September 2009
NSF 09/26/EPADWCTR
EPA/600/R-09/075

Environmental Technology Verification Report

Removal of Microbial Contaminants in Drinking Water

Koch Membrane Systems, Inc. Targa® 10-48-35-PMC™ Ultrafiltration Membrane, as Used in the Village Marine Tec. Expeditionary Unit Water Purifier

Prepared by

NSF International

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

ETV ETV ETV

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**ULTRAFILTRATION MEMBRANE MODULE**
APPLICATION:	**REMOVAL OF MICROBIAL CONTAMINANTS IN DRINKING WATER**
PRODUCT NAME:	**TARGA® 10-48-35-PMC™ ULTRAFILTRATION MEMBRANE MODULE, AS USED IN THE VILLAGE MARINE TEC. EXPEDITIONARY UNIT WATER PURIFIER**
VENDOR:	**KOCH MEMBRANE SYSTEMS, INC.**
ADDRESS:	**850 MAIN STREET WILMINGTON, MA 01887**
PHONE:	**MAIN - 888-677-5624 CUSTOMER SERVICE – 800-343-0499**
FAX:	**978-657-5208**
EMAIL:	**INFO@KOCHMEMBRANE.COM**

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 Koch Membrane Systems, Inc. Targa® 10-48-35-PMC™ Ultrafiltration (UF) Membrane, as used in the Village Marine Tec. Expeditionary Unit Water Purifier. 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 test.

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

Testing of the Koch Membrane Systems, Inc. Targa® 10-48-35-PMC™ Ultrafiltration (UF) Membrane was conducted as part of the ETV verification of the US Navy Office of Naval Research's (ONR) Expeditionary Unit Water Purifier (EUWP), manufactured by Village Marine Tec. The EUWP uses the Targa 10-48-35-PMC membrane module in the UF treatment step. During field verification testing of the EUWP, removal of *Bacillus* endospores was measured as a surrogate for removal of *Cryptosporidium parvum* oocysts (see the full verification report for a discussion about the appropriateness of using *Bacillus* endospores as a surrogate for *C. parvum*). The observed log reductions were below what had previously been observed during lab challenge testing of the same UF membrane fibers, indicating that either there were membrane integrity problems, or that there were endospores present on the filtrate side of the UF modules that were sloughing off. To test whether there was poor membrane integrity within the UF modules, NSF and EPA had the field testing organization randomly select two UF modules from the field tested EUWP and send them to NSF to conduct additional microbial challenges under controlled laboratory conditions.

The UF modules were challenged with approximately 4 $\log_{10}$ per milliliter (mL) of *B. atrophaeus* endospores, and 5 $\log_{10}$ per liter (L) of formalin-fixed *C. parvum* oocysts. Each challenge test was 30 or 45 minutes in length, and was conducted at a target flux of 38 gallons per day per square foot (gfd), which is the target flux for UF module operation in the EUWP. The membranes removed a minimum of 2.4 $\log_{10}$ per mL of *B. atrophaeus*, and 4.3 $\log_{10}$ per L of *C. parvum*.

PRODUCT DESCRIPTION

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

The UF modules used in the EUWP are Koch Targa 10-48-35-PMC membrane modules, with endcaps designed and manufactured by Village Marine Tec. The Targa 10-48-35-PMC is a 10.75 inch x 48 inch module (not including the endcaps). The membrane fibers are made of polysulfone, with a nominal fiber inner diameter of 0.9 millimeters. The nominal membrane surface area for the module, using the fiber inner diameter, is 554 square feet. The nominal molecular weight cutoff rating for the membrane is 100,000 Daltons.

VERIFICATION TESTING DESCRIPTION

Selection of Modules

After completion of field testing of the EUWP UF system at Selfridge Air National Guard Base in July and August of 2007, two UF modules from the EUWP were chosen at random for the lab challenge tests. The modules chosen were serial numbers KM840643-4015 and KM849697-5021. Prior to the summer 2007 field test, each UF module was individually integrity tested using a pressure decay test. The pressures were measured from 0 to 10 minutes, with a starting applied pressure of approximately 15 psig. KM840643-4015 had a pressure decay rate of 0.21 psig/min. This module was checked for compromised fibers; one was found and plugged. KM840643-4015 was then retested, and the new pressure decay rate was 0.17 psig/min. KM849697-5021 had a pressure decay rate of 0.13 psig/min. No fibers were plugged for this module. For the tests described in this VS, KM840643-4015 was designated as Module 1, and KM849697-5021 was designated as Module 2.

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.

Methods and Procedures

The testing methods are detailed in the document *Test/QA Plan for the Microbial Seeding Challenge Study of the Koch Membrane Systems Targa 10-48-35-PMC UF Membrane*. Two UF membrane modules were tested for removal of pathogenic protozoa using two different surrogate organisms – endospores of the bacteria *Bacillus atrophaeus* (ATCC 9372, deposited as *B. subtilis* var. *niger*), and formalin-fixed *C. parvum* oocysts. *Bacillus* endospores were chosen as a challenge organism because field testing of the EUWP also examined *Bacillus* endospore removal. Note that the test protocol was not designed to achieve the regulatory requirements for membranes under the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). This verification did not address long-term performance, membrane cleaning, or full-scale field maintenance and operation issues. These items are addressed in the verification reports for the full EUWP system.

The testing was conducted in December 2007 and February 2008. In December 2007 the UF membranes were challenged with both *Bacillus* endospores and *C. parvum*. In February 2008, the membranes were challenged again with *C. parvum* to confirm that the oocysts found in one filtrate sample from the December 2007 test was not due to sample contamination.

The UF modules were not sanitized immediately prior to testing. The UF modules were cleaned in September 2007 following EUWP field testing. The cleaning procedure used was that prescribed in the EUWP operation and maintenance manual. Prior to the challenge tests, the modules were flushed for approximately 15 minutes using deionized water.

Before and after testing, the membranes underwent a pressure decay membrane integrity test following the procedure in ASTM Standard D6908 – *Standard Practice for Integrity Testing of Water Filtration Membrane Systems*.

Each UF module was tested individually. The membranes were challenged with both organisms simultaneously. In the EUWP, the Targa 10-48-35-PMC is operated at a target flux of 38 gfd, with a reject flow rate of 10% of the feed flow. To approximate these operation conditions, the target feed flow rate was set at 16.2 gallons per minute (gpm), and the target filtrate flow rate was 14.6 gpm. For the December 2007 tests, the membranes were challenged with each organism for 30 minutes, with feed and filtrate samples collected at start-up, 15 minutes, and 30 minutes. For the February 2008 *C. parvum* retest, the membranes were challenged for 45 minutes, with feed and filtrate samples collected at 15, 30, and 45 minutes. All samples were analyzed for the challenge organism(s) in triplicate.

VERIFICATION OF PERFORMANCE

For presentation of the challenge organism data, the observed triplicate feed and filtrate counts were averaged by calculating geometric means. Non-detect results were treated as one organism per unit volume for the purpose of calculating the means.

Table VS-1 presents the *B. atrophaeus* endospores data. Note that endospores were found in the module flush samples, despite the UF system chemical cleaning that was conducted after the August 2007 field test of the EUWP UF system. The modules were forward flushed for 15 minutes on December 10 using deionized water, and the flush samples were collected at the end of this flush. The modules were flushed again on December 11 for approximately one minute immediately prior to conducting the microbial challenges. The module flush samples had no *C. parvum*, but greater than 1 $\log_{10}$ of endospores (25 and 15 CFU/100 mL). Tryptic Soy Agar (TSA) was supposed to be substituted for nutrient agar in the SM9218 enumeration method for the endospores, in order to be able to distinguish the challenge endospores from wild-type endospores already present in the membrane modules from the field testing. *B. atrophaeus* gives orange colonies with a distinctive morphology on TSA. However, due to

miscommunication between the DWS Center and the NSF Microbiology Lab, the *B. atrophaeus* endospores were enumerated on nutrient agar, so they could not be distinguished from the wild-type endospores.

The log removal value (LRV_{test}) for the endospore challenges show log removals between 2 and 3, but this data cannot be considered a true picture of UF module performance due to the flush sample counts. It is possible that many of the endospores in the filtrate samples did not come through the membranes, but rather were already present on the filtrate side due to contamination from the previous field tests. At time 0 the endospore counts for both modules were higher than those at 15 and 30 minutes, indicating that the endospores continued to be rinsed out of the filtrate side after the start of the challenges. The UF modules were chemically cleaned at the end of the August 2007 field test, but it is possible that the cleaning procedure did not completely remove all of the endospores.

Table VS-1. December 2007 *B. atrophaeus* Endospores Reduction Data

		Feed		Filtrate		
	Sample Point	Geometric Mean (CFU/mL)	Log_{10}	Geometric Mean (CFU/mL)	Log_{10}	Log Reduction
Module 1	Flush			24.8	1.4	
	Start-Up	$1.74x10^4$	4.24	69	1.8	2.4
	15 Minutes	$1.57x10^4$	4.20	13	1.1	3.1
	30 Minutes	$1.66x10^4$	4.22	14	1.2	3.0
	Overall Geometric Mean	$1.66x10^4$	4.22	23	1.4	2.8
Module 2	Flush			15	1.2	
	Start-Up	$2.02x10^4$	4.31	175	2.2	2.1
	15 Minutes	$1.65x10^4$	4.22	57	1.8	2.4
	30 Minutes	$1.75x10^4$	4.24	47	1.7	2.5
	Overall Geometric Mean	$1.80x10^4$	4.26	78	1.9	2.4

Table VS-2 presents the December 2007 *C. parvum* challenge data, and Table VS-3 the February 2008 *C. parvum* challenge data. For the December 2007 test, all filtrate samples were below the detection limit, except for the Module 2 30-minute sample. Because oocysts were found in this sample, *C. parvum* retests were conducted in February 2008. No *C. parvum* was detected in the Module 1 filtrate samples from the December 2007 challenge, but it was found in both the 30-minute and 45-minute samples from the retest. *C. parvum* was also found in the Module 2 30-minute filtrate sample, as was the case with the December 2007 challenge. However, no *C. parvum* was detected in the Module 2 45-minute filtrate sample. In spite of the *C. parvum* filtrate counts, the UF membrane still removed greater than 4 logs of the oocysts.

Table VS-2. December 2007 *C. parvum* Reduction Data

		Feed		Filtrate		
	Sample Point	Geometric Mean (Cysts/L)	Log_{10}	Geometric Mean (Cysts/L)	Log_{10}	Log Reduction
Module 1	Flush			<1	0.0	
	Start-Up	$1.2x10^5$	5.1	<1	0.0	5.1
	15 Minutes	$7.5x10^4$	4.9	<1	0.0	4.9
	30 Minutes	$7.1x10^4$	4.9	<1	0.0	4.9
	Overall Geometric Mean	$8.6x10^4$	5.0	<1	0.0	5.0
Module 2	Flush			<1	0.0	
	Start-Up	$1.1x10^5$	5.0	<1	0.0	5.0
	15 Minutes	$8.4x10^4$	4.9	<1	0.0	4.9
	30 Minutes	$8.4x10^4$	4.9	47	1.7	3.2
	Overall Geometric Mean	$9.2x10^4$	4.9	3.6	0.6	4.3

Table VS-3. February 2008 *C. parvum* Reduction Retest Data						
		Feed		Filtrate		
	Sample Point	Geometric Mean (Cysts/L)	Log_{10}	Geometric Mean (Cysts/L)	Log_{10}	Log Reduction
Module 1	Flush			<1	0.0	
	Start-Up	$6.3x10^4$	4.8	<1	0.0	4.8
	30 Minutes	$6.2x10^4$	4.8	2	0.4	4.4
	45 Minutes	$7.9x10^4$	4.9	1	0.0	4.9
	Overall Geometric Mean	$6.8x10^4$	4.8	0.7	0.0	4.7
Module 2	Flush			<1	0.0	
	Start-Up	$5.7x10^4$	4.8	<1	0.0	4.8
	30 Minutes	$5.6x10^4$	4.8	4	0.6	4.2
	45 Minutes	$5.1x10^4$	4.7	<1	0.0	4.7
	Overall Geometric Mean	$5.5x10^4$	4.7	1.6	0.2	4.5

The December 2007 and February 2008 pre-test and post-test pressure decay rate calculations are shown in Tables VS-4 and VS-5, respectively. Note that two pressure decay rates were calculated, one for the entire test, and another for just the span of 10 to 20 minutes. The 10 to 20 minute calculation was included because ASTM D6908 suggests allowing the pressure decay rate to stabilize before conducting the official pressure decay test. The higher pressure decay rate was not reflected in the *Bacillus* endospore and *C.parvum* reduction data. It is possible that the higher Module 1 pressure decay rate was due to air leaks out of the temporary plumbing on the test rig.

Table VS-4. December 2007 Pressure Decay Rates				
	Pre-Test		Post-Test	
Time (min.)	Module 1	Module 2	Module 1	Module 2
10-20 Minute Pressure Decay Rate (psig/min)	0.3	0.08	0.45	0.08
0-20 Minute Pressure Decay Rate (psig/min)	0.35	0.09	0.74	0.1

Table VS-5. February 2008 Pressure Decay Test Data				
	Pre-Test		Post-Test	
Time (min.)	Module 1	Module 2	Module 1	Module 2
10-20 Minute Pressure Decay Rate (psig/min)	0.3	0.2	0.4	0.2
0-20 Minute Pressure Decay Rate (psig/min)	0.6	0.25	0.4	0.2

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 09/29/09

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

Original signed by Robert Ferguson 09/11/09

Robert Ferguson Date
Vice President
Water Systems
NSF International

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

Availability of Supporting Documents

Copies of the test protocol, the verification statement, and the verification report (NSF report # NSF 09/26/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/info/etv
   EPA web site: http://www.epa.gov/etv

September 2009

Environmental Technology Verification Report

Removal of Microbial Contaminants in Drinking Water

Koch Membrane Systems, Inc.
Targa® 10-48-35-PMC™ Ultrafiltration Membrane, as Used in the Village Marine Tec. Expeditionary Unit Water Purifier

Prepared by:

Mike Blumenstein, Senior Project Manager
Bruce Bartley, Technical Manager
NSF International
Ann Arbor, Michigan 48105

and

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

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

Notice

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded and managed, or partially funded and collaborated in, the research described herein. It has been subjected to the Agency's peer and administrative review and has been approved for publication. Any opinions expressed in this report are those of the author (s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Foreword

The EPA is charged by Congress with protecting the nation's air, water, and land 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, the EPA's Office of Research and Development provides data and science support that can be used to solve environmental problems and to build the scientific knowledge base needed to manage our ecological resources wisely, to understand how pollutants affect our health, and to prevent or reduce environmental risks.

The Environmental Technology Verification (ETV) Program has been established by the EPA to verify the performance characteristics of innovative environmental technology across all media and to report this objective information to permitters, buyers, and users of the technology, thus substantially accelerating the entrance of new environmental technologies into the marketplace. Verification organizations oversee and report verification activities based on testing and quality assurance protocols developed with input from major stakeholders and customer groups associated with the technology area. ETV consists of six environmental technology centers. Information about each of these centers can be found on the internet at http://www.epa.gov/etv.

Under a cooperative agreement, NSF International has received EPA funding to plan, coordinate, and conduct technology verification studies for the ETV "Drinking Water Systems Center" and report the results to the community at large. The DWS Center has targeted drinking water concerns such as arsenic reduction, microbiological contaminants, particulate removal, disinfection by-products, radionuclides, and numerous chemical contaminants. Information concerning specific environmental technology areas can be found on the internet at http://www.epa.gov/nrmrl/std/etv/verifications.html.

Acknowledgments

The authors wish to acknowledge the support of all those who helped plan and conduct the verification test, analyze the data, and prepare this report. We sincerely appreciate the involvement and support of all staff from the NSF testing laboratory who were involved with testing activities for this verification. In particular, we would like to thank Rob Herman, Director of the NSF Drinking Water Treatment Systems Laboratory, William Allen III, the lead laboratory technician for this project, Robert Donofrio, PhD, Director of the NSF Microbiology Laboratory, Robin Bechanko, Senior Microbiologist, and Joe Terrell, Supervisor of QA and Safety.

Finally, we would like to thank Richard Sakaji, PhD, East Bay Municipal Utility District, and Craig Patterson, U.S. EPA, for their reviews of this verification report.

Table of Contents

Appendices

List of Tables

List of Figures

Abbreviations and Acronyms

ALCR	air-liquid conversion ratio
ASTM	ASTM International
ATCC	American Type Culture Collection
°C	degrees Celsius
CFU	colony forming units
cm	centimeter
Da	Daltons
DWS	Drinking Water Systems
EPM	electrophoretic mobility
ETV	Environmental Technology Verification
EUWP	Expeditionary Unit Water Purifier
°F	degrees Fahrenheit
ft^2	square feet
FTO	Field Testing Organization
gfd	gallons per square foot per day
gpd	gallons per day
gpm	gallons per minute
h	hours
HCl	hydrochloric acid
HPC	heterotrophic plate count
in	inch(es)
L	liter
Lpm	liters per minute
LRV	log removal value
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MFGM	Membrane Filtration Guidance Manual
mg	milligram
mL	milliliter
mm	millimeter
mM	milliMolar
MWCO	molecular weight cutoff
NaOH	sodium hydroxide
ND	non-detect
NRMRL	National Risk Management Research Laboratory
NSF	NSF International (formerly known as National Sanitation Foundation)
NSWCCD	Naval Surface Warfare Command – Carderock Division
NTU	Nephelometric Turbidity Unit
ONR	Office of Naval Research
ORD	Office of Research and Development
psi	pounds per square inch
psig	pounds per square inch, gauge
QA	quality assurance
QC	quality control

QMP	Quality Management Plan
RPD	relative percent difference
SM	Standard Methods for the Examination of Water and Wastes
SNL	Sandia National Laboratory
SOP	standard operating procedure
TARDEC	Tank Automotive Research, Development, and Engineering Center
TDS	total dissolved solids
TOC	total organic carbon
TSA	tryptic soy agar
UF	ultrafiltration
µg	microgram
µm	micrometer
µS	microSiemens
USBR	United States Bureau of Reclamation
USEPA	United States Environmental Protection Agency
VCF	volumetric concentration factor

Chapter 1
Introduction

1.1 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; 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

Testing of the Koch Membrane Systems, Inc. Targa® 10-48-35-PMC™ Ultrafiltration (UF) Membrane was conducted as part of the ETV verification of the US Navy Office of Naval Research's (ONR) Expeditionary Unit Water Purifier (EUWP), manufactured by Village Marine Tec. The EUWP uses the Targa 10-48-35-PMC membrane module in the UF treatment step. During field verification testing of the EUWP, removal of *Bacillus* endospores was measured as a surrogate for removal of *Cryptosporidium parvum* (see Appendix A for a discussion about the appropriateness of using *Bacillus* endospores as a surrogate for *C. parvum*). The observed log reductions were below what had previously been observed during lab challenge testing of the same UF membrane fibers, indicating that either there were membrane integrity problems, or that there were endospores present on the filtrate side of the UF modules that were sloughing off. To test whether there was poor membrane integrity within the UF modules, NSF and EPA had the field testing organization randomly select two UF modules from the field tested EUWP and send them to NSF to conduct additional microbial challenges under controlled laboratory conditions.

Note that the test protocol was not designed to achieve the regulatory requirements for membranes under the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR).

Also, this verification does not address long-term performance over the life of the membrane, cleaning of the membranes, nor any other maintenance and operation. These items are covered under verification testing of the full-scale EUWP.

1.3 Testing Participants and Responsibilities

EUWP design, construction, and testing was overseen by a federal multi-agency team composed of representatives from Office of Naval Research (ONR); Army Tank-Automotive Research, Development, and Engineering Center (TARDEC); Naval Surface Warfare Command – Carderock Division (NSWCCD); United States Department of Interior Bureau of Reclamation (USBR); and Sandia National Laboratories (SNL). The manufacturer, Village Marine Tec., was contracted to design and build the EUWP to the team's Generation 1 specifications using the above requirements and 2004 state-of-the-art technology.

The organizations involved with verification testing were:

- NSF
- USEPA
- ONR
- TARDEC
- USBR
- Village Marine Tec.

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

1.3.1 NSF International

NSF is an independent, not-for-profit organization dedicated to public health and safety, and to protection of the environment. Founded in 1944 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, MI 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
Contact: Mr. Bruce Bartley, Project Manager
Email: bartley@nsf.org

1.3.2 U.S. Environmental Protection Agency

USEPA, through its Office of Research and Development (ORD), 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.

1.3.3 U.S. Navy ONR

The U.S. Navy Office of Naval Research provided oversight of the EUWP development program which involved developing high productivity water treatment units for land and shipboard military and civilian emergency preparedness applications. The Office of Naval Research also provided funding for the EUWP ETV testing project.

Contact Information:
Office of Naval Research
Logistics Thrust Program
Operations Technology Division
800 N. Quincy St.
Arlington, VA 22217
Contact: Major Alan Stocks
Phone: 703-696-2561
Email: stocksa@onr.navy.mil

1.3.4 U.S. Army TARDEC

TARDEC served as the field testing organization (FTO) for the full EUWP verifications at Selfridge Air National Guard Base, MI and Port Hueneme, CA.

Contact Information:
U.S. Army TARDEC
c/o NFESC, ESC32
1100 23rd Avenue
Point Hueneme, CA 93043
Contact: Mr. Mark Miller
Phone: 805-982-1315
Email: mark.c.miller@navy.mil

1.3.5 U.S. Bureau of Reclamation

USBR was the FTO for the full EUWP verification in Gallup, NM. USBR also provided field operations and technical support for the other field verification tests.

Contact Information:
U.S. Bureau of Reclamation
Denver Federal Center (D-8230), PO Box 25007
Denver, CO 80225
Contact: Ms. Michelle Chapman
Phone: 303-445-2264
Email: mchapman@do.usbr.gov

1.3.6 Koch Membrane Systems, Inc.

Koch Membrane Systems, Inc. supplies the UF membranes for the EUWP. Koch Membrane Systems, Inc. was responsible for providing logistical and technical support, as needed.

Contact Information: Koch Membrane Systems, Inc.
850 Main Street
Wilmington, MA 01887

Chapter 2
Product Description

2.1 UF Membranes General Description

UF membranes remove contaminants from water through sieving based on the size of the membrane pores relative to the physical size of the contaminant. A common arrangement for the membranes is in hollow fibers, with the fibers "potted" in a resin. The flow of water through the fibers is typically "inside-out," where the water flows into the inside of the fibers at one end of the module and then flows through the fiber wall leaving contaminants behind. UF membranes can be classified by pore size or the molecular weight cutoff (MWCO) point. Pore sizes generally range from 0.01 to 0.05 micrometer (μm). Typical MWCO points are 10,000 to 500,000 Daltons (Da), with 100,000 being a common MWCO rating for drinking water treatment. With these specifications, UF membranes can remove viruses, bacteria, and protozoan cysts, as well as large molecules such as proteins, and suspended solids.

2.2 Targa 10-48-35-PMC UF Membrane Description

The UF modules used in the EUWP are Koch Targa 10-48-35 PMC modules with end caps designed and manufactured by Village Marine Tec. The Targa 10-48-35-PMC is a 10.75 inch (in) x 48 in UF membrane module. The membrane fibers are made of polysulfone. The module specifications are listed below in Table 2-1.

The UF membranes in the EUWP are operated at a target flux of approximately 38 gallons per day per square foot (gfd), based on the inner diameter surface area. The membranes were operated at a similar flux during the laboratory microbial challenges.

Table 2-1. Targa 10-48-35-PMC Specifications

Parameter	Specification
Dimensions:	
Nominal Fiber Inner Diameter	0.035 in (0.9 millimeters (mm))
Module Outside Diameter	10.75 in (273 mm)
Module Length	48 in (1219 mm)
Nominal Membrane Surface Area (Inner)	554 square feet (ft^2) (51.5 square meters (m^2))
Nominal MWCO	100,000 Da
Operating Limits:	
Max. Inlet Pressure	45 pounds per square inch (psi)
Max. Temperature	104 °F (40 °C)
Min. Temperature	32 °F (0 °C)
Max. Production Transmembrane Pressure	30 psi
Max. Backflush Transmembrane Pressure	20 psi

2.3 Modules Chosen for Testing

Some of the UF modules, as installed in the EUWP UF skid, are shown in Figure 2-1. The two UF modules tested were chosen at random from the EUWP. The UF modules had been operated in the EUWP system for 1,520 hours over three field tests, as of August 24, 2007.

The modules chosen were serial numbers KM840643-4015 and KM849697-5021. Prior to field testing of the EUWP UF system at Selfridge Air National Guard Base in July and August of 2007, each UF module was individually integrity tested using a pressure decay test. The pressures were measured from 0 to 10 minutes, with a starting applied pressure of approximately 15 psig. KM840643-4015 had a pressure decay rate of 0.21 psig/min. This module was checked for compromised fibers; one was found and plugged. KM840643-4015 was then retested, and the new pressure decay rate was 0.17 psig/min. KM849697-5021 had a pressure decay rate of 0.13 psig/min. No fibers of this module were plugged.

For the tests described in this report, module KM840643-4015 was designated as Module 1, and KM849697-5021 was designated as Module 2.

Figure 2-1. UF modules in the EUWP UF skid.

Chapter 3
Methods and Procedures

3.1 Introduction

The challenge tests were conducted in December of 2007 and February of 2008. The tests followed the procedures described in the *Test/QA Plan for the Microbial Seeding Challenge Study of the Koch Membrane Systems Targa® 10-48-35-PMC™ UF Membrane Module, as Used in the Village Marine Tec. Expeditionary Unit Water Purifier (EUWP), Gen. 1.* The challenge protocol was adapted from the *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants.* The test/QA plan is included in this report as Appendix B.

3.2 Challenge Organisms

Two UF membrane modules were tested for removal of pathogenic protozoa using two different surrogate organisms – endospores of *Bacillus atrophaeus* (American Type Culture Collection (ATCC) 9372, deposited as *B. subtilis* var. *niger*), and formalin-fixed *C. parvum* oocysts.

Note that no virus or bacteria challenges were conducted, and neither of the challenge organisms is a suitable surrogate for viruses or vegetative bacteria.

As discussed in Section 1.2, *Bacillus* endospores were used as a challenge organism because endospore removal was measured during previous field testing as a surrogate for *C. parvum.* See Appendix A for *Bacillus* endospores as a surrogate for *C. parvum.* For these laboratory challenge tests, formalin-fixed *C. parvum* oocysts were also used because it was not cost prohibitive to do so (versus during field testing), and challenging with *Bacillus* endospores and *C. parvum* side-by-side allowed a direct comparison of the removal efficiency of one versus the other.

B. atrophaeus was purchased from Presque Isle Cultures of Erie, PA. The *C. parvum* oocysts were purchased from Sterling Parasitology Lab of Tuscon, AZ.

3.3 Test Apparatus

The modules were plumbed to a test station in the NSF Drinking Water Treatment Systems Laboratory. The test station uses a 1,200-gallon stainless steel tank or a 1,200-gallon polyethylene tank to hold the challenge water. Figure 3-1 shows the UF modules plumbed to the test rig. Figure 3-2 is a schematic diagram of the test rig.

Figure 3-1. UF modules plumbed to test station in NSF testing laboratory.

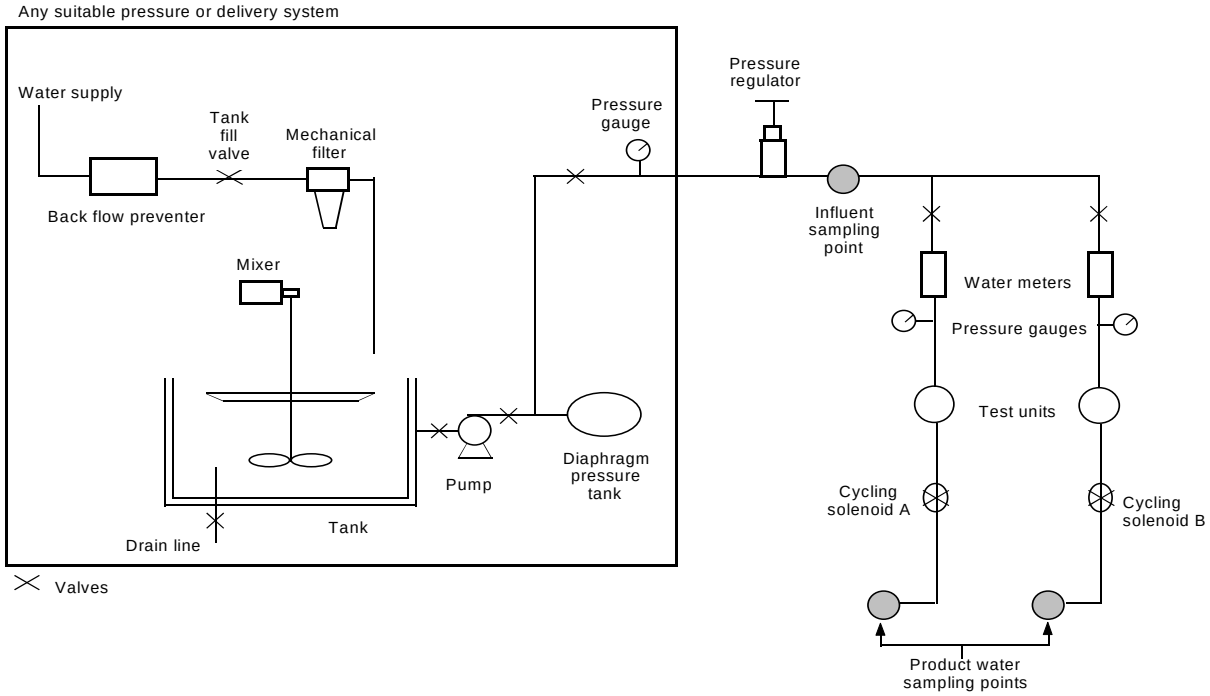

Figure 3-2. Schematic diagram of tank rig test station

3.4 Test Rig and UF Membrane Module Sanitization

The test rig was sanitized prior to testing according to NSF standard operating procedure (SOP). The process is proprietary, and uses multiple chemicals as sanitizers. After sanitization, the test rig was flushed until a less-than-detectable concentration of sanitizing agent was present. The UF modules were not sanitized immediately prior to testing. The UF modules were cleaned in September 2007 following EUWP field testing. The cleaning procedure used was that prescribed in the EUWP operation and maintenance manual. Prior to the laboratory challenge tests, the modules were flushed for approximately 15 minutes using deionized water.

3.5 UF Module Integrity Tests

Before and after testing, the membranes underwent a pressure decay membrane integrity test following the procedure in ASTM Standard D6908 – *Standard Practice for Integrity Testing of Water Filtration Membrane Systems*.

3.6 Membrane Module Operation

As discussed in Section 2.2, the TARGA 10-48-35-PMC UF membranes are operated at a flux of approximately 38 gfd in the EUWP system, so this flux was targeted for the microbial challenges. A flux of 38 gfd equals a filtrate flow rate of approximately 14.6 gpm. The membranes were operated with a retentate flow of approximately 10% of the feed, as they are in the EUWP. Therefore, to achieve a filtrate flow rate of 14.6 gpm, the target feed flow rate was 16.2 gpm.

The modules were challenged individually. The same tank of challenge water was used for both tests.

3.7 Test Water Composition

Local tap water was treated by carbon filtration, reverse osmosis, and deionization to make the base water (RO/DI water) for the tests. This water was low in particulates, thus representing a worse case for testing because there were few suspended particles to which the challenge organisms could attach. Note that suspended particle concentrations were not analyzed during testing.

The RO/DI water has the following QC requirements for use in the NSF testing laboratory:

- Conductivity ≤ 2 microSiemens per centimeter (μS/cm) at 25°C;
- TOC < 100 micrograms per liter (μg/L);
- Total chlorine ≤ 0.05 milligrams (mg)/L; and
- Heterotrophic bacteria plate count (HPC) < 100 colony forming units per milliliter (CFU/mL).

Of the above parameters, only total chlorine was measured specifically for this verification. The other parameters are measured periodically by NSF as part of the internal QA/QC program for test water quality.

The base water was adjusted to meet the requirements of Table 3-1.

Table 3-1. Water Quality Requirements

Parameter	Value	Chemical for Adjustment
Alkalinity	100 ± 10 mg/L	sodium bicarbonate ($NaHCO_3$)
pH	7.5 ± 0.5	hydrochloric acid (HCl) or sodium hydroxide (NaOH)
Temperature	20 ± 2.5 °C	none

Grab samples were collected at the start of each challenge period for analysis of total chlorine, alkalinity, pH, temperature, total dissolved solids, and turbidity. The pH was also measured at the end of the challenge period.

The challenge organisms were added to the tank of water at a sufficient titer to achieve the following target challenge organism concentrations:

- *B. atrophaeus* – approximately $1x10^4$ CFU/mL
- *C. parvum* – approximately $1x10^5$ oocysts/L

Note that both organisms were added to the same tank of water, so that there was a simultaneous challenge with both organisms.

3.8 Challenge Test Procedure

Immediately prior to beginning the tests, the influent challenge holding tank was mixed for a minimum of 10 minutes using a recirculation pump.

The initial inlet water pressure was set as necessary to deliver a feed flow rate of approximately 16.2 gpm. For the December 2007 tests, the modules were operated for 30 minutes. Feed and filtrate samples for challenge organism enumeration were collected at start-up, after 15 minutes of operation, and after 30 minutes of operation. For the February 2008 *C. parvum* retests, the modules were operated for 45 minutes, and feed and filtrate samples were collected at 15, 30, and 45 minutes.

3.9 Analytical Methods, and Accuracy and Precision Limits

A list of laboratory analytical methods can be found in Table 3-2. All samples for *B. atrophaeus* and *C. parvum* were analyzed in triplicate.

Table 3-2. Analytical Methods for Laboratory Analyses

Parameter	Method	NSF Reporting Limit	Lab Accuracy (% Recovery)	Lab Precision (%RPD[1])	Hold Time (days)	Sample Container	Sample Preservation
Alkalinity (total, as $CaCO_3$)	EPA 310.2	5 mg/L	90-110	≤ 13	14	1 L plastic	none
pH	SM 4500-H^{+}[2]	NA	NA	≤ 10	(3)	NA	none
TDS	SM 2540 C	5 mg/L	90-110	≤ 10	7	1 L plastic	none
Total Chlorine	SM 4500-Cl G	0.05 mg/L	90-110	≤ 10	(3)	NA	none
Turbidity	SM 2130	0.1 NTU[4]	95-105		(3)	NA	none
Bacillus Endospores	SM9218	1 CFU/100 mL	—	—	30 h[5]	1 L plastic	store at 3 ± 2 °C
Cryptosporidium Oocysts	EPA 1623	1 oocyst/L	—	—	72 h	1 L plastic	store at 3 ± 2 °C

(1) RPD = Relative Percent Deviation
(2) SM = Standard Methods for the Examination of Water and Wastewater
(3) Immediate analysis required
(4) NTU = Nephelometric Turbidity Unit
(5) h = hours

3.9.1 Water Quality Analytical Instruments

The following are the analytical instruments used for water quality measurements:

- Alkalinity – SmartChem Discrete Analyzer;
- pH – Orion Model SA 720 meter;
- Temperature – Omega Model HH11 digital thermometer, or equivalent;
- Total Chlorine – Hach DR/2010 spectrophotometer using AccuVac vials; and
- Turbidity – Hach 2100N turbidimeter.

Chapter 4
Results and Discussion

As stated in Section 2.3, module KM840643-4015 was designated as Module 1, and KM849697-5021 was designated as Module 2.

The challenge tests were conducted on December 11, 2007 and February 14, 2008. The December 2007 tests were conducted with both *B. atrophaeus* and *C. parvum*. During the December 2007 test, the Module 2 30-minute filtrate sample had a mean *C. parvum* count of 47 oocysts/L, so *C. parvum* challenges were conducted again on February 14, 2008 to confirm the apparent *C. parvum* breakthrough. For the February 14 retests, it was decided to operate the UF modules for 45 minutes to see whether *C. parvum* breakthrough, if observed, was a function of time. The results for the retest indicate that breakthrough was not time dependent.

For presentation of the challenge organism data in this chapter, the observed triplicate feed and filtrate counts were averaged by calculating geometric means. Non-detect results were treated as one organism per unit volume for the purpose of calculating the means. The triplicate counts for each sample are presented in Appendix C.

4.1 December 11, 2007 Challenges

The modules were forward flushed for 15 minutes on December 10 using deionized water, and the flush samples were collected at the end of this flush. The modules were flushed again on December 11 for approximately one minute immediately prior to conducting the microbial challenges. Table 4-1 presents the *B. atrophaeus* endospores challenge data, and Table 4-2 the *C. parvum* challenge data. The module flush samples had no *C. parvum*, but greater than 1 $\log_{10}$ of endospores (25 and 15 CFU/100 mL). Tryptic Soy Agar (TSA) was supposed to be substituted for nutrient agar in the SM9218 enumeration method for the endospores, in order to be able to distinguish the challenge endospores from wild-type endospores already present in the membrane modules from the field testing. *B. atrophaeus* gives orange colonies with a distinctive morphology on TSA. However, due to miscommunication between the DWS Center and the NSF Microbiology Lab, the *B. atrophaeus* endospores were enumerated on nutrient agar, so they could not be distinguished from the wild-type endospores.

The log removal value (LRV_{test}) for the endospore challenges show log removals between 2 and 3, but this data cannot be considered a true picture of UF module performance due to the flush sample counts. It is possible that many of the endospores in the filtrate samples did not come through the membranes, but rather were already present on the filtrate side due to contamination from the previous field tests. At time 0 the endospore counts for both modules were higher than those at 15 and 30 minutes, indicating that the endospores continued to be rinsed out of the filtrate side after the start of the challenges. The UF modules were chemically cleaned at the end of the August 2007 field test, but it is possible that the cleaning procedure did not completely remove all of the endospores.

C. parvum was found in one filtrate sample, that for Module 2 at 30 minutes. Because of the *C. parvum* breakthrough, retests for oocyst removal only were conducted on February 14, 2008. See Section 4.2 for the retest data and discussion.

Table 4-1. December 2007 *B. atrophaeus* Endospores Reduction Data

	Sample Point	Feed		Filtrate		Log Reduction
		Geometric Mean (CFU/mL)	Log_{10}	Geometric Mean (CFU/mL)	Log_{10}	
Module 1	Flush			24.8	1.4	
	Start-Up	$1.74x10^4$	4.24	69	1.8	2.4
	15 Minutes	$1.57x10^4$	4.20	13	1.1	3.1
	30 Minutes	$1.66x10^4$	4.22	14	1.2	3.0
	Overall Geometric Mean	$1.66x10^4$	4.22	23	1.4	2.8
Module 2	Flush			15	1.2	
	Start-Up	$2.02x10^4$	4.31	175	2.2	2.1
	15 Minutes	$1.65x10^4$	4.22	57	1.8	2.4
	30 Minutes	$1.75x10^4$	4.24	47	1.7	2.5
	Overall Geometric Mean	$1.80x10^4$	4.26	78	1.9	2.4

Table 4-2. December 2007 *C. parvum* Reduction Data

	Sample Point	Feed		Filtrate		Log Reduction
		Geometric Mean (Oocysts/L)	Log_{10}	Geometric Mean (Oocysts/L)	Log_{10}	
Module 1	Flush			<1	0.0	
	Start-Up	$1.2x10^5$	5.1	<1	0.0	5.1
	15 Minutes	$7.5x10^4$	4.9	<1	0.0	4.9
	30 Minutes	$7.1x10^4$	4.9	<1	0.0	4.9
	Overall Geometric Mean	$8.6x10^4$	5.0	<1	0.0	5.0
Module 2	Flush			<1	0.0	
	Start-Up	$1.1x10^5$	5.0	<1	0.0	5.0
	15 Minutes	$8.4x10^4$	4.9	<1	0.0	4.9
	30 Minutes	$8.4x10^4$	4.9	47	1.7	3.2
	Overall Geometric Mean	$9.2x10^4$	4.9	3.6	0.6	4.3

Immediately after the 15-minute flushes on December 10, the modules were subjected to a pressure decay test. A post-challenge pressure decay test was run the next day. The pre-test and post-test pressure decay data is shown in Table 4-3. Note that two pressure decay rates were calculated, one for the entire test, and another for just the span of 10-20 minutes. The 10-20

minute calculation was included because ASTM D6908 suggests allowing the pressure decay rate to stabilize before conducting the official pressure decay test. Module 1 had higher pressure decay rates than Module 2, as it did in July of 2007 when pressure decay tests were conducted prior to the field test (see Section 2.3 for further discussion). However, the higher pressure decay rate for Module 1 was not reflected in the endospore and oocyst reduction data.

Table 4-3. December 2007 Pressure Decay Test Data

Time (min.)	Pre-Test		Post-Test	
	Module 1	Module 2	Module 1	Module 2
0	17	18	20	20
1	17	17.8	17.5	19.8
2	16	17.8	16.5	19
3	16	17.8	15.2	19
4	15.5	17.8	14.5	19
5	15	17.8	13.5	19
6	15	17.2	12	19
7	14.4	17.1	11	19
8	14	17.1	11	18.9
9	13.4	17.1	10	18.8
10	13	17	9.7	18.8
11	13	17	9	18.8
12	12.5	17	8.5	18.5
13	12	17	8	18.5
14	12	17	7.7	18.5
15	11.5	17	7.2	18.5
16	11	17	7	LE(1)
17	11	16.8	6.2	18.5
18	11	16.5	6	18.5
19	11	16.2	5.5	18.2
20	10	16.2	5.2	18
0-20 Minute Pressure Decay Rate (psig/min)	0.35	0.09	0.74	0.10
10-20 Minute Pressure Decay Rate (psig/min)	0.30	0.08	0.45	0.08

(1) Lab data recording error

It is possible that the higher Module 1 pressure decay rates were due to air leaks out of the temporary plumbing on the test rig. The pressure decay rates can be translated into an expected log removal values (LRV_{DIT}) for *Cryptosporidium* using the equations in Chapter 4 of the USEPA Membrane Filtration Guidance Manual (MFGM). The LRV_{DIT} ranged from 2.22 to 3.14 for Module 1, and from 3.09 to 3.78 for Module 2. These LRV are much lower than those observed for *C. parvum*, with the exception of the Module 2 30-minute sample. The LRV_{DIT} calculations are presented in Table 4-4.

The equation used here to calculate LRV_{DIT} is Equation 4.7 of the MFGM, which is expressed as follows:

$$LRV_{DIT} = \log\left(\frac{Q_p \bullet ALCR}{Q_{air} \bullet VCF}\right) \qquad \text{(MFGM Equation 4.7)}$$

where:

LRV_{DIT} = log removal value equating to measured pressure decay rate;
Q_p = membrane unit design capacity filtrate flow rate (liters per minute, Lpm);
ALCR = air-liquid conversion ratio (dimensionless);
Q_{air} = flow of air through a critical membrane breach during a pressure decay test (Lpm); and
VCF = volumetric concentration factor (dimensionless).

For equation 4.7, Q_p was set at 55.26 Lpm to equal the target flow rate given in Section 3.6, while ALCR and Q_{air} were calculated as described below.

The VCF is the ratio of the concentration of suspended solids on the feed side of the membrane at point x in the membrane unit (in this case, point X along each membrane fiber), relative to that of the influent feed to the membrane unit. Systems with higher VCF will allow for increased passage of pathogens through a membrane breach as opposed to a system with a VCF of 1. Depending on the system design, the VCF may vary spatially, and/or temporally. The VCF will increase temporally if the concentrate stream is recycled back into the feed water. For this ETV verification, and for the field testing ETV verifications of the EUWP UF system, the concentrate stream was not recycled, so the UF membrane was considered to be a plug-flow reactor. For a plug-flow reactor, the VCF only increases spatially as the feed water travels along the length of the UF fibers. Table 2.1 in Section 2.5.2.1 of the MFGM gives flow-weighted averages and maximum values for the VCF for various recovery rates. Both the flow-weighted average of 2.56 and maximum of 10 for a 90% recovery rate were input into Equation 4.7. The maximum VCF of 10 could be expected at or near the outlet end of the feed side of the membrane, as the 90% recovery setting has allowed the suspended solids concentration to increase ten-fold as a slug of the feed water travels through the UF fibers.

For the ALCR, Equation C.4 in the MFGM was used. This equation is for the Darcy pipe flow model for turbulent flow through a membrane breach. The equation is expressed as follows:

$$ALCR = 170 \bullet Y \bullet \sqrt{\frac{(P_{test} - BP) \bullet (P_{test} + P_{atm})}{(460 + T) \bullet TMP}} \qquad \text{(MFGM Equation C.4)}$$

where:

ALCR = air-liquid conversion ratio (dimensionless);
Y = net expansion factor for compressible flow through a pipe to a larger area (dimensionless);
P_{test} = direct integrity test pressure (psig)
BP = backpressure on the system during the integrity test (psi)
P_{atm} = atmospheric pressure (psia)
T = water temperature (°F)
TMP = maximum transmembrane pressure during normal operation

To calculate ALCR, the following values were used for the variables:

Y = 0.612;
P_{test} = initial applied pressure in Table 4.3 for each integrity test;
BP = 1.7 psi (4 feet of water at 0.43 psi/ft);
P_{atm} = 14.7 psi;
T = 68 °F; and
TMP = 30 psig.

Using these values, the ALCR was calculated for each pressure decay test by inputting the initial applied pressure. The ALCR value was then input into Equation 4.7.

Q_{air} also needed to be calculated for the LRV_{DIT} equation. Q_{air} was calculated using Equation 4.8 of the MFGM, which is expressed as follows:

$$Q_{air} = \frac{\Delta P_{test} \bullet V_{sys}}{P_{atm}} \qquad \text{(MFGM Equation 4.8)}$$

where:

Q_{air} = flow of air (Lpm);
ΔP_{test} = rate of pressure decay during the integrity test (psig/min);
V_{sys} = volume of pressurized air in the system during the integrity test (L); and
P_{atm} = atmospheric pressure (psi).

To calculate Q_{air}, the following values were used for the variables:

ΔP_{test} = the pressure decay rates in Table 4.3 for each integrity test (psig/min);
V_{sys} = 13.8 L; and
P_{atm} 14.7 psi.

Note that the LRV_{DIT} associated with the maximum VCF of 10 are approximately 0.6 $\log_{10}$ lower than those for the flow-weighted average VCF of 2.56. This indicates that a membrane breach at the outlet end of a fiber could be expected to allow up to 0.6 $\log_{10}$ more of *Cryptosporidium* through the breach, as opposed to a breach at the point where the VCF is 2.56.

Table 4-4. December 2007 Pressure Decay Test LRV_{DIT}				
Pressure Decay Test	**Pressure Decay Timeframe**	**Pressure Decay Rate (ΔP_{test})**	**VCF**	**LRV_{DIT} (log_{10})**
Module 1 Pre-Test	0 to 20 minutes	0.35	2.56	3.08
			10	2.49
	10 to 20 minutes	0.30	2.56	3.14
			10	2.55
Module 1 Post-Test	0 to 20 minutes	0.74	2.56	2.81
			10	2.22
	10 to 20 minutes	0.45	2.56	3.03
			10	2.44
Module 2 Pre-Test	0 to 20 minutes	0.09	2.56	3.69
			10	3.10
	10 to 20 minutes	0.08	2.56	3.74
			10	3.15
Module 2 Post-Test	0 to 20 minutes	0.10	2.56	3.68
			10	3.09
	10 to 20 minutes	0.08	2.56	3.78
			10	3.19

Table 4-5 displays the UF module operational data and water chemistry data for the December 11, 2007 challenges. The filtrate flow rates were above the target of 14.6 gpm, thus giving fluxes above 38 gfd. These higher fluxes, plus the low-particle test water, gave a more conservative test than the field test conditions for the full EUWP.

Table 4-5. December 2007 Operational Data and Water Chemistry Data		
Sample	**Module 1**	**Module 2**
Feed Flow at Start-up (gpm)	17.15	17.04
Filtrate Flow at Start-up (gpm, calculated)	15.42	15.40
Reject Flow at Start-up (gpm)	1.73	1.64
Membrane Flux at Start-up (gfd)	40.08	40.03
Feed Flow at 30 Minutes (gpm)	16.99	17.71
Filtrate Flow at 30 Minutes (gpm, calculated)	15.16	16.05
Reject Flow at 30 Minutes (gpm)	1.83	1.66
Membrane Flux at 30 Minutes(gfd)	39.41	41.72
Inlet Pressure at Start-up (psig)	14	14
Inlet Pressure at 30 Minutes (psig)	15	NR(1)
Feed Water Chemistry at Start-up:		
Alkalinity (mg/L $CaCO_3$)	110	
pH	7.67	
Temperature (°C)	19.9	
Total Chlorine (mg/L)	<0.05	
TDS (mg/L)	120	
Turbidity (NTU)	0.14	
pH at End of Challenge	7.72	

(1) not recorded

4.2 February 14, 2008 *C. parvum* Retest

As discussed in Section 4.1, *C. parvum* challenges were conducted again to confirm the breakthrough observed for Module 2. The results of these challenges are presented in Table 4-6. NSF and USEPA decided not to run the *B. atrophaeus* challenges over again because funding was not available to run both challenge organisms. The retests were carried out to 45 minutes to determine if breakthrough was correlated to the time of operation. Prior to the retest, the modules were backflushed for approximately 5 minutes, then forward flushed for 10 minutes. Deionized water was used for both the backflush and forward flush. The technician conducting the tests noted that during the backflush, the effluent contained high levels of suspended solids.

No *C. parvum* was detected in the Module 1 filtrate samples from the December 2007 challenge, but it was found in both the 30-minute and 45-minute samples from the retest. *C. parvum* was also found in the Module 2 30-minute filtrate sample, as was the case with the December 2007 challenge. However, no *C. parvum* was detected in the Module 2 45-minute filtrate sample. These results do not indicate the *C. parvum* breakthough was related to the time of operation. In spite of the *C. parvum* filtrate counts, the UF membrane still removed greater than 4 logs of the oocysts.

Table 4-6. February 2008 *C. parvum* Reduction Retest Data

		Feed		Filtrate		
	Sample Point	Geometric Mean (Oocysts/L)	Log_{10}	Geometric Mean (Oocysts/L)	Log_{10}	Log Reduction
Module 1	Flush			<1	0.0	
	Start-Up	$6.3x10^4$	4.8	<1	0.0	4.8
	30 Minutes	$6.2x10^4$	4.8	2	0.4	4.4
	45 Minutes	$7.9x10^4$	4.9	1	0.0	4.9
	Overall Geometric Mean	$6.8x10^4$	4.8	0.7	0.0	4.7
Module 2	Flush			<1	0.0	
	Start-Up	$5.7x10^4$	4.8	<1	0.0	4.8
	30 Minutes	$5.6x10^4$	4.8	4	0.6	4.2
	45 Minutes	$5.1x10^4$	4.7	<1	0.0	4.7
	Overall Geometric Mean	$5.5x10^4$	4.7	1.6	0.2	4.5

The pre-test and post-test pressure decay test data is shown in Table 4-7. As with the December 2007 pressure decay data, two pressure decay rates are given. Again, the higher pressure decay rate for Module 1 is not reflected in the filtrate *C. parvum* counts.

Table 4-7. February 2008 Pressure Decay Test Data				
	Pre-Test		Post-Test	
Time (min.)	Module 1	Module 2	Module 1	Module 2
0	20	20	20	20
1	18	19	20	20
2	17	19	20	20
3	16	19	20	19.5
4	15	18	19.5	19.5
5	15	18	19.5	19
6	14	18	19	19
7	13.5	18	18	19
8	12	18	NR	19
9	11	18	17	18.5
10	11	17	16	18
11	10	17	16	NR
12	10	17	15	18
13	9	16	15	18
14	9	16	14	18
15	9	16	14	17.5
16	9	16	13	17
17	8	15	13	17
18	8	15	12.5	17
19	8	15	12	16.5
20	8	15	12	16
10-20 Minute Pressure Decay Rate (psig/min)	0.3	0.2	0.4	0.2
0-20 Minute Pressure Decay Rate (psig/min)	0.6	0.25	0.4	0.2

As with the December 2007 pressure decay data, the February 2008 decay data was used to calculate LRV_{DIT} for each pressure decay test. These calculations are presented in Table 4.8. The same variable values were used for these calculations as for the December 2007 calculations. The LRV_{DIT} for Module 1 ranged from 2.31 to 3.20 log_{10}, while those for Module 2 ranged from 2.69 to 3.38. As with the December 2007 LRV_{DIT}, the February 2008 LRV_{DIT} are approximately 1 log_{10} or more below the observed *C. parvum* LRV_{test}.

Table 4-8. February 2008 Pressure Decay Test LRV_{DIT}				
Pressure Decay Test	**Pressure Decay Timeframe**	**Pressure Decay Rate (ΔP_{test})**	**VCF**	**LRV_{DIT} (log_{10})**
Module 1 Pre-Test	0 to 20 minutes	0.60	2.56	2.90
			10	2.31
	10 to 20 minutes	0.30	2.56	3.20
			10	2.61
Module 1 Post-Test	0 to 20 minutes	0.40	2.56	3.08
			10	2.49
	10 to 20 minutes	0.40	2.56	3.08
			10	2.49
Module 2 Pre-Test	0 to 20 minutes	0.25	2.56	3.28
			10	2.69
	10 to 20 minutes	0.20	2.56	3.38
			10	2.79
Module 2 Post-Test	0 to 20 minutes	0.20	2.56	3.38
			10	2.79
	10 to 20 minutes	0.20	2.56	3.38
			10	2.79

Table 4-9 displays the UF module operational data and water chemistry data for the February 14, 2008 *C. parvum* challenges. As with the December 2007 challenges, the filtrate flow rates were above the target of 14.6 gpm, thus giving fluxes above 38 gfd.

Table 4-9. February 2008 Operational Data and Water Chemistry Data		
Sample	**Module 1**	**Module 2**
Feed Flow at Start-up (gpm)	18.05	17.60
Filtrate Flow at Start-up (gpm, calculated)	16.26	15.92
Reject Flow at Start-up (gpm)	1.79	1.68
Membrane Flux at Start-up (gfd)	42.3	41.4
Feed Flow at 45 Minutes (gpm)	16.5	17.79
Filtrate Flow at 45 Minutes (gpm, calculated)	14.85	16.12
Reject Flow at 45 Minutes (gpm)	1.65	1.67
Membrane Flux 45 Minutes (gfd)	38.6	41.9
Inlet Pressure at Start-up (psig)	20.4	18.8
Inlet Pressure at 45 Minutes (psig)	18.0	18.6
Feed Water Chemistry at Start-up:		
Alkalinity (mg/L $CaCO_3$)	87	
pH	7.55	
Temperature (°C)	19	
Total Chlorine (mg/L)	<0.05	
TDS (mg/L)	100	
Turbidity (NTU)	<0.1	
pH at End of Challenge	7.59	

4.3 Conclusions

These results indicate that the UF modules in the EUWP are not capable of providing a sole barrier to microorganisms by themselves. However, it is important to note that the modules had 1,520 hours of operation prior to the laboratory challenges. The modules had been through three field tests, one using tertiary wastewater as the source, and two tests using fresh surface water as the source. Also, the EUWP as a whole includes RO treatment downstream of the UF modules, and then chlorination of the RO permeate to provide finished drinking water.

Chapter 5
Quality Assurance/Quality Control

5.1 Introduction

An important aspect of verification testing is the quality assurance and quality control (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, accuracy, precision, and completeness.

Because this 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 2007).

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 audit during testing to ensure the proper procedures were followed. The audit yielded no significant findings.

5.3 Sample Handling

All samples analyzed by the NSF Chemistry and Microbiology Laboratories were labeled with unique ID numbers. All samples were analyzed within allowable holding times.

5.4 Chemistry Laboratory 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* (NSF, 2007).

The NSF QA/QC requirements are all compliant with those given in the EPA method or Standard Method for the parameter. Also, every analytical method has an NSF SOP governing the procedure.

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.

5.5.2 Negative Controls

For each sample batch processed, an unused membrane filter and a blank with 100 mL of buffered, sterilized dilution water was 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 the geometric means 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 are correct.

5.7 Data Review

NSF QA/QC staff reviewed the raw data records for compliance with QA/QC requirements. As required in the ETV Quality Management Plan (QMP), NSF ETV staff checked at least 10% 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 UF membranes under normal use conditions. The membranes were to be operated at fluxes similar to those they encounter in the full EUWP system. The test fluxes were higher than the typical EUWP flux, which gave a more conservative test. The test water was of very low turbidity, and low particle count to minimize the potential for microbial adhesion to suspended particles, which could enhance log reduction.

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, and turbidity meters was checked daily during the calibration procedures using certified check standards. Alkalinity and TDS 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. At least one out of every ten samples for alkalinity was analyzed in duplicate. Duplicate municipal drinking water samples were analyzed for pH, total chlorine, and turbidity as part of the daily calibration process. Precision of duplicate analyses was measured by use of the following equation to calculate 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 and TDS were batched with other non-ETV samples. 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, as presented in Table 5-1.

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:

$$\%C = (V/T) \times 100$$

where:

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

All planned samples were collected, and all had valid results. One inlet pressure recording was missed, that for Module 2 at 30 minutes during the December 2007 challenges. A total of eight inlet pressure measurements were planned, including the February 2008 *C. parvum* retest. The one missed recording gives a completeness percentage of 87.5% for this parameter, which exceeds the completeness requirements in Table 5-1.

Chapter 6
References

APHA, AWWA, and WEF (1999). *Standard Methods for the Examination of Water and Wastewater*, 20th Edition.

ASTM International (2003). D 6908-03, Standard Practice for Integrity Testing of Water Filtration Membrane Systems.

USEPA (2005). *Membrane Filtration Guidance Manual* (EPA 815-R-06-009).

USEPA and NSF International (2005). *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants.*

Appendix A
Bacillus Endospores as a Surrogate for *Cryptosporidium parvum* Oocysts

The EPA LT2ESWTR allows the use of a surrogate for *C. parvum*, provided the surrogate is conservative. The EPA MFGM specifically discusses *Bacillus subtilis* as a surrogate, but states "Because there is limited data currently available regarding the use of *Bacillus subtilis* in membrane challenge studies, a characterization of this organism would be necessary to determine whether it could be used as a *Cryptosporidium* surrogate…" The MFGM also states "Based on the size…*Bacillus subtilis* could potentially be considered a conservative surrogate…pending a comparison of other characteristics (e.g., shape, surface charge, etc.)…"

1. Organism Size and Shape

C. parvum is spherical in shape, while *Bacillus* endospores are ellipsoidal in shape (football shaped). *C. parvum* has a diameter of 4-6 μm. *Bacillus* endospores are approximately 0.8 μm in diameter, and 1.8 μm in length. Therefore, *Bacillus* endospores are a conservative surrogate for *C. parvum*, no matter what the orientation of the endospore is when it impacts the test membrane.

Baltus et. al. (2008) studied membrane rejection of bacteria and viruses with different length vs. diameter aspect ratios. They theorized, based on a transport model for rod-shaped particles, that rejection would improve as the aspect ratio (length vs. diameter) increased for a fixed particle volume. However, their experimental results contradicted this, with similar rejection rates for particles with a range of aspect ratios. The model assumed that particles would impact the membrane with equal frequency for all particle orientations. They theorize that instead, an end-on orientation was favored for transport of the particles in the water stream. They concluded that microorganism removal by membranes could be conservatively estimated using only the rod diameter in transport models. These findings add an additional safety factor to using *Bacillus* endospores as a surrogate for *C. parvum*.

2. Electrophoretic Mobility and Isoelectric Point

A suitable surrogate should have a surface charge similar to *C. parvum*, as measured through the isoelectric point and electrophoretic mobility (EPM). The isoelectric point is the pH at which the particle has a neutral surface charge in an aqueous environment. Below this point the particle has a net positive charge, above it a net negative charge. Many studies have pegged the isoelectric point of *C. parvum* between pH values of 2 and 4, thus it would have a negative surface charge in the neutral pH range. The isoelectric point can be found by measuring the EPM of the particle at various pH values. The pH where the EPM is zero is classified as the isoelectric point.

Lytle et. al. (2002) measured the EPM of both *C. parvum* and *B. subtilis* endospores in solutions of increasing buffer concentration (0.915 millimolar (mM) 9.15 mM, and 91.5 mM KH_2PO_4). They found that increasing the buffer concentration also increases the EPM toward a positive value. The buffer concentration of the test water for the Siemens tests was approximately 1 mM. Therefore, the 0.915 mM data from this study should be the most accurate representation of the

C. parvum and *B. subtilis* EPM for the ETV tests. In 0.915 mM solutions at pH values between 7 and 8, they observed EPM of approximately -2.2 to -2.6 µm cm V^{-1} s^{-1} for *C. parvum*, and -1.9 to -2.2 µm cm $V^{-1}s^{-1}$ for *B. subtilis*. For *B. subtilis*, the researchers did not measure an isoelectric point at any buffer concentration. For *C. parvum*, they did find an isoelectric point at a pH around 2.5, but only for the 9.15 mM solution. For both organisms, the 0.915 mM solution generally gave lower (more negative) EPM values than the solutions with higher buffering capacity.

3. Aggregation

The NSF Microbiology Laboratory microscopically examined a sample of the *B. atrophaeus* stock solutions purchased for the tests. The sample was suspended in sterile, buffered, deionized water and stirred at moderate speed for 15 minutes. The estimated cell density was $1x10^9$ CFU/100 mL, which is approximately 100 times higher than the suspensions injected into the pilot units to challenge the UF membranes. Figure 1 is a photograph of the *B. atrophaeus* endospores in the sample. The magnification is 1000x oil immersion with differential interference contrast microscopy. No evidence of endospore aggregation was found.

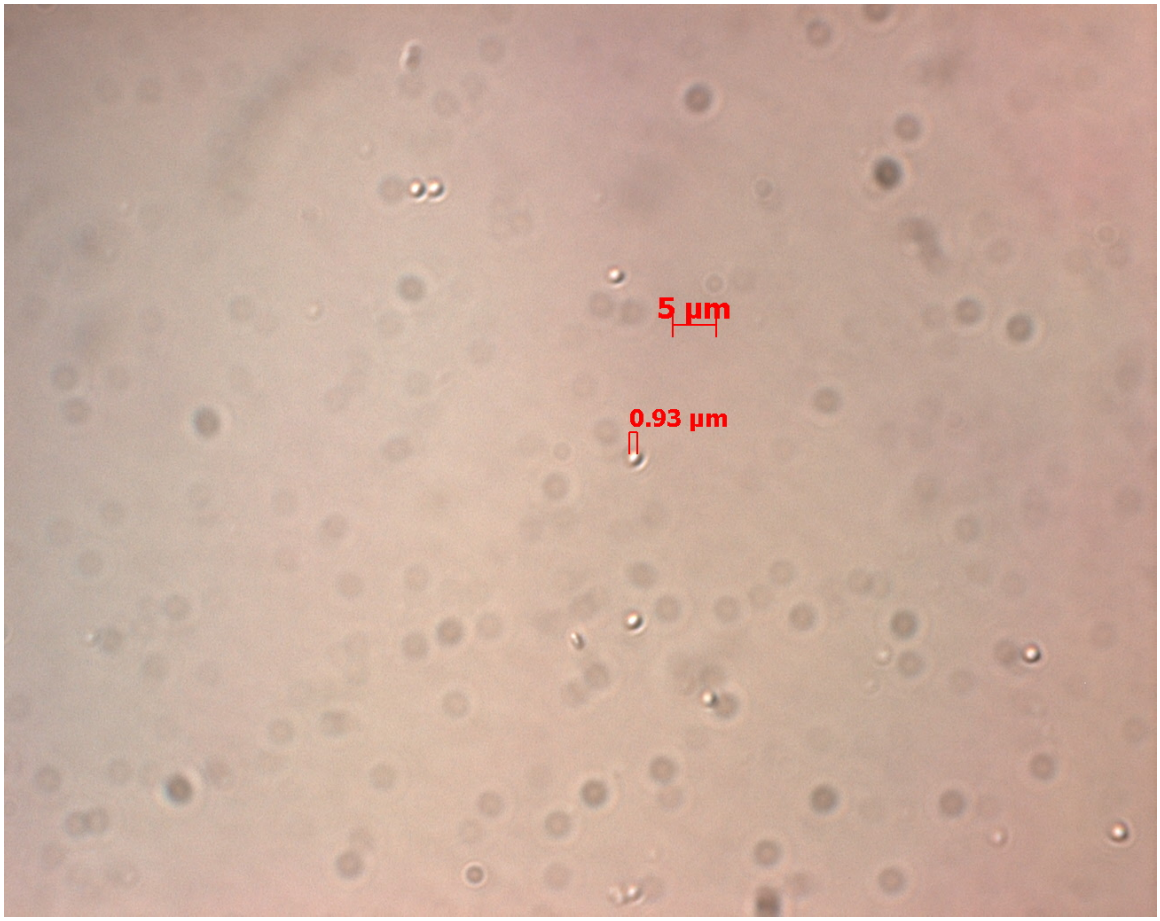

Figure B-1. Mono-dispersed *B. atrophaeus* endospores used for challenge tests.

References

Baltus, R. E., A. R. Badireddy, W. Xu, and S. Chellam (2009). Analysis of Configurational Effects on Hindered Convection of Nonspherical Bacteria and Viruses across Microfiltration Membranes. *Industrial and Engineering Chemistry Research.* In press.

Brush, C. F., M. F. Walter, L. J. Anguish, and W. C. Ghiorse (1998). Influence of Pretreatment and Experimental Conditions on Electrophoretic Mobility and Hydrophobicity of *Cryptosporidium parvum* Oocysts. *Applied and Environmental Microbiology.* 64: 4439-4445.

Butkus, M. A., J. T. Bays, and M. P. Labare (2003). Influence of Surface Characteristics on the Stability of *Cryptosporidium parvum* Oocysts. *Applied and Environmental Microbiology.* 69: 3819-3825.

Lytle, D. A., C. H. Johnson, and E. W. Rice (2002). A Systematic Comparison of the Electrokinetic Properties of Environmentally Important Microorganisms in Water. *Colloids and Surfaces B: Biointerfaces*. 24: 91-101.

Appendix B
Test/Quality Assurance Project Plan

Contact Mr. Bruce Bartley at 734-769-5148 or bartley@nsf.org for a copy of this document.

Appendix C
Challenge Organism Triplicate Counts

Table C-1. Module 1 *B. atrophaeus* Triplicate Counts		
	Triplicate Counts (CFU/mL)	
Sample	Feed	Filtrate
Start-up	$2.02x10^4$, $1.42x10^4$, $1.85x10^4$	94, 52, 67
15 Minutes	$1.90x10^4$, $1.28x10^4$, $1.59x10^4$	12, 15, 12
30 Minutes	$1.80x10^4$, $2.04x10^4$, $1.24x10^4$	13, 16, 14

Table C-2. Module 2 *B. atrophaeus* Triplicate Counts		
	Triplicate Counts (CFU/mL)	
Sample	Feed	Filtrate
Start-up	$2.22x10^4$, $2.05x10^4$, $1.81x10^4$	217, 190, 129
15 Minutes	$2.02x10^4$, $1.64x10^4$, $1.36x10^4$	51, 63, 57
30 Minutes	$1.70x10^4$, $1.91x10^4$, $1.65x10^4$	56, 46, 41

Table C-3. December 2007 Module 1 *C. parvum* Triplicate Counts		
	Triplicate Counts (Oocysts/L)	
Sample	Feed	Filtrate
Start-up	$1.36x10^5$, $1.44x10^5$, $9.8x10^4$	<1, <1, <1
15 Minutes	$1.01x10^5$, $7.0x10^4$, $5.9x10^4$	<1, <1, <1
30 Minutes	$7.9x10^4$, $5.4x10^4$, $8.5x10^4$	1, 1, <1

Table C-4. December 2007 Module 2 *C. parvum* Triplicate Counts		
	Triplicate Counts (Oocysts/L)	
Sample	Feed	Filtrate
Start-up	$1.29x10^5$, $1.00x10^5$, $1.14x10^5$	<1, <1, <1
15 Minutes	$9.2x10^4$, $8.6x10^4$, $7.4x10^4$	<1, <1, <1
30 Minutes	$8.3x10^4$, $9.6x10^4$, $7.5x10^4$	62, 39, 42

Table C-5. February 2008 Module 1 *C. parvum* Triplicate Counts		
	Triplicate Counts (Oocysts/L)	
Sample	Feed	Filtrate
15 Minutes	$6.8x10^4$, $5.6x10^4$, $6.7x10^4$	<1, <1, <1
30 Minutes	$5.7x10^4$, $6.1x10^4$, $6.7x10^4$	2, 3, 2
45 Minutes	$1.0x10^5$, $8.6x10^4$, $5.7x10^4$	<1, <1, <1

Table C-6. February 2008 Module 2 *C. parvum* Triplicate Counts		
	Triplicate Counts (Oocysts/L)	
Sample	Feed	Filtrate
15 Minutes	$6.1x10^4$, $5.4x10^4$, $5.5x10^4$	<1, <1, <1
30 Minutes	$3.9x10^4$, $7.2x10^4$, $6.4x10^4$	8, 2, 5
45 Minutes	$4.3x10^4$, $5.1x10^4$, $6.2x10^4$	<1, <1, <1