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NSF 03/07/EPADWCTR

Environmental Technology Verification Report

Physical Removal of Microbiological & Particulate Contaminants in Drinking Water

US Filter 3M10C Microfiltration Membrane System
Chula Vista, California

Prepared by

NSF International

Under a Cooperative Agreement with
EPA 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:	**MEMBRANE FILTRATION USED IN DRINKING WATER TREATMENT SYSTEMS**		
APPLICATION:	**PHYSICAL REMOVAL OF MICROBIOLOGICAL & PARTICULATE CONTAMINANTS IN DRINKING WATER**		
TECHNOLOGY NAME:	**US FILTER 3M10C MICROFILTRATION MEMBRANE SYSTEM**		
TEST LOCATION:	**CHULA VISTA, CALIFORNIA**		
COMPANY:	**US FILTER**		
ADDRESS:	**600 ARRASMITH TRAIL AMES, IOWA 50010**	PHONE: FAX:	**(515) 232-4121 (515) 232-2571**
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The U.S. Environmental Protection Agency (EPA) supports the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations, 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.

NSF International (NSF) in cooperation with the EPA operates the Drinking Water Systems (DWS) Center, one of seven ETV Centers. The DWS Center recently evaluated the performance of a membrane system used in drinking water treatment system applications. This verification statement provides a summary of the test results for the US Filter 3M10C Microfiltration (MF) Membrane System. MWH, an NSF-qualified field testing organization (FTO), performed the verification testing. NSF provided technical and quality assurance oversight of the verification testing described in this ETV report, including an audit of nearly 100% of the data.

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ABSTRACT

Verification testing of the US Filter 3M10C membrane system was conducted over a 44-day test period at the Aqua 2000 Research Center in Chula Vista, California. The test period extended from July 24, 2002 to September 5, 2002. The source water was a blend of Colorado River and State Project Water. Verification testing was conducted at manufacturer-specified operating conditions. The membrane unit was operated in dead-end mode at a constant flux of 24 gfd (41 L/hr-m^2) with feedwater recovery of 91 percent. The membrane showed some fouling at the end of the test period. The manufacturer-recommended cleaning procedure was effective in recovering membrane productivity. Additional data was added to this report from previous California Department of Health Services (CDHS) testing (conducted independently from ETV testing) on the system to supplement particle removal data. Raw water particle counts differed between the ETV testing period and the CDHS testing period; the average for the 3-5 micron size range during the ETV testing was 1,100 particles/mL and the average for the 2-5 micron size range during the CDHS testing was 2,000 particles/mL. The average raw water count for the 5-15 micron size range for the ETV testing was 950 particles/mL whereas during the CDHS testing it was 810 particles/mL. During the ETV testing, the membrane system achieved particle removals in the range 2.3 log to 3.5 log with an average of 3.1 log for the 3-5 micron size range, and particle removal in the range 2.7 log to 3.6 log with an average of 3.1 log for the 5-15 micron size range. For the CDHS testing, particle removals observed were in the range 2.6 log to 4.7 log with an average of 3.8 log for the 2-5 micron size range and particle removal in the range 2.6 log to 4.3 log with an average of 3.9 log for the 5-15 micron size range.

TECHNOLOGY DESCRIPTION

The equipment tested in this ETV is the US Filter 3M10C Microfiltration Membrane System. The 3M10C package plant contains 3 pressure vessels with one membrane module per pressure vessel. Each stainless steel pressure vessel is 4.5 inches (11cm) in diameter and approximately 55 inches (140 cm) long. The top and bottom of the pressure vessels are attached to headers that distribute feed water to the pressure vessels and collect permeate. The skid-mounted unit includes all major equipment elements and controls with the exception of an air compressor that was used to operate pneumatic valves and supply the pressurized air used during backwash. The footprint of the unit is approximately 57 inches (145 cm) long by 39 inches (99 cm) wide. The height of the unit, including the 5 inch (13 cm) base is approximately 87 inches (221 cm). The unit is skid mounted and can be moved with a forklift and transported by truck.

The US Filter 3M10C unit has an Allen Bradley programmable logic controller (PLC). The PLC controls the opening and closing of pneumatic valves and the operation of pumps required for filtration and backwash. The backwash frequency and the length of time the system spends in each backwash phase are set by entering values into the appropriate screen on the PLC. A constant filtrate flow during filtration cannot be maintained by the PLC so the flow had to be manually adjusted by manipulating the filtrate valve. The 3M10C MF unit has digital flow, pressure and temperature measurement, and a data logger to acquire operating information digitally.

The US Filter 3M10C unit has two alternating operating modes known as filtration and backwash. When in the filtration mode, feed water is pumped from the feed tank to both the top and bottom of the modules. The pressurized feed water is directed around a central permeate tube in the module end-caps to the outside surface of the hollow fibers. Permeate passes through the pores of the membrane to the inside of the hollow fibers and is collected from both ends of the module through a central permeate tube in the module end-caps. The package plant operates in dead-end mode only, with no recirculation flow on the feed side of the membrane. During backwash, the feed pump shuts down and valves are repositioned. An air compressor pressurizes both the feed and permeate side of the membrane to approximately 90 psi. The pressure is then released from the feed side of the membrane, dislodging the cake layer from the membrane surface. Feed water is then pumped from the bottom of the module to flush the dislodged debris. This is followed by a final rewetting phase where both sides of the membrane are again pressurized to approximately 90 psi to force water into the membrane pores before resuming the next filtration cycle. The backwash phase lasts approximately two minutes. The long-term operation of the US Filter MF unit frequently results in the accumulation of materials on the membrane surface, which are not effectively removed by backwash. This is called membrane fouling and is observed as a gradual increase in the pressure required to force water through the membrane pores. Once a critical upper pressure has been reached, normal operation is discontinued and the membrane undergoes chemical cleaning. Chemical cleaning typically involves the use of acid solutions to restore efficient operation of the membrane.

The pressure vessel of the US Filter 3M10C unit contains three model M10C polypropylene membrane modules. The manufacturer estimates that these 4.7 inch (12 cm) diameter by 45.5 inch (1.157 m) length modules each contain approximately 20,000 fibers. The 3M10C module is a hollow fiber configuration, manufactured from polypropylene, with a nominal pore size of 0.20 microns. At this pore size, the membrane is expected to remove particulates, including protozoa and bacteria.

VERIFICATION TESTING DESCRIPTION

Test Site

The verification test site was the City of San Diego's Aqua 2000 Research Center at 1500 Wueste Road in Chula Vista, California. The Research Center includes office and lab trailers, a covered concrete test pad and a dedicated operations staff with substantial membrane experience. The source water for testing was the San Diego Aqueduct pipeline. This water consists of Colorado River water and State Project water, which are two of the major raw drinking water supplies in Southern California.

Methods and Procedures

Turbidity, pH, chlorine and temperature analyses were conducted daily at the test site according to Standard Methods for the Examination of Water and Wastewater, 20th Ed. (APHA, et. al., 1998). Standard Methods, 20th Ed. (APHA, 1998) and Methods for Chemical Analysis of Water and Wastes (EPA, 1979) were used for analyses conducted at The City of San Diego Laboratory. These included alkalinity, total and calcium hardness, total dissolved solids (TDS), total suspended solids (TSS), total organic carbon (TOC), ultraviolet absorbance at 254 nanometers (UV254), total coliform, and heterotrophic plate count (HPC). Total and calcium hardness analyses were conducted every other week. All other analyses were conducted weekly. Online Hach 1900 WPC particle counters and 1720D turbidimeters continuously monitored these parameters in both the raw water and membrane system filtrate. The particle counters were set up to enumerate particle counts in the following size ranges: 2-3 um, 3-5 um, 5-7 um, 7-10 um, 10-15 um and > 15 um. Data from the online particle counters and turbidimeters were stored at one-minute intervals on a computer.

VERIFICATION OF PERFORMANCE

System Operation

Verification testing was conducted at the manufacturer-specified operating conditions. The membrane unit was operated at a constant flux of 24 gfd (41 L/hr-m^2) with feedwater recovery of 91 percent. Permeate flow rate was set by entering the target flow in a screen on the PLC. Backwash frequency was every 22 minutes. Backwash volume averaged 41 gallons (155 liters). The system was operated during the test period with moderate fouling throughout the testing period until it reached the end of the testing period. The temperature adjusted specific flux decreased from 3 to 1.6 gfd/psi at 20°C (75 to 38 L/hr-m^2-bar at 20°C) over the 44 days of the test period.

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Membrane cleaning was performed according to the manufacturer-recommended procedure. A citric acid solution (2 percent) followed by a high pH cleaning solution was prepared in the feed storage tank and recirculated through the feed side of the membrane. The 2 percent citric acid cleaning solution was prepared by dissolving 8 pounds (17 kg) of citric acid in the feed tank. The pH of this solution was in the range 2 to 2.5. The citric acid solution was recirculated through the feed side of the membrane for 120 minutes at a flow of 32 gpm (121 L/min) with a feed pressure of approximately 9 psi. After discarding the cleaning solution and rinsing the system with feed water, the same cleaning procedure was followed using a high pH cleaning solution. The high pH cleaning solution was made by adding 1 gallon (3.7 liters) of Memclean EAX2 to the feed tank. The pH of this solution was in the range of 12-13. The manufacturer-recommended cleaning procedure was effective in recovering specific flux. The recovery of specific flux for the cleanings at the end of the test period was 100 percent indicating no irreversible fouling.

No incident of broken fibers occurred during the test period. Air pressure-hold tests were manually conducted two times during the test period. These tests indicate that the fibers were intact during the testing period with a pressure loss of less than 1.5 psi per minute. In addition, automatic air pressure hold tests were performed by the system every 24 hours during the testing. Automatic air pressure-hold tests were conducted by selecting the integrity test from the appropriate PLC screen. The air pressure-hold test on the US Filter system was conducted by pressurizing the feed side of the membrane. If any of the membrane fibers were compromised, one would expect significant loss of held pressure (>1.5 psi every minute) across the membrane element. The air pressure-hold test results show that there were no compromises in membrane integrity during the test period. The automated pressure-hold test performed every 24 hours was set to shut the system down when pressure decays were greater than 1.5 psi/min. There was no shut down of the system because of unacceptable automated pressure-hold results during the test period.

Source Water

The source water for the ETV testing consisted of a blend of Colorado River and State Project Water delivered to the test site via the San Diego Aqueduct. The source water had the following average water quality during the test period: TDS 521 mg/L, total hardness 253 mg/L, alkalinity 125 mg/L, TOC 2.6 mg/L, pH 8.3, temperature 27 °C and turbidity 0.75 NTU.

Particle Removal

Total suspended solids in the filtrate were removed to below the detection limit for the analysis for all samples analyzed (<1 mg/L to <10 mg/L). Filtrate turbidity was 0.1 NTU or less 95 percent of the time. The system achieved particle removals of up to 3.5 logs for *Cryptosporidium*-sized (3-5 um) particles and particle removals of up to 3.6 logs for *Giardia*-sized (5-15 um) particles. The range of log removals was 2.3 log to 3.5 log and the average was 3.1 log for the 3-5 micron particles, while the range was 2.7 log to 3.6 log and the average 3.1 log for the 5-15 micron particles. Four hour average raw water and filtrate particle levels and daily average particle removal in these size ranges for the test period are presented in the following table:

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US Filter 3M10C MF System Particle Counts and Particle Removals for ETV Test Period						
	3-5 um Particles			5-15 um Particles		
	Raw Water (#/mL)	Filtrate (#/mL)	Log Removal	Raw Water (#/mL)	Filtrate (#/mL)	Log Removal
Average	1100	1.2	3.1	950	0.86	3.1
Standard Deviation	450	1.7	0.29	630	0.97	0.27
95% Confidence Interval	1000-1200	0.98-1.4	3.0-3.2	870-1000	0.73-0.99	3.0-3.2
Minimum	290	0.23	2.3	190	0.23	2.7
Maximum	2300	13	3.5	3800	6.1	3.6

ETV-Reviewed Supplemental Particle Count Data

Additional particle removal data has been included in the testing report from previous California Department of Health Services (CDHS) testing. This particle removal data was collected during CDHS testing at the A. H. Bridge Plant, in Rancho Cucamonga, CA, owned by Cucamonga County Water District (CCWD) on two days (5/17/2001 and 5/18/2001) (Adham, 2001). This testing was done to obtain CDHS approval process for the same US Filter 3M10C system that was tested during this ETV. Hence, this data is directly applicable even though this data was collected independently from the ETV testing. The system was operated at a flux of 50 gfd and transmembrane pressures ranging from 20 to 23 psi during the period of CDHS particle data collection. The 3M10C MF system achieved log removals of 2.6 log to 4.7 log with an average of 3.8 log for the 2-5 micron particles and a range of 2.6 log to 4.3 log and an average of 3.9 log for the 5-15 micron particles during the CDHS testing. Summary statistics for particles in the raw water, particles in the membrane filtrate and log removal of particles, based on data collected at the one-minute sampling interval over the 24-hour collection period, are presented in the following table:

US Filter 3M10C MF System Particle Counts and Particle Removals for CDHS Testing						
	2-5 um Particles			5-15 um Particles		
	Raw Water (#/mL)	Permeate (#/mL)	Log Removal	Raw Water (#/mL)	Permeate (#/mL)	Log Removal
Average	2000	0.68	3.8	810	0.19	3.9
Standard Deviation	90	0.84	0.55	56	0.24	0.43
95% Confidence Interval	2000 - 2000	0.64 - 0.72	3.8 - 3.8	810 - 810	0.18 - 0.20	3.9 - 3.9
Minimum	1700	0.046	2.6	650	0.046	2.6
Maximum	2200	1.8	4.7	950	1.8	4.3

All CDHS testing data was reviewed according to the ETV Drinking Water Systems Quality Management Plan and ETV Program Policies. Although the calibration of the particle counters and the verification of calibration for the CDHS testing were outside of the time frame recommended in the ETV Technology-Specific Test Plan (11 months vs. within two months and five months vs. immediately before testing, respectively), both the raw and permeate particle counters gave comparable responses to the same microsphere solution (Figure 3-5); therefore, log removals should be comparable. Also, the particle counters were made by the same manufacturer and were the same model. The calibration did occur within the one-year time frame recommended by the particle counter manufacturer.

Microbial Removal

Total Coliforms and HPC were analyzed on a weekly basis during both ETV test periods. Raw water total coliforms averaged 560 MPN/100 mL during the test periods. Total coliforms were not detected in

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the filtrate. HPC averaged 2000 cfu/mL in the raw water while filtrate levels of HPC averaged 140 cfu/mL.

Operation and Maintenance Results

Operation was initiated by entering target filtrate flow rate, backwash frequency and time of each backwash phase in the appropriate PLC screen. Backwash flow rate was adjusted manually using a valve. As the membrane system fouled, the permeate valve was manually readjusted to maintain a constant permeate flow rate.

No chemicals were consumed during routine operation of the system. During a typical chemical cleaning, 8 pounds (17 kg) of citric acid and 1.0 gallon (3.7 liter) of high pH cleaning solution (Memclean EAX2) were consumed. The manufacturer supplied an Operations and Maintenance Manual that was helpful in explaining the setup, operation and maintenance of the ETV test system.

Original Signed by
Hugh W. McKinnon *06/12/03*

Hugh W. McKinnon Date
Director
National Risk Management Research Laboratory
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Original Signed by
Gordon Bellen *06/17/03*

Gordon Bellen Date
Vice President
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NSF International

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

Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants,* dated April 20, 1998 and revised May 14, 1999, the Verification Statement, and the Verification Report (NSF Report #03/07/EPADWCTR) are available from the following sources:
(NOTE: Appendices are not included in the Verification Report. Appendices are available from NSF upon request.)

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

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Physical Removal of Microbiological & Particulate Contaminants in Drinking Water

US Filter 3M10C Microfiltration Membrane System
Chula Vista, California

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Notice

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Foreword

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

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

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

Hugh W. McKinnon, Director
National Risk Management Research Laboratory

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Abbreviations and Acronyms

C	Celsius degrees
CDHS	California Department of Health Services
cfu	Colony forming unit(s)
CIP	Clean in place
C_f	Feed concentration
C_p	Permeate concentration
cm	Centimeter
CRW	Colorado River water
d	Day(s)
DI	Deionized
DOC	Dissolved organic carbon
DWS	Drinking Water System
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
FOD	Field Operations Document
ft^2	Square foot (feet)
FTO	Field Testing Organization
gfd	Gallon(s) per day per square foot of membrane area
gpd	gallon per day
gpm	Gallon(s) per minute
HPC	Heterotrophic plate count
hr	Hour(s)
ICR	Information Collection Rule
in Hg	Inch(es) of Mercury
J_{S_i}	Initial specific transmembrane flux
J_{S_f}	Final specific transmembrane flux
J_S	Specific flux
$J_{S_{i0}}$	Initial specific transmembrane flux at t=0 of membrane operation
J_t	Permeate flux
J_{tm}	Transmembrane flux
kg	Kilogram(s)
L	Liter(s)
m^2	Square meter(s)
m^3/d	Cubic meter(s) per day
MF	Microfiltration
mgd	Million gallons per day
mg/L	Milligram(s) per liter
min	Minute(s)
mL	Milliliter(s)
MPN	Most probable number
NIST	National Institute of Standards and Technology
NSF	NSF International
NTU	Nephelometric turbidity unit(s)
O&M	Operations and Maintenance
P_i	Pressure at inlet of membrane module
P_o	Pressure at outlet of membrane module
P_p	Permeate pressure
P_{tm}	Transmembrane pressure
PC	Personal computer
PLC	Programmable logic Controller
ppm	Parts per million
psi	Pound(s) per square inch
PVC	Polyvinyl chloride
Q_f	Feed flow
Q_p	Permeate flow
Q_r	Recycle flow
QA	Quality assurance
QC	Quality control
S	Membrane surface area
scfm	Standard cubic feet per minute
slpm	Standard liter per minute
sec	Second(s)
SPW	State Project Water
T	Temperature
TC	Total coliform bacteria
TOC	Total organic carbon
TDS	Total dissolved solids
TSS	Total suspended solids
um	Micron(s)
UV254	Ultraviolet light absorbance at 254 nanometer

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The time and outstanding efforts provided by the manager of Aqua 2000 Research Center, Bill Pearce with the City of San Diego is gratefully acknowledged. The authors would also like to thank Dana Chapin and Susan Brannian from the City of San Diego Water Laboratory for facilitating the water quality analyses in the study.

The author would also like to acknowledge the manufacturer of the equipment employed during the ETV program (US Filter, Warrendale, PA) for their continuous assistance throughout the ETV test operation periods and for providing partial funding to the project. In particular, the authors would like to thank Paul Gallagher and Lisa Thayer from US Filter for their continuous support.

The authors gratefully acknowledge the contributions of the following co-workers from MWH: Karl Gramith, Natalie Flores and Rene Lucero.

Chapter 1
Introduction

1.1 Environmental Technology Verification (ETV) Purpose and Program Operation

The U.S. Environmental Protection Agency (EPA) has 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 substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups which consist 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 (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International entered into an agreement on October 1, 2000 with the Environmental Protection Agency (EPA) to form a Drinking Water Systems Center dedicated to technology verifications. With assistance through an EPA grant, NSF manages an Environmental Technology Verification (ETV) Center that provides independent performance evaluations of drinking water technologies. This DWS program evaluated the performance of the US Filter 3M10C microfiltration (MF) system used in package drinking water treatment system applications.

This report provides the ETV results for the US Filter 3M10C membrane system.

1.2 Project Participants

Figure 1-1 is an organization chart showing the project participants and the lines of communication established for the ETV. The Field Testing Organization (FTO) was MWH, a NSF-qualified FTO, which provided the overall management, operations, data management and report preparation for the ETV. The microfiltration membrane manufacturer for the ETV was US Filter. The City of San Diego provided the test site and conducted water quality analyses through their State-certified Water Quality laboratory.

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1.3 Definition of Roles and Responsibilities of Project Participants

1.3.1 Field Testing Organization Responsibilities

The specific responsibilities of the FTO, MWH, were to:

- Provide the overall management of the ETV through the project manager and the project engineers.
- Provide all needed logistical support, the project communication network, and all scheduling and coordination of the activities of all participants.
- Provide operations staff.
- Manage, evaluate, interpret and report on data generated in the ETV.
- Evaluate the performance of the microfiltration membrane technology according to the Product Specific Test Plan (PSTP) and the testing, operations, quality assurance/quality control (QA/QC), data management and safety protocols contained therein.
- Provide all quality control (QC) information.
- Provide all data generated during the ETV in hard copy and electronic form in a common spreadsheet or database format.
- Prepare the ETV report.

1.3.2 Manufacturer Responsibilities

The specific responsibilities of the microfiltration membrane manufacturer, US Filter, were to:

- Provide complete, field-ready equipment for the ETV at the testing site.
- Provide logistical and technical support as required throughout the ETV.
- Provide funding for the project.
- Attend project meetings as necessary.

1.3.3 City of San Diego Responsibilities

The specific responsibilities of the City staff were to:

- Provide set-up according to the PSTP and the testing, operations, QA/QC, data management and safety protocols.
- Provide the necessary and appropriate space for the equipment to be tested in the ETV.
- Provide all necessary electrical power, feedwater and other utilities as required for the ETV.
- Provide all necessary drains to the test site.
- Provide all off-site water quality analyses prescribed in the PSTP according to the QA/QC protocols contained therein.
- Provide laboratory reports with the analytical results to the data manager.
- Provide detailed information on the analytical procedures implemented.

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1.3.4 NSF Responsibilities

NSF was responsible for administration of the testing program. Specific responsibilities of the NSF were to:

- Develop test protocols and qualify FTOs.
- Review and approve PSTPs.
- Conduct inspections and make recommendations based on inspections.
- Conduct financial administration of the project.
- Review all project reports and deliverables.

1.3.5 EPA Responsibilities

The specific responsibilities of EPA were to:

- Initiate the ETV program.
- Review final reports.

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Chapter 2
Equipment Description and Operating Processes

The equipment tested in this ETV is the US Filter 3M10C Package Microfiltration Membrane System. With a nominal pore size of 0.2 micron, the 3M10C membranes are designed to remove particulate material, including protozoa and bacteria. The 3M10C package plant contains 3 pressure vessels with one membrane module per pressure vessel. Each stainless steel pressure vessel is 4.5 inches (11cm) in diameter and approximately 55 inches (140 cm) long. The top and bottom of the pressure vessels are attached to headers that distribute feed water to the pressure vessels and collect permeate.

A photograph of the US Filter pressure-driven package plant is shown in Figure 2-1. The photograph shows the wiring cabinet and control panel (upper left), feed pump (lower left), feed water storage tank and three stainless steel pressure vessels with upper and lower headers. The skid mounted unit includes all major equipment elements and controls with the exception of an air compressor that was used to operate pneumatic valves and supply the pressurized air used during backwash. The spatial requirements and locations of major system components and instruments on the US Filter MF unit are shown in Figure 2-2. The footprint of the unit is approximately 57 inches (145 cm) long by 39 inches (99 cm) wide. The height of the unit, including the 5 inch (13 cm) base is approximately 87 inches (221 cm). The unit is skid mounted and can be moved with a forklift and transported by truck.

The test unit has two phases of operation: filtration and backwash. In the filtration phase, feed water is pumped from the feed tank to both the top and bottom of the modules. The pressurized feed water is directed around a central permeate tube in the module end-caps to the outside surface of the hollow fibers. Permeate passes through the pores of the membrane to the inside of the hollow fibers and is collected from both ends of the module through a central permeate tube in the module end-caps. The package plant operates in dead-end mode only, with no recirculation flow on the feed side of the membrane. During backwash, the feed pump shuts down and valves are repositioned. An air compressor pressurizes both the feed and permeate side of the membrane to approximately 90 psi. The pressure is then released from the feed side of the membrane, dislodging the cake layer from the membrane surface. Feed water is then pumped from the bottom of the module to flush the dislodged debris. This is followed by a final rewetting phase where both sides of the membrane are again pressurized to approximately 90 psi to force water into the membrane pores before resuming the next filtration cycle. The backwash phase lasts approximately two minutes.

The long-term operation of the US Filter MF unit frequently results in the accumulation of materials on the membrane surface, which are not effectively removed by backwash. This is called membrane fouling and is observed as a gradual increase in the pressure required to force water through the membrane pores. Once a critical upper pressure has been reached, normal operation is discontinued and the membrane undergoes chemical cleaning. Chemical cleaning typically involves the use of acid solutions to restore efficient operation of the membrane.

The US Filter MF unit uses three model M10C polypropylene membrane modules. Table 2-1 provides the specification of membranes used in the US Filter MF membrane system. The information in Table 2-1 is taken from a letter supplied by the system manufacturer, US Filter (see Appendix A). The M10C module is a hollow-fiber, outside-in configuration membrane with nominal pore size of 0.2 micron. At this pore size, the membrane is expected to remove particulate material, including protozoa and bacteria.

2.1 Description of the Treatment Train and Unit Processes

Figure 2-3 presents a schematic diagram of the US Filter MF system. The test system has two alternating operation modes: filtration and backwash.

The operation of the MF membrane system is summarized in the following steps:

1. During the filtration phase of operation, the feed pump draws water from the feed tank and directs it to the upper and lower header assemblies. The feed tank is filled from a pressurized influent pipe through an automatically controlled level switch. The feed pump provides the pressure needed to filter the water through the membranes. The pump operates at a constant rotational speed, drawing feed water from the bottom of the feed tank and directing it to the upper and lower membrane header assemblies and through these assemblies to the outside surface of the membrane fibers. The transmembrane pressure, and thus the flow rate through the membranes, is varied by manually adjusting a valve on the permeate side of the system.
2. The pressure forces water through the pores of the membrane to the inside of the fibers. The permeate water flows both up and down the inside of the fibers to an isolated portion of the upper and lower membrane headers where it is collected and routed to the permeate piping. The length of the filtration phase of operation is primarily dependent on the source water quality and permeate flow rate. After completion of the filtration phase, the system suspends normal operation and begins the backwash phase.
3. Backwash is initiated automatically based on a timer. The objective of the backwash is to remove solids and organics that have accumulated on the feed side (outside) of the membrane surface during filtration. A PLC automatically operates the pumps and valves required to accomplish the backwash.

There are six distinct portions of the backwash. They are:

- drain membrane lumens,
- feed side fast flush with air and feed water to feed side,
- pressurize feed and permeate side to 90 psi,
- air backwash (release pressure on feed side)
- feed side flush with feed water (sweep)
- rewet membrane by pressuring both sides to 90 psi.

4. Backwash wastewater was directed to drain during ETV testing. At the completion of backwash, the PLC readjusts the appropriate valves and restarts the system in filtration mode.

After extended periods of operation, typically on the order of weeks to months, the pressure required to force water through the membrane pores increases because some of the materials that accumulate on the membrane surface and within the pores are not effectively removed by backwash. This process is called membrane fouling. Once the system reaches a critical

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pressure, the system is shut down and a chemical cleaning is performed to restore membrane efficiency. The US Filter ETV test system was considered fouled when the transmembrane pressure reached 29 psi (2.0 bar) at the operating flow rate. Cleaning the US Filter unit is accomplished by the recirculation of a citric acid solution with pH between 2.0 and 2.5 for approximately 120 minutes. When in cleaning mode, the system automatically shuts off the flow of feed water to the feed tank. The cleaning solution is prepared in the feed tank using either clean water supplied from outside the system (tap water or low TDS water) or cleaning water prepared by the system by recirculating filtered feed water to the feed tank for 10 minutes. The operator adds chemicals to the feed tank and recirculation of the cleaning solution begins (the feed water is shut off at this time). The cleaning solution can optionally be heated to 32 °C to assist cleaning. Once the recirculation phase of cleaning has completed, the unit stops. At this point, the operator can request an extended soak period or direct cleaning chemicals to waste (with neutralization, if required). After completing chemical cleaning, the system automatically performs a number of backwashes to rinse the membrane. The system then shuts down and must be restarted manually before returning to regular filtration and backwash cycles.

The system also includes the following minor operating modes as described below:

1. Rewet. A rewet step can be performed manually from the control panel when the system is shut down. This would typically be performed if there were a concern that the membrane pores are not properly wetted.
2. Drain down. A drain down step can be performed manually from the control panel to remove water from the feed and permeate side of the membrane. In addition, the feed tank is drained to the low level switch.
3. Sonic test. A sonic test can be performed manually from the control panel to check for air leaks through compromised fibers. During this test, water is drained from the fiber lumens and the permeate side is pressurized to approximately 15 psi (1.0 bar) with compressed air. The operator listens for leaks through the stainless steel pressure vessel wall.
4. Sonic reset. This option is selected from the control panel after the completion of a sonic test to return the system to normal operation.
5. Pressure decay. Pressure decay tests can be operated manually from the control panel and automatically based on a timer. The system can be set to give a warning alarm at a pressure decay greater than 1.5 psi/min (0.10 bar/min) and shut down the system on a pressure decay test greater than 2.0 psi/min (0.14 bar/min). The initial pressure must be between 10 psi (0.69 bar) and 17 psi (1.2 bar). The pressure decay test, like the sonic test, is performed to check the integrity of the membrane fibers. During the test, the membrane lumens are drained and pressurized to approximately 15 psi (1.0 bar). The system is allowed to stabilize for two minutes and the pressure decay is recorded over the next two minutes. The pressure decay per minute is reported on the PLC screen. A pressure decay of less than 1.5 psi/min is considered acceptable and indicates the membrane integrity is not compromised.

Filtration, in the US Filter MF unit, is accomplished with three US Filter Model M10C MF membrane modules. Each module is cylindrical in shape with a diameter of 4.7 inches (12 cm) and a length of 46 inches (117 cm) and the manufacturer estimates that each module contains

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approximately 20,000 hollow fibers that are potted at both the top and bottom of the module. The length of each hollow fiber is 38.1 inches (97 cm) and each fiber has an inside diameter of approximately 0.25 mm and an outside diameter of approximately 0.55 mm. The flow direction is from the outside of the fibers to the inside of the fibers, thus the active surface area of each module is approximately 361 ft^2 (33.5 m^2). The membranes have a nominal pore size of 0.2 micron and are made of polypropylene, which is hydrophobic. The maximum transmembrane pressure is 29 psi (2.0 bar). The membranes can be operated over a wide range of pH, and at temperatures up to approximately 38°C. The polypropylene membrane material is not chlorine tolerant.

2.2 Description of Physical Construction/Components of the Equipment

The US Filter MF unit is skid-mounted with a footprint of approximately 57 inches (145 cm) long by 39 inches (99 cm) wide. The height of the unit, including the 5 inch (13 cm) base is approximately 87 inches (221 cm). The unit is skid mounted and can be moved with a forklift and transported by truck. The US Filter MF unit is self-contained, requiring only connections to feedwater, backwash tank, drain and electrical. The electrical requirements of the system are 230 or 480 volt three-phase, 60 Hz power.

The major components of the US Filter ETV test unit included:

- Three 361 ft^2 (33.5 m^2) US Filter M10C polypropylene MF modules 4.7 inches (12cm) diameter by 45.5 inch (116 cm) length, housed in stainless steel pressure vessels
- PLC-based control system with data storage
- Feed pump
- Manually operated permeate flow control valve
- Feed storage/cleaning tank
- Air compressor
- Pneumatic valves
- Rotary electronic feed and permeate flow meters
- Analog feed and permeate pressure gauges
- Electronic feed and permeate pressure sensors
- Digital feed thermometer.

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Chapter 3
Materials and Methods

3.1 Testing Site Name and Location

The test site selected for the ETV program was the City of San Diego's Aqua 2000 Research Center at 1500 Wueste Road in Chula Vista, California.

Additional particle removal data has been included in the testing report from previous California Department of Health Services (CDHS) testing. This particle removal data was collected during CDHS testing at the A. H. Bridge Plant, in Rancho Cucamonga, CA, owned by Cucamonga County Water District, during two days between 5/17/2001 and 5/18/2001 (Adham, 2001). The testing was done as a part of the CDHS approval process for operating the US Filter 3M10C system at full-scale water treatment facilities in the State of California. The 3M10C package plant that was tested during CDHS testing is the same model tested during this ETV. The CDHS testing was conducted independently of the ETV testing, although the same FTO collected the data for the CDHS testing and the ETV testing and the data were reviewed by the ETV DWS Center in accordance with the ETV QMP and ETV Program Policies.

3.1.1 Site Background Information

The Aqua 2000 Research Center was established in 1995 to conduct most of the research work related to the water repurification project of the City of San Diego. The Center has dedicated full time operators with substantial experience in operating membrane systems. The site has access to both Otay Lake raw water and the San Diego County Water Authority's Aqueduct System raw water. Sufficient influent water supply, electrical power, and proper drainage lines were provided to the ETV test system treatment train.

3.1.2 Test Site Description

Figure 3-1 is a schematic diagram of the test site and the location of the US Filter MF unit. Below is a list of the facilities and equipment that were available at the test site.

Structural

- 5,000 square foot asphalt pad.
- Shading to protect from sunlight.
- Potable water connections.
- San Diego County Water Authority's Aqueduct System connections.
- Drainage sump connected to the full-scale plant washwater basin.
- Chemical containment area.
- Full electrical supply.
- Chemical safety shower and eyewash.
- An operations trailer with office space, laboratory space for onsite water quality analyses and computers.

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On-Site Laboratory

- DR 4000 Spectrophotometer by Hach
- Ratio/non-ratio 2100N Turbidimeter by Hach
- pH/Temperature meter by Accumet Research (AR-15)
- Portable conductivity meter by Fisher (No. 09-327-1)

Asphalt Test Pad

- Raw water and cleaning chemical waste storage tanks.
- Chemical feed systems.
- Two 1720D on-line Hach turbidimeters
- Two 1900WPC on-line Hach particle counters

Raw Water Intake

The raw water was delivered to the test site from the San Diego County Water Authority aqueduct pipeline.

Handling of Treated Water and Residuals

The Aqua 2000 Research Center has a drainage system that connects to the Otay Filtration Plants washwater basin, which is ultimately returned to Otay Lake. Treated water and backwash water used during testing were directed to the washwater basin. Cleaning chemical wastes were stored in a separate waste storage tank and trucked off site for proper disposal.

3.2 Source/Raw Water Quality

The source of feedwater for the ETV testing is San Diego Aqueduct Water. The aqueduct is supplied primarily from Lake Skinner that receives Colorado River Water (CRW) from the West Portal of the San Jacinto Tunnel, and State Project Water (SPW) from Lake Silverwood. A typical blending ratio of these two waters in Lake Skinner is 70 percent CRW and 30 percent SPW. The lower total dissolved solids (TDS) SPW is added to maintain the TDS of Lake Skinner at approximately 500 mg/L or less (depending on availability of SPW). The aqueduct water is characterized by relatively high levels of total dissolved solids, hardness and alkalinity, with moderate levels of organic material and relatively low turbidity.

Figure 3-2 illustrates Lake Skinner water quality for the period of November 1997 through November 1998, which is typical for this source water. The stable quality of the water is apparent in all parameters illustrated in Figure 3-2. Hardness ranged from 200 to 298 mg/L as $CaCO_3$, alkalinity ranged from 108 to 130 mg/L as $CaCO_3$ and calcium ranged from 47 to 75 mg/L as Ca (118 to 188 mg/L as $CaCO_3$). The hardness levels are quite high, with relatively high alkalinity as well. TDS ranged from 429 to 610 mg/L, indicating the relatively high level of salinity in this source water. pH ranged from 8.26 to 8.45 during the year.

Figure 3-3 illustrates turbidity, temperature and TOC for Lake Skinner water. Turbidity was relatively low with a range of 1.10 to 3.50 nephelometric turbidity units (NTU). Lake Skinner exhibits relatively warm temperatures throughout the year, typical of many water supplies in the southwestern and southeastern United States. The temperature range was 13 to 27°C. Annual

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low temperatures on the order of 10°C are typical of this supply. The levels of organic material, as quantified by TOC, are moderate in this supply. The TOC range was 2.33 to 2.94 mg/L.

3.3 Environmental Technology Verification Testing Plan

This section describes the tasks completed for the ETV. The test equipment was operated 24 hours a day, seven days a week, with operations staff on-site Monday through Friday (excluding holidays) for one 8-hour shift each day. Tasks that were performed by the operations and engineering staff are listed below:

Task 1: Characterization of Membrane Flux and Recovery

Task 2: Evaluation of Cleaning Efficiency

Task 3: Evaluation of Finished Water Quality

Task 4: Reporting of Membrane Pore Size

Task 5: Membrane Integrity Testing

Task 6: Data Management

Task 7: Quality Assurance/Quality Control

An overview of each task is provided below.

3.3.1 Task 1: Characterization of Membrane Flux and Recovery

The objective of this task is to evaluate the membrane operational performance. Membrane productivity was evaluated relative to feedwater quality. The rates of transmembrane pressure increase and/or specific flux decline were used, in part, to evaluate operation of the membrane equipment under the operating conditions being verified and under the raw water quality conditions present during the testing period.

Work Plan

After set-up and shakedown of the membrane equipment, membrane operation was established at the flux condition being verified in this ETV. Testing took place over a single test period of more than 30 days. Substantial specific flux decline did not occur before the end of the test period. Chemical cleaning was performed at the end of the testing period. Measurement of the membrane system flows, pressures and temperatures were collected at a minimum of twice a day.

3.3.2 Task 2: Evaluation of Cleaning Efficiency

An important aspect of membrane operation is the restoration of membrane productivity after specific flux decline has occurred. The objective of this task is to evaluate the effectiveness of chemical cleaning for restoring finished water productivity to the membrane system. The recovery of specific flux and the fraction of original specific flux lost were determined after each chemical cleaning.

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Work Plan

The membrane was operated at the flux condition being verified in this ETV until such time as the termination criteria were reached. The two criteria for cleaning of the membrane were: 1) reaching the maximum transmembrane pressure operational limit of the membrane (TMP > 29 psi), or, 2) completing the 30-day test period. The membrane was chemically cleaned when either of these termination criteria was reached. Chemical cleaning was performed in accordance to the manufacturer procedure (see Appendix A). For the feedwater utilized in this ETV, the manufacturer recommended their typical chemical cleaning procedure using a citric acid cleaning solution.

The first cleaning step uses a two percent citric acid solution in raw water, with pH in the range 2.0 to 2.5. This is followed by a high pH cleaning step using caustic solution in feedwater, with pH in the range 12 to 13. On the recommendation of US Filter, a proprietary high pH cleaning agent, Memclean EAX2, manufactured by US Filter, was used instead of caustic.

To determine cleaning efficiency, flux-pressure profiles were developed at each stage of the chemical cleaning procedure (i.e., before cleaning and after chemical solution). The slope of the flux-pressure profile represents the specific flux of the membrane at each cleaning stage and was used to calculate the cleaning efficiency indicators. Two primary indicators of cleaning efficiency and restoration of membrane productivity were examined in this ETV:

1. The immediate recovery of membrane productivity, as expressed by the ratio between the final specific flux value of the current filtration run (Js_f) and the initial specific flux (Js_i) measured for the subsequent filtration run:

   Recovery of Specific Flux = $100 \times [1 - (Js_f \div Js_i)]$

   where: Js_f = specific flux (gallon/ft^2/day (gfd)/psi, L/(hr-m^2)/bar) at end of current run (final)
   Js_i = specific flux (gfd/psi, L/(hr-m^2)/bar) at beginning of subsequent run (initial)

2. The loss of specific flux capabilities is expressed by the ratio between the initial specific flux for any given filtration run (Js_i) and the specific flux (Js_{io}) at time zero, as measured at the initiation of the first filtration run in a series:

   Loss of Original Specific Flux = $100 \times [1 - (Js_f \div Js_{io})]$

   where: Js_{io} = specific flux (gfd/psi, L/(hr-m^2)/bar) at time t = 0 of membrane testing

3.3.3 Task 3: Evaluation of Finished Water Quality

The objective of this task is to evaluate the quality of water produced by the ETV test system. Many of the water quality parameters described in this task were measured on-site. Analyses of the remaining water quality parameters were performed by the City of San Diego Laboratory, a State-certified analytical laboratory.

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Work Plan

The parameters monitored during this ETV and the methods used for their measurement are listed in Table 3-1. Finished water quality was evaluated relative to feedwater quality and operational conditions.

3.3.4 Task 4: Reporting of Membrane Pore Size

Membranes for particle and microbial removal do not have a single pore size, but rather have a distribution of pore sizes. Membrane rejection capabilities are limited by the maximum membrane pore size.

Work Plan

The manufacturer was asked to supply the 90 percent and the maximum pore size of the membranes being tested in the ETV. The manufacturer was also asked to identify the general method used in determining the pore size values.

3.3.5 Task 5: Membrane Integrity Testing

A critical aspect of any membrane process is the ability to verify that the process is producing a specified water quality on a continual basis. For example, it is important to know whether the membrane is providing a constant barrier to microbial contaminants. The objective of this task is to evaluate one or more integrity monitoring methods for the membrane system.

Work Plan

The selected methods for monitoring of membrane integrity of the Manufacturer's MF system during this study are described below:

Air Pressure-Hold Test

The air pressure-hold test, also called the pressure-decay test, is one of the direct methods for evaluation of membrane integrity. This test can be conducted on several membrane modules simultaneously; thus, it can test the integrity of a full rack of membrane modules used for full-scale systems. The test is conducted by pressurizing the permeate side of the membrane after which the pressure is held and the decay rate is monitored over time. Minimal loss of the held pressure (less than 1.5 psi per minute) at the permeate side indicates a passed test, while a significant decrease of the held pressure indicates a failed test.

Particle Counting

On-line particle counting in the size ranges of 2-3 microns (um), 3- 5 um, 5-7 um, 7-10 um, 10-15 um and >15 um was used in this ETV as an indirect method of monitoring membrane integrity.

3.3.6 Task 6: Data Management

The objective of this task is to establish the protocol for management of all data produced in the ETV and for data transmission between the FTO and the NSF.

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Work Plan

According to EPA/NSF ETV protocols, a data acquisition system was used for automatic entry of on-line testing data into computer databases. Specific parcels of the computer databases for online particle and turbidity were then downloaded for importing into Excel as a comma delimited file. These specific database parcels were identified based on discrete time spans and monitoring parameters. In spreadsheet form, data were manipulated into a convenient framework to allow analysis of membrane equipment operation. For those parameters not recorded by the data acquisition system, field-testing operators recorded data and calculations by hand in laboratory notebooks. Daily measurements were recorded on specially prepared data log sheets as appropriate.

The database for the project was set up in the form of custom-designed spreadsheets. The spreadsheets were capable of storing and manipulating each monitored water quality and operational parameter from each task, each sampling location, and each sampling time. Data from the log sheets were entered into the appropriate spreadsheet. Following data entry, the spreadsheet was printed out and the printout was checked against the handwritten data sheet. Any corrections were noted on the hard copies and corrected on the screen, and then a corrected version of the spreadsheet was printed out. Each step of the verification process was initialed by the field testing operator or engineer performing the entry or verification step.

Data from the outside laboratory were received and reviewed by the field testing operator. Data from the City of San Diego Water Quality lab were received both electronically and in hardcopy printouts generated from the electronic data.

3.3.7 Task 7: Quality Assurance/Quality Control

An important aspect of verification testing is the protocol developed for quality assurance and quality control. The objective of this task is to assure the high quality of all measurements of operational and water quality parameters during the ETV.

Work Plan

Equipment flow rates and pressures were documented and recorded on a routine basis. A routine daily walk-through during testing was performed each morning to verify that each piece of equipment or instrumentation was operating properly. On-line monitoring equipment, such as flow meters, were checked to confirm that the read-out matches the actual measurement and that the signal being recorded was correct. Below is a list of the verifications conducted:

Monitoring Equipment

System Pressure Gauges
Pressure and vacuum gauges supplied with the membrane systems tested were verified against grade 3A certified pressure or vacuum gauges purchased at the start of ETV testing. The certified pressure and vacuum gauges were manufactured by Ashcroft and have an accuracy of 0.25% over their range (0-30 psi pressure). The US Filter system feed and permeate pressure gauges were consistently accurate to within five percent or less.

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System Flow Rates
Membrane system flow rates were verified volumetrically on a monthly basis near the beginning and end of the test period. System flows were diverted to a 55 gallon graduated tank for approximately two minutes. The measured flow rate was compared with flows indicated on the PLC LCD screen. Measured and indicated flows agreed to within three percent for the permeate rotary flow meter.

Analytical Methods

pH
An Accumet Research Model AR15 laboratory pH meter was used to conduct routine pH readings at the test facility. Daily calibration of the pH meter using pH 4, 7 and 10 buffers was performed. The slope obtained after calibration was recorded. The temperature of the sample when reading sample pH was also recorded.

Temperature
Accuracy of the raw water inline thermometer was verified against a National Institute for Standards and Technology (NIST)-certified thermometer on July 24, 2002 and September 5, 2002. Comparisons were made at three temperatures covering the range of anticipated raw water temperatures. In all cases, the raw water thermometer compared to within ± 0.2°C of the NIST-certified thermometer.

Turbidity
On-line turbidimeters were used for measurement of turbidity in the raw and permeate waters, and a bench-top turbidimeter was used for measurement of the feedwater and backwash wastewater.

<u>On-line Turbidimeters:</u> Hach 1720D on-line turbidimeters were used during testing to acquire raw and permeate turbidities at one-minute intervals. The following procedures were followed to ensure the integrity and accuracy of these data:

- A primary calibration of the on-line turbidimeters (using formazin primary standards) was performed near the beginning of the test periods.
- Aquaview + data acquisition software was used to acquire and store turbidity data. Data were stored to the computer database each minute. After initial primary calibration of the turbidimeters, zero, mid-level and full-strength signals (4, 12 and 20 mA) were output from each turbidimeter to the data acquisition software. The signals received by the data acquisition software from all four on-line turbidimeters had less than one percent error over their range of output (0, 1 and 2 NTU for permeate, and 0, 10 and 20 NTU for feed) as stored in the Aquaview database.
- The manufacturer's specified acceptable flow range for these turbidimeters is 200 to 750 mL/min. The flow range targeted during testing was 200 mL/min +/- 10 mL/min for feedwater and 200 mL/min +/- 10 mL/min for permeate. On-line turbidimeter flows were verified manually with a graduated cylinder and stopwatch daily.
- Turbidimeter bodies were drained and sensor optics cleaned on an as-needed basis.
- On-line turbidities were compared to desktop turbidities when turbidity samples were collected. Comparative calibrations of the raw water on-line turbidimeter against the Hach

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2100N desktop turbidimeter were conducted on an as-needed basis during the course of the testing when the difference between on-line and desktop turbidity readings were greater than approximately 10 percent.

- Approximately 50 parts per million (ppm) free chlorine solution was pumped through turbidity sample lines as needed to clean potential buildup from these lines.

Desktop Turbidimeters: A Hach 2100N desktop turbidimeter was used to perform onsite turbidity analyses of raw water, backwash and permeate samples. Readings were recorded in non-ratio operating mode. The following quality assurance and quality control procedures were followed to ensure the integrity and accuracy of onsite laboratory turbidity data:

Primary calibration of turbidimeter according to manufacturer's specification was conducted on a weekly basis. Secondary standard calibration verification was performed on a daily basis. Five secondary standards (stray light, 0-2 NTU, 0-20 NTU, 0-200 NTU, and 200-4000 NTU) were recorded after primary calibration and on a daily basis for the remaining 6 days until the next primary calibration. Proficiency samples with a known turbidity of 1.40 NTU were purchased from a commercial supplier. Turbidity proficiency samples were prepared and analyzed every two weeks.

Particle Counting

Hach 1900 WPC light blocking particle counters were used to monitor particles in raw and permeate waters. These counters enumerate particles in the range 2 to 800 microns.

The particle counters were factory calibrated. Factory calibrations took place on June 04, 2002. The manufacturer recommends factory calibration on a yearly basis. The following procedures were followed to ensure the integrity and accuracy of the on-line particle data collected:

- Aquaview software was configured to store particle counts in the following size ranges: 2-3 um, 3-5um, 5-7um, 7-10um, 10-15um and >15um.
- To demonstrate the comparative response of the particle counters, NIST traceable monospheres were purchased from Duke Scientific in the following sizes: 2um, 4um, 10um and 20um. Duke monospheres were added to constantly stirred deionized (DI) water and pumped to one of the constant head flow controllers using a peristaltic pump. The flow from this controller was then directed to each of the particle counters for approximately 10 minutes. The same solution was used for each particle counter (raw water and permeate).

The precise concentration of each monosphere was not known, but based on Duke Scientific estimates the following approximate concentration of each monosphere was present in the test solution:

- 2um 1,000 - 10,000/mL
- 4um 100 - 1,000/mL
- 10um 10 - 100/mL
- 20um 1 - 10/mL

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A typical response of the particle counters to this monosphere solution near the test period is presented in Figure 3-4. The figures show a good comparative response between the raw water and permeate particle counters to the same monosphere solution.

Flows through the particle counters were maintained at 200+/- 10 mL/min with constant head devices. Flows were verified on a daily basis with a graduated cylinder and stopwatch. Flows were observed to be extremely consistent (typically within 2 mL/min of the target flow rate). Free chlorine solutions of approximately 50 mg/L were run through particle counters on an as-needed basis to remove potential buildup.

ETV-Reviewed Supplemental Particle Counting Data: Documentation of the calibration of the CDHS particle counters on June 22, 2000 (10 months before CDHS testing) has been provided in Appendix B. Figure 3-5 presents the particle counter verification plot for US Filter 3M10C membrane system approval testing conducted for the CDHS on December 11, 2000. This plot shows a good comparative response between raw water and permeate particle counters during CDHS calibration verification. Comparison of Figures 3-4 and 3-5 shows a comparable response during both ETV testing and CDHS testing. Although the calibration of the particle counters and the verification of calibration for the CDHS testing were outside of the time frame recommended in the ETV Technology-Specific Test Plan (11 months vs. within two months and five months vs. immediately before testing, respectively), both the raw and permeate particle counters gave comparable responses to the same microsphere solution (Figure 3-5); therefore, log removals should be comparable. Also, the particle counters were made by the same manufacturer and were same model and the calibration did occur within the one year time frame recommended by the particle counter manufacturer.

Chemical and Microbial Water Quality Parameters

The analytical work for the study was performed by the City of San Diego Laboratory, which is a State of California certified water laboratory. All water samples were collected in appropriate containers (containing preservatives as applicable) prepared by the City of San Diego laboratory. Samples for analysis of Total Coliforms (TC) and Heterotrophic Plate Count (HPC) analysis were collected in bottles supplied by the City of San Diego laboratory and transported with an internal cooler temperature of approximately 2 to 8°C to the analytical laboratory. All samples were preserved, stored, shipped and analyzed in accordance with appropriate procedures and holding times. All reported results had acceptable QA and met method-specific QC guidelines, which was confirmed by letters from the City of San Diego Water Quality and Marine Microbiology Laboratories (Appendix A).

3.4 Calculation of Membrane Operating Parameters

3.4.1 Permeate Flux

The average permeate flux is the flow of permeate water divided by the surface area of the membrane. Permeate flux is calculated according to the following formula:

$$J_t = Q_p \div S$$

where: J_t = permeate flux at time t (gfd, $L/(hr\text{-}m^2)$)

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Q_p = permeate flow (gallon per day (gpd), L/hr)
S = membrane surface area (ft^2, m^2)

Flux is expressed only as gfd and L/(hr-m^2) in accordance with EPA/NSF ETV protocol.

3.4.2 Specific Flux

The term specific flux is used to refer to permeate flux that has been normalized for the transmembrane pressure. The equation used for calculation of specific flux is:

$$J_{tm} = J_t \div P_{tm}$$

where: J_{tm} = specific flux at time t (gfd/psi, L/(hr-m^2)/bar)
J_t = permeate flux at time t (gfd, L/(hr-m^2))
P_{tm} = transmembrane pressure (psi, bar)

3.4.3 Transmembrane Pressure

The average transmembrane pressure for membrane systems is in general calculated as follows:

$$P_{tm} = [(P_i + P_o) \div 2] - P_p$$

where: P_{tm} = transmembrane pressure (psi, bar)
P_i = pressure at the inlet of the membrane module (psi, bar)
P_o = pressure at the outlet of the membrane module (psi, bar)
P_p = permeate pressure (psi, bar)

In the case of the US Filter 3M10C system, the inlet pressure is the same as the outlet pressure ($P_i = P_o$), so the above equation can be modified to:

$$P_{tm} = P_i - P_p$$

where: P_{tm} = transmembrane pressure (psi, bar)
P_i = pressure at the inlet of the membrane module (psi, bar)
P_p = permeate pressure (psi, bar)

3.4.4 Temperature Adjustment for Flux Calculation

Temperature corrections to 20°C for transmembrane flux were made to account for the variation of water viscosity with temperature. The following equation was employed:

$$J_t \text{ (at 20°C)} = [Q_p \times e^{(-0.0239 \times (T - 20))}] \div S$$

where: J_t = instantaneous flux (gfd, L/(hr-m^2))
Q_p = permeate flow (gpd, L/hr)
T = temperature (°F, °C)
S = membrane surface area (ft^2, m^2)

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3.4.5 Feedwater System Recovery

The recovery of permeate from feedwater is the ratio of permeate flow to feedwater flow:

$$\% \text{ System Recovery} = 100 \times (Q_p/Q_f)$$

where: Q_p = permeate flow (gpd, L/hr)
Q_f = feed flow to the membrane (gpd, L/hr)

3.4.6 Rejection

The rejection of contaminants by membrane process was calculated as follows:

$$R = (1 - \frac{C_P}{C_F}) * 100\%$$

where: R = Rejection (%)
C_P = Permeate water concentration (mg/L)
C_F = Raw water concentration (mg/L)

3.5 Calculation of Data Quality Indicators

3.5.1 Precision

As specified in Standard Methods (Method 1030 C), precision is specified by the standard deviation of the results of replicate analyses. An example of replicate analyses in this ETV is the biweekly analysis of turbidity proficiency samples. The overall precision of a study includes the random errors involved in sampling as well as the errors in sample preparation and analysis.

$$\text{Precision} = \text{Standard Deviation} = \sqrt{\left[\sum_{i=1}^{n} (\overline{X}_i - \overline{X})^2 \div (n - 1)\right]}$$

where: $\overline{X}$ = sample mean
$\overline{X}_i$ = *i*th data point in the data set
n = number of data points in the data set

3.5.2 Relative Percent Deviation

For this ETV, duplicate samples were analyzed to determine the overall precision of an analysis using relative percent deviation. An example of duplicate sampling in this ETV is the daily duplicate analysis of turbidity samples using the bench-top turbidimeter.

$$\text{Relative Percent Deviation} = 100 \times [(x_1 - x_2) \div \overline{x}]$$

where: $\overline{x}$ = sample mean
x_1 = first data point of the set of two duplicate data points
x_2 = second data point of the set of two duplicate data points

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3.5.3 Accuracy

Accuracy is quantified as the percent recovery of a parameter in a sample to which a known quantity of that parameter was added. An example of an accuracy determination in this ETV is the analysis of a turbidity proficiency sample and comparison of the measured turbidity to the known level of turbidity in the sample.

$$\text{Accuracy} = \text{Percent Recovery} = 100 \times [X_{measured} \div X_{known}]$$

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

3.5.4 Statistical Uncertainty

For the water quality parameters monitored, 95 percent confidence intervals were calculated. The following equation was used for confidence interval calculation:

$$\text{Confidence Interval} = \bar{x} \pm [t_{n-1,1-(\alpha/2)} \times (S/\sqrt{n})]$$

where:
- $\bar{x}$ = sample mean
- S = sample standard deviation
- n = number of independent measurements included in the data set
- t = Student's t distribution value with n-1 degrees of freedom
- α = significance level, defined for 95 percent confidence as: 1 - 0.95 = 0.05

According to the 95 percent confidence interval approach, the α term is defined to have the value of 0.05, thus simplifying the equation for the 95 percent confidence interval in the following manner:

$$\text{95 Percent Confidence Interval} = \bar{x} \pm [t_{n-1,0.975} \times (S/\sqrt{n})]$$

3.6 Testing Schedule

The ETV schedule is illustrated in Figure 3-6. The testing program took place starting in July 2002 and was completed by early September 2002.

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Chapter 4
Results and Discussion

This chapter presents the data obtained under each task of the ETV program of the US Filter MF system.

4.1 Task 1: Characterization of Membrane Flux and Recovery

The operating conditions for the US Filter MF membrane system are provided in Table 4-1. The manufacturer established the operating parameters for the ETV testing. The membrane system ran at a target flux of 24 gfd (41 L/hr-m^2). Filtration cycle length was 22 minutes followed by a 180 second backwash. Feed water consumed during backwash was 40.8 gallons (154 liters). The feed water recovery was 91 percent during the testing period.

Figure 4-1 provides the membrane transmembrane pressure and temperature profiles for the test period. Operational readings were taken approximately five minutes before and after backwash. These are displayed on the figures as pairs of data points at nearly the same point in time. The data point taken before backwash has the higher transmembrane pressure value. During the test period, the clean membrane transmembrane pressure began at approximately 7 psi. The transmembrane pressure stabilized at 7 to 10 psi for approximately 4 weeks and then fouled more rapidly over the remainder of the filter run, reaching a final transmembrane pressure of approximately 14 psi.

Figure 4-1 also provides the membrane flux and specific flux profiles for the test period. The target flux during the test period was 24 gfd (41 L/hr-m^2). The average temperature adjusted membrane flux was 21 gfd at 20°C (35 L/hr-m^2 at 20°C). The temperature adjusted specific flux decreased from 3 to 1.6 gfd/psi at 20°C (75 to 38 L/hr-m2-bar at 20°C) over the 44 days of the test period. The gap in operational data between August 16, 2002 and August 20, 2002 was due to failure of a solenoid controlling the air to one of the pneumatic valves. The test unit was not operational over this period. The same data in Figure 4-1 is also provided in Appendix A of this report, but with metric units.

For the particle data collection for the CDHS approval testing of the US Filter MF membrane on May 17 and 18, 2001 (independently from ETV testing), the system was operated at a flux of 50 gfd with transmembrane pressures ranging from 20.5 to 23 psi. Water temperature ranged from 10 to 13 degrees centigrade.

4.2 Task 2: Evaluation of Cleaning Efficiency

Chemical cleanings were performed when the membrane fouled (transmembrane pressure of 29 psi [2 bar]), or the end of a test period was reached. During the test period the transmembrane pressure did not reach 29 psi so a cleaning was necessary only at the end of the test period. The manufacturer’s cleaning procedure was a two-step process. A citric acid cleaning solution was used first, followed by a high pH cleaning solution. The 2 percent citric acid cleaning solution was prepared by dissolving 8 pounds (17 kg) of citric acid to the feed tank. The pH of this solution was in the range 2 to 2.5. The citric acid solution was recirculated through the feed side

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of the membrane for 120 minutes at a flow of 32 gpm (121 L/min) with a feed pressure of approximately 9 psi. After discarding the cleaning solution and rinsing the system with feed water, the same cleaning procedure was followed using a high pH cleaning solution. The high pH cleaning solution was made by adding 1 gallon (3.7 liters) of Memclean EAX2 to the feed tank. The pH of this solution was in the range of 12-13.

The flux-pressure profiles of the membrane system before and after the chemical cleaning procedure are shown in Figure 4-2. The slope of the flux-pressure profile represents the specific flux of the membrane before and after each cleaning stage and was used to calculate the cleaning efficiency indicators. These are listed in Table 4-2. The recovery of specific flux for the cleanings at the end of the test period was 100 percent indicating no irreversible fouling.

The same data in Figure 4-2 is also provided in Appendix A of this report, but with metric units. In addition, the manufacturer's detailed cleaning procedure is included in Appendix A.

4.3 Task 3: Evaluation of Finished Water Quality

Several water quality parameters were monitored during testing. Below is a summary of the water quality data.

4.3.1 Turbidity, Particle Concentration and Particle Removal

Figures 4-3 presents the on-line turbidity profile for the US Filter MF membrane system during the test period. The figure shows online turbidity for raw and permeate water and desktop turbidity for raw water, permeate and backwash waste. The desktop turbidity data are summarized in Table 4-3 and the online turbidity data are summarized in Table 4-4. For the testing period, the raw water turbidity was in the range of 0.70-0.80 NTU. The turbidity of the backwash wastewater averaged 7.3 NTU. The permeate turbidity was typically below 0.1 NTU.

Figures 4-4 presents the particle count profile (2-3 um, 3-5 um, 5-7um, 7-10 um, 10-15 um and >15 um) collected during the test period. The data presented represent 4-hour average values of data collected at one-minute intervals. The online particle count data are summarized in Table 4-4. For the testing period, the feed particle concentration of the *Cryptosporidium*-sized particles (3-5 um) was typically in the range of 1,000-1,200 particle/mL while the combined *Giardia*-sized particles (5-7um, 7-10 um and 10-15 um) was in the range 900 to 1,000 particle/mL. The permeate concentration in these size ranges was typically in the range of 0.4 to 1.0 particle/mL. The gap in the particle data near August 16, 2002 was due to failure of a solenoid controlling the air to one of the pneumatic valves. The test unit was not operational over this period.

Figure 4-5 presents the log removal of particles (2-3 um, 3-5 um, 5-7 um, 7-10 um, 10-15 um, and >15 um) based on raw and permeate particle count data collected during the test period. Data presented on this plot represent one-day average values of data collected at one-minute intervals. Removal ranged from 2.3 to 3.5 logs with an average of 3.1 logs for the *Cryptosporidium*-sized particles (3-5 um) and from 2.7 to 3.6 logs with an average of 3.1 logs for the *Giardia*-sized particles (5-7 um, 7-10 um and 10-15 um). The online particle removal data are summarized in Table 4-4.

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To assist in assessing test system performance, Figure 4-6 presents the probability plots of the membrane system permeate turbidity and particle removal data for the *Cryptosporidium*-sized particles (3-5 um) and *Giardia*-sized particles (5-15 um) during the test period. The figure shows that the permeate turbidity was 0.1 NTU or below 95 percent of times and that removal of particles (3-5 um and 5-15 um) was greater than 2.5 logs 95 percent of times.

4.3.1.1 ETV-Reviewed Supplemental Particle Counting Data. Figure 4-7 presents the particle count profile (2-5 um and 5-15 um) for the US Filter MF system during CDHS membrane approval testing of the 3M10C system conducted at the A. H. Bridge Plant in Rancho Cucamonga, California on May 17 and 18, 2001 (independently from ETV testing). The figure shows feed particle concentration of the *Cryptosporidium*-sized particles (2-5 um) were typically in the range of 1,000-1,200 particle/mL while the *Giardia*-sized particles (5-15 um) were in the range 900 to 1,000 particle/mL. The permeate concentration in these size ranges was typically in the range of 0.46 to 1.0 particle/mL. The online particle count data are summarized in Table 4-5. Although the calibration of the particle counters and the verification of calibration for the CDHS testing were outside of the time frame recommended in the ETV Technology-Specific Test Plan (11 months vs. within two months and five months vs. immediately before testing, respectively), both the raw and permeate particle counters gave comparable responses to the same microsphere solution (Figure 3-5); therefore, log removals should be comparable. Also, the particle counters were made by the same manufacturer and were same model and the calibration did occur within the one year time frame recommended by the particle counter manufacturer.

Figure 4-8 presents the log removal of particles (2-5 um, 5-15 um) based on raw and permeate particle count data collected during CDHS testing at Rancho Cucamonga, California (independently from ETV testing). Data presented on this plot represent values of data collected at one-minute intervals. Removals ranged from 2.6 to 4.7 logs with an average of 3.8 log for the *Cryptosporidium*-sized particles (2-5 um) and from 2.2 to 4.3 logs with an average of 3.9 log for the *Giardia*-sized particles (5-15 um). The online particle removal data are summarized in Table 4-5.

Figure 4-9 presents the probability plots of the membrane system particle removal for the *Cryptosporidium*-sized particles (2-5 um) and *Giardia*-sized particles (5-15 um) during CDHS testing at Rancho Cucamonga, California (independently from ETV testing). The plot shows that particle removals in these size ranges were greater than 2.9 logs, for 2-5 um particles, and 3.1 logs, for 5-15 um particles, 95 percent of times. The plot also shows that particle removals in this low particle count feed water were greater than 4.0 logs approximately 40 percent of times for *Cryptosporidium*-sized particles and removals were greater than 4.0 logs approximately 50 percent of times for *Giardia*-sized particles.

4.3.2 Indigenous Bacteria Removal

The removal of naturally occurring bacteria was also monitored during the ETV study (see Table 4-6). The influent total coliform bacteria ranged from 580 to 1200 most probable number (MPN)/100 mL. Total coliform bacteria were not detected in the permeate of the US Filter MF membrane system during the test period. This represents a log removal ranging from greater than 1 log to greater than 3.2 log. HPC bacteria were reduced by the filtration process. HPC bacteria in the raw water ranged from 12 to 2000 colony forming units (cfu)/mL while HPC

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bacteria in the US Filter MF permeate ranged from 1 to 430 cfu/mL. This represents a log removal ranging from 0.4 log to 3 log. Previous studies (Jacangelo et al., 1995) have demonstrated that HPC bacteria can be introduced on the permeate side of the membrane rather than by penetration through it.

4.3.3 Other Water Quality Parameters

Table 4-6 presents the results of water quality parameters across the US Filter MF system. As expected, no change was observed in the alkalinity, total dissolved solids, total hardness, and calcium hardness of the water across the membrane system. Also, reduction in dissolved organic material in the permeate was not observed as expected, as MF does not remove dissolved constituents.

The total suspended solids (TSS) in the backwash waste reached as high as 41 mg/L, while the permeate TSS remained consistently below the detection limit (1 mg/L).

A mass balance could not be conducted on total suspended solids across the membrane system because the feed TSS measurements were consistently below the detection limit of 1.0 mg/L.

4.4 Task 4: Reporting Membrane Pore Size

A request was submitted to the membrane manufacturer to provide the 90 percent and maximum pore size of the membrane being verified. In their response letter, US Filter indicated that they used a porometer (designed by US Filter) for pore size distribution measurement. They also indicated that this instrument is of a proprietary design and is used in a manner conforming generally to ASTM F-316 Standard Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test and that the pore size distribution data has been correlated with microbial removal performance. On this basis they report the maximum pore size of the membrane at 0.45 micron and the 90 percent pore size at 0.20 micron.

The above information is taken from a letter supplied by the US Filter, which is included in Appendix A of this report. This is provided for informational purposes only and the results were not verified during the ETV testing.

4.5 Task 5: Membrane Integrity Testing

Figure 4-10 shows the results of the air pressure-hold tests conducted on the MF membrane during the test period. The air pressure-hold test on the US Filter system was conducted by pressurizing the feed side of the membrane. If any of the membrane fibers were compromised, one would expect significant loss of held pressure (>1.5 psi every minute) across the membrane element. The air pressure-hold test results show that there were no compromises in membrane integrity during the test period. The US Filter membrane system includes an automated pressure-hold test. The automated pressure-hold test was performed every 24 hours and was set to shut the system down when pressure decays were greater than 1.5 psi/min. There was no shut down of the system because of unacceptable automated pressure-hold results during the test period.

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Permeate particle counts would be expected to noticeably increase if the membrane modules were compromised (Adham et. al., 1995). During testing of the US Filter MF system, this could not be verified as there was no fiber breakage.

4.6 Task 6: Data Management

4.6.1 Data Recording

Data were recorded manually on operational and water quality data sheets prepared specifically for the study. In addition, other data and observations such as the system calibration results were recorded manually on laboratory and QC notebooks. Data from the online particle counters and turbidimeters were also recorded every minute by a computerized data acquisition system. All of the raw data sheets are included in Appendix C of this report.

4.6.2 Data Entry, Validation, and Reduction

Data were first entered from raw data sheets into similarly designed data entry forms in a spreadsheet. Following data entry, the spreadsheet was printed and checked against handwritten datasheets. All corrections were noted on the electronic hard copies and then corrected on the screen. The hardcopy of the electronic data are included in Appendix D of this report.

4.7 Task 7: Quality Assurance/Quality Control (QA/QC)

The objective of this task is to assure the high quality and integrity of all measurements of operational and water quality parameters during the ETV program. Below is a summary of the analyses conducted to ensure the correctness of the data.

4.7.1 Data Correctness

Data correctness refers to data quality, for which there are five indicators:

- Representativeness
- Statistical Uncertainty
- Completeness
- Accuracy
- Precision

Calculation of the above data quality indicators were outlined in the Materials and Methods section. All water quality samples were collected according to the sampling procedures specified by the EPA/NSF ETV protocols, which ensured the representativeness of the samples. Below is a summary of the calculated indicators.

4.7.2 Statistical Uncertainty

Ninety-five percent confidence intervals were calculated for the water quality parameters of the US Filter MF system for which eight or more samples were analyzed. These include turbidity, particle count and particle removal. Ninety-five percent confidence intervals were presented in summary tables in the discussion of Task 3 – Finished Water Quality.

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4.7.3 Completeness

Data completeness refers to the amount of data collected during the ETV study as compared to the amount of data that were proposed in the FOD. Calculation of data completeness was made for onsite water quality measurements, laboratory water quality measurements, and operational data recording. These calculations are presented in Appendix A of this report. All the data sets were more than 85 percent complete, which met the objective of the ETV program.

4.7.4 Accuracy

Accuracy is quantified as the percent recovery of a parameter in a sample to which a known quantity of that parameter was added. An example of an accuracy determination in this ETV is the analysis of a turbidity proficiency sample and comparison of the measured turbidity to the known level of turbidity in the sample. Calculation of data accuracy was made to ensure the accuracy of the onsite desktop turbidimeter used in the study. Accuracy ranged from 97 to 108 percent of the proficiency sample known values. Comparative calibration of online turbidimeters with the desktop turbidimeters was performed as corrective action as needed. All accuracy calculations are presented in Appendix A.

4.7.5 Precision and Relative Percent Deviation

Duplicate water quality samples were analyzed to determine the consistency of sampling and analysis using relative percent deviation. Calculations of relative percent deviation (RPD) for duplicate samples are included in Appendix A of this report. Ideally, the RPDs should be less than 10% for all samples. During testing, the relative percent deviation for analyses not near the lower detection limit were within 15 percent for onsite analyses, within 59 percent for water quality analyses, and within 75 percent for microbial analyses. Relative percent deviation calculations for online and desktop turbidimeter results were also conducted. These observed relative percent deviation ranges are acceptable. Appendix A has explanations from the City of San Diego Lab regarding the relatively high RPDs observed for total coliform and HPC measurements.

4.8 Additional ETV Program Requirements

4.8.1 Operation and Maintenance (O&M) Manual

The O&M Manual for the US Filter MF system supplied by the manufacturer was reviewed during the ETV testing program. The review comments for the O&M manual are presented in Table 4-7. The review found the O&M manual to be a useful resource. The manual makes good use of tables and graphics to organize and clarify the presentation of material. The manual would benefit from less emphasis on technical detail and a more general description of process objectives.

4.8.2 System Efficiency and Chemical Consumption

The efficiency of the small-scale US Filter MF system was calculated based on the electrical usage and water production of the system. The data are presented in Table 4-8. Overall, an efficiency of only 3 percent was calculated for the system. This system efficiency is in the range of many small-scale low pressure membrane systems.

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The chemical consumption of the system was also estimated based on the operating criteria used during the ETV program. Table 4-9 provides a summary of the chemical consumption of the US Filter MF system.

4.8.3 Equipment Deficiencies Experienced During the ETV Program

The equipment deficiencies experienced during the testing are listed in Table A-8 in Appendix A and summarized below.

US Filter MF Membrane System

At the beginning of the shakedown period for the testing it was observed that one of the lower membrane header end plates was leaking because of a crack on the endplate. This endplate was replaced before the start of the testing period. At this time it was also noted that the temperature probe was corroded and was not operational. This part was replaced also.

During the testing on August 16, 2002 the solenoid controlling automatic valve, AV2, failed. The solenoid started leaking air and caused the valve to remain open. The system was shutdown and the solenoid was replaced on August 22, 2002.

Online Turbidimeters and Particle Counters

The turbidimeters and particle counters operated reliably during the testing and only routine maintenance activities were required. The particle counters had to be cleaned during the testing because high permeate particle counts were observed. Also the dessicant pack in the feed particle counter was replaced when the low DC light came on.

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Chapter 5
References

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Tables and Figures

Table 2-1. Characteristics of the US Filter MF M10C Microfiltration Membrane.

	Units	Value
Membrane Manufacturer		US Filter Memcor Products
Membrane Model		M10C
Commercial Designation		M10C
Available Operating Modes		Continuous Microfiltration (CMF)
Approximate Size of Membrane Module	in (m)	45.5 (1.157) long x 4.7 (0.119) dia
Active Membrane Area	ft^2 (m^2)	360.7(33.52)
Number of Fibers per Module		20,000
Number of Modules (Operational)		3
Inside Diameter of Fiber	mm	0.25
Outside Diameter of Fiber	mm	0.55
Approximate Length of Fiber	in (m)	38.1(0.970)
Flow Direction		Out - in
Nominal Molecular Weight Cutoff	Daltons	N/A
Absolute Molecular Weight Cutoff	Daltons	N/A
Nominal Membrane Pore Size	micron	0.20
Membrane Material/Construction		Polypropylene
Membrane Surface Characteristics		Hydrophobic
Membrane Charge		Slightly negative at neutral pH
Design Operating Pressure	psi (bar)	22 (1.5)
Design Flux at Design Pressure	gfd (l/hr-sq m)	25 gfd typical (42.5)
Maximum Transmembrane Pressure	psi (bar)	29 (2.0)
Standard Testing pH		6.8
Standard Testing Temperarture	degF (degC)	68(20)
Acceptable Range of Operating pH Values		2-13
Maximum Permissible Turbidity	NTU	500
Chlorine/Oxidant Tolerance		No oxidants

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Table 3-1. Water Quality Analytical Methods.

Parameter	Facility	Standard Method
General Water Quality		
pH	On-Site	4500H+
Alkalinity	Laboratory	2320 B
Total Hardness	Laboratory	2340 C
Calcium Hardness	Laboratory	3500Ca D
Temperature	On-Site	2550 B
Total Suspended Solids	Laboratory	2540 D
Total Dissolved Solids	Laboratory	2540 C
Particle Characterization		
Turbidity (Bench-Top)	On-Site	2130 B
Turbidity (On-Line)	On-Site	Manufacturer
Particle Counts (On-Line)	On-Site	Manufacturer
Organic Material Characterization		
TOC and DOC	Laboratory	5310 B
UV Absorbance at 254 nm	Laboratory	5910 B
Microbiological Analyses		
Total Coliform	Laboratory	9223 B
HPC Bacteria	Laboratory	9215 B

Table 4-1. US Filter MF Membrane System Operating Conditions.

Parameter	Unit	
Test Period		1
Run		R-01
Start Date & Time		7/24/2002 10:59
End Date & Time		9/5/2002 14:29
Run Length	days - hrs	43 days - 4 hrs
Run Terminating Condition		Time
Filter Cycle Length	min	22
Feed Flow	gpm (lpm)	18.3 (69.3)
Filtrate Flow	gpm (lpm)	18.3 (69.3)
Operating Flux	gfd (L/hr-m^2)	24 (41)
Backwash Settings		
Backwash Cycle Length	sec	180
Backwash Filtrate Consumed	gal (liter)	0 (0)
Fast Flush Feedwater Consumed	gal (liter)	40.8 (154.4)
Feed Water Recovery	%	91

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Table 4-2. Evaluation of Cleaning Efficiency for US Filter MF Membrane.

Clean Number	Clean Date	Specific Flux @20degC Before Clean Jsf gfd/psi (l/hr-m2-bar)	Specific Flux @20degC After Clean Jsi gfd/psi (l/hr-m2-bar)	Loss of Original Specific Flux 100(1 - Jsf / Jsio) %	Recovery of Specific Flux 100(1-(Jsi / Jsio)) %
Start	7/23/02	---	3.2(79)	---	---
Test Run	9/6/02	1.7(42)	3.2 (79)	47	100

Table 4-3. Onsite Lab Water Quality Analyses for US Filter MF Membrane System.

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
Raw Water							
pH		28	8.3	8.1 - 8.4	8.3	0.080	8.2 - 8.3
Desktop Turbidity	NTU	56	0.70	0.35 - 1.3	0.75	0.27	0.65 - 0.80
Temperature	degC	56	26.5	25.3 – 28.0	26.7	0.780	26.5 – 26.9
Filtrate							
Desktop Turbidity	NTU	56	0.05	0.05 - 0.10	0.05	0.01	0.05 - 0.05
Backwash Waste							
Turbidity	NTU	56	6.4	2.1 - 20	7.2	4.0	6.2- 8.3

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Table 4-4. Summary of Online Particle and Turbidity Data for US Filter MF Membrane System.

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
Raw Water							
Turbidity	ntu	230	0.70	0.30 - 1.4	0.70	0.25	0.65 - 0.75
> 2 um Particles	#/mL	230	3900	1000 - 8700	3500	1600	3300 - 3700
2-3 um Particles	#/mL	230	1600	520 - 2800	1400	560	1300 - 1500
3-5 um Particles	#/mL	230	1200	290 - 2300	1100	450	1000 - 1200
5-15 um Particles	#/mL	230	990	190 - 3800	950	630	870 - 1000
5-7 um Particles	#/mL	230	500	110 - 1600	480	280	440 - 520
7-10 um Particles	#/mL	230	310	57 - 1800	320	280	280 - 360
10-15 um Particles	#/mL	230	150	29 - 410	150	91	140 - 160
>15 um Particles	#/mL	230	71	15 - 220	74	46	68 - 80
Filtrate							
Turbidity	ntu	230	0.05	0.05 - 0.10	0.05	0.024	0.05 - 0.05
> 2 um Particles	#/mL	227	1.9	0.87 - 26	3.9	4.6	3.3 - 4.5
2-3 um Particles	#/mL	227	0.80	0.34 - 15	1.7	2.3	1.4 - 2.0
3-5 um Particles	#/mL	227	0.52	0.23 - 13	1.2	1.7	0.98 - 1.4
5-15 um Particles	#/mL	227	0.48	0.23 - 6.1	0.86	0.97	0.73 - 0.99
5-7 um Particles	#/mL	227	0.21	0.087 - 4.3	0.47	0.64	0.39 - 0.55
7-10 um Particles	#/mL	227	0.13	0.069 - 1.4	0.24	0.26	0.21 - 0.27
10-15 um Particles	#/mL	227	0.11	0.050 - 0.48	0.15	0.097	0.14 - 0.16
>15 um Particles	#/mL	227	0.090	0.045 - 0.33	0.11	0.056	0.10 - 0.12
Log Removal 2-3 um Particles		39	2.9	2.5 - 3.4	3.0	0.27	2.9 - 3.1
Log Removal 3-5 um Particles		39	3.0	2.3 - 3.5	3.1	0.29	3.0 - 3.2
Log Removal 5-15 um Particles		39	3.0	2.7 - 3.6	3.1	0.27	3.0 - 3.2
Log Removal 5-7 um Particles		39	3.1	2.6 - 3.7	3.1	0.28	3.0 - 3.2
Log Removal 7-10 um Particles		39	3.0	2.7 - 3.7	3.1	0.26	3.0 - 3.2
Log Removal 10-15 um Particles		39	3.0	2.3 - 3.4	3.0	0.32	2.9 - 3.1
Log Removal >15 um Particles		39	2.8	2.2 - 3.2	2.8	0.29	2.7 - 2.9

Table 4-5. Summary of Online Particle Data in *Cryptosporidium* (2-5 um) and *Giardia* (5-15 um) Size Ranges for US Filter Membrane System During CDHS Testing at Rancho Cucamonga, California (May 17-18, 2001).

	2-5 um particles			5-15 um particles		
	Raw Water (#/mL)	Permeate (#/mL)	Log Removal	Raw Water (#/mL)	Permeate (#/mL)	Log Removal
Average	2000	0.68	3.8	810	0.19	3.9
Standard Deviation	90	0.84	0.55	56	0.24	0.43
95% Confidence Interval	2000 - 2000	0.64 - 0.72	3.8 - 3.8	810 - 810	0.18 - 0.20	3.9 - 3.9
Minimum	1700	0.046	2.6	650	0.046	2.6
Maximum	2200	5.1	4.7	950	1.8	4.3

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Table 4-6. Summary of Lab Water Quality Analyses for the US Filter MF Membrane System.

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
Raw Water							
Alkalinity	mg/L as $CaCO_3$	5	124	122 - 129	125	N/A	N/A
Total Hardness	mg/L as $CaCO_3$	4	248	245 - 270	253	N/A	N/A
Calcium Hardness	mg/L as $CaCO_3$	4	157	145 - 165	156	N/A	N/A
Total Suspended Solids	mg/L	5	<10	<1.0 - <10	<10	N/A	N/A
Total Dissolved Solids	mg/L	5	517	510 - 533	521	N/A	N/A
TOC	mg/L	5	2.6	2.5 - 2.7	2.6	N/A	N/A
DOC*	Mg/L	4	2.6	2.6 - 3.1	2.7	N/A	N/A
UV254[+]	/cm	5	0.05	0.05 - 0.06	0.05	N/A	N/A
Total Coliform	#/100 mL	4	240	12 - 1950	560	N/A	N/A
HPC[E]	cfu/mL	5	1100	660 - 5700	2000	N/A	N/A
Filtrate							
Alkalinity	mg/L as $CaCO_3$	5	127	124 - 129	126	N/A	N/A
Total Hardness	mg/L as $CaCO_3$	4	261	257 - 264	261	N/A	N/A
Calcium Hardness	mg/L as $CaCO_3$	5	160	150 - 180	163	N/A	N/A
Total Suspended Solids	mg/L	5	<10	<1 - <10	<10	N/A	N/A
Total Dissolved Solids	mg/L	5	518	514 - 526	520	N/A	N/A
TOC	mg/L	5	2.6	2.5 - 2.6	2.6	N/A	N/A
DOC*	mg/L	4	2.7	2.5 - 2.8	2.7	N/A	N/A
UV254[+]	/cm	4	0.05	0.04 - 0.06	0.05	N/A	N/A
Total Coliform	#/100 mL	4	<1	<1 - <1	<1	N/A	N/A
HPC[E]	cfu/mL	4	67	1 - 430	140	N/A	N/A
Backwash Waste							
Total Suspended Solids	mg/L	5	7	5 - 41	15	N/A	N/A
Total Coliform	#/100 mL	5	2400	150 - 9200	2900	N/A	N/A

N/A indicates parameters were not calculated because less than 8 samples were collected during testing period.
[*] = DOC – No lab fortified blank analyzed on July 24, 2002. Full QC not satisfied for DOC on this day.
[E] = Estimated value – analytical limitations on July 24, 2002.
[+] = Data outliers for values for samples collected on July 24, 2002.

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Table 4-7. Review of Manufacturer's Operations and Maintenance Manual for the US Filter MF Membrane System.

O & M Manual	Grade	Comment
Overall Organization	+	• The O&M Manual is well organized. The Table of Contents includes the following main sections: Overview, Control Systems, Installation and Commissioning, Operation, General Maintenance, and Drawings. • The manual also includes the following appendices: Material Safety Data Sheets, and Glossary of Terms. • The manual will benefit from less emphasis on technical detail and a more general description of process objectives.
Operations Sections	+	• Includes general safety procedures, startup procedures, description of different operational cycles, Clean in Place description and shutdown and storage procedures. These sections describe positions of all manual valves during system operation. Initial startup includes section detailing preliminary checks that should be made before start up. • Shut down procedure sections include normal shutdown for events such as maintenance or long-term storage, and emergency shutdown procedures. Also includes section on long-term shutdown of unit. • The control section also includes sections on alarms, control logic with tables showing position of all automatic valves during each phase of filtration and backwash modes, operator interface section with detailed descriptions of all screens on the Allen Bradley PLC. • The operations sections are extremely well organized and make excellent use of tables and graphics.
Maintenance Section	+	• Includes sections detailing system operations recommendations, and safety procedures. • Maintenance sections discuss preventative maintenance and provides a checklist of maintenance procedures to be performed daily, weekly, monthly, quarterly, semiannually and annually. • This section has an extensive trouble shooting guide and instructions on module removal, repair and replacement.

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Table 4-7 (contd.). Review of Manufacturer's Operations and Maintenance Manual for the US Filter MF Membrane System.

O & M Manual	Grade	Comment
Troubleshooting	+	• Manual includes a troubleshooting section within the General Maintenance section. It has a description of all alarm conditions and tables for each alarm condition detailing possible causes and solutions.
Ancillary Equipment Information	+	• Ancillary equipment is described in the detailed drawings provided. However, no separate section is devoted to description of the ancillary equipment.
Drawings and Schematics	+	• Overall makes good use of drawings and schematics. • Should include process schematics showing water flow during filtration and backwash. • Includes schematics of the Allen Bradley PanelView display and all associated screens.
Use of Tables	+	• Manual makes very good use of tables to organize and present information.
OVERALL COMMENT	+	• An excellent O&M Manual. It is well organized, well written, clear and complete. An excellent Table of Contents makes locating information in the manual a simple process. • The manual includes good use of graphics to assist the reader's understanding.

Note: Grade of "+" indicates acceptable level of detail and presentation, grade of "-" indicates the manual would benefit from improvement in this area.

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Table 4-8. Efficiency of the US Filter MF Membrane System.

Parameter	Unit	Value
ELECTRICAL USE		
Voltage	Volt - three phase	460
Feed Pump Current	Amp	3.1
Feed Pump Power	Watt	2500
WATER PRODUCTION		
Transmembrane Pressure	psi	8.8
	pascal	6.1E+04
Flow Rate	gpm	18.4
	m^3/s	1.2E-03
Power	Watt	71
EFFICIENCY	%	**3%**

Table 4-9. Chemical Consumption for the US Filter MF Membrane System.

	Unit	Value
Cleaning Chemicals [1]		
Citric Acid 2%	lb (kg)	8 (3.6)
Memclean EAX2	gal (L)	1 (3.75)

[1] Chemical use per cleaning

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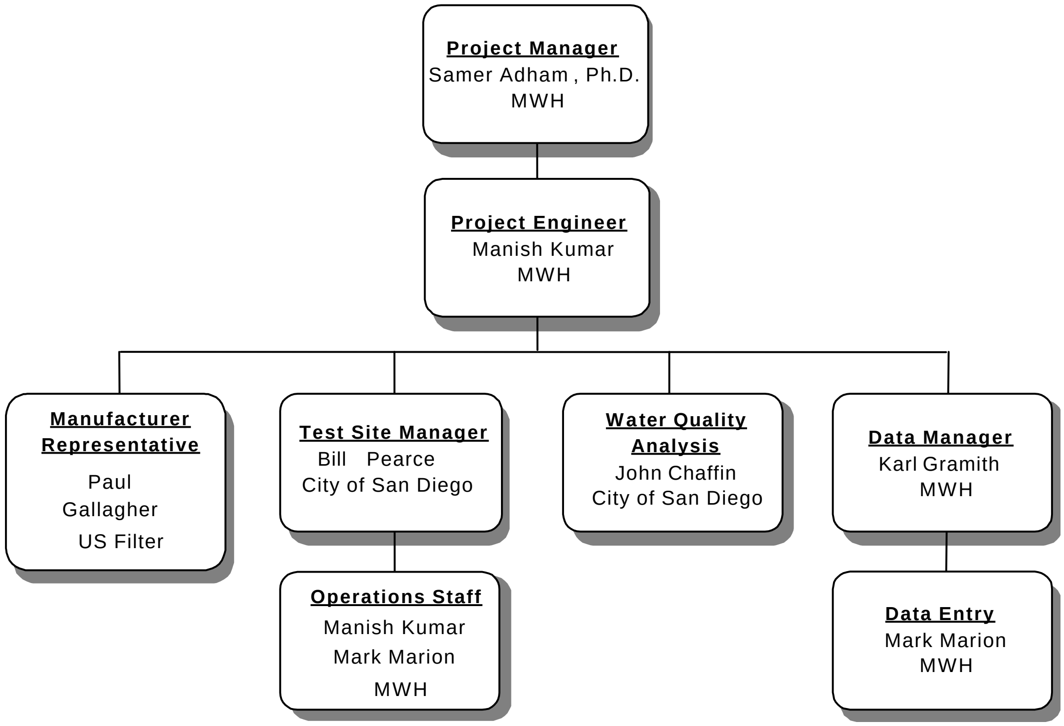

Figure 1-1. Organizational Chart Showing Lines of Communication.

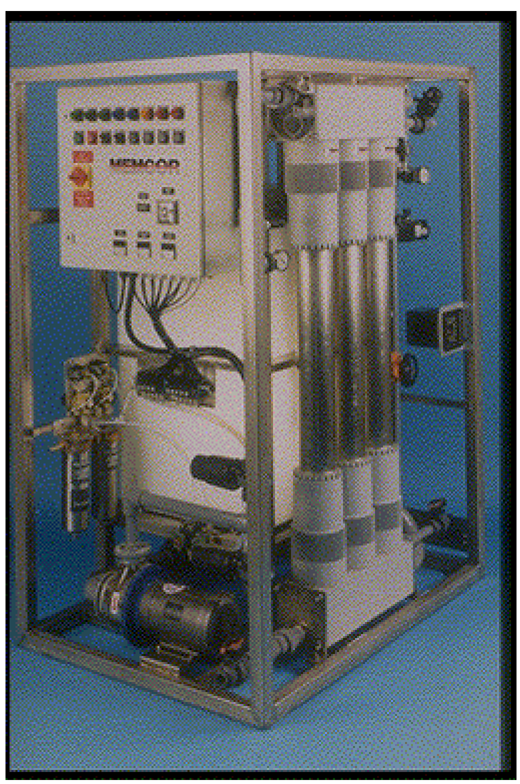

Figure 2-1. Photograph of ETV Test Unit.

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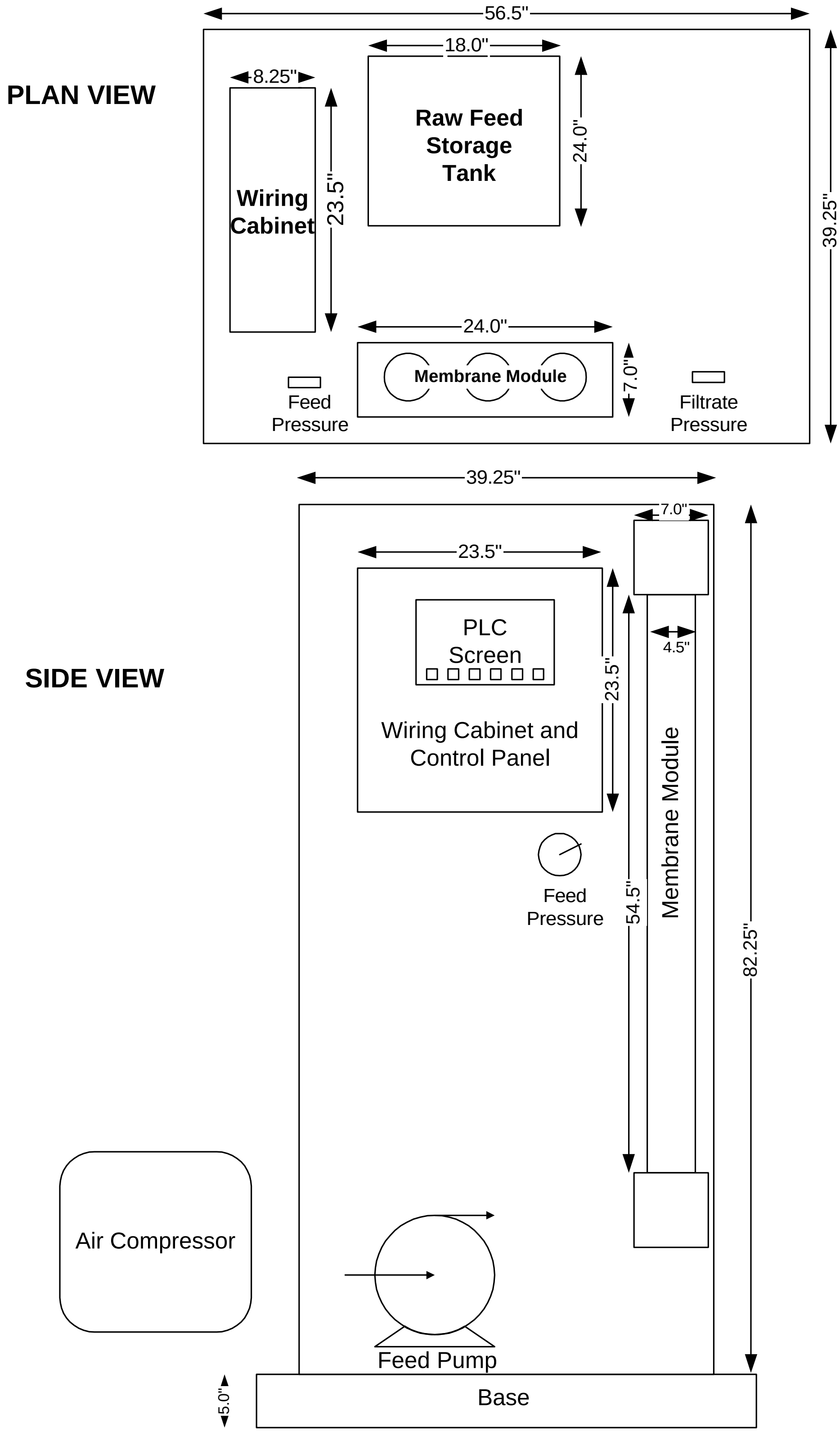

Figure 2-2. Spatial Requirements for the US Filter MF Unit.

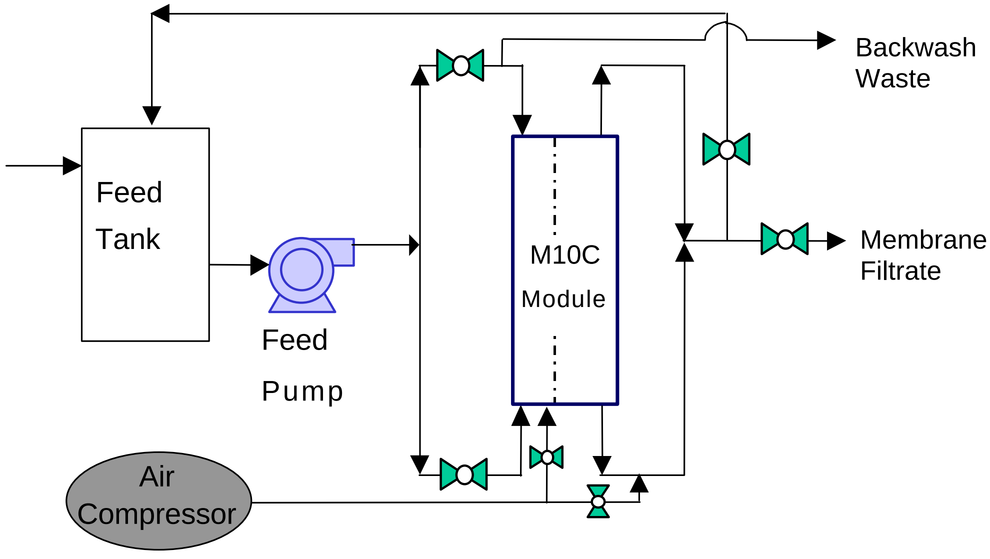

Figure 2-3. Schematic Diagram of the US Filter 3M10C Membrane Process.

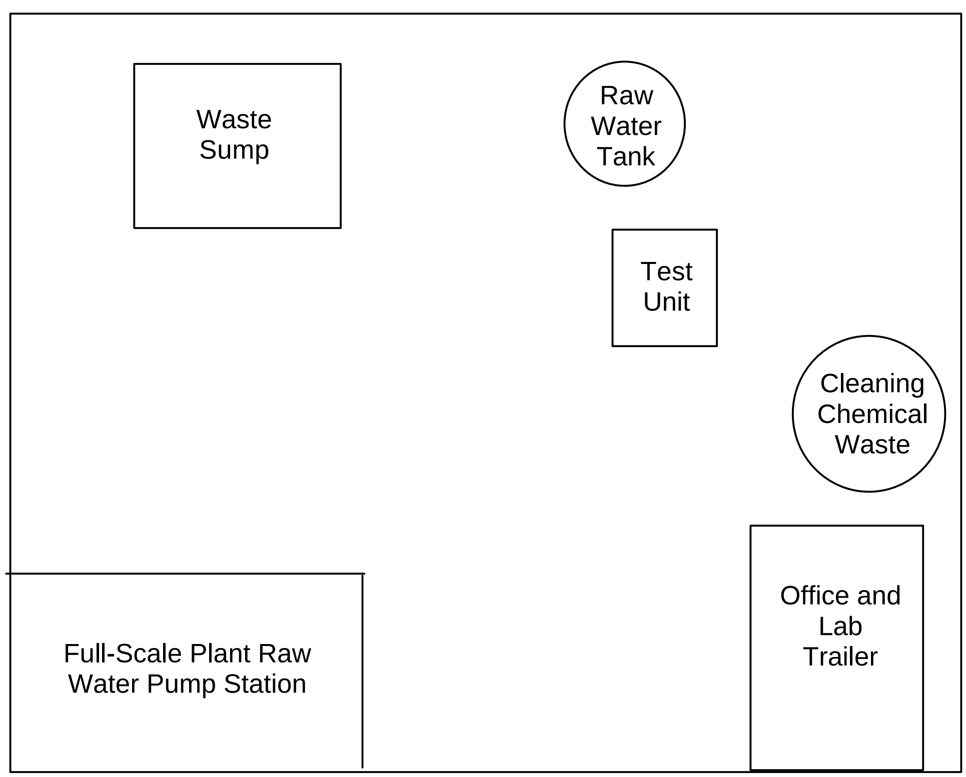

Figure 3-1. Schematic of Aqua 2000 Research Center Test Site.

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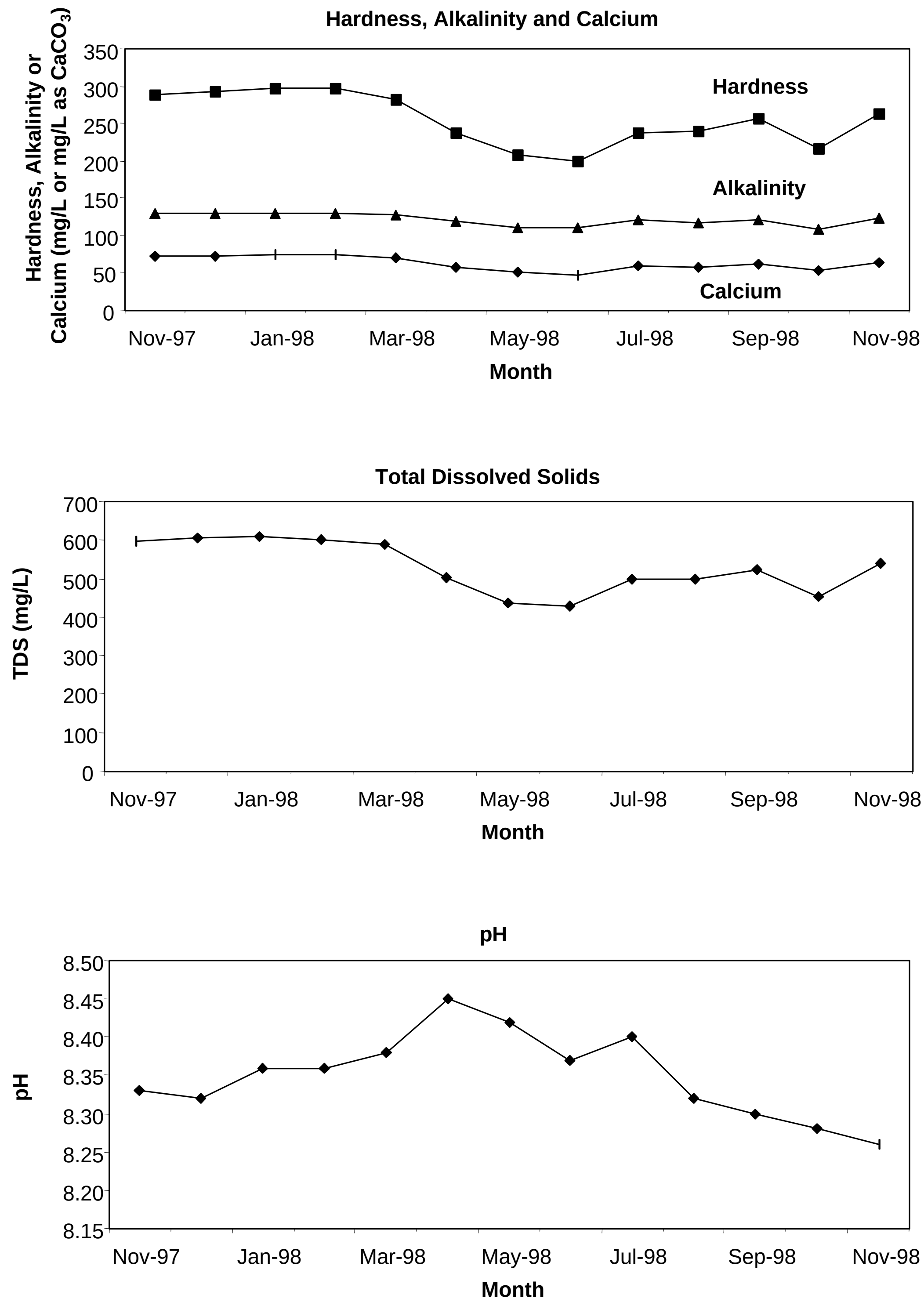

Figure 3-2. Lake Skinner Raw Water Quality.

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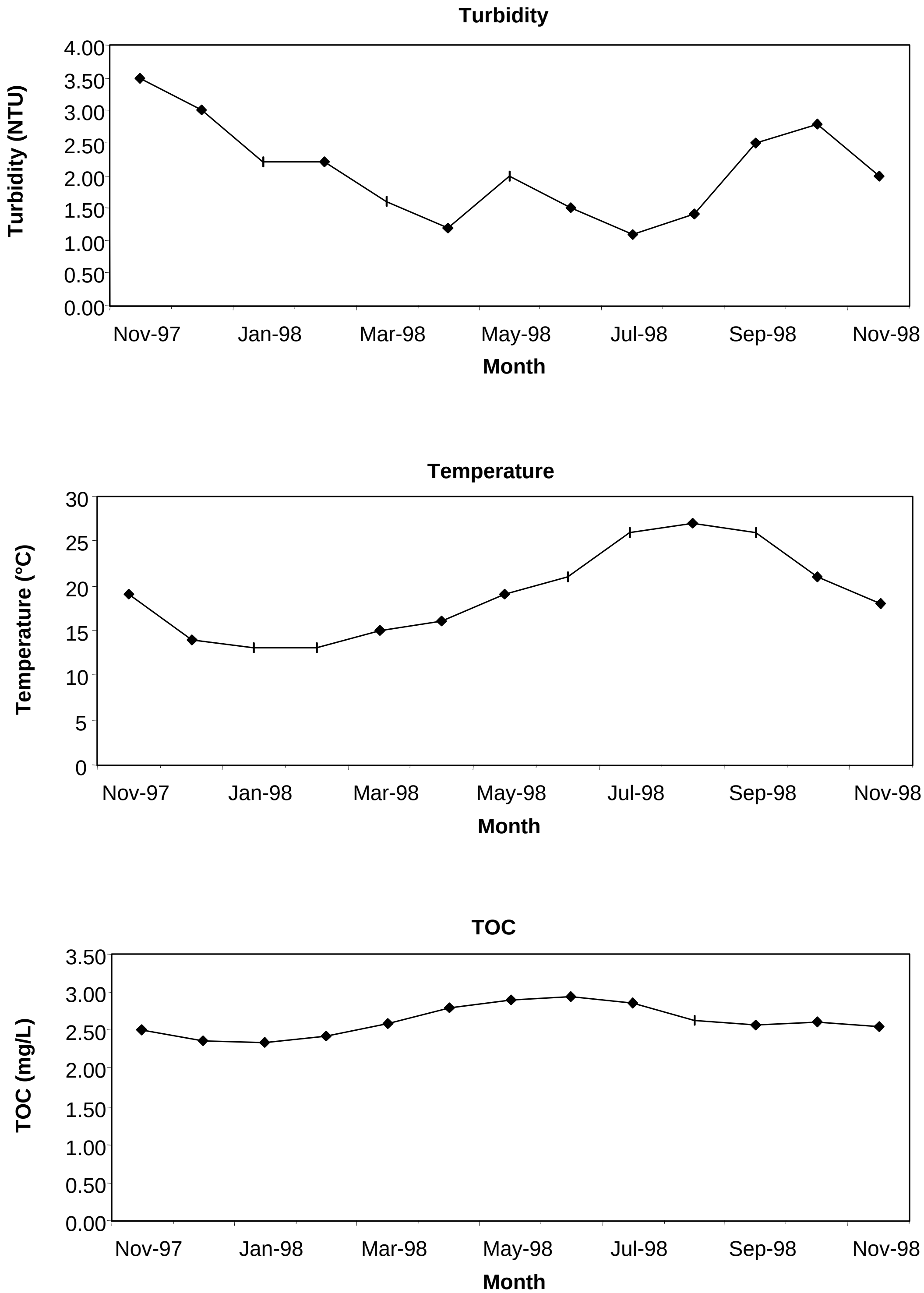

Figure 3-3. Lake Skinner Raw Water Quality.

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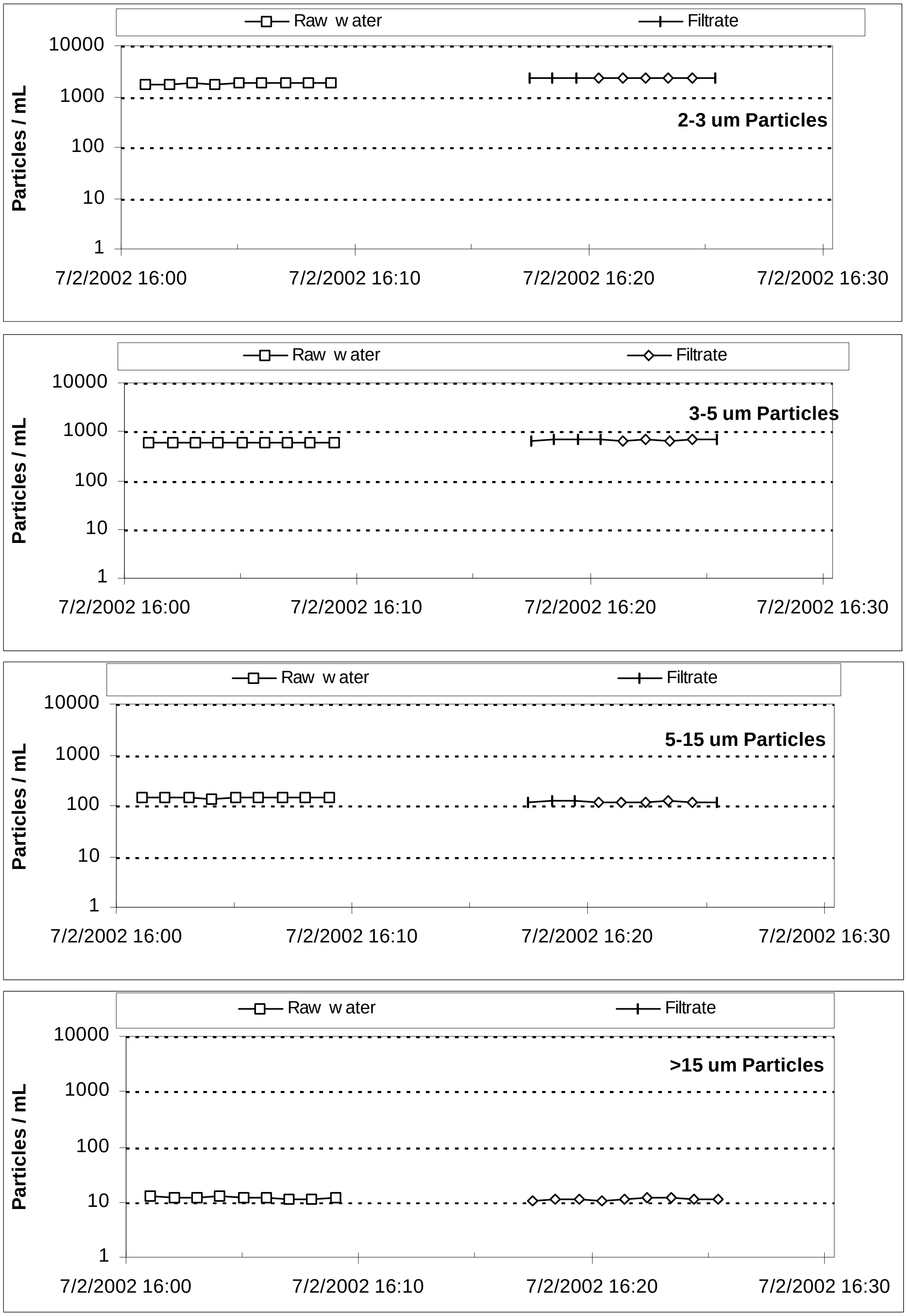

Figure 3-4. Response of Online Particle Counters to Duke Monosphere Solution.

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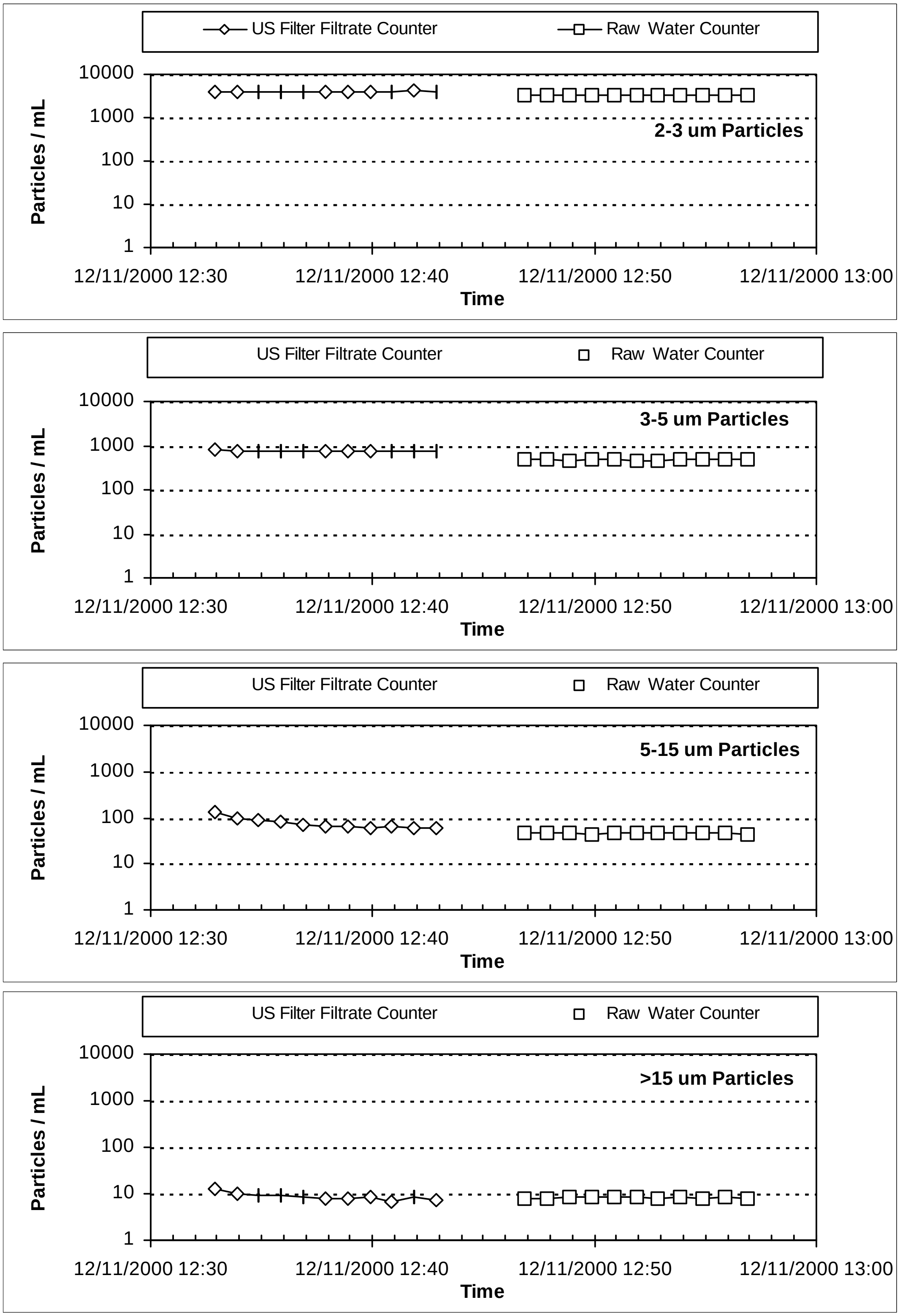

Figure 3-5. Response of Online Particle Counters to Duke Monosphere Solution During CDHS Testing at Rancho Cucamonga, California.

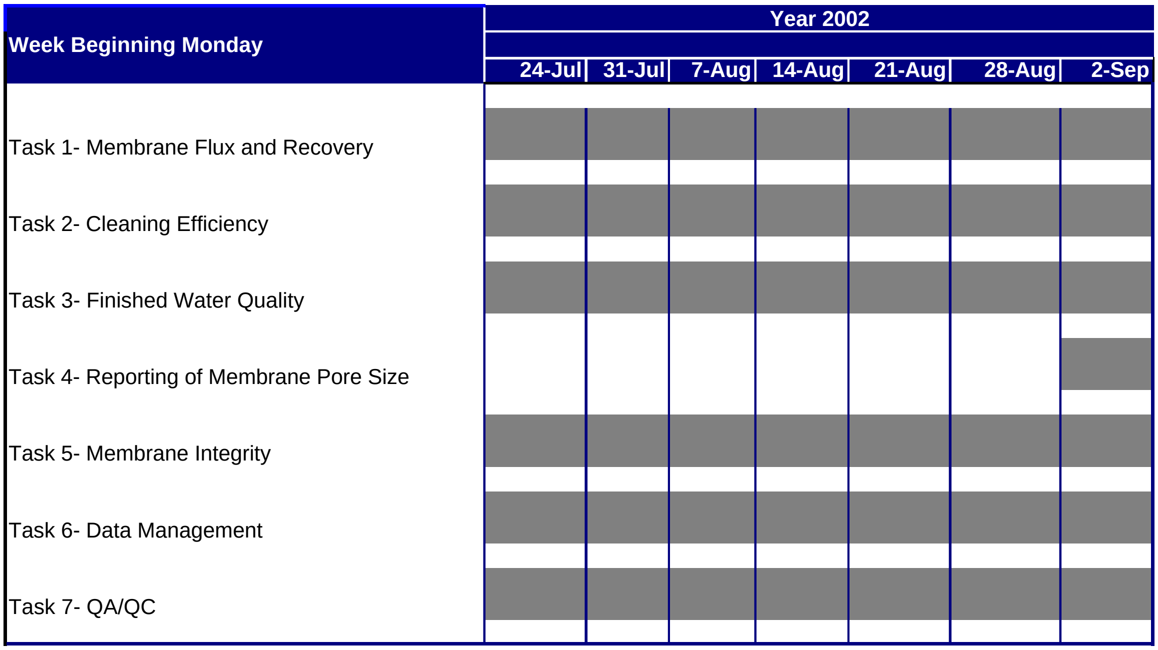

Figure 3-6. Membrane Verification Testing Schedule.

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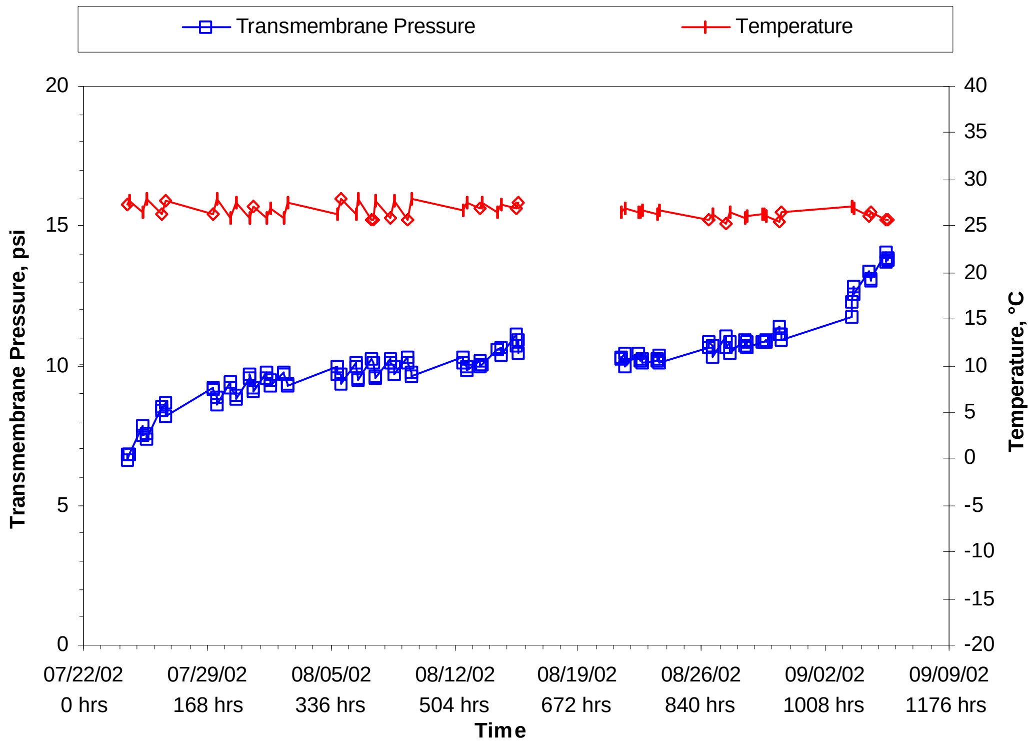

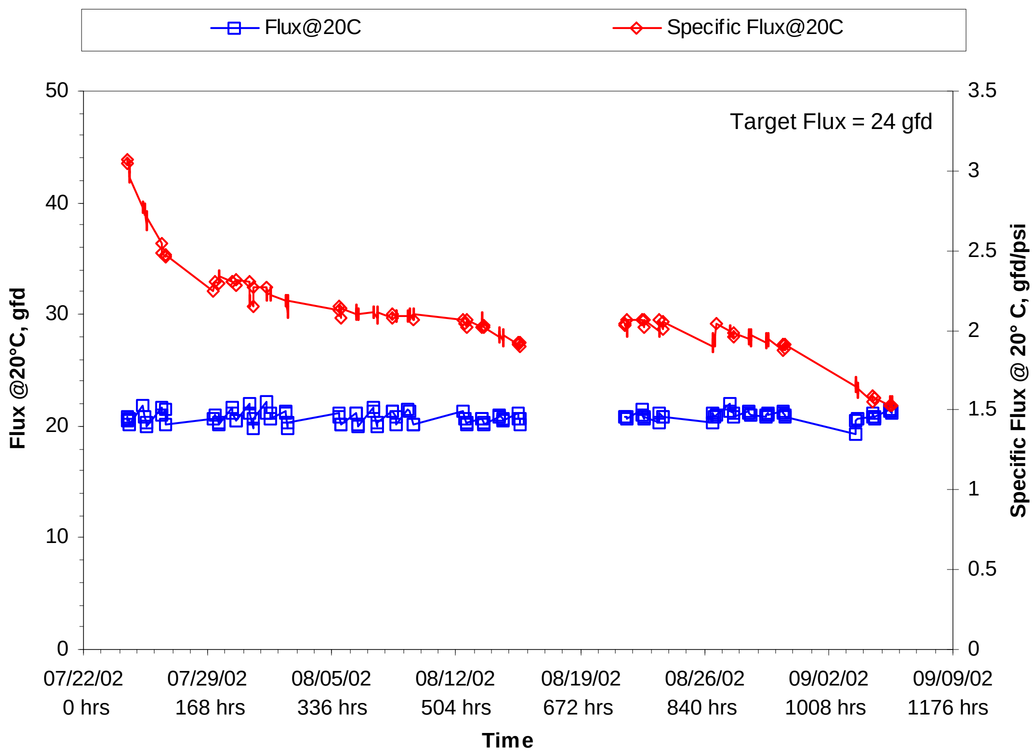

Note: Gap in data between 8/16/02 and 8/22/02 due to shutdown

Figure 4-1. Operational Data for the US Filter MF Membrane System.

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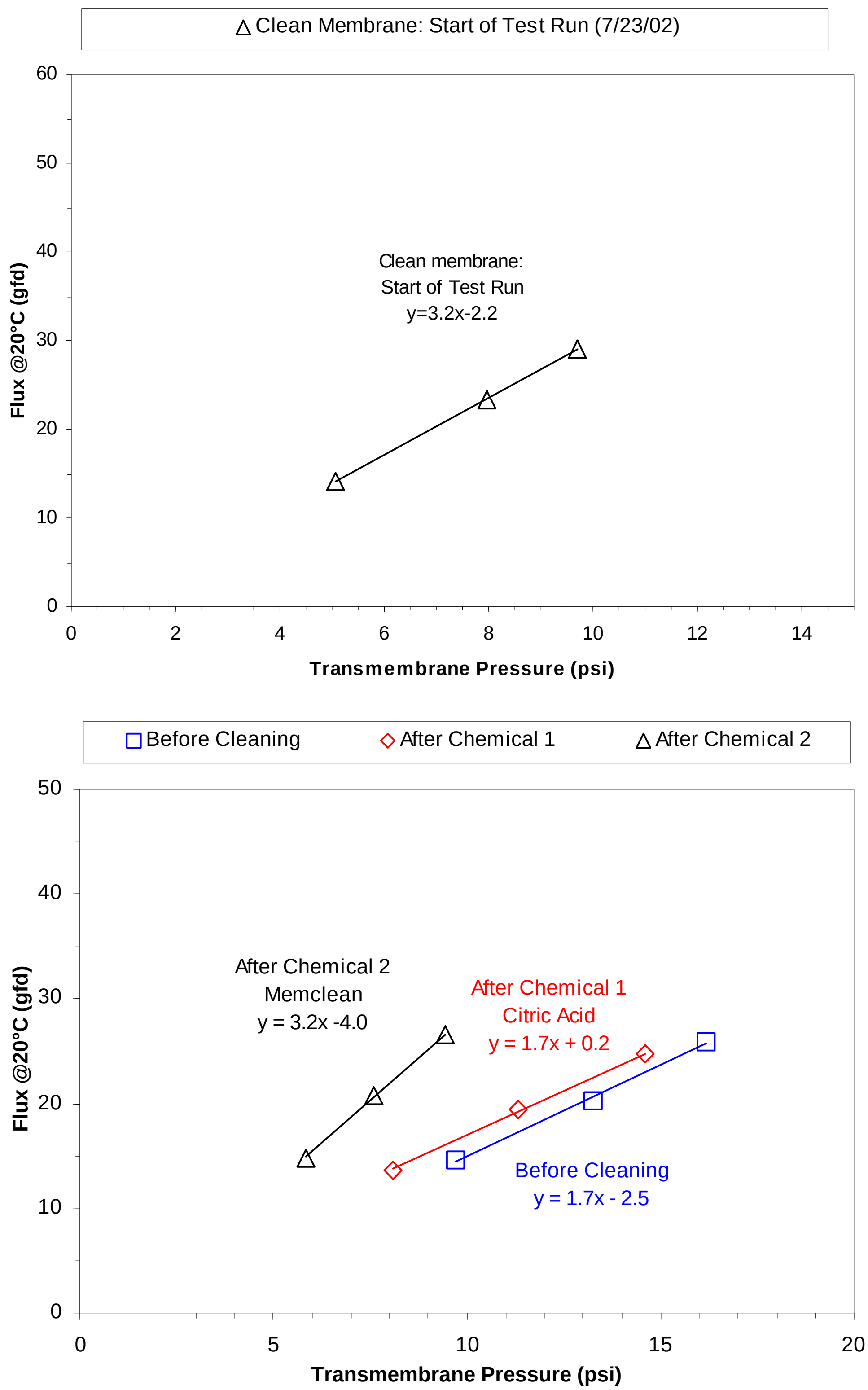

Figure 4-2. Clean Water Flux Profile During Membrane Chemical Cleaning.

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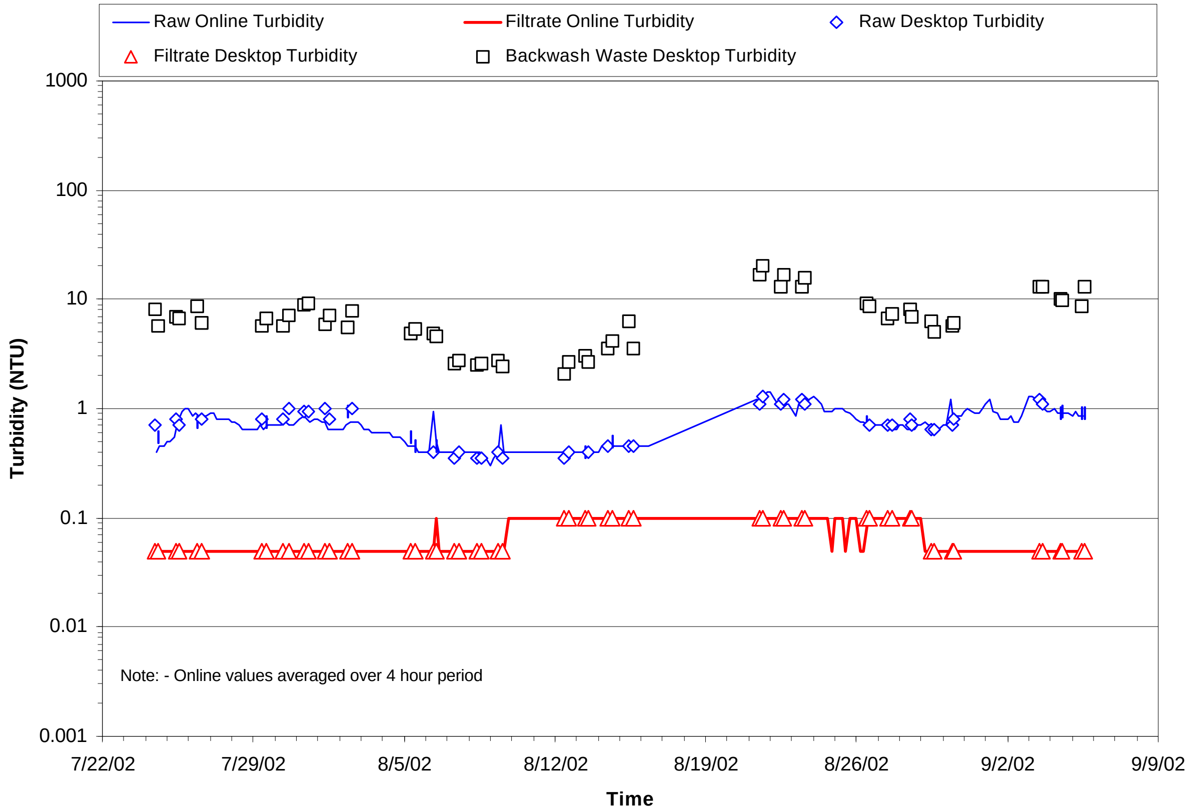

Figure 4-3. Turbidity Profile for Raw Water and US Filter MF Membrane System.

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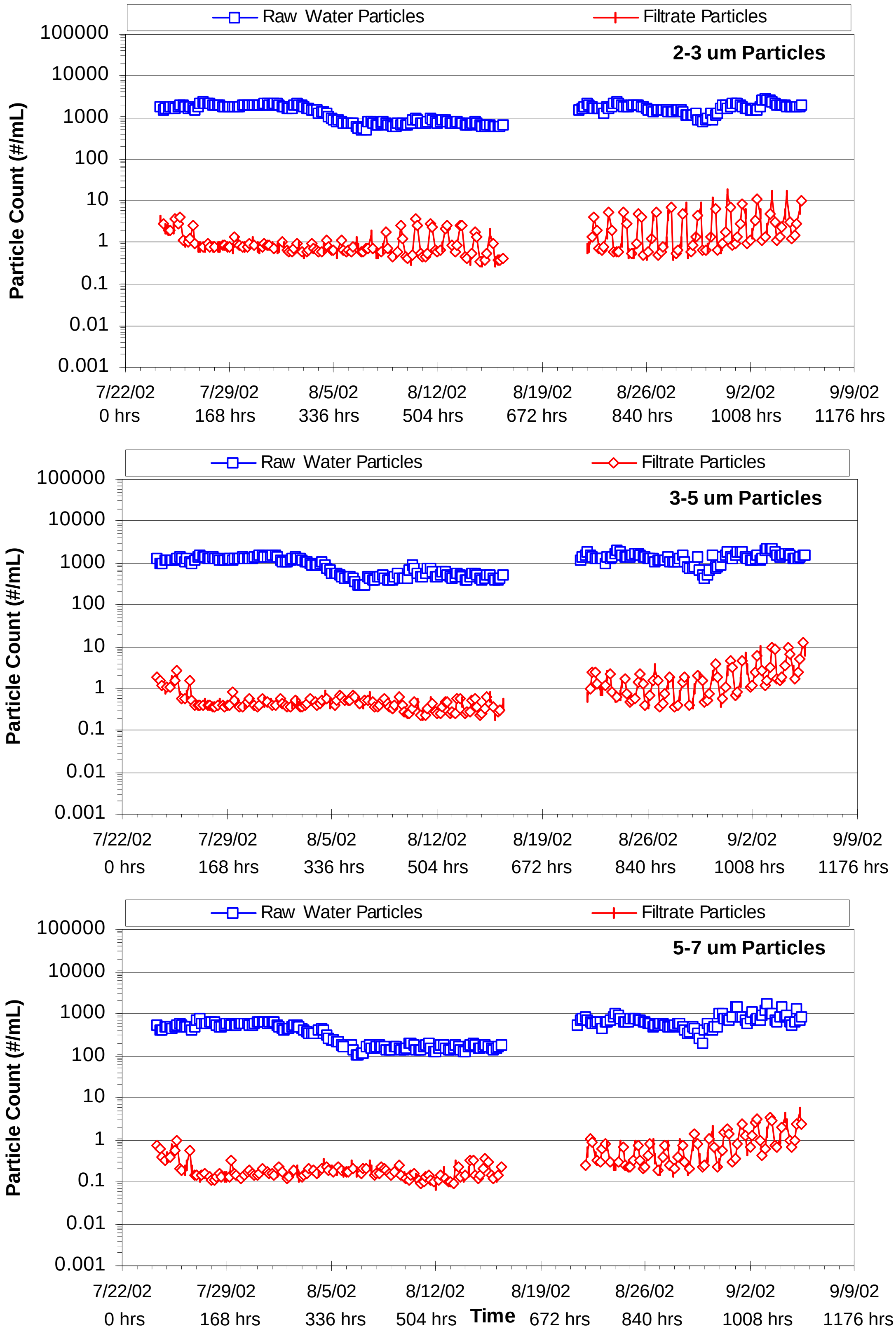

Note: Gap in data between 8/16/02 and 8/22/02 due to shutdown

Figure 4-4. Particle Counts for Raw Water and US Filter Permeate.

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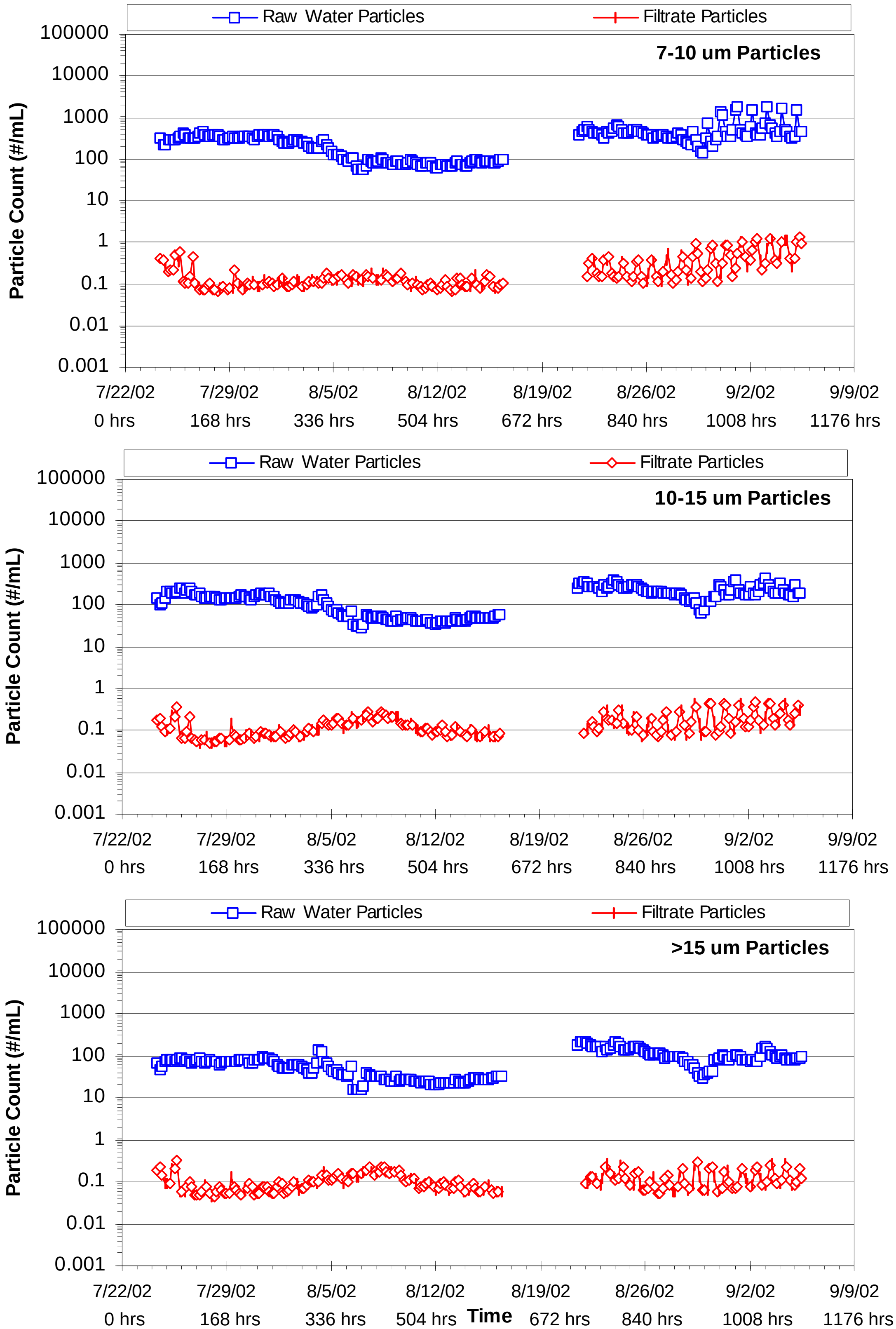
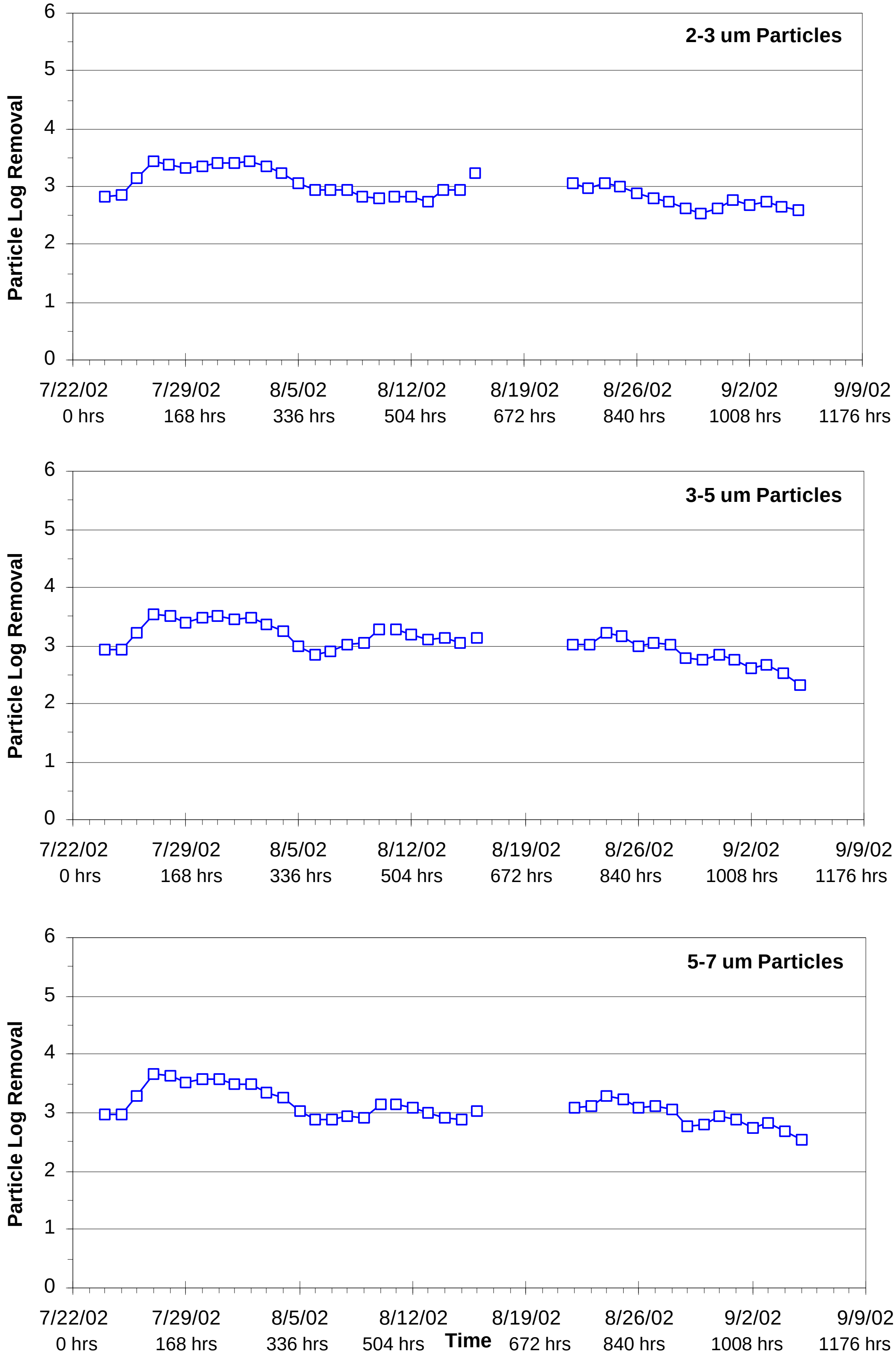


Note: Gap in data between 8/16/02 and 8/22/02 due to shutdown

Figure 4-4. (contd)



Note: Gap in data between 8/16/02 and 8/22/02 due to shutdown

Figure 4-5. Particle Removal for US Filter MF Membrane System.

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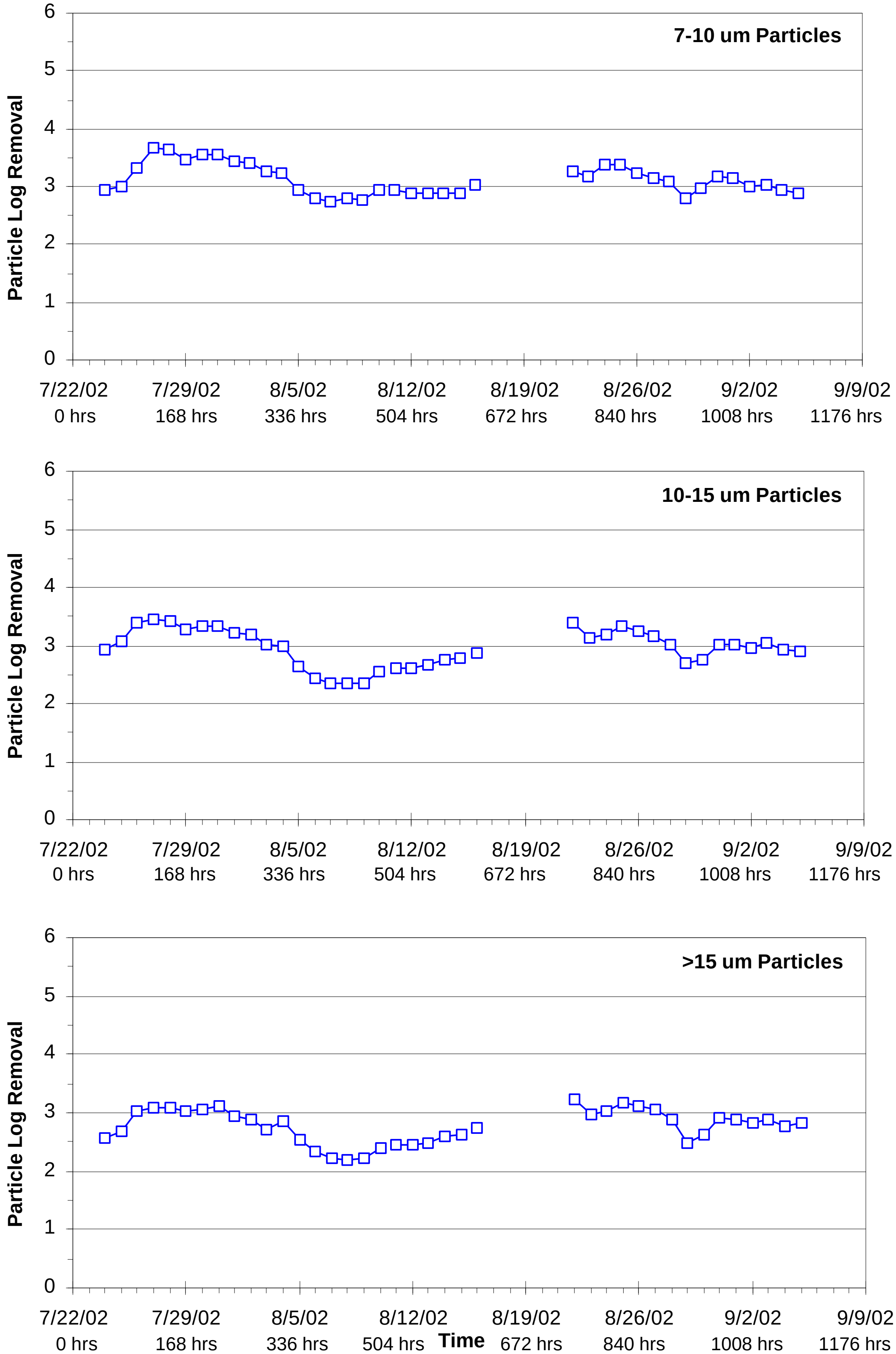

Note: Gap in data between 8/16/02 and 8/22/02 due to shutdown

Figure 4-5. (Contd.)

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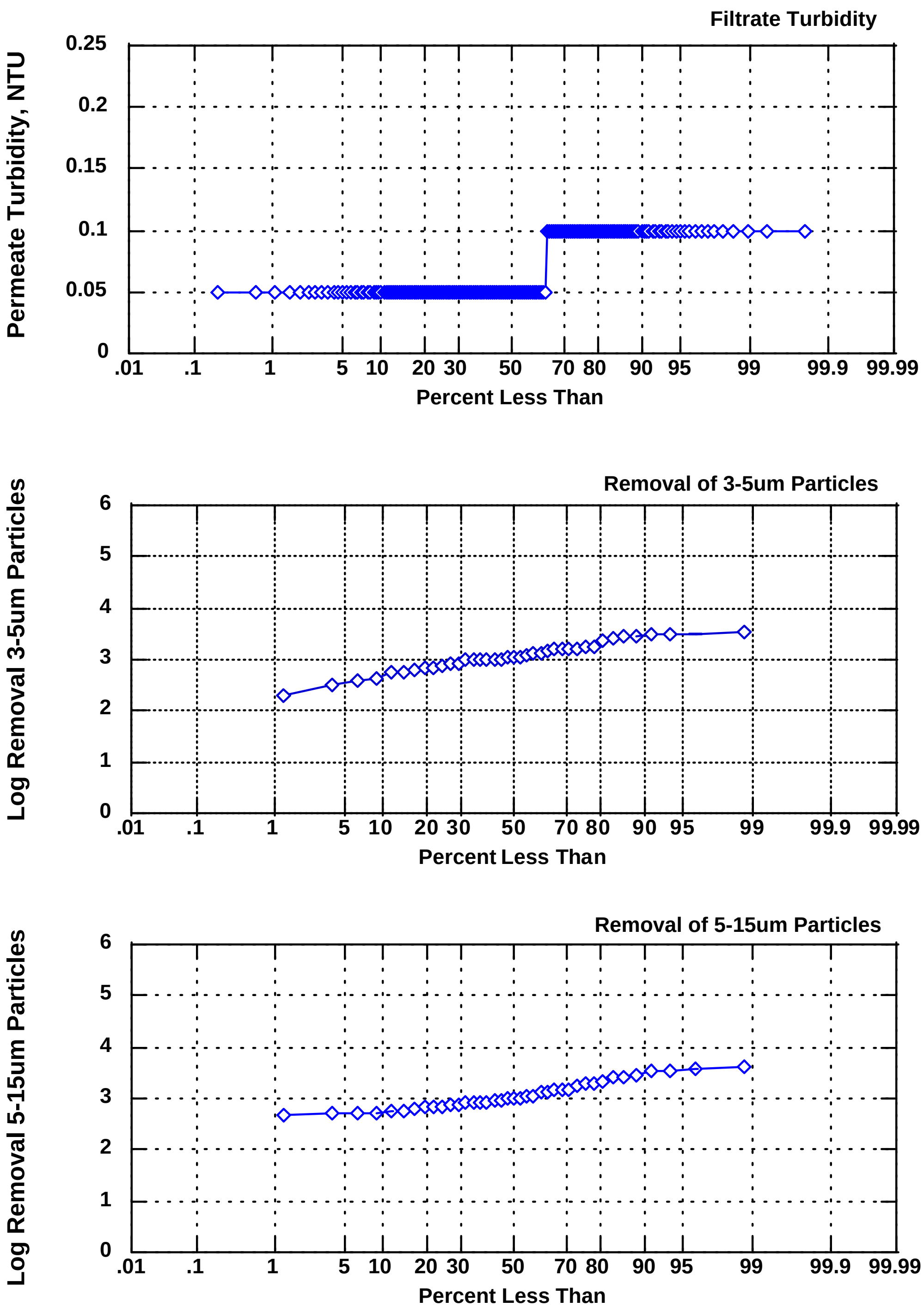
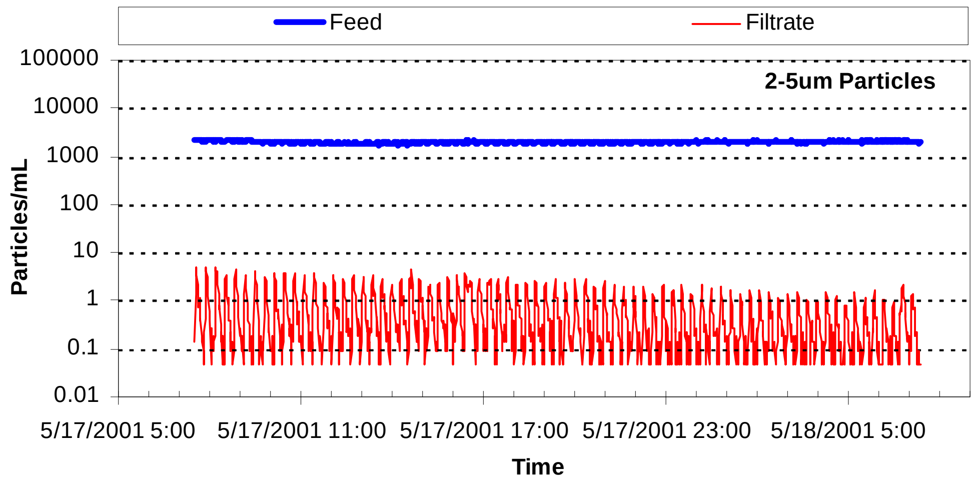


Figure 4-6. Probability Plots of Permeate Turbidity and Log Removal of Particles for the US Filter MF Membrane System.



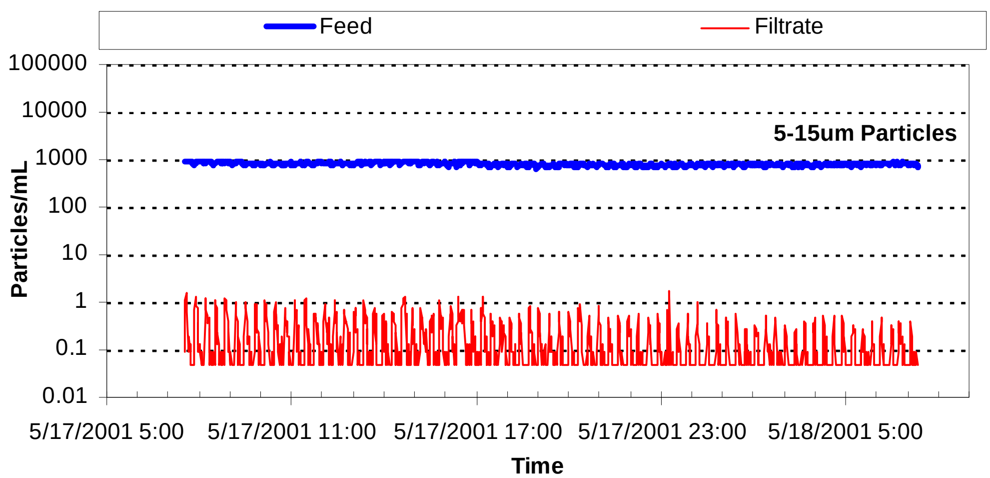


Figure 4-7. Particle Counts for Raw Water and US Filter Permeate in *Cryptosporidium* (2-5um) and *Giardia* (5-15um) Size Ranges During CDHS Testing of US Filter Membrane System (May 17-18, 2001).

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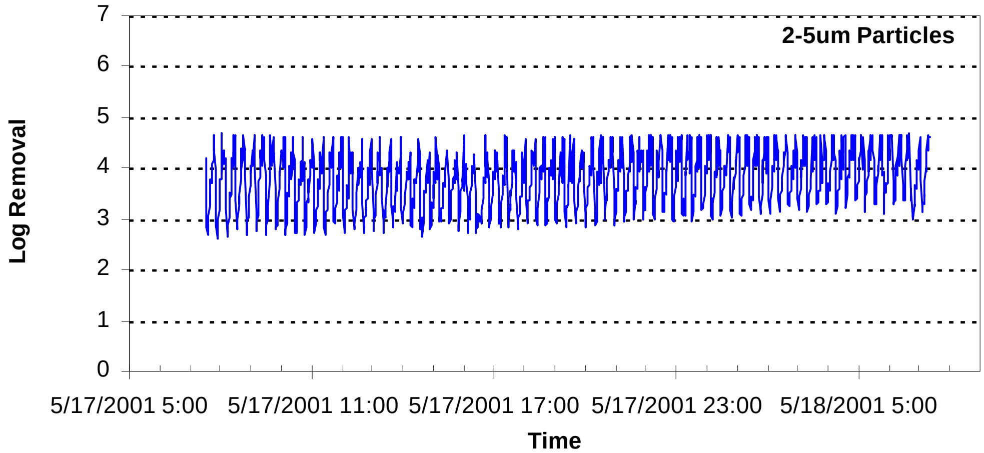

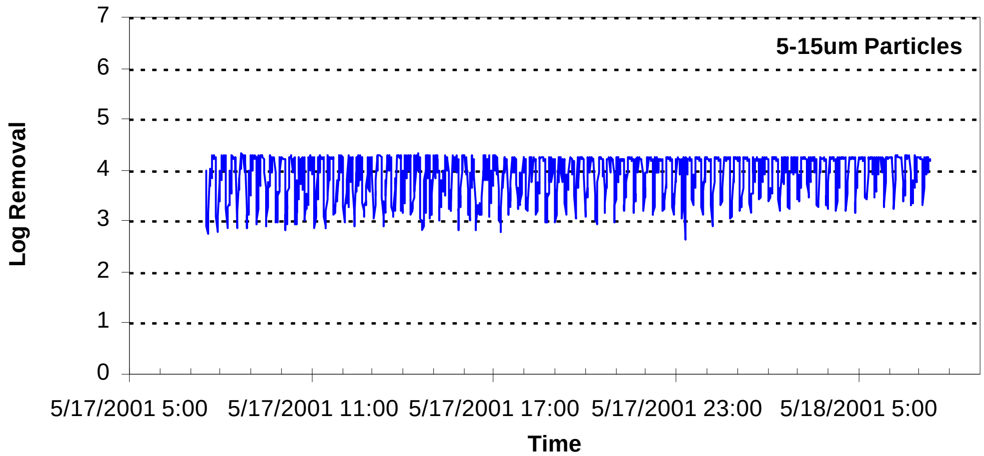

Figure 4-8. Removal of *Cryptosporidium*-sized (2-5um) and *Giardia*-sized (5-15um) Particles by US Filter MF Membrane System During CDHS Testing at Rancho Cucamonga, California (May 17-18, 2001).

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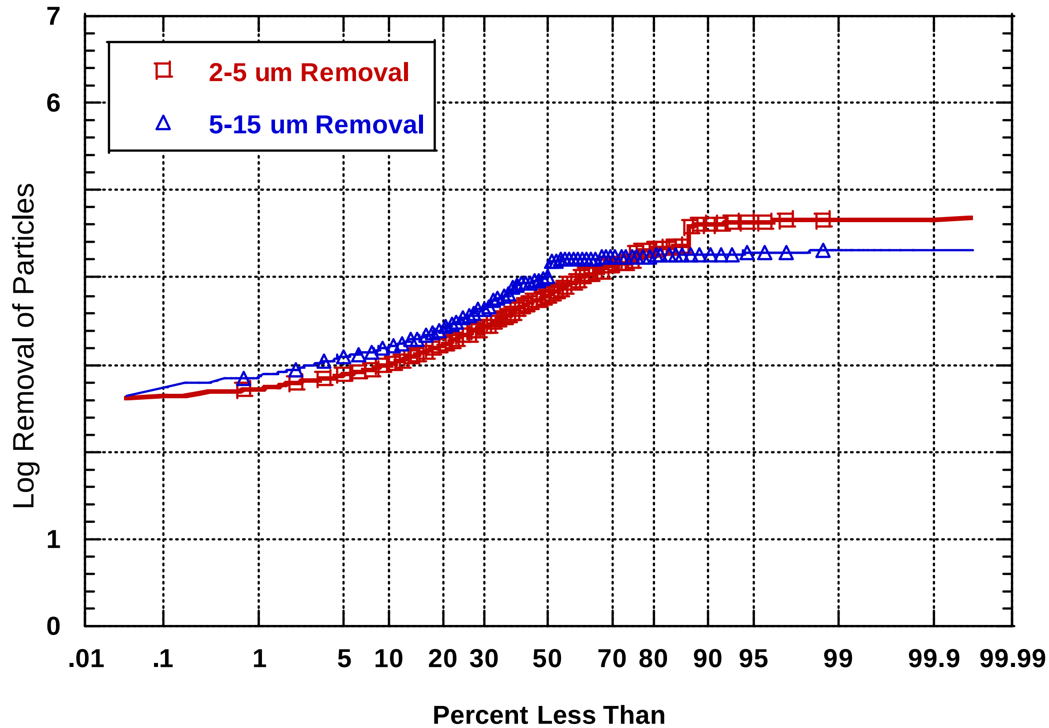

Figure 4-9. Probability Plot of Log Removal of Particles in *Cryptosporidium* (2-5um) and *Giardia* (5-15um) Size Ranges for the US Filter MF Membrane System During CDHS Testing at Rancho Cucamonga, California (May 17-18, 2001).

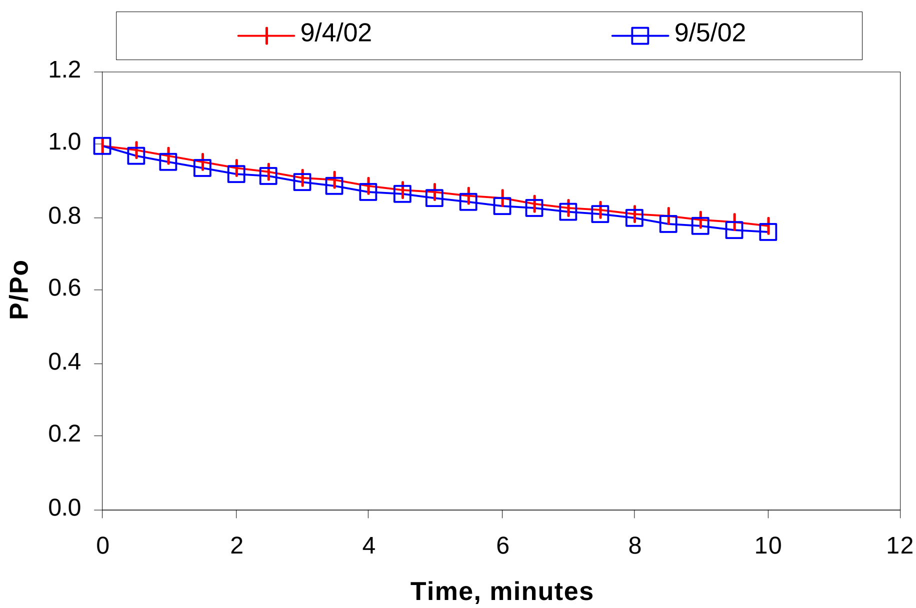

Figure 4-10. Air Pressure Hold Test Data.

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