September 2000
NSF 00/03/EPADW395

Environmental Technology Verification Report

Physical Removal of Particulate Contaminants in Drinking Water

Aquasource North America Ultrafiltration System Model A35 Escondido, California

Prepared by

NSF International

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

ETV ETV ETV

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**MEMBRANE FILTRATION USED IN PACKAGED DRINKING WATER TREATMENT SYSTEMS**		
APPLICATION:	**PHYSICAL REMOVAL OF PARTICULATE CONTAMINANTS IN ESCONDIDO, CALIFORNIA**		
TECHNOLOGY NAME:	**ULTRAFILTRATION SYSTEM MODEL A35**		
COMPANY:	**AQUASOURCE NORTH AMERICA**		
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and 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 Treatment Systems (DWTS) Pilot, one of 12 technology areas under ETV. The DWTS Pilot recently evaluated the performance of an ultrafiltration membrane system used in package drinking water treatment system applications. This verification statement provides a summary of the test results for the Aquasource Ultrafiltration System Model A35 (Aquasource UF unit). Montgomery Watson, a NSF-qualified field testing organization (FTO), performed the verification testing.

ABSTRACT

Verification testing of the Aquasource UF unit was conducted over two test periods at the Aqua 2000 Research Center in San Diego, California. The first test period, from March 5,1999 to April 19, 1999 represented winter/spring conditions. The second test period, from August 25, 1999 to September 28, 1999 represented summer/fall conditions. 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 at a constant flux of 60 gfd (100 L/hr-m^2) with feedwater recoveries ranging from 88 to 94 percent, depending on the backwash frequency. During Test Period 1, membrane fouling due to algae bloom was observed towards the end of the operating period. During Test Period 2, the system ran without any noticeable loss of specific flux. The manufacturer recommended cleaning procedure was effective in recovering membrane productivity. The membrane system achieved significant removal of particulate contaminants and bacteria (described later).

TECHNOLOGY DESCRIPTION

The Aquasource UF unit is comprised of two M1A35 hollow fiber UF membrane modules mounted on a transportable skid. The skid is constructed of reinforced fiberglass and steel, and can be shipped by truck. The unit is completely self-contained, including all the components required for operation. The only connections to the Aquasource UF unit are a raw water connection to the feed pump, drain lines for filtrate tank overflow and backwash waste, and electrical power. The unit requires approximately 30 ft^2 (2.8 m^2) of floor space.

The Aquasource UF unit has an Allen Bradley touchscreen programmable logic controller (PLC). The touchscreen includes schematic displays of the treatment train showing which pumps are operating and which valves are open. The PLC maintains a constant filtrate flow during filtration by automatically adjusting feed pump speed and controls pumps and valves during backwash. The operating parameters for the Aquasource UF unit are adjusted by entering values in screens of the PLC touchscreen. The Aquasource unit has electronic flow, pressure and temperature measurement and a data logger which stores operating information digitally. This information can be accessed both locally, with a personal computer connected by cable, or remotely over phone lines.

The Aquasource UF unit has two alternating operating modes. These are filtration and backwash. During filtration, raw water is driven under pressure through pores in the UF membrane. Treated water is collected from the filtrate side of the membrane. At the end of the filtration cycle, the system initiates a backwash. During backwash, the feed pump shuts down, valves are repositioned, and the backwash pump starts. The backwash pump draws treated water from the filtrate storage tank, chlorinates it, and forces the water under pressure in the reverse direction through the fibers. With the flow of water now from the outside of the fiber to the inside of the fiber, the backwash water exits the inside of the fibers at the fiber ends, carrying with it particulate material accumulated during filtration. Chlorine added to the backwash water assists in oxidizing organics that have accumulated on the membrane surface. The long-term operation of the package 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 quantified by a gradual increase in the pressure required to maintain the desired flux. Once a critical upper pressure has been reached, normal operation is discontinued and the membrane undergoes chemical cleaning. Chemical cleaning involves the use of detergent and chlorine solutions to restore efficient operation of the membrane.

The Aquasource UF unit has two M1A35 membrane modules. These 4 inch (10 cm) diameter modules use the same fiber as the larger surface area L1B35 modules which are used in full-scale applications. The M1A35 is a hollow fiber configuration, manufactured from a cellulose acetate derivative, with nominal molecular weight cut-off of 100,000 Daltons. This corresponds with a pore diameter of approximately 0.01 micron.

VERIFICATION TESTING DESCRIPTION

Test Site

The verification test site was the City of San Diego's Aqua 2000 Research Center at 14103 Highland Valley Road in Escondido, 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 Lake Skinner water via the San Diego Aqueduct. Lake Skinner water consists of Colorado River water and State Project water, 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, 19^{th} Ed. (APHA, et. al., 1995). Standard Methods, 19^{th} Ed. (APHA, 1995) 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, 5-15 um, and > 15 um. Data from the online particle counters and turbidimeters were stored at 1-minute intervals on a computer. Simulated distribution system (SDS) disinfection-by-product (DBP) formation tests were conducted during each test period. For this testing, the uniform formation conditions of the EPA Information Collection Rule were followed. DBP analyses were conducted according to EPA Method 502.2 for trihalomethanes and EPA Method 552.2 for haloacetic acids.

VERIFICATION OF PERFORMANCE

System Operation

Verification testing was conducted at manufacturer specified operating conditions. The membrane unit was operated at a constant flux of 60 gfd (100 L/hr-m^2) with feedwater recoveries ranging from 88 to 94 percent, depending on the backwash frequency. The PLC automatically maintained constant flux by increasing pump speed as transmembrane pressure increased due to fouling. Backwash frequency was initially set to every 60 minutes, but was increased to every 30 minutes near the end of Test Period 1 because of fouling due to algae. Backwash volume was consistent, averaging 24 gallon (90 L) over both test periods. Backwash chlorine concentration averaged 7 mg/L over both test periods. The system initially ran for 31 days in Test Period 1 with decrease in specific flux from 12 to 8.5 gfd/psi (300 to 210 L/hr-m^2). It then fouled to specific flux 4.8 gfd/psi (70 L/hr-m^2/bar) over a period of 7 day likely due to an algae bloom in the source water. After cleaning, the unit fouled overnight at the same operation conditions, again due to algae. The system was cleaned a second time and put into service at reduced flux of 51 gfd (87 L/hr-m^2) and backwash frequency of every 30 minutes. The unit ran for three days under these conditions until Test Period 1 was terminated. The system ran all of Test Period 2 at an average specific flux of 12 gfd/psi (300 L/hr-m^2/bar) and no loss of specific flux was observed throughout the testing period.

Membrane cleaning was performed according to manufacturer recommended procedure. Proprietary cleaning solutions were prepared in a 5-gallon cleaning tank and recirculated across the feed side of the membrane at approximately 50 gpm (190 lpm). Flux-pressure profiles were performed after each cleaning step to evaluate recovery of specific flux. The manufacturer recommended cleaning procedure was effective in recovering specific flux. Loss of original, new membrane flux was 21 percent after the first cleaning in Test Period 1 and only increased to 22 percent after the second cleaning in Test Period 1. Specific flux was recovered to new membrane conditions upon cleaning at the end of Test Period 2, possibly due to warmer weather conditions, and hence warmer cleaning solutions.

Air pressure-hold tests were conducted near the beginning and end of each test period to assess membrane integrity. Air pressure-hold tests were conducted by opening the feed side of the membrane to atmosphere and pressurizing the filtrate side of the membrane. Once pressurized, the loss of held pressure on the filtrate side was monitored over 10 minutes. All air pressure-hold tests had minimal loss (< 1 psi every 5 minutes) of held pressure, indicating the membranes were intact during both test periods.

Source Water Results

The source water for the ETV testing consisted of a blend of Colorado River water 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 two test periods: TDS 500/500 mg/L, hardness 240/230 mg/L, alkalinity 120/120 mg/L, TOC 2.5/3.6 mg/L, pH 8.3/8.2, temperature 17/28 and turbidity 1.3/1.4 NTU.

Particle Removal Results

Total suspended solids in the filtrate were removed to below the detection limit for the analysis (1 mg/L), for all samples analyzed. Filtrate turbidity was 0.05 NTU or less 95 percent of the time. The test system removed greater than 3 logs of both Cryptospordium-sized (3-5 um) particles and Giardia-sized (5-15 um) particles, 95 percent of the time. Four hour average raw water and filtrate particle levels and daily average particle removal in these size ranges for Test Periods 1 and 2 are presented in the following table:

Aquasource M1A35 UF System Particle Concentrations and Particle Removals for Test Periods 1/2

	3-5 um Particles			5-15 um Particles		
	Raw Water (#/mL)	Filtrate (#/mL)	Log Removal	Raw Water (#/mL)	Filtrate (#/mL)	Log Removal
Average	2300/2000	0.15/0.26	4.1/4.0	1400/1200	0.11/0.21	4.1/3.8
Standard Deviation	630/490	0.08/0.19	0.16/0.29	650/520	0.06/0.18	0.23/0.33
95% Confidence Interval	2200-2400/ 1900-2100	0.14-0.16/ 0.25-0.29	4.0-4.2/ 3.9-4.1	1300-1500/ 1100/1300	0.10-0.12/ 0.13-0.24	4.0-4.2/ 3.7-3.9
Minimum	640/780	0.06/0.08	3.8/3.4	290/290	0.05/0.06	3.7/3.2
Maximum	5200/5000	0.83/0.89	4.5/4.4	3900/5800	0.62/1.3	4.6/4.4

Microbial Removal Results

Total Coliforms and HPC were analyzed on a weekly basis during both ETV test periods. Raw water total coliforms averaged 15 and 57 MPN/100mL during Test Periods 1 and 2, respectively. No total coliforms were detected in the filtrate. HPC were significantly reduced. HPC averaged 120 and 640 cfu/mL in the raw water for Test Periods 1 and 2. Filtrate levels of HPC averaged 1 and 70 cfu/mL. The presence of HPC in the filtrate is most likely due to growth of bacteria in the filtrate piping rather than passage of bacteria through the membrane.

Disinfection by-Product Precursor Removal Results

The Aquasource UF unit demonstrated no significant removal of simulated distribution system (SDS) disinfection-by-product (DBP) precursor materials. From the data collected (one comparison per test period), and the variability of TTHM and HAA testing, the SDS DBP results do not demonstrate any reduction in these DBPs.

Operation and Maintenance Results

Operation was initiated by entering the target flow and backwash frequency in the appropriate PLC touchscreen. These parameters were automatically maintained at set levels by the system controls. Backwash times were manually adjusted on the PLC touchscreen to achieve a backwash volume of approximately 24 gallon (90 liter). Backwash pump speed was manually adjusted on the variable frequency drive controller to achieve a backwash pressure of between 36 and 40 psi (2.5 and 2.8 bar). As the membrane system fouled, the backwash volume tended to decrease and backwash pressure tended to increase, so these parameters required manual readjustment with the time interval between readjustment depending on rate of specific flux loss. The sodium hypochlorite dosing pump required initial manual adjustment to achieve a target chlorine dose in the backwash water of 5-8 mg/L.

Operation of the membrane unit consumed 0.08 gal (0.30 L) of 10% sodium hypochlorite per day to chlorinate backwash water. No other chemicals were consumed during routine operation of the system. During a typical chemical cleaning, 2.7 pounds (1.2 kg) of a proprietary formula were consumed in both prewash and wash steps. The manufacturer supplied an Operations and Maintenance manual that was helpful in explaining the setup, operation and maintenance of the ETV test system.

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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 #00/03/EPADW395) are available from the following sources:
(NOTE: Appendices are not included in the Verification Report. Appendices are available from NSF upon request.)

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

September 2000

Environmental Technology Verification Report

Physical Removal of Particulate Contaminants in Drinking Water

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Notice

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Foreword

The following is the final report on an Environmental Technology Verification (ETV) test performed for the NSF International (NSF) and the United States Environmental Protection Agency (EPA) by Montgomery Watson, in cooperation with Aquasource North America. The test was conducted in 1999 at the Aqua 2000 Research Center in San Diego, California.

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

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

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

Table of Contents

Section | Page

Table of Contents, continued

Table of Contents, continued

List of Tables

List of Figures

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	Filtrate concentration
cm	Centimeter
CRW	Colorado River water
d	Day(s)
DBP	Disinfection by-product
DOC	Dissolved organics carbon
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
gpm	Gallon(s) per minute
HAA5	Sum of five measured haloacetic acids
HPC	Heterotrophic plate count bacteria
hr	Hour(s)
ICR	Information Collection Rule
in Hg	Inch(es) of Mercury
J_t	Filtrate flux
J_{tm}	Transmembrane flux
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
kg	Kilogram(s)
L	Liter(s)
m^2	Square meter(s)
m^3/d	Cubic meter(s) per day
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	Filtrate pressure
P_{tm}	Transmembrane pressure
PC	Personal computer
DWTS	Drinking Water Treatment System
PLC	Programmable logic Controller
ppm	Parts per million
psi	Pound(s) per square inch
PVC	Polyvinyl chloride
Q_f	Feed flow
Q_p	Filtrate flow
Q_r	Recycle flow
QA	Quality assurance
QC	Quality control
S	Membrane surface area
SDS	Simulated distribution system
scfm	Standard cubic feet 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
TTHM	Total trihalomethanes
um	Micron(s)
UF	Ultrafiltration
UFC	Uniform formation conditions
UV254	Ultraviolet light absorbance at 254 nanometer

Acknowledgements

The authors would like to thank the EPA, for sponsoring the ETV program and providing partial funding for the study. In particular, the authors would like to thank Jeffrey Q. Adams, Project Officer with the EPA, for his continuous support throughout the project.

The authors would also like to thank NSF, for administrating the ETV program. The time and continuous guidance provided by the following NSF personnel is gratefully acknowledged: Bruce Bartley, Carol Becker, and Kristie Wilhelm.

The time and outstanding efforts provided by the manager of Aqua 2000 Research Center, Paul Gagliardo with the City of San Diego is gratefully acknowledged. The authors would also like to thank Jeff Williams from the Aqua 2000 Center operation team for his assistance in operating the membrane system. The authors would also like to thank Dana Chapin from the City of San Diego Water Laboratory for facilitating most of the water quality analyses in the study. In addition, the authors would like to thank Yildiz Chambers from the City of San Diego Marine Microbiology Laboratory for co-ordinating the microbial analyses in the study.

The authors would also like to acknowledge the manufacturer of the equipment employed during the ETV program (Aquasource North America, Richmond, VA) 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 Michael Dimitriou and Miles Beamguard from Aquasource for their continuous support.

The authors gratefully acknowledge the contributions of the following co-workers from Montgomery Watson: Anthony Huang, Rion Merlo, Lina Boulos, 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; stakeholders 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 (NSF) in cooperation with the EPA operates the Drinking Water Treatment Systems (DWTS) Pilot, one of 12 technology areas under ETV. This DWTS Pilot evaluated the performance the Aquasource Model A35 ultrafiltration (UF) system used in package drinking water treatment system applications.

This report provides the ETV results for Aquasource Model A35 UF 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 Montgomery Watson, a NSF-qualified FTO, which provided the overall management of the ETV through the project manager and project engineer. The ultrafiltration membrane manufacturer for the ETV was Aquasource. The operations management and staff were from the test site at the City of San Diego Metropolitan Wastewater Department, Aqua 2000 Research Center in Escondido, California. The City of San Diego laboratory, a State-certified laboratory, provided water quality analyses. Data management and final report preparation were performed by the FTO, Montgomery Watson.

1.3 Definition of Roles and Responsibilities of Project Participants

1.3.1 Field Testing Organization Responsibilities

The specific responsibilities of the FTO, Montgomery Watson, 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.
- Manage, evaluate, interpret and report on data generated in the ETV.
- Evaluate the performance of the ultrafiltration membrane technology according to the Field Operating Document (FOD) and the testing, operations, quality assurance/quality control (QA/QC), data management and safety protocols contained therein.
- Provide all quality control (QC) information in the ETV report.
- Provide all data generated during the ETV in hard copy and electronic form in a common spreadsheet or database format.

1.3.2 Manufacturer Responsibilities

The specific responsibilities of the ultrafiltration membrane manufacturer, Aquasource North America, 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 partial funding for the project.
- Attend project meetings as necessary.

1.3.3 Operator and Test Site Staff Responsibilities

The specific responsibilities of the operations and test site staff from the City of San Diego Metropolitan Wastewater Department were to:

- Provide set-up, shake-down, operations, maintenance and on-site analytical services according to the FOD 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.

1.3.4 Water Quality Analyst Responsibilities

The specific responsibilities of the water quality analytical staff from the City of San Diego Laboratory were to:

- Provide all off-site water quality analyses prescribed in the FOD according to the QA/QC protocols contained therein.
- Provide reports with the analytical results to the data manager.
- Provide detailed information on the analytical procedures implemented.

1.3.5 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 FODs.
- Conduct inspections and make recommendations based on inspections.
- Conduct financial administration of the project.
- Review all project reports and deliverables.

1.3.6 EPA Responsibilities

The specific responsibilities of EPA were to:

- Initiate the ETV program.
- Provide significant project funding.
- Review final reports.

Chapter 2
Equipment Description and Operating Processes

The equipment tested in the ETV is Aquasource's package ultrafiltration (UF) membrane system. The test unit is comprised of two M1A35 hollow fiber UF membrane modules mounted on a transportable skid. A photograph of the Aquasource UF unit is shown in Figure 2-1. The skid is constructed of reinforced fiberglass and steel, and can be shipped by truck. The Aquasource unit is completely self-contained, including all the components required for operation. The only connections to the unit are a raw water connection to the feed pump, drain lines for filtrate tank overflow and backwash waste, and electrical power. The unit requires approximately 30 ft^2 (2.8 m^2) of floor space. The spatial requirements and locations of major components and instruments of the Aquasource UF unit are shown in Figure 2-2.

The Aquasource unit has an Allen Bradley touchscreen programmable logic controller (PLC). The touchscreen includes schematic displays of the treatment train showing which pumps are operating and which valves are open. The PLC maintains a constant filtrate flow during filtration by automatically adjusting feed pump speed, and controls pumps and valves during backwash. The operating parameters for the Aquasource unit are adjusted by entering values in screens of the PLC touchscreen.

The Aquasource UF unit has electronic flow, pressure and temperature measurement and a data logger which stores operating information digitally. This information can be accessed locally, with a personal computer (PC) connected by cable, or remotely over phone lines.

The Aquasource UF unit has two alternating operating modes. These are filtration and backwash. During filtration, raw water is driven under pressure through pores in the UF membrane. Treated water is collected from the filtrate side of the membrane and directed to drain. The filtration cycle typically lasts from 30 to 90 minutes. At the end of the filtration cycle, the system initiates a backwash. During backwash, the feed pump shuts down, valves are repositioned, and the backwash pump starts. The backwash pump draws treated water from the filtrate storage tank, chlorinates it, and forces the water under pressure in the reverse direction through the fibers. With the flow of water now from the outside of the fiber to the inside of the fiber, the backwash water exits the inside of the fibers at the fiber ends, carrying with it particulate material accumulated during filtration. The backwash waste stream is directed to drain. Chlorine added to the backwash water assists in oxidizing organics that have accumulated on the membrane surface. The backwash cycle typically lasts from 45 to 90 seconds, after which the unit returns to filtration mode.

The long-term operation of the 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 quantified by a gradual increase in the pressure required to maintain a desired flux. Once a critical upper pressure has been reached, normal operation is discontinued and the membrane undergoes chemical cleaning. Chemical cleaning involves the use of detergent and chlorine solutions to restore efficient operation of the membrane.

The Aquasource UF unit has two M1A35 membrane modules. These 4 inch (10 cm) diameter modules contain the same fiber as the larger surface area L1B35 which are used in full-scale systems.

The M1A35 is a hollow fiber configuration with nominal molecular weight cut-off of 100,000 Daltons. This corresponds with a pore diameter of approximately 0.01 micron. At this pore size, the M1A35 membrane is expected to remove particulate material, including protozoa, bacteria and virus.

2.1 Description of the Treatment Train and Unit Processes

Figure 2-3 presents a schematic diagram of the Aquasource UF unit. The test system has two alternating operation modes: filtration and backwash.

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

1. The feed pump provides the pressure needed to filter the water through the membranes (up to approximately 35 psi or 2.4 bars).
2. After the feed pump, the water passes through a pre-filter. Pre-filtration at 200 microns ensures the removal of large particles prior to the feed flow entering the modules in order to protect the heads of the modules from clogging. The pre-filter is backwashed automatically as part of the membrane backwash sequence.
3. From the pre-filter, water continues to the membrane modules. In dead-end filtration mode, the feed water is directed to the bottom end of the modules. At the module end, raw water enters the inside of the fibers and is forced, under pressure, to the outside, or filtrate side, of the membrane.
4. The filtrate water exits the modules through a port in the cylindrical fiberglass membrane housing and is collected in a 100 gallon (379 L) filtrate tank. Excess filtrate overflows the filtrate tank and is directed to drain. The modules filter on a cycle of 30 to 90 minutes between backwashes.
5. Backwash is initiated automatically based on a timer. A PLC automatically operates pumps and valves to accomplish a backwash.
6. Backwash is at 36 to 38 psi (2.5 to 2.6 bars) at a rate of approximately 10 to 35 gpm (38 to 130 L/min) for a 45 to 90 second cycle. The backwash water is pumped from the filtered water tank and is chlorinated at 4 to 8 mg/L. The backwash feed water is pumped into the filtrate port of each module and forced from the outside membrane surface through membrane pores to the inside of the fibers. This is the reverse flow direction from normal filtration. The backwash water then exits the fiber ends carrying accumulated solids and organics from the inside of the fibers. Waste from the backwash cycle is routed to drain.
7. At the completion of backwash, the PLC stops the backwash pump, readjusts the appropriate valves and restarts the system in filtration mode.

The Aquasource UF system has two available filtration modes: dead-end and recirculation. In this ETV study, only the dead-end filtration was verified. In dead-end, or direct-flow mode the feed pump directs raw water to the bottom end of the modules. The valve in the recirculation loop, just below the recirculation pump (see Figure 2-3) is closed, and the recirculation pump does not operate. All raw water entering the insides of the fibers from the bottom of the module passes through the membrane pores as filtrate. The valves in the schematic of the Aquasource UF system presented in Figure 2-3 are configured for filtration in dead-end mode. Dead-end mode is the most energy efficient mode of operation since the recirculation pump is not used. Dead-end filtration mode was used throughout the Aquasource UF ETV testing.

Recirculation mode is employed with higher turbidity, higher suspended solids source waters. In this operating mode, the valve in the recirculation loop is open and the recirculation pump operates. Feed water enters the recirculation loop and is drawn by the recirculation pump to the tops of the modules. The recirculation flow is maintained at approximately 40 gpm (150 lpm). This produces an average flow velocity of water through the fiber inner core of approximately 3 ft/sec (0.9 m/s). This cross-flow inhibits the accumulation of solids on the membrane surface. Concentrate exiting the bottom end of the module mixes with raw water before being redirected to the top of the module.

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 material is not effectively removed by backwash. This process is called membrane fouling. Once the system reaches a maximum recommended pressure, the system is shut down and a chemical cleaning is performed to restore membrane productivity. Aquasource defines this upper pressure in terms of temperature corrected specific flux. The membrane is considered fouled when specific flux decreases to 4.9 to 5.3 gfd/psi at 20°C (120 to 130 L/hr-m^2-bar at 20°C). Cleaning the Aquasource unit is a multi-step process. The proprietary cleaning agent U43 is first used. If specific flux was not significantly (> 90%) restored by U43 solution, cleaning with U59 solution is performed. Cleaning solutions of U43 contain free chlorine and detergents. Solutions of U59 contain detergents and metal chelating agents.

Each step in the cleaning process involves preparing approximately 4 gallons of preheated cleaning solution in a cleaning tank contained on the membrane system skid. The recirculation pump is then turned on and solution from the cleaning tank is drawn into the recirculation loop. This solution is recirculated through the feed side, inside, of the fibers with no filtrate flow. The solution recirculates at approximately 50 gpm (190 lpm). A portion of this flow is recirculated through the cleaning tank. Each cleaning step lasts from 30 to 60 minutes. A typical cleaning would involve a 30 minute prewash step with U43 followed by a 30 minute wash with U43. After this cleaning step, the specific flux recovery would be evaluated, and if sufficient (i.e. > 90%), the membrane would be put back in service. If not, a U59 cleaning would be performed. This step requires approximately 90 minutes.

Filtration, in the Aquasource test unit, is accomplished with two M1A35 UF membrane modules. The M1A35 is a hollow fiber configuration with each fiber potted at the top and bottom. Each fiber (see Table 2-1) has an inside diameter of approximately 0.035 inch (0.93 mm), an outside diameter of 0.043 inch (1.1 mm) and is 3.9 feet (1.2 m) long. With 2,060 fibers per module, the surface area of each module is approximately 78 square feet (7.2 square meter). The membrane is composed of a cellulose acetate derivative. The membrane surface has a slightly positive charge and is slightly hydrophilic. The membrane can tolerate a constant free chlorine residual of 1.0 – 2.0 mg/L and can operate with pH in the range 4.0 to 8.5. The fibers are contained in a fiberglass cylinder, which is also referred to as the module.

The fiber ends are embedded on both ends in an epoxy resin glued to the fiberglass cylinder. Due to this potting arrangement, there is no possible contact between the raw water inside the fibers and the treated water (filtrate) outside the fibers other than through failure of the fibers or potting material.

2.2 Description of Physical Construction/Components of the Equipment

The ETV test system is a skid-mounted unit with a footprint of approximately 7 feet 3 inches (2.2 m) long by 4 feet 2 inches (1.3 m) deep. The test unit is 7 feet 7 inches (2.3 m) in height. The frame of the test unit was constructed of tubular fiberglass. This structure is placed on a wooden base. At a weight of 1800 pounds (820 Kg), the unit can be moved with a forklift and transported by truck. The test unit is self contained, requiring only connections to feedwater, drain and electrical. The electrical requirements of the system are 20 amps of 480 volt 3-phase power.

The major components of the Aquasource ETV test system included:

- Two 78 ft^2 (7.2 m^2) Aquasource M1A35 UF modules
- PLC-based control system
- Data logging and downloading capability
- Backwash pump
- Feed pump
- Recirculation pump
- Filtrate storage tank
- Backwashable 200 micron pre-filter
- Air compressor
- Pneumatic valves
- Sodium hypochlorite tank and metering pump
- Digital rotary flow meters
- Digital and analog pressure gauges
- Digital and analog feed thermometer
- Chemical cleaning tank.

Chapter 3
Materials and Methods

3.1 Testing Site Name and Location

The test site selected for the ETV program is the City of San Diego's Aqua 2000 Research Center at 14103 Highland Valley Road in Escondido, California.

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. This site is also connected to San Diego County Water Authority's Aqueduct System. Sufficient influent water supply, electrical power, and proper drainage lines were provided to the ETV test system treatment train. Filtrate and backwash waste streams were directed to the City of San Diego sewer system.

3.1.2 Test Site Description

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

Structural
- 5,000 square foot concrete pad.
- Semi-permanent shading to protect from sunlight.
- Potable water connections.
- San Diego County Water Authority's Aqueduct System connections.
- Drainage system connected to a wastewater plant.
- Chemical containment area.
- Sufficient lighting for 24-hour operation.
- Full electrical supply.
- Chemical safety shower and eyewash.
- An operations trailer with conference room, offices, and computers.
- A laboratory trailer for on-site water quality analyses.

Instrumentation/Equipment

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)
- Two total organic carbon (TOC) analyzers (Sievers Model No. 800)

Concrete Pad

- Feed, filtrate, backwash, and waste storage tanks.
- Chemical Cleaning Skid with hot water supply.
- Chemical Feed Systems.
- Micro 2000 On-line Chlorine Analyzer
- Four 1720D On-line Hach Turbidimeters
- Four 1900WPC On-line Hach Particle Counters

Raw Water Intake

The raw water was delivered to the test site through schedule 80 PVC pipe. The San Diego Aqueduct connection was approximately 1 mile away from the test site. The available water flow rate was 150 gpm.

Collection of Raw Water

The raw water was directed to a covered tank with an overflow system. The feedwater pipe of the ETV test unit was connected to the covered raw water tank.

Handling of Treated Water and Residuals

The Aqua 2000 research center has a drainage system that connects to a wastewater treatment plant. All of the filtrate water, backwash water, and any chemicals used were directed to waste.

3.2 Source/Feed Water Quality

The source of feedwater for the ETV testing is San Diego Aqueduct Water. The aqueduct is supplied primarily from Lake Skinner which 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 the figure. Hardness ranged from 200 through 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 C aCO_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 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 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 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 verification 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 two 30-day test periods. When substantial specific flux decline occurred before the end of the 30-day test period, chemical cleaning was performed and (if necessary) adjustments to the operational strategy were made. 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.

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 minimum specific flux operational limit of the membrane, 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 which requires the use of proprietary cleaning agent U43 and, if necessary, U59. U43 cleaning solutions consist of detergents and chlorine with a pH of approximately 8 and free chlorine residual of 50 to 100 mg/L. U59 cleaning solutions consist of detergents, metal chelating agents and pH 8.5. In some instances, a third chemical is also used which consists of primarily citric acid solution to remove inorganic fouling material such as iron and manganese.

To determine cleaning efficiency, flux-pressure profiles were developed at each stage of the chemical cleaning procedure (i.e., before cleaning, after first chemical solution, after second 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:

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

where: Js_f = specific flux (gfd/psi, L/(h-m^2)/bar) at end of current run (final)

Js_i = specific flux (gfd/psi, L/(h-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:

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

where: Js_{io}= specific flux (gfd/psi, L/(h-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.

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.

Simulated Distribution System (SDS) Test Protocol
The SDS DBP test simulates full-scale disinfection by spiking a water sample with a disinfectant and holding the spiked sample in the dark at a designated temperature and contact time. For this testing, the uniform formation conditions (UFC) specified by the Information Collection Rule (ICR) were used, as follows:

- Incubation period: 24 ± 1 hours
- Incubation temperature: 20 ± 1°C
- Buffered pH of 8.0 ± 0.2
- 24-hour free chlorine residual: 1.0 ± 0.4 mg/L

For each SDS sample, three incubation bottles were set up. At the end of the incubation period, each sample was analyzed for the final disinfectant residual and the sample with the residual closest to the 1.0 ± 0.4 mg/L range was used for the specified DBP analyses, total trihalomethanes (TTHMs) and the sum of 5 measured haloacetic acids (HAA5). The four trihalomethanes comprising TTHM are chloroform, bromoform, dibromochloromethane and bromodichloromethane. The five haloacetic acids included in HAA5 are monobromoacetic acid, dibromoacetic acid, monochloroacetic acid, dichloroacetic acid and trichloroacetic acid. A sixth haloacetic acid, bromochloroacetic acid, was also reported, but this DBP is not included in the calculation of the regulated parameter HAA5.

One liter, amber glass bottles with Teflon lined caps were used to store the SDS samples during incubation. These bottles were stored in a temperature-controlled incubator at the specified temperature. All glassware used for preparation of the SDS samples and reagents were chlorine demand free.

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 UF system during this study are described below:

Air Pressure-Hold Test

The air pressure-hold 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 filtrate side of the membrane after which the pressure is held and the decay rate is monitored over time. Minimal loss of the held pressure (generally less than 1 psi every 5 minutes) at the filtrate 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 um, 3- 5 um, 5-15 um, >15 um was used in this ETV as an indirect method of monitoring membrane integrity.

Turbidity Monitoring

On-line turbidity monitoring was also 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.

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 importation 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 onsite lab and City of San Diego Microbiology lab were entered into the data spreadsheets, corrected, and verified in the same manner as the field data. 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 (QA) and quality control (QC). 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 is operating properly. On-line monitoring equipment, such as flow meters, are checked to confirm that the read-out matches the actual measurement and that the signal being recorded is correct. Below is a list of the verifications conducted:

Monitoring Equipment

System Pressure Gauges

Pressure gauges supplied with the membrane system tested were verified against grade 3A certified pressure 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, 0-30 in Hg vacuum). Where possible, system gauges were removed and tested over the expected range of operating pressures against the verification gauge, using a portable hand pump. The Aquasource system lower feed, upper feed and filtrate pressure gauges were typically accurate to within 0.3 psi over the course of testing.

System Flow Rates

Membrane system flow rates were verified volumetrically on a monthly basis near the beginning and end of each test period. System flows were diverted to a 55 gallon graduated tank for approximately 2 minutes. The measured flow rate was compared with flows indicated on rotameters. Measured and indicated flows agreed to within 2 percent for the filtrate rotary flow meter and backwash flow totalizer.

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 feed water inline thermometer was verified against an National Institute of Standards and Technology (NIST) certified thermometer on 4/14, 6/16 and 12/12/99. 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 degrees centigrade of the NIST certified thermometer.

Turbidity

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

On-line Turbidimeters: Hach 1720D online turbidimeters were used during testing to acquire raw and filtrate turbidities at 1-minute intervals. The following procedures were followed to ensure the integrity and accuracy of these data:

- a primary calibration of the on-line turbidimeters 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 on-line turbidimeters had less than one percent error over their range of output (0, 1 and 2 NTU for filtrate, 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 250 to 750 mL/min. The flow range initially targeted during testing was 500 mL/min +/- 100 mL/min. On-line turbidimeter flows were verified manually with a graduated cylinder and stopwatch daily.
- turbidimeter bodies were drained and sensor optics cleaned approximately every week 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 2100N desktop turbidimeter were conducted on an as needed basis during the course of the testing when the difference between online and desktop turbidity readings were greater than 10 percent.
- Approximately 50 ppm free chlorine solution was pumped through turbidity sample lines as needed to clean potential buildup from these lines.

Bench-top Turbidimeters: A Hach 2100N desktop turbidimeter was used to perform onsite turbidity analyses of raw water, backwash and filtrate 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. Three secondary standards (approx. 0.8 NTU, 1.8 NTU and 20 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 0.8 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 filtrate waters. These counters enumerate particles in the range 2 to 800 microns (um).

The particle counters were factory calibrated. Factory calibrations took place in October, 1998. 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:

- The Aquaview software was configured to store particle counts in the following size ranges: 2-3 um, 3-5um, 5-15um 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 DI water. The same monosphere solution was then 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 monosphere solution was used for each particle counter (raw water and filtrate).

The precise concentration of the monosphere solution 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

A typical response of the particle counters to the same monosphere solution, near both test periods, is presented in Figure 3-4. The response of the raw and filtrate particle counters to the same monosphere solution were within 35 percent in all of the size ranges that were monitored. The figures show a good comparative response of the raw water and filtrate 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 stop watch. Flows were observed to be extremely consistent (typically within 2 mL/min of the target flow rate). Fifty mg/L free chlorine was run through particle counters for on an as needed basis to remove potential buildup.

Chemical and Microbial Water Quality Parameters

The analytical work for the study was performed by the City of San Diego Water Quality and Marine Microbiology Laboratories, which are a State of California certified laboratories. 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 under aseptic conditions in bottles supplied by the City of San Diego Marine Microbiology 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). For the Marine Microbiology Laboratory, these QC procedures included the use of positive / negative controls, blanks and sterility checks.

3.4 Calculation of Membrane Operating Parameters

3.4.1 Filtrate Flux

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

$$J_t = Q_p \div S$$

where J_t = filtrate flux at time t (gfd, L/(hr-m^2))
Q_p = filtrate flow (gpd, L/h)
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 filtrate 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 = filtrate flux at time t (gfd, L/(hr-m^2))
P_{tm} = transmembrane pressure (psi, bar)

3.4.3 Transmembrane Pressure

The average transmembrane pressure is 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 = filtrate 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:

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

where J_{tm} = instantaneous flux (gfd, L/(hr-m^2))
Q_p = filtrate flow (gpd, L/hr)
T = temperature, (°F, °C)
S = membrane surface area (ft^2, m^2)

3.4.5 Feedwater System Recovery

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

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

where Q_p = filtrate 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 = Filtrate water concentration, (mg/L)
C_F = Feed 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
$\overline{x}_i$ = ith 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

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:

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:

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 3-5. The testing program took place starting in March 1999, and finishing by the end of September 1999. Test Period 1 represented the winter/spring seasons and Test Period 2 represented the summer/autumn seasons.

Chapter 4
Results and Discussion

This chapter presents the data obtained under each task of the ETV program of the Aquasource UF system.

4.1 Task 1: Characterization of Membrane Flux and Recovery

The operating conditions for the Aquasource UF membrane system are provided in Table 4-1. The operating conditions verified in both testing periods were similar and were determined by the manufacturer. The membrane system ran at a target flux of 60 gfd (100 L/hr-m^2) during the majority of Test Period 1 and all of Test Period 2. Near the end of Test Period 1, a chemical cleaning was performed on the membrane. The test system was operated at the same flux of 60 gfd after this cleaning, but a rapid membrane fouling was observed apparently due to algae bloom episode. After a second cleaning, the flux was decreased to 51 gfd (85 L/hr-m^2) for 3 days until the run was terminated at the end of Test Period 1. The backwash frequency during the majority of Test Period 1 was 60 minutes. The backwash frequency was increased to every 30 minutes for 3 days near the end of Test Period 1, to minimize the membrane fouling rate, and was maintained at every 30 minutes for all of Test Period 2. The backwash typically lasted for 48 seconds and consumed approximately 24 gallon (89 liter) of stored filtrate. A free chlorine residual of 4 to 8 mg/L was targeted in the backwash feedwater. Feedwater recovery was 94 percent for the majority of Test Period 1 when the backwash frequency was every 60 minutes. The feedwater recovery decreased to 88 percent for Test Period 2 because of the increase in the backwash frequency to every 30 minutes, and the resultant increased consumption of stored filtrate for backwashing the membrane. The system was operated in dead-end filtration mode during both test periods, hence there was no recirculation flow.

Figure 4-1 (A and B) provides the membrane transmembrane pressure and temperature profiles for Test Periods 1 and 2. For Test Period 1, the clean membrane transmembrane pressure began at approximately 5 psi. The transmembrane pressure remained relatively constant at approximately 7 psi until April 6, 1999, when the unit fouled over a period of six days to a pressure of 18 psi. The membrane was then chemically cleaned with pressure restored to 6 psi. The membrane fouled overnight after less than 1-day operation after which the membrane was chemically cleaned again and returned to service at the lower flux and increased backwash frequency. The cause of the rapid fouling at the end of Test Period 1 was believed to be algae based on daily buildup of algae in the raw water particle counter and verbal verification of an algae bloom at Lake Skinner by the Aqueduct operations staff. Algae counts were not quantified. Transmembrane pressure when running the system on the warmer water encountered during Test Period 2 was consistently in the range 4 to 5 psi. There was no significant fouling during Test Period 2.

Figure 4-2 (A and B) provides the membrane flux and specific flux data profiles for Test Periods 1 and 2. The target flux during the majority of Test Period 1 and all of Test Period 2 was 60 gfd (100 L/hr-m^2). For Test Period 1 (winter/spring), the average temperature adjusted membrane flux was approximately 63 gfd at 20°C. Due to the relatively higher water temperatures during Test Period 2 (summer/autumn), a lower average temperature adjusted membrane flux of approximately 49 gfd at 20°C was calculated. The temperature adjusted specific flux decreased from 12 gfd/psi at 20°C to 4 gfd/psi at 20°C over 38 days during Test Period 1, with rapid fouling experienced over the last 6 of these days. Chemical cleaning recovered specific flux to approximately 9 gfd/psi at 20°C. Temperature adjusted specific flux actually increased over the first 3 days of operation using the warmer raw water of Test Period 2. After this, temperature adjusted specific flux remained relatively constant at approximately 12 gfd/psi at 20°C.

The same data in Figures 4-1 and 4-2 are also provided in Appendix A of this report, but with metric units.

4.2 Task 2: Evaluation of Cleaning Efficiency

Chemical cleanings were performed when the membrane fouled (temperature adjusted specific flux 4.9 gfd/psi [120 L/hr-m^2-bar] at 20°C), or the end of a test period was reached. The manufacturer's cleaning procedure was a multiple step process. The first step of the cleaning procedure was prewashing with U43, a proprietary chlorine and detergent solution. 2.7 lb (1.2 kg) of U43 was dissolved in about 4 gal (15 L) of hot tap water. This solution was added to a 5 gallon cleaning tank located on the ETV test system. The cleaning tank is plumbed into the recirculation loop. Cleaning solution is drawn from the bottom of the tank into the recirculation loop before the recirculation pump and is returned to the cleaning tank through tubing plumbed into the recirculation loop on the discharge side of the pump. After repositioning valves, the recirculation pump is started and this solution is recirculated through the insides of the fibers, with no filtrate flow, for a period of 30 minutes at a recirculation flow of approximately 50 gpm (190 lpm). After completing the prewash, the second step in the cleaning procedure is a U43 wash. The same 30 minute washing procedure is followed during this cleaning step. Upon completing the U43 wash, a flux-pressure profile is conducted and the specific flux of the membrane is determined. If the loss of original specific flux is greater than 10% after the U43 wash, the next cleaning step was performed. Typically the next step would be washing with U59, a solution of detergents and metal chelating agents. The U59 cleaning procedure is similar to the previous steps, but involves 4 cycles of recirculating the cleaning solution for 10 minutes, followed by soaking for 10 minutes. After the rapid fouling incidents, caused by algae, encountered in Test Period 1, the manufacturer recommended cleaning with 0.3 lb (0.12 kg) citric acid and 200 mL household ammonia in 4 gal (15 L) water.

The flux-pressure profiles of the membrane system at different stages of the chemical cleaning procedure for Test Periods 1 and 2 are shown in Figures 4-3 and 4-4, respectively. 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. These are listed in Table 4-2. The recovery of specific flux for the two cleanings in Test Period 1 was 55 and 59 percent, respectively. The cleaning in the second test period had only 10 percent specific flux recovery because the membrane was not significantly fouled before cleaning.

New membranes are generally expected to have a noticeable loss of the original specific flux values after the first operation cycle. After that, a much lower irreversible fouling rate is usually observed (if any) as the membrane gets conditioned to the water chemistry. This was evident in the data presented in Table 4-2, where the maximum loss of original specific flux was observed after the first chemical cleaning. Minimal additional loss of original specific flux was experienced after the second cleaning. All of the original specific flux lost in Test Period 1 (winter/spring) was recovered in the final cleaning at the end of Test Period 2 (summer/autumn). This is possibly due to the higher temperatures of the solution used for chemical cleaning in the warmer weather. Since no consistent trend was observed for the loss of the original specific flux data, the usable membrane life can not be estimated.

The same data in Figures 4-3 and 4-4 are 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 4-5 and 4-6 present the on-line turbidity profile for the Aquasource UF membrane system during Testing Periods 1 and 2, respectively. The figures show online turbidity for raw and filtrate water and desktop turbidity for raw water, filtrate 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 both testing periods, the raw water turbidity was in the range of 1-3 NTU. The turbidity of the backwash wastewater averaged about 16 NTU, while the filtrate turbidity was consistently below 0.1 NTU.

Figures 4-7 and 4-8 present the particle count profile (2-3 um, 3-5 um, and 5-15 um, >15 um) collected during Test Periods 1 and 2, respectively. The data presented represent 4-hour average values of data collected at one minute intervals. For both testing periods, the feed particle concentration of the *Cryptosporidium*-sized particles (3-5 um) and *Giardia*-sized particles (5-15 um) were in the range of 1,000 to 10,000 particle/mL, while the filtrate concentration was typically in the range of 0.1 to 1 particle/mL. The gap in the filtrate particle data for Test Period 1 occurring on approximately March 24, 1999 was due to contamination of the filtrate tank with bird droppings. Gaps in the particle data near the end of Test Period 1 are due to shutdown periods for the two chemical cleanings.

Figures 4-9 and 4-10 present the log removal of particles (2-3 um, 3-5 um, and 5-15 um, >15 um) based on raw and filtrate particle count data collected during Test Periods 1 and 2, respectively. Data presented on this plot represent 1-day average values of data collected at one minute intervals. Overall, 3.0 to 4.5 logs removal was consistently achieved for the *Cryptosporidium*-sized particles (3-5 um) and *Giardia*-sized particles (5-15 um). The online turbidity and particle removal data are summarized in Table 4-4.

To assist in assessing test system performance, Figure 4-11 presents the probability plots of the membrane system filtrate turbidity and particle removal data for the *Cryptosporidium*-sized particles (3-5 um) and *Giardia*-sized particles (5-15 um). The figure shows that the filtrate turbidity was 0.05 NTU or less 95 percent of times and that removal of particles (3-5 um and 5-15 um) was greater than 3 logs 95 percent of times.

4.3.2 Indigenous Bacteria Removal

The removal of naturally occurring bacteria was also monitored during the ETV study (see Table 4-5). The raw water total coliform bacteria ranged from <2 to 50 MPN/100mL during Test Period 1 and from 2 to 170 MPN/100mL during Test Period 2. Total coliform bacteria were not detected (<2 MPN/100mL) in the filtrate of the Aquasource UF membrane system during both testing periods. HPC bacteria were also reduced significantly by membrane filtration, however, HPC was enumerated in the filtrate especially during the warmer weather of Test Period 2. Previous studies (Jacangelo et al., 1995) have demonstrated that HPC bacteria can be introduced on the filtrate side of the membrane rather than by penetration through it.

4.3.3 Other Water Quality Parameters

Table 4-6 presents the results of general water quality parameters across the Aquasource UF system for Test Periods 1 and 2. As expected, no change was observed in the alkalinity, total dissolved solids, total hardness, and calcium hardness of the water across the membrane system. No change was observed in total organic carbon and UV254 across the membrane system.

The total suspended solids (TSS) in the backwash waste reached as high as 43 mg/L (during Test Period 1), while the filtrate TSS remained consistently below the detection limit (1.0 – 1.3 mg/L).

Table 4-7 presents the mass balance conducted on total suspended solids across the membrane system. Five of the seven calculated results showed fair correlation between calculated and measured waste stream TSS.

4.3.4 Removal of Simulated Distribution System Disinfection By-Product Precursors (Optional)

Simulated distribution system disinfection by-product formation tests were conducted during each test period. The tests were conducted under the Uniform Formation Conditions established under the EPA Information Collection Rule. SDS DBP formation tests were conducted on both raw water and filtrate. The results of these tests are presented in Table 4-8. From the data collected (one comparison per test period), and the variability of TTHM and HAA testing, the SDS DBP results do not demonstrate any reduction in these DBPs.

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. Aquasource responded that the M1A35 UF membrane has 90 percent molecular weight cut-off of 100,000 Daltons (approximately 0.012 um pore size) and a 95 percent molecular weight cut-off of 180,000 Daltons (approximately 0.018 um pore size).

Aquasource determined the molecular weight cut-off distribution in accordance with French Standard AFNOR X 45-103.

The above information are taken from a memorandum supplied by the manufacturer 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 4-12 shows the results of the air pressure-hold tests conducted on the UF membrane at the beginning and end of both testing periods. If any of the membrane fibers were compromised, one would expect significant loss of held pressure (> 1 psi every 5 minutes) across the membrane element. Since no significant change in the held pressure (< 0.5 psi every 5 minutes) was observed during both testing periods, it would be reasonable to assume that the membrane modules were uncompromised during both testing periods. The above is also confirmed with the turbidity profiles shown in Figures 4-5 and 4-6 and the particle count profiles shown in Figures 4-7 and 4-8. The particle concentrations in the filtrate would be expected to noticeably increase if the membrane module were compromised (Adham et. al., 1995, Montgomery Watson, 2000).

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 particle counters and turbidimeters were also recorded via data acquisition systems. All of the raw data sheets are included in Appendix B 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 C 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 NSF 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 Aquasource UF system. These include turbidity, particle concentrations, particle removal, and indigenous bacteria. Ninety-five percent confidence intervals were presented in summary tables in the discussion of Task 3 – Finished Water Quality.

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 on-site water quality measurements, laboratory water quality measurements, and operational data recording. These calculations are presented in Appendix A of this report. Nearly all parameters were 100 percent complete. Overall, the database of laboratory water quality data and operational readings was 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 of all measured values for turbidity proficiency samples was 90 percent or greater for all proficiency samples analyzed. Comparative calibration of online turbidimeters with the desktop turbidimeter was performed as corrective actions as needed. 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 for duplicate samples and between on-line and desktop turbidimeters are included in Appendix A of this report. The relative percent deviation for analyses not near the lower detection limit were within 16 percent for onsite analyses, within 11 percent for other general water quality analyses, and within 19 percent for microbial analyses. Thus, no data were excluded from the database.

4.8 Additional ETV Program Requirements

4.8.1 Operation and Maintenance (O&M) Manual

The O&M manual for the Aquasource UF system supplied by the manufacturer was reviewed during the ETV testing program. The review comments for the O&M manual are presented in Table 4-9. Overall, the review found the O&M manual to be an extremely useful resource. The manual is well organized, concise, clear and complete. The manual makes excellent use of tables and graphics. The manual would be improved if it included a list of component parts, manufacturers and model numbers. Also, some valve numbers referenced in the manual were not labeled on the test system. This could be remedied by including a schematic or diagram in the O&M manual with all valves labeled.

4.8.2 System Efficiency and Chemical Consumption

The efficiency of the small-scale Aquasource UF system was calculated based on the electrical usage and water production of the system. These data are presented in Table 4-10. Overall, an efficiency of only 4.1 percent was calculated for the system, which is typical of many small-scale low pressure membrane systems.

The chemical consumption of the system was also estimated based on the operating criteria used during the ETV program. Table 4-11 provides a summary of the chemical consumption of the small-scale Aquasource UF system.

4.8.3 Equipment Deficiencies Experienced During the ETV Program

Test Period 1

Aquasource UF Membrane System
On approximately April 16, 1999 the readings from the filtrate rotary flow meter became erratic. Sometimes the readings were higher than feed flow readouts and sometimes lower. The rotary measurement unit was removed from its seat, checked and found to be operating freely, but the erratic readings continued. Since the test unit flow control logic used the feed flow meter signal to determine system flow setpoints, this did not affect the operation of the unit. The feed flowmeter readouts remained consistent and accurate over the course of testing. Because of the erratic filtrate flow readings, all filtrate flow calculations were made based on the feed flow readout after April 16, 1999.

Another minor problem had to do with the backwash sodium hypochlorite feed system. The metering pump would sometimes partially or completely lose prime. This is a common problem with sodium hypochlorite feed systems which operate intermittently as the solution tends to produce oxygen as it degrades and therefore is prone to degassing within the pump head and feed tubing.

Online Turbidimeters and Particle Counters
At the start of Test Period 1, the flow rate to the Hach 1720D on-line turbidimeters was maintained at 500 mL per minute as per the manufacturers recommendation. During the course of testing, on some days during the heat of the day, the on-line filtrate turbidity values were up to

50 percent higher than samples of filtrate analyzed on the desktop turbidimeter. Representatives from Hach were contacted. Cleanings and calibration checks were performed on all turbidimeters, but the on-line units still read significantly higher. The flowrate to the online turbidimeter was decreased in a stepwise fashion. When the flow was reduced to approximately 225 mL/min, the turbidity readings on the online filtrate turbidimeter stabilized at the expected levels. The Hach representative speculated that the problem was due to inadequate degassing in the 1720D online turbidimeter. The degassing capability was improved by reducing the flow rate through the instrument. Based on the Hach representative's recommendation, flow rates were decreased to approximately 200 mL/min on all online turbidimeters after March 26, 1999. It is possible that as the weather warms, this degassing problem also may affect the performance of online particle counters.

Test Period 2

Aquasource UF Membrane System

No new membrane system deficiencies were encountered during the second test period. The system ran the entire test period without incident.

A chronological listing of all problems experienced during ETV testing of the Aquasource UF system, along with their associated corrective actions, is provided in Appendix A of this report.

Chapter 5
References

Adham, S.S., J.G. Jacangelo, and J-M. Laîné (1995). Low pressure membranes: assessing integrity, *Journal AWWA*, 87(3)62-75.

APHA, AWWA and WPCF (1992). *Standard Methods for Examination of Water and Wastewater*. 18th ed. Washington, D.C. APHA.

Montgomery Watson (2000), *California Department of Health Services Testing for Aquasource Ultrafiltration Membrane.* Final Report prepared for Aquasource North America, April 2000.

Tables and Figures

Table 2-1. Characteristics of the Aquasource ultrafiltration membrane.

	Units	Value
Model		M1A35
Commercial Designation		M1A35
ID Number		MIO339
Available Operating Modes		dead-end, crossflow
Approximate Size of Membrane Module	ft (m)	4.3 (1.3) long x 0.33 (0.10) diameter
Active Membrane Area per Module	sq ft (sq m)	78 (7.2)
Number of Fibers per Module		2,060
Number of Modules		2
Inside Diameter of Fiber	inches (mm)	0.035 (0.93)
Outside Diameter of Fiber	inches (mm)	0.043 (1.1)
Approximate Length of Fiber	ft (m)	3.9 (1.2)
Flow Direction		Inside - Out
Nominal Molecular Weight Cutoff	Daltons	100,000
Absolute Molecular Weight Cutoff	Daltons	180,000
Nominal Membrane Pore Size	micron	0.01
Absolute Membrane Pore Size	micron	0.02
Membrane Material / Construction		Cellulose Acetate Derivative
Membrane Surface Characteristics		Slightly Hydrophilic
Membrane Charge		Slightly Positive
Design Operating Pressure	psi (bar)	na
Design Flux (at Design Pressure)	gfd	na
Maximum Transmembrane Pressure	psi (bar)	13 (0.9) dead-end, 22 (1.5) crossflow
Acceptable Range of Operating pH		4.0 - 8.5
Acceptable Range of Operating Temperature	degF (degC)	35 - 95 (1.7 - 35)
Maximum Permissible Turbidity	NTU	na
Chlorine / Oxidant Tolerance	mg/L	1.0 - 2.0 ppm constant

Note: na = not available

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
Total Trihalomethanes	Laboratory	EPA Method 502.2
Haloacetic Acids	Laboratory	EPA Method 552.2
Microbiological Analyses		
Total Coliform	Laboratory	9221 B
HPC Bacteria	Laboratory	9215 B

Table 4-1. Aquasource UF membrane system operating conditions.

Parameter	Unit				
Test Period		1	1	1	2
Run		1-1	1-2	1-3	2-1
Start Date & Time		3/5/99 11:00	4/13/99 13:15	4/16/99 14:14	8/25/99 11:00
End Date & Time		4/12/99 13:15	4/15/99 6:51	4/19/99 9:44	9/28/99 8:44
Run Length	days - hrs	38 days 2 hrs	1 day 18 hrs	2 days 20 hrs	33 days 22 hrs
Run Terminating Condition		Fouled	Fouled	Time	Time
Filter Cycle Length	min	60	60	30	30
Feed Flow	gpm (lpm)	6.4 (24)	6.4 (24)	5.5 (21)	6.4 (24)
Filtrate Flow	gpm (lpm)	6.4 (24)	6.4 (24)	5.5 (21)	6.4 (24)
Recirculation Flow	gpm (lpm)	0 (0)	0 (0)	0 (0)	0 (0)
Flux	gfd (l/hr-m^2)	60 (100)	60 (100)	51 (87)	60 (100)
Backwash Cycle Length	sec	48	48	54	48
Backwash Volume	gal (liter)	24 avg (89)	24 avg (89)	22 avg (84)	24 avg (87)
Target Chlorine Dose	mg/L	4 - 8	4 - 8	4 - 8	4 - 8
Feed Water Recovery	%	94%	94%	87%	88%

Table 4-2. Evaluation of cleaning efficiency for the Aquasource UF membrane.

Test Period	Clean After Run	Run Termination 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)	Recovery of Specific Flux 100(1 - Jsf/Jsi) %	Loss of Original Specific Flux 100(1-(Jsi / Jsio)) %
1	Start	3/5/99 11:00	---	**10 (256) Jsio**	---	---
1	1-1	4/12/99 13:15	3.7 (90)	8.2 (200)	55	21
1	1-2	4/15/99 6:51	3.3 (82)	8.1 (200)	59	22
2	2-1	9/28/99 8:44	9.4 (230)	11 (260)	10	-0.39

Table 4-3. Onsite lab water quality analyses for the Aquasource UF membrane system.

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
TEST PERIOD 1							
Raw Water							
pH		41	8.3	8.0 - 8.7	8.3	0.14	8.3 - 8.3
Desktop Turbiditiy	NTU	77	1.2	0.80 - 3.1	1.3	0.36	1.2 - 1.4
Temperature	degC	77	16	11 - 28	17	3.6	16 - 18
Filtrate							
Desktop Turbiditiy	NTU	42	0.050	0.050 - 0.050	0.050	0.0091	0.050 - 0.050
Backwash Waste							
Desktop Turbiditiy	NTU	71	16	2.0 - 120	19	18	15 - 23
TEST PERIOD 2							
Raw Water							
pH		26	8.3	8.0 - 8.4	8.2	0.098	8.2 - 8.2
Desktop Turbiditiy	NTU	51	1.4	0.70 - 2.5	1.4	0.37	1.3 - 1.5
Temperature	degC	52	28	19 - 35	28	4.8	27 - 29
Filtrate							
Desktop Turbiditiy	NTU	24	0.050	0.050 - 0.050	0.050	0.0017	0.050 - 0.050
Backwash Waste							
Desktop Turbiditiy	NTU	47	12	4.5 - 45	13	6.3	11 - 15

Table 4-4. Summary of online turbidity and particle count data for the Aquasource UF membrane system.

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
TEST PERIOD 1							
Raw Water							
Turbidity	ntu	263	1.4	0.85 - 5.8	1.4	0.45	1.3 - 1.5
> 2 um Particles	#/mL	291	7000	2200 - 16000	7300	2000	7100 - 7500
2-3 um Particles	#/mL	291	3600	1200 - 6500	3600	730	3500 - 3700
3-5 um Particles	#/mL	291	2200	640 - 5200	2300	630	2200 - 2400
5-15 um Particles	#/mL	291	1200	290 - 3900	1400	650	1300 - 1500
>15 um Particles	#/mL	291	43	11 - 730	70	88	60 - 80
Filtrate							
Turbidity	ntu	231	0.050	0.050 - 0.10	0.050	0.0033	0.050 - 0.050
> 2 um Particles	#/mL	202	0.37	0.14 - 3.5	0.41	0.30	0.37 - 0.45
2-3 um Particles	#/mL	202	0.17	0.076 - 2.0	0.18	0.15	0.16 - 0.20
3-5 um Particles	#/mL	202	0.14	0.063 - 0.83	0.15	0.076	0.14 - 0.16
5-15 um Particles	#/mL	202	0.091	0.045 - 0.62	0.11	0.061	0.10 - 0.12
>15 um Particles	#/mL	202	0.041	0.040 - 0.37	0.049	0.031	0.045 - 0.053
Log Removal 2-3 um Particles		36	4.3	3.9 - 4.5	4.3	0.16	4.2 - 4.4
Log Removal 3-5 um Particles		36	4.2	3.8 - 4.5	4.1	0.16	4.0 - 4.2
Log Removal 5-15 um Particles		36	4.1	3.7 - 4.6	4.1	0.23	4.0 - 4.2
Log Removal >15 um Particles		36	3.0	2.0 - 4.0	3.0	0.46	2.8 - 3.2
TEST PERIOD 2							
Raw Water							
Turbidity	ntu	200	1.4	0.55 - 5.9	1.3	0.47	1.2 - 1.4
> 2 um Particles	#/mL	201	6700	3200 - 16000	6700	1400	6500 - 6900
2-3 um Particles	#/mL	201	3500	1800 - 5000	3500	520	3400 - 3600
3-5 um Particles	#/mL	201	2000	780 - 5000	2000	490	1900 - 2100
5-15 um Particles	#/mL	201	1100	290 - 5800	1200	520	1100 - 1300
>15 um Particles	#/mL	201	68	13 - 680	72	56	64 - 80
Filtrate							
Turbidity	ntu	185	0.050	0.050 - 0.10	0.050	0.0037	0.049 - 0.051
> 2 um Particles	#/mL	199	0.59	0.28 - 2.8	0.79	0.53	0.72 - 0.86
2-3 um Particles	#/mL	199	0.21	0.099 - 0.88	0.27	0.17	0.25 - 0.29
3-5 um Particles	#/mL	199	0.20	0.077 - 0.89	0.26	0.19	0.23 - 0.29
5-15 um Particles	#/mL	199	0.14	0.062 - 1.3	0.21	0.18	0.18 - 0.24
>15 um Particles	#/mL	199	0.037	0.036 - 0.072	0.038	0.0046	0.037 - 0.039
Log Removal 2-3 um Particles		34	4.2	3.6 - 4.5	4.2	0.25	4.1 - 4.3
Log Removal 3-5 um Particles		34	4.0	3.4 - 4.4	4.0	0.29	3.9 - 4.1
Log Removal 5-15 um Particles		34	3.8	3.2 - 4.4	3.8	0.33	3.7 - 3.9
Log Removal >15 um Particles		34	3.2	2.9 - 3.8	3.2	0.19	3.1 - 3.3

Table 4-5. Summary of the microbial water quality analyses for the Aquasource UF membrane system.

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
TEST PERIOD 1							
Raw Water							
Total Coliforms	MPN/100mL	4	4.5	<2 - 50	15	23	-7.5 - 38
HPC	cfu/mL	4	120	14 - 240	120	93	29 - 210
Filtrate							
Total Coliforms	MPN/100mL	4	<2	<2 - <2	<2	0.00	<2 - <2
HPC	cfu/mL	4	1	<1 - 1	1	0.00	1 - 1
Backwash Waste							
Total Coliforms	MPN/100mL	4	<2	<2 - 2	<2	0.00	<2 - 2
TEST PERIOD 2							
Raw Water							
Total Coliforms	MPN/100mL	4	29	2 - 170	57	76	-17 - 130
HPC	cfu/mL	4	660	450 - 800	640	170	470 - 810
Filtrate							
Total Coliforms	MPN/100mL	4	<2	<2 - <2	<2	0.00	<2 - <2
HPC	cfu/mL	4	9	2 - 250	70	120	-48 - 190
Backwash Waste							
Total Coliforms	MPN/100mL	4	19	2 - 80	30	35	-4.3 - 64

Note: All calculations involving results with below detection limit values used the detection limit value in the calculation as a conservative estimate.

Table 4-6. Summary of general water quality analyses for the Aquasource UF membrane system.

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
TEST PERIOD 1							
Raw Water							
Alkalinity	mg/L $CaCO^3$	4	120	100 - 130	120	12	110 - 130
Total Hardness	mg/L $CaCO^3$	3	240	200 - 280	240	42	190 - 290
Calcium Hardness	mg/L $CaCO^3$	3	150	120 - 220	160	48	110 - 210
Total Suspended Solids	mg/L	4	5.0	1.9 - 9.5	5.4	3.6	1.9 - 8.9
Total Dissolved Solids	mg/L	4	490	410 - 600	500	75	430 - 570
TOC	mg/L	4	2.5	2.3 - 2.9	2.5	0.3	2.2 - 2.8
UV254 Unfiltered	/cm	8	0.07	0.06 - 0.09	0.07	0.01	0.06 - 0.08
UV254 Filtered	/cm	6	0.07	0.06 - 0.08	0.07	0.008	0.06 - 0.08
Filtrate							
Alkalinity	mg/L $CaCO^3$	4	120	100 - 130	110	11	99 - 120
Total Hardness	mg/L $CaCO^3$	3	240	200 - 280	240	40	190 - 290
Calcium Hardness	mg/L $CaCO^3$	3	150	120 - 220	160	52	100 - 220
Total Suspended Solids	mg/L	4	<1.0	<1.0 - <1.0	<1.0	0.00	<1.0 - <1.0
Total Dissolved Solids	mg/L	4	490	420 - 590	500	71	430 - 570
TOC	mg/L	2	2.4	2.3 - 2.5	2.4	0.2	2.1 - 2.7
UV254 Unfiltered	/cm	4	0.06	0.05 - 0.06	0.06	0.005	0.06 - 0.06
Backwash Waste							
Total Suspended Solids	mg/L	4	17	11 - 43	22	14	8.3 - 36
TEST PERIOD 2							
Raw Water							
Alkalinity	mg/L $CaCO^3$	4	110	110 - 120	120	2.2	120 - 120
Total Hardness	mg/L $CaCO^3$	1	230	230 - 230	230	undefined	undefined
Calcium Hardness	mg/L $CaCO^3$	0	-	-	-	-	-
Total Suspended Solids	mg/L	4	2.8	1.8 - 4.9	3.1	1.3	1.8 - 4.4
Total Dissolved Solids	mg/L	4	500	480 - 510	500	11	490 - 510
TOC	mg/L	3	3.6	3.4 - 3.7	3.6	0.1	3.5 - 3.7
UV254 Unfiltered	/cm	3	0.07	0.07 - 0.10	0.08	0.01	0.07 - 0.09
UV254 Filtered	/cm	3	0.06	0.06 - 0.06	0.06	0.003	0.06 - 0.06
Filtrate							
Alkalinity	mg/L $CaCO^3$	4	110	110 - 120	110	1.7	110 - 110
Total Hardness	mg/L $CaCO^3$	2	220	220 - 230	220	4.2	210 - 230
Calcium Hardness	mg/L $CaCO^3$	0	-	-	-	-	-
Total Suspended Solids	mg/L	4	<1.0	<1.0 - <1.3	<1.1	0.2	<0.9 - <1.3
Total Dissolved Solids	mg/L	4	500	470 - 510	490	14	480 - 500
TOC	mg/L	4	3.0	2.4 - 3.2	2.9	0.4	2.5 - 3.3
UV254 Unfiltered	/cm	3	0.06	0.06 - 0.06	0.06	0.0006	0.06 - 0.06
Backwash Waste							
Total Suspended Solids	mg/L	4	11	5.9 - 26	13	8.8	4.4 - 22

Note: All calculations involving results with below detection limit values used the detection limit value in the calculation as a conservative estimate.

Table 4-7. Comparison of calculated and measured total suspended solids for the Aquasource UF membrane system.

Date	Filtrate Flow (gpm)	Filtration Cycle Length (min)	Volume Filtered (gal)	Backwash Volume (gal)	Measured Raw TSS (mg/L)	Measured Backwash TSS (mg/L)	Calculated Backwash TSS (mg/L)
TEST PERIOD 1							
3/23/99	6.4	60	384	21.0	7.3	42.6	130
3/30/99	6.4	60	384	23.0	2.8	16	47
4/6/99	6.4	60	384	21.0	9.5	17.8	170
4/15/99	5.5	30	165	22.0	1.95	11.4	15
TEST PERIOD 2							
9/8/99	6.4	30	192	22.5	2.4	8.6	20
9/13/99	6.4	30	192	23.5	1.8	13.2	15
9/20/99	6.4	30	192	22.5	4.9	25.8	42

Table 4-8. Removal of simulated distribution system disinfection by-product precursors for the Aquasource UF membrane system.

Parameter		Unit	Raw Water	Filtrate	Percent Reduction
TEST PERIOD 1					
Organic Material					
	TOC [1]	mg/L	2.5	2.4	4.0
	UV254 Unfiltered [1]	/cm	0.070	0.060	14
SDS DBP					
	Bromoform	ug/L	0.7	0.65	
	Dibromochloromethane	ug/L	28.1	26.2	
	Bromodichloromethane	ug/L	12	12.2	
	Chloroform	ug/L	32.6	31	
	Total THMs	**ug/L**	**73.4**	**70.1**	**4.6**
	Monobromoacetic Acid	ug/L	< 0.1	< 0.1	
	Dibromoacetic Acid	ug/L	2.82	2.85	
	Monochloroacetic Acid	ug/L	< 0.3	< 0.3	
	Dichloroacetic Acid	ug/L	11.5	11	
	Trichloroacetic Acid	ug/L	8.92	7.24	
	Bromochloroacetic Acid	ug/L	7.47	7.23	
	HAA5[2]	**ug/L**	**23.2**	**21.1**	**9.3**

[1] median value
[2] Bromochloroactetic acid not included in HAA5 concentration value.

Parameter		Unit	Raw Water	Filtrate	Percent Reduction
TEST PERIOD 2					
Organic Material					
	TOC [1]	mg/L	3.6	3	17
	UV254 Unfiltered [1]	/cm	0.070	0.060	14
SDS DBP					
	Bromoform	ug/L	1.18	1.72	
	Dibromochloromethane	ug/L	22	22.6	
	Bromodichloromethane	ug/L	13.1	14.2	
	Chloroform	ug/L	32.3	28.6	
	Total THMs	**ug/L**	**68.6**	**67.1**	**2.1**
	Monobromoacetic Acid	ug/L	< 0.5	< 0.5	
	Dibromoacetic Acid	ug/L	3.3	3.68	
	Monochloroacetic Acid	ug/L	< 1	< 1	
	Dichloroacetic Acid	ug/L	12.6	11.3	
	Trichloroacetic Acid	ug/L	10.5	7.31	
	Bromochloroacetic Acid	ug/L	7.99	8.19	
	HAA5[2]	**ug/L**	**26.4**	**22.3**	**15**

[1] median value
[2] Bromochloroactetic acid not included in HAA5 concentration value.

Table 4-9. Review of manufacturer's operations and maintenance manual for the Aquasource UF membrane system.

O & M Manual	Grade *	Comment
Overall Organization	+	• The O&M manual is very well organized. The table of contents includes sections on definition of terms, a flow diagram, membrane characteristics, general discussion of production and backwash modes, installation, pre-operation checks, operation, operating settings, cleaning, alarms, maintenance and definition of calculated parameters
Operations Sections	+	• Since most modifications to system settings are performed from the Allen Bradley Touchscreen display, the operations sections focus on a description of all the screens available from this display, how to reach these screens, and how to modify settings within the screens • Operations sections include tables giving backwash time settings as a function of water temperature and backwash chlorine level as a function of water temperature and backwash frequency. • Manual includes a thorough description of membrane cleaning, but not all valve numbers referenced in the manual were identified on the ETV test unit
Maintenance Section	+	• Includes maintenance section organized by frequency of maintenance
Alarms	+	• Includes a description of alarm conditions and steps required to clear alarm conditions
Troubleshooting	-	• Manual does not include a troubleshooting section
Ancillary Equipment Information	-	• Component equipment manufacturers and model numbers were not included in the O&M manual
Drawings and Schematics	+	• Includes schematics of water flows during all operating modes • Schematics of the Allen Bradley PanelView display and all associated screens • The schematic of test unit flows, showing valve and pump locations and numbers, in section 6 should include all automatic and manual valves
Use of Tables	+	• Manual makes good use of tables including flow rate required to achieve a specified temperature corrected flux, backwash time settings as a function of water temperature and minimum chlorine concentration as a function of water temperature

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

Table 4-9. Continued

O & M Manual	Grade	Comment
OVERALL COMMENT	+	• Overall, an excellent O&M manual. It is very well organized, concise, clear and complete • The manual includes an excellent use of graphics to assist the reader's understanding • The manual should include as an appendix a list of components used on the on the test unit such as pumps, flow meters, valves and pressure gauges including manufacturer and model number • The manual referenced valve numbers on the test unit in discussions of operations and membrane cleaning. A number of these valves were not labeled on the unit tested, requiring a call to Aquasource personnel to clarify. To remedy this, the schematic of the test unit in section 6 should be modified to include all automated and manual valves

Table 4-10. Efficiency of the Aquasource UF membrane system.

Parameter	Unit	Value
ELECTRICAL USE		
Voltage	Volt - three phase	240
Feed Pump Current	Amp	2.0
Feed Pump Power	Watt	470
WATER PRODUCTION		
Transmembrane Pressure	psi	7.0
	Pa	4.8E+04
Flow Rate	gpm	6.4
	m3/s	4.0E-04
Power	Watt	19
EFFICIENCY	%	**4.1%**

Table 4-11. Chemical consumption for the Aquasource UF membrane system.

	Unit	Value
Backwash Chlorine [1]		
Average Chlorine Dose	mg/L	7.2
Stock Chlorine Concentration	%	10
Average Backwash Volume	gal (L)	24 (89)
Chlorine Stock Volume per Backwash	mL	6.5
Backpulse Per Day	#	48
Stock Chlorine Use Per Day	Gal (L)	0.08 (0.31)
Cleaning Chemicals		
U43 Prewash	lb (kg)	2.7 (1.2)
U43 Wash	lb (kg)	2.7 (1.2)
U59 Wash [2]	lb (kg)	3.0 (1.4)

[1] Based on average chlorine dose and average backwash volume

[2] U59 wash conducted only if significant fouling remains following U43 wash

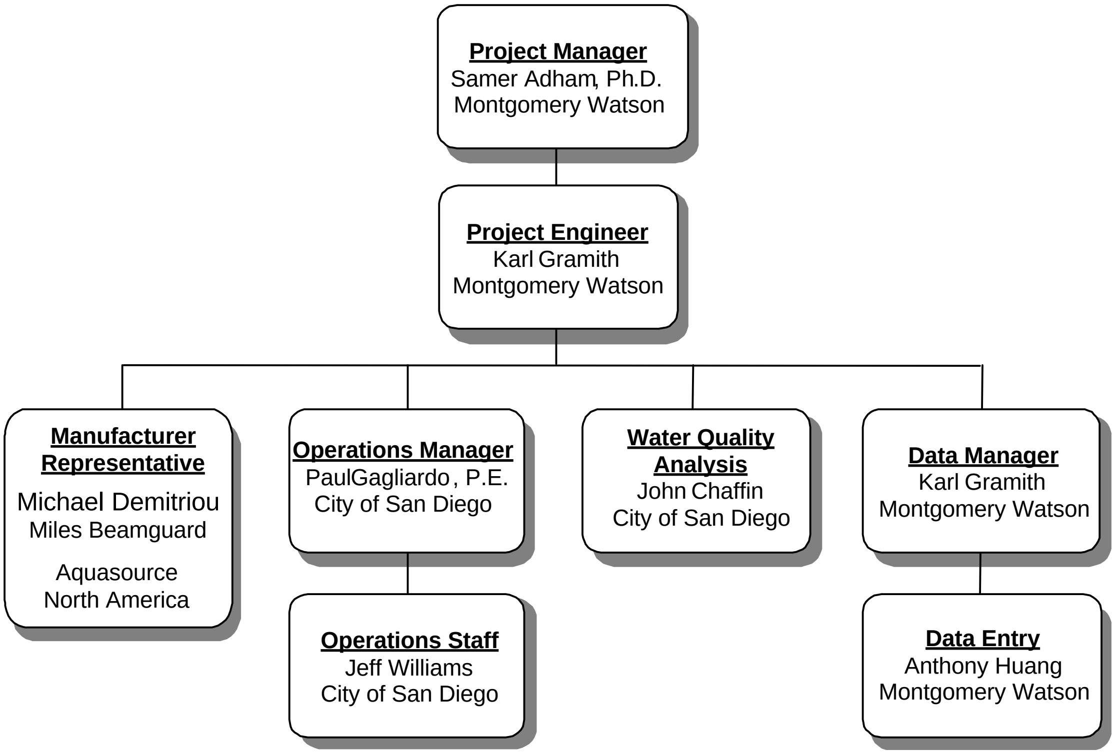


Figure 1-1. Organizational chart showing lines of communication.

Figure 2-1. Photograph of the ETV test unit.

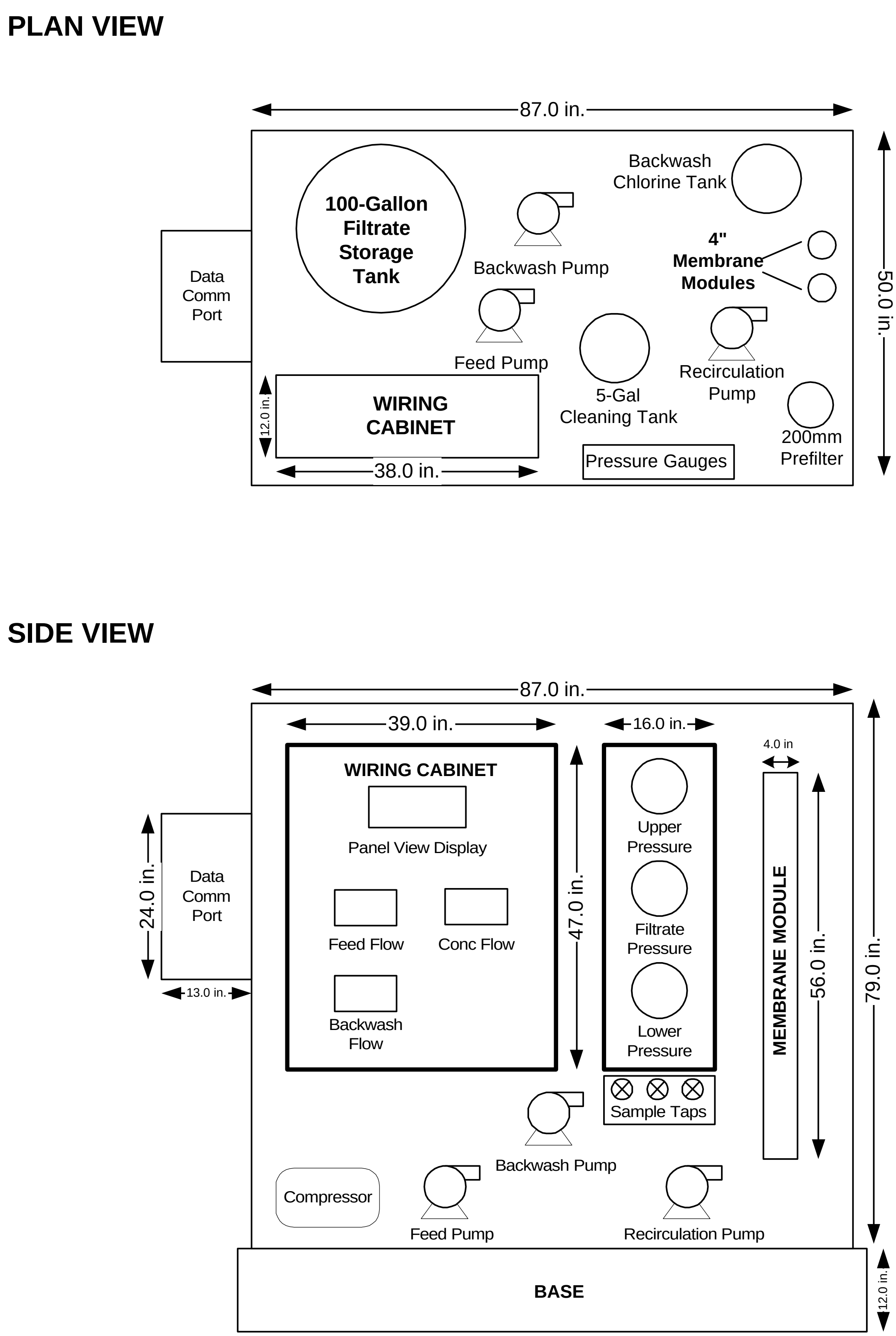


Figure 2-2. Spatial requirements for the Aquasource UF unit.

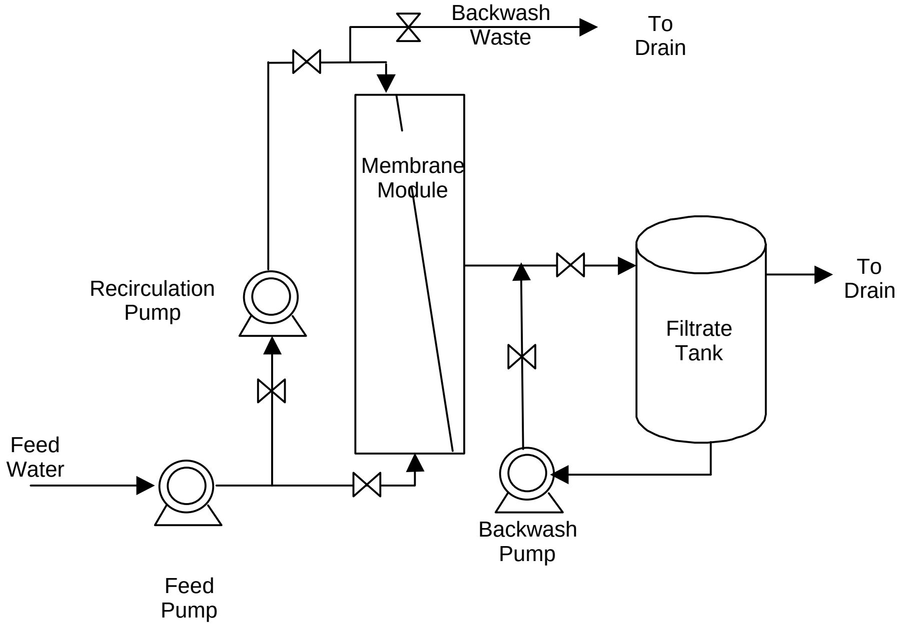


Figure 2-3. Schematic diagram of the Aquasource UF membrane process.

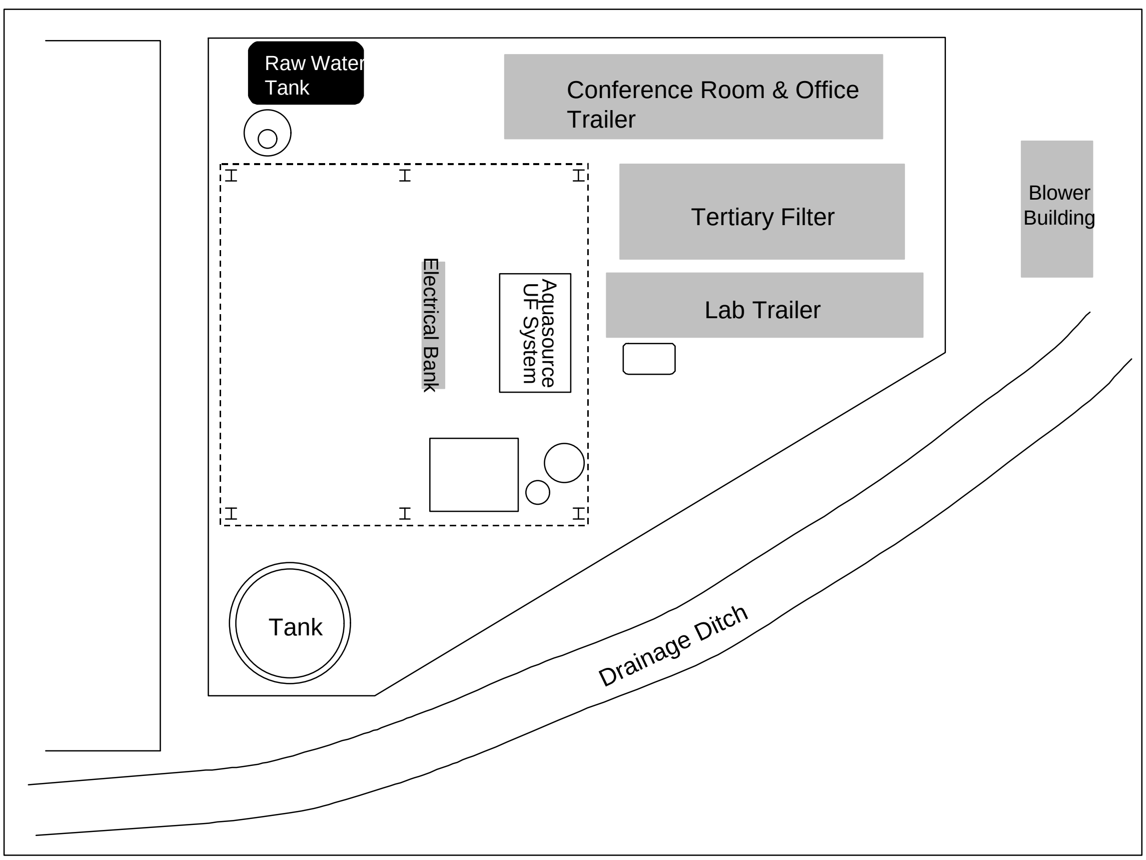


Figure not drawn to scale.

Figure 3-1. Schematic of Aqua 2000 Research Center test site.

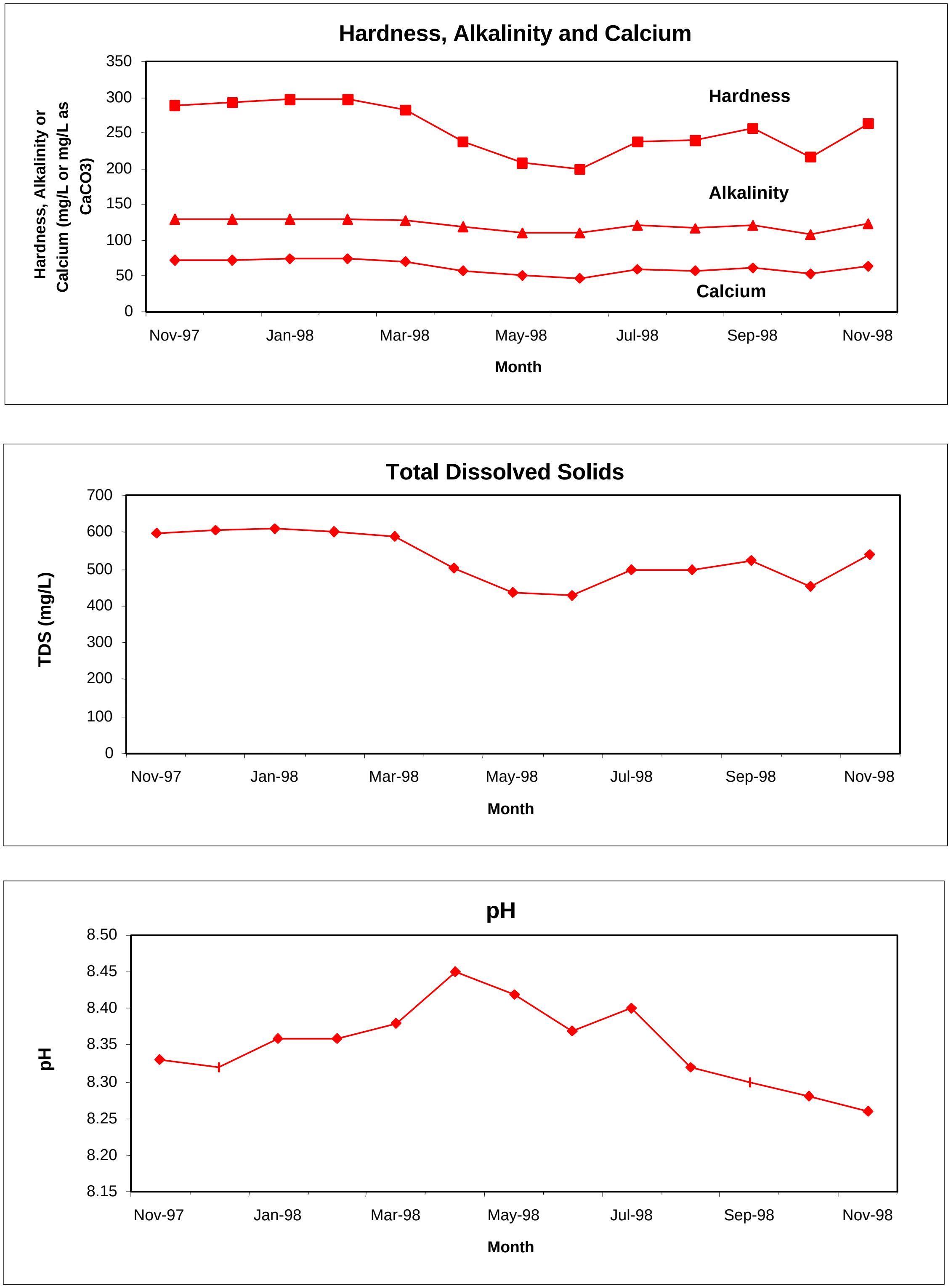


Figure 3-2. Lake Skinner raw water quality.

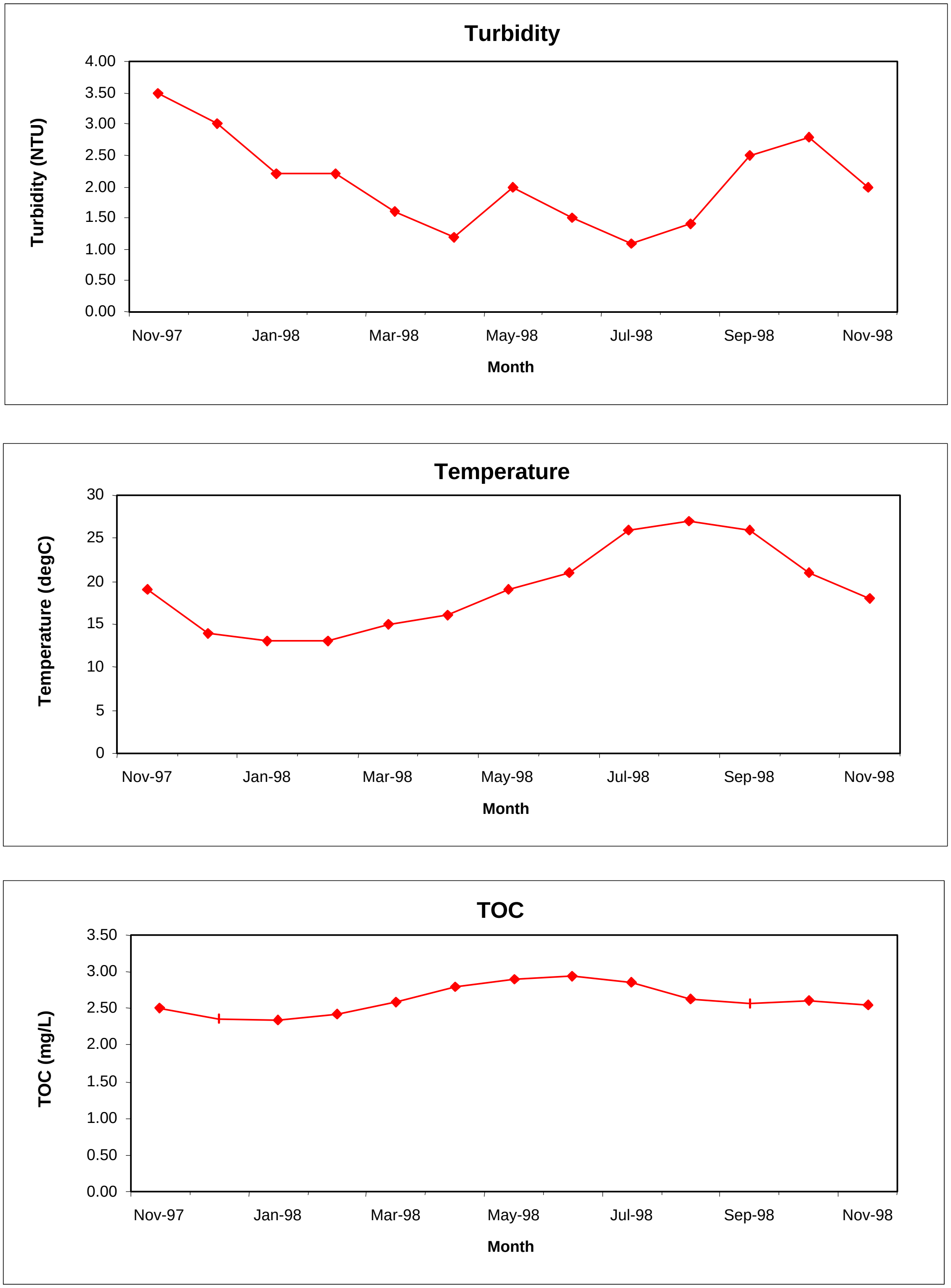


Figure 3-3. Lake Skinner raw water quality.

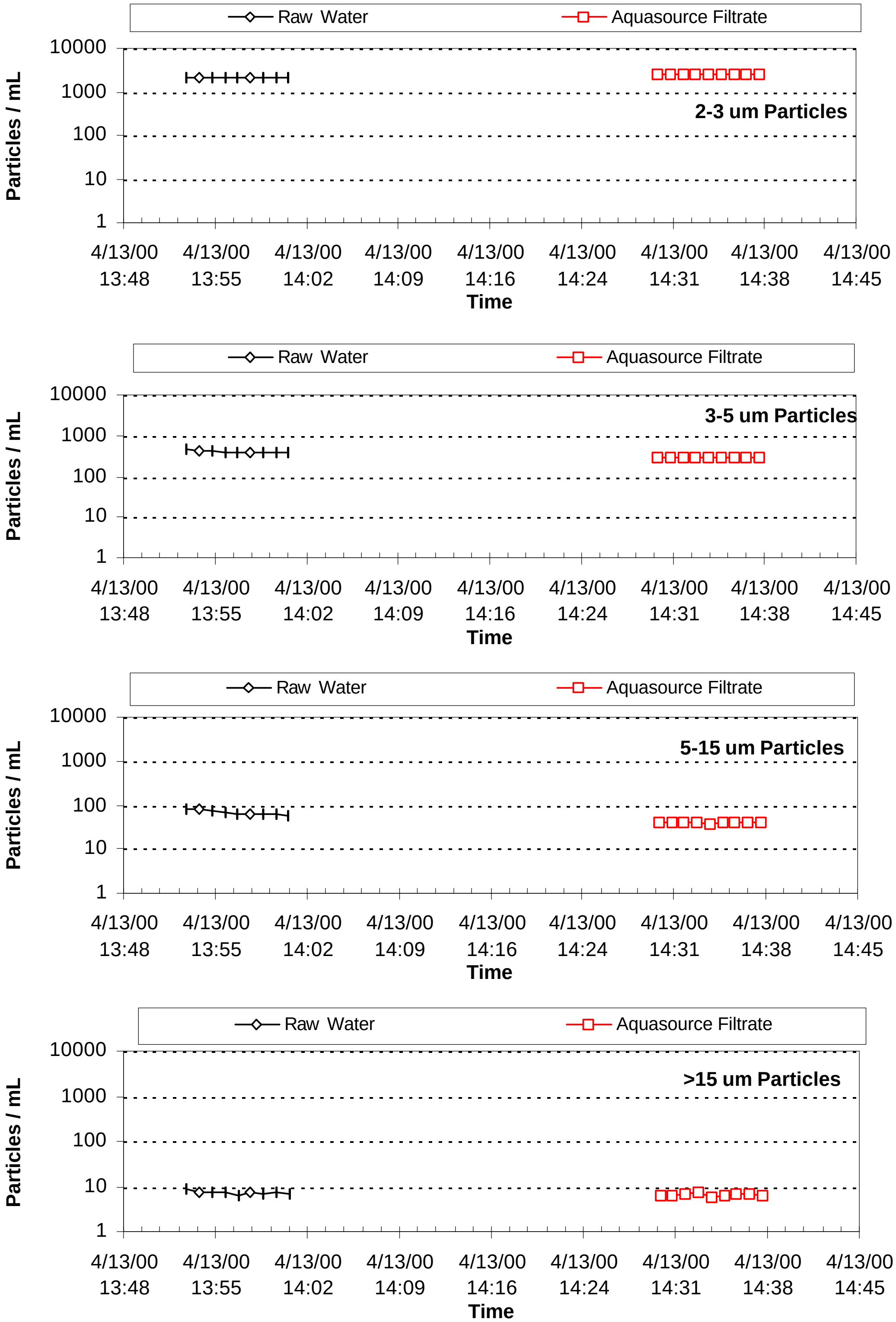


Figure 3-4. Response of online particle counters to Duke Monosphere Solution.

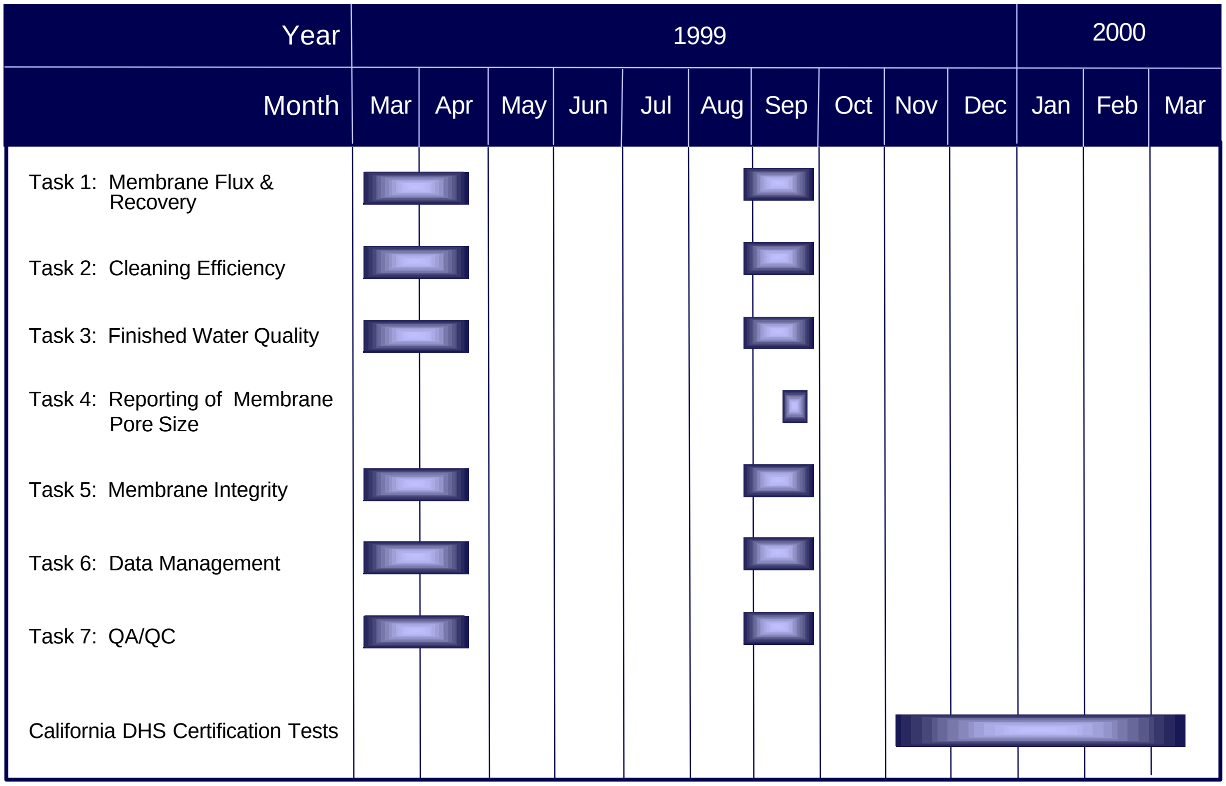
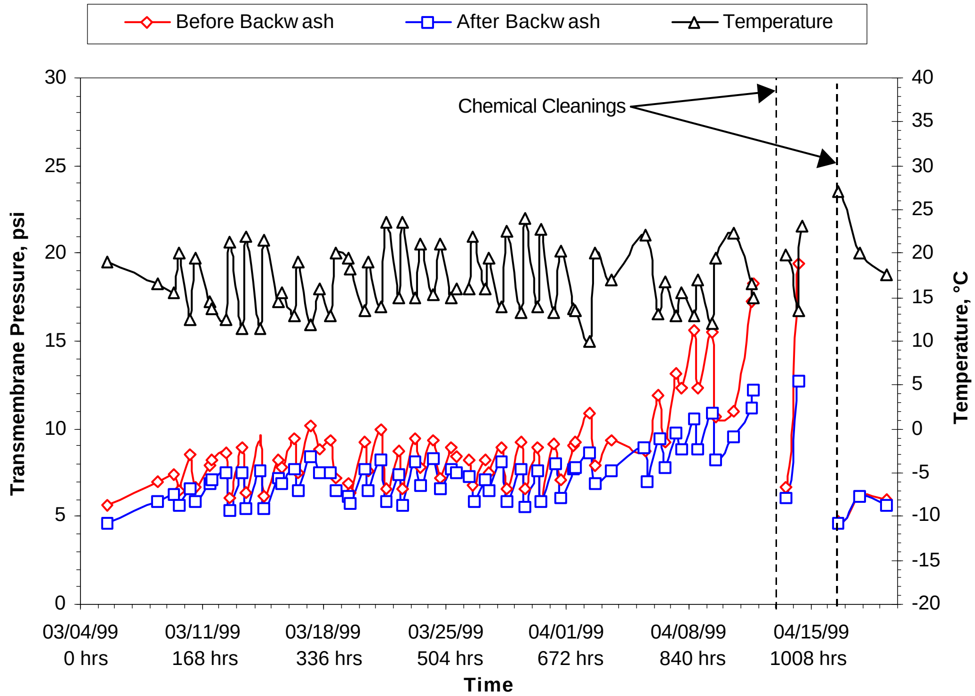
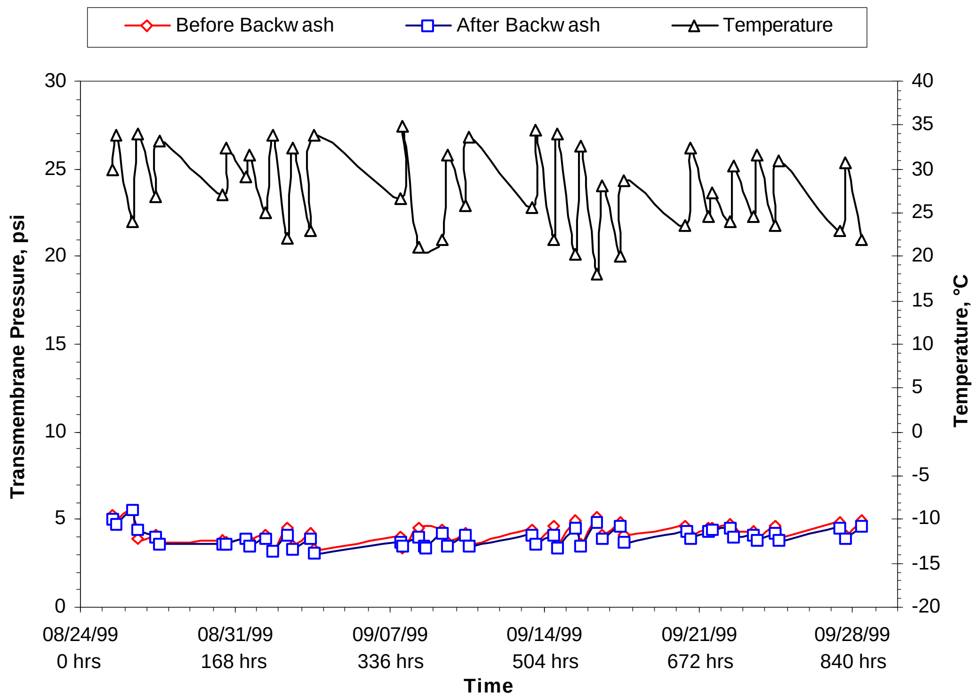


Figure 3-5. Membrane verification testing schedule.

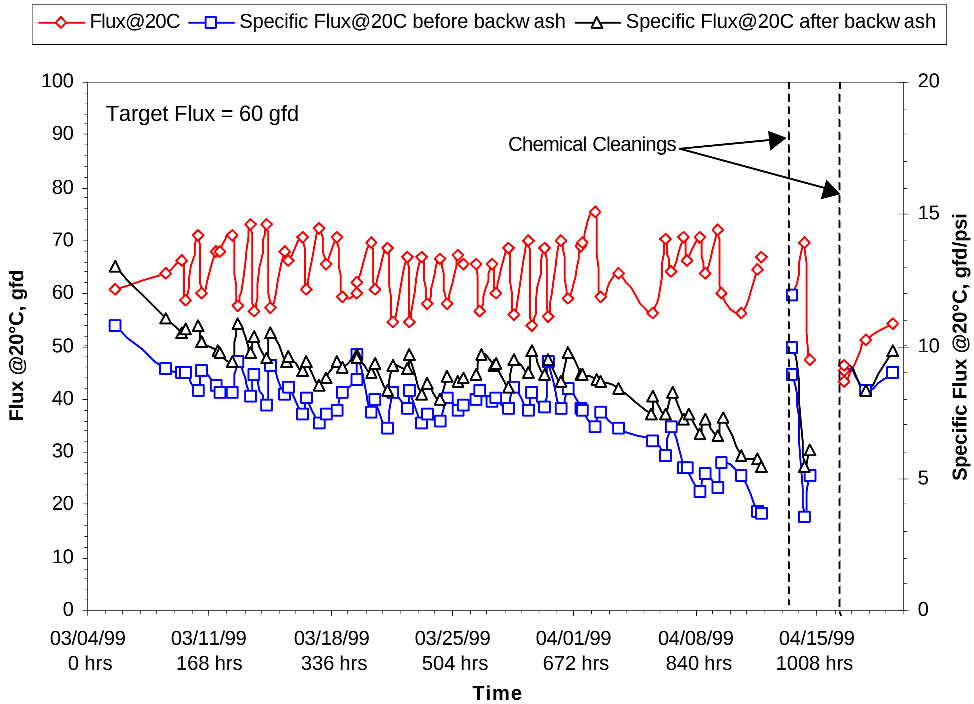


A – Test Period 1.

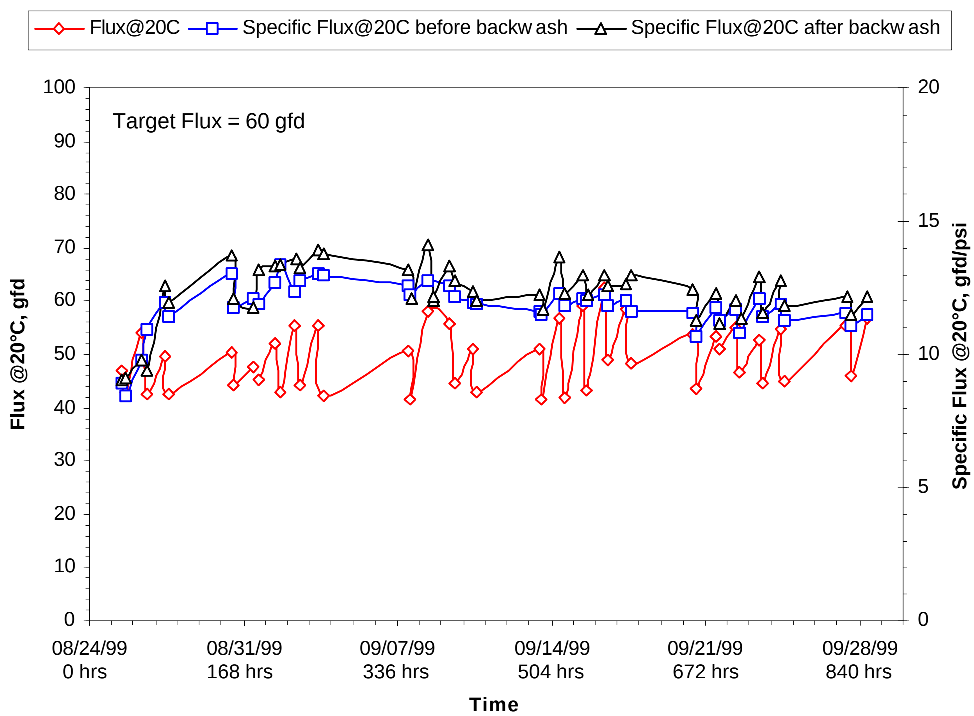


B – Test Period 2.

Figure 4-1. Transmembrane pressure and temperature profiles for the Aquasource UF membrane system.

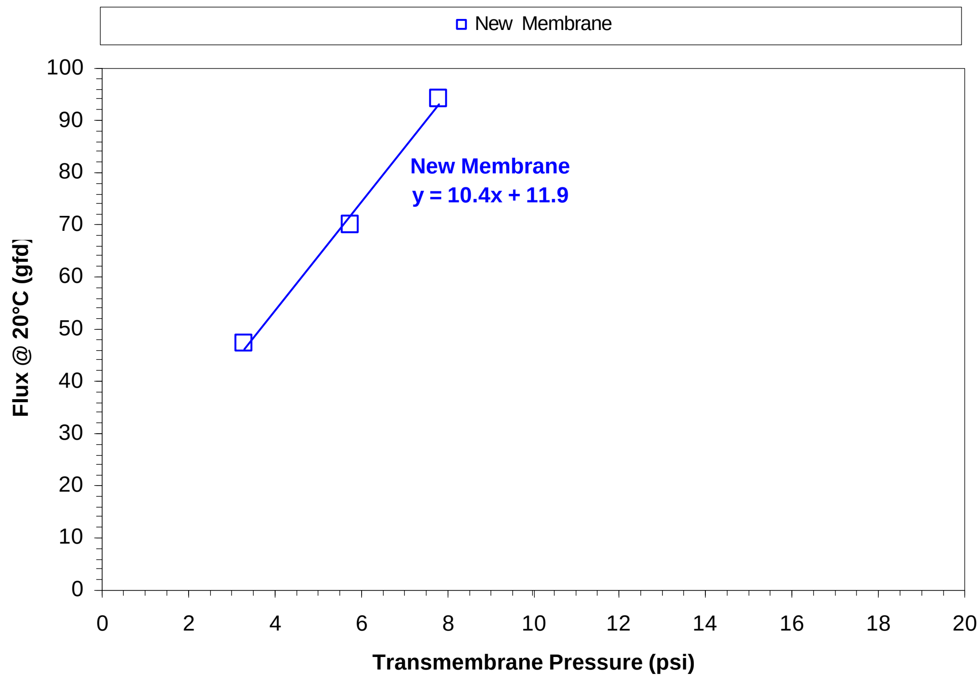


A – Test Period 1.

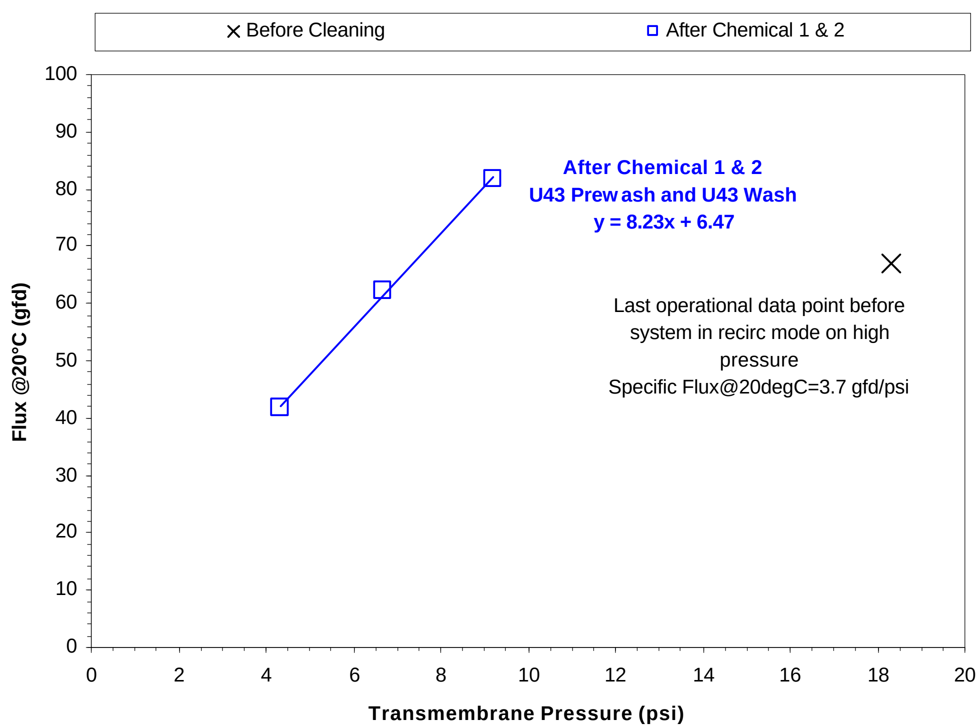


B – Test Period 2.

Figure 4-2. Operational flux and specific flux profiles for the Aquasource UF membrane system.

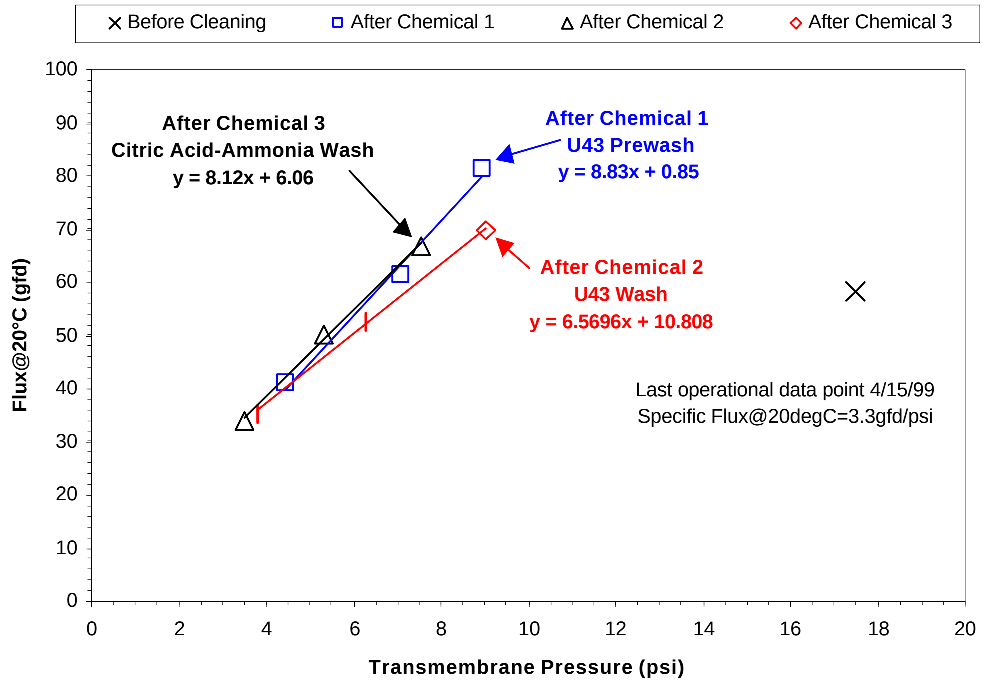


A – New membrane: start of Test Period 1.



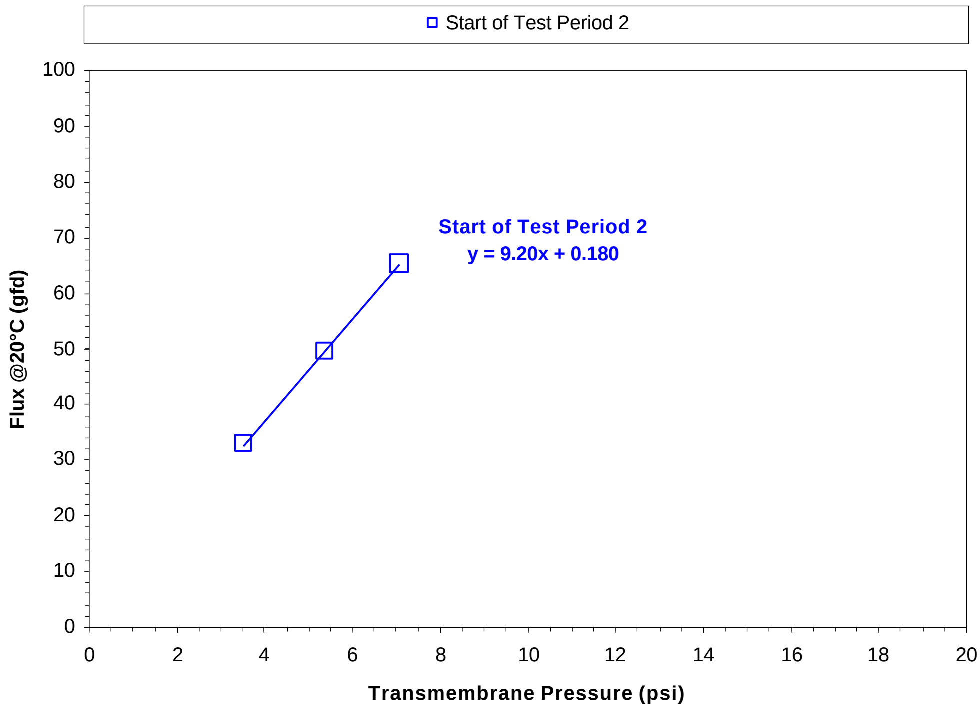
B – Test Period 1: cleaning 1-1 (4/13/99).

Figure 4-3. Clean water flux profile during membrane chemical cleanings – Test Period 1.

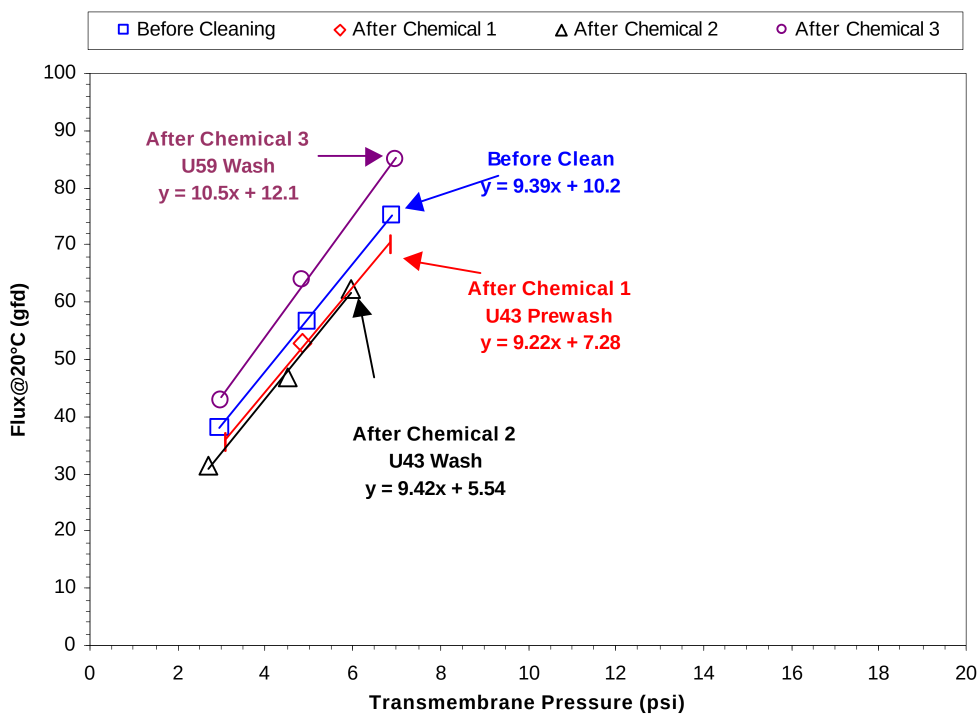


C –Test Period 1: cleaning 1-2 (4/16/99).

Figure 4-3. Continued.



A – Clean membrane: start of Test Period 2.



B – Test Period 2: cleaning 2-1 (9/28/99).

Figure 4-4. Clean water flux profile during membrane chemical cleanings – Test Period 2.

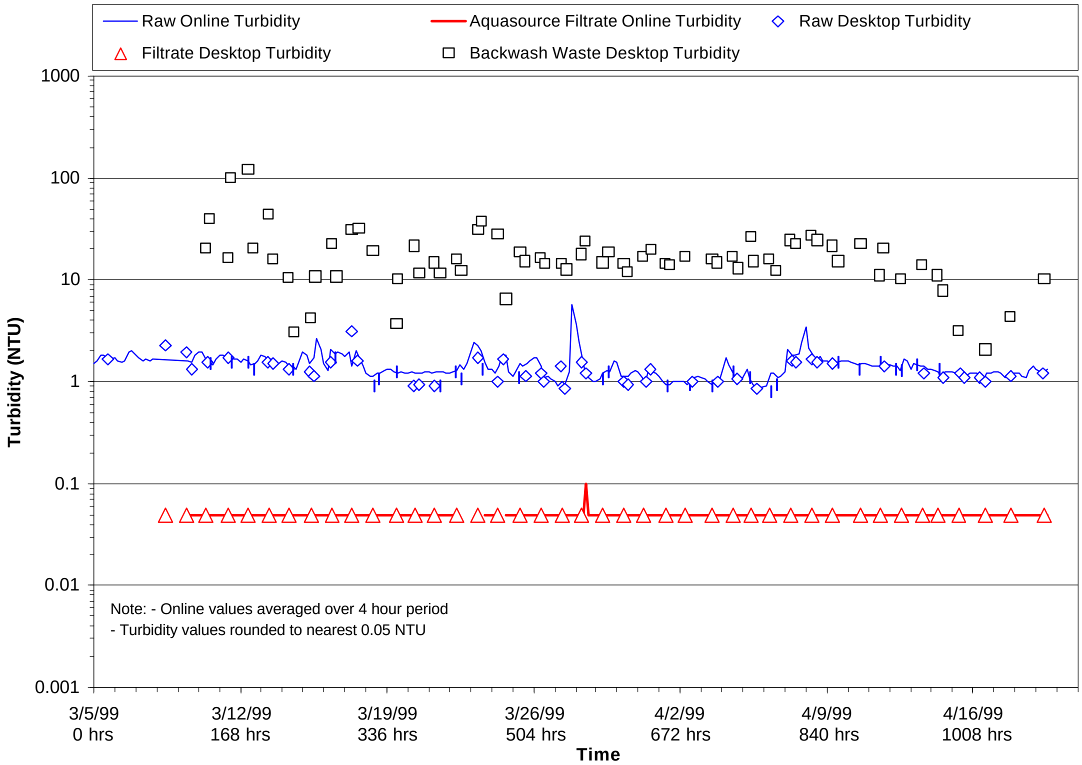


Figure 4-5. Turbidity profile for raw water and Aquasource UF membrane system – Test Period 1.

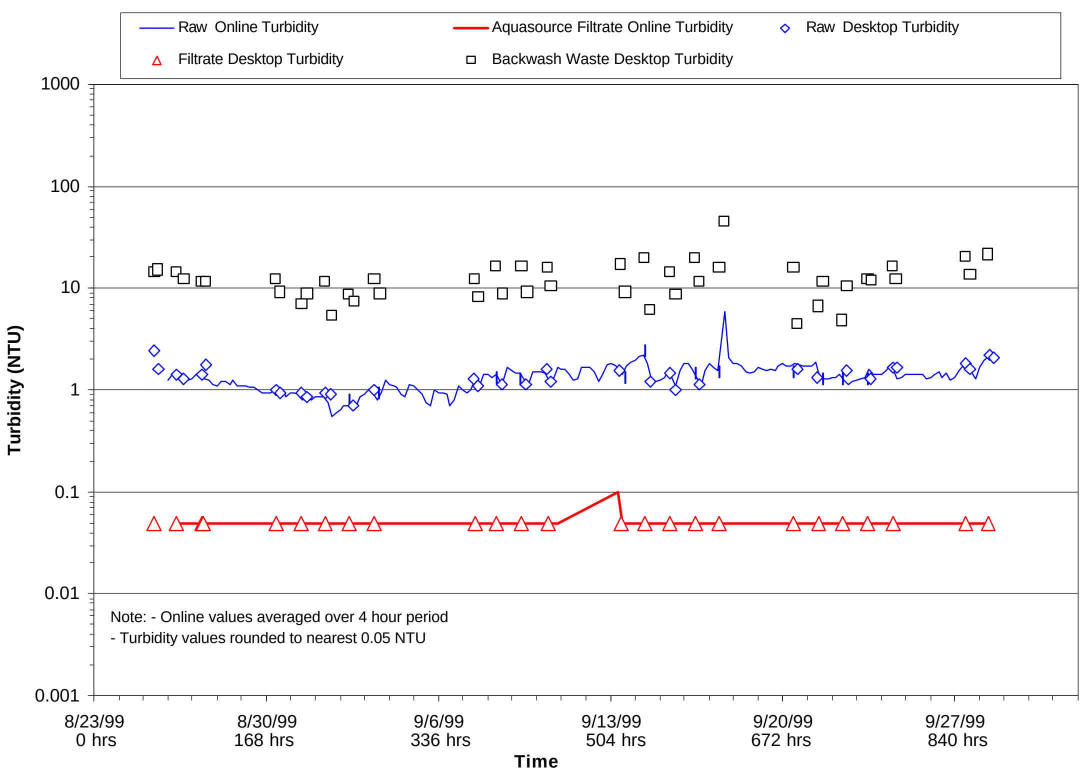
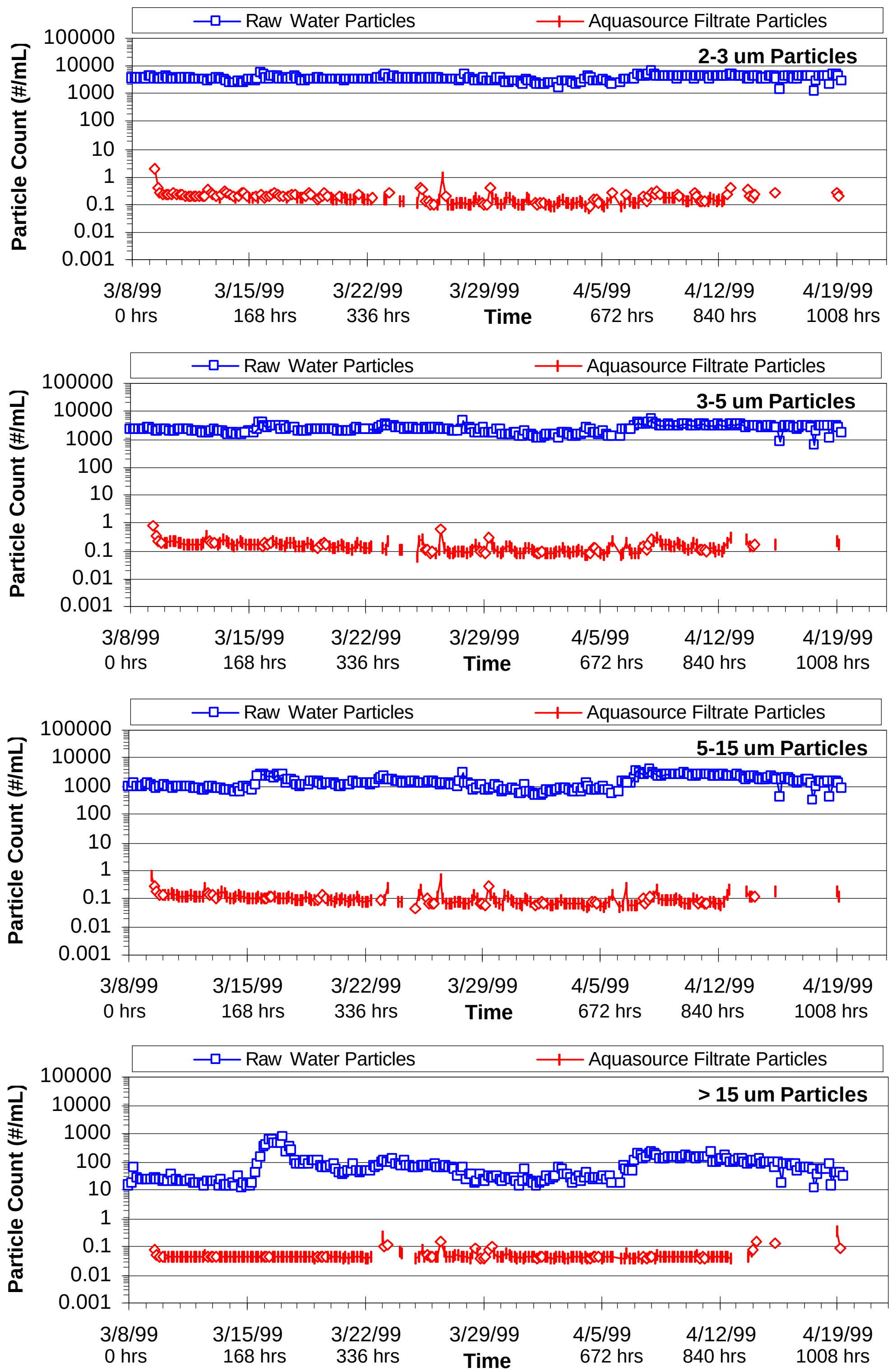
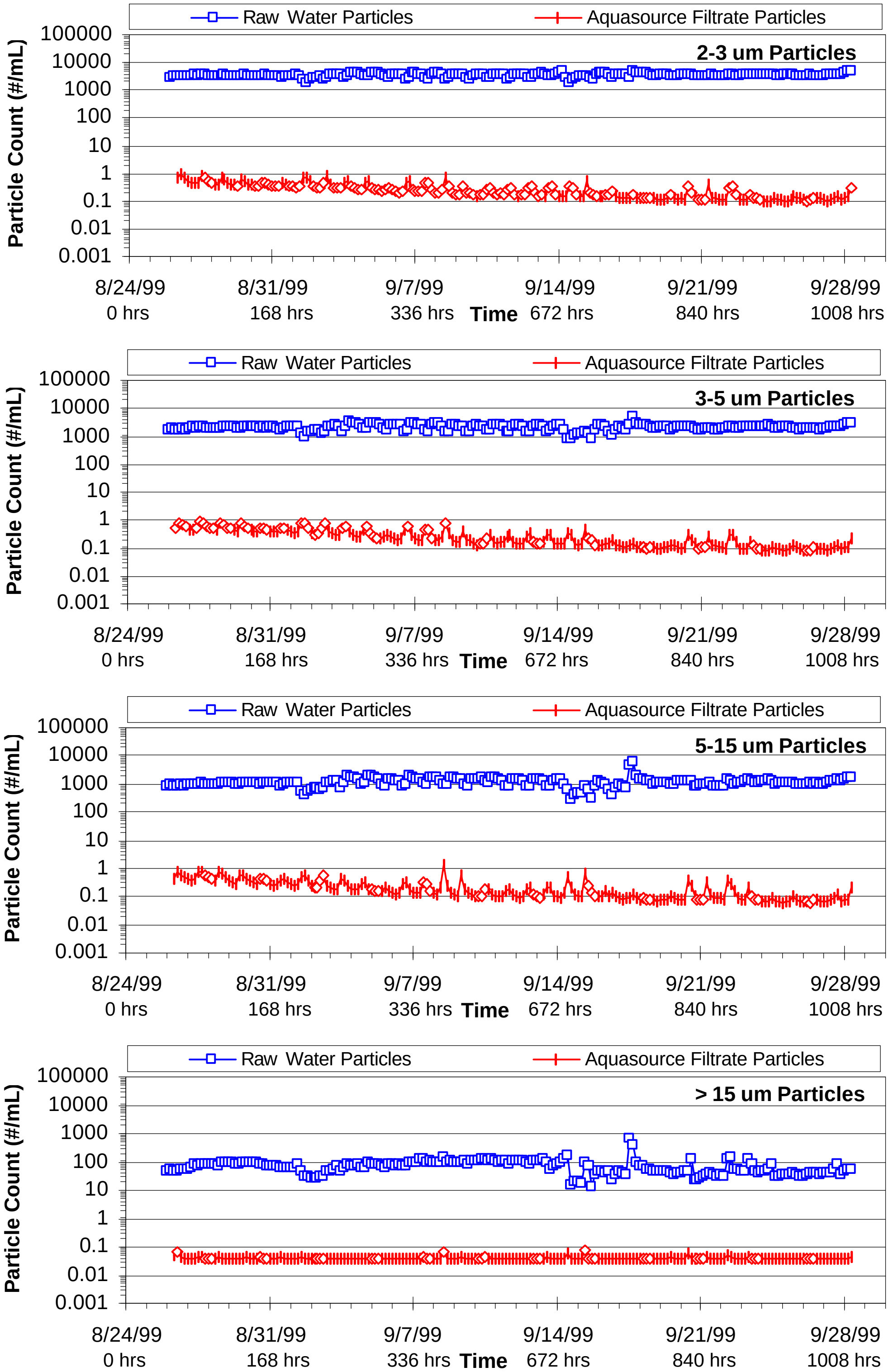


Figure 4-6. Turbidity profile for raw water and Aquasource UF membrane system – Test Period 2.



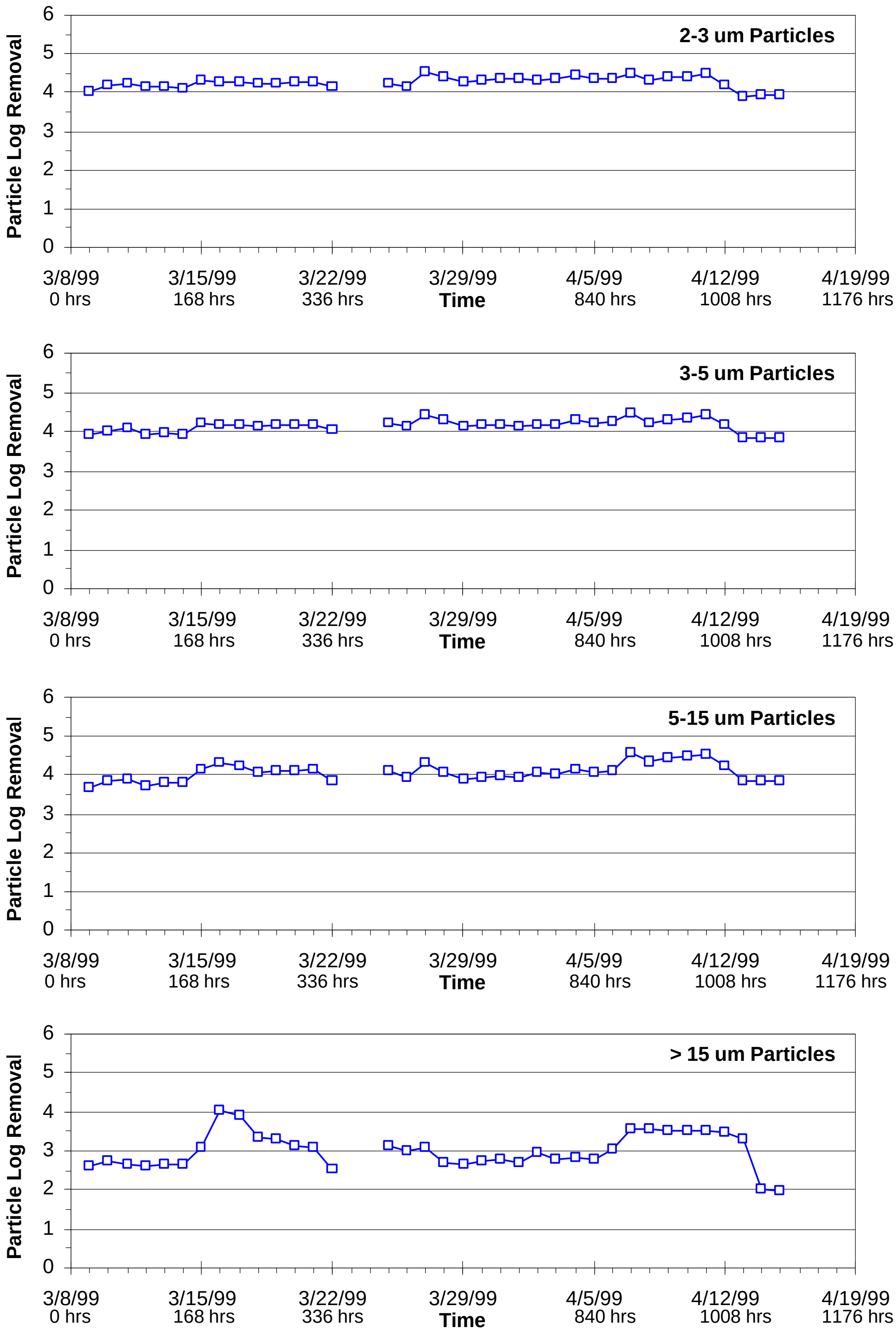
Note: Online values averaged over 4-hour period. Gap in data at 3/24/99 due to filtrate contamination, gap in data at end of test period due to 2 shutdowns for chemical cleaning.

Figure 4-7. Particle count profile for raw water and Aquasource UF system filtrate – Test Period 1.



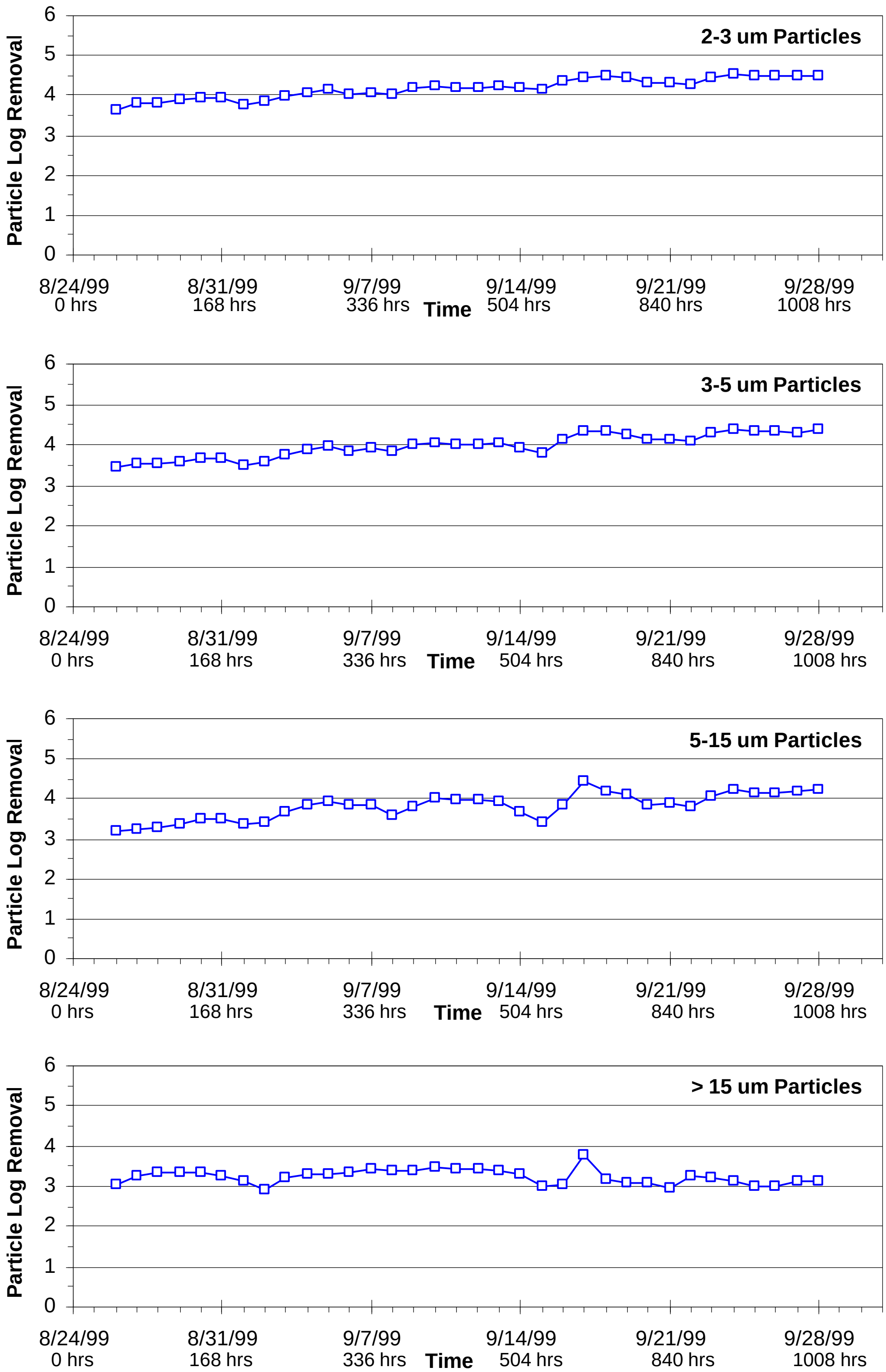
Note: Online values averaged over 4-hour period.

Figure 4-8. Particle count profile for raw water and Aquasource UF system filtrate – Test Period 2.



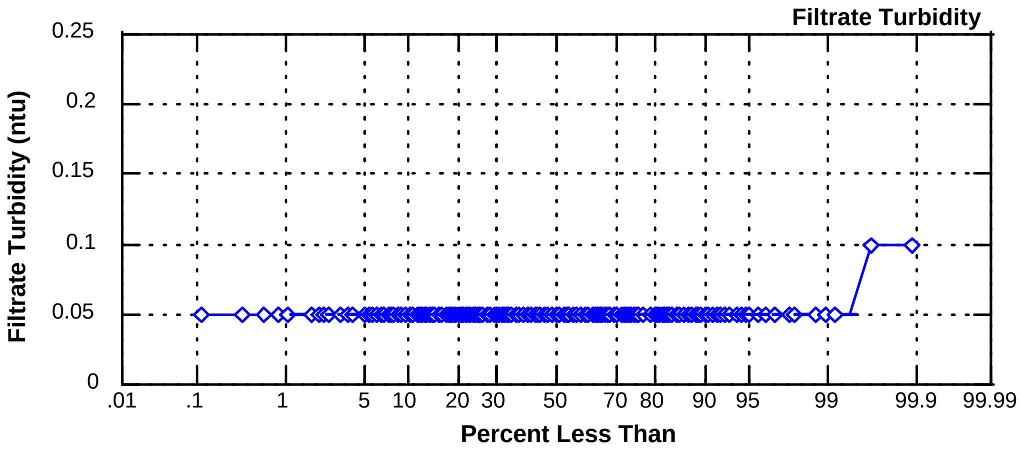
Note: Online values averaged over 1-day period. Gap in data at 3/24/99 due to filtrate contamination, gap in data at end of test period due to 2 shutdowns for chemical cleaning.

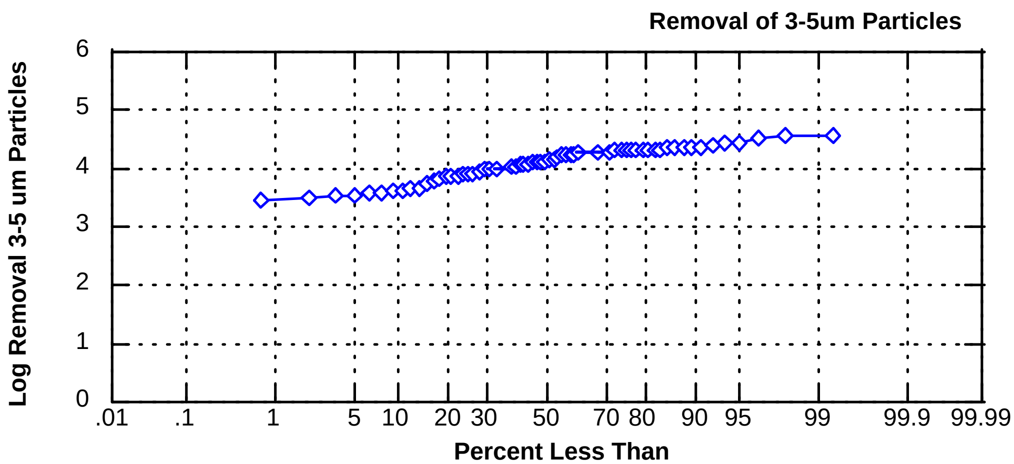
Figure 4-9. Particle removal for Aquasource UF system – Test Period 1.



Note: Online values averaged over 1-day period.

Figure 4-10. Particle removal for Aquasource UF system – Test Period 2.





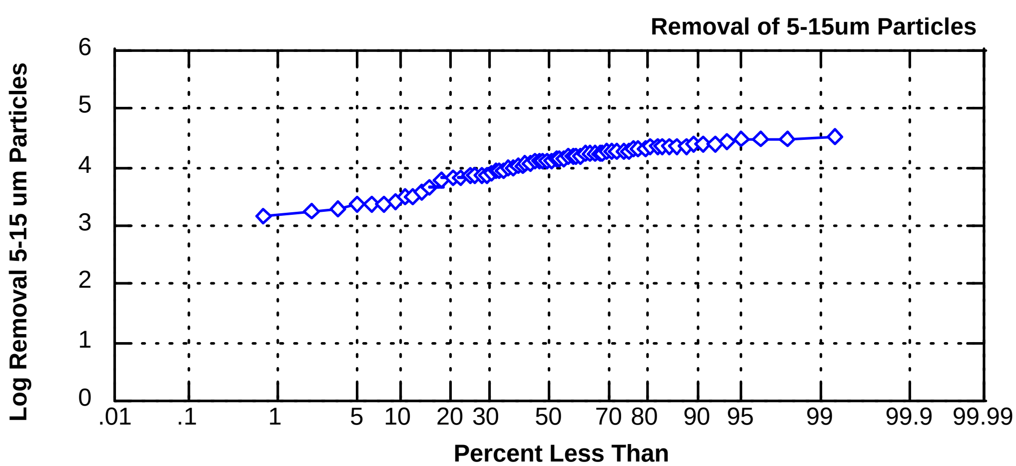
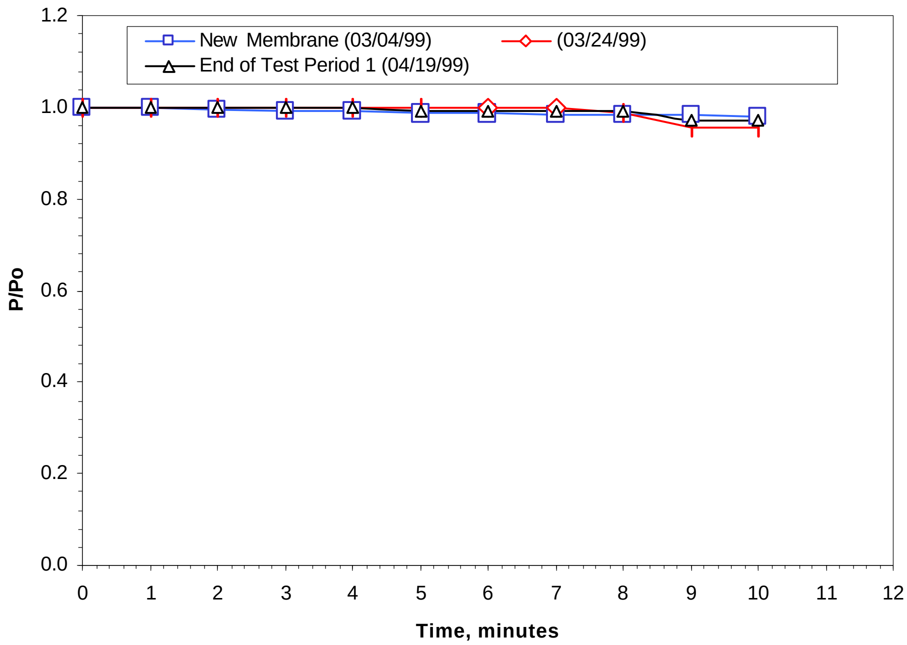
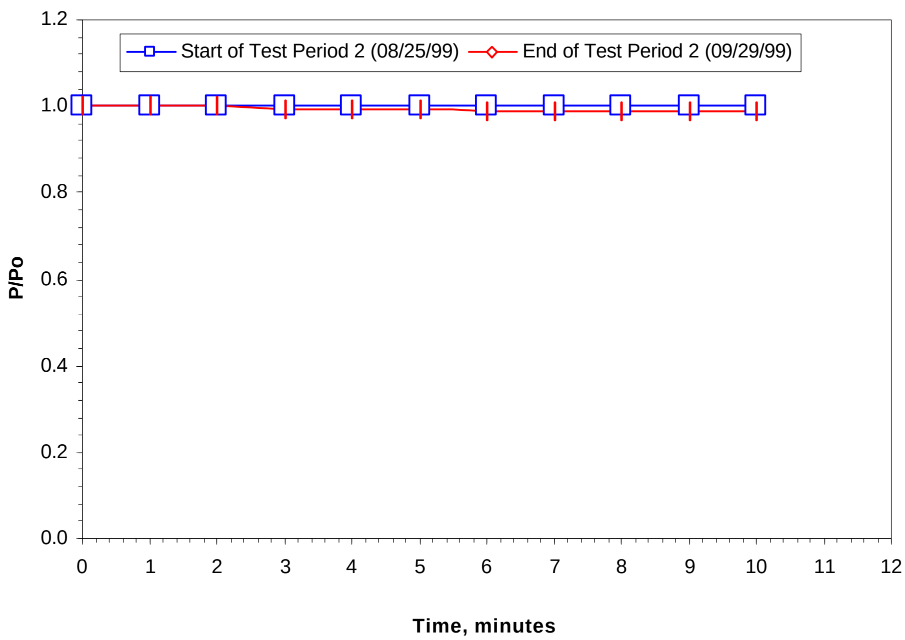


Figure 4-11. Probability plots of filtrate turbidity and log removal of particles for the Aquasource UF membrane system.



A – Test Period 1.



B – Test Period 2.

Figure 4-12. Air pressure hold test results for the Aquasource UF membrane system.