June 2001
NSF 01/05/EPADW395

Environmental Technology Verification Report

Physical Removal of Microbiological and Particulate Contaminants in Drinking Water

ZENON
ZeeWeed® ZW-500 Ultrafiltration Membrane System
Sandy, OR

Prepared by

NSF International

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

ETV ETV ETV

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**MEMBRANE FILTRATION USED IN PACKAGED DRINKING WATER TREATMENT SYSTEMS**
APPLICATION:	**PHYSICAL REMOVAL OF MICROBIOLOGICAL AND PARTICULATE CONTAMINANTS IN DRINKING WATER**
TECHNOLOGY NAME:	**ZEEWEED® ZW-500 ULTRAFILTRATION SYSTEM**
TEST LOCATION:	**SANDY, OREGON**
COMPANY:	**ZENON ENVIRONMENTAL SYSTEMS INC.**
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

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

NSF International (NSF) in cooperation with the EPA operates the Drinking Water Treatment Systems (DWTS) program, one of 12 technology areas under ETV. The DWTS 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 ZENON

ZeeWeed™ ZW-500 Membrane Filtration System. CH2M HILL, an NSF-qualified field testing organization, performed the verification testing.

ABSTRACT

The ZeeWeed® ZW-500 membrane filtration system was evaluated over the course of three test periods, for a minimum of 30 days each, under a variety of water quality conditions. During the test periods, the feed water turbidity ranged from less than 1 ntu to over 200 ntu.

The ZeeWeed® ZW-500 unit produced water with turbidity of 0.05 ntu or less 95 percent of the time and obtained three to four log removal of particles greater than 2 microns in size. Microbial challenge studies showed that the ZeeWeed® ZW-500 membrane provided better than 4-log removal of *Cryptosporidium*, 3-log removal of viruses, and 3-log removal of *Giardia*. In many cases, the log removals of *Giardia* and *Cryptosporidium* were limited by the number of organisms in the feed.

The permeate flux (normalized to 20°C) exceeded 45 gfd and was typically greater than 65 gfd. Vacuum-based membrane systems are limited in flux based on the inherent water permeability of the membrane and the maximum suction head (vacuum) produced by the permeate pump. Based on the low rate of membrane fouling, increased fluxes would have been possible during the first and second test periods with a larger permeate pump. Permeate recovery was typically 94 to 95 percent.

TECHNOLOGY DESCRIPTION

The ZeeWeed® process uses hollow-fiber ultrafiltration (UF) membranes immersed in a process tank containing source water to be treated. The hollow-fiber membrane is designed to exclude particulate matter exceeding 0.157 microns in size, including *Cryptosporidium* oocysts and *Giardia* cysts, from the treated water stream.

The loose, hollow fiber membranes are assembled into modules by connecting the fibers at both ends (manifolding). During treatment, a vacuum is applied to the inside (lumen side) of the fibers at each manifold. The resulting difference in pressure across the wall of the membrane causes water to flow from the outside of the fiber (feed side) through the membrane pores to the inside, thus becoming filtered (treated) water. The vacuum applied corresponds to the transmembrane pressure for the system.

VERIFICATION TESTING DESCRIPTION

Test Site

The testing was performed at the City of Portland's Bureau of Water Headworks located near Sandy, Oregon. The raw water source was Bull Run Reservoir #2, an impoundment of water from the Bull Run River, on the southwest flank of Mt. Hood.

This source is characterized by low total organic carbon and total dissolved solids, and low to moderate turbidity. During Period 3, turbidity of the source water was augmented with natural clays from the watershed. The pH was typically in the range 6.8-7.2. The temperature ranged from 4.5 to 16°C. Table VS-1 summarizes feed water quality during the test periods.

Table VS-1. Average Feed-Water Quality

Parameter	Units	Period 1	Period 2	Period 3
Alkalinity	mg/L as $CaCO_3$	7.3	6.5	9.6
Total Hardness	mg/L as $CaCO_3$	7.0	5.9	8.2
Calcium Hardness	mg/L as $CaCO_3$	3.9	3.5	4.9
Total Dissolved Solids	mg/L	21 to 22	18	23
Total Suspended Solids	mg/L	8	1	20
Total Coliforms	MPN/100 mL	13	<1	<1
Heterotrophic Plate Count	MPN/100 mL	126	13	74
Total Organic Carbon	mg/L	1.57	0.89	0.93
UV 254	cm^{-1}	0.058	0.037	0.038
SDS TTHM	µg/L	46	28.6	27.2
SDS HAA6	µg/L	73	35.8	27.3
Turbidity (average and range)	ntu	2.14 (0.5 to 10.0)	0.49 (0.4 to 0.7)	18 (0.3 to 250)
Particle Count (>2 µm) (average and range)	#/mL	9,807 (4,000 to 19,500)	4,613 (3,000 to 7,500)	10,094 (1,200 to 27,000)

Methods and Procedures

The package system was operated under the conditions recommended by the manufacturer and monitored 24 hours per day during each test period. During routine operation, the following analyses were performed onsite:

- feed water pH (daily)
- feed water temperature (on-line)
- feed water turbidity (on-line)
- permeate turbidity (on-line)
- concentrate turbidity (on-line)
- particle counts in feed water and concentrate (on-line)

The following samples were collected weekly (unless otherwise indicated) and analyzed at an off-site laboratory:

- alkalinity
- total and calcium hardness
- total dissolved solids
- heterotrophic plate count
- total organic carbon
- UV absorbency at 254 nm
- simulated distribution system total trihalomethanes (monthly)
- simulated distribution system haloaceticacids (monthly)

Total suspended solids and total coliform samples were collected weekly from the feed water, permeate, and concentrate.

Microbial challenge tests were performed to evaluate removal of pathogens of concern in drinking water. The challenge tests were performed just after the membranes were cleaned to be sure that there was no screening effect from particles that had built up on the membrane surface. MS-2 phage and formalin-fixed *Giardia cysts* and *Cryptosporidium oocysts* were added to a large tank, mixed well with the feed water and treated with the ZeeWeed® ZW-500 membrane filtration system. Samples were then collected from the feed, concentrate, and permeate. *Giardia* and *Cryptosporidium* analyses were performed in the permeate using USEPA Method 1623 and 1622, respectively. The MS-2 phage concentrations were measured using SM18 9211D.

During the third and final test period, the turbidity of the feed water was augmented with sediment from the watershed, which had been previously observed to increase the turbidity of the reservoir during severe rain events. The turbidity was increased to as high as 250 ntu and averaged 18 ntu during this test period.

VERIFICATION OF PERFORMANCE

System Operation

Table VS-2 summarizes the membrane flux and recovery, two of the critical performance criteria. During test periods one and two, the membrane flux was limited only by the vacuum pump supplied with the unit. Increased fluxes would have been possible. During the third test period the turbidity was great enough that increased flux would not have been possible. The ZW-500 membrane filtration system was capable of handling a wide variety of turbidities, up to 250 ntu, without sacrificing flux or recovery.

Table VS-2. Summary of Membrane Operational Parameters

Test Period	Mean Temperature	Flux (95 percent confidence interval)	Recovery (95 percent confidence interval)
1	5.8°C	49.7 ± 0.3 gfd	94.5 ±0.1%
2	6.2° C	48.6 ± 0.1 gfd	94.7 ±0.03%
3	15° C	46.2 ± 0.3 gfd	94.4 ±0.1%

The membranes operated for an interval of 30 days between cleanings even when treating water with high turbidity. Cleaning with chlorine typically restored the specific flux.

Water Quality Results

Table VS-3 summarizes the turbidity and particle removal observed during the test. The ZW-500 membrane system provided excellent turbidity and particle removal. The turbidity was equal to or less than 0.05 ntu in 95% of all samples during all three test periods. The particle counts were less than 30 particles per mL and particle removal exceeded 3.5 log 95 percent of the time. The results indicate that this membrane system is able to effectively remove particles and provide drinking water under a variety of conditions. These removals were also exhibited during the microbial challenge studies. Table VS-4 summarizes the observed performance. *Cryptosporidium* was always below detection in the permeate and the log removal results were limited by the detection limit in the permeate and the amount measured in the feed. Although some *Giardia* were detected in the permeate, the concentrations detected were typically less than 1 organism per liter of water. The virus removal goals were exceeded on a consistent basis. In summary, the ZeeWeed® ZW-500 membrane system provided 3.2 to 3.6-log removal of viruses, >4.3 log removal of *Cryptosporidium*, and >3.3 log removal of *Giardia*. The ZeeWeed® ZW-500 membrane filtration process provided excellent removal of pathogens.

Table VS-3. Summary of Particle Removal

Test Period	Turbidity (ntu) at 95 percent confidence[1]	Particle Counts (particles per mL >2 microns) at 95 percent confidence
1	0.04	1.0
2	0.05	5.0
3	0.05	28

[1]95 percent of the values in permeate are less than the value shown

Table VS-4. Summary of Microbe Removal

Test Period	*Giardia*	*Cryptosporidium*	MS-2 Phage
1	>3.3 log	>5.4 log	3.6 log
2	4.7 log	>4.3 log	3.6 log
3	5.0 log	>5.0 log	3.3 log

Operation and Maintenance Results

The ZeeWeed® membrane system was easy to operate. Very few adjustments were needed to maintain operation. The automated operations system worked very well. Operation did require a dependable source of electrical power. On several occasions, power surges caused the unit to shut down and required an operator to start it back up.

The manufacturer's pressure hold test demonstrated the ability to confirm if a fiber was severed or if the membrane surface was damaged (pin-pricked). Additionally, integrity testing indicated an apparent restoration of integrity over time due to plugging of the defect by solids within the process tank.

Membrane integrity monitoring using a particle counter confirmed the sensitivity of a particle counter in detecting particles in the permeate. However, particle counting may be an inadequate integrity monitoring technique if particles are being formed downstream of the membrane due to oxidation or other precipitate forming process.

Cleaning did require some informed judgement on the part of the operator. A working knowledge of the control panel and ability to prepare a 200-mg/L chlorine solution were needed to adequately clean the membranes. The operations manual provided the instructions needed to operate the control panel and provided guidance for cleaning.

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E. Timothy Oppelt	Date
Director	
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Original Signed by Gordon Bellen	*07/26/01*
Gordon Bellen	Date
Vice President	
Federal Programs	
NSF International	

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

Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing for Removal of Microbiological and Particulate Contaminants in Drinking Water*, dated February 1999, the Verification Statement, and the Verification Report (NSF Report #01/05/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)

June 2001

Environmental Technology Verification Report

Physical Removal of Microbiological and Particulate Contaminants in Drinking Water

ZENON Environmental Systems Inc. ZeeWeedº ZW-500 Ultrafiltration System

Prepared for:

NSF International
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Prepared by:

CH2M HILL
Corvallis, Oregon 97330

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

Jeffrey Q. Adams, Project Officer
National Risk Reduction Research Laboratory
U.S. Environmental Protection Agency
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Notice

The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development has financially supported and collaborated with NSF International (NSF) under Cooperative Agreement No. CR 824815. This verification effort was supported by Drinking Water Treatment Systems 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 CH2M HILL, in cooperation with ZENON Environmental Systems and the Portland Bureau of Water. The test was conducted during December 1998 through October 1999 at the City of Portland's Bureau of Water headworks, located near Sandy, Oregon.

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 are made available to regulators, developers, consulting engineers, and those in the public health and environmental protection industries. This encourages more rapid availability of approaches to better protect the environment.

The EPA has partnered with NSF, an independent, not-for-profit testing and certification organization dedicated to public health, safety and protection of the environment, to verify performance of small package drinking water systems that serve small communities under the Drinking Water Treatment Systems (DWTS) ETV 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 (FTOs) to conduct verification testing under the approved protocols.

The ETV DWTS 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 CH2M HILL.

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Abbreviations and Acronyms

CI	Confidence Interval
CIP	Clean-in-place
Cl2	Chlorine
Deg C	Degrees Celsius
ETV	Environmental Technology Verification
Fe	Iron
FI	Flow Indicator
FOD	Field Operations Document
FTO	Field Testing Organization
FV	Float Valve
g/L	Grams per liter
gfd	Gallons per square foot per day
gpm	Gallons per minute
HAAs	Halo acetic acids
HAA6	Sum of the following six: haloacetic acids, chloroacetic acid, bromoacetic acid, dichloroacetic acid, trichloroacetic acid, bromo-chloroacetic acid, and dibromoacetic acid.
Hg	Mercury
Hp	Horsepower
in	Inches
L	Liters
LCS	Laboratory control samples
LPM	Liters per minute
LSL	Level Switch Low
mg/L	Milligrams per liter
MPN	Most probable number
MSDS	Material Safety Data Sheets
MS/MSD	Matrix spike/matrix spike duplicates
NaOCl	Sodium hypochlorite
NSF	NSF International, formerly known as the National Sanitation Foundation
ntu	Nephelometric turbidity units
P	Pressure
PCV	Pressure Control Valve
PLC	Programmable Logic Controller
ppm	Parts per Million
psi	Pounds per square inch
psig	Pounds per square inch (gauge)
PSL	Pressure Switch Low
QA	Quality assurance
QC	Quality control
scfm	Standard cubic feet per minute
SDS	Simulated distribution system
SqFt	Square Feet
SV	Solenoid Valve

SWTR	Surface Water Treatment Rule
TMP	Transmembrane pressure
TTHM	Total trihalomethane (sum of chloroform, bromodichloro-methane, chlorodibromo-methane, and bromoform)
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
V	Valve
WSWRD	Water Supply and Water Resources Division
ZWMF	ZeeWeed® Membrane Filtration

Definitions of Operational Parameters

Feed Water: Water Introduced to the ZeeWeed® system
Permeate: Membrane-filtered, treated water produced by the ZeeWeed® system
Concentrate: Wastewater produced by the ZeeWeed® system
Permeate Flux: Permeate flow divided by the surface area of the membrane. As a formula:

$$J_t = \frac{Q_p}{S}$$

Where: J_t = Permeate flux at time t (gallons per square foot per day)
Q_p = System permeate flow at time t (gpd)
S = Membrane surface area in contact with the feed water (ft^2)

Feed Water System Recovery: The recovery of permeate from feed water stated as the ratio of permeate flow to feed water flow:

$$\%\ \text{System Recovery} = 100\ \text{x}\left[\frac{Q_p}{Q_f}\right]$$

Where: Q_p = Permeate flow (gpd)
Q_f = Feed flow to the membrane system (gpd)

Transmembrane Pressure (TMP): The average transmembrane pressure calculated as:

$$P_{tm} = \frac{(P_i + P_o)}{2} - P_p$$

Where: P_{tm} = Transmembrane pressure (psi)
P_i = Pressure at the inlet of the membrane module (psig)
P_o = Pressure at the outlet side of the membrane module (psig)
P_p = Permeate pressure (psig)

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

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

Where: J_{tm} = Specific flux at time t (gfd/psi)
J_t = Permeate flux at time t (gfd)
P_{tm} = Transmembrane pressure (psi)

Membrane Fouling: A reduction in permeate flux that can be restored by mechanical or chemical means is termed "reversible" fouling. In contrast, "irreversible fouling" is defined as a permanent loss in permeate flux capacity that cannot be restored. The fouling of membranes designed for particle or microbial removal is primarily attributed to deposition of materials on the membrane surface and/or in the membrane pores. Membrane fouling produces an increase in transmembrane pressure and a reduction in specific flux.

Temperature-Normalized Flux: Temperature corrections to 20°C for permeate flux were made to correct for changes in water flow through the membrane caused by the variation of water viscosity with temperature using the following formula:

$$J_{tm}(20°C) = \frac{Q_p * e^{-0.0239*(T-20)}}{S}$$

Where:
- J_{tm} = Instantaneous flux (gfd)
- Q_p = System permeate flow (gpd)
- T = Temperature (°C)
- S = Membrane surface area (ft^2)

ACKNOWLEDGMENTS

The Field Testing Organization, CH2M HILL, was responsible for all elements in the testing sequence, including collection of samples, calibration and verification of instruments, data collection and analysis, data management, data interpretation and the preparation of this report.

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The laboratories selected for non-microbiological analytical work of this study were:

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Contact Person: Mark Boedigheimer

and

Portland Water Bureau Laboratories
2010 N. Interstate Avenue
Portland, OR 97227
Contact Person: Alberta Seierstad

The laboratory selected for microbiological analytical work of this study was:

Bio-Vir Laboratory, Inc.
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Benicia, CA 94510
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The Manufacturer of the Equipment was:

ZENON Environmental Systems
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CH2M HILL wishes to acknowledge the input and hard work of the individuals involved in this project.

CH2M HILL
Paul Mueller, Project Engineer
Jim Lozier, Senior Advisor
Kathy McKinley, Laboratory Manager
Mike Keblin, Package Plant Engineer

Jason Oppenheimer, Package Plant Engineer
Gregg Thompson, Package Plant Engineer

The Portland Water Bureau was responsible for day to day operation of the package plant and several analyses as outlined in the Field Operations Document.

Steve Schenk, Project Manager
Mark Knudson, Senior Advisor
Alberta Seierstad, Laboratory Manager
Leonard Cutis, Lead Package Plant Operator

ZENON Environmental Systems provided startup assistance and technical input.

Graham Best, Project Manager
Jodi Cumin, Package Plant Engineer

We wish to thank Bruce Bartley, Project Manager and Carol Becker, Project Engineer of NSF International for their input and guidance throughout the testing and report preparation.

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 Drinking Water Treatment Systems (DWTS) program, one of 12 technology areas under ETV. The DWTS program evaluated the performance of the ZENON ZeeWeed® ZW-500 system, which is a membrane used in package drinking water treatment system applications. The performance testing evaluated the system's ability to treat water ranging from 1 to over 200 nephelometric turbidity units (ntu) and provide removal of *Cryptosporidium*, viruses, and *Giardia*. This document provides the verification test results for the ZENON ZeeWeed® ZW-500 system.

1.2 Testing Participants and Responsibilities

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

NSF International
CH2M HILL
Portland Water Bureau
Bio-Vir
ZENON Environmental Inc.
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. Inspections of the field analytical and data gathering and recording procedures and of the microbiological seeding procedures were conducted by NSF. NSF also provided review of the Field Operations Document (FOD) and this report.

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1.2.2 Field Testing Organization

CH2M HILL, an engineering consulting firm, conducted the verification testing of the ZENON ZeeWeed® ZW-500 system. CH2M HILL is a NSF-qualified Field Testing Organization (FTO) for the Packaged Drinking Water Treatment System ETV project.

CH2M HILL was responsible for conducting the verification testing for three approximately one month test periods over the course of 298 calendar days. CH2M HILL provided all needed logistical support, established a communications network, and scheduled and coordinated activities of all participants. CH2M HILL was responsible for ensuring that the testing location and feed water conditions were such that the verification testing could meet its stated objectives. CH2M HILL prepared the FOD, oversaw the verification testing, managed, evaluated, interpreted and reported on the data generated by the testing, as well as evaluated and reported on the performance of the technology.

CH2M HILL and Portland Water Bureau employees conducted the onsite analyses and data recording during the testing. Oversight of the daily tests was provided by the CH2M HILL's Project Manager and Project Director.

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1.2.3 Manufacturer

The treatment system is manufactured by ZENON Environmental Systems, a manufacturer of membrane systems for the treatment of water and wastewater for municipal and industrial sectors.

The manufacturer was responsible for supplying a field-ready membrane filtration system equipped with all necessary components including treatment equipment, instrumentation and controls and an operations and maintenance manual. The manufacturer was responsible for providing logistical and technical support as needed as well as providing technical assistance to CH2M HILL during operation and monitoring of the equipment undergoing field verification testing.

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1.2.4 Analytical Laboratory

Three laboratories were involved in this project. Table 1-1 summarizes the analyses performed.

Table 1-1. Summary of Laboratory Responsibilities

Laboratory	Test Period	Parameters Analyzed
CH2M HILL's Applied Sciences Laboratory	First Test Period	TOC[1], UV-254[2] Total Coliforms, HPC[3], TDS[4], TSS[5], Calcium Hardness, Alkalinity, Total Hardness
Portland Water Bureau	Second Test Period	TOC, UV-254, Total Coliforms, HPC, TDS, TSS, Calcium Hardness, Alkalinity, Total Hardness
Portland Water Bureau	Third Test Period	TOC, UV-254, Total Coliforms, HPC, TDS, TSS, Calcium Hardness, Alkalinity, Total Hardness
Bio-Vir	All Three Test Periods	All analyses of *Giardia*, *Cryptosporidium*, and MS-2 phage. Bio-Vir also supplied the microbiological samples for the challenge tests

[1] TOC = total organic carbon
[2] UV-254 = absorption of ultraviolet light at a wavelength of 254 nanometers
[3] HPC = heterotrophic plate count
[4] TDS = total dissolved solids
[5] TSS = total suspended solids

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Fax: (707) 747-1751
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1.2.5 U.S. Environmental Protection Agency

The EPA through its Office of Research and Development has financially supported and collaborated with NSF under Cooperative Agreement No. CR 824815. This verification effort was supported by Drinking Water Treatment Systems project 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

Testing was performed at the Portland Bureau of Waterworks' Bull Run Headworks facility, located near Sandy, Oregon. A location map for the site and of the Bull Run watershed is presented in Figure 1-1.

Figure 1-2 shows where the test system was located in

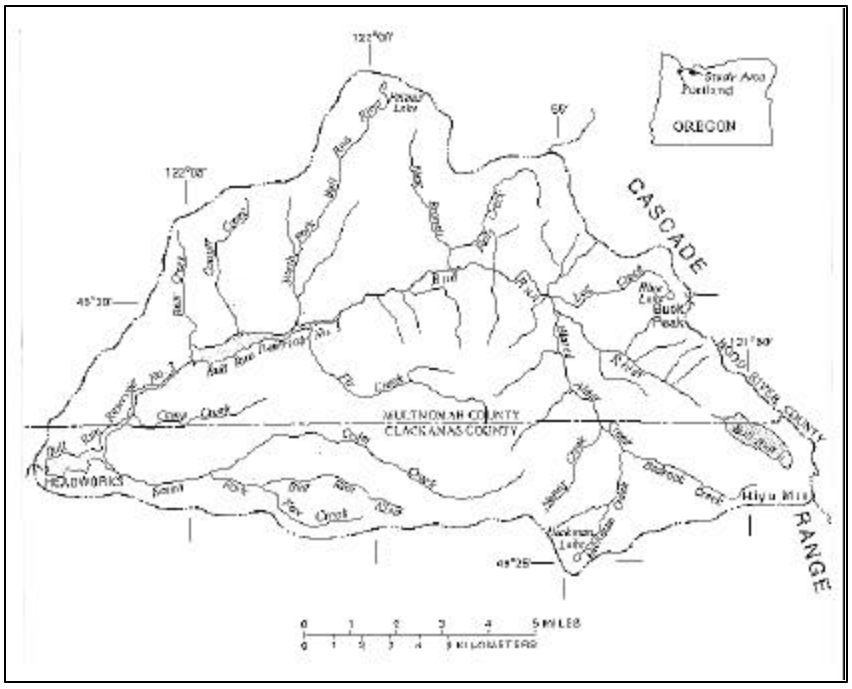


Figure 1-1. Location Map

Screen House #2 at the headworks site. Water for the study was taken from an existing 3" PVC line which supplies raw water for cleaning the traveling screens at the headworks. The 3" line was supplied by gravity pressure (45 pounds per square inch) directly from the main raw water line. This supply was directly representative of raw water entering the Portland water system.

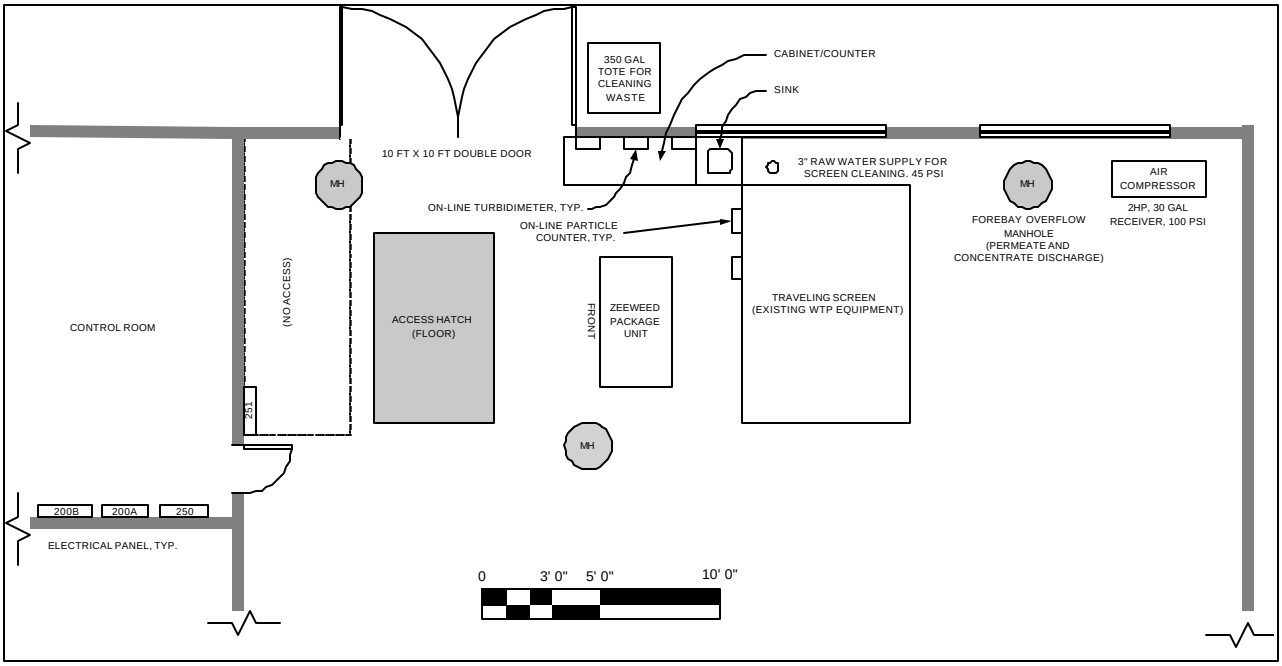


Figure 1-2. Location of Test System in Screen House #2 at Headworks Site

1.3.1 Source Water

The source water for the verification testing was Bull Run Reservoir #2, an impoundment of water from the Bull Run River, on the southwest flank of Mt. Hood.

The water quality is generally quite good with low TOC (<2 mg/L), low alkalinity low hardness, and low turbidity (typically less than one). The water quality during the first test period (December 11, 1998 to January 14, 1999) is summarized in Table 1-2. This test period was characterized by a storm that increased the turbidity to 10 ntu.

Table 1-2. Feed Water Quality During Test Period 1

	Parameter								
	Total Alkalinity (mg/l)	Total Hardness (mg/l)	TDS (mg/l)	TSS (mg/l)	Total Coliforms (MPN/100 ml)	HPC (cfu/ml)	TOC (mg/l)	UVA (cm^{-1})	Turbidity (ntu)
Average	7.3	7.0	21	5	13	126	1.6	0.058	2.1
Minimum	5.5	2.5	<5	1	4	50	1.4	0.054	0.5
Maximum	8.5	14.3	50	13	22	273	1.9	0.063	10
Std. Dev.	1.3	5.1	20	5	8	104	0.24	0.005	0.3
95% Confid Int	6.0 – 8.6	2.0 – 12.0	1 – 41	0 – 10	5 – 21	24 – 228	1.4 – 1.8	0.053 – 0.063	0.0 – 4.4

During the second Test Period the water quality was more stable as shown in Table 1-3.

Table 1-3. Feed Water Quality During Test Period 2

	Parameter								
	Total Alkalinity (mg/l)	Total Hardness (mg/l)	TDS (mg/l)	TSS (mg/l)	Total Coliforms (MPN/100 ml)	HPC (cfu/ml)	TOC (mg/l)	UVA (cm^{-1})	Turbidity (ntu)
Average	6.5	5.9	18	0.9	0.6	13	0.89	0.037	0.49
Minimum	6.1	5.7	16	0.3	0.5	4	0.80	0.032	0.377
Maximum	6.9	6.3	19	2.0	1.0	36	1.1	0.045	0.70
Std. Dev.	0.3	0.3	2	0.8	0.3	15	0.14	0.006	0.09
95% Confid Int	6.2 – 6.8	5.6 – 6.2	17 – 19	0.1 – 1.7	0.4 – 0.8	0 – 28	0.75 – 1.0	0.031 – 0.043	0.48 – 0.50

During the third Test Period, the turbidity was augmented with natural clays that were found on the watershed. Table 1-4 summarizes the feed water quality.

Table 1-4. Feed Water Quality During Test Period 3

	Parameter								
	Total Alkalinity (mg/l)	Total Hardness (mg/l)	TDS (mg/l)	TSS (mg/l)	Total Coliforms (MPN/100 ml)	HPC (cfu/ml)	TOC (mg/l)	UVA (cm^{-1})	Turbidity (ntu)
Average	9.6	8.2	23	20	0.6	74	0.93	0.038	18
Minimum	7.9	7.1	21	1.0	0.5	25	0.75	0.031	0.28
Maximum	12	9.4	26	85	1.0	130	1.1	0.064	199
Std. Dev.	1.6	1.1	2.0	37	0.2	50	0.14	0.014	36
95% Confid Int	8.2 – 11.0	7.2 – 9.2	21 – 25	0 – 52	0.4 – 0.8	25 – 123	0.81 – 1.1	0.025 – 0.051	12.5 – 23.5

1.3.2 Package Plant Effluent Discharge

The effluent of the package treatment unit was passed to the floor drain in the building that housed the package unit. No discharge permits were required.

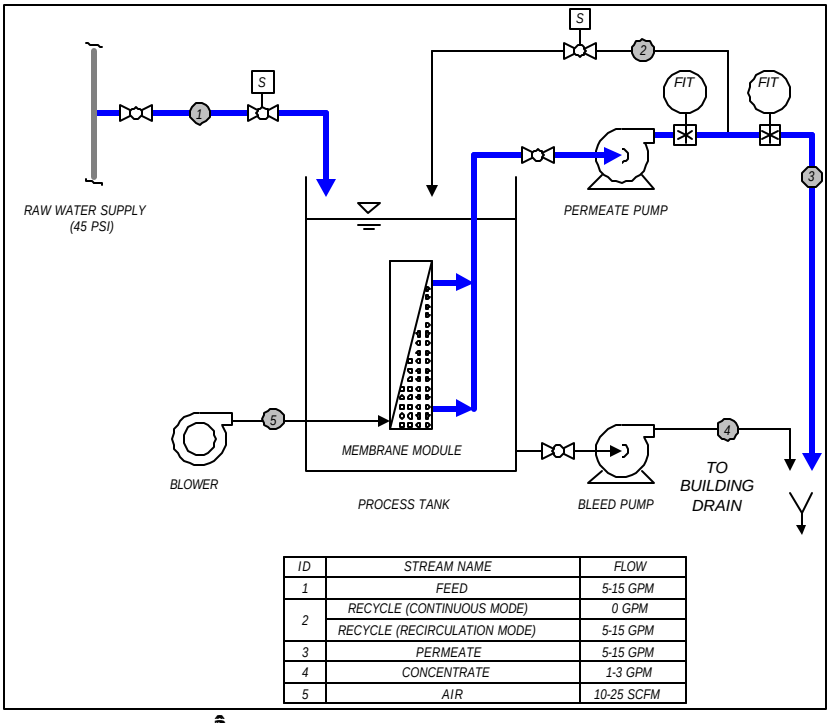
Chapter 2
Equipment Description and Operating Processes

The unit tested was a package unit containing a hollow fiber ultrafiltration membrane module that utilizes a vacuum applied to the inside (lumen) of the hollow fiber to produce filtered water. The system tested uses a single ZeeWeed® ZW-500 module with approximately 700,000 membrane fibers, providing approximately 512 square feet of exterior membrane surface area. The membrane module is placed in a process tank, which continuously receives feed water to be treated. A small waste flow of concentrate from the process, containing particulates and solids rejected by the membrane, is continuously pumped from the process tank. The system tested utilized all the pumps, valves, and appurtenances that would normally be used in a full-scale, multi-module system. The following text describes the system tested in more detail.

2.1 Equipment Description

A simplified process schematic of the ZeeWeed® process is shown in Figure 2-1. The package unit used in this study has the ability to operate with or without permeate recycle (known as recirculation mode and continuous mode, respectively). The system was operated without recycle in this study.

During treatment, a vacuum is applied to the inside (lumen side) of the fibers at each manifold. The resulting difference in pressure across the wall of the membrane causes water to flow from the outside of the fiber (feed side) through the membrane pores to the inside, thus becoming filtered (treated) water. The vacuum applied corresponds to the transmembrane pressure for the system.



ID	STREAM NAME	FLOW
1	FEED	5-15 GPM
2	RECYCLE (CONTINUOUS MODE)	0 GPM
	RECYCLE (RECIRCULATION MODE)	5-15 GPM
3	PERMEATE	5-15 GPM
4	CONCENTRATE	1-3 GPM
5	AIR	10-25 SCFM

Figure 2-1. ZeeWeed® Process Schematic

The undesired accumulation of foulants at the outside surface of the fibers was controlled by the following:

- Continuous introduction of air below the surface of the module to cause agitation of the fibers and scour suspended solids from the surface of the membrane, thereby mechanically removing the foulants (air scour).
- Regular backpulsing of the membranes (actuation of automatic valves to reverse the permeate pump, forcing chlorinated treated water through the membrane fibers from inside to

outside). The backpulse regime was held constant throughout the study, using a duration of 15 seconds and an interval of 15 minutes.

- Periodic chemical cleaning with a 200-500 mg/L chlorine solution. Cleaning was performed at the end of each 30-day test period, regardless of the TMP at that time. The time between cleanings may have been longer if the cleanings were performed when the TMP became excessive rather than on a 30-day cycle.

These conditions are typical of full-scale applications. Some minor modifications of chemical cleaning or backpulse frequency and duration are considered on a case by case basis, but were not altered during this test, even during periods of turbidity augmentation.

The ZeeWeed® system evaluated in this study included the following components:

- ZeeWeed® permeate (vacuum) pump
- One ZeeWeed® ZW-500 ultrafiltration module with 512 ft^2 of effective membrane surface area
- A 185-gallon process tank
- Air Scour Blower
- Air compressor for actuation of pneumatic valves
- Integrated clean-in-place (CIP) tank
- Instrumentation and controls

Photograph 1. ZENON ZW-500 Package Unit

Photograph 2. Test Site

2.2 Operating Process

The ZeeWeed® process operates in a direct flow, outside-in configuration where the flow of water is from the outside of the hollow fiber membrane to the inside. Particulates and microbes larger than the membrane pore size remain on the outer surface of the fibers and never enter the membrane to cause fouling and plugging.

The ZeeWeed® ZW-500 uses an immersed membrane and operates under a slight vacuum of 2 to 8 psi, instead of under pressure.

Chlorine was added to the back pulse cycle to improve membrane-cleaning efficiency. A concentration of 5 mg/L of chlorine was the target during the back pulse.

The ZeeWeed® ultrafilter cassette is immersed inside the process tank, where solids accumulate and are mixed up without interfering with the operation of the membrane. According to the manufacturer, the membranes can operate in solids environments as high as two percent.

The manufacturer reports that the ZeeWeed® membrane is resistant to chlorine in concentrations as high as 200 mg/L, potassium permanganate in concentrations up to 100 mg/L, and chlorine dioxide at concentrations up to 5 mg/L. Concentrations higher than these should be avoided. The acceptable pH range for continuous operation is 5-9. Avoid pH values outside of this range except during chemical cleaning.

Chapter 3
Methods and Procedures

3.1 Testing Approach

Testing was conducted in three, 4- to 6-week test periods. The conditions of these test periods are summarized in Table 3-1.

Table 3-1. Summary of Test Periods

Characteristic	Test Period 1	Test Period 2	Test Period 3
Testing Date	December 11, 1998 to January 14, 1999	March 18 to May 22, 1999	August 18 to October 5, 1999
Hours of Operation	763 hours	801 hours	905 hours
Raw Water Turbidity	0.4-10 ntu	0.3-0.8 ntu	0.3 to 0.9 ntu for 20 days >100 ntu for 1 day (augmented with turbidity from the watershed) 10 to 50 ntu for 9 days (augmented with turbidity from the watershed)
Microbial Challenge Tests	1000 (10^3) *Giardia* per Liter	49,000 ($10^{4.3}$) *Giardia* per Liter	8,500 ($10^{3.8}$) *Giardia* per Liter
	130,000 ($10^{5.1}$) *Cryptosporidium* per Liter	9,500 ($10^{4.0}$) *Cryptosporidium* per Liter	4,250 ($10^{3.6}$) *Cryptosporidium* per Liter
	510,000 ($10^{5.7}$) MS-2 phage per mL	1,000,000 (10^6) MS-2 phage per mL	450,000 ($10^{5.7}$) MS-2 phage per mL
Temperature	4-7° C	5-8° C	14 to 18° C
Flux	45 gfd[1]	50 gfd	44 to 45 gfd
Recovery	94 to 95%	94 to 95%	94 to 95%
Backpulse Interval	15 minutes	15 minutes	15 minutes
Backpulse duration	15 seconds	15 seconds	15 seconds

[1] gallons per square foot per day

The approach included operating the unit, measuring system performance and determining the following:

- Membrane Flux and Operation
- Finished Water Quality
- Membrane Integrity Testing
- Cleaning Efficiency
- Microbial Challenge Testing
- Membrane Pore Size

The approach and procedures for the evaluation of these parameters is discussed in greater detail in the following sections.

3.1.1 Membrane Performance

Permeate vacuum and flow, concentrate flow and permeate recoveries were monitored to quantify membrane performance. The results were expressed in terms of a temperature-corrected specific flux value (e.g., gallons per square inch per day/psi to gallons per square foot per day/psi or L/m^2-hr•bar) and permeate recovery. In this and subsequent sections, the use of the term specific flux refers to temperature-corrected specific flux. Additional operating parameters, listed in Table 3-2, were monitored.

The rate of specific flux decline is a function of water quality and operational conditions. A lower rate of specific flux decline implies that a longer operational time can be achieved by the package unit before chemical cleaning is required.

3.1.2 Finished Water Quality

The objective of this task was to assess the ability of the membrane equipment to meet the water quality goals specified by the manufacturer. The following water quality parameters were measured:

- turbidity
- particle counts
- alkalinity, total and calcium hardness
- total dissolved solids
- total suspended solids
- total coliforms
- heterotrophic plate count (HPC)
- total organic carbon
- UV absorbance (at 254 nanometers)
- simulated distribution system trihalomethanes (SDS THMs)
- simulated distribution system haloacetic acids (SDS HAAs)

3.1.3 Membrane Integrity Testing

Monitoring of membrane integrity was performed to ensure that an adequate barrier was continuously being provided by all fibers within the module. In this study, particle count and turbidity data were used as an indirect method for verifying membrane integrity.

In the ZeeWeed® ZW-500 membrane filtration process tank a permeate pump pulls the clean water through the membrane and out of the process tank. The rejected water, particulates, and microorganisms remain behind in the process tank where they are concentrated. The concentrated particles remain mixed in the process tank by the turbulent action of the membrane air scour until they are wasted, either intermittently or continuously. In the system evaluated, concentrate wasting was performed continuously by pumping. At 95 percent recovery, the particle concentration in the concentrate stream is increased approximately twenty-fold relative to the feed.

The particulate content of the product water was monitored at all times during operation using a particle counter. The ZeeWeed® ZW-500 membrane filtration product water is typically degassed upstream of the permeate pump to avoid cavitation and to maintain a consistently primed system. A side benefit of this degassing is that the product water is low in entrained air bubbles, which can cause false particle count readings. A degasser was not installed on the

package unit upstream of the permeate pump. Instead, a degasser was installed upstream of the particle counter by CH2M HILL to prevent gas bubbles from causing false positives.

3.1.4 Cleaning Efficiency

The objective of this task was to evaluate the effectiveness of the manufacturer's recommended chemical cleaning procedures to restore membrane productivity. The manufacturer's standard cleaning regime for treatment of surface water using chlorinated permeate was employed. Cleaning effectiveness was gauged by how well specific flux was restored to original levels. The following two primary indicators of cleaning efficiency were used:

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

$$\text{Recovery of Specific Flux} = 100 * \left[1 - \frac{Js_f}{Js_i} \right]$$

Where: Js_f = Specific flux at end of current run (gfd/psi)
Js_i = Specific flux at beginning of subsequent run (gfd/psi)

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

$$\text{Loss of Original Specific Flux} = 100 * \left[1 - \frac{Js_f}{Js_{io}} \right]$$

Where: Js_{io} = Specific flux at time zero point of testing (gfd/psi)

3.1.5 Microbial Challenge Testing

Microbial removal testing was performed to demonstrate that the ZeeWeed® ZW-500 ultrafiltration system could reliably reject *Giardia, Cryptosporidium,* and MS-2 bacteriophage. These organisms were chosen to provide some variety in the types and sizes of microorganisms to indicate the range of membrane microbial removal capabilities. *Giardia* cysts were selected since this microorganism was one of the driving forces behind the SWTR. *Cryptosporidium* was also used because it is targeted for regulation. MS-2 Bacteriophage was used to model virus removal because it is similar in size (0.025 m), shape (icosahedron) and nucleic acid to polio virus and hepatitis. In addition, MS-2 Bacteriophage has been suggested in the SWTR Guidance Manual as an organism to use when conducting studies of microbial removal (EPA, 1990).

3.2 Field Operations Procedures

The membrane system was operated and manned continuously during each test period. The facility was manned 24 hours a day to prevent interruptions. The operators logs are included in Appendix A.

3.2.1 Equipment Operation Procedures

ZENON's operating instructions for the ZeeWeed® ZW-500 ultrafiltration system are included as Appendix B to this document. The primary operational parameters for this system were permeate flow, backpulse frequency and duration, and concentrate rate.

3.2.2 Pre-Test Optimization

Pre-test optimization was performed before the first test period in this study (from September 1998 to December 9, 1998) to familiarize the operations personnel with the equipment while the Field Operations Document was being prepared.

3.2.3 Membrane Flux and Operation

At the beginning of each test period the specific permeate flux was determined using the following system optimization procedures as recommended by the manufacturer:

1. Introduce feed water into the filtration chamber.
2. Set flux to 28 gallons per square foot per day (gfd) (10 gallons per minute [gpm]), and air flow to 15 standard cubic feet per minute (scfm).
3. Operate the system for at least two backpulse cycles to determine the recovery of the membranes (one hour minimum).
4. Record the TMP consistently two minutes before and two minutes after backpulsing to observe recovery of the membranes.
5. Repeated steps 3 and 4 with the flux set at the following: 14, 42, and 56 gfd (5, 15, and 20 gpm, respectively).

The above procedure was repeated with the air flow set to 5 scfm/module, and again with the airflow set to 18 scfm per module. The transmembrane pressure was recorded before and after each backpulse to determine if the different air flow rates affected the specific flux and/or the transmembrane pressure.

Table 3-2 presents the operational data collection schedule. The test site was staffed 24 hours per day. One set of readings was taken per 8-hour shift.

Table 3-2. Operational Parameters Measured

Parameter	Frequency
Hour Meter Reading	3 times per day
Vacuum Before and After Backpulse (Transmembrane Pressure)	3 times per day
Backpulse Duration	3 times per day
Backpulse Frequency	3 times per day
Backpulse Pressure	3 times per day
Backpulse Loss in CIP Tank	3 times per day
Feed Water Flow	3 times per day
Permeate Flow	3 times per day
Process Tank Aeration Rate	3 times per day
Concentrate Rate	3 times per day
Permeate Temperature	3 times per day
Process Tank Level	3 times per day

Transmembrane pressure was measured by the vacuum applied to the membranes. The system programmable logic controller (PLC) displayed the vacuum measured before and after each backpulse.

3.2.4 Water Quality Sampling and Analysis

Water quality data were collected at regular intervals during each period of membrane testing, as indicated in Table 3-3. On-line turbidimeters (Hach Model 1720D) were provided for feed, permeate, and concentrate streams. On-line particle counters (Met One Model PCX) were provided for feed and permeate streams. Data from the on-line instruments was logged into a computer and reported at 2-hour intervals. pH was monitored on site once per day.

Off site analysis was provided by either the Portland Water Bureau Water Quality Laboratory or by the CH2M HILL Applied Sciences Laboratory in Corvallis, Oregon. A breakdown of analyses by lab is presented in Table 3-4, along with a list of analytical methods used.

Table 3-3. Summary of Sample Plan

Parameter	Sampling Frequency	Sample Location		
		Feed	Permeate	Concentrate
On-Site Analyses				
pH	Daily	●		
Temperature	Daily	●		
Turbidity	On-Line	●	●	●
Particle Counts	On-Line	●	●	
Laboratory Analyses				
Alkalinity	Weekly	●	●	
Total/Calcium Hardness	Weekly	●	●	
Total Dissolved Solids	Weekly	●	●	
Total Suspended Solids	Weekly	●	●	●
Total Coliforms	Weekly	●	●	●
Heterotrophic Plate Count	Weekly	●	●	
Total Organic Carbon	Weekly	●	●	
UVA	Weekly	●	●	
SDS TTHM	Monthly	●	●	
SDS HAA6	Monthly	●	●	

Table 3-4. Summary of Analytical Methods Used at Each Laboratory

	Analysis Location			Method Reference		
Parameter	On Site	Portland Water Bureau Lab	CH2M HILL Corvallis Lab	*Standard Methods* [1]	USEPA [2]	Instrument
On-Site Analyses						
pH	●			4500-H^+ B	150.1/150.2	
Temperature	●			2550 B		
Turbidity	●					Hach 1720 D
Particle Counts	●					Met One PCX
Laboratory Analyses						
Alkalinity		●		2320 B		
Total/Calcium Hardness		●		2340 C/Ca D		
Total Dissolved Solids		●		2540 D		
Total Suspended Solids		●		2540 C		
Total Coliforms		●		9215 B		
Heterotrophic Plate Count		●		9215 B		
Total Organic Carbon		●		5310 C		
UVA		●		5910 B		
SDS TTHM			●		502.2	
SDS HAA			●	6251 B		

[1] Standard Methods for the Examination of Water and Wastewater, 20th edition, American Water Works Association, 1998.

[2] USEPA Office of Ground Water and Drinking Water. Available via National Technical Information Service (NTIS).

3.3 Membrane Integrity Testing

The manufacturer tested membrane integrity when the membrane system was first set up before verification testing began. The manufacturer applied backpressure on the membranes and checked for passage of air into the process tank by visually checking for bubbles in the process tank. Technical representatives from CH2M HILL witnessed this test to verify integrity.

During the verification test, the on-line particle count and turbidity data generated in the Finished Water Quality task was used as an indirect monitoring method for membrane integrity. Integrity testing is specific to each type of membrane system and there is no industry-accepted procedure for use on all systems. ZENON frequently uses a pressure hold test to evaluate the integrity of its membranes. In their experience, a decrease in pressure of no more than 0.3 psi in 2 minutes indicates that the membranes are intact. A pressure-hold test was performed at the end of the third test period. A pressure regulator was attached to the inlet manifold of the membranes and

the valving was adjusted to force air to go through the membrane cassette. The pressure was carefully increased to about 4 psi, and then monitored every minute for 10 minutes.

To enhance the resolution of the particle-based integrity testing data, turbidity and particle augmentation to the raw water was employed. The methodology and procedures for performing the turbidity spiking is discussed in Section 3.6, Microbial Challenge Testing.

3.4 Removal of Simulated Distribution System Disinfection By-Product Precursors

Measurement of Simulated Distribution System (SDS) Disinfection By-Product (DBP) Precursors, listed as an optional task in the *EPA/NSF ETV Test Plan*, was performed in this verification test. SDS DBP measurements were performed on the membrane feed water and permeate in order to determine the DBP-precursor removal capabilities of the ZeeWeed® ZW-500 ultrafiltration system. SDS-DBP testing was used to estimate the formation of trihalomethanes and haloacetic acids.

The SDS method was performed by spiking a water sample with chlorine and holding the sample in the dark under formation conditions that approximate the detention time and chlorine residual provided in the Portland Water Bureau distribution system. The conditions used were identical to those being used by the Portland Water Bureau under evaluations being performed for the Information Collection Rule for Public Water Systems (Subpart M of the National Primary Drinking Water Regulations, Section 141.141(e)). These conditions are as follows:

- Incubation period 30 hours
- Incubation temperature 14°C
- Buffered pH 7.4
- 24-hour chlorine residual 0.5-1.0 mg/L

An incubator adjusted to hold the temperature at 14°C was used. The temperature of the incubator was checked before and after the incubation period to assure that the correct temperature was used.

3.5 Cleaning Efficiency

Chemical cleaning of the ZeeWeed® ZW-500 ultrafiltration system was typically performed when the transmembrane pressure following a backpulse was greater than 18 inches of mercury (in Hg (8.8 psi)). Depending on the water quality, chemical cleaning may be required every 4 to 12 weeks. For the purposes of this study, a cleaning was performed at the end of the 30 days of operation during each test period. During this testing the transmembrane pressure did not reach 18 in Hg in before the cleanings.

The vendor-recommended cleaning procedures were used. For treatment of surface waters, the optimal cleaner for the ZeeWeed® ZW-500 ultrafiltration system is 200 mg/L of chlorine and that is what was used for this test. The cleaning agent can vary with the type of foulant to be removed. About 35-L of 200 mg/L chlorinated water was backpulsed by pumping the chlorinated water from the CIP tank to the inside of the membrane fibers and through the membrane. At the end of the first period, cleaning was performed with an empty process tank and the cleaning

solution trickled down vertically along the fibers. The spent cleaning solution collected at the bottom of the tank and was pumped out by the reject pump to a holding tank for neutralization prior to discharge. During the second and third periods a full-tank cleaning was also performed whereby the membranes were allowed to soak overnight in a strong chlorine solution (200 to 250 mg/L).

Detailed operating procedures for performing a chemical cleaning of the ZeeWeed® ZW-500 ultrafiltration system are included in Appendix B.

Flow, pressure, and temperature data were collected during the cleaning procedure. The pH, turbidity, chlorine concentration, and TDS of the applied and spent cleaning solution were measured and recorded. Visual observations of the spent solution were also made, noting the color and degree of suspended matter present.

3.6 Microbial Challenge Testing

For public health reasons, it was not possible to use viable protozoan cysts and oocysts for the seeding studies at the study site. Therefore, inactivated *Cryptosporidium parvum* organisms fixed in 10 percent formalin and *Giardia* organisms fixed in 5 percent formalin were used. *Giardia muris* was used in the first test period, a combination of *Giardia muris* and *Giardia lamblia* was used in the second test period, and *Giardia lamblia* was used in the third test period. Organism stocks were stored under refrigeration in the dark at 4°C until use in the seeding studies. Formalin is expected to increase the rigidity of the cysts and oocysts, but the difference in solution strength is not expected to impact removal by the membrane. Aliquots for use in each seeding study were delivered on ice to the package plant on the day of the testing. The organisms were introduced to a spike tank that was used to feed the membrane system.

The seeding experiments were conducted under the operating conditions in which the membranes are most vulnerable to the passage of microorganisms. The water was a low turbidity water to aid in the measurement of *Giardia*, *Cryptosporidium* and MS-2 phage. The membranes were challenged within 48 hours following membrane cleaning, before a significant foulant layer has had an opportunity to develop (based on TMP increase). The foulant layer can aid in the removal of microbial contaminants.

The microbes were well mixed in about 500 gallons of feed water then introduced to the membranes over a relatively short period of time, approximately 30 minutes. The reservoir was completely mixed during preparation of the seeded feed water and throughout the filtration period. The feed water was tested to assure that known concentrations were fed. Previous experience has demonstrated that some cysts are lost when microbes are introduced so it was important to actually measure the influent concentration. The concentrations in the feed water, process tank and permeate were used to determine the log removals. In some cases, the microbe concentration in the permeate was below detection. When this occurred, log removals were calculated using half the detection limit. For quality assurance, the log removals were calculated in two ways. The first way used the concentrations in the influent stream and in the permeate. The second way used the concentrations in the reject stream and in the permeate. In other words, a mass balance approach was used. For reporting purposes, the lower of the two calculated log removals was listed in this document as the log removal.

Once filtration began, transmembrane pressure and permeate flux were recorded. Sample volumes of the feed water, permeate and concentrate were recorded. Bio-Vir Laboratories, Inc. (Benicia, CA) performed the analyses of the microbial species, and sample volumes were processed according to the instruction provided by Bio-Vir. Bio-Vir is a USEPA-approved laboratory for the measurement of the organisms used in this study.

The microbes were measured in the feed water, permeate, and concentrate streams. A grouped sampling approach was used to assure that all samples were handled in an identical fashion. Handling the samples in an identical fashion was important to obtain similar sample recovery. The MS-2 bacteriophage concentrations were measured using SM18 9211D. This method was modified by the use of a top agar rather than a bottom agar. An E. coli bacteria was used as the host. At the time the ETV test was conducted, USEPA Method 1623 for analysis of *Giardia* was not yet approved. However, the method used for *Giardia* analysis was 1622 modified for *Giardia*, and the procedure used was the same as what is known as USEPA Method 1623 today. The *Cryptosporidium* analysis was performed on a 20-liter sample in the treated water, using USEPA Method 1622."

Duplicate samples of both feed, permeate, and concentrate samples were collected during each of the seeding studies. Samples were stored at 1°C and processed within 24 hours. Enumeration of organisms in the feed and permeate samples was performed by Bio-Vir. Bio-Vir also provided a technician to perform the first two field seeding tests and to train CH2M HILL staff to perform subsequent field testing.

In advance of the challenge test the materials to be used were ordered from Bio-Vir. The biological samples were stored in the dark at 4^{o} C until used in the challenge tests. During the first two test periods the following procedures were followed:

1. The membranes were cleaned.
2. The process tank was emptied.
3. The backwash frequency was adjusted to 60 minutes so that it did not interfere with the test.
4. The spike tank was filled with approximately 500 gallons of source water.
5. Between 10^{8} and 10^{9} formalin-fixed *Giardia* cysts, 10^{8} to 10^{9} formalin-fixed *Cryptosporidium* oocysts, and 10^{11} to 10^{12} MS-2 bacteriophage were added to the stock tank.
6. The process tank was filled with the water from the stock tank that contained the microbes.
7. When the water level reached the appropriate point in the process tank, the membrane treatment was started at a flow rate of 10 gpm.
8. Feed water *Giardia* and *Cryptosporidium* samples were collected two times during the spike period. Collection times were 15 and 25 minutes into the test.
9. Permeate and concentrate *Giardia* and *Cryptosporidium* were collected at 20 minutes and 30 minutes into the test. A 5-minute lag was provided to allow for passage of the water through the membrane.

10. Feed water MS-2 bacteriophage samples were collected twice during the spike period at 15 and 25 minutes into the test.

11. Permeate and concentrate samples for MS-2 analysis were collected at 20 minutes and 30 minutes into the test.

12. The samples were then shipped overnight to Bio-Vir where the samples were analyzed within 24 hours.

The data from the first two test periods showed that the concentration of microbes in the process tank was less than expected given the mass balance results. Based on a mass balance at 95 percent recovery, and the observations with turbidity and TSS, the microbe concentrations in the process tank are expected to be 20 times greater than in the feed water. It is significant that the process tank contains 20 times greater concentration of microbes than the feed water because the membranes are in the process tank and are exposed to a microbe concentration that is 20 times greater than the feed concentration. In the third test period, the microbe seed was adjusted to provide a concentration in the process tank that was 20 times greater than in the feed water. During the third test period, the following procedure was used:

1. The membrane was backwashed.
2. The feed tank was filled with water.
3. Supply lines to the feed tank were closed.
4. Flow through the membrane package unit was stopped while the three microbial cultures (*Giardia*, *Cryptosporidium*, and MS-2 bacteriophage) were added.
5. The volume of culture added was adjusted so that the concentration in the membrane process tank was 20 times greater than that in the feed tank.
6. The membrane unit was restarted.
7. After about a minute, permeate samples of *Cryptosporidium* and *Giardia* were collected.
8. Samples of the feed, permeate, and concentrate streams were collected just before the first backwash.
9. The permeate sample filter was changed at midway through the feed tank volume to provide a duplicate sample. A Gelman Envirochek™ polyether sulfone sampling filter with a nominal pore size of 1 micron was used.
10. A few minutes after backwash, feed, permeate, and concentrate streams were sampled for the second time.
11. Samples were packaged and refrigerated until shipped to Bio-Vir.

The calculation of concentrate TSS is as follows:

$$TSS_{conc} = \frac{TSS_{feed} \times \left(Q_{perm} + Q_{concentrate}\right) - Q_{perm} \times TSS_{perm}}{Q_{concentrate}}$$

Where:

TSS_{conc}	=	TSS in the concentrate
TSS_{feed}	=	TSS in the feed
Q_{perm}	=	The permeate flow
$Q_{concentrate}$	=	The flow of the concentrate stream, often called the concentrate rate, because the flow is minor compared with the permeate and feed flow
TSS_{perm}	=	TSS in the permeate

The log removals were calculated as follows:

$$Log\ removal = -\log\left[\frac{permeate}{feed}\right]$$

Where the permeate is the concentration of microbes in the permeate stream and feed is the concentration of microbes in the feed stream. In all cases, the feed concentration was compared to the concentrate concentration to verify the system was at equilibrium when samples were collected. If the system was not at equilibrium, a second calculation of log removal was used. The feed concentration was represented as concentrate concentration ÷ concentration factor. Solids are expected to concentrate by a factor of 20 based on 95 percent recovery and complete rejection of those solids. For reporting purposes, the lower of the two log removals was reported. This approach is a conservative approach that avoids overstating the log removals.

During the third test period, more microbes were added to the process tank so that the concentrate and feed were close to equilibrium concentrations when the samples were collected. So the above formula only applies to the first two test periods.

In some cases the concentration of microbes in the permeate is below detection. When this occurred, the log removals were calculated using half the detection limit.

3.7 Operating Procedure for Turbidity Augmentation

During the third test period, turbidity augmentation was employed to increase the feed water turbidity. Water from a "stock" turbid water tank, as described below, was blended with the raw water. A schematic for this system is presented in Figure 3-1.

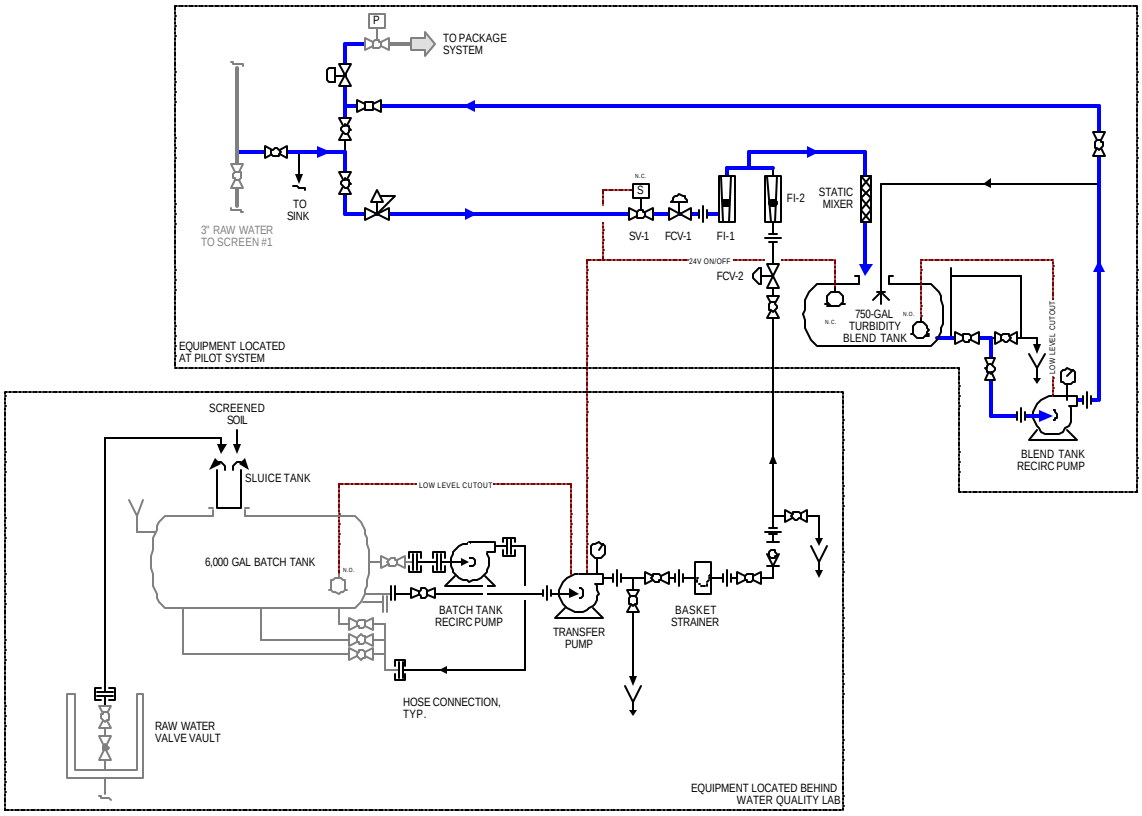


Figure 3-1. Natural Sediment Turbidity Augmentation System

Natural clay soil was selected for turbidity augmentation after interview with plant staff to determine the source of natural turbidity. A search of the watershed was conducted to find outcroppings of red clay-like material cited as the source of the turbidity. The stock turbid water was prepared by placing one or two shovel loads of natural clay soil from the watershed in a 10-gallon bucket. Raw water was continuously added to the bucket to suspend the clay soil. The bucket was placed on top of a manway that provided access to the 6,000 gallon tank. The overflow from the bucket was very turbid and over-flowed directly into the 6,000 gallon tank through the manway. Additional clay soil was added to the bucket as needed during the work day. The flow rate of the water into bucket was set to approximate the flow rate out of the 6,000 gallon tank. The water in the 6,000 gallon tank is referred to as the "stock turbid solution." The stock turbid solution was then transferred to a 750 gallon blending tank where it was blended with raw water to provide the target feed turbidity. This blended water was then fed to the membrane process tank.

The following procedure was used for preparation of spiked turbidity feed water.

1. Calibrate Flow Rates

   – Use graduated container and stopwatch and set the flow rates for flow streams.

2. Prepare Initial Stock Solution

   - Make sure the 6,000 gallon stock tank was filled and mixed. Mixing required 2-4 hours of operating the gas powered mixing pump.
   - While the tank was filling and mixing, clay solids were worked into the 6,000 gallon stock tank using a bucket and shovel which allowed the finer particles to wash up and out of the bucket and into the stock tank while larger heavy particles remained in the bucket. Continue working solids until turbidity in the stock tank reached 180-200 NTU (usually about 3-4 hours).

3. Initiate System Operation

   - Set rotameters at the blend manifold so that the desired feed turbidity was reached in the 750 gallon blend tank.
   - Attempt to balance the flow of raw water in and average flow of stock water out of the 6,000 gallon stock tank so it did not run dry between visits. This was accomplished using a 5 gallon bucket and a timer.
   - Clean dirt trap on transfer pump.

3.8 Membrane Pore Size

A request was submitted to the manufacturer to provide the 90 percent and maximum pore size of the membrane being verified. ZENON determines the pore size distribution using flow porometry in accordance with ASTM-F316 *Standard Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test.* The above information are taken from a letter supplied by the manufacturer which is included in Appendix F of this report. This is provided for informational purposes only and the results were not verified during the ETV testing.

3.9 Quality Control Checks

3.9.1 Operational Parameters

Table 3-5 summarizes the daily, monthly, seasonal, and annual quality assurance methods that were employed on operational parameters taken during the test.

Table 3-5. Quality Assurance Procedures

		Quality Assurance Methodology			
Parameter	Measurement Method	Daily	Weekly	Once per Test Period (Monthly)	Once over course of Study (Annual)
Vacuum Before and After Backpulse (Transmembrane Pressure)	PLC Readout from pressure indicator/transmitter			Verify good condition of all tubing and connections, replace if necessary	Factory calibrated prior to equipment shipment
Backpulse Duration	PLC controlled based on operator input				PLC function checked prior to equipment shipment
Backpulse Frequency	PLC controlled based on operator input				PLC function checked prior to equipment shipment
Backpulse Pressure	PLC Readout from pressure indicator/transmitter			Verify good condition of all tubing and connections, replace if necessary	Factory calibrated prior to equipment shipment
Backpulse Loss in CIP Tank	Drawdown on graduated CIP tank				
Permeate Flow	Rotameter		Clean rotameter	Verify meter reading volumetrically with stop watch	
Process Tank Aeration Rate	Rotameter		Clean rotameter		
Feed Water Temperature	PLC Readout of temperature indicator/transmitter			Verify good condition of sensor and connections, replace if necessary	Field calibrated at start of study
Concentrate Rate	Volumetric	Verify flow rate with graduated cylinder and stopwatch			
Process Tank Level	PLC readout from level indicator/transmitter			Verify good condition of all tubing and connections, replace if necessary	Factory calibrated prior to equipment shipment

3.9.2 Analyses

The sample handling procedures are outlined in Table 3-6. In addition, the quality assurance and quality control procedures detailed in the Quality Assurance Plans for each laboratory were followed. These procedures were followed and the holding times were met.

Table 3-6. Sample Handling Methods

Analyte	Sample Container	Preservative	Shipping/ Storage	Maximum Holding Time
Alkalinity, and Total Dissolved Solids	1 L polypropylene	None	4°C	14 days
Total Suspended Solids	1 L polypropylene	None	4°C	7 days
Total/Calcium Hardness	60 mL polypropylene	1+1 HNO_3	None	6 months
Total Coliforms and Heterotrophic Plate Count	500 mL polypropylene	None	4°C	8 hours
Total Organic Carbon	40 mL Amber glass VOC Vial	H_2SO_4	4°C	7 days
UVA	40 mL Amber glass VOC Vial	None	4°C	24 hours
SDS TTHM and SDS THAA	1 Liter Amber glass	None	4°C	7 days

3.9.3 On-Line Instrumentation

3.9.3.1 Turbidity

Turbidity analyses were performed according to Standard Method 2130. On-line turbidimeters were used for measurement of turbidity in the permeate, feed water, and concentrate. On-line turbidimeters were left on continuously during system operation. Any problems experienced with the instruments were logged in the operations logbook. Any subsequent modifications or enhancements made to the turbidimeters were also noted.

The *EPA/NSF ETV Test Plan* requires periodic verification of on-line turbidimeter readings using a bench-top turbidimeter. In this study, such verification was made three times per week during operation. On-line turbidimeters were maintained as follows:

- Initial calibration was performed using a Formazin primary standard purchased from Hach.
- Calibration checks against Hach Company's GELEX secondary standard as specified in the manufacturer's operation and maintenance manual were performed weekly. If the calibration check showed the instrument to be off by more than 10%, the instrument was recalibrated with the primary standard.
- Cleaning of the optical lens as specified in the manufacturer's operation and maintenance manual (weekly).
- Verification of the sample flow rate using a volumetric measurement. Instrument bulbs were checked daily.
- Verification that the LED readout matches the data recorded on the data acquisition system, if the latter is employed (weekly).
- Cleaning of the turbidimeter reservoir (monthly).

3.9.3.2 Particle Counts

On-line particle counters were employed for measurement of particle concentrations in the feed and permeate water. The particle counter units used were model PCX as manufactured by Met One, Grants Pass, Oregon. The units were configured to measure and record particle counts in the following particle size ranges:

- 2-3 µm
- 3-5 µm
- 5-7 µm
- 7-10 µm
- 10-15 µm
- >15 µm

A log book was kept to record any problems experienced with the particle counting instruments. No problems were observed with the particle counters.

The particle counters were new and were factory calibrated prior to delivery. Calibration data are included in Appendix C. The on-line particle counters were maintained as follows:

- Volumetric verification of sample flowrate at the manufacturer-recommended 100 mL/min (daily).
- Cleaning of the sensor using the procedure outlined in the manufacturer's O&M manual (weekly).
- Cleaning of the sample tubing by vigorous flushing (weekly).

The particle counters were factory-configured and calibrated to measure and record the total number of particles per mL in the size ranges identified above.

The instruments were configured to take a reading once per minute. The instrument software generated a database entry every 5 minutes, reflecting the average of readings taken during this period. The software also generated a report once per day with 2-hour averages of the database. A total of 12 sets of readings per day of operation were reported. The database of raw readings is included in Appendix D.

The two-hour average readings of particle count and turbidity were compiled into a spreadsheet database to evaluate the ability of the ZeeWeed® ZW-500 ultrafiltration system to meet performance criteria.

3.9.4 Quality Assurance of Turbidity Augmentation

Tests were performed to assure that the turbidity being added was representative of a suspension that may occur during a high turbidity event. Samples of both the stock turbid water (before dilution) and the water fed to the membrane were collected. The waters were placed in a 1,000 mL graduated cylinder, then the location of the interface between turbid water and clearer water was recorded over a period of three to five hours as the suspension settles. In this test, a turbidity suspension that settles very slowly would be representative of turbid water containing fine particulate matter that would be found in many surface waters after heavy runoff.

Chapter 4
Results and Discussion

4.1 Membrane Flux and Operation

Figure 4-1 shows the transmembrane pressure over time for the three 30-day test periods. When the turbidity varied, the transmembrane pressure trends showed some peaks and valleys. In general, the TMP increased when the turbidity initially increased and then decreased as the system recovered. This is an indication that the membrane system was able to recover from the temporary fouling effects of increased feed water solids loads. When the turbidity was steady, the transmembrane pressure increased steadily throughout the test period.

Figure 4-2 shows the actual and temperature-corrected permeate flux during the three test periods. The flux remained relatively constant at a value near the target flux in each test period reflecting good operational control of the permeate flow. The target flux was 45, 50, and 45 gfd for test periods one, two, and three respectively. Figure 4-3 shows the specific flux at 20°C. Specific flux was between 12 and 14 gfd/psi at the beginning of the test period and decreased to 8 at the end of Test Periods 1 and 2, and to 4 at the end of Test Period 3.

Figure 4-4 shows the permeate recovery during all three test periods was controlled at the target range of 94 and 95 percent.

4.2 Cleaning Efficiency

Table 4-1 summarizes the membrane cleaning conditions and results for each test period. In each test period the membrane did not need to be cleaned before the end of the 30-day test period. In Test Period 2, a full-tank cleaning procedure was used to determine whether this procedure was warranted. The full-tank cleaning procedure is described in Appendix B, page 11. The specific flux (at 20^{o}C) at the beginning of testing was 11.6 gfd/psi. Figure 4-5 shows the cleaning efficiency during each test period. It is notable that the membrane package unit was operated and cleaned between the official NSF test periods and the specific flux at the beginning of a test period did not match that after cleaning of the previous test period. This operation did not impact cleaning efficiency.

4.3 Membrane Life

Membrane life is difficult to assess. At the time of this report, there have not been any ZW500 systems in service more than three years. The manufacturer reports that in this three-year time, there has been no broken fibers, nor a need to replace any membrane modules. In this test, the ZW500 system was operated for three test periods over the course of one year, and membrane life is expected to last much longer. Membrane life was assessed by looking for signs of irreversible fouling.

Irreversible fouling can be is observed if the TMP increases from one cleaning to the next. From Table 4-1, it is seen that the TMP at the start of each run did not increase steadily with time and was 5.6, 5.4, and 4.6 psi for. Likewise, the specific flux at the start of each run did not decrease and was 11.6, 13.1, and 11.8 gfd/psi @ 20°C for test periods 1, 2, and 3, respectively. Thus there was no evidence of irreversible fouling.

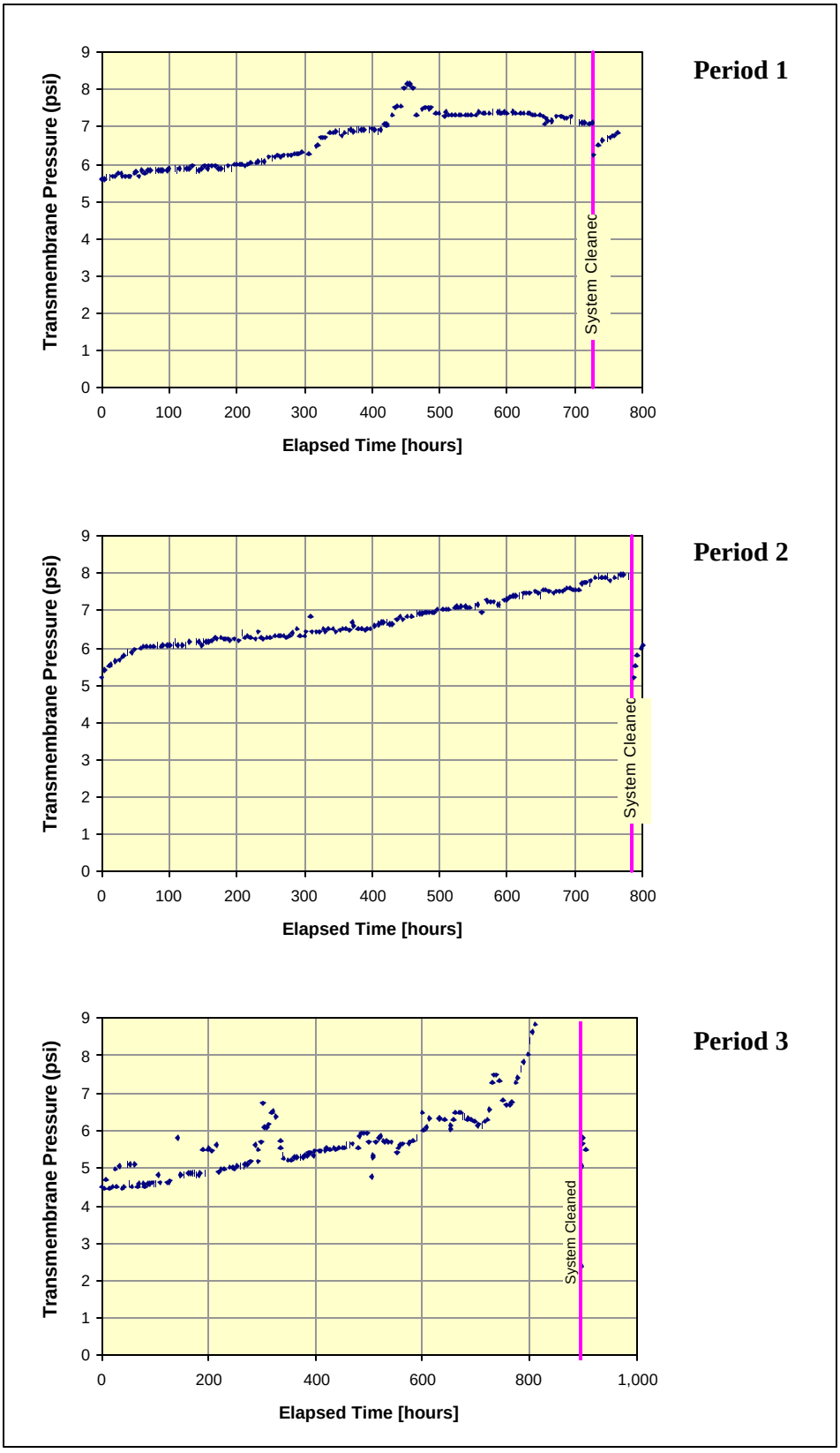


Figure 4-1. Transmembrane Pressure During the 3 Test Periods

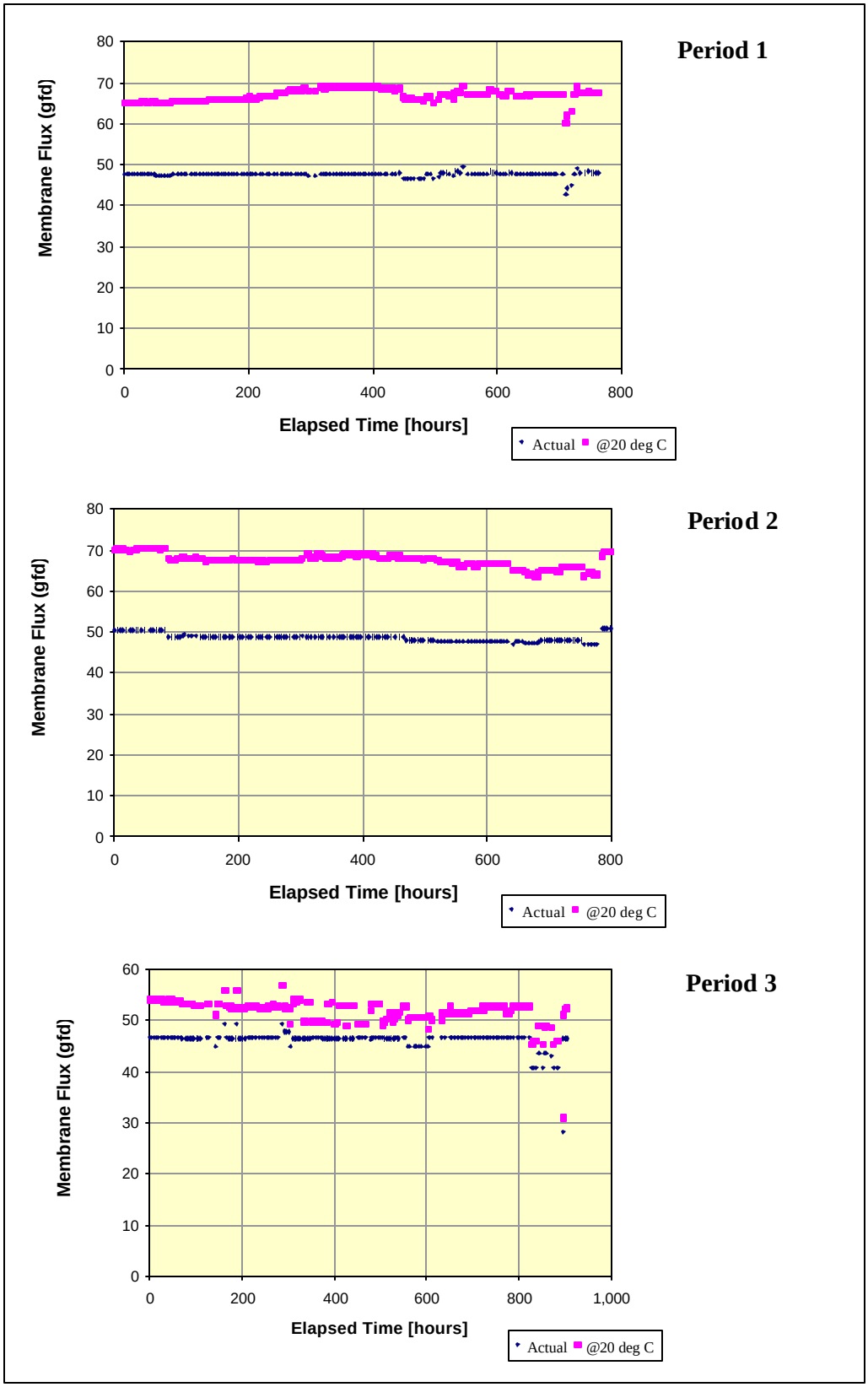


Figure 4-2. Membrane Flux During the 3 Test Periods

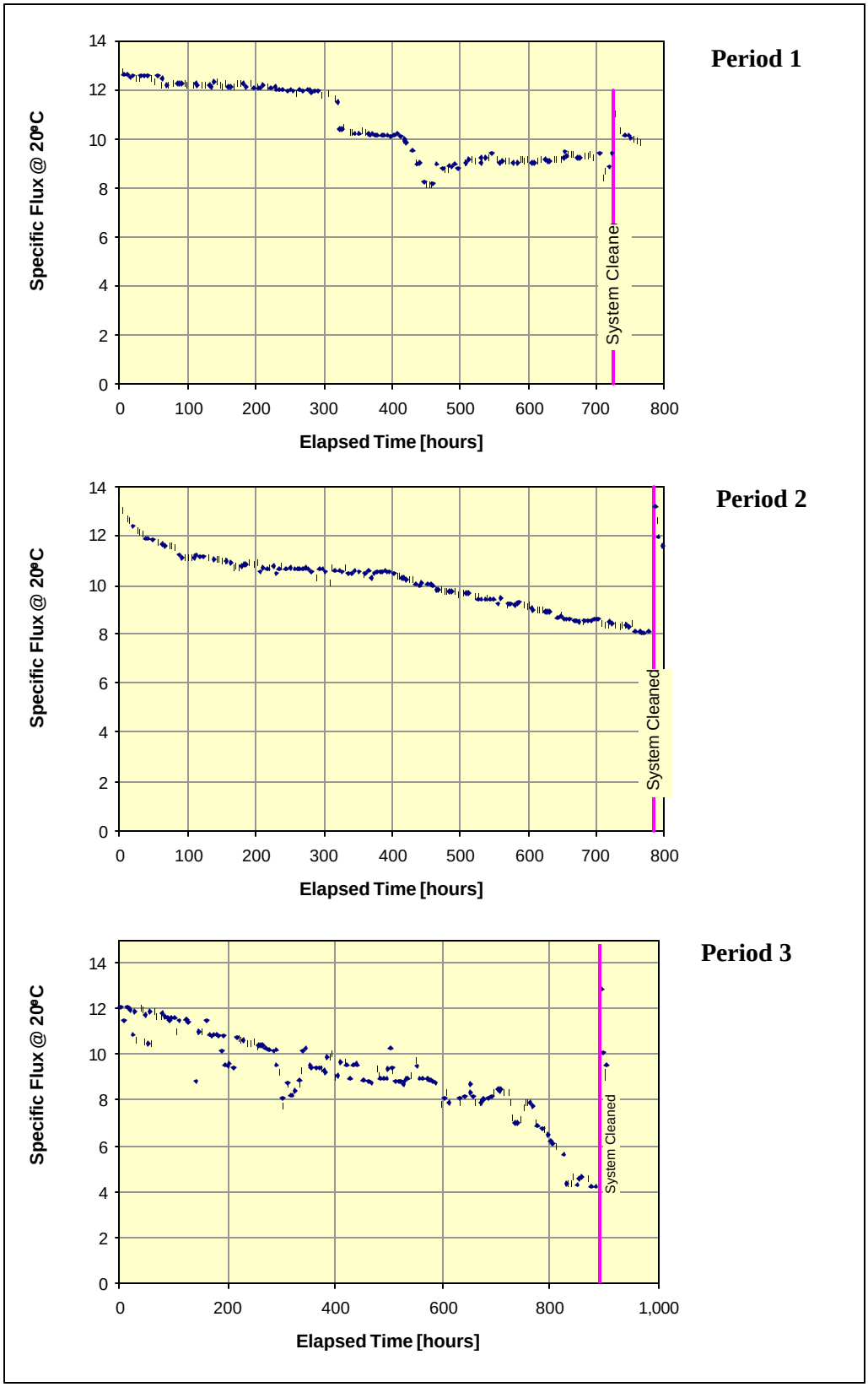


Figure 4-3. Specific Flux During the 3 Test Periods

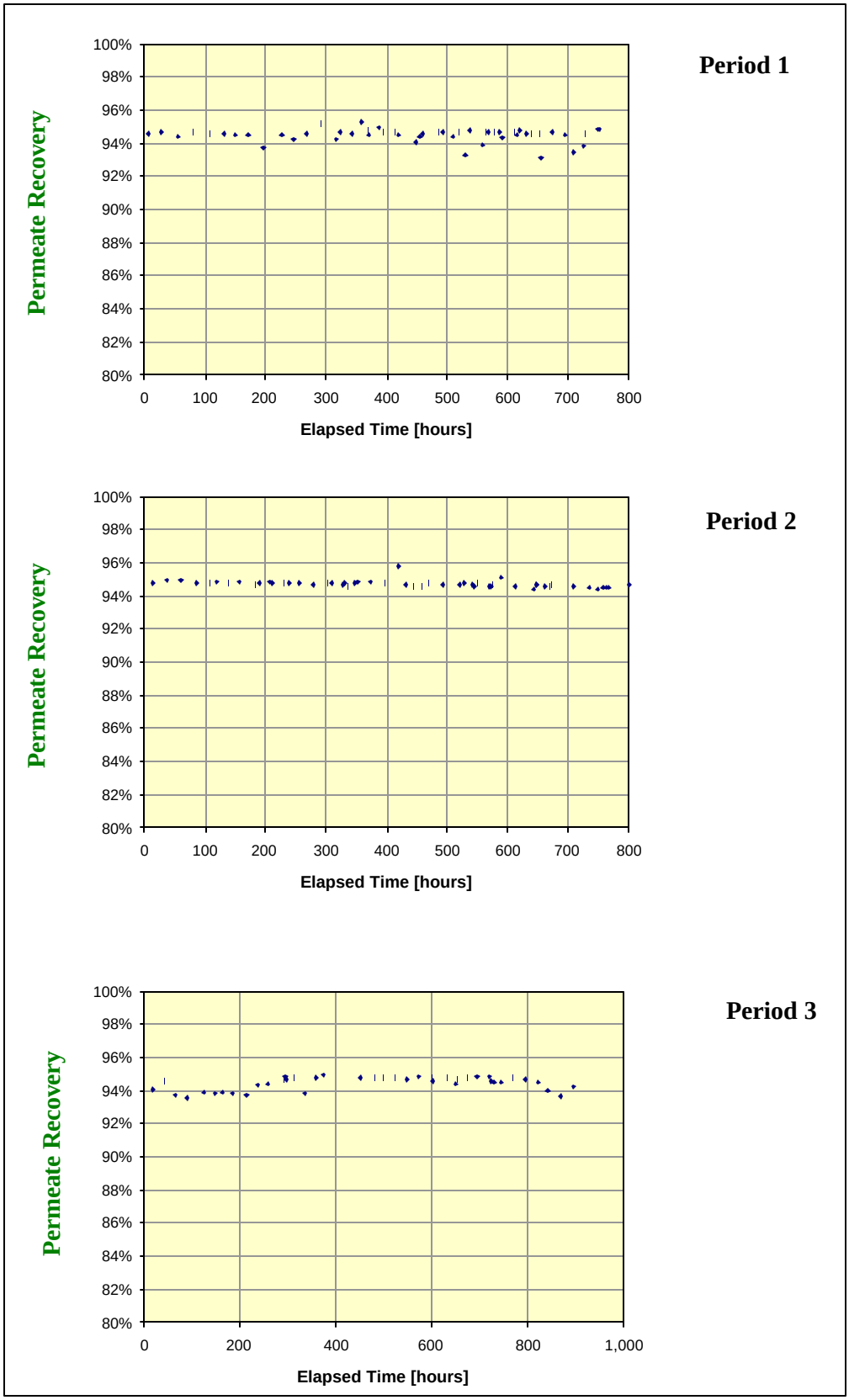


Figure 4-4. Product Recovery for the 3 Test Periods

Table 4-1. Cleaning Efficiency

Parameter		Test Period 1			Test Period 2			Test Period 3		
Procedure type		Empty-tank cleaning			Full-tank cleaning			Full-tank cleaning		
Chemical used		200 to 250 mg/L chlorine			200 to 250 mg/L chlorine			200 to 250 mg/L chlorine		
Temperature (deg C)		6.0			6.0			15.0		
Cleaning regime		Drained process tank 20 L solution backpulse 15 min. soak (empty tank) 20 L solution backpulse 15 min. soak (empty tank) 20 L solution backpulse 15 min. soak (empty tank) 20 L solution backpulse 15 min. soak (empty tank)			Drained Process Tank Filled with chlorine solution (200 to 250 mg/L) 700 L solution backpulse 15 min. soak (full tank) 700 L solution backpulse 15 min. soak (full tank) Recirculated bleach solution from CIP tank to process tank through membranes back to CIP Soaked overnight			Drained process tank Filled with chlorine solution (200 to 250 mg/L) 40 L solution backpulse 15 min. soak (full tank) 35 L solution backpulse 15 min. soak (full tank) Filled process with 200 mg/L chlorine solution Soaked overnight		
Operation Parameter		Start of Run	Prior to Cleaning	After Cleaning	Start of Run	Prior to Cleaning	After Cleaning	Start of Run	Prior to Cleaning	After Cleaning
Flux	gfd	47.7	45.6	48.1	50.3	47.5	50.9	46.7	41.5	46.4
Temperature	deg C	7.0	5.8	5.9	6.1	6.1	7.0	13.9	15.2	15.3
Flux @ 20 deg C	gfd	65.0	64.0	67.4	70.1	66.3	69.5	54.0	46.6	51.9
TMP	psi	5.6	7.1	6.8	5.4	7.5	6.1	4.6	10.6	5.5
Specific Flux	gfd/psi @ 20 deg	11.6	9.0	9.9	13.1	8.9	11.5	11.8	4.4	9.5
Recovery of Specific Flux			9%			23%			54%	
Loss of Original Specific Flux			22%			23%			62%	

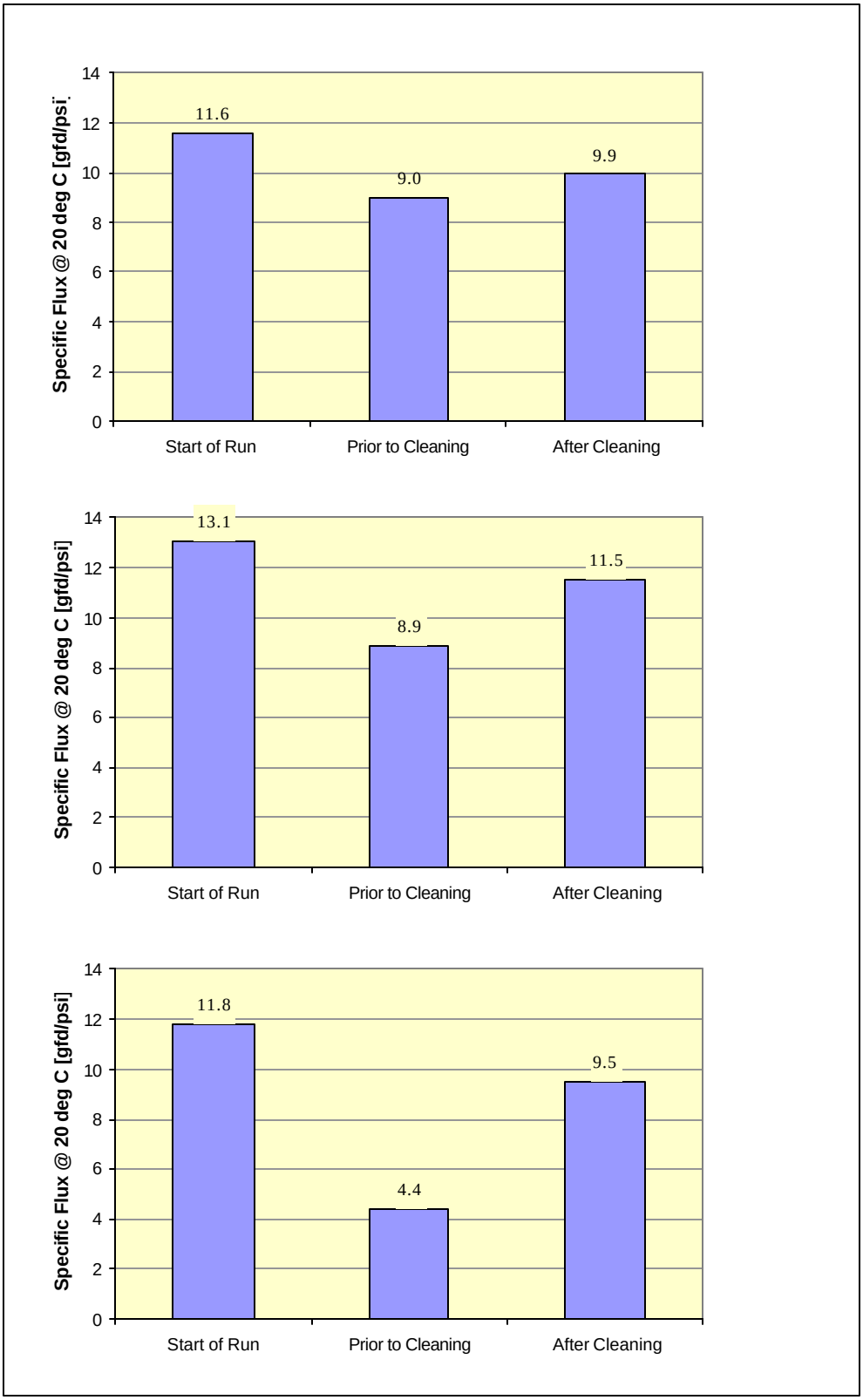


Figure 4-5. Cleaning Efficiency for the 3 Test Periods

On recent bids, ZENON has offered warranties on its membranes ranging from five to ten years and ZENON recommends planning on a life of ten years. Based on these estimates, the membrane life can be expected to be five to ten years.

4.4 Finished Water Quality

Figure 4-6 shows the feed and permeate turbidity during the three test periods. Although the feed turbidity varied from 0.2 to over 200 ntu, the permeate turbidity remained low and stable between 0.02 and 0.05 ntu. During the first test period a storm event caused the feed and concentrate turbidities to increase just after 400 hours of testing. The feed turbidity increased to about 10 ntu. During the second test period the turbidity remained steady at less than one ntu. During the third test period turbidity was added to the water resulting in feed turbidities as great as 250 ntu. The turbidity was also quite variable during this time.

Figure 4-7 shows the feed and permeate particle counts, greater than two micron, during the three 30-day test periods. During the first test period, the particle counts greater than 2 micron were mainly less than 10 particles per mL in the permeate stream. During the second test period, the particle counts greater than 2 micron in the permeate were generally less than 10 per mL until about 600 hours into the test. At this time, the pattern of permeate particle counts became more erratic and the particle counts increased to greater than 10 per mL.

The cause of the increase in particle counts during this period was traced to the CIP tank. It was observed that the particle counts tended to increase after each backpulse. A change in the type of chlorine tablet used to maintain the chlorine concentration in the CIP tank was coincident with the change in particle counts. It was theorized that the new type of chlorine tablet was causing the increase in particle counts. If the chlorine tablets were to contain particles, it would impart these particles to the water when it dissolved. These particles would then be introduced to the permeate when during the backflush. When the chlorine tablet was changed back to the original type, the particle counts became more steady and were again less than 10 particles per mL.

During the third test period, challenge tests were being performed causing the feed-water particle counts to increase as turbidity was introduced. Often times the permeate particle counts also increased. Because the particles are many times greater than the pore sizes it can be concluded that during this third test period either the membrane integrity was compromised allowing particles to pass through the membrane or particles were being formed downstream of the membrane.

Figures 4-8 through 4-10 show the particle counts in the different size ranges. In general, the number of particles decreases with increasing particle size. There is also a greater change in particle counts as the particle size increases. The number of particles greater than 15 microns increases from 20 to 800 during the storm in test period 1 and fluctuates between 10 and 1000 as in test period three. The increase in particles in test period 3 corresponds to the addition of natural clays to simulate storm events.

Figures 4-11 and 4-12 show the log removal of particles during the test periods. The wide variation in log removals during period 3 was a reflection of changing particle concentrations in

the feed water. During the periods of turbidity augmentation, the particle counts would increase in the feed water and the log removals would, in turn, increase. The log removals were greater

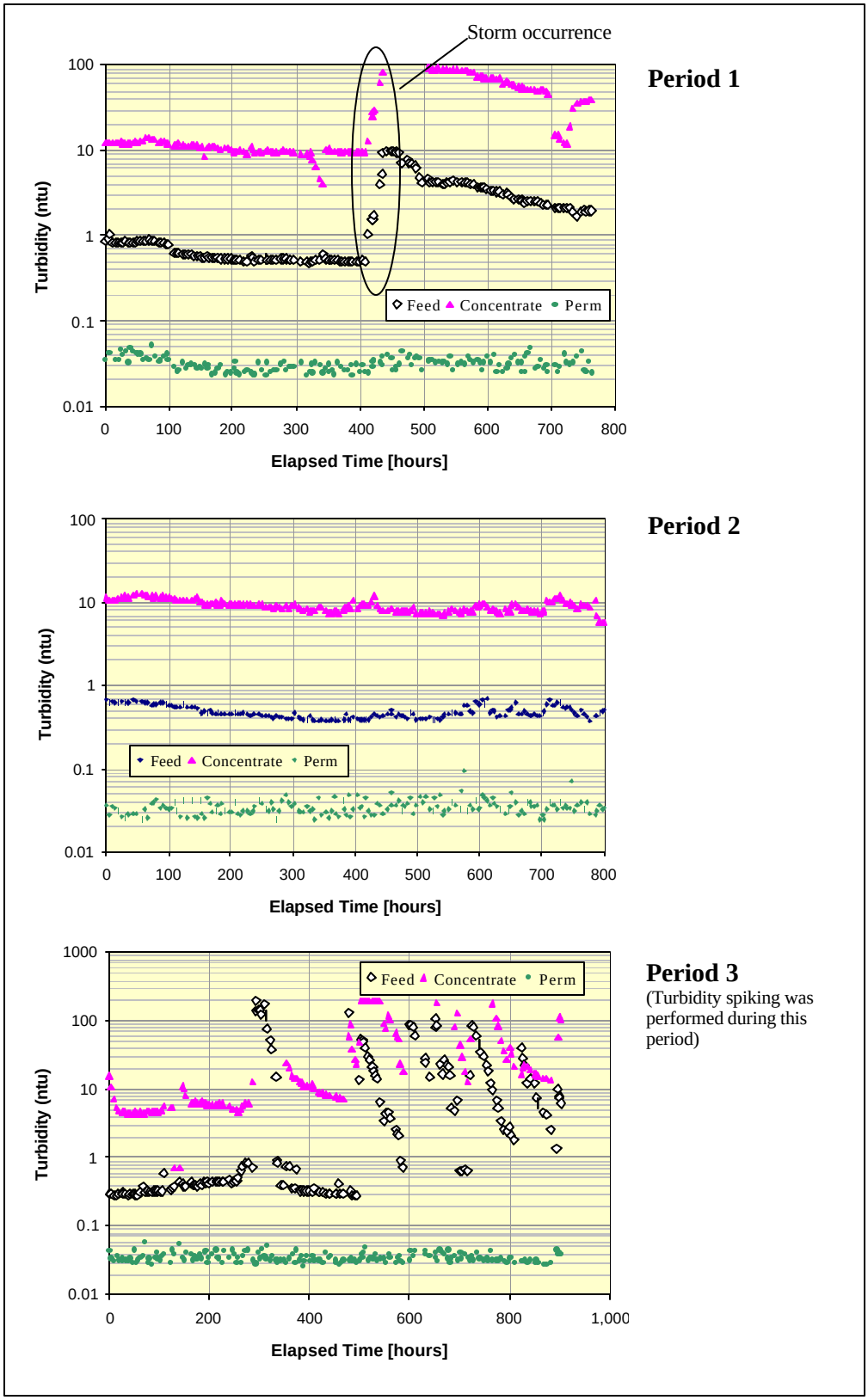


Figure 4-6. Turbidity During the 3 Test Periods

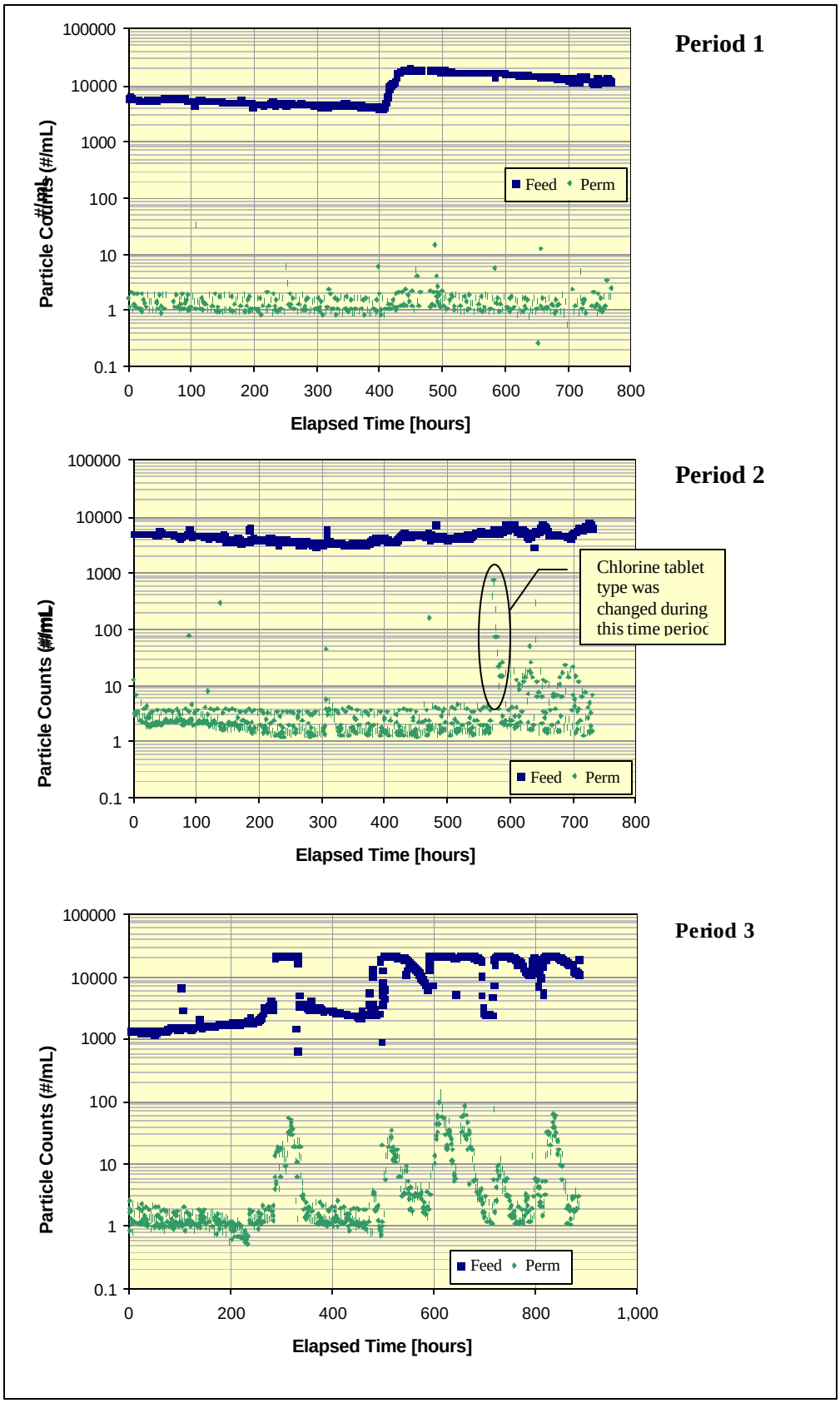


Figure 4-7. Particle Counts (>2 μm)

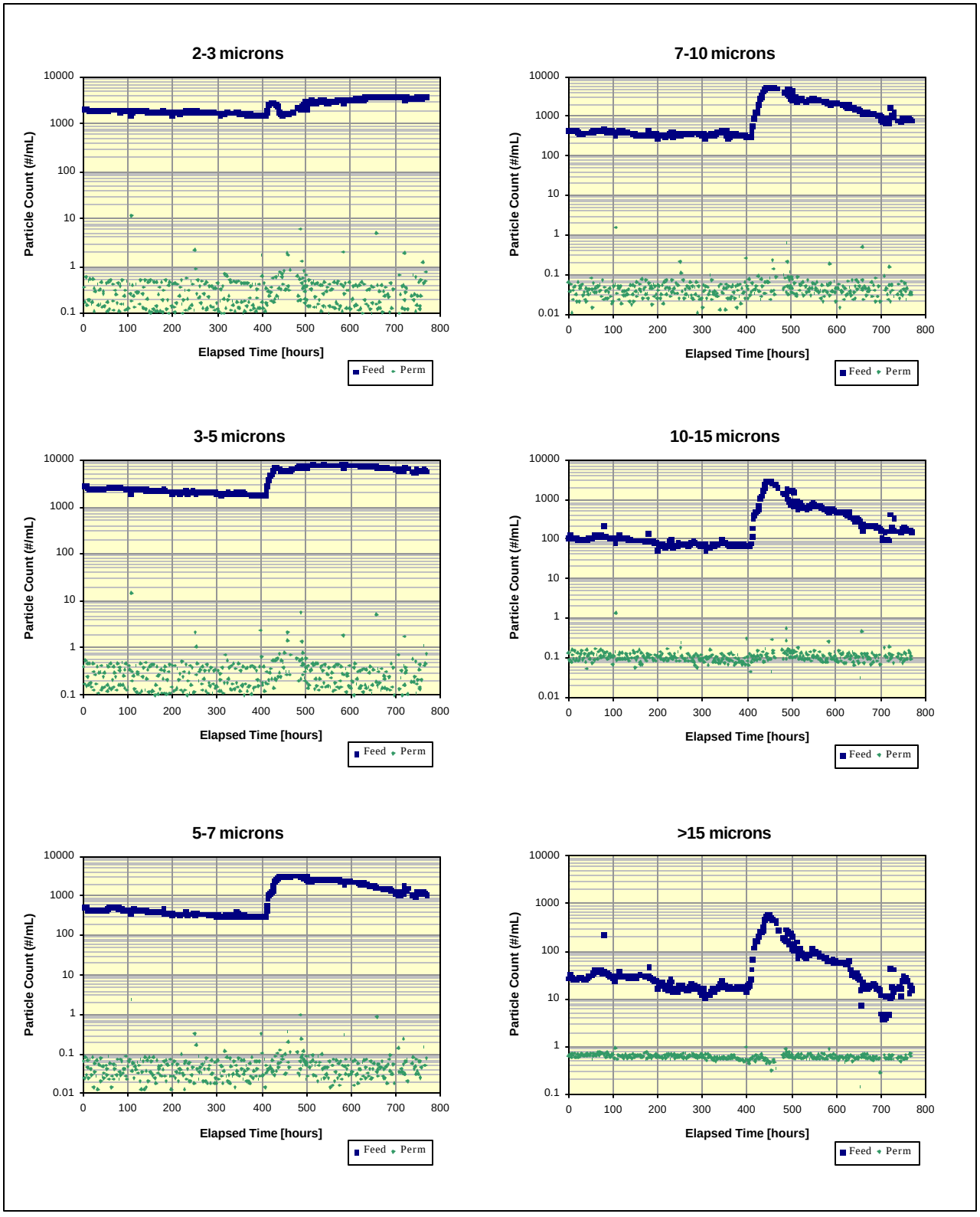


Figure 4-8. Period 1 Particle Counts by Size

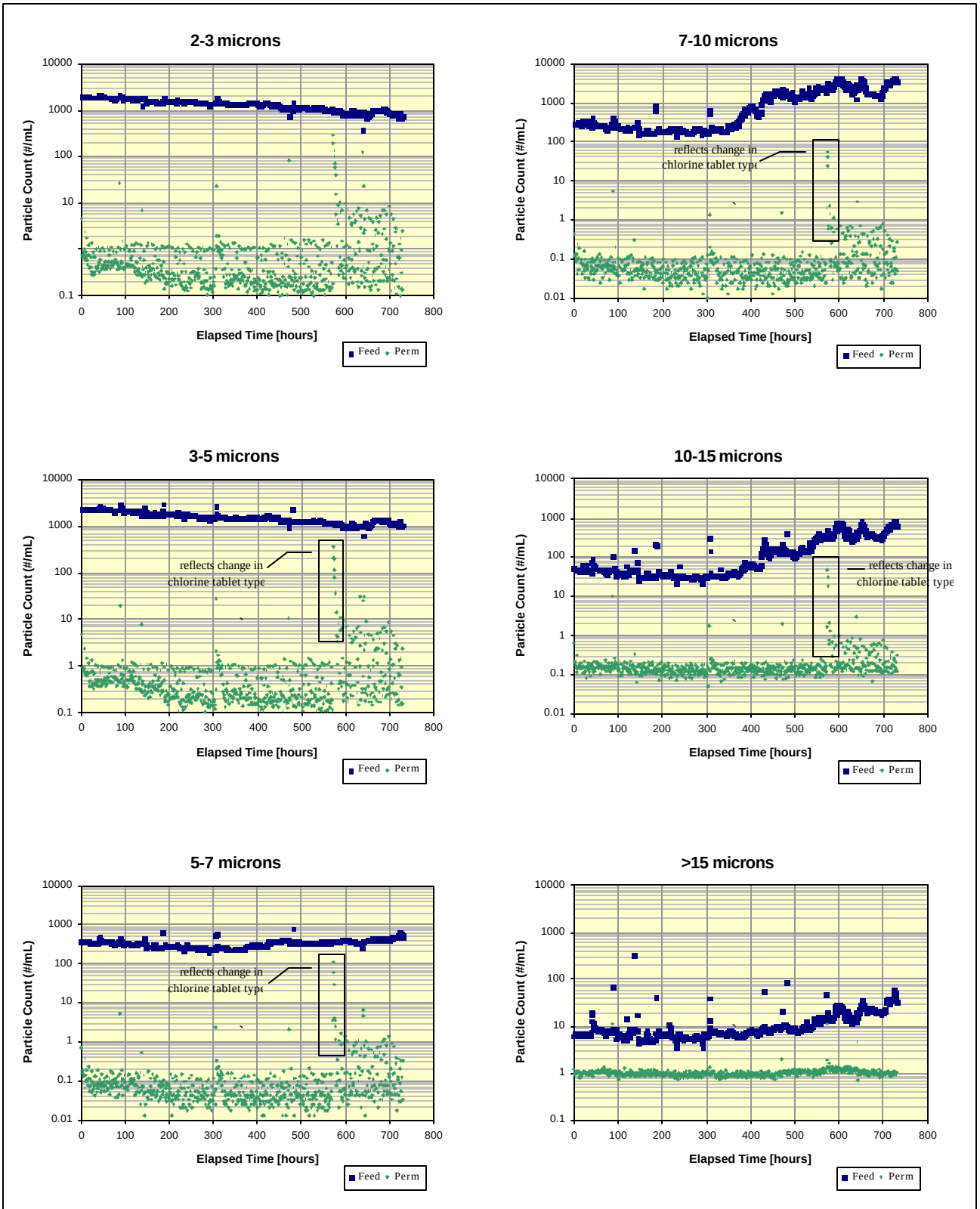


Figure 4-9. Period 2 Particle Counts by Size

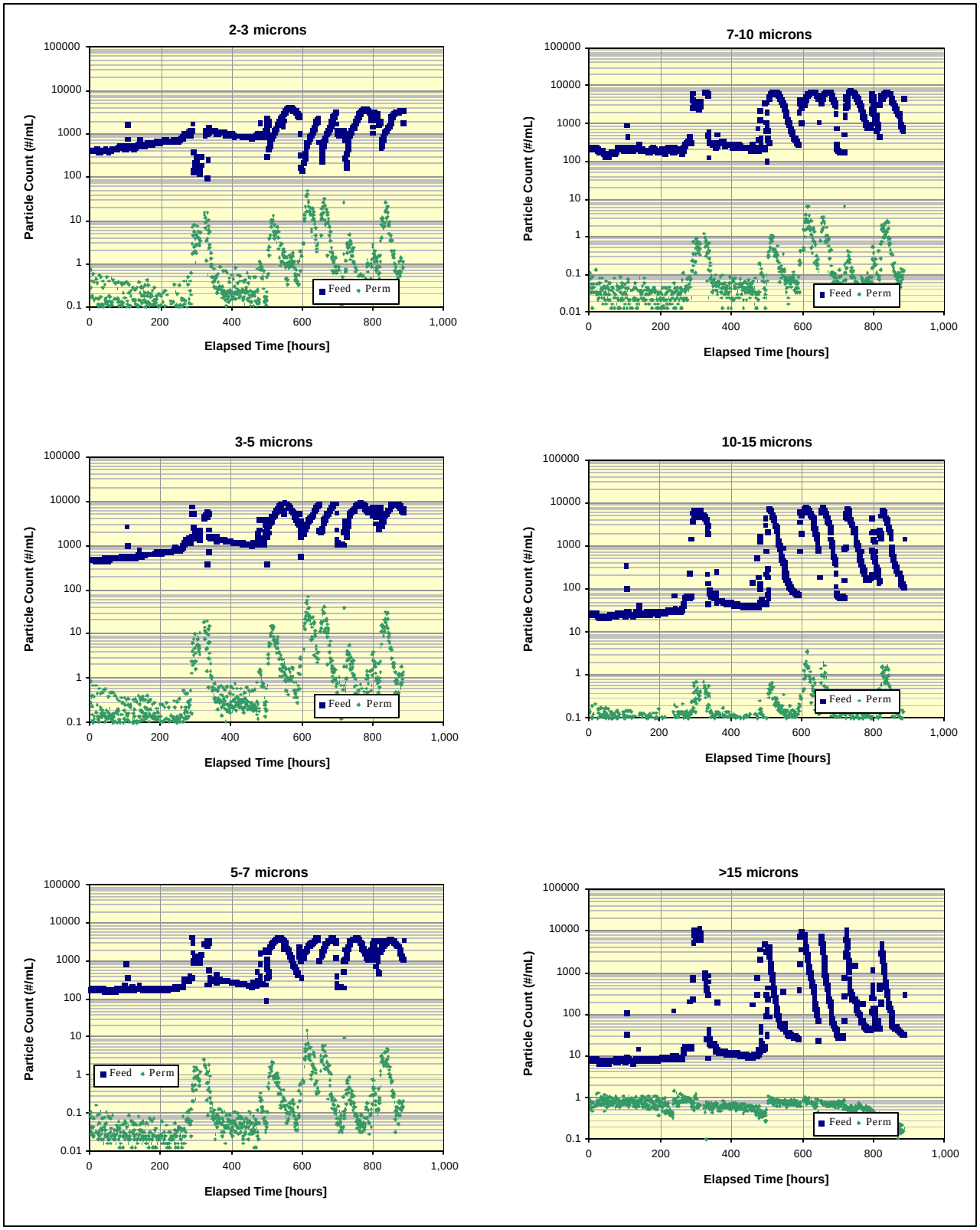


Figure 4-10. Period 3 Particle Counts by Size

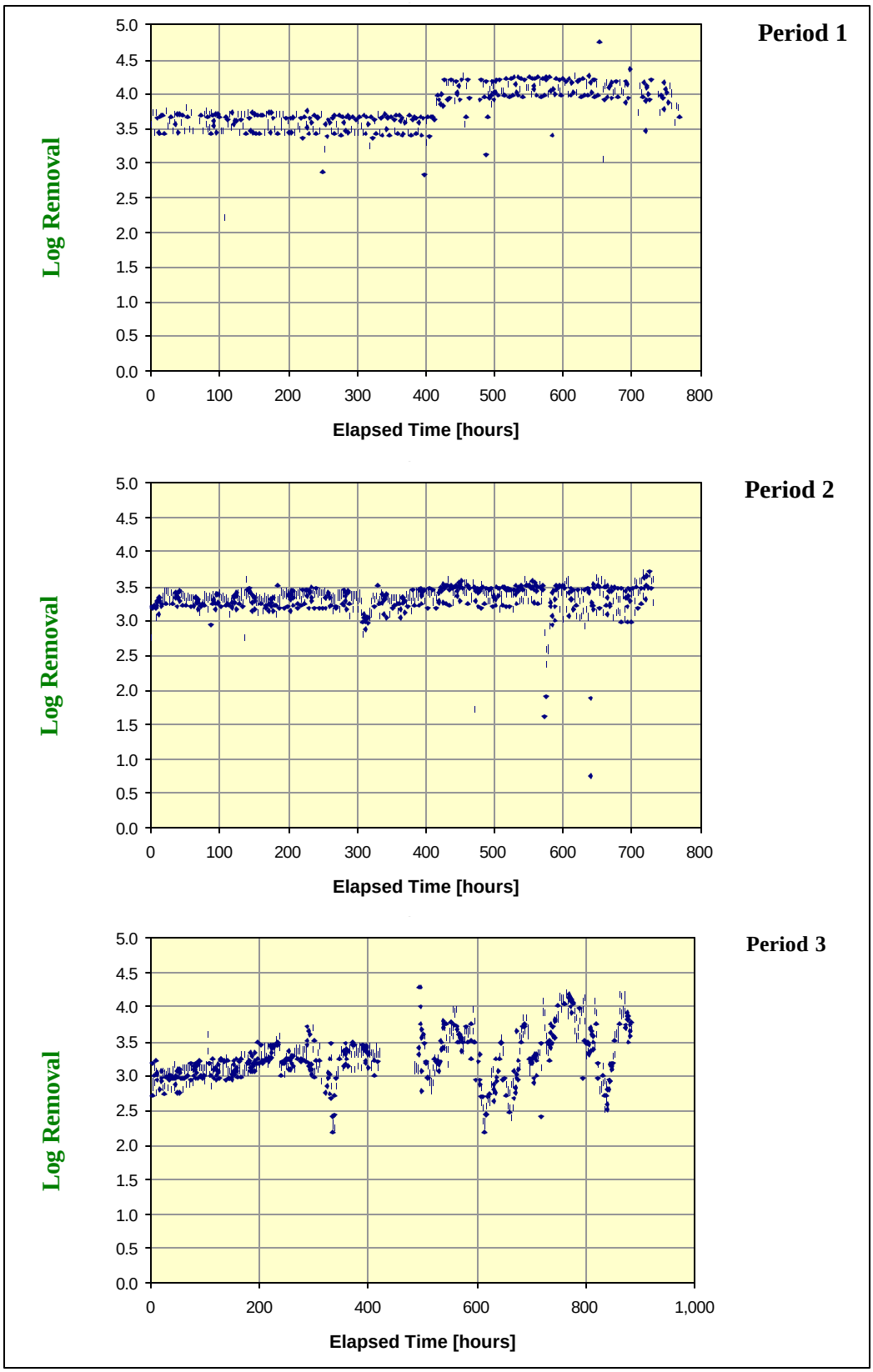


Figure 4-11. Particle Log Removal

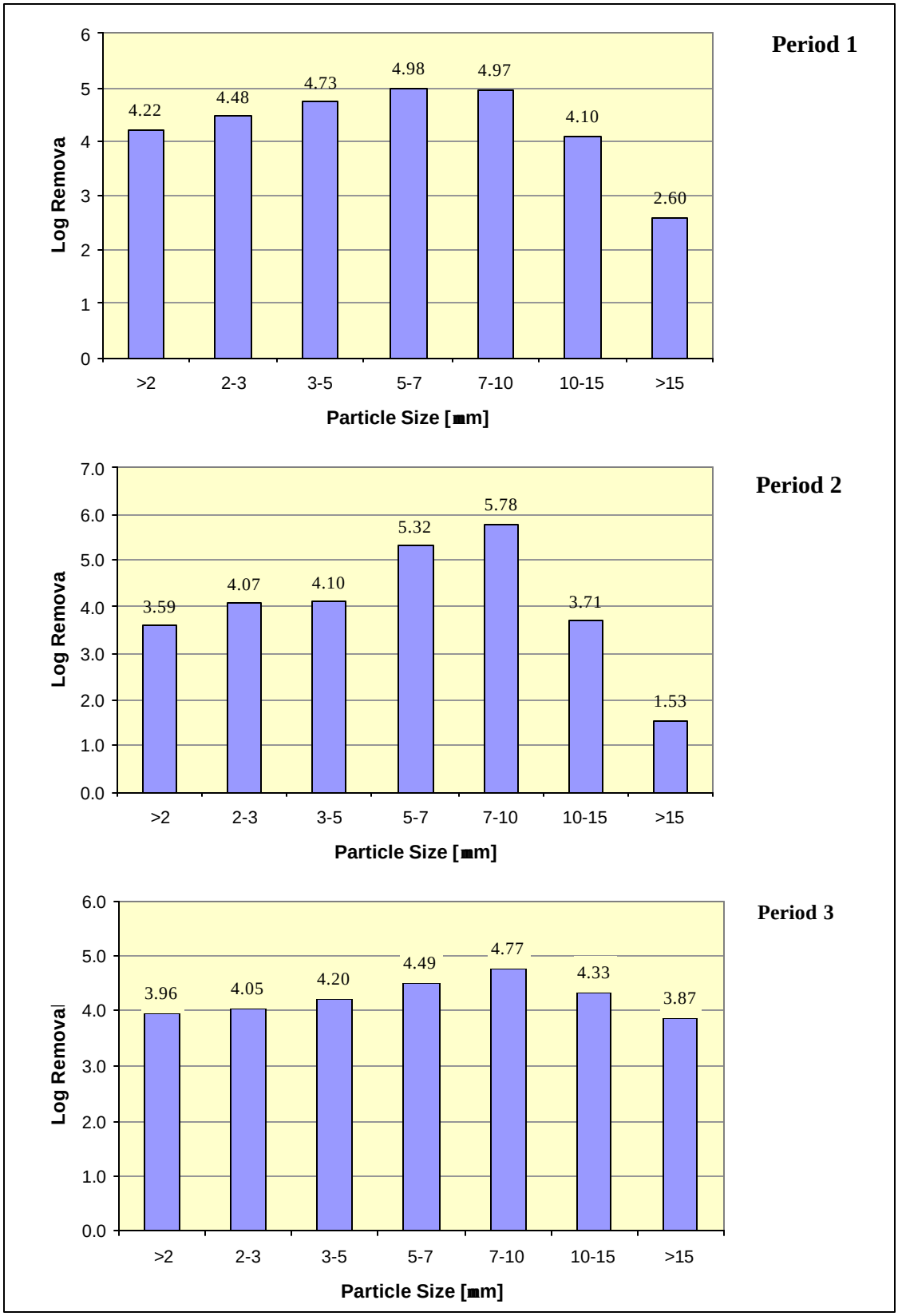


Figure 4-12. 95th Percentile Particle Removal (of individual calculated values) for the 3 Test Periods

with increasing particle size up to 10 micron, where the log removals started to decrease. The decrease in log removal with increasing size past 10 microns is a result of fewer of the larger particles in the feed water.

The data in Table 4-2 shows the contrast between the suspended solids concentration in the concentrate calculated from a mass balance through the membrane system to that measured in the concentrate stream.

Table 4-2. Comparison of TSS Measured in Concentrate with that Calculated From a Mass Balance

			TSS (mg/L)			
	Flows (LPM)				Concentrate	
Date	Permeate	Concentrate	Feed	Perm	Measured	Calculated
12/15/1998	64.4	3.5	13	<5	10	206.1
12/21/1998	64.4	3.5	<2.5	<2.5	7	1.3
12/28/1998	64.4	3.5	<5	<5	18	2.5
01/05/1999	64.4	3.5	3	<2.5	55	35.2
03/24/1999	65.7	3.5	<0.5	<0.5	9.5	0.3
03/31/1999	65.9	3.5	0.5	<0.5	16.0	5.2
04/07/1999	64.7	3.5	2.0	1.0	12.0	20.5
04/14/1999	64.0	3.5	1.0	<0.5	15.0	14.7
08/24/1999	62.8	3.2	1.0	<0.5	1.5	15.7
08/30/1999	66.2	3.2	2.0	<0.5	25.0	38.2
09/07/1999	62.5	3.2	1.5	<0.5	18.0	25.9
09/20/1999	60.6	3.2	85.0	<0.5	2,030	1,689
09/27/1999	62.8	3.2	12.0	<0.5	43.0	242.7
Average	64.0	3.4	9.5	0.8	174	173

Notes: Values below detection were considered to be half of the detection limit when used in the mass balance calculation.
Flow rates are expressed in LPM rather than gpm to make the calculation of TSS concentration easier to follow.

It should be noted that the measurements for the permeate and feed are often below detection, making it difficult to calculate the concentrate concentration. The uncertainty of the concentration contributed to the differences between measured and calculated concentrate values. The difference may also be a result of the time lag between the feed TSS and concentrate TSS. The solids retention time is estimated to be two hours in the process tank, resulting in a lag between changes in the influent and changes in the concentrate. TSS values below detection were assumed to contain a TSS concentration half of the detection limit for the purposes of the calculation. It is notable that when the average TSS concentrations are compared, the measured value is very similar to the calculated value. While individual data may be off, it appears that the average mass balance is in agreement. It is important that the solids in the process tank be completely mixed and that the TSS sample to be representative of the average concentrate TSS

concentration for the calculated and measured concentrations to be in complete agreement. Other package studies conducted by CH2M HILL have shown that measured TSS levels in the concentrate are consistently lower than the calculated values (Lozier, Personal Communication, February 2001).

A similar evaluation was performed using turbidity instead of TSS. The advantage of using turbidity is that the detection limit was low enough to allow the calculation to be performed. The results, shown in Figure 4-13 shows the relationship between the measured turbidity in the concentrate and that calculated using a mass balance model. Some of the outliers resulted from the time it takes for changes in turbidity in the feed water to be reflected in the concentrate that accumulates in the process tank. The turbidity outliers show the potential error that can occur when a time lag is not considered.

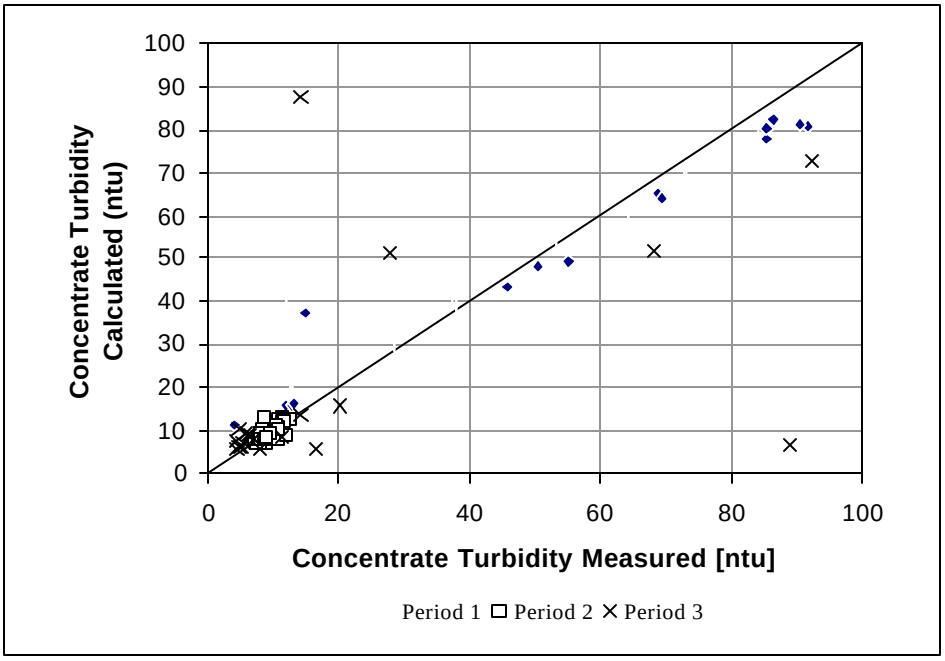


Figure 4-13. Concentrate Turbidity Measured vs. Calculated

Tables 4-3 through 4-8 summarize the water quality for each test period. Table 4-9 shows the log removal of HPC and TC during the three test periods. In most cases the HPC and total coliforms were below detection in the permeate and log removals could not be calculated. Where they were detected the log removals were lower than observed for particle removal or the microbial challenge test results presented later. The low log removals were likely a result of microbial growth in the sampling tubes sloughing off.

Table 4-3. Water Quality Summary for Feed Water in Period 1

Parameter	Units	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Alkalinity	mg/L as $CaCO_3$	7.3	5.5	8.5	1.3	6.0 - 8.6
Total Hardness	mg/L as $CaCO_3$	7.0	2.5	14.3	5.1	2.0 - 12.0
Calcium Hardness	mg/L as $CaCO_3$	3.9	2.5	6.6	1.8	2.1 - 5.7
Total Dissolved Solids	mg/L	21.4	<5	50	20	1 - 41
Total Suspended Solids	mg/L	5	1	13	5	0 - 10
Total Coliforms	MPN/100 mL	13	4	22	8	5 - 21
Heterotrophic Plate Count	CFU/mL	126	50	273	104	24 - 228
Total Organic Carbon	mg/L	1.6	1.4	1.9	0.24	1.4 - 1.8
UV 254	cm^{-1}	0.058	0.054	0.063	0.005	0.053 - 0.063
SDS TTHM	µg/L	46	N/A	N/A	N/A	N/A
SDS HAA6	µg/L	73	N/A	N/A	N/A	N/A
Turbidity	ntu	2.1	0.5	10	0.3	0.0 - 4.4
Particle Count (>2 µm)	#/mL	9,807	3,935	19,531	5,551	9,058 - 10,556

N/A = Not applicable as only one sample was analyzed.

Values below detection were considered to be half of the detection limit when used in calculations.

Table 4-4. Water Quality Summary for Permeate in Period 1

Parameter	Units	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Alkalinity	mg/L as $CaCO_3$	6.6	5.5	7.5	0.9	5.8 - 7.4
Total Hardness	mg/L as $CaCO_3$	5.1	2.4	7.4	2.1	3.1 - 7.1
Calcium Hardness	mg/L as $CaCO_3$	3.2	2.4	3.9	0.6	2.6 - 3.8
Total Dissolved Solids	mg/L	26	2.5	54	25	2.0 - 50
Total Suspended Solids	mg/L	2	1	3	1	1 - 3
Total Coliforms	MPN/100 mL	1	1	1	0	Not applicable, standard deviation is 0
Heterotrophic Plate Count	CFU/mL	2	1	4	2	0 - 4
Total Organic Carbon	mg/L	1.3	1.1	1.6	0.20	1.1 - 3.4
UV 254	cm^{-1}	0.044	0.034	0.052	0.008	0.036 - 0.052
SDS TTHM	µg/L	40	N/A	N/A	N/A	N/A
SDS HAA6	µg/L	72.3	N/A	N/A	N/A	N/A
Turbidity	ntu	0.032	0.023	0.052	0.006	0.031 - 0.033
Particle Count (>2 µm)	#/mL	1	0	4	1	1 - 1

N/A = Not applicable as only one sample was analyzed.

Table 4-5. Water Quality Summary for Feed Water in Period 2

Parameter	Units	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Alkalinity	mg/L as $CaCO_3$	6.5	6.1	6.9	0.3	6.2 - 6.8
Total Hardness	mg/L as $CaCO_3$	5.9	5.7	6.3	0.3	5.6 - 6.2
Calcium Hardness	mg/L as $CaCO_3$	3.5	3.3	3.8	0.2	3.3 - 3.7
Total Dissolved Solids	mg/L	18	16	19	2	17 - 19
Total Suspended Solids	mg/L	0.9	0.3	2.0	0.8	0.1 - 1.7
Total Coliforms	MPN/100 mL	0.6	0.5	1.0	0.3	0.4 - 0.8
Heterotrophic Plate Count	CFU/mL	13	4	36	15	0 - 28
Total Organic Carbon	mg/L	0.89	0.80	1.1	0.14	0.75 - 1.0
UV 254	cm^{-1}	0.037	0.032	0.045	0.006	0.031 - 0.043
SDS TTHM	µg/L	28.6	N/A	N/A	N/A	N/A
SDS HAA6	µg/L	35.8	N/A	N/A	N/A	N/A
Turbidity	ntu	0.49	0.37	0.70	0.09	0.48 - 0.50
Particle Count (>2 µm)	#/mL	4,613	2,948	7,452	932	4,477 - 4,749

N/A = Not applicable as only one sample was analyzed.

Table 4-6. Water Quality Summary for Permeate in Period 2

Parameter	Units	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Alkalinity	mg/L as $CaCO_3$	6.4	5.7	6.9	0.5	5.9 - 6.9
Total Hardness	mg/L as $CaCO_3$	5.9	5.7	6.2	0.2	5.7 - 6.1
Calcium Hardness	mg/L as $CaCO_3$	3.5	3.3	3.7	0.2	3.3 - 3.7
Total Dissolved Solids	mg/L	18	16	19	1	17 - 19
Total Suspended Solids	mg/L	0.4	0.3	1.0	0.4	0.0 - 0.8
Total Coliforms	MPN/100 mL	0.5	0.5	0.5	0	Not applicable, standard deviation is 0
Heterotrophic Plate Count	CFU/mL	0.5	0.5	0.5	0	Not applicable, standard deviation is 0
Total Organic Carbon	mg/L	0.69	0.65	0.75	0.05	0.64 - 0.74
UV 254	cm^{-1}	0.029	0.024	0.037	0.006	0.024 - 0.034
SDS TTHM	µg/L	24.5	N/A	N/A	N/A	N/A
SDS HAA6	µg/L	34.1	N/A	N/A	N/A	N/A
Turbidity	ntu	0.035	0.025	0.095	0.008	0.034 - 0.036
Particle Count (>2 µm)	#/mL	3.2	0	181	15.3	1.0 - 5.4

N/A = Not applicable as only one sample was analyzed.

Table 4-7. Water Quality Summary for Feed Water in Period 3

Parameter	Units	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Alkalinity	mg/L as $CaCO_3$	9.6	7.9	12	1.6	8.2 - 11.0
Total Hardness	mg/L as $CaCO_3$	8.2	7.1	9.4	1.1	7.2 - 9.2
Calcium Hardness	mg/L as $CaCO_3$	4.9	4.2	5.5	0.6	4.4 - 5.0
Total Dissolved Solids	mg/L	23	21	26	2.0	21 - 25
Total Suspended Solids	mg/L	20	1.0	85	37	0 - 52
Total Coliforms	MPN/100 mL	0.6	0.5	1.0	0.2	0.4 - 0.8
Heterotrophic Plate Count	CFU/mL	74	25	130	50	25 - 123
Total Organic Carbon	mg/L	0.93	0.75	1.1	0.14	0.81 - 1.1
UV 254	cm^{-1}	0.038	0.031	0.064	0.014	0.025 - 0.051
SDS TTHM	µg/L	27.2	26.3	28.1	1.3	25.4 - 29.0
SDS HAA6	µg/L	27.3	26.6	27.9	0.9	26.0 - 28.6
Turbidity	ntu	18	0.28	199	36	12.5 - 23.5
Particle Count (>2 µm)	#/mL	10,094	1,248	27,114	8,794	8,540 - 11,648

Table 4-8. Water Quality Summary for Permeate in Period 3

Parameter	Units	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Alkalinity	mg/L as $CaCO_3$	9.5	8.6	11.0	0.9	8.7 - 10.3
Total Hardness	mg/L as $CaCO_3$	8.0	7.2	9.3	0.9	7.2 - 8.8
Calcium Hardness	mg/L as $CaCO_3$	4.8	4.2	5.5	0.5	4.4 - 5.2
Total Dissolved Solids	mg/L	23	21	25	1.0	22 - 24
Total Suspended Solids	mg/L	0.25	0.25	0.25	0	Not applicable, standard deviation is 0
Total Coliforms	MPN/100 mL	0.5	0.5	0.5	0	Not applicable, standard deviation is 0
Heterotrophic Plate Count	CFU/mL	1.4	0.5	5.0	2.0	0.0 - 3.2
Total Organic Carbon	mg/L	0.81	0.55	1.0	0.17	0.66 - 0.97
UV 254	cm^{-1}	0.021	0.013	0.029	0.006	0.016 - 0.026
SDS TTHM	µg/L	17.9	14	21.8	5.5	10.3 - 25.5
SDS HAA6	µg/L	13.9	10.5	17.3	4.8	7.3 - 20.6
Turbidity	ntu	0.036	0.027	0.059	0.006	0.035 - 0.037
Particle Count (>2 µm)	#/mL	5.9	0	94	12.4	3.7 - 8.1

Table 4-9. HPC and Total Coliform for Each Test Period

	HPC (CFU/mL)			Total Coliform (MPN/100 mL)		
Test Period	**Feed**	**Permeate**	**Log removal**	**Feed**	**Permeate**	**Log removal**
1	273	4	1.8	17	<1	>1.2
1	53	<1[2]	>1.7	4	<1	>0.6
1	50	<1	>1.7	8	<1	>0.9
1	127	1	2.1	22	<2	>1.0
2	5	<1	>0.7	<1	<1	≥0
2	36	<1	>1.6	1	<1	≥0
2	4	<1	>0.6	<1	<1	≥0
2	8	<1	>0.9	<1	<1	≥0
3	25	5	0.7	<1	<1	≥0
3	39	<1	>1.6	<1	<1	≥0
3	130	<1	>2.1	<1	<1	≥0
3	–[1]	<1		<1	<1	≥0
3	100	<1	>2.0	<2	<1	0 – 0.3

[1] – (dash) indicates that the sample was not analyzed

[2] – Values below detection limit were considered to be at detection limit for the calculation of log removal. The log removal value was then expressed as greater than the value calculated.

4.5 Membrane Pore Size

A request was submitted to the manufacturer to provide the 90 percent and maximum pore size of the membrane being verified. ZENON Membrane Systems responded that the ZeeWeed® OCP UF membrane has a 90 percent pore size of 0.04 um and an absolute pore size of 0.10 um. ZENON determines the pore size distribution using flow porometry in accordance with ASTM-F316 *Standard Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test.* The above information are taken from a letter supplied by the manufacturer which is included in Appendix F of this report. This is provided for informational purposes only and the results were not verified during the ETV testing.

4.6 Membrane Integrity Testing

Particle counts were used to indirectly monitor the integrity of the membranes. The results are shown previously in Figures 4-7 and 4-11. During the third test period, it appeared that particles greater than 2 microns were passing the membranes. Given a maximum pore size of 0.10 microns, the membranes must have lost some integrity or alternatively, particles were being detected which originated downstream of the membrane. A pressure-hold test was performed at the end of this third test period to evaluate integrity. The results of this test are shown in Figure 4-14. It is significant that the results of the pressure hold test were within acceptable bounds provided by the manufacturer (less than 0.4 psi drop from an initial pressure of 4.0 psi in 2 minutes) and indicated that the membranes passed the manufacturer's integrity test.

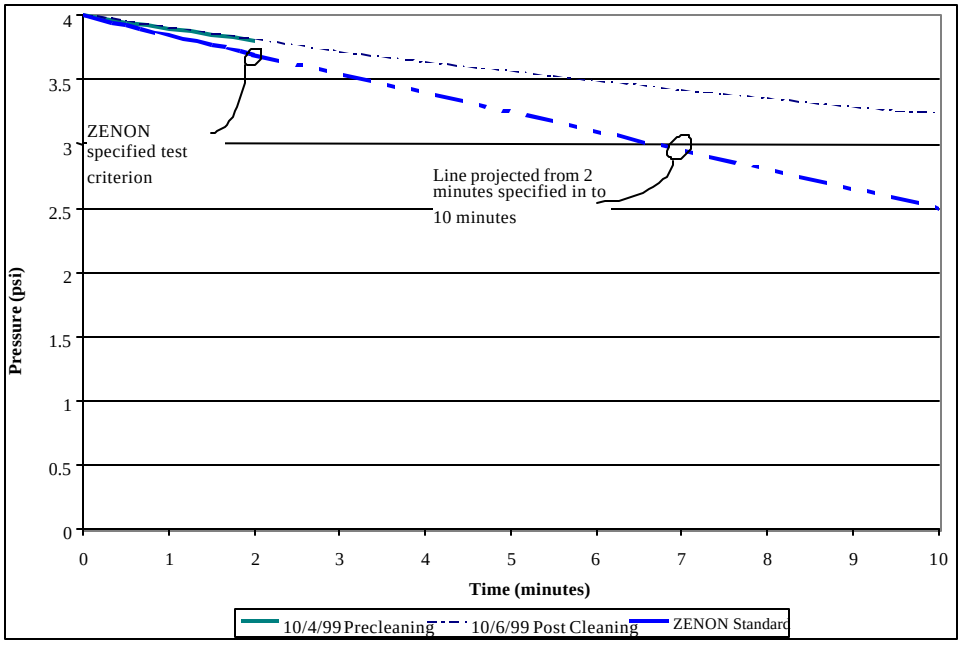


Figure 4-14. Pressure Hold Test Results (ZENON Package) for Test Period 3

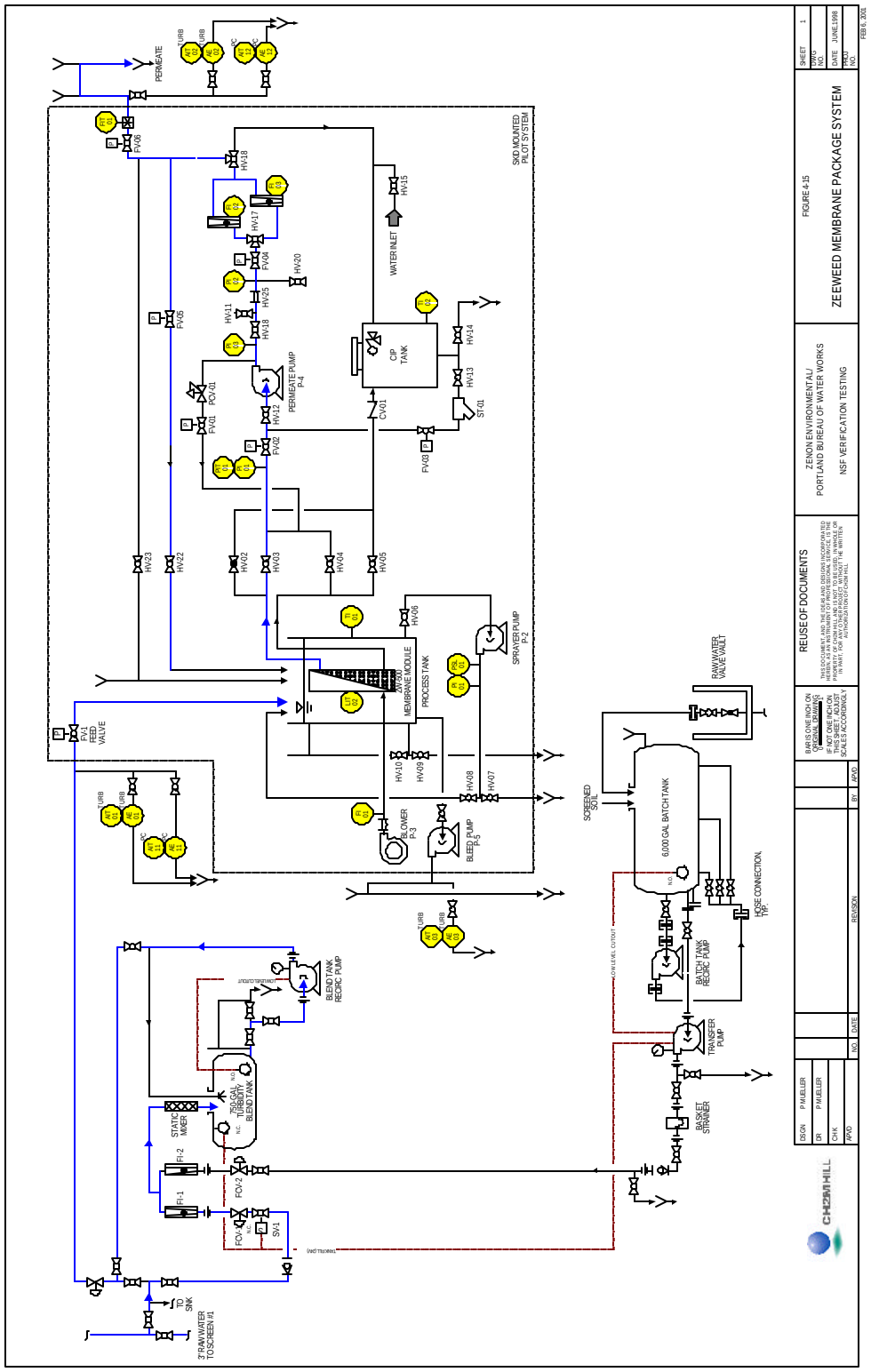
The high particle counts during period three are in direct conflict with other indicators of integrity:

- The results of the pressure drop integrity test
- Turbidity data (Figure 4-6)
- Microbial challenge test (presented later in Section 4.7)

Particle counts may be a more sensitive measure of membrane integrity than the other indicators of integrity. Other causes of the high particle counts include:

- Contamination from a cross connection
- Inaccuracies with the particle counter
- Bubbles in the permeate water

The process flow diagram, Figure 4-15, was studied to determine if contaminated water could have found its way into the permeate side of the membranes if a valve failure occurred. It was determined that a properly plumbed unit could not have encountered contamination of the permeate flow. Particle counter error was ruled out because the particle counter was calibrated before the study began and the high particle counts did not occur randomly. Rather they were correlated with high particle counts in the feed water. At the beginning of the study, two bubble traps were installed between the ZW-500 membrane system and the permeate particle counter to avoid counting bubbles as particles. As such, contamination, particle counter error, and bubbles are not considered plausible explanations for the high particle counts. However, it was not possible to confirm whether the high particle counts were passing through the membrane or being formed downstream of the membrane.



Recognizing that the higher particle counts correlate strongly with the feed water turbidity during the turbidity augmentation, a potential explanation is that the turbid solution contained higher

than normal levels of dissolved impurities, such as dissolved iron or manganese, that could be readily oxidized downstream of the membrane.

4.7 Microbial Challenge Testing

The data in Table 4-10 summarize feed and permeate concentrations of *Giardia*, *Cryptosporidium* and MS-2. The log removals of *Giardia*, *Cryptosporidium*, and MS-2 bacteriophage are shown in Figure 4-16. The log removals were based on the permeate quality relative to 1/20 of the measured concentrate concentration. As discussed previously in Section 3, the concentration of particles in the process tank is 20 times greater than in the feed tank.

Table 4-10. Summary of Microbial Test Results Showing Average Microbial Densities in Each Sample

Sample	Period 1	Period 2	Period 3
Giardia Feed	1,000 per L	49,000 per L	8,500 per L
Giardia Concentrate	2,000 per L	144,500 per L	239,000 per L
Giardia Permeate	<0.05 per L	0.15 per L	0.12 per L
Cryptosporidium Feed	130,000 per L	9,500 per L	4,250 per L
Cryptosporidium Concentrate	270,000 per L	21,000 per L	71,000 per L
Cryptosporidium Permeate	<0.05 per L	<0.05 per L	<0.04 per L
MS-2 phage Feed	510,000 per mL	950,000 per mL	450,000 per mL
MS-2 phage Concentrate	515,000 per mL	2,000,000 per mL	11,350,000 per mL
MS-2 phage Permeate[1]	6 per mL	25 per mL	280 per mL

[1] 0 was used to calculate an average concentration when one of the results was below the detection limit.

In Figure 4-16, the log removals that are shown as *greater than* were based on the detection limit.

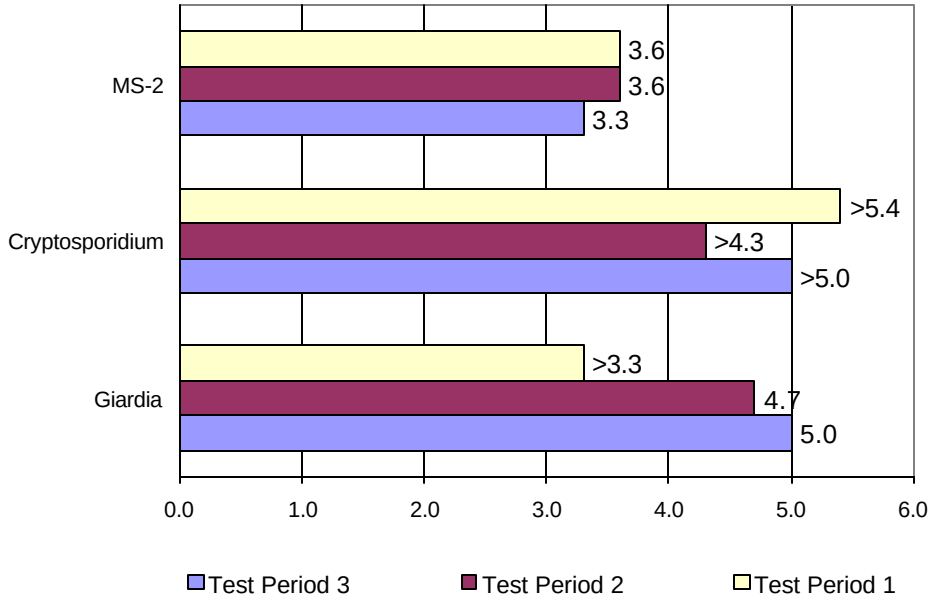


Figure 4-16. Log Removal of Microbes

Given that the pore size of the membranes were found to be as great as 0.157 microns, three to four log removal of viruses was unexpected. The large log removal may be a result of the viruses attaching to the surface of particulates too large to pass through the membranes or adsorbing to the membrane material. It was surprising that *Cryptosporidium* were removed to a greater extent than were *Giardia*. *Cryptosporidium* were below detection in the permeate in all samples. Conversely, *Giardia* was observed in the permeate during two of the three test periods. Given the size of *Giardia* cysts (about 4 by 7 microns) it is unlikely that the cysts passed through intact membranes. The presence of *Giardia* in the permeate may be an artifact of the analytical tests. Though the methods used are accepted in the scientific community as among the best available, they are not as accurate as many of the methods used for the detection of chemicals in the environment and false positives have been recorded (Clancy, 1994 and 2000). The permeate concentrations may be false positives. To be conservative, the results will be treated as real, but it is recognized that it is incongruous to pass *Giardia*, but not *Cryptosporidium* based on size alone. Additional studies of *Giardia* and *Cryptosporidium* removal with damaged fibers are presented in Appendix E.

The purpose of testing with damaged fibers was to determine how the membranes performed with damaged fibers and what could be used as a surrogate to show the presence of damaged fibers. This test was performed at the end of the third test period, after the membranes had been cleaned.

Two modes of damaging the fibers were used. First a fiber was pin-pricked, and its performance evaluated, then the same fiber was completely severed and its performance monitored, and finally the damaged fiber was blocked off and its performance monitored. Figure 4-17 shows a fiber being blocked-off with epoxy after it had been severed.

Figure 4-17. Scalloped Off Damaged Fiber with Epoxy

The operational parameters during the test were as shown in Table 4-11. The water quality during the test is shown in Table 4-12.

Good removals were observed with the intact and with the pinpricked fibers. It was difficult to tell that the pinpricked fiber was damaged at all based on the log removals. In contrast, there was a significant degradation in log removals when the membrane fiber was severed.

Refer to Table 4-13 for a summary of log removal of microorganisms. Good removals were observed with the intact and with the pinpricked fibers. It was difficult to tell that the pinpricked fiber was damaged at all based on the log removals. Neither the virus nor *Cryptosporidium* log removals declined when

the fiber was pinpricked or severed. In contrast, there was a significant degradation in log *Giardia* removal when the membrane fiber was severed.

Table 4-11. Operating Conditions During Testing

Parameter	Value
Transmembrane Pressure	5 to 6 psi
Specific Flux at 20°C	9.0 to 10.0 gfd/psi
Recovery	94%
Backpulse interval	15 minutes
Backpulse Duration	15 seconds

Table 4-12. Water Quality During Testing

Parameter	Value
Temperature	15°C
Turbidity	1 to 10 ntu
Particle Counts	17,000 to 19,000 per mL > 2 micron
pH	7.0 to 7.5
TOC	<1 mg/L

Table 4-13 summarizes the log removal of microorganisms.

Table 4-13. Log Removals in Intact, Damaged, and Severed Membrane Fibers

Membrane Condition	Giardia	Cryptosporidium	MS-2 Phage
Intact	4.9	>5.0	3.2
Pinprick	5.0	>4.7	3.7
Severed	3.5	5.2	3.5

*Permeate samples were below detection and log removals were calculated using permeate detection limit and expressing the log removals as greater than.

Turbidity and particle counts were measured to determine whether either of these commonly monitored surrogates were capable of detecting a damaged fiber. The results, summarized in Table 4-14, indicate that neither turbidity nor particle counts were able to detect the pin prick. Both of these measurements remained the same after the fiber was compromised with the pinprick. Turbidity remained at 0.038 and particle counts remained at 12 per mL > 2 microns. Turbidity is not sensitive enough to detect damaged membranes. The average turbidity only increased to 0.098 ntu (from 0.038) in the severed fiber. Normally turbidities of less than 0.1 ntu are considered acceptable. Particle counts proved to be a more sensitive measure, increasing from 12 per mL to 912 per mL when the fiber was severed.

Table 4-14. Usefulness of Surrogate Measures of Membrane Performance

Membrane Condition	Turbidity (NTU)	Particles > 2 micron per mL
Intact Membrane	0.038	12
Pinprick	0.038	12
Severed	0.098	912

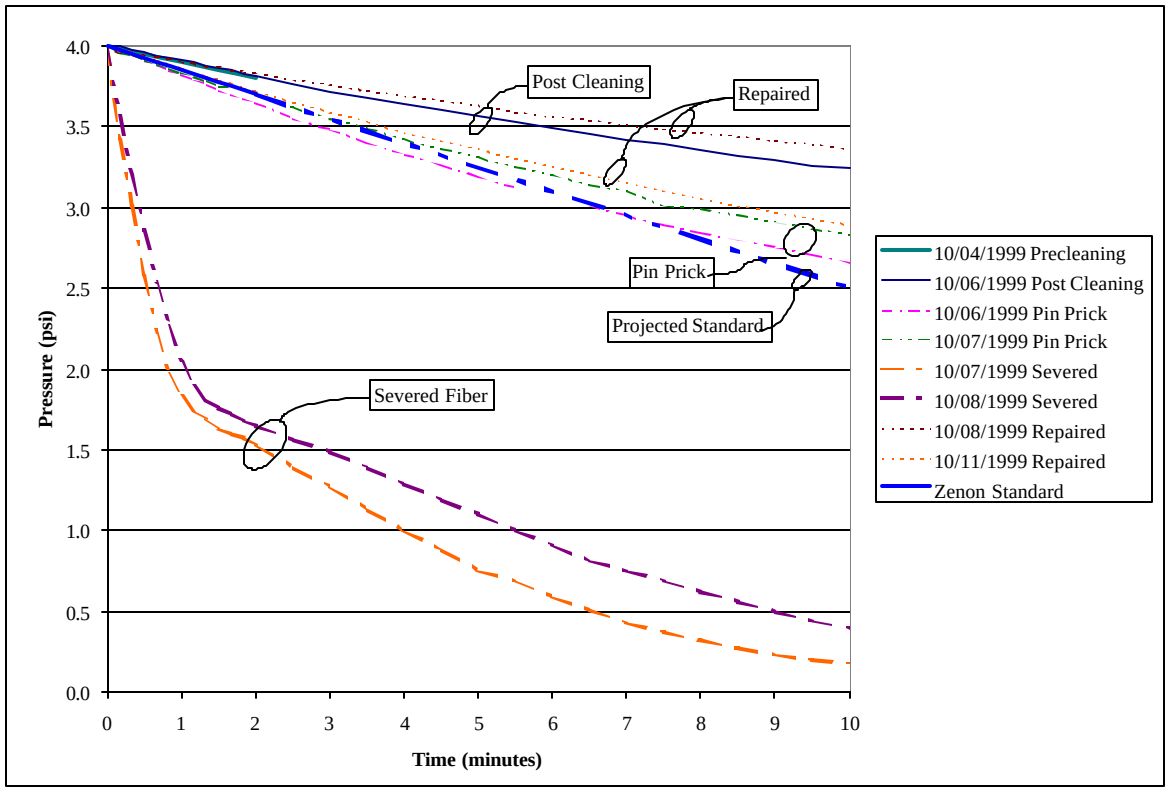


Figure 4-18. Pressure Test Results

The pressure test results shown in Figure 4-18 illustrate a number of points. First, the membranes met the ZeeWeed™ specification before the fibers were damaged. After the pin prick, the system failed the pressure hold test (but just barely). However, after about 12 hours of operation, the system then passed the pressure hold test. It is theorized that the suspended material in the process tank coated the surface of the membrane fiber, including the surface with the pinprick, and acted to partially plug the pinprick hole. When the severed fiber was tested, the membrane system failed the pressure test in dramatic fashion. It is interesting to note that the rate of pressure dissipation lessened with 12 hours operations time even with the severed fiber. It appears that some bridging of suspended materials across the open ends of the fiber occurred. Finally, when the ends of the severed fiber were sealed with epoxy, the membrane system again passed the pressure hold test. These tests demonstrate that the pressure hold test can be used to detect a single broken fiber or a pinpricked fiber. The manufacturer's fiber repair technique was also determined to be simple and effective.

4.8 Operations and Maintenance

ZENON's operating instructions for the ZeeWeed™ equipment are included as Appendix B to this document. The primary variables that required operator input were permeate flow, backpulse frequency and duration, concentrate rate, and air flow rate.

4.8.1 Normal Operation

The ZENON Package Unit was controlled with an Allen Bradley PLC. Once the operating parameters were set, this automated system required little operator input during normal operations. Plant technicians recorded operating data three times a day. Concentrate flow rate, permeate flow rate, and air flow rate were controlled with manual adjustments. Concentrate flow rate was verified using a watch and graduated cylinder. Rotameters were used to check the latter two.

4.8.2 Backwash

The PLC automatically initiated a backpulse every 15 minutes as programmed by the operator. During the 15 seconds of backpulse, permeate production stopped. Permeate with a low concentration of chlorine was used for the backpulse. Chlorine was provided with a calcium hypochlorite tablet. New tablets were added periodically to maintain 5 mg/L chlorine.

4.8.3 Equipment Breakdown

Equipment breakdowns, improper operations, and power outages caused the system to cease operations. The most commonly identified cause of long term inoperability was the failure of the support equipment, such as feed pumps. Feed pumps, which supplied raw water to the unit, were site-specific and were not controlled by the PLC. After a power failure, the technicians reactivated the unit using the PLC but did not manually restart the feed pumps. The PLC would then shut down the unit due to low water.

Other long-term shutdowns were caused by feed line ruptures and removal of the compressed air supply to the unit. In a permanent installation, less failure would be expected and dedicated technicians would be familiar with the unit and its components.

4.8.4 Equipment Maintenance

The unit operated independently during the study with no significant maintenance of mechanical equipment. Longer term operation would require routine maintenance to ensure smooth operation. Items typically requiring attention include valves, blowers, and pumps.

During the test period, repairs were minimal and included replacement of the water level sensor and replacement of the feed-tank fill valve. Auxiliary equipment, including the concentrate pump, required replacement.

Maintaining the monitoring equipment was a major component of maintenance. Turbidimeter maintenance included cleaning the cases and sensors and flushing the sample lines. Particle counters were flushed and the flow rates adjusted. The turbidimeter required more maintenance with high turbidities (greater than 50 ntu) caused blockage in sample lines and sensor housing. The overall level of instrumentation maintenance would not be unique to membrane treatment.

4.8.5 Cleaning

The most significant maintenance event included chemical cleaning of the membrane. In this test, cleaning was performed every 30 days. Based on the test results, cleaning cycle would be greater than 30 days when the turbidity is less than 10 ntu. Cleaning caused the system to be out of service for up to 24 hours. During this time, the system was backwashed and soaked in a chlorine solution.

A larger plant would need to be sized to have redundant process tanks to maintain the design flow rate while one tank is out of service for cleaning much like a media filter plant is designed to accommodate periodic backwashing of filters.

4.8.6 Power Supply Requirements

Power consumption was not measured in this test. The package plant's electrical requirements were 230 V, 60 Hertz, 60 Amps, single-phase current. Power consumption was measured on this same model in a separate ETV study (USEPA/NSF 2000) by using an electric meter. The unit used 77-kilowatt hours (kWh) per day on average.

4.9 Quality Assurance/Quality Control

4.9.1 Turbidity Augmentation

The turbid water used to augment turbidity in the third test period was tested to determine the stability of the suspension. A suspension that settled very slowly would be representative of the turbid water containing fine particulate matter that would be found after heavy runoff. The results of this test are shown in Figure 4-19. The settling test was started at 8:30 a.m. and the columns were observed throughout the day. Pictures were periodically taken to record the results. Even after several hours of settling, no interface between turbid and clear water appeared, indicating the presence of a very stable suspension representative of fine particulate matter found in surface waters after heavy runoff.

Figure 4-19. Settling of Augmented Turbidity

4.9.2 Instrumentation/Operation

The on-line turbidimeters silted in when the turbidity exceeded 50 ntu. This only occurred in the raw water samples and the units were cleaned out and checked for calibration daily.

The turbidimeters were calibrated weekly. At the same time the electronic signal was also checked to be sure the correct turbidity was being logged in the electronic data sheet. There were no errors in this signal during the test periods.

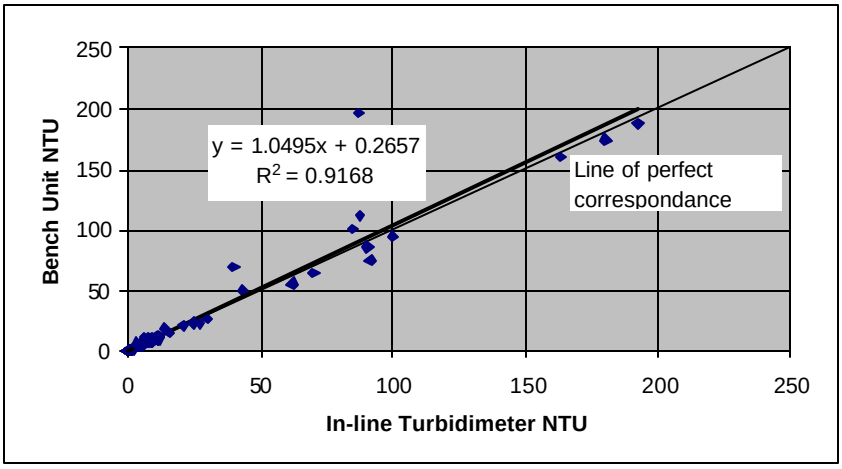


Figure 4-20. Comparison Between In-line and Bench Turbidimeters

The in-line turbidimeters were compared to a bench unit. A comparison of the turbidity from the two instruments is shown in Figure 4-20. The correspondence between the two instruments was good.

The feed rate to the turbidimeters was checked daily to be sure that it was within the recommended range of between 400 and 600 mL/min. If it was not in this range, the flow rate was adjusted. Flows outside the recommended range will still yield reasonable results, but some settling may occur in the on-line instrument when the flows are too low and bubbles may occur when flows are too high. Most of the flows were within range. Some days the flow was not checked as summarized in Table 4-15.

Table 4-15. Summary of Exceptions to QA/QC Plan for Turbidimeter Flow

Test Period/Date	Exception
1 – 12/22/98 and 12/23/98	Flow rate not checked. On 12/24/98 flow rate was checked and found to be acceptable
1 – 12/30/98	Flow rate not checked. On 12/31/98 and flow rate was checked and found to be acceptable
1 – 1/09/99 through 1/11/99	Flow rate not checked. On 1/12/99 and flow rate was checked and found to be acceptable
2 – 3/19/99 through 3/21/99	Flow rate not checked. On 3/22/99 and flow rate was checked and found to be acceptable in the concentrate and permeate lines, but not in the feed line.
2 – 3/29/99 and 3/30/99	Flow rate not checked. On 3/31/99 and flow rate was checked and found to be acceptable in the concentrate and permeate lines, but low in the feed line. Flow was adjusted to within recommended range.
2 – 4/16/99	Flow rate not checked. On 4/17/99 and flow rate was checked and found to be acceptable in the concentrate and permeate lines, but low in the feed line. Flow was adjusted to within recommended range.
3 – 9/5/99	Flow rate not checked. On 9/6/99 and flow rate was checked and found to be acceptable in the permeate line, but low in the feed and concentrate lines. Flows were adjusted to within recommended range.
3 – 9/7/99	Flow rate not checked. On 9/8/99 and flow rate was checked and found to be acceptable in the permeate line, high in the feed line, and low (0) in the concentrate line. Flows were adjusted to within recommended range.
3 – 9/27/99	Flow rate not checked. On 9/28/99 and flow rate was checked and found to be acceptable in all lines.

The particle counter flow was checked daily to assure it was 100 mL/min. The flow rate to the particle counter was critical and the particle counts were in error in direct relationship to the deviation from the target flow rate. The flows were checked and adjusted as needed to provide a flow of 100 mL/min. Table 4-16 summarizes some statistics that show that the flows in the feed stream and permeate stream were close to the target, especially after adjustment. In general, the permeate stream was closer to the 100 mL/min target than the feed stream. The 95 percent confidence intervals were tight and close to the target, indicating that the particle count data is both accurate and precise.

The on-line particle counters were only able to measure up to 22,000 particles. During some periods of test period 3, the particle counts in the raw water exceeded 22,000.

The sample lines to and from the particle counters and the turbidimeters were cleaned and flushed three times per week to minimize a build up of material that could dislodge and cause extraneous readings.

Table 4-16. Statistics Summarizing the Flows to the Particle Counters

	Particle Counter on Feed Stream		Particle Counter on Permeate Stream	
	Before Adjustment	**After Adjustment**	**Before Adjustment**	**After Adjustment**
Mean Flow (mL/min)	98	99	100	100
Minimum Flow (mL/min)	80	95	86	95
Maximum Flow (mL/min)	108	107	106	106
Standard Deviation	4.8	2.8	3.0	1.8
95% Confidence Interval of Flow (mL/min)	97 to 98	99 to 100	99 to 101	100 to 101

4.9.3 Data Quality Evaluation

The data quality evaluation indicated that the data from the Applied Sciences Laboratory and Bio-Vir were of high quality and suitable for making interpretations. Case narratives were not provided by the Portland Water Bureau but verbal discussions with staff indicated there were no incidences of holding time violations or problems with sample handling. The data are believed to be of high quality.

4.9.3.1 Qualifiers

Sample results that were not within the acceptance limits (indicated by the query process) were appended with a qualifying flag. The data qualifier flags consisted of a single- or double-letter code that indicated a possible data quality issue. The qualifying flags originated during the data review, validation, and database query processes. The data qualifier flags were included in the data summary tables for end data users. The following flags were used:

- **U** = Undetected. Samples were analyzed for this analyte, but the analyte was not detected above the sample-specific method detection limit (MDL).
- **UJ =** Detection limit estimated. Samples were analyzed for this analyte, but the results were reported as not detected. Analytes near the MDL may not be detected due to low recoveries or holding time issues.
- **J** = Estimated. The analyte was present, but the reported value may not be accurate or precise. The J qualifier was also used by the laboratory for analytes detected between the MDL and the reporting limit (RL).
- **R =** Rejected. The data are unusable. (Note: Analyte/compound may or may not be present.)
- **B =** Blank contamination. The analyte was detected in blank samples. Sample measurement value is not distinguishable from blank measurement results. Any existing "=" or "J" flags are combined with the B.

4.9.3.2 Sample Handling

Proper sample handling and chain-of-custody procedures verify the integrity of the field sample. The chain-of-custody and laboratory case narrative were reviewed to determine if any sample handling procedures might affect sample integrity of the quality of analytical result. All coolers were received by the laboratory in good condition. All requested analyses were performed.

4.9.3.3 Holding Times

Holding time criteria monitor sample integrity that may be compromised over time. The sample holding times for the THM samples in Sample ID 930501 and 930502 (water samples collected March 31, 1999) were exceeded. Holding times were not grossly exceeded (7 days maximum, 1-day exceedance) and the measured results for these samples are thought to be valid. All other samples were analyzed within their EPA-approved holding time criteria. Therefore, all other samples met holding time quality control (QC) acceptance criteria.

4.9.3.4 Method Blanks

Data from method blanks were used to determine when detected concentrations should be attributed to laboratory contamination rather than inherent sample conditions. According to the case narratives, a method blank was analyzed with every analytical batch. All method blanks were contamination-free.

4.9.3.5 Precision and Accuracy

Precision and accuracy of laboratory performance are evaluated by the analysis of matrix spike/matrix spike duplicates (MS/MSD) surrogate recoveries, and laboratory control samples (LCS). LCS are reagent water matrices spiked with target analytes and recoveries should be within the laboratory established control limits to meet accuracy QC acceptance criteria.
LCS recoveries were not provided for each analytical batch. According to the case narrative, all except two recoveries were within the laboratory established control limits. The two exceptions were with the SDS HAA samples collected September 27, 1999:

- Monochloroacetic Acid (62%) and Monobromoacetic Acid (67%) recoveries did not meet acceptance criteria. All other spike acceptance criteria were met.
- Surrogate recovery (61%) in LCS did not meet acceptance criteria. All other surrogate recovery acceptance criteria were met.

These compounds were normally present in concentrations below the reporting limit and the impact on the data integrity is deemed to be minimal.

MS/MSD duplicate pairs are native samples that have been spiked with target compounds. Organics data are not qualified on the basis on MS/MSD results alone. However repeated failure of an analyte to meet established QA/QC criteria might indicate a bias for this compound in the

matrix. According to the case narratives, all acceptance criteria were met for the matrix spike samples.

4.9.3.6 Continuing Calibration

Continuing calibration criteria monitor analytical performance and proper compound identification on a daily or more frequent basis. According to the case narrative all of the percent difference results for all target compounds were within the QC control limits.

Chapter 5
References

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

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