope)		
Chloroform		
Dichlorvos		
Mercuric Chloride		
Methomyl		
Mevinphos		
Oxamyl		
Paraquat		
Sodium Fluoroacetate		
Strontium Chloride (nonradioactive isotope)		
Strychnine		

The target challenge concentrations were as follows:

- Chemicals: 1 ± 0.5 mg/L;
- *B. diminuta*: $\geq 1 \times 10^6$ CFU/100 mL; and
- MS2 and fr: $\geq 1 \times 10^4$ PFU/mL.

The M-2400 was plumbed to a test rig in the NSF testing lab and was calibrated for operation according to the instructions in the M-2400 operation manual.

The M-2400 was challenged with each organism or chemical individually, except for cadmium, cesium, and strontium, which were combined into one challenge. Each challenge was 30 minutes in length. For the microbial challenges, influent and permeate samples were collected for organism enumeration at start-up, after 15 minutes of operation, and after 30 minutes of operation. For the chemical challenges, influent and permeate samples were collected at start-up and 30 minutes. All samples were analyzed in triplicate.

The MAXVOC FF-975 was conditioned with water containing chloroform prior to being challenged. The purpose of the conditioning was to load the carbon with chloroform to a degree that simulated contaminant loading halfway through its effective lifespan. The MAXVOC FF-975 chemical challenges were also 30 minutes in length. As described above, the filter was only challenged with the chemicals that the RO membrane did not remove to 20 µg/L or below. Based on this criterion, the filter was challenged with chloroform, dichlorvos, mercury, and methomyl. The target challenge concentrations were the maximum permeate levels measured during the RO membrane challenges. The target flow rate for the challenges was 1.85 gpm, which was the highest permeate flow rate measured during the RO membrane challenges.

VERIFICATION OF PERFORMANCE

The results of the M-2400 microbial challenges are presented below in Tables VS-2 and VS-3. The triplicate influent and permeate counts for each sample point were averaged by calculating geometric means. The mean organism counts for each sample point were then averaged geometrically to give an overall mean influent and permeate count for each challenge. The overall mean counts are presented here. These counts were $\log_{10}$ transformed, and $\log_{10}$ reductions were calculated for each challenge.

Table VS-2. M-2400 Virus Challenge Results

Challenge	Mean Influent (PFU/mL)	$\log_{10}$ of Influent	Mean Permeate (PFU/mL)	$\log_{10}$ of Effluent	$\log_{10}$ Reduction
fr	9.4×10^4	5.0	121	2.1	2.9
MS2	5.5×10^4	4.7	49	1.7	3.1

Table VS-3. M-2400 Bacteria Challenge Results

Challenge	Mean Influent (CFU/100 mL)	$\log_{10}$ of Influent	Mean Permeate (CFU/100 mL)	$\log_{10}$ of Effluent	$\log_{10}$ Reduction
1st *B. diminuta*	2.0×10^7	7.3	5.7×10^4	4.8	2.5
KanR *B. diminuta*	7.0×10^6	6.9	2.8×10^3	3.4	3.5
2nd *B. diminuta*	6.9×10^6	6.8	1.1×10^4	4.1	2.7

The results of the M-2400 chemical challenges are presented in Table VS-4. The triplicate influent and permeate measurements were averaged by calculating the arithmetic mean. The means for each sample point were then averaged to give an overall mean influent and permeate for each challenge. As with the microbial challenge data, the overall means are presented here. Percent reductions were calculated from the influent and permeate concentrations.

Note that there are two entries in Table VS-3 for *B. diminuta*. A second challenge was conducted after it was noticed that the RO membrane operating pressure had risen above Watts Premier's recommended maximum of 150 psig (pounds per square inch, gauge). The system inlet pressure did not rise, but the membrane operating pressure created by the booster pump did rise after the system was initially calibrated with the operating pressure set at 150 psig. The recorded RO membrane operating pressures ranged from 160 to 172 psig for the microbial challenges and the cadmium/cesium/strontium, mercury, strychnine, paraquat, and aldicarb challenges. To see if the higher operating pressures affected the membrane's ability to filter out microorganisms, the *B. diminuta* challenge was conducted again. A comparison of the data in Table VS-3 does not indicate that the higher pressure affected membrane performance. The data from the chemical challenges at the higher pressures does not indicate that chemical rejection performance was compromised. Therefore, no other challenges were conducted again with a lower membrane operating pressure.

Table VS-4. M-2400 Chemical Challenge Results

Chemical	Mean Influent (μg/L)	Mean Effluent (μg/L)	Percent Reduction
Aldicarb	830	3	>99
Benzene	680	6.4	>99
Cadmium	970	1.4	>99
Carbofuran	920	2.6	>99
Cesium	1100	16	99
Chloroform	790	28	97
Dichlorvos	1700	16	>99
Mercury	1200	750	38
Methomyl	990	45	96
Mevinphos	920	5.6	>99
Oxamyl	1000	4	>99
Paraquat	480	ND (1)	>99
Sodium Fluoroacetate	800	ND (20)	98
Strontium	990	2	>99
Strychnine	900	ND (5)	>99

Based on the RO membrane permeate concentrations, the MAXVOC FF-975 filter was challenged with chloroform, dichlorvos, mercury, and methomyl. The results for these challenges are presented in Table VS-5. As with the RO membrane chemical challenge data, mean influents and effluents were calculated for each challenge. Percent reductions were then calculated using the overall mean influents and effluents.

Table VS-5. MAXVOC FF-975 Chemical Challenge Data

Chemical	Target Influent (μg/L)	Measured Mean Influent (μg/L)	Mean Effluent (μg/L)	Percent Reduction
Chloroform	72	82	3.2	96
Dichlorvos	25	36	ND (0.2)	>99
Mercury	910	730	10	99
Methomyl	48	56	1	98

The microbial challenges data shows that the M-2400 RO membrane alone can be expected to remove more than 2 logs (>99%) of bacteria and viruses from contaminated water. The RO membrane alone also removed greater than 96% of all challenge chemicals except mercury. The chemical challenges data in Tables VS-4 and VS-5 shows that the M-2400 and MAXVOC FF-975 combined would remove 99% or more of all challenge chemicals but sodium fluoroacetate, whose percent reduction was capped at 98% because of the high detection limit of 20 μg/L for the chemical.

QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

NSF provided technical and quality assurance oversight of the verification testing as described in the verification report, including a review of 100% of the data. NSF QA personnel also conducted a technical systems audit during testing to ensure the testing was in compliance with the test plan. A complete description of the QA/QC procedures is provided in the verification report.

Original signed by Sally Gutierrez 09/22/06

Sally Gutierrez Date
Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original signed by Robert Ferguson 09/07/06

Robert Ferguson Date
Vice President
Water Systems
NSF International

Availability of Supporting Documents

Copies of the test protocol, the verification statement, and the verification report (NSF report # NSF 06/23/EPADWCTR) are available from the following sources:

1. ETV Drinking Water Systems Center Manager (order hard copy)
   NSF International
   P.O. Box 130140
   Ann Arbor, Michigan 48113-0140

2. Electronic PDF copy
   NSF web site: http://www.nsf.org/etv
   EPA web site: http://www.epa.gov/etv

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Watts Premier Incorporated
M-2400 Point-of-Entry Reverse Osmosis
Drinking Water Treatment System

Prepared by:

NSF International
Ann Arbor, Michigan 48105

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 (USEPA), through its Office of Research and Development (ORD), has financially supported and collaborated with NSF International (NSF) under Cooperative Agreement No. R-82833301. This verification effort was supported by the Drinking Water Systems (DWS) Center, operating under the Environmental Technology Verification (ETV) Program. This document has been peer-reviewed, reviewed by NSF and USEPA, and recommended for public release.

Foreword

The U.S. Environmental Protection Agency (USEPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, USEPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by USEPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

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Abbreviations and Acronyms

ANSI	American National Standards Institute
ASTM	ASTM International (formerly American Society of Testing Materials)
ATCC	American Type Culture Collection
°C	degrees Celsius
CFU	colony forming unit
cm	centimeter
DWS	Drinking Water Systems
ETV	Environmental Technology Verification
°F	degrees Fahrenheit
ft^2	square foot or feet
GC/MS	gas chromatography/mass spectrometry
gfd	gallons per square foot per day
gpd	gallons per day
gpm	gallons per minute
HCl	hydrochloric acid
HPC	heterotrophic plate count
HPLC	high pressure liquid chromatography
ICP-MS	inductively coupled plasma – mass spectrometry
KanR	kanamycin resistant
L	liter
lbs	pounds
mL	milliliter
nm	nanometer
NaOH	Sodium Hydroxide
NRMRL	National Risk Management Research Laboratory
NSF	NSF International (formerly National Sanitation Foundation)
NTU	nephelometric turbidity units
ORD	Office of Research and Development
PBDW	phosphate-buffered dilution water
PFU	plaque forming unit
POE	point-of-entry
POU	point-of-use
psi	pounds per square inch
psig	pounds per square inch, gauge
QA	quality assurance
QC	quality control
QA/QC	quality assurance/quality control
RO	reverse osmosis
RPD	relative percent difference
SDI	silt density index
SLB	saline lactose broth
SOP	standard operating procedure
TDS	total dissolved solids
TMP	transmembrane pressure

Abbreviations and Acronyms, Cont'd.

TNTC	too numerous to count
TOC	total organic carbon
TSA	tryptic soy agar
TSB	tryptic soy broth
µg	microgram
µL	microliter
µm	micrometer
µS	microSieman
USEPA	U. S. Environmental Protection Agency
VOC	volatile organic carbon

Acknowledgments

NSF International (NSF) 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.

The manufacturer of the equipment was:

Watts Premier Incorporated
1725 West Williams Drive
Suite C-20
Phoenix, AZ 85027

NSF wishes to thank the members of the expert technical panel for their assistance with development of the test plan.

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Chapter 1
Introduction

1.1 Environmental Technology Verification (ETV) Program Purpose and Operation

The U.S. Environmental Protection Agency (USEPA) 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 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; with stakeholder groups consisting of buyers, vendor organizations, and permitters; 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; by conducting field or laboratory testing, collecting and analyzing data; and by 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.

The USEPA has partnered with NSF International (NSF) under the ETV Drinking Water Systems (DWS) Center to verify performance of drinking water treatment systems that benefit the public and small communities. It is important to note that verification of the equipment does not mean the equipment is "certified" by NSF or "accepted" by USEPA. Rather, it recognizes that the performance of the equipment has been determined and verified by these organizations under conditions specified in ETV protocols and test plans.

1.2 Purpose of Verification

The purpose of this verification was to evaluate treatment system performance under a simulated intentional or accidental chemical or microbiological contamination event. Because any contamination event would likely be short-lived, long-term performance of the treatment system was not investigated. Each chemical or microbial challenge was only one half-hour long.

1.3 Development of Test/Quality Assurance (QA) Plan

USEPA's "Water Security Research and Technical Support Action Plan" (USEPA, 2004) identifies the need to evaluate point-of-use (POU) and point-of-entry (POE) treatment system capabilities for removing likely contaminants from drinking water. As part of the ETV Program, NSF developed a test/QA plan for evaluating reverse osmosis (RO) drinking water treatment systems for removal of chemical and microbial contaminants. To assist in this endeavor, NSF assembled expert technical panels, which gave suggestions on a protocol design prior to development of the test/QA plan. Panel members included experts from USEPA, United States

Army, and United States Centers for Disease Control and Prevention, Division of Parasitic Diseases, as well as a water utility microbiologist, a university professor, and an independent consultant in the POU drinking water treatment systems industry.

The product-specific test/QA plan for evaluating the M-2400 was entitled *Test/QA Plan for Verification Testing of the Watts PremierM-2400 Point-of-Entry Drinking Water Treatment System for Removal of Microbial and Chemical Contaminants.* This test/QA plan calls for challenge tests with actual chemicals of concern, but surrogate bacteria and viruses in place of testing with the actual microorganisms of concern. Please note that this test plan does not cover chemical contaminants derived from microorganisms, such as algal toxins, ricin or botulinum toxin.

By participating in this ETV, Watts Premier has obtained USEPA- and NSF-verified independent test data indicating potential user protection against intentional or accidental chemical or microbiological contamination of drinking water. The M-2400 RO system is not marketed as being effective at removing bacteria, viruses, nor all of the challenge chemicals. This verification is a demonstration of possible performance. Verifications following a US EPA approved test/QA plan serve to notify the public of the possible level of protection against chemical or microbiological contaminants afforded to them by the use of the verified system.

Please note that in the event of system exposure to microbial contaminants, the user should replace the RO membrane and all other pre- and post-membrane filters, and also sanitize the system and its plumbing using bleach or another sanitizing agent. The removed RO membrane and filter cartridges should be handled with extreme caution as biohazards.

1.4 Challenge Chemicals and Microorganisms

The challenge chemicals and surrogate microorganisms used for this verification are given below in Table 1-1. See Section 3.2 for more discussion about the challenge substances.

Table 1-1. Challenge Chemicals and Microorganisms

Chemicals	Bacteria	Viruses
Aldicarb	*Brevundimonas diminuta*	fr
Benzene		MS2
Cadmium		
Carbofuran		
Cesium		
Chloroform		
Dichlorvos		
Mercury		
Methomyl		
Mevinphos		
Oxamyl		
Paraquat		
Sodium Fluoroacetate		
Strontium		
Strychnine		

1.5 Testing Participants and Responsibilities

The ETV testing of the M-2400 was a cooperative effort between the following participants:

NSF
Watts Premier, Inc.
USEPA

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

1.5.1 NSF International

NSF is a not-for-profit organization dedicated to public health and safety, and to 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. The USEPA partnered with NSF to verify the performance of drinking water treatment systems through the USEPA's ETV Program.

NSF performed all verification testing activities at its Ann Arbor location. NSF prepared the test/QA plan, performed all testing, managed, evaluated, interpreted, and reported on the data generated by the testing, and reported on the performance of the technology.

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

1.5.2 Watts Premier

The verified system is manufactured by Watts Premier, a division of Watts Water Technologies. Watts Premier manufactures industrial, food service, POE, and POU water treatment systems.

The manufacturer was responsible for supplying the test units and for providing logistical and technical support as needed.

Contact Information: Watts Premier Incorporated
1725 West Williams Drive
Suite C-20
Phoenix, AZ 85027
Phone: 800-752-5582
Fax: 623-931-0191
Contact Person: Mr. Shannon Murphy
Email: murphysp@wattsind.com

1.5.3 U.S. Environmental Protection Agency

USEPA, through its Office of Research and Development, has financially supported and collaborated with NSF under Cooperative Agreement No. R-82833301. This verification effort was supported by the DWS Center, operating under the ETV Program. This document has been peer-reviewed, reviewed by USEPA, and recommended for public release.

Chapter 2
Equipment Description

2.1 Activated Carbon Treatment Process

Activated carbon removes organic chemicals from water through adsorption. The chemicals are attracted to and attach to the surface of the carbon through electrostatic interactions. The adsorbent properties of activated carbon are a function of the raw material used and the activation process. Once the carbon is saturated with adsorbed molecules, it must be replaced.

2.2 Reverse Osmosis Treatment Process

Membrane technologies are among the most versatile water treatment processes because of their ability to effectively remove a wide variety of contaminants. RO membranes operate by the principal of cross-flow filtration. In this process, the influent water flows over and parallel to the filter medium and exits the system as reject water. Under pressure, a portion of the water diffuses through the membrane becoming "permeate." The membrane allows water molecules to pass through its pores, but not most dissolved inorganic chemical molecules and larger molecular weight organic chemical molecules. These molecules are concentrated in and washed away with the reject water stream. RO membranes also remove suspended solids and microorganisms through mechanical filtration.

Water passage through the RO membrane to generate permeate is known as "flux." It is a function of applied pressure, water temperature, and the osmotic pressure of the solution under treatment. Increasing the applied pressure will increase the permeate rate. However, a higher flux will tend to promote more rapid fouling of the membrane. Membrane element manufacturers usually provide limits with regard to the maximum applied pressures to be used as a function of feed water quality and other factors.

Unlike activated carbon, which reaches an exhaustion point and needs to be replaced, the reduction capabilities of RO membranes remain in effect until the membrane is compromised. Monitoring of membrane performance can be conducted by measuring the total dissolved solids (TDS) concentration of the permeate water.

2.3 M-2400 Equipment Description

The M-2400 is a skid-mounted RO system in a carbon steel frame with powder coating. The system is 27" wide, 32" deep, and 57" high. A photograph of the system is shown in Figure 2-1.

The main system components are:

- 3/4 horsepower, 330 gallons per hour feed pump to increase the water pressure to the RO membrane;
- sediment and/or carbon pre-membrane filters;

- one 4” x 40” (10 centimeter [cm] x 102 cm) RO membrane module inside a stainless steel pressure vessel;
- control panel with permeate and concentrate flow meters, valves to adjust the concentrated and recycle flows, and pressure gauges to measure the RO membrane operating pressure, concentrate back-pressure, and storage tank pressure (for use with a pressure tank); and
- optional pressure tank or open-to-atmosphere tank for storage of treated water.

Figure 2-1. M-2400 RO system.

Under normal operation, raw water entering the system first passes through a sediment or carbon pre-filter to remove large particles. The pre-filter effluent is then sent through a booster pump and then on to the RO membrane. Water passing through the membrane is collected in a permeate line that can be plumbed to a storage tank. A portion of the concentrate water from the membrane module can be recycled back into the feed water line depending on the desired recovery for the system. The remainder of the concentrate is sent to the drain. The recycle rate can be manually adjusted with a needle control valve.

The M-2400 has an automatic 12-second membrane flush using permeate water. The system can be programmed so the rinse occurs when unit operation ceases, for operation on a short-duty cycle, or on a certain frequency for operation on an extended-duty cycle.

The system as tested did not include a pre-membrane filter or a permeate storage tank. During testing, a valve on the permeate line was slowly shut to increase the back-pressure on the membrane to a point at which the automatic flush initiated. However, since there was no permeate storage tank to supply the flush water, the flush only lasted a few seconds, until the water in the permeate line was gone. **Please note that the observed operation and membrane performance may not apply to a system operated with a pressurized storage tank, due to back-pressure on the membrane from the tank.**

The M-2400 operation specifications are presented in Table 2-1. The RO membrane specifications are presented in Table 2-2.

Table 2-1. M-2400 Equipment Specifications

Parameter	Specification
Dry Weight	350 pounds (lbs.)
Wet Weight	1750 lbs.
Feed Water:	
Temperature	1.7° to 38°C (35° to 100° F)
Max. Feed Flow Rate	5.5 gallons per minute (gpm)
Feed Water Pressure	25 to 80 pounds per square inch, gauge (psig)
Membrane Operating Pressure	150 psig
PH	2 to 11
Hardness	< 290 milligrams per liter (mg/L)
Iron	< 0.1 mg/L
Manganese	< 0.05 mg/L
Silica	< 75 mg/L
TDS	< 2500 mg/L
Turbidity	< 1 Nephelometric turbidity units (NTU)
Permeate Flow Rate	~1.67 gpm
Drain Connection:	Floor drain within 10 feet of system, 1 ¼ inch connection
Electrical Requirements:	
RO Processor	115 volts/11 amps
Delivery Pump	115 volts/12.4 amps

Table 2-2. RO Membrane Specifications

Parameter	Specification
Membrane Manufacturer	Applied
Membrane Element Model Number	M-T4040 ALE
Size of Element	4" X 40"
Active Membrane Surface Area per Element	82 square feet (ft^2)
Molecular Weight Cut-Off	80 – 100 Daltons
Membrane Material Construction	Dow Filmtec
Membrane Hydrophobicity	Hydrophobic
Reported Membrane Charge	Negative
Scroll Width	38 inches
Design Pressure	150 psig
Design Flux at Design Pressure	34 gallons per square foot per day (gfd)
Variability of Design Flux	± 15%
Design Specific Flux at 25°C	0.24 gfd/psig
Standard Testing Recovery	50-75%
Standard Testing pH	8
Standard Testing Temperature	25°C
Design Cross-Flow Velocity	0.6 ft/s
Maximum Flow Rate to an Element	16 gpm
Minimum Flow Rate to an Element	4 gpm
Required Feed Flow to Permeate Flow Ratio	1:5
Maximum Element Recovery	75%
Rejection of Reference Solute and Conditions of Test (e.g., Solute type and concentration)	80-99%
Variability of Rejection of Reference Solute	-0%, +1%
Acceptable Range of Operating Pressures (psi, bar)	Dependent on Water Temperature
Acceptable Range of Operating pH Values	2 – 11
Typical Pressure Drop across a Single Element	6 psi
Maximum Permissible Silt Density Index (SDI)	4
Maximum Permissible Turbidity	1 NTU
Chlorine/Oxidant Tolerance	With Carbon Pre-Filter

2.4 M-2400 Operation and Maintenance Requirements

No maintenance was required during the test period. Under normal operation, periodic replacement of the pre-membrane filter(s) and RO membrane is required. Pre-membrane filter replacement is dependant upon inlet water quality; it is recommended that pre-membrane filters be inspected after the first six months of operation to determine replacement need. Membranes should be tested for TDS reduction after one month of use in order to establish initial reduction capabilities. Following that, the system should be checked annually. In some cases, based upon incoming water chemistry, antiscalants can be used to extend the life of the RO membrane. Watts Premier estimates membrane life to be two years or longer.

The system does not require any manual backflush maintenance; it automatically flushes the RO membrane for 12 seconds after every operation period.

There are no special licensing requirements to operate the M-2400.

2.5 Flowmatic MAXVOC-FF975 Activated Carbon Filter

Watts Premier offers the Flowmatic MAXVOC-FF975 activated carbon filter as an optional post-RO treatment step for the permeate water. This filter is designed to remove organic chemicals, which may pass through the membrane. The addition of the MAXVOC-FF975 to the M-2400 system offers a treatment system that can remove a wide variety of inorganic and organic chemicals from drinking water, as well as microorganisms.

The MAXVOC-FF975 uses a 4.625" by 9.75" activated carbon block filter that can effectively treat water at a flow rate of 2 gpm. This rated service flow works well with the M-2400, which operates with a permeate flow rate of approximately 1.67 gpm.

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Chapter 3
Methods and Procedures

3.1 Introduction

The challenge tests followed the procedures described in the *Test/QA Plan for Verification Testing of the Watts Premier M-2400 Point-of-Entry Reverse Osmosis Drinking Water Treatment System for Removal of Microbial and Chemical Contaminants*.

The microbial and chemical challenge protocols were adapted from the *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants.*

The purpose of this verification was not to evaluate the production of drinking water from an untreated source water, but rather, to evaluate the system's ability to remove chemicals and microorganisms from drinking water. As such, this verification will not evaluate the cleaning efficiency of the system, nor the flux recovery of the membrane after backwashing or cleaning.

One M-2400 system and one Flowmatic MAXVOC FF-975 filter were tested. No pre-membrane filter or permeate water storage tank were included with the M-2400 test unit. The M-2400 was challenged with both the microorganisms and chemicals, but the MAXVOC filter was only challenged with chemicals. The MAXVOC filter has a nominal pore size rating of 0.5 microns (μm), which is not small enough to retain the challenge organisms.

For the chemical challenge tests, the M-2400 was tested first. The MAXVOC carbon filter was then tested separately for reduction of the chemicals that the RO membrane did not remove to 20 micrograms per liter (μg/L) or lower. Testing the carbon filter separately from the RO membrane allowed an evaluation of the efficacy of each treatment step.

3.2 Challenge Substances

3.2.1 Bacteria and Virus Surrogates

The bacteria surrogate was the bacteria *Brevundimonas diminuta* (American Type Culture Collection (ATCC) strain 19146). It was chosen based on its small size. It is the accepted bacteria of choice for testing filters and membranes designed to retain bacteria and is used in the ASTM International (ASTM) Standard Test Method for Determining Bacterial Retention of Membrane Filters Utilized for Liquid Filtration. The smallest identified bacterium of concern is *Francisella tularensis*, which can be as small as 0.2 μm in diameter. *B. diminuta* has a minimum size of 0.2 to 0.3 μm in diameter.

The bacteria was used in its "normal" state, and also was genetically engineered to be resistant to the antibiotic kanamycin. This allowed the use of growth media amended with kanamycin to prohibit heterotrophic bacteria from also growing. The "normal" and kanamycin resistant (KanR) strains were used in individual challenges.

The virus surrogates were the coliphages fr and MS2. These phages were chosen as surrogates based on their size and isoelectric points. Fr is 19 nanometers (nm) in diameter with an isoelectric point at pH 8.9, and MS2 is 24 nm in diameter with an isoelectric point at pH 3.9. The isoelectric point is the pH at which the virus is neutrally charged. The viruses have varying isoelectric points, so they will have different surface charges, or different strengths of negative or positive charge at the different pH values. In solutions above the isoelectric point, the virus is negatively charged and below it, the virus is positively charged. Therefore, in the test water at pH 7.5, MS2 should be negatively charged and fr should be positively charged. This approach served to evaluate whether electrostatic forces play a role in virus retention in addition to mechanical filtration.

The viruses were purchased from Biological Consulting Services of North Florida and the bacteria were purchased from ATCC. The viruses were purchased in adequate volumes so that volumes of the suspensions received were added directly to the test water. The bacteria were cultivated at NSF to obtain the challenge suspensions. Section 3.8.2.2 describes the method used to create the bacteria challenges.

3.2.2 Chemicals

The challenge chemicals used in this product verification are listed in Table 3-1. They were chosen as chemicals of interest by the USEPA.

Table 3-1. Challenge Chemicals

Organic Chemicals	Inorganic Chemicals
Aldicarb	Cadmium Chloride
Benzene	Cesium Chloride (nonradioactive isotope)
Carbofuran	Mercuric Chloride
Chloroform	Strontium Chloride (nonradioactive isotope)
Dichlorvos	
Methomyl	
Mevinphos	
Oxamyl	
Paraquat	
Sodium Fluoroacetate	
Strychnine	

3.3 Test Apparatus

The M-2400 test unit was plumbed to a “tank rig” test station in the NSF testing laboratory. The tank rig uses a 500-gallon stainless steel or a 500-gallon polyethylene tank to hold the influent challenge water. See Figure 3-1 for a schematic diagram of the tank rig. Figure 3-2 shows the M-2400 plumbed to a tank rig test station.

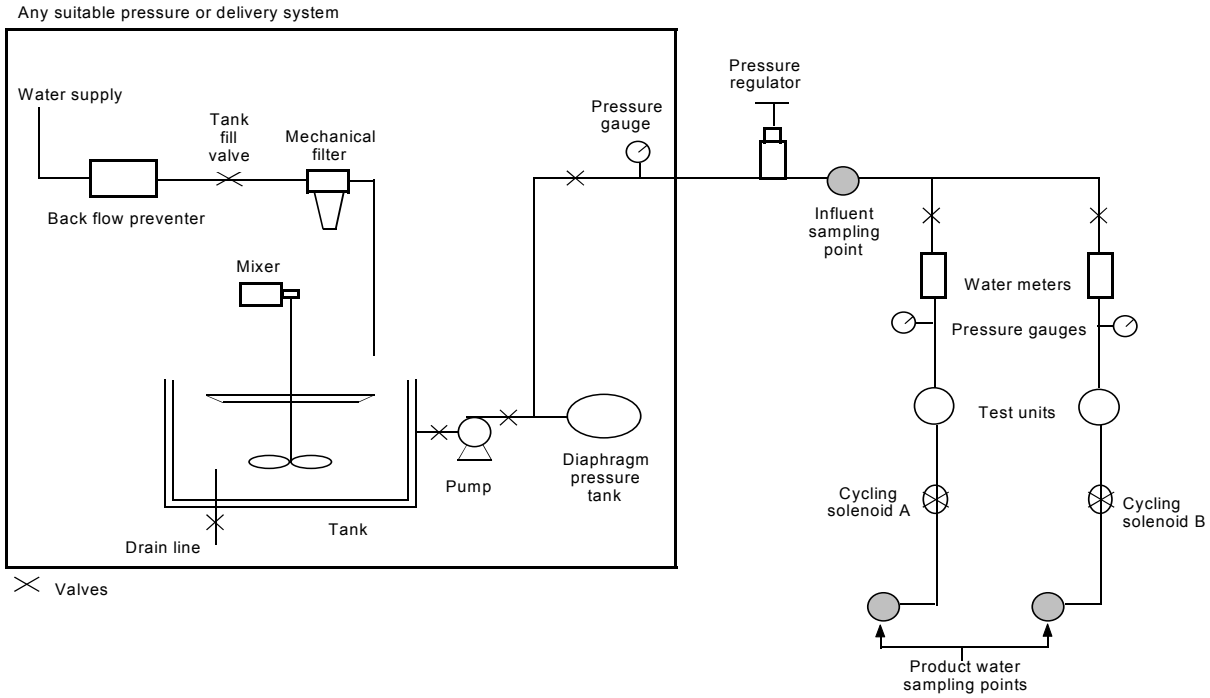

Figure 3-1. Schematic diagram of "tank rig" test station.

The MAXVOC carbon filter was plumbed to an "injection rig" test station in the NSF testing laboratory. The injection rigs use common tanks to hold the test water minus the challenge chemical. Fresh water is periodically added to the tank as it is being used. Online monitors and a computer system automatically control the water level and water chemistry. Downstream of the feed water tank, a precisely controlled injection syringe is used to inject the challenge chemical into the influent water. Immediately downstream of the injection point lies a motionless in-line mixer to assure complete mixing of the challenge water. No schematic diagram of the injection rig is available due to the proprietary nature of the design.

3.4 Task 1: Test Unit Start-Up, Conditioning and RO Membrane Integrity Test

3.4.1 Test Unit Start-Up

The test unit was calibrated for operation according to the instructions in the M-2400 Installation, Operation, & Maintenance Manual, so that the RO membrane operating pressure was set at 150 psig. With an operating pressure of 150 psig, the influent flow rate was 3.72 gpm, the permeate flow rate was 1.87 gpm, and the concentrate flow rate was 1.96 gpm.

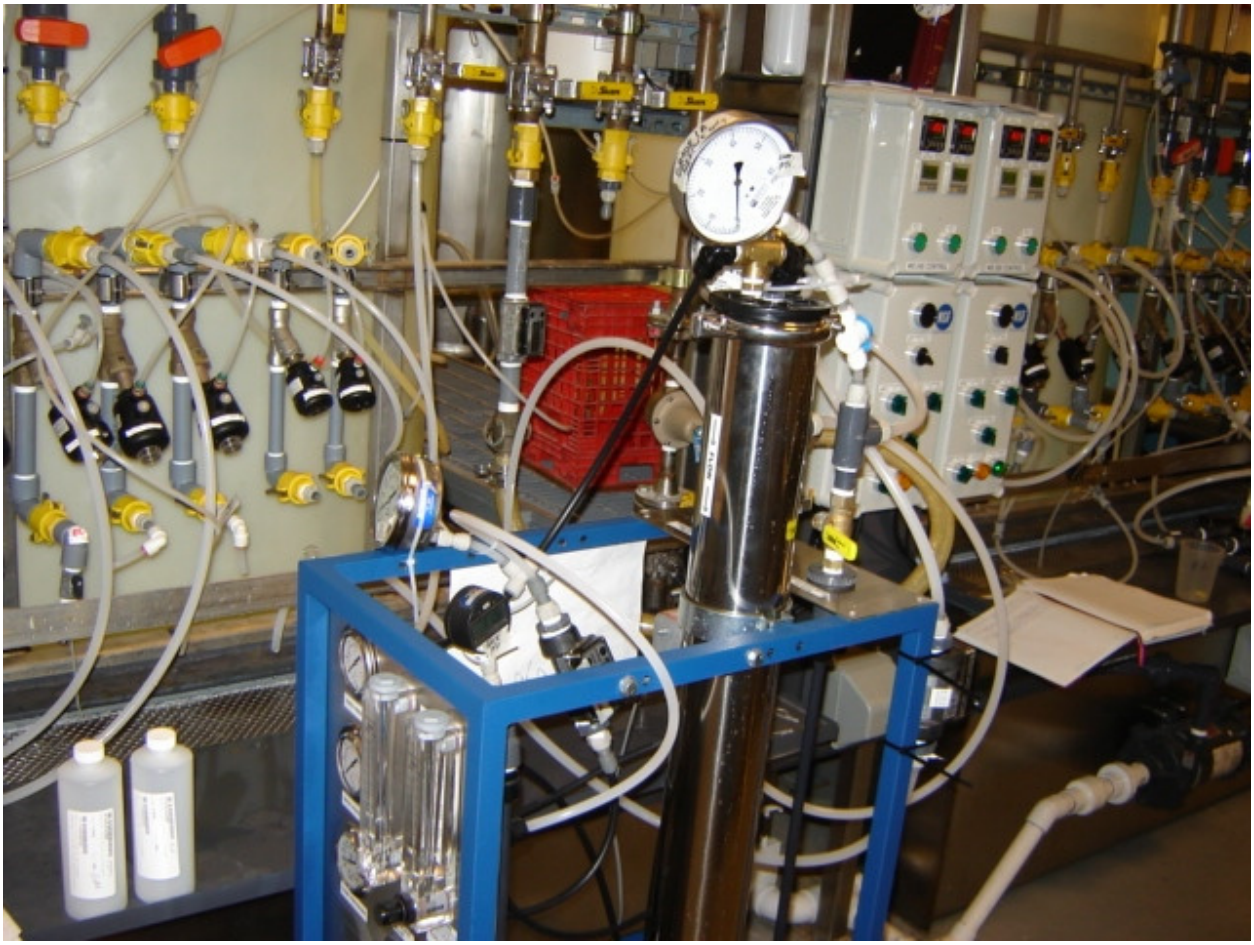

Figure 3-2. M-2400 plumbed to test rig in NSF testing laboratory.

3.4.2 RO Membrane Conditioning

The system was conditioned by operating it for one hour using the test water described in Section 3.7.1.1. After completion of the conditioning period, TDS reduction of the system was measured (using conductivity) to verify that the system was operating properly.

3.4.3 MAXVOC Filter Conditioning

The MAXVOC filter was operated using the test water described in Section 3.7.1.2 for 1,300 gallons. This is the volume equal to one-half of Watts Premier's claimed chemical reduction capacity of 2,600 gallons for the filter. Chloroform was added to the test water to achieve an average influent concentration of 300 ± 90 µg/L, which is the influent challenge concentration for the volatile organic chemical (VOC) reduction test in *NSF/ANSI Standard 53, Drinking water treatment units – health effects* (NSF International, 2005a) (chloroform is the surrogate chemical for the Standard 53 VOC reduction claim). The chloroform served to load the carbon to a degree that simulated contaminant loading in the middle of its effective lifespan.

The filter was operated at a flow rate of 2 gpm, at an inlet water pressure of 60 ± 3 psig, on a ten minutes on, ten minutes off cycle. Influent samples were collected for analysis of chloroform, pH, TDS, temperature, total organic carbon (TOC), and turbidity at start-up, 650 gallons, and at the 1,300-gallon point. Effluent samples were also collected for chloroform analysis at the same sample points.

Until the challenge tests began, the filter was stored with the conditioning water still in it, and the inlet and outlets were closed off by valves or were plugged, so that the chloroform remained on the carbon.

3.5 Task 2: System Operation Characterization

The following system parameters were measured and reported for each challenge test:

- Influent, permeate, and concentrate flow rates;
- Operating pressure of the RO membrane;
- Concentrate line back pressure on the RO membrane; and
- Permeate line pressure (the permeate discharge was to atmosphere – 0 to 1 psig; therefore, the measurement was discontinued after the first few runs).

From these measurements, the following operational parameters were calculated:

- Pressure drop across the RO membrane
- Permeate Flux – The average permeate flux is the flow of permeate water divided by the surface area of the membrane. Permeate flux was calculated according to the following formula:

$$J_t = \frac{Q_p}{S}$$

where J_t = permeate flux at time t (gfd);
Q_p = permeate flow (gpd [gallons per day]); and
S = membrane surface area (ft^2).

- Feedwater system recovery – The recovery of permeate from feed water is given as the ratio of permeate flow to feed water flow:

$$\%\,\text{System Recovery} = 100 \cdot \left[\frac{Q_p}{Q_f} \right]$$

where Q_p = permeate flow (gpd) and
Q_f = feed flow to the membrane (gpd).

- Specific flux – The specific flux is the flux normalized for the transmembrane pressure (TMP). Specific flux was calculated with the following equation:

$$J_{tm} = \frac{J_t}{TMP}$$

where: J_{tm} = Specific flux at time t (gfd/psig);
TMP = Transmembrane pressure across the membrane (psig); and
J_t = permeate flux at time t (gfd). Temperature-corrected flux values were employed.

Transmembrane pressure was calculated using the following equation:

$$TMP = \left[\frac{(P_f + P_c)}{2}\right] - P_p$$

where: TMP = transmembrane pressure (psig);
P_f = feed pressure on the membrane (psig);
P_c = outlet pressure on the concentrate side of the membrane (psig); and
P_p = permeate pressure on the treated water side of the membrane (psig).

Note that the M-2400 permeate line was open to the atmosphere for this verification test, so the permeate gauge pressure was essentially zero. Therefore, the transmembrane pressure was just the average of the inlet pressure and outlet pressure.

The permeate flux, J_t, was corrected to 25°C to account for the variation of water viscosity with temperature. The following empirically derived equation was used to provide temperature corrections for specific flux calculations:

$$J_t \text{ (at 25 °C)} = \frac{Q_p \times e^{-0.0239\,(T-25)}}{S}$$

where: J_t = permeate flux at time t (gfd);
Q_p = permeate flow (gpd);
S = membrane surface area (ft^2); and
T = temperature of the feed water (°C).

3.6 Task 3: Microbial Challenge Test Procedure

3.6.1 Test Water

Local tap water was treated by carbon filtration, RO, and deionization to make the base water for the tests. The base water had the following characteristics:

- conductivity ≤ 2 microSiemans per centimeter (µS/cm) at 25°C;
- TOC < 100 µg/L;
- total chlorine < 0.05 mg/L; and
- heterotrophic plate count (HPC) bacteria < 100 colony forming units per milliliter (CFU/mL).

Only total chlorine was measured specifically for this verification. The other parameters are measured periodically by NSF as part of the internal quality assurance/quality control (QA/QC) program for test water quality.

The base water was adjusted to meet the following characteristics:

- addition of sodium bicarbonate ($NaHCO_3$) to achieve an alkalinity (as $CaCO_3$) of 100 ± 10 mg/L prior to pH adjustment;
- the pH was adjusted if necessary with hydrochloric acid (HCl) or sodium hydroxide (NaOH) to reach a value of 7.5 ± 0.5.
- temperature of 20 ± 2.5 °C.

The appropriate challenge organism, suspended in phosphate buffered dilution water (PBDW), was added to the base water to create the challenge water. The target challenge concentration for *B. diminuta* was ≥ 1 X 10^6 CFU/100 mL. The target concentrations for MS2 and fr were ≥ 1 X 10^4 plaque forming units per milliliter (PFU/mL).

Grab samples for analysis of total chlorine, alkalinity, TDS, and turbidity were collected prior to the start of each challenge period, before addition of the challenge organism suspension. Temperature and pH were measured at time 0. The pH was also measured at the end of each challenge period.

3.6.2 Sanitizing the Test Apparatus

To keep the HPC population to a minimum, the test apparatus was cleaned and sanitized prior to the start of testing activities according to an NSF standard operating procedure (SOP). The process is proprietary, and uses multiple chemicals as sanitizers. After sanitization, the test apparatus was flushed until a less-than-detectable concentration of sanitizing agent was present.

3.6.3 Challenge Test Procedure

The M-2400 was challenged with each organism individually. The influent challenge holding tank was mixed after addition of the challenge organism for a minimum of 30 minutes using a recirculation pump prior to beginning the test.

The inlet water pressure was set to 60 ± 3 psig and the test unit was operated continuously for 30 minutes. Influent and effluent samples for bacteria or virus analysis were collected at start-up, at 15 minutes, and at 30 minutes. The influent, permeate, and concentrate flow rates, and the RO membrane operating and back pressures were recorded at start-up and at 30 minutes.

All samples for bacteria and virus analysis were analyzed in triplicate. For each sample point, an appropriate volume was first collected into a sterile container, and then the triplicate aliquots were drawn aseptically from this volume. Single samples were collected for the water chemistry parameters.

At the end of each challenge period, the RO membrane was backflushed with permeate water using the system's automatic rinse cycle. The rinse was engaged by closing off a valve on the permeate line, decreasing the pressure differential across the membrane (membrane feed side pressure minus membrane permeate side pressure) to a certain set-point. As described in Section 2.3, under normal operation with a storage tank, the flush is 12 seconds. However, since the system was operated without a storage tank for this verification, the flush lasted approximately three seconds, since the only flush water available was the volume in the permeate line and on the permeate side in the membrane vessel.

After the flush, the feed water supply was turned off. The unit was not operated between the challenge periods. Prior to the next chemical challenge, the system was flushed for approximately 15 minutes using the test water minus the challenge organism.

3.7 Task 4: Chemical Challenge Tests

As discussed in Section 3.1, the M-2400 RO membrane was challenged with all of the chemicals in Table 3-1, but the MAXVOC carbon filter was challenged with only the chemicals that the RO membrane did not remove to below 20 μg/L. Separate challenges were conducted for each chemical, except for cadmium chloride, cesium chloride, and strontium chloride, which were combined into one challenge.

3.7.1 Test Water

3.7.1.1 RO Membrane Challenge Water

Local tap water was treated by carbon filtration, RO, and deionization to make the RO membrane test water. Sodium chloride was added for TDS, and the pH was adjusted if necessary with HCl or NaOH for all challenges but sodium fluoroacetate. The NaCl interfered with analysis for sodium fluoroacetate, so none was added to the challenge water, nor was the pH adjusted for that challenge. The test water had the following characteristics prior to addition of the challenge chemical(s):

- pH – 7.5 ± 0.5;
- TDS (by conductivity) – 750 ± 75 mg/L;
- temperature – 25 ± 1 °C;
- total chlorine – ≤ 0.05 mg/L; and
- turbidity – ≤ 1 NTU.

To this test water, the challenge chemical(s) were added at a concentration of 1 ± 0.5 mg/L. The allowable tolerance on the challenge concentrations was plus or minus 50%, because due to analytical procedure lengths, the tests were conducted without waiting for confirmation of the concentration from the chemistry laboratory.

Grab samples for analysis of total chlorine, alkalinity, TDS, and turbidity were collected prior to the start of each challenge period, before addition of the challenge chemical to the test water. After the challenge chemical was added to the test water tank, the water was mixed for a minimum of 30 minutes using a recirculation pump prior to beginning test unit operation.

Temperature and pH were measured at time zero. The pH was also measured at the end of each challenge period.

3.7.1.2 Carbon Filter Conditioning and Challenge Water

The test water for carbon filter conditioning and testing was the "general test water" specified in NSF/American National Standards Institute (ANSI) Standard 53. This water is Ann Arbor municipal drinking water that is adjusted, if necessary, to have the following characteristics prior to addition of the challenge chemical:

- pH – 7.5 ± 0.5;
- temperature – 20 ± 2.5 °C;
- TDS – 200-500 mg/L;
- TOC – > 1.0 mg/L; and
- turbidity – ≤ 1 NTU.

Note that the TOC parameter only has a minimum level specified, since it is the natural TOC in the municipal water supply. The TOC level at the tap is usually in the range of 1.5 to 2.5 mg/L.

TDS, pH, and temperature were maintained in the appropriate range by the test rig's on-line monitoring system with automatic delivery of chemicals and temperature adjustment capabilities. Grab samples were analyzed for pH, temperature, TDS, TOC, total chlorine, and turbidity at the start of each challenge period. The pH was also measured at 30 minutes. The samples were collected upstream of the injection point for the challenge chemical.

The target challenge chemical concentrations for the MAXVOC tests were the maximum effluent levels measured during the RO tests. The allowable tolerance on the challenge concentrations was plus or minus 50%, because due to analytical procedure lengths, the tests were conducted without waiting for confirmation of the concentration from the chemistry laboratory.

3.7.2 Challenge Test Procedures

3.7.2.1 RO Membrane Challenge Testing

The M-2400 was challenged with each chemical individually, except for cadmium, cesium, and strontium, which were combined into one challenge. The inlet water pressure was set to 60 ± 3 psig, and the system was operated continuously for 30 minutes using the appropriate challenge water. Influent and effluent samples for challenge chemical analysis were collected at start-up and at 30 minutes. The influent, permeate, and concentrate flow rates, and the RO membrane operating and back pressures were measured at start-up and at 30 minutes.

Following each challenge, the RO membrane was backflushed, as described in Section 3.6.3. The unit was not operated between the challenge periods. Prior to the next chemical challenge, the unit was flushed for five minutes using the test water in section 3.7.1.1 without any challenge chemical present.

All samples for challenge chemical analysis were collected in triplicate. Single samples were collected for the water chemistry parameters.

3.7.2.2 MAXVOC Challenge Testing

As with the RO membrane challenges, each MAXVOC filter challenge was also 30 minutes. The target flow rate was the maximum permeate flow rate measured during the RO membrane challenges (1.85 gpm during the cadmium/cesium/strontium challenge). The inlet water pressure was set to 60 ± 3 psig. Influent and effluent samples for challenge chemical analysis were collected at start-up and at 30 minutes. The influent flow rate and water pressure were recorded at start-up.

All samples for challenge chemical analysis were collected in triplicate. Single samples were collected for the water chemistry parameters.

3.8 Analytical Methods

3.8.1 Water Quality Analytical Methods

The following are the analytical methods used during verification testing. All analyses followed procedures detailed in NSF SOP's.

- Alkalinity was measured according to USEPA Method 310.2 with the SmartChem Discrete Analyzer. Alkalinity was expressed as mg/L $CaCO_3$.
- pH measurements were made with a Beckman 350 pH meter. The meter was operated according to the manufacturer's instructions, which are based on Standard Method 4500-H^+.
- Water temperature was measured using an Omega model HH11 digital thermometer, or equivalent.
- TDS for the TDS reduction system check test was measured through conductivity according to Standard Method 2510 using a Fisher Scientific Traceable™ Conductivity Meter. This method has been validated for use with the test water; NSF uses this method for analysis of samples from TDS reduction tests in *NSF/ANSI 58 – 2005, Reverse osmosis drinking water treatment systems* (NSF International, 2005b).
- The TDS in the carbon filter conditioning and challenge water was measured gravimetrically. The method used was an adaptation of USEPA Methods 160.3 and 160.4. An appropriate amount of sample was placed in a pre-weighed evaporating dish. The sample was evaporated and dried at 103-105 °C to a constant weight. The dish was then weighed again to determine the total solids weight.
- Total chlorine was measured according to Standard Method 4500-Cl G with a Hach Model DR/2010 spectrophotometer using AccuVac vials.
- Total Hardness was measured according to USEPA Method 310.1 using a SmartChem Discrete Analyzer.
- TOC was measured according to Standard Method 5310C using a Teledyne Technologies Company Tekmar Dohrmann Phoenix 8000 UV-Persulfate TOC analyzer.

- Turbidity was measured according to Standard Method 2130 using a Hach 2100N turbidimeter.

3.8.2 Microbiology Analytical Methods

3.8.2.1 Sample Processing, and Enumeration of Viruses

The viruses were enumerated using a double agar layer method published in *NSF/ANSI Standard 55 – Ultraviolet Microbiological Water Treatment Systems* (NSF International 2005c) for enumerating MS2. This method is similar to the double agar layer method in USEPA Method 1601.

Four to eighteen hours prior to sample processing, 100 microliters (μL) of the appropriate host *E. coli* suspension was pipetted into tubes containing 10 mL of fresh tryptic soy broth (TSB), and incubated at 35 °C. After incubation, 100 μL volumes of the resulting *E. coli* culture were transferred to sterile, capped test tubes.

All samples were enumerated in triplicate. All samples were serially diluted for enumeration, and the effluent samples were also enumerated directly. One-milliliter volumes of the sample or dilution were pipetted into the *E. coli* suspension test tubes. The tubes were vortexed for a minimum of 30 seconds to "mate" the bacteria and virus, and then 4 mL of molten, tempered TSB plus 1% agar was added to each tube. These mixtures were then poured over tryptic soy agar (TSA) plates and allowed to solidify. The plates were incubated at 35 °C for 18-24 hours. Virus plaques were counted using a Quebec Colony Counter.

3.8.2.2 *B. diminuta* Cultivation and Challenge Suspension Preparation

The bacteria was purchased from ATCC and rehydrated with nutrient broth. After 48 hours of incubation at 30°C, 5 mL of the nutrient broth culture was added to 50 mL of nutrient broth, and the resultant cultures were incubated for 48 hours at 30°C. Freezer stocks were then obtained from the nutrient broth culture, and these stocks were stored at -80°C until use.

To obtain the challenge suspensions, two 10 mL tubes of TSB were inoculated with 0.1 mL of stock culture. These tubes were incubated at 35°C for 24 hours. Then 2 mL from either tube was pipetted into eight flasks containing 1 L of Saline Lactose Broth (SLB). The eight flasks were put on a shaker and incubated in a 35°C water bath for 24 hours. The contents of all eight flasks were added to 200 gallons of base test water to create the challenge waters. The use of SLB ensures that the cells are smaller in diameter. *B. diminuta* cells grown in nutrient broth can have diameters greater than 0.5 μm. Cells grown in SLB have been measured by NSF to have diameters ranging from 0.3 to 0.5 μm.

The challenge preparation procedure was identical for both the normal *B. diminuta* and the KanR *B. diminuta*, the only difference was that for the KanR bacteria, the SLB was amended with 50 μg/L of kanamycin, and 10 μg/L of tetracycline.

3.8.2.3 Sample Processing and Enumeration of *B. diminuta*

All samples were enumerated in triplicate using a membrane filtration method based on Standard Method 9215 D. All samples were serially diluted for enumeration with sterile PBDW, and the effluent samples were also enumerated directly. For the influent samples, 1 mL volumes of either the straight sample or dilutions were pipetted into sterile glass vacuum filtration funnels, and 25 mL of PBDW was also poured into the funnels. For the effluent samples, 100 mL of the straight sample and the dilutions were pipetted into the funnels. The contents were then vacuum filtered through sterile 0.1 μm membrane filters. The funnels were rinsed three times with approximately 5 mL of PBDW, and the rinse water was also suctioned through the filters. The membrane filters were aseptically removed from the apparatuses and placed onto R2A agar plates. The plates were incubated at 30 °C for 48 hours. Characteristic *B. diminuta* colonies were counted with a Quebec Colony Counter.

The sample processing and enumeration procedures were identical for both the normal *B. diminuta* and the KanR *B. diminuta*, the only difference was that the R2A agar was amended with 50 μg/L of kanamycin and 10 μg/L of tetracycline for enumeration of the KanR bacteria.

3.8.3 Challenge Chemical Analytical Methods

- Aldicarb, Carbofuran, Methomyl, and Oxamyl were measured by high pressure liquid chromatography (HPLC) according to USEPA Method 531.1 or 531.2.
- Dichlorvos and Mevinphos were measured by gas chromatography/mass spectrometry (GC/MS) according to USEPA Method 525.2.
- Cadmium, Cesium, Mercury, and Strontium were measured by Inductively Coupled Plasma – Mass Spectrometry (ICP-MS) according to USEPA Method 200.8.
- Benzene and Chloroform were measured by purge and trap capillary gas chromatography according to USEPA Method 502.2.
- There is no standard analytical method for strychnine. NSF developed a method to measure it using reverse phase HPLC with ultraviolet lamp detection.
- Paraquat was measured by HPLC according to USEPA Method 549.1.
- Sodium Fluoroacetate was measured by ion chromatography according to USEPA Method 300.1.

Chapter 4
Results and Discussion

4.1 TDS Reduction Membrane Integrity Check

Prior to the start of challenge testing, the TDS reduction capability of the M-2400 was evaluated as a gross membrane integrity check. The system was challenged with 680 mg/L of NaCl. The permeate TDS level was 11 mg/L, indicating that membrane integrity was intact.

4.2 System Operation Characterization

Tables 4-1 and 4-2 give the operation data and calculations for the microbial and chemical challenges, respectively. The following system operation parameters were measured at the beginning and end of each challenge test:

- Influent flow rate;
- Permeate flow rate;
- Reject flow rate;
- RO membrane operating pressure; and
- RO membrane concentrate line back pressure.

The permeate pressure was recorded for the first few challenges, but was always around 1 psig since the permeate line was open to atmosphere for this verification. Therefore, the lab technicians stopped recording it, and it was treated as zero for the purpose of calculating the transmembrane pressure (see Section 3.5 for equation).

The transmembrane pressure, permeate flux normalized to 25°C, and specific flux were calculated for each challenge using the start-up operation data.

As discussed in Section 3.4.1, the M-2400 Installation, Operation, and Maintenance Manual states that the RO membrane operating pressure should be set 150 psig. The manual also states that the system should not be operated with the membrane operating pressure over 150 psig, so that the membrane is not damaged. The membrane operating pressure was set at 150 psig for the initial system calibration on January 26, 2006, but the system was not re-calibrated before each challenge for the first three weeks of challenges. When the first *B. diminuta* and KanR *B. diminuta* challenges were conducted on January 30, the recorded membrane operating pressures were 155 psig and 158 psig, respectively. The data from these two challenges is not presented in this report because the influent challenge concentrations were too low. The membrane operating pressure was at 160 psig the next day, and rose to 172 psig by February 20. At this point, NSF decided to recalibrate the system each day challenges were conducted, so that the membrane operating pressure remained close to 150 psig. The challenges conducted at membrane operating pressures above 150 psig were all microbial challenges, as well as the cadmium/cesium/ strontium, mercury, strychnine, paraquat, and aldicarb chemical challenges. To check whether the higher membrane operating pressures adversely affected the performance of the membrane for mechanical filtration of the viruses and bacteria, the *B. diminuta* challenge was conducted again with a membrane operating pressure of 149 psig. The $\log_{10}$ reductions from this challenge,

discussed in Section 4.3, indicate that the higher pressure did not significantly impact the mechanical reduction performance of the membrane. The system performed well against the chemicals at higher pressure, so no chemical challenges were conducted again.

The data is organized by the date of each challenge in Tables 4-1 and 4-2 so that the potential impact of the higher membrane operating pressures on the operation parameters can be more easily discerned.

Table 4-1. M-2400 Microbial Challenges Operation and Water Chemistry Data

Sample	MS2	fr	First *B. diminuta* Challenge	Kanamycin Resistant *B. diminuta*	Second *B. diminuta* Challenge
Challenge Date	01/31/06	02/02/06	02/14/06	02/14/06	03/08/06
Start-up Operation Data					
System Influent Flow Rate (gpm)	3.63	3.63	3.58	3.58	2.84
Permeate Flow Rate (gpm)	1.69	1.81	1.80	1.83	1.50
Reject Flow Rate (gpm)	2.00	1.90	1.88	1.85	1.44
Feed Water Recovery (%)	46.6	49.9	50.3	51.1	52.8
Membrane Operating Pressure (psig)	160	162	166	160	149
Concentrate Back-Pressure (psig)	157	160	164	160	144
Transmembrane Pressure (TMP) (psig)	159	161	165	160	147
Permeate Flux (normalized to 25°C) (gfd)	35.1	35.8	37.4	34.5	29.7
Specific Flux (gfd/psig)	0.22	0.22	0.23	0.22	0.20
30 Minute Operation Data					
System Influent Flow Rate (gpm)	3.61	3.58	3.54	3.58	2.89
Permeate Flow Rate (gpm)	1.72	1.81	1.77	1.82	1.40
Reject Flow Rate (gpm)	1.89	1.88	1.90	1.87	1.61
Membrane Operating Pressure (psig)	162	162	166	164	149
Concentrate Back-Pressure (psig)	159	160	164	160	144
Transmembrane Pressure (TMP) (psig)	161	161	165	162	147
Permeate Flux (normalized to 25°C) (gfd)	35.7	35.8	36.7	34.3	27.7
Specific Flux (gfd/psig)	0.22	0.22	0.22	0.21	0.19
Start-up Influent					
Alkalinity (mg/L $CaCO_3$)	92	68	60	68	68
PH	7.6	7.8	7.7	8.0	7.9
Temperature (°C)	18	20	18	22	20
Total Chlorine (mg/L)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)
TDS (mg/L)	83	57	57	58	78
Turbidity (NTU)	ND (0.1)	0.4	0.2	6.8	ND (0.1)
30 Minute Influent					
PH	7.6	7.8	7.8	8.0	7.9

Table 4-2. M-2400 Chemical Challenges Operation and Water Chemistry Data

Sample	Cadmium, Cesium, Strontium	Mercury	Strychnine	Paraquat	Aldicarb	Carbofuran	Oxamyl	Methomyl	Dichlorvos	Mevinphos	Chloroform	Benzene	Sodium Fluoroacetate
Challenge Date	02/01/06	02/16/06	02/17/06	02/20/06	02/20/06	02/21/06	02/21/06	02/21/06	02/22/06	02/22/06	02/22/06	02/23/06	04/07/06
Start-up Operation Data													
System Influent Flow Rate (gpm)	3.58	3.57	3.53	3.39	3.57	3.06	3.13	3.06	3.06	3.11	3.04	2.87	3.05
Permeate Flow Rate (gpm)	1.85	1.78	1.80	1.74	1.75	1.58	1.59	1.62	1.58	1.53	1.54	1.50	1.50
Reject Flow Rate (gpm)	1.81	1.83	1.80	1.78	1.79	1.60	1.62	1.54	1.60	1.65	1.52	1.47	1.55
Feed Water Recovery (%)	51.7	49.9	51.0	51.3	49.0	51.6	50.8	52.9	51.6	49.2	50.7	52.3	49.2
Membrane Operating Pressure (psig)	160	170	168	171	172	152	150	150	150	146	146	150	144
Concentrate Back-Pressure (psig)	156	169	166	169	170	150	146	148	146	144	144	146	140
Transmembrane Pressure (TMP) (psig)	158	170	167	170	171	151	148	149	148	145	145	148	142
Permeate Flux (normalized to 25°C) (gfd)	32.5	31.3	32.4	30.6	31.5	27.7	28.6	27.8	28.4	27.5	27.0	26.3	29.0
Specific Flux (gfd/psig)	0.21	0.18	0.19	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.19	0.18	0.20
30 Minute Operation Data													
System Influent Flow Rate (gpm)	3.58	3.57	3.53	3.44	3.53	3.03	3.09	3.01	3.01	3.06	3.04	2.87	3.05
Permeate Flow Rate (gpm)	1.83	1.78	1.75	1.75	1.76	1.57	1.57	1.58	1.52	1.52	1.53	1.52	1.49
Reject Flow Rate (gpm)	1.82	1.83	1.81	1.75	1.77	1.61	1.61	1.54	1.61	1.67	1.54	1.48	1.56
Membrane Operating Pressure (psig)	159	166	168	170	172	150	149	150	150	146	148	148	143
RO Concentrate Back-Pressure (psig)	154	164	166	168	170	146	146	146	146	144	145	144	139
Transmembrane Pressure (TMP) (psig)	157	165	167	169	171	148	148	148	148	145	147	146	141
Permeate Flux (normalized to 25°C) (gfd)	32.1	31.3	31.5	30.7	31.7	27.6	28.2	27.1	27.3	27.3	26.9	26.7	28.8
Specific Flux (gfd/psig)	0.21	0.19	0.19	0.18	0.19	0.19	0.19	0.18	0.18	0.19	0.18	0.18	0.20
Start-up Influent													
PH	7.8	7.6	7.4	7.5	7.4	7.7	7.4	7.7	7.3	7.4	7.3	7.2	4.9
Temperature (°C)	25	25	24	25	24	25	24	26	24	24	25	25	21
Total Chlorine (mg/L)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	ND (0.05)	0.05	ND (0.05)
TDS (mg/L)	800	740	710	770	810	770	550	790	790	740	750	810	ND (2)
Turbidity (NTU)	ND (0.1)	0.1	0.1	0.2	0.1	0.1	0.3	0.1	ND (0.1)	0.1	ND (0.1)	ND (0.1)	ND (0.1)
Start-up Effluent TDS (mg/L)	13	11	9	12	10	10	6	10	11	10	10	10	ND(2)
30-Minute Influent													
PH	7.8	7.6	7.3	7.5	7.5	7.7	7.4	7.7	7.3	7.4	–	7.3	4.8
TDS (mg/L)	800	740	700	770	790	780	540	800	790	750	740	800	ND (2)
30-Minute Effluent TDS (mg/L)	15	11	9	12	10	10	6	11	11	10	10	11	ND (2)

4.3 RO Membrane Microbial Challenges

The microbial challenges were conducted first, prior to the chemical challenges, to avoid any possibility that any residual chemical on the membrane could kill a portion of the challenge organisms, giving a positive bias to the performance of the membrane. However, bacteria challenge retests were necessary after the first chemical challenge of cadmium, cesium, and strontium had been conducted, because the measured influent concentrations for *B. diminuta* and KanR *B. diminuta* during the first bacteria challenges were too low. The data for the first round of bacteria challenges is not reported here.

Before the bacteria challenges were conducted a second time, the M-2400 was flushed with approximately 500 gallons of water. Then the system was taken off-line, and the test rig plumbing was sanitized with iodine.

Also, as discussed in the previous section, the *B. diminuta* challenge was conducted a third time (second reported set of data) to evaluate whether system performance would be better at a lower RO membrane operating pressure (149 psig versus 172 psig). The M-2400 was only flushed for approximately five minutes immediately prior to this last bacteria challenge, but it was also flushed for one hour immediately after the last chemical challenge.

The bacteria and virus challenge data is presented in Table 4-3. The water chemistry data for each challenge was presented in Table 4-1. For each sample point, the geometric mean of the triplicate CFU or PFU count is given. The CFU or PFU counts were $\log_{10}$ transformed, and $\log_{10}$ reductions were calculated for each sample point. Geometric mean influents and effluents were calculated for each challenge, and log reductions were also calculated from the means. The individual triplicate CFU/PFU counts for each sample point and the water chemistry data for each challenge can be found in Appendix A in Tables A-1 through A-5.

The M-2400 achieved mean reductions of approximately 3 logs for the viruses. The minimum log reduction was 2.5 for the fr challenge 15-minute sample point, and the maximum log reduction was 3.3 for both challenges at the start-up sample point.

The bacteria reduction data varied more than the virus data. The minimum log reduction was 1.3 for the 02/14/06 *B. diminuta* challenge start-up sample point, while the maximum log reduction was 3.5, achieved at both the 15-minute and 30-minute sample points for the KanR *B. diminuta* challenge. A comparison of the 02/14/06 *B. diminuta* challenge data to the 03/08/06 *B. diminuta* challenge data shows that the decrease in the RO membrane operating pressure did not improve the bacteria reduction performance of the system.

Table 4-3. M-2400 Microbial Challenge CFU or PFU Counts and Log Reductions

	MS2	fr	1st *B. diminuta*	KanR *B. diminuta*	2nd *B. diminuta* Challenge
Challenge Date	01/31/06	02/02/06	02/14/06	02/14/06	03/08/06
Start-up Samples					
Influent (CFU/100 mL or PFU/mL)	$7.1x10^4$	$1.28x10^5$	$3.0x10^7$	$6.6x10^6$	$8.6x10^6$
Log_{10} of Influent	4.9	5.11	7.5	6.8	6.9
Permeate (CFU/100 mL or PFU/mL)	38	66	$1.49x10^6$	$2.7x10^3$	$3.2x10^3$
Log_{10} of Permeate	1.6	1.8	6.17	3.4	3.5
Log_{10} Reduction	3.3	3.3	1.3	3.4	3.4
15-Minute Samples					
Influent (CFU/100 mL or PFU/mL)	$4.9x10^4$	$7.7x10^4$	$2.5x10^7$	$7.0x10^6$	$5.1x10^6$
Log_{10} of Influent	4.7	4.9	7.4	6.9	6.7
Permeate (CFU/100 mL or PFU/mL)	46	233	$1.24x10^4$	$2.8x10^3$	$2.55x10^4$
Log_{10} of Permeate	1.7	2.4	4.09	3.4	4.41
Log_{10} Reduction	3.0	2.5	3.3	3.5	2.3
30-Minute Samples					
Influent (CFU/100 mL or PFU/mL)	$4.9x10^4$	$8.5x10^4$	$1.0x10^7$	$7.5x10^6$	$7.5x10^6$
Log_{10} of Influent	4.7	4.9	7.0	6.9	6.9
Permeate (CFU/100 ml or PFU/mL)	69	116	$9.8x10^3$	$2.8x10^3$	$1.78x10^4$
Log_{10} of Permeate	1.8	2.1	4.0	3.4	4.25
Log_{10} Reduction	2.9	2.8	3.0	3.5	2.6
Means					
Influent (CFU/100 mL or PFU/mL)	**$5.5x10^4$**	**$9.4x10^4$**	**$2.0x10^7$**	**$7.0x10^6$**	**$6.9x10^6$**
Log_{10} of Influent	**4.7**	**5.0**	**7.3**	**6.9**	**6.8**
Permeate (CFU/100 mL or PFU/mL)	**49**	**121**	**$5.7x10^4$**	**$2.8x10^3$**	**$1.1x10^4$**
Log_{10} of Effluent	**1.7**	**2.1**	**4.8**	**3.4**	**4.1**
Log_{10} Reduction	**3.1**	**2.9**	**2.5**	**3.5**	**2.7**

4.4 RO Membrane Chemical Challenges

The RO membrane chemical challenge data is presented below in Table 4-4. The water chemistry data for each challenge was presented in Table 4-2. The samples from each sample point were analyzed in triplicate. The arithmetic means were calculated from the triplicate analyses for each sample point. The overall mean influents and permeates were then calculated for each challenge. Table 4-2 gives the overall mean influent and permeate for each challenge, and the percent reductions calculated from these numbers. See Tables A-6 and A-7 in Appendix A for the triplicate influent and effluent data for each sample point. Note that for non-detect effluent samples, the detection limits were used for the purpose of calculating the means and percent reductions.

As discussed in Section 4-2, the aldicarb, cadmium/cesium/strontium, paraquat, and strychnine challenges were conducted with the RO membrane operating pressure above 150 psig. However, in spite of this, the membrane performed well against all chemicals but mercury, which was expected based on the results of previous RO membrane ETV tests with mercury. Excluding the

mercury reduction data, the minimum percent reduction was 96%, for methomyl. Ten of the 15 chemicals were removed by greater than 99%.

Table 4-4. M-2400 Chemical Challenge Data

Chemical	Mean Influent (µg/L)	Mean Effluent (µg/L)	Percent Reduction
Aldicarb	830	3	>99
Benzene	680	6.4	>99
Cadmium	970	1.4	>99
Carbofuran	920	2.6	>99
Cesium	1100	16	99
Chloroform	790	28	97
Dichlorvos	1700	16	>99
Mercury	1200	750	38
Methomyl	990	45	96
Mevinphos	920	5.6	>99
Oxamyl	1000	4	>99
Paraquat	480	ND (1)	>99
Sodium Fluoroacetate	800	ND (20)	98
Strontium	990	2	>99
Strychnine	900	ND (5)	>99

4.5 MAXVOC Carbon Filter Chemical Challenges

As discussed in Section 3.4.3, prior to being challenged the MAXVOC carbon filter was conditioned to one-half of the stated chemical reduction capacity using water containing chloroform at a target concentration of 300 µg/L. The water chemistry data for the conditioning water is shown below in Table 4-5. Note that it appears that the influent and effluent chloroform samples at 1,300 gallons may have been mislabeled, and if so, the influent chloroform concentration was approximately twice what it should have been. However, if this is the case, the extra chloroform loaded onto the carbon did not adversely affect the performance of the filter, as evidenced by the carbon filter challenge data in Table 4-6.

Table 4-5. MAXVOC FF-975 Filter Conditioning Water Chemistry Data

Parameter	Start-Up	650 Gal.	1,300 Gal.
Influent Water Chemistry			
Chloroform (µg/L)	310	340	21
pH	7.3	7.2	7.4
Temperature (°C)	20	19	20
TDS (mg/L)	280	270	280
Total Chlorine (mg/L)	2.60	2.02	1.96
TOC* (mg/L)	1.7	1.9	3.2
Turbidity (NTU)	0.1	ND (0.1)	0.1
Effluent Chloroform (µg/L)	ND (0.5)	1.3	700

*Injection of chloroform into the influent stream was turned off when TOC samples were collected.

The filter was challenged with chloroform, dichlorvos, mercury, and methomyl based on the criteria that the MAXVOC carbon filter be challenged with the chemicals that the RO membrane did not remove to 20 µg/L or below at each sample point. The MAXVOC challenge data is presented below in Table 4-6. As with the RO membrane challenges, mean influents and effluents were calculated for each challenge. The individual triplicate influent and effluent data for each sample point is presented in Table A-8 in Appendix A. Note that the total chlorine level for the methomyl challenge water was only 0.32 mg/L. It was discovered that methomyl is chlorine sensitive, so the challenge water specified in Section 3.7.1.2 was treated by activated carbon filtration upstream of the challenge chemical injection point. Also, sodium thiosulfate was added to all samples collected for methomyl analysis.

The MAXVOC filter removed all four chemicals to a degree that the carbon filter and the M-2400 together as a treatment train would remove 99% or more of all of the challenge chemicals at a 1 mg/L concentration, except for sodium fluoroacetate, whose percent reduction was limited by the high detection limit.

Table 4-6. MAXVOC FF-975 Chemical Challenge Data

Sample	Chloroform (03/24/06)	Dichlorvos (03/24/06)	Mercury (03/22/06)	Methomyl (04/04/06)
Target Influent (µg/L)	72	25	910	48
Mean Influent (µg/L)	82	36	730	56
Mean Effluent (µg/L)	3.2	ND (0.2)	10	1
Percent Reduction	96	>99	99	98
Flow Rate (gpm)	1.90	1.89	1.89	1.88
Inlet Pressure (psig)	60.3	60.3	60.3	60.9
Start-up Water Chemistry				
pH	7.3	7.2	7.3	7.2
Temperature (°C)	20	21	20	21
TDS (mg/L)	290	270	260	290
Total Chlorine (mg/L)	2.26	1.96	2.44	0.32
TOC (mg/L)	1.9	2.1	1.9	1.8
Turbidity (NTU)	0.1	ND (0.1)	0.2	ND (0.1)
30-Minute pH	7.3	7.2	7.3	7.2

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Chapter 5
Quality Assurance/Quality Control

5.1 Introduction

An important aspect of verification testing is the QA/QC procedures and requirements. Careful adherence to the procedures ensured that the data presented in this report was of sound quality, defensible, and representative of the equipment performance. The primary areas of evaluation were representativeness, precision, accuracy, and completeness.

Because the ETV was conducted at the NSF testing lab, all laboratory activities were conducted in accordance with the provisions of the *NSF International Laboratories Quality Assurance Manual* (NSF 2004).

5.2 Test Procedure QA/QC

NSF testing laboratory staff conducted the tests by following a USEPA-approved test/QA plan created specifically for this verification. NSF QA Department staff performed an informal audit during testing to ensure the proper procedures were followed. The audit yielded no findings.

5.3 Sample Handling

All samples analyzed by the NSF Chemistry and Microbiology Laboratories were labeled with unique ID numbers. These ID numbers appear in the NSF laboratory reports for the tests. All samples were analyzed within allowable holding times.

5.4 Chemistry Analytical Methods QA/QC

The calibrations of all analytical instruments, and the analyses of all parameters complied with the QA/QC provisions of the *NSF International Laboratories Quality Assurance Manual*.

The NSF QA/QC requirements are all compliant with those given in the USEPA method or Standard Method for the parameter. Also, each analytical instrument has an NSF SOP governing its use.

5.5 Microbiology Laboratory QA/QC

5.5.1 Growth Media Positive Controls

All media were checked for sterility and positive growth response when prepared and when used for microorganism enumeration. The media was discarded if growth occurred on the sterility check media, or if there was an absence of growth in the positive response check. Both *E. coli* hosts for the viruses were plated on TSA and incubated with the virus enumeration plates during sample enumeration as a second positive growth control. *B. diminuta* from the stock cultures was plated on R2A agar and incubated with the bacteria enumeration plates as a positive control.

5.5.2 Negative Controls

All samples were enumerated in triplicate. For each sample batch processed, an unused membrane filter and a blank with 100 mL of PBDW filtered through the membrane were also placed onto the appropriate media and incubated with the samples as negative controls. No growth was observed on any blanks.

5.6 Documentation

All laboratory activities were documented using specially prepared laboratory bench sheets and NSF laboratory reports. Data from the bench sheets and laboratory reports were entered into Excel spreadsheets. These spreadsheets were used to calculate average influents and effluents, and $\log_{10}$ reductions for each challenge. One hundred percent of the data entered into the spreadsheets was checked by a reviewer to confirm all data and calculations were correct.

5.7 Data Review

NSF QA/QC staff reviewed the raw data records for compliance with QA/QC requirements. NSF ETV staff checked 100% of the data in the NSF laboratory reports against the lab bench sheets.

5.8 Data Quality Indicators

The quality of data generated for this ETV is established through four indicators of data quality: representativeness, accuracy, precision, and completeness.

5.8.1 Representativeness

Representativeness refers to the degree to which the data accurately and precisely represent the expected performance of the RO system under normal use conditions. The test protocol was designed to be a conservative evaluation of product performance. The test water was of very low turbidity to minimize the potential for microbial adhesion to suspended particles, which could enhance apparent log reduction. The surrogates were chosen because of their small size. The virus surrogate challenges were carried out at pH 6, 7.5, and 9 to assess whether pH affects the performance of the RO membrane.

Representativeness was ensured by consistent execution of the test protocol for each challenge, including timing of sample collection, sampling procedures, and sample preservation. Representativeness was also ensured by using each analytical method at its optimum capability to provide results that represent the most accurate and precise measurement it is capable of achieving.

5.8.2 Accuracy

Accuracy was quantified as the percent recovery of the parameter in a sample of known quantity. Accuracy was measured through use of both matrix spikes of a known quantity, and certified standards during calibration of an instrument. The following equation was used to calculate percent recovery:

$$\text{Percent Recovery} = 100 \times [(X_{known} - X_{measured})/X_{known}]$$

where: X_{known} = known concentration of the measured parameter
$X_{measured}$ = measured concentration of parameter

Accuracy of the benchtop chlorine, pH, TDS, and turbidity meters was checked daily during the calibration procedures using certified check standards. Alkalinity and total hardness were analyzed in batches. Certified QC standards and/or matrix spikes were run with each batch.

The percent recoveries of all matrix spikes and standards were within the allowable limits for all analytical methods.

5.8.3 Precision

Precision refers to the degree of mutual agreement among individual measurements and provides an estimate of random error. One sample per batch was analyzed in duplicate for the TDS measurements. Duplicate municipal drinking water samples were analyzed for pH, total chlorine, and turbidity as part of the daily calibration process. One out of every ten samples for alkalinity and total hardness was analyzed in duplicate. Precision of duplicate analyses was measured by use of the following equation to calculate relative percent difference (RPD):

$$RPD = \left| \frac{S_1 - S_2}{S_1 + S_2} \right| \times 200$$

where:

S_1 = sample analysis result; and

S_2 = sample duplicate analysis result.

All RPDs were within NSF's established allowable limits for each parameter. Please note that samples from this evaluation for alkalinity, TDS, and total hardness were batched with other non-ETV samples when being analyzed by the NSF laboratory. The duplicate analysis requirements apply to the whole batch, not just the samples from this ETV.

5.8.4 Completeness

Completeness is the proportion of valid, acceptable data generated using each method as compared to the requirements of the test/QA plan. The completeness objective for data generated during verification testing is based on the number of samples collected and analyzed for each parameter and/or method. Table 5-1 presents the completeness requirements.

Table 5-1. Completeness Requirements

Number of Samples per Parameter and/or Method	Percent Completeness
0-10	80%
11-50	90%
> 50	95%

Completeness is defined as follows for all measurements:

$$\%C = (V/T) \text{ X } 100$$

where:

%C = percent completeness;
V = number of measurements judged valid; and
T = total number of measurements.

5.8.4.1 Parameters with less than 100% Completeness

All parameters met the minimum completeness requirements presented in Table 5-1. However, a few samples were missed or did not have reportable results. The following parameters had less than 100% completeness:

- 15-Minute effluent samples for the fr challenge – One of the triplicate analyses was too numerous to count (TNTC) in the un-diluted sample, but was <1 PFU/mL in the $1x10^2$ dilution. No $1x10^1$ dilution was analyzed. Seventeen of eighteen fr samples were reported, giving a completeness of 94%.
- RO membrane chloroform challenge – pH was not measured at 30 minutes. A total of 36 pH measurements were required by the test plan. The one missed measurement gives a completeness of 97%.
- RO membrane mevinphos challenge – Triplicate sample 3 for the 30-minute effluent sample point was not reported due to low recovery of the internal standard for the sample. There was not enough sample left to re-extract the mevinphos and reanalyze for it. Eleven of twelve mevinphos samples had reportable data, giving a completeness of 92%.

5.9 Measurements Outside of the Test/QA Plan Specifications

- The RO membrane dichlorvos challenge influent samples were all above the maximum target concentration of 1.5 mg/L. The high challenge concentration may have caused the 30-Minute effluent samples to be over 20 μg/L, requiring the MAXVOC carbon filter be challenged with the chemical. However, the carbon filter removed the chemical to below the detection limit, so the high challenge concentration for the RO membrane challenge did not adversely affect the reported performance of the M-2400/MAXVOC filter combination.
- The influent sample concentrations for the RO membrane paraquat challenge were all below the minimum target concentration of 0.5 mg/L. However, the effluent samples were all below the detection limit of 1 μg/L. The challenge was not conducted again because it is unlikely that doubling the influent challenge concentration would lead to an increase in the effluent concentration to 20 μg/L or above.
- The TDS of the RO membrane oxamyl challenge water was 550 mg/L at start-up, and 540 mg/L at 30 minutes. This is below the minimum target level of 675 mg/L. The low TDS level is not a significant deviation from the test plan because the target TDS concentration of 750 mg/L is mainly to provide an adequate TDS challenge to the membrane along with the challenge chemical to serve as a membrane integrity check. An influent TDS concentration of 550 mg/L was adequate to accomplish this goal.
- Total chlorine is specified as less then the detection limit of 0.05 mg/L for the RO membrane challenge water; exposure to chlorine can adversely affect the integrity of RO membranes. For the benzene RO membrane challenge, total chlorine was measured at the detection limit of 0.05 mg/L. This is not a significant deviation, because the chlorine concentration was too low to be of a concern.

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Chapter 6
References

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Appendix A
Challenge Data

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Table A-1. First *B. diminuta* Challenge

Sample	Influent/Permeate Triplicate Counts (CFU/100mL)	Influent/Permeate Geometric Mean(CFU/100mL)	Log_{10} Influent/ Permeate	Log_{10} Reduction
Start-Up Influent	$3.5x10^7$, $3.0x10^7$, $2.6x10^7$	$3.0x10^7$	7.5	
15-Minute Influent	$2.3x10^7$, $2.7x10^7$, $2.6x10^7$	$2.5x10^7$	7.4	
30-Minute Influent	$1.76x10^7$, $2.7x10^7$, $2.15x10^6$	$1.0x10^7$	7.0	
Mean Influent		$2.0x10^7$	7.3	
Start-Up Permeate	$1.51x10^6$, $1.36x10^6$, $1.62x10^6$	$1.49x10^6$	6.17	1.3
15-Minute Permeate	$1.35x10^4$, $1.20x10^4$, $1.17x10^4$	$1.24x10^4$	4.09	3.3
30-Minute Permeate	$1.12x10^4$, $9.7x10^3$, $8.7x10^3$	$9.8x10^3$	4.0	3.0
Mean Permeate		$5.7x10^4$	4.8	2.5

Table A-2. Second *B. diminuta* Challenge

Sample	Influent/Permeate Triplicate Counts (CFU/100mL)	Influent/Permeate Geometric Mean(CFU/100mL)	Log_{10} Influent/ Permeate	Log_{10} Reduction
Start-Up Influent	$8.7x10^6$, $7.9x10^6$, $9.2x10^6$	$8.6x10^6$	6.9	
15-Minute Influent	$6.7x10^6$, $3.2x10^6$, $6.1x10^6$	$5.1x10^6$	6.7	
30-Minute Influent	$9.0x10^6$, $9.9x10^6$, $4.7x10^6$	$7.5x10^6$	6.9	
Mean Influent		$6.9x10^6$	6.8	
Start-Up Permeate	$9.9x10^3$, $2.5x10^3$, $1.3x10^3$	$3.2x10^3$	3.5	3.4
15-Minute Permeate	$3.15x10^4$, $2.48x10^4$, $2.12x10^4$	$2.55x10^4$	4.41	2.3
30-Minute Permeate	$1.67x10^4$, $1.98x10^4$, $1.71x10^4$	$1.78x10^4$	4.25	2.6
Mean Permeate		$1.1x10^4$	4.1	2.7

Table A-3. Kanamycin Resistant *B. diminuta*

Sample	Influent/Permeate Triplicate Counts (CFU/100mL)	Influent/Permeate Geometric Mean(CFU/100mL)	Log_{10} Influent/ Permeate	Log_{10} Reduction
Start-Up Influent	$7.5x10^6$, $5.7x10^6$, $6.6x10^6$	$6.6x10^6$	6.8	
15-Minute Influent	$7.7x10^6$, $8.5x10^6$, $5.3x10^6$	$7.0x10^6$	6.9	
30-Minute Influent	$6.6x10^6$, $8.8x10^6$, $7.3x10^6$	$7.5x10^6$	6.9	
Mean Influent		$7.0x10^6$	6.9	
Start-Up Permeate	$2.8x10^3$, $2.5x10^3$, $2.8x10^3$	$2.7x10^3$	3.4	3.4
15-Minute Permeate	$3.0x10^3$, $2.5x10^3$, $2.8x10^3$	$2.8x10^3$	3.4	3.5
30-Minute Permeate	$2.7x10^3$, $3.3x10^3$, $2.5x10^3$	$2.8x10^3$	3.4	3.5
Mean Permeate		$2.8x10^3$	3.4	3.5

Table A-4. fr Challenge

	Influent/Permeate Triplicate Counts (PFU/mL)	Influent/Permeate Geometric Mean (PFU/mL)	Log_{10} Influent/ Permeate	Log_{10} Reduction
Start-Up Influent	$1.52x10^5$, $1.38x10^5$, $1.01x10^5$	$1.28x10^5$	5.11	
15-Minute Influent	$7.1x10^4$, $6.7x10^4$, $9.6x10^4$	$7.7x10^4$	4.9	
30-Minute Influent	$8.5x10^4$, $9.5x10^4$, $7.6x10^4$	$8.5x10^4$	4.9	
Mean Influent		$9.4x10^4$	5.0	
Start-Up Permeate	63, 54, 85	66	1.8	3.3
15-Minute Permeate	245, 222, #	233	2.4	2.5
30-Minute Permeate	143, 110, 99	116	2.1	2.8
Mean Permeate		121	2.1	2.9

Table A-5. MS2 Challenge

	Influent/Permeate Triplicate Counts (PFU/mL)	Influent/Permeate Geometric Mean (PFU/mL)	Log_{10} Influent/ Permeate	Log_{10} Reduction
Start-Up Influent	$7.2x10^4$, $6.7x10^4$, $7.3x10^4$	$7.1x10^4$	4.9	
15-Minute Influent	$4.6x10^4$, $5.2x10^4$, $5.0x10^4$	$4.9x10^4$	4.7	
30-Minute Influent	$4.6x10^4$, $5.4x10^4$, $4.7x10^4$	$4.9x10^4$	4.7	
Mean Influent		$5.5x10^4$	4.7	
Start-Up Permeate	37, 36, 40	38	1.6	3.3
15-Minute Permeate	47, 49, 42	46	1.7	3.0
30-Minute Permeate	80, 56, 72	69	1.8	2.9
Mean Permeate		49	1.7	3.1

Table A-6. Organic Chemical RO Membrane Challenges

Sample	Aldicarb (µg/L)	Benzene (µg/L)	Carbofuran (µg/L)	Chloroform (µg/L)	Dichlorvos (µg/L)	Methomyl (µg/L)	Mevinphos (µg/L)	Oxamyl (µg/L)	Paraquat (µg/L)	Sodium Fluoroacetate (µg/L)	Strychnine (µg/L)
Start-up Influent											
Triplicate Sample 1	840	750	930	800	1600	950	830	1100	540	1400	890
Triplicate Sample 2	840	690	920	830	1600	1000	870	1000	450	660	900
Triplicate Sample 3	830	660	910	800	1700	1000	950	1100	470	680	900
Mean	**840**	**700**	**920**	**810**	**1600**	**980**	**880**	**1100**	**490**	**910**	**900**
Start-up Permeate											
Triplicate Sample 1	3	ND (0.5)	1.7	1.3	5.1	40	5.2	3	ND (1)	ND (20)	ND (5)
Triplicate Sample 2	3	ND (0.5)	1.8	1.7	7.4	42	5.5	4	ND (1)	ND (20)	ND (5)
Triplicate Sample 3	3	ND (0.5)	1.9	1.5	11	42	4.5	4	ND (1)	ND (20)	ND (5)
Mean	**3**	**ND (0.5)**	**1.8**	**1.5**	**7.8**	**41**	**5.1**	**4**	**ND (1)**	**ND (20)**	**ND (5)**
30-Minute Influent											
Triplicate Sample 1	830	670	920	740	2000	1000	950	1000	470	680	900
Triplicate Sample 2	820	640	910	750	1700	1000	1000	1000	460	680	890
Triplicate Sample 3	830	650	930	830	1800	1000	940	1000	470	670	890
Mean	**830**	**650**	**920**	**770**	**1800**	**1000**	**960**	**1000**	**470**	**680**	**890**
30-Minute Permeate											
Triplicate Sample 1	3	12	3.4	43	25	48	6.5	4	ND (1)	ND (20)	ND (5)
Triplicate Sample 2	3	13	3.4	46	23	48	6.4	4	ND (1)	ND (20)	ND (5)
Triplicate Sample 3	3	12	3.4	72	24	48	#	4	ND (1)	ND (20)	ND (5)
Mean	**3**	**12**	**3.4**	**54**	**24**	**48**	**6.5**	**4**	**ND (1)**	**ND (20)**	**ND (5)**
Overall Mean Influent	**830**	**680**	**920**	**790**	**1700**	**990**	**920**	**1000**	**480**	**800**	**900**
Overall Mean Permeate	**3**	**6.4**	**2.6**	**28**	**16**	**45**	**5.6**	**4**	**ND (1)**	**ND (20)**	**ND (5)**
Percent Reduction	**>99**	**>99**	**>99**	**97**	**>99**	**96**	**>99**	**>99**	**>99**	**98**	**>99**

Table A-7. Inorganic Chemical RO Membrane Challenges

Sample	Cadmium (µg/L)	Cesium (µg/L)	Mercury (µg/L)	Strontium (µg/L)
Start-up Influent				
Triplicate Sample 1	1000	1100	1100	1000
Triplicate Sample 2	1000	1100	1100	1000
Triplicate Sample 3	990	1100	1100	1000
Mean	**1000**	**1100**	**1100**	**1000**
Start-up Permeate				
Triplicate Sample 1	0.4	20	650	1
Triplicate Sample 2	0.8	14	580	1
Triplicate Sample 3	0.6	13	540	1
Mean	**0.6**	**16**	**590**	**1**
30-Minute Influent				
Triplicate Sample 1	940	1000	1200	970
Triplicate Sample 2	980	1100	1200	1000
Triplicate Sample 3	930	1000	1200	970
Mean	**950**	**1000**	**1200**	**980**
30-Minute Permeate				
Triplicate Sample 1	2.3	16	890	2
Triplicate Sample 2	2.2	16	910	2
Triplicate Sample 3	2.3	16	900	2
Mean	**2.3**	**16**	**900**	**2**
Overall Mean Influent	**970**	**1100**	**1200**	**990**
Overall Mean Permeate	**1.4**	**16**	**750**	**2**
Percent Reduction	**>99**	**99**	**38**	**>99**

Table A-8. MAXVOC Carbon Filter Challenges

Sample	Chloroform (µg/L)	Dichlorvos (µg/L)	Mercury (µg/L)	Methomyl (µg/L)
Target Influent Conc.	72	25	910	48
Start-up Influent				
Triplicate Sample 1	79	38	790	55
Triplicate Sample 2	74	43	830	56
Triplicate Sample 3	80	29	750	57
Mean	**78**	**37**	**790**	**56**
Start-up Effluent				
Triplicate Sample 1	2.9	ND (0.2)	7.6	ND (1)
Triplicate Sample 2	3.1	ND (0.2)	7.1	ND (1)
Triplicate Sample 3	2.9	ND (0.2)	6.5	ND (1)
Mean	**3.0**	**ND (0.2)**	**7.1**	**ND (1)**
30-Minute Influent				
Triplicate Sample 1	88	33	580	57
Triplicate Sample 2	84	40	720	56
Triplicate Sample 3	85	35	690	56
Mean	**86**	**36**	**660**	**56**
30-Minute Effluent				
Triplicate Sample 1	3.4	ND (0.2)	13	ND (1)
Triplicate Sample 2	3.6	ND (0.2)	12	ND (1)
Triplicate Sample 3	3.5	ND (0.2)	12	2
Mean	**3.5**	**ND (0.2)**	**12**	**1**
Overall Mean Influent	**82**	**36**	**730**	**56**
Overall Mean Permeate	**3.2**	**ND (0.2)**	**10**	**1**
Percent Reduction	**96**	**>99**	**99**	**98**