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Environmental Technology Verification Report

Removal of Viruses in Drinking Water – Ultrafiltration Module with a Cut Fiber

Dow Chemical Company – Dow Water & Process Solutions

SFD-2880 Ultrafiltration Module

Prepared by

NSF International

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

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THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**ULTRAFILTRATION MEMBRANE**
APPLICATION:	**REMOVAL OF VIRUSES IN DRINKING WATER**
PRODUCT NAME:	**SFD-2880 ULTRAFILTRATION MODULE**
VENDOR:	**THE DOW CHEMICAL COMPANY – DOW WATER SOLUTIONS**
ADDRESS:	**1691 SWEDE ROAD MIDLAND, MI 48674**
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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 Dow Water Solutions SFD-2880 ultrafiltration (UF) module for removal of viruses under a scenario where one UF fiber was broken. The challenge test was conducted under controlled laboratory conditions at NSF's testing laboratory in Ann Arbor, MI. Testing of the SFD-2880 UF module was conducted to verify virus reduction following the requirements of the Department of Health Victoria (Australia) *Draft guidelines for validating treatment processes for pathogen reduction, supporting Class A water recycling schemes in Victoria*. The Department of Health Victoria guideline is largely based on the product-specific challenge requirements of the EPA Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) and accompanying EPA Membrane Filtration Guidance Manual (MFGM).

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 purpose of this verification was a cut fiber challenge study for the Dow Chemical Company SFD-2880 UF membrane module. MS2 coliphage virus was the surrogate challenge organism. The challenge tests followed the requirements of the Department of Health Victoria (Australia) *Draft guidelines for validating treatment processes for pathogen reduction, supporting Class A water recycling schemes in Victoria*.

Five new fully integral modules were challenged with MS2. Then, one fiber in each module was cut, and the modules were all tested again with MS2. The modules were operated at a target flux of 70 gallons per square foot per day (gfd), which equates to a flow of 40.3 gallons per minute (gpm). The test data did not show any significant reduction in virus removal with a cut-fiber, so a second round of testing was conducted with higher MS2 challenge concentrations. For the retests, the cut-fiber challenges were conducted first, followed by the intact module tests after the cut fibers were pinned. The average log removal value (LRV) was calculated for each module, as well as LRVs for each feed/filtrate sample pair. From this data, the $LRV_{C\text{-}TEST}$ was determined as the lowest mean LRV, and also the lowest sample pair LRV. Table VS-i provides a summary of the $LRV_{C\text{-}TEST}$ data.

Table VS-i. $LRV_{C\text{-}TEST}$ for Each Round of Testing

	Intact Modules		Cut Fiber	
Tests	**Mean LRV**	**Lowest LRV**	**Mean LRV**	**Lowest LRV**
Round 1	3.73	3.44	3.44	2.98
Round 2	2.59	2.39	2.46	2.37

To evaluate whether there was significantly lower virus removal with a cut fiber, the LRVs for each feed/filtrate sample pair were pooled together, and the paired-difference t statistic was calculated using Microsoft® Excel®. The intact module vs. cut-fiber t statistic for the first round of tests is 1.15. This value is below the critical t value of 2.15, indicating that virus removal was not significantly impacted by the cut fiber. For the second round of tests, the paired-difference t statistic is 5.00, this time demonstrating a statistically significant drop in LRV.

PRODUCT DESCRIPTION

The following information was provided by Dow and was not verified.

The Dow SFD-2880 UF membrane module measures 4.7 inches in diameter by 45.5 inches in length. The membrane fibers are made of polyvinylidene fluoride (PVDF). Water flow through the membrane fibers is outside to inside. The modules can operate in deposition (dead-end) or suspension modes. The nominal pore size is 0.03 µm. The maximum recommended flux is 70 gfd, with a maximum recommended feed pressure of 44 pounds per square inch (psi), and a maximum transmembrane pressure of 30 psi.

VERIFICATION TEST DESCRIPTION

Virus Surrogate

The modules were challenged with the MS2 coliphage virus (ATCC 15597-Bl) as a surrogate for enteric viruses, as required by the Victoria draft guidelines for virus removal credits. MS2 is generally accepted as an enteric virus surrogate for size-exclusion technologies due to its small size (approximately 22-26 nanometers). The USEPA MFGM references MS2 as an acceptable surrogate for enteric viruses because it is similar in size and shape to poliovirus and hepatitis virus.

Methods and Procedures

All tests were conducted at the NSF International testing laboratories following the requirements of the EPA-approved *Test/QA Plan for Validating the Dow Chemical Company SFD-2880 Ultrafiltration Membrane Module for Virus Reduction Following the Department of Health Victoria (Australia) Draft Guidelines for Validating Treatment Processes for Pathogen Reduction.* The Victoria guidelines support the regulatory approval process for Class A water recycling schemes. For membrane filtration products, the guidelines are largely based on the product-specific challenge requirements of the LT2ESWTR and accompanying EPA MFGM.

The intact module and cut-fiber tests were conducted twice, in two separate rounds of testing. The second round of testing was conducted because the data from the first round did not show any significant reduction in virus retention between the intact and cut-fiber challenges. For the first round, NSF tested the five intact modules in January 2011. Then Dow representatives visited the testing laboratory to cut the fibers, and the cut-fiber tests were conducted in March 2011. As required in the Department of Health Victoria guideline, one fiber in each module was cut as close as possible to the potting resin on the filtrate end of the module. The retests were conducted in May 2011, with the cut-fiber tests conducted first, followed by the intact module challenges after Dow representatives pinned the cut fibers. Each of the five modules submitted for testing was challenged individually. The target flux for membrane operation was Dow's maximum recommended value of 70 gfd at 25 °C, which equals a flow rate of 40.3 gpm. Before and after each challenge test, each module was subjected to a pressure decay test to satisfy the non-destructive performance test requirement in Section 3.6 of the MFGM.

Immediately prior to testing, each module was forward flushed at approximately 40 gpm. For the first round of tests conducted in January and March, each module was flushed for five minutes. At the start of the retest round in May, the laboratory engineer noticed that after five minutes of flushing, there were still bubbles visible in the filtrate hose line. The engineer flushed Module 1 for an additional three minutes until bubbles were no longer visible. The engineer had to flush Module 2 for a total of 22 minutes to clear the bubbles. At this point, the engineer decided to install bleed valves in the reject port caps for Modules 3, 4 and 5 to allow for evacuation of the air. After the pressure decay tests for these three modules, the bleed valve was opened and the flow of water started at 40 gpm. The valves were kept open until all the air had escaped. This allowed the testing engineer to return to the flush time of five minutes.

The duration of each challenge test was approximately 35 minutes. The MS2 suspension was injected into the feed stream at start-up, after 15 minutes of operation, and after 30 minutes of operation. After at least one minute of injection to pass the equilibrium volume, grab samples were collected from the feed and filtrate sample taps. After each round of sample collection, injection of the challenge organism suspension was turned off, and clean feed water was pumped through the modules at 40 gpm until the next sampling point.

VERIFICATION OF PERFORMANCE

The LT2ESWTR and MFGM specify that an LRV for the test ($LRV_{C\text{-}TEST}$) be calculated for each module tested, and that the LRVs for each module are then combined to yield a single $LRV_{C\text{-}TEST}$ for the product.

If fewer than 20 modules are tested, as was the case for this verification, the $LRV_{C\text{-}TEST}$ is simply the lowest LRV for the individual modules. However, the rule does not specify a method to calculate $LRV_{C\text{-}TEST}$ for each module. Suggested options in the MFGM include:

- Calculate a LRV for each feed/filtrate sample pair, then calculate the average of the individual sample point LRVs;
- Average all of the feed and filtrate counts, then calculate a single LRV for the module; or
- Calculate a LRV for each feed/filtrate sample pair, select the LRV for the module as the lowest (most conservative of the three options).

Options 1 and 2 give $LRV_{C\text{-}TEST}$ values that are either identical, or only a few hundredths or less different, so for this verification, options 1 and 3 are used to calculate LRVs.

First Round Results

The MS2 LRVs for the first round of tests are presented in Table VS-ii. The intact module $LRV_{C\text{-}TEST}$, using the overall mean LRV calculations in Table VS-ii, is 3.73. The $LRV_{C\text{-}TEST}$ based on the lowest individual sample pair log reduction is 3.44. Under the cut-fiber scenario, the $LRV_{C\text{-}TEST}$ from the overall means is 3.44, while that from the lowest individual sample pair log reduction is 2.98.

Table VS-ii. First Round LRV Calculations

	Intact Modules		Cut Fiber	
Module #	**Mean LRV**	**Lowest LRV**	**Mean LRV**	**Lowest LRV**
Module 1	3.92	3.85	3.44	3.10
Module 2	3.73	3.44	3.72	2.98
Module 3	4.55	4.09	4.73	4.19
Module 4	3.82	3.65	4.93	4.65
Module 5	4.17	3.90	4.49	4.30

To evaluate whether there was significantly lower virus removal with a cut fiber, the LRVs for the feed/filtrate sample pairs were pooled together, and the paired-difference t statistic was calculated using Microsoft® Excel®. The mean LRV for all five intact modules is 4.04, with individual sample pair LRVs ranging from 3.44 to 5.16. The mean LRV for the cut-fiber tests is actually higher, at 4.26, with a range of 2.98 to 5.74. The paired-difference t statistic for the two sets of LRVs is 1.15, which is below the critical t value of 2.15 (14 degrees of freedom) that denotes a significant difference with a confidence of 95%.

The intact module pressure decay rates ranged from 0.000 to 0.052 psi/min, while those for the cut-fiber scenario ranged from 0.734 to 1.292 psi/min, indicating that there was indeed a significant integrity breach.

A possible explanation for why there was no significant difference between the intact module and cut-fiber scenarios arises from the testing engineer's observation of air bubbles in the filtrate during the pre-test flushes for the retests, as discussed above. If a portion of the air introduced for the pressure decay test was still trapped at the top of the module during the challenge test, the cut fiber at the top of the module may have never been in contact with the challenge water during the first round of tests; it may have been in a pocket of air trapped at the top of the module. This theory is bolstered by a comparison of the feed pressure data for the first round of tests versus the retests. For the first round of tests, above 20 psi driving pressure was needed for eight of the ten test runs to achieve the target flux, compared with less than 18 psi for the retests. If air was trapped in the modules, thus occluding a significant portion of the

membrane surface area, a higher driving pressure would be needed to achieve the target flux, due to the smaller surface area.

To attempt to discern a significant difference in LRV between the intact modules and modules with a cut fiber, NSF and Dow decided to re-run the tests on the same five modules using a higher MS2 challenge.

Second Round Results

The LRVs for the second round of tests are displayed in Table VS-iii. The intact module $LRV_{C\text{-}TEST}$, using the overall mean LRV calculations in Table VS-iii, is 2.59. The $LRV_{C\text{-}TEST}$ based on the lowest individual sample pair log reductions is 2.39. Under the cut-fiber scenario, the $LRV_{C\text{-}TEST}$ from the overall means is 2.46, while that from the lowest individual sample pair log reductions is 2.37. The intact module pressure decay rates ranged from 0.000 to 0.035 psi/min, while those for the cut-fiber tests ranged from 0.970 to 1.284 psi/min.

Table VS-iii. Second Round LRV Calculations

	Intact Modules		Cut Fiber	
Module #	**Mean LRV**	**Lowest LRV**	**Mean LRV**	**Lowest LRV**
Module 1	3.39	3.23	3.13	3.12
Module 2	3.10	2.90	2.67	2.66
Module 3	3.36	3.09	2.93	2.87
Module 4	3.27	3.04	2.77	2.53
Module 5	2.59	2.39	2.46	2.37

In contrast to the first round LRV data, the retest data set does show a statistically significant difference in virus retention between the intact and cut-fiber scenarios. The mean LRV for all five intact modules is 3.14, with a range of 2.39 to 3.62. The mean LRV for the cut-fiber tests is 2.79, with a range of 2.37 to 3.14. The paired-difference t statistic for the two sets of LRV's is 5.00, which is above the critical t value of 2.15 for a significant difference at the 95% confidence level.

The pressure decay rates indicated a catastrophic loss of membrane integrity, but the corresponding loss of virus retention was not as large. For the retests, the cut-fiber pressure decay rates were approximately 30 times higher than those for the intact modules. This translates into an approximate 1.5 log loss of membrane integrity. However, the MS2 reduction data only shows a mean LRV loss of 0.35 logs.

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 Annette Gatchett
for Cynthia Sonich Mullin *05/04/12*

Cynthia Sonich-Mullin Date
Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original signed by Pierre Sbabo *05/04/12*

Pierre Sbabo Date
Vice President
Water Systems
NSF International

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Availability of Supporting Documents
Copies of the test protocol, the verification statement, and the verification report (NSF report # NSF 12/35/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

March 2012

Environmental Technology Verification Report

Removal of Microbial Contaminants in Drinking Water-Ultrafiltration Module with a Cut Fiber

Dow Chemical Company – Dow Water Solutions

SFD-2880 Ultrafiltration Module

Prepared by:

NSF International
Ann Arbor, Michigan 48105

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

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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.

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Abbreviations and Acronyms

ATCC	American Type Culture Collection
°C	degrees Celsius
cm	centimeter
ETV	Environmental Technology Verification
°F	degrees Fahrenheit
ft	foot(feet)
gfd	gallons per square foot per day
gpm	gallons per minute
in	inch(es)
L	liter
LRV	log removal value
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
m	meter
MFGM	Membrane Filtration Guidance Manual
mg	milligram
mL	milliliter
mm	millimeter
MWCO	molecular weight cutoff
NRMRL	National Risk Management Research Laboratory
NSF	NSF International (formerly known as National Sanitation Foundation)
NTU	Nephelometric Turbidity Unit
ORD	Office of Research and Development
PFU	plaque forming unit
psi	pounds per square inch
PVDF	polyvinylidene fluoride
QA	quality assurance
QC	quality control
RPD	relative percent difference
SM	Standard Methods for the Examination of Water and Wastewater
TDS	total dissolved solids
TMP	trans membrane pressure
TOC	total organic carbon
TSS	total suspended solids
UF	ultrafiltration
µg	microgram
µm	microns
µS	microsiemens
USEPA	U. S. Environmental Protection Agency

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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 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 a cut fiber challenge study for the Dow Chemical Company SFD-2880 ultrafiltration membrane module. MS2 coliphage virus was the surrogate challenge organism. The challenge tests followed the requirements of the Department of Health Victoria (Australia) *Draft guidelines for validating treatment processes for pathogen reduction, supporting Class A water recycling schemes in Victoria*. These requirements are largely based on the USEPA Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) and Membrane Filtration Guidance Manual (MFGM). The Victoria guideline requires validation of the critical limits for the direct integrity test and indirect integrity monitoring, and also demonstration of the resolution and sensitivity of the direct integrity test and evidence showing correlation between continuous indirect integrity monitoring and membrane integrity. These requirements were not included in this verification, as these requirements are site-specific.

This verification does not address long-term performance, or performance over the life of the membrane. Also, this verification test did not evaluate cleaning of the membranes, nor any other maintenance and operation.

1.3 Testing Participants and Responsibilities

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: 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 Dow Chemical Company

The Dow Chemical Company supplied the tested membrane modules, and also provided logistical and technical support, as needed.

Contact: The Dow Chemical Company – Dow Water Solutions
1691 N. Swede Road
Midland, MI 48674
Contact: Daryl Gisch
Phone: 989-636-9254
Email: dgisch@dow.com

Chapter 2
Product Description

2.1 UF Membrane 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 can be either "inside-out" or "outside-in". 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 microns (μm). Typical MWCO points are 10,000 to 500,000 Daltons, 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 SFD-2880 Membrane Module Description

The Dow SFD-2880 is a polyvinylidene fluoride (PVDF) hollow fiber ultrafiltration membrane module. The module specifications and operating parameters are listed in Table 2-1. The SFD-2880 is a pressure driven module, with the normal operating flow orientation from the outside to the inside of the fibers. The SFD-2880 is certified to NSF/ANSI Standard 61, which establishes minimum public health related requirements for drinking water system components.

Table 2-1. SFD-2880 Specifications

Parameter	Specification
Dimensions:	
Module outside diameter	8.9 inches (in) (225 millimeters (mm))
Module length	92.9 in (2360 mm)
Module volume	10.3 gallons (gal) (39 liters (L))
Nominal membrane pore size	0.03 µm
Maximum membrane pore size	0.05 µm
Average active membrane area (outer)	829 square feet (ft^2) (77 square meters (m^2))
Operating Limits:	
Filtrate flux range at 25°C	24-70 gallons per square foot per day (gfd) (40-120 $L/m^2/hr$)
Flow range	13.6-40.9 gallons per minute (gpm) (3.1-9.3 m^3/hr)
Operating temperature range	34-104 Fahrenheit (°F) (1-40 Celcius (°C))
Max. inlet module pressure	44 pounds per square inch (psi) (3.0 bar)
Max. transmembrane pressure (TMP)	30 psi (2.1 bar)
Operating pH range	2 – 11
Max. NaOCl	2,000 milligrams per L (mg/L)
Max. Total Suspended Solids (TSS)	100 mg/L
Max. Turbidity	300 Nephelometric Turbidity Units (NTU)

A diagram of the SFD-2880 module is pictured in Figure 2-1. The module design allows for an optional reject line connection, but this port was closed off for the challenge tests. The modules were operated in dead-end mode.

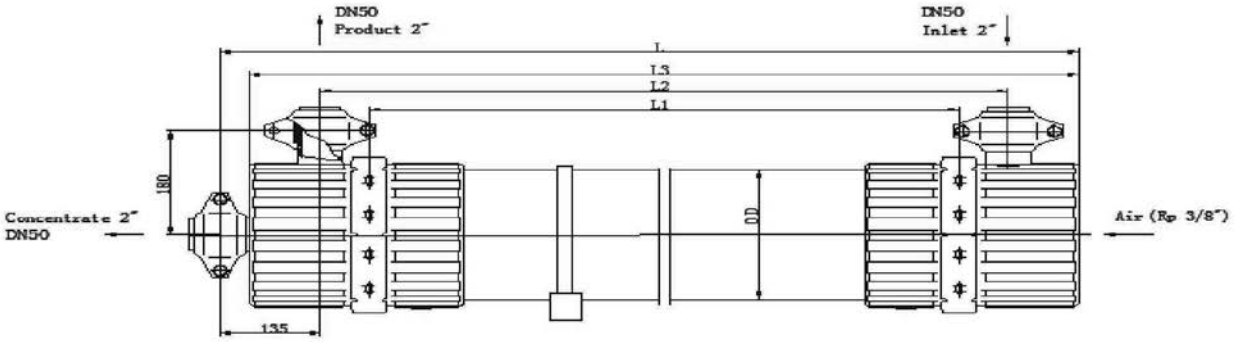

Figure 2-1. Diagram of the SFD-2880 UF module.

Dow supplied five new UF modules for testing. There was no seasoning period, other than that specified by Dow to sufficiently rinse out the membrane preservative and wet the membranes. See Section 3.5 for a description of the UF module conditioning procedure. The serial numbers of the tested modules are listed in Table 2-2. The modules were randomly selected by Dow personnel from existing inventory. The module numbers in the first column are the numbers used in Chapter 4 to identify each module.

Table 2-2. Serial Numbers of Tested Modules

Module	Serial Number
1	PE10K03682
2	PE10K03708
3	PE10K03508
4	PE10K03672
5	PE10K03705

Chapter 3
Methods and Procedures

3.1 Introduction

The tests followed the procedures described in the *Test/QA Plan for Validating the Dow Chemical Company SFD-2880 Ultrafiltration Membrane Module for Virus Reduction Following the Department of Health Victoria (Australia) Draft Guidelines for Validating Treatment Processes for Pathogen Reduction.* The Victoria Guidelines support the regulatory approval process for Class A water recycling schemes. The Department of Health Victoria guideline refers to the USEPA MFGM for the challenge testing requirements. The test/QA plan is available from NSF upon request.

NSF International performed all testing activities in their Ann Arbor, Michigan laboratory. The NSF Microbiology Laboratory performed all MS2 analyses. The intact module and cut-fiber tests were conducted twice, in two separate rounds of testing. The second round of testing was conducted because the data from the first round did not show any significant reduction in virus retention between the intact and cut-fiber challenges. For the first round, NSF tested the five intact modules in January 2011. Then Dow representatives visited the testing laboratory to cut the fibers, and the cut-fiber tests were conducted in March 2011. See Section 3.2 for discussion of the fiber cutting procedure. The retests were conducted in May 2011. The cut-fiber challenges were conducted first, followed by the intact module challenges. Again, Dow representatives visited the testing laboratory, this time to pin the cut fibers and to check for any other integrity problems after the cut-fiber retests were completed.

3.2 UF Fiber Cutting Procedure

As required in the Department of Health Victoria guideline, one fiber in each module was cut as close as possible to the potting resin on the filtrate end of the module. Dow representatives drilled a hole through the wall of each module. Then, using needle-nosed pliers, they reached in and pulled one fiber out into the opening, and cut out approximately one inch of the fiber. See Figure 3-1 for a photo of a cut fiber in a module. In the photo, the potting resin starts approximately at the bottom of the gray end cap visible at the top of the photo. They then plugged the hole in the module wall. After a fiber was cut, the filtrate end cap was removed and the Dow representatives applied a layer of water to the top of the potting resin, covering the fiber outlets. Air pressure was then applied to the module to look for any other compromised fibers. See Figure 3-2 for a photo of air coming out of the cut fiber, but from no other fibers in one of the modules. If any other fiber leaks were detected, the fiber in question was plugged.

Figure 3-1. Photo of a cut fiber in one of the Dow SFD-2880 modules tested.

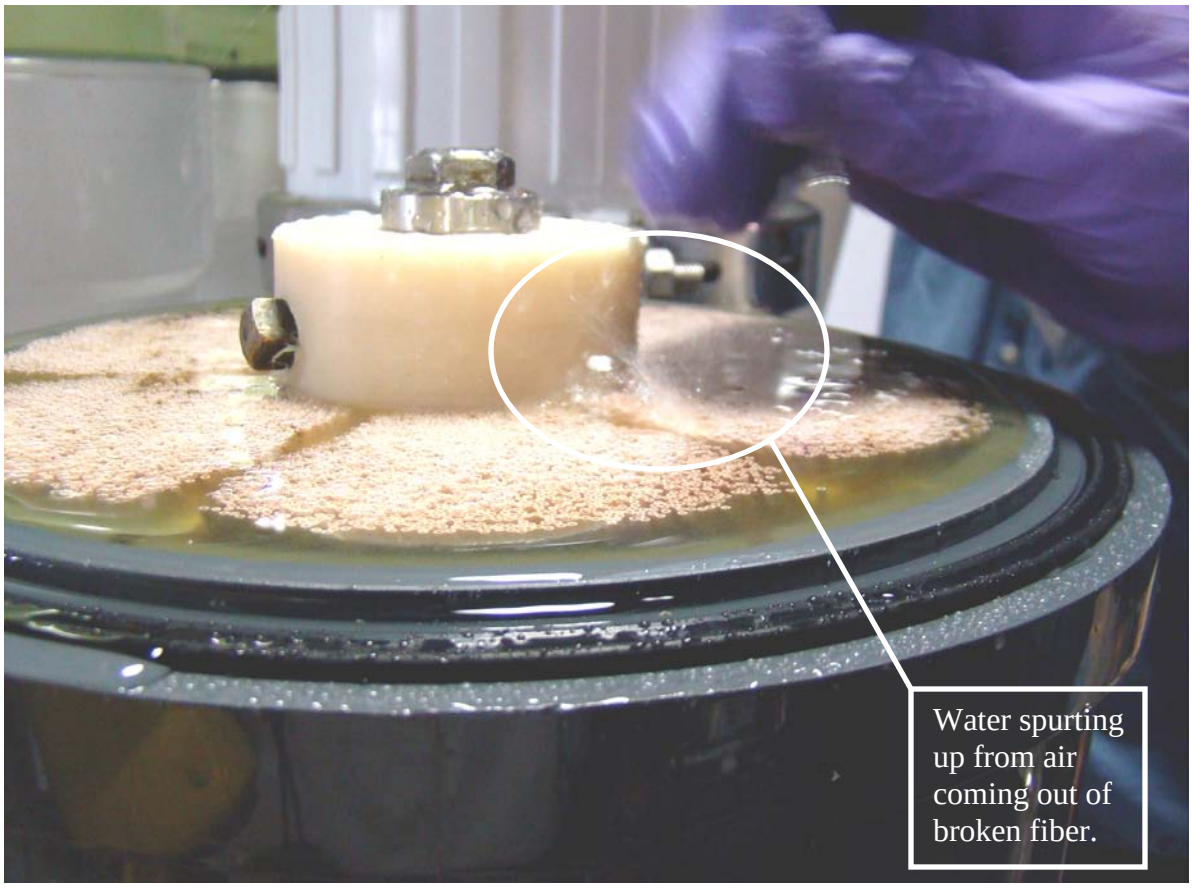

Figure 3-2. Photo of a cut fiber leaking air.

3.3 Virus Surrogate

The modules were challenged with the MS2 coliphage virus (ATCC 15597-Bl) as a surrogate for enteric viruses, as required by the Victoria draft guidelines for virus removal credits. MS2 is generally accepted as an enteric virus surrogate for size-exclusion technologies due to its small size (approximately 22-26 nanometers). The USEPA MFGM references MS2 as an acceptable surrogate for enteric viruses because it is similar in size and shape to poliovirus and hepatitis virus. The target feed concentration was $5x10^5$ plaque forming units per milliliter (PFU/mL) for the first round of testing. For the second round, the target feed concentration was increased to $5x10^6$ PFU/mL in an attempt to discern a significant difference in virus retention between the fully intact and cut-fiber scenarios.

The MS2 stock suspension was purchased from Biological Consulting Services of North Florida, Inc.

3.4 Test Apparatus

The modules were tested in a test rig constructed specifically for these tests. The test rig construction conformed to the requirements of the MFGM. See Figure 3-3 for a schematic diagram of the test rig, and Figure 3-4 for a photo of the test rig.

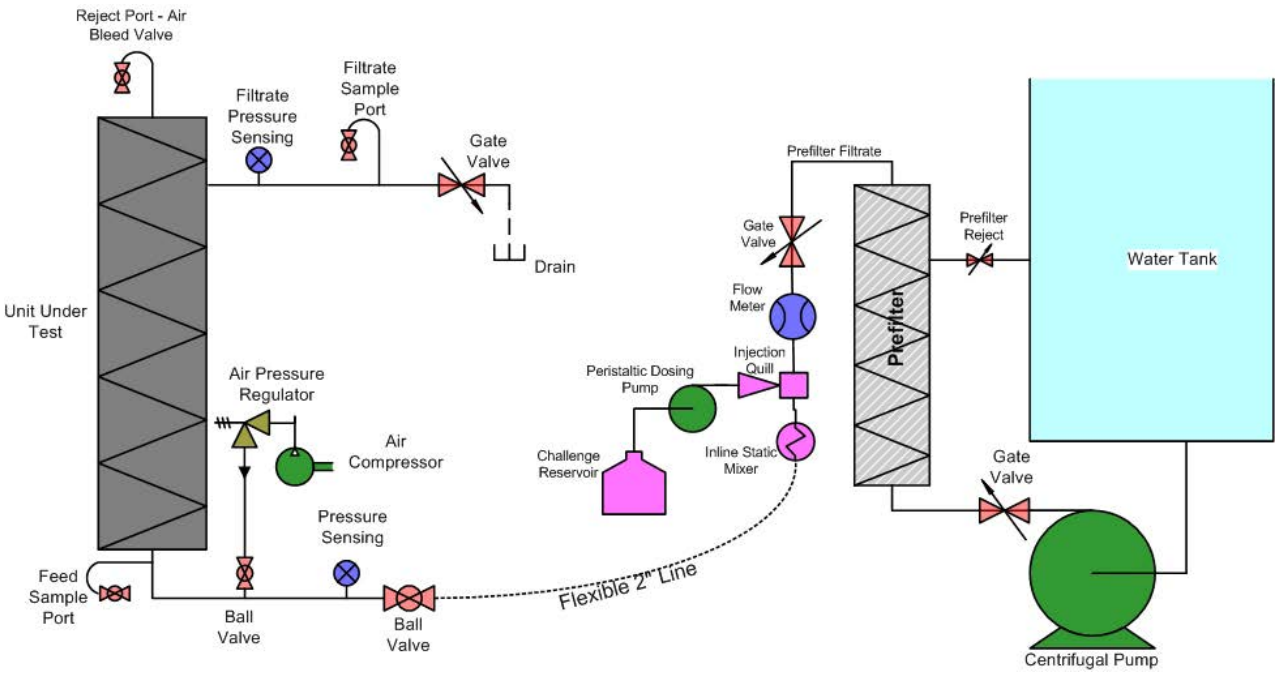

Figure 3-3. Schematic diagram of the test rig used for verification testing.

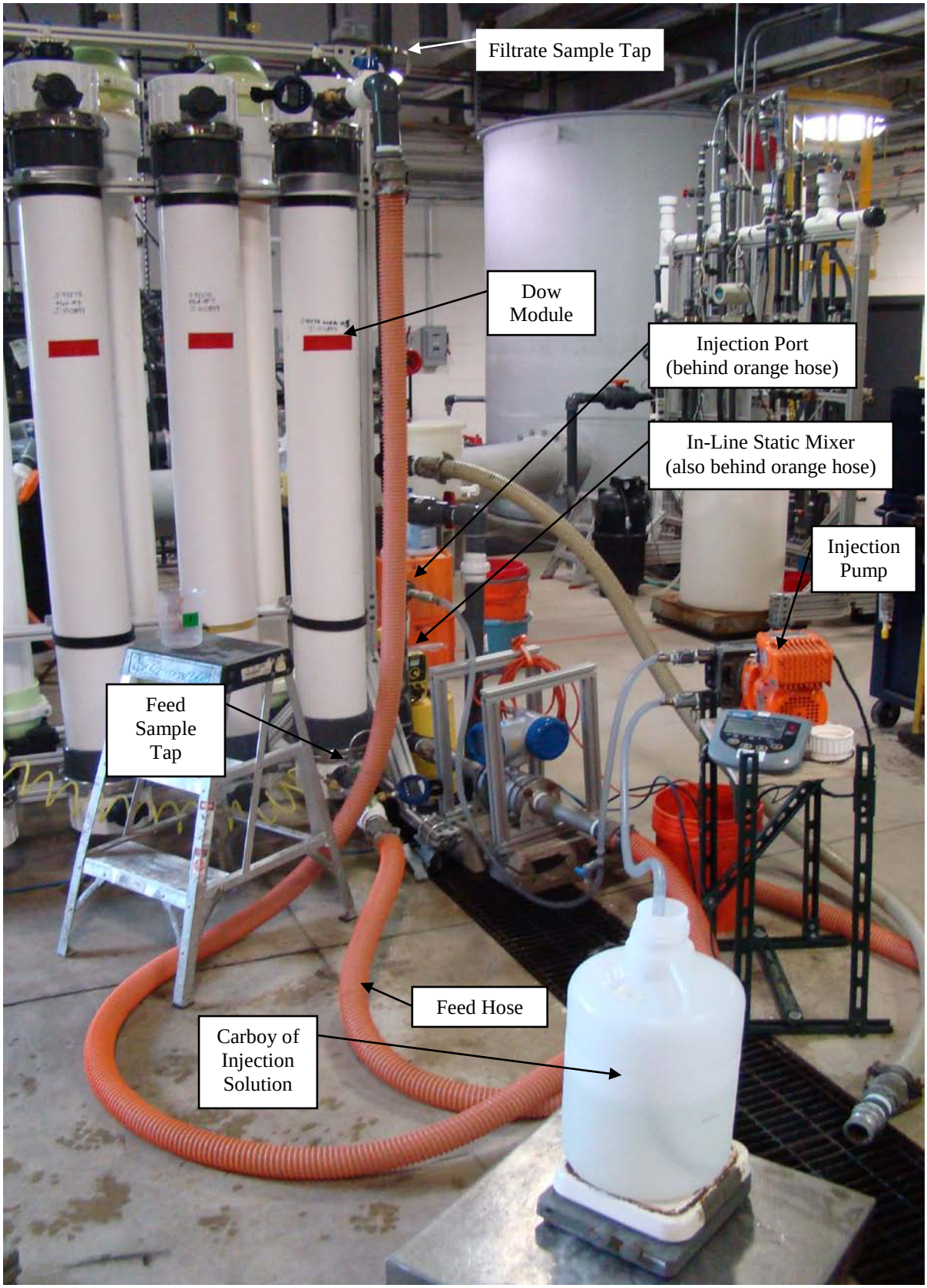

Figure 3-4. Photo of the test rig.

The challenge organisms were introduced into the feed water by intermittent injection during the challenge tests. Injection and mixing of the organisms followed the guidelines of the MFGM. Specifically, the total stock solution volume injected into the feed stream during each challenge test was between 0.5 and 2 percent of the total spiked test solution volume, a chemical metering pump that delivered a steady flow of the challenge solution was used, and the injection port included a quill extending into the middle of the feed pipe. The static mixer was placed downstream of the injection point, and more than ten pipe diameters upstream of the feed sample tap, as suggested in the MFGM.

The feed and filtrate sample taps were located immediately upstream and downstream of the UF module, as shown in Figure 3-4. Both had a quill extending into the middle of the pipe as suggested in the MFGM. The taps were metal, and were flame-sterilized prior to sample collection.

3.5 Test Water Composition

For the first round of tests in January and March of 2011, Ann Arbor municipal water was treated by activated carbon filtration, reverse osmosis, ultraviolet disinfection, and deionization at the NSF Laboratory to make the base water for the tests. A 4,000-gallon water supply tank was filled with the base water. Sodium bicarbonate was added to the base water in sufficient quantity to provide alkalinity at a target concentration of 100 ± 10 mg/L as calcium carbonate. The pH was then lowered with hydrochloric acid into the target range of 7.5 ± 0.5.

For the May retests, the test water was Ann Arbor municipal water treated only by activated carbon filtration and ultrafiltration upstream of the challenge organism injection point. No sodium bicarbonate was added, and the pH was not adjusted. NSF had wished to switch from deionized water to dechlorinated tap water due to limitations in the laboratory's deionized water supply. In between the rounds of testing, NSF's State Advisory Panel approved the switch to de-chlorinated tap water. Dow also approved of the change.

Immediately prior to each challenge test, feed samples were collected for analysis of total chlorine, alkalinity, pH, temperature, total dissolved solids (TDS), total organic carbon (TOC), and turbidity. These samples were collected prior to injection of the challenge organism.

3.6 UF Module Conditioning

The Dow SFD-2880 modules were "brand new" when challenged. Prior to testing, the modules were rinsed and conditioned with the deionized water described in Section 3.4, following a proprietary procedure supplied by Dow. Prior to the second round of testing, Dow requested that each module be forward flushed at approximately 40 gpm for 30 minutes using tap water.

3.7 Test Rig Sanitization

The Dow module conditioning procedure included an hour long flush with a sodium hypochlorite solution at approximately 400 mg/L of total chlorine. This procedure was sufficient to sanitize the test rig prior to testing. The test rig plumbing was also sanitized in between each challenge test. This was accomplished by connecting the feed and filtrate plumbing together, and flushing for approximately ten minutes using tap water with injection of a sodium

hypochlorite solution that was approximately 12% free chlorine. Then, injection of the sanitizing solution was stopped and the plumbing was flushed with dechlorinated tap water until the chlorine residual from the filtrate sample tap was <0.5 mg/L.

3.8 UF Module Integrity Tests

Before and after each challenge test, each module was subjected to a pressure decay test to satisfy the non-destructive performance test requirement in Section 3.6 of the MFGM. The test procedure followed ASTM D6908-03 *Standard Practice for Integrity Testing of Water Filtration Membrane Systems*. The water was drained from the feed side of the membrane, but not the filtrate side. Approximately 30 psi of pressure was applied to the feed side and the remaining pressure was recorded every minute to chart the pressure decay. The test length was 10 minutes for the intact module tests in the first round of testing, and 20 minutes for all subsequent tests. The baseline decay rate of the pressurized portion of the test rig was also measured for the same lengths of time once per day for each day of testing, with the exception of the cut-fiber tests in the second round of testing. It was decided to eliminate this step for the cut-fiber tests since the baseline decay rate of the test rig was so small compared to the pressure decay of the UF modules with the cut fibers.

3.9 Microbial Challenge Test Procedure

Each of the SFD-2880 modules submitted for testing was challenged individually, as shown in the photo of the test rig in Figure 3-4. The target flux for membrane operation was Dow's maximum recommended value of 70 gfd at 25 °C, which equals a flow rate of approximately 40.3 gpm.

After completion of the pre-challenge pressure decay test described in Section 3.8, the module to be tested was forward flushed at 40 gpm to force out the air introduced from the pressure decay test. For the first round of tests conducted in January and March, each module was flushed for five minutes. At the start of the retest round in May, the laboratory engineer noticed that after five minutes of flushing, there were still bubbles visible in the filtrate hose line. The engineer flushed Module 1 for an additional three minutes until bubbles were no longer visible. The engineer had to flush Module 2 for a total of 22 minutes to clear the bubbles. At this point, it was decided to install bleed valves in the reject port caps for Modules 3, 4 and 5 to allow evacuation of the air. After the pressure decay tests for these three modules, the bleed valve was opened and the flow of water started at 40 gpm. The valves were kept open until all the air had escaped. This allowed the testing engineer to return to the flush time of five minutes. See Figure 3-5 for a photo of the bleed valve installed on Module 4.

At the end of the forward flush two feed and two filtrate samples were collected. One sample of each process stream served as a negative control, and was analyzed for MS2. The second sample pair was spiked with MS2 to serve as positive controls. The testing engineer spiked these samples with a measured aliquot of the challenge suspension immediately after collection, and the spiked samples were submitted to the NSF Microbiology Laboratory with the other samples from that challenge test. The spiked samples served to verify that the MS2 was stable in the feed and filtrate waters over the course of the test and up to the time that the samples were processed by the Microbiology Laboratory.

Figure 3-5. Bleed valve installed on reject port cap.

Each challenge test was approximately 35 minutes in length, with the MS2 suspension injected into the feed stream at start-up, after 15 minutes of operation, and after 30 minutes of operation. Sections 3.10.2, 3.10.4, and 3.12.4 of the MFGM describe the requirements for the challenge test sampling plan. The MFGM requires that feed and filtrate samples not be collected until at least three hold-up volumes of water spiked with MS2 have passed through the membrane, to allow for establishment of equilibrium (equilibrium volume). The hold-up volume is defined as the "unfiltered test solution volume that would remain in the system on the feed side of the membrane at the end of the test." Dow's specification sheet for the SFD-2880 gives the module volume as 10.3 gal. It is assumed that this volume is the total water holding volume of the module, not just the volume of the feed side of the membranes. As such, its use as the hold-up volume will add a safety factor to the hold-up volume calculation.

The MFGM also specifies that the challenge organism suspension be injected upstream of a static mixer, and that the feed sample tap be at least 10 pipe diameters downstream of the static mixer. Further, the feed sample tap shall be placed as close as possible to the module inlet. The pipe and hoses used for the test rig were 2 inches in diameter (DN50) to match the inlet and outlet fittings on the SFD-2880. Therefore, the feed sample tap was required to be least 20 inches downstream of the static mixer. As shown in Figure 3-4, the challenge suspension

injection port and the static mixer are separated from the feed sample tap by a stretch of flexible hose that was approximately 175 inches in length. One hundred and seventy-five inches of 2-inch diameter pipe has a volume of approximately 2.6 gal. The maximum expected pipe volume plus the module volume gives a hold-up volume of approximately 13 gal. If the hold-up volume is 13 gal, then the equilibrium volume is 39 gal. The target challenge flow rate was 40.3 gpm, so the MS2 suspension was injected for at least one minute prior to sampling to meet the requirement of passing the equilibrium volume.

After at least one minute of injection at each challenge point, a grab sample was first collected from the filtrate sample tap, and then from the feed sample tap. The sample taps were flame sterilized prior to sample collection. Also, at least 100 mL was collected and discarded prior to sample collection to flush the taps. After sample collection was complete, MS2 injection was stopped, and the test water minus MS2 was pumped through the modules until the next sampling point.

Note that the Victoria draft guidelines call for collection of three sample pairs at each collection point, for a total of nine feed and nine filtrate samples. This did not occur for this verification test. Instead, the testing engineer collected one feed and one filtrate sample at each sampling point for a total of three samples from each process stream per test. These samples were analyzed in triplicate to obtain nine feed counts and nine filtrate counts per test.

3.10 Analytical Methods

A list of laboratory analytical methods can be found in Table 3-1. Single samples of adequate volume were collected for challenge organism enumeration, and were analyzed in triplicate.

Table 3-1. Analytical Methods for Laboratory Analyses

Parameter	Method	NSF Reporting Limit	Sample Hold Time
Alkalinity (total, as $CaCO_3$)	USEPA 310.2	5 mg/L	14 days
pH	SM[1] 4500-H^+ B	NA[2]	none[3]
TDS	SM 2540 C	5 mg/L	7 days
Total Chlorine	SM 4500-Cl G	0.05 mg/L	none[3]
TOC (mg/L)	SM 5310C	0.1 mg/L	28 days
Turbidity	SM 2130	0.1 NTU	none[3]
MS2	NSF 55[4]	1 PFU/mL	30 hours

(1) SM = Standard Methods
(2) Not Applicable
(3) Immediate analysis required
(4) Method published in NSF/ANSI Standard 55 – Ultraviolet Microbiological Water Treatment Systems. Method is similar to EPA Method 1601.

Chapter 4
Results and Discussion

4.1 Introduction

As discussed in Section 3.1, there were two rounds of testing conducted for this study. Each module was tested twice as an intact, integral module, and twice with a cut fiber. The retests were conducted because the data from the first round of tests failed to show any significant difference in virus retention between the intact and cut-fiber scenarios.

For presentation of the challenge organism data in this chapter, the observed triplicate counts were averaged by calculating geometric means. Geometric means <1 were rounded up to 1, unless all three triplicate analyses had no organisms found. The virus counts in the "Overall Mean" rows are also geometric means. The mean counts were $\log_{10}$ transformed for the purpose of calculating log removal values (LRV). The LRV's in the "Overall Mean" rows are the arithmetic means of the individual sample point LRVs. The triplicate counts for each sample are presented in Appendix B.

The LT2ESWTR and MFGM specify that an LRV for the test ($LRV_{C\text{-}TEST}$) be calculated for each module tested, and that the LRVs for each module are then combined to yield a single $LRV_{C\text{-}TEST}$ for the product. If fewer than 20 modules are tested, as was the case for this verification, the $LRV_{C\text{-}TEST}$ is simply the lowest LRV for the individual modules. However, the rule does not specify a method to calculate the LRV for each module. Suggested options in the MFGM include:

1. Calculate a LRV for each feed/filtrate sample pair, then calculate the average of the individual sample point LRVs;
2. Average all of the feed and filtrate counts, and then calculate a single LRV for the module; or
3. Calculate a LRV for each feed/filtrate sample pair, select the LRV for the module as the lowest (most conservative of the three options).

Options 1 and 2 give $LRV_{C\text{-}TEST}$ values that are either identical, or within a few hundredths of each other, so in this report options 1 and 3 were used to calculate the LRV for each module.

4.2 First Round Results and Discussion

The intact module MS2 challenge data from the first round of testing is presented in Table 4-1, while the cut-fiber challenge data is presented in Table 4-2. The intact module $LRV_{C\text{-}TEST}$, using the overall mean LRV calculations in Table 4-1, is 3.73. The $LRV_{C\text{-}TEST}$ based on the lowest individual sample pair log reductions is 3.44. Both $LRV_{C\text{-}TEST}$ values are from the Module 2 data. Under the cut-fiber scenario, the $LRV_{C\text{-}TEST}$ from the overall means is 3.44, while that from the lowest individual sample pair log reductions is 2.98. These $LRV_{C\text{-}TEST}$ values are from Modules 1 and 2, respectively.

Table 4-1. First Round Intact Module MS2 Challenge Results						
		Feed		Filtrate		
Module	Sample Point	Geometric Mean (PFU/mL)	Log_{10}	Geometric Mean (PFU/mL)	Log_{10}	LRV
Module 1	1 Minute	$1.41x10^6$	6.15	$1.69x10^2$	2.23	3.92
	15 Minutes	$1.69x10^6$	6.23	$1.74x10^2$	2.24	3.99
	30 Minutes	$1.34x10^6$	6.13	$1.90x10^2$	2.28	3.85
	Overall Mean	$1.47x10^6$	6.17	$1.77x10^2$	2.25	3.92
Module 2	1 Minute	$1.23x10^5$	5.09	$4.5x10^1$	1.65	3.44
	15 Minutes	$2.7x10^5$	5.43	$3.7x10^1$	1.57	3.86
	30 Minutes	$3.2x10^5$	5.51	$4.2x10^1$	1.62	3.89
	Overall Mean	$2.2x10^5$	5.34	$4.1x10^1$	1.61	3.73
Module 3	1 Minute	$4.4x10^5$	5.64	$3x10^0$	0.48	5.16
	15 Minutes	$3.7x10^5$	5.57	$1.5x10^1$	1.18	4.39
	30 Minutes	$4.5x10^5$	5.65	$3.6x10^1$	1.56	4.09
	Overall Mean	$4.2x10^5$	5.62	$1.2x10^1$	1.07	4.55
Module 4	1 Minute	$3.2x10^5$	5.51	$4.6x10^1$	1.66	3.85
	15 Minutes	$3.8x10^5$	5.58	$8.5x10^1$	1.93	3.65
	30 Minutes	$2.8x10^5$	5.45	$3.0x10^1$	1.48	3.97
	Overall Mean	$3.2x10^5$	5.51	$4.9x10^1$	1.69	3.82
Module 5	1 Minute	$7.4x10^5$	5.87	$5.8x10^1$	1.76	4.11
	15 Minutes	$5.9x10^5$	5.77	$7.4x10^1$	1.87	3.90
	30 Minutes	$1.30x10^6$	6.11	$4.1x10^1$	1.61	4.50
	Overall Mean	$8.3x10^5$	5.92	$5.6x10^1$	1.75	4.17

Table 4-2. First Round Cut-Fiber MS2 Challenge Results						
		Feed		Filtrate		
Module	Sample Point	Geometric Mean (PFU/mL)	Log_{10}	Geometric Mean (PFU/mL)	Log_{10}	LRV
Module 1	1 Minute	$1.14x10^5$	5.06	$1.0x10^1$	1.00	4.06
	15 Minutes	$1.1x10^5$	5.04	$7.6x10^1$	1.88	3.16
	30 Minutes	$1.0x10^5$	5.00	$8.0x10^1$	1.90	3.10
	Overall Mean	$1.1x10^5$	5.03	$3.9x10^1$	1.59	3.44
Module 2	1 Minute	$2.93x10^5$	5.47	$7x10^0$	0.85	4.62
	15 Minutes	$3.1x10^5$	5.49	$8.7x10^1$	1.94	3.55
	30 Minutes	$2.8x10^5$	5.45	$2.97x10^2$	2.47	2.98
	Overall Mean	$1.1x10^5$	5.03	$5.7x10^1$	1.75	3.72
Module 3	1 Minute	$5.5x10^5$	5.74	$1x10^0$	0.00	5.74
	15 Minutes	$6.3x10^5$	5.80	$3.5x10^1$	1.54	4.26
	30 Minutes	$5.4x10^5$	5.73	$3.5x10^1$	1.54	4.19
	Overall Mean	$5.7x10^5$	5.76	$1.1x10^1$	1.03	4.73
Module 4	1 Minute	$6.5x10^5$	5.81	$3x10^0$	0.48	5.33
	15 Minutes	$4.0x10^5$	5.60	$6x10^0$	0.78	4.82
	30 Minutes	$4.9x10^5$	5.69	$1.1x10^1$	1.04	4.65
	Overall Mean	$5.0x10^5$	5.70	$6x10^0$	0.77	4.93
Module 5	1 Minute	$7.9x10^5$	5.90	$1.2x10^1$	1.08	4.82
	15 Minutes	$9.0x10^5$	5.95	$4.5x10^1$	1.65	4.30
	30 Minutes	$7.2x10^5$	5.86	$3.2x10^1$	1.51	4.35
	Overall Mean	$8.0x10^5$	5.90	$2.6x10^1$	1.41	4.49

To evaluate whether there was significantly lower virus removal with a cut fiber, the LRVs for the feed/filtrate sample pairs in Tables 4-1 and 4-2 were pooled together, and the paired-difference t statistic was calculated using Microsoft® Excel®. The mean LRV for all five intact modules is 4.04, with individual sample pair LRVs ranging from 3.44 to 5.16. The mean LRV for the cut-fiber tests is actually higher, at 4.26, with a range of 2.98 to 5.74. These intact-module LRV values are somewhat higher than those observed for the SFD-2880 during previous ETV testing (mean LRV of 3.48, range of 2.37 to 4.58) (USEPA and NSF, 2011). The paired-difference t statistic for the two sets of LRVs is 1.15, which is below the critical t value of 2.15 for a two-tailed test with an alpha (α) of 0.05 and 14 degrees of freedom. Therefore, the t statistic does not indicate a significant difference in performance with a confidence of 95%.

A possible explanation for why there was no significant difference in virus removal between the intact module and cut-fiber scenarios arises from the testing engineer's observation of air bubbles in the filtrate during the pre-test flushes for the retests, as discussed in Section 3.9. If a portion of the air introduced for the pressure decay test was still trapped at the top of the module during the challenge test, the cut fiber at the top of the module may have never been in contact with the challenge water during the first round of tests; it may have been in a pocket of air trapped at the top of the module. This theory is bolstered by a comparison of the feed pressure data for the first round of tests versus the retests. For the first round of tests, above 20 psi driving pressure was needed for eight of the ten test runs to achieve the target flux, compared with less than 18 psi for the retests. If air was trapped in the modules, thus occluding a significant portion of the membrane surface area, a higher driving pressure would be needed to achieve the target flux, due to the smaller surface area.

To attempt to discern a significant difference in LRV between the intact modules and modules with a cut fiber, NSF and Dow decided to re-run the tests on the same five modules using a higher MS2 challenge. The results and discussion for the retests are presented below in Section 4.3.

The pre-challenge and post-challenge pressure decay data for the first round of testing is presented in Table 4-3. The intact module pressure decay rates were similar to those observed by NSF for the SFD-2880 module during previous testing activities (USEPA and NSF, 2011), ranging from 0.000 to 0.052 psi/min. The pressure decay rates for the cut-fiber scenario ranged from 0.734 to 1.292 psi/min, indicating that there was indeed a significant integrity breach.

The module operational data for the first round of challenge tests is listed in Table 4-4 and the water chemistry data is presented in Table 4-5. Many of the alkalinity measurements were below the target range of 90-110 mg/L, but all of the pH readings were within the target range of 7.0-8.0.

Table 4-3. First Round Pressure Decay Results							
Module	**Test**	**Starting Pressure (psi)**	**Final Pressure (psi)**	**Elapsed Time (min)**	**Decay Rate (psi/min)**	**Background Decay Rate (psi/min)**	**Corrected Decay Rate (psi/min)**
Module 1	Intact Pre-Test	30.01	29.81	10.00	0.020	0.010	0.010
	Intact Post-Test	30.11	30.03	10.00	0.008	0.010	-0.002
	Cut Fiber Pre-Test	31.50	9.95	20.00	1.078	0.012	1.066
	Cut Fiber Post-Test	31.20	5.13	20.00	1.304	0.012	1.292
Module 2	Intact Pre-Test	30.40	30.12	10.00	0.028	0.013	0.015
	Intact Post-Test	30.72	30.07	10.00	0.065	0.013	0.052
	Cut Fiber Pre-Test	31.40	8.18	20.00	1.161	0.012	1.149
	Cut Fiber Post-Test	31.50	8.59	20.00	1.146	0.012	1.134
Module 3	Intact Pre-Test	30.70	30.54	10.00	0.016	0.013	0.003
	Intact Post-Test	30.68	30.46	10.00	0.022	0.013	0.009
	Cut Fiber Pre-Test	31.50	14.00	20.00	0.875	0.000	0.875
	Cut Fiber Post-Test	31.25	16.58	20.00	0.734	0.000	0.734
Module 4	Intact Pre-Test	30.56	30.22	10.00	0.034	0.015	0.019
	Intact Post-Test	30.69	30.32	10.00	0.037	0.015	0.022
	Cut Fiber Pre-Test	31.45	8.09	20.00	1.168	0.000	1.168
	Cut Fiber Post-Test	31.60	16.39	20.00	0.761	0.000	0.761
Module 5	Intact Pre-Test	30.70	30.54	10.00	0.016	0.015	0.001
	Intact Post-Test	30.38	29.90	10.00	0.048	0.015	0.033
	Cut Fiber Pre-Test	31.40	6.00	20.00	1.270	0.004	1.266
	Cut Fiber Post-Test	31.45	14.99	20.00	0.823	0.004	0.819

Table 4-4. First Round Module Operation Data									
		Filtrate Flow Rate (gpm)		**Flux (gfd)**		**Feed Pressure (psi)**		**Filtrate Pressure (psi)**	
Challenge Test	**Date**	**0 Min.**	**30 Min.**	**0 Min**	**30 Min**	**0 Min.**	**30 Min.**	**0 Min.**	**30 Min.**
Module 1 Intact	01/24/11	40.6	40.5	70.5	70.3	23.45	22.60	1.06	0.98
Module 2 Intact	01/25/11	40.9	40.1	71.0	69.7	23.16	22.40	2.29	2.17
Module 3 Intact	01/25/11	40.6	40.1	70.5	69.7	24.75	23.95	2.51	2.22
Module 4 Intact	01/27/11	40.3	40.7	70.0	70.7	24.29	23.82	1.43	1.42
Module 5 Intact	01/27/11	40.7	40.0	70.7	69.5	22.10	21.21	1.22	1.03
Module 1 Cut	03/02/11	40.5	40.4	70.3	70.2	19.60	16.40	4.09	3.64
Module 2 Cut	03/02/11	40.8	40.2	70.9	69.8	19.40	16.50	4.50	3.63
Module 3 Cut	03/03/11	41.1	40.6	71.4	70.5	22.90	17.20	2.71	2.15
Module 4 Cut	03/03/11	39.7	40.3	69.0	70.0	20.80	16.60	2.37	2.12
Module 5 Cut	03/04/11	40.5	40.6	70.3	70.5	20.44	15.80	2.83	2.36

Table 4-5. First Round Feed Water Chemistry Data							
Challenge Test	**Alkalinity (mg/L $CaCO_3$)**	**pH**	**Temp. (°C)**	**Total Chlorine (mg/L)**	**TDS (mg/L)**	**TOC (mg/L)**	**Turbidity (NTU)**
Module 1 Intact	97	7.41	17.6	<0.05	110	<0.1	0.11
Module 2 Intact	98	7.17	17.9	<0.05	110	0.1	0.11
Module 3 Intact	95	7.38	18.4	<0.05	120	0.1	0.12
Module 4 Intact	86	7.69	18.3	<0.05	130	<0.1	0.13
Module 5 Intact	88	7.52	19.0	<0.05	100	0.1	0.12
Module 1 Cut	83	7.80	20.1	<0.05	110	<0.1	0.19
Module 2 Cut	84	7.80	19.8	<0.05	100	<0.1	0.11
Module 3 Cut	83	7.84	18.8	<0.05	100	<0.1	0.15
Module 4 Cut	83	7.82	19.1	<0.05	100	0.4	0.12
Module 5 Cut	90	7.94	18.7	<0.05	110	<0.1	0.12

4.3 Retest Results and Discussion

The MS2 challenge retest data is displayed in Tables 4-6 and 4-7. The intact module $LRV_{C\text{-}TEST}$ from the overall means is 2.59. The $LRV_{C\text{-}TEST}$ based on the lowest individual sample pair log reductions is 2.39. Both $LRV_{C\text{-}TEST}$ values are from the Module 5 data. Under the cut-fiber scenario, the $LRV_{C\text{-}TEST}$ from the overall means is 2.46, while that from the lowest individual sample pair log reductions is 2.37. Both of these $LRV_{C\text{-}TEST}$ values also come from the Module 5 test data.

Table 4-6. Retest Intact Module MS2 Challenge Results						
		Feed		**Filtrate**		
Challenge Test	**Sample Point**	**Geometric Mean (PFU/mL)**	**Log_{10}**	**Geometric Mean (PFU/mL)**	**Log_{10}**	**LRV**
Module 1	1 Minute	$2.7x10^6$	6.43	$6.9x10^2$	2.84	3.59
	15 Minutes	$2.8x10^6$	6.45	$1.26x10^3$	3.10	3.35
	30 Minutes	$3.0x10^6$	6.48	$1.79x10^3$	3.25	3.23
	Overall Mean	$2.8x10^6$	6.45	$1.2x10^3$	3.06	3.39
Module 2	1 Minute	$4.5x10^6$	6.65	$1.60x10^3$	3.20	3.45
	15 Minutes	$3.9x10^6$	6.59	$4.5x10^3$	3.65	2.94
	30 Minutes	$3.4x10^6$	6.53	$4.3x10^3$	3.63	2.90
	Overall Mean	$3.9x10^6$	6.59	$3.1x10^3$	3.49	3.10
Module 3	1 Minute	$6.1x10^6$	6.79	$1.48x10^3$	3.17	3.62
	15 Minutes	$5.4x10^6$	6.73	$2.3x10^3$	3.36	3.37
	30 Minutes	$5.3x10^6$	6.72	$4.3x10^3$	3.63	3.09
	Overall Mean	$5.6x10^6$	6.75	$2.4x10^3$	3.39	3.36
Module 4	1 Minute	$5.1x10^6$	6.70	$1.88x10^3$	3.27	3.43
	15 Minutes	$4.1x10^6$	6.61	$3.7x10^3$	3.57	3.04
	30 Minutes	$5.0x10^6$	6.70	$2.3x10^3$	3.36	3.34
	Overall Mean	$4.7x10^6$	6.67	$2.5x10^3$	3.40	3.27
Module 5	1 Minute	$6.9x10^6$	6.84	$1.25x10^4$	4.10	2.74
	15 Minutes	$5.2x10^6$	6.72	$1.24x10^4$	4.09	2.63
	30 Minutes	$3.2x10^6$	6.51	$1.31x10^4$	4.12	2.39
	Overall Mean	$4.9x10^6$	6.69	$1.26x10^4$	4.10	2.59

Table 4-7. Retest Cut-Fiber Module MS2 Challenge Results						
		Feed		Filtrate		
Challenge Test	Sample Point	Geometric Mean (PFU/mL)	Log_{10}	Geometric Mean (PFU/mL)	Log_{10}	LRV
Module 1	1 Minute	$6.1x10^6$	6.79	$4.5x10^3$	3.65	3.14
	15 Minutes	$5.4x10^6$	6.73	$4.0x10^3$	3.60	3.13
	30 Minutes	$5.0x10^6$	6.70	$3.8x10^3$	3.58	3.12
	Overall Mean	$5.5x10^6$	6.74	$4.1x10^3$	3.61	3.13
Module 2	1 Minute	$8.8x10^5$	5.94	$1.82x10^3$	3.26	2.68
	15 Minutes	$7.9x10^5$	5.90	$1.72x10^3$	3.24	2.66
	30 Minutes	$8.8x10^5$	5.94	$1.81x10^3$	3.26	2.68
	Overall Mean	$8.5x10^5$	5.93	$1.78x10^3$	3.25	2.67
Module 3	1 Minute	$9.1x10^5$	5.96	$1.16x10^3$	3.06	2.90
	15 Minutes	$8.3x10^5$	5.92	$1.13x10^3$	3.05	2.87
	30 Minutes	$1.0x10^6$	6.01	$9.5x10^2$	2.98	3.03
	Overall Mean	$9.2x10^5$	5.96	$1.1x10^3$	3.03	2.93
Module 4	1 Minute	$3.0x10^6$	6.48	$4.3x10^3$	3.63	2.85
	15 Minutes	$3.5x10^6$	6.54	$4.2x10^3$	3.62	2.92
	30 Minutes	$3.6x10^6$	6.56	$1.1x10^4$	4.03	2.53
	Overall Mean	$3.4x10^6$	6.53	$5.8x10^3$	3.76	2.77
Module 5	1 Minute	$1.9x10^6$	6.28	$5.3x10^3$	3.72	2.56
	15 Minutes	$1.52x10^6$	6.18	$5.3x10^3$	3.72	2.46
	30 Minutes	$1.21x10^6$	6.08	$5.1x10^3$	3.71	2.37
	Overall Mean	$1.5x10^6$	6.18	$5.2x10^3$	3.72	2.46

In contrast to the first round LRV data, the retest data set does show a stastically significant difference in virus retention between the intact and cut-fiber scenarios. The mean LRV for the intact modules is 3.14, with a range of 2.39 to 3.62. The mean LRV for the cut-fiber tests is 2.79, with a range of 2.37 to 3.14. The paired-difference t statistic for the two sets of LRV's is 5.00, which is above the critical t value is 2.15 for a significant difference at the 95% confidence level.

The retest pressure decay data is displayed in Table 4-8. The observed pressure decay rates were similar to those from the first round of tests in Table 4-3. The intact module pressure decay rates ranged from 0.000 to 0.035 psi/min, while those for the cut-fiber tests ranged from 0.970 to 1.284 psi/min. Note that the test rig background pressure decay rates were not measured for the cut-fiber tests, since the background decay rates measured during the first round of tests were so low compared to the pressure decays attributed to the cut fibers.

The pressure decay rates indicated a catastrophic loss of membrane integrity, but the corresponding loss of virus retention was not as large. For the retests, the cut-fiber pressure decay rates were approximately 30 times higher than those for the intact modules. This translates into an approximate 1.5 log loss of membrane integrity. However, the MS2 reduction data only shows a mean LRV loss of 0.35 logs.

Table 4-8. Retest Pressure Decay Results								
Module	**Test**	**Date**	**Starting Pressure (psi)**	**Final Pressure (psi)**	**Elapsed Time (min)**	**Decay Rate (psi/min)**	**Background Decay Rate (psi/min)**	**Corrected Decay Rate (psi/min)**
Module 1	Intact Pre-Test	05/18/2011	30.90	30.02	20.00	0.044	0.038	0.006
	Intact Post-Test	05/18/2011	31.55	30.81	20.00	0.037	0.038	0.000
	Cut Fiber Pre-Test	05/11/2011	30.60	5.54	20.00	1.253	NM	1.253
	Cut Fiber Post-Test	05/11/2011	30.60	5.18	20.00	1.271	NM	1.271
Module 2	Intact Pre-Test	05/18/2011	31.10	29.87	20.00	0.062	0.038	0.024
	Intact Post-Test	05/18/2011	31.42	30.43	20.00	0.050	0.038	0.012
	Cut Fiber Pre-Test	05/12/2011	30.90	11.51	20.00	0.970	NM	0.970
	Cut Fiber Post-Test	05/12/2011	30.85	7.06	20.00	1.190	NM	1.190
Module 3	Intact Pre-Test	05/19/2011	30.24	29.35	20.00	0.044	0.038	0.007
	Intact Post-Test	05/19/2011	30.38	29.69	20.00	0.034	0.038	-0.003
	Cut Fiber Pre-Test	05/12/2011	31.50	9.35	20.00	1.108	NM	1.108
	Cut Fiber Post-Test	05/12/2011	31.00	9.38	20.00	1.081	NM	1.081
Module 4	Intact Pre-Test	05/19/2011	30.64	29.20	20.00	0.072	0.038	0.035
	Intact Post-Test	05/19/2011	30.60	29.34	20.00	0.063	0.038	0.026
	Cut Fiber Pre-Test	05/12/2011	30.50	8.57	20.00	1.097	NM	1.097
	Cut Fiber Post-Test	05/12/2011	30.50	7.34	20.00	1.158	NM	1.158
Module 5	Intact Pre-Test	05/19/2011	31.88	30.66	20.00	0.061	0.038	0.023
	Intact Post-Test	05/19/2011	30.33	29.51	20.00	0.041	0.038	0.003
	Cut Fiber Pre-Test	05/13/2011	31.00	5.32	20.00	1.284	NM	1.284
	Cut Fiber Post-Test	05/13/2011	30.60	5.09	20.00	1.276	NM	1.276

The retest module operation data is presented in Table 4-9, and the water chemistry data is presented in Table 4-10. As discussed in Section 4.2, the feed pressures for the retests were lower than those for the first round of tests, which may have been due to the extra effort to purge the modules of air left over from the pressure decay tests. The water chemistries for the retests are different from those of the first round due to the switch from buffered, deionized water to dechlorinated tap water. The alkalinities and pH are similar for the two water sources, but the TDS and TOC are higher for the tap water, as expected. The turbidity of the tap water was in the same range (0.1 to 0.2 NTU) as that for the deionized water, with the exception of two higher measurements at 0.29 NTU.

Table 4-9. Retest Module Operation Data									
		Filtrate Flow Rate (gpm)		Flux (gfd)		Feed Pressure (psi)		Filtrate Pressure (psi)	
Challenge Test	Date	0 Min.	30 Min.	0 Min	30 Min	0 Min.	30 Min.	0 Min.	30 Min.
Module 1 Intact	05/18/11	40.5	40.3	70.3	70.0	15.16	14.97	0.94	0.90
Module 2 Intact	05/18/11	40.4	40.5	70.2	70.3	14.67	14.47	0.58	0.55
Module 3 Intact	05/19/11	40.6	39.9	70.5	69.3	16.88	16.33	1.37	1.21
Module 4 Intact	05/19/11	40.3	40.3	70.0	70.0	16.53	16.50	0.86	0.89
Module 5 Intact	05/19/11	40.4	40.3	70.2	70.0	15.60	15.24	0.93	0.86
Module 1 Cut	05/11/11	40.2	40.7	69.8	70.7	17.76	17.50	1.41	1.50
Module 2 Cut	05/12/11	40.5	40.4	70.3	70.2	15.43	15.13	0.74	0.71
Module 3 Cut	05/12/11	40.5	39.9	70.3	69.3	17.50	16.98	1.71	1.60
Module 4 Cut	05/12/11	40.9	40.3	71.0	70.0	17.90	17.52	1.93	1.76
Module 5 Cut	05/13/11	40.3	40.1	70.0	69.7	15.05	14.73	1.13	1.10

Table 4-10. Retest Feed Water Chemistry Data							
Challenge Test	Alkalinity (mg/L $CaCO_3$)	pH	Temp. (°C)	Total Chlorine (mg/L)	TDS (mg/L)	TOC (mg/L)	Turbidity (NTU)
Module 1 Intact	100	8.03	15.8	<0.05	410	1.5	0.10
Module 2 Intact	85	7.56	14.5	<0.05	390	1.4	0.11
Module 3 Intact	88	7.52	15.7	<0.05	400	1.3	0.10
Module 4 Intact	88	7.44	14.4	<0.05	400	1.3	0.17
Module 5 Intact	91	7.22	14.4	<0.05	420	1.4	0.16
Module 1 Cut	83	7.61	11.9	<0.05	390	1.4	0.29
Module 2 Cut	79	7.28	16.1	<0.05	390	1.3	0.15
Module 3 Cut	82	7.23	14.0	<0.05	400	1.3	0.12
Module 4 Cut	83	7.51	13.6	<0.05	390	1.3	0.29
Module 5 Cut	90	7.35	15.2	<0.05	390	1.3	0.15

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, 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.

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.

5.2.1 Test Negative Controls and Matrix Spikes

The results of the test negative control (module flush) samples are listed in the Results and Discussion chapter along with the test data. The test negative control (module flush) and matrix spike results are presented below in Table 5-1. The Microbiology Laboratory targeted spiking the samples with an amount of the MS2 stock that would yield a PFU count that was similar to the feed count. The volume spiked varied depending on the concentration of the stock solution.

There were some flush samples with MS2 detected at low levels, but only one filtrate sample had detectible MS2. The retest Module 3 cut-fiber filtrate flush sample had 2 PFU/mL detected. This low concentration of contamination, if still present during the test, would not have significantly affected the results of the test, due to the high filtrate counts of approximately 3 $\log_{10}$.

Table 5-1. Flush Sample and Matrix Spike Results				
		Sample Description	**Feed (geometric mean, PFU/mL)**	**Filtrate (geometric mean, PFU/mL)**
First Round of Tests	Intact Module Tests	Module 1 Flush Samples	<1	<1
		Module 1 Matrix Spikes	$1.1x10^6$	$8.1x10^5$
		Module 2 Flush Samples	<1	<1
		Module 2 Matrix Spikes	$1.3x10^5$	$2.8x10^5$
		Module 3 Flush Samples	2	<1
		Module 3 Matrix Spikes	$7.6x10^5$	$7.0x10^5$
		Module 4 Flush Samples	2	<1
		Module 4 Matrix Spikes	$4.3x10^5$	$2.9x10^5$
		Module 5 Flush Samples	<1	<1
		Module 5 Matrix Spikes	$2.9x10^5$	$4.9x10^5$
	Cut-Fiber Scenario Tests	Module 1 Flush Samples	<1	<1
		Module 1 Matrix Spikes	$2.9x10^5$	$3.0x10^5$
		Module 2 Flush Samples	<1	<1
		Module 2 Matrix Spikes	$1.0x10^5$	$9.0x10^4$
		Module 3 Flush Samples	<1	<1
		Module 3 Matrix Spikes	$4.3x10^5$	$3.1x10^5$
		Module 4 Flush Samples	<1	<1
		Module 4 Matrix Spikes	$3.1x10^5$	$2.8x10^5$
		Module 5 Flush Samples	<1	<1
		Module 5 Matrix Spikes	$4.9x10^4$	$3.5x10^4$
Retests	Intact Module Tests	Module 1 Flush Samples	<1	<1
		Module 1 Matrix Spikes	$3.2x10^5$	$3.2x10^5$
		Module 2 Flush Samples	2	<1
		Module 2 Matrix Spikes	$2.6x10^5$	$4.5x10^5$
		Module 3 Flush Samples	<1	<1
		Module 3 Matrix Spikes	$2.5x10^5$	$4.8x10^5$
		Module 4 Flush Samples	9	<1
		Module 4 Matrix Spikes	$3.6x10^5$	$4.3x10^5$
		Module 5 Flush Samples	2	<1
		Module 5 Matrix Spikes	$5.0x10^5$	$4.2x10^5$
	Cut-Fiber Scenario Tests	Module 1 Flush Samples	<1	<1
		Module 1 Matrix Spikes	$6.1x10^5$	$5.6x10^5$
		Module 2 Flush Samples	<1	<1
		Module 2 Matrix Spikes	$1.7x10^5$	$1.6x10^5$
		Module 3 Flush Samples	<1	2
		Module 3 Matrix Spikes	$7.0x10^5$	$8.0x10^5$
		Module 4 Flush Samples	1	<1
		Module 4 Matrix Spikes	$3.9x10^5$	$5.6x10^5$
		Module 5 Flush Samples	<1	<1
		Module 5 Matrix Spikes	$2.9x10^5$	$2.0x10^5$

5.3 Sample Handling

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

5.4 Chemistry Laboratory QA/QC

The calibrations of all meters, gauges, and 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, every analytical method has an NSF standard operating 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.

5.5.3 Estimate of Analytical Uncertainty

Per the requirements of NSF's ISO 17025 accreditation, the Microbiology Laboratory was required to estimate the uncertainty of its analytical methods. The laboratory calculated that the uncertainty associated with the top-agar overlay method for enumerating MS2 was 29%.

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 Microsoft™ Excel® spreadsheets. These spreadsheets were used to calculate the geometric means and $\log_{10}$ reductions. 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. As required in the ETV Quality Management Plan, 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 is a qualitative term that expresses "the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, a process condition, or an environmental condition." 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 is a measure of the deviation of the analytical value from the true value. Since true values for samples can never be known, accuracy measurements are made through analysis of certified standards or QC samples of a known quantity.

Accuracy was maintained through the following items:

- Maintaining consistent sample collection procedures, including sample locations, timing of sample collection, and sampling procedures;
- Calibrated instruments; and
- Laboratory control samples (e.g., method blanks, duplicates, matrix spikes, matrix spike duplicates, and performance evaluation samples).

Recoveries for spiked samples were calculated in the following manner:

$$\text{Percent Recovery} = \frac{100*(SSR - SR)}{SA}$$

where: SSR = spiked sample result
SR = sample result
SA = spike amount added

Recoveries for laboratory control samples were calculated as follows:

$$\text{Percent Recovery} = \frac{100*(Found\ Concentration)}{True\ Concentration}$$

For acceptable analytical accuracy, the recoveries must be within control limits.

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 NSF Laboratory Quality Assurance Manual establishes the frequency of spike sample analyses at 10% of the samples analyzed for chemical analyses. Laboratory control samples are also run at a frequency of 10%. The recovery limits specified for the parameters in this verification, excluding microbiological analyses, were 70-130% for laboratory-fortified samples and 85-115% for laboratory control samples. The NSF QA department reviewed the laboratory

records and found that all recoveries were within the prescribed QC requirements. Calibration requirements were also achieved for all analyses.

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.

Acceptable analytical precision for the verification test was set at an RPD of 30%.

All RPD 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 5-2.

Table 5-2. 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.

One hundred percent completeness was achieved for all aspects of this verification. All planned testing activities were conducted as scheduled, and all planned samples were collected for challenge organism and water chemistry analysis.

Chapter 6
References

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Appendix A
Test/Quality Assurance Project Plan

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

Appendix B
Challenge Organism Triplicate Counts

Table B-1. First Round Intact Module MS2 Triplicate Counts							
		Feed (PFU/mL)			Filtrate (PFU/mL)		
Module	**Sample**	**Count 1**	**Count 2**	**Count 3**	**Count 1**	**Count 2**	**Count 3**
Module 1	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$1.05x10^6$	$1.21x10^6$	$9.2x10^5$	$9.3x10^5$	$8.5x10^5$	$6.8x10^5$
	1 Minute	$1.52x10^6$	$1.26x10^6$	$1.45x10^6$	$1.71x10^2$	$1.41x10^2$	$1.99x10^2$
	15 Minutes	$1.81x10^6$	$1.46x10^6$	$1.82x10^6$	$1.67x10^2$	$1.47x10^2$	$2.14x10^2$
	30 Minutes	$1.41x10^6$	$1.21x10^6$	$1.42x10^6$	$1.88x10^2$	$1.75x10^2$	$2.23x10^2$
Module 2	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$1.20x10^5$	$1.45x10^5$	$1.32x10^5$	$1.13x10^5$	$1.40x10^5$	$1.19x10^5$
	1 Minute	$1.13x10^5$	$1.40x10^5$	$1.19x10^5$	$3.5x10^1$	$3.8x10^1$	$6.9x10^1$
	15 Minutes	$2.6x10^5$	$2.9x10^5$	$2.5x10^5$	$3.3x10^1$	$2.3x10^1$	$6.5x10^1$
	30 Minutes	$4.0x10^5$	$2.8x10^5$	$2.9x10^5$	$4.1x10^1$	$3.6x10^1$	$5.0x10^1$
Module 3	Flush	2	1	2	<1	<1	<1
	Matrix Spike	$7.3x10^5$	$7.4x10^5$	$8.1x10^5$	$7.5x10^5$	$6.7x10^5$	$6.8x10^5$
	1 Minute	$5.7x10^5$	$4.5x10^5$	$3.3x10^5$	2	<1	8
	15 Minutes	$3.7x10^5$	$3.4x10^5$	$4.0x10^5$	$1.4x10^1$	$2.0x10^1$	$1.2x10^1$
	30 Minutes	$5.1x10^5$	$3.6x10^5$	$4.9x10^5$	$2.7x10^1$	$3.8x10^1$	$4.6x10^1$
Module 4	Flush	3	2	2	<1	<1	<1
	Matrix Spike	$5.0x10^5$	$4.2x10^5$	$3.9x10^5$	$3.0x10^5$	$3.1x10^5$	$2.6x10^5$
	1 Minute	$3.3x10^5$	$3.5x10^5$	$2.8x10^5$	$3.9x10^1$	$4.3x10^1$	$5.8x10^1$
	15 Minutes	$3.6x10^5$	$4.5x10^5$	$3.4x10^5$	$8.7x10^1$	$1.12x10^2$	$6.4x10^1$
	30 Minutes	$2.9x10^5$	$3.0x10^5$	$2.6x10^5$	$2.6x10^1$	$1.5x10^1$	$7.2x10^1$
Module 5	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$3.2x10^5$	$2.9x10^5$	$2.7x10^5$	$4.6x10^5$	$5.3x10^5$	$4.9x10^5$
	1 Minute	$7.7x10^5$	$7.0x10^5$	$7.4x10^5$	$3.6x10^1$	$6.2x10^1$	$8.7x10^1$
	15 Minutes	$6.4x10^5$	$7.5x10^5$	$4.3x10^5$	$8.6x10^1$	$5.8x10^1$	$8.2x10^1$
	30 Minutes	$1.26x10^5$	$1.30x10^5$	$1.34x10^5$	$3.1x10^1$	$4.5x10^1$	$5.0x10^1$

Table B-2. First Round Cut-Fiber Module MS2 Triplicate Counts							
		Feed (PFU/mL)			Filtrate (PFU/mL)		
Module	**Sample**	**Count 1**	**Count 2**	**Count 3**	**Count 1**	**Count 2**	**Count 3**
Module 1	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$3.1x10^5$	$2.9x10^5$	$2.7x10^5$	$2.7x10^5$	$2.9x10^5$	$3.3x10^5$
	1 Minute	$1.11x10^5$	$1.08x10^5$	$1.22x10^5$	8	$1.1x10^1$	$1.2x10^1$
	15 Minutes	$1.17x10^5$	$1.04x10^5$	$9.7x10^4$	$6.9x10^1$	$6.8x10^1$	$9.3x10^1$
	30 Minutes	$8.8x10^4$	$1.03x10^5$	$1.19x10^5$	$7.8x10^1$	$9.1x10^1$	$8.4x10^1$
Module 2	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$9.7x10^4$	$8.8x10^4$	$1.04x10^5$	$9.2x10^4$	$9.4x10^4$	$9.0x10^4$
	1 Minute	$3.1x10^5$	$2.9x10^5$	$2.8x10^5$	6	8	6
	15 Minutes	$3.2x10^5$	$3.3x10^5$	$2.7x10^5$	$8.3x10^1$	$8.2x10^1$	$9.6x10^1$
	30 Minutes	$3.0x10^5$	$2.6x10^5$	$2.9x10^5$	$2.9x10^2$	$3.0x10^2$	$3.0x10^2$
Module 3	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$4.7x10^5$	$4.1x10^5$	$4.0x10^5$	$2.9x10^5$	$3.0x10^5$	$3.4x10^5$
	1 Minute	$5.5x10^5$	$6.0x10^5$	$5.1x10^5$	<1	1	<1
	15 Minutes	$6.3x10^5$	$6.7x10^5$	$6.0x10^5$	$3.9x10^1$	$4.2x10^1$	$2.7x10^1$
	30 Minutes	$5.1x10^5$	$5.3x10^5$	$5.7x10^5$	$3.2x10^1$	$3.6x10^1$	$3.7x10^1$
Module 4	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$2.7x10^5$	$3.2x10^5$	$3.6x10^5$	$2.9x10^5$	$2.7x10^5$	$2.8x10^5$
	1 Minute	$6.8x10^5$	$6.7x10^5$	$6.0x10^5$	2	5	3
	15 Minutes	$3.3x10^5$	$3.8x10^5$	$5.2x10^5$	4	6	7
	30 Minutes	$7.1x10^5$	$3.4x10^5$	$4.9x10^5$	8	9	$2.1x10^1$
Module 5	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$4.7x10^4$	$5.1x10^4$	$5.0x10^4$	$3.9x10^4$	$3.6x10^4$	$3.1x10^4$
	1 Minute	$6.2x10^5$	$8.7x10^5$	$9.3x10^5$	$1.0x10^1$	9	$1.7x10^1$
	15 Minutes	$1.04x10^6$	$9.8x10^5$	$7.1x10^5$	$3.3x10^1$	$5.4x10^1$	$5.0x10^1$
	30 Minutes	$8.9x10^5$	$7.6x10^5$	$5.6x10^5$	$2.9x10^1$	$3.4x10^1$	$3.3x10^1$

Table B-3. Retest Intact Module MS2 Triplicate Counts							
		Feed (PFU/mL)			Filtrate (PFU/mL)		
Module	**Sample**	**Count 1**	**Count 2**	**Count 3**	**Count 1**	**Count 2**	**Count 3**
Module 1	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$2.6x10^5$	$3.4x10^5$	$3.7x10^5$	$3.3x10^5$	$3.8x10^5$	$2.5x10^5$
	1 Minute	$2.6x10^6$	$2.8x10^6$	$2.6x10^6$	$6.3x10^2$	$7.7x10^2$	$6.7x10^2$
	15 Minutes	$3.0x10^6$	$2.8x10^6$	$2.7x10^6$	$1.30x10^3$	$1.25x10^3$	$1.23x10^3$
	30 Minutes	$3.5x10^6$	$2.7x10^6$	$3.0x10^6$	$1.85x10^3$	$1.95x10^3$	$1.59x10^3$
Module 2	Flush	1	5	3	<1	<1	<1
	Matrix Spike	$2.03x10^5$	$2.7x10^5$	$3.1x10^5$	$4.3x10^5$	$5.0x10^5$	$4.1x10^5$
	1 Minute	$5.6x10^6$	$5.7x10^6$	$2.9x10^6$	$1.61x10^3$	$1.56x10^3$	$1.63x10^3$
	15 Minutes	$3.5x10^6$	$3.6x10^6$	$4.8x10^6$	$4.9x10^3$	$4.2x10^3$	$4.3x10^3$
	30 Minutes	$4.9x10^6$	$2.9x10^6$	$2.8x10^6$	$4.0x10^3$	$4.2x10^3$	$4.7x10^3$
Module 3	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$2.5x10^5$	$2.5x10^5$	$2.6x10^5$	$5.0x10^5$	$5.2x10^5$	$4.3x10^5$
	1 Minute	$6.8x10^6$	$7.4x10^6$	$4.5x10^6$	$1.88x10^3$	$1.24x10^3$	$1.38x10^3$
	15 Minutes	$7.2x10^6$	$5.2x10^6$	$4.3x10^6$	$2.9x10^3$	$2.5x10^3$	$1.65x10^3$
	30 Minutes	$6.4x10^6$	$5.8x10^6$	$4.0x10^6$	$3.9x10^3$	$4.3x10^3$	$4.8x10^3$
Module 4	Flush	13	19	3	<1	<1	<1
	Matrix Spike	$4.1x10^5$	$3.3x10^5$	$3.4x10^5$	$4.0x10^5$	$4.8x10^5$	$4.2x10^5$
	1 Minute	$5.0x10^6$	$5.6x10^6$	$4.6x10^6$	$2.17x10^3$	$1.69x10^3$	$1.80x10^3$
	15 Minutes	$4.1x10^6$	$3.7x10^6$	$4.5x10^6$	$2.7x10^3$	$3.8x10^3$	$4.8x10^3$
	30 Minutes	$8.4x10^6$	$3.6x10^6$	$4.2x10^6$	$2.7x10^3$	$2.6x10^3$	$1.72x10^3$
Module 5	Flush	4	<1	<1	<1	<1	<1
	Matrix Spike	$4.5x10^5$	$3.9x10^5$	$7.2x10^5$	$3.8x10^5$	$4.6x10^5$	$4.3x10^5$
	1 Minute	$1.02x10^7$	$5.7x10^6$	$5.7x10^6$	$1.31x10^4$	$1.26x10^4$	$1.17x10^4$
	15 Minutes	$7.3x10^6$	$5.3x10^6$	$3.6x10^6$	$1.38x10^4$	$1.34x10^4$	$1.03x10^4$
	30 Minutes	$4.3x10^6$	$3.0x10^6$	$2.5x10^6$	$1.45x10^4$	$1.22x10^4$	$1.27x10^4$

Table B-4. Retest Cut-Fiber Module MS2 Triplicate Counts							
		Feed (PFU/mL)			Filtrate (PFU/mL)		
Module	**Sample**	**Count 1**	**Count 2**	**Count 3**	**Count 1**	**Count 2**	**Count 3**
Module 1	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$4.6x10^5$	$8.5x10^5$	$5.7x10^5$	$5.1x10^5$	$6.6x10^5$	$5.1x10^5$
	1 Minute	$7.2x10^6$	$5.5x10^6$	$5.6x10^6$	$4.5x10^3$	$4.6x10^3$	$4.4x10^3$
	15 Minutes	$6.4x10^6$	$4.2x10^6$	$5.9x10^6$	$3.7x10^3$	$4.3x10^3$	$4.1x10^3$
	30 Minutes	$6.1x10^6$	$4.2x10^6$	$4.8x10^6$	$4.2x10^3$	$2.9x10^3$	$4.5x10^3$
Module 2	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$1.67x10^5$	$1.74x10^5$	$1.77x10^5$	$1.63x10^5$	$1.58x10^5$	$1.68x10^5$
	1 Minute	$8.7x10^5$	$9.8x10^5$	$8.1x10^5$	$2.06x10^3$	$1.73x10^3$	$1.68x10^3$
	15 Minutes	$6.7x10^5$	$8.1x10^5$	$9.0x10^5$	$1.90x10^3$	$1.51x10^3$	$1.76x10^3$
	30 Minutes	$9.1x10^5$	$8.7x10^5$	$8.7x10^5$	$1.92x10^3$	$1.81x10^3$	$1.72x10^3$
Module 3	Flush	<1	<1	<1	1	2	3
	Matrix Spike	$7.2x10^5$	$7.5x10^5$	$6.3x10^5$	$8.1x10^5$	$7.5x10^5$	$8.5x10^5$
	1 Minute	$1.00x10^6$	$9.2x10^5$	$8.3x10^5$	$1.25x10^3$	$1.16x10^3$	$1.09x10^3$
	15 Minutes	$8.6x10^5$	$1.01x10^6$	$6.5x10^5$	$1.14x10^3$	$1.26x10^3$	$1.00x10^3$
	30 Minutes	$1.16x10^6$	$1.05x10^6$	$9.0x10^5$	$9.4x10^2$	$9.1x10^2$	$1.00x10^3$
Module 4	Flush	1	<1	<1	<1	<1	<1
	Matrix Spike	$4.1x10^5$	$4.1x10^5$	$3.6x10^5$	$5.9x10^5$	$4.9x10^5$	$6.1x10^5$
	1 Minute	$2.43x10^6$	$3.4x10^6$	$3.2x10^6$	$5.4x10^3$	$4.6x10^3$	$3.3x10^3$
	15 Minutes	$3.8x10^6$	$3.8x10^6$	$3.0x10^6$	$4.9x10^3$	$4.8x10^3$	$3.1x10^3$
	30 Minutes	$4.9x10^6$	$3.7x10^6$	$2.6x10^6$	$1.45x10^4$	$9.5x10^3$	$8.9x10^3$
Module 5	Flush	<1	<1	<1	<1	<1	<1
	Matrix Spike	$2.9x10^5$	$3.5x10^5$	$2.5x10^5$	$2.0x10^5$	$1.82x10^5$	$2.34x10^5$
	1 Minute	$2.7x10^6$	$1.49x10^6$	$1.66x10^6$	$6.0x10^3$	$4.8x10^3$	$5.1x10^3$
	15 Minutes	$1.34x10^6$	$1.60x10^6$	$1.64x10^6$	$6.7x10^3$	$4.3x10^3$	$5.1x10^3$
	30 Minutes	$1.22x10^6$	$1.32x10^6$	$1.11x10^6$	$7.0x10^3$	$5.0x10^3$	$3.8x10^3$