May 2000
NSF 00/07/EPADW395

# Environmental Technology Verification Report

## Physical Removal of *Cryptosporidium* oocysts and *Giardia* cysts in Drinking Water

## Aquasource North America Ultrafiltration System Model A35 Pittsburgh, PA

Prepared by

NSF International

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

**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: | ***GIARDIA* AND *CRYPTOSPORIDIUM* REMOVAL** | | |
| TECHNOLOGY NAME: | **MODEL A35 ULTRAFILTRATION SYSTEM** | | |
| TEST LOCATION: | **PITTSBURGH, PA** | | |
| COMPANY: | **AQUASOURCE NORTH AMERICA** | | |
| ADDRESS: | **2924 EMERYWOOD PARKWAY**<br>**RICHMOND, VA 23060** | PHONE:<br>FAX: | **(804) 672-8160**<br>**(804) 672-8135** |
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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 Package Drinking Water Treatment Systems (PDWTS) program, one of 12 technology areas under ETV. The PDWTS program recently evaluated the performance of a membrane filtration system used in package drinking water treatment system applications. This verification statement provides a summary of the test results for the Aquasource North America Model A35 Ultrafiltration System. Gannett Fleming, Inc., an NSF-qualified field testing organization (FTO), performed the verification testing.

## ABSTRACT

Verification testing of the Aquasource Ultrafiltration Treatment System Model A35 was conducted from December 1 to December 31, 1998. The treatment system underwent microbial challenge testing on January 22, 1999, and demonstrated a 5.5 $log_{10}$ removal of *Giardia* cysts and a 6.5 $log_{10}$ removal of *Cryptosporidium* oocysts. Source water characteristics were: turbidity average 0.078 Nephlometric Turbidity Units (NTU), pH 8.5, and temperature 8.0°C. During the thirty-day verification test, the system was operated at a flux recommended by the manufacturer of 112 liter per square meter per hour ($l/m^2/h$) (65.9 gallon per square foot per day [gfd]) at 8.0°C which equates to 155 $l/m^2/h$ at 20 °C (91.2 gfd at 68°F). The average transmembrane pressure was 0.65 bar (b) (9.4 pounds per square inch [psi]). The feed water recovery of the treatment system during the study was 94%. Chemical cleaning of the treatment system was conducted as part of the verification testing.


## TECHNOLOGY DESCRIPTION

Ultrafiltration (UF) processes are generally used to remove microbial contaminants such as *Giardia* and *Cryptosporidium* and other particulate contaminants from drinking water. The Aquasource UF membrane is a hollow fiber made of cellulose acetate. It has a 0.02µm nominal pore size and utilizes inside-out flow. Water is applied under pressure to the inside of the hollow fiber membrane. The membrane consists of a thin film acting as a sieve. The membrane is a physical barrier, providing removal of particulate contaminants. Permeate (filtered water) is collected from the outside of the fiber and carried to the permeate outlet.

The Aquasource Ultrafiltration Treatment System Model A35 system is a skid mounted, stand alone system. The required connections are for the water supply, a sewer connection for the discharge of backwash and chemical cleaning wastes and electrical service. The treatment system consists of two membrane modules, supply pump, backwash reservoir and pump, chemical cleaning equipment and necessary gauges and controls. The unit is equipped with a 200 µm prefilter to remove large debris from the feed water prior to introduction to the membranes. The treatment system is capable of operating in an automatic mode with limited operator intervention.

For this test program, a dead end flow configuration was used. The particles that are removed from the feed water clog the hollow fiber membrane. At a preset time, determined by raw water quality, the treatment system was backwashed. This was accomplished by reversing the flow direction and forcing the permeate back through the fibers from outside to inside. The permeate was chlorinated using a small diaphragm pump which adds sodium hypochlorite to the permeate prior to backwash. During backwash, the particles were removed and the backwash water was carried to waste.

## VERIFICATION TESTING DESCRIPTION

### *Test Site*

The verification testing site was the Pittsburgh Water and Sewer Authority's (PWSA's) open air Highland Reservoir No. 1, Pittsburgh, Pennsylvania. The source water for the verification testing was treated surface water drawn from the Allegheny River. It underwent coagulation with ferric chloride, sedimentation, filtration, and disinfection using free chlorine at PWSA's Aspinwall treatment plant prior to being pumped to the Highland Reservoir No. 1. The influent to the treatment unit was drawn from the reservoir effluent lines. The verification testing was limited to the performance of the equipment to remove *Cryptosporidium* oocysts and *Giardia* cysts, because the source water was obtained from an open reservoir.

***Methods and Procedures***

All field analyses (i.e. pH, turbidity, chlorine residual, temperature) were conducted daily using portable field equipment according to Standard Methods for the Examination of Water and Waste Water, 18th Ed., (APHA, et. al., 1992). Likewise, Standard Methods, 18th Ed., (APHA, 1992) and Methods for Chemical Analysis of Water and Wastes (EPA, 1979) were used for analyses conducted in PWSA's laboratory. These analyses included total alkalinity, total hardness, total organic carbon (TOC), dissolved organic carbon (DOC), total dissolved solids (TDS), total suspended solids (TSS), algae (number and species), Ultraviolet Absorbance at 254 nanometers ($UVA_{254}$), total coliform, and heterotrophic plate counts (HPC). Total alkalinity, total hardness and TDS analyses were conducted monthly. All other laboratory parameters were analyzed weekly.

Microbial challenge was performed using *Giardia* cysts and *Cryptosporidium* oocysts. Procedures developed by EPA for use during the Information Collection Rule (ICR) were employed for the identification and enumeration of *Giardia* cysts and *Cryptosporidium* oocysts (EPA, ICR Microbial Laboratory Manual, EPA, April 1996). The protozoans were added to a fifty (50) gallon (190 liter) drum. This drum was filled with the feed water. A total of 8,720,000 of *Giardia* cysts and 91,770,000 of *Cryptosporidium* oocysts were added to the feed water reservoir. The turbidity of the feed water was 0.09 NTU during the microbial removal challenge testing. This stock suspension was constantly mixed using a drum mixer. A diaphragm pump was used to add the protozoans to the membranes on the pilot unit. The pump was operated at about 0.85 gallons per minute (gpm), (3.2 liter per minute) and was capable of overcoming the pressure in the feed water line of the pilot unit. Samples of the permeate were collected using a polypropylene wound filter with a nominal pore size of 1.0 µm. One thousand liters (264 gallons) of permeate water was filtered through the sampling vessel at one gpm (3.8 liter per minute). In addition, aliquots of the stock suspension were collected and analyzed to calculate concentrations of the microbes in the feed water. Backwash was delayed until the end of the collection period. Samples of the backwash were collected and analyzed to verify that the parasites were added to the system and removed by the filters.

**VERIFICATION OF PERFORMANCE**

***System Operation***

The treatment system was fully automated and capable of normal operations without manual intervention. The unit automatically operates in the filtration and backwash modes. All operational data, flows, pressures, turbidity and particle counts were recorded on data logging software. Manual intervention was required for chemical cleaning and to occasionally refill the tank of sodium hypochlorite used during backwash. A representative of the manufacturer conducted daily checks of the system although this was not necessary for operational control.

The flux selected by the manufacturer for the ETV study was 112 liter per square meter per hour ($l/m^2/h$) (65.9 gallon per square foot per day [gfd]) at 8.0°C which equates to 155 $l/m^2/h$ at 20 °C (91.2 gfd at 68°F). The flow rate was recorded twice per day and the water temperature was recorded once per day. The flow rate of the treatment system averaged 26.8 liter per minute (lpm) (7.09 gallon per day [gpm]).

The average feed pressure was 0.84 b (12 psi). The average filtrate pressure was 0.20 b (2.9 psi). The amount of pressure lost as the water is filtered through the membrane is referred to as transmembrane pressure (TMP). It is calculated by averaging the feed water pressure and the retentate pressure and subtracting the filtrate pressure from that average. The average TMP for the system was 0.65 b (9.4 psi). For this test program, a filtration cycle of 60 minutes was used. Every 60 minutes the system was backwashed. Each backwash required 60 minutes to complete; 15 seconds for various valve operations

and 45 seconds for the backwash itself. Approximately 25 gallons (95 liters) of permeate were used to backwash the membranes.

The feed water recovery of the treatment system during the study was 94%. This figure was calculated by comparing the amount of water needed to backwash the membranes to the total amount of water filtered by the system.

The effectiveness of the chemical cleaning process was measured by the recovery of specific flux and loss of original specific flux. Chemical cleaning was conducted at the end of the test period as required by the ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contamination (EPA/NSF April, 1998). Data collected before and after the chemical cleaning was used to calculate recovery of specific flux and the loss of original specific flux. Since the membrane had not accumulated a significant amount of material that could not be removed with backwashing due to the high quality of the feed water, the recovery of specific flux cleaning was negligible. Data from the beginning of the thirty-day testing period and just prior to cleaning was used to calculate the loss of original specific flux. The loss was 10 %.

System integrity was demonstrated as required by the ETV protocol. Tests were conducted on an intact membrane system and on one that had been intentionally compromised. The air pressure hold test detected a compromised membrane.

***Water Quality Results***

During the microbial challenge testing that occurred on January 22, 1999, the Aquasource Model A35 UF System demonstrated a 5.5 $\log_{10}$ removal of *Giardia* cysts and a 6.5 $\log_{10}$ removal of *Cryptosporidium* oocysts. The $\log_{10}$ removals were limited by the amount of the parasites which were present in the stock feed solution, the percentage of the permeate that could be sampled, and the percent recovery of the analytical methodology. There were no *Giardia* cysts or *Cryptosporidium* oocysts observed in the permeate. During the microbial challenge testing, the feed water characteristics were: turbidity average 0.09 NTU, pH 8.2, temperature 1.7 $^{o}$C.

During the thirty-day ETV operation of the Aquasource Model A35 UF System reductions were seen in HPC, algae, turbidity and particle counts. HPC averaged 260 CFU/100ml in the feed water and 11 CFU/100ml in the permeate. Algae concentrations averaged 90 cells/ml in the feed water and five cells/ml in the permeate. This reported average was the result of one cell observed in one of the four samples with a level of detection of eight cells/ml. The presence of HPC and algae in the permeate may have been due to the inability to completely disinfect the Tygon sample lines. The average turbidity concentration in the feed water was 0.078 NTU and 0.022 NTU in the permeate. Particle counts were reduced from an average of 86 total counts/ml in the feed water to an average 0.56 total counts/ml in the permeate. A reduction in TSS of 0.075 mg/l on average was observed. This represented a 50% reduction in TSS, although given the low concentration of TSS in the feed water it may be hard to extrapolate this percent removal to other locations. Total coliform reduction could not be demonstrated due to the absence of total coliforms in the feed water and permeate throughout the test.

Temperature of the feed water during the thirty-day ETV study was somewhat variable with a high of 11.0$^{o}$C, a low of 3.2$^{o}$C, and an average of 8.0$^{o}$C. The membrane pilot unit had little or no effect on total alkalinity, total hardness, TDS, TOC and $UVA_{254}$. The following table presents the water quality reductions of the feed water and filtered water samples collected during the 30 days of operation:

**Feed Water Quality / Filtered Water Quality**
**Aquasource Model A35 UF Treatment System**

| | Total Coliforms (cfu/100 ml) | HPC (cfu/100 ml) | Algae (cells/ml) | Turbidity (NTU) | Particle Counts (particles/ml) |
|---|---|---|---|---|---|
| Average[1] | 0/0 | 260/11 | 90/5 | 0.078/0.022 | 86/0.56 |
| Minimum[1] | 0/0 | 70/2 | 40/<8 | 0.060/0.021 | ---- |
| Maximum[1] | 0/0 | 460/30 | 136/8 | 0.10/0.029 | ---- |
| Std. Dev.[1] | 0/0 | 160/13 | 39/2 | 0.011/0.0036 | ---- |
| 95% Confidence Interval[1] | N/A* | (103, 417)/ (0, 24) | (51, 129)/ (3, 7) | (0.073, 0.081)/ (0.021, 0.023) | ---- |

1 – Concentration of feed water/concentration of filtered water.
N/A* = Not Applicable because standard deviation = 0
---- = Statistical measurements on cumulative data not calculated.
Note: Calculated averages for less than results (<) utilize half of the Level of Detection (Gilbert, 1987).

***Operation and Maintenance Results***

Maintenance requirements on the treatment system did not appear to be significant but were difficult to quantify due to the short duration of the study. There was a failure of the system during the verification testing. A solenoid valve on the backwash system of the prefilter stuck closed and caused the unit to automatically shut down. The manufacturer's representative was notified and rectified the problem the following day by manually exercising the valve. The unit was off line for slightly more than 27 hours. The failure appeared to be caused by environmental conditions: freezing of the solenoid valve due to extremely low temperatures in the trailer housing the treatment system. This was caused by a failure of the enclosure's heating system. Changes were made in the method of heating the trailer in order to prevent any more failures due to environmental conditions.

The Operating and Maintenance (O&M) Manual provided by Aquasource was available for review on-site and was referenced occasionally during the testing. Particularly, the manual was consulted during the cleaning procedure and to diagnose the alarm codes during the aforementioned system shutdown. The manual was well organized and a valuable resource during the testing period.

*Original Signed by*
*E. Timothy Oppelt* *5/24/00*

E. Timothy Oppelt Date
Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

*Original Signed by*
*Tom Bruursema* *5/31/00*

Tom Bruursema Date
General Manager
Environmental and Research Services
NSF International

**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 #00/07/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 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/etv (electronic copy)

3. EPA web site http://www.epa.gov/etv (electronic copy)

May 2000

# Environmental Technology Verification Report

# Physical Removal of *Cryptosporidium* oocysts and *Giardia* cysts in Drinking Water

# Aquasource North America Ultrafiltration System Model A35 Pittsburgh, PA

Prepared for:

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Prepared by:

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

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## Notice

The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development has financially supported and collaborated with NSF International (NSF) under Cooperative Agreement No. CR 824815. This verification effort was supported by Package Drinking Water Treatment Systems Pilot operating under the Environmental Technology Verification (ETV) Program. This document has been peer reviewed and reviewed by NSF and EPA and recommended for public release.

## 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 Gannett Fleming, Inc., in cooperation with Aquasource North America. The test was conducted during December of 1998 at the New Highland Pump Station, Pittsburgh Water and Sewer Authority, Pittsburgh, Pennsylvania.

Throughout its history, the EPA has evaluated the effectiveness of innovative technologies to protect human health and the environment. A new EPA program, the Environmental Technology Verification Program (ETV) 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 is 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 Package Drinking Water Treatment Systems (PDWTS) ETV Pilot Project. 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.

The ETV PDWTS is being conducted by NSF 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.

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## Abbreviations and Acronyms

| | |
|---|---|
| ac | acre |
| AWWA | American Water Works Association |
| b | bar |
| $CaCO_3$ | Calcium Carbonate |
| CCP | Composite Correction Program |
| cfu | colony forming unit |
| CIP | Clean in place |
| $Cl_2$ | Chlorine |
| $^oC$ | Degrees Celsius |
| DI | deionized |
| DOC | Dissolved Organic Carbon |
| EPA | U.S. Environmental Protection Agency |
| ESWTR | Enhanced Surface Water Treatment Rule |
| ETV | Environmental Technology Verification |
| $^oF$ | Degrees Fahrenheit |
| FOD | Field Operations Document |
| ft | feet |
| $ft^2$ | feet squared |
| FTO | Field Testing Organization |
| gfd | Gallon per square foot per day |
| gpm | Gallon per minute |
| hp | Horse Power |
| HPC | Heterotrophic Plate Count |
| hr | hour |
| ICR | Information Collection Rule |
| in | inch |
| kD | Kilo Daltons |
| L | Liters |
| lbs | pounds |
| $l/h/m^2$ | liter per hour per square meter |
| $l/h/m^2/b$ | liter per hour per square meter per bar |
| m | meter |
| MF | Microfiltration |
| MG | million gallon |
| MGD | million gallon per day |
| mg/L | milligram per liter |
| ml | milliliters |
| mm | millimeters |
| MSDS | Material Safety Data Sheets |
| N/A | Not Applicable |
| NIST | National Institute of Standards and Technology |
| NSF | NSF International (formerly known as National Sanitation Foundation) |
| nm | nanometers |
| NTU | Nephlometric Turbidity Units |

| | |
|---|---|
| od | outside diameter |
| O&M | Operations and Maintenance |
| PADEP | Pennsylvania Department of Environmental Protection |
| PC | personal computer |
| PPE | Personal Protective Equipment |
| ppm | parts per million |
| psi | pounds per square inch |
| psid | pounds per square inch differential |
| PDWTS | Packaged Drinking Water Treatment System |
| PWSA | Pittsburgh Water and Sewer Authority |
| QA/QC | Quality Assurance / Quality Control |
| scfm | standard cubic feet per minute |
| SDI | Silt Density Index |
| SDWA | Safe Drinking Water Act |
| SWTR | Surface Water Treatment Rule |
| TDS | Total Dissolved Solids |
| TMP | Transmembrane pressure |
| TOC | Total Organic Carbon |
| TSS | Total Suspended Solids |
| UF | Ultrafiltration |
| µm | Micron |
| $UVA_{254}$ | Ultraviolet Absorbance at 254nm |

## ACKNOWLEDGMENTS

The Field Testing Organization, Gannett Fleming, Inc., was responsible for all elements in the testing sequence, including collection of samples, calibration and verification of instruments, data collection and analysis, data management, data interpretation and the preparation of this report.

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P.O. Box 67100
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Phone: 717-763-7211
Contact Person: Mr. Gene Koontz

The laboratory selected for microbiological analysis and non-microbiological, analytical work of this study was:

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Pittsburgh, PA 15238
Phone: 412-782-7552
Contact Person: Mr. Stanley States, Ph.D., Director of Analytical Services

The Manufacturer of the Equipment was:

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Phone: (804) 756-7680
Contact Person: Mr. Michael F. McLaughlin, President

Gannett Fleming wishes to thank NSF International, especially Bruce Bartley, Project Manager, Carol Becker and Kristie Wilhelm, Environmental Engineers, and Tina Beaugrand, Microbiology Laboratory Auditor, for providing guidance and program management.

The Pittsburgh Water and Sewer Authority staff including Dr. Stanley States, Director of Analytical Services, Raymond Wisloski, Water Treatment Plant Manager, Chester Grassi, Assistant Plant Manager, and Mickey Schuering, Water Treatment Technician provided invaluable analytical and operational assistance.

Michael McLaughlin, President, Denis Vial, Technical Director, Johannes Nollen, Field Engineer, and Miles Beamguard, Application Engineer of Aquasource North America are to be commended for providing the treatment system and excellent technical and product expertise. George Pitcairn, Manufacturers Representative for Ralph L. Stemler Inc. provided daily system checks for Aquasource North America.

# Chapter 1
# Introduction

## 1.1 ETV Purpose and Program Operation

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 (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 Package Drinking Water Treatment Systems (PDWTS) program, one of 12 technology areas under ETV. The PDWTS program evaluated the performance the Aquasource Ultrafiltration (UF) Treatment System Model A35, which is a membrane filtration system used in package drinking water treatment system applications. The performance claim evaluated during field testing of the Aquasource UF Treatment System Model A35 was that the system is capable of a minimum 3 $\log_{10}$ removal of *Giardia* cysts and 2 $\log_{10}$ removal of *Cryptosporidium* oocysts. This document provides the verification test results for the Aquasource UF Treatment System Model A35.

## 1.2 Testing Participants and Responsibilities

The ETV testing of the Aquasource UF Treatment System Model A35 was a cooperative effort between the following participants:

NSF International
Gannett Fleming, Inc.
Aquasource NA Corporation
Pittsburgh Water and Sewer Authority
U.S. Environmental Protection Agency

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

### *1.2.1 NSF International*

NSF is a not-for-profit testing and certification organization dedicated to public health safety and the protection of the environment. Founded in 1946 and located in Ann Arbor, Michigan, NSF has been instrumental in the development of consensus standards for the protection of public health and the environment. NSF also provides testing and certification services to ensure that products bearing the NSF Name, Logo and/or Mark meet those standards. The EPA partnered with the NSF to verify the performance of package drinking water treatment systems through the EPA's ETV Program.

NSF provided technical oversight of the verification testing. An audit of the field analytical and data gathering and recording procedures was conducted. NSF also provided review of the Field Operations Document (FOD) and this report.

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### *1.2.2 Gannett Fleming, Inc.*

Gannett Fleming, Inc., a consulting engineering firm, conducted the verification testing of the Aquasource UF Treatment System Model A35. Gannett Fleming is a NSF-qualified Field Testing Organization (FTO) for the Packaged Drinking Water Treatment System ETV pilot project.

The FTO was responsible for conducting the verification testing for 30 calendar days. The FTO provided all needed logistical support, established a communications network, and scheduled and coordinated activities of all participants. The FTO was responsible for ensuring that the testing location and feed water conditions were such that the verification testing could meet its stated objectives. The FTO prepared the FOD, oversaw the pilot testing, managed, evaluated, interpreted and reported on the data generated by the testing, as well as evaluated and reported on the performance of the technology.

FTO employees conducted the onsite analyses and data recording during the testing. Oversight of the daily tests was provided by the FTO's Project Manager and Project Director.

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### *1.2.3 Manufacturer*

The treatment system is manufactured by Aquasource North America a specialized subsidiary of Infilco Degrémont, Inc. (Richmond, Virginia) and Aquasource S.N.C. (Paris, France Aquasource North America specializes in providing ultrafiltration membranes and systems to the water industry.

The manufacturer was responsible for supplying a field-ready membrane filtration pilot plant equipped with all necessary components including treatment equipment, instrumentation and controls and an operations and maintenance manual. The unit was capable of continuous, safe 24 hour per day operation with minimal operator attention. The unit was equipped with safety devices to provide for automatic shut down of the pilot plant in the event of loss of feed water or any other condition that would either damage the pilot plant or render data generated by the unit to be not reliable. The manufacturer was responsible for providing logistical and technical support as needed as well as providing technical assistance to the FTO during operation and monitoring of the equipment undergoing field verification testing.

Representatives of the manufacturer were utilized to conduct chemical clean in place (CIP), membrane integrity testing and examined daily operational data that was automatically recorded by the treatment system.

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### *1.2.4 Host and Analytical Laboratory*

The verification testing was hosted by the Pittsburgh Water and Sewer Authority (PWSA). PWSA serves water to over 500,000 people from its 120 million gallon per day (MGD) surface water treatment plant located in the Aspinwall section of the City of Pittsburgh. PWSA was interested in examining the use of membrane filtration to treat water which had been stored in its Highland Reservoir No. 1, an open finished water reservoir.

PWSA's laboratory provided collection and analytical services for Total Alkalinity, Total Hardness, Total Dissolved Solids (TDS), Total Suspended solids (TSS), Total Coliforms, Heterotrophic Plate Count (HPC), Total Organic Carbon (TOC), Ultraviolet Absorbance at 254 nanometers (nm) ($UVA_{254}$), and Algae. In addition, PWSA supplied operational support and analytical services for the microbial removal testing. PWSA's laboratory is certified by the Pennsylvania Department of Environmental Protection (PADEP) for analysis of Microbiological, Inorganic, and Organic compounds in water. Additionally, the laboratory has received Protozoa Laboratory Approval from the EPA under the Information Collection Rule (ICR) Program. Copies of the Laboratory Approval Statements are attached in Appendix A.

Contact Information:

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Phone: 412-782-7552
Fax: 412-782-7564
Contact: Stanley States, Ph.D. Director of Analytical Services

### *1.2.5 U.S. Environmental Protection Agency*

The EPA through its Office of Research and Development has financially supported and collaborated with NSF under Cooperative Agreement No. CR 824815. This verification effort was supported by Package Drinking Water Treatment Systems Pilot operating under the ETV Program. This document has been peer reviewed and reviewed by NSF and EPA and recommended for public release.

## 1.3 Verification Testing Site

The verification testing site was at the PWSA's Highland Reservoir No. 1. The physical location of the treatment unit was the New Highland Pumping Station at the corner of North Negley Avenue and Mellon Terrace in the Highland Park section of the City of Pittsburgh, Pennsylvania. The treatment unit was in an enclosure located at the rear of the pumping station and received its feed water from the influent lines of the pumping station.

### *1.3.1 Source Water*

The source water for the verification testing was finished drinking water that was stored in PWSA's open, lined Highland Reservoir No. 1. The reservoir is 18 acres (ac) with an average depth of 20 feet (ft) and contains 120 million gallons (MG) of water. The water that is stored in Highland Reservoir No. 1 is treated surface water drawn from the Allegheny River. The water stored in the reservoir has undergone coagulation with ferric chloride, sedimentation, filtration, and disinfection using free chlorine at PWSA's Aspinwall Treatment prior to being pumped to the reservoir. The influent to the Aquasource UF Treatment System Model A35 was drawn from the reservoir effluent lines. The effluent from the reservoir is not tested by PWSA and the

Authority has little historical data regarding the quality of the reservoir water. The verification testing was limited to the performance of the equipment to remove *Cryptosporidium* oocysts and *Giardia* cysts, because the source water was obtained from an open reservoir. The performance was evaluated during challenge seeding studies of *Cryptosporidium* oocysts and *Giardia* cysts.

During the study the feed water turbidity ranged from 0.060 to 0.10 Nephlometric Turbidity Units (NTU) with an average of 0.078 NTU. pH was within the range of 8.3 to 8.6 with an average of 8.5. Total Alkalinity as $CaCO_3$ ranged from 59 to 71 mg/l with an average of 63 mg/l. Average Hardness, as $CaCO_3$, was 154 mg/l and ranged from 150 to 158 mg/l. TOC ranged from 1.36 to 1.73 mg/l with an average of 1.56 mg/l. $UVA_{254}$ was 0.019 mg/l on average, with a range of 0.016 to 0.022 mg/l. TDS averaged 296 mg/l and the range was 280 to 313 mg/l. TSS averaged 0.016 mg/l and ranged from non detectable to 0.30 mg/l. HPC ranged from 70 to 460 colony forming units (cfu)/ml and averaged 260 cfu/ml. No coliform bacteria were detected in the feed water. Temperature averaged 8.0°C, ranging from 3.2°C to 11.0°C. The algae levels during the verification testing averaged 90 cell/ml, with a range of 40 to 136 cells/ml. The above information is presented in Table 1-1 below.

**Table 1-1. Aquasource UF Treatment System Model A35 Feed Water Quality**

| | Parameter | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total Alkalinity as $CaCO_3$ (mg/l) | Total Hardness as $CaCO_3$ (mg/l) | TDS (mg/l) | TSS (mg/l) | Total Coliforms (cfu/100 ml) | HPC (cfu/100 ml) | TOC (mg/l) | UVA (cm –1) | Algae (cells/ml) | Turbidity (NTU) |
| Average | 63 | 154 | 296 | 0.16 | 0 | 260 | 1.56 | 0.019 | 90 | 0.078 |
| Minimum | 59 | 150 | 280 | <0.05 | 0 | 70 | 1.36 | 0.016 | 40 | 0.060 |
| Maximum | 71 | 158 | 313 | 0.30 | 0 | 460 | 1.73 | 0.022 | 136 | 0.10 |
| Std. Dev. | 5.6 | N/A | N/A | 0.16 | 0 | 160 | 0.155 | 0.0028 | 39 | 0.011 |
| 95% Confid Int | (58, 68) | N/A | N/A | (0.0069, 0.32) | N/A[1] | (103, 417) | (1.41, 1.72) | (0.016, 0.022) | (51, 129) | (0.074, 0.082) |

N/A = Not applicable because the sample size (n) was 2.
N/A[1] = Not applicable because standard deviation = 0
Note: Calculated averages for less than results (<) utilize half of the Level of Detection (0.05 mg/l) or 0.025 mg/l in these calculations. Per Statistical Methods for Environmental Pollution Monitoring, Richard O. Gilbert, Van Nostrand Reinhold, 1987.

### *1.3.2 Pilot Effluent Discharge*

The effluent of the pilot treatment unit was piped to an existing catch basin that is part of the PWSA sanitary sewer collection system. No discharge permits were required.

# Chapter 2
# Equipment Description and Operating Processes

## 2.1 Equipment Description

The equipment tested in this ETV program was the Aquasource Ultrafiltration System Model A35. The membrane used in the A35 Treatment System is a hollow fiber ultrafiltration membrane that is 0.93 millimeters (mm) in diameter (0.035 inch) and 1.30 meters (m) long (4.3 feet). The membranes are made of cellulose acetate and have a nominal pore size in the range of 10 to 20 nanometers (nm) with a molecular weight cutoff of approximately 180 Kilo Daltons (kD) for 90% retention.

The membrane filters are contained in a fiberglass cylinder called the module. The modules used in the A35 Treatment System are designated M1A35. The modules are vertically mounted on the treatment skid. The filtration surface area provided in a module is approximately 7.2 $m^2$ (77.4 $ft^2$). The M1A35 module used in this treatment study contains 15,904 fibers arranged in 7 bundles, each bundle maintained in plastic netting. Figure 2-1 is a photograph of water permeating through the fibers. Figure 2-2 is a pictorial representation of the flow path through the individual fiber.

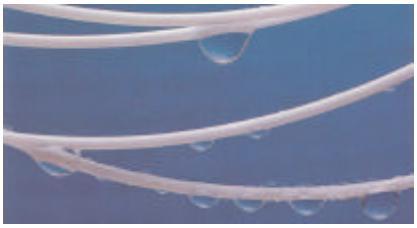


**Figure 2-1. Water permeating through the fibers**

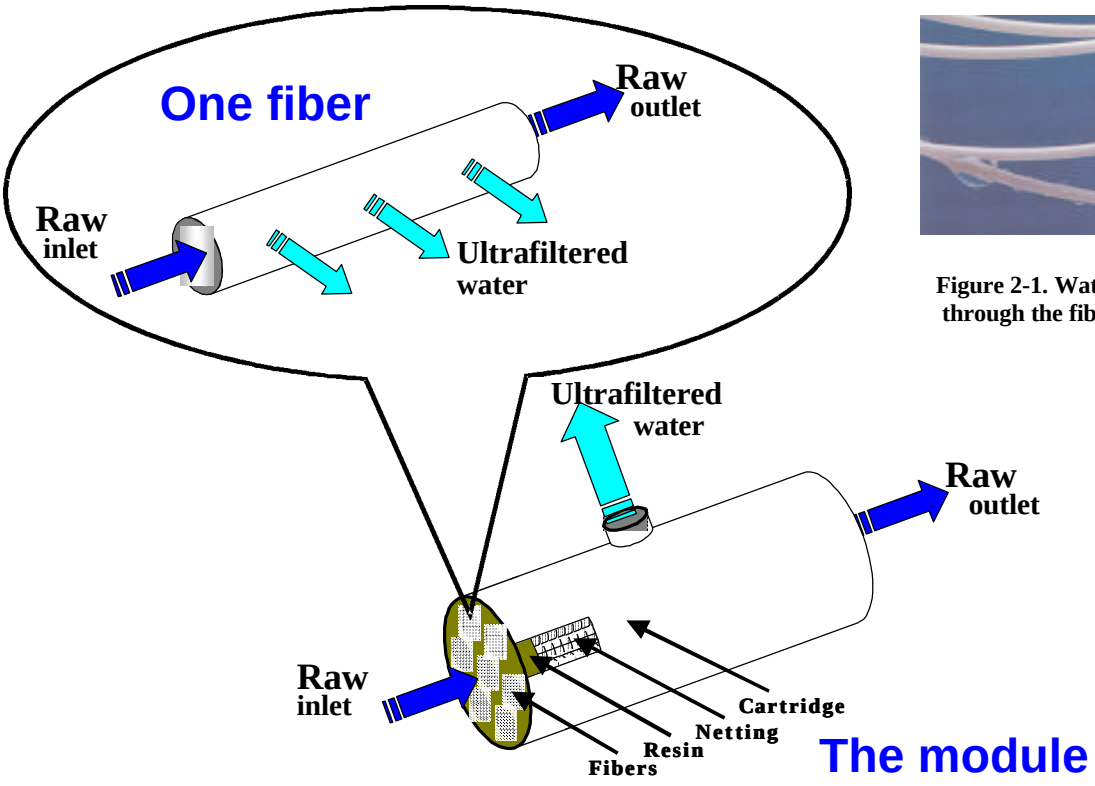



**Figure 2-2. Flow path through fibers and modules**

The fibers are fastened on both ends with an epoxy resin glued to the fiberglass cylinder so there is no contact in between the raw water inside the fibers and the treated water (permeate) outside the fibers.

The raw water goes to the inside of each fiber via one of the heads of the module. Due to the difference of pressure in between the inside and the outside of the fibers, water is driven through the fibers. During filtration, the membrane retains the suspended solids, microorganisms and organic macromolecules forming a cake on the inner side of the ultrafiltration membrane. The process is called inside-out flow.

A summary of membrane characteristics as reported by the manufacturer is as follows:

| | |
|---|---|
| Membrane classification ..... | ultrafiltration |
| Membrane material ..... | cellulose acetate |
| Membrane type ..... | hollow fiber |
| Membrane flow path..... | inside out |
| Filtration mode ..... | dead end or cross flow |
| pH tolerance ..... | 4 - 8.5 |
| Temperature tolerance..... | 1 - 35° C (33 - 95° F) |

The following major equipment components are provided on the A35 Treatment System's self contained skid mounted unit:

One (1) feed pump,

One (1) pre-filter,

One (1) recirculation pump,

Two (2) Aquasource M1A35 ultrafiltration modules,

One (1) backwash pump,

One (1) filtrate tank,

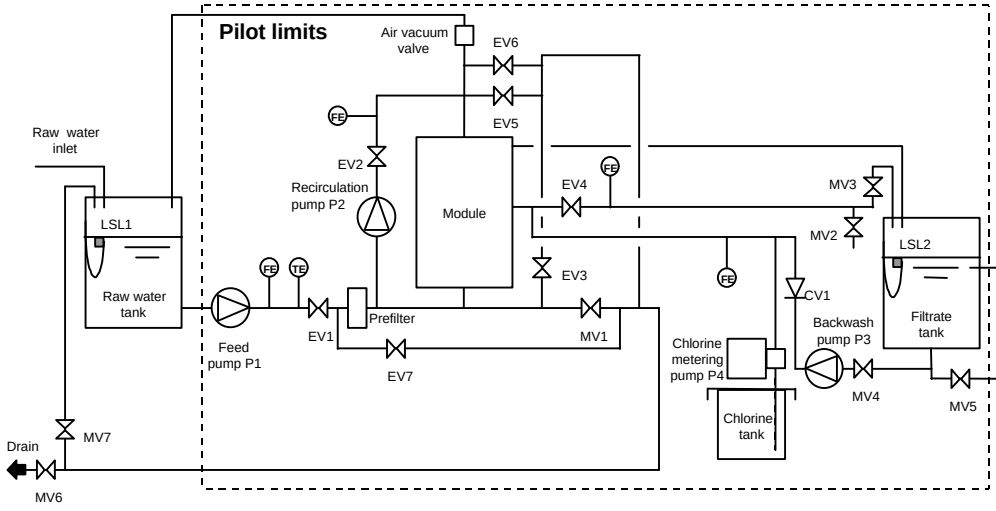
One (1) air compressor,

One (1) sodium hypochlorite tank with one (1) metering pump.

One (1) control panel

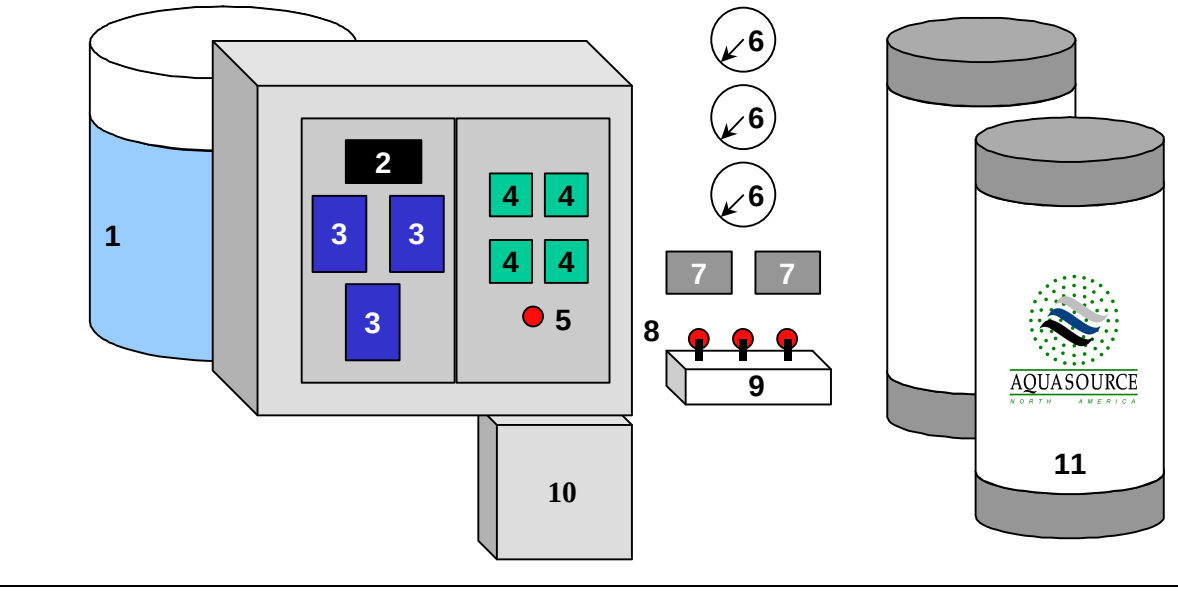
The raw water tank is provided, separate of the skid mounted pilot unit.

The schematic in Figure 2-3 is a representation of all treatment system equipment and related names. Figure 2-4 illustrates the location of the main equipment on the unit.




CV *x* : Check valve
FE : Flow element
MV *x*: Manually operated valve
TE : Temperature element
EV *x* : Pneumatically actuated valve
LSL *x*: Level switch low
P *x* : Pump

**Figure 2-3. Treatment system equipment schematic**




1 Filtrate tank
2 Allen Bradley Panel View 550,
3 Pumps VFDs,
4 Flow meters,
5 Emergency stop,
6 Manometers,
7 Pressure switch,
8 Sampling valves,
9 Sink,
10 Solenoid valves cabinet,
11 Modules

**Figure 2-4. Major equipment location**

Figure 2-5 represents as a flow schematic of the Aquasource unit.

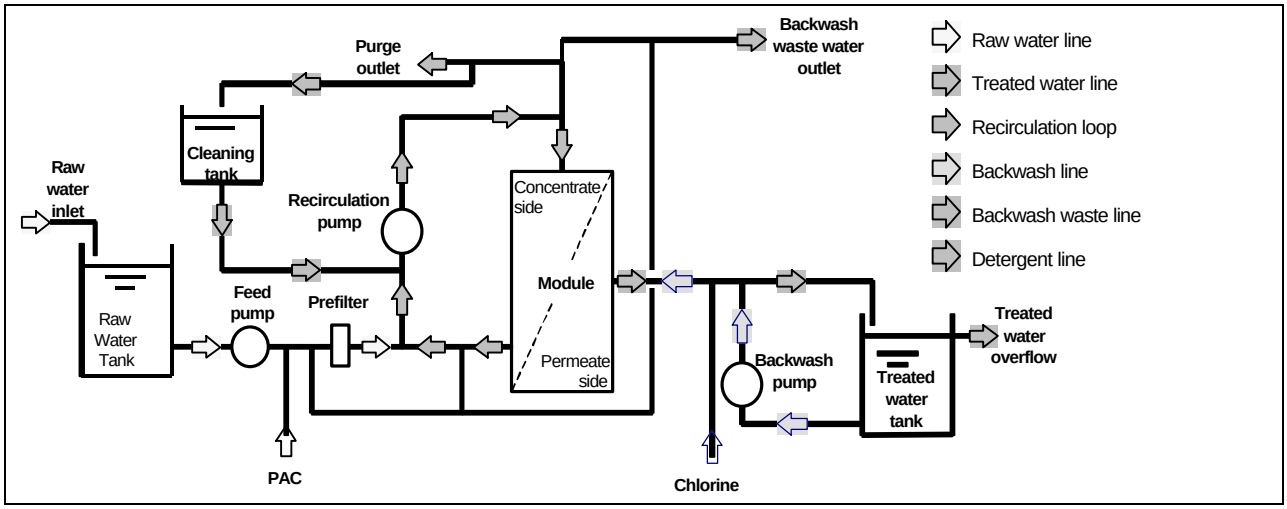



**Figure 2-5. Flow schematic**

The data plate affixed to the treatment system contains the following information.

a. Equipment name: Aquasource Pilot System
b. Model #: A35
c. Manufacturer: Aquasource; 2924 Emerywood Parkway; Richmond, VA 23060
d. Electrical requirements: 480Volts, 30 Amps, 3 phase
e. Serial number: #6
f. Warning and caution statements: N/A
g. Capacity or output rate: 10 gpm

According to the manufacturer, the treatment system is capable of handling feed water turbidity up to 500 NTU. Turbidity challenge testing was not done during this verification so this feed water limitation was not field verified. There are no documented upper limits for concentrations of *Giardia* and *Cryptosporidium* in the feed water. The manufacturer's O&M manual states that the membranes have a pH tolerance of 4 to 8.5 and a temperature tolerance of 1 to 35$^{o}$C.

The following is a photograph of the A35 system on-site during testing.


**Photograph 1. Aquasource Ultrafiltration System Model A35 showing piping, membrane modules and prefilter.**

## 2.2 Operating Process

### *2.2.1 Feed Water*

The feed water is pumped into the filtration loop by the feed pump. The feed pump provides the pressure needed to drive the raw water through the fibers. In normal operation the feed flow is equal to the instantaneous production flow, ensuring a constant production rate.

### *2.2.2 Prefiltration*

A 200 µm raw water prefilter removes large particles prior to the feed flow entering the modules. The prefilter protects the heads of the modules against clogging. Prefiltration is performed with an automatic backwashed prefilter. Backwashing of the prefilter is done with permeate during the backwash of the modules. No chlorine is added to the permeate during backwash of the prefilter.

### *2.2.3 Filtration*

The unit can operate in two modes:

- Cross flow filtration: The recirculation pump, installed on the skid-mounted unit, minimizes clogging of the membrane by circulating feed water at a high velocity inside the fibers. This mode is used only when the raw water contains a rather high concentration of suspended solids, such as during spring runoff, winds or rainstorms, or with powdered activated carbon (PAC) addition.
- Dead end filtration: The recirculation pump is stopped. This mode is used when the raw water is low in suspended solids. In dead end filtration, raw water goes inside the lumen of the fibers from the bottom head of the modules to the upper head with a decreasing velocity. This mode is also called frontal filtration.

The unit was operated in dead-end filtration mode due to the low level of suspended solids in the feed water at the test site.

The manufacturer reports that typically during filtration, the pressure drop across the module is approximately 0.2 bar (b) (≈ 3 pound per square inch [psi]) at 20°C. The recommended maximum transmembrane pressure is 0.8 b (≈ 12 psi). The permeate pressure can be as low as 0.2 b (≈ 3 psi). Thus, the maximum pressure at the bottom head of a module, which will allow the unit to automatically switch from dead-end to recirculation, is about 1.1 b (≈ 16 psi).

Figure 2-6 is a schematic representation of the flow path in dead-end mode.

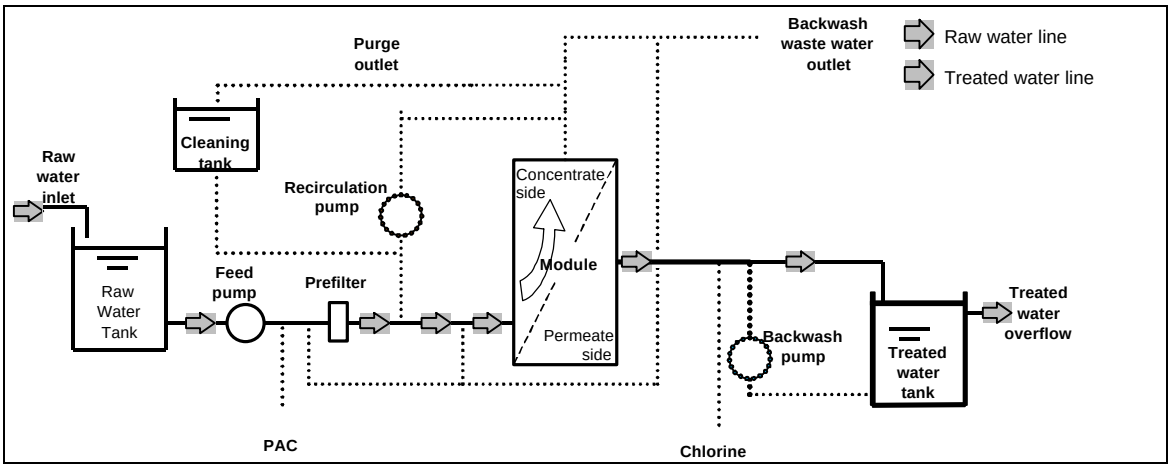



**Figure 2-6. Dead-end filtration flow path schematic**

### *2.2.4 Backwash/Reverse Flow*

During normal operation, the A35 unit alternates between the filtration mode and the backwash mode. These backwashes are called cycle backwashes (or automatic backwashes).

Periodically permeate is sent back under pressure in the reverse direction (backwash) to restore the effectiveness of the membrane. Only chlorinated ultrafiltered water is used for backwash purposes. A backwash pump, drawing water from the filtrate tank, provides the water for backwash under pressure. Backwash is performed at a pressure of about 2.5 bar (≈ 36 psig) at the module permeate inlet. During the backwash, blow-down valves are opened to discharge the concentrate stream (backwash wastewater) to waste. Following backwash, the filtration cycle automatically resumes.

The backwash is automatically initiated after a preset filtration time. The frequency is dependent on raw water quality, and will occur between every 20 minutes to three hours. For this verification study a backwash frequency of 60 minutes was used due to the low amount of solids in the feed water.

Backwash duration varies as a function of the water temperature and the clogging of the membrane to maintain a constant volume sent through the fibers. The duration of the module's backwash is usually set from 45 to 75 seconds. Forty-five seconds was the backwash duration for the verification study. The total length of a backwash cycle which includes the necessary valve operations is from 55 to 85 seconds and corresponds to the non-production duration. Sixty seconds was the total length of the backwash cycle for the study.

During backwash, backwash water (permeate) is chlorinated to enhance backwash efficiency. Chlorine is used as a disinfectant to protect the membrane against biological contamination on the permeate side and as an oxidant for the organic matter. Sodium hypochlorite is added to the backwash water (except during the backwash of the prefilter) at a concentration between 5 and 10 mg/L as free chlorine. Sodium hypochlorite concentration is adjusted as a function of the backwash duration and the backwash frequency and to have at least 0.5 ppm of free chlorine in the backwash wastewater.

The following occurs sequentially during a cycle backwash:

1) Backwash of the top head of the modules.
2) Backwash of the bottom head of the modules.
3) Backwash of the both heads of the modules.
4) Backwash of the recirculation loop and bottom head.
5) Backwash of the prefilter.
6) Production resumes.

The cycle backwash steps are shown in Figures 2-7 through 2-10.

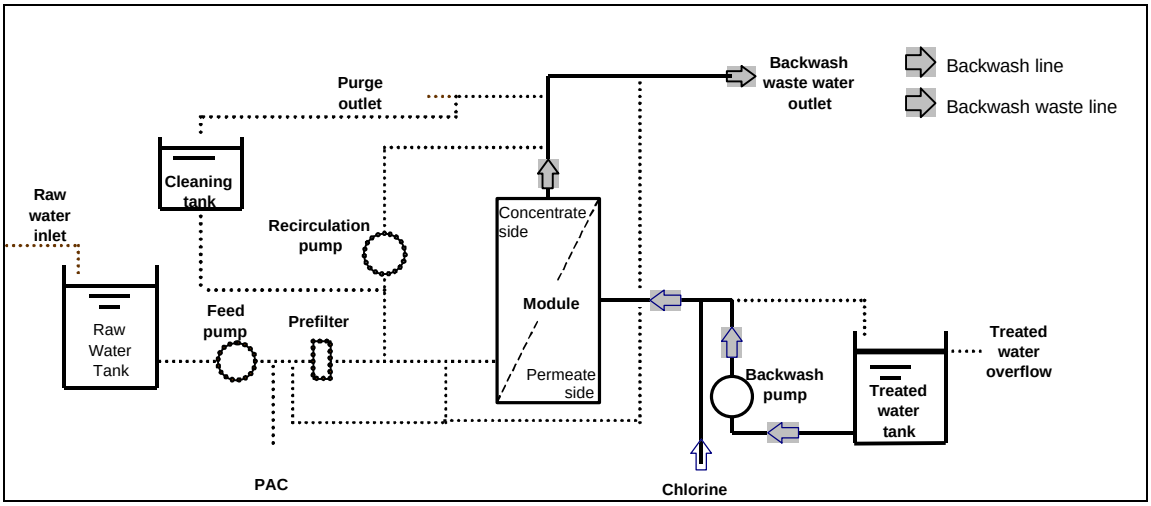



**Figure 2-7. Backwash of top head flow schematic**

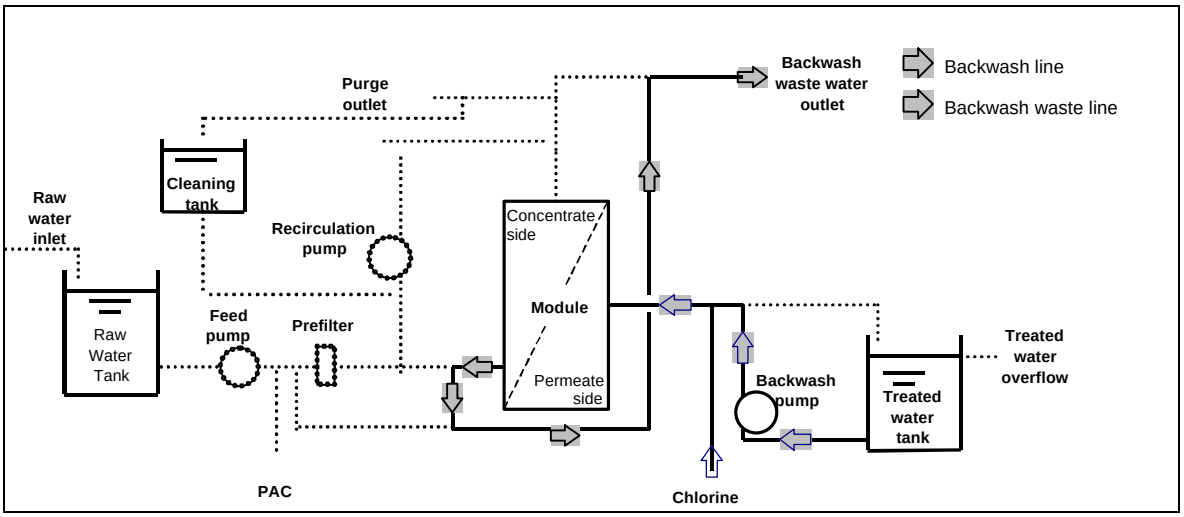



**Figure 2-8. Backwash of bottom head flow schematic**

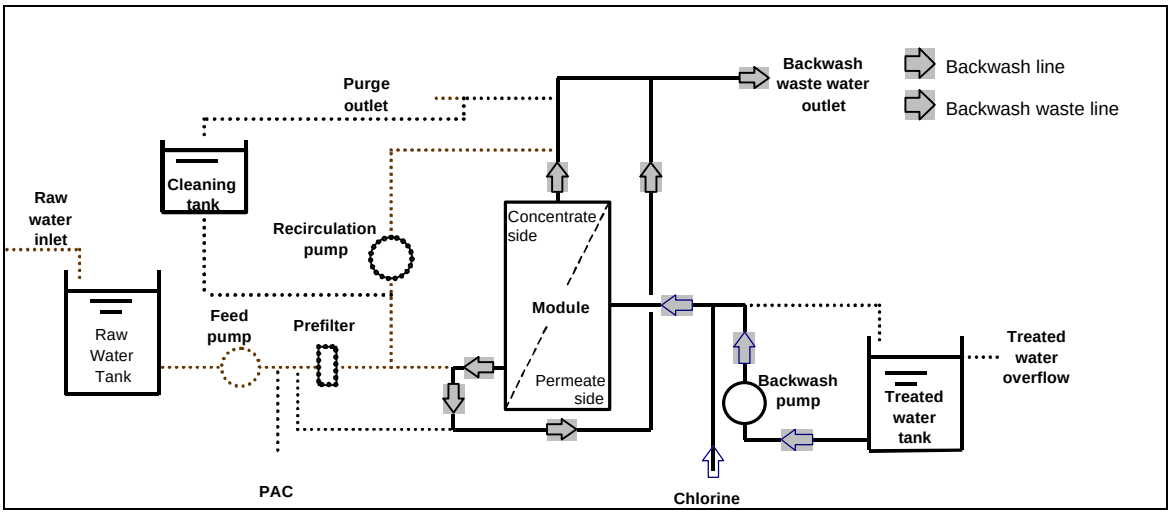



**Figure 2-9. Backwash of both heads flow schematic**

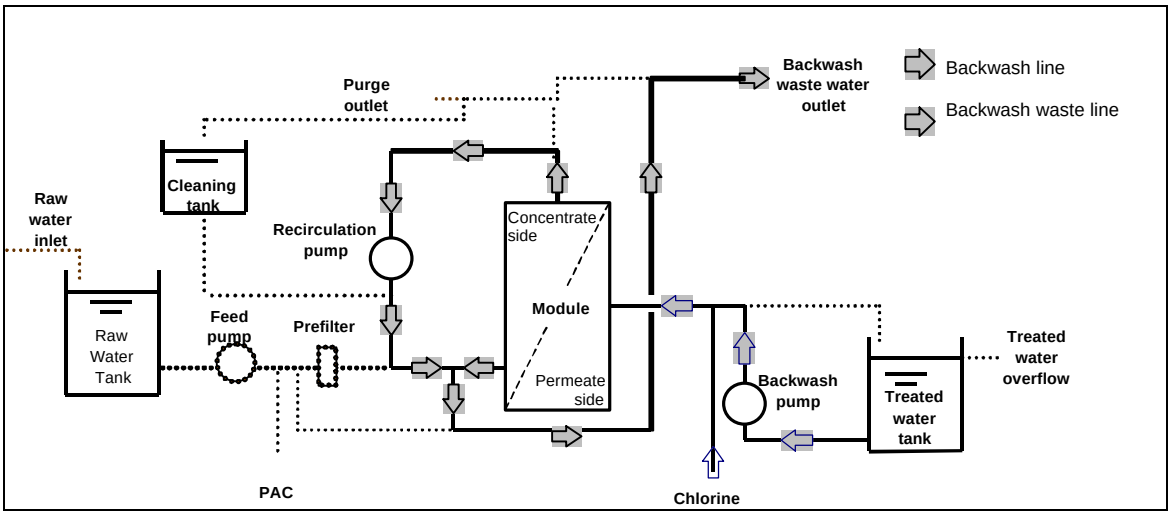



**Figure 2-10. Backwash of recirculation loop and bottom head flow schematic**

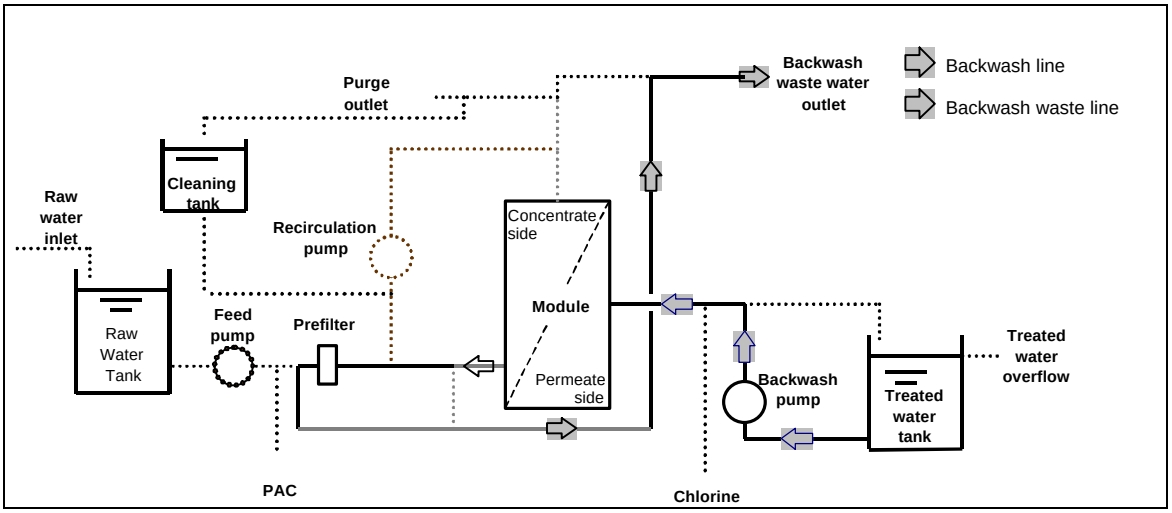



**Figure 2-11. Backwash of prefilter**

### *2.2.5 Chemical Cleaning*

Periodically, membrane cleaning is performed using a detergent-type cleaning solution. The function of the cleaning solution is to loosen and/or dissolve fouling matter that has adhered to the surface of the membrane or to the porous structure of the membrane. The frequency of detergent cleaning depends on the raw water quality. The manufacturer reports that the cleaning operation is performed about once a year for ground waters with occasional turbidity spikes. For waters having higher TOC levels, cleaning may need to be more often. Cleaning was not required due to loss of flux during the verification testing period but was performed at the end of the thirty day testing as required by the ETV Protocol. The manufacturer estimated that the cleaning interval would be approximately 3-6 months for the type of feed water used in this verification testing period.

After preparing the cleaning solution in the detergent tank, the solution is circulated through the membranes using the recirculation pump. After cleaning, the modules are rinsed with raw water.

Aquasource NA provides the detergents for the cleaning of the membranes. Three detergents may be used. Ultrasil 43 (detergent and free chlorine) will remove organic fouling. Ultrasil 59 (detergent and complexing agent) will remove organic and mineral fouling. An acid based detergent will remove iron and manganese fouling. Ultrasil 43 was used for pre-cleaning and cleaning during the verification testing.

The manufacturer recommends that with organic and mineral fouling, a pre-cleaning with Ultrasil 43, followed by a cleaning with Ultrasil 43, and a second cleaning with Ultrasil 59 are performed. With iron and manganese fouling, the cleaning sequence is modified to cleaning with the acid based detergent, followed by a cleaning with Ultrasil 43 or Ultrasil 59 depending on the water quality. Figure 2-12 is a schematic representation of the chemical cleaning process.

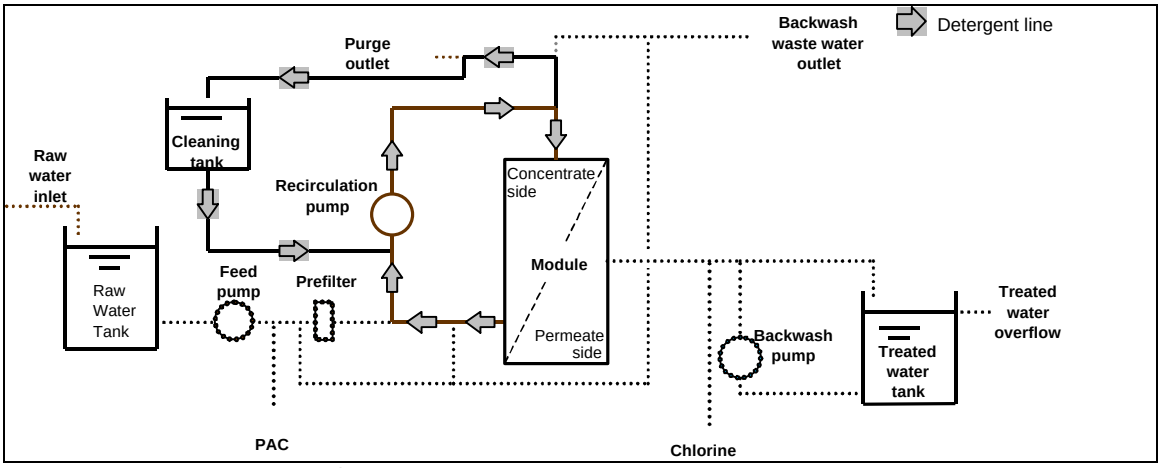



**Figure 2-12. Chemical cleaning flow schematic**

# Chapter 3
# Methods and Procedures

## 3.1 Experimental Design

The experimental design of this verification study was developed to provide accurate information regarding the performance of the treatment system. The impact of field operations as they relate to data validity was minimized, as much as possible, through the use of standard sampling and analytical methodology. Due to the unpredictability of environmental conditions and mechanical equipment performance, this document should not be viewed in the same light as scientific research conducted in a controlled laboratory setting. Adequate field analytical controls were in place during the verification and allow valid conclusions to be drawn from the gathered data.

### *3.1.1 Objectives*

The verification testing was undertaken to evaluate the performance of Aquasource Ultrafiltration Treatment System Model A35. Specifically evaluated were the manufacturer's stated equipment capabilities and equipment performance relative to water quality regulations. Operational requirements and maintenance requirements of the system were also evaluated. The details of each of these evaluations are discussed below.

3.1.1.1 Evaluation of Stated Equipment Capabilities

The Aquasource Ultrafiltration Treatment System Model A35 was tested to show that it was capable of providing a minimum 3 $\log_{10}$ removal of *Giardia* cysts and 2 $\log_{10}$ removal of *Cryptosporidium* oocysts from the source water. *Giardia* and *Cryptosporidium* removal challenge testing was conducted to demonstrate acceptable protozoan removal capability.

3.1.1.2 Evaluation of Equipment Performance Relative to Water Quality Regulations

Drinking water regulations require, for filtration plants treating surface water, a minimum of 3 $\log_{10}$ removal/inactivation of *Giardia* cysts from feed to finished waters, that finished water turbidity at no time exceeds 5 NTU and that at least 95% of the daily finished water turbidity samples be less than 0.5 NTU. (EPA, Surface Water Treatment Rule [SWTR], 1989). Recently promulgated rules have modified the SWTR to include a lower turbidity standard, less than 0.3 NTU in 95% of the daily finished water turbidity samples, and a requirement to provide a 2 $\log_{10}$ removal of *Cryptosporidium* oocysts (EPA, Enhanced Surface Water Treatment Rule (ESWTR), 1999). Both these rules grant the “log removal credit” if the treatment facility achieves the required turbidity levels.

The treatment system's ability to achieve required finished water turbidity levels was not verifiable due to the fact that the feed water already was in compliance with drinking water turbidity regulations. $\text{Log}_{10}$ removal for *Giardia* cysts and *Cryptosporidium* oocysts was quantified using microbial removal challenge testing although there is no provision for this type of testing in the regulations.

3.1.1.3 Evaluation of Operational Requirements

An overall evaluation of the operational requirements for the treatment system was undertaken as part of the verification. This evaluation was qualitative in nature. The manufacturer's Operations and Maintenance (O&M) manual (Aquasource NA 1998) and experiences during the daily operation were used to develop a subjective judgement of the operational requirements of the system. The O&M manual is attached to this report as Appendix B.

3.1.1.4 Evaluation of Maintenance Requirements

Verification testing also evaluated the maintenance requirements of the treatment system. Not all of the system's maintenance requirements were necessary due to the short duration of the testing cycle. The O&M manual details various maintenance activities and their frequencies (Aquasource, 1998). This information, as well as experience with common pieces of equipment (i.e. pumps, valves etc.) was used to evaluate the maintenance requirements of the treatment system.

### *3.1.2 Equipment Characteristics*

The qualitative, quantitative and cost factors of the tested equipment were identified, in so far as possible, during the verification testing. The relatively short duration of the testing cycle creates difficulty in reliably identifying some of the qualitative, quantitative and cost factors. The qualitative factors examined during verification testing were susceptibility to changes in environmental conditions, operational reliability, and equipment safety. The quantitative factors examined during verification testing were power supply requirements, consumable requirements, waste disposal technique, and length of operating cycle. The cost factors examined during verification testing were power supply, consumables, and waste disposal. It is important to note that the figures discussed here are for the Aquasource Pilot System Model A35. This treatment unit operated at 155 liter per square meter per hour ($l/m^2/h$) at $20^oC$ (91.2 gallon per square foot per day [gfd] at $68^oF$). Costs will increase with increasing flow.

## 3.2 Water Quality Consideration

Characterization of the treated water quality was the driving force behind the development of the experimental design of the ETV. The water quality and microbial analyses which were conducted were selected to demonstrate the treatment effectiveness of the manufacturer's equipment. The feed and filtrate analytical parameters which were analyzed as part of the testing and the sampling frequency are presented in Table 3-1.

**Table 3-1. Analytical Data Collection Schedule**

| Parameter | Frequency | Feed | Filtrate | Backwash Waste |
|---|---|---|---|---|
| Onsite Analytes | | | | |
| Temperature | Daily | 1 | 0 | 0 |
| pH | Daily | 1 | 0 | 0 |
| Turbidity | Daily | 2 | Continuous | 2 |
| Particle Counts | Daily | Continuous | Continuous | 0 |
| Chlorine Residual | During Cleaning | 1 (Backwash feed water) | 0 | 1 |
| Laboratory Analytes | | | | |
| Total Alkalinity | Monthly | 1 | 1 | 0 |
| Total Hardness | Monthly | 1 | 1 | 0 |
| TDS | Monthly | 1 | 1 | 0 |
| TSS | Weekly | 1 | 1 | 1 |
| Total Coliforms | Weekly | 1 | 1 | 1 |
| HPC | Weekly | 1 | 1 | 0 |
| TOC | Weekly | 1 | 1 | 0 |
| UVA | Weekly | 1 | 1 | 0 |
| Algae | Weekly | 1 | 1 | 0 |
| Giardia and Cryptosporidium | Once during challenge testing | 3 | Composite | 0 |

## 3.3 Recording Data

Operational and water quality data was recorded to document the results of the verification testing.

### *3.3.1 Operational Data*

Operational data was read and recorded for each day of the testing cycle. The operational parameters and frequency of readings are listed in Table 3-2 below.

**Table 3-2. Operational Data Collection Schedule**

| Parameter | Frequency |
|---|---|
| Raw Flow | 2/day |
| Feed Water Temperature | 1/day |
| Electric Power Use | 1/day |
| Influent module/vessel pressure | 2/day |
| Effluent module/vessel pressure | 2/day |
| Filtrate pressure | 2/day |
| Filtrate flow | 2/day |

In addition to these parameters, data was collected during chemical cleaning and membrane integrity testing. Operational data collected during these tasks is discussed in Sections 3.8.2 and 3.8.5.

### *3.3.2 Water Quality Data*

Table 3-1 lists the daily, weekly, and monthly water quality samples that were collected. The results of the daily on-site analyses were recorded in the operations log book. The weekly and

monthly laboratory analyses were recorded in laboratory log books and reported to the FTO on separate laboratory report sheets. The data spreadsheets are attached to this report as Appendix C.

## 3.4 Communications, Logistics and Data Handling Protocol

With the number of verification participants involved in the study it was important for the FTO to coordinate communication between all parties. Documentation of study events was facilitated through the use of log books, photographs, data sheets and chain of custody forms. Data handling is a critical component of any equipment evaluation or testing. Care in handling data assures that the results are accurate and verifiable. Accurate sample analysis is meaningless without verifying that the numbers are being entered into spreadsheets and reports accurately and that the results are statistically valid.

### *3.4.1 Introduction*

The data management system used in the verification testing program involved the use of computer spreadsheet software and manual recording methods for recording operational parameters for the membrane filtration equipment on a daily basis. Weekly and monthly water quality testing data was submitted to the FTO by PWSA Laboratory representatives, verified, and entered into computer spreadsheets.

### *3.4.2 Objectives*

There were two primary objectives of the data handling portion of the study. One objective was to establish a viable structure for the recording and transmission of field testing data such that the FTO provides sufficient and reliable operational data for the NSF for verification purposes. A second objective was to develop a statistical analysis of the data, as described in "A Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants" (EPA/NSF. EPA/NSF ETV Protocol – Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contamination, NSF, April, 1998).

### *3.4.3 Procedures*

The data handling procedures were used for all aspects of the verification test. Procedures existed for the use of the log books used for recording the operational data, the documentation of photographs taken during the study, the use of chains of custody forms, the gathering of on-line measurements, entry of data into the customized spreadsheets, and the methods for performing statistical analyses.

3.4.3.1 Log Books

Field log books were bound with numbered pages and labeled with project name. The log book is attached to this report as Appendix D. Log books were used to record equipment operating data. Each line of the page was dated and initialed by the individual responsible for the entries.

Errors had one line drawn through them and the line was initialed and dated. Field testing operators recorded data and calculations by hand in laboratory notebooks. Daily measurements were recorded on specially prepared data log sheets. The laboratory notebook was photocopied weekly. The original notebooks were stored on-site; the photocopied sheets were stored at the office of the FTO. This procedure eased referencing the original data and offered protection of the original record of results. Treatment unit operating logs included a description of the membrane filtration equipment (description of test runs, names of visitors, description of any problems or issues, etc); such descriptions were provided in addition to experimental calculations and other items.

3.4.3.2 Photographs

All photographs were logged in the field logbook. These entries include time, date, direction, subject of photo and the identity of the photographer.

3.4.3.3 Chain of Custody

Samples which were collected by PWSA representatives and hand delivered to the laboratory were logged into the laboratory's sample record upon arrival at the laboratory. During an audit by NSF representatives, the use of chain of custody forms was requested. Subsequent samples were collected and hand delivered to the laboratory accompanied by chain of custody forms. The chain of custody forms are included in Appendix E.

3.4.3.4 Inline Measurements

Data from the computers recording the on-line measurements were copied to disk at least on a weekly basis. This information was stored on site and at the FTO's office.

3.4.3.5 Spreadsheets

The database for the project was set up in the form of custom-designed spreadsheets. The spreadsheets are capable of storing and manipulating each monitored water quality and operational parameter from each task, each sampling location, and each sampling time. All data from the laboratory notebooks and data log sheets were entered into the appropriate spreadsheet. Data entry into the spreadsheets was conducted at the FTO's office by designated operators. All recorded calculations were also checked at this time. 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. Spreadsheet printouts are included in Appendix C of this report.

3.4.3.6 Statistical Analysis

Water quality data developed from grab samples collected during filter runs, the operational data recorded in the logbook, and the inline data were analyzed for statistical uncertainty. The FTO

calculated the average, minimum, maximum, standard deviation, and the 95% confidence intervals. The statistics developed are helpful in demonstrating the degree of reliability with which water treatment equipment can attain quality goals.

### 3.5 Recording Statistical Uncertainty

The FTO calculated a 95% confidence interval for selected water quality parameters. These calculations were also carried out on data from inline monitors and for grab samples of turbidity, total coliform, HPC, TOC and total suspended and total dissolved solids. The equation used is:

$$95\%\ \textit{confidence interval} = \overline{X} \pm t_{n-1,0.975}\left(S/\sqrt{n}\right)$$

where: $\overline{X}$ is the sample mean;
S is the sample standard deviation;
n is the number of independent measurements included in the data set; and
t is the Student's t distribution value with n-1 degrees of freedom;

Results of these calculations are expressed as the sample mean +/- the statistical variation.

### 3.6 Verification Testing Schedule

The verification testing commenced on December 1, 1998, with the initiation of daily testing. The unit ran in normal mode (dead end flow, 155 $l/m^2/h$ at $20^oC$ flux, 60-minute backwash interval). Daily testing concluded on December 31. Data was logged for a total of 726 hours of treatment system operation. Twenty-one hours of run time were lost due to a failure of the treatment system. Loss of the heating system in the treatment system enclosure caused a solenoid to freeze and the treatment system to automatically shut down on December 23.

Specialized tasks were not conducted until the conclusion of the daily testing for a variety of reasons. *Giardia* and *Cryptosporidium* removal challenge testing was delayed until January 22, 1999 because of the unavailability of challenge organisms (i.e. of *Giardia* cysts and *Cryptosporidium* oocysts).

The cleaning efficiency task was performed on February 16, 1999, due to unavailability of manufacturer's field technicians to assist in the procedure until that time. Membrane integrity testing was done on February 17, 18 after the conclusion of the cleaning evaluation.

### 3.7 Field Operations Procedures

In order to assure data, validity NSF Verification Testing Plan procedures were followed. This ensured the accurate documentation of both water quality and equipment performance. Strict adherence to these procedures resulted in verifiable performance of equipment.

### *3.7.1 Equipment Operations*

The operating procedures used during the verification study were described in the Operations Manual. (Appendix B) (Aquasource, 1998). Analytical procedures were described in equipment operations manual and PWSA's Laboratory Quality Assurance Plan (Appendix F) (Pittsburgh Water and Sewer Authority. Laboratory Quality Assurance Plan, January, 1997).

3.7.1.1 Operations Manual

The Operations Manual for the treatment system was housed on-site, attached to the Field Operations Document, and attached to this report as Appendix B. Additionally, operating procedures and equipment descriptions are described in detail in Chapter 2 of this report.

3.7.1.2 Analytical Equipment

The following analytical equipment was used during the verification testing:

- A Fisher Accumet Model AP61 portable pH meter was used for pH analyses.
- A Hach 2100P portable turbidimeter was used for turbidity analyses.
- A Hach Pocket Colorimeter was used for Chlorine for chlorine analyses.
- An Ertco 1003-FC NIST traceable thermometer was used for temperature analyses. The thermometer had a range –1 to 51$^{o}$C with scale divisions of 0.1$^{o}$C.

The treatment unit used a Hach 1720D turbidimeter for filtrate turbidity and Met One PCX particle counters for particle analysis.

### *3.7.2 Initial Operations*

Initial operations allowed the equipment manufacturer to refine the unit's operating procedures and to make operational adjustments as needed to successfully treat the source water. Information gathered during system start up and optimization would have been used to refine the FOD, if necessary. No adjustment to the FOD was necessary as a result of the initial operations. The unit was on site the last week of September 1998 and was operated for two months to establish the optimum treatment scheme prior to initiation of verification testing.

The major operating parameters examined during initial operations were flux, transmembrane pressure, backwash frequency, and the efficiency of the treatment unit.

3.7.2.1 Flux

Production capacity of a membrane system is usually expressed as flux. Flux is the water flow rate through the membrane divided by the surface area of the membrane. Flux is calculated from the flow rate and membrane surface area and it is typically expressed as liter per square meter per hour (l/m$^2$/h) or gallon per square foot per day (gfd). The surface area of the membrane used for the verification testing was 14.4 m$^2$. It is customary to refer to flux normalized to 20$^{o}$C or 68$^{o}$F. Lower temperatures increase the viscosity of water and decrease the amount of permeate that can be produced from a given area. The formula used to calculate the system flux is:

Flux (in $l/m^2/h$) = (Flow (gpm) * 3.785 l/gal*60 minutes/hour)/membrane area ($m^2$)
Flux (in gfd) = (Flow (gpm) * 1440 minute/day)/ membrane area ($ft^2$)
A manufacturer supplied coefficient, which is calculated from the temperature of the feed water, was used to normalize the flux to 20°C (68°F). The formula used for the calculation is:

$$\text{Coefficient} = 1/(0.4122+(1.3558^{-0.04179*\text{Water temperature}}))$$

The feed pressure to the membrane is adjusted to maintain the selected flux. This usually requires an increase in feed pressure to maintain the selected flux. In order to take this change in feed pressure into account, a parameter known as specific flux can be calculated. Specific flux is calculated by dividing the flux of the system (as calculated above) by the transmembrane pressure. The specific flux is expressed in liter per square meter per hour per bar at 20 °C ($l/m^2/h/b$ at 20°C) or gallon per square foot per day per psi (gfd/psi at 68°F). By plotting the inverse of specific flux, known as permeability, on to a semi log curve and extrapolating the trend line, an estimation of the expected cleaning date can be made.

3.7.2.2 Transmembrane Pressure

The pressures of the feed water were recorded twice per day. Since the Aquasource unit feeds water to the top and bottom of the vertically mounted filter columns, the pressure at the top and bottom of the filter column is measured and recorded. The average of these two readings is used as the feed pressure to the system. The filtrate pressure was recorded twice per day. The amount of pressure lost as the water is filtered through the membrane is referred to as transmembrane pressure (TMP).

3.7.2.3 Backwash

Backwashing of the filter is accomplished by forcing permeate under pressure in the reverse direction through the hollow fiber membrane. This removes the particles that have been deposited on the membrane and carries them to waste. Five percent sodium hypochlorite (bleach) was added to the backwash water before it enters the membrane to enhance backwash efficiency and prevent microbiological fouling of the filter. The target for the total chlorine residual in the backwash waste was 5 mg/l for the verification testing. The pilot automatically initiates a backwash after a preset filtration time. Membranes used on feed waters with low solids loading can operate with longer filtration cycles than those used on feed waters with higher solids loading. The filtration interval was set initially to accommodate the quality of the feed water. Adjustments to the backwash interval are made based on the maintenance of flux. That is, if the backwash is not able to maintain flux at a particular level, the frequency of backwashing is increased.

For this test program, a backwash interval of one minute every 60 minutes was used. Actual backwash time of the membrane was 45 seconds, the other 15 seconds was for cessation of the filtration cycle, valve operation and restart of the system. This backwash scenario was proven to be appropriate for flux maintenance during the study. The unit used approximately 25 gallons of permeate to backwash the membranes each cycle.

The prefilter was backwashed as part of the membrane backwashing sequence. Prefilter backwashing is the last portion of the system backwash. Permeate was passed through the prefilter in the opposite direction of normal flow. Approximately 8% of the total backwash, or two gallons in the case of this verification testing, is used to backwash the prefilter.

3.7.2.4 Percent Feed Water Recovery

In order to calculate the feed water recovery of the treatment system, the net production of the unit is divided by the total production of the unit. Multiplying the average flow rate by the filtration run time gives the total amount produced for the run. The net production is calculated by subtracting the amount of permeate required to backwash the system from the total amount produced. Dividing the net production by the total production and multiplying the result by 100 equals the percent water recovery of the system.

## 3.8 Verification Task Procedures

The procedures for each task of the verification testing were developed in accordance with the requirements in the EPA/NSF ETV Protocol (EPA/NSF, 1998). The Verification Tasks were as follows:

- Task 1 Membrane Flux and Operation
- Task 2 Cleaning Efficiency
- Task 3 Finished Water Quality
- Task 4 Reporting of Maximum Membrane Pore Size
- Task 5 Membrane Integrity Testing
- Task 6 Microbial Removal

Detailed descriptions of each task are provided in the following sections.

### *3.8.1 Task 1: Membrane Flux and Operation*

Membrane flux and operational characteristics were identified in this task. The purpose of this evaluation was to quantify operational characteristics of the UF equipment. Information regarding this task was collected throughout the length of the 30-day verification study.

The objectives of this task were to:

1. Establish appropriate operational parameters;
2. Demonstrate the product water recovery achieved;
3. Monitor the rate of flux decline over extended operation; and
4. Monitor raw water quality.

Standard operating parameters for filtration, backwash, and chemical cleaning were established through the use of the manufacturer's O&M Manual and the initial operations of the treatment system. After establishment of these parameters, the unit was operated under those conditions. Operational data was collected according to the schedule presented in Table 3-2.

3.8.1.1 Filtration

The flux selected by the manufacturer for the verification study was 155 l/m$^2$/h at 20$^o$C (91.2 gfd at 68$^o$F. The treatment unit adjusted flow as necessary to maintain this flux.

3.8.1.2 Backwash

The filtration cycle was 60 minutes for the verification study. The backwash required 60 seconds to complete; 15 seconds for system shutdown and various valve operations and 45 seconds for the backwash itself.

The interval between backwashes is determined based on the maintenance of flux. That is, if the backwash frequency is not able to maintain flux at a particular level, it is increased. The backwash frequency used during the study was capable of maintaining the flux selected for the verification testing.

The procedure for backwashing is detailed in the O&M Manual and will not be presented here. The normal backwash is an automatic function of the unit; the only adjustments which can be made are to frequency, duration, and pressure. Procedures for making these adjustments are detailed in the O&M Manual.

3.8.1.3 Chemical Cleaning

Chemical cleaning was to be instituted when the backwashing sequence was unable to restore the specific flux to above 120 l/m$^2$/h/b at 20$^o$C (4.9 gfd/psi at 68$^o$F). Due to the short duration of the verification testing and high quality of the feed water, chemical cleaning was not dictated by operational parameters; cleaning was conducted as per protocol requirements at the conclusion of the verification test.

The procedure used to perform chemical cleaning is presented in the O&M Manual and Section 3.8.2 will not be presented here.

### *3.8.2 Task 2: Cleaning Efficiency*

Cleaning efficiency procedures were identified in this task. The objectives of this task were to:

1. To evaluate the effectiveness of chemical cleaning for restoring finished water productivity to the membrane system.
2. Confirm manufacturer's cleaning practices are sufficient to restore membrane productivity.

Chemical cleaning, if required during the testing period, was to be instituted when the backwashing sequence was unable to restore the specific flux to above 120 l/m$^2$/h/b at 20 $^o$C (4.9 gfd/psi at 68$^o$F). If chemical cleaning was not required during the testing, it was to be performed at the conclusion of the 30-day period. The membranes were cleaned using manufacturer's recommendations February 16, 1999.

Prior to cleaning, the treatment system was operated at the conditions as described in Section 3.8.1. Operational data, including flow and pressure, were collected prior to cleaning. After cleaning, the system was restarted and operated a sufficient period of time to establish post cleaning, specific rate of flux recovery. Operational data, including flow and pressure, were collected after cleaning. Table 3-3 details all the operational and analytical data collected before, during, and following cleaning.

3.8.2.1 Analytical & Operational Data Collection Schedule

Data was collected before, during, and following cleaning according to Table 3-3.

**Table 3-3. Analytical & Operational Data Collection Schedule - Chemical Cleaning**

| Parameter | Frequency |
|---|---|
| pH of cleaning solution initial | 1/episode |
| pH of cleaning solution during process | 1/episode |
| pH of cleaning solution final | 1/episode |
| TDS of cleaning solution initial | 1/episode |
| TDS of cleaning solution during process | 1/episode |
| TDS of cleaning solution final | 1/episode |
| Turbidity of cleaning solution initial | 1/episode |
| Turbidity of cleaning solution during process | 1/episode |
| Turbidity of cleaning solution final | 1/episode |
| Oxidant residual initial | 1/episode |
| Oxidant residual final | 1/episode |
| Visual observation of backwash waste initial | 1/episode |
| Visual observation of backwash waste final | 1/episode |
| Flow of UF unit prior to cleaning | 1/episode |
| Pressure of UF unit prior to cleaning | 1/episode |
| Temperature of UF unit prior to cleaning | 1/episode |
| Flow of UF unit after cleaning | 1/episode |
| Pressure of UF unit after cleaning | 1/episode |
| Temperature of UF unit after cleaning | 1/episode |

3.8.2.2 Cleaning Procedures

The procedure used to perform chemical cleaning is presented in the O&M Manual (Appendix B).

### *3.8.3 Task 3: Finished Water Quality*

Procedures for the collection and analysis of finished water quality samples are identified in this task. The purpose of this task was to demonstrate whether the manufacturer's stated treatment goals are attainable. The goal of this portion of the ETV was to demonstrate the treatment unit's ability to consistently produce water with a turbidity of less than <0.1 NTU and comply with current and future regulations in the SWTR and ESWTR as they apply to filtration. Since the feed water was consistently less than 0.1 NTU and a turbidity challenge was not performed, this stated capability was not verified.

Testing on finished water was conducted throughout the length of the 30-day run. Procedures for sample collection and analysis, analytical equipment operation, analytical equipment calibration and calibration results are discussed in Section 3.8.3.1.

3.8.3.1 Sample Collection and Analysis Procedure

Finished water samples were collected and analyzed monthly for total alkalinity, total hardness, and TDS. Weekly collection and analysis of finished water samples was performed for TSS, total coliforms, HPC, TOC, UV absorbance, and algae. Collection and analysis of *Giardia* and *Cryptosporidium* was conducted during the microbial removal challenge testing. A summary of the sampling schedule is presented in Table 3-1.

Sample collection and analysis was performed according to procedures adapted from Standard Methods (APHA et.al., 1992) and Methods for Chemical Analysis of Water and Wastes (EPA, March, 1979).

### *3.8.4 Task 4: Reporting of Maximum Membrane Pore Size*

Determination of the maximum membrane pore size was to be done to assess a UF unit's ability to sieve particles of particular sizes. The FTO was to conduct a bubble point test, air pressure hold test, diffusive air flow test, or sonic wave sensing on the type of membrane in use during the verification study. The test was to be conducted by a state or EPA certified laboratory. Due to the extremely high cost of this test and the reliability of data available from membrane manufacturers, the ETV Steering Committee modified this requirement. The 1999 Protocol requires the reporting of the maximum membrane pore size by the manufacturer based on recommendation by the Steering Committee.

The manufacturer requested a waiver to permit the reporting of maximum membrane pore size in lieu of maximum pore size determination. This waiver was granted based on the modified Protocol requirement (NSF 1999).

### *3.8.5 Task 5: Membrane Integrity Testing*

Procedures for the testing of membrane integrity are identified in this task. The experimental objective of this task was to assess the membrane's integrity through the use of an air pressure hold test, turbidity reduction monitoring, and particle count reduction monitoring.

Membranes provide a physical barrier against the passage of particles and most types of microbial contamination. If the membrane is compromised, that is not intact, this barrier is lost. It is important to be able to detect when a membrane is compromised.

The three procedures, air pressure hold test, turbidity reduction monitoring, and particle count reduction monitoring were conducted on intact and compromised membranes. The tests were conducted prior to and after the intentional breaking of a fiber.

3.8.5.1 Air Pressure Hold Test

In order to conduct this test, it was necessary to remove the membrane vessel from the treatment unit. The membrane unit filtrate side was drained. The membrane itself was fully wetted (i.e. membrane pores were filled with water). The membrane was air pressurized up to 2.0 b (29 psi). The filtrate side was sealed and the pressure decline rate was monitored using an air pressure gauge. An intact membrane would be demonstrated by minimal pressure loss, i.e. 0.07 b (1.0 psi) every 5 minutes. Air pressure loss was also compared to the loss that was obtained when testing a compromised membrane. Pressure data was collected initially and then every two minutes during the pressure hold test.

3.8.5.2 Turbidity Reduction Monitoring

Turbidity of feed and filtrate water was monitored continuously with in-line equipment. An intact membrane would be expected to show a 90% reduction in turbidity from feed to filtrate. Due to the high quality of the feed water (the average feed turbidity was 0.078 NTU) showing a 90% reduction, 0.0078 NTU, was beyond the capability of the turbidimeters. Filtrate turbidity between an intact and a compromised membrane was compared. An increase of 100% was used as an indication of a compromised membrane.

3.8.5.3 Particle Count Reduction Monitoring

Particle count reductions from source to finished water of 99.9% would demonstrate an intact membrane. Due to the high quality of the feed water (the average cumulative feed water particle counts were 86 total counts per ml) showing a 99.9% reduction was pushing the limits of the instrumentation. Particle counts were measured continuously with in-line equipment. Differences between filtrate particle counts from an intact and a compromised membrane were compared. An increase of 100% was used as an indication of a compromised membrane.

### *3.8.6 Task 6: Microbial Removal*

The primary goal of water treatment is to provide water that is free of disease producing organisms. Most of these organisms are removed or rendered non-infectious through the use of conventional treatment practices like sedimentation, filtration, and disinfection. Not all disease producing organisms are reliably removed by these conventional processes. Membrane filtration offers the advantage of providing a physical barrier against the passage of two of these organisms, *Giardia* and *Cryptosporidium*.

The purpose of this task was to demonstrate the treatment unit's ability to provide a minimum 3 $\log_{10}$ removal from source water to plant effluent of *Giardia* cysts and 2 $\log_{10}$ *Cryptosporidium* oocysts. Participation in this task was optional. The manufacturer opted to participate in the microbial removal challenge.

Microbial challenge testing took place on January 22, 1999. The procedures for the preparation of the feed water stock, stock addition, sample collection and analysis, and calibration are

presented below. Table 3-1 contains the parameters and frequency of analytical data collection. Table 3-2 contains the parameters and frequency of operational data collection.

Procedures used for testing the effectiveness of the treatment system in removing *Giardia* cysts and *Cryptosporidium* oocysts are identified in this section. The testing schedule, the experimental objectives, procedures, and data collection schedule are discussed below.

3.8.6.1 Feed Water Stock Preparation

Challenge organisms were concentrated stock suspensions of formalin fixed *Giardia lamblia* cysts and formalin fixed *Cryptosporidium parvum* oocysts. The suspensions were added to a reservoir using a pipette as that reservoir was being filled with 50 gallons of feed water. A cocktail of both protozoans was added to the same feed water reservoir and fed simultaneously to the treatment system. The concentration of the organisms was determined from the stock suspensions by replicate hemocytometer. Five two ml samples were taken from the feed water reservoir. These samples were examined and the quantity of cysts and oocysts were determined. This was used as a check of the replicate hemocytometer counts.

Source water concentrations were fed into the treatment system immediately before the membrane vessels over approximately 60 minutes. Seeding began immediately after a backwash cycle. The feed water stock reservoir was gently mixed during this process.

3.8.6.2 Sample Collection Procedure

After the suspension was prepared and before the initiation of filtration, samples were collected to establish the initial titer of the microorganisms in the suspension. The feed suspension was pumped into the feed water line immediately before the membrane vessels. Once filtration had begun, the operational parameters, as presented in Table 3-2, were recorded. Daily analytical testing as presented in Table 3-1 was conducted. One thousand liters (264 gallons) of permeate water were then passed through a 1µm pore sized yarn wound filter at a rate of one gallon per minute (3.785 liter per minute). Sample volumes of feed water, filtrate water and back washwater were recorded. Samples were processed and analyzed by PWSA's EPA qualified laboratory according to EPA protocols. (EPA, April, 1996). A minimum of three replicates of the filtered water sample were analyzed.

## 3.9 QA/QC Procedures

Maintenance of strict QA/QC procedures is important, in that if a question arises when analyzing or interpreting data collected for a given experiment, it will be possible to verify exact conditions at the time of testing.

### *3.9.1 Daily QA/QC Verification Procedures*

Daily QA/QC procedures were performed on the on-line turbidimeter and inline particle counter flow rates and inline turbidimeter readout.

3.9.1.1 Inline Turbidimeter Flow Rate

The inline turbidimeter flow rate was verified volumetrically over a specific time. Effluent from the unit was collected into a graduated cylinder while being timed. Acceptable flow rates, as specified by the manufacturer, ranged from 250 ml/minute to 750 ml/minute (0.066 - 0.20gpm). The target flow rate was 500 ml/minute (0.13gpm). Adjustments to the flow rate were made by adjusting the valve controlling flow to the unit. Fine adjustments to the flow rate were difficult to make. If adjustments to the flow rate were made, they were noted in the operational / analytical data notebook.

3.9.1.2 Inline Particle Counter Flow Rate

The flow rate for the feed water and filtrate inline particle counters was verified volumetrically over a specific time. Effluent from the units was collected into a graduated cylinder while being timed. Acceptable flow rates, as specified by the manufacturer, ranged from 90 ml/minute to 110 ml/minute (0.024 – 0.029 gpm). The target flow rate was 100 ml/minute (0.026 gpm). Care was taken to maintain the flow rate between 95 ml/minute and 105 ml/minute (0.025 – 0.028 gpm). Changes to the flow rate were made by adjusting the level of the discharge from the overflow weir. If adjustments to the flow rate were made they were noted in the operational / analytical data logbook.

3.9.1.3 Inline Turbidimeter Readout

Inline turbidimeter readings were checked against a properly calibrated bench model. Samples of the filtrate were collected and analyzed on a calibrated bench turbidimeter. The readout of the bench model and the online turbidimeter were recorded. Exact agreement between the two turbidimeters is not likely due to the differences in the analytical techniques of the two instruments.

### *3.9.2 Bi-Weekly QA/QC Verification Procedures*

Bi-weekly QA/QC procedures were performed on the inline flow meter. Meter was checked to determine if cleaning was necessary and verification of flow was performed.

3.9.2.1 Inline Flow Meter Clean Out

Examination of the inline flow meters indicated that clean out was not required during the verification testing. This was due to the short duration of the study and the high quality of the feed water.

3.9.2.2 Inline Flow Meter Flow Verification

Verification of the readout of the feed, filtrate, and backwash flow meters was conducted bi-weekly during the testing period. This was done by taking the difference in the totalizer reading over a specific period of time and comparing it to a volume collected over the same time period. The feed meter was verified by shutting off the feed water flow to the feed tank, drawing the

tank down, measuring the amount of water drawn from the tank, and comparing it to the totalizer reading. The filtrate meter was verified by dropping the level of the water in the filtrate tank, allowing the tank to fill with filtrate, measuring the amount of water that entered the tank, and comparing it to the totalizer reading. The backwash meter was verified by measuring the draw down of the filtrate tank during backwash and comparing the amount used to the totalizer reading.

### *3.9.3 Procedures for QA/QC Verifications at the Start of Each Testing Period*

Verifications of the inline turbidimeter, pressure gauges/transmitters, tubing and particle counters were conducted. These verification procedures follow.

3.9.3.1 Inline Turbidimeter

The inline turbidimeter reservoir was cleaned by removing the plug from the bottom of the unit and allowing the body to drain. The body of the unit was then flushed with water. The unit was recalibrated following manufacturer's recommendations.

3.9.3.2 Pressure Gauges/Transmitters

Pressure gauge readouts were compared to the display on the control screen, although the readings taken directly from the gauges were entered into the operational/analytical data log book. Pressure gauge readings were verified through the use of a dead test meter. Procedures for the use of the meter were included with the meter. Generally, the procedure consisted of placing the gauge on the meter adding weight to the meter and comparing the reading obtained to the known amount of weight.

3.9.3.3 Tubing

The tubing and connections associated with the treatment system were inspected to verify that they were clean and did not have any holes in them. Also, the tubing was inspected for brittleness or any condition which could cause a failure.

3.9.3.4 Inline Particle Counters

Calibration of the particle counter is generally performed by the instrument manufacturer. The calibration data was provided by the instrument manufacturer for entry into the software calibration program. Once the calibration data was entered, it was verified using calibrated mono-sized polymer microspheres. Microspheres of 5*u*m, 10*u*m and 15*u*m were used for particle size verification. The following procedure was used for instrument calibration verification:

- Analyze the particle concentration in the dilution water;
- Add an aliquot of the microsphere solution to the dilution water to obtain a final particle concentration of 2,000 particles per ml;

- Analyze a suspension of each particle size separately to determine that the peak particle concentration coincides with the diameter of particles added to the dilution water;
- Prepare a cocktail containing all three microsphere solutions to obtain a final particle concentration of approximately 2,000 particles per ml of each particle size; and
- Analyze this cocktail to determine that the particle counter output contains peaks for all the particle sizes.

### *3.9.4 On-Site Analytical Methods*

Procedures for daily calibration, duplicate analysis, and performance evaluation for pH, temperature, residual chlorine are discussed in the following sections.

3.9.4.1 pH

Analysis for pH was performed according to *Standard Methods* 4500-$H^+$. A two-point calibration of the pH meter was performed each day the instrument was in use. Certified pH buffers in the expected range were used. After the calibration, a third buffer was used to check linearity. The values of the two buffers used for calibration, the efficiency of the probe (calculated from the values of the two buffers), and the value of the third buffer used as a check were recorded in the logbook.

pH measurements do not lend themselves to "blank" analyses. Duplicates were run once a day. Performance evaluation samples were analyzed during the testing period. Results of the duplicates and performance evaluation were recorded.

3.9.4.2 Temperature

Readings for temperature were conducted in accordance with *Standard Methods* 2550. Raw water temperatures were obtained once per day by submerging the thermometer in the feed water reservoir. A National Institute of Standards and Technology (NIST) certified thermometer having a range of – 1$^o$C to +51$^o$C (30$^o$F to 120 $^o$F), subdivided in 0.1$^o$C (0.2 $^o$F) increments was used for all temperature readings.

Temperature measurements do not lend themselves to "blank" analyses. Duplicates were run on every sample. The temperature of the feed water was not recorded until two like readings were obtained, indicating that the thermometer had stabilized. Two equivalent readings were considered to be duplicate analyses.

3.9.4.3 Residual Chlorine Analysis

Chlorine residual analyses were taken on the backwash waste according to *Standard Methods* 4500 Cl G. The unit was received new (factory calibrated) and daily calibration was not necessary.

The backwash wastewater was collected, during backwash, twice per day. The entire amount of wash water from a backwash was collected in a reservoir for analysis.

Dilution of the backwash waste (1ml of backwash waste to 5ml deionized (DI) water) was necessary due to the high level of residual total chlorine.

Blanks for chlorine analyses were done by analyzing DI water daily. Duplicates were run once a day. Performance evaluation samples were analyzed during the testing period. Results of the duplicates and performance evaluation were recorded.

3.9.4.4 Turbidity Analysis

Turbidity analyses were performed according to *Standard Methods* 2130. The bench-top turbidimeter was calibrated at the beginning of verification test and on a weekly basis using primary turbidity standards according to manufacturer's recommendations. Primary turbidity standards of 0.1, 0.5 and 5.0 NTU were checked after calibration to verify instrument performance. Deviation of more than 10 % of the true value of the primary standards indicated that recalibration or corrective action should be undertaken on the turbidimeter. Secondary standards were used on a daily basis to verify calibration.

Blanks for turbidity analyses were done by analyzing DI water daily. Duplicates were run on feed water turbidity and backwash waste once a day. Performance evaluation samples were analyzed during the testing period. Results of the duplicates and performance evaluation were recorded.

### *3.9.5 Chemical and Biological Samples Shipped Off-Site for Analyses*

PWSA's in-house laboratory was used for the analysis of chemical and biological parameters. PWSA's QA Plan outlines sample collection and preservation methods (PWSA, 1997) (Appendix F). Sample collection was done by representatives of PWSA.

3.9.5.1 Organic Parameters

Organic parameters analyzed during the verification testing were TOC and $UVA_{254}$.

Samples for analysis of TOC and UVA were collected in glass bottles supplied by the PWSA laboratory and hand carried to the laboratory by a PWSA representative immediately after collection. TOC and UVA samples were collected, preserved, and held in accordance with *Standard Method* 5010B. Storage time before analysis was minimized in accordance to *Standard Methods.*

Analyses of the TOC samples were done according to methodology outlined in PWSA's QA Plan which is based on *Standard Methods* 5310 C. Analyses of the UVA samples were done according to methodology outlined in PWSA's QA Plan which is based on *Standard Methods* 5910 B.

3.9.5.2 Microbiological Parameters

Microbiological parameters analyzed during the verification testing were Total Coliform, HPC, Protozoa and Algae, *Giardia* and *Cryptosporidium*. Microbiological samples were collected according to procedures outlined in PWSA's QA Plan and hand delivered to the laboratory by a PWSA representative immediately following collection. Samples were processed for analysis by the PWSA laboratory within the time specified for the relevant analytical method. The laboratory kept the samples refrigerated at 1-5$^{o}$C (34 $^{o}$F - 41 $^{o}$F) until initiation of analysis.

Algae samples were preserved with Lugol's solution after collection and stored at a temperature of approximately 1-5$^{o}$C (34 $^{o}$F - 41 $^{o}$F) until counted.

Algae samples were analyzed according to *Standard Method* 10200 F. Total coliforms were analyzed using procedures presented in PWSA's QA Plan. These procedures are based on *Standard Methods* 9222B. HPC analyses were conducted according to procedures presented in PWSA's QA plan. These procedures are based on *Standard Methods* 9215D. Protozoans were analyzed using procedures developed by EPA for use during the Information Collection Rule (EPA, 1996).

3.9.5.3 Inorganic Parameters

Inorganic parameters analyzed during the verification testing were Total Alkalinity, Total Hardness, TDS, and TSS.

Inorganic chemical samples were collected, preserved and held in accordance with *Standard Methods* 3010B. Particular attention was paid to the sources of contamination as outlined in *Standard Method* 3010C. The samples were hand delivered to the laboratory by a representative of PWSA immediately following collection. The laboratory kept the samples at approximately 1-5$^{o}$C (34 $^{o}$F - 41 $^{o}$F) until initiation of analysis.

Total alkalinity analyses were conducted according to Method 150.1 (EPA, 1979). Total Hardness analyses were conducted according to Method 130.2 (EPA, 1979). TDS analyses were conducted according to *Standard Methods* 2540C. TSS analyses were conducted according to *Standard Methods* 2540D.

# Chapter 4
# Results and Discussions

## 4.1 Introduction

The verification testing was for the Aquasource Pilot System Model A35 manufactured by Aquasource NA. Initial operations were conducted in September and November 1998 to establish operating parameters for the system. The testing commenced on December 1, 1998 and concluded its 30-day period on December 31, 1998. Microbial challenge testing was conducted on January 22, 1999, chemical cleaning was performed on February 16, 1999, and membrane integrity testing was performed on February 17 and 18, 1999.

This section of the verification report will present the results of the testing and offer discussion of the results. Results and discussions of initial operations, equipment characteristics, membrane flux and operation, cleaning efficiency, finished water quality, maximum membrane pore size, membrane integrity testing, and microbial removal will be presented in this section. Also the results of the daily, bi-weekly and initial QA/QC procedures will be presented in this section.

## 4.2 Initial Operations Period Results

An initial operations period allowed the equipment manufacturer to refine the unit's operating procedures and to make operational adjustments as needed to successfully treat the source water. The unit was on site the last week of September 1998 and was operated for two months during the initial operations period to establish the optimum treatment scheme prior to initiation of verification testing. The primary goals of the initial operations were to establish a flux rate, the expected transmembrane pressure, backwash frequency appropriate for the feed water quality, and the efficiency of the unit.

### *4.2.1 Flux*

The flux was gradually increased from 101 $l/m^2/h$ at 20°C to 151 $l/m^2/h$ at 20°C (59.6 gfd at 68 °F to 89 gfd at 68 °F) during the initial operations period. Based on the data collected during the initial operations period, the manufacturer determined that the treatment unit would be capable of operating at 155 $l/m^2/h$ at 20°C (91.2 gfd at 68 °F). This was a flux of 112 $l/m^2/h$ at 8.0°C (65.9 gfd at 50°F). The initial specific flux was 250 $l/m^2/h/b$ at 20°C (10 gfd/psi at 68°F), 190 $l/m^2/h/b$ at 9.9°C (110 gfd/psi at 50°F).

### *4.2.2 Transmembrane Pressure*

The TMP during the initial operations period varied with the flux. TMP ranged from 0.33b to 0.83b (4.8 psi to 12 psi) during the initial operations period.

### *4.2.3 Backwash Frequency*

During the initial operations period, backwash frequencies of 30 and 60 minutes were investigated. Based on the results of the initial operations period, it was determined that a

backwash interval of one minute every 60 minutes would be used during the verification testing. Actual backwash time of the membrane was 45 seconds, the other 15 seconds was for cessation of the filtration cycle, valve operation and restart of the system. This backwash scenario proved to be appropriate for flux maintenance during the study. The unit used approximately 25 gallons (95 liters) of permeate to backwash the membranes each cycle.

## 4.3 Verification Testing Results and Discussion

The results and discussions of membrane flux and operation, cleaning efficiency, finished water quality reporting of maximum membrane pore size, membrane integrity testing, and microbial removal tasks of the verification testing are presented below.

### *4.3.1 Task 1: Membrane Flux and Operation*

The parameters of flow, feed and filtrate pressures, backwash frequency and volumes, and the feed water temperature were used to establish membrane flux and operational characteristics. TMP and rate of specific flux decline were established from these parameters. The results of the TMP and rate of specific flux decline are presented below. Date of chemical cleaning was February 16, 1999. A calculation of the treatment unit efficiency is presented.

4.3.1.1 Transmembrane Pressure Results

Transmembrane pressure fluctuated from 0.58b to 0.76b (8.4 psi to 11 psi). The average TMP during the testing was 0.65b (9.4 psi). Table 4-1 presents a summary of the daily unit pressure readings and TMP. Figure 4-1 presents a graph of daily TMP results. A complete tabular summary of the data is presented in Appendix C.

**Table 4-1. Daily Unit Pressure Readings and Transmembrane Pressure**

| | Upper Vessel Pressure (psi) | Lower Vessel Pressure (psi) | Filtrate Pressure (psi) | Transmembrane Pressure (psi) |
|---|---|---|---|---|
| Average | 12 | 13 | 2.9 | 9.4 |
| Minimum | 10 | 12 | 2.1 | 8.4 |
| Maximum | 14 | 15 | 3.6 | 11 |
| Standard Deviation | 0.69 | 0.63 | 0.36 | 0.53 |
| 95% Confidence Interval | (12, 12) | (12, 13) | (2.9, 3.0) | (9.2, 9.5) |

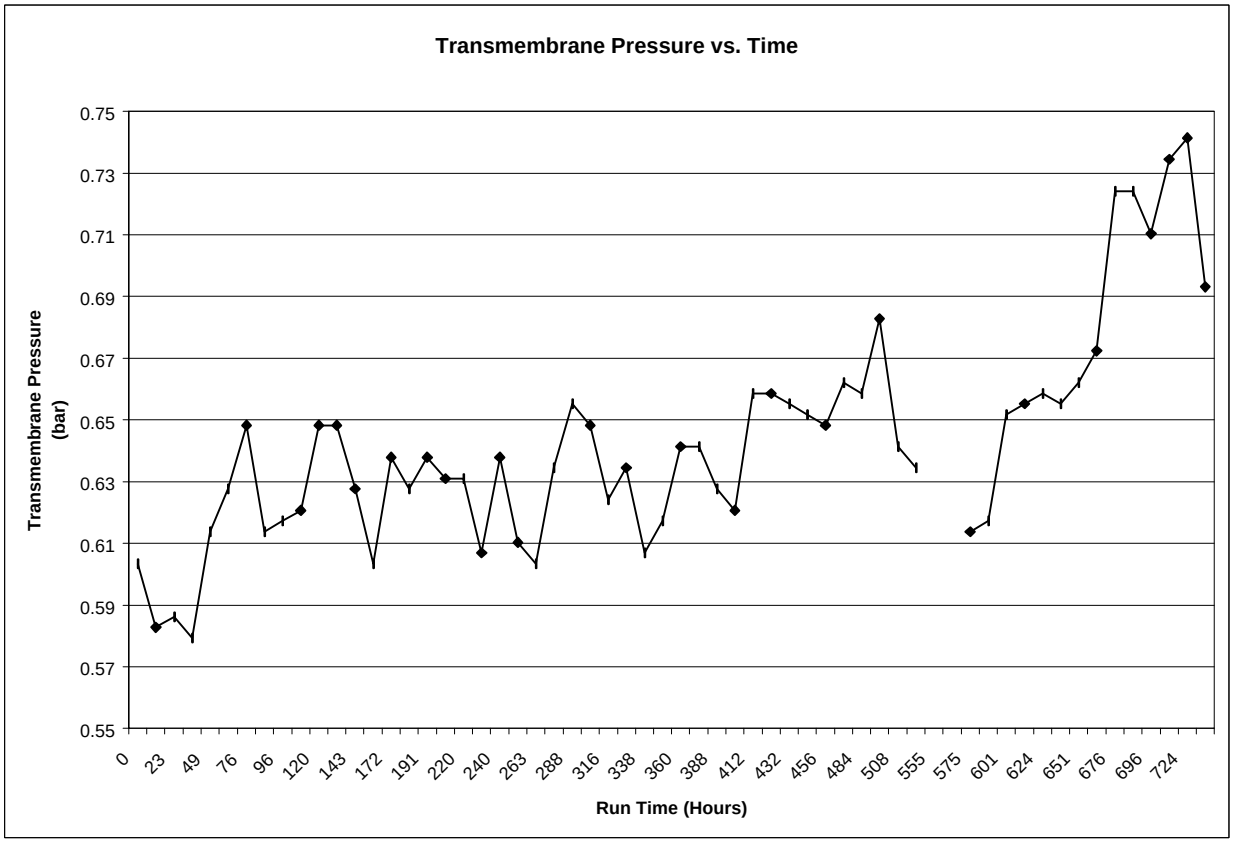



**Figure 4-1. Transmembrane Pressure vs. Time**

As depicted in Figure 4-1, the TMP tended to increase over the course of the verification testing. The increase was not unexpected and seemed to indicate that the treatment system was capable of operation at the selected flux and backwash protocol on this feed water.

The increase in TMP may be due to the accumulation of particles on the membrane surface. The backwash protocol may not have removed all of the particulate material from the membrane. Another possibility is that there was some accumulation of algae or bacteria on the membrane. (The addition of chlorine to the backwash water is intended to control the accumulation of these substances.) An accumulation of material on the membrane would, most likely, cause an increase in TMP in the system by limiting the available membrane surface area.

The TMP fluctuated somewhat from day to day with subsequent day's readings sometimes being lower than the previous day's results. This would seem to argue against the accumulation of material on the membrane. But examination of the overall TMP trend clearly shows an increase with time. The explanation of why TMP sometimes decreased from day to day may be due to the fact that the operational readings were taken at various times in the operational cycle. The feed pressure increased as the time to the next backwash decreased. If the pressure and flow readings were taken shortly after the completion of a backwash cycle, a lower TMP would result. Likewise, if the readings were taken just prior to the initiation of a backwash cycle, a higher TMP would result.

There was a noticeable decrease in TMP between run time 485 hours and 555 hours. This may have been related to the system shut down caused by the previously discussed failure of the enclosure's heating system. Allowing the membranes to "relax" may have caused some of the accumulated particles to be released from the membranes. There is no empirical evidence for this supposition. Overall the increase in TMP during the 30-day testing period was slight. This would seem to indicate that the selected flux and backwash protocol was appropriate for this feed water quality.

4.3.1.2 Specific Flux Results

The specific flux of the treatment system was 240 l/h/m$^2$/b at 20$^o$C (10 gfd/psi at 68$^o$F) on average. The specific flux varied from a minimum of 220 l/m$^2$/h/b at 20$^o$C to 260 l/m$^2$/h/b at 20$^o$C (9.0 gfd/psi at 68$^o$F to 11 gfd/psi at 68$^o$F) during the testing. Table 4-2 presents a summary of the specific flux of the treatment system. Figure 4-2 presents a graph of daily specific flux results.

**Table 4-2. Specific Flux**

| | Specific Flux (l/m$^2$/h/b @20$^o$C) |
|---|---|
| Average | 240 |
| Minimum | 220 |
| Maximum | 260 |
| Standard Deviation | 7.2 |
| Confidence Interval | (240, 240) |

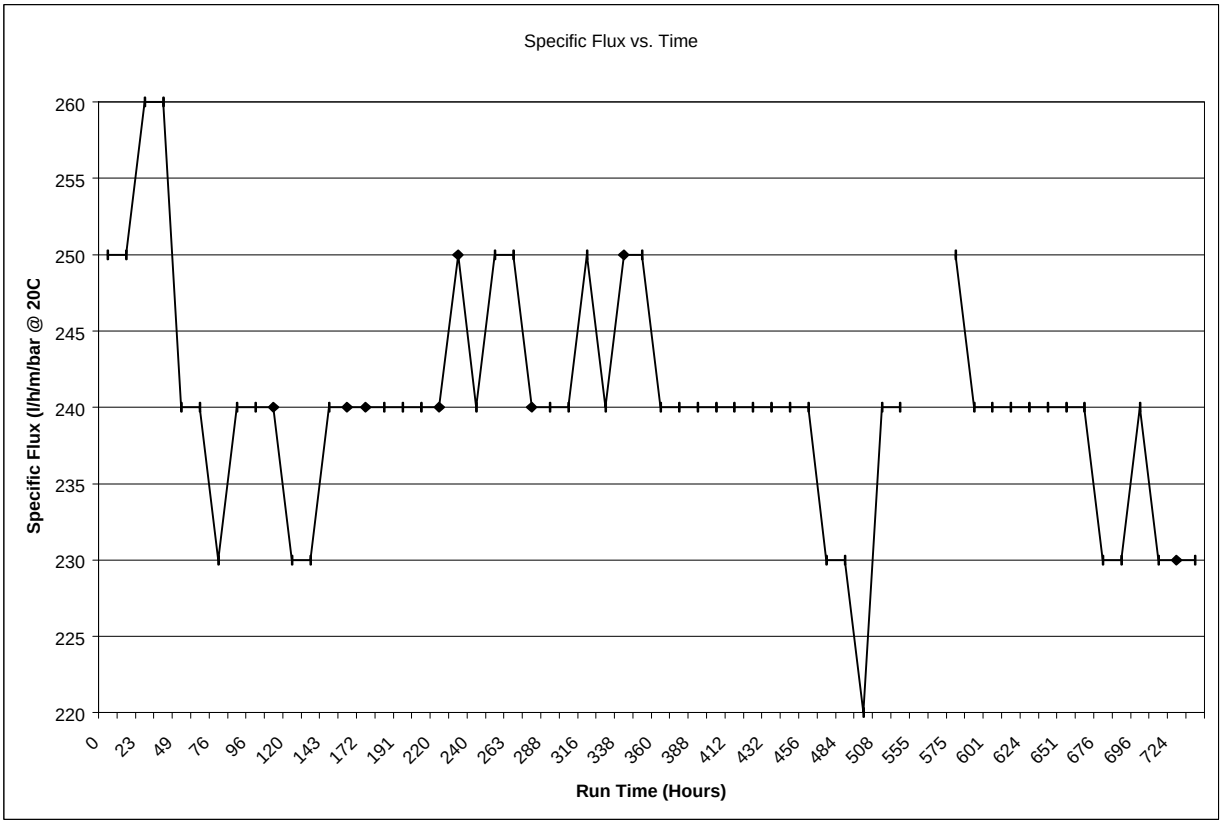



**Figure 4-2. Specific Flux Decline vs. Time**

As depicted in Figure 4-2, specific flux declined over the course of the verification testing. The specific flux is a function of the flux and the TMP of the system. As the TMP of the system increases the specific flux declines. The specific flux decline did not appear to be excessive during the testing. There were two episodes of significant decline of specific flux decline. The first occurrence was between run time 25 hours and 75 hours, when the flux declined from 260 $l/m^2/h/b$ at $20^oC$ to 230 $l/m^2/h/b$ at $20^oC$. This correlates to increase in TMP during that time frame. The increase of TMP may have been due, as previously discussed, to variations in the time in the operational cycle when readings were taken. The second occurrence was on December 21, there was a slight increase in TMP and a slight decrease in flux that combined to create this reading.

4.3.1.3 Cleaning Episodes

Aquasource recommends that cleaning be instituted when the backwashing sequence is unable to restore the specific flux to above 120 $l/m^2/h/b$ at $20^oC$ (4.9 gfd/psi at $68^oF$). Due to the short duration and high quality of the feed water, chemical cleaning was not required during the 30-day test run. Cleaning was conducted as per ETV protocol requirements on February 16, 1999. Results of that cleaning are presented in Section 4.3.2.

4.3.1.4 Percent Feed Water Recovery

The percent feed water recovery of the treatment system was calculated by comparing the net production to the total water filtered. The following equation was used:

$$\text{Percent feed water recovery} = 100 * [Q_p/Q_f]$$

where: $Q_p$ = filtrate flow (gpd)
$Q_f$ = feed flow to membrane

Using the above equation the following calculation was performed:
Filtrate flow = flow (gpm) * minutes/day = filtrate flow (gpd)
Filtrate flow = 7.0 gpm*1440 minute/day = 10080 gpd
Feed flow to membrane = filtrate flow + backwash volume
Feed flow = 10080 gpd + (25 gal/bw/hr * 24 hr/day) = 10680 gpd

Percent feed water recovery = 100 * [10080/10860] = 94%

### *4.3.2 Task 2: Cleaning Efficiency*

Cleaning was conducted on February 16, 1999. The cleaning was a two-stage process consisting of a pre-cleaning and cleaning step. The pre-cleaning consists of circulating the cleaning solution through the membranes for 30 minutes; the cleaning step consists of circulating the cleaning solution through the membranes for 45 minutes. A detailed description of the cleaning process is presented in the manufacturer's O&M Manual (Appendix B).

Data on the characteristics of the cleaning solution before, during, and after cleaning was collected. Operational parameters were recorded before and after cleaning. The cleaning solution data was used to characterize the cleaning solution and waste generated by cleaning of the membranes. The operational data was collected to facilitate the calculation of the recovery of specific flux and the loss of original specific flux.

4.3.2.1 Results of Cleaning Episodes

Table 4-3 below presents the chemical and physical characteristics of the cleaning solution. Table 4-4 presents the results of the operational parameters collected before, during, and after the cleaning procedure.

**Table 4-3. Chemical and Physical Characteristics of Cleaning Solution**

| | | Prewash | | Second Wash | |
|---|---|---|---|---|---|
| Parameter | unit | Result | Dup. | Result | Dup. |
| pH of Cleaning Solution Initial | | 8.1 | 8.1 | 8.4 | 8.4 |
| pH of Cleaning Solution During Process | | 9.2 | 9.2 | 8.6 | 8.6 |
| pH of Cleaning Solution Final | | 9.1 | 9.1 | 8.6 | 8.6 |
| TDS of Cleaning Solution Initial | (mg/l) | 110,558 | | 96,698 | |
| TDS of Cleaning Solution During Process | (mg/l) | 4,216 | | 22,318 | |
| TDS of Cleaning Solution Final | (mg/l) | 3,288 | | 29,336 | |
| Turbidity of Cleaning Solution Initial | (NTU) | 11.10 | 11.30 | 9.20 | 9.23 |
| Turbidity of Cleaning Solution During Process | (NTU) | 9.11 | 9.81 | 5.56 | 5.39 |
| Turbidity of Cleaning Solution Final | (NTU) | 8.40 | 8.42 | 2.88 | 3.00 |
| Oxidant Residual Initial | (mg/l) | 86 | 90 | 25 | 25 |
| Oxidant Residual Final | (mg/l) | 32 | 37 | 21 | 22 |
| Visual Observation of Backwash Waste Initial | | Clear, some air | | Clear, some air | |
| Visual Observation of Backwash Waste Final | | Soapy, cloudy (air), slightly brownish cast | | Soapy, no brown | |

**Table 4-4. Operational Parameter Results - Cleaning Procedure**

| | | | Prewash | Second Wash |
|---|---|---|---|---|
| Parameter | Unit | Time | Result | Result |
| Flow of UF Unit Prior to Cleaning | (gpm) | 11:00 | 6.3 | |
| Pressure of UF Unit Prior to Cleaning (Upper) | (psi) | 11:00 | 12 | |
| Pressure of UF Unit Prior to Cleaning (Lower) | (psi) | 11:00 | 13 | |
| Pressure of UF Unit Prior to Cleaning (Filtrate) | (psi) | 11:00 | 2.4 | |
| Temperature of UF Unit Prior to Cleaning | ($^{o}$C) | 11:00 | 3.7 | 3.7 |
| Flow of UF Unit After Cleaning | (gpm) | 13:37 | | 6.3 |
| Pressure of UF Unit After Cleaning (Upper) | (psi) | 13:37 | | 11 |
| Pressure of UF Unit After Cleaning (Lower) | (psi) | 13:37 | | 13 |
| Pressure of UF Unit After Cleaning (Filtrate) | (psi) | 13:37 | | 1.9 |
| Temperature of UF Unit After Cleaning | ($^{o}$C) | 13:37 | | 3.7 |
| Recirculation Flow – during cleaning | (gpm) | | 30 | 30 |

4.3.2.2 Calculation of Recovery of Specific Flux and Loss of Original Specific Flux

The following equation was used to calculate the recovery of specific flux:

Recovery of specific flux = 100 X (1- ($Js_f$ / $Js_i$))
where: $Js_f$ = Specific flux (gfd/psi , l/m$^2$/h/b) at end of current run (final)

$Js_i$ = Specific flux (gfd/psi, $l/m^2/h/b$) when the system was restarted after completion of the cleaning procedure (initial)

The specific flux prior to the start of the cleaning process was: 220 $l/m^2/h/b$ at 20°C (9.0 gfd/psi at 68°F). The specific flux when the system was restarted after the completion of the washing procedure was 220 $l/m^2/h/b$ at 20°C (9.0 gfd/psi at 68°F).

Using these figures in the above equation resulted in a recovery of specific flux of -0.34%.

The following equation was used calculate the loss of original specific flux:

Loss of original specific flux = 100 X (1- ($Js_i$ / $Js_{io}$))
where: $Js_{io}$ = Specific flux (gfd/psi , $l/m^2/h/b$) at time zero point of membrane testing

The specific flux at time zero point of membrane testing was 250 $l/m^2/h/b$ at 20°C (10 gfd/psi at 68°F). The specific flux when the system was restarted after the completion of the washing procedure was 220 $l/m^2/h/b$ at 20°C (9.0 gfd/psi at 68°F).

Using these figures in the above equation resulted in a loss of original specific flux of 12%.

4.3.2.3 Discussion of Results

Aquasource recommends that cleaning be instituted when the backwashing sequence is unable to restore the specific flux to above 120 $l/h/m^2/bar$ at 20°C (4.9 gfd/psi at 68°F). Due to the short duration and high quality of the feed water, chemical cleaning was not dictated by operational parameters. However, a chemical cleaning is required by the ETV Protocol and was performed on February 16, 1999.

The procedure used for chemical cleaning was well defined in the operations manual and required minor manual effort. Loading of the detergent, mixing it into solution, and initiation of the cleaning procedure required approximately two hours of effort by the operator.

The characterization of the cleaning wastewater indicated that the solution was moderately basic, with a pH of 9.1 in the pre-cleaning waste and 8.6 in the final cleaning waste, had turbidity of not exceeding 12 NTU, high TDS, with the final waste at nearly 30,000 mg/l, and total chlorine residuals of 20 mg/l to 30 mg/l. The wastewater during the pre-cleaning had a slight brown cast and a “soapy” appearance.

Aquasource indicated that no hazardous material is present in the cleaning detergent. The presence of hazardous materials in the wastewater would be dependent on the quality of the feed water. Depending on local regulations, the waste stream may be able to be discharged to the sanitary sewer system.

Examination of the operational data shows a slight recovery of specific flux. This may indicate that the cleaning procedure was not capable of restoring membrane performance because of irreversible fouling of the membrane or that this particular cleaning event was not effective.

The loss of original specific flux was 12%. This may indicate that some irreversible degradation of the membrane had occurred. However, given the poor performance of the cleaning procedure's recovery of specific flux, it may again indicate that the cleaning event was not effective.

### *4.3.3 Task 3: Finished Water Quality*

The results of the testing of the feed water for Total Alkalinity, Total Hardness, TDS, TSS, Total Coliforms, HPC, TOC, $UVA_{254,}$ and Algae are presented in Table 4-5. The results of the testing of the finished water for Total Alkalinity, Total Hardness, TDS, TSS, Total Coliforms, HPC, TOC, $UVA_{254,}$ and Algae are presented in Table 4-6. A complete data table is presented in Appendix C.

**Table 4-5. Feed Water Quality**

| | Parameter | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total Alkalinity | Total Hardness | Total Dissolved Solids | Total Suspended Solids | Total Coliforms | HPC | TOC | UVA | Algae |
| | (mg/l) | (mg/l) | (mg/l) | (mg/l) | (cfu/100 ml) | (cfu/100 ml) | (mg/l) | (cm –1) | (cells/ml) |
| Average | 63 | 154 | 296 | 0.16 | 0 | 260 | 1.56 | 0.019 | 90 |
| Minimum | 59 | 150 | 280 | <0.05 | 0 | 70 | 1.36 | 0.016 | 40 |
| Maximum | 71 | 158 | 313 | 0.30 | 0 | 460 | 1.73 | 0.022 | 136 |
| Std. Dev. | 5.6 | N/A | N/A | 0.16 | 0 | 160 | 0.155 | 0.0028 | 39 |
| 95% Confid Int | (58, 68) | N/A | N/A | (0.0069, 0.320 | N/A[1] | (103, 417) | (1.41, 1.72) | (0.016, 0.022) | (51, 129) |

N/A = Not applicable because the sample size (n) was 2.
N/A[1] = Not applicable because standard deviation = 0
Note: Calculated averages for less than results (<) utilize half of the Level of Detection (0.05 mg/l) or 0.025 mg/l in these calculations. (Gilbert, 1987).

**Table 4-6. Finished Water Quality**

| | Parameter | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total Alkalinity | Total Hardness | Total Dissolved Solids | Total Suspended Solids | Total Coliforms | HPC | TOC | UVA | Algae |
| | (mg/l) | (mg/l) | (mg/l) | (mg/l) | (cfu/100 ml) | (cfu/100 ml) | (mg/l) | (cm –1) | (cells/ml) |
| Average | 65 | 150 | 296 | 0.088 | 0 | 11 | 1.73 | 0.018 | 5 |
| Minimum | 60 | 146 | 271 | <0.050 | 0 | 2 | 1.34 | 0.015 | <8 |
| Maximum | 73 | 154 | 321 | 0.20 | 0 | 30 | 2.26 | 0.020 | 8 |
| Std. Dev. | 5.9 | N/A | N/A | 0.083 | 0 | 13 | 0.387 | 0.0021 | 2 |
| 95% Confid Int | (59, 71) | N/A | N/A | (0.062, 0.17) | N/A[1] | (0, 24) | (1.35, 2.11) | (0.016, 0.020) | (3, 7) |

N/A = Not applicable because the sample size (n) was 2.
N/A[1] = Not applicable because standard deviation = 0.
Note: Calculated averages for less than results (<) utilize half of the Level of Detection (0.05 mg/l) or 0.025 mg/l in these calculations. (Gilbert, 1987).

The following observations were made after examination of the results of feed and finished water testing. Significant reductions were seen in HPC. HPC averaged 260 CFU/100ml in the feed water. Permeate HPC concentrations were 11 CFU/100ml on average. This was likely due to the

physical removal of the bacteria on the membrane surface. (The presence of HPC in the permeate may have been due to the inability to completely disinfectant the Tygon sample lines.)

Algae concentrations were reduced. Feed water contained 90 cells/ml on average. Average permeate algae concentrations were 5 cells/ml. The reported average finished water concentration was the result of one cell observed in one of the four samples with a level of detection of 8 cells/ml. The removal of algae through the system was likely due to the physical removal of the algae cells on the membrane surface. (Permeate algae presence may have been due to growth in the Tygon sample lines.)

A reduction of 0.072 mg/L TSS was observed on average. This represented approximately a 50% reduction in TSS; although given the low concentration of TSS in the feed water it may be hard to extrapolate this percent removal to other locations.

The membrane pilot unit had little or no effect on the total alkalinity, total hardness, TDS, TOC, and $UVA_{254.}$ This was not unexpected since these parameters are not present in the water as solid constituents and are not amenable to reduction by physical straining.

Total coliform reduction could not be demonstrated due to the absence of total coliforms in the feed water and permeate throughout the test.

Temperature of the feed water changed dramatically during the thirty day testing from a high of 11°C to a low of 3.2°C (52°F to 38 °F). The average temperature was 7.6°C (46°F).

4.3.3.1 Turbidity Results and Removal

Results of testing for turbidity in the feed and finished water were examined to verify the stated turbidity treatment ability. Since the feed water turbidity was consistently less than 0.1 NTU and a turbidity challenge was not conducted this stated treatment goal was not verifiable. A summary of the results is presented in Tables 4-7 and 4-8. A complete data table is presented in Appendix C. A graph of this data is presented as Figure 4-3.

**Table 4-7. Turbidity Analyses Results and Removal**

| Sample Parameter | Feed (Bench Top) Turbidity | Turbidity (duplicate) | Filtrate (In-line) Turbidity | Amount Removed |
|---|---|---|---|---|
| | (NTU) | (NTU) | (NTU) | (NTU) |
| Average | 0.078 | 0.078 | 0.022 | 0.055 |
| Minimum | 0.060 | 0.050 | 0.021 | 0.039 |
| Maximum | 0.10 | 0.10 | 0.029 | 0.079 |
| Standard Deviation | 0.011 | 0.012 | 0.0036 | 0.011 |
| 95% Confidence Interval | (0.075, 0.081) | (0.074, 0.082) | (0.021, 0.023) | (0.051, 0.059) |

**Table 4-8. Filtrate Turbidity Results – Four Hour In-line Readings**

| Parameter | Turbidity (NTU) |
|---|---|
| Average | 0.020 |
| Minimum | 0.015 |
| Maximum | 0.045 |
| Standard Deviation | 0.0036 |
| 95% Confidence Interval | (0.020, 0.021) |

The turbidity of the permeate was very low throughout the duration of the verification testing. The inline permeate turbidimeter readings averaged 0.022 NTU; the benchtop turbidimeter readings averaged 0.045 NTU. While this may initially appear to be a significant difference, it is most likely due to the low level of turbidity in the feed and finished water and the differences in methodology of the two pieces of analytical equipment. The discrepancy between these two results can be explained by differences in the analytical techniques between the online and benchtop turbidimeter and the low level of turbidity in the permeate. The benchtop turbidimeter uses a glass cuvette to hold the sample; this cuvette can present some optical difficulties for the benchtop turbidimeter. The inline turbidimeter has no cuvette to present a possible interference with the optics of the instrument. The low level of turbidity in the permeate also can create analytical difficulties, particularly for the benchtop. Manufacturer's specifications state that stray light interference is less than 0.02 NTU. Stray light interference approaching this level at the low turbidity levels tested could account for the differences in the readings. The low level of turbidity in the feed water does not allow for conclusions to be drawn regarding the unit's ability to produce finished water with turbidities of less than 0.1 NTU.

Figure 4-3 shows the results of the four-hour permeate turbidity readings. Particle count readings from run time 532 hours to 560 hours are not available due to a failure of the treatment enclosure heating system. The loss of heat caused a solenoid valve that controlled flow to the prefilter during backwash to freeze automatically shutting down the treatment unit.

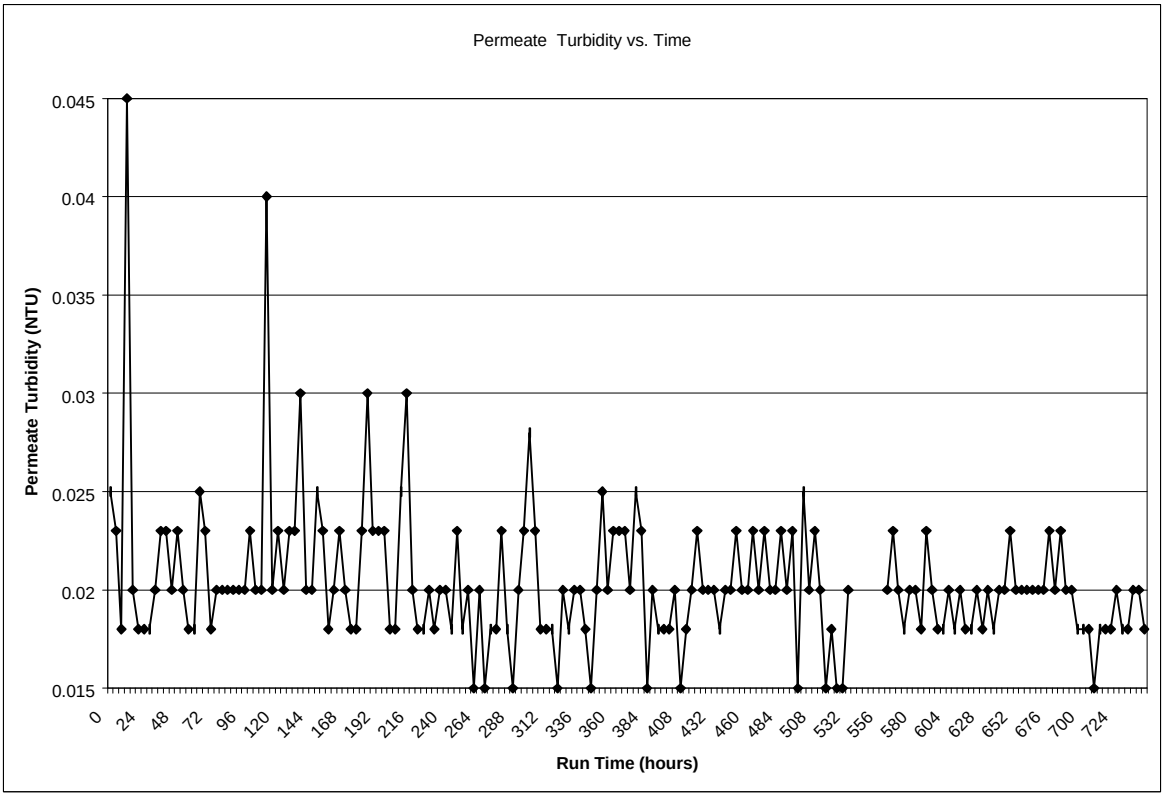



**Figure 4-3. Four-Hour Permeate Turbidity**

### 4.3.3.2 Particle Count Results and Removal

Particle count readings were taken on a continuous basis and recorded every 10 minutes. Average particle count calculations were calculated from these readings. Average feed water particle counts are presented in Table 4-9. Average finished water particle counts are presented in Table 4-10. Daily average cumulative counts for feed and finished water and the $\log_{10}$ particle removals are presented in Table 4-11. A complete data table is presented in Appendix C. Figures 4-4 and 4-5 depict results of four hour particle counts for feed water and permeate. Figure 4-6 graphically depicts daily $\log_{10}$ removals for cumulative particle counts.

**Table 4-9. Feed Water Particle Counts**

| | Size | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2-3µm | 3-5µm | 5-7µm | 7-10µm | 10-15µm | >15µm | Cumulative |
| Average | 32 | 40 | 7.1 | 5.0 | 1.4 | 0.51 | 86 |
| Minimum | 3.0 | 4.0 | 0.55 | 0.60 | 0.025 | 0 | N/A |
| Maximum | 510 | 1200 | 510 | 830 | 660 | 480 | N/A |
| Standard Deviation | 14 | 23 | 8.0 | 13 | 10 | 7.4 | N/A |
| 95% Confidence Interval | (31, 32) | (39, 40) | (6.9, 7.4) | (4.6, 5.4) | (1.1, 1.7) | (0.30, 0.73) | N/A |

N/A = Not Applicable. Statistical measurements on cumulative data do not generate meaningful data.
Note: Due to results obtained during the QA/QC task involving verification of the calibration of the particle counters the above readings were on average 22% lower than actual. See instrument QA/QC verification results in Section 4.5.3.

**Table 4-10. Finished Water Particle Counts**

| | Size | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2-3µm | 3-5µm | 5-7µm | 7-10µm | 10-15µm | >15µm | Cumulative |
| Average | 0.22 | 0.22 | 0.028 | 0.024 | 0.014 | 0.058 | 0.56 |
| Minimum | 0 | 0 | 0 | 0 | 0 | 0 | N/A |
| Maximum | 16 | 26 | 6.8 | 7.4 | 3.8 | 10 | N/A |
| Standard Deviation | 0.82 | 0.86 | 0.14 | 0.14 | 0.084 | 0.23 | N/A |
| 95% Confidence Interval | (0.20, 0.24) | (0.19, 0.24) | (0.024, 0.032) | (0.020, 0.028) | (0.012, 0.016) | (0.051, 0.065) | N/A |

N/A = Not Applicable. Statistical measurements on cumulative data do not generate meaningful data.
Note: Due to results obtained during the QA/QC task involving verification of the calibration of the particle counters the above readings were on average 22% lower than actual. Due to extremely low results in the 10 µm size range results of the 7-10 µm and 10-15 µm the reliability of these counts should be considered questionable. See instrument QA/QC verification results in Section 4.5.3.

**Table 4-11. Daily Average Cumulative Particle Counts Feed and Finished Water, $Log_{10}$ Particle Removal**

| Date | Permeate | Feed | $Log_{10}$ Removal |
|---|---|---|---|
| 12/1/99 | 0.60 | 88 | 2.2 |
| 12/2/99 | 0.72 | 83 | 2.1 |
| 12/3/99 | 0.47 | 76 | 2.2 |
| 12/4/99 | 0.32 | 66 | 2.3 |
| 12/5/99 | 0.70 | 70 | 2.0 |
| 12/6/99 | 1.0 | 78 | 1.9 |
| 12/7/99 | 0.59 | 97 | 2.2 |
| 12/8/99 | 0.50 | 100 | 2.3 |
| 12/9/99 | 0.64 | 100 | 2.2 |
| 12/10/99 | 0.45 | 100 | 2.4 |
| 12/11/99 | 0.36 | 100 | 2.4 |
| 12/12/99 | 0.30 | 110 | 2.6 |
| 12/13/99 | 0.16 | 98 | 2.8 |
| 12/14/99 | 0.23 | 110 | 2.7 |
| 12/15/99 | 0.72 | 94 | 2.1 |
| 12/16/99 | 0.36 | 80 | 2.4 |
| 12/17/99 | 0.21 | 75 | 2.6 |
| 12/18/99 | 0.44 | 75 | 2.2 |
| 12/19/99 | 0.91 | 66 | 1.9 |
| 12/20/99 | 0.79 | 64 | 1.9 |
| 12/21/99 | 0.43 | 77 | 2.2 |
| 12/22/99 | 0.60 | 130 | 2.3 |
| 12/23/99 | 0.29 | 120 | 2.6 |
| 12/24/99 | 1.1 | 93 | 1.9 |
| 12/25/99 | 0.41 | 80 | 2.3 |
| 12/26/99 | 0.32 | 66 | 2.3 |
| 12/27/99 | 0.37 | 58 | 2.2 |
| 12/28/99 | 0.36 | 72 | 2.3 |
| 12/29/99 | 0.26 | 57 | 2.3 |
| 12/30/99 | 0.36 | 74 | 2.3 |
| 12/31/99 | 0.30 | 67 | 2.3 |

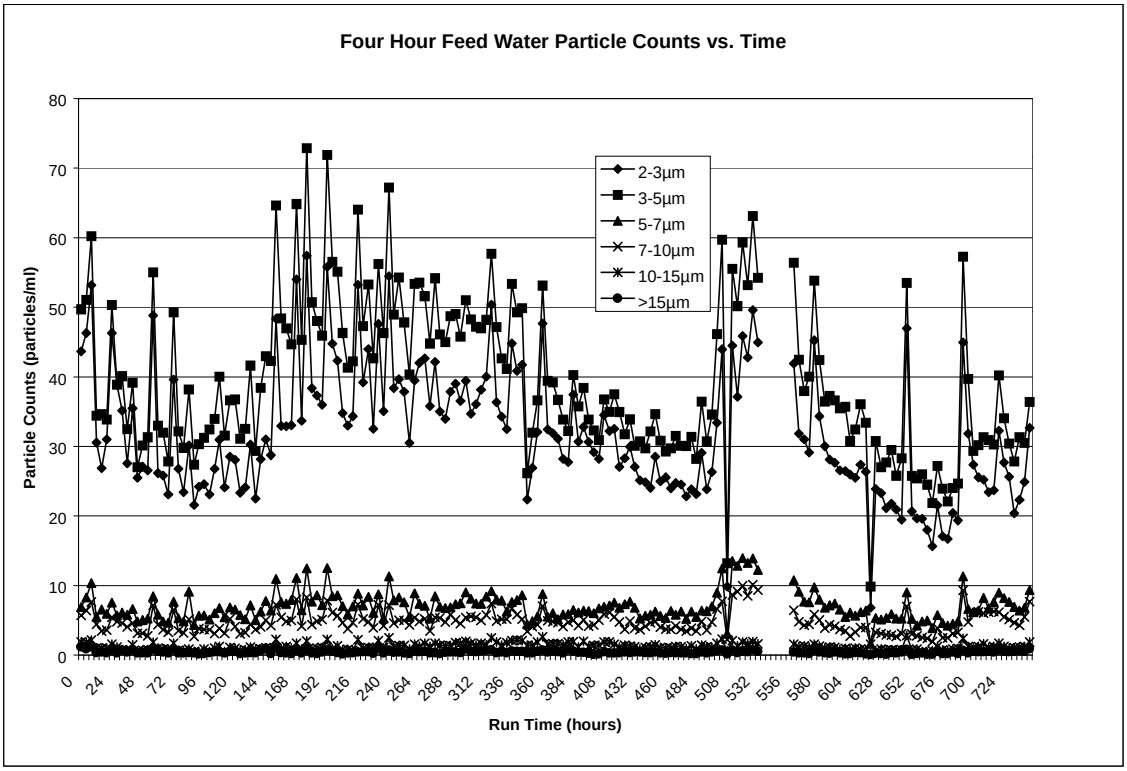



**Figure 4-4. Four Hour Feed Water Particle Counts**

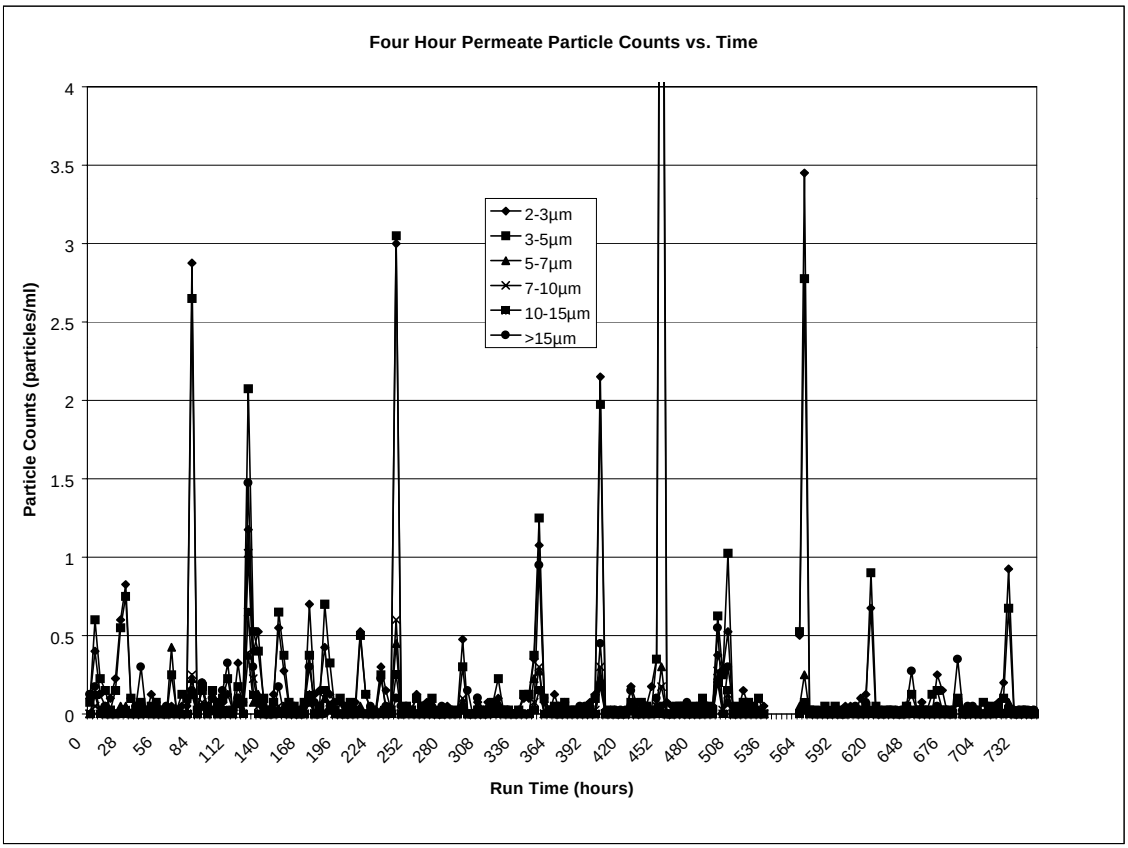



**Figure 4-5. Four Hour Permeate Particle Counts**

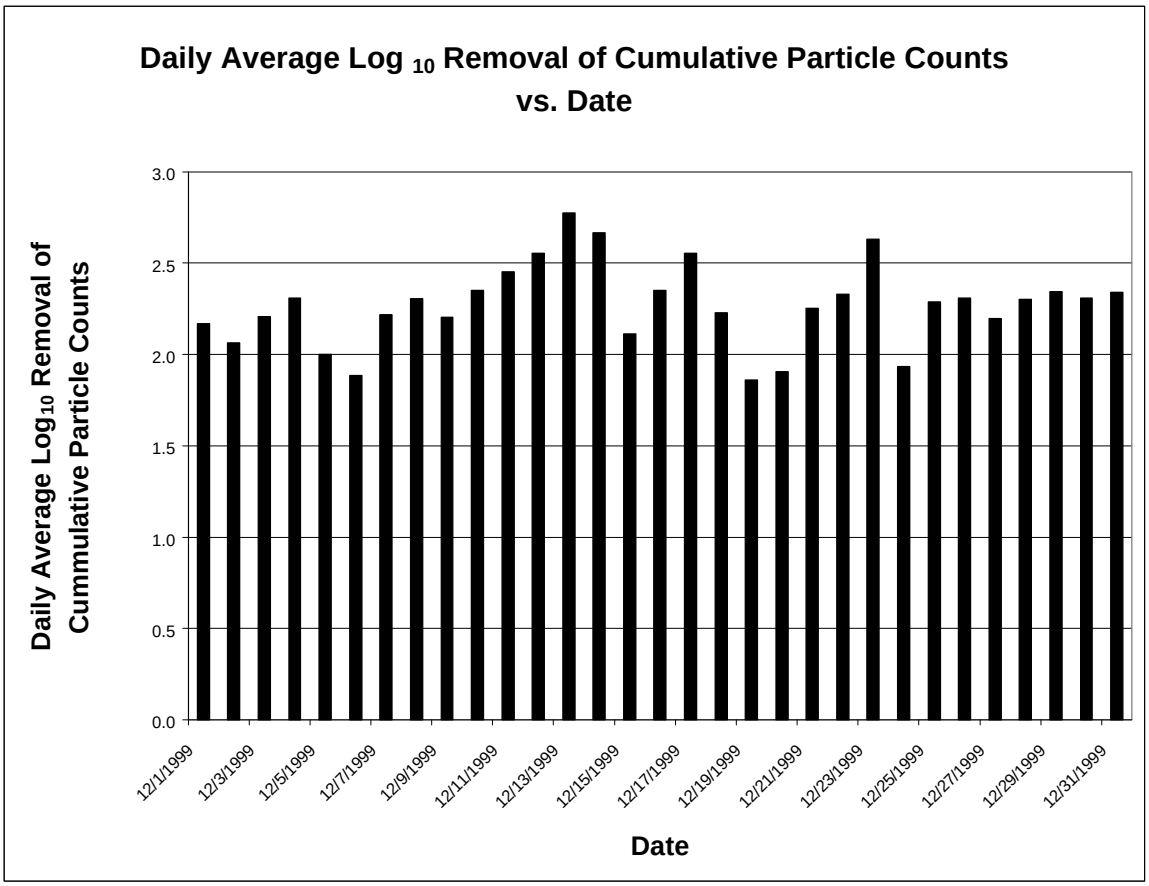



**Figure 4-6. Daily Average $Log_{10}$ Cumulative Particle Removal Graph**

Particle counting of feed and finished water was conducted throughout the testing period. The feed water cumulative counts averaged 86 particles per ml. The finished water cumulative counts averaged 0.56 counts per ml. The average $log_{10}$ removal for the cumulative counts was 2.3.

The low particle counts for each size range in the filtrate water indicated good system performance throughout the testing period. The treatment system demonstrated effective particle removal.

4.3.3.3 Backwash Wastewater Testing Results

Daily and weekly testing was conducted on the backwash wastewater. The results of the testing are listed in Table 4-13 and Table 4-14. A complete data table is presented in Appendix C.

**Table 4-12. Daily Backwash Wastewater Testing Results – Summary**

| | Parameter | | | |
|---|---|---|---|---|
| | Turbidity (NTU) | Turbidity (dup) (NTU) | Chlorine Residual (mg/l) | Chlorine Residual (dup) (mg/l) |
| Average | 0.66 | 0.67 | 5.48 | 5.51 |
| Minimum | 0.28 | 0.32 | 0.80 | 0.75 |
| Maximum | 1.6 | 1.63 | 7.50 | 7.50 |
| Standard Deviation | 0.35 | 0.33 | 1.2 | 1.2 |
| 95% Confidence Interval | (0.057, 0.075) | (0.55, 0.79) | (5.0, 5.9) | (5.0, 5.9) |

**Table 4-13 Weekly Backwash Wastewater Testing Results**

| | Parameter | | |
|---|---|---|---|
| | TSS (mg/l) | Total Coliforms (cfu/100 ml) | HPC (cfu/100 ml) |
| Average | 0.36 | 0 | 26 |
| Minimum | 0.050 | 0 | 6 |
| Maximum | 0.50 | 0 | 64 |
| Standard Deviation | 0.21 | 0 | 33 |
| 95% Confidence Interval | (0.16, 0.57) | N/A | (0, 58) |

N/A = Not applicable because standard deviation = 0.

The turbidity of the backwash waste was somewhat variable but averaged 0.66 NTU. The chlorine residual was relatively consistent averaging 5.5 mg/l. TSS content in the backwash waste was relatively consistent; indicating that the backwash procedure was removing some particulate material. Total coliforms were absent in the backwash waste but HPC was observed.

4.3.3.4 Total Suspended Solids Mass Balance

The mass balance of TSS was calculated from the amount of suspended solids entering the treatment system, the amount in the finished water, and the amount in the backwash waste. There is a portion of the TSS which will not be removed by backwashing and accumulates on the membrane; the majority of this accumulated material is dissolved and removed by chemical cleaning.

To calculate the amount of TSS in the treatment stream the following equation was:
lbs/day = Amount of TSS in mg/l * ((8.34lb/) / (mg/l *MG))*Flow MG

Pounds of TSS in feed water:
Average feed water TSS (from Table 4-5) = 0.16 mg/l

Calculate the feed water flow in MG: (7.0 gpm) * (1440 min/day) = 10080 gal/day / (1,000,000 MG/gal) = 0.01008 MGD.

lbs/day = 0.16 mg/l*((8.34lb) / (mg/l *MG))*0.01008MGD = 0.013 lbs/day

Pounds of TSS in finished water:
Average finished water TSS (from Table 4-6) = 0.088 mg/l

Calculate the finished water flow in MG: (7.0 gpm)* (1440 min/day) = 10080 gal/day / 1,000,000 gal/ MG = 0.01008 MGD.

lbs/day = 0.088 mg/l*((8.34lb) / (mg/l *MG))*0.01008MGD = 0.0074 lbs/day

Pounds of TSS in backwash wastewater:
Average wastewater TSS (from Table 4-13) = 0.36 mg/l

Calculate the amount of wastewater produced daily in MG: (25 gallons per backwash)* (24 backwashes per day) = 600 gallon per day / 1,000,000 gal/MG = 0.00060 MGD

lbs/day = 0.36 mg/l*((8.34lb) / (mg/l *MG))*0.0006MGD = 0.0018 lbs/day

Pounds of TSS accumulating on membrane:
This value is the difference between the amount of TSS added to the membrane and the amount of TSS removed during backwash. The majority of this portion of the TSS is removed during the chemical cleaning process. The amount of TSS in the cleaning waste is not quantifiable due to the nature of the solids in the waste (i.e. TDS).

The TSS mass balance equals:
Pounds of TSS in influent = pounds of TSS in effluent + pounds of TSS in backwash waste + pounds of TSS accumulating on the membrane.

0.013 lbs/day TSS in influent = 0.0074 lbs/day TSS in effluent + 0.0018 lbs/day TSS in backwash waste +0.0042 lbs/day accumulating on the membrane.

The TSS mass balance calculation would seem to indicate that the backwashing procedure was not effective at removing the particulate material deposited on the membrane. According to the calculation almost three times as much TSS was left on the membrane as was removed during backwashing. It would seem that if this were actually occurring that the system TMP would have increased more significantly during the test period and that the recovery of specific flux after chemical cleaning would have been greater than what was seen during the verification testing. A more likely explanation is that the TSS in the backwash water was higher than the average of the weekly analyses indicated. The daily backwash waste turbidity readings were quite variable. This variability and the limited number of TSS samples taken from the wastewater may have allowed under estimation of the TSS removed during the backwash process.

### *4.3.4 Task 4: Reporting of Maximum Membrane Pore Size*

The manufacturer reports that the membrane used during the verification testing has a maximum pore size of 180 kD (20 nm) and that 90% of the pores in their membrane are equal to or less than 120 kD (10 nm). These results were generated through the use of AFNOR X45 103 Standard. This information is provided for informational purposes only. These results are provided by the equipment manufacturer and were not verified during the ETV testing. Appendix G contains a report from Aquasource in which the results of a number of different

analytical methods are discussed. Appendix Three of the manufacturer's membrane pore size report is the AFNOR X45 103 method.

### *4.3.5 Task 5: Membrane Integrity Testing*

Membranes provide a physical barrier against the passage of particles and most types of microbial contamination. If the membrane is compromised, that is not intact, this barrier is lost. It is important to be able to detect when a membrane is compromised. Methods for detecting a compromised membrane are air pressure hold test, turbidity reduction monitoring, and particle count reduction monitoring. These tests were run on an intact membrane and one that had been intentionally compromised. Testing was conducted February 17 and February 18, 1999. A complete data table is presented in Appendix C.

4.3.5.1 Air Pressure Hold Test Results

The membrane vessel with the intact membrane was removed from the treatment unit and the filtrate side was drained. The membrane itself was fully wetted (i.e. membrane pores were filled with water). The membrane was air pressurized up to 2.00 b (29.0 psi). The filtrate side was sealed and the pressure decline rate was monitored using an air pressure gauge.

At time zero the air pressure was 2.02 b (29.3 psi), after five minutes the air pressure was 2.00 b (29.0 psi). At 10 minutes the air pressure inside the membrane was 1.98 b (28.7 psi), this demonstrated that the membrane was intact. (An intact membrane would be expected to lose no more than 0.07 b [1.02 psi] every five minutes.)

Air pressure loss was also compared to the loss that was obtained when testing a compromised membrane. The membrane was intentionally compromised by removing the membrane vessel, exposing the fibers themselves and severing a fiber.

At time zero the air pressure was 2.00 b (29.0 psi), after two minutes the air pressure was 0.63 b (9.14 psi). At four minutes the air pressure inside the membrane was zero b (zero psi), this demonstrated that the membrane was compromised.

4.3.5.2 Turbidity Reduction Monitoring

Turbidity of feed and filtrate water was monitored. An intact membrane would be expected to show a 90% reduction in turbidity from feed to filtrate. Due to the high quality of the feed water, the average feed turbidity was 0.078 NTU, showing a 90% reduction, 0.0078 NTU, was beyond the capability of the turbidimeters. Filtrate turbidity between an intact and a compromised membrane was compared. An increase of 100 % was used as an indication of a compromised membrane.

The turbidity in the filtrate in the two hours before the membrane was compromised averaged 0.023 NTU. The turbidity of the filtrate in the hour after the membrane was compromised was 0.022 NTU.

Turbidity reduction monitoring between feed and finished water was not possible due to the low feed water turbidity level. The filtrate turbidity produced by an intact membrane was not significantly different than the filtrate turbidity produced by a compromised membrane. Comparison of the filtrate turbidity between intact and compromised membranes was not a reliable way to detect a compromised membrane for the low turbidity feed water at the test site.

4.3.5.3 Particle Count Reduction Monitoring

Particle count reductions from source to finished water of 99.9% could demonstrate an intact membrane. Due to the high quality of the feed water, the average cumulative feed water particle counts were 86 total counts per ml, showing a 99.9% reduction was pushing the limits of the instrumentation. Differences between filtrate particle counts from an intact and a compromised membrane were compared. An increase of 100% was used as an indication of a compromised membrane.

The average cumulative particle count of the filtrate in the two hours before the membrane was compromised was 2.2 counts/ml. The average cumulative particle count of the filtrate in the hour after the membrane was compromised was 4.1 counts/ml.

Particle count reduction monitoring between feed and finished water was difficult due to high quality of the feed water. The specified reduction from feed to finished to demonstrate an intact membrane was 99.9%. The average particle count percent removal during the verification (with the intact membrane) was 99.5%. Particle counts of the compromised membrane were 85% higher than those produced by the intact membrane. This method of detecting a compromised membrane may be useful as an indication of a compromised membrane but caution should be used in relying on this method solely for a feed water with low particle count concentrations.

### *4.3.6 Task 6: Microbial Removal*

The purpose of this task was to demonstrate the treatment unit's ability to provide a minimum 3 $\log_{10}$ removal from source water to plant effluent of *Giardia* cysts and a 2 $\log_{10}$ *Cryptosporidium* oocysts. The *Giardia* and *Cryptosporidium* challenge took place on January 22, 1999. The system operated at a manufacturer recommended flux of 153 $l/m^2/h$ at 20$^oC$ (90.4 gfd at 68$^oF$) and an average specific flux of 220 $l/m^2/h/b$ at 20$^oC$ (8.9 gfd/psi) during the *Giardia* and *Cryptosporidium* removal challenge testing.

4.3.6.1 Feed Water Concentrations

During the *Giardia* and *Cryptosporidium* removal challenge testing the feed water had a pH of 8.2, a turbidity of 0.09 NTU, and a temperature of 1.7 $^oC$. Based on the results of the replicate hemocytometer counts, a total of 8,720,000 *Giardia* cysts and 91,770,000 *Cryptosporidium* oocysts were added to 50 gallons of feed water in the feed water reservoir. This resulted in a concentration of 174,400 *Giardia* cysts per gallon and 1,835,400 *Cryptosporidium* oocysts per gallon in the feed water. The stock suspension of feed water and the cysts and oocysts was constantly mixed using a drum mixer. A diaphragm pump was used to add the stock suspension to the treatment unit. The pump was operated at about 0.85 gpm, (3.2 liter per minute) and was

capable of overcoming the pressure in the feed water line of the pilot unit. The feed water from the feed water reservoir was fed to the system for approximately 60 minutes.

As a QC check of the hemocytometer counts, a composite of the feed water was created from five two-ml aliquots taken at five to ten minute intervals. Microscopic examination of the results of this composite indicated 8,360,000 *Giardia* cysts and 82,270,000 *Cryptosporidium* oocysts. These results were 4.1% and 10.3%, respectively, less, than the results obtained from the hemocytometer counts. The hemocytometer counts were used to calculate the initial concentration of the feed water per EPA protocols and due to the uncertain nature of sampling and mixing of the suspension, which could render the composite sample results questionable. The feed water results of the replicate hemocytometer counts are presented in Table 4-14. The microscopic examination results of the composite sample are presented in Table 4-15. Bench data sheets and report from the laboratory are enclosed in Appendix H.

**Table 4-14. *Giardia* and *Cryptosporidium* Stock Suspension Results by Hemocytometer Counts**

| | *Giardia* Cysts | *Cryptosporidium* Oocysts |
|---|---|---|
| Average count (oocysts or cysts/0.0001 ml) | 109 | 1,311 |
| Standard Deviation | 17 | 74 |
| 95% Confidence Interval | (97, 121) | (1,238, 1,384) |
| Total cysts and oocysts added to feed water reservoir (8 ml of *Giardia* stock suspension, 7 ml *Cryptosporidium*) | 8,720,000 | 91,770,000 |
| Feed Water Amount Confidence Interval | (7,760,000, 9,680,000) | (86,660,000, 96,880,000) |

**Table 4-15. *Giardia* and *Cryptosporidium* Stock Suspension Results by Microscopic Examination**

| | *Giardia* Cysts | *Cryptosporidium* Oocysts |
|---|---|---|
| Presumptive count (oocysts or cysts/ml) | 44 | 433 |
| Total cysts and oocysts added to feed water reservoir | 8,360,000 | 82,270,000 |

4.3.6.2 Permeate Concentrations

No *Giardia* cysts or *Cryptosporidium* oocysts were identified in the permeate as shown by the absence of cysts and oocysts on the 1 µm yarn wound capture filter. These results demonstrated a 5.5 $\log_{10}$ removal of *Giardia* cysts and a 6.5 $\log_{10}$ removal of *Cryptosporidium* oocysts using the hemocytometer counts of the feed water. During the *Giardia* and *Cryptosporidium* removal challenge testing, the filtrate had a turbidity of 0.022 NTU and an average cumulative particle counts of 1.8 counts/ml.

The $\log_{10}$ removal of *Giardia* cysts or *Cryptosporidium* oocysts was calculated by first dividing the amount of permeate sampled by the total amount of permeate filtered by the system. In this case, one gallon per minute was filtered through the sampling filter compared to seven gallons per minute of permeate produced by the treatment system. This result was applied to the total amount of cysts added to the treatment system and used to calculate the total amount of cysts which could have been trapped on the sampling filter. This number was converted to its $\log_{10}$

equivalent. The percent recovery of the test method at the PWSA laboratory is 25%, this means that the lowest number of cyst or oocysts that could be detected is four. That is, if four cysts or oocysts were in the permeate one of them would be detected. This number, four, was also converted to its $\log_{10}$ equivalent. The final log removal calculation was made by subtracting the $\log_{10}$ of the number of cysts added to the sampling filter less the $\log_{10}$ of the number of cysts trapped on the sampling filter, in this case zero, and then subtracting the $\log_{10}$ of the number four. Table 4-16 presents the concentrations and the $\log_{10}$ removal calculations of the *Giardia* cysts and *Cryptosporidium* oocysts.

**Table 4-16. *Giardia* and *Cryptosporidium* Challenge $Log_{10}$ Removal Calculation**

| | *Giardia* Cyst Removal | *Cryptosporidium* Oocyst Removal |
|---|---|---|
| Cysts/oocysts in Feed Reservoir *(from Table 4-14)* | 8,720,000 | 91,770,000 |
| Cysts/oocysts Added to Capture Filter *(The total number of cysts/oocysts in Feed Reservoir multiplied by 14.3% because the system was pumping at 7gpm and sampled at 1gpm. Effectively, only 14.3% of the total cysts/oocysts added could have been detected on the capture filter.)* | 1,245,000 | 13,100,000 |
| $Log_{10}$ of Cysts/oocysts Added to Capture Filter | 6.1 | 7.1 |
| $Log_{10}$ of Method Recovery *(PWSA laboratory method recovery is 25%, i.e. 1 in 4.)* | 0.60 | 0.60 |
| $Log_{10}$ Removal *(Difference of $Log_{10}$ of Cysts/oocysts Added to Capture Filter and $Log_{10}$ of Method Recovery)* | 5.5 | 6.5 |

4.3.6.3 Backwash Examination

Examination of the wastewater was conducted to assure that the protozoans were added to the membrane system, the organisms were removed by the membrane and that the backwashing procedure was capable of removing the protozoans from the membrane system. Five hundred ml of the backwash waste was collected and examined. Both *Giardia* cysts and *Cryptosporidium* oocysts were observed in the sample. Quantification of the numbers of each organism in the sample was not done.

4.3.6.4 Operational and Analytical Data Tables

The operation of the treatment system was monitored during the challenge testing. Pressure readings and flow rates were recorded. Results of these readings are presented in Tables 4-17 and 4-18. Turbidity and particle count readings were taken during the challenge testing. Samples for feed water turbidity and particle counts were collected upstream of the point where the *Giardia* cysts and *Cryptosporidium* oocysts were added to the feed water stream. Results of the turbidity and particle count readings are presented in Tables 4-19 4-20, and 4-21. Backwash of the system was delayed, as per protocol requirements, until after the challenge testing was completed. Samples of backwash water before and after the challenge were collected and analyzed. Results of these analyses are presented in Table 4-22.

**Table 4-17. Pressure Readings and Calculations During Microbial Removal Testing**

| Date | Time | Upper Vessel Pressure (psi) | Lower Vessel Pressure (psi) | Filtrate Pressure (psi) | Transmembrane Pressure (psi) |
|---|---|---|---|---|---|
| 1/22/99 | 11:40 | 13 | 15 | 3.2 | 118 |
| 1/22/99 | 12:28 | 12 | 13 | 3.0 | 9.7 |
| 1/22/99 | 14:00 | 11 | 12 | 2.1 | 9.8 |

**Table 4-18. Specific Flux During Microbial Removal Testing**

| Date | Time | Specific Flux ($l/m^2/h/b$ @$20^oC$) |
|---|---|---|
| 1/22/99 | 11:40 | 210 |
| 1/22/99 | 12:28 | 230 |
| 1/22/99 | 14:00 | 220 |

**Table 4-19. Turbidity Analyses Results and Removal During Microbial Removal Testing**

| Date | Time | Feed Turbidity (NTU) | Feed Turbidity (duplicate) (NTU) | Filtrate Turbidity (NTU) | Amount Removed (NTU) |
|---|---|---|---|---|---|
| 1/22/99 | 12:10 | 0.090 | 0.080 | 0.022 | 0.068 |
| 1/22/99 | 14:05 | 0.090 | N/A | N/A | N/A |

N/A = Not applicable. Only one sample per day required by protocol.
Note: Feed water turbidity sampled prior to injection of challenge feed solution.

**Table 4-20. Feed Water Particle Counts 1/22/1999**

| | Size | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2-3µm | 3-5µm | 5-7µm | 7-10µm | 10-15µm | >15µm | Cumulative |
| Average | 35 | 39 | 5.9 | 4.5 | 1.3 | 0.62 | 86 |
| Minimum | 0 | 0 | 0 | 0 | 0 | 0 | N/A |
| Maximum | 67 | 86 | 8.1 | 6.5 | 2.0 | 1.8 | N/A |
| Std Dev | 9.0 | 11 | 0.36 | 1.1 | 0.37 | 0.36 | N/A |
| Confid Int | (32, 36) | (36, 42) | (5.5, 6.3) | (4.2, 4.7) | (1.2, 1.4) | (0.53, 0.72) | N/A |

N/A = Not Applicable. Statistical measurements on cumulative data do not generate meaningful data.
Note: Feed water particle counts sampled prior to injection of challenge feed solution.

**Table 4-21. Finished Water Particle Counts 1/22/1999**

| | Size | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2-3µm | 3-5µm | 5-7µm | 7-10µm | 10-15µm | >15µm | Cumulative |
| Average | 0.44 | 0.91 | 0.12 | 0.098 | 0.048 | 0.14 | 1.8 |
| Minimum | 0 | 0 | 0 | 0 | 0 | 0 | N/A |
| Maximum | 7.7 | 19 | 1.5 | 1.5 | 0.57 | 1.4 | N/A |
| Std Dev | 1.1 | 3.0 | 0.037 | 0.24 | 0.10 | 0.25 | N/A |
| Confid Int | (0.14, 0.74) | (0.14, 1.7) | (0.035, 0.16) | (0.035, 0.16) | (0.021, 0.074) | (0.071, 0.20) | N/A |

N/A = Not Applicable. Statistical measurements on cumulative data do not generate meaningful data.

**Table 4-22. Daily Backwash Wastewater Testing Results During Microbial Removal Testing**

| Date | Time | Turbidity (NTU) | Turbidity (dup) (NTU) | Chlorine Residual (mg/l) | Chlorine Residual (dup) (mg/l) |
|---|---|---|---|---|---|
| 1/22/99 | 15:30 | 2.30 | 2.06 | 3.25 | 3.35 |
| 1/22/99 | 16:30 | 2.11 | N/A | N/A | N/A |

N/A = Not applicable. Only one sample per day required by protocol.

Testing of the feed, finished and backwash water for Total Alkalinity, Total Hardness, TDS, TSS, Total Coliforms, HPC, TOC, UVA was not conducted during the challenge testing procedure.

4.3.6.5 Discussion of Results

No *Giardia* cysts or *Cryptosporidium* oocysts were observed in the permeate. The membranes appeared to successfully remove all of the *Giardia* cysts and *Cryptosporidium* oocysts introduced into the treatment system. Since the percent recovery of the analytical method is 25% there is a slight possibility that some cysts or oocysts passed through the membrane and were not identified during analysis. Nevertheless, the treatment system provided 5.5 $\log_{10}$ removal of *Giardia* cysts and a 6.5 $\log_{10}$ removal of *Cryptosporidium* oocysts. These results indicate that the treatment system would be capable of successfully complying with the current protozoan removal requirements of the SWTR and ESWTR if used on this source water. The current provisions are 3 $\log_{10}$ removal of *Giardia* cysts and 2 $\log_{10}$ removal of *Cryptosporidium* oocysts as stated in Section 3.1.1.2.

The $\log_{10}$ removals were limited by the amount of the parasites which were present in the stock feed solution, the percentage of the permeate that could be sampled and the percent recovery of the analytical methodology. Higher feed concentrations, percentage of permeate examined and percent recovery of the analytical methods may yield higher $\log_{10}$ removals.

## 4.4 Equipment Characteristics Results

The qualitative, quantitative and cost factors of the tested equipment were identified during verification testing, in so far as possible. The results of these three factors are limited due to the relatively short duration of the testing cycle.

### *4.4.1 Qualitative Factors*

Qualitative factors that were examined during the verification testing were the susceptibility of the equipment to changes in environmental conditions, operational reliability, and equipment safety.

4.4.1.1 Susceptibility to Changes in Environmental Conditions

Changes in environmental conditions that cause degradation in feed water quality can have an impact on the treatment system. The short duration of the testing cycle and the stable nature of the feed water minimized the opportunity for significant changes in environmental conditions.

As previously stated the reservoir water was treated (coagulated, flocculated, settled, filtered, and disinfected) surface water that had been pumped from PWSA's Aspinwall treatment plant. The fact that the feed water was finished drinking water stored in an open reservoir limited the opportunity for significant changes in feed water quality. No environmental upsets significant enough to affect feed water quality occurred during testing.

Since the treatment unit was housed in a trailer and is not exposed to the elements, opportunities for environmental upsets were limited. Failure of environmental controls in the treatment system enclosure did occur during the test period and caused a system shut down. This was not a failure of the treatment system; the heating system of the unit's enclosure failed causing an automatic solenoid valve controlling the flow of backwash water to the prefilter to fail. This resulted in an automatic system shut down. Restoration of heat to the enclosure and exercising of the solenoid allowed the system to be restarted. The unit was off line for slightly more than 27 hours.

4.4.1.2 Operational Reliability

During the verification test the unit operated in the automatic mode. An automatic system shut down occurred on December 23 when the enclosure's heating system failed as described earlier. Restoration of heat to the enclosure and exercising of the solenoid allowed the system to be restarted. The restoration of heat and restart of the system was not completed until December 24 and testing recommenced.

Manual operation was required for chemical cleaning of the system and to refill the container of sodium hypochlorite used to supply chlorine to the backwash water. A representative of the manufacturer visited the site daily primarily to download and transmit data from the PCs. While on-site, the representative also visually checked the system.

4.4.1.3 Equipment Safety

Evaluation of equipment safety was conducted as part of the verification testing. Evaluation of the safety of the treatment system was done by examination of the components of the system and identification of hazards associated with these components. A judgement as to the safety of the treatment system was made from these evaluations.

There are safety hazards associated with high voltage electrical service and pressurized water. The electrical service was connected according to local code requirements and did not represent an unusual safety risk. The water pressure inside the treatment system was relatively low and did not represent an unusual safety risk.

The sodium hypochlorite used for membrane backwashing created a safety concern. The use of appropriate personal protective equipment (PPE) minimizes the risk of exposure when handling the chemical. The prompt and proper clean up of spills also minimizes the hazards associated with this chemical.

The cleaning chemical Ultrasil 43 is a fine powder containing detergent and chlorine. The powdery nature and chemical make-up of this substance could cause irritation to the nose and

throat if it was accidentally released into the air. The use of appropriate PPE minimizes the risk of exposure to this substance. The detergent in the Ultrasil 43 could produce slippery conditions if accidentally spilled and mixed with water. The prompt and proper clean up of spills minimizes the hazards associated with this chemical.

No injuries or accidents occurred during the testing.

### *4.4.2 Quantitative Factors*

Quantitative factors that were examined during verification testing were power supply requirements, consumable requirements, waste disposal technique, and length of operating cycle. Cost factors for the above items are discussed where applicable. It is important to note that the figures discussed here are for the Aquasource Pilot System Model A35 operating at 155 l/m$^2$/h at 20$^o$C (91.2 gfd at 68$^o$C). Costs will vary if the system is operated at different flux rates.

#### 4.4.2.1 Power Supply Requirements

The unit was operated with 480V 3 phase 60Hz service with 20 Amp current as required by the O&M manual. Daily power consumption of the treatment unit was determined by reading a dedicated electric meter. The electric meter was installed by a certified electrician according to the local electric code.

It became apparent after the first few days that the meter was not operating properly; it was actually reading lower each day. It was determined that the electric meter was running backwards. Due to the short duration of the study and the inability of the electric contractor to respond in a timely manner it was not possible to change the meter before the end of the study.

According to information obtained from the meter manufacturer, the meter reading was not accurate and can not be used for the purpose of this study.

#### 4.4.2.2 Consumable Requirements

Consumable commodities included sodium hypochlorite and Ultrasil 43, which was the cleaning chemical used during the verification testing. Sodium hypochlorite was added to the permeate used for backwashing. The total chlorine residual in the backwash waste was 5.5 mg/l. This level of chlorine residual required approximately 1 gallon of 12.5% sodium hypochlorite per month. Each stage of the two-stage chemical cleaning episode requires 2.7 lbs. of Ultrasil 43 and about 10 gallons of permeate to dissolve the detergent.

#### 4.4.2.3 Waste Disposal

The wastes generated by the treatment system were backwash water and the chemical cleaning wastes. The microbial challenge testing also generated wastes during the verification testing. All of these wastes were disposed of to an existing catch basin that was connected to PWSA's sewerage system. The unit produced approximately 600 gpd of backwash water during verification testing.

The backwash waste was finished water, residual chlorine and solids removed from the membrane; it required no treatment prior to discharge to the sewers. The average concentration of TSS in the backwash waste was 0.36 mg/l. The range of TSS concentration was from 0.05mg/l to 0.50 mg/l. The chlorine concentration in the backwash wastewater averaged 5.51 mg/l and ranged from 0.75 mg/l to 7.50 mg/l. A complete presentation of the backwash waste water data is included in Appendix C.

The chemical cleaning wastes contained dissolved solids, a surfactant, and a chlorine residual. The concentration of the dissolved solids in the precleaning wastes was 3,288 mg/l. The second cleaning wastes contained 29,336 mg/l. The residual chlorine in the precleaning waste was 32 mg/l in the second cleaning waste the residual chlorine was 25 mg/l. The pH of the precleaning wastes was 8.1; the pH of the second cleaning waste was 8.4. The concentration of the surfactant in the cleaning wastes was not determined.

The microbial challenge utilized formalin fixed *Giardia* cysts and *Cryptosporidium* oocysts. The backwash waste from the challenge test was collected, chlorinated, and stored for 3 days prior to discharge.

4.4.2.4 Length of Operating Cycle

There were two "operating cycles" to be considered; the filtration cycle and the interval between chemical cleaning. The lengths of these operating cycles are site specific and determined by the manufacturer after evaluation of the feed water quality. These cycle lengths are easily field adjustable if necessary; no adjustments were required for this verification.

The filtration cycle is the length of time between system backwashes. The interval between backwashes is made based on the maintenance of flux. That is, if the backwash is not able to maintain flux at a particular level, the frequency of backwashing is increased. The filtration cycle was 60 minutes for the verification study. The backwash required 60 seconds to complete, which included 15 seconds for system shutdown and various valve operations and 45 seconds for the backwash itself.

The interval between chemical cleaning was not readily apparent due to the short duration of the study and the high quality of the feed water. The treatment system did not reach the termination criteria for initiation of chemical cleaning. Aquasource recommends that cleaning be done when the specific flux reaches 120 $l/m^2/h/b$ at $20^oC$ (4.9 gfd/psi at $68^oF$). The specific flux should never be allowed to reach 100 $l/m^2/h/b$ at $20^oC$ (4.1 gfd/psi at $68^oF$). Based on feed water quality at the test site, the initial operations experience, and verification testing results, the manufacturer estimated that the cleaning interval would be about three months at this site.

## 4.5 QA/QC Results

The daily, bi-weekly, initial, and the analytical laboratory QA/QC verification results are presented below.

### *4.5.1 Daily QA/QC Results*

Daily readings for the inline turbidimeter flow rate and readout and inline particle counter flow rate QA/QC results were taken and recorded.

The inline filtrate turbidimeter flow rate averaged 503 ml/minute. To determine the flow rate of the inline filtrate turbidimeter the flow was measured using a graduated cylinder and stop watch. The maximum rate measured during the testing was 534 ml/minute; the minimum was 354 ml/minute. The acceptable range of flows as specified by the manufacturer is 250 ml/minute to 750 ml/minute. No adjustment of the flow rate was required during the verification testing.

The readout from the inline turbidimeter averaged 0.023 NTU; the average from the benchtop turbidimeter was 0.04 NTU. The discrepancy between these two results can be explained by differences in the analytical techniques between the online and benchtop turbidimeter and the low level of turbidity in the permeate. The benchtop turbidimeter uses a glass cuvette to hold the sample; this cuvette can present some optical difficulties for the benchtop turbidimeter. The online turbidimeter has no cuvette to present a possible interference with the optics of the instrument. The low level of turbidity in the permeate also can create analytical difficulties, particularly for the benchtop. Manufacturer's specifications state that stray light interference is less than 0.02. Stray light interference approaching this level at the low turbidity levels tested could account for the differences in the readings.

The feed water particle counter flow rate averaged 98 ml/minute. To determine the flow rate of the inline feed water turbidimeter the flow rate was measured using a graduated cylinder and stop watch. The maximum flow rate measured was 103 ml/minute; the minimum was 93 ml/minute. The target flow rate specified by the manufacturer is 100 ml/minute. Efforts were made to keep the flow rate between 95 ml/minute to 105 ml/minute. Adjustments to the flow rate were required 12 times during the verification study.

The finished water particle counter flow rate averaged 98 ml/minute. The flow rate was measured using a graduated cylinder and stop watch. The maximum flow rate measured was 104 ml/minute; the minimum was 95 ml/minute. The target flow rate specified by the manufacturer is 100 ml/minute. Efforts were made to keep the flow rate between 95 ml/minute to 105 ml/minute. Adjustments to the flow rate were required 11 times during the verification study.

### *4.5.2 Bi-weekly QA/QC Verification Results*

Every two weeks checks were made on the inline flow meters; the meters were cleaned out if necessary and the flow readouts were verified.

The flow meters were inspected. Clean out of the meters was not necessary due to the high quality of the feed and finished water.

The flow meter readout was verified during the testing. The readout was compared to the results obtained from the actual amount measured using a graduated cylinder and stopwatch. The acceptable range of accuracy for the feed, finished and backwash meters was +/- 10%. The feed

water meter readout averaged 1.75% higher than actual according to the results obtained during the flow verification. The finished water meter readout averaged 3.85% higher than actual according to the results obtained during the flow verification. The backwash meter readout averaged 2.00% lower than actual according to the results obtained during the flow verification.

### *4.5.3 Results of QA/QC Verifications at the Start of Each Testing Period*

At the start of the testing period the inline turbidimeter was cleaned out and recalibrated, the pressure gauges/transmitters readouts were verified, the tubing was inspected, and the inline particle counter calibration was checked.

The inline turbidimeter reservoir was drained and cleaned and the unit was recalibrated according to manufacturer's recommendations. No corrective action was required as a result of these activities.

The upper membrane, lower membrane and filtrate pressure gauges were checked prior to the start of testing. Dead weights of 5,10, 15, 20, 30, and 40 pounds were used. The upper membrane pressure gauge averaged 4.9 psi (0.34b), 9.9 psi (0.68b), 14.9 psi (1.03b), 19.9 psi (1.37b), 29.9 psi (2.06b), and 39.8 psi (2.74b) when tested with the above weights. The lower membrane pressure gauge averaged 4.9 psi (0.34b), 9.85 psi (0.68b), 14.75 psi (1.02b), 19.75 psi (1.36b), 29.55 psi (2.04b), and 39.45 psi (2.72b) when tested with the above weights. The filtrate pressure gauge averaged 5.7 psi (0.39b), 10.67 psi (0.74b), 15.67 psi (1.08b), 20.57 psi (1.42b), 30.57 psi (2.11b), and 40.2 psi (2.77b) when tested with the above weights. These results were considered satisfactory.

The tubing used on the treatment system was inspected prior to the initiation of testing. The tubing was in good condition and replacement was not necessary.

The calibration of the inline particle counters was checked. The cocktail of microspheres was prepared to give an initial concentration of 2,000 particles/ml for each of the 5 µm, 10 µm, and 15 µm sized particles.

The feed water particle counter showed an average response for the 5 µm size of 1,552.24 counts/ml; the 10 µm size showed an average response of 1467.24 counts/ ml; the 15 µm size showed an average response of 1654.41 counts/ ml. This corresponds to a difference of 22%, 27%, and 17% respectively in particle counts. These results were outside of the generally recognized range of +/- 10 %. The manufacturer of the particle counters was contacted to determine what corrective action could be utilized to rectify this low response. The technical representative indicated that unit would have to have been returned to the factory for recalibration. The representative indicated that the lead time for this service was in excess of one month. Due to the short duration of the testing schedule and the treatment system manufacturer's time constraints this was not a feasible option. The technical representative indicated that the calibration procedure consisted of adjusting the "threshold" of the unit. This consists of adjusting the output of the unit to match the concentration of the standard being analyzed. The representative indicated that this "threshold" adjustment is analogous to increasing the readout of the unit by the percent differences obtained during the calibration check

procedure. The average percent difference for the three standards used was 22%. The readings for feed water particle counts obtained during the verification testing should be increased by 22% to account for the low response of the feed water particle counter.

The finished water particle counter showed an average response for the 5 µm size of 1,699.55 counts/ml; the 10 µm size showed an average response of 629.85 counts/ ml; the 15 µm size showed an average response of 1644.97 counts/ ml. This corresponds to a difference of 15%, 69%, and 18% respectively in particle counts. These results were outside of the generally recognized range of +/- 10 %. As was the case with the feed water particle counter the long lead time for recalibration by the manufacturer precluded recalibration of the instrument. The average percent difference for the 5 µm and 15 µm standards was 16%. The readings for finished water particle counts in the 2-7 µm and the >15 µm obtained during the verification testing should be increased by 16% to account for the low response of the finished water particle counts. Due to extremely low results in the 10 µm size range the reliability of the 7-10 µm and 10-15 µm particle counts should be considered questionable.

The particle counters used during the testing were Met-One PCX models. The units had capabilities of measuring particles as small as 2 µm and a coincidence error of less than 10 %.

Particle counter model, serial number, calibration certificate, and calculation of coincidence error are included in Appendix I.

### *4.5.4 Analytical Laboratory QA/QC*

Samples for analyses conducted on feed and finished water are listed in Table 3-1. QA/QC procedures are based on Standard Methods, 18$^{th}$ Ed., (APHA, 1992) and Methods for Chemical Analysis of Water and Wastes, (EPA 1979)

The laboratory participated in the ICR laboratory approval program sponsored by the EPA. QA/QC results from this program as they relate to microbial testing are attached in Appendix H. The analyses conducted as part of this program include samples with unknown amounts *Giardia* cysts and *Cryptosporidium* oocysts. These samples were analyzed and the results submitted to EPA for evaluation. These blind QA/QC samples were analyzed for 18 months as part of the ICR lab program and served as the QA/QC component of the microbial testing for the verification testing. Results of these QA/QC samples indicate that the controls in place were adequate to render the data obtained from the challenge testing acceptable.

Calibration and QA/QC results of the analytical instrumentation used to conduct the analyses listed in Table 3-1 on finished water is recorded and kept on file at the PWSAs laboratory. All QA/QC results for the analytical instrumentation indicate that adequate controls were in place to render the data obtained acceptable.

# Chapter 5
# References

The following references were used in the preparation of this report:

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