February 2000
NSF 00/09/EPADW395

Environmental Technology Verification Report

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

Pall Corporation
WPM-1 Microfiltration Pilot System
Pittsburgh, PA

Prepared by

NSF International

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

ETV ETV ETV

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**MEMBRANE FILTRATION USED IN PACKAGED DRINKING WATER TREATMENT SYSTEMS**		
APPLICATION:	***GIARDIA* AND *CRYPTOSPORIDIUM* REMOVAL**		
TECHNOLOGY NAME:	**WPM-1 MICROFILTRATION SYSTEM**		
TEST LOCATION:	**PITTSBURGH, PA**		
COMPANY:	**PALL CORPORATION**		
ADDRESS:	**2200 NORTHERN BLVD** **EAST HILLS, NY 11548**	PHONE: FAX:	**(516) 484-5400** **(516) 484-3216**
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International (NSF) in cooperation with the EPA operates the Package Drinking Water Treatment Systems (PDWTS) program, one of 12 technology areas under ETV. The PDWTS program recently evaluated the performance of a membrane filtration system used in package drinking water treatment system applications. This verification statement provides a summary of the test results for the Pall Corporation WPM-1 Microfiltration System. Gannett Fleming, Inc., an NSF-qualified field testing organization (FTO), performed the verification testing.

ABSTRACT

Verification testing of the Pall Corporation WPM-1 Microfiltration Pilot System was conducted from February 3 to March 5, 1999. The treatment system underwent microbial challenge testing on February 5, 1999, and demonstrated a 5.8 $\log_{10}$ removal of *Giardia* cysts and a 6.8 $\log_{10}$ removal of *Cryptosporidium* oocysts. Source water characteristics were: turbidity average 0.10 Nephlometric Turbidity Units (NTU), pH 7.7, and temperature 3.6°C. During the thirty-day verification test, the system was operated at a flux recommended by the manufacturer of 77 gallons per square foot per day (gfd) at 3.8°C which equates to 120 gfd at 20 °C. The average transmembrane pressure was 24 pounds per square inch (psi). The feed water recovery of the treatment system during the study was 96%. Chemical cleaning of the treatment system was conducted as part of the verification testing.

TECHNOLOGY DESCRIPTION

Microfiltration (MF) processes are generally used to remove microbial contaminants such as *Giardia* and *Cryptosporidium* and other particulate contaminants from drinking water. The Pall WPM-1 membrane is a hollow fiber type microfiltration membrane made of polyvinylidenefluoride (PVDF). It has a 0.1 micrometer (µm) nominal pore size and utilizes outside-in flow. Water is applied under pressure to the outside of the hollow fiber membrane. The membrane consists of a thin film acting as a sieve. The membrane is a mechanical barrier, providing removal of particulate contaminants. Permeate (filtered water) is collected from the inside of the fiber and carried to the permeate outlet.

The Pall Corporation WPM-1 MF Pilot System is a skid mounted, stand alone system. The only required connections are for the water supply, electrical service, and a sewer connection for the discharge of backwash and chemical cleaning wastes. The treatment system consists of one membrane module, supply pump, backwash reservoir and pump, chemical cleaning equipment and necessary gauges and controls. The unit is equipped with a 400 µm bag type prefilter to remove large debris from the feed water prior to introduction to the membranes. The treatment system is capable of operating in an automatic mode with limited operator intervention.

For this test program, an Excess Recirculation (XR) flow configuration was used. XR flow utilizes water, which flows tangentially across the upstream side of the filter membrane. To maintain stable flow over the short term, a backwash cycle called a Reverse Filtration (RF) cycle was performed. At a preset time determined by raw water quality, the treatment system was backwashed. This was accomplished by reversing the flow direction; forcing the permeate back through the fibers from inside to outside. (The permeate was chlorinated using a small diaphragm pump which added sodium hypochlorite to the permeate prior to backwash.) Every other backwash included an air scrub (AS) to agitate the surface of the membrane and improve the removal of the particulate material.

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 (UVA_{254}), total coliform, and heterotrophic plate counts (HPC). Total alkalinity, total hardness and TDS analyses were conducted monthly. All other laboratory parameters were analyzed weekly.

Microbial challenge was performed using *Giardia* cysts and *Cryptosporidium* oocysts. Procedures developed by EPA for use during the Information Collection Rule (ICR) were employed for the identification and enumeration of *Giardia* cysts and *Cryptosporidium* oocysts (EPA, ICR Microbial Laboratory Manual, EPA, April 1996). The protozoans were added to a fifty (50) gallon (190 liter) drum. This drum was filled with the feed water. A total of 10,768,000 *Giardia* cysts and 104,548,000 *Cryptosporidium* oocysts were added to the feed water reservoir. The turbidity of the feed water was 0.10 NTU during the microbial removal challenge testing. This stock suspension was constantly mixed using a drum mixer. A diaphragm pump was used to add the protozoans to the membranes on the pilot unit. The pump was operated at about 0.85 gallons per minute (gpm) (3.2 liter per minute) and was capable of overcoming the pressure in the feed water line of the pilot unit. Samples of the permeate were collected using a polypropylene wound filter with a nominal pore size of 1.0 µm. One thousand liters (264 gallons) of permeate water was filtered through the sampling vessel at one gpm (3.8 liter per minute). In addition, aliquots of the stock suspension were collected and analyzed to calculate concentrations of the microbes in the feed water. Backwash was delayed until the end of the collection period. Samples of the backwash were collected and analyzed to verify that the parasites were added to the system and removed by the filters.

VERIFICATION OF PERFORMANCE

System Operation

The treatment system was fully automated and capable of normal operations without manual intervention. The unit automatically operates in the filtration and backwash modes. All operational data, flows, pressures, turbidity, and particle counts are recorded on data logging software. Manual intervention is required for chemical cleaning and to occasionally refill the tank of sodium hypochlorite used during backwash.

The system was operated at a flux recommended by the manufacturer of 77 gfd at 3.8°C (120 gfd 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 4.0 gpm (15 liter per minute) and ranged from 3.9 to 4.0 gpm (15 liter per minute).

The average feed pressure was 30 psi (2.1 bar [b]). The average retentate pressure was 28 psi (1.9 b). The filtrate pressure was recorded twice per day. The average filtrate pressure was 5.1 psi (0.35 b). The amount of pressure lost as the water is filtered through the membrane is referred to as transmembrane pressure (TMP). It is calculated by averaging the feed water pressure and the retentate pressure and subtracting the filtrate pressure from that average. The average TMP for the system was 24 psi (1.6 b). For this test program, a RF interval of once every 30 minutes was used. Every other RF cycle, i.e. once every hour, utilized an AS cycle. The unit used approximately 3.0 gallons of permeate to backwash the membranes during a RF cycle. AS followed by RF required 6.2 gallons of permeate.

The percent water recovery of the treatment system during the study was 96%. This figure was calculated by comparing the amount of water needed to backwash the membranes to the total amount of water filtered by the system.

The effectiveness of the chemical cleaning process was measured by the recovery of specific flux and loss of original specific flux. Chemical cleaning was conducted at the end of the test period as required by the ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contamination (EPA/NSF April, 1998). Data collected before and after the chemical cleaning was used to calculate recovery of specific flux and the loss of original specific flux. The chemical cleaning recovered 73% of the specific flux. Data from when the membranes were placed into service and just after cleaning was used to calculate the loss of original specific flux. The loss of original specific flux was 9.0%.

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

Water Quality Results

During the microbial challenge testing that occurred on February 5, 1999, the Pall WPM-1 MF system demonstrated a 5.8 $\log_{10}$ removal of *Giardia* cysts and a 6.8 $\log_{10}$ removal of *Cryptosporidium* oocysts. The $\log_{10}$ removals were limited by the amount of the parasites which were present in the stock feed solution, the percentage of the permeate that could be sampled, and the percent recovery of the analytical methodology. There were no *Giardia* cysts or *Cryptosporidium* oocysts observed in the permeate. During the microbial challenge testing, the feed water characteristics were: turbidity average 0.10 NTU, pH 7.7, temperature 3.6 ^{o}C.

During the thirty-day ETV operation of the Pall WPM-1 system, treatment reductions were seen in HPC, algae, turbidity, and particle counts. HPC concentrations averaged 11 colony forming units (cfu)/100ml in the feed water and 4 cfu/100ml in the permeate. The presence of HPC in the permeate may have been due to inadequate disinfection of the Tygon tubing used for water sampling and to the lid design of the RF tank which permitted some environmental contaminants to intrude into the permeate side of the system. Pall reports that the RF tank has been redesigned with a protective lid. Algae concentrations averaged 19 cells/ml in the feed water and <8 cells/ml in the permeate. The turbidity concentration in the feed water was 0.088 NTU and 0.026 NTU in the permeate. The Pall WPM-1 reduced feed water particle counts from an average 120 total counts per ml to an average of 0.54 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 permeate throughout the test. The following table presents the water quality reductions of the feed water and filtered water samples collected during the 30 days of operation:

Feed Water Quality / Filtered Water Quality
Pall Corporation WPM-1 Microfiltration System

	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)	Algae (cells/ml)	Turbidity (NTU)	Particle Counts (particles/ml)
Average[1]	0/0	11/4	19/<8	0.088/0.026	120/0.54
Minimum[1]	0/0	2/0	8/<8	0.060/0.024	----
Maximum[1]	0/0	22/12	32/<8	0.14/0.032	----
Standard Deviation [1]	0/0	10/5	9.1/0	0.018/0.0013	----
95% Confidence Interval[1]	N/A/ N/A	(2, 19)/ (0, 8)	(11, 27)/ N/A	(0.083, 0.092)/ (0.026, 0.026)	----

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

Temperature of the feed water during the thirty-day ETV study was fairly stable with a high of 4.5°C, a low of 3.4°C, and an average of 3.8°C. The membrane pilot unit had little or no effect on total alkalinity, total hardness, TOC, TDS, and UVA_{254}.

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 Pall Corporation 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.

Original Signed by
E. Timothy Oppelt 3/6/00

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

Original Signed by
Tom Bruursema 3/6/00

Tom Bruursema
General Manager
Environmental and Research Services
NSF International

Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants* dated April 20, 1998 and revised May 14, 1999, the Verification Statement, and the Verification Report (NSF Report #00/09/EPADW395) are available from the following sources:
(NOTE: Appendices are not included in the Verification Report. Appendices are available from NSF upon request.)

Drinking Water Systems ETV Pilot Manager (order hard copy)
NSF International
P.O. Box 130140
Ann Arbor, Michigan 48113-0140

NSF web site: http://www.nsf.org/etv (electronic copy)

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

February 2000

Environmental Technology Verification Report

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

Pall Corporation WPM-1 Microfiltration Pilot System Pittsburgh, PA

Prepared for:

NSF International
Ann Arbor, Michigan 48105

Prepared by:

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

Jeffrey Q. Adams, Project Officer
National Risk Management Research Laboratory
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Notice

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

Foreword

The following is the final report on an Environmental Technology Verification (ETV) test performed for the NSF International (NSF) and the United States Environmental Protection Agency (EPA) by Gannett Fleming, Inc., in cooperation with Pall Corporation. 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 Environmental Technology Verification Program (ETV) has been instituted to verify the performance of innovative technical solutions to environmental pollution or human health threats. ETV was created to substantially accelerate the entrance of new environmental technologies into the domestic and international marketplace. Verifiable, high quality data on the performance of new technologies is made available to regulators, developers, consulting engineers, and those in the public health and environmental protection industries. This encourages more rapid availability of approaches to better protect the environment.

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

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

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Abbreviations and Acronyms

ac	acres
AS	Air Scrub
AWWA	American Water Works Association
b	bar
$CaCO_3$	Calcium Carbonate
CCP	Composite Correction Program
cfu	colony forming unit
CIP	clean in place
Cl_2	chlorine
^oC	degrees Celsius
DI	deionized
DOC	Dissolved Organic Carbon
EPA	U.S. Environmental Protection Agency
ESWTR	Enhanced Surface Water Treatment Rule
ETV	Environmental Technology Verification
^oF	degrees Fahrenheit
FOD	Field Operations Document
ft	feet
ft^2	feet squared
FTO	Field Testing Organization
gfd	gallon per square foot per day
gpm	gallon per minute
hp	horse power
HPC	Heterotrophic Plate Count
hr	hour
ICR	Information Collection Rule
in	inch
kD	Kilo Daltons
L	liters
lbs	pounds
$l/m^2/h$	liter per square meter per hour
$l/m^2/h/b$	liter per square meter per hour per bar
lpm	liter per minute
m	meter
MF	Microfiltration
MG	million gallon
MGD	million gallon per day
mg/L	milligram per liter
ml	milliliters
mm	millimeters
MSDS	Material Safety Data Sheets
N/A	Not Applicable
NIST	National Institute of Standards and Technology

NSF	NSF International (formerly known as National Sanitation Foundation)
nm	nanometers
NTU	Nephlometric Turbidity Units
od	outside diameter
O&M	Operations and Maintenance
PADEP	Pennsylvania Department of Environmental Protection
PC	personal computer
PPE	Personal Protective Equipment
ppm	parts per million
psi	pounds per square inch
psid	pounds per square inch differential
PDWTS	Packaged Drinking Water Treatment System
PVC	Polyvinylchloride
PVDF	Polyvinylidenefluoride
PWSA	Pittsburgh Water and Sewer Authority
QA/QC	Quality Assurance/Quality Control
RF	Reverse Flow
scfm	standard cubic feet per minute
SDI	Silt Density Index
SDWA	Safe Drinking Water Act
SST	stainless steel
SWTR	Surface Water Treatment Rule
TDS	Total Dissolved Solids
TMP	Transmembrane Pressure
TOC	Total Organic Carbon
TSS	Total Suspended Solids
µm	micrometers
UVA_{254}	Ultraviolet Absorbance at 254nm
XR	Excess Recirculation

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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Phone: 717-763-7211
Contact Person: Mr. Gene Koontz

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

Pittsburgh Water and Sewer Authority
900 Freeport Road
Pittsburgh, PA 15238
Phone: 412-782-7552
Contact Person: Mr. Stanley States, Ph.D., Director of Analytical Services

The Manufacturer of the Equipment was:

Pall Corporation
2200 Northern Boulevard
East Hills, NY 11548
Phone: (516) 484-5400
Contact Person: Michelle Frisch, Senior Sales Engineer

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

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

Michelle Frisch, Senior Sales Engineer, Lou Mattera, Senior Project Engineer, Jim Moy, Field Engineer, and Jen Hays, Senior Test Engineer Pall Corporation are to be commended for providing the treatment system and excellent technical and product expertise. John and Brian Regan, President and Vice president for Biltmore Products Company provided assistance during the pilot setup and tear down as well as assistance during the pilot operation.

Chapter 1
Introduction

1.1 ETV Purpose and Program Operation

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International (NSF) in cooperation with the EPA operates the Package Drinking Water Treatment Systems (PDWTS) program, one of 12 technology areas under ETV. The PDWTS program evaluated the performance the Pall Corporation WPM-1 Microfiltration (MF) Pilot System, which is a membrane filtration system used in package drinking water treatment system applications. The performance claim evaluated during field testing of the Pall WPM-1 MF System was that the system is capable of a minimum 3 $\log_{10}$ removal of *Giardia* cysts and 2 $\log_{10}$ removal of *Cryptosporidium* oocysts. This document provides the verification test results for the Pall WPM-1 MF System.

1.2 Testing Participants and Responsibilities

The ETV testing of the Pall WPM-1 MF System was a cooperative effort between the following participants:

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

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

1.2.1 NSF International

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

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

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1.2.2 Gannett Fleming, Inc.

Gannett Fleming, Inc., a consulting engineering firm, conducted the verification testing of the Pall WPM-1 MF System. Gannett Fleming is a NSF-qualified Field Testing Organization (FTO) for the Packaged Drinking Water Treatment System ETV pilot project.

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

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

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Contact: Gene Koontz, Project Director
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1.2.3 Manufacturer

The treatment system is manufactured by Pall Corporation, a manufacturer of membrane and microporous, non-woven filtration and separation products to municipal and industrial water users. Based in East Hills, New York, Pall Corporation has manufacturing facilities located in the United States, Puerto Rico, England, Ireland, Germany, Holland, Japan, China, and India.

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

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

Contact Information:
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Phone: (516) 484-5400
Contact Person: Michelle Frisch, Senior Sales Engineer
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1.2.4 Host and Analytical Laboratory

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

PWSA's laboratory provided collection and analytical services for Total Alkalinity, Total Hardness, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Total Coliforms, Heterotrophic Plate Count (HPC), Total Organic Carbon (TOC), Ultraviolet Absorbance at 254 nanometers (UVA_{254}), and Algae. In addition, PWSA supplied operational support and analytical services for the microbial removal testing. PWSA's laboratory is certified by the Pennsylvania Department of Environmental Protection (PADEP) for analysis of Microbiological,

Inorganic, and Organic compounds in water. Additionally, the laboratory has received Protozoa Laboratory Approval from the EPA under the Information Collection Rule (ICR) Program. Copies of the Laboratory Approval Statements are attached in Appendix A.

Contact Information:

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Pittsburgh, PA 15238
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Fax: 412-782-7564
Contact: Stanley States, Ph.D. Director of Analytical Services

1.2.5 U.S. Environmental Protection Agency

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

1.3 Verification Testing Site

The verification testing site was at the PWSA's Highland Reservoir No. 1. The physical location of the treatment unit was the New Highland Pumping Station at the corner of North Negley Avenue and Mellon Terrace in the Highland Park section of the City of Pittsburgh, Pennsylvania. The treatment unit was 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 Pall WPM-1 MF 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 verification testing was limited to the performance of the equipment to remove *Cryptosporidium* oocysts and *Giardia* cysts, because the source water was obtained from an open reservoir. The performance was evaluated during challenge seeding studies of *Cryptosporidium* oocysts and *Giardia* cysts.

During the thirty-day ETV test period, the feed water turbidity ranged from 0.060 to 0.14 Nephlometric Turbidity Units (NTU) with an average of 0.088 NTU. pH was within the range of

7.6 to 8.0 with an average of 7.8. Total alkalinity as $CaCO_3$ ranged from 37 to 48 mg/l with an average of 42 mg/l. Average hardness, as $CaCO_3$, was 95 mg/l and ranged from 84 to 104 mg/l. TOC ranged from 2.0 to 2.6 mg/l with an average of 2.3 mg/l. UVA_{254} was 0.022 mg/l on average, with a range of 0.020 to 0.030 mg/l. TDS averaged 200 mg/l and the range was 170 to 270 mg/l. TSS averaged 0.19 mg/l and ranged from non-detectable to 0.55 mg/l. No coliform bacteria were detected in the feed water. The feed water cumulative particle counts averaged 120 counts/ml. Temperature averaged 3.8°C, ranging from 3.4°C to 4.5°C. The alga levels during the verification testing averaged 19 cell/ml, with a range of 8 to 32 cells/ml. A summary of the feed water quality information is presented in Table 1-1 below.

Table 1-1. Pall Corporation WPM-1 MF Pilot System Feed Water Quality

	Parameter									
	Total Alkalinity (mg/l)	Total Hardness (mg/l)	TDS (mg/l)	TSS (mg/l)	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)	TOC (mg/l)	UVA (cm –1)	Algae (cells/ml)	Turbidity (NTU)
Average	42	95	200	0.19	0	11	2.3	0.022	19	0.088
Minimum	37	84	170	<0.050	0	2	2.0	0.020	8.0	0.060
Maximum	48	100	270	0.55	0	22	2.6	0.030	32	0.14
Std. Dev.	4.5	7.3	38.9	0.27	0	9.7	0.2	0.0045	9.1	0.018
95% Confid Int	(38, 46)	(89, 100)	(170, 240)	(-0.040, 0.42)	N/A	(2.5, 20)	(2.1, 2.5)	(0.018, 0.026)	(11, 27)	(0.07, 0.11)

N/A = Not Applicable because standard deviation = 0

Note: Calculated averages for less than results (<) utilize half of the Level of Detection (0.05 mg/l) or 0.025 mg/l in these calculations. Per Statistical Methods for Environmental Pollution Monitoring, Richard O. Gilbert, Van Nostrand Reinhold, 1987.

1.3.2 Pilot Effluent Discharge

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

Chapter 2
Equipment Description and Operating Processes

2.1 Equipment Description

The equipment tested in this ETV program was Pall Corporation WPM-1 Microfiltration Pilot System. The modules used in the WPM-1 Treatment System was the Microza USV-3003 module with PVC housing. The PVC housings accommodate bundles of 1800 PVDF hollow fiber membranes, rated at 0.1 micrometer (µm). The hollow fiber membranes are 1.4 millimeters (mm) outside diameter and 0.8 mm inside diameter. The fibers contain thousands of micro-pores from 0.1 to 0.004 µm in diameter. This correlates to a 13,000 Dalton (molecular weight) rating.

The module is vertically mounted on the treatment skid. The filtration surface area provided in a module is approximately 75 ft^2.

The fibers are potted in epoxy, and arranged so that the feed flow enters the bottom of the module and flows on the outside of the fibers. Water passes into the fiber interior core via the pores. Contaminates which cannot pass through the pores remain exterior to the filter module. Water which enters the fibers' hollow interior is conducted into the interior of the filter module and exits as clean permeate. This 'outside-in' flow path provides for larger effective membrane area, and allows higher flux rates than most other membranes.

2.1.1 Membrane Characteristics

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

Membrane classification	Microfiltration
Membrane material	PVDF
Membrane type	hollow fiber
Membrane flow path.....	outside in
Filtration mode	Recirculation
pH tolerance	1- 10
Temperature tolerance.....	1 - 35° C (33 - 95° F)

2.1.2 Major Equipment Components

The following major equipment components are provided on the WPM-1 Treatment System:

Modules:

(1) Microza USV-3003 module with PVC housing. These are 1.12 meter long, 3" diameter PVC housings that accommodate bundles of 1800 PVDF hollow fibers, rated at 0.1 micron.

Pre-filter:

FSI 304 stainless steel (SST) bag filter housings with 400 micron polyester mesh bag filters.

Tanks:

Feed Tank:

10 gallon rectangular tank, flat bottom, closed top, SST stand.

Reverse Filtration Tank:

10 gallon rectangular tank, flat bottom, closed top, SST stand.

Chlorine Tank:

15 Liter polyethylene carboy, removable top.

Piping:

General: Sch 80, PVC, socket welded or threaded

Chlorine tubing: 3/8" OD Teflon PVDF

Air piping: 1/4" OD 304 SST tubing.

Pumps:

Feed Pump:

Goulds G&L Type SST/1ST centrifugal, 304 SST, 1x1.25-6 EPR elastomers, carbon/ceramic single mechanical seal, 1.5 horse power (hp) 3450 RPM, 230-460/60/3 inverter duty TEFC motor, and ABB ACS-2P1-1 variable frequency drive. Design: ambient temperature water, 20 GPM @ 100 ft. TDH.

Reverse Filtration Pump:

Goulds G&L Type SST/1ST centrifugal, 304 SST, 1x1.25-6, EPR elastomers, carbon/ceramic single mechanical seal, 1.5 hp 3450 RPM, 230-460/60/3 inverter duty TEFC motor, and ABB ACS-2P1-1 variable frequency drive. Design: ambient temperature water, 20 GPM @ 100 ft. TDH.

Chemical Feed Pump:

Blue - White 15N302I with adjustable stroke, 0.7 - 35 GPD.

Valves:

Asahi, Duo Block True Union PVC w/ EPDM Elastomers

Instrumentation:

Level Switches - SIE SK1-20-M30-P-B-S-Y2

Pressure Transmitters - Setra C207, 0-100 psig, w/865 option (Nema 4 housing).

Temperature Transmitters - Pyromation RTD type. # R1T185L 48 2.5 65 T 401 1 85 1750C-00

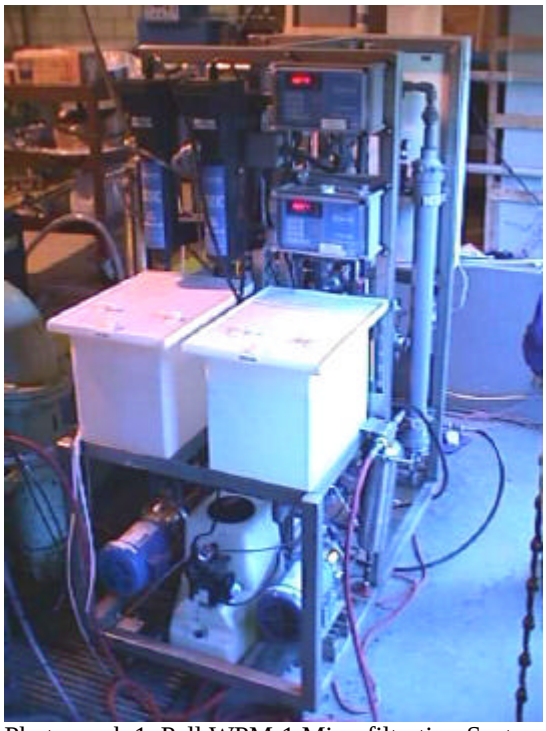
Flow meters - Signet - #3-8512 incl 3-8512-PO & #3-8011.

Turbidimeter - Hach 1720C. 44000-10 1720C w/44156-00 Calibration Kit

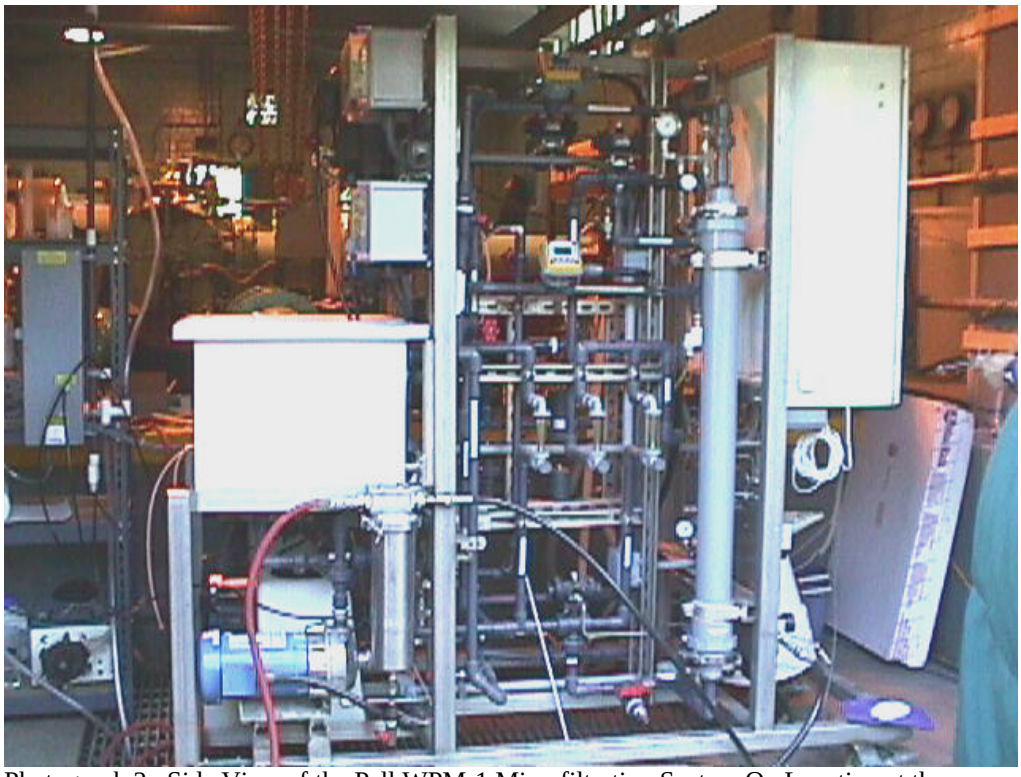
Controls:

GE Fanuc Model 331 PLC with Nematron W5000 flat panel computer running Wonderware Intouch Human Machine Interface software, housed in a NEMA 4 enclosure.

The following two photographs were taken of the equipment while it was on-site at the PWSA Highland Reservoir No. 1 location for testing:



Photograph 1. Pall WPM-1 Microfiltration System On Location at the PWSA Site.



Photograph 2. Side View of the Pall WPM-1 Microfiltration System On Location at the PWSA Site.

2.1.3 Data Plate

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

a. Equipment name: WPM-1 Pilot System
b. Model #: WPM-1 Pilot System
c. Manufacturer: Pall Corporation, 2200 Northern Boulevard, East Hills, NY 11548
d. Electrical requirements: 208 – 240 VAC, 15Amps, 1 phase
e. Serial number: 2114562
f. Warning and caution statements: N/A
g. Capacity or output rate: 1 –5 gallons per minute (gpm)

2.2 Operating Process

2.2.1 Feed Water

The feed water is pumped into the filtration system by the feed pump. The feed pump provides the pressure needed to drive the raw water through the fibers.

2.2.2 Prefiltration

A disposal 400µm bag filter removes large particles prior to the feed flow entering the modules. The prefilter protects the membrane fibers against clogging. The prefilter is visually inspected regularly. The prefilter is cleaned or replaced during CIP procedures or as indicated by the visual inspection or as dictated by raw water quality.

2.2.3 Filtration

During normal (forward) flow, the module receives an inlet flow. This flow enters the bottom of the module, and flows up the module on the outside of the hundreds of hollow fibers that run the length of the module. Of this, 95% 'permeates' through the fiber surface, travels up the inside of the hollow fiber, and flows into the Reverse Filtration Tank before leaving the system as clean water. The remaining five percent is recycled back to the Feed Tank as Excess Recirculation (XR). This XR flow prevents the accumulation of any gasses that may come out of solution in the module, and helps to ensure even flow distribution throughout the module. Figure 2-1 illustrates the flow path during forward flow.

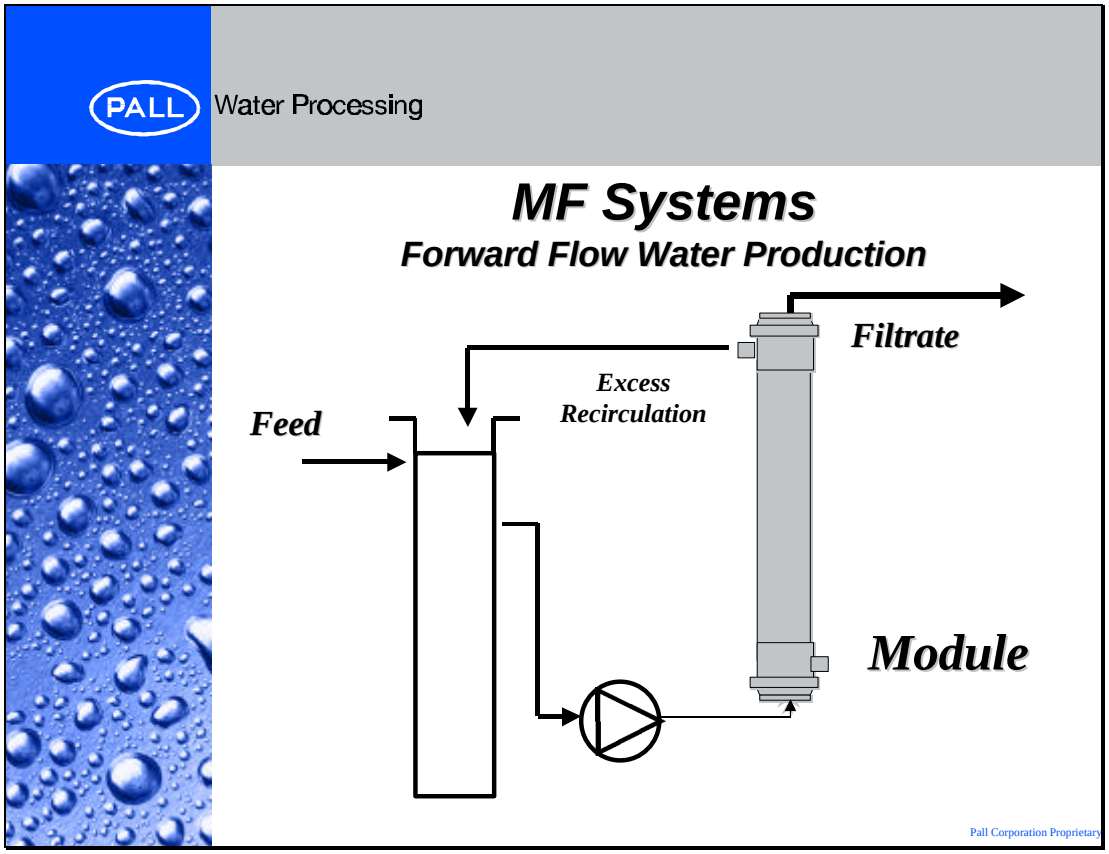


Figure 2-1. Forward Flow Water Production

2.2.4 Backwash/Reverse Filtration

As water is filtered through the membrane surface, a film of rejected particulates accumulates on the surface of the fibers. With greater accumulation, this gradually impedes the permeate flow. To maintain stable flow over the short term, a periodic cleaning cycle, called a Reverse Filtration (RF) Cycle, is performed. RF serves to keep module flux high. It is analogous to "backwashing" where filter flow is reversed. The reverse flow allows the particles trapped at the membrane to free the membrane pores and direct their exit from the system. This eliminates the flow restriction arising from particles plugging membrane pores.

To aid in cleaning the module, and particularly in removing any bio-burden on the membrane surfaces, chlorine, in the form of 12.5% sodium hypochlorite, is injected into the RF flow stream. The level of chlorine in the RF feed is approximately 20 mg/L. Valves direct all chlorine-laden RF-clean flow to waste.

Reverse filtration is not totally effective in cleaning the membrane fibers, and occasionally, a more vigorous cleaning is required. Pall calls the method Air Scrubbing (AS). This is a two step process. The first step consists of bubbling about 3 standard cubic feet per minute (scfm) of compressed air through each module with no water flow. The air is introduced into the feed connection of the module. Gaseous air will not pass through the fibers, so this air stays on the

feed side of the membrane. The air bubbles shake the fibers, sloughing off material that resists the RF cycle.

The second part of the AS cycle serves as a rinse and flush. Air is still bubbled up through the module, but water is also circulated through the feed side of the module. This is even more effective in cleaning the module surface. AS is an energetic process. For this reason, the number of AS cycles must be kept to the minimum required to keep the modules clean. Figure 2-2 illustrates the flow path during RF and AS.

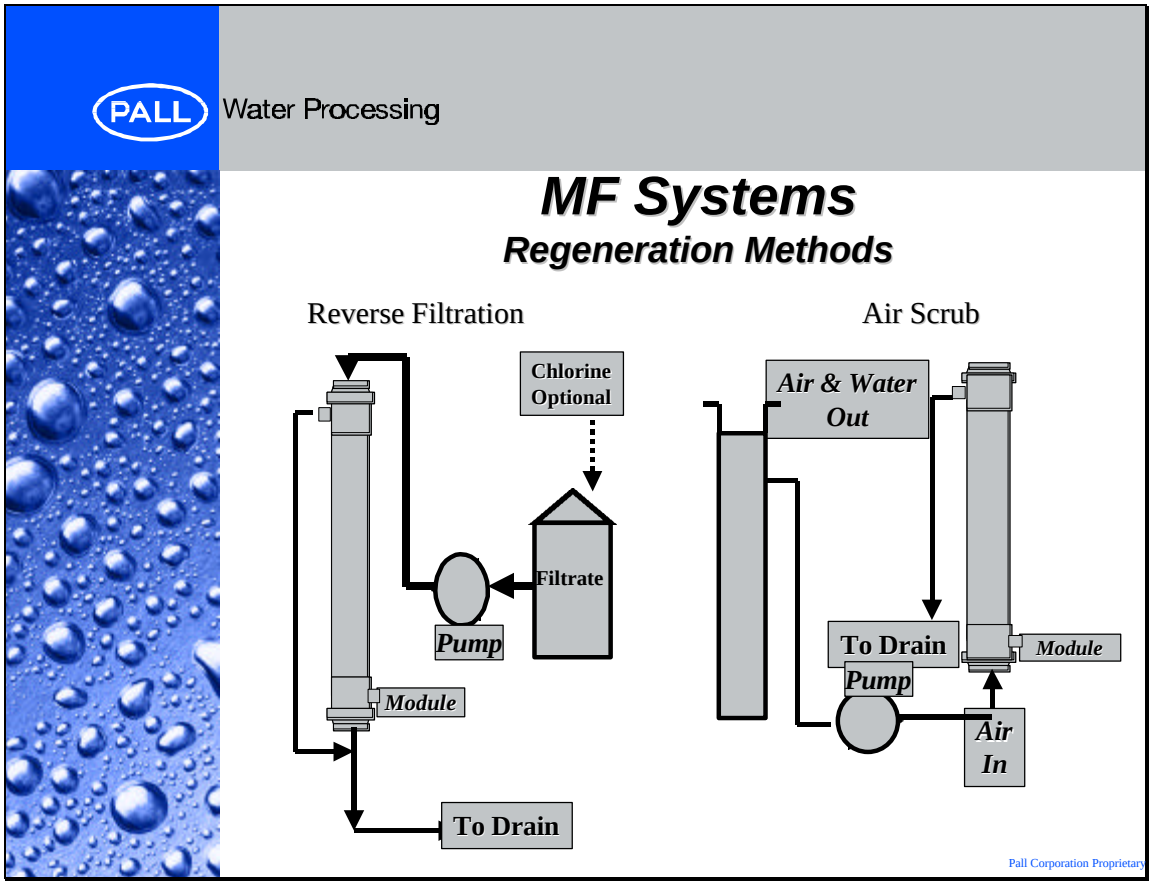


Figure 2-2. Flow Path During Reverse Filtration and Air Scrub

2.2.5 Chemical Cleaning

Even AS cycles leave some residue on the module fibers, and must be augmented by occasional chemical cleaning. In the WPM-1 system, the CIP process requires scheduled down-time and the entire system must be taken off line for several hours. In new systems, the CIP cycle is initially scheduled every two to three months. The nature of the foulants affects the cleaning frequency. As flow or incoming contaminant levels increase, it is likely that the CIP frequency will increase, accordingly.

The CIP process is done manually on the Pilot Skid (CIP is generally automated for larger, permanent systems). The system is drained, and then refilled with permeate. Sodium hydroxide is added to the permeate and circulated through the system for 20 minutes. Then citric acid is added to the permeate and circulated through the system for 20 minutes. The solution is drained, and more permeate (or other clean water) is added and circulated to rinse the system. The MF system is now ready to go back on line. For some applications, sodium hypochlorite can be substituted for the citric acid.

Figure 2-3 is a schematic representation of the chemical cleaning process.

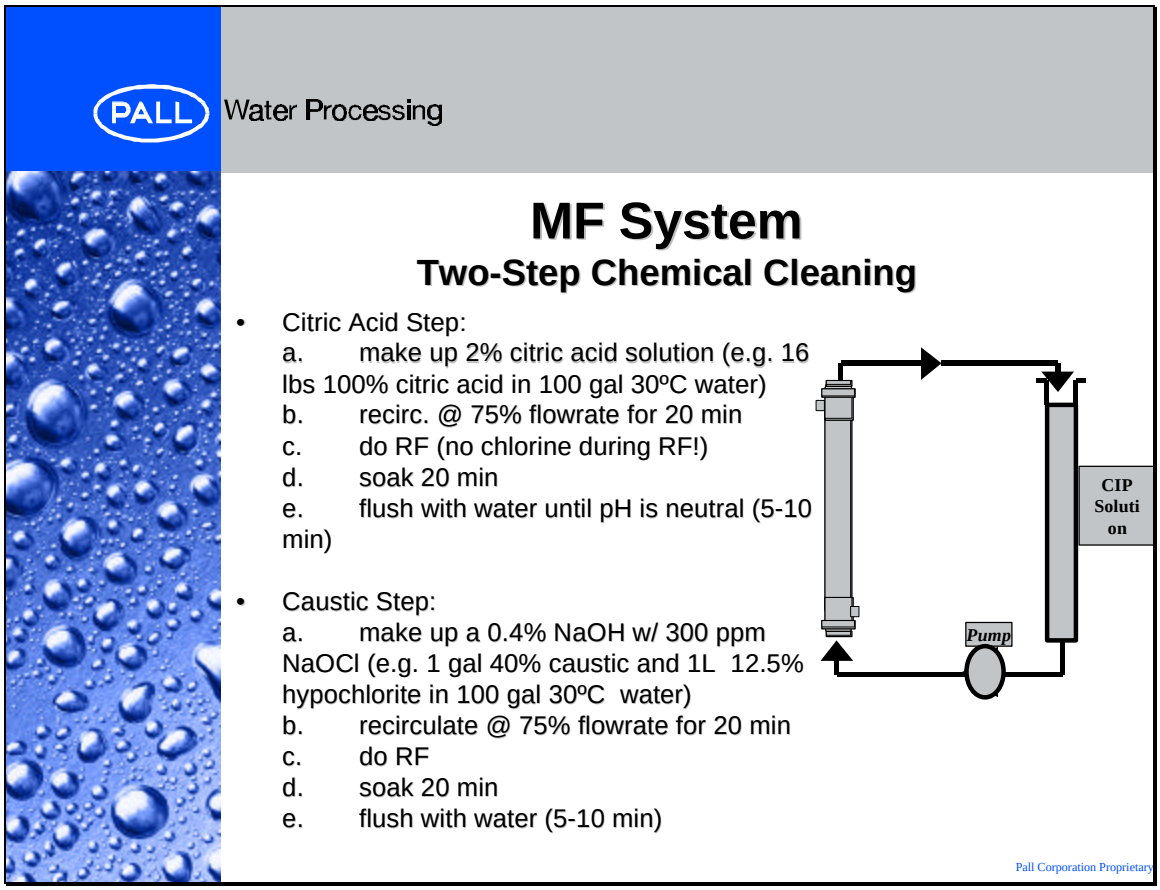


Figure 2-3. Chemical Cleaning Procedure and Flow Schematic

Chapter 3
Methods and Procedures

3.1 Experimental Design

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

3.1.1 Objectives

The verification testing was undertaken to evaluate the performance of the Pall Corporation WPM-1 MF Pilot 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 Pall WPM-1 Microfiltration treatment unit was tested to show that it was capable of providing a minimum 3 $\log_{10}$ removal of *Giardia* cysts and 2 $\log_{10}$ removal of *Cryptosporidium* oocysts from the source water and consistently producing water with a turbidity of less than <0.1 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 $\log_{10}$ removal/inactivation of *Giardia* cysts from feed to finished waters, that finished water turbidity at no time exceeds 5 NTU and that at least 95% of the daily finished water turbidity samples be less than 0.5 NTU. (EPA, Surface Water Treatment Rule [SWTR], 1989). Recently promulgated rules have modified the SWTR to include a lower turbidity standard, less than 0.3 NTU in 95% of the daily finished water turbidity samples, and a requirement to provide a 2 $\log_{10}$ removal of *Cryptosporidium* oocysts (EPA, Enhanced Surface Water Treatment Rule [ESWTR], 1999). Both these rules grant the “log removal credit” if the treatment facility achieves the required turbidity levels.

The treatment system's ability to achieve required finished water turbidity levels was not verifiable due to the fact that the feed water already was in compliance with drinking water turbidity regulations. 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 (Membrane System Operating Manual, Pall Corporation, February, 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 (Pall, 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.

3.1.1 Equipment Characteristics

The qualitative, quantitative and cost factors of the tested equipment were identified, in so far as possible, during the verification testing. The relatively short duration of the testing cycle creates difficulty in reliably identifying some of the qualitative, quantitative and cost factors. The qualitative factors examined during verification testing were susceptibility to changes in environmental conditions, operational reliability, and equipment safety. The quantitative factors examined during verification testing were power supply requirements, consumable requirements, waste disposal technique, and length of operating cycle. The cost factors examined during verification testing were power supply, consumables, and waste disposal. It is important to note that the figures discussed here are for the Pall Corporation WPM-1 MF Pilot System. This treatment unit operated at 77 gallons per square foot per day (gfd) at 3.8^{o}C (120 gfd at 20^{o}C). Costs will increase with increasing flow.

3.2 Water Quality Consideration

Characterization of the treated water 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. Treated water analyses (filtrate) and their frequencies are listed in Table 3-1.

Table 3-1. Analytical Data Collection Schedule				
Parameter	Frequency	Feed	Filtrate	Backwash Waste
Onsite Analytes				
Temperature	Daily	1	0	0
pH	Daily	1	0	0
Turbidity	Daily	2	Continuous	2
Particle Counts	Daily	Continuous	Continuous	0
Chlorine Residual	During Cleaning	1 (Backwash feed water)	0	1
Laboratory Analytes				
Total Alkalinity	Monthly	1	1	0
Total Hardness	Monthly	1	1	0
TDS	Monthly	1	1	0
TSS	Weekly	1	1	1
Total Coliforms	Weekly	1	1	1
HPC	Weekly	1	1	0
TOC	Weekly	1	1	0
UVA_{254}	Weekly	1	1	0
Algae	Weekly	1	1	0
Giardia and Cryptosporidium	Once during challenge testing	3	Composite	0

3.3 Recording Data

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

3.3.1 Operational Data

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

Table 3-2. Operational Data Collection Schedule	
Parameter	Frequency
Raw Flow	2/day
Feed Water Temperature	1/day
Electric Power Use	1/day
Influent module/vessel pressure	2/day
Effluent module/vessel pressure	2/day
Filtrate pressure	2/day
Filtrate flow	2/day

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

3.3.2 Water Quality Data

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

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

3.4 Communications, Logistics and Data Handling Protocol

With the number of verification participants involved in the study it was important for the FTO to coordinate communication between all parties. Documentation of study events was facilitated through the use of 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 was 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 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

Photographs were logged in the field log book. These entries include time, date, direction, subject of 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 audit by NSF representatives, the use of chain of custody forms was requested. Subsequent samples were collected and hand delivered to the laboratory accompanied by chain of custody forms. The chain of custody forms are included in Appendix E.

3.4.2.4 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, TSS and TDS. The equation used is:

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

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

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

3.6 Verification Testing Schedule

The verification testing commenced on February 3, 1999 with the initiation of daily testing. The unit ran in normal mode (XR flow, 77 gfd at 3.8°C flux [20 gfd at 20°C], 30-minute backwash interval). Daily testing concluded on March 5. Data was logged for a total of 723 hours of treatment system operation. Six hours of run time was lost due to a power failure at the pumping station on March 3. Power was restored and the treatment unit was restarted after approximately six hours of downtime.

Giardia and *Cryptosporidium* removal challenge testing was conducted February 5, 1999.

The cleaning efficiency task was performed on March 10, 1999. Membrane integrity testing was done on March 11 after the conclusion of the cleaning evaluation.

3.7 Field Operations Procedures

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

3.7.1 Equipment Operations

The operating procedures for the Pall WPM-1 are described in the Operations Manual (Appendix B) (Pall 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 NIST traceable thermometer was used for temperature analyses. The thermometer had a range –1 to 51^{o}C with scale divisions of 0.1^{o}C.

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

3.7.3 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 (Appendix G), if necessary. No adjustment to the FOD was necessary as a result of the initial operations. The unit was on site in February 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, backwash frequency, and the percent water recovery of the treatment unit.

3.7.3.1 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 expressed as gfd. The surface area of the membrane used for the verification testing was 75 ft^2. It is customary to refer to flux normalized to 20^{o}C (68^{o}F). Lower temperatures increase the viscosity of water and decrease the amount of permeate that can be produced from a given area.

The feed pressure to the membrane is adjusted to maintain the selected flux. This usually requires an increase in feed pressure to maintain the selected flux. In order to take this change in feed pressure into account, a parameter known as specific flux can be calculated. Specific flux is calculated by dividing the flux of the system by the transmembrane pressure. The specific flux is expressed in gallon per square foot per day per pounds per square inch (gfd/psi) at 68^{o}F.

3.7.3.2 Transmembrane Pressure

The pressures of the feed water were recorded twice per day. Since the Pall unit utilizes XR flow the pressure of the retentate is also recorded. The average of these two readings is used as the feed pressure to the system. The filtrate pressure was recorded twice per day. The amount of pressure lost as the water is filtered through the membrane is referred to as transmembrane pressure (TMP).

3.7.3.3 Backwash (Reverse Filtration)

As water is filtered through the membrane surface, a film of rejected particulates accumulates on the surface of the fibers. With greater accumulation, this gradually impedes the permeate flow. To maintain stable flow over the short term, a periodic RF cleaning cycle is performed. RF is a cleaning method used to keep module flux high. It is analogous to "backwashing" where filter flow is reversed. The reverse flow allows the particles trapped at the membrane to free the membrane pores and direct their exit from the system. This eliminates the flow restriction arising from particles plugging membrane pores.

RF typically takes place every 15-30 minutes. In the RF cleaning, the feed flow is stopped, and clean permeate is pumped backwards through the module from the inside of the fibers out through the pores. Typically, RF rate of flow is fixed at around 1.5 - 2 times the forward flow rate, washing away the accumulated contaminates. This reverse flow is short lived - a typical RF duration could be 20 seconds of every 24 minutes. This RF water exits the XR port near the top of the module. RF is generally diverted to drain to prevent the concentrated contaminants from reentering the flow path. Drainage of RF constitutes the majority of the lost feed flow (approximately 5%).

To aid in cleaning the module, and particularly in removing any bio-burden on the membrane surfaces, chlorine, in the form of 12.5% sodium hypochlorite, is injected into the RF flow stream. The level of chlorine in the RF feed is approximately 20 mg/L. Valves direct all chlorine-laden RF- clean flow to waste.

Reverse filtration is not totally effective in cleaning the membrane fibers, and occasionally AS, a more vigorous cleaning, is required. AS is a two step process. The first step consists of bubbling about 3 scfm of compressed air through each module with no water flow. The air is introduced into the feed connection of the module. Gaseous air will not pass through the fibers, so this air stays on the feed side of the membrane. The air bubbles shake the fibers, sloughing off material that resists the RF cycle.

The second part of the AS cycle serves as a rinse and flush. Air is still bubbled up through the module, but water is also circulated through the feed side of the module. This is even more effective in cleaning the module surface. Air Scrubbing is an energetic process. For this reason, the number of AS cycles must be kept to the minimum required to keep the modules clean.

For this test program, a RF interval of once every 30 minutes was used. Every other RF cycle i.e. once every hour utilized an AS cycle. The unit used approximately 3 gallons of permeate to

backwash the membranes each cycle during a RF cycle. AS followed by RF required 6.2 gallons of permeate.

3.7.3.4 Percent Feed Water Recovery

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

3.8 Verification Task Procedures

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

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

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

3.8.1 Task 1: Membrane Flux and Operation

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

The objectives of this task were to:

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

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

3.8.1.1 Filtration

The flux selected for the verification study was 77 gfd at 3.8°C (120 gfd at 20°C). The rate was selected by the manufacturer after examination of the initial operation data.

3.8.1.2 Backwash

The filtration cycle was 30 minutes for the verification study. The duration of the RF was 30 seconds.

The interval between backwashes is determined based on the ability of the unit to maintain a stable flow over the short term. That is, if the backwash frequency is not able to maintain a stable flow over the short term, it is increased. The backwash frequency used during the study was capable of maintaining a stable flow.

The procedure for backwashing is detailed in the O&M Manual (Appendix B). The normal backwash is an automatic function of the unit; the only adjustments which can be made are to frequency, duration, and pressure. Procedures for making these adjustments are detailed in the O&M Manual.

3.8.1.3 Chemical Cleaning

Chemical cleaning was to be instituted when the backwashing sequence was unable to maintain system TMP below 30 pounds per square inch differential (psid).

The cleaning was a two-stage process consisting of a citric acid cleaning and a caustic/chlorine cleaning. The citric acid cleaning consists of mixing a 2% citric acid solution, adding the solution to the membrane module, allowing the membrane to soak for one half hour, circulating the solution through the treatment system for 20–30 minutes. The system is then put through a RF cycle to rinse the citric acid solution from the system. The caustic/chlorine cleaning consists of mixing a 0.1N NaOH solution. Four hundred mg/l NaOCl is added to the caustic solution. The solution is added to the membrane module and the membrane is soaked for one hour. The solution is then recirculated for one hour. The system is then put through a RF cycle to rinse the caustic/chlorine solution from the system. The cleaning solutions were heated to 27°C - 38°C. The manufacturer recommends heating the cleaning solution when the temperature of the permeate water is less than 15°C. According to the manufacturer, the heated cleaning solutions maintains the solubility of the chemicals in the solutions and enhances the cleaning of the membrane. A detailed description of the cleaning process is in the manufacturer's O&M Manual (Appendix B).

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 finished water productivity to the membrane system.
2. Confirm manufacturer's cleaning practices are sufficient to restore membrane productivity.

Chemical cleaning, if required during the testing period, was to be instituted when the backwashing sequence was unable to maintain system TMP below 30 psid. If chemical cleaning was not required during the testing, it was to be performed at the conclusion of the 30-day period. The membranes were cleaned using manufacturer's recommendations March 10, 1999.

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

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

Parameter	Frequency
pH of cleaning solution initial	1/episode
pH of cleaning solution during process	1/episode
pH of cleaning solution final	1/episode
TDS of cleaning solution initial	1/episode
TDS of cleaning solution during process	1/episode
TDS of cleaning solution final	1/episode
Turbidity of cleaning solution initial	1/episode
Turbidity of cleaning solution during process	1/episode
Turbidity of cleaning solution final	1/episode
Oxidant residual initial	1/episode
Oxidant residual final	1/episode
Visual observation of backwash waste initial	1/episode
Visual observation of backwash waste final	1/episode
Flow of MF unit prior to cleaning	1/episode
Pressure of MF unit prior to cleaning	1/episode
Temperature of MF unit prior to cleaning	1/episode
Flow of MF unit after cleaning	1/episode
Pressure of MF unit after cleaning	1/episode
Temperature of MF 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 can be summarized in the following steps:

1. Put the system in Manual Mode, and fill the Permeate Tank.
2. Drain the feed side of the system.
3. Fill the feed tank with permeate and chemicals.
4. Recirculate cleaning solution.
5. Reduce chlorine in the solution and drain.
6. Fill the Permeate Tank with water and chemicals.
7. Recirculate cleaning solution on permeate side of system.
8. Pump solution into interconnect piping, and soak.
9. Reduce chlorine and pump down permeate side.
10. Flush system.
11. Place in Automatic and restart system.

A recording table is included in the O&M manual to record pump speeds, chemicals used, etc. during each chemical cleaning operation. These data may be useful in tracking system performance, or reducing the amount of time that the cleaning cycle requires.

For the verification testing, a chemical cleaning solution of 0.1N caustic soda plus 400 parts per million (ppm) of sodium hypochlorite was recirculated through the membranes for 1 hour and then 2% citric acid was recirculated through the membranes for ½ hour. Approximately 100 gallons of both solutions were used. The manufacturer recommended heating the solutions to 27-38^{o}C to enhance the solubility of the cleaning chemicals and to maintain the solubility of the chemicals in the solutions because the temperature of the permeate water was less than 15^{o}C.

3.8.3 Task 3: Finished Water Quality

Procedures for the collection and analysis of finished water quality samples are identified in this task. The purpose of this task was to demonstrate whether the manufacturer's stated treatment capabilities 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 also to comply with current and future regulations in the SWTR and ESWTR as they apply to filtration. 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.

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

3.8.3.1 Sample Collection and Analysis Procedure

Finished water samples were collected and analyzed monthly for total alkalinity, total hardness, and TDS. Weekly collection and analysis of finished water samples was performed for TSS, total coliforms, HPC, TOC, UVA_{254}, 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 a MF 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 ETV 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 mechanical barrier against the passage of particles and most types of microbial contamination. If the membrane is compromised, that is not intact, this barrier is lost. It is important to be able to detect when a membrane is compromised.

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

3.8.5.1 Air Pressure Hold Test

In order to conduct this test, it was necessary to remove the membrane vessel from the treatment unit. The membrane unit filtrate side was drained. The membrane itself was fully wetted (i.e. membrane pores were filled with water). The membrane was air pressurized up to 15 psi. The filtrate side was sealed and the pressure decline rate was monitored every thirty seconds using an air pressure gauge. An intact membrane would be demonstrated by minimal pressure loss, i.e. 1 psi every 5 minutes. Air pressure loss was also compared to the loss that was obtained when testing a compromised membrane.

3.8.5.2 Turbidity Reduction Monitoring

Turbidity of feed and filtrate water was continuously 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 0.088 NTU) showing a 90% reduction, 0.0088 NTU, was beyond the capability of the turbidimeters. Filtrate turbidity between an intact and a compromised membrane was compared. An increase of 100% was used as an indication of a compromised membrane.

3.8.5.3 Particle Count Reduction Monitoring

Particle count reductions from source to finished water of 99.9% would demonstrate an intact membrane. Due to the high quality of the feed water (the average cumulative feed water particle counts were 120 total counts per ml) showing a 99.9% reduction was pushing the limits of the instrumentation. Particle 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: Giardia and Cryptosporidium Removal

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

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

Giardia and *Cryptosporidium* challenge testing took place on February 5, 1999. The procedures for the preparation of the feed water stock, stock addition, sample collection and analysis, and calibration are presented below.

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

3.8.6.1 Feed Water Stock Preparation

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

3.8.6.2 Stock Addition Procedure

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

3.8.6.2 Sample Collection Procedure

After the suspension was prepared and before the initiation of filtration, samples were collected to establish the initial titer of the microorganisms. The feed suspension was pumped into the feed water line immediately before the membrane vessels. Once filtration had begun, the operational

parameters, as presented in Table 3-2, were recorded. Daily analytical testing as presented in Table 3-1 was conducted. One thousand liters (264 gallons) of permeate water were then passed through a 1µm pore sized yarn wound filter at a rate of one gallon per minute (3.785 liter per minute). Sample volumes of feed water, filtrate water and back washwater were recorded. Samples were processed and analyzed by PWSA's EPA qualified laboratory according to EPA protocols. (EPA, April, 1996). A minimum of three replicates of the filtered water sample were analyzed.

3.9 QA/QC Procedures

Maintenance of strict quality assurance and 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 log book by including the flow rate prior to adjustment in parentheses next to the description of what adjustment was made.

3.9.1.2 Inline Particle Counter Flow Rate

The flow rate 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. Changes to the flow rate were made by adjusting the level of the discharge from the overflow weir. If adjustments to the flow rate were made they were noted in the operational/analytical data log book by including the flow rate prior to adjustment in parentheses 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 online turbidimeter were recorded. Exact agreement between the two turbidimeters is not likely due to the differences in the analytical techniques of the two instruments.

3.9.2 Bi-Weekly QA/QC Verification Procedures

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

3.9.2.1 Inline Flow Meter Clean Out

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

3.9.2.2 Inline Flow Meter Flow Verification

Verification of the readout of the permeate, and retentate 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 permeate meter was verified by collecting the entire volume of permeate over a timed period and comparing the amount collected to the totalizer readings. The retentate meter was verified by collecting the retentate returning to the feed water tank over a timed period and comparing it to the flow rate displayed on the retentate flow meter. Due to the small volume of retentate that could be collected the totalizer reading could not be used.

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

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

3.9.3.1 Inline Turbidimeter

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

3.9.3.2 Pressure Gauges / Transmitters

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

3.9.3.3 Tubing

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

3.9.3.4 Inline Particle Counters

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

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

3.9.4 On-Site Analytical Methods

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

3.9.4.1 pH

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

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

3.9.4.2 Temperature

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

The backwash wastewater was collected, during backwash, twice per day. The entire amount of wash water from a backwash was collected in a reservoir for analysis. Dilution of the backwash waste (1ml of backwash waste to 5ml deionized [DI] water) was necessary due to the high level of residual total chlorine.

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

3.9.4.4 Turbidity Analysis

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

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

3.9.5 Chemical and Biological Samples Shipped Off-Site for Analyses

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

3.9.5.1 Organic Parameters

Organic parameters analyzed during the verification testing were TOC and UVA_{254}. Samples for analysis of TOC and UVA_{254} were collected in glass bottles supplied by the PWSA laboratory and hand carried to the laboratory by a PWSA representative immediately after collection. TOC and UVA_{254} samples were collected, preserved, and held in accordance with *Standard Method* 5010B. Storage time before analysis was minimized in accordance to *Standard Methods.*

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

3.9.5.2 Microbiological Parameters

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

Algae samples were preserved with Lugol's solution after collection and stored at a temperature of approximately 1-5^{o}C until counted. Lugol's solution is prepared by dissolving 20 grams of potassium iodide and 10 grams iodine crystals in 200ml of distilled water containing 20 ml of glacial acetic acid.

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

3.9.5.3 Inorganic Parameters

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

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

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

Chapter 4
Results and Discussion

4.1 Introduction

The verification testing for the Pall Corporation WPM-1 Pilot System which occurred at the PWSA's Highland Reservoir No. 1 site in Pittsburgh, Pennsylvania, commenced on February 3, 1999, and concluded its 30-day period on March 5, 1999. *Giardia* and *Cryptosporidium* challenge testing was conducted on February 5, 1999, chemical cleaning was performed on March 10, 1999, and membrane integrity testing was performed on March 11, 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, finished water quality, maximum membrane pore size, membrane integrity testing, and *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, backwash frequency appropriate for the feed water quality, and the efficiency of the unit. The unit was on site in February 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 59 to 161 gfd at 20^{o}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 120 gfd at 20^{o}C (82 l/m^{2}/h at 20^{o}C) (which equates to 77 gfd at 3.8^{o}C, the temperature of the feed water during testing). This corresponded to an initial specific flux of 5.4 gfd/psi at 20^{o}C when the TMP at time zero of testing is taken into account.

4.2.2 Transmembrane Pressure

The TMP during the initial operations period varied with the flux. TMP ranged from 3.6 psi to 29.6 psi during the initial operations period.

4.2.3 Backwash Frequency

During the initial operations period, backwash frequencies of 30 and 60 minutes were investigated. Based on the results of the initial operations period, it was determined that a backwash would occur every 30 minutes alternating between RF and AS cycles. That is the first backwash in an hour would be a RF cycle. The next backwash would be an AS cycle followed

by a RF cycle. This alternating pattern was maintained throughout the verification testing. The RF duration was 30 seconds; the AS cycle was 60 seconds. This backwash scenario proved to be appropriate for flux maintenance during the study. The amount of permeate used during a RF cycle was approximately 3 gallons; AS followed by RF required 6.2 gallons of permeate.

4.3 Verification Testing Results and Discussion

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

4.3.1 Task 1: Membrane Flux and Operation

The parameters of flow, feed and filtrate pressures, backwash frequency and volumes, and the feed water temperature were used to establish membrane flux and operational characteristics. TMP and rate of specific flux decline were established from these parameters. The results of the TMP and rate of specific flux decline are presented below. Date of chemical cleaning was March 10, 1999. A calculation of the feed water recovery of the treatment system is presented.

4.3.1.1 Transmembrane Pressure Results

Transmembrane pressure fluctuated from 22 to 26 psid during the 30 day testing. The average TMP during the testing was 24 psid. Table 4-1 presents a summary of the daily unit pressure readings and TMP. Figure 4-1 presents a graph of daily TMP results. A complete tabular summary of the data is presented in Appendix C.

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

	Feed Pressure (psi)	Retentate Pressure (psi)	Filtrate Pressure (psi)	Transmembrane Pressure (psid)
Average	30	28	5.1	24
Minimum	27	25	3.4	22
Maximum	32	31	5.9	26
Standard Deviation	1.4	1.3	0.57	1.1
Confidence Interval	(29, 30)	(28, 29)	(4.9, 5.2)	(24, 24)

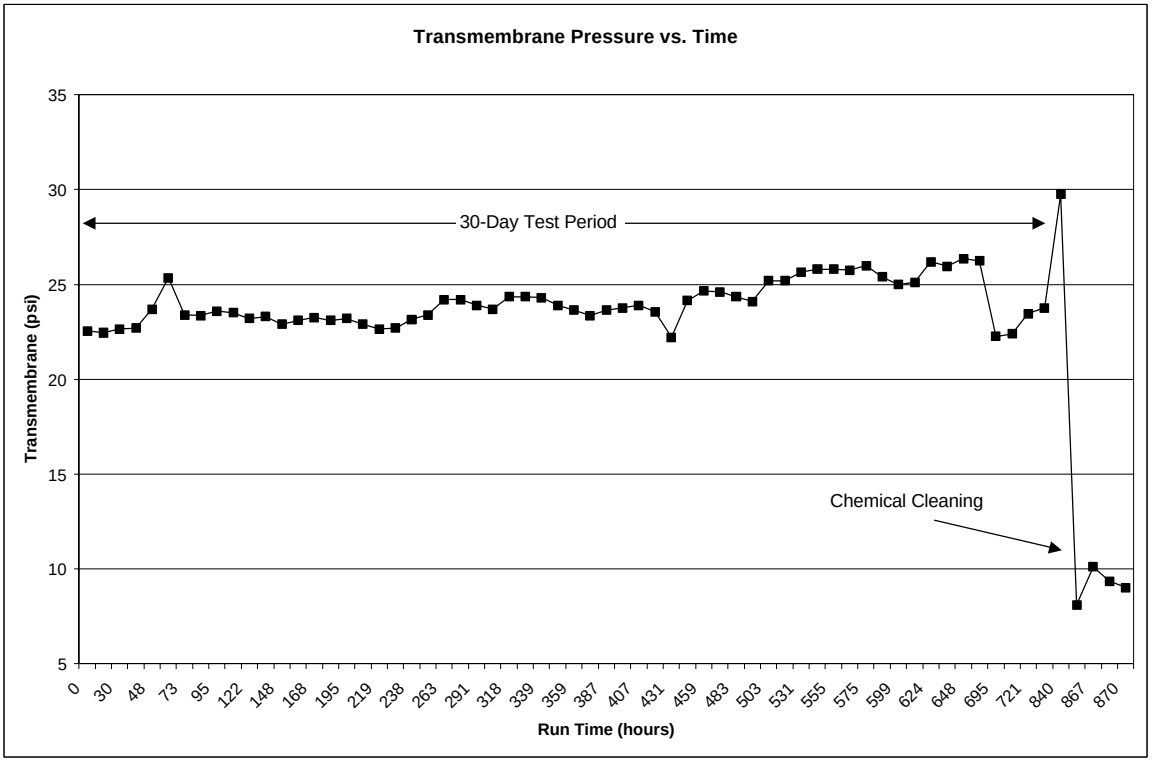


Figure 4-1. Transmembrane Pressure vs. Time

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 backwash protocol on this feed water.

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

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

There was a noticeable decrease in TMP between run time 650 hours and 695 hours. This may have been related to the system shut down caused by a power failure which occurred on March 3.

Allowing the membranes to "relax" may have caused some of the accumulated particles to be released from the membranes. There is no empirical evidence for this supposition. The decrease in TMP between run time 845 hours and 850 hours was a result of the chemical cleaning process.

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

4.3.1.2 Specific Flux Results

The specific flux of the treatment system ranged from 4.6 to 5.5 gfd/psi at 20°C (45 to 54 l/m^2/h/b at 20°C) and on average was 5.0 gfd/psi at 20°C (50 l/m^2/h/b at 20°C) during the 30-day verification test period. Table 4-2 presents a summary of the specific flux of the treatment system during the 30-day test period. Figure 4-2 presents a graph of daily specific flux results during the 30-day test period and during the cleaning operations that occurred after the 30-day test.

Table 4-2. Specific Flux

	Specific Flux during 30-day test period (gfd/psi @20°C)
Average	5.0
Minimum	4.6
Maximum	5.5
Standard Deviation	0.22
Confidence Interval	(5.0, 5.1)

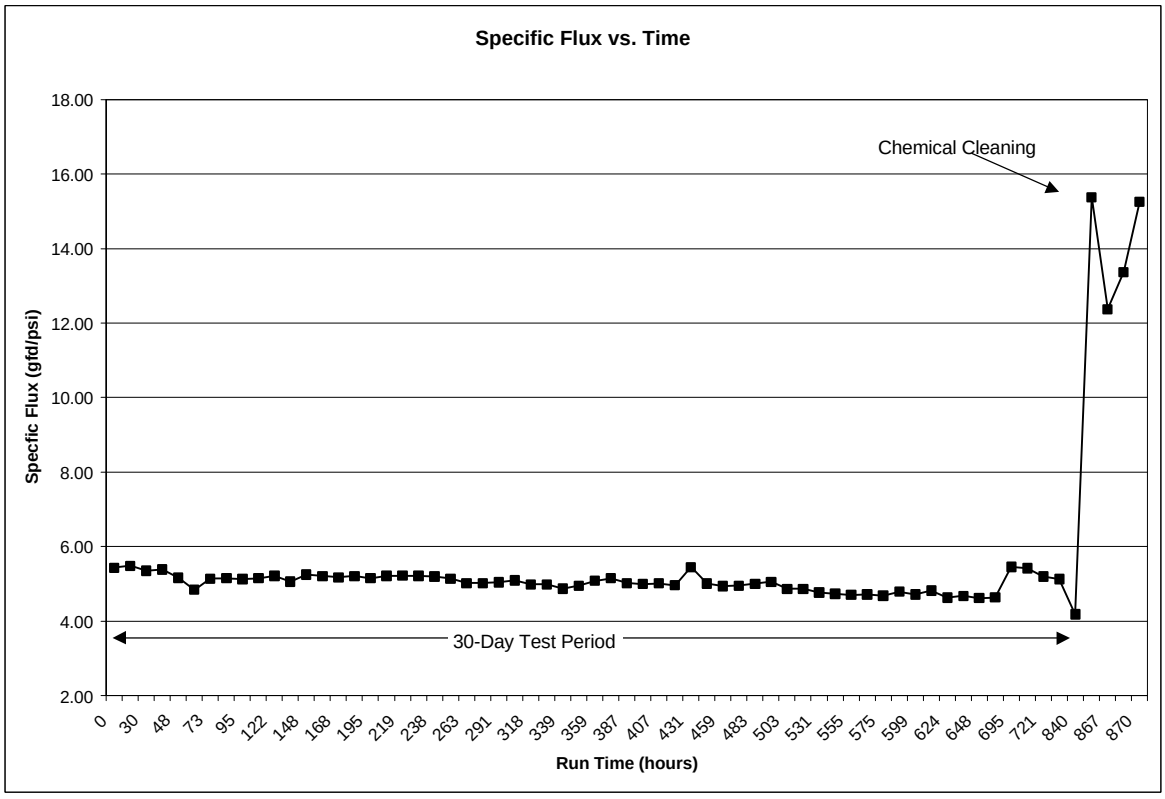


Figure 4-2. Specific Flux Decline vs. Time

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. That is, the unit appeared to be capable running at the selected conditions during the verification testing.

The sharp increase in specific flux on March 10 was a result of the chemical cleaning process.

4.3.1.3 Cleaning Episodes

Pall recommends that cleaning be instituted when the backwashing sequence is unable to maintain system TMP below 30 psid. The membranes were cleaned as per protocol requirements using manufacturer's recommendations March 10, 1999. Results of that cleaning are presented in Section 4.3.2.

4.3.1.4 Percent Feed Water Recovery

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

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

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

Using the above equation the following calculation was performed:
Filtrate flow = flow (gpm) * minutes/day = filtrate flow (gpd)
Filtrate flow = 4.0 gpm*1440 minute/day = 5760 gpd
Feed flow to membrane = filtrate flow + backwash volume
Feed flow = 5760 gpd + (3 gal/backwash/hr * hr/day)
+ (6.2 gal/backwash with AS/hr * hr/day) = 5980 gpd

Percent feed water recovery = 100 * [5760/5980] = 96%

4.3.2 Task 2: Cleaning Efficiency

Cleaning was conducted March 10, 1999. The cleaning was a two-stage process consisting of a citric acid cleaning and a caustic/chlorine cleaning. The citric acid cleaning consists of mixing a 2% citric acid solution, adding the solution to the membrane module, allowing the membrane to soak for one half hour, circulating the solution through the treatment system for 20–30 minutes. The system is then put through a RF cycle to rinse the citric acid solution from the system. The caustic/chlorine cleaning consists of mixing a 0.1N NaOH solution. 400 mg/l NaOCl is added to the caustic solution. The solution is added to the membrane module and the membrane is soaked for one hour. The solution is then recirculated for one hour. The system is then put through a RF cycle to rinse the caustic/chlorine solution from the system. The cleaning solutions were

heated to 27°C - 38°C. The manufacturer recommends heating the cleaning solution when the temperature of the permeate water is less than 15°C. According to the manufacturer, the heated cleaning solutions maintains the solubility of the chemicals in the solutions and enhances the cleaning of the membrane. A detailed description of the cleaning process is in the manufacturer's O&M Manual (Appendix B).

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

4.3.2.1 Results of Cleaning Episodes

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

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

		Citric Acid Cleaning		Caustic Cleaning	
Parameter	unit	Result	Dup.	Result	Dup.
pH of Cleaning Solution Initial		2.1	2.1	12.3	12.4
pH of Cleaning Solution During Process		2.2	2.2	12.6	12.6
pH of Cleaning Solution Final		2.2	2.2	12.6	12.6
TDS of Cleaning Solution Initial	(mg/l)	4,714		12,582	
TDS of Cleaning Solution During Process	(mg/l)	10,061		10,530	
TDS of Cleaning Solution Final	(mg/l)	10,025		5,862	
Turbidity of Cleaning Solution Initial	(NTU)	0.25	0.27	4.8	4.8
Turbidity of Cleaning Solution During Process	(NTU)	0.83	0.83	6.1	5.9
Turbidity of Cleaning Solution Final	(NTU)	0.81	0.81	0.34	0.32
Oxidant Residual Initial	(mg/l)	N/A	N/A	320	
Oxidant Residual Final	(mg/l)	N/A	N/A	124	
Visual Observation of Backwash Waste Initial		light yellow green		Milky	
Visual Observation of Backwash Waste Final		light yellow green		gray after soak, light green after recirculation	

Table 4-4. Operational Parameter Results - Cleaning Procedure

Parameter	Unit	Time	Citric Acid Cleaning Result	Caustic Cleaning Result
Flow of MF Unit Prior to Cleaning	(gpm)	10:30	4.0	
Pressure of MF Unit Prior to Cleaning (Feed)	(psi)	10:30	35	
Pressure of MF Unit Prior to Cleaning (Retentate)	(psi)	10:30	34	
Pressure of MF Unit Prior to Cleaning (Filtrate)	(psi)	10:30	5.0	
Temperature of MF Unit Prior to Cleaning	(°C)	10:30	2.9	2.9
Flow of MF Unit After Cleaning	(gpm)	15:50		4.0
Pressure of MF Unit After Cleaning (Feed)	(psi)	15:50		11
Pressure of MF Unit After Cleaning (Retentate)	(psi)	15:50		10
Pressure of MF Unit After Cleaning (Filtrate)	(psi)	15:50		2.3
Temperature of MF Unit After Cleaning	(°C)	15:50		2.9
Recirculation Flow – during cleaning	(gpm)	15:50	4.0	4.0

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:

Recovery of specific flux = 100 X (1- (Js_f / Js_i))
where: Js_f = Specific flux (gfd/psi) at end of current run (final)
Js_i = 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: 4.2 gfd/psi at 20^{o}C. The specific flux when the system was restarted after the completion of the washing procedure was: 15 gfd/psi at 20^{o}C

Using these figures in the above equation resulted in a recovery of specific flux of 73 %.

The following equation was used calculate the loss of original specific flux:
Loss of original specific flux = 100 X (1- (Js_i / Js_{io}))
where: Js_{io} = Specific flux (gfd/psi) at time zero point of membrane testing

The specific flux of the system when the membrane was placed into service in October 23, 1998, was 17 gfd/psi at 20^{o}C. The specific flux when the system was restarted after the completion of the cleaning procedure was 15 gfd/psi at 20^{o}C.

Using these figures in the above equation resulted in a loss of original specific flux of 9.0 %.

4.3.2.3 Discussion of Results

Pall recommends that cleaning be instituted when the backwashing sequence is unable to maintain system TMP below 30 psid. The membranes were cleaned as per protocol requirements using manufacturer's recommendations March 10, 1999.

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

The characterization of the citric acid cleaning wastewater indicated that the solution was acidic, with a pH of 2.2. The citric acid cleaning waste had a turbidity of 0.81 NTU and a TDS of 10,025 mg/l. No chlorine was used in conjunction with the citric acid solution. The caustic/chlorine cleaning waste had a pH of 12.6, a turbidity of 0.34 NTU, and a TDS of 5,862 mg/l. The total chlorine residuals of the caustic/chlorine cleaning waste was 120 mg/l. The wastewater during the citric acid cleaning waste had a light yellow-green color. The caustic/chlorine cleaning waste also had a light green color.

The cleaning solutions are mixed from 100% citric acid, caustic soda, and 12.5% NaOCl. Care must be taken when handling these materials to avoid injury. No hazardous materials are present in the cleaning solutions. The presence of hazardous materials in the wastewater would be

dependent on the quality of the feed water. Depending on local regulations, the waste stream may be able to be discharged to the sanitary sewer system.

Examination of the operational data and the recovery of specific flux showed that the cleaning procedure did restore 73 % of the specific flux to the treatment system. This indicates that the cleaning procedure was capable of restoring membrane performance.

The loss of original specific flux was 9.0 %. This may indicate that some irreversible degradation of the membrane had occurred.

4.3.3 Task 3: Finished Water Quality

Results of testing for turbidity in the feed and finished water were examined to verify the stated turbidity treatment ability. Since the feed water turbidity was consistently less than 0.1 NTU and a turbidity challenge was not conducted this stated treatment goal was not verifiable. A graph depicting daily $\log_{10}$ removals for cumulative particle counts will be presented. Bacteria and algae removal results were examined. Examination of TOC and UVA_{254} testing results, as well as testing results for the inorganic parameters total alkalinity, total hardness, TDS, and TSS was conducted. A TSS mass balance calculation will be presented. Graphs of four-hour readings for turbidity and particle count results will be shown.

4.3.3.1 Turbidity Results and Removal

Results of testing for turbidity in the feed and finished water were examined. A summary of the results is presented in Tables 4-5 and 4-6. A complete data table is presented in Appendix C. A graph of this data is presented as Figure 4-3.

Table 4-5. Turbidity Analyses Results and Removal

Sample Parameter	Feed Turbidity (NTU)	Feed Turbidity (duplicate) (NTU)	Filtrate Turbidity (NTU)	Daily Amount Removed (NTU)
Average	0.088	0.090	0.026	0.062
Minimum	0.060	0.060	0.024	0.034
Maximum	0.14	0.13	0.032	0.095
Standard Deviation	0.018	0.018	0.0013	0.017
Confidence Interval	(0.083, 0.092)	(0.084, 0.097)	(0.026, 0.026)	(0.056, 0.068)

Table 4-6. Filtrate Turbidity Results – Four Hour Readings

	Turbidity (NTU)
Average	0.016
Minimum	0.016
Maximum	0.026
Standard Deviation	0.0016
Confidence Interval	(0.016, 0.016)

The permeate turbidity was very low throughout the duration of the verification testing. The inline permeate turbidimeter readings averaged 0.026 NTU; the benchtop turbidimeter readings

averaged 0.042 NTU. While this may initially appear to be a significant difference, it is most likely due to the low level of turbidity in the feed and finished water and the differences in methodology of the two pieces of analytical equipment. The discrepancy between these two results can be explained by differences in the analytical techniques between the online and benchtop turbidimeter and the low level of turbidity in the permeate. The benchtop turbidimeter uses a glass cuvette to hold the sample; this cuvette can present some optical difficulties for the benchtop turbidimeter. The inline turbidimeter has no cuvette to present a possible interference with the optics of the instrument. The low level of turbidity in the permeate also can create analytical difficulties, particularly for the benchtop. Manufacturer's specifications state that stray light interference is less than 0.02. Stray light interference approaching this level at the low turbidity levels tested could account for the differences in the readings.

Figure 4-3 shows the results of the four-hour permeate turbidity readings. Due to problems associated with the data logging equipment on the treatment unit the turbidity readings from run time 596 hour to 684 hour were lost and are not available.

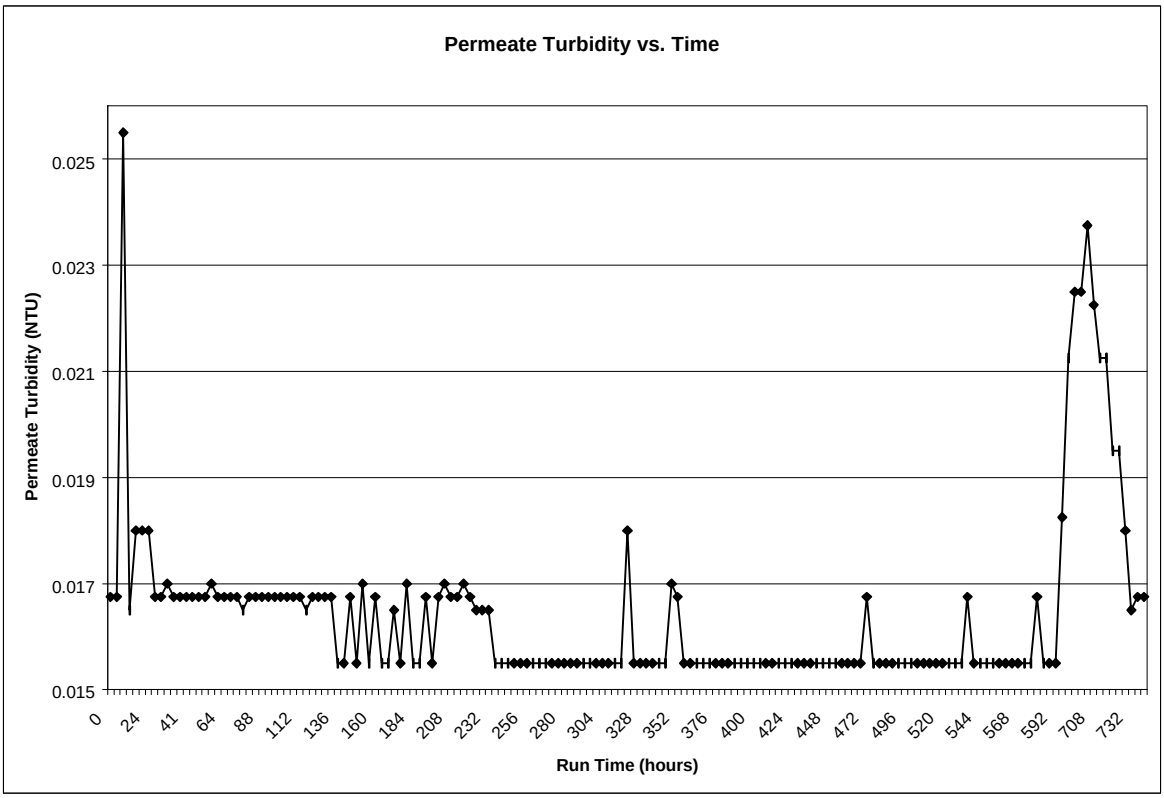


Figure 4-3. Four-Hour Permeate Turbidity

4.3.3.2 Particle Count Results and Removal

Particle count readings were taken on a continuous basis and recorded every 15 minutes. Average particle count calculations were calculated from these readings. The feed water

cumulative counts averaged 120 particles per ml. The finished water cumulative counts averaged 0.54 counts per ml. The average $\log_{10}$ removal for the cumulative counts was 2.5.

The low particle counts for each size range in the filtrate water indicated good system performance throughout the testing period. The treatment system seems to be an effective removal mechanism for particle removal.

Average feed water particle counts are presented in Table 4-7. Average finished water particle counts are presented in Table 4-8. Daily average cumulative counts for feed and finished water and the $\log_{10}$ particle removals are presented in Table 4-9. A complete data table is presented in Appendix C. Figures 4-4 and 4-5 depict results of four hour particle counts for feed water and permeate. Figure 4-6 graphically depicts daily $\log_{10}$ removals for cumulative particle counts. The particle count readings from run time 640 hour to 732 hour were lost and are not available due to problems associated with the data logging equipment on the treatment unit.

Table 4-7. Feed Water Particle Counts

	Size						
	2-3µm	3-5µm	5-7µm	7-10µm	10-15µm	>15µm	Cumulative
Average	60	37	10.5	5.8	2.2	0.75	120
Minimum	0	0	0	0	0	0	N/A
Maximum	980	680	260	480	490	93	N/A
Standard Deviation	34	23	7.2	9.7	9.7	2.0	N/A
Confidence Interval	(59, 62)	(36, 38)	(10, 11)	(5.5, 6.2)	(1.8, 2.5)	(0.67, 0.82)	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 5 µm readings were 20% lower than actual. Due to extremely low results in the 10 µm and 15 µm size range the results of the 7-10 µm, 10-15 µm, and >15 µm should be considered questionable. See instrument QA/QC verification results in Section 4.5.3.

Table 4-8. Finished Water Particle Counts

	Size						
	2-3µm	3-5µm	5-7µm	7-10µm	10-15µm	>15µm	Cumulative
Average	0.21	0.16	0.081	0	0.045	0.044	0.54
Minimum	0	0	0	0	0	0	N/A
Maximum	72	59	20	0	10	9.5	N/A
Standard Deviation	2.2	1.6	0.63	0	0.29	0.20	N/A
Confidence Interval	(0.13, 0.29	(0.10, 0.22)	(0.058, 0.10)	N/A[1]	(0.034, 0.056)	(0.037, 0.051)	N/A

N/A = Not Applicable. Statistical measurements on cumulative data do not generate meaningful data.
N/A[1] = Not Applicable. Confidence interval not calculated because standard deviation equals zero.
Note: Due to results obtained during the QA/QC task involving verification of the calibration of the particle counters the above readings were on average 16% lower than actual. See instrument QA/QC verification results in Section 4.5.3.

Table 4-9. Daily Average Cumulative Particle Counts Feed and Finished Water, Log_{10} Particle Removal

Date	Feed	Permeate	Log_{10} Removal
2/3/1999	120	1.4	1.9
2/4/1999	130	0.79	2.2
2/5/1999	130	0.64	2.3
2/6/1999	130	0.28	2.7
2/7/1999	120	0.36	2.5
2/8/1999	120	0.27	2.6
2/9/1999	120	0.24	2.7
2/10/1999	94	0.25	2.6
2/11/1999	85	0.24	2.6
2/12/1999	130	0.35	2.6
2/13/1999	150	0.24	2.8
2/14/1999	150	0.30	2.7
2/15/1999	140	0.17	2.9
2/16/1999	120	0.20	2.8
2/17/1999	130	0.19	2.8
2/18/1999	91	0.16	2.7
2/19/1999	80	0.17	2.7
2/20/1999	71	0.22	2.5
2/21/1999	70	0.31	2.4
2/22/1999	69	0.33	2.3
2/23/1999	67	0.32	2.3
2/24/1999	73	0.22	2.5
2/25/1999	89	0.19	2.7
2/26/1999	79	0.15	2.7
2/27/1999	71	0.46	2.2
3/3/1999	190	7.9	1.4
3/4/1999	210	1.8	2.0
3/5/1999	240	0.51	2.7

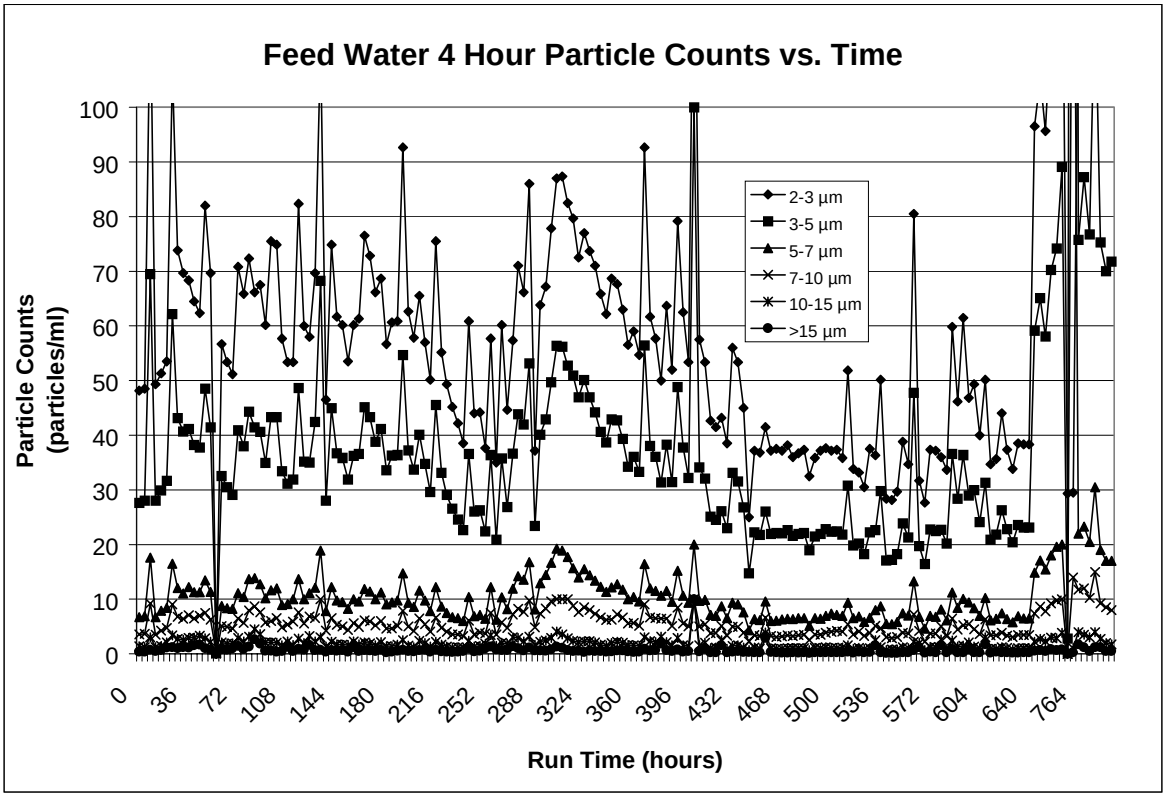


Figure 4-4. Four Hour Feed Water Particle Counts

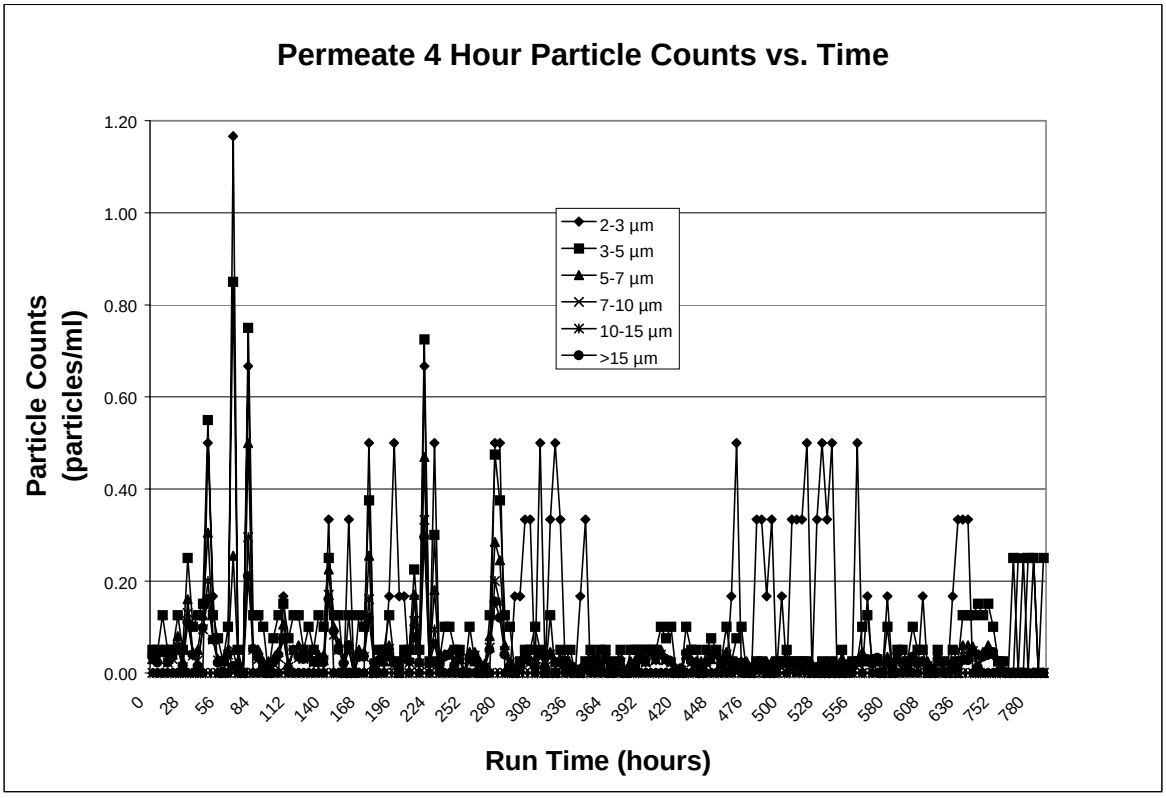


Figure 4-5. Four Hour Permeate Particle Counts

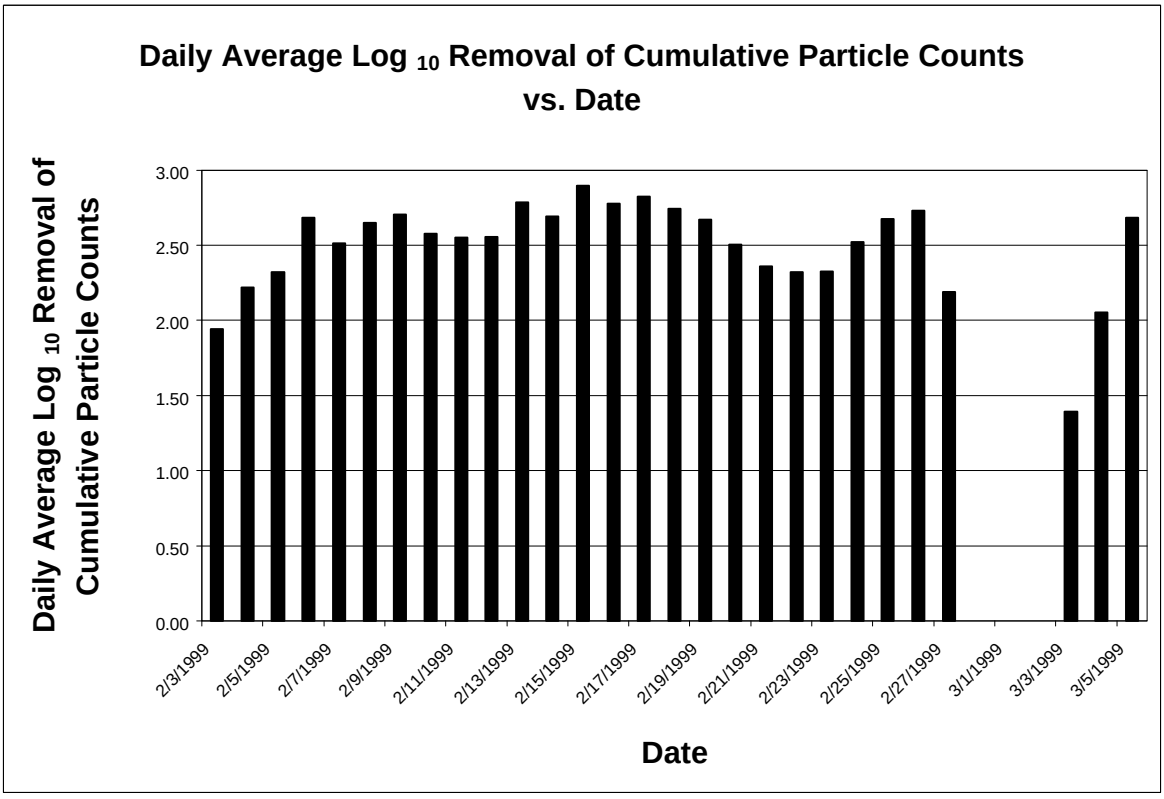


Figure 4-6. Daily Average Log_{10} Cumulative Particle Removal Graph

4.3.3.3 Feed and Finished Water Testing Results

The results of the testing of the feed water for Total Alkalinity, Total Hardness, TDS, TSS, Total Coliforms, HPC, TOC, UVA_{254} and Algae are presented in Table 4-10. The results of the testing of the finished water for Total Alkalinity, Total Hardness, TDS, TSS, Total Coliforms, HPC, TOC, UVA_{254}, and Algae are presented in Table 4-11. A complete data table is presented in Appendix C.

Table 4-10. Feed Water Testing Results

	Parameter								
	Total Alkalinity (mg/l)	Total Hardness (mg/l)	TDS (mg/l)	TSS (mg/l)	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)	TOC (mg/l)	UVA (cm –1)	Algae (cells/ml)
Average	42	95	204	0.19	0	11	2.32	0.02	19
Minimum	37	84	168	<0.05	0	2	2.01	0.02	8
Maximum	48	104	266	0.55	0	22	2.56	0.03	32
Std. Dev.	5	7	39	0.27	0	10	0.22	0.004	9.1
Confidence Interval	(38, 46)	(88, 101)	(170, 240)	(-0.02, 0.43)	N/A	(2, 19)	(2.13, 2.50)	(0.02, 0.03)	(11, 27)

N/A = 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 4-11. Finished Water Quality

	Parameter								
	Total Alkalinity (mg/l)	Total Hardness (mg/l)	TDS (mg/l)	TSS (mg/l)	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)	TOC (mg/l)	UVA (cm –1)	Algae (cells/ml)
Average	40	98	213	0.55	0	4	4.02	0.020	<8
Minimum	36	92	178	<0.05	0	0	3.21	0.020	<8
Maximum	43	110	284	1.15	0	12	4.86	0.020	<8
Std. Dev.	2.6	7.5	43.1	0.64	0	5	0.78	0.000	0
Confidence Interval	(38, 42)	(91.4, 104.6)	(175, 251)	(-0.07, 1.17)	N/A	(0, 8)	(3.25, 4.78)	N/A	N/A

N/A = Not Applicable because standard deviation = 0

Note: Calculated averages for less than results (<) utilize half of the Level of Detection (0.05 mg/l) or 0.025 mg/l in these calculations. (Gilbert, 1987).

The following observations were made after examination of the results of feed and finished water testing.

Reductions were seen in HPC. HPC averaged 11 colony forming units (cfu)/100ml in the feed water. Permeate HPC concentrations were 4 cfu/100ml on average. The presence of HPC in the permeate may have been due to inadequate disinfection of the Tygon tubing used for water sampling and to the lid design of the RF tank which permitted some environmental contaminants to intrude into the permeate side of the system. Pall reports that the RF tank has been redesigned with a protective lid.

Algae concentrations were reduced. Feed water contained 19 cells/ml on average. No algae was detected in the permeate in the four samples analyzed during the verification testing.

No improvement in TSS was observed; in fact analyses indicated that the permeate TSS was slightly higher than the feed TSS. The feed TSS was 0.21 mg/l on average; the permeate TSS averaged 0.56 mg/l. Possible explanations for TSS increase in field studies are particulate shedding from the membranes and analytical error due to methodologies in the TSS analyses. As previously noted, however, the Pall WPM-1 MF system uses membranes that are manufactured from a polyvinylidenefluoride polymer. The manufacturer reports that there has never been any evidence of the polyvinylidenefluoride polymer membranes shedding mass into the permeate. The most likely explanation for the increase of TSS in the permeate involve the analyses themselves. 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. It should also be noted that an examination of the TSS results for the feed water and permeate indicate that the 95% confidence interval for each actually overlap.

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

TOC and UVA_{254} were not well removed from the feed water. The values of UVA_{254} in both the feed water and permeate were very similar as the respective confidence intervals overlapped and average values were nearly identical. These results suggested that the microfiltration membrane did not affect dissolved organic chemicals.

The TOC values were higher in the permeate than in the feed water by approximately 2 mg/L. The TOC values were consistently higher in each of the four samples analyzed. These same samples were also analyzed for dissolved organic carbon (DOC) and showed that most (>90%) of the TOC was from the DOC (PWSA laboratory report in Appendix H). Considering that the UVA_{254} values were nearly identical between the feed water and permeate, the TOC/DOC is most likely from dissolved organic chemicals not absorbing at the 254-nanometer wavelength.

There are very few sources of DOC that could account for the observed increase in TOC. Biological growth in the plumbing systems of the treatment system is the most likely source of DOC in the permeate. The membrane package plant, which included plumbing components and the membrane module, was on line at the test site for one year prior to the ETV testing. The plumbing components of the package plant were made of polyvinylchloride (PVC). Also, the membrane module cleaning cycle was composed of citric acid soak and caustic/chlorine (0.1N NaOH solution) rinse and was not used on the permeate line from the module and therefore would not have resulted in any major disinfection in the permeate sample line. Bacterial growth may have occurred throughout the plumbing system during the year prior to ETV testing and the resulting bio-film may have contributed to the DOC, although no biofilm growth on the plumbing or biolfilm sloughing was observed during visual inspections. Without additional research, which is outside of this verification study, the actual source of DOC is not known, but considering the circumstances of testing, unexpected bacterial growth prior to this testing could account for the observed increase in the TOC/DOC. Total coliform reduction could not be demonstrated due to the absence of total coliforms in the feed water and permeate throughout the test.

Temperature of the feed water was fairly stable during the thirty day testing from a high of 4.5^{o}C to a low of 3.4^{o}C. The average temperature was 3.8^{o}C.

4.3.3.4 Backwash Wastewater Testing Results

Daily and weekly testing was conducted on the backwash wastewater. The results of the testing are listed in Table 4-12 and Table 4-13. A complete data table is presented in Appendix C.

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

	Parameter			
	Turbidity (NTU)	Turbidity (dup) (NTU)	Chlorine Residual (mg/l)	Chlorine Residual (dup) (mg/l)
Average	0.74	0.79	3.6	3.6
Minimum	0.13	0.12	2.1	2.1
Maximum	3.4	3.5	6.0	5.2
Standard Deviation	0.68	0.82	1.1	1.1
Confidence Interval	(0.57, 0.91)	(0.50, 1.1)	(3.2, 4.0)	(3.2, 4.0)

Table 4-13. Weekly Backwash Wastewater Testing Results

	Parameter		
	TSS (mg/l)	Total Coliforms (cfu/100 ml)	HPC (cfu/100 ml)
Average	0.22	0	50
Minimum	<0.05	0	5
Maximum	0.60	0	130
Standard Deviation	0.23	0	68
Confidence Interval	(0.013, 0.42)	N/A	(-27, 127)

N/A = 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 turbidity of the backwash waste was quite variable but averaged 0.74 NTU. The chlorine residual was relatively consistent averaging 3.6 mg/l. TSS content in the backwash waste was somewhat variable; but the backwash procedure appeared to be removing some particulate material. Total coliforms were absent in the backwash waste but HPC was observed.

4.3.3.5 Total Suspended Solids Mass Balance

The protocol requires that a calculation of the mass balance of TSS be performed. The calculation was to be done from the amount of suspended solids entering the treatment system, the amount in the finished water, and the amount in the backwash waste. The difference in these two results would equal the portion of the TSS which will not be removed by backwashing and accumulates on the membrane. The majority of this accumulated material, presumably, would be dissolved and removed by chemical cleaning.

As previously mentioned, the permeate TSS was slightly higher than the feed TSS. A discussed in Section 4.3.3.3 these results are possibly due to the relatively low levels of TSS in the feed water and analytical limitations. Due to the nature of the analytical results the TSS mass balance can not be calculated.

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 0.3 µm and that 90% of the pores in their membrane are equal to or less than 0.19 µm. The manufacturer reports that these results were generated through the use of ASTM Method F316-86 (Test Method for Pore Size Characterization of Membrane Filters for Use with Aerospace Fluids – Version 86) and Scanning Electron Microscopy photomicrograph analysis. This is provided for informational purposes only. These results are provided by the equipment manufacturer and were not verified during the ETV testing. Appendix I contains an informational brochure with a graphic representation of the above information.

4.3.5 Task 5: Membrane Integrity Testing

The methods employed for detecting a compromised membrane during the ETV test were the 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 March 11, 1999 after the completion of the chemical cleaning, as is standard procedure for the manufacturer. A complete data table is presented in Appendix C. The following is a discussion of the membrane integrity testing results.

4.3.5.1 Air Pressure Hold Test Results

The membrane vessel with the intact membrane was removed from the treatment unit and the filtrate side was drained. The membrane itself was fully wetted (i.e. membrane pores were filled with water). The membrane was air pressurized up to 16 psi. The filtrate side was sealed and the pressure decline rate was monitored using an air pressure gauge.

At time zero the air pressure was 16.1 psi, after three minutes the air pressure was 15.9 psi. At five minutes the air pressure inside the membrane was 15.8 psi, this demonstrated that the membrane was intact. (An intact membrane would be expected to lose no more than 1 psi every five minutes.)

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

At time zero the air pressure was 18.5 psi, after two minutes the air pressure was 7.3 psi. At five minutes the air pressure inside the membrane was zero psi. This demonstrated that the membrane was compromised.

4.3.5.2 Turbidity Reduction Monitoring

Turbidity of feed and filtrate water was monitored. An intact membrane would be expected to show a 90% reduction in turbidity from feed to filtrate. Due to the high quality of the feed water, the average feed turbidity was 0.088 NTU, showing a 90% reduction, 0.0088 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 15 hours before the membrane was compromised averaged 0.033 NTU. The turbidity of the filtrate in the two hours after the membrane was compromised was 0.14 NTU. The permeate turbidity was somewhat variable during the run with the compromised membrane. It fluctuated from a maximum of 0.36 NTU to a minimum of 0.016 NTU.

Turbidity reduction monitoring between feed and finished water was not possible due to the low feed water turbidity level. The filtrate turbidity produced by an intact membrane was significantly lower than the filtrate turbidity produced by a compromised membrane. Comparison of the filtrate turbidity between intact and compromised membranes did detect a compromised membrane. Given the variability in permeate turbidity during the run with the compromised membrane care should be taken in using this method for detecting a compromised membrane.

4.3.5.3 Particle Count Reduction Monitoring

Particle count reductions from source to finished water of 99.9% could indicate an intact membrane. The average cumulative feed water particle counts were 120 total counts per ml, showing a 99.9% reduction would equal total cumulative counts of 0.12 counts per ml. Average permeate particle counts throughout the verification testing were 0.54 counts per ml. Therefore a 99.9% reduction could not be used as an indication of an intact membrane. Differences between filtrate particle counts from an intact and a compromised membrane were compared. An increase of 100% was used as an indication of a compromised membrane.

The average cumulative particle count of the filtrate in the 15 hours before the membrane was compromised was 0.52 counts/ml. The average cumulative particle count of the filtrate in the two hours after the membrane was compromised was 82 counts/ml. The permeate particle counts were somewhat variable during the run with the compromised membrane. They fluctuated from a maximum of 640 counts per ml to a minimum of zero counts per ml. In fact, only two of eight counts were in excess of 0.75 count per ml. This variability of the particle count readings raises some question as to the reliability of using particle counts as an indication of a compromised membrane. Care should be taken in relying on this method solely to detect a compromised membrane.

4.3.6 Task 6: Giardia and Cryptosporidium Removal

The purpose of this task was to demonstrate the treatment unit's ability to provide a minimum 3 $\log_{10}$ removal from feed water to plant effluent of *Giardia* cysts and a 2 $\log_{10}$ *Cryptosporidium* oocysts. The *Giardia* and *Cryptosporidium* challenge took place on February 5, 1999. The system operated at a manufacturer recommended flux of 120 gfd at 20^{o}C (77 gfd at 3.6^{o}C) and an average specific flux of 5.0 gfd/psi at 20^{o}C (50 l/m^{2}/h/b at 20^{o}C) during the *Giardia* and *Cryptosporidium* removal challenge testing.

4.3.6.1 Feed Water Concentrations

During the *Giardia* and *Cryptosporidium* removal challenge testing, the feed water had a pH of 7.7, a turbidity of 0.10 NTU, and a temperature of 3.6^{o}C. Based on the results of hemocytometer replicate counts, a total of 10,768,000 *Giardia* cysts and 104,548,000 *Cryptosporidium* oocysts were added to 50 gallons of feed water in the feed water reservoir. This resulted in a concentration of 215,360 *Giardia* cysts per gallon and 2,090,960 *Cryptosporidium* oocysts per gallon in the feed water. The stock suspension of feed water and the cysts and oocysts was constantly mixed using a drum mixer. A diaphragm pump was used to add the stock suspension to the Pall WPM-1 unit. The pump was operated at about 0.85 gpm, (3.2 liter per minute) and was capable of overcoming the pressure in the feed water line of the pilot unit. The feed water from the feed water reservoir was fed to the system for approximately 60 minutes.

As a QC check of the hemocytometer counts, a composite of the feed water was created from five two-ml aliquots taken at five to ten minute intervals. Microscopic examination of the results of this composite indicated 11,780,000 *Giardia* cysts and 101,080,000 *Cryptosporidium* oocysts. These results were 9.4 % greater and 3.3% less, respectively, than the results obtained from the

hemocytometer counts. The hemocytometer counts were used to calculate the initial concentration of the feed water per EPA protocols and due to the uncertain nature of sampling and mixing of the suspension, which could render the composite sample results questionable. The feed water results of the replicate hemocytometer counts are presented in Table 4-14. The microscopic examination results of the composite sample are presented in Table 4-15. Bench data sheets and report from the laboratory are enclosed in Appendix H.

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

	Giardia Cysts	*Cryptosporidium* Oocysts
Average count (oocysts or cysts/0.0001ml)	134	1,306
Standard Deviation	12	8
Confidence Interval	(122, 146)	(1,298, 1,314)
Total cysts and oocysts added to feed water reservoir (8 mls of stock suspension)	10,768,000	104,548,000
Feed Water Amount Confidence Interval	(9,760,000, 11,680,000)	(103,840,000, 105,120,000)

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

	Giardia Cysts	*Cryptosporidium* Oocysts
Presumptive count (oocysts or cysts/ml)	62	532
Total cysts and oocysts added to feed water reservoir	11,780,000	101,080,000

4.3.6.2 Permeate Concentrations

No *Giardia* cysts or *Cryptosporidium* oocysts were identified in the permeate as shown by the absence of cysts and oocysts on the 1 µm yarn wound capture filter. These results demonstrated a 5.8 $\log_{10}$ removal of *Giardia* cysts and a 6.8 $\log_{10}$ removal of *Cryptosporidium* oocysts using the hemocytometer counts of the feed water. During the *Giardia* and *Cryptosporidium* removal challenge testing, the filtrate had a turbidity of 0.026 NTU and an average cumulative particle counts of 0.65 counts/ml.

The $\log_{10}$ removal of *Giardia* cysts or *Cryptosporidium* oocysts was calculated by first dividing the amount of permeate sampled by the total amount of permeate filtered by the system. In this case, one gallon per minute was filtered through the sampling filter compared to four gallons per minute of permeate produced by the treatment system. This result was applied to the total amount of cysts added to the treatment system and used to calculate the total amount of cysts which could have been trapped on the sampling filter. This number was converted to its $\log_{10}$ equivalent. The percent recovery of the test method at the PWSA laboratory is 25%, this means that the lowest number of cyst or oocysts that could be detected is four. That is, if four cysts or oocysts were in the permeate one of them would be detected. This number, four, was also converted to its $\log_{10}$ equivalent. The final log removal calculation was made by subtracting the $\log_{10}$ of the number of cysts added to the sampling filter less the $\log_{10}$ of the number of cysts trapped on the sampling filter, in this case zero, and then subtracting the $\log_{10}$ of the number four. Table 4-16 presents the concentrations and the $\log_{10}$ removal calculations of the *Giardia* cysts and *Cryptosporidium* oocysts.

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

	Giardia Cyst Removal	*Cryptosporidium* Oocyst Removal
Cysts/oocysts in Feed Reservoir *(from Table 4-14)*	10,768,000	104,548,000
Cysts/oocysts Added to Capture Filter *(The total number of cysts/oocysts in Feed Reservoir multiplied by 25% because the system was pumping at 4gpm and sampled at 1gpm. Effectively, only 25% of the total cysts/oocysts added could have been detected on the capture filter.)*	2,692,000	26,140,000
Log_{10} of Cysts/oocysts Added to Capture Filter	6.4	7.4
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)*	5.8	6.8

4.3.6.3 Backwash Examination

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

4.3.6.4 Operational and Analytical Data Tables

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

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

Date	Time	Feed Pressure (psi)	Retentate Pressure (psi)	Filtrate Pressure (psi)	Transmembrane Pressure (psi)
02/05/99	10:24	29	26	3	24
02/05/99	13:20	28	30	3	25

Table 4-18. Specific Flux During *Giardia* and *Cryptosporidium* Removal Testing

Date	Time	Specific Flux (gfd/psi @20°C)
02/05/99	10:24	5.2
02/05/99	13:20	4.8

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

		Feed		Filtrate	
Date	Time	Turbidity (NTU)	Turbidity (duplicate) (NTU)	Turbidity (NTU)	Amount Removed (NTU)
02/05/99	10:50	0.10	0.11	0.026	0.074
02/05/99	12:45	0.09			

Note: Feed water turbidity sampled prior to injection of challenge feed solution.

Table 4-20. Feed Water Particle Counts 2/5/1999

	Size						
	2-3µm	3-5µm	5-7µm	7-10µm	10-15µm	>15µm	Cumulative
Average	71	42	12	6.5	2.2	0.68	130
Minimum	0.17	0.12	0.090	0.090	0.24	0.060	N/A
Maximum	130	77	20	10	4.6	2.1	N/A
Std Dev	21	12	3.6	1.9	0.84	0.32	N/A
Confidence Interval	(67, 76)	(39, 44)	(11, 12)	(6.0, 6.9)	(2.1, 2.4)	(0.61, 0.74)	N/A

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

Table 4-21. Finished Water Particle Counts 2/5/1999

	Size						
	2-3µm	3-5µm	5-7µm	7-10µm	10-15µm	>15µm	Cumulative
Average	0.20	0.22	0.11	0.0	0.064	0.049	0.64
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	N/A[1]
Maximum	8.3	7.3	4.2	0.0	1.9	0.97	N/A[1]
Std Dev	0.97	0.82	0.44	0.0	0.20	0.10	N/A[1]
Confidence Interval	(0.0060, 0.40)	(0.054, 0.38)	(0.024, 0.20)	N/A	(0.025, 0.10)	(0.028, 0.070)	N/A[1]

N/A = Not applicable because standard deviation = 0.
N/A[1] = Not Applicable. Statistical measurements on cumulative data do not generate meaningful data.

Table 4-22. Daily Backwash Wastewater Testing Results During *Giardia* and *Cryptosporidium* Removal Testing

Date	Time	Turbidity (NTU)	Turbidity (dup) (NTU)	Chlorine Residual (mg/l)	Chlorine Residual (dup) (mg/l)
02/05/99	11:15	1.66	1.67	2.20	2.40
02/05/99	12:45	0.25			

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

4.3.6.5 Discussion of Results

No *Giardia* cysts or *Cryptosporidium* oocysts were observed in the permeate. The membranes appeared to successfully remove all of the *Giardia* cysts and *Cryptosporidium* oocysts introduced into the treatment system. Since the percent recovery of the analytical method is 25% there is a slight possibility that some cysts or oocysts passed through the membrane and were not identified during analysis. Nevertheless, the treatment system provided 5.8 $\log_{10}$ removal of *Giardia* cysts and a 6.8 $\log_{10}$ removal of *Cryptosporidium* oocysts. These results indicate that the treatment system would be capable of successfully complying with the current protozoan removal requirements of the SWTR and ESWTR, if used on this source water. The current provisions are 3 $\log_{10}$ removal of *Giardia* cysts and 2 $\log_{10}$ removal of *Cryptosporidium* oocysts as stated in Section 3.1.1.2.

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

4.4 Equipment Characteristics Results

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

4.4.1 Qualitative Factors

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

4.4.1.1 Susceptibility to Changes in Environmental Conditions

Changes in environmental conditions that cause degradation in feed water quality can have an impact on the treatment system. The short duration of the testing cycle and the stable nature of the feed water minimized the opportunity for significant changes in environmental conditions. As previously stated the reservoir water was treated (coagulated, flocculated, settled, filtered, and disinfected) surface water that had been pumped from PWSA's Aspinwall treatment plant. The fact that the feed water was finished drinking water stored in an open reservoir limited the opportunity for significant changes in feed water quality. No environmental upsets significant enough to affect feed water quality occurred during testing. Since the treatment unit was housed in the pumping station and is 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. A power failure occurred at the pumping station on March 3 and caused the treatment system to shut down. After the system was reset by Pall personnel, the treatment unit was restarted.

Manual operation was required for chemical cleaning of the system and to refill the container of sodium hypochlorite used to supply chlorine to the backwash water. Data was transmitted daily to Pall headquarters. After examination of the data, necessary operational changes could be made remotely from Pall's offices. Not all of the operational parameters could be changed from the remote location. 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 and pressurized water. The electrical service was connected according to local code requirements and did not represent an unusual safety risk. The water pressure inside the treatment system was relatively low and did not represent an unusual safety risk.

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

The cleaning chemicals, citric acid and sodium hydroxide are hazardous chemicals. The use of appropriate PPE minimizes the risk of exposure to this substance. The prompt and proper clean up of spills minimizes the hazards associated with this chemical.

No injuries or accidents occurred during the testing.

4.4.2 Quantitative Factors

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

Cost factors for the above items are discussed where applicable. It is important to note that the figures discussed here are for the Pall Corporation WPM-1 Pilot System operating at 77 gfd at 3.8^{o}C (120 gfd at 20^{o}C). Costs will vary if the system is operated at different flux rates.

4.4.2.1 Power Supply Requirements

The unit was operated with 208 – 240 VAC, single phase, 15 Amp current as required by the O&M manual. Daily power consumption of the treatment unit was determined by reading a dedicated electric meter. The electric meter was installed by a certified electrician according to the local electric code.

It became apparent after the first days that the meter was not registering electric usage. It was determined that the electric meter was not functioning. Due to the short duration of the study and the inability of the electric contractor to respond in a timely manner it was not possible to change the meter before the end of the study.

4.4.2.2 Consumable Requirements

Consumable commodities included sodium hypochlorite and the cleaning chemicals, citric acid and sodium hydroxide. Sodium hypochlorite was added to the permeate used for backwashing. The total chlorine residual in the backwash waste was 3.6 mg/l. This level of chlorine residual required approximately 1/2 gallon of 12.5% sodium hypochlorite per month. The chemical cleaning episode requires 8 lbs. (3600 g) of citric acid and about 1.7 lbs (760 g) sodium hydroxide. Each of these chemicals is added to approximately 50 gallons of permeate.

4.4.2.3 Waste Disposal

The wastes generated by the treatment system were backwash water and the chemical cleaning wastes. The *Giardia* and *Cryptosporidium* 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 220 gpd of backwash water during verification testing.

The characterization of the citric acid cleaning wastewater indicated that the solution was acidic, with a pH of 2.2. The citric acid cleaning waste had a turbidity of 0.81 NTU and a TDS of 10,025 mg/l. No chlorine was used in conjunction with the citric acid solution. The caustic/chlorine cleaning waste had a pH of 12.6, a turbidity of 0.34 NTU, and a TDS of 5,862 mg/l. The total chlorine residual of the caustic/chlorine cleaning waste was 120 mg/l. The wastewater during the citric acid cleaning had a light yellow-green color.

The backwash waste was finished water, residual chlorine and solids removed from the membrane; it required no treatment prior to discharge to the sewers. The average concentration of TSS in the backwash waste was 0.21 mg/l. The range of TSS concentration was from less than 0.050 mg/l to 0.60 mg/l. The chlorine concentration in the backwash wastewater averaged 3.6 mg/l and ranged from 2.2 mg/l to 6.0 mg/l.

A complete presentation of the backwash wastewater data is included in Appendix C.

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

4.4.2.4 Length of Operating Cycle

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

The filtration cycle is the length of time between system backwashes. The interval between backwashes is made based on the maintenance of flux. That is, if the backwash is not able to maintain flux at a particular level, the frequency of backwashing is increased. The filtration cycle was 30 minutes for the verification study. The unit under went a system backwash twice per hour. One of the backwashes was a RF cycle and the other was a RF/AS cycle.

The interval between chemical cleaning is estimated to be 30 days. Pall recommends that cleaning be done when the RF and RF/AS cycles are unable to maintain a TMP of less than 30 psid. The unit had undergone chemical cleaning 13 days prior to the start of the verification testing. The TMP reached 30 psid 5 days after the conclusion of the 30 day testing.

4.5 QA/QC Results

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

4.5.1 Daily QA/QC Results

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

The inline feed water turbidimeter flow rate averaged 399 ml/minute. The flow rate was verified volumetrically using a graduated cylinder and stop watch. The maximum rate measured, during the testing was 660 ml/minute; the minimum was 50 ml/minute. This occurred on the first day and after conferring with Pall representatives to verify that the instrument did not have specialized operating parameters, the flow rate was adjusted to within its normal operating 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 11 of the 30 days of testing.

The readout from the inline turbidimeter averaged 0.055 NTU; the average from the benchtop turbidimeter was 0.088 NTU. The discrepancy between these two results can be explained by differences in the analytical techniques between the online and benchtop turbidimeter and the low level of turbidity in the 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 online 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. Manufacturer's specifications state that stray light interference is less than 0.02. Stray light interference approaching this level at the low turbidity levels tested could account for the differences in the readings.

The inline filtrate turbidimeter flow rate averaged 400 ml/minute. To determine the flow rate of the inline filtrate turbidimeter, the flow was measured using a graduated cylinder and stop watch. The maximum rate measured during the testing was 650 ml/minute; the minimum was 50 ml/minute. This occurred on the first day and after conferring with Pall representatives to verify that the instrument did not have specialized operating parameters, the flow rate was adjusted to within its normal operating 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 4 of the 30 days of testing.

The readout from the inline turbidimeter averaged 0.026 NTU; the average from the benchtop turbidimeter was 0.042 NTU. The discrepancy between these two results can be explained by differences in the analytical techniques between the online and benchtop turbidimeter and the low level of turbidity in the permeate. The benchtop turbidimeter uses a glass cuvette to hold the sample; this cuvette can present some optical difficulties for the benchtop turbidimeter. The online turbidimeter has no cuvette to present a possible interference with the optics of the instrument. The low level of turbidity in the permeate also can create analytical difficulties, particularly for the benchtop. Manufacturer's specifications state that stray light interference is less than 0.02. Stray light interference approaching this level at the low turbidity levels tested could account for the differences in the readings.

The feed water particle counter flow rate averaged 99.5 ml/minute. To determine the flow rate of the inline filtrate turbidimeter, the flow was measured using a graduated cylinder and stop watch. The maximum flow rate measured was 104 ml/minute; the minimum was 94 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 two times during the verification study.

The finished water particle counter flow rate averaged 97.9 ml/minute. The flow rate was verified using a graduated cylinder and stop watch. The maximum flow rate measured was 102 ml/minute; the minimum was 95 ml/minute. The target flow rate specified by the manufacturer is 100 ml/minute. Efforts were made to keep the flow rate between 95 ml/minute to 105 ml/minute. Adjustments to the flow rate were required one time during the verification study.

4.5.2 Bi-weekly QA/QC Verification Results

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

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

The flow meter readout was verified during the testing. The readout was compared to the results obtained from the actual amount measured using a graduated cylinder and stopwatch. The acceptable range of accuracy for the feed, finished and backwash meters was +/- 10%. The permeate water meter readout averaged 2.5 % higher than actual according to the results obtained during the flow verification. The retentate water meter readout averaged 3.8 % lower than actual according to the results obtained during the flow verification. The treatment system did not have a backwash 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 feed water and permeate pressure gauges were checked prior to the start of testing. (The manufacturer was unable to remove the retentate pressure gauge from the treatment unit.) Dead weights of 5,10, 15, 20, and 30 pounds were used. The feed water pressure gauge averaged 4.1 psi, 9.0 psi, 14.0 psi, 18.9 psi, and 28.9 psi when tested with the above weights. The permeate pressure gauge averaged 4.2 psi, 9.8 psi, 14.2 psi, 19.8 psi, and 29.5 psi when tested with the above weights. These results were considered satisfactory.

The tubing used on the treatment system was inspected for cracks and flaws which could have caused unexpected failure prior to the initiation of testing. The tubing was in good condition and replacement was not necessary.

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

The feed water particle counter showed an average response for the 5 µm size of 1,600 counts/ml; the 10 µm size showed an average response of 1,200 counts/ ml; the 15 µm size showed an average response of 860 counts/ ml. This corresponds to a difference of 20%, 64%, and 132% 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 5 µm standard used was 20%. The readings for 5 µm feed water particle counts obtained during the verification testing should be increased by 20% to account for the low response of the 5 µm size range of the feed water particle counter. Due to extremely low results in the 10 µm and 15 µm size range the reliability of the 7-10 µm, 10-15 µm, and >15 µm particle counts should be considered questionable.

The finished water particle counter showed an average response for the 5 µm size of 1,800 counts/ml; the 10 µm size showed an average response of 1,700 counts/ ml; the 15 µm size showed an average response of 1,600 counts/ ml. This corresponds to a difference of 10%, 15%, and 22% respectively in particle counts. The 10 µm and 15 µm results were outside of the generally recognized range of +/- 10 %. The manufacturer of the particle counters was contacted as described above. The average percent difference for the 5 µm, 10 µm, and 15 µm standards was 16%. The readings for finished water particle counts obtained during the verification testing should be increased by 16% to account for the low response of the finished water particle counts

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 J.

4.5.4 Analytical Laboratory QA/QC

Samples for analyses conducted on feed and finished water are listed in Table 4-1. 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. The PWSA's QA/QC results from the ICR 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 results of the analytical instrumentation used to conduct the analyses listed in Table 4-1 on finished water is recorded and kept on file at the PWSA laboratory.

Chapter 5
References

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

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