

US EPA ARCHIVE DOCUMENT

Environmental Technology Verification Report

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

ZENON

ZeeWeed[®] ZW-500 Ultrafiltration
Membrane System
Pittsburgh, PA

Prepared by



NSF International



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

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THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM



U.S. Environmental Protection Agency



NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	MEMBRANE FILTRATION USED IN PACKAGED DRINKING WATER TREATMENT SYSTEMS		
APPLICATION:	<i>GIARDIA AND CRYPTOSPORIDIUM REMOVAL IN PITTSBURGH, PENNSYLVANIA</i>		
TECHNOLOGY NAME:	ZEEWEED® ZW-500 ULTRAFILTRATION SYSTEM		
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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 permittees; 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) pilot, one of 12 technology areas under ETV. The PDWTS pilot 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 ZENON

Environmental Inc. ZeeWeed® ZW-500 UF Drinking Water System. Gannett Fleming, Inc., an NSF-qualified field testing organization (FTO), performed the verification testing.

ABSTRACT

Verification testing of the ZENON Environmental Inc. ZeeWeed® ZW-500 UF Drinking Water System was conducted from February 6 to March 7, 1999. The treatment system underwent *Giardia* and *Cryptosporidium* removal challenge testing on March 2, 1999, and demonstrated a 53 log₁₀ removal of *Giardia* cysts and a 6.4 log₁₀ removal of *Cryptosporidium* oocysts. Source water characteristics were: turbidity average 0.09 Nephelometric Turbidity Units (NTU), pH 7.8, and temperature 3.8°C. During the thirty-day verification test, the system was operated at a flux recommended by the manufacturer of 53 gallons per square foot per day (gfd) at 39°F (3.8°C) (91 liters per meter squared per hour [l/m²/h]) which equates to 94 gfd at 68°F (169 l/m²/h at 20°C). The average transmembrane pressure was 7.5 pounds per square inch (psi) (0.52 bar [b]). The feed water recovery of the treatment system during the study was 95%. 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. UF is generally capable of removing particle sizes as small as 0.01 μm. The Zenon OCP ultrafiltration membrane is a hollow fiber made of a proprietary polymeric compound. It has a 0.03 μm nominal pore size and utilizes outside-in flow. A vacuum is applied to the inside of the hollow fiber membrane drawing the feed water into the lumen of the fiber. The membrane is a mechanical barrier, providing removal of particulate contaminants. Filtrate is collected from the inside of the fiber and drawn to the filtrate outlet.

The ZeeWeed® ZW-500 is a stand alone system. The only required connections are for the water supply, a sewer connection for the discharge of bleed waste water and chemical cleaning wastes and electrical service. The treatment system consists of one membrane module and reservoir, a filtrate (vacuum) pump, an air blower, chemical cleaning equipment and necessary gauges and controls. The treatment system is capable of operating in an automatic mode with limited operator intervention.

For this test program filtrate was drawn from both the top and bottom of each hollow fiber. The filtrate pump was used to pull feed water through the membrane. Particulate material which is removed from the membrane surface through air agitation and periodic back pulsing is constantly removed from the system using a peristaltic bleed pump.

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, sedimentation, filtration, and disinfection 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 (UVA₂₅₄), 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 formalin-fixed *Giardia lamblia* cysts and *Cryptosporidium parvum* 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 8,625,000 *Giardia* cysts and 109,643,000 *Cryptosporidium* oocysts were added to the feed water reservoir. The turbidity of the feed water was 0.12 NTU during the *Giardia* and *Cryptosporidium* 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 treatment unit. The pump was operated at about 0.85 gallons per minute (gpm) (3.2 liter per minute [lpm]). Samples of the filtrate were collected using a polypropylene wound filter with a nominal pore size of 1.0 μm . One thousand liters (264 gallons) of filtrate 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. Samples of the bleed water 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. All operational data, flows, vacuum, turbidity and particle counts are recorded on data logging software. Manual intervention is required for chemical cleaning. For this test program filtrate was drawn from both the top and bottom of each hollow fiber. The filtrate pump was used to pull feed water through the membrane.

The system was operated at a flux recommended by the manufacturer of 53 gfd at 39 °F (3.8°C) (91 l/m²/h) which equates to 94 gfd at 68 °F (169 l/m²/h at 20°C). 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 9.4 gpm (36 lpm) and ranged from 7.6 to 14 gpm (29 to 53 lpm).

The average vacuum applied to the system was -7.5 psi (-0.52 b). Since the membranes are immersed in a tank at atmospheric pressure the absolute value of the vacuum applied to the system is equivalent to the transmembrane pressure (TMP) of the unit. The average TMP for the system was 7.5 psi (0.52 b).

In order to minimize the amount of particulate material accumulating on the surface of the fibers, air is constantly introduced into the system to gently agitate the fibers. An airflow of 7.5 standard cubic feet per minute (scfm) was used during the verification testing. This agitation tends to remove particles adhering to the fibers. In order to remove particles not eliminated by the air agitation, flow is periodically reversed through the fibers. This is referred to as back pulsing. The back pulsing was done every 10

minutes for 20 seconds. A backpulse of one and a half to two times the filtrate flux is generally used to ensure the most effective removal particulate material. Chlorine was added to the back pulse water at a level of approximately 4 to 6 mg/l. The particulate material which is removed from the membrane surface through air agitation and periodic back pulsing is constantly removed from the system using a peristaltic bleed pump.

The feed water recovery of the treatment system during the study was 95%. This figure was calculated by comparing the amount of water bled from the system to the total amount of water introduced into 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 were used to calculate recovery of specific flux and the loss of original specific flux. The chemical cleaning recovered 57% of the specific flux. Data from when the membranes were placed into service and just after cleaning were used to calculate the loss of original specific flux. The loss of original specific flux was 32%.

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 after it was intentionally compromised.

Water Quality Results

During the *Giardia* and *Cryptosporidium* removal challenge testing that occurred on March 2, 1999, the ZeeWeed® ZW-500 system demonstrated a 5.3 log₁₀ removal of *Giardia* cysts and a 6.4 log₁₀ removal of *Cryptosporidium* oocysts. The log₁₀ removals were limited by the amount of the parasites which were present in the stock feed solution, the percentage of the filtrate that could be sampled, and the percent recovery of the analytical methodology. There were no *Giardia* cysts or *Cryptosporidium* oocysts observed in the filtrate. During the challenge testing, the feed water characteristics were: turbidity average 0.12 NTU, pH 7.8, temperature 3.6 °C.

During the thirty-day ETV operation of the ZeeWeed® ZW-500 system, treatment reductions were seen in heterotrophic plate counts (HPC), algae, turbidity, and particle counts. HPC concentrations averaged 179 cfu/100 ml in the feed water and 6 cfu/100 ml in the filtrate. The presence of HPC in the filtrate may have been due to inadequate disinfection of the Tygon tubing used for water sampling. Algae concentrations averaged 18 cells/ml in the feed water and <8 cells/ml in the filtrate. The turbidity concentration in the feed water was 0.09 NTU and 0.03 NTU in the filtrate. The treatment system reduced feed water particle counts from an average of 64 total counts per ml to an average of 0.70 total counts per ml in the filtrate. Total coliform reduction could not be demonstrated due to the absence of total coliforms in the feed water and filtrate throughout the test. The following table presents the water quality reductions of the feed water and filtrate samples collected during the 30 days of operation:

Feed Water Quality / Filtrate Water Quality
ZENON ZeeWeed® ZW 500 Drinking Water Treatment System

	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)	Algae (cells/ml)	Turbidity (NTU)	Particle Counts (particles/ml)
Average ¹	0/0	179/6	18/<8	0.09/0.03	64/0.70
Minimum ¹	0/0	94/2	8/<8	0.06/0.02	----
Maximum ¹	0/0	308/18	24/8	0.13/0.04	----
Standard Deviation ¹	0/0	92/8	8/2	0.02/0.004	----
95% Confidence Interval ¹	N/A/ N/A	(89,268)/ (0, 14)	(10,26)/ (<8, <8)	(0.08, 0.09)/ (0.02, 0.03)	----

¹ – Concentration of feed water/concentration of filtrate.

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).

Temperature of the feed water during the thirty-day ETV study was fairly stable with a high of 40.1°F (4.5°C), a low of 37.9°F (3.3°C), and an average of 38.8°F (3.8°C). The treatment system unit had little or no effect on dissolved constituents such as total alkalinity, total hardness, TOC, TDS, and UVA₂₅₄.

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. The only interruption of the process occurred due to a power failure at the pumping station. After power was restored to the pumping station the treatment system was restarted and placed back into service.

The Operating and Maintenance (O&M) Manual provided by ZENON Environmental was available for review on-site and was referenced occasionally during the testing. Particularly, the manual was consulted during the cleaning procedure. The manual was well organized and a valuable resource during the testing period.

<p style="text-align: center;"><i>Original Signed by</i> <u>E. Timothy Oppelt</u></p> <hr/> <p>E. Timothy Oppelt Director National Risk Management Research Laboratory Office of Research and Development United States Environmental Protection Agency</p>	<p>8/28/00</p> <hr/> <p>Date</p>	<p style="text-align: center;"><i>Original Signed by</i> <u>Tom Bruursema</u></p> <hr/> <p>Tom Bruursema General Manager Environmental and Research Services NSF International</p>	<p>8/31/00</p> <hr/> <p>Date</p>
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NOTICE: Verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and NSF make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of corporate names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products. This report is not a NSF Certification of the specific product mentioned herein.

Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants* dated April 20, 1998 and revised May 14, 1999, the Verification Statement, and the Verification Report (NSF Report #00/06/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.org/etv> (electronic copy)
3. EPA web site: <http://www.epa.gov/etv> (electronic copy)

August 2000

Environmental Technology Verification Report

Physical Removal of *Cryptosporidium* Oocysts and *Giardia* Cysts in Drinking Water

ZENON Environmental Inc. ZeeWeed® ZW-500 Ultrafiltration System

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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 (USEPA) by Gannett Fleming, Inc., in cooperation with ZENON Environmental Inc. The test was conducted during February and March 1999 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 ETV Program, has been instituted to verify the performance of innovative technical solutions to environmental pollution or human health threats. ETV was created to substantially accelerate the entrance of new environmental technologies into the domestic and international marketplace. Verifiable, high quality data on the performance of new technologies are made available to regulators, developers, consulting engineers, and those in the public health and environmental protection industries. This encourages more rapid availability of approaches to better protect the environment.

The EPA has partnered with NSF, an independent, not-for-profit testing and certification organization dedicated to public health, safety and protection of the environment, to verify performance of small package drinking water systems that serve small communities under the 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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- E. Laboratory Chain of Custody Forms
- F. PWSA Laboratory QA/QC Plan
- G. Manufacturer's Membrane Pore Size Report
- H. Laboratory Reports and *Giardia* and *Cryptosporidium* Challenge Bench Sheets
- I. Particle Counter Information
- J. Package Plant Photos
- K. Field Operations Document

Abbreviations and Acronyms

ac	acre
b	bar
CaCO ₃	Calcium Carbonate
cfu	Colony forming unit
CIP	Clean in place
Cl ₂	Chlorine
°C	Degrees Celsius
DI	Deionized
EPA	Environmental Protection Agency
ESWTR	Enhanced Surface Water Treatment Rule
ETV	Environmental Technology Verification
°F	Degrees Fahrenheit
FOD	Field Operations Document
ft	Foot
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
ICR	Information Collection Rule
kwh	kilowatt hour
L	Liters
lbs	Pounds
lpm	liter per minute
m	meter
MG	million gallon
MGD	million gallon per day
mg/l	milligram per liter
ml	milliliters
N/A	Not Applicable
NIST	National Institute of Standards and Technology
NSF	NSF International (formerly known as National Sanitation Foundation)
nm	nanometers
NTU	Nephelometric Turbidity Units
O&M	Operations and Maintenance
PADEP	Pennsylvania Department of Environmental Protection
PC	personal computer
PPE	Personal Protective Equipment
psi	pounds per square inch
PDWTS	Packaged Drinking Water Treatment System
PWSA	Pittsburgh Water and Sewer Authority

QA/QC
scfm
SWTR
TDS
TMP
TOC
TSS
UF
 μm
UVA₂₅₄

Quality Assurance / Quality Control
standard cubic feet per minute
Surface Water Treatment Rule
Total Dissolved Solids
Transmembrane pressure
Total Organic Carbon
Total Suspended Solids
Ultrafiltration
Micron
Ultraviolet Absorbance at 254 nm

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

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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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Gannett Fleming wishes to thank the participants in this test, especially Bruce Bartley, Project Manager, Carol Becker and Kristie Wilhelm, Environmental Engineers, and Tina Beaugrand, Microbiology Laboratory Auditor of NSF International 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.

Steve Watzek, Manager/Business Development, Graham Best, Drinking Water Process Manager, Doreen Benson, Pilot Project Manager are to be commended for providing the treatment system and excellent technical and product expertise. Mike Fishbaugh provided daily onsite system checkout and readings of the treatment unit.

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 permittees; 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 of the ZENON Environmental Inc. ZeeWeed® ZW-500 Ultrafiltration (UF) Drinking Water System manufactured by ZENON Environmental Inc, which is a membrane filtration system used in package drinking water treatment system applications. The performance claim evaluated during field testing of the ZeeWeed® ZW-500 system was that the system is capable of a minimum 3 log₁₀ removal of *Giardia* cysts and 2 log₁₀ removal of *Cryptosporidium* oocysts. This document provides the verification test results for the ZENON Environmental Inc. ZeeWeed® ZW-500 UF Drinking Water System.

1.2 Testing Participants and Responsibilities

The ETV testing of the ZeeWeed® ZW-500 System was a cooperative effort between the following participants:

NSF International
Gannett Fleming, Inc.
Zenon Environmental Inc.
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 onsite inspection of the field analytical and data gathering and recording procedures was conducted by NSF. 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 ZeeWeed® ZW-500 system. Gannett Fleming is a NSF-qualified Field Testing Organization (FTO) for the ETV PDWTS 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 verification 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 ZENON Environmental Inc., a developer and manufacturer of membrane technologies for water treatment, wastewater treatment, and water reuse. ZENON Environmental Inc. is based in Burlington, Ontario.

The manufacturer was responsible for supplying a field-ready UF membrane filtration package 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 protective devices to provide for automatic shut down of the package plant in the event of loss of feed water or any other condition that would either damage the package 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 were automatically recorded by the treatment system.

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Contacts: Graham Best/Drinking Water Process Mgr.
Email: gbest@zenonenv.com

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) (UVA₂₅₄), and Algae. In addition, PWSA supplied operational support and analytical services for the *Giardia* and *Cryptosporidium* 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.

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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 PDWTS 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 was conducted 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 housed in the pumping station itself 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 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, sedimentation, filtration, and disinfection at PWSA's Aspinwall Treatment prior to being pumped to the reservoir. The influent to the ZeeWeed® ZW-500 system 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.

During the study the feed water turbidity ranged from 0.06 to 0.14 NTU with an average of 0.09 NTU. pH was within the range of 7.7 to 8.1 with an average of 7.8. Total alkalinity as calcium carbonate (CaCO₃) ranged from 37 to 43 milligrams per liter (mg/l) with an average of 39 mg/l. Average hardness, as CaCO₃, was 103 mg/l and ranged from 98 to 108 mg/l. TOC ranged from 1.66 to 2.02 mg/l with an average of 1.89 mg/l. All of the samples analyzed for UVA₂₅₄ yielded results of 0.020 cm⁻¹. TDS averaged 229 mg/l and the range was 176 to 300 mg/l. TSS averaged 0.29 mg/l and ranged from non detectable to 1.00 mg/l. HPC ranged from 94 to 308 colony forming units (cfu) per milliliter (ml) and averaged 179 cfu/ml. No coliform bacteria were detected in the feed water. Temperature averaged 3.8 degrees Celsius (°C), ranging from 3.3°C

to 4.5°C. The algae levels during the verification testing averaged 18 cells/ml, with a range of 8 to 24 cells/ml. The above information is presented in Table 1-1 below.

Table 1-1. Feed Water Quality

	Parameter									
	Total Alkalinity (mg/l as CaCO ₃)	Total Hardness (mg/l as CaCO ₃)	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	39	103	229	0.29	0	179	1.89	0.020	18	0.09
Minimum	37	98	176	<0.05	0	94	1.66	0.020	8	0.06
Maximum	43	108	300	1.00	0	308	2.02	0.020	24	0.14
Std. Dev.	2.6	N/A	60.8	0.48	0	92	0.163	0.000	8	0.02
95% Confid Int	(36, 42)	N/A	(169, 289)	(0, 0.75)	N/A ¹	(89, 269)	(2.13, 2.50)	N/A ¹	(10, 26)	(0.08, 0.09)

N/A = Not applicable because the sample size (n) was 2.

N/A¹ = 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 Effluent Discharge

The effluent of the treatment unit, (i.e. the filtrate, bleed waste, and chemical cleaning waste) 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 ZENON Environmental Inc. ZeeWeed® ZW-500 UF Drinking Water System. A ZW-500 ZeeWeed® membrane cassette was used in the treatment system. OCP is the manufacturer’s designation for their drinking water membrane. The membrane cassette was immersed in a ZeeWeed® tank. This process tank was constructed of stainless steel and had a 185 gallon (700 liter) mean operating volume. The membrane cassette was 6.6 ft. x 2.5 ft x 0.7 ft (2.0 m x 0.75 m x 0.2 m) (L x H x W). This provided a filtration surface area of 253 feet squared (ft²) (23.5 m²). The fibers contain thousands of pores. The pore size was 0.1 micron (μm) absolute, 0.03 μm nominal in diameter. This correlates to approximately 120 Kilo Dalton (absolute), 100 Kilo Dalton (nominal) molecular weight cutoff rating.

As previously mentioned the membrane cassette was immersed in the process tank. The process tank and necessary ancillary equipment were mounted on the treatment skid.

The individual fibers were potted (attached) top and bottom in epoxy. The epoxy potting ensures that no feed water may enter the filtrate side of the treatment system without having passed through the membrane. Water was drawn into the fiber interior core via the pores. Contaminants, which cannot pass through the pores, remain exterior to the filter module as reject. Water which passes through the membrane exits as clean filtrate.

2.1.1 Membrane Fiber Characteristics

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

Membrane classification.....	Ultrafiltration
Membrane material	Proprietary Polymer
Membrane type	hollow fiber
Membrane flow path.....	outside in
Filtration mode	Once through / constant waste bleed
pH tolerance	5-9 (operational), 2-10.5 (cleaning)
Temperature tolerance.....	1 - 40° C (33 - 95° F)

2.1.2 Major Equipment Components

The following major equipment components are provided on the ZeeWeed® ZW-500 System:

- Stainless steel ZeeWeed® tank (185 US gallons mean operating volume).
- Polypropylene CIP tank (20 US gallons operating volume).
- Becker DT 4.40, 2 Horsepower (Hp), Carbon Vane Blower (P 3 - air supply for membranes).
- Service Filtration GNOK Series Self-priming Centrifugal Pump (P 4 -filtrate pump).

- Goulds NPE, 1 Hp, Centrifugal Pump (P 2 - sprayer pump).
- Feed Solenoid Valve - An one inch pneumatic (air actuated, normally closed) ball valve.

Ancillary equipment that was used with the treatment system:

- Masterflex I/P Peristaltic Bleed Pump (P 05).
- 1" normally closed air actuated pneumatic ball valve.
- An electrical transformer.
- 4 Hp air compressor.

The individual components are interconnected with the necessary piping, valving, wiring, and controls. The membranes, influent, effluent, vacuum, and air piping are assembled into a cassette that is partially submerged into the process tank.

2.1.3 Data Plate

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

- a. Equipment name: ZENON Environmental Inc. ZeeWeed® ZW-500 UF Drinking Water System
- b. Membrane Model #: ZW-500
- c. Manufacturer: ZENON Environmental Inc. 845 Harrington Court, Burlington, Ontario
- d. Electrical requirements: 230 V, 60 Amps, 60 Hertz, single phase
- e. Serial number: FS 102
- f. Warning and caution statements: High Voltage Inside
- g. Capacity or output rate: 2 to 15 US gallons per minute (gpm)

2.1.4 System Photograph

A photograph of the ZeeWeed® ZW-500 System used for the ETV testing is included in this section of the report. Photograph 1 shows the layout of the unit and the location of various pieces of equipment including the control panel, process tank, bleed pump and ancillary equipment.



Photograph 1. The ZENON Environmental Inc. ZeeWeed® ZW-500 UF Drinking Water System showing control panel, process tank, bleed pump and ancillary equipment.

2.2 Operating Process

2.2.1 Feed Water

The feed water flows from Highland No. 1 Reservoir to the booster pumps in the New Highland booster station the influent to the treatment system is drawn from discharge of the booster station pumps. An air actuated solenoid valve controls the level of the feed water in the process tank.

2.2.2 Prefiltration

There is no prefiltration equipment utilized on the treatment system.

2.2.3 Filtration

During the filtration cycle, feed water enters the process tank. The filtrate pump is placed down stream of the membrane cassette. The placement of the membranes on the suction side of the filtrate pump creates a vacuum inside the membrane fibers. The vacuum pulls the feed water through the membrane fibers creating the flow through the system. During normal operation the

vacuum is applied to the top and bottom head of the membrane cassette, allowing flow from both heads of the cassette. Figure 2-1 illustrates the flow path during normal operation.

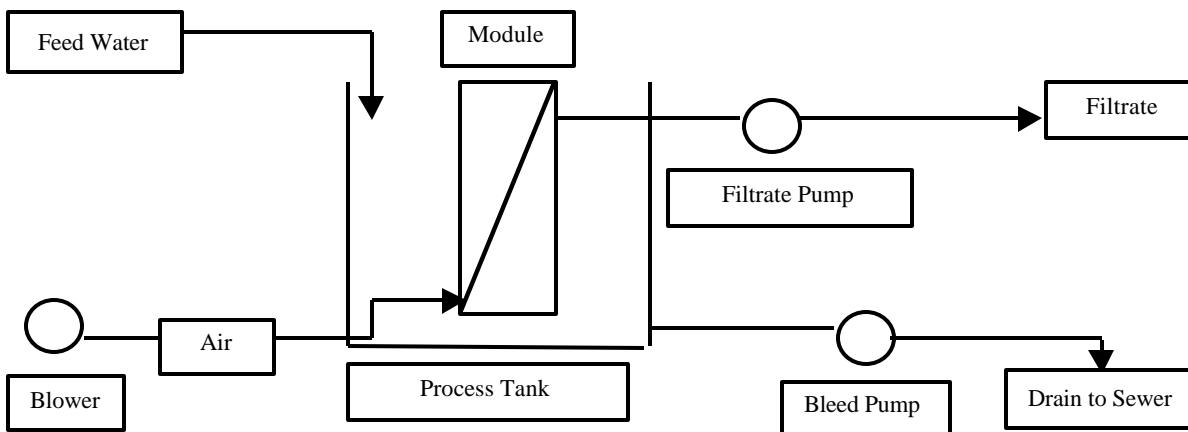


Figure 2-1. Flow Path During the Filtration Cycle

2.2.4 Air Agitation/Backpulsing

As water is filtered through the membrane surface, a film of rejected particulates accumulates on the surface of the fibers. The filtrate flow is gradually impeded as particles accumulate on the surface of the membrane. The treatment system utilizes two methods to control this particulate accumulation. Air is introduced to the bottom of the process tank on a continuous basis. This air agitates the outer surface of the membrane loosening any particles that adhere to the membrane surface. Periodically, the system undergoes a “backpulse”. Backpulsing is the reversal of flow through the membrane fibers. This flow reversal forcefully removes particles which have tightly adhered to the membrane fibers. The frequency and duration of the back pulse is adjustable and is determined by the feed water quality and the ability to maintain the desired flux rate. Backpulsing is accomplished by operating pneumatic valves, drawing filtrate from the CIP tank, and reversing the flow through the membrane fibers. A peristaltic pump is used to constantly remove a small portion of the water from the process tank. This pump is referred to as the bleed pump. Particulate material that is loosened from the membrane by air agitation or backpulsing is removed from the process tank by the bleed pump.

To aid in cleaning the membrane fibers, chlorine is added to the back pulse water. Sodium hypochlorite dosing can be done using a small chemical metering pump. During the verification testing calcium hypochlorite tablets were placed into the CIP tank. The use of the hypochlorite tablets resulted in a free chlorine residual in the backpulse water of 4-6 mg/l.

The reject removed by the bleed pump was discharged to an existing sewer. Figure 2-2 illustrates the flow path during backpulsing.

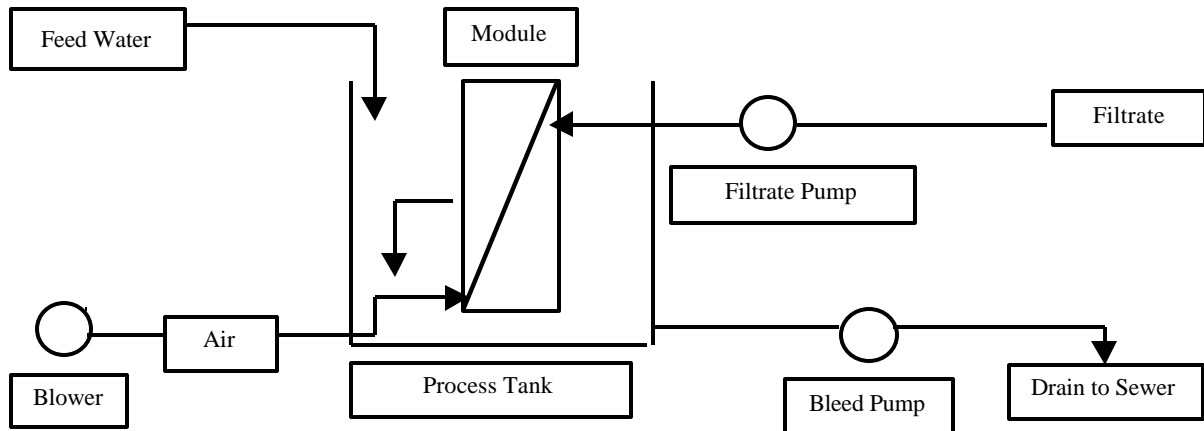


Figure 2-2. Flow Path During the Backpulse Cycle

2.2.5 Chemical Cleaning

Air agitation and back pulsing are not totally effective at removing particulate material from the membrane surface. These procedures must be augmented by occasional chemical cleaning. This procedure is referred to as Clean-In-Place (CIP). The required cleaning frequency is determined by the flow rate of the treatment system and the contaminant level in the feed water. The frequency of cleaning for this feed water is estimated to be between one and three months.

The CIP process was done manually using a full tank soak cleaning procedure. This was done by draining the process tank and refilling it with clean water. (In this case water from the pump station was used.) The soak water was dosed with 255 mg/l of chlorine. The membranes were soaked in this solution overnight (18 hours). The chlorine soak was followed by a citric acid soak. The process tank was drained and refilled with clean water. A 650 mg/l solution of citric acid was created by adding citric acid to the process tank. The membranes were soaked in this solution for four hours. Following the cleaning procedure the system is drained, rinsed, refilled and production resumed.

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.

3.1.1 Objectives

The verification testing was undertaken to evaluate the performance of the ZENON Environmental Inc. ZeeWeed® ZW-500 UF Drinking Water System. Specifically evaluated were the manufacturer's stated equipment capabilities and equipment performance relative to water quality regulations. Also evaluated were the operational requirements and maintenance requirements of the system. The details of each of these evaluations are discussed below.

3.1.1.1 Evaluation of Stated Equipment Capabilities

The ZeeWeed® ZW-500 system was tested to show that it was capable of providing a minimum 3 log₁₀ removal of *Giardia* cysts and 2 log₁₀ removal of *Cryptosporidium* oocysts from the source water and consistently producing water with a turbidity of less than 0.1 Nephelometric Turbidity Units (NTU). *Giardia* and *Cryptosporidium* removal challenge testing was conducted to demonstrate acceptable protozoan removal capability. Since turbidity challenge testing was not done during the course of the study and the turbidity of the feed water was quite low, turbidity removal capabilities were not verified during the course of the testing.

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 log₁₀ 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 filtrate turbidity samples, and a requirement to provide a 2 log₁₀ 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 filtrate turbidity levels was not verifiable due to the fact that the feed water already was in compliance with drinking water turbidity regulations. Log 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 (Panel View Standard ZeeWeed[®] Pilot System Manual August, 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 (ZENON, 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.

3.1.2.1 Qualitative Factors

The qualitative factors examined during verification testing were susceptibility to changes in environmental conditions, operational reliability, and equipment safety.

3.1.2.2 Quantitative Factors

The quantitative factors examined during verification testing were power supply requirements, consumable requirements, waste disposal technique, and length of operating cycle.

3.1.2.3 Cost Factors

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 ZeeWeed[®] ZW-500 system. This treatment unit operated at 53 gfd at 3.8°C (91 l/m²/h) which equates to 94 gfd at 68 degrees Fahrenheit (°F) (170 l/m²/h at 20°C). Costs will increase with increasing flow.

3.2 Water Quality Consideration

The focus of the ETV program is the verification that the tested treatment systems are capable of achieving their stated equipment capabilities. These capabilities invariably refer to the production of water meeting specific quality goals. In order to evaluate the effectiveness of the

treatment system, it is necessary to know the objective of the study and the quality of the water before and after treatment.

3.2.1 ETV Objective

The overall objective of the ETV program is to facilitate the deployment of innovative technologies through performance verification and information dissemination. Specifically, this ETV study was undertaken to demonstrate that the ZeeWeed® ZW-500 system was capable of providing a minimum 3 log₁₀ removal of *Giardia* cysts and 2 log₁₀ *Cryptosporidium* oocysts from source water to plant effluent and consistently producing water with a turbidity of less than 0.1 NTU.

3.2.2 Feed Water Quality

The source water for the verification testing of the ZeeWeed® ZW-500 system was from the open-air Highland Reservoir No. 1. The reservoir is 18 acres with an average depth of 20 ft and contains 120 MG of water. The water that is stored in Highland Reservoir No. 1 is treated surface water drawn from the Allegheny River. It has undergone coagulation, sedimentation, filtration, and disinfection at PWSA’s Aspinwall Treatment Plant prior to being pumped to the Highland No. 1 reservoir. The influent to the ZeeWeed® ZW-500 system 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 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	Bleed Waste (Reject)
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 (Backpulse 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

3.2.3 Filtrate Quality

Characterization of the filtrate quality of the system was the driving force behind the development of the experimental design of the ETV. The water quality and microbial analyses

were selected to demonstrate the treatment effectiveness of the manufacturer's equipment. Filtrate analyses and their frequencies are listed in Table 3-1 above.

In addition to analyses of total coliform and HPC, analyses for *Giardia* cysts and *Cryptosporidium* oocysts were conducted during the microbial removal phase of the evaluation. These analyses were conducted using procedures developed by EPA for use during the ICR for the identification and enumeration of *Giardia* cysts and *Cryptosporidium* oocysts (EPA, April 1996).

3.3 Recording Data

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

3.3.1 Operational Data

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

Parameter	Frequency
Feed flow	2/day
Feed water temperature	1/day
Electric power use	1/day
Filtrate applied vacuum	2/day
Filtrate flow	2/day

In addition to these parameters, data were collected during chemical cleaning and membrane integrity testing. Operational data collected during these tasks are 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 to which the above data were entered 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 logbooks, 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.

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 were submitted to the FTO by PWSA Laboratory representatives, verified, and entered into computer spreadsheets.

3.4.1 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 the "EPA/NSF ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants" (EPA/NSF 1998).

3.4.2 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 inline measurements, entry of data into the customized spreadsheets, and the methods for performing statistical analyses.

3.4.2.1 Log Books

Field log books were bound with numbered pages and labeled with the 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. Although the FTO attempted to initial and date each page and individual line entries review of the log book at the conclusion of testing indicated that in a few instances the entries had not been initialed. 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.

3.4.2.2 Photographs

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

3.4.2.3 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 inspection 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.

3.4.2.4 Inline Measurements

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

3.4.2.5 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.

3.4.2.6 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, total suspended and total dissolved solids. The equation used is:

$$95\% \text{ confidence interval} = \bar{X} \pm t_{n-1,0.975} (S/\sqrt{n})$$

where: \bar{X} is the sample mean;
S is the sample standard deviation;
n is the number of independent measurements included in the data set;
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 February 6, 1999 with the initiation of daily testing. The unit ran in normal mode (53 gfd at 39°F [91 l/m²/h at 3.8°C] which equates to 94 gfd at 68°F [169 l/m²/h at 20°C] constant air flow, back pulse 20 seconds every 10 minutes). Daily testing concluded on March 7.

Giardia and *Cryptosporidium* removal challenge testing was conducted March 2, 1999.

The cleaning efficiency task was performed on April 15 & 16, 1999. Membrane integrity testing was done on April 15 prior to 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 for the ZeeWeed® ZW-500 system are described in the Operations Manual (Appendix B) (ZENON, 1998). Analytical procedures are described in PWSA's Laboratory Quality Assurance Plan (Appendix F) (PWSA 1997).

3.7.1.1 Operations Manual

The Operations Manual for the treatment system was housed on-site and is attached to this report as Appendix B. Additionally, operating procedures and equipment descriptions were 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 analyses.
- An Ertco 1003-FC National Institute of Standards and Technology (NIST) traceable thermometer was used for temperature analyses. The thermometer had a range -1 to 51°C with scale divisions of 0.1°C.

The treatment unit used a Hach 1720C 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 from September of 1998 conducting pilot testing for the PWSA. The treatment system was operated until the start of the verification testing to establish the optimum treatment scheme.

The major operating parameters examined during initial operations were flux, transmembrane pressure, backpulse 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 gallon per square foot per day (gfd) or liter per hour per square meter (l/m²/h). The surface area of the membrane used for the verification testing was 253 ft² (23.5 m²). It is customary to refer to flux normalized to 68°F or 20°C. Lower temperatures increase the viscosity of water and decrease the amount of filtrate that can be produced from a given area. The formula used to calculate the system flux is:

$$\begin{aligned}\text{Flux (in gfd)} &= (\text{Flow (gpm)} * 1440 \text{ minute/day}) / \text{membrane area (ft}^2\text{)} \\ \text{Flux (in l/m}^2\text{/h)} &= (\text{Flow (gpm)} * 3.785 \text{ l/gal} * 60 \text{ minutes/hour}) / \text{membrane area (m}^2\text{)}\end{aligned}$$

A manufacturer-supplied coefficient, which is calculated from the temperature of the feed water, was used to normalize the flux to 68°F (20°C). The formula used for the calculation for water temperatures less than 68°F (20°C) is:

$$\text{Coefficient} = 1.035^{(20 - \text{Water temperature } (^{\circ}\text{C}))}$$

The coefficient is then multiplied by the flux to obtain the flux normalized to 68°F (20°C).

$$\text{Flux (at uncorrected water temperature)} * \text{Coefficient} = \text{Flux (normalized to 68}^{\circ}\text{F (20}^{\circ}\text{C))}$$

The vacuum applied to the membrane is adjusted to maintain the selected flux. Maintaining the selected flux usually requires an increase in the vacuum. In order to take this change in vacuum into account, a parameter known as specific flux can be calculated. Specific flux is calculated by dividing the flux of the system by the transmembrane pressure (TMP). The specific flux is expressed in gfd per pounds per square inch (psi) at 20°C.

3.7.2.2 Transmembrane Pressure

The vacuum applied to the membrane was recorded twice per day. Since the membranes are immersed in a tank at atmospheric pressure, the absolute value of the vacuum applied to the system is equivalent to the TMP of the unit.

3.7.2.3 Air Agitation/Backpulsing

As water is filtered through the membrane surface, a film of rejected particulates accumulates on the surface of the fibers. The filtrate flow is gradually impeded as particles accumulate on the surface of the membrane. The treatment system utilizes two methods to control this particulate accumulation. Air is introduced to the bottom of the process tank on a continuous basis. This air agitates the outer surface of the membrane loosening any particles that adhere to the membrane surface. Periodically, the system undergoes a “backpulse”. Backpulsing is the reversal of flow through the membrane fibers. This flow reversal forcefully removes particles which have tightly adhered to the membrane fibers. Backpulsing is accomplished by operating pneumatic valves, drawing filtrate from the CIP tank, and reversing the flow through the membrane fibers. The manufacturer recommends that the backpulse flux be 1.5 to two times the filtrate flux. Backpulsing was done for 20 seconds every 10 minutes. A peristaltic pump is used to constantly remove a small portion of the water from the process tank. This pump is referred to as the bleed pump. Particulate material that is loosened from membrane by air agitation or backpulsing is removed from the process tank by the bleed pump.

To aid in cleaning the membrane fibers, chlorine is added to the backpulse water. Sodium hypochlorite dosing can be done using a small chemical metering pump. During the 30 day test calcium hypochlorite tablets were placed into the CIP tank. The use of the hypochlorite tablets resulted in a free chlorine residual in the backpulse water of 4-6 mg/l.

The wastewater removed by the bleed pump was discharged to an existing sewer.

3.7.3.4 Percent Feed Water Recovery

The percent feed water recovery of the treatment system was calculated by comparing the net production to the amount of wastewater bled from the system. The process tank was filled through the use of a solenoid valve. The valve would open when the tank level dropped to a predetermined point; the tank would then refill and the solenoid valve would close. This ‘fill and drain’ cycle caused the feed water flows recorded daily to be quite erratic and generally higher than the average feed water flow of the system. Since the bleed flow and the filtrate flow were constant these two values were added together to calculate the feed water flow. Therefore the percent feed water recovery of the system was calculated by dividing the filtrate flow by the sum of the filtrate and bleed flows and multiplying that result by 100.

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 (NSF, 1998). The Verification Tasks were as follows:

- Task 1 - Membrane Flux and Operation
- Task 2 - Cleaning Efficiency
- Task 3 - Filtrate 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 feed water quality.

Standard operating parameters for filtration, backpulse, 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 were collected according to the schedule presented in Table 3-2.

3.8.1.1 Filtration

The flux selected for the verification study was 94 gfd at 68°F (169 l/m²/h at 20°C).

3.8.1.2 Air Agitation/Backpulsing

As previously discussed, the treatment system utilized air agitation and backpulsing to remove particles from the membrane surface.

Air agitation consisted of introduction of 7.5 standard cubic feet per minute (scfm) of air on a continuous basis. The air flow agitated the surface of the fibers and caused some of the particles adhering to fibers to be removed.

In order to remove particles not eliminated by the air agitation, flow is periodically reversed through the fibers. This is referred to as backpulsing. The backpulsing was done every 10 minutes for 20 seconds.

Backpulsing is accomplished by operating pneumatic valves, drawing filtrate from the CIP tank, and reversing the flow through the membrane fibers.

The interval between backpulses is determined based on the ability of the unit to maintain stable operating conditions. That is, if the backpulse frequency and duration are not able to maintain a stable flow and TMP over the short term, they are increased. The backpulse frequency and duration used during the study were capable of maintaining a stable operating conditions.

Particulate material that is loosened from the membrane by air agitation or backpulsing is removed from the process tank by the bleed pump. The bleed pump is a peristaltic pump that constantly bleeds a small portion of the water from the process tank.

3.8.1.3 Chemical Cleaning

The manufacturer generally recommends that chemical cleaning be instituted when the system TMP approaches 8 psi. The manufacturer indicated that depending on the feed water quality and verification testing results the TMP can be allowed to reach 12 psi. The latter criterion was recommended for use during the verification testing.

The cleaning was a two-stage process consisting of soaking the membrane in a chlorine solution and then soaking the membrane in a citric acid solution. The concentrations of the solutions and soak times were determined by the manufacturer. The results of the cleaning were evaluated by the manufacturer and a standard procedure for the concentrations of the solutions and soak times were established for the site.

For the verification testing the full tank soak cleaning procedure was used. The procedure was done manually. It consisted of draining the process tank and refilling it with clean water. (In this case water from the pump station was used.) The clean soak water was dosed with 255 mg/l of chlorine. The membranes were soaked in this solution overnight (18 hours). The chlorine soak was followed by a citric acid soak. The process tank was drained and refilled with clean water. A 650 mg/l solution of citric acid was created by adding citric acid to the process tank. The membranes were soaked in this solution for four hours. Following the cleaning procedure the system was drained, rinsed, and flushed. The system was then refilled and production resumed.

The procedure used to perform chemical cleaning and alternate cleaning procedures are presented in detail in the O&M Manual.

3.8.2 Task 2: Cleaning Efficiency

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

1. Evaluate the effectiveness of chemical cleaning for restoring filtrate 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 air agitation and backpulsing were unable to maintain system TMP <12 psi. If chemical cleaning was not required during the testing, it was to be performed at the conclusion of the 30-day period. Although the system did not reach a 12 psi TMP during the 30 day test, the system was cleaned per protocol requirements on April 15-16, 1999. The membranes were cleaned using manufacturer's recommendations.

Prior to cleaning, the treatment system was operated at the conditions as described in Section 3.8.1. Operational data, including flow and vacuum, were collected prior to cleaning. After

cleaning, the system was restarted and operated for a sufficient period of time to establish post-cleaning specific rate of flux recovery. Operational data, including flow and vacuum, were collected after cleaning. Table 3-3 details all the operational and analytical data collected before, during and following 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 bleed waste initial	1/episode
Visual observation of bleed waste final	1/episode
Flow of UF unit prior to cleaning	1/episode
Vacuum 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
Vacuum of UF unit after cleaning	1/episode
Temperature of UF unit after cleaning	1/episode

3.8.2.1 Cleaning Procedures

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

The chemical cleaning process consisted of soaking the membranes in a 255 mg/l solution of chlorine, draining the tank, soaking the membranes in 650 mg/l citric acid solution, draining the tank, rinsing the membranes, and flushing the system.

3.8.3 Task 3: Filtrate Quality

Procedures for the collection and analysis of filtrate 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 conducted, this stated treatment goal was not verifiable.

Testing on filtrate 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 3.8.1.3.

3.8.3.1 Sample Collection and Analysis Procedure

Filtrate samples were collected and analyzed monthly for total alkalinity, total hardness, and TDS. Weekly collection and analysis of filtrate samples was performed for TSS, total coliforms, HPC, TOC, UV absorbance, and algae. 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 the 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 ETV Protocol Revision requires the reporting of the maximum membrane pore size by the manufacturer based on recommendation by the Steering Committee (EPA/NSF 1999).

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 (EPA/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

The manufacturer provided the following procedure to be used in conducting the air pressure hold test:

1. Membrane pores must be wet and air bubbles removed (make sure no bubbles are in filtrate flow meter).
2. Make sure the process tank level is at the set level determined by the project manager (or owner) (all pressure hold tests must be done at the same operating level).

3. Shut off the system (filtrate pump and the blower air).
4. Close valves to isolate the membrane.
5. Make sure the pressure regulator is in the closed position before opening the air intake valve (do not allow a pressure >7 psi on the membranes).
6. Open the air intake and slowly open the pressure regulator to a pressure of 4 psi.
7. Hold the pressure at 4 psi for three minutes to flush water out of the membrane lumens.
8. Keep adjusting the pressure regulator until the pressure on the round pressure gauge stabilizes at 4 psi for at least 30 seconds.
9. Close hand valve to hold the air in the membrane.
10. Record the pressure decay over 2 minutes.

An intact membrane would be expected to lose no more than 1 psi every two minutes.

3.8.5.2 Turbidity Reduction Monitoring

Turbidity of feed water and filtrate 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 0.09 NTU) showing a 90% reduction, 0.009 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 feed water to filtrate 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 64 total counts per ml) showing a 99.9% reduction was beyond the limits of the instrumentation. Particles counts were monitored continuously and the 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-causing organisms. Most of these organisms are traditionally removed or rendered non-infectious through the use of conventional treatment practices like sedimentation, filtration, and disinfection. Not all disease-causing 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 log₁₀ removal from source water to plant effluent of *Giardia* cysts and 2 log₁₀ removal of *Cryptosporidium* oocysts. Participation in this task was optional. The manufacturer opted to participate in the microbial removal challenge.

Giardia and *Cryptosporidium* removal challenge testing took place on March 2, 1999. The procedures for the preparation of the feed water stock, stock addition, sample collection and analysis, and calibration are presented below.

Procedures for the testing the effectiveness of 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 counts. Five two-ml samples were taken from the feed water reservoir. These samples were examined and the quantity of cysts and oocysts was determined. This was used as a check of the replicate hemocytometer counts.

3.8.6.2 Stock Addition Procedure

Source water concentrations were fed into the treatment system immediately before the process tank over approximately 60 minutes. The feed water stock reservoir was gently mixed during this process.

3.8.6.3 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. The feed suspension was pumped into the feed water line immediately before the process tank. 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 filtrate were then passed through a 1 μ m pore sized yarn wound filter at a rate of one gallon per minute (3.785 liter per minute). Sample volumes of feed water, filtrate and backwash water 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 Quality Assurance/Quality Control (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. The following QA/QC procedures were utilized during the verification testing.

3.9.1 Daily QA/QC Verification Procedures

Daily QA/QC procedures were performed on the inline 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. The target flow rate was 500 ml/minute. 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 by including the flow rate prior to adjustment in parenthesis next to the description of what adjustment was made.

3.9.1.2 Inline Particle Counter Flow Rate

The flow rates for the feed water and filtrate inline particle counters were 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. The target flow rate was 100 ml/minute. Care was taken to maintain the flow rate between 95 ml/minute and 105 ml/minute. Flow rate to the particle counter was controlled by an integral overflow weir. Adjusting the height of the overflow weir altered the flow rate through the particle counter. If adjustments to the flow rate were made they were noted in the operational/analytical data logbook by including the flow rate prior to adjustment in parenthesis next to the description of what adjustment was made.

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 inline 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. The 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 feed flow and the filtrate 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 collecting the entire volume of feed water over a timed period and comparing the amount collected to the totalizer readings. The filtrate meter was verified by collecting the entire volume of filtrate over a timed period and comparing the amount collected to the totalizer readings.

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 dead test meter, adding weight to the meter, and comparing the reading obtained to the known amount of weight. The "pressure" gauge used on the treatment system was actually a vacuum/pressure gauge. The pressure side of the gauge was verified using the dead test meter.

3.9.3.3 Tubing

The tubing and connections associated with the treatment system were inspected to verify that they were clean and in good condition.

3.9.3.4 Inline Particle Counters

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

- 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, and turbidity 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 samples were recorded.

3.9.4.2 Temperature

Readings for temperature were conducted in accordance with *Standard Methods* 2550. Feed water temperatures were obtained once per day by submerging the thermometer in the feed water reservoir. A NIST certified thermometer having a range of -1°C to $+51^{\circ}\text{C}$, subdivided in 0.1°C 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 bleed waste according to *Standard Methods* 4500 Cl G. The unit was received new (factory calibrated) and daily calibration was not necessary.

The bleed wastewater was collected and analyzed twice per day.

Blanks for chlorine analyses were done by analyzing deionized (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 samples 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 bleed waste once a day. Performance evaluation samples were analyzed during the testing period. Results of the duplicates and performance evaluation samples 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 UVA₂₅₄.

Samples for analysis of TOC and UVA₂₅₄ 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 UVA₂₅₄ samples were collected, preserved, and held in accordance with *Standard Method* 5010B. Storage time before analysis was minimized in accordance to *Standard Methods*.

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

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° C until initiation of analysis.

Algae samples were preserved with Lugol's solution after collection and stored at a temperature of approximately 1-5° C 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 Method* 9222B. HPC analyses were conducted according to procedures presented in PWSA's QA plan. These procedures are based on *Standard Method* 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 Method* 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° C 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 Method* 2540C. TSS analyses were conducted according to *Standard Method* 2540D.

Chapter 4 Results and Discussions

4.1 Introduction

The verification testing for the ZENON Environmental Inc. ZeeWeed® ZW-500 UF Drinking Water System which occurred at the PWSA's Highland Reservoir No. 1 site in Pittsburgh, Pennsylvania, commenced on February 6, 1999 and concluded its 30-day period on March 7, 1999. *Giardia* and *Cryptosporidium* challenge testing was conducted on March 2, 1999, chemical cleaning was performed on April 15 and 16, 1999, and membrane integrity testing was performed on April 15, 1999.

This section of the verification report presents the results of the testing and offers a discussion of the results. Results and discussions of the following are included: initial operations, equipment characteristics, membrane flux and operation, cleaning efficiency, filtrate quality, maximum membrane pore size, membrane integrity testing, *Giardia* and *Cryptosporidium* removal, and QA/QC.

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 primary goals of the initial operations period were to establish a flux rate, the expected transmembrane pressure, backpulse frequency appropriate for the feed water quality, and the efficiency of the unit. The unit was on site in September of 1998 until the end of ETV testing and was operated to establish the optimum treatment scheme prior to initiation of verification testing.

4.2.1 Flux

Flux rates from 22 to 110 gfd at 68°F (37 to 190 l/m²/h at 20°C) were examined 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 94 gfd at 68°F (169 l/m²/h at 20°C) (which equates to 53 gfd at 39°F [91 l/m²/h at 3.8°C]). This corresponds to an initial specific flux of 20 gfd/psi at 68°F (482 l/m²/h/b at 20°C), or 11 gfd/psi at 39°F (278 l/m²/h/b at 3.8°C).

4.2.2 Transmembrane Pressure

The TMP during the initial operations period varied with the flux. TMP ranged from 0.9 psi to 9.6 psi (0.06 bar [b] to 0.7 b) during the initial operations period.

4.2.3 Backpulse Frequency

During the initial operations period, backpulse frequencies of 10 and 15 minutes were investigated. The duration of the backpulse was varied from 7.5 to 20 seconds. Based on the results of the initial operations period, it was determined that a backpulse of 20 seconds would occur every 10 minutes. Solids were removed from the system through the means of a bleed pump. The bleed pump constantly bled a small quantity of the feed water from the process tank. The bleed pump flow was constant. The bleed pump operated at 1,750 ml per minute throughout the verification testing.

4.3 Verification Testing Results and Discussion

The results and discussions of membrane flux and operation, cleaning efficiency, filtrate 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, filtrate pressures, backpulse 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 and are presented in Table 4-1 and 4-2 respectively. Date of chemical cleaning was April 15-16, 1999. A calculation of the percent feed water recovery is presented.

4.3.1.1 Transmembrane Pressure Results

Transmembrane pressure fluctuated from 6.4 psi to 8.9 psi during the 30 day testing. The average TMP during the testing was 7.5 psi. Table 4-1 presents a summary of the TMP. Figure 4-1 presents a graph of daily TMP results. A complete tabular summary of the data is presented in Appendix C.

	Transmembrane Pressure (psi)
Average	7.5
Minimum	6.4
Maximum	8.9
Standard Deviation	0.66
95% Confidence Interval	(7.3, 7.7)

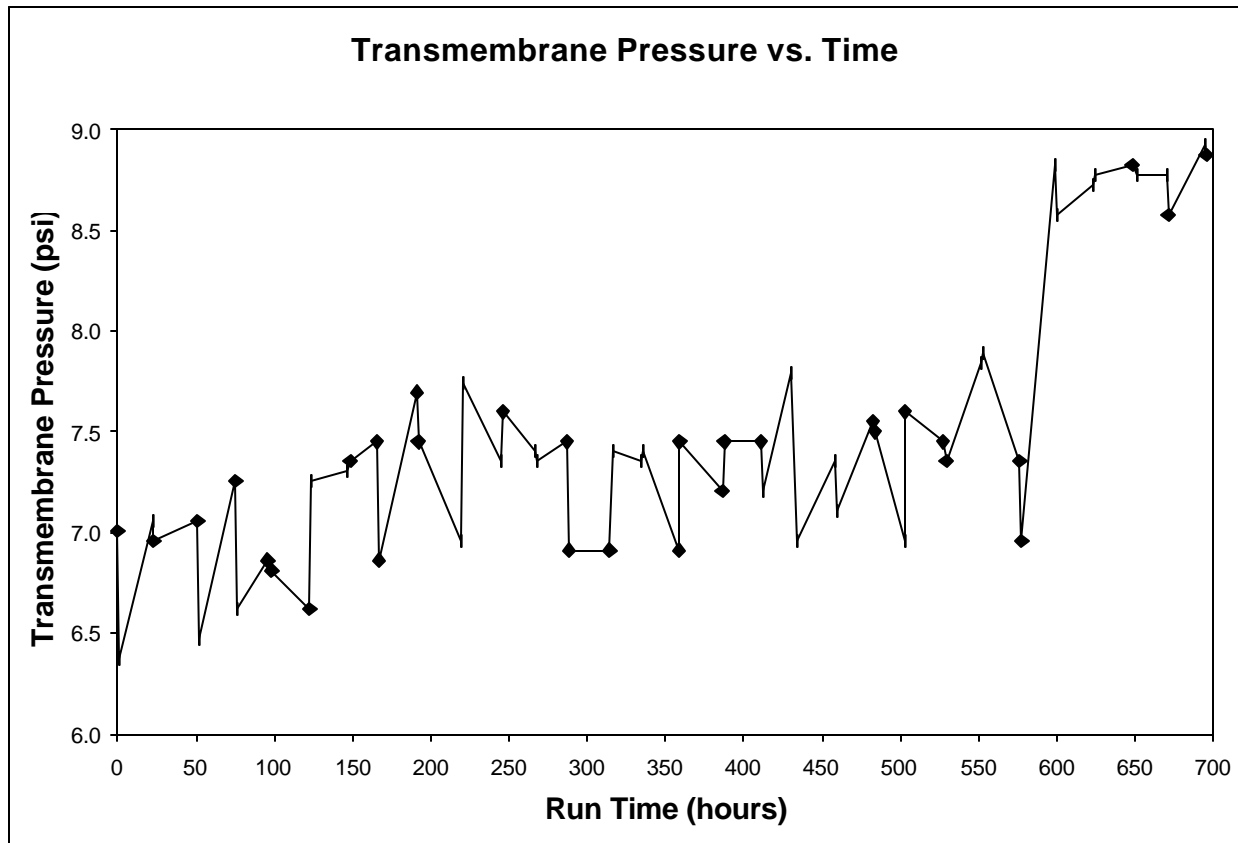


Figure 4-1. Transmembrane Pressure vs. Time

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

The increase in TMP may be due to the accumulation of particles on the membrane surface. The backpulse 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 backpulse 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. Vacuum applied to the membrane increased as the time to the next backpulse decreased. If the pressure and flow readings were taken shortly after the completion of a backpulse cycle, a lower TMP would result. Likewise if the readings were taken just prior to the initiation of a backpulse cycle, a higher TMP would result.

There was a noticeable decrease in TMP between run time hours 553 to 578. Although this decrease occurred during challenge testing, no changes in system operation were instituted in relation to the challenge test. The reason for this decrease is unknown although it may be due to the slightly variable flow rate observed during the testing. As the flow rate changed from reading to reading the TMP would also slightly change. There was a noticeable increase in TMP from run time hours 578 to 599. There was an increase in system flux between run time hours 553 to 576. The flux increased from 53 to 77 gfd (90 to 130 l/m²/h). The manufacturer has suggested that this sudden increase in flux accelerated the fouling of the membrane, resulting in the increased TMP.

The cleaning conducted on April 15 and 16 decreased the TMP from 8.8 psi to 4.4 psi.

Overall the increase in TMP during the 30-day testing period was slight. This would seem to indicate that the selected flux and backpulse protocol was appropriate for this feed water quality.

4.3.1.2 Specific Flux Results

The specific flux of the treatment system was 13 gfd/psi at 68°F (330 l/m²/h/b at 20°C) on average. The specific flux varied from a minimum of 11 gfd/psi at 20°C to 25 gfd/psi at 68°F (264 l/m²/h/b to 621 l/m²/h/b at 20°C) during the 30 day testing period. 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 (gfd/psi @20°C)
Average	13
Minimum	11
Maximum	25
Standard Deviation	2.3
Confidence Interval	(12, 13)

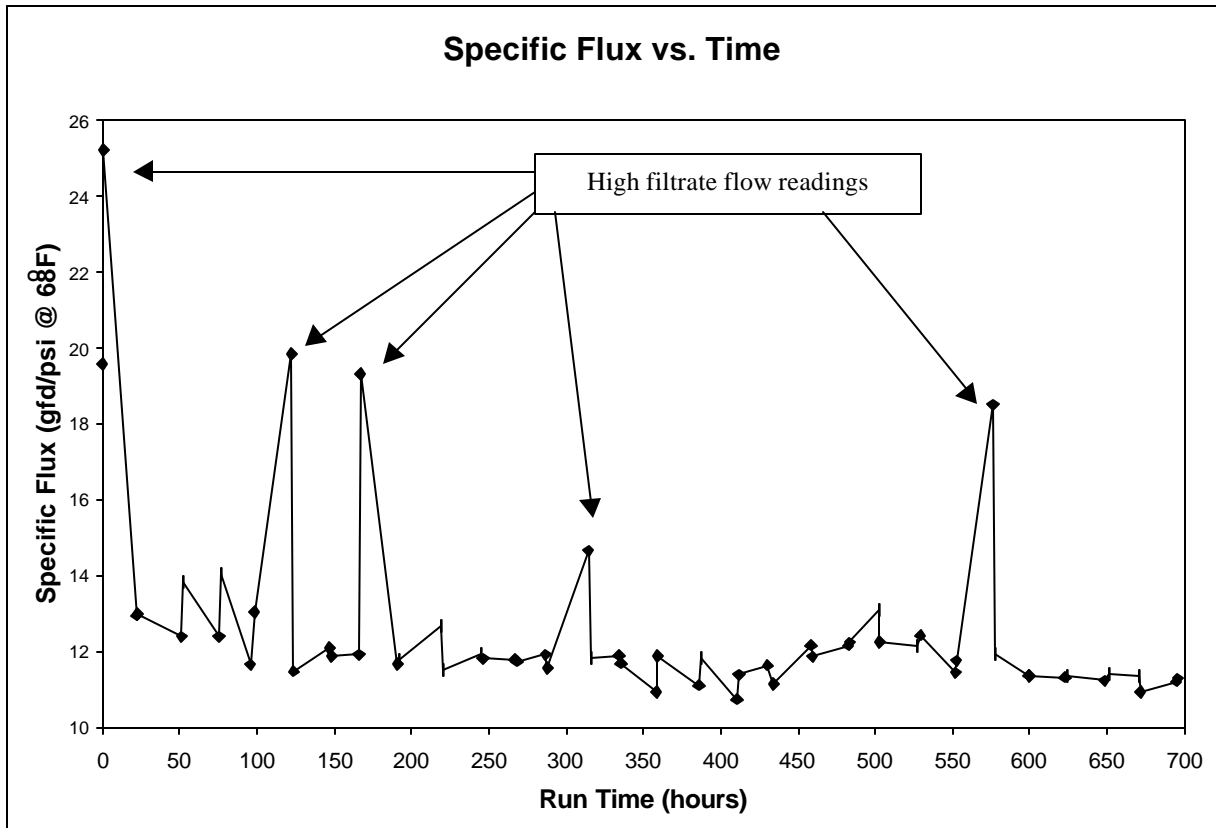


Figure 4-2. Specific Flux Decline vs. Time

As depicted in Figure 4-2, specific flux slightly 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 decrease in specific flux during the testing period was due to the increase in TMP. The specific flux decline did not appear to be excessive during the testing.

There were five instances of a slight decrease or an increase and then a decrease of the specific flux. These were at run time one hour, at run time 123 hour, at run time 167 hour, at run time 314 hour, and at run time 576 hour. The reason for these variations can be traced to a fluctuation in the instantaneous flow through the system. In each instance the filtrate flow of the system increased from near the average of 9.4 gpm to a value between 10.4 gpm and 14.2 gpm. The reading on the filtrate flow meter was somewhat variable during the testing. These variations were of very short duration, typically lasting less than one minute. It would seem that these increases were transient in nature and not indicative of true long term system performance.

4.3.1.3 Cleaning Episodes

The membranes were cleaned as per protocol requirements using manufacturer's recommendations on April 15 - 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 amount of wastewater bled from the system. The process tank was filled through the use of a solenoid valve. The valve would open when the tank level dropped to a predetermined point; the tank would then refill and the solenoid valve would close. This caused the feed water flows recorded daily to be quite erratic and generally higher than the average feed water flow of the system. Since the bleed flow and the filtrate flow were constant these two values were added together to calculate the feed water flow. Therefore the percent feed water recovery of the system was calculated by dividing the filtrate flow by the sum of the filtrate and bleed flows. The following equation was used:

$$\text{Percent Feed Water Recovery} = ((\text{FF}/(\text{FF} + \text{BWF})) * 100$$

where: FF = filtrate flow
BWF = Bleed wastewater flow

Using the above equation the following calculation was performed:

$$\text{Filtrate flow} = \text{flow (gpm)} * \text{minutes/day} = \text{filtrate flow (gpd)}$$

$$\text{Filtrate flow} = 9.4 \text{ gpm} * 1440 \text{ minutes/day} = 13536 \text{ gpd}$$

$$\text{Feed flow to membrane} = \text{filtrate flow} + \text{bleed wastewater flow}$$

$$\text{Feed flow} = 13536 \text{ gpd} + ((1750 \text{ ml/min} * (1 \text{ gal}/3785\text{ml}) * 1440 \text{ min/day})) = 14202 \text{ gpd}$$

$$\text{Percent feed water recovery} = 100 * [13536/ 14202] = 95\%$$

4.3.2 Task 2: Cleaning Efficiency

Cleaning was conducted April 15-16, 1999. Data on the characteristics of the cleaning solution before, during, and after cleaning were collected. Operational parameters were recorded before and after cleaning. The cleaning solution data were used to characterize the cleaning solution and waste generated by cleaning of the membranes. The operational data were 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

Parameter	Unit	Chlorine Cleaning		Citric Acid Cleaning	
		Result	Dup.	Result	Dup.
pH of Cleaning Solution Initial		9.1	9.1	2.6	2.6
pH of Cleaning Solution During Process		9.0	9.0	2.6	2.6
pH of Cleaning Solution Final		8.9	8.9	2.7	2.7
TDS of Cleaning Solution Initial	(mg/l)	680		1342	
TDS of Cleaning Solution During Process	(mg/l)	798		1392	
TDS of Cleaning Solution Final	(mg/l)	622		1020	
Turbidity of Cleaning Solution Initial	(NTU)	1.32	1.36	0.86	0.87
Turbidity of Cleaning Solution During Process	(NTU)	0.88	0.79	0.92	0.96
Turbidity of Cleaning Solution Final	(NTU)	0.99	1.02	1.52	1.60
Chlorine Residual Initial	(mg/l)	198	190	-	-
Chlorine Residual Final	(mg/l)	121	114	-	-
Visual Observation of Cleaning Waste Initial			clear		clear
Visual Observation of Cleaning Waste Final			clear		clear

Table 4-4. Operational Parameter Results - Cleaning Procedure

Parameter	Unit	Time	Chlorine Cleaning	Citric Acid Cleaning
			Result	Result
Flow of UF Unit Prior to Cleaning	(gpm)	14:30	8.6	
Vacuum Applied to UF Unit Prior to Cleaning	(psi)	14:30	-8.8	
Temperature of UF Unit Prior to Cleaning	(°C)	14:30	12.3	
Flow of UF Unit After Cleaning	(gpm)	16:00		9.9
Vacuum Applied to UF Unit After to Cleaning	(psi)	16:00		-4.4
Temperature of UF Unit After Cleaning	(°C)	16:00		12.0

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:

$$\text{Recovery of specific flux} = 100 * (1 - (J_{Sf} / J_{Si}))$$

where: J_{Sf} = Specific flux (gfd/psi) at end of current run (final)
 J_{Si} = Specific flux (gfd/psi) when the system was restarted after completion of the cleaning procedure (initial)

The specific flux prior to the start of the cleaning process was 7.3 gfd/psi at 68°F. The specific flux when the system was restarted after the completion of the cleaning procedure was 17 gfd/psi at 68°F.

Using these fluxes in the above equation resulted in a recovery of specific flux of 57%.

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

$$\text{Loss of original specific flux} = 100 * (1 - (J_{Si} / J_{Sio}))$$

where: J_{Sio} = Specific flux (gfd/psi) at time zero point of membrane testing

The specific flux at time zero point of membrane testing was 25 gfd/psi at 68°F. The specific flux when the system was restarted after the completion of the cleaning procedure was 17 gfd/psi at 68°F.

Using these fluxes in the above equation resulted in a loss of original specific flux of 32%.

4.3.2.3 Discussion of Results

ZENON generally recommends that cleaning be instituted when the TMP approaches and does not stabilize at less than or equal to 8 psi. The manufacturer indicates that this TMP cut off value is site-specific and determined by the feed water quality at the test site. The TMP cutoff used for this verification testing was 12 psi.

The procedure used for chemical cleaning was defined in the operations manual and required some manual effort. Mixing the cleaning agents into solution, and initiation of the cleaning procedure required approximately four hours of effort by the operator.

The chlorine cleaning solution waste had a pH of 8.9, a turbidity of 0.99 NTU, and a TDS of 622 mg/l. The total chlorine residual of the chlorine cleaning solution waste was 121 mg/l. The citric acid cleaning solution wastewater indicated that the solution was acidic, with a pH of 2.7. The citric acid cleaning waste had a turbidity of 1.52 NTU and a TDS of 1020 mg/l. No chlorine was used in conjunction with the citric acid solution. Both the chlorine cleaning solution waste and the citric acid cleaning solution waste were clear.

The cleaning solutions are mixed from 12.5% NaOCl and 100% citric acid. Care must be taken when handling these materials to avoid injury. Although the stock chemicals from which the cleaning solutions are mixed can cause personal injury, there are no hazardous materials present in the waste from the cleaning procedures. The presence of hazardous materials in the wastewater would be dependent on the quality of the feed water. Local regulations allowed the waste stream to be discharged to the sanitary sewer system.

Examination of the operational data and the recovery of specific flux showed that the cleaning procedure did restore 57% of the specific flux to the treatment system. This indicated that the cleaning procedure was capable of restoring some of the membrane performance.

The loss of original specific flux was 32%. This may indicate that some irreversible fouling of the membrane had occurred. However, it may also indicate that the cleaning event was not completely effective.

4.3.3 Task 3: Filtrate Quality

The results of the testing of the feed water for Total Alkalinity, Total Hardness, TDS, TSS, Total Coliforms, HPC, TOC, UVA₂₅₄, and Algae are presented in Table 4-5. The results of the testing of the filtrate for Total Alkalinity, Total Hardness, TDS, TSS, Total Coliforms, HPC, TOC, UVA₂₅₄, and algae are presented in Table 4-6. A complete data table is presented in Appendix C.

Table 4-5. Feed Water Testing Results

	Total Alkalinity (mg/l as CaCO ₃)	Total Hardness (mg/l as CaCO ₃)	TDS (mg/l)	Parameter TSS (mg/l)	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)	TOC (mg/l)	UVA (cm ⁻¹)	Algae (cells/ml)
Average	39	103	229	0.29	0	179	1.89	0.02	18
Minimum	37	98	176	<0.05	0	94	1.66	0.02	8
Maximum	43	108	300	1.0	0	308	2.02	0.02	24
Std. Dev.	2.6	N/A	60.8	0.48	0	92	0.163	0.00	8
95% Confid Int	(37, 42)	N/A	(169, 288)	(0, 0.75)	N/A ¹	(89, 268)	(1.73, 2.05)	N/A ¹	(10, 26)

N/A = Not applicable because the sample size (n) was 2.

N/A¹ = 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. Filtrate Testing Results

	Total Alkalinity (mg/l) as CaCO ₃	Total Hardness (mg/l) as CaCO ₃	TDS (mg/l)	Parameter TSS (mg/l)	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)	TOC (mg/l)	UVA (cm ⁻¹)	Algae (cells/ml)
Average	39	99	236	0.10	0	6	2.17	0.02	<8
Minimum	38	94	150	<0.05	0	2	2.01	0.02	<8
Maximum	41	104	313	0.40	0	18	2.40	0.02	8
Std. Dev.	1.4	N/A	87.0	0.20	0	8.0	0.185	0.00	2
95% Confid Int	(38, 40)	N/A	(150, 321)	(0, 0.30)	N/A ¹	(0, 14)	(1.99, 2.35)	N/A ¹	(<8, <8)

N/A = Not applicable because the sample size (n) was 2.

N/A¹ = 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 water and filtrate testing.

Reductions were seen in HPC. HPC averaged 179 cfu/100ml in the feed water. Filtrate HPC concentrations were 6 cfu/100ml on average. (The presence of HPC in the filtrate may have been due to the inability to completely disinfect the Tygon sample lines.)

Algae concentrations were reduced. Feed water contained 18 cells/ml on average. Average filtrate algae concentrations were 5 cells/ml. The reported average filtrate 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. (Filtrate algae presence may have been due to growth in the Tygon sample lines.)

Removal in TSS was observed; a reduction of 0.19 mg/l on average.

The treatment system had little or no effect on the total alkalinity, and total hardness. This was expected as these parameters are dissolved in solution and will pass through UF membranes.

TOC and UVA₂₅₄ were not well removed from the feed water. In fact, the average TOC in the filtrate was slightly higher than the TOC in the feed water. Examination of the confidence intervals of the results of the two sets of analyses indicates that the difference did not represent a statistically significant increase. The equivalent nature of the feed water and filtrate TOC results indicate that the bulk of the TOC in the feed water is dissolved in solution.

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

Temperature of the feed water was fairly stable during the thirty day testing from a high of 4.5°C to a low of 3.3°C (40°F to 38 °F). The average temperature was 3.8°C (39 °F).

4.3.3.1 Turbidity Results and Removal

Results of testing for turbidity in the feed water and filtrate 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 Table 4-7. A complete data table is presented in Appendix C.

Table 4-7. Turbidity Analyses Results and Removal

Sample Parameter	Feed (bench top)		Filtrate (inline)	Amount Removed
	Turbidity	Turbidity (duplicate)	Turbidity	
	(NTU)	(NTU)	(NTU)	(NTU)
Average	0.09	0.09	0.03	0.06
Minimum	0.06	0.06	0.02	0.03
Maximum	0.14	0.13	0.04	0.10
Standard Deviation	0.02	0.02	0.004	0.02
95% Confidence Interval	(0.08, 0.09)	(0.08, 0.10)	(0.02, 0.03)	(0.05, 0.07)

Due to a problem with the data logging program used on the treatment system the inline filtrate turbidity data were not accurately recorded. The 10 minute readings from February 6 to February 23 were recorded by the data logger as -0.002 NTU. The data logger failed on February 24 and did not begin recording data until March 12. Due to these difficulties four hour turbidity data can not be presented.

The turbidity of the filtrate was very low throughout the duration of the verification testing. The inline filtrate turbidimeter readings averaged 0.03 NTU; the benchtop turbidimeter readings averaged 0.04 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 filtrate 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 inline and benchtop turbidimeter and the low level of turbidity in the filtrate. 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 filtrate 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 filtrate with turbidities of less than 0.1 NTU.

4.3.3.2 Particle Count Results and Removal

Average feed water particle counts are presented in Table 4-8. Average filtrate particle counts are presented in Table 4-9. Daily average cumulative counts for feed water and filtrate and the log₁₀ particle removals are presented in Table 4-10. A complete data table is presented in Appendix C. Figures 4-3 and 4-4 depict results of four hour particle counts for feed water and filtrate. Figure 4-5 graphically depicts daily log₁₀ removals for cumulative particle counts.

Table 4-8. Feed Water Particle Counts

	Size						Cumulative
	2-3 μm	3-5 μm	5-7 μm	7-10 μm	10-15 μm	>15 μm	
Average	7.1	43	7.1	5.5	1.4	0.62	64
Minimum	0	0	0	0	0	0	N/A
Maximum	22	130	22	21	8.6	10	N/A
Std. Dev.	3.9	24	3.9	2.5	0.68	0.42	N/A
95%	(6.9, 7.2)	(42, 44)	(6.9, 7.2)	(5.4, 5.6)	(1.4, 1.4)	(0.60, 0.64)	N/A
Confid Int							

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 15 μm readings were 16% lower than actual. Due to extremely low results in the 5 μm and 10 μm size range, the reliability of the 2-3 μm , 3-5 μm , 5-7 μm and 7-10 μm particle counts should be considered questionable. See instrument QA/QC verification results in Section 4.5.3.

Table 4-9. Filtrate Particle Counts

	Size						Cumulative
	2-3 μm	3-5 μm	5-7 μm	7-10 μm	10-15 μm	>15 μm	
Average	0.33	0.13	0.06	0.05	0.02	0.10	0.70
Minimum	0	0	0	0	0	0	N/A
Maximum	41	6.0	6.0	6.0	2.5	2.4	N/A
Std. Dev.	1.2	0.21	0.21	0.18	0.07	0.19	N/A
95%	(0.28, 0.38)	(0.12, 0.14)	(0.05, 0.07)	(0.04, 0.06)	(0.02, 0.02)	(0.01, 0.11)	N/A
Confid Int							

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 15 μm readings were 18% lower than actual. Due to extremely low results in the 5 μm and 10 μm size range, the reliability of the 2-3 μm , 3-5 μm , 5-7 μm and 7-10 μm particle counts should be considered questionable. See instrument QA/QC verification results in Section 4.5.3.

Table 4-10. Daily Average Cumulative Particle Counts - Feed Water and Filtrate, Log₁₀ Particle Removal

Date	Feed	Filtrate	Log ₁₀ Removal
2/6/1999	88	1.4	1.8
2/7/1999	80	1.2	1.8
2/8/1999	82	1.0	1.9
2/9/1999	82	0.92	2.0
2/10/1999	67	0.71	2.0
2/11/1999	62	0.75	1.9
2/12/1999	113	0.68	2.2
2/13/1999	95	0.53	2.2
2/15/1999	79	0.48	2.2
2/16/1999	76	0.51	2.2
2/17/1999	82	0.53	2.2
2/18/1999	58	0.62	2.0
2/19/1999	63	0.48	2.1
2/20/1999	49	0.40	2.1
2/21/1999	49	0.57	1.9
2/22/1999	42	0.53	1.9
2/23/1999	45	0.69	1.8
2/24/1999	50	0.46	2.0
2/25/1999	108	1.0	2.0
2/26/1999	54	0.71	1.9
2/27/1999	51	1.2	1.6
2/28/1999	94	1.1	1.9
3/1/1999	102	0.63	2.2
3/2/1999	107	0.41	2.4
3/3/1999	132	1.3	2.0
3/4/1999	168	2.5	1.8
3/5/1999	164	0.55	2.5
3/6/1999	194	0.39	2.7
3/7/1999	180	0.36	2.7

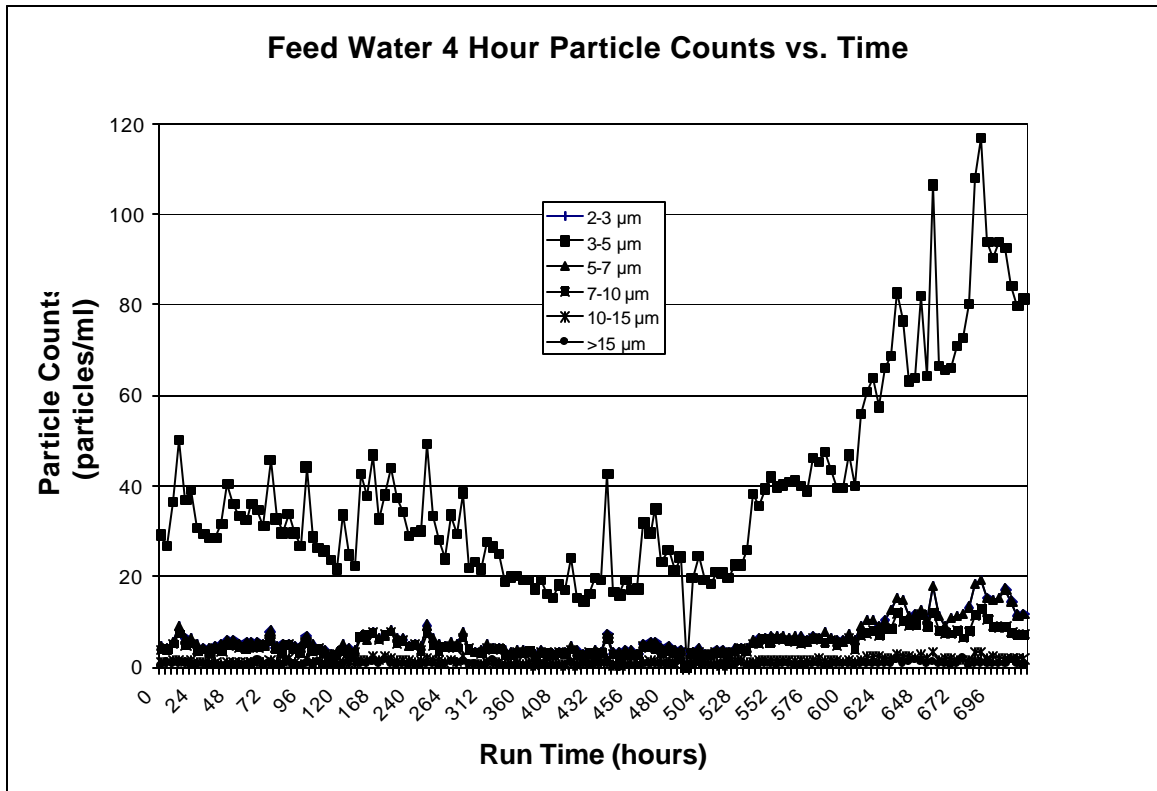


Figure 4-3. Four Hour Feed Water Particle Counts

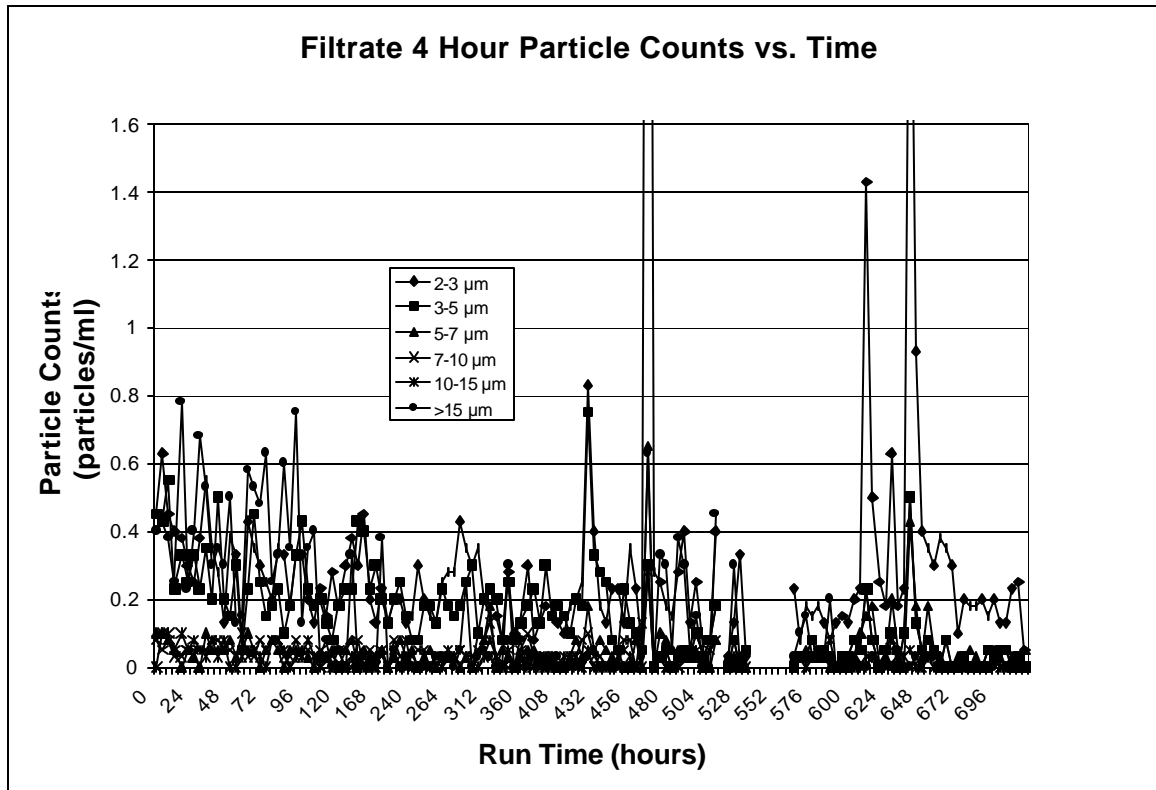


Figure 4-4. Four Hour Filtrate Particle Counts

Particle counting of feed water and filtrate was conducted throughout the testing period. The feed water cumulative counts averaged 64 particles per ml. The filtrate cumulative counts averaged 0.70 counts per ml. The average \log_{10} removal for the cumulative counts was 2.1.

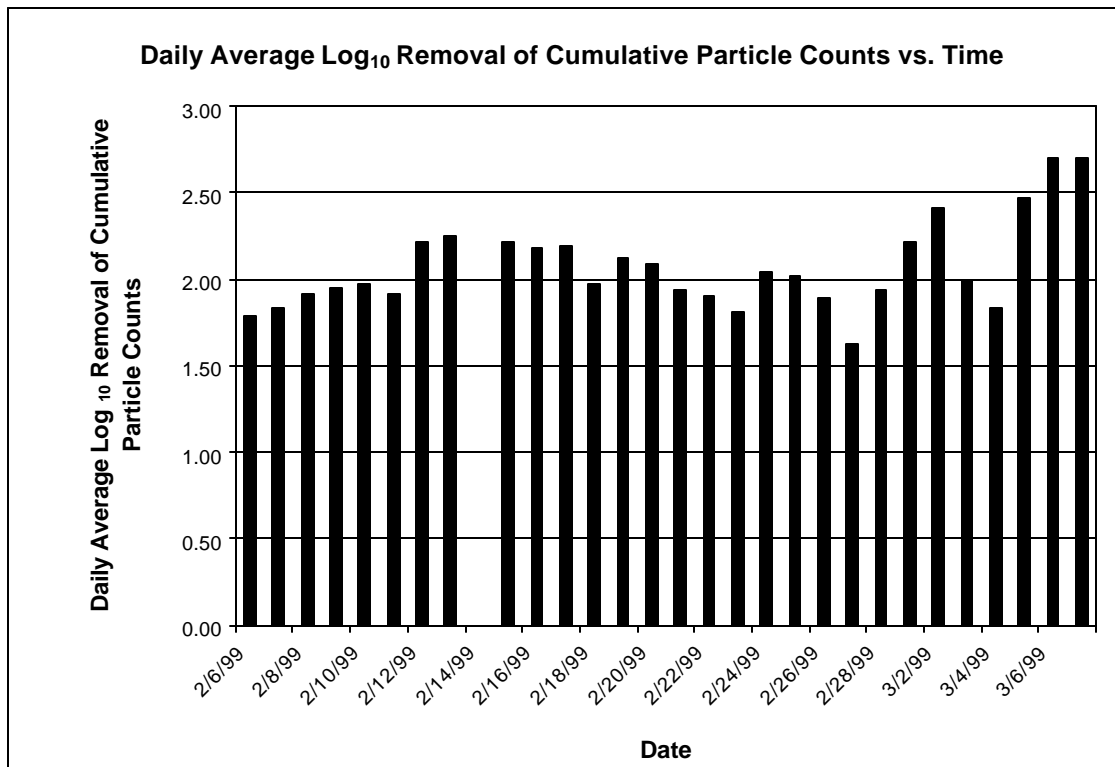


Figure 4-5. Daily Average Log₁₀ Cumulative Particle Removal

The low particle counts for each size range in the filtrate indicated good system performance throughout the testing period. The treatment system seems to be an effective removal mechanism for particle removal. However, given the poor results of the particle counter calibration check (see Section 4.5.3), caution should be used when drawing inferences about particle removal.

4.3.3.3 Bleed Wastewater Testing Results

Daily and weekly testing was conducted on the water bled from the bottom of the process tank. The results of the testing are listed in Table 4-11 and Table 4-12. A complete data table is presented in Appendix C.

Table 4-11. Daily Bleed Wastewater Testing Results – Summary

Parameter	Parameter			
	Turbidity (NTU)	Turbidity (dup) (NTU)	Chlorine Residual (mg/l)	Chlorine Residual (dup) (mg/l)
Average	0.76	0.76	0.72	0.71
Minimum	0.35	0.38	0.53	0.49
Maximum	1.66	1.19	0.99	0.97
Standard Deviation	0.29	0.25	0.10	0.10
95% Confidence Interval	(0.69, 0.83)	(0.67, 0.85)	(0.68, 0.76)	(0.68, 0.76)

Table 4-12. Weekly Bleed Wastewater Testing Results

	Parameter		
	TSS (mg/l)	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)
Average	0.43	0	22
Minimum	0.20	0	12
Maximum	0.80	0	40
Standard Deviation	0.26	0	13
95% Confidence Interval	(0.17, 0.68)	N/A	(9, 35)

N/A = Not applicable because standard deviation = 0

The turbidity of the bleed wastewater averaged 0.76 NTU. The chlorine averaged 0.72 mg/l. TSS content in the waste was somewhat variable; but the backpulse procedure appeared to be removing some particulate material. Total coliforms were absent in the bleed wastewater 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 filtrate, and the amount in the bleed wastewater. There is a portion of the TSS which will not be removed by backpulsing and accumulates on the membrane; the majority of this accumulated material is presumably dissolved and removed by chemical cleaning.

To calculate the amount of TSS in the treatment stream the following equation was used:

$$\text{Pounds/day (lbs/day)} = \text{Amount of TSS in mg/l} * [(8.34\text{lb}) / (\text{mg/l} * \text{MG})] * \text{Flow MGD}$$

Pounds of TSS in feed water:

$$\text{Average feed water TSS (from Table 4-5)} = 0.29 \text{ mg/l}$$

$$\text{Calculate the feed water flow in MG: } (9.9 \text{ gpm}) * (1440 \text{ min/day}) = 14256 \text{ gal/day} / (1,000,000 \text{ gal/MG}) = 0.01426 \text{ MGD.}$$

$$\text{lbs/day} = 0.29 \text{ mg/l} * [(8.34\text{lb}) / (\text{mg/l} * \text{MG})] * (0.01426 \text{ MGD}) = 0.035 \text{ lbs/day}$$

Pounds of TSS in filtrate:

$$\text{Average filtrate TSS (from Table 4-6)} = 0.10 \text{ mg/l}$$

$$\text{Calculate the filtrate flow in MG: } (9.4 \text{ gpm}) * (1440 \text{ min/day}) = 13536 \text{ gal/day} / (1,000,000 \text{ gal/MG}) = 0.01354 \text{ MGD.}$$

$$\text{lbs/day} = 0.10 \text{ mg/l} * [(8.34\text{lb}) / (\text{mg/l} * \text{MG})] * (0.01354 \text{ MGD}) = 0.011 \text{ lbs/day}$$

Pounds of TSS in bleed wastewater:

$$\text{Average wastewater TSS (from Table 4-12)} = 0.43 \text{ mg/l}$$

Calculate the amount of bleed wastewater produced daily in MG:

$$(1750 \text{ ml/minute}) / (3785 \text{ ml/gallon}) = 0.462 \text{ gpm}$$

$(0.462 \text{ gpm} * 1400 \text{ minute/day}) = 666 \text{ gallons per day}$
 $665 \text{ gallons per day} / (1,000,000 \text{ gal/MG}) = 0.000666 \text{ MGD}$

$\text{lbs/day} = 0.43 \text{ mg/l} * [(8.34 \text{ lb}) / (\text{mg/l} * \text{MG}) * 0.000666 \text{ MGD}] = 0.0024 \text{ lbs/day}$

Pounds of TSS accumulating on membrane:

This figure is the difference between the amount of TSS added to the membrane and the amount of TSS removed during continuous bleed. 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 bleed waste + pounds of TSS accumulating on the membrane.

$0.035 \text{ lbs/day TSS in influent} = 0.011 \text{ lbs/day TSS in effluent} + 0.0024 \text{ lbs/day TSS in bleed waste} + 0.022 \text{ lbs/day accumulating on the membrane.}$

The TSS mass balance calculation would seem to indicate that the backpulsing procedure was not effective at removing the particulate material deposited on the membrane. According to the calculation, twice as much TSS was left on the membrane as was removed during backpulsing. 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 bleed wastewater was higher than the average of the weekly analyses indicated. The daily bleed wastewater 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 backpulse process. The results could be a function of the relatively low levels of TSS in the feed water. The laboratory uses Standard Method 2540 D. According to the Standard Methods in the Precision Section of the method, the standard deviation at 15 mg/l was 5.2 mg/l, a coefficient of variation of 33%. At higher concentrations, the coefficient of variation decreases, 10 % at 242 mg/l. (APHA et al., 1992). There is a relative lack of precision with Standard Method 2540 D at low levels and low levels were seen in the testing. The laboratory was contacted and reported that at the low levels tested the method is very poor at generating meaningful results.

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 0.1 μm and that 90% of the pores in their membrane are equal to or less than 0.03 μm . These results were generated through the use of ASTM Method F316 Standard Test Methods for Pore Size Characterization of Membrane Filters by Bubble Point and Mean Flow Pore Test. These results were provided by the manufacturer and were not verified during the ETV testing. Appendix G contains the manufacturer's statement confirming this information.

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 April 15, 1999. A complete data table is presented in Appendix C.

4.3.5.1 Air Pressure Hold Test Results

At time zero, during testing of the intact membrane the air pressure was 4.00 psi (0.276 b). After three minutes the air pressure was 3.97 psi (0.274 b). This demonstrated that the membrane was intact. (According to the manufacturer, an intact membrane would be expected to lose no more than 1 psi every two minutes).

Air pressure loss was also compared to the loss that was obtained when testing a compromised membrane. The membrane was intentionally compromised by severing a fiber.

At time zero the air pressure was 4.00 psi (0.276 b). After two minutes the air pressure was 2.00 psi (0.138 b). This demonstrated that the membrane was compromised.

4.3.5.2 Turbidity Reduction Monitoring

Turbidity of feed water and filtrate 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 0.09 NTU) showing a 90% reduction, 0.009 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 8 hours before the membrane was compromised averaged 0.022 NTU. The turbidity of the filtrate in the two hours after the membrane was compromised was 0.027 NTU.

Turbidity reduction monitoring between feed water and filtrate 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 feed water to filtrate of 99.9% would demonstrate an intact membrane. The average cumulative feed water particle counts were 64 total counts per ml, showing a 99.9% reduction was beyond 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.

Due to a problem with the data logging program used on the treatment system, the inline filtrate particle count data were not accurately recorded during the hour the system was run with the broken fiber. This failure does not allow for evaluation of particle counting as a method for detecting a compromised membrane.

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 log₁₀ removal of *Giardia* cysts and a 2 log₁₀ removal of *Cryptosporidium* oocysts from the feed water. The *Giardia* and *Cryptosporidium* challenge took place on March 2, 1999. The system operated at a manufacturer-recommended flux of 110 gfd at 68°F (190 l/m²/h at 20°C) and an average specific flux of 12 gfd/psi (300 l/m²/h/b at 20°C) during the *Giardia* and *Cryptosporidium* removal challenge testing. The results of the testing are summarized in the laboratory report enclosed in Appendix H.

4.3.6.1 Feed Water Concentrations

During the *Giardia* and *Cryptosporidium* removal challenge testing the feed water had a pH of 7.8, a turbidity of 0.12 NTU, and a temperature of 3.6°C.

Three replicate hemocytometer counts were performed on the stock solutions. The average of these replicate counts were then used to calculate stock concentrations. The average stock solutions contained 1.15 x 10⁶ and 1.32 x 10⁷ (oo)cysts per milliliter for *Giardia* and *Cryptosporidium*, respectively.

Fifty gallons of feed water were then spiked with 7.5 mls and 8.3 mls of the *Giardia* and *Cryptosporidium* stock suspensions, respectively. As presented in Table 4-13, a total of 8,625,000 *Giardia* cysts and 109,643,000 *Cryptosporidium* oocysts were added to the 50 gallons of feed water. This resulted in a theoretical concentration of 276,000 *Giardia* cysts and 2,192,860 *Cryptosporidium* oocysts per gallon of feed water. The spiked feed water containing the cysts and oocysts was constantly mixed using a drum mixer. A diaphragm pump was used to add the spiked feed water to the treatment unit. The pump was operated at about 0.85 8pm (3.2 liter per minute). The stock solution from the feed water reservoir was fed to the system for approximately 60 minutes.

As a QC check, five two-ml aliquots were taken from the spiked feed water reservoir at five to ten minute intervals. A composite of these five aliquots was prepared. A microscopic examination of this composite showed concentrations of 48 and 560 (oo)cysts per milliliter for *Giardia* and *Cryptosporidium*, respectively, in the 50 gallons of spiked feed water. Therefore, multiplying these results by the total volume (50 gallons or 190,000 mls), 9,126,000 *Giardia* cysts and 106,400,000 *Cryptosporidium* oocysts had been added to the feed water reservoir (see Table 4-14). These results are 5.8% greater and 3.0% less, respectively than the results based on the hemocytometer counts of the stock solutions and milliliters of stock added.

To assess log removals, the hemocytometer counts presented in Table 4-13 were used rather than the results in Table 4-14. This is because the concentrations of the stock solution were determined per EPA protocols and also due to the uncertain nature of sampling and mixing of the spiked feed water solution, which could render the composite sample results questionable. Bench data sheets and report from the laboratory are enclosed in Appendix H.

Table 4-13. *Giardia* and *Cryptosporidium* Stock Suspension Results by Hemocytometer Counts

	<i>Giardia</i> Cysts	<i>Cryptosporidium</i> Oocysts
Average count (oocysts or cysts/0.0001 ml)	115	1,321
Standard Deviation	11	26
95% Confidence Interval	(105, 126)	(1,295, 1,346)
Total cysts and oocysts added to feed water reservoir (7.5 mls of <i>Giardia</i> stock suspension, 8.3 mls <i>Cryptosporidium</i>)	8,625,000	109,643,000
Feed Water Amount Confidence Interval	(7,877,974; 9,422,026)	(107,543,144; 111,527,523)

Table 4-14. Feed Water Reservoir Concentrations of *Giardia* and *Cryptosporidium* by Microscopic Examination

	<i>Giardia</i> Cysts	<i>Cryptosporidium</i> Oocysts
Presumptive count (oocysts or cysts/ml)	48	560
Total cysts and oocysts added to feed water reservoir	9,126,000	106,400,000

4.3.6.2 Filtrate Concentrations

The filtrate was sampled as described in the EPA’s ICR Method for detecting *Giardia* Cysts and *Cryptosporidium* Oocysts (EPA, 1996). No *Giardia* cysts or *Cryptosporidium* oocysts were identified in the filtrate as shown by the absence of cysts and oocysts on the 1 µm nominal porosity, yarn-wound capture filter.

The log₁₀ removal of *Giardia* cysts and *Cryptosporidium* oocysts was calculated as follows.

1. The amount of filtrate sampled was divided by the total amount of filtrate filtered by the system. In this case, one gallon per minute was filtered through the sampling filter compared to ten gallons per minute of filtrate produced by the treatment system, with a result of 0.1.
2. 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. In this case 0.1 times the results presented in Table 4-13.
3. This result of Step 2 above was then converted to its log₁₀ equivalent.
4. The percent recovery of the ICR test method at the PWSA laboratory is 25%; this means that the lowest number of cysts or oocysts that could be detected is four. That is, if four cysts or oocysts were in the filtrate, one of them would be detected. This number, four, was also converted to its log₁₀ equivalent.
5. The final log removal calculation was made by subtracting the log₁₀ of the number four from the log₁₀ number of cysts added to the sampling filter (Step 3 above). Table 4-15

presents the concentrations and the log₁₀ removal calculations of the *Giardia* cysts and *Cryptosporidium* oocysts.

Based on this procedure for calculating log removals, these results demonstrated a 5.3 log₁₀ removal of *Giardia* cysts and a 6.4 log₁₀ removal of *Cryptosporidium* oocysts.

During the *Giardia* and *Cryptosporidium* removal challenge testing, the filtrate had a turbidity of 0.028 NTU and an average cumulative particle counts of 0.31 counts/ml.

Table 4-15. *Giardia* and *Cryptosporidium* Challenge Log₁₀ Removal Calculation

	<i>Giardia</i> Cyst Removal	<i>Cryptosporidium</i> Oocyst Removal
Cysts/oocysts in Feed Reservoir (from Table 4-13)	8,625,000	109,643,000
Cysts/oocysts added to capture Filter (The total number of cysts/oocysts in Feed Reservoir multiplied by 10% because the system was pumping at 10 gpm and sampled at 1gpm. Effectively, only 10% of the total cysts/oocysts added could have been detected on the capture filter.)	862,500	10,964,300
Log ₁₀ of cysts/oocysts added to capture filter	5.9	7.0
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)	5.3	6.4

4.3.6.3 Bleed Wastewater 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 backpulsing procedure was capable of removing the protozoans from the membrane system. Five hundred ml of the bleed wastewater were 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 4-16 and 4-17. 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 4-18, 4-19, and 4-20. Samples of bleed wastewater before and after the challenge were collected and analyzed. Results of these analyses are presented in Table 4-21.

Table 4-16. Transmembrane Pressure Readings During Microbial Removal Testing

Date	Time	Transmembrane Pressure (psi)
3/2/99	11:40	7.4
3/2/99	13:00	7.0

Table 4-17. Specific Flux During Microbial Removal Testing

Date	Time	Specific Flux (gfd/psi @20°C)
3/2/99	11:40	19
3/2/99	13:00	12

Table 4-18. Turbidity Analyses Results and Removal During Microbial Removal Testing

Date	Time	Feed		Filtrate	Amount Removed (NTU)
		Turbidity (NTU)	Turbidity (duplicate) (NTU)	Turbidity (NTU)	
3/2/99	11:20	0.12	0.13	0.030	0.093
3/2/99	13:15	0.11	N/A	N/A	N/A

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

Table 4-19. Feed Water Particle Counts 3/2/99

	Size						Cumulative
	2-3 μm	3-5 μm	5-7 μm	7-10 μm	10-15 μm	>15 μm	
Average	6.5	43	6.5	5.8	1.5	0.67	64
Minimum	0	0	0	0	0	0	N/A
Maximum	8.7	54	8.7	7.3	2.1	3.6	N/A
Std Dev	0.83	4.9	0.83	0.78	0.27	0.41	N/A
95% Confid Int	(4.9, 8.2)	(34, 53)	(4.9, 8.2)	(4.3, 7.4)	(0.99, 2.1)	(0, 1.5)	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 15 μm readings were 16% lower than actual. Due to extremely low results in the 5 μm and 10 μm size range, the reliability of the 2-3 μm , 3-5 μm , 5-7 μm and 7-10 μm particle counts should be considered questionable. See instrument QA/QC verification results in Section 4.5.3.
 Feed particle counts sampled prior to injection of challenge feed solution.

Table 4-20. Filtrate Particle Counts 3/2/99

	Size						Cumulative
	2-3 μm	3-5 μm	5-7 μm	7-10 μm	10-15 μm	>15 μm	
Average	0.14	0.03	0.03	0.03	0.02	0.07	0.31
Minimum	0.03	0	0	0	0	0	N/A
Maximum	0.30	0.13	0.10	0.13	0.10	0.63	N/A
Std Dev	0.06	0.03	0.03	0.03	0.02	0.09	N/A
95% Confid Int	(0.022, 0.26)	(0, 0.087)	(0, 0.081)	(0, 0.087)	(0, 0.063)	(0, 0.25)	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 15 μm readings were 18% lower than actual. Due to extremely low results in the 5 μm and 10 μm size range, the reliability of the 2-3 μm , 3-5 μm , 5-7 μm and 7-10 μm particle counts should be considered questionable. See instrument QA/QC verification results in Section 4.5.3.

Table 4-21. Daily Bleed Wastewater Testing Results During Microbial Removal Testing

Date	Time	Turbidity	Turbidity (dup)	Chlorine Residual	Chlorine Residual (dup)
		(NTU)	(NTU)	(mg/l)	(mg/l)
3/2/99	11:15	1.17	1.19	0.70	0.67
3/2/99	13:10	1.08			

Testing of the feed, filtrate, and bleed wastewater 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 filtrate. The membranes appeared to successfully remove all of the *Giardia* cysts and *Cryptosporidium* oocysts introduced into the treatment system. Since the 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 5.3 log₁₀ removal of *Giardia* cysts and 6.4 log₁₀ 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 log₁₀ removal of *Giardia* cysts and 2 log₁₀ removal of *Cryptosporidium* oocysts as stated in Section 3.1.1.2.

The log₁₀ removals were controlled by the amount of the parasites which were present in the stock feed solution, the percentage of the filtrate that could be sampled and the percent recovery of the analytical methodology. Higher feed concentrations, percentage of filtrate examined and percent recovery of the analytical methods may yield higher log₁₀ 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 the pumping station and was not exposed to the elements, opportunities for environmental upsets were limited.

4.4.1.2 Operational Reliability

During the verification test, the unit operated in the automatic mode. Manual operation was required for chemical cleaning of the system. A representative of the manufacturer visited the site daily to visually inspect the system, record operating parameters, and enter the operational data into a personal computer (PC). This data was transmitted to the manufacturer who would review the data and make any operational changes that were necessary. No significant operational changes were necessary throughout the verification testing.

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. The electrical service was connected according to local code requirements and did not represent an unusual safety risk.

The calcium hypochlorite used for membrane backpulsing 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 stock chemicals from which the cleaning chemicals are mixed, citric acid and sodium hypochlorite, are hazardous chemicals. The use of appropriate PPE minimizes the risk of exposure to the stock chemicals while the dilution is being made. The prompt and proper clean up of spills minimizes the hazards associated with these chemicals.

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 ZeeWeed® ZW-500 system operating at 94 gfd at 68°F (170 l/m²/h at 20°C). Costs will vary if the system is operated at different flux rates.

4.4.2.1 Power Supply Requirements

The treatment unit's electrical requirements were 230 V, 60 Hertz, 60 Amps, single phase current. Daily power consumption was determined by reading a dedicated electric meter. The electric meter was installed by a certified electrician according to the local electric code.

The unit used an average of 77 kilowatt hours (kwh) per day. The highest recorded daily usage was 98 kwh; the minimum daily usage was 59 kwh. The differences in these readings can most likely be explained by the differences in elapsed time between the daily readings. The electric meter readings were taken daily but not necessarily exactly 24 hours after the previous readings. The 59 kwh consumption was calculated from readings which were taken 22 hours apart. The 98 kwh consumption was calculated from readings taken 28 hours apart. There was also some extrapolation of the meter readings done. If the arm of the last dial was between two numbers the lower number was recorded.

4.4.2.2 Consumable Requirements

Consumable commodities included calcium hypochlorite and the cleaning chemicals, citric acid and sodium hypochlorite. Calcium hypochlorite was added to the filtrate used for backpulsing. The total chlorine residual in the backpulse waste was 0.72 mg/l. This level of chlorine residual required approximately 1 lb. calcium hypochlorite per month. The chemical cleaning episode requires one gallon of sodium hypochlorite and about one lb (455 g) citric acid. Each of these chemicals is added to approximately 185 gallons of clean water in the process tank.

4.4.2.3 Waste Disposal

The wastes generated by the treatment system were bleed wastewater 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 666 gpd of bleed wastewater during verification testing.

The chlorine cleaning waste had a pH of 8.9, a turbidity of 0.99 NTU, and a TDS of 622 mg/l. The total chlorine residual of the chlorine cleaning waste was 121 mg/l. The chlorine cleaning waste was clear in appearance. The characterization of the citric acid cleaning waste indicated that the solution was acidic, with a pH of 2.7. The citric acid cleaning waste had a turbidity of 1.52 NTU and a TDS of 1020 mg/l. The citric acid cleaning waste was clear in appearance.

The bleed wastewater was feed water, filtrate, 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 bleed waste was 0.43 mg/l. The range of TSS concentration was from 0.20 mg/l to 0.80 mg/l. The chlorine residual in the bleed wastewater averaged 0.72 mg/l and ranged from 0.53 mg/l to 0.99 mg/l. A complete presentation of the bleed wastewater data is included in Appendix C.

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

4.4.2.4 Length of Operating Cycle

The operating cycle to be considered was the interval between chemical cleanings. The length of this operating cycle is site-specific and determined by the manufacturer after evaluation of the feed water quality. The cycle lengths are easily field adjustable if necessary; no adjustments were required for this verification.

The interval between chemical cleaning is estimated to be 30 days for the Pittsburgh test site. For the Pittsburgh test site, ZENON recommended that cleaning be done when the air agitation and backpulsing were unable to maintain system TMP <12 psi. The manufacturer estimates that interval between chemical cleanings would be four weeks when the feed water temperature is less than 10° C and may be extended to eight week periods when the feed water temperature is greater than or equal to 10°C.

4.5 QA/QC Results

The daily, bi-weekly, initial, on-site, 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 feed water turbidimeter flow rate averaged 452 ml/minute. The flow rate was measured using a graduated cylinder and stop watch. The maximum rate measured, during the testing was in excess of 1000 ml/minute; the minimum was 0 ml/minute. These flows were immediately adjusted to return them to the acceptable flow range. The acceptable range of flows as specified by the manufacturer is 250 ml/minute to 750 ml/minute. The flow rate required adjustment on six of the 30 days of testing.

The readout from the inline feed water turbidimeter averaged 0.060 NTU; the average from the benchtop turbidimeter was 0.09 NTU. The discrepancy between these two results can be explained by differences in the analytical techniques between the inline and benchtop turbidimeter and the low level of turbidity in the feed water. 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 feed water also can create analytical difficulties, particularly for the benchtop turbidimeter. 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 inline filtrate turbidimeter flow rate averaged 477 ml/minute. The flow rate was measured using a graduated cylinder and stop watch. The maximum rate measured during the testing was 850 ml/minute; the minimum was 0 ml/minute. The acceptable range of flows as specified by

the manufacturer is 250 ml/minute to 750 ml/minute. The flow rate required adjustment on three of the 30 days of testing.

The readout from the inline filtrate turbidimeter averaged 0.027 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 inline and benchtop turbidimeter and the low level of turbidity in the filtrate. 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 filtrate also can create analytical difficulties, particularly for the benchtop turbidimeter. 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 feed water particle counter flow rate averaged 97 ml/minute. The flow rate was measured using a graduated cylinder and stop watch. The maximum flow rate measured was 101 ml/minute; the minimum was 85 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 four times during the verification study.

The filtrate particle counter flow rate averaged 95.4 ml/minute. The flow rate was measured using a graduated cylinder and stop watch. The maximum flow rate measured was 100 ml/minute; the minimum was 88 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 five 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 water and filtrate.

The flow meter read out was verified during the testing. The acceptable range of accuracy for the feed and filtrate meters was +/- 10%. The filtrate water meter readout averaged 3.4% higher than actual according to the results obtained during the flow verification. The feed water meter readout averaged 4.5% higher than actual according to the results obtained during the flow verification. The treatment system did not have a backpulse meter.

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 filtrate pressure/vacuum gauge was checked prior to the start of testing. This was the only pressure gauge on the treatment unit. Dead weights of 5, 10, and 15 pounds were used. The filtrate pressure gauge averaged 5.1 psi, 9.9 psi, 15.0 psi 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 834 counts/ml; the 10 μm size showed an average response of 834 counts/ml; the 15 μm size showed an average response of 1684 counts/ml. This corresponds to a difference of 58%, 58%, and 16% 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 percent difference for the 15 μm standard used was 16%. The readings for 15 μm feed water particle counts obtained during the verification testing should be increased by 16% to account for the low response of the 15 μm size range of the feed water particle counter. Due to extremely low results in the 5 μm and 10 μm size range the reliability of the 2-3 μm , 3-5 μm , 5-7 μm and 7-10 μm particle counts should be considered questionable.

The filtrate particle counter showed an average response for the 5 μm size of 899 counts/ml; the 10 μm size showed an average response of 1061 counts/ml; the 15 μm size showed an average response of 1,636 counts/ml. This corresponds to a difference of 55%, 47%, and 18% 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. 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 percent difference for the 15 μm standard used was 18%. The readings for 15 μm feed water particle counts obtained during the verification testing should

be increased by 18% to account for the low response of the 15 μm size range of the filtrate particle counter. Due to extremely low results in the 5 μm and 10 μm size range the reliability of the 2-3 μm , 3-5 μm , 5-7 μm and 7-10 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 On-Site Analytical QA Results

QA procedures for pH, temperature, residual chlorine, and turbidity included daily calibration, duplicate analysis, and performance evaluation. Results for the above procedures for each of the parameters are discussed in the following sections.

4.5.4.1 pH

QA results for pH analyses included a daily calibration, duplicate analysis, and performance evaluation sample analysis. 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. The acceptable range for the instrument linearity was 95 –105%. All daily calibrations yielded an acceptable linearity result. Acceptable duplicate results were +/- 0.1 pH unit. All duplicate analyses were acceptable. Results obtained from the analysis of the performance evaluation sample were compared to the certified value reported by the sample manufacturer. The pH obtained from the field analysis was 6.02. The certified pH value of the sample was 6.00 with an acceptable range of 5.80 to 6.20. Appendix C contains the results from the duplicate pH analyses.

4.5.4.2 Temperature

QA results for temperature analysis consisted of daily duplicate analysis. The acceptable range of the duplicate results was +/- 0.1°C. All duplicate analyses were acceptable. Appendix C contains the results from the duplicate temperature analyses.

4.5.4.3 Residual Chlorine

QA results for residual chlorine analyses consisted of duplicate analysis and performance evaluation sample analysis. The acceptable range for duplicate analyses was +/- 0.1 mg/l. All duplicate analyses were acceptable. Results obtained from the analysis of the performance evaluation sample were compared to the certified value reported by the sample manufacturer. The residual chlorine obtained from the field analysis was 2.02 mg/l. The certified value of the sample was 2.15 mg/l with an acceptable range of 1.61 to 2.27 mg/l. Appendix C contains the results from the duplicate chlorine analyses.

4.5.4.4 Turbidity

QA results for the turbidity analyses consisted of a weekly calibration, daily calibration check, duplicate analysis, and performance evaluation sample analysis. The weekly calibration was conducted according to manufacturer's recommendations and the results checked against third party primary calibration standards. After the weekly calibration, secondary standards were analyzed and the results were used to assign an acceptable range to the secondary standards. The secondary standards were utilized for the daily calibration check. The results of the analysis of the secondary standards were compared to the acceptable range established during the weekly calibration. If the results were outside of the acceptable range the instrument was recalibrated. All weekly calibrations and daily calibration checks were acceptable. Duplicate analyses were conducted daily on the feed water and the bleed water. The acceptable range for duplicate analyses was +/- 10%. All duplicate analyses were acceptable. Results obtained from the analysis of the performance evaluation sample were compared to the certified value reported by the sample manufacturer. The turbidity obtained from the field analysis was 2.04 NTU. The certified value of the sample was 1.76 NTU with an acceptable range of 1.50 to 2.06 NTU. Appendix C contains the results from the duplicate turbidity analyses.

4.5.5 Analytical Laboratory QA/QC

Samples for analyses conducted on feed and filtrate are listed in Table 3-1. QA/QC procedures are based on Standard Methods, 18th 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 filtrate is recorded and kept on file at the PWSA's 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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