May 2003
NSF 03/05/EPADWCTR

Environmental Technology Verification Report

Physical Removal of Particulate Contaminants in Drinking Water

Polymem
Polymem UF120 S2 Ultrafiltration Membrane Module
Luxemburg, Wisconsin

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 DRINKING WATER TREATMENT SYSTEMS**	
APPLICATION:	**PHYSICAL REMOVAL OF PARTICULATE CONTAMINANTS IN DRINKING WATER**	
TECHNOLOGY NAME:	**POLYMEM UF120 S2 ULTRAFILTRATION MEMBRANE MODULE**	
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The U.S. Environmental Protection Agency (EPA) supports 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, stakeholder groups (consisting 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 Systems (DWS) Center, one of seven ETV Centers under ETV. The DWS Center recently evaluated the performance of an ultrafiltration membrane used in drinking water treatment system applications. This verification statement provides a summary of the test results for the Polymem UF120 S2 Ultrafiltration Membrane Module. Carollo Engineers, P.C., an NSF-qualified field testing organization (FTO), performed the verification testing. NSF provided technical and quality assurance oversight of the verification testing described in this ETV report.

ABSTRACT

Verification testing of the Polymem UF120 S2 Ultrafiltration Membrane Module was conducted over a 46-day period at the Green Bay Water Utility Filtration Plant, Luxemburg, Wisconsin. The ETV testing described herein was funded in conjunction with a 12-month membrane pilot study funded by the Energy Center of Wisconsin. The Energy Center of Wisconsin chose to participate because the overall scope of the ETV testing fit into the scope of the longer, energy focused study. The testing was performed from March 11, 2002 through April 26, 2002, representing winter/spring conditions when, historically, feed water quality was most difficult to treat. The feed water was Lake Michigan. Verification testing was conducted at optimized conditions based on pilot testing conducted during the 12 months proceeding the verification test period. The testing was performed using a "generic" custom membrane pilot plant (CMPP) capable of operating with a variety of membrane modules that are housed in pressure vessels. Therefore, this ETV testing verified the operation of the membrane module itself, not membrane-specific process equipment. The membrane unit was operated in dead-end mode during two test runs, each at a constant specific flux of 40 and 30 l/h-m^2 (24 and 18 gfd), respectively. Feed water recoveries ranged from 89-96 percent. The two test runs were operated for approximately 12.5 and 32.7 days, respectively. The UF module was chemically cleaned using a "proof of concept" effort based on procedures recommended by the manufacturer. The cleaning procedures were effective in restoring membrane productivity. The membrane module achieved significant removal of particulate contaminants and bacteria, producing an average filtrate turbidity of 0.05 NTU and an average of 4.2 log removal of total particles (>2 ìm in size). Average feed turbidity and total particle counts were 1.3 NTU and 4,281 particles/ml, respectively.

TECHNOLOGY DESCRIPTION

The Polymem UF120 S2 Ultrafiltration Module is comprised of 19 individual polysulfone hollow-fiber membrane bundles housed in a PVC pressure vessel. The bundles are potted on the effluent side of the module, forming a U-shaped configuration and provide a total of 114 m^2 (1227 ft^2) of active membrane surface area. The membrane, classified as an ultrafiltration membrane, has a nominal pore size of 0.01 µm as specified by Polymem and was not verified in this verification test. This pore size should provide a physical barrier to particulate matter, bacteria, protozoans, and viruses when membrane fibers are intact and operated within the recommended operating ranges.

The membrane module is designed for operation in a dead-end mode, reducing power consumption over traditional cross flow membrane products, as recirculation pumps are not required. The flow configuration is outside to inside. This forces the accumulation of particulate matter, pathogens, and suspended solids on the outside of the membrane fiber. The recommended backwash procedure includes simultaneous hydraulic backwash, air scour, and chlorine injection. Backwash is accomplished by pumping filtrate water from the inside to the outside of the fiber. This water is then discharged to waste. An inlet for air scour is provided at the level of the potting resin via air diffusers located inside the module. This design makes minimum chemical cleaning intervals of 30 days possible without exceeding the maximum allowable transmembrane pressure (terminal transmembrane pressure) of 2 bar (29 psi). The membrane system and operating strategy (flux, recovery, and backwash intervals) are typically designed for a 30-day chemical cleaning interval. However, significant changes in water quality will effect membrane performance. Temperature fluctuation, increases in natural organic matter, turbidity, and pH changes may have the potential to increase membrane fouling rates.

Some fraction of the particulate matter and dissolved constituents in the feed water can accumulate on the membrane surface and cannot be removed by hydraulic backwash and air scour. This leads to rise in transmembrane pressure during normal operation. Once the terminal transmembrane pressure has been reached (29 psi), the membrane must be taken off-line to remove this matter from the membrane with a

chemical clean. The membrane polymer is designed to be tolerant to a variety of chemicals, including chlorine, acids, bases, and chelating agents commonly used for chemical cleaning.

Critical to this testing was the use of a "generic" CMPP. The CMPP was not provided by Polymem. The CMPP used has the capacity to feed, backwash, and clean a variety of pressure vessel-type MF/UF modules. Therefore, this testing verified the operation of the membrane module under a given set of operational parameters, not membrane-specific process equipment.

VERIFICATION TESTING DESCRIPTION

Test Site

The testing site was the Green Bay Water Utility Filtration Plant located at 6183 Finger Road in Luxemberg, Wisconsin. The Green Bay Water Utility Filtration Plant is fed by one or both of two raw water intakes located on the western shore of Lake Michigan in Kewaunee, Wisconsin. The raw water is pumped to the filtration plant in Luxemberg, Wisconsin. A small amount of chlorine (<0.30 mg/L) is added at each intake to prevent growth of zebra mussels during transmission from intake to the treatment facility. The CMPP used for this testing was located approximately 200 feet from the raw water channel at the filtration plant. A submersible pump located 3 feet below the free water surface fed the CMPP via 2-inch schedule 80 PVC pipe, and 1.5-inch PVC tubing.

Methods and Procedures

Onsite bench-top analyses including turbidity, pH, chlorine, and temperature were conducted daily at the test site according to *Standard Methods for the Examination of Water and Wastewater, 20th Edition* (APHA, 1998) and by *Methods for Chemical Analysis of Water and Wastes* (EPA, 1979), where applicable. *Standard Methods for the Examination of Water and Wastewater, 20th Edition* (APHA, 1998) was followed for total coliform analyses conducted at Northern Lake Service, Inc. (NLS), Crandon, Wisconsin and MWH Laboratories, Pasadena, California. Other analyses conducted by NLS were conducted using *Standard Methods for the Examination of Water and Wastewater, 18th Edition* (APHA, 1992) and by *Methods for Chemical Analysis of Water and Wastes* (EPA, Revision 1983), where applicable. Laboratory analyses included alkalinity, total and calcium hardness, total dissolved solids (TDS), total suspended solids (TSS), total organic carbon (TOC), ultraviolet absorbance at 254 nanometers (UVA), total coliform and heterotrophic plate count (HPC). Alkalinity and total and calcium hardness analyses were conducted once per month. TDS analyses were conducted every other week. TOC and UVA analyses were conducted twice per week. TSS, total coliforms, and HPC analyses were conducted five days per week. Online particle counters and turbidimeters continuously monitored both the feed and membrane filtrate waters. The particle counters were set up to enumerate particle counts in the following size ranges: total (>2 µm), 2-3 µm, 3-5 µm, 5-15 µm, and >15 µm. Data from the online particle counters were stored at 5-minute intervals on a dedicated computer. Online turbidity measurements were recorded at 10-minute intervals. Challenge testing, microbial or otherwise, was not performed as part of this study; particle removal was quantified based on turbidity and particle counter data.

VERIFICATION OF PERFORMANCE

System Operation

Verification testing conditions were established based on pilot study optimization results conducted from May 2001 to March 2002. The membrane unit was operated at a constant specific flux of 40 L/h-m^2 (24 gfd) for the first 12.5 days of operation (Run 1) and 30 L/h-m^2 (18 gfd) during the remaining 32.7 days of operation (Run 2). Production backwashes were performed at 50-minute intervals using an average volume of 39 and 30 gallons for Runs 1 and 2, respectively. System recoveries ranged from 89-96 percent

throughout the testing. The backwash chlorine concentration was set at 5 mg/L for the duration of the testing.

Test Runs 1 and 2 yielded normalized specific flux decline rates of 7.2 L/h-m^2/bar/day (0.29 gfd/psi/d) and 1.7 L/h-m^2/bar/day (0.069 gfd/psi/d), respectively. The improvement in fouling control during Run 2 is likely due to the lower target normalized flux. It should be noted that the 25 percent decrease in specific flux led to a 260 percent increase in run time before a required chemical cleaning (12.5 vs. 32.7 days).

A total of three membrane cleanings were performed based on the manufacturer's recommended procedure. A high pH (11-12) chlorine solution (200 mg/L) was injected into the membrane module and was allowed to soak for at least 4 hours. Flux data was collected after each chemical cleaning to evaluate specific flux recovery. The first cleaning was performed prior to membrane operation. Therefore, recovery information was not available for this cleaning. The recovery of specific normalized flux for Chemical Cleaning #'s 2 and 3 was 62 and 73 percent, respectively. Cleaning #2 was performed at ambient water temperature, [14-18.6°C (57-65.5°F)], pH = 12.2, and an average total chlorine concentration of 164 mg/L, for 8 hours. Because recovery of specific flux following Cleaning # 2 was low, Cleaning # 3 was performed with a similar cleaning solution but at elevated solution temperature [22-31°C (72-88°F)], for an extended soaking period. Despite these changes, the specific flux recovery was marginal (73 percent). This may be explained in part by the lack of chemical recirculation. This is because the CMPP was not equipped with heating and recirculation equipment typically used to perform clean-in-place (CIP) procedures on this membrane.

Membrane integrity monitoring was conducted prior-to and after this testing. Air pressure-hold tests were conducted by opening the feed side of the membrane to the atmosphere and applying approximately 10 psi to the filtrate side of the membrane. Once pressurized, the loss of filtrate side pressure was recorded over a two-minute period. The first membrane integrity test yielded a zero pressure loss with time. The test at the end of system operation yielded a pressure loss of 0.35 psi/min, which was within the manufacturers recommended feed side pressure loss (<0.36 psi/min). However, during this test, visual observations showed a steady stream of air bubbles released to the feed side of the membrane. This suggested that a membrane fiber (or fibers) and membrane integrity may have been compromised. Following ETV testing, the membrane module filtrate end cap was removed to further investigate the bubbles noted during the final integrity test. This investigation followed the integrity test/repair procedures outlined in the Polymem UF120 S2 Operations and Maintenance (O&M) Manual. One broken fiber was identified and repaired. One subsequent pressure decay test, performed as described above, yielded a zero loss in pressure and no visual indicators of a loss of membrane integrity (no bubbles were detected).

Water Quality Results

The equipment verification testing described in this report was executed using raw Lake Michigan water obtained from the Green Bay Water Utility Filtration Plant. Water used for CMPP operation was drawn from the process prior to any treatment (other than Cl_2 addition for zebra muscle control) at the water facility and was pumped approximately 200 feet to the skid mounted CMPP located inside a module trailer unit. Table VS-1 below presents the results of the general water quality characterization for both feed and filtrate waters throughout the ETV verification test. The feed water had the following average water quality during this evaluation: Cl_2 residual 0.05 mg/L, alkalinity 110 mg/L as CaCO3, total hardness 130 mg/L as CaCO3, calcium hardness 88 mg/L as CaCO3, TSS 1.3 mg/L, TDS 187 mg/L, TOC 2.3 mg/L, UVA 0.024 cm^{-1}, algae 34 #/ml, temperature 3°C (37°F), and pH 7.8. As expected, there was no notable change in alkalinity, total hardness, calcium hardness, or total dissolved solids across the membrane module. However, there was a small reduction in TOC in the filtrate.

Total suspended solids were measured throughout the testing as an indication of particle removal potential. Filtrate TSS was typically below the detection limit with 32 out of 37 samples reported at or below the level of detection. Like HPC data, some of the filtrate samples were detected at higher than expected levels. These results are likely due to the fact that feed and filtrate samples were so near the detection limit of the analysis. Due to the length of time the equipment was in use prior to the ETV testing, it is also possible that material had built up in the portion of sample piping permanently fixed to the CMPP skid. Although the sample ports were allowed to flush prior to sample collection, accumulated material may have sloughed off during some of the sampling periods.

As presented in Table VS-1, average feed and filtrate bench top turbidities were 1.3 and 0.05 NTU, respectively. Continuously monitored filtrate turbidity was 0.035 NTU or less 90 percent of the time. Average feed and filtrate total particle counts were 4,281 and 4 particles/ml, respectively. Table VS-2 summarizes the particulate log removal data. Average particle log removals of 4.2, 4.1, 4.1, 3.4, 3.3, 2.9, and 2.2 were achieved for particle size ranges of >2 um, 2-3, 3-5, 5-7, 7-10, 10-15, and >15 um, respectively. The 90th percentile for feed and filtrate total particle counts (>2 #/ml) was approximately 9,911 and 2 particles/ml, respectively. The membrane system removed 3.1 logs of total particles 90 percent of the time. A few of the filtrate particle count data were recorded by the data logger as 0.00 particle/ml (below the detection limit of the instrument). Since these data were recorded as zero values, log removal data could not be calculated for these data points and were not included in the statistical analyses. Because the membrane system produced relatively consistent filtrate particle counts, log removals increased during periods when feed water particle counts were higher and decreased during periods when feed water particle counts were lower. Relatively higher particle counts were measured in the filtrate immediately following a backwash due in part to hydraulic and air bubble turbulence. As a result, particle removals were decreased during these events.

A sensitivity analysis was performed on the data collected from one 24-hour period to determine the potential effects of backwash events on calculated log removals. Data from March 14, 2002 were chosen for this analysis due to the clusters of relatively lower log removal data during that time period, thereby representing a worse case scenario. Log removals calculated for the raw data set (data including backwash events) were 3.2 logs or greater, 90 percent of the time. Log removals calculated for the data set excluding data obviously collected during backwash events, increased to 3.6 logs or greater, 90 percent of the time.

Table VS-3 summarizes total coliform and HPC data. Total coliform enumeration results showed feed concentration ranging from <1.1-23 MPN/100 ml. Filtrate results for total coliform enumeration were reported below the detection limit of <1 MPN/100ml. HPC were significantly reduced. Feed water HPC ranged up to 330 CFU/ml. 33 of 38 filtrate HPC samples were at or below the method detection limit of 2 CFU/ml.

Table VS-1 General Water Quality for Both Feed and Filtrate Waters

Parameter	Units	Feed Water	Filtrate
Cl_2 –Residual[(1)]	mg/L	0.05	--
Alkalinity	mg/L as $CaCO_3$	110	110
Total Hardness	mg/L as $CaCO_3$	130	130
Calcium Hardness	mg/L as $CaCO_3$	88	87
TSS[(2)]	mg/L	1.3	1.2
TDS	mg/L	187	203
TOC	mg/L	2.3	2.0
UVA	cm^{-1}	0.024	0.019
Algae	#/ml	34.4	--
pH	Units	7.80	--
Temperature	°C (°F)	3.4 (38)	--
Bench Top Turbidity	NTU	1.3	0.05
Particles >2 µm	#/ml	4281	4

(1) Measured as part of the daily sampling activities of the Green Bay Water Utility Filtration Plant (GBWUFP).
(2) Limit of detection = 1 mg/L

Table VS-2 Particulate Log Removal

Particle Size	Average Feed Count, #/ml	Average Filtrate Count #/ml	Average Log Removal
>2 um	4,281	4	4.2
2-3 um	1,602	1	4.1
3-5 um	1,880	1	4.1
5-7 um	325	0	3.4
7-10um	305	0	3.3
10-15 um	127	1	2.9
>15 um	41	2	2.2

Table VS-3 Average Microbial Water Quality

Parameter	Units	Feed Water	Filtrate	Backwash Water
Total Coliforms [(1)]	MPN/100 ml	6.2	<1.1	<1.1
HPC [(2)]	CFU/ml	17	2	24

(1) Limit of detection = 1.1 MPN/100 ml
(2) Limit of detection = 2 CFU/ml

Operation and Maintenance Results

Operating conditions were established in a Programmable Logic Controller (PLC) prior to beginning the test. These conditions included flux rate, production dwell time, backwash procedures (interval and duration), alarm condition settings, chemical feed doses, and data logging intervals. A notable exception to the logged parameters is air scour flow rate. With the exception of backwash duration, these parameters were not adjusted during operation. Backwash duration was adjusted as needed to maintain a recovery of at least 90 percent and ranged from 60-120 seconds. Backwash chlorine was set to a dose of 5 mg/L and was checked daily through onsite analyses.

Operation of the membrane consumed approximately 0.05 and 0.03 lbs/day of sodium hypochlorite during test Runs 1 and 2, respectively. Chemical cleanings each consumed 0.06 lbs of sodium hypochlorite and approximately 1.5-2 lbs of sodium hydroxide.

Original Signed by Clyde R. Dempsey for Hugh W. McKinnon *06/10/03*	*Original Signed by Gordon Bellen* *06/13/03*
Hugh W. McKinnon Date	Gordon Bellen Date
Director	Vice President
National Risk Management Research Laboratory	Research
Office of Research and Development	NSF International
United States Environmental Protection Agency	

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

Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants*, dated May 14, 1999, the Verification Statement, and the Verification Report (NSF Report # NSF 02/05/EPADWCTR) are available from the following sources:

(NOTE: Appendices are not included in the Verification Report. Appendices are available from NSF upon request.)

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

2. NSF web site: http://www.nsf.org/etv/dws/dws_reports.html and from http://www.nsf.org/etv/dws/dws_project_documents.html (electronic copy)

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

May 2003

Environmental Technology Verification Report

Physical Removal of Particulate Contaminants in Drinking Water

Polymem UF120 S2 Ultrafiltration Membrane Module

Luxemburg, Wisconsin

Prepared for:

NSF International
Ann Arbor, MI 48105

Prepared by:

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

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Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Hugh W. McKinnon, Director
National Risk Management Research Laboratory

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Abbreviations and Acronyms

b	Bar
°C	Degrees Celsius
cfm	Cubic feet per minute
CFU	Colony Forming Units
CIP	Clean-in-place
Cl_2	Chlorine
CMPP	Custom Membrane Pilot Plant
CPU	Central Processing Unit
DWS	Drinking Water System
EPA	United States Environmental Protection Agency
°F	Degrees Fahrenheit
Fe	Iron
ft^2	Feet squared
FTO	Field Testing Organization
GBWUFP	Green Bay Water Utility Filtration Plant
gfd	Gallons per square foot per day
gpm	Gallons per minute
HMI	Human-Machine Interface
HPC	Heterotrophic Plate Count
hr	Hour
IESWTR	Interim Enhanced Surface Water Treatment Rule
kWh	Kilowatt hour
L	Liters
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
m^2	Meters squared
MF/UF	Microfiltration/Ultrafiltration
mg/L	Milligrams per liter
mL	Milliliter

µm	Micrometers
MPN	Most Probable Number
MSDS	Material Safety Data Sheets
NaOCl	Sodium Hypochlorite
NaOH	Sodium Hydroxide
NLS	Northern Lake Service, Inc.
NSF	NSF International
NTU	Nephelometric Turbidity Units
P	Pump
P/A	Presence/Absence
PLC	Programmable Logic Controller
ppm	Parts per million
psi	Pounds per square inch
PSTP	Product Specific Test Plan
QA/QC	Quality Assurance/Quality Control
SCFM	Standard cubic feet per minute
SDWA	Safe Drinking Water Act
STP	Standard Temperature and Pressure
SUVA	Specific Ultraviolet Absorbance
TDS	Total Dissolved Solids
TMP	Transmembrane Pressure
TOC	Total Organic Carbon
TSS	Total Suspended Solids
VFD	Variable Frequency Drive

ACKNOWLEDGMENTS

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

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

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

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Carollo Engineers, P.C. and Polymem wishes to thank the Energy Center of Wisconsin for supporting this study.

Carollo Engineers, P.C. wishes to thank Patricia Terry, Ph.D. - University of Wisconsin Green Bay and the Green Bay Water Utility for their help during this study.

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; stakeholder 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.

The EPA has partnered with NSF International (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 drinking water systems that serve small communities under the ETV Drinking Water Systems (DWS) Center. A goal of verification testing is to enhance and facilitate the acceptance of small drinking water treatment equipment by state drinking water regulatory officials and consulting engineers while reducing the need for testing of equipment at each location where the equipment's use is contemplated. NSF will meet this goal by working with manufacturers and NSF-qualified Field Testing Organizations (FTO) to conduct verification testing under the approved protocols. It is important to note that verification of the equipment does not mean that the equipment is "certified" by NSF or "accepted" by EPA. Rather, it recognizes that the performance of the equipment has been determined and verified by these organizations for those conditions tested by the FTO.

The DWS Center evaluated the performance the Polymem UF120 S2 Ultrafiltration Membrane Module, which is a membrane filtration technology used in drinking water treatment system applications. The test evaluated the membrane module's ability to physically remove microbial and particulate contaminants. This document provides the verification test results for the Polymem UF120 S2 Ultrafiltration Membrane Module.

1.2 Testing Participants

The FTO was Carollo Engineers, P.C., which provided the overall management of the ETV. The ultrafiltration membrane manufacturer for the ETV was Polymem. The operations management and staff were from the University of Wisconsin-Green Bay and Carollo Engineers. Laboratory analyses were performed by Northern Lake Service, Inc. (NLS), Crandon, Wisconsin and

Montgomery Watson Laboratories, Pasadena, California (total coliform enumeration only). Data management and final report preparation were performed by the FTO, Carollo Engineers, P.C.

1.3 Definition of Roles and Responsibilities of Project Participants

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

1.3.1 NSF Responsibilities

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 drinking water treatment systems through the EPA's ETV Program.

NSF provided technical oversight of the verification testing. An audit of the field analytical and data gathering and recording procedures was conducted. NSF also provided review of the Product Specific Test Plan (PSTP) and this report.

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1.3.2 Field Testing Organization Responsibilities

Carollo Engineers, P.C. conducted the verification testing of the Polymem UF120 S2 Ultrafiltration Membrane Module. Carollo Engineers, P.C. is an NSF-qualified FTO for the ETV Drinking Water Systems Center.

The FTO was responsible for conducting the verification testing for 30 calendar days. FTO employees conducted the onsite analyses and data recording during the testing. The specific responsibilities of the FTO, Carollo Engineers, P.C., were to:

- Provide the overall management of the ETV through the project manager and the project engineers.
- Provide needed logistical support, the project communication network, and scheduling and coordination of the activities of participants.
- Manage, evaluate, interpret and report on data generated in the ETV.

- Evaluate the performance of the ultrafiltration membrane technology according to the PSTP and the testing, operations, quality assurance/quality control (QA/QC), data management and safety protocols contained therein.
- Provide quality control (QC) information in the ETV report.
- Provide data generated during the ETV in hard copy and electronic form in a common spreadsheet or database form.

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1.3.3 Manufacturer Responsibilities

The specific responsibilities of the ultrafiltration membrane manufacturer, Polymem, were to:

- Provide complete, field-ready equipment for the ETV at the testing site.
- Provide logistical and technical support as required throughout the ETV.
- Provide partial funding for the project.
- Attend project meetings as necessary.

Contact Information:

Polymem
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1.3.4 Operator and Test Site Staff Responsibilities

The specific responsibilities of operations and test site staff from the University of Wisconsin at Green Bay, Carollo Engineers, P.C., and Green Bay Water Utility, were to:

- Provide set-up, shakedown, operations, maintenance and on-site analytical services according to the PSTP and the testing, operations, QA/QC, data management and safety protocols.
- Provide the necessary and appropriate space for the equipment to be tested in the ETV.
- Provide necessary electrical power, feedwater and other utilities as required for the ETV.
- Provide necessary drains from the test site.

Contact Information:

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24200 Nicolet Dr.
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1.3.5 Water Quality Analyst Responsibilities

The specific responsibilities of the water quality analytical staff from the NLS and MWH Laboratories were to:

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

Contact Information:

Northern Lake Service, Inc.
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1.3.6 EPA Responsibilities

The EPA through its Office of Research and Development has financially supported and collaborated with NSF under Cooperative Agreement No. R-82833301. This verification effort was supported by the DWS Center operating under the ETV Program. This document has been peer reviewed and reviewed by NSF and EPA and recommended for public release.

1.3.7 Funding Source

The ETV testing described herein was funded in conjunction with a 12-month membrane pilot study funded by the Energy Center of Wisconsin. The 12-month study, focused not only on the power requirements of membrane filtration plants, but also on promoting the use of more effective and less energy intensive water treatment technologies. The Energy Center of

Wisconsin chose to participate because the overall scope of the ETV testing fit into of the scope of the longer, energy focused study.

1.4 Verification Testing Site

1.4.1 Site Description

The testing site was the Green Bay Water Utility Filtration Plant (GBWUFP) located at 6183 Finger Road in Luxemberg, Wisconsin. The plant utilizes pre-ozonation, coagulation, flocculation, sedimentation, granular media filtration, and chlorination prior to distribution to the City of Green Bay. The plant also has facilities for recycling filter washwater, which include settling lagoons and washwater recycle basins.

The GBWUFP is fed by two raw water intakes located on the western shore of Lake Michigan in Kewaunee, Wisconsin. The primary intake structure is located approximately one mile off shore at a depth of 50 feet and is operated year round; a second intake structure located 3000 feet off shore at a depth of 30 feet is operated during peak demand periods to supplement the primary intake. The raw water is pumped to the filtration plant in Luxemberg, Wisconsin. Chlorine is added at each intake to prevent growth of zebra mussels during transmission from intake to the treatment facility. Residual chlorine concentrations (as Cl_2) in the feed water at the treatment facility were collected during the ETV test and tested by GBWUFP staff and are included in Table 1-1. The chlorine residual during the test averaged 0.05 mg/L. Because chlorine is added at the intake, "raw" Lake Michigan water was not available at the site. However, the low reported chlorine levels were not expected to significantly effect membrane performance.

The pilot plant was located approximately 200 feet from the raw water channel at the filtration plant and was fed by either or both of the GBWUFP raw water intakes. A submersible pump located 3 feet below the free water surface fed the pilot plant via 2-inch schedule 80 PVC pipe, and 1.5-inch PVC tubing. A tee fitting divided flow to serve two pilot plant units and was located approximately 20 feet from each pilot plant trailer feed connection. Ball valves located on each branch provided flow-splitting control. Pictures of the project site are included in Appendix A.

1.4.2 Source/Feed Water

The equipment verification testing described in this report was executed using raw Lake Michigan water obtained from the GBWUFP. Water used for pilot plant operation was drawn from the process prior to any treatment at the water facility (other than chlorine addition for zebra mussel control) and was pumped approximately 200 feet to the skid mounted pilot plant located inside a module trailer unit.

GBWUFP staff monitor Lake Michigan water quality as part of normal plant operations. In general, Lake Michigan can be characterized as a high quality raw water. Based on historical data, the raw water can be characterized by low average turbidity. However, fall and winter storm events can significantly increase turbidity for several days at a time. Seasonal variations may also cause significant variation on water temperature and correlate to algae blooms. Alkalinity, pH, and TOC show less seasonal variation than turbidity and temperature. Specific feed water quality data collected throughout this verification testing are reported in Table 1-1. The feed water had the following average water quality during this evaluation: Cl_2 residual 0.05

mg/L, alkalinity 110 mg/L as $CaCO_3$, total hardness 130 mg/L as $CaCO_3$, calcium hardness 88 mg/L as $CaCO_3$, total dissolved solids (TDS) 187 mg/L, total suspended solids (TSS) 1.3 mg/L, total organic carbon (TOC), 2.3 mg/L, UVA 0.024 per cm^{-1}, algae 34/ml, pH 7.8, temperature 3°C (37°F), total coliform 5.0 MPN/100ml, HPC 17 CFU/ml, and turbidity 1.3 NTU.

1.4.3 Pilot Effluent Discharge

Sanitary sewers do not exist at the testing site. Therefore, the effluent (filtrate and backwash) of the pilot treatment unit was routed to the beginning of the GBWUFP facilities for recycling with filter washwater. Chemical cleaning wastes were neutralized and disposed of off site.

1.5 Background

The Interim Enhanced Surface Water Treatment Rule (IESWTR), promulgated in 1998, established stringent filtered water quality standards for systems serving over 10,000 people. Promulgated at the same time as the IESTWR, was the Stage 1 Disinfectant and Disinfection Byproduct Rule (Stage 1 D/DBPR) to regulate levels of disinfectant residuals and byproducts in the distribution system of water systems of all sizes. Emerging regulations due in the calendar year 2001, include the Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) that will extend the requirements of the IESWTR to systems serving less than 10,000 people. Stage 2 LT2ESWTR will be applicable to systems of all sizes treating surface water and groundwater under the influence of surface water. The LT2ESWTR "Agreement in Principal" includes regulation of *Cryptosporidium*, and technologies that utilities must utilize to remove it from their water source. These emerging regulations require greater removal of pathogens, lower filter effluent turbidity standards, and lower disinfectant byproduct concentrations in the distribution system.

In order to meet these more stringent regulations, water utilities are evaluating numerous treatment options including low-pressure membrane filtration such as microfiltration (MF) and ultrafiltration (UF). Although not directly verified in this ETV test, these types of membrane systems are designed to remove bacteria, protozoa, and in the case of UF membranes, viruses. In the coming years, most water systems using surface water or groundwater under the influence of surface water will need to evaluate their capacity to meet these objectives. These systems constitute the majority of the market for the product being evaluated in this report.

At the time this report was written, amendments to the Surface Water treatment Rule (SWTR), as mandated by the Safe Drinking Water Act (SDWA) were actively being negotiated. While final rules and amendments were being negotiated, the implications of these new rules were well known in the industry, and many water utilities were focusing their plant upgrade and new construction on these anticipated standards.

Chapter 2
Equipment Description and Operating Processes

2.1 General Equipment Description

Critical to the verification testing was the use a "generic" custom membrane pilot plant (CMPP). The CMPP was not provided by the membrane manufacturer, Polymem. The CMPP used has the capacity to feed, backwash and clean a variety of MF/UF modules that are housed in pressure vessels. Therefore, this ETV testing verified the operation of the membrane module under a given set of operational parameters, not membrane-specific process equipment. A description of the equipment used in the process is provided in this section.

2.2 UF120 S2 Ultrafiltration Membrane Module Description

2.2.1 General Description

The Polymem UF120 S2 Ultrafiltration Membrane Module is comprised of 19 individual polysulfone hollow-fiber membrane bundles housed in a PVC pressure vessel. The bundles are potted on the effluent side of the module, forming a U-shaped configuration and provide a total of 114 m^2 (1227 ft^2) of active membrane surface area. The nominal pore size, as specified by Polymem and not verified in this ETV test, is 0.01 µm, and is classified as an ultrafiltration membrane. This pore size should provide a physical barrier to bacteria, protozoans, and viruses when membrane fibers are intact and operated within the recommended operating ranges.

The membrane module is designed to be operated in a dead-end mode, reducing power consumption over traditional cross flow membrane products, as recirculation pumps are not required. The flow configuration is outside to inside. This forces the accumulation of particulate matter, pathogens, and suspended solids on the outside of the membrane fiber. The recommended backwash procedure includes simultaneous hydraulic backwash, air scour, and chlorine injection. Backwash is accomplished by pumping filtrate water from the inside to the outside of the fiber. This water is then discharged to waste. An inlet for air scour is provided at the level of the potting resin via air diffusers located inside the module.

Some fraction of the particulate matter and dissolved constituents in the feed water can accumulate on the membrane surface and cannot be removed by hydraulic backwash and air scour. This leads to a rise in transmembrane pressure during normal operation. Once the terminal transmembrane pressure has been reached (29 psi), the membrane must be taken off-line to remove this matter from the membrane with a chemical clean. The membrane system and operating strategy (flux, recovery, and backwash intervals) are typically designed for a 30-day chemical cleaning interval. However, significant changes in water quality will effect membrane performance. Temperature fluctuation, increases in natural organic matter, turbidity, pH changes, and high flux rates may have the potential to increase membrane fouling rates.

The membrane polymer is tolerant to a variety of chemicals, including chlorine, acids, bases, and chelating agents commonly used for chemical cleaning. Photographs of the module, detailed specifications, and typical operating parameters are included in Appendix A. Backwash and chemical cleaning chlorine dose tolerances and pH ranges are also included.

2.2.2 Environmental Requirements of UF120 S2 Membrane

The membrane module should be placed in a location that is protected from high winds, freezing conditions, direct sunlight, and precipitation that may damage process piping and electrical equipment.

2.2.3 Materials of Construction of UF120 S2 Membrane

The membrane module's (and CMPP skid) influent and effluent connections are standard-sized schedule 80 PVC allowing for adaptability to custom designed membrane systems. The membrane module itself is housed in a PVC vessel. Connection to the feed side of the module is made via 3-inch schedule 80 PVC threaded into the inlet of the module. Connection on the filtrate side of the module is made with a 12-inch stainless steel mechanical coupling and a 12-inch by 3-inch PVC reducer. As noted, the membrane is polysulfone, potted on the filtrate side of the module body with polyeurothane. A ¼-inch air scour diffuser inlet is provided at the potting level to aid in cleaning efficacy. The membrane module weighs 99 pounds when empty and 187 pounds when full of water. The length and diameter of the module are 37 and 12 inches, respectively.

2.3 Operating Process

The typical UF process consists of pumps, piping, and control systems capable of performing basic functions necessary for membrane filtration. The process consists of a feed water pump, membrane module, backwash pump, chemical feed systems, filtrate and chemical storage. Feed pumping is used during production cycles to provide flow at the necessary pressure for driving water across the membrane surface. At regular intervals (30-120 minutes), the feed pump is turned off, and the backwash pump moves water into the effluent side of the membrane at an elevated pressure for short periods of time (60 seconds) to remove accumulated solids from the membrane surface. The hydraulic backwash is used in unison with air distributed through diffusers located inside the membrane module. A schematic of the CMPP process including pumps, piping schematic, sample ports, chemical feeds, and UF120 S2 membrane location is included in the process and instrumentation diagram (Figure 2-1).

Because production backwashes do not remove all particulate matter from the membrane surface, periodic chemical cleanings must be performed to restore membrane permeability. Chemical cleanings are performed by soaking the membrane fibers in an appropriate solution, followed by a rinsing cycle. This procedure takes approximately 8 hours to perform, and must be manually initiated through the Programmable Logic Control (PLC) interface.

Periodic direct integrity monitoring checks to ensure that membrane fibers are not compromised (therefore allowing passage of particulate contaminants larger than the membrane pore size) are performed at regular intervals and generally prescribed by the regulatory agency responsible for the water system. On the CMPP used in the verification, this is a manual operation. The process, in general, is to pressurize the inside of the membrane fibers with air, and measure the pressure decay rate. For the UF120 S2 membrane, the acceptable decay rate limit specified by Polymem is 0.36 psi/min. Decay rates in excess of this limit indicate that fiber integrity may be compromised.

CMPP equipment requires a 3-phase/480 V power supply to run pumps and variable frequency drives (VFD). A transformer located in the VFD panel converts the power to 120 V single phase for the PLC panel.

2.3.1 Process Instrumentation

The CMPP skid is equipped with a PLC unit that provides a significant degree of automation. The PLC maintains flow rates, pressures, control valve positions, and flow during backwashes and chemical cleans. The PLC also has the ability to shut down the system in case of a high level alarm (high transmembrane pressure, low liquid levels, low chemical tank levels, etc.). The process can be configured for the specific application through a Windows-based interface. Backwash and cleaning procedures, flow, pressure, alarms, and dose set points can be customized via the PLC panel. This greatly reduces the required operator training and time requirements. Functions can be adjusted, initiated, and monitored remotely. The system can be operated without a full-time operator; however, operators are necessary for routine system maintenance (e.g., analytical sampling, compressor maintenance, and to maintain acceptable volumes in chemical storage tanks), maintaining water quality monitoring devices, performing integrity tests, and trouble-shooting.

Critical data including flow rate, transmembrane pressure, flux, specific flux, temperature, and turbidity can be downloaded remotely for analysis. However, maintenance issues including cleaning pre-filters, filling feed tanks, and required sampling must be performed by on-site personnel. Data collection with the exception of particle count data and manual gage readings can be done remotely with remote control software over a standard telephone line.

2.3.2 Consumables

2.3.2.1 Chemicals

Chemicals used by the membrane are readily available commodity products [chlorine, sodium hydroxide (NaOH), or acid if necessary]. Typical chemical consumption includes low doses of chlorine [approximately 2 pounds per module per month as sodium hypochlorite (NaOCl)] during production backwashes (occurring every 30 to 120 minutes) and during chemical cleaning (0.05 pounds per module per month) if performed once each month. NaOH is also typically used for removal of organic compounds during monthly chemical cleaning (2.4 pounds per module per month). Chemical cleaning wastes can be disposed of in sanitary sewers as allowed by local code. If necessary, these chemicals can be quenched (chlorine) or neutralized (acid or caustic) prior to discharge. Sanitary sewers do not exist at the site. Therefore, chemical cleaning residuals were neutralized and disposed of off-site.

2.3.2.2 Power

Power requirements for MF/UF membrane systems are driven primarily by feed water pumping requirements. Operating pressures vary significantly over the course of chemical cleaning intervals, depending on operating strategies and feed water quality. Typical operating pressures (estimated from previous studies with the Polymem membrane on Lake Michigan water) range from 5 to 15 psi. Based on a constant operating pressure of 15 psi, feed pumping power requirements are approximately 0.157 kWh per day per gpm of feed water flow.

2.3.3 Product Performance Capabilities

The UF120 S2 membrane is capable of removal of solids primarily through a physical sieving mechanism. The UF120 S2 membrane will remove coliforms, HPC, and other particulate matter from the feed water. The manufacturer's stated performance capabilities were used to shape the data quality objectives (DQO) and testing plan used for this ETV test.

Note: Challenge testing, microbial or otherwise, was not performed as part of this study; particle removal was quantified based on turbidity and particle counter data.

Chapter 3
Methods and Procedures

This chapter includes a detailed discussion of the ETV experimental plan, testing conditions, methods, and sampling parameters and frequency. In addition, this chapter details field operational and maintenance procedures, quality assurance and quality control, and analytical methods used throughout the ETV testing.

3.1 Environmental Technology Verification Testing Plan

3.1.1 Task 1: Membrane Flux and Recovery

The objective of this task was to demonstrate: 1) appropriate operational conditions for the membrane module; 2) the product water recovery achieved by the membrane module; and 3) the rate of specific flux decline observed over extended membrane filtration operation.

3.1.1.1 Work Plan

Fouling rates of a membrane are functions of both water quality and operational conditions. Several months of pilot plant operation were completed using the test water source prior to the verification testing. Optimized operational conditions were estimated based on these data, which were collected prior to March 1, 2002. The verification testing took place over a continuous 46-day period beginning March 11, 2002 and ending April 26, 2002. This time frame was established to test the ability of the membrane to operate with cold water and during a period of time when there have historically been turbidity spikes in the GBWUFP raw water. The operational data used in the testing are shown in Table 3-1 and include flux, recovery, backwash interval, data logging interval, production backwash chlorine concentration, air scour flow rate, and terminal transmembrane pressure. The first run was set at a constant normalized flux of 40 l/h-m^2 (24 gfd) at 20°C (68°F). The second run of testing was set at a constant normalized flux of 30 l/h-m^2 (18 gfd) at 20°C (68°F). The system was operated at constant normalized flux to minimize temperature related viscosity effects on transmembrane pressure and to facilitate interruption of flux loss rate.

Operating conditions were set through the PLC human-machine interface (HMI) prior to beginning the test. These conditions included flux rate, production dwell time, backwash procedures (interval and duration), alarm condition settings, chemical feed doses, and data logging intervals. With the exception of backwash duration, these parameters were not adjusted during operation. Backwash duration was adjusted as needed to maintain a recovery of at least 90 percent. Recovery was determined daily by visually observing the total backwash volume used during a production backwash cycle as indicated on the filtrate tank site glass. Total production volumes were determined using the filtrate flow rate at the end of a production cycle and multiplying by the total production cycle time (i.e. 50 minutes).

During the test run, specific operational data were collected to quantify fouling rates and hydraulic performance. The operational data and the collection frequency are shown in Table 3-2 and include: feed/filtrate flow rate, feed/filtrate pressure, feed temperature, transmembrane pressure, flux and specific flux at 20°C (68°F), and recovery.

3.1.2 Task 2: Chemical Cleaning Efficiency

The objective of this task was to demonstrate the effectiveness of chemical cleaning for restoring the specific flux of the membrane module. The cleaning procedures used were selected from the manufacturer's recommended cleaning strategies, as indicated in the Operations and Maintenance (O&M) Manual. The task was intended to serve as a "proof of concept" effort.

3.1.2.1 Work Plan

Prior to beginning the ETV testing, a membrane chemical cleaning procedure was performed to ensure that the module was clean and that the storage solution had been purged. In addition, chemical cleanings were performed once terminal transmembrane pressure was reached in order to restore membrane permeability. Lake Michigan water has low concentrations of dissolved minerals. Therefore, after membrane fouling, a chlorine solution at a pH of 11-12 was used to oxidize and dissolve organic foulants, and to remove bacterial growth. A total of three chemical cleanings were performed for this testing as a "proof of concept" effort: 1) prior to beginning the verification test, 2) after approximately 12.5 days, just prior to when the terminal transmembrane pressure was reached, and 3) at the end of the 46 days of run time.

The membrane module was chemically cleaned, per the manufacturers recommended cleaning strategies, with approximately 200 mg/L chlorine and sufficient caustic soda to maintain a pH of 11-12 (5000-7500 mg/L NaOH). The chemicals were dosed automatically with chemical metering pumps and set points entered into the PLC. Doses were verified by measuring total chlorine and pH on site immediately following chemical injection. The first two cleanings were performed at ambient temperature while the final cleaning was performed at elevated temperatures of approximately 27°C (81°F). Prior to beginning the verification test, the new membrane was allowed to soak in the chemical cleaning solution for a period of 4 hours. The two subsequent chemical cleans were allowed to soak for 8 and 48 hours, after production periods 1 and 2, respectively. Following the chemical cleaning soak, the module was backwashed with sufficient volume of filtrate to purge the system of the chemical solution (>30 gallons) and was placed in filter-to-waste mode for 90 seconds. A baseline transmembrane pressure versus flux trend was established immediately following each chemical clean. Chemical cleaning wastes were neutralized and disposed of off site.

Table 3-3 provides information on the chemicals used and conditions of the chemical cleaning procedure including chlorine consumption, chemical cleaning steps, pH and Cl_2 of cleaning residuals, and the volume of water required for chemical cleaning. Detailed procedures are included in the membrane and CMPP O&M Manuals in Appendices A and B. Table 3-4 shows the timing and location of samples collected during each chemical cleaning. The samples were tested for parameters including temperature, pH, TDS, and turbidity. In addition, specific flux, flux, transmembrane pressure, and flow rate was recorded. Collected data were used to verify cleaning conditions and assess cleaning effectiveness.

Estimates of specific flux recovery, cleaning efficacy and assessment of irreversible loss of membrane specific flux were reported for estimating the usable life of the membrane. A calculation of specific flux recovery and original specific flux loss, as defined in the

ETV Protocol for Equipment Verification Testing for Physical Removal of Microbial and Particulate Contaminants (May 1999) were calculated as follows:

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

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

Js_f = specific flux at end of current run
Js_i = specific flux at beginning of subsequent run
Js_{io} = specific flux at beginning of membrane test run

3.1.3 Task 3: Finished Water Quality

The objective of this task was to assess the ability of the membrane module to meet the water quality objectives outlined by Polymem.

3.1.3.1 Work Plan

To adequately define ETV conditions and to assess the contaminant rejection capacity of the UF120 S2, feed, filtrate, and backwash water quality were monitored over the course of the testing. Water quality monitoring was performed per the requirements of the *EPA/NSF ETV Protocol for Equipment Verification Testing for Physical Removal of Microbial and Particulate Contaminants* (May 1999). The parameters, sampling frequency, and specific sampling locations are presented in Table 3-5. On-site analysis was performed by the CMPP operator. Off-site analysis was performed by NLS, Crandon, WI. Total coliform enumeration was performed by MWH Laboratories, Pasadena, California. NLS and MWH state certification documents are provided in Appendix C. Sampling procedures are detailed in the Section 3.1.7, Task 7: QA/QC.

3.1.4 Task 4: Reporting of Membrane Pore Size

The objective of this task was to report the 90 percent and maximum pore size for the Polymem UF120 S2 ultrafiltration membrane.

3.1.4.1 Work Plan

The nominal pore size of the UF120 S2 membrane module used in this ETV study was determined by the manufacturer through the use of multiple methods including scanning electron microscopy (SEM), flow porometry, and particle retention testing. The UF120 S2 membrane is an asymmetric hollow fiber with a dense layer containing small pores on the inside and outside, and a less dense structure containing relatively larger pores. SEM images were used at multiple resolutions to estimate the size of the pores in the membrane. Flow porometry (Lee, et al., 1997; Hernandez, et al., 1999; Mietton and Courtois, 1997) was used to determine the mean size of the pores in the membrane (including the less dense middle layer).

3.1.5 Task 5: Membrane Integrity Testing

The objective of this test was to demonstrate the methodology to be employed for monitoring membrane integrity, and to verify the integrity of the membrane fibers.

3.1.5.1 Work Plan

Following the initial and final chemical cleanings, an integrity test was performed consisting of direct measurements including a pressure decay and visual bubble test. Indirect measurements of membrane integrity were made throughout the ETV testing by means of on-line particle count and turbidity data. The pressure decay and bubble test methodology is included in the membrane O&M Manual in Appendix A and involved the steps described below.

3.1.5.2 Direct Methods of Membrane Integrity Testing

Pressure Decay Methodology

- Operating the module without air scour for several shortened backwash cycles to remove air trapped between membrane fibers.
- Pressurizing the inside of the membrane fibers with air through a valve located on the CMPP filtrate piping to 10 psi.
- Opening the feed sample valve so the outside of the membrane fibers is at atmospheric pressure during the test.
- Recording measurements from the filtrate pressure transmitter on the HMI every 15 seconds until the 2-minute test has been completed.
- The membrane technical specifications state that a pressure decay rate of greater than 50 mbar over a 2-minute period (0.36 psi/min) could indicate a compromise in membrane integrity.

Bubble check

- If bubbles are noted in the vertical, transparent section of the CMPP feed water piping during the pressure decay test, this indicates that fibers have broken.

3.1.5.3 Indirect Methods of Membrane Integrity Testing

In-line particle counting and turbidity data were used as an indirect method of monitoring membrane integrity. Increases in particle counts or turbidity in the filtrate serve as indicators of potential fiber breakage. The advantage of this method was that it could be used during normal operation and did not require the module to be taken out of service as with the direct methods described above.

3.1.6 Task 6: Data Handling Protocol

The objective of this task was to establish a viable structure for the recording and transmission of field data such that the operational data collected was sufficient and reliable for execution of the PSTP.

3.1.6.1 Work Plan

Water quality and hydraulic data was maintained on site. Critical process parameters including pressures, temperature, turbidity, flow rates, and chemical doses were automatically stored on the membrane skid mounted PLC Central Processing Unit (CPU). This data was also backed up on a separate personal computer. This data was recorded at a maximum of 10-minute intervals throughout the ETV testing. In addition, online feed and filtrate turbidities were verified once per day with bench-top measurements. Backwash turbidity was measured twice per day with bench-top analysis and was not monitored by online instrumentation.

Feed and filtrate particle count data were recorded at 5-minute intervals for the following size ranges: 2-3 µm, 3-5 µm, 5-7 µm, 7-10 µm, 10-15 µm, and >15 µm. The instrument communicates via a RS485 protocol, therefore a RS485/RS232 adapter was required in order to communicate with the computer used to collect the data. Particle count data was collected on a dedicated computer located adjacent to the CMPP skid. Both feed and filtrate particle counter calibration were field verified with microspheres. Further details on the field verification procedures are provided in Section 3.1.7.

pH, alkalinity, total hardness, calcium hardness, TDS, TSS, TOC, and UVA data were recorded in tabular format as results were received from the analytical testing laboratory. MWH Laboratories, Pasadena, California performed total coliform enumeration. Remaining laboratory analyses were performed by NLS, Crandon, Wisconsin. Likewise, results from biological samples were recorded in a tabular format. Specifically designed daily log sheets were filled out to include other details of the test such as field tests, maintenance activities, water type, backwash procedures, operating cycles, names of visitors, problems, etc. and were logged by the operator in a bound notebook. Additionally, QA/QC information including manual checks of pressure, flow and temperature transmitters, results of on-site analyses, instrumentation flow rates, and other pertinent information were logged in the same manner. Chain of custody records for off-site laboratory analysis, on-site calibration, and verification of on-line instrumentation were also recorded. Copies of the laboratory notebooks and data log sheets are included in Appendix D. Table 3-6 summarizes the information management for this testing including how the information was collected and stored and the reported format.

3.1.7 Task 7: Quality Assurance/Quality Control

The objective of this task was to maintain strict QA/QC methods and procedures during the test run.

3.1.7.1 Work Plan

The quality assurance project plan (QAPP) for this verification testing specifies procedures that were used to ensure data quality and integrity. Careful adherence to these procedures ensures that data generated from the verification testing provided sound analytical results that serve as the basis for this performance evaluation. The components of the QAPP for this ETV include:

- Routine field procedures;
- Analytical methods;
- Water quality precision and accuracy;
- Critical equipment precision and accuracy;
- Methodology for use of blanks;
- Description of procedures for performance evaluation samples;
- Outline for duplicate sampling;
- Procedures used to ensure data correctness;
- Procedures for calculating indicators of data quality;
- Outline for data reporting; and
- Development of corrective action plan.

3.1.7.2 Routine Procedures

The following procedures were performed prior to the test run:

- In-line turbidimeter reservoirs were cleaned out and calibrated against a 20 NTU standard.
- Particle counters were field-verified using microspheres.
- In-line flow meter was cleaned and the meter output was verified with a bucket and stopwatch method.
- Sample tubing was checked.

The following procedures were performed daily:

- Routine daily walkthroughs were conducted to verify that each piece of equipment or instrument was operating properly.
- In-line turbidimeter flow rates were verified.
- In-line turbidimeter readings were checked against a properly calibrated bench model.
- In-line particle counter flow rates were verified.
- Chemical feed pump flow rates were verified.
- Pressure transmitters were checked against pressure gauges that were calibrated against NIST-traceable standards.

The following procedure was performed at the start of the run, and every 2 weeks thereafter:

- In-line flow meter readings were verified with a bucket and stopwatch method.

3.1.7.3 Analytical Methods

Onsite bench-top analyses including turbidity, pH, chlorine, and temperature were conducted daily at the test site according to *Standard Methods for the Examination of Water and Wastewater, 20th Edition* (APHA, 1998) and by *Methods for Chemical Analysis of Water and Wastes* (EPA, 1979), where applicable. *Standard Methods for the Examination of Water and Wastewater, 20th Edition* (APHA, 1998) was followed for total coliform analyses conducted at NLS, Crandon, Wisconsin and MWH Laboratories, Pasadena, California. Other analyses conducted by NLS were conducted using *Standard Methods for the Examination of Water and Wastewater, 18th Edition* (APHA, 1992) and by *Methods for Chemical Analysis of Water and Wastes* (EPA, Revision 1983), where applicable. The analytical methods utilized for this test to monitor feed, filtrate, and backwash water quality are further described below:

pH – Analysis for pH was performed according to Standard Method 4500-H+. A 3-point calibration of the pH meter used in this study was performed daily.

Temperature – Measurement of temperature was conducted in accordance with Standard Method 2550 B. This was done daily to check the in-line temperature transmitter on the CMPP.

In-Line Turbidity – Feed and filtrate water in-line turbidity measurements were logged continuously on the CMPP. The feed and filtrate turbidimeters were calibrated weekly with primary calibration standards purchased from the turbidimeter manufacturer. In addition, lenses were cleaned weekly according to the manufacturer's instructions. The data logging readout was checked daily against the local turbidimeter display value. Turbidimeter flow rates were checked daily to ensure that they were within the range required by the manufacturer.

Bench-top Turbidity – Turbidity analysis was performed daily according to Standard Methods 2130 with a bench-top turbidimeter for feed, filtrate, and backwash samples. These results were used to verify in-line measurements. The bench-top turbidimeter (Hach 2100 AN) was checked daily against primary standards (0.061, 20, 200 NTU).

The method for collecting grab samples consisted of running a slow, steady stream from the sample tap, triple-rinsing a dedicated sample beaker in this stream, allowing the sample to flow down the side of the beaker to minimize bubble entrainment. The sample vial was double-rinsed with the sample, carefully pouring from the beaker down the side of the sample vial, wiping the sample vial clean, inserting the sample vial into the turbidimeter, and recording the measured turbidity upon a stable readout.

Particle Counting – In-line particle counting was performed on both feed and filtrate waters. Prior to the study, the instrument calibration was field-verified using microspheres as described in Section 3.1.7.5. Current instrument and particle standard calibration certificates and methods for demonstration of coincidence error are provided in Appendix E.

TOC and UV_{254} Absorbance – Water samples were collected by Carollo Engineers. Samples were collected in containers supplied by NLS. Samples were held, preserved, and shipped in a cooler at approximately 4°C (39°F) to NLS in accordance with Standard Method 5010B. TOC analysis followed Standard Method 5310B, UV Absorbance followed Standard Method 5910B.

Microbial Parameters – Water samples were collected by Carollo Engineers. Samples were collected in containers supplied by the testing laboratory and sent to NLS (or MWH) in a cooler at approximately 4°C (39°F). Total coliform densities were reported in MPN/100 mL, following Standard Method 9221. Total coliform was analyzed as "present" or "absent" using Standard Method 9223. HPC densities were reported as colony forming units (cfu) per mL, per Standard Method 9215B.

Total Alkalinity – Water samples were collected by Carollo Engineers. Samples were collected in containers provided by NLS, and shipped in a cooler at approximately 4°C (39°F). Samples were collected in accordance with Standard Method 3010B. Analysis was conducted per Standard Method 2320B.

Total and Calcium Hardness – Water samples were collected by Carollo Engineers. Samples were collected in containers provided by NLS, and shipped in a cooler at approximately 4°C (39°F). Analysis was conducted per EPA Method 200.7.

Total Dissolved Solids – Water samples were collected by Carollo Engineers. Samples were collected in containers provided by NLS, and shipped in a cooler at approximately 4°C (39°F). Analysis was conducted per EPA Method 160.1.

Total Suspended Solids – Water samples were collected by Carollo Engineers. Samples were collected in containers provided by NLS, and shipped in a cooler at approximately 4°C (39°F). Analysis was conducted per EPA Method 160.2.

Total Chlorine – Total chlorine was measured daily by the Green Bay Water Utility, using spectrophotometer methods, following HACH Method 8167 (equivalent to Standard Method 4500-Cl G). Sample results were provided by Green Bay Water Utility. In addition, one chlorine measurement was taken from the CMPP feed water following HACH Method 8167, as noted above, and served as verification of the readings reported by the Green Bay Water Utility.

3.1.7.4 Water Quality Precision and Accuracy

Table 3-7 describes the methodology used in this ETV for the measurement of precision and accuracy for each water quality analysis performed during the test run. Duplicate samples for analysis are also shown for on-site grab sample analysis. The sampling location for each duplicate grab sample was the filtrate water.

3.1.7.5 Critical Equipment Precision and Accuracy

Flow Meter – Water flow rates were verified prior to the start of the testing and every 2 weeks thereafter. The verification was performed by bucket and stopwatch methods as follows. The filtrate reservoir on the CMPP skid contains a sight glass. This sight glass contains five-

gallon graduations. Following a backwash (when the reservoir is drawn down) a constant flow rate was established and the operator calculated the amount of time that it takes 50 gallons of filtrate water to accumulate in the filtrate reservoir. This data was used to calculate the average flow rate and was checked against the flow rate as indicated on the data acquisition system of the CMPP.

Pressure Transmitters – Pressure transmitters are located in both the feed and filtrate side of the membrane module. These pressure transmitters output an analog signal to the PLC indicating the gauge pressure measured as a function of time. Both of the pressure transmitters were checked against an independent measurement in the form a pressure gauge (calibrated to NIST traceable standards) mounted on both feed and filtrate sides of the membrane module. Pressure as indicated on the data acquisition system of the CMPP was checked against the pressure gauge readings 7 times per week.

In-Line Particle Counters – Factory calibration of particle counters was performed prior to the start of the study. However, prior to the study, the instrument calibration was field-verified using microspheres. Polystyrene sphere suspensions were purchased from EPS Analytical Standards with concentration certifications provided (Appendix E). The testing was performed with spheres with diameters of 2, 5 and 10 µm. The particle counter (MetOne) manufacturer's recommended field procedures were used. Particle suspension concentrations of 1000 particles per ml were used. The 2 µm particle suspension was supplied at a concentration of 1x109 particles per ml and required field dilution with a micropipette. Particle suspensions for 5 and 10 µm were supplied at a concentration of 1000 particles per ml from the manufacturer and did not require in-field dilution. The guidelines used to perform the verification are listed below. Results of this verification are presented in Chapter 4.

- The particle counter was thoroughly cleaned using the manufacturer's supplied cleaning solution.
- The particle counter was then flushed using purified reverse osmosis water for a period of at least 30 minutes.
- Microsphere suspensions were continuously stirred gently, to prevent entraining air bubbles into the fluid.
- A peristaltic pump was used to transfer the suspension to the instrument at the required steady flow rate of 100 ml/min for a period of at least 5 minutes to obtain stable readings.
- Measurements were electronically logged on a data acquisition system every 2 minutes, and the results were checked against the concentration and size of microspheres in the stock solution.

In-line Turbidimeters – In-line turbidimeters were calibrated according to manufacturer's methods with a 20 NTU standard, provided by the manufacturer. Calibration of turbidimeters was performed in advance of the verification period and once per week throughout the testing. In-line turbidity measurements were checked daily against a properly calibrated bench-top instrument.

3.1.7.6 Methodology for Use of Blanks

The methodology for using method blanks is summarized in Table 3-8.

Spiked Samples

Spike samples were utilized by NLS for the water quality parameters listed in Table 3-8. Spike samples were not used for analyses performed in the field. NLS utilized one spike sample per QA/QC batch. Each batch consisted of approximately 10 samples analyzed for a single parameter.

Travel Blanks

In order to assess potential travel related contamination, a total of four travel blanks were to be submitted to the laboratory during the verification testing. The laboratory was to analyze half of the travel blanks for total organic carbon and half for total coliforms. However, these travel blanks were not performed and are a deficiency of this report.

3.1.7.7 Performance Evaluation Sample

An evaluation sample was analyzed in accordance with the procedures of NLS. The performance evaluation sample submitted was a 20 NTU turbidity standard. This performance evaluation sample was submitted at the start of the verification study by Carollo Engineers to NLS and was returned with a reported value of 21 NTU.

3.1.7.8 Outline for Duplicate Sampling

Duplicate sampling was performed according to the outline presented in Table 3-7

3.1.7.9 Procedures Used to Ensure Data Correctness

The procedures used to ensure data correctness are detailed in Section 3.3 “Calculation of Data Quality Indicators.”

3.1.7.10 Procedures Used to Calculate Indicators of Data Quality

The procedures used to calculate indicators of data quality are detailed in Section 3.3 “Calculation of Data Quality Indicators.”

3.1.7.11 Outline for Data Reporting

Reports were prepared by Carollo Engineers, P.C. Data was reported in a draft and final ETV report, submitted by Carollo Engineers, P.C. Status reports were not submitted due to the short duration of the tests.

3.1.7.12 Corrective Action Plan

The corrective action plan for each of the tested water quality parameters is summarized in Table 3-9.

3.1.8 Task 8: Operational Conditions and Maintenance

The objective of this task was to maintain appropriate operational conditions and maintenance throughout the verification testing.

3.1.8.1 Work Plan

Technical specifications for the Polymem module were provided for this testing and include normal operating ranges for temperature, pressure, flow, chemical compatibility, instructions for conditioning, storage, integrity testing, fiber repair, and chemical cleaning. Carollo evaluated the instructions and procedures in the membrane O&M Manual for their applicability during the verification test. The CMPP O&M Manual is included in Appendix B. It contains procedures for filtration, backwashing, chemical cleaning, and routine maintenance. Troubleshooting guidance is also included.

3.2 Calculation of Operating Parameters

3.2.1 Flux

Membrane flux was calculated as follows:

$$\text{Flux} = \frac{Q_{filtrate}}{Area}$$

Where:
$Q_{filtrate}$ = filtrate flow rate
Area = total active membrane surface area

3.2.2 Specific Flux

Specific Flux was calculated as follows:

$$\text{Specific Flux} = \frac{Flux}{TMP}$$

Where:
Flux = the result of the flux calculation as shown above
TMP = transmembrane pressure

3.2.3 Normalized Specific Flux

Normalized Specific Flux was calculated as follows:

$$\text{Normalized Specific Flux} = \frac{SpecificFlux}{e^{0.0239*(T-20)}}$$

Where:
Specific Flux = the result of the specific flux calculation as shown above
T = Temperature in Celsius

3.2.4 Feedwater System Recovery

Feed Water Recovery was calculated as follows:

$$\text{Recovery} = \left[1 - \frac{V_{BW}}{V_{total}}\right] * 100\%$$

Where:
V_{total} = total volume of filtrate produced in a production cycle based on average flow rate and a production cycle duration of 50 minutes.
V_{BW} = total volume of filtrate used during a production backwash cycle

3.3 Calculation of Data Quality Indicators

Data quality parameters as specified in the ETV protocol include representativeness, statistical uncertainty, accuracy, and precision. This section details how each of these parameters was considered throughout this testing.

3.3.1 Representativeness

As specified by the ETV Protocol (EPA/NSF 1999), representativeness of operational parameters entails collecting a sufficient quantity of data during operation to be able to detect a change in operational parameters. As specified, detecting a plus or minus 10 percent change in operating parameter is sufficient for proper QA/QC. Operational parameters including flow rate, membrane feed, and filtrate pressures were recorded a minimum of five days a week, which NSF specifies as sufficient for tracking changes in operational conditions that exceed this 10 percent range.

In addition to ensuring representativeness of operational parameters, representativeness of water quality samples was ensured by executing consistent sample collection procedures. These procedures considered sample location, timing of sample collection, sample procedures, sample preservation, sample packaging, and sample shipping as detailed below.

Sample Locations – The water quality monitoring matrix was presented in Table 3-5, which presents the water quality monitoring plan for feed, filtrate, and backwash streams of the CMPP. Further guidance on sampling locations is included in the O&M Manual/Standard Operating Procedures for the CMPP presented in Appendix B.

Timing of Sample Collection – Feed water quality sampling was performed within one hour of filtrate water quality sampling to ensure that the filtrate water sample was representative of the membrane feed water quality. Filtrate water quality was relatively consistent throughout the duration of the production cycle. However, it is not unusual for turbidity or particle counts to be slightly higher at the beginning of a production cycle. Since this represents the worst case water quality, filtrate water samples were collected within the first 15 minutes of a production cycle. The PLC on the CMPP has a timer, which clearly indicated the duration of a particular production cycle.

The backwash procedure consisted of a three-step procedure. Step 1 included hydraulic backwashing, air scour, and chlorine addition followed by a short rest period of approximately five seconds. Step 2 repeated Step 1. Step 3 of the backwash procedure was only hydraulic; air scour and chlorine addition were not utilized. Backwash samples were collected at the beginning of the second backwash cycle. The backwash sample tap was opened throughout the duration of the backwash procedure to ensure that a representative sample was collected.

Sampling Procedures, Preservation, Packaging, and Transport – Prior to the collection of each individual water quality sample, the sample tap was allowed to run a minimum of 30 seconds in order to purge the sample tap and sample line of stagnant water. Samples were then collected. Additional considerations and procedures for individual water quality parameters are included below:

pH – pH samples were collected at the sample tap in polypropylene beakers and immediately tested for pH. The temperature at which the pH reading is made was also recorded.

Temperature – In addition to temperature transmitter readings (recorded continuously on the PLC), temperature gauge readings were manually recorded daily. Temperature was also recorded while measuring pH. Special preparation or sampling procedures were not necessary for this measurement.

Turbidity (Bench-top) – The method for collecting bench-top turbidity samples followed the procedure recommended in the testing protocol developed by the NSF. The procedure was as follows:

- The slow steady stream was run from the sample tap.
- A dedicated sample cell was triple rinsed with the sample.
- The sample was allowed to flow down the side of the cell to minimize bubble entrainment.
- The sample cell was wiped clean.
- The sample cell was immediately inserted into the turbidimeter.
- The measured turbidity was recorded upon reading stabilization.

Alkalinity – Samples were collected in a polyethylene or borosilicate bottle provided by the analytical laboratory. The sample was closed tightly and immediately placed into the sample cooler for transport to the analytical laboratory. Sample agitation and prolonged exposure to the air was avoided.

Total Hardness – Procedures for sampling total hardness followed alkalinity sampling procedures.

Calcium Hardness – Samples were collected by the procedures for alkalinity and total hardness.

Total Dissolved Solids – Resistant glass or plastic sample bottles were used as provided by the analytical laboratory. Samples were collected and immediately placed into the sample cooler for

transport to the analytical laboratory. Analysis began as soon possible as specified by EPA Method 160.1.

Total Suspended Solids – Sampling for total suspended solids followed the same procedure as specified by total dissolved solids.

Total Coliform and HPC – Sample containers were provided by the analytical laboratory. Aseptic sampling techniques were used as follows:

- Sample bottles were kept closed until they were filled.
- Sample taps were removed, allowed to soak in a chlorine solution for a minimum of two minutes, rinsed, and reconnected to the sample valve. Water was then allowed to run through the tap for a minimum of two minutes. The sample tap was flamed prior to sampling.
- The cap of the sample container was removed without touching the surface of the cap or neck of the bottle.
- The sample container was filled without rinsing and the cap was replaced immediately.
- Samples were refrigerated immediately after collection and transported to the laboratory in coolers with frozen blue ice.
- Samples were refrigerated upon receipt at the laboratory and analyzed within holding times specified in their standard method.

3.3.2 Statistical Uncertainty

For data sets of eight or more, statistical uncertainty was calculated for grab sample analyses including TOC, turbidity, HPC, UV_{254}, and TSS. This was done by calculating the 95 percent confidence interval in the following manner:

$$95\%\ \text{Confidence Interval} = \overline{X} \pm t_{n-1,0.975}\left(S/\sqrt{n}\right)$$

Where:
$\overline{X}$ = sample mean
t = student t-test with n-1 degrees of freedom
S = sample standard deviation
n = number of independent measurements

3.3.3 Accuracy

Accuracy was quantified as the percent recovery of a parameter in a sample to which a known quantity of that parameter was added. For this testing an example of accuracy determination in the ETV was the analysis of a turbidity proficiency sample in comparison of the measured turbidity of the known level of turbidity of the sample.

$$\text{Accuracy} = \text{Percent Recovery} = 100 * \left[\left(x_{known} - x_{measured}\right) \div x_{known}\right]$$

Where:
x_{known} = known concentration of analyte added to the sample
$x_{measured}$ = measured concentration of parameter

3.3.4 Precision

Precision refers to the degree of mutual agreement among individual measurements that provides an estimate of random error. The standard deviation and relative standard deviation recorded from sample analysis were reported as a means to quantify sample precision. The percent relative standard deviation was calculated in the following manner. The standard deviation is as follows:

$$\text{Precision Deviation} = \left[\frac{\sum_{i=1}^{N} \left(\bar{x}_i - \bar{x} \right)^2}{n-1} \right]^{1/2}$$

Where:
x = sample mean
x_i = *i*th data point in the data set
n = number of data points in the set

As specified in the ETV protocol provided by the NSF, the percent relative standard deviation for drinking water samples must be less than 30 percent or acceptable precision under the verification testing program.

$$\text{Relative Percent Deviation} = \frac{x_1 - x_2}{\bar{x}} * 100\%$$

Where:
x = sample mean
x_1 = first data point of the set of two duplicate data points
x_2 = second data point of the set of two duplicate data points

3.4 Safety Measures

Membrane – The membrane was inspected for visual damage prior to installation, and operated within the manufacturer's pressure and flow ranges.

Electrical – The electrical work for the CMPP was performed prior to the start of this study by a licensed electrical contractor in accordance with local codes.

Chemicals – Non-compatible chemicals (acids/bases/chlorine/preservation solutions) were stored separately from one another at the pilot site. Material Safety Data Sheets were stored on site and are provided in Appendix F.

3.5 Testing Schedule

Field operations specific to the PSTP began February 28, 2002. Testing specific to the PSTP began March 11, 2002. The verification testing was terminated on April 26, 2002 after 46 days of operation. Field activities related to this testing were finalized May 3, 2002.

The following key events took place during the test run.

- Conduct initial chemical clean to establish baseline conditions – Day 0;
- Conduct integrity test – Day 0;
- Start continuous membrane filtration pilot testing including sample collection, and hydraulic performance monitoring as described in Chapter 4 of this report – Day 1;
- First chemical Clean – Day 12;
- End filtration operations – Day 46;
- Second chemical cleaning – Day 51; and
- Conduct integrity testing – Day 54.

Chapter 4
Results and Discussion

4.1 Task 1: Characterization of Membrane Flux and Recovery

The operating conditions for the Polymem UF120 S2 module are provided in Table 4-1. These test conditions were established based on previous pilot study optimization results conducted from May 2001 to March 2002. The membrane system ran at a constant normalized flux of 40 L/hr-m^2 (24 gfd) for the first 12.5 days of operation during the ETV test (Run 1). At the end of Run 1, the membrane was chemically cleaned to restore flux and to reduce the required transmembrane pressure. The remaining run time was operated at a constant specific flux of 30 L/hr-m^2 (18 gfd) (Run 2).

The backwash interval, or production cycle, was set at 50 minutes of operational run time throughout the testing and was followed by a total production backwash time ranging from 60-120 seconds. The backwash cycle duration was adjusted throughout the testing to maintain a system recovery of at least 90 percent. Backwash water was chlorinated at a target dose of 5 mg/L for the entire duration of the testing and was verified with daily sampling.

Figure 4-1 shows a time series plot of TMP, normalized flux, normalized specific flux, and system recovery data throughout the test. Operational flux and temperature data are presented as a time series plot in Figure 4-2. Table 4-2 summarizes operational data collected throughout the testing. System recovery was calculated daily based on average flow rates and total backwash volumes as measured on a daily basis by plant operators. Recovery ranged from 89-96 percent throughout the 46-days of testing. The figures show a plant shut down on 4/18/02 resulting from a power outage at the CMPP. When the plant was restarted, the default operational setpoints (different from the target operational data) caused discontinuity in the data. When these set points were changed back to the target values, system operations returned to normal.

At the start of Run 1 (clean membrane), the TMP began at approximately 0.34 bar (5 psi). During Run 1, there was a nearly linear rise in TMP at a rate of approximately 0.087 bar per day (1.5 psi/day). After a chemical clean, the TMP was restored to approximately 0.45 bar (6.5 psi) and decreased to approximately 0.41 bar (6 psi) within one hour of start up. During Run 2, the TMP remained stable near 6 psi for approximately 24 hours. The remainder of Run 2 produced a nearly linear rise in TMP of approximately 0.039 bar per day (0.57 psi/day).

Normalized specific flux at the start of Run 1 was approximately 118 L/hr-m^2-b (4.79 gfd/psi). Due to fouling, normalized specific flux decreased to approximately 28 L/hr-m^2-b (1.1 gfd/psi) by the end of Run 1 with a TMP of 1.43 bar (21 psi). Chemical cleaning restored the normalized specific flux to approximately 74 L/hr-m^2-b (3.0 gfd/psi). Run 2 lasted nearly 33 additional days without another chemical clean. At the time the testing was terminated (at the end of Run 2), the normalized specific flux was approximately 17 L/hr-m^2-b (0.70 gfd/psi) with a TMP of 1.7 bar (25 psi). The improvement in specific flux decline trends during Run 2 is likely due to the lower target normalized flux. It should be noted that the 25 percent decrease in normalized flux led to a 260 percent increase in run time before a required chemical cleaning (12.5 vs. 32.7 days).

Following a review of the data, the manufacturer suggested that the following changes may have adversely impact the specific flux decline rate:

- Low Air Scour Flow Rate: Polymem suggested that flow rates are typically 5 m^3/hr (2.9 cfm) at standard temperature and pressure (STP). This information is not included in the O&M Manual provided by Polymem.
- The Run 1 flux rate was selected based on a recovery of 90 percent; however, the membrane was operated at a median recovery of 94 percent.

4.2 Task 2: Evaluation of Cleaning Efficacy

A total of three chemical cleanings were performed for this testing as a "proof of concept" effort: 1) Prior to beginning the verification test. This initial chemical cleaning was performed on 3/5/02 instead of the first day of the testing (3/11/02) because CMPP equipment verification and the testing of membrane baseline flux conditions required a few days of work prior to the official ETV starting date of 3/11/02; 2) following Run 1 when the transmembrane pressure reached 1.4 bar (21 psi). Although the terminal transmembrane pressure of the membrane module was 29 psi, during Run #1 of the ETV testing, the rate of TMP rise was such that the terminal pressure would have been exceeded during the weekend when no operator would have been present to stop the unit. This run was ended somewhat prematurely to avoid possible fiber and module damage; and 3) following Run 2 at the end of ETV testing, when the transmembrane pressure reached 1.7 bar (25 psi). Tables 4-3 and 4-4 summarize collected chemical cleaning water quality and hydraulic data, respectively. It should be noted that, for Chemical Cleaning #3, the TDS samples were analyzed exceeding the EPA sampling holding times. Table 4-5 summaries the collected chemical cleaning efficacy data.

The recovery of specific normalized flux for Chemical Cleaning #s 2 and 3 was 62 and 73 percent, respectively. Chemical cleaning conditions (chlorine concentration, pH) were selected from the manufacturer's recommended procedures. Cleaning # 2 was performed at ambient water temperature, [14-18.6°C (57-65.5°F)], pH = 12.2, and an average total chlorine concentration of 164 mg/L, for 8 hours.

Because recovery of specific flux was low, Cleaning # 3 was performed with a similar cleaning solution but at elevated solution temperature [22 - 31°C (72-88°F)], for an extended soaking period. Despite these changes the specific flux recovery was marginal (73 percent).

Following a review of the data, the manufacturer suggested that, due to the observed calcium hardness (average of 88 mg/L during ETV test), some $CaCO_3$ fouling could have occurred and an acid clean would be necessary to restore the specific flux. Additionally, recirculation of the cleaning solution during cleaning has been shown to produce higher specific flux recoveries than those observed on other source waters (Hugaboom, et. al, 2001). Further optimization would be required to improve these recoveries, however, this was not the goal of the study. Despite the low specific flux recoveries, the goal of providing "proof of concept" was achieved. Ideal conditions would likely produce much greater cleaning efficiency. Therefore, an accurate account of the usable membrane life cannot be estimated. The manufacturer's recommended cleaning procedure is included in Appendix A.

4.3 Task 3: Evaluation of Finished Water Quality

Result summary sheets for off-site analyses are provided in Appendix G.

4.3.1 Turbidity, Particle Counts, and Particle Removal

Figure 4-3 presents the on-line and bench-top turbidity profiles recorded throughout the testing. The figure shows data for feed, filtrate, and backwash water. The bench-top turbidity analysis results are summarized in Table 4-6 including feed, filtrate, and backwash water analyses. On-line turbidity data are summarized in Table 4-7. Overall, there was close mutual agreement between bench-top and online measurements. As shown in Table 4-7, feed water turbidity ranged from 0.2 to over 19 NTU with an average of 1.3 NTU. Bench-top backwash water turbidity averaged about 11 NTU. Bench-top filtrate turbidity was typically below 0.05 NTU. Online turbidity data showed two anomalous filtrate readings dated 3-19-02 and 3-22-02 with readings of 0.002 and 0.45 NTU, respectively. These data were not included in statistical analyses. Due to the size of the database for online turbidity and particle counts, this data is not included in the appendix. However, this data is on file with the NSF.

Table 4-7 also shows online feed and filtrate particle count data. Total feed particle concentrations (>2 µm) averaged about 4,300 particles/ml. Filtrate particle counts averaged 4 particles/ml. The 90th percentile for feed and filtrate total particle counts (>2 #/ml) was approximately 9,911 and 2 particles/ml, respectively. Average particle log removals of 4.2, 4.1, 4.1, 3.4, 3.3, 2.9, and 2.2 were achieved for particle size ranges of >2 um, 2-3, 3-5, 5-7, 7-10, 10-15, and >15 um, respectively. The membrane system removed 3.1 logs of total particles 90 percent of the time. It should be noted that the particle count instruments collected sample volumes of 100 ml per each data point. If no particles were detected in that sample volume in the filtrate, the filtrate particle count data was recorded as 0.00 particle/ml (below the detection limit for the instrument of 1 particle). Since these data were recorded as zero values, log removal data could not be calculated for these data points and were not included in the statistical analyses. Because the membrane system produced relatively consistent filtrate particle counts, log removals increased during periods when feed water particle counts were higher and decreased during periods when feed water particle counts were lower.

Figures 4-4 through 4-10 present the time series particle count profile data (>2 µm, 2-3 µm, 3-5 µm, 5-7 um, 7-10 µm, 10-15 µm, and >15 µm) that was collected throughout the testing. Figures 4-11 through 4-17 show log removal profiles for each particle size. The presented data was collected at 5-minute intervals and includes data collected during backwashes. Evaluation of the time series data showed relatively higher particle counts during, and immediately following, a backwash. As a result, particle removals were decreased during these times. These consistently brief occurrences caused log removal data to decrease or even become negative for short periods. The reasons for this are described below.

During backwash cycles, the feed pump was turned off thereby halting flow to the feed particle counter. Because the particle counter output depends on flow rate, this decrease in flow to the particle counter resulted in lower particle counts.

The filtrate particle counter data was affected during backwash cycles as well. The surge in flow during backwash cycles can cause hydraulic and air bubble turbulence in the particle counter feed weir. The stirring up accumulated particles within the weir itself and introduction of air bubbles lead to higher particle counts. Furthermore, the piping used for backwashes was fed from the bottom of the filtrate tank that may have accumulated particles and air bubbles (caused by increases in temperature and subsequent degassing) during the stagnant 50-minutes of a production cycle.

The figures also show higher filtrate particle count data immediately following chemical cleanings for the same reasons are described above. After system stabilization (within approximately 4 hours), filtrate particle counts reached typical low-level readings.

For evaluation purposes the data for turbidity, particle counts, and log removal were plotted as frequency distribution curves. Frequency distribution curves are shown in Figures 4-18 through 4-28. The 90th percentile for feed and filtrate turbidity was 3.5 and 0.035 NTU, respectively. The 90th percentile for feed and filtrate total particle counts (>2 #/ml) was approximately 9,911 and 2 particles/ml, respectively. It should be noted that filtrate particle count average (as shown in Table 4-7) was higher than the 90th percentile. This is due to the fact that statistical averaging is largely effected by higher values, especially when the majority of the data is near zero as was the case in the filtrate particle count data set.

Figures 4-29 and 4-30 show a sensitivity analysis performed on particle count data collected from one 24-hour period performed to determine the potential effects of backwash events on calculated log removals. Data from March 14, 2002 was chosen for this analysis due to the clusters of relatively lower log removal data, thereby representing a worse case scenario. Figure 4-29 presents the “raw” time series of feed and filtrate particle count data (>2 µm) that was collected throughout the 24-hour period and includes markers indicating likely backwash events. The presented particle count data was collected at 5-minute intervals and includes data collected during backwashes. Figure 4-30 presents the time series of feed and filtrate particle count data (>2 µm) collected throughout the same 24-hour period, with the particle count data removed that were likely collected during backwash events. It should be noted that Figures 4-29 and 4-30 are plotted on a log scale. As such, differences in filtrate particle counts are more apparent than with the feed count data. As shown in Figure 4-30, filtrate particle counts did not exceed 10 #/ml when the filtrate particle counts recorded during the backwash events were excluded from the data set.

Figure 4-31 shows the log removal frequency distribution curves calculated for the raw data set (data including backwash events) and for the data excluding particle count data likely collected during backwash events. Log removals (>2 µm) for the raw data set and for the data set without particle counts likely collected during backwash events were 3.2 or greater 90 percent of the time and 3.6 or greater 90 percent of the time, respectively.

4.3.2 Microbial Removal

The removal of naturally occurring bacteria was also monitored throughout the ETV study. A summary of this data is shown in Table 4-8. Total coliform bacteria were analyzed through two means: 1) through a “presence/absence” (P/A) test and 2) through total coliform enumeration.

One of the P/A test results, from the sample collected on 3/18/02, confirmed the presence of total coliforms in the feed water. However, total coliforms were not detected in the corresponding filtrate sample. Total coliform bacteria was detected in one P/A filtrate sample on 4/12/02 and one P/A backwash sample on 4/22/02. Total coliform enumeration results showed feed concentrations ranging from <1.1-23 MPN/100 ml. Filtrate and backwash sample results for total coliform enumeration were reported as <1.1 MPN/100 ml, which is the method detection limit.

33 of the 38 filtrate HPC samples were at or below the method detection limit of 2 CFU/ml. Some filtrate samples were reported to have notable HPC counts. However, the samples reported to have HPC counts of greater than 2 CFU/ml showed higher HPC counts in the filtrate than in the feed. It was not believed that these HPC results were indicative of a breach in membrane integrity. Possible reasons that may account for these results as described below.

Previous studies (Jacangelo et al., 1995) have demonstrated that HPC bacteria can be introduced on the filtrate side of the membrane rather than by penetration through it. Furthermore, the high degree of variability between duplicate samples is indicative of the high degree of error and sensitivity associated with HPC sampling and analysis, especially near the method detection limit (see Section 4.7 Quality Assurance/Quality Control) as was the case for this testing.

Sampling taps were removed and disinfected thoroughly with a chlorine solution and flame. However, approximately 10 feet of filtrate sample tubing was permanently affixed to the CMPP skid and was unavailable for disinfection in this manner. This CMPP was in operation onsite for several months prior to the ETV study and experienced occasional periods of down time. Sample taps were flushed prior to sampling. However, it is possible that HPC bacteria accumulated in this sample tubing and sloughed off during ETV testing. Contamination may also have occurred because the sampling was not performed in a sterile environment.

4.3.3 Other Water Quality Parameters

Table 4-9 presents the results of the general water quality characterization. There was no notable change in alkalinity, total hardness, calcium hardness, or total dissolved solids across the membrane module, which was expected as dissolved inorganics tend to pass through UF membranes. However, there was a small reduction in TOC in the filtrate. Two feed water samples were collected for alkalinity both resulting in a measured value of 110 mg/L as $CaCO_3$. The two feed water samples collected for total hardness resulted in a measured value of 130 mg/L as $CaCO_3$. Feed water calcium hardness ranged from 87-88, with an average of 88 mg/L as $CaCO_3$. Feed water total dissolved solids ranged from 150-210, with an average of 187 mg/L. Two filtrate samples were collected for alkalinity both resulting in a measured value of 110 mg/L as $CaCO_3$. The two filtrate samples collected for total hardness resulted in a measured value of 130 mg/L as $CaCO_3$. The two filtrate samples collected for calcium hardness resulted in a measured value of 87 mg/L as $CaCO_3$. Filtrate total dissolved solids ranged from 190-210, with an average of 203 mg/L.

Total suspended solids were measured throughout the testing as an indication of particle removal potential. The TSS in the backwash water reached as high as 41 mg/L. Filtrate TSS was typically below the detection limit with 32 out of 37 samples reported at or below the level of detection. Like HPC data, some of the filtrate TSS samples were detected at higher than expected levels.

However, each filtrate sample with detectable TSS was reported as greater than its corresponding feed water sample. These results are likely due to the fact that feed and filtrate samples were so near the detection limit of the analysis. Due to the length of time the equipment was in use prior to the ETV testing, it is also possible that material had built up in the portion of sample piping permanently fixed to the CMPP skid. Although the sample ports were allowed to flush prior to sample collection, accumulated material may have sloughed off during some of the sampling periods. Specifically, TSS data collected on April 5, 2002 showed strong evidence of a sample mix-up. Feed, filtrate, and backwash TSS values were reported as <1, 22, and 1 mg/L, respectively. This data was excluded from statistical analysis.

Table 4-10 presents the mass balance conducted on the TSS results obtained throughout the testing. In the cases where the measured TSS was below the detection limit (<1 mg/L), half of the detection limit was used for the calculations. Six of the 36 calculated results showed positive correlation (<50% relative percent deviation) between calculated and measured backwash water TSS. These relatively poor correlations may in part be due to the feed water TSS being close to the method detection limit. In addition, backwash water samples were collected during the second cycle of the backwash. It is likely that the majority of TSS were flushed out during the first cycle of the backwash. Therefore, the reported backwash water TSS concentration may not accurately represent the entire backwash water volume consumed.

4.4 Task 4: Reporting Membrane Pore Size

The nominal pore size of the UF120 S2 membrane module used in this ETV study was determined through the use of multiple methods; however, the manufacturer has not determined a pore size distribution. Methods used in determining nominal pore size include scanning electron microscopy (SEM), flow porometry, and particle retention testing. The first two methods are described here.

The membrane is an asymmetric hollow fiber with dense layer containing small pores on the inside and outside, and a less dense structure containing larger pores. SEM images were used at multiple resolutions to estimate the size of the pores in the membrane. Based on these images, the estimated nominal pore diameter is less than 100 nanometers (nm).

Flow porometry (Lee, et al., 1997; Hernandez, et al., 1999; Mietton and Courtois, 1997) was used to determine the mean size of the pores in the membrane (including the less dense middle layer). The mean pore diameter used in this procedure was determined to be less than 50 nm. The above data are taken from a letter supplied by the manufacturer that is included in Appendix H. This data is provided for informational purposes only and the results were not verified during the ETV testing.

4.5 Task 5: Membrane Integrity Testing

A total of two membrane integrity tests were performed for this testing: 1) prior to the start of the test and 2) following the final chemical cleaning. The first integrity test was performed with an applied air pressure of 10 psi. Measurements of air pressure were taken every 15 seconds for a period of 2 minutes. Over the course of the 2 minutes there was zero loss in pressure and no visual indicators of a loss of membrane integrity (no bubbles were detected). The second

integrity test was again performed with an applied pressure of 10 psi. Measurements were taken every 15 seconds for a period of 2 minutes. The test was repeated 4 times yielding an average pressure drop of 0.35 psi/min. This was within the allowable pressure drop as specified by the manufacturer (<0.36 psi/min). However, during the visual inspection a small amount of air bubbles were noted in the vertical, transparent section of the CMPP feed water piping. This suggests that a fiber (or fibers) may have broken.

In addition to the visual air bubble test, in-line particle counting and turbidity data was used as an indirect method of monitoring membrane integrity. Increases in particle counts or turbidity in the filtrate serve as indicators of potential fiber breakage. During the ETV testing, there were no significant increases in filtrate particle counts or turbidity that would have indicated a loss in membrane integrity. However, following ETV testing (but prior to any further operation of the membrane module) on 6/5/02, the membrane module filtrate end cap was removed to further investigate the bubbles noted during the final integrity test. This investigation followed the integrity test/repair procedures outlined in the Polymem UF120 S2 O&M Manual. One broken fiber was identified and repaired. One subsequent pressure decay test, performed as described above, yielded a zero loss in pressure and no visual indicators of a loss of membrane integrity (no bubbles were detected).

4.6 Task 6: Data Management

4.6.1 Data Recording

Water quality and hydraulic data was maintained on site. Critical process parameters including pressures, temperature, turbidity, flow rates, and chemical doses were automatically stored on the membrane skid mounted PLC CPU. This data was also backed up on a separate personal computer. This data was recorded at a maximum of 10-minute intervals throughout the ETV testing. Feed and filtrate count data was recorded at 5-minute intervals for the following size ranges: 2-3 µm, 3-5 µm, 5-7 µm, 7-10 µm, 10-15 µm, and >15 µm.

Data were manually recorded in tabular format for water quality parameters received from NLS including alkalinity, total hardness, calcium hardness, TDS, TSS, TOC, and UVA. Likewise, results from biological samples were recorded in a tabular format.

Onsite bench-top analyses were recorded in specifically designed daily log sheets. Other details of the ETV testing such as field analyses, maintenance activities, water type, backwash procedures, operating cycles, names of visitors, problems, etc. were logged by the operator in a bound notebook. Additionally, QA/QC information including manual checks of pressure, flow and temperature transmitters, results of on-site analyses, instrumentation flow rates, and other pertinent information were logged in the same manner. Chain of custody records for off-site laboratory analysis, on-site calibration, and verification of on-line instrumentation were also recorded. Copies of the laboratory notebooks and data log sheets are included in Appendix D.

4.6.2 Data Entry, Validation, and Reduction

Data were entered from data sheets into similarly designed data entry forms in electronic spreadsheet format. Following data entry, the spreadsheets were printed and checked against

handwritten datasheets. All corrections were noted on the hard copies and were then corrected on the electronic copy. The hard copies of the electronic data are included in Appendix D.

4.7 Task 7: Quality Assurance/Quality Control (QA/QC)

QA/QC results and chain of custody records reported by NLS and MWH are included in Appendix I.

4.7.1 Data Correctness

There are five indicators of data correctness including representativeness, statistical uncertainty, completeness, accuracy, and precision. This section includes the summary of analyses conducted to ensure correctness of the data. The methods used for data analysis are outlined in Chapter 3. Sampling and testing protocols were conducted per the requirements of the *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbial and Particulate Contaminants* (May 1999).

4.7.1.1 Representativeness

Representativeness of the data was ensured through strict adherence to sampling and testing methods outlined in Chapter 3. In addition, sampling efforts were coordinated so that sampling was conducted at a consistent time and location throughout the testing.

4.7.1.2 Statistical Uncertainty

For data sets of eight or more, statistical uncertainty was calculated for grab sample analysis including TOC, turbidity, HPC, UV_{254}, and TSS. In addition, statistical uncertainty was calculated for online measurements such as flux, flow rate, temperature, system recovery, etc. Statistical uncertainty was evaluated by calculating the 95 percent confidence interval. The results were presented in the previous sections.

4.7.1.3 Completeness

Data completeness refers to the amount of data collected during the ETV testing compared to the amount of data proposed in the PSTP. Data completeness was determined for onsite water quality measurement, laboratory water quality measurement, and operational data recording. Completeness tables can be found in Appendix J. Nearly 100 percent of the parameters were complete. However, travel blank samples were not collected during this testing. CMPP feed water chlorine residual was scheduled for testing once per week to verify the daily measurements collected as a part of the GBWUFP. Only one CMPP sample was collected during the first day of testing to verify the readings recorded by the utility. It should also be noted that the backwash water total coliform sample collected on 4/17/02 was not analyzed due to NLS error.

4.7.1.4 Accuracy

Accuracy was quantified as the percent recovery of a parameter in a sample to which a known quantity of that parameter was added. Accuracy determination in this ETV testing was performed by the analysis of a turbidity proficiency sample and onsite bench-top turbidimeter standards. A

comparison was made between the measured turbidity and the known turbidity level of the standard. Bench-top turbidity accuracy ranged from 84-113 percent with an average of 98 percent. The accuracy of the turbidity proficiency sample analyzed by NLS from a sample collected on 3/12/02 was 95 percent. This data is included in Appendix I. Accuracy was also ensured by calibration of bench-top and online turbidimeters as well as particle counter and flow meter verification as outlined in Chapter 3. Results for the online particle counter calibration verification are shown in Tables 4-11 and 4-12 for the feed and filtrate particle counters, respectively. Standards for 2, 5 and 10 um particle sizes were used for the verification. Each standard solution had a total particle concentration of 1000 particles/ml. The data show good correlation between the tested standard and particle counter output. A minor amount of particles were detected outside of the range of each standard. This is likely due to the standard solutions, which contain a distribution of particle sizes rather than a pure concentration of one particle size. Accuracy data is presented in Appendix D.

4.7.1.5 Precision and Relative Percent Deviation

Duplicate measurements were taken throughout the ETV testing as outlined in Chapter 3. Each duplicate measurement was analyzed to determine the consistency of sampling and analysis using relative percent deviation. The relative percent deviations averaged within 9 percent for onsite bench-top turbidity measurements. General water quality parameters (hardness, calcium hardness, alkalinity, algae, TDS, TOC, and UVA) sampled for the waters (feed, filtrate, and backwash) were as high as 40 percent with an average of 9 percent relative deviation. TSS analyses were as high as 189 percent (backwash) with an average of 50 percent relative deviation. HPC analyses for the feed and filtrate were as high as 150 percent with an average of 30 percent relative deviation. These data are included in Appendix G.

Relative percent deviation is greatly effected when analytical measurements are close to the lower detection limit. Specifically filtrate HPC and TSS were largely effected in this manner. 33 out of 38 filtrate HPC results were at or below the detection limit. 32 of 37 TSS results were at or below the detection limit.

4.8 Operational Conditions and Maintenance

4.8.1 Overall Operation and Maintenance

There were no major reoccurring problems experienced during this ETV testing program. However, plant operators noticed a few occasions of air bubble entrapment in the particle counter feed lines signaled by a decrease in particle counter flow. Influent waters were approximately 4°C (39°F) while the CMPP trailer was kept near 20°C (68°F). This temperature difference could have caused degassing of dissolved species and subsequent entrapment of air bubbles; however, air bubble introduction during backwash flow surges was the likely cause of entrapment of air bubbles. Particle counter feed flow rates were verified daily and corrective action was taken if flow restrictions were found. A small tubing brush was used to remove the air bubbles.

4.8.2 System Chemical Consumption

Chemical consumption was calculated for the system based on data collected throughout the testing. Daily measurements of total backwash volume and chlorine dose were used to estimate daily consumption of chlorine for production backwashes. Chemical cleaning chemical consumption was based on the input parameters for sodium hydroxide and chlorine. Chemical dosing was verified through onsite pH and chlorine measurements taken immediately following chemical injection.

Table 4-13 provides a summary of chemical consumption during the ETV test. For Run 1, a total of 0.61 pounds of chlorine (as NaOCl) were consumed for production backwashes. The chemical cleaning following Run 1 consumed 0.06 pounds of chlorine (as NaOCl) and 2.04 pounds of NaOH (as NaOH). For Run 2, a total of 1.06 pounds of chlorine (as NaOCl) were consumed for production backwashes. The chemical cleaning following Run 2 used 0.06 pounds of chlorine (as NaOCl) and 1.47 pounds of NaOH (as NaOH).

4.8.3 Review of Operations Manual

After reviewing the O&M Manual provided by Polymem, the following points were noted:

- The O&M Manual should be reviewed for grammar and word usage;
- The air scour flow rate during backwash should be specified;
- Chemical cleaning information should contain the recommendation that heated water be used if cleaning is inefficient at ambient temperatures;
- Pages 4 and 8 recommend procedures for integrity testing and for identifying a compromised fiber. The O&M Manual should be clarified to explicitly state the purpose of these two procedures.

4.8.4 Equipment Deficiencies Experienced During the ETV Program

4.8.4.1 Online Particle Counting

Throughout the testing there were no mechanical problems with the particle counter equipment. However, there was one period of approximately three days from 3/29/02 3:48 to 3/31/02 17:10 in which collected particle count data was unavailable for retrieval from the data logging software. The operators experienced similar problems prior to the start of the ETV testing. The data logging software technical support staff were unsuccessful in diagnosing this problem. In addition, plant operators noticed a few occasions of air bubble entrapment in the particle counter feed lines as described in section 4.8.1.

4.8.4.2 Membrane Equipment and Online Turbidimeters

One CMPP shut down was experienced during the testing during the night of 4/18/02 due to lightning. The online turbidimeters experienced damage resulting from an electrical overload and were out of commission until replacement parts were available during the first week of May. The CMPP shut down lasted approximately 10 hours. Operational staff successfully restarted the CMPP with no concerns outside of the online turbidimeters.

Chapter 5
References

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Chapter 6
Vendor Comments

Polymem submitted the following comments on the DRAFT report to the NSF. These comments were not included in the body of the text.

1. The pilot plant [CMPP] was not equipped with a dedicated air compressor for providing air for production backwashes. As a result, the airflow rate dropped below the specified flow rate during backwashing.

2. Concerning airflow rate during backwashing, the manufacturer typically recommends a constant flow rate of 3 to 5 m^3/h at standard temperature and pressure. Due to the limited capacity of the compressor, this recommendation was not strictly followed.

3. An acid cleaning was not performed following Run 1, which may have increased the specific flux.

4. It is believed that the membrane fibers were uncompromised during the test run as evidenced by the turbidity and particle count profiles. If membrane integrity had been compromised, it would be expected to find a notable increase in particle concentrations in the filtrate.

Tables and Figures

Table 1-1. Lake Michigan Feed Water Quality Data

Parameter	Units	Count	Median[1]	Range	Average	Standard Deviation	95% Confidence Interval
Cl_2 –Residual[2]	mg/L	42	0.05	0.03-0.06	0.05	0.008	0.05-0.05
Alkalinity	mg/L as $CaCO_3$	2	N/A	110-110	110	N/A	N/A
Total Hardness	mg/L as $CaCO_3$	2	N/A	130-130	130	N/A	N/A
Calcium Hardness	mg/L as $CaCO_3$	2	N/A	87-88	88	N/A	N/A
TDS	mg/L	3	200	150-210	187	N/A	N/A
TSS	mg/L	37	<1	<1-8.0	1.3	1.8	1.3-1.3
Total Coliforms	P/A	38	N/A	A-P[3]	N/A	N/A	N/A
Total Coliforms	MPN/ 100 ml	5	<1.1	<1.1-23	5.0	N/A	N/A
HPC	CFU/ml	38	3	<2-330	17	56	16-17
TOC	mg/L	13	2.2	1.6-3.4	2.3	0.5	2.3-2.3
UVA	cm^{-1}	13	0.022	0.017-0.043	0.024	0.007	0.024-0.024
Algae	#/ml	3	32.8	32.6-37.8	34.4	N/A	N/A
pH	-	40	7.79	7.67-8.01	7.80	0.071	7.73-7.88
Temperature	^{o}C (°F)	76	2.9 (37)	1.9-6.5 (35-44)	3.4 (38)	1.6	3.4-3.4 (38-38)
Turbidity (Bench-top)	NTU	39	1.0	0.40-4.5	1.3	0.9	1.3-1.3

1) Values reported as non-detect were assumed to be one-half of the detection limit for the purposes of statistical evaluation.
2) Measured as part of the daily sampling activities of the GBWUFP.
3) NLS testing procedures for total coliform were reported as “presence “ or “absence”. One sample collected on 3/18/02 tested positive for total coliforms.

Table 3-1 Verification Conditions

Operating Parameter	Verification Test Value
Flux	30-40 l/h-m^2 @ 20°C [1] (18-24 gfd)
Recovery	>90% [2]
Backwash Interval	50 min[3]
Data Logging Interval	10 minutes (4 times per backwash cycle)
Production Backwash Chlorine Concentration	5 mg/L
Air Scour Flow Rate	Approximately 2 cfm
Terminal Transmembrane Pressure	29 psi

1) Test flux was determined based on results of pilot testing prior to the verification study.
2) Recovery was at least 90%, however the exact values were calculated daily during verification testing and are reported in Chapter 4.
3) Backwash duration was set to achieve minimum recovery criteria.

Table 3-2 Operational Data

Operation Parameter	Frequency
Feed/Filtrate Water Flow[1]	Continuous
Feed Pressure	Continuous
Feed Temperature	Continuous
Filtrate Pressure	Continuous
Transmembrane Pressure	Continuous
Flux @ 20°C	Continuous
Specific Flux @ 20°C	Continuous
Recovery	Daily

1) Feed flow equals filtrate flow as measured on the filtrate side.

Table 3-3 Chemical Cleaning Procedures and Conditions

Chemical	Approximate Quantity	
Sodium Hypochlorite	0.05 lb (as NaOCl) /module/month	
Sodium Hydroxide	2.4 lb (as NaOH)/module/month	
Cleaning Step	**Hydraulic Condition**	**Duration**
Step 1 – Chemical backwash	Backwash to drain	60 seconds or approx. 35 gal
Step 2 – Cleaning soak	Soak at elevated temperatures not to exceed 90°F (32°C)	4, 8, and 44 hours(1)
Step 3 – Cleaning rinse	Backwash to drain	90 seconds
Residual Characteristic	**Approximate Value**	
pH	10-12	
Residual Chlorine	150 mg/L as Cl_2	
Total Volume of Residual	150 gallons/module/cleaning	

1) Three chemical cleans were included as part of this testing. The first clean took place prior to membrane operation and was allowed to soak for 4 hours. The second and third chemical cleans were performed after elevated TMPs were reached and were allowed to soak for 8 and 44 hours, respectively.

Table 3-4 Cleaning Verification Data

Analytical Parameter	Sample Timing
Temperature	2,3,4,5
pH	2,3,4,5
TDS	2,3,4,5
Turbidity	2,3,4,5
Visual observations	2,3,4,5
Operational Data	**Sample Timing**
Specific Flux @ 20°C	1,5
Flux @ 20°C	1,5
Transmembrane pressure	1,5
Flow rate	1,5

1) Prior to stopping production step.
2) Immediately following chemical dosing backwash for chemical cleaning.
3) 120 minutes following chemical dosing backwash for chemical cleaning.
4) During cleaning rinse backwash at the end of the chemical soaking period.
5) During production immediately following rinsing.

Table 3-5 Water Quality Sampling Schedule

Parameter	Sampling Frequency	Feed	Filtrate	Backwash
On-Site Analysis				
pH	1/day	X		
Temperature	Continuous	X		
Turbidity (in-line)[1] [2]	Continuous	X	X	2/day
Particle Counts (in-line)[3]	Continuous	X	X	
Total Chlorine[4]	1/week	X		
Off-Site Laboratory Analysis				
Alkalinity	1/month	X	X	
Total Hardness	1/month	X	X	
Calcium Hardness	1/month	X	X	
TDS	2/month	X	X	
TSS	5/week	X	X	X
Total Coliforms	5/week	X	X	X
HPC	5/week	X	X	
TOC	2/week	X	X	
UVA	2/week	X	X	

1) Turbidity data was recorded at 10-minute intervals.
2) Online feed and filtrate turbidities were verified once per day with bench-top measurements. Backwash turbidity was measured twice per day with bench-top analysis and was not monitored by online instrumentation.
3) Particle count data was recorded at 10-minute intervals.
4) Backwash samples were analyzed once per day for total chlorine to verify the target dose of 5 mg/L. Feed water chlorine was monitored daily by the GBWUFP and was verified by means of a pilot plant grab sample prior to ETV testing.

Table 3-6 Data Management

Data Type	Documentation Format	Reporting Format
Membrane Hydraulic Data	SCADA	Plots
Chemical Cleaning Observations/Measurements	Notebook	Table
Production Backwash Observations/Measurements	Notebook	Table
In-line Feed/Filtrate Turbidity	SCADA	Plots
In-line Feed/Filtrate Particle Counts	Dedicated Computer	Plots
In-line instrument flow measurements	Notebook	Table
Daily Walkthrough Observations	Notebook	Table
Monthly QA\QC Observations	Notebook	Table
Off-site analyses	Feed and validated data from NLS	Table/Plots
On-site analyses		
pH, temperature, turbidity, conductivity	Notebook	Table/Plots
Photographs	Notebook	-

Table 3-7 Methods for Measuring Precision and Accuracy

Parameter	Precision	Accuracy
pH	7 measurements per week with duplicates (100%)	Daily 3-point calibration with pH buffers at 4, 7, and 10
Temperature	7 measurements per week with duplicates (100%)	Initial and weekly testing against NIST thermometer
Total Chlorine[(1)]	7 measurements per week	Instrument "Zeroed" daily
Bench-Top Turbidity	14 measurements per week with weekly duplicates (14%)	Daily checks against primary standards (0, 20, 200 NTU)
Alkalinity	One duplicate (100%)	NLS standard procedures
Total Hardness	One duplicate (100%)	NLS standard procedures
Calcium Hardness	One duplicate (100%)	NLS standard procedures
Total Dissolved Solids	4 measurements with 1 duplicate (25%)	NLS standard procedures
Total Suspended Solids	60 measurements with 12 duplicates (20%)	NLS standard procedures
Total Organic Carbon	4 measurements per week with 1 duplicate (25%)	NLS standard procedures
UV Absorbance	4 measurements per week with 1 duplicate (25%)	NLS standard procedures
Total Coliform/HPC	15 each measurements per week with 3 duplicates (20%)	NLS standard procedures

1) Samples were collected and analyzed daily by GBWUFP as part of normal operating procedures. For verification, pilot plant feed waters were measured for chlorine at the beginning of the verification testing.

Table 3-8 Sample Methodology

Parameter	Methodology for All Samples	Method
pH	Certified pH buffers	Standard Method 4500-H+
Temperature	None	Standard Method 2550B
Turbidity (Bench-top)	Ultra pure water as necessary	Standard Method 2130
Alkalinity	NLS standard procedures	Standard Methods 3010B, 2320B
Total Hardness	NLS standard procedures	EPA Method 200.7
Calcium Hardness	NLS standard procedures	EPA Method 200.7
Total Dissolved Solids	NLS standard procedures	Standard Method 2540C
Total Suspended Solids	NLS standard procedures	EPA Method 160.2
Total Organic Carbon	NLS standard procedures	Standard Method 5310B
UV Absorbance	NLS standard procedures	Standard Methods 5910B
Total Coliform/HPC	NLS and MWH Laboratories standard procedures	Standard Methods 9223/9215B (NLS) Standard Method 9221 (MWH)

Table 3-9 Corrective Action Plan

Parameter	Acceptance Criteria	Sequence of Steps for Corrective Action
Any Duplicate	≤ 10% apart	• Re-sample duplicates • Check instrument calibration; recalibrate instrument
Any Method Blank	See Table 3.8; criteria set by EPA-certified laboratory performing the analysis	• See Table 3.8; perform procedures specified to each analysis as determined by the state-certified, third-party, or EPA-accredited laboratory performing the analysis
Any Performance Evaluation (PE) or Proficiency Sample	Within recovery specified for each PE or proficiency sample	• Check and verify all steps in sample collection and analysis • Re-do PE or proficiency sampling and analysis
pH	≤ 10% difference from previous day; ≤ 1 pH unit difference from previous measurements	• Resample • Check instrument calibration • Re-calibrate instrument
Temperature	≤ 20% difference from previous day	• Check for change in feed water source to supply
Turbidity (Bench-top)	No increasing or decreasing trend indicated by results of bi-weekly proficiency samples. Measurement deviates less than ±10% from standard.	• Verify turbidimeter operation and status of sample tap • Perform routine maintenance/cleaning of instrument • Verify calibration using secondary standards • Re-calibrate using primary standards
Alkalinity, Total Hardness, Calcium Hardness, Total Dissolved Solids	≤ 20% difference from previous reading	• Verify change in feed water source or supply
Total Suspended Solids (filtrate)	Assuming very low TSS concentrations, ≤ 100% difference from previous reading	• Verify corresponding increase in turbidity • Re-sample • Check membrane integrity

Table 4-1 Operational Conditions

Operating Parameter	Units		
Run Period	**-**	**1**	**2**
Start Date and Time	-	3/11/02 08:30	3/24/02 19:36
End Date and Time	-	3/23/02 22:17	4/26/02 12:22
Run Length	day:hrs	12 days 14 hrs	32 days 17 hours
Termination Condition	-	Fouling	Time
Normalized Flux (20 ^{o}C)[1]	L/h-m^2 (gfd)	40 (24)	30 (18)
Recovery[2]	%	>90	>90
Backwash Interval	minutes	50	50
Backwash Duration[3]	seconds	60-120	60-120
Hydraulic Data Logging Interval	minutes	10 (4 per backwash cycle)	10 (4 per backwash cycle)
Particle Count Logging Interval	minutes	5	5
Production Backwash Chlorine Dose Setpoint	mg/L	5	5
Air Scour Flow Rate	cfm	Approximately 2	Approximately 2
Terminal Transmembrane Pressure	Bar (psi)	1.4 (21)	1.7 (25)

1) Test flux was determined based on results of pilot testing prior to the verification study.
2) Recovery was at least 90%. The exact values were calculated during verification testing and are reported in Chapter 4.
3) Backwash duration was set to achieve minimum recovery criteria.

Table 4-2 Summary of Operational Data

Parameter	Units	Count	Median	Range	Average	Standard Deviation	95% Confidence Interval
Run 1							
Flux	L/h-m^2 (gfd)	1396	23.8 (14.0)	17.9-25.4 (10.5-15.0)	23.8 (14.0)	0.5	23.8-23.8 (14.0 – 14.0)
Flow Rate	gpm	1396	12.0	9.0-12.8	12.0	0.3	12.0-12.0
Temperature	^oC (°F)	1397	2.2 (36)	1.5-3.2 (35-38)	2.2 (36)	0.3	2.2-2.2 (36-36)
Recovery	%	13	94	89-96	93	1.3	93-94
Specific Flux Decline at 20^oC(1)	L/h - m^2-bar-d (gfd/psi-d)	N/A	N/A	N/A	7.2 (0.29)	N/A	N/A
Run 2							
Flux	L/h-m^2 (gfd)	2738	18.5 (10.9)	16.1-24.2 (9.48-14.3)	18.7 (11.0)	0.98	18.8-18.8 (11.1-11.1)
Flow Rate	gpm	2738	9.3	8.1-12.2	9.4	0.49	9.4-9.4
Temperature	^oC (°F)	2738	3.3 (38)	1.6-6.8 (35-44)	3.5 (38)	1.31	3.5-3.5 (38-38)
Recovery	%	27	94	89-95	94	1.2	93-94
Specific Flux Decline at 20^oC(2)	L/h -m^2-bar-d (gfd/psi-d)	N/A	N/A	N/A	1.7 (0.069)	N/A	N/A

1) Average daily specific flux decline for the duration of the Period 1.
2) Average daily specific flux decline for the duration of the Period 2.

Table 4-3 Summary of Chemical Cleaning Water Quality Analyses

Parameter	Units	Sample Collection Time: Prior to Clean	Start of Clean	During Clean			Backwash Rinse	Production after Clean
Chemical Cleaning 1[1] March 5, 2002								
Time	(hours)	t<0	t=0	t=2			t=4	t= next run
Temperature	°C (°F)	N/A	8.3 (47)	7.8 (46)			3.3 (38)	3.3 (38)
pH		N/A	12.5	12.6			8.6	7.9
TDS	mg/L	N/A	--	--			--	--
Turbidity	NTU	N/A	1.1	0.5			--	0.1
Total Cl_2	mg/L	N/A	215	192			0.46	--
Chemical Cleaning 2 [2] March 24, 2002								
Time	(hours)	t<0	t=0	t=2	t=8		t=8	t=next run
Temperature	°C (°F)	2 (36)	14 (57)	15.8 (60.4)	--		18.6 (65.5)	7.5 (46)
pH		7.8	12.2	12.2	--		12.18	8.1
TDS	mg/L	--	4100	4700	5900		130	120
Turbidity	NTU	0.032	28.8	10.9	--		12.3	0.121
Total Cl_2	mg/L	5.1	160	168	--		72	0.7
Chemical Cleaning 3 [3] May 1, 2002								
Time	(hours)	t<0	t=0	t=2	t=22	t=44	t=44	t=next run
Temperature	°C (°F)	6.3 (43)	22 (72)	25 (77)	28 (82)	31 (88)	16 (61)	6.1 (43)
pH		--	12.0	11.9	11.9	11.9	11.9	--
TDS[4]	mg/L	--	3900	4500	5600	6500	3600	--
Turbidity	NTU	0.037	31.1	17.6	17.2	15.7	10.9	--
Total Cl_2	mg/L	--	186	180	176	180	174	--

1) Chemical Cleaning 1 was conducted prior to membrane operation. The total soaking duration for chemical cleaning 1 was four hours.
2) Chemical Cleaning 2 was allowed to soak for eight hours.
3) Chemical Cleaning 3 was allowed to soak for 44 hours.
4) These samples were analyzed exceeding the EPA holding times for TDS.

Table 4-4 Summary of Chemical Cleaning Hydraulic Analyses

Parameter	Units	Value Prior to Chemical Clean	Value Following Chemical Clean
Chemical Cleaning 1[(1)] March 5, 2002			
Flux	l/h-m^2 (gfd)	N/A[(1)]	24 (14)
Normalized Flux	l/h-m^2 (gfd)	N/A	39 (23)
Specific Flux	l/h-m^2-b (gfd/psi)	N/A	68 (2.8)
Normalized Specific Flux	l/h-m^2-b (gfd/psi)	N/A	118 (4.79)
TMP	psi	N/A	5
Flow Rate	gpm	N/A	12
Chemical Cleaning 2 March 24, 2002			
Flux	l/h-m^2 (gfd)	23.5 (13.8)	19.2 (11.3)
Normalized Flux	l/h-m^2 (gfd)	39.4 (23.2)	30.4 (17.9)
Specific Flux	l/h-m^2-b (gfd/psi)	16.5 (0.670)	45 (1.8)
Normalized Specific Flux	l/h-m^2-b (gfd/psi)	27.7 (1.12)	74.0 (3.01)
TMP	psi	20.7	6.1
Flow Rate	gpm	11.8	10
Chemical Cleaning 3 May 1, 2002			
Flux	l/h-m^2 (gfd)	20.3 (12.0)	21 (12)
Normalized Flux	l/h-m^2 (gfd)	29.7 (17.5)	32 (19)
Specific Flux	l/h-m^2-b (gfd/psi)	11.8 (0.479)	42 (1.7)
Normalized Specific Flux	l/h-m^2-b (gfd/psi)	17.2 (0.698)	63 (2.6)
TMP	psi	25.1	7.2
Flow Rate	gpm	10.2	10.6

1) Chemical Cleaning 1 was performed prior to membrane operation. Therefore, this information was not available.

Table 4-5 Summary of Chemical Cleaning Efficacy

Cleaning Number	Date	Normalized Specific Flux Prior to Cleaning L/h-m^2-b (gfd/psi)	Normalized Specific Flux Following Cleaning L/h-m^2-b (gfd/psi)	Recovery of Specific Flux (%)	Loss of Original Specific Flux (%)
1	3-5-02	--[1]	118 (4.79)	--[1]	--[1]
2 (end of period 1)[2]	3-23-02	28 (1.1)	74[3] (3.0)	62[4]	37[4]
3 (end of period 2)[5]	5-1-02	17 (0.70)	63 (2.6)	73	47

1) Testing began with a new module. Therefore, this information was not available.
2) The end of period 1 was following approximately 12.5 days of non-stop operation at a constant specific flux of 40 L/hr-m^2 (24 gfd).
3) The readings were 67 L/h-m^2-b immediately after chemical cleaning and stabilized after an increase to 74 L/h-m^2-b.
4) The manufacturer's recommendations include chemical recirculation at elevated temperature [90-95°F (32-35°C)]. However, no recirculation loop or heating coil was used for this cleaning.
5) The end of period 2 was following approximately 33 days of non-stop operation at a constant specific flux of 30 L/h-m^2 (18 gfd).

Table 4-6 Summary of Onsite Bench-top Turbidity Data

Parameter	Units	Count	Median	Range	Average	Standard Deviation	95% Confidence Interval
Feed Water							
pH		40	7.79	7.67-8.01	7.80	0.07	7.73-7.88
Temperature	°C (°F)	76	2.9 (37)	1.9-6.5 (35-44)	3.4 (38)	1.6	3.4-3.4 (38-38)
Turbidity	NTU	39	1.0	0.4-4.5	1.3	0.9	1.3-1.3
Filtrate							
Turbidity	NTU	41	0.05	0.05-0.10	0.05	0.01	0.05-0.05
Backwash Water							
Turbidity	NTU	78	11	1.7-21	11	3.6	11-11

Table 4-7 Summary of Online Turbidity and Particle Count Data

Parameter	Units	Count	Median	Range	Average	Standard Deviation	95% Confidence Interval	90th Percentile
Feed Water								
Turbidity	NTU	4,124	0.85	0.25-19	1.3	1.4	1.3-1.3	2.9
>2 um Particles	#/ml	11,175	2,835	0-21,529	4,281	3731	4,278-4,283	9911
2-3 um Particles	#/ml	11,175	1,201	0-4,676	1,602	1,095	1,601-1,603	-
3-5 um Particles	#/ml	11,175	1,208	0-8,772	1,880	1,691	1,879-1,881	-
5-7 um Particles	#/ml	11,175	178	0-3,289	325	394	325-326	-
7-10 um Particles	#/ml	11,175	153	0-5,590	305	430	305-306	-
10-15 um Particles	#/ml	11,175	60	0-3,628	127	194	127-127	-
> 15 um Particles	#/ml	11,175	19	0-1,336	41	69	41-41	-
Filtrate								
Turbidity	NTU	4,124	0.0532	0.00-0.05	0.05	0.007	0.05-0.05	0.05
>2 um Particles	#/ml	11,175	0.00	0-6,125	4	65	4-4	2
2-3 um Particles	#/ml	11,175	0.00	0-2,862	1	28	1-1	-
3-5 um Particles	#/ml	11,175	0.00	0-2,850	1	28	1-1	-
5-7 um Particles	#/ml	11,175	0.00	0-249	0	3	0-0	-
7-10 um Particles	#/ml	11,175	0.00	0-135	0	3	0-0	-
10-15 um Particles	#/ml	11,175	0.00	0-140	1	4	1-1	-
> 15 um Particles	#/ml	11,175	0.00	0-313	2	16	2-2	-
Log Removal of Particles(1)								**10th Percentile**
>2 um Particles		8,941	4.4	-1.9-5.9	4.2	0.9	4.2-4.2	3.1
2-3 um Particles		6,016	4.3	-1.9-5.3	4.1	0.7	4.1-4.1	3.3
3-5 um Particles		6,261	4.3	-1.9-5.5	4.1	0.8	4.1-4.1	3.2
5-7 um Particles		3,567	3.6	-1.7-5.1	3.4	0.8	3.4-3.5	2.6
7-10 um Particles		4,032	3.4	-1.4-5.2	3.3	0.8	3.3-3.3	2.4
10-15 um Particles		3,651	3.0	-1.5-5.0	2.9	0.9	2.9-2.9	2.0
> 15 um Particles		6,185	2.4	-2.8-4.7	2.2	0.9	2.2-2.2	1.1

1) Evaluation of the time series data showed relatively higher particle counts during, and immediately following, a backwash. As a result, particle removals were decreased during these times. Some of these consistently brief occurrences caused log removal data to become negative for short periods. Negative data points were not included in the statistical analysis for log removals.

Table 4-8 Summary of Microbial Water Quality

Parameter	Units	Count	Median[1]	Range	Average	Standard Deviation	95% Confidence Interval
Feed Water							
Total Coliforms	P/A	38	N/A[2]	A-P[2]	A	N/A	N/A
	MPN/100 ml	4	<1.1	<1.1-23	6.2	N/A	N/A
HPC	CFU/ml	38	3	<2-330	17	56	16-17
Filtrate							
Total Coliforms	P/A	38	N/A	A-P[3]	N/A	N/A	N/A
	MPN/100 ml	4	<1.1	<1.1-<1.1	<1.1	N/A	N/A
HPC	CFU/ml	38	<2	<2-22	2	4	2-2
Backwash Water[4]							
Total Coliforms	P/A	36	N/A	A-P[3]	N/A	N/A	N/A
	MPN/100 ml	3	<1.1	<1.1-<1.1	<1.1	N/A	N/A
HPC	CFU/ml	37	10	<2-190	24	42	24-24

1) Values reported as non-detect were assumed to be one-half of the detection limit for the purposes of statistical evaluation.
2) The feed sample taken on 3/18/02 reported the presence of total coliforms. NLS testing procedures for total coliform were reported as “presence” or “absence”.
3) One of 38 filtrate samples and one of 37 backwash samples tested positive for the presence of coliforms. These samples were collected on 4/12/02 and 4/22/02, respectively.
4) Sampled during the second cycle of the production backwash.

Table 4-9 General Water Quality Parameters

Parameter	Units	Count	Median[1]	Range	Average	Standard Deviation	95% Confidence Interval
Feed Water							
Cl_2 – Residual[2]	mg/L	42	0.05	0.03-0.06	0.05	0.01	0.05-0.05
Alkalinity	mg/L as $CaCO_3$	2	N/A	110-110	110	N/A	N/A
Total Hardness	mg/L as $CaCO_3$	2	N/A	130-130	130	N/A	N/A
Calcium Hardness	mg/L as $CaCO_3$	2	N/A	87-88	88	N/A	N/A
TSS	mg/L	37	<1	<1-8.0	1.3	1.8	1.3-1.3
TDS	mg/L	3	200	150-210	187	N/A	N/A
TOC	mg/L	13	2.2	1.6-3.4	2.3	0.5	2.3-2.3
UVA	cm^{-1}	13	0.022	0.017-0.043	0.024	0.007	0.024-0.024
Algae	#/ml	3	32.8	32.6-37.8	34.4	N/A	N/A
Filtrate							
Alkalinity	mg/L as $CaCO_3$	2	N/A	110-110	110	N/A	N/A
Total Hardness	mg/L as $CaCO_3$	2	N/A	130-130	130	N/A	N/A
Calcium Hardness	mg/L as $CaCO_3$	2	N/A	87-87	87	N/A	N/A
TSS	mg/L	37	<1	<1-9.0	1.2	1.9	1.2-1.2
TDS	mg/L	3	210	190-210	203	N/A	N/A
TOC	mg/L	19	2.0	1.6-3.0	2.0	0.3	2.0-2.0
UVA	cm^{-1}	19	0.019	0.015-0.027	0.019	0.003	0.019-0.019
Backwash Water[3]							
Cl_2	mg/L	40	4.8	2.0-11.7	4.7	1.5	4.7-4.7
TSS	mg/L	36	20.	<1-41	20	10	20-20

1) Values reported as non-detect were assumed to be one-half of the detection limit for the purposes of statistical evaluation.
2) Measured as part of the daily sampling activities of the GBWUFP.
3) Sampled during the second cycle of the production backwash.

Table 4-10 TSS Mass Balance

Date	Filtrate Flow (gpm)	Filtration Cycle Length (min)	Volume Filtered (gal)	Backwash Volume (gal)	Measured Feed TSS[1] (mg/L)	Measured Backwash TSS[1][2] (mg/L)	Calculated Backwash TSS (mg/L)	RPD[3] %
Test Period 1								
3/11/2002	12	50	600	50	1.0	0.5	12	184
3/11/2002	12	50	600	50	0.5	4	6	40
3/12/2002	12	50	600	40	8.0	26	120	129
3/13/2002	12	50	600	55	6.0	3	65	182
3/14/2002	12	50	600	50	1.0	23	12	63
3/15/2002	12	50	600	32	0.5	40	9	124
3/18/2002	12	50	600	45	1.0	41	13	102
3/19/2002	12	50	600	40	0.5	25	8	108
3/20/2002	12	50	600	37	0.5	31	8	117
3/21/2002	12	50	600	35	1.0	24	17	33
3/21/2002	12	50	600	35	2.0	24	34	35
3/22/2002	12	50	600	34	0.5	19	9	73
Test Period 2								
3/25/2002	9.4	50	470	50	4.0	14	38	91
3/26/2002	9.4	50	470	42	0.5	20	6	113
3/27/2002	9.4	50	470	38	0.5	14	6	77
3/28/2002	9.4	50	470	36	0.5	10	7	42
3/28/2002	9.4	50	470	36	4.0	13	52	120
3/29/2002	9.4	50	470	30	1.0	27	16	53
4/1/2002	9.4	50	470	33	0.5	14	7	65
4/2/2002	9.4	50	470	32	0.5	2	7	114
4/3/2002	9.4	50	470	30	0.5	20	8	87
4/4/2002	9.4	50	470	30	0.5	0.5	8	176
4/4/2002	9.4	50	470	30	0.5	17	8	74
4/8/2002	9.4	50	470	26	0.5	29	9	105
4/9/2002	9.4	50	470	25	0.5	26	9	94
4/10/2002	9.4	50	470	32	0.5	23	7	103
4/11/2002	9.4	50	470	27	0.5	15	9	53
4/11/2002	9.4	50	470	27	0.5	20	9	79
4/15/2002	9.4	50	470	24	0.5	22	10	77
4/16/2002	9.4	50	470	28	0.5	12	8	35
4/17/2002	9.4	50	470	28	0.5	30	8	113
4/18/2002	9.4	50	470	28	0.5	20	8	82
4/18/2002	9.4	50	470	28	0.5	21	8	86
4/19/2002	9.4	50	470	30	0.5	36	8	129
4/22/2002	9.4	50	470	24	0.5	27	10	94
4/23/2002	9.4	50	470	24	0.5	16	10	48

1) Values reported as non-detect (<1 mg/l) were assumed to be one-half of the detection limit (0.5 mg/l) for the purposes of this evaluation.
2) Sampled during the second cycle of the production backwash.
3) Relative Percent Deviation.

Table 4-11 Summary of Verification Data for the Feed Water Particle Counter

Parameter	Units	Count	Median	Range	Average	Standard Deviation[1]	95% Confidence Interval[1]
2 um Particle Standard at a Concentration of 1000 #/ml							
>2 um Particles	#/ml	3	1143.7	1141.7-1332.2	1205.9	N/A	N/A
2-3 um Particles	#/ml	3	720.0	714.8-753.7	729.5	N/A	N/A
3-5 um Particles	#/ml	3	303.2	302.2-406.8	337.4	N/A	N/A
5-7 um Particles	#/ml	3	43.5	41.9-63.4	49.6	N/A	N/A
7-10 um Particles	#/ml	3	41.5	39-60.1	46.9	N/A	N/A
10-15 um Particles	#/ml	3	27.4	25.9-33.2	28.8	N/A	N/A
> 15 um Particles	#/ml	3	13.2	12.9-15.1	13.7	N/A	N/A
5 um Particle Standard at a Concentration of 1000 #/ml							
>2 um Particles	#/ml	3	1127.4	1108.4-1130.9	1122.2	N/A	N/A
2-3 um Particles	#/ml	3	129.9	129.5-132.3	130.6	N/A	N/A
3-5 um Particles	#/ml	3	780.5	774.8-780.9	778.7	N/A	N/A
5-7 um Particles	#/ml	3	149.6	147.5-150.9	149.3	N/A	N/A
7-10 um Particles	#/ml	3	37.5	35.8-39.5	37.6	N/A	N/A
10-15 um Particles	#/ml	3	17.9	14.8-18	16.9	N/A	N/A
> 15 um Particles	#/ml	3	8.3	6-13	9.1	N/A	N/A
10 um Particle Standard at a Concentration of 1000 #/ml							
>2 um Particles	#/ml	3	952.1	944-954.6	950.2	N/A	N/A
2-3 um Particles	#/ml	3	43.8	36.5-47.3	42.5	N/A	N/A
3-5 um Particles	#/ml	3	70.5	60.6-70.7	67.2	N/A	N/A
5-7 um Particles	#/ml	3	26.8	25.5-27.2	26.5	N/A	N/A
7-10 um Particles	#/ml	3	585.1	579.2-587.2	583.8	N/A	N/A
10-15 um Particles	#/ml	3	212.9	212.4-220.1	215.1	N/A	N/A
> 15 um Particles	#/ml	3	11.3	6.1-27.7	15.0	N/A	N/A

1) Less than eight data points exist for this data. Therefore, this statistical analysis was not performed.

Table 4-12 Summary of Verification Data for the Filtrate Water Particle Counter

Parameter	Units	Count	Median	Range	Average	Standard Deviation[1]	95% Confidence Interval[1]
2 um Particle Standard at a Concentration of 1000 #/ml							
>2 um Particles	#/ml	2	N/A[2]	1089.7-1126.4	1108.0	N/A	N/A
2-3 um Particles	#/ml	2	N/A[2]	639.1-647.7	643.4	N/A	N/A
3-5 um Particles	#/ml	2	N/A[2]	333.7-348.3	341.0	N/A	N/A
5-7 um Particles	#/ml	2	N/A[2]	42.6-47.3	45.0	N/A	N/A
7-10 um Particles	#/ml	2	N/A[2]	39.2-43.4	41.3	N/A	N/A
10-15 um Particles	#/ml	2	N/A[2]	23.5-28.5	26.0	N/A	N/A
> 15 um Particles	#/ml	2	N/A[2]	11.3-11.5	11.4	N/A	N/A
5 um Particle Standard at a Concentration of 1000 #/ml							
>2 um Particles	#/ml	5	727.9	719.4-732.8	727.4	N/A	N/A
2-3 um Particles	#/ml	5	68.3	67.1-69	68.1	N/A	N/A
3-5 um Particles	#/ml	5	564.0	557-571.6	564.3	N/A	N/A
5-7 um Particles	#/ml	5	81.5	75.4-87.4	81.9	N/A	N/A
7-10 um Particles	#/ml	5	5.9	4.7-6.3	5.7	N/A	N/A
10-15 um Particles	#/ml	5	1.2	0.7-2.5	1.5	N/A	N/A
> 15 um Particles	#/ml	5	5.9	3-8.9	6.0	N/A	N/A
10 um Particle Standard at a Concentration of 1000 #/ml							
>2 um Particles	#/ml	4	840.4	830.6-849.6	840.3	N/A	N/A
2-3 um Particles	#/ml	4	49.7	47-56.1	50.6	N/A	N/A
3-5 um Particles	#/ml	4	113.3	108.9-117.4	113.2	N/A	N/A
5-7 um Particles	#/ml	4	46.6	45.1-50.3	47.2	N/A	N/A
7-10 um Particles	#/ml	4	476.0	471.1-484.6	476.9	N/A	N/A
10-15 um Particles	#/ml	4	145.9	144.4-147.1	145.8	N/A	N/A
> 15 um Particles	#/ml	4	6.4	4.4-9.2	6.6	N/A	N/A

1) Less than eight data points exist for this data. Therefore, this statistical analysis was not performed.
2) Less than three data points exist for this data. Therefore, this statistical analysis was not performed.

Table 4-13 Chemical Consumption Analysis

Operation	Approximate Total Product Volume Produced (gal)[1]	Approximate Total Backwash Volume Used (gal)[2]	Chlorine Consumed (lbs as NaOCl)[3]	NaOH Consumed (lbs as NaOH)[4]
Run 1	197,463	13,822	0.61	NA
Chemical Clean 2	NA	35	0.06	2.04
		Total for Period 1	**0.67**	**2.04**
Run 2	402,388	24,143	1.06	NA
Chemical Clean 3	NA	32	0.06	1.47
		Total for Period 2	**1.12**	**1.47**

1) Based on average flow data from Table 4.2 and a complete production and backwash cycle time of 55 minutes.
2) Based on daily observations of production backwash volumes and observation during each chemical clean.
3) Based on a production cycle backwash chlorine dose of 5 mg/L and chemical cleaning dose of 200 mg/L as verified through onsite analysis.
4) Based on the programmed dose of 7,000 and 5,500 mg/L for Chemical Cleanings 2 and 3, respectively.

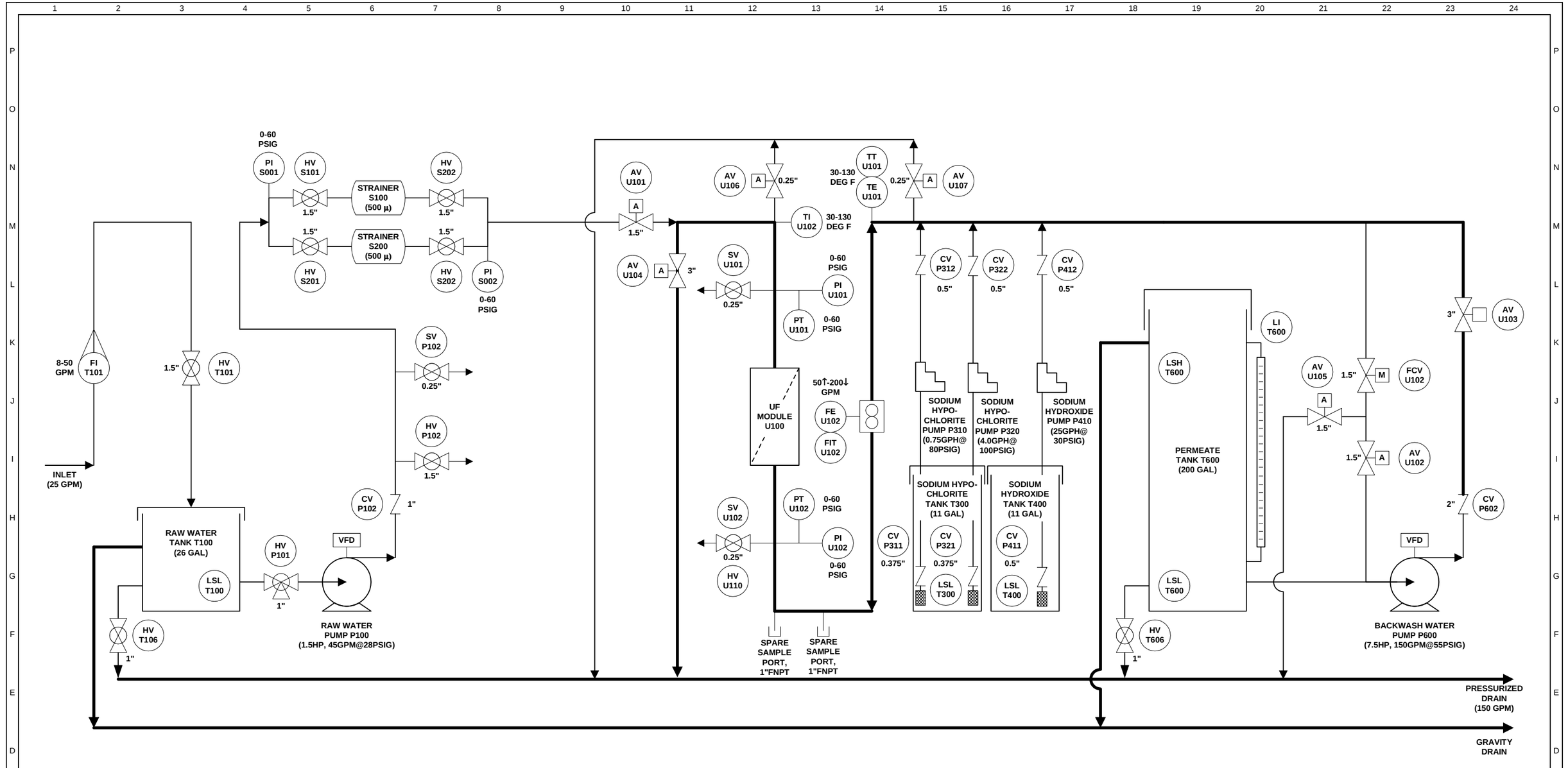


Figure 2.1

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED
TOLERANCES ARE AS FOLLOWS, UNLESS OTHERWISE NOTED

1/X	±1/8
1/XX	±1/16
.0X	±.01
.00X	±.005
ANGLES	±1°

REFERENCE DRAWINGS

TITLE: UF PILOT PROCESS & INSTRUMENTATION DIAGRAM

CLIENT: CAROLLO ENGINEERS - BOISE	PROJECT: UF PILOT #1
DESIGN BY: EJH	DESIGN DATE: 6-18-99
DRAWN BY: EJH	DRAWN DATE: 6-18-99
CHECK BY:	CHECK DATE:
RELEASED FOR: FABRICATION	P.O.:
FILE NAME: P&ID	REVISION: 3

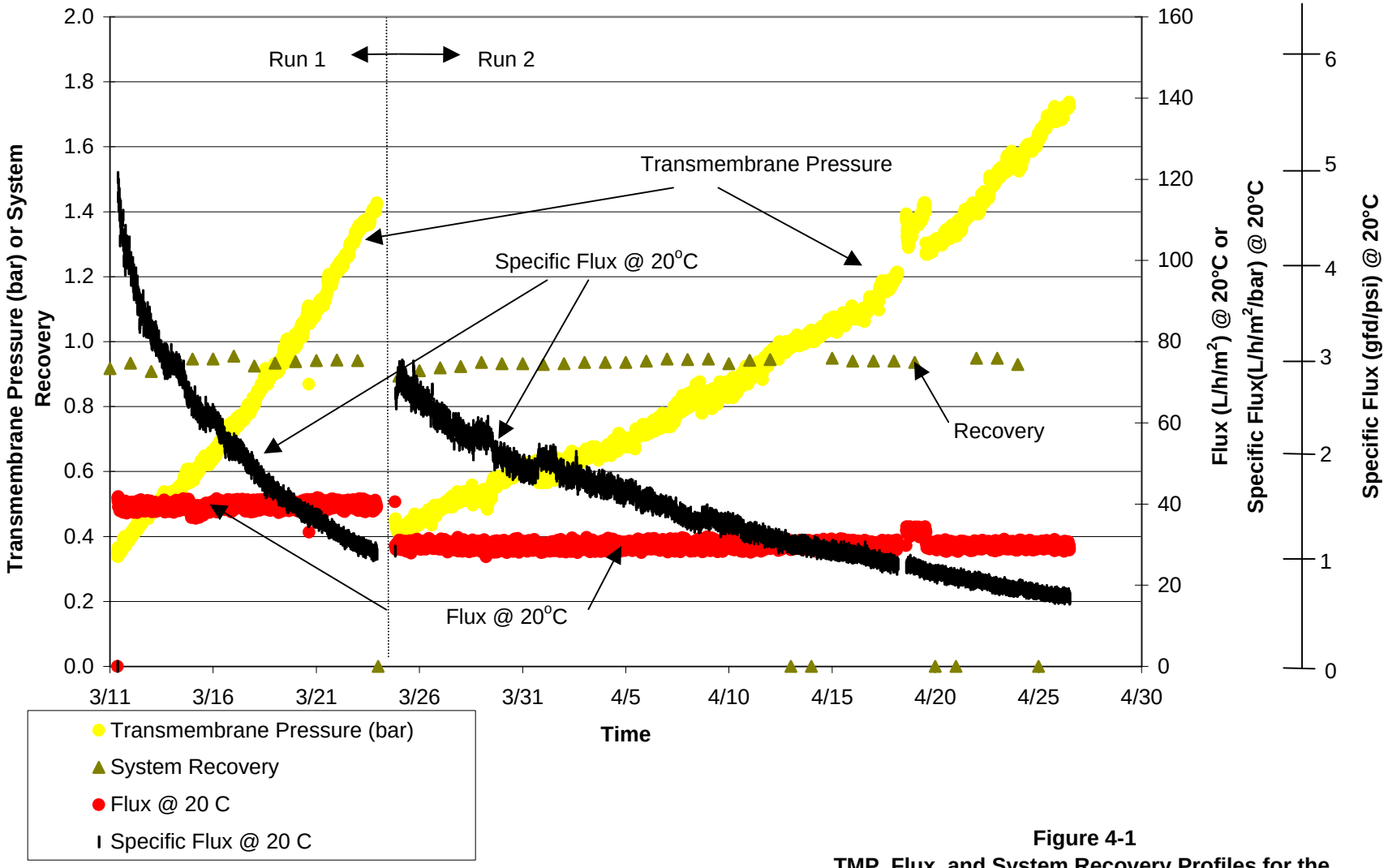
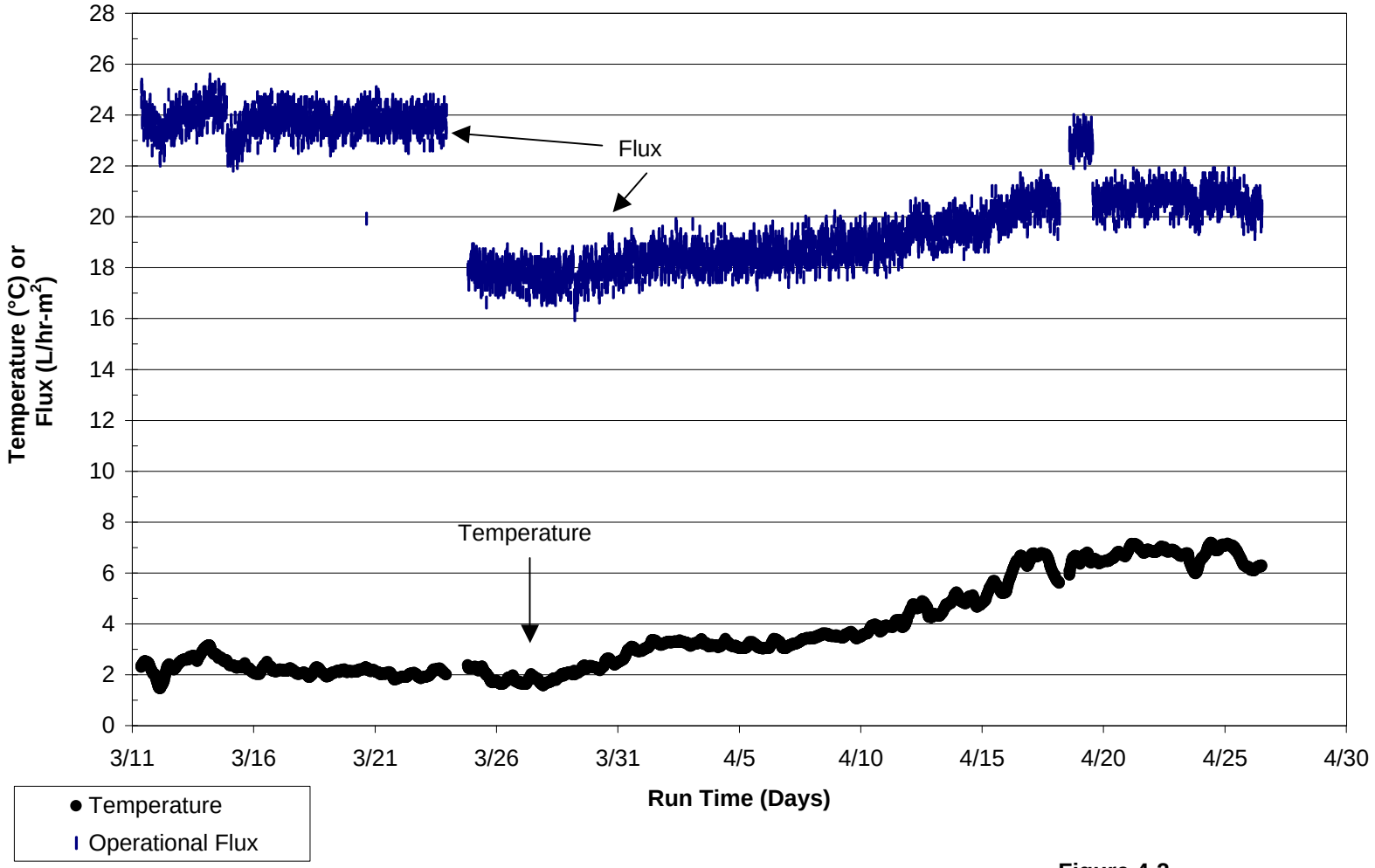


Figure 4-1
TMP, Flux, and System Recovery Profiles for the Polymem UF Module UF120 S2 Membrane Module

Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.



Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-2
Operational Flux and Temperature Profiles for the Polymem UF Module UF120 S2 Membrane Module

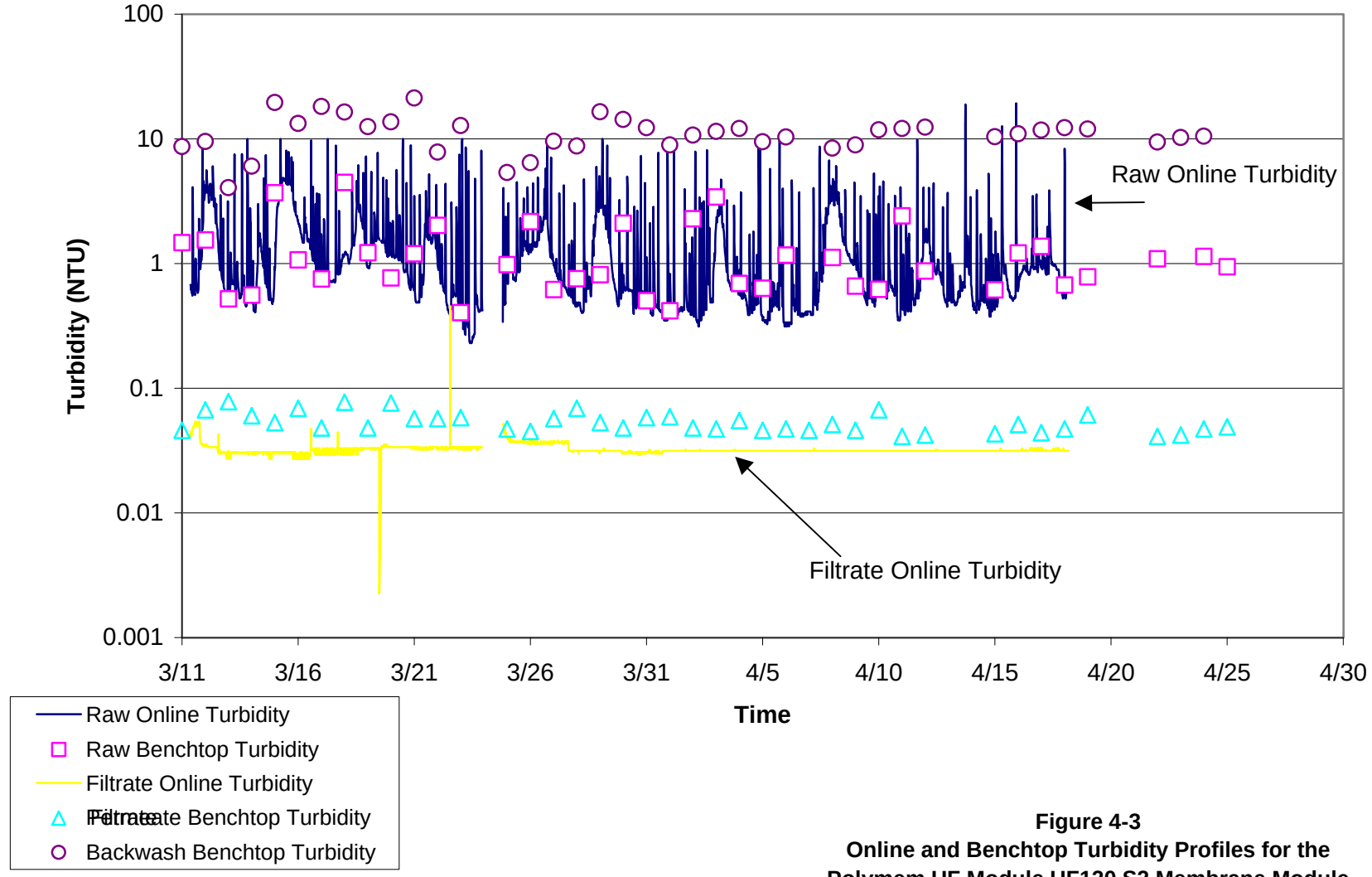
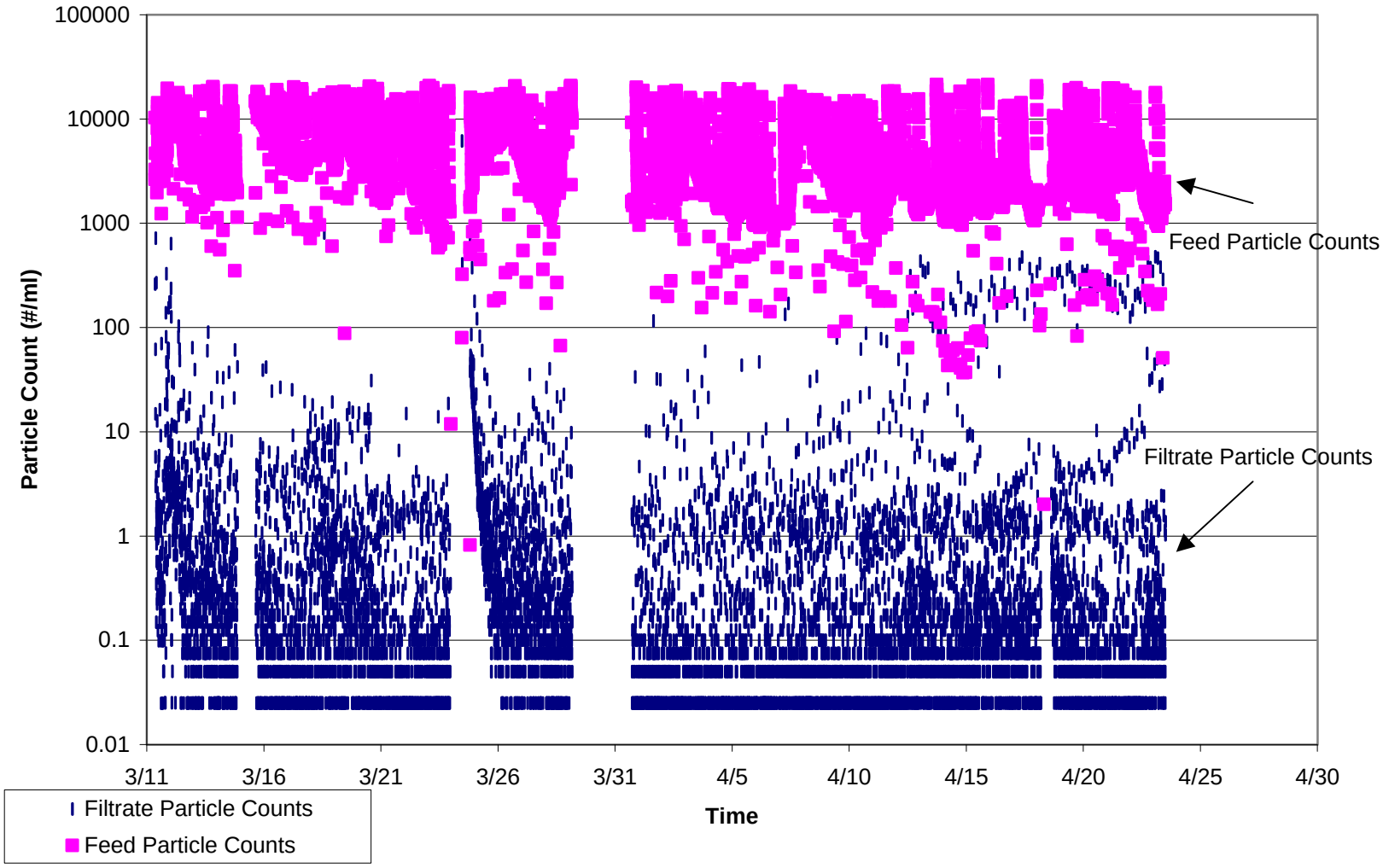


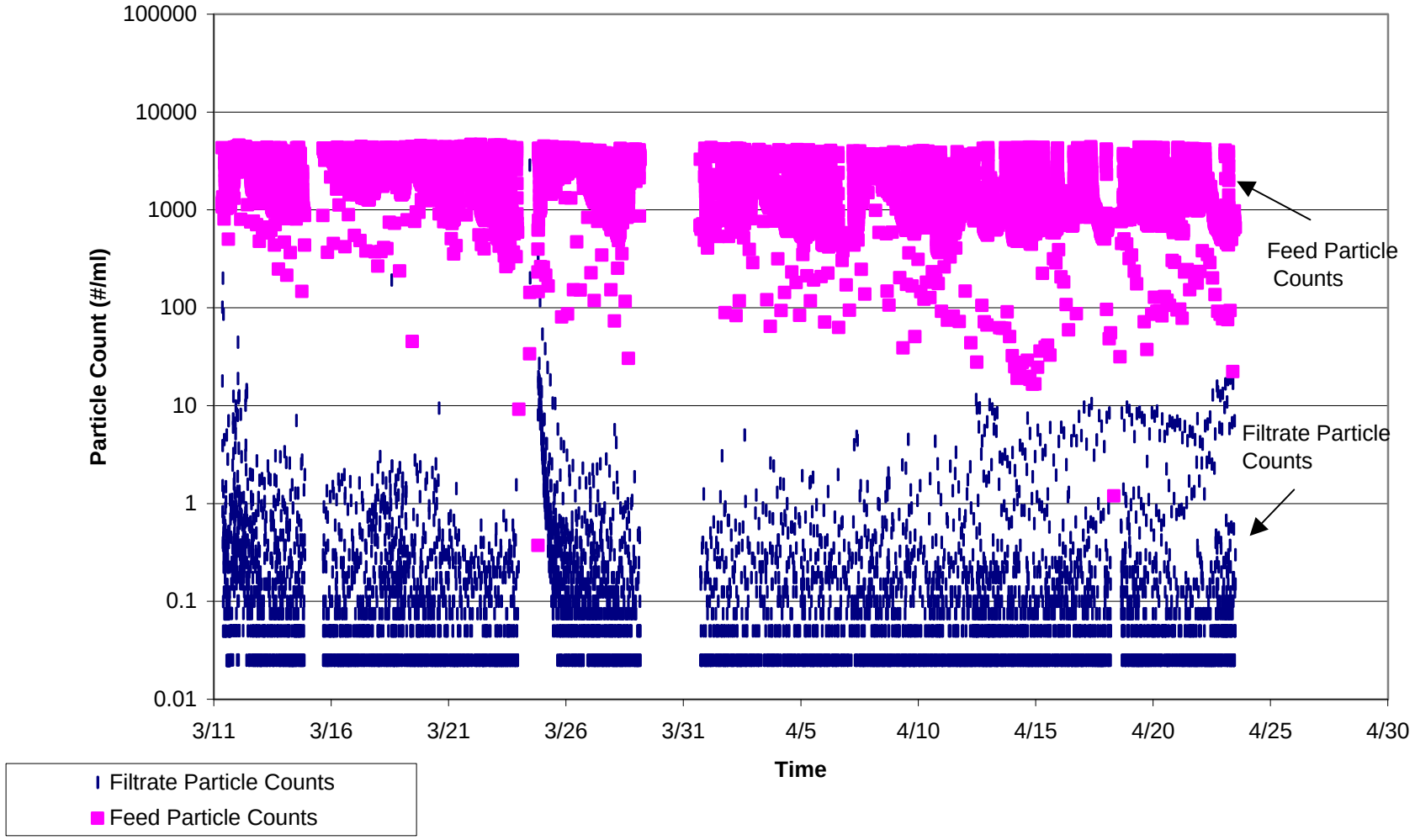
Figure 4-3
Online and Benchtop Turbidity Profiles for the Polymem UF Module UF120 S2 Membrane Module

Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.



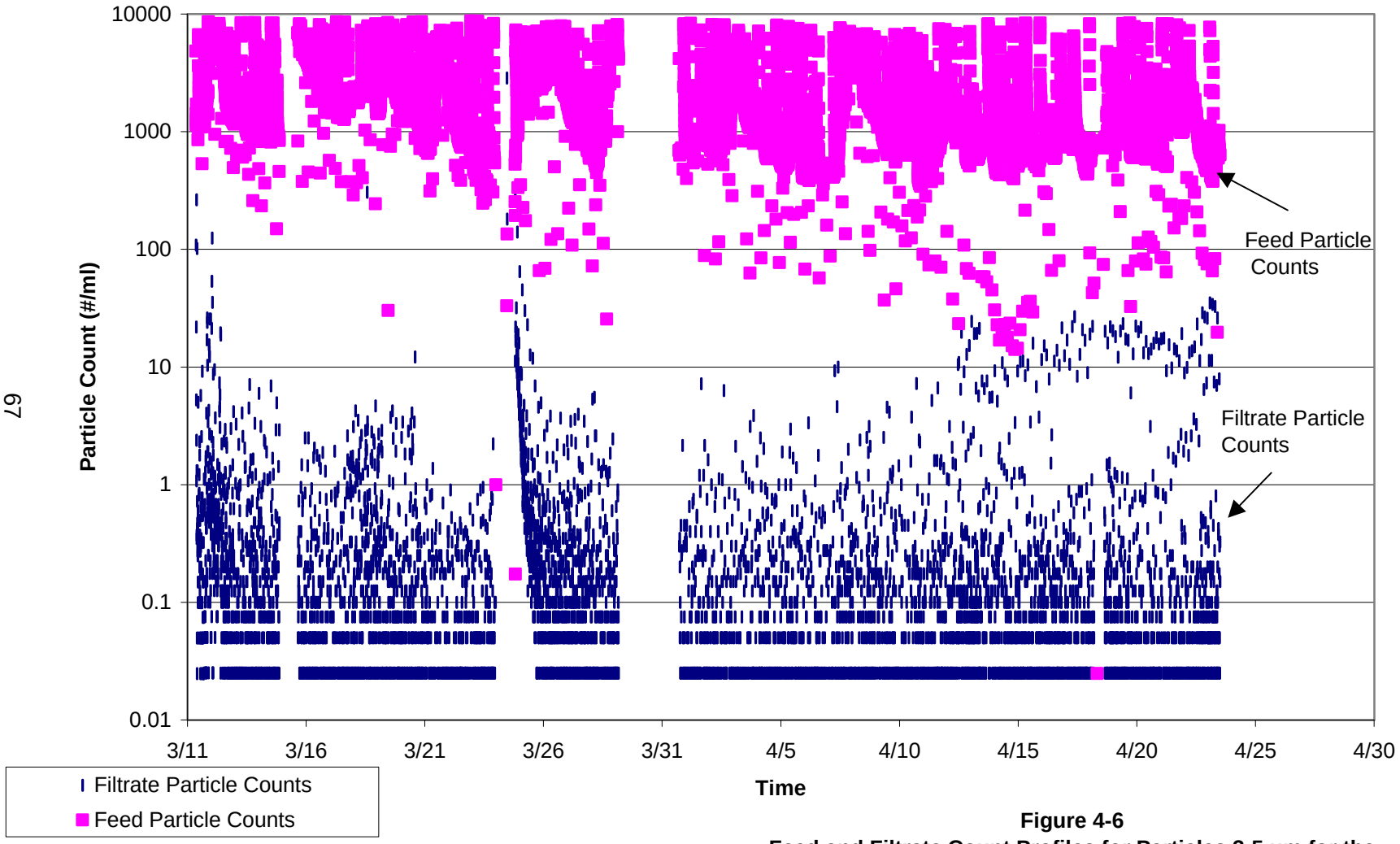
Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-4
Feed and Filtrate Count Profiles for Particles >2 um for the Polymem UF Module UF120 S2 Membrane Module



Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-5
Feed and Filtrate Count Profiles for Particles 2-3 um for the Polymem UF Module UF120 S2 Membrane Module



Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-6
Feed and Filtrate Count Profiles for Particles 3-5 um for the Polymem UF Module UF120 S2 Membrane Module

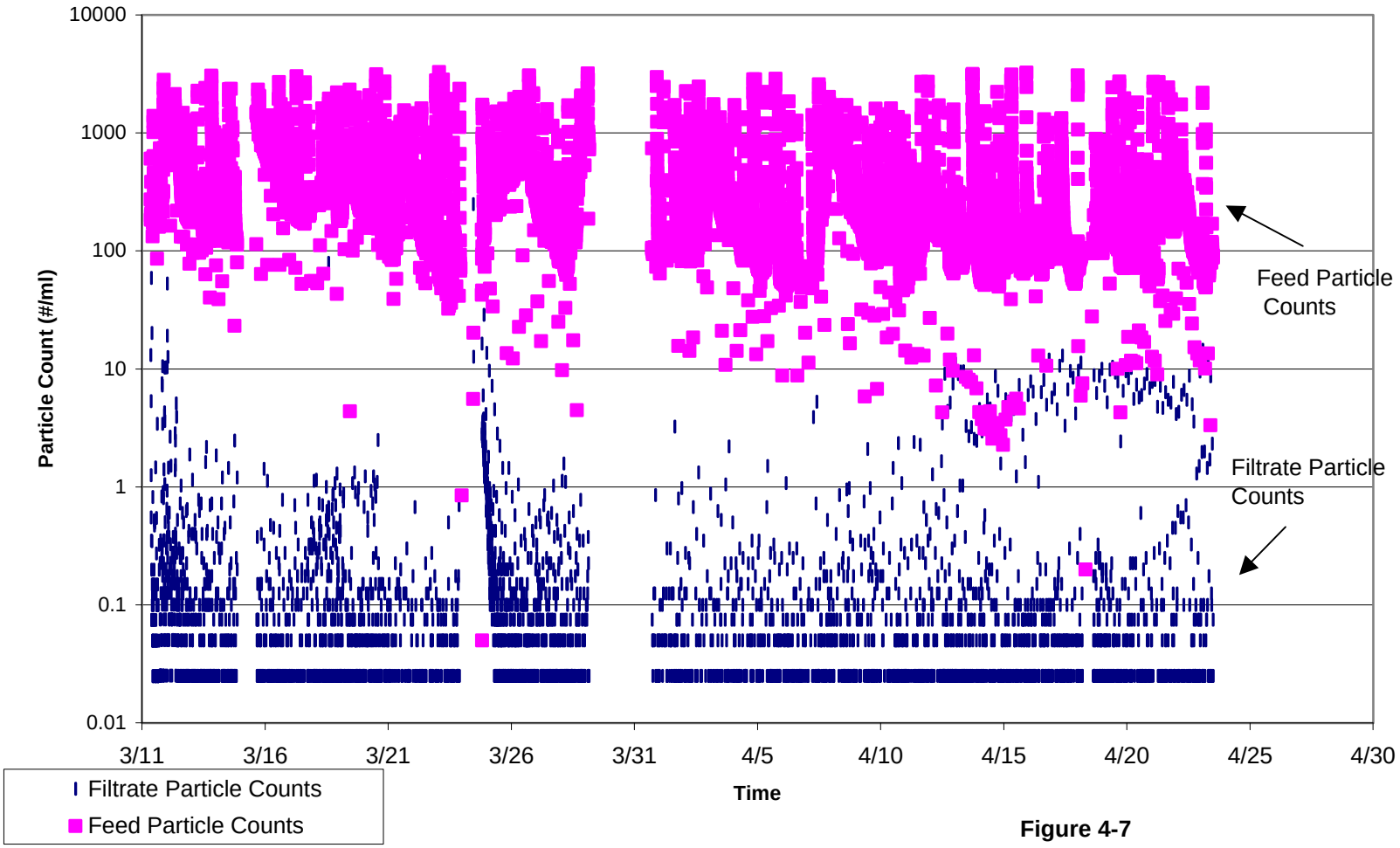
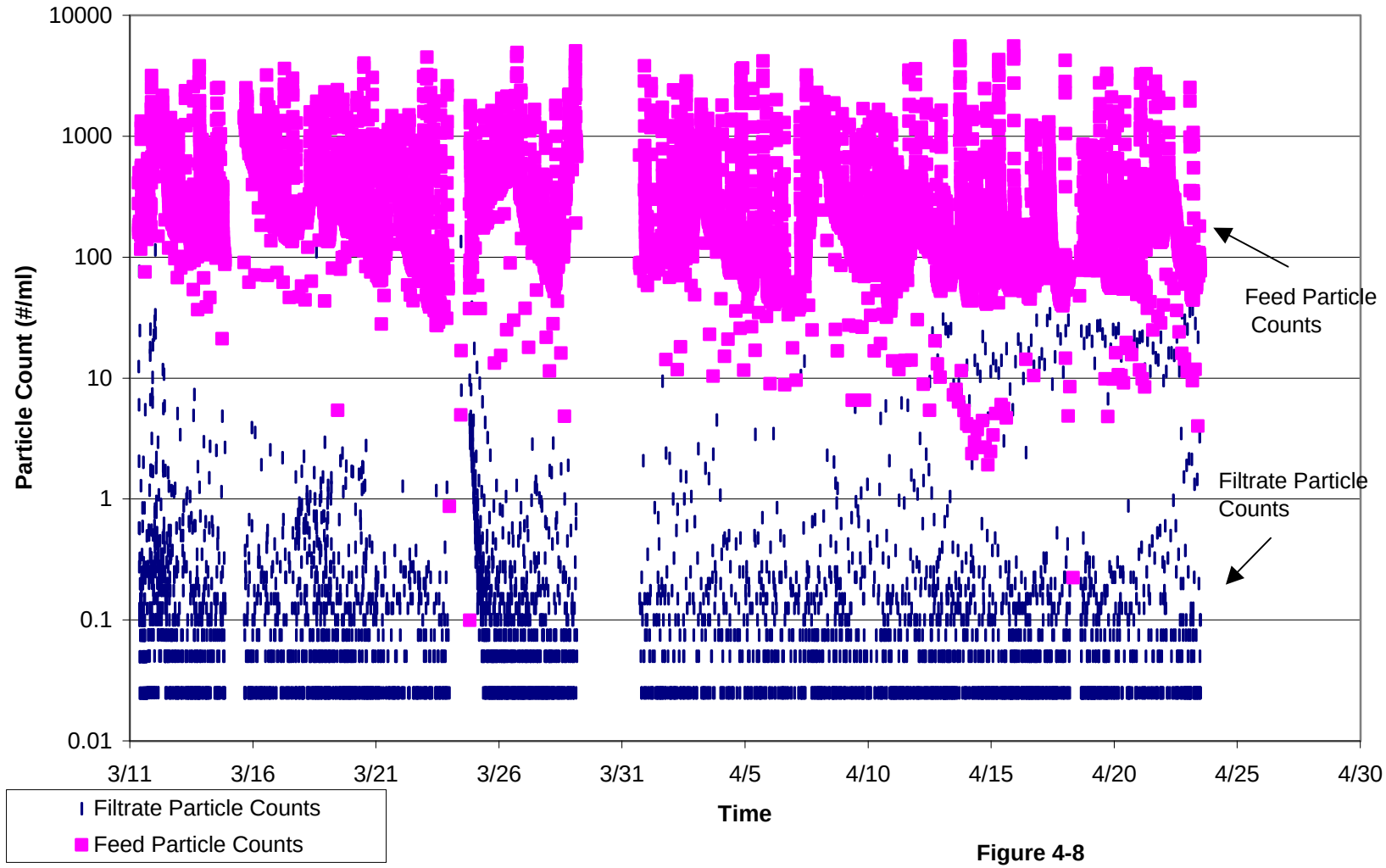


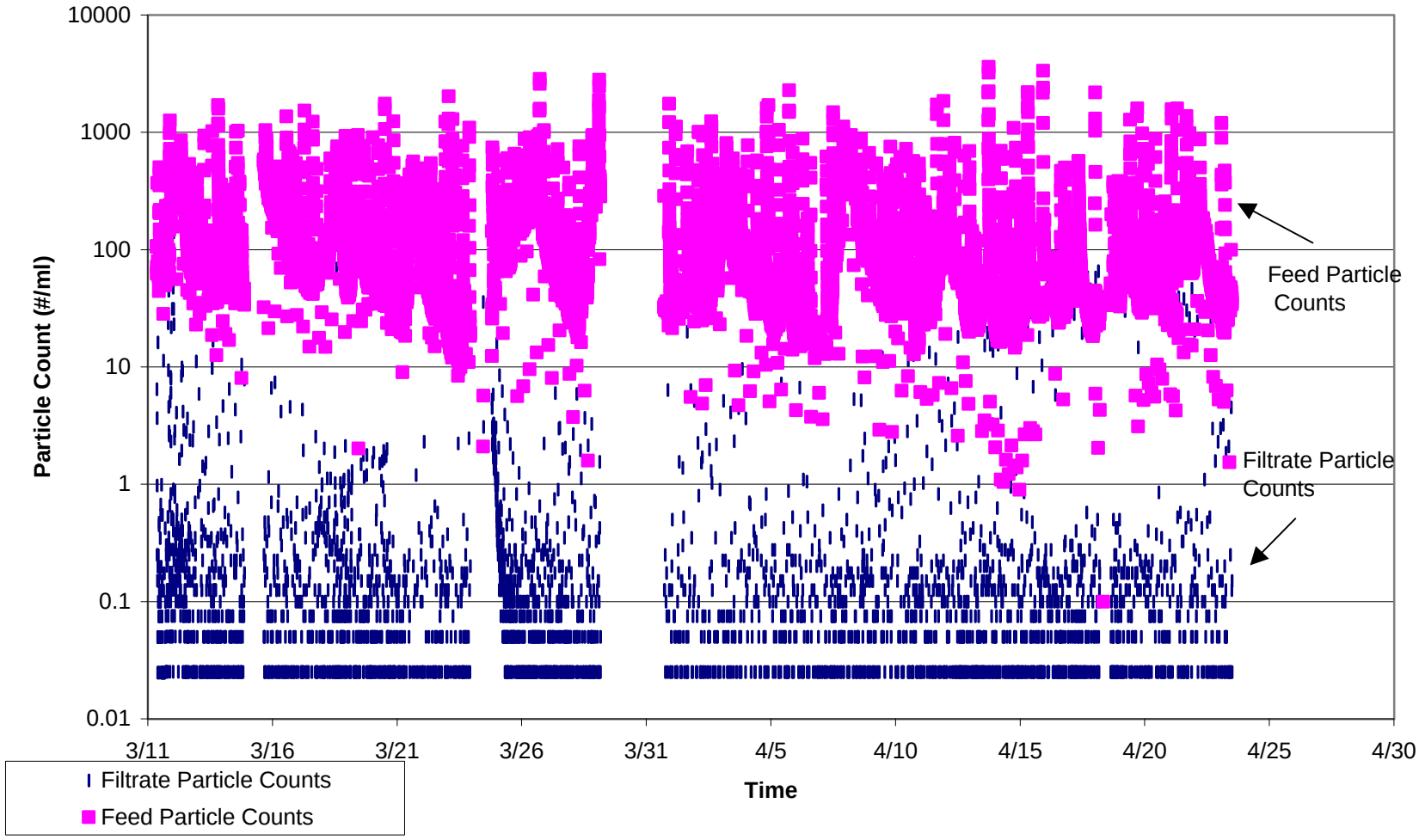
Figure 4-7
Feed and Filtrate Count Profiles for Particles 5-7 um for the Polymem UF Module UF120 S2 Membrane Module

Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.



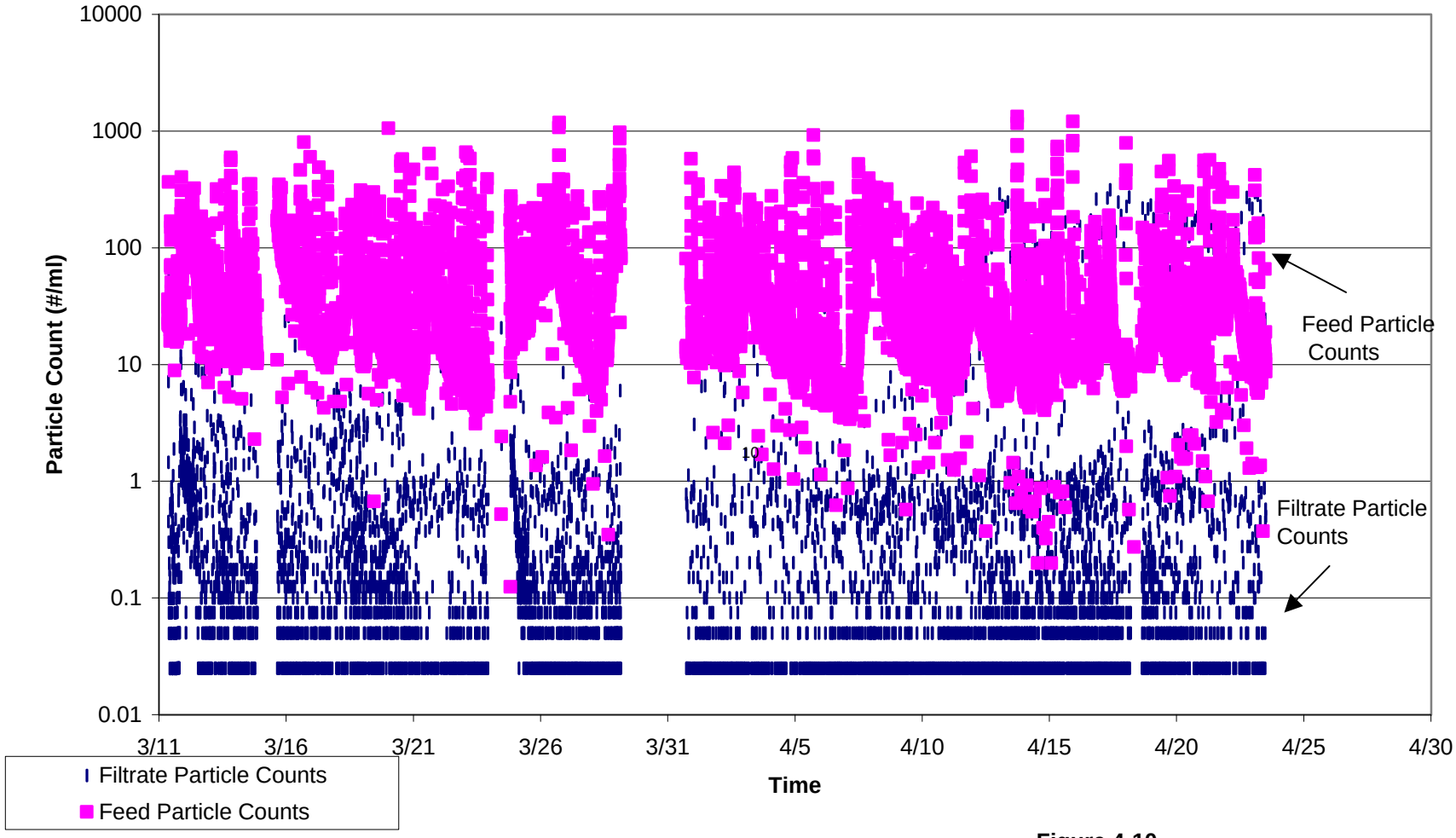
Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-8
Feed and Filtrate Count Profiles for Particles 7-10 um for the Polymem UF Module UF120 S2 Membrane Module



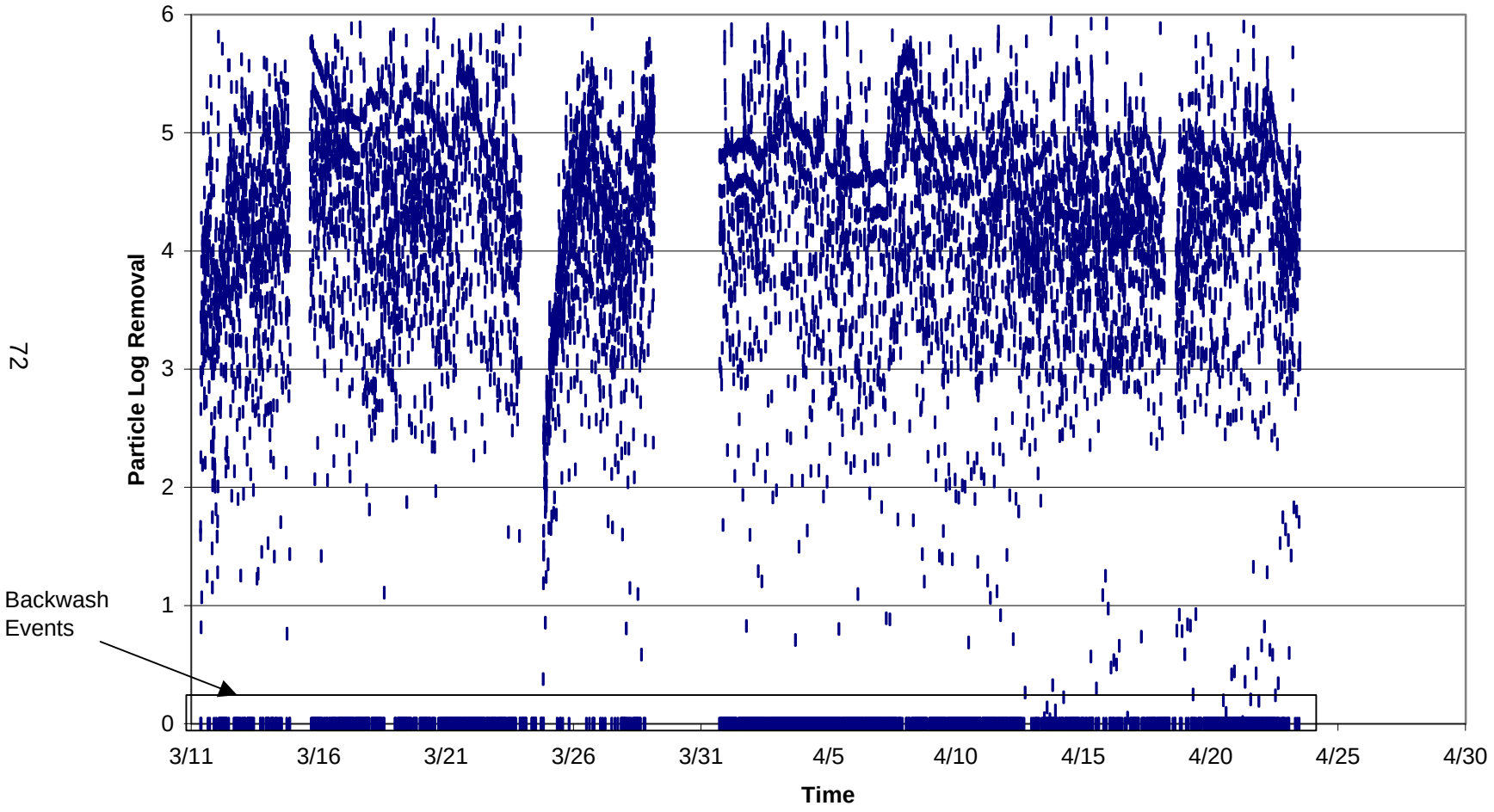
Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-9
Feed and Filtrate Count Profiles for Particles 10-15 um for the Polymem UF Module UF120 S2 Membrane Module



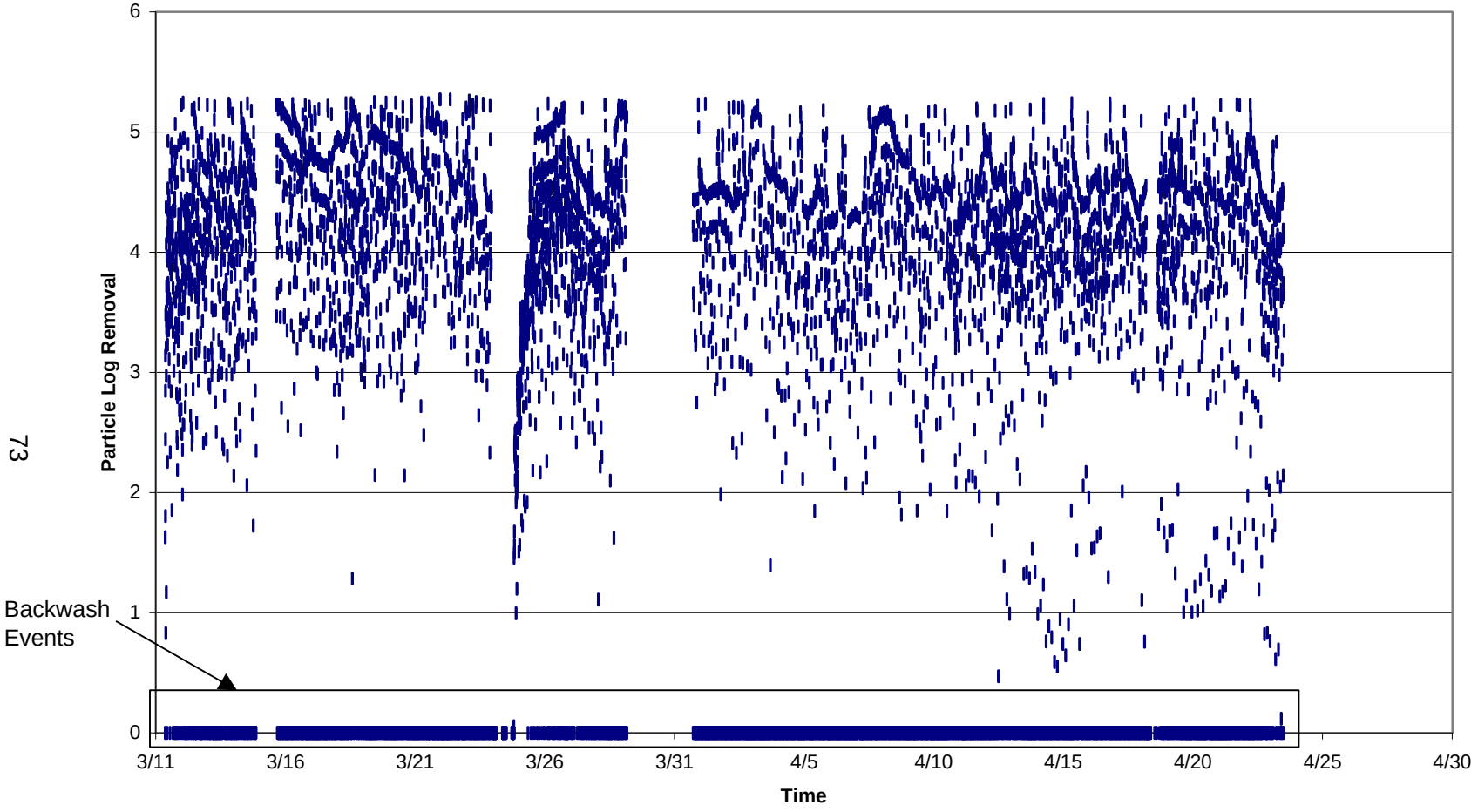
Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-10
Feed and Filtrate Count Profiles for Particles >15 um for the Polymem UF Module UF120 S2 Membrane Module



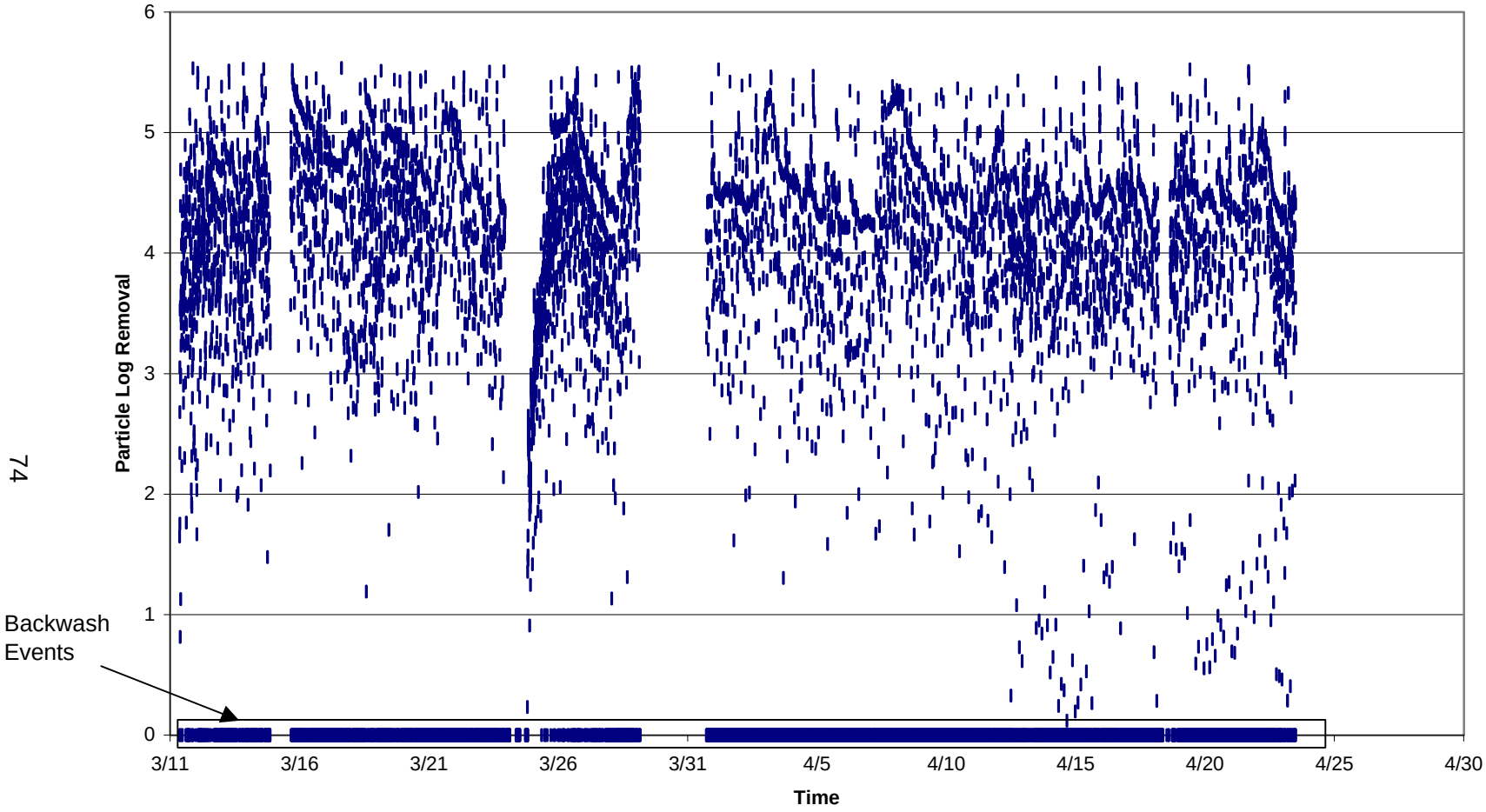
Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-11
Log Removal Profile for Particles >2 um in Size for the Polymem UF Module UF120 S2 Membrane Module



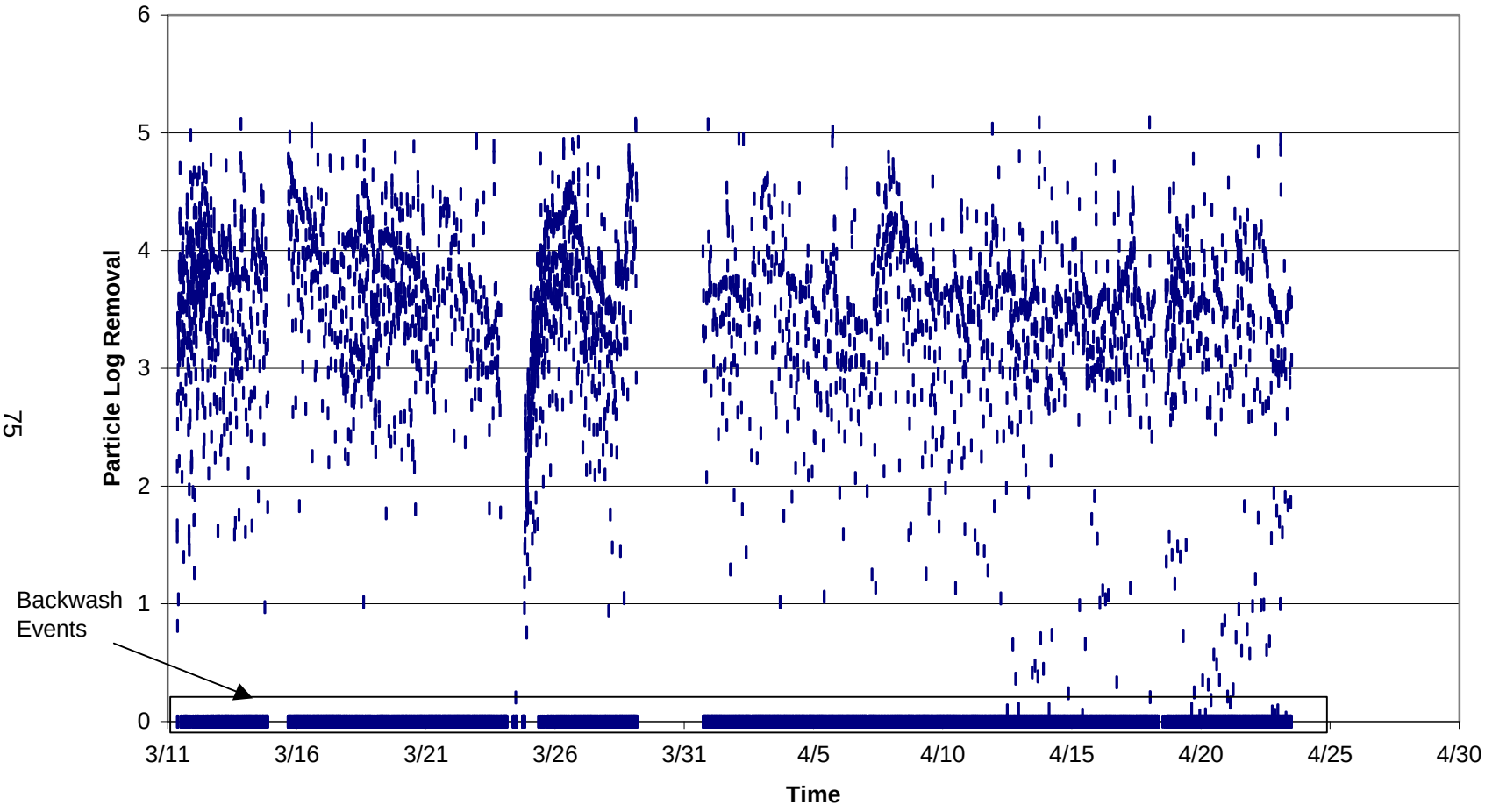
Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-12
Log Removal Profile for Particles 2-3 um in Size for the Polymem UF Module UF120 S2 Membrane Module



Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

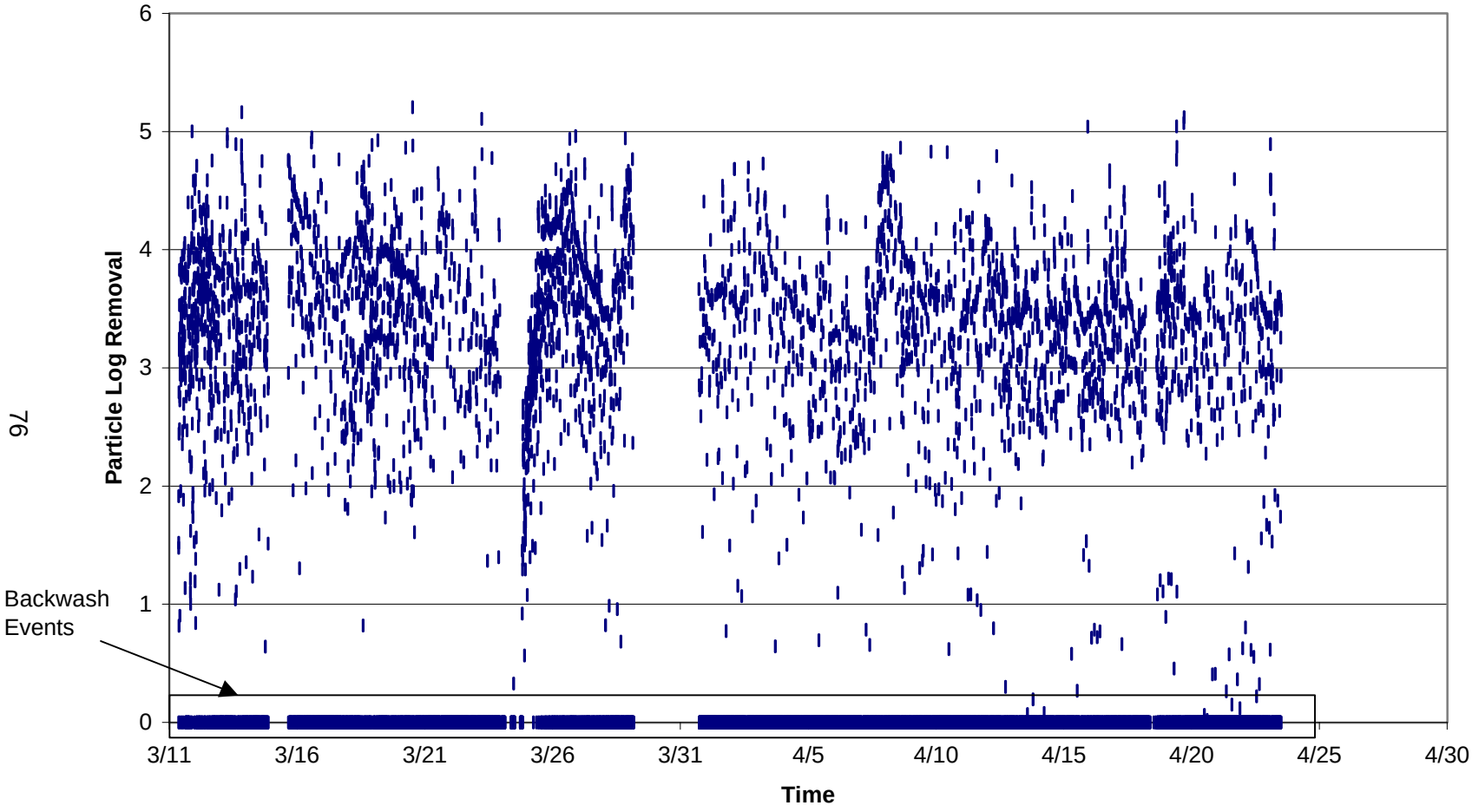
Figure 4-13
Log Removal Profile for Particles 3-5 um in Size for the Polymem UF Module UF120 S2 Membrane Module



75

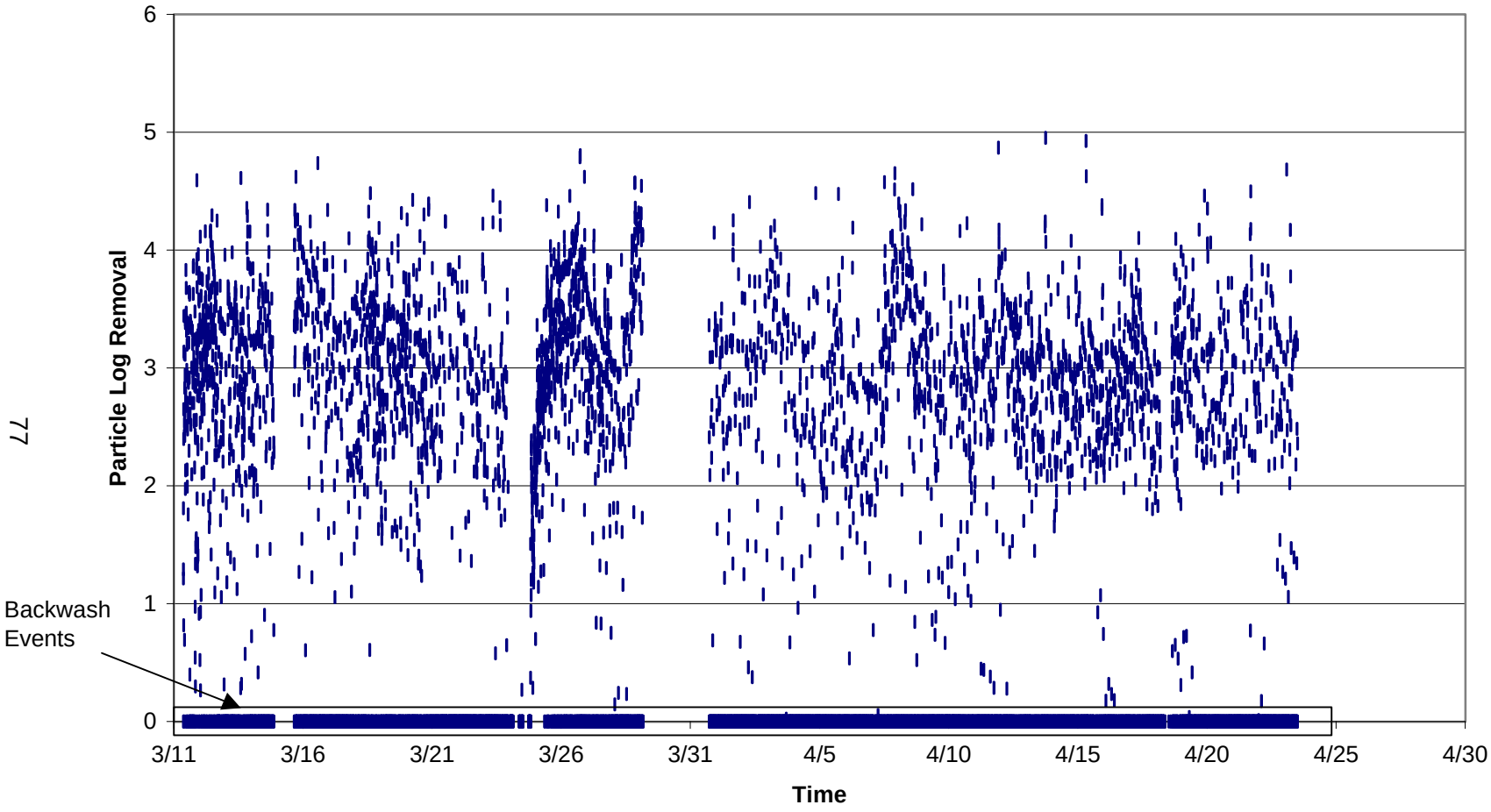
Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-14
Log Removal Profile for Particles 5-7 um in Size for the Polymem UF Module UF120 S2 Membrane Module



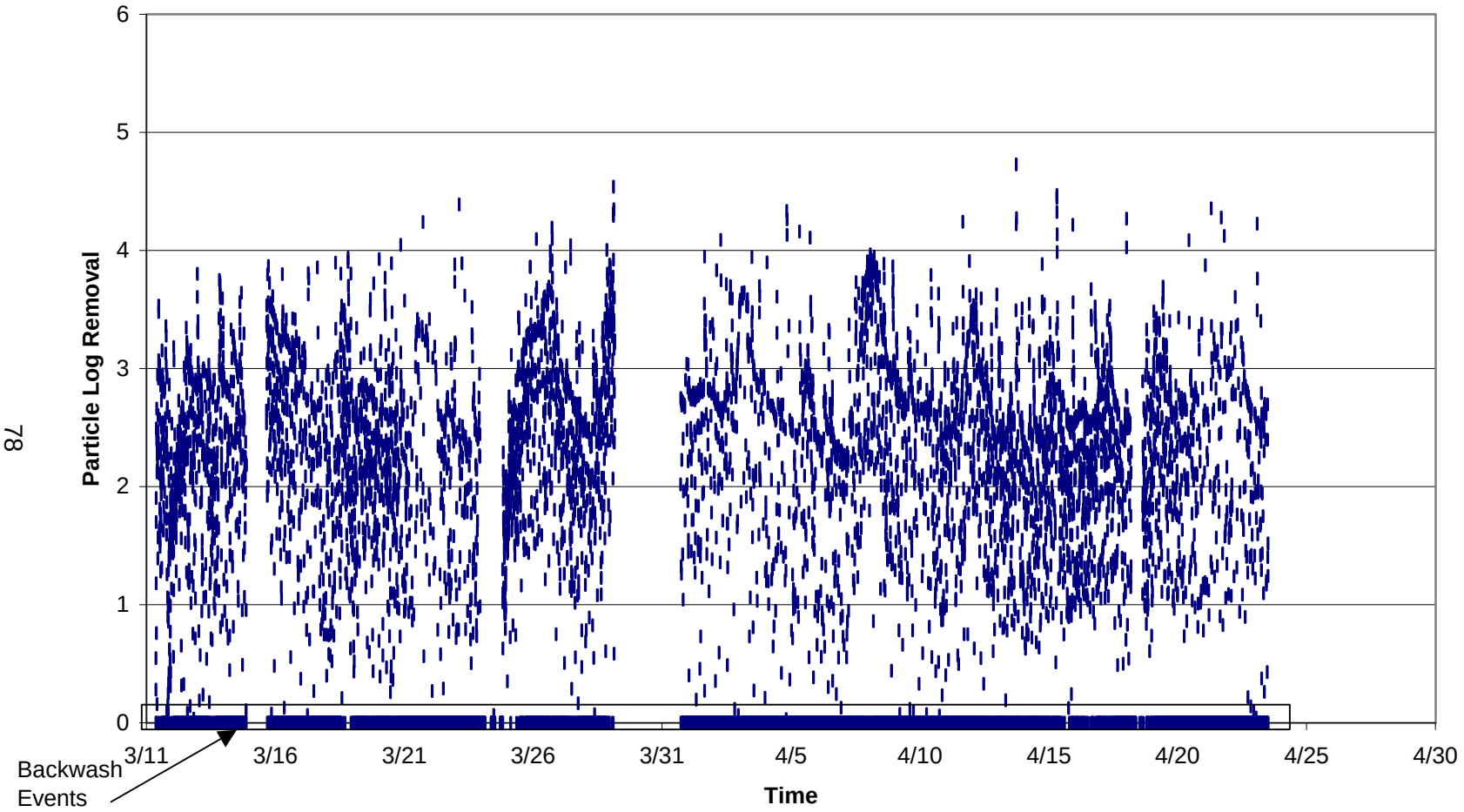
Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-15
Log Removal Profile for Particles 7-10 um in Size for the Polymem UF Module UF120 S2 Membrane Module



Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-16
Log Removal Profile for Particles 10-15 um in Size for the Polymem UF Module UF120 S2 Membrane Module



Note: The membrane unit was off-line for 21 hours and 10 minutes following Run 1 for chemical cleaning. In addition, on 4/18/02, the membrane unit was shut down for approximately 10 hours due to lightning.

Figure 4-17
Log Removal Profile for Particles >15 um in Size for the Polymem UF Module UF120 S2 Membrane Module

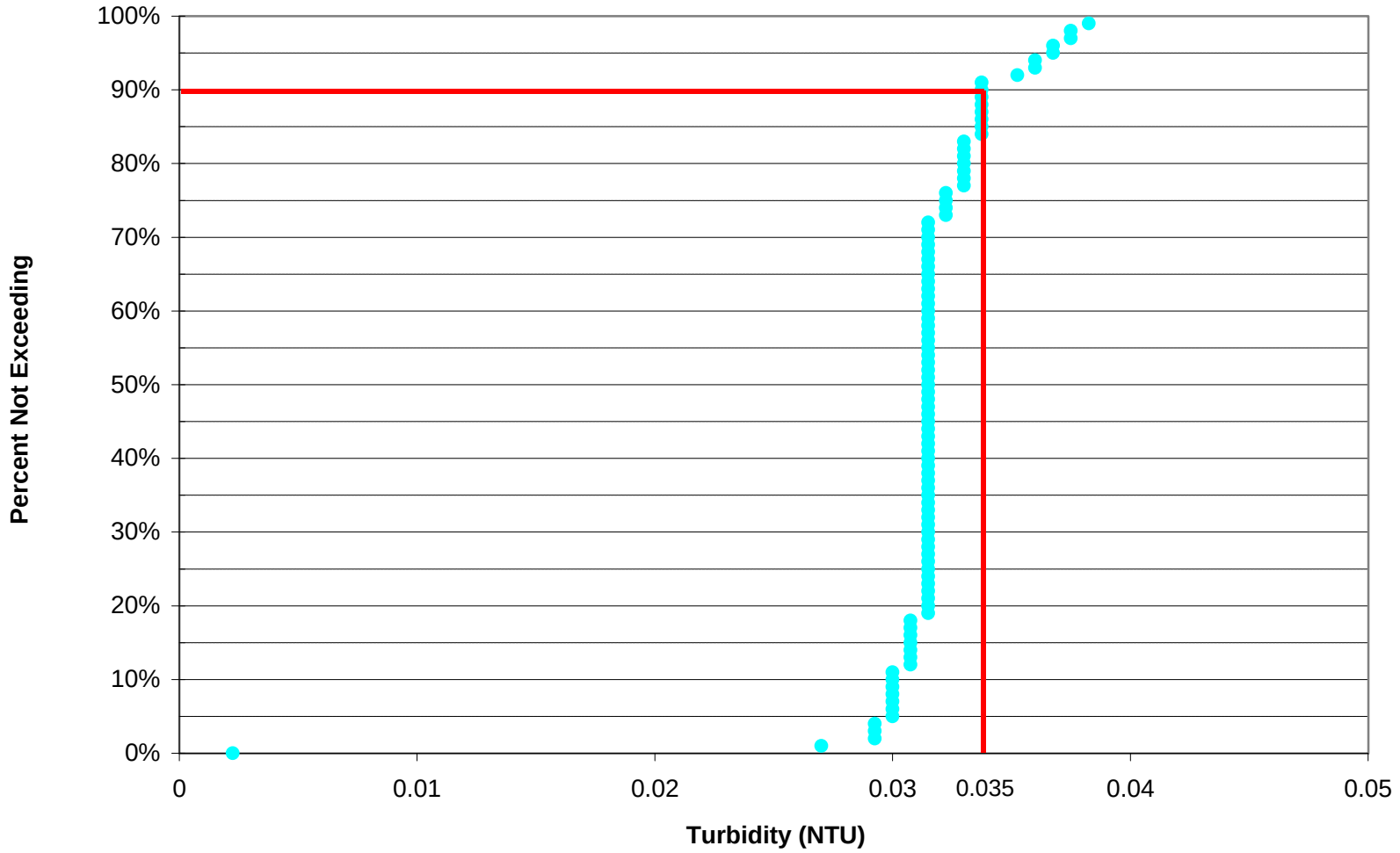


Figure 4-18
A Frequency Distribution of Filtrate Turbidity for the Polymem UF Module UF120 S2 Membrane Module

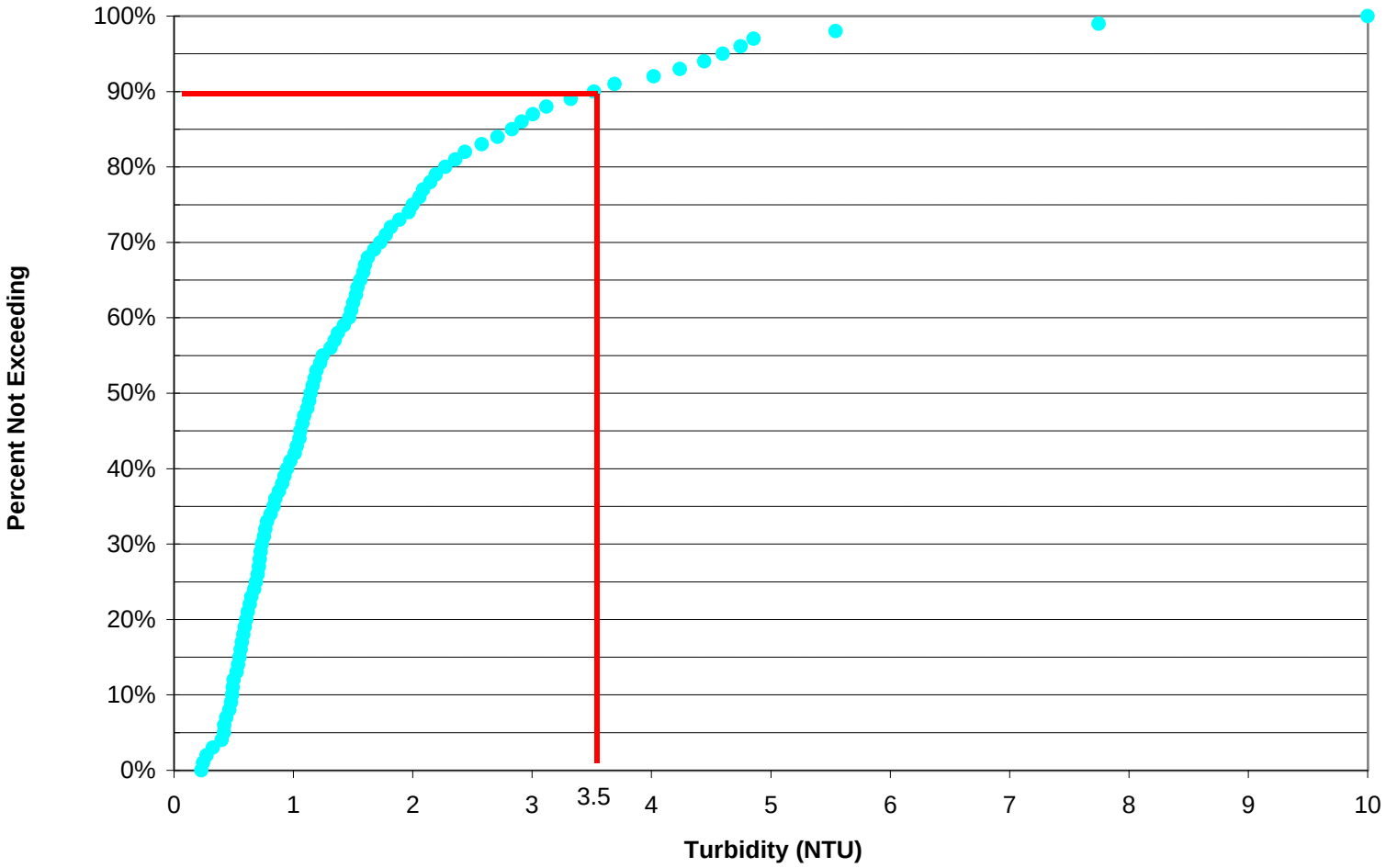


Figure 4-19
A Frequency Distribution of Feed Water Turbidity for the Polymem UF Module UF120 S2 Membrane Module

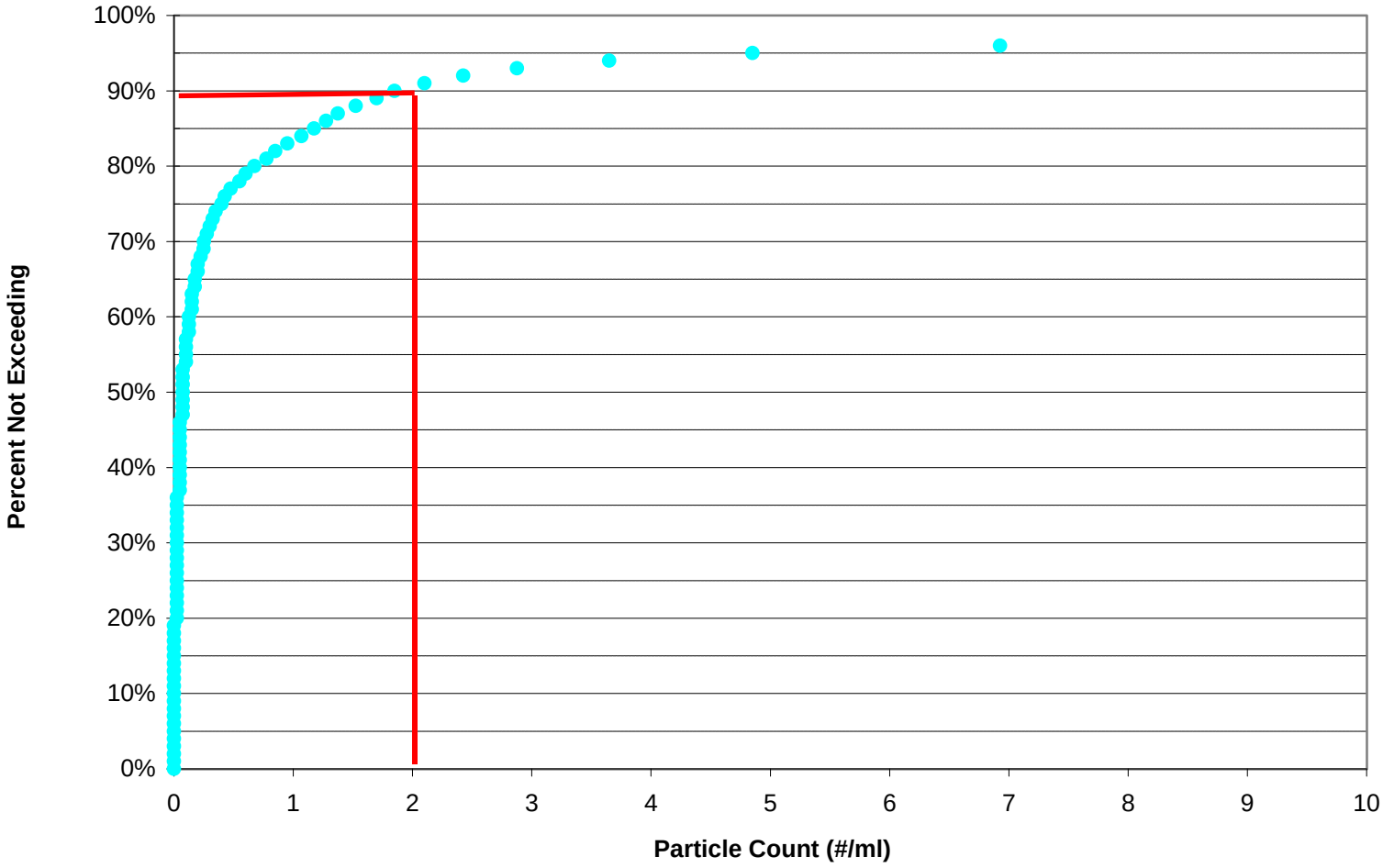


Figure 4-20
A Frequency Distribution for Filtrate Partilces >2 um for the Polymem UF Module UF120 S2 Membrane Module

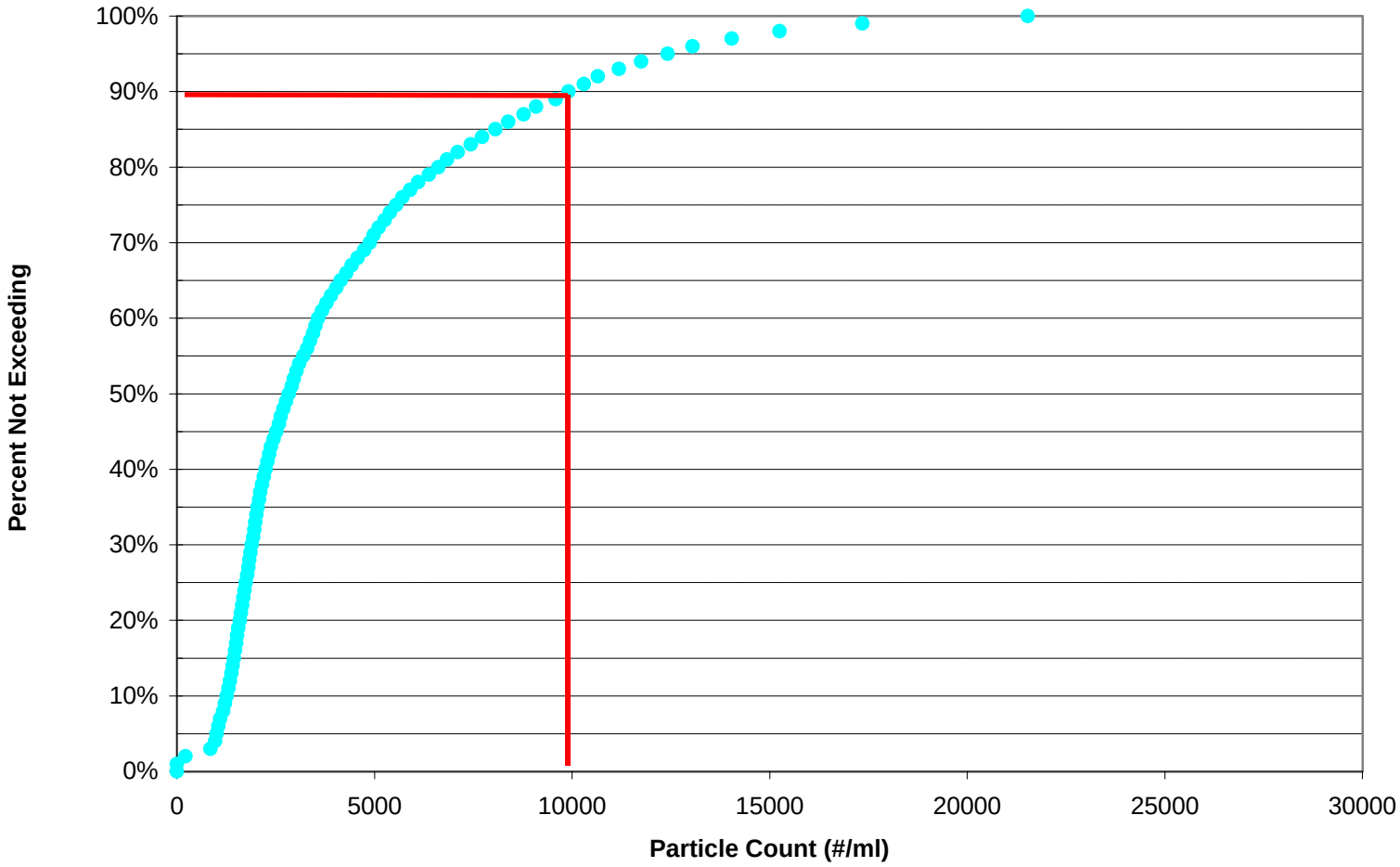


Figure 4-21
A Frequency Distribution for Feed Water Partilces >2 um for the Polymem UF Module UF120 S2 Membrane Module

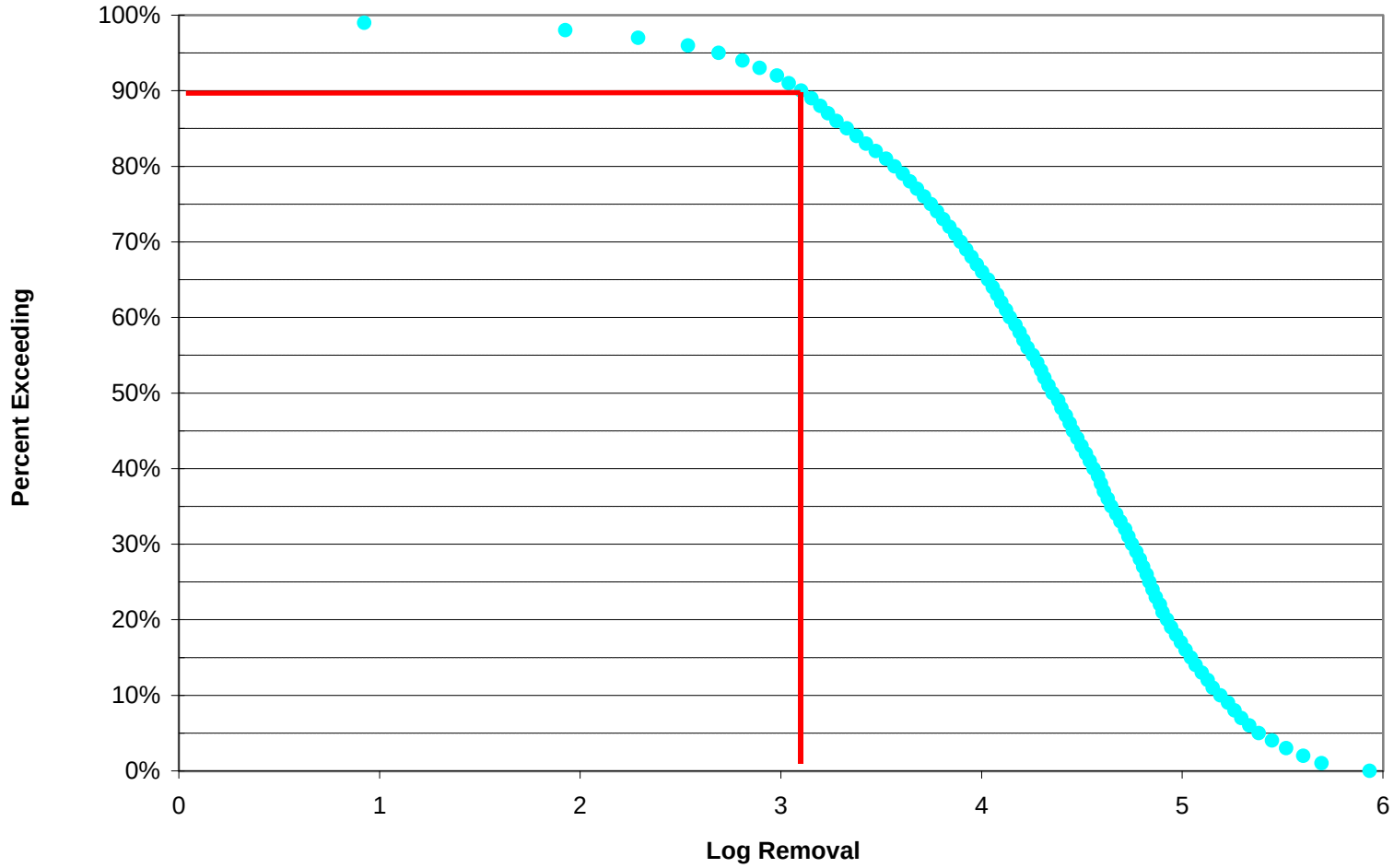


Figure 4-22
A Frequency Distribution of Log Removal for Particles >2 um for the Polymem UF Module UF120 S2 Membrane Module

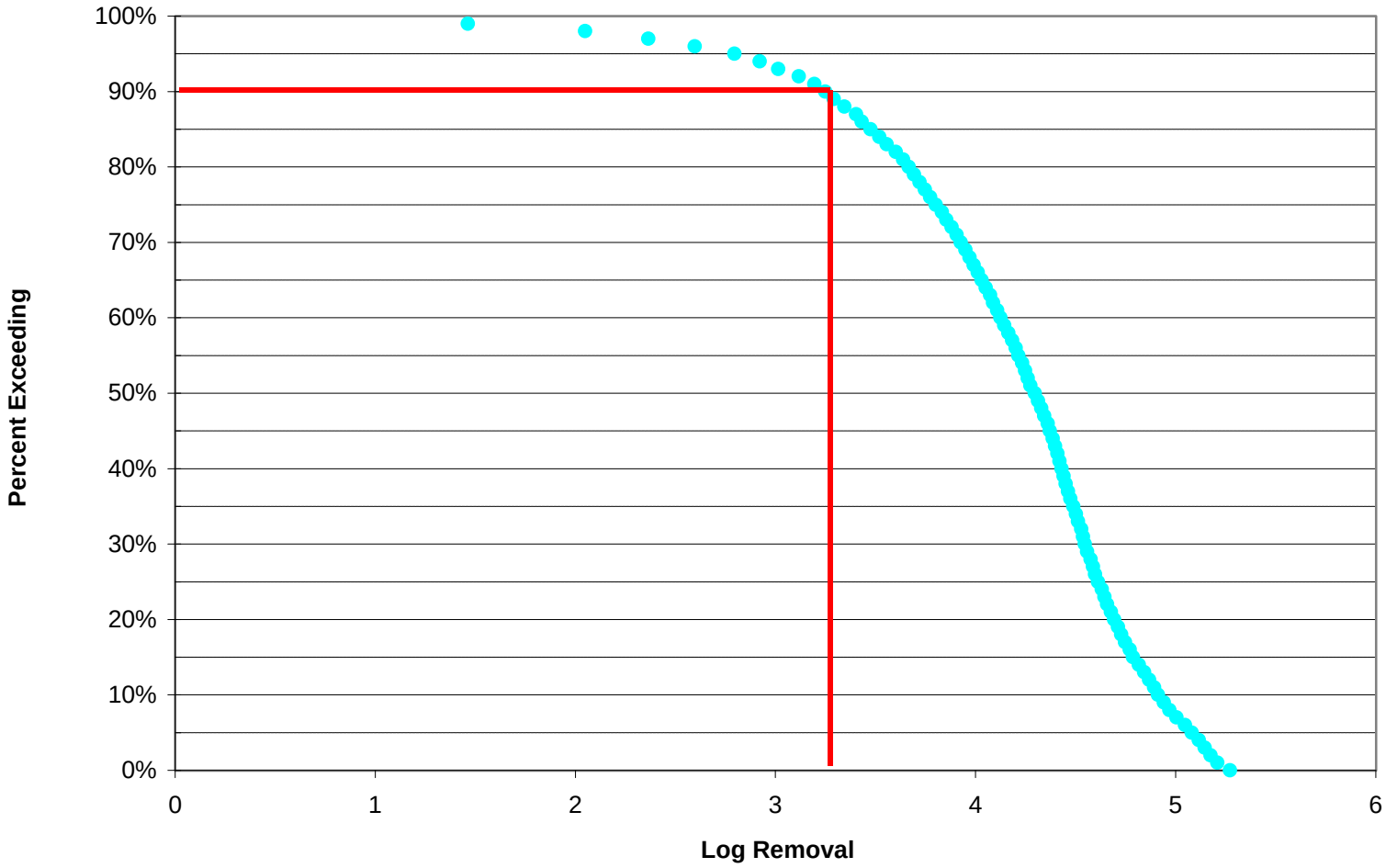


Figure 4-23
A Frequency Distribution of Log Removal for Particles 2-3 um for the Polymem UF Module UF120 S2 Membrane Module

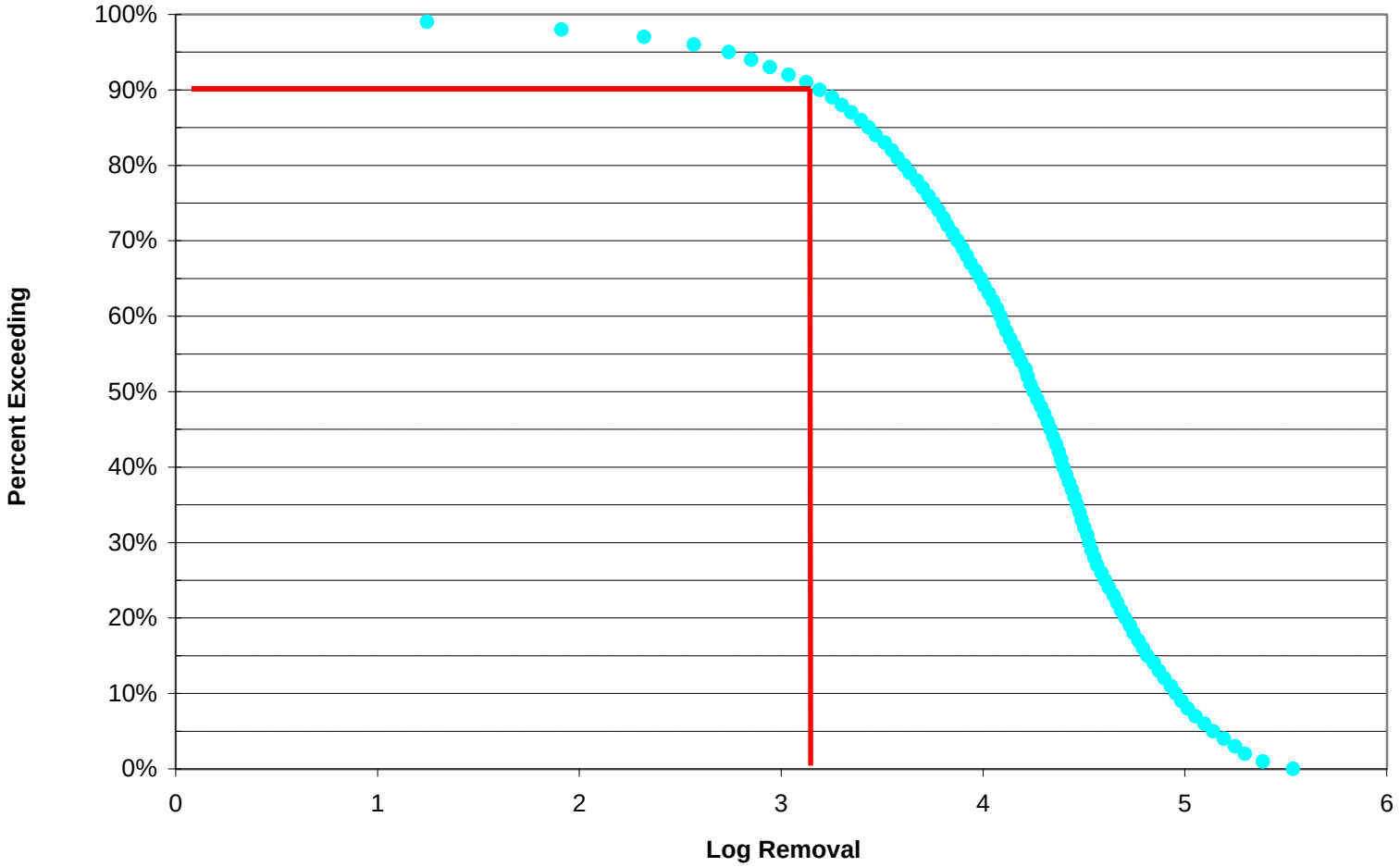


Figure 4-24
A Frequency Distribution of Log Removal for Particles 3-5 um for the Polymem UF Module UF120 S2 Membrane Module

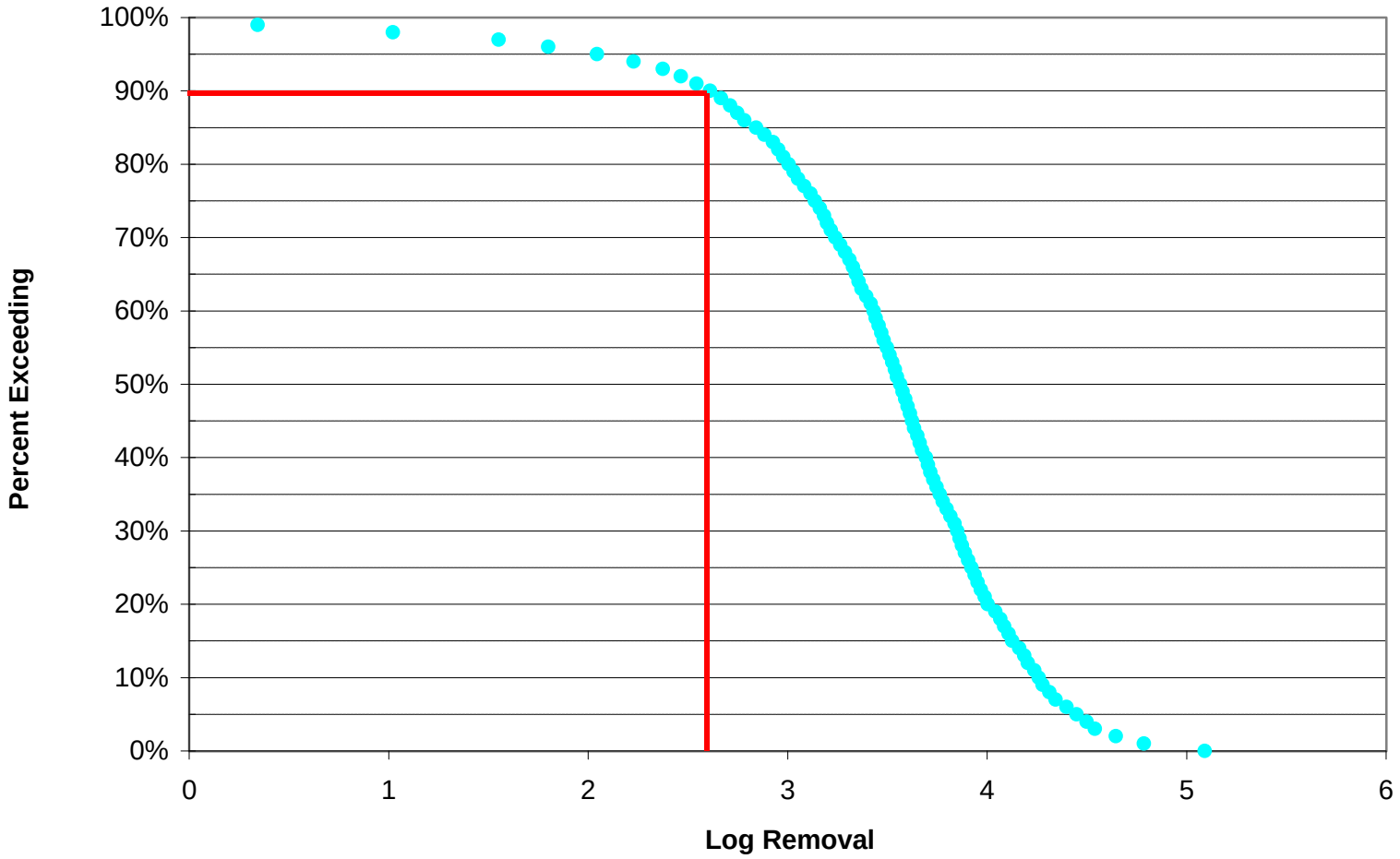


Figure 4-25
A Frequency Distribution of Log Removal for Particles 5-7 um for the Polymem UF Module UF120 S2 Membrane Module

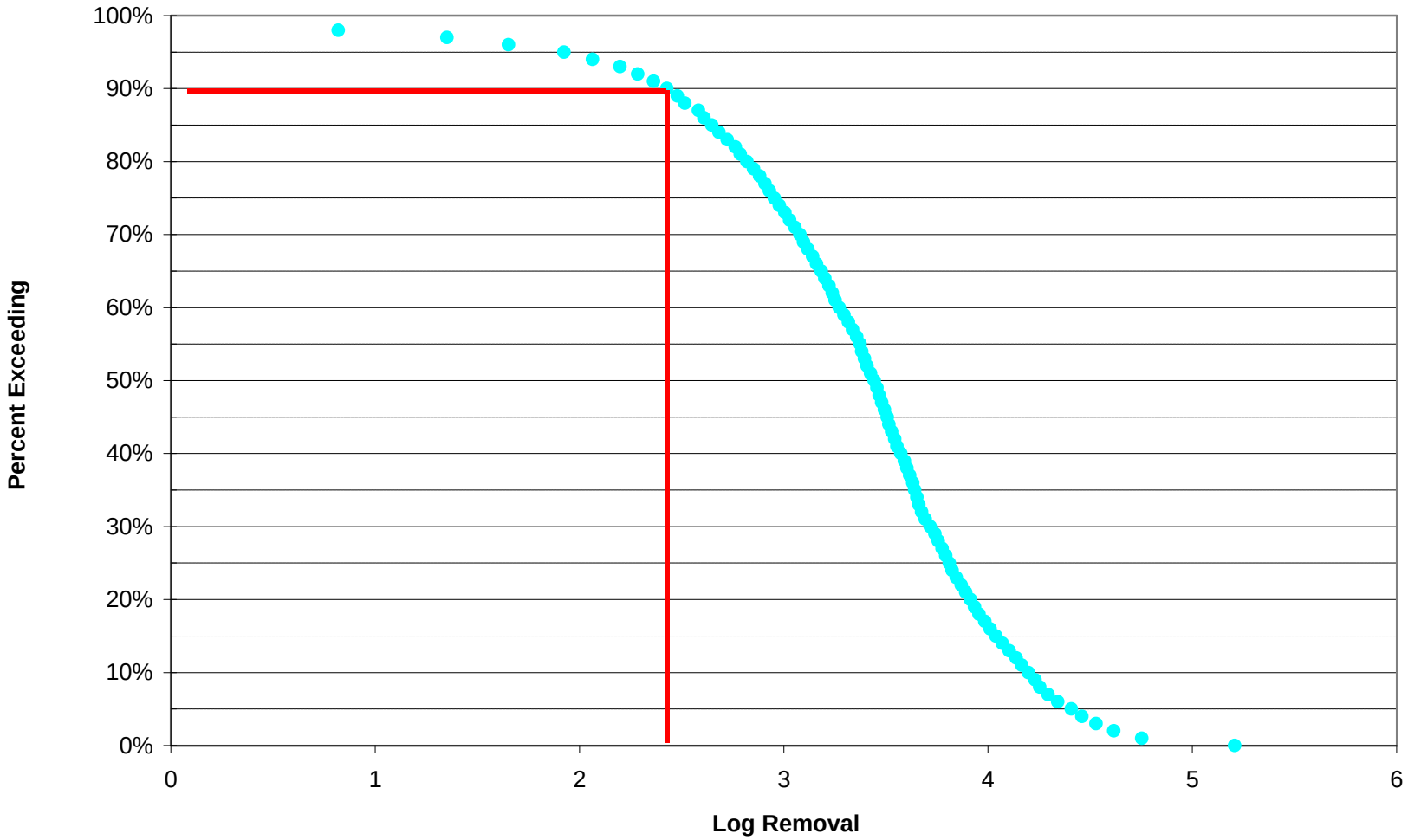


Figure 4-26
A Frequency Distribution of Log Removal for Particles 7-10 um for the Polymem UF Module UF120 S2 Membrane Module

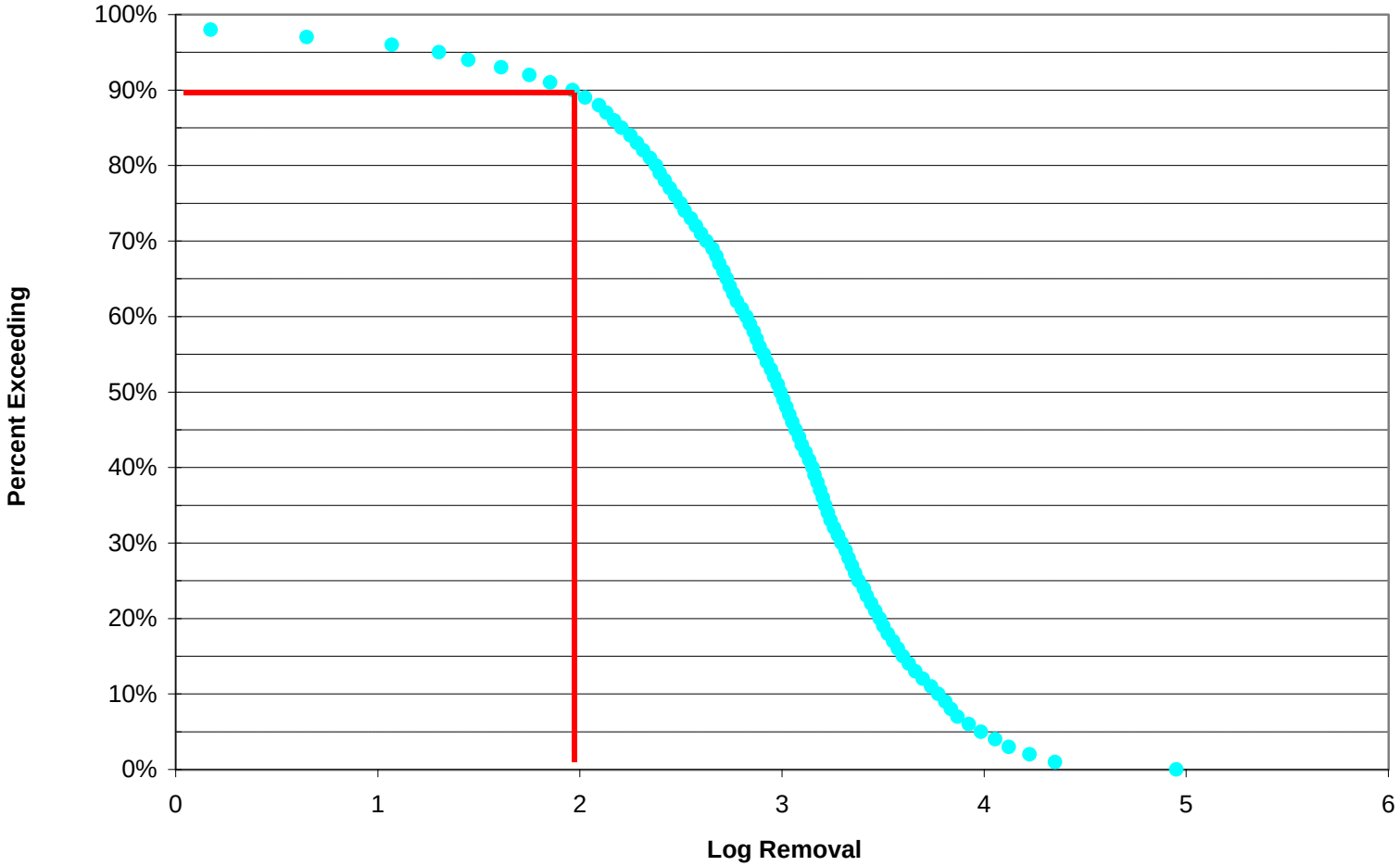


Figure 4-27
A Frequency Distribution of Log Removal for Particles 10-15 um for the Polymem UF Module UF120 S2 Membrane Module

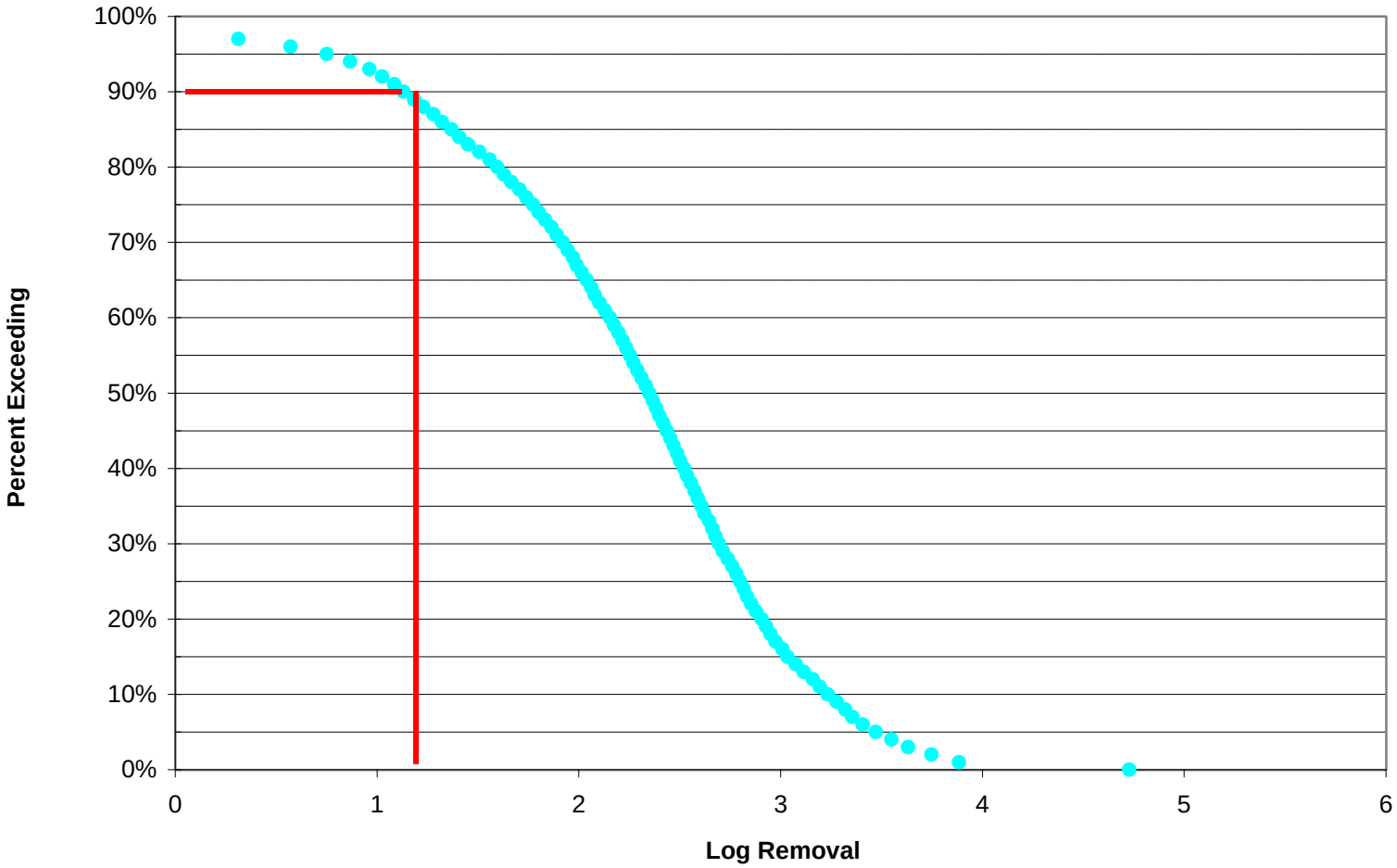


Figure 4-28
A Frequency Distribution of Log Removal for Particles >15 um for the Polymem UF Module UF120 S2 Membrane Module

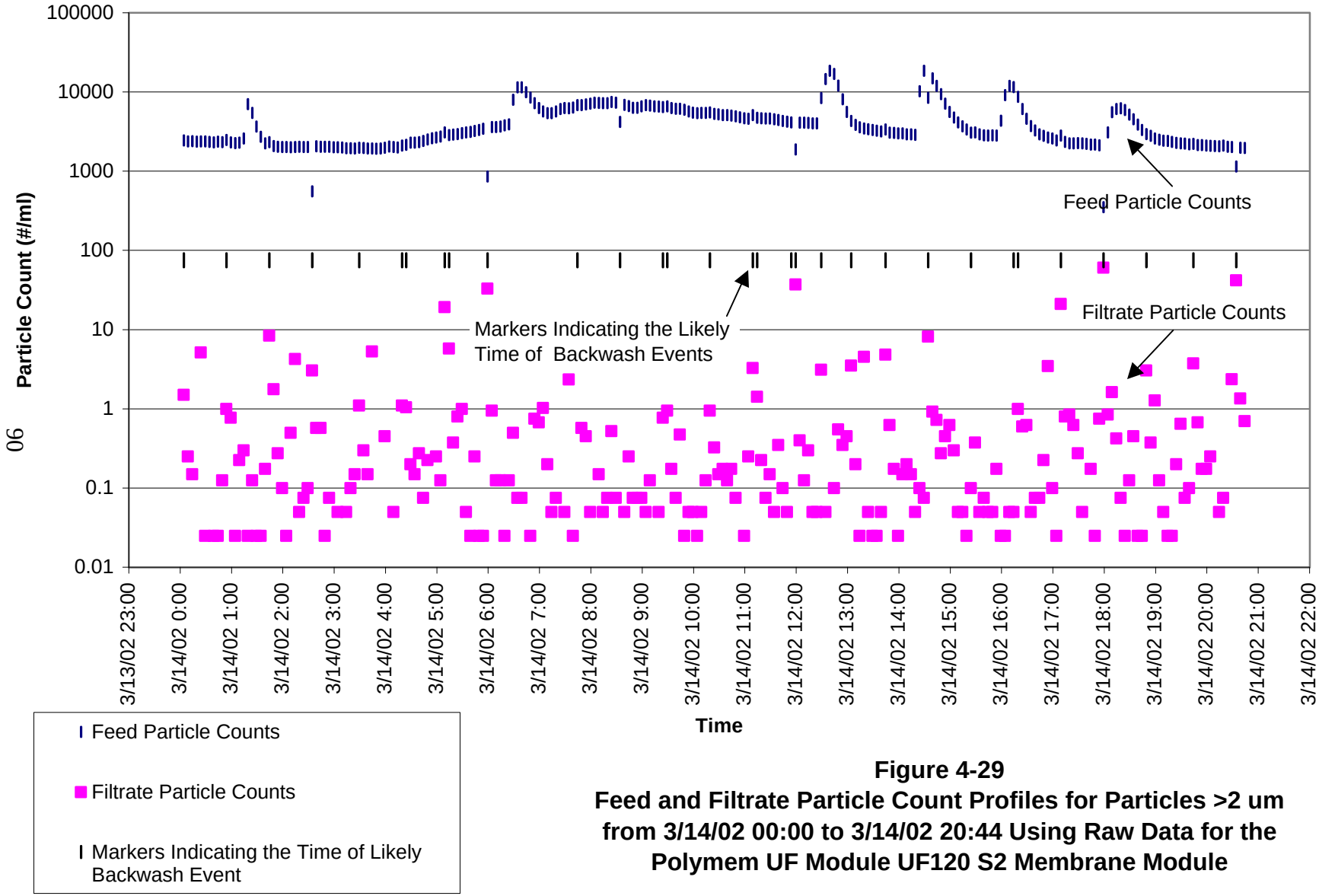


Figure 4-29
Feed and Filtrate Particle Count Profiles for Particles >2 um from 3/14/02 00:00 to 3/14/02 20:44 Using Raw Data for the Polymem UF Module UF120 S2 Membrane Module

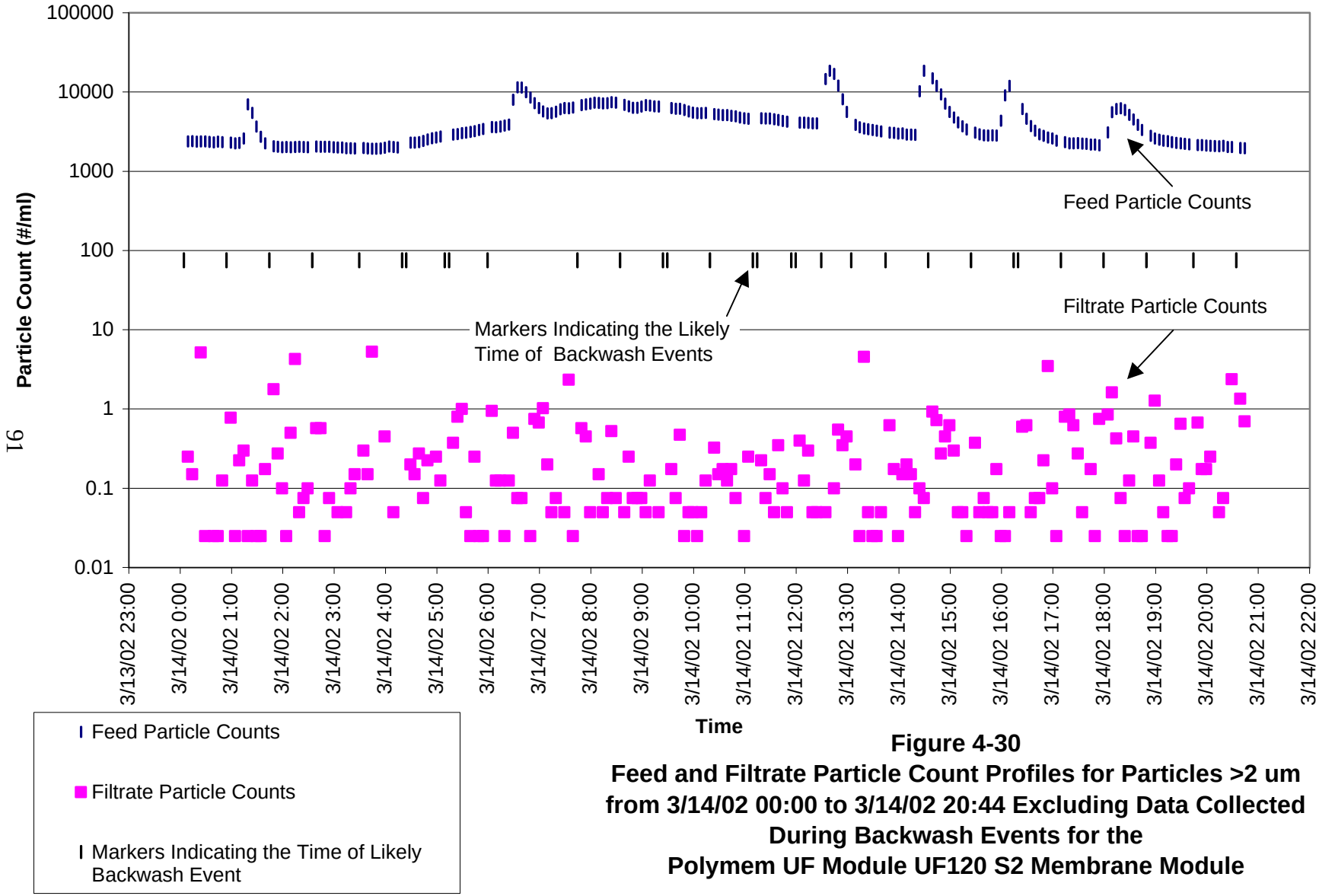


Figure 4-30
Feed and Filtrate Particle Count Profiles for Particles >2 um from 3/14/02 00:00 to 3/14/02 20:44 Excluding Data Collected During Backwash Events for the Polymem UF Module UF120 S2 Membrane Module

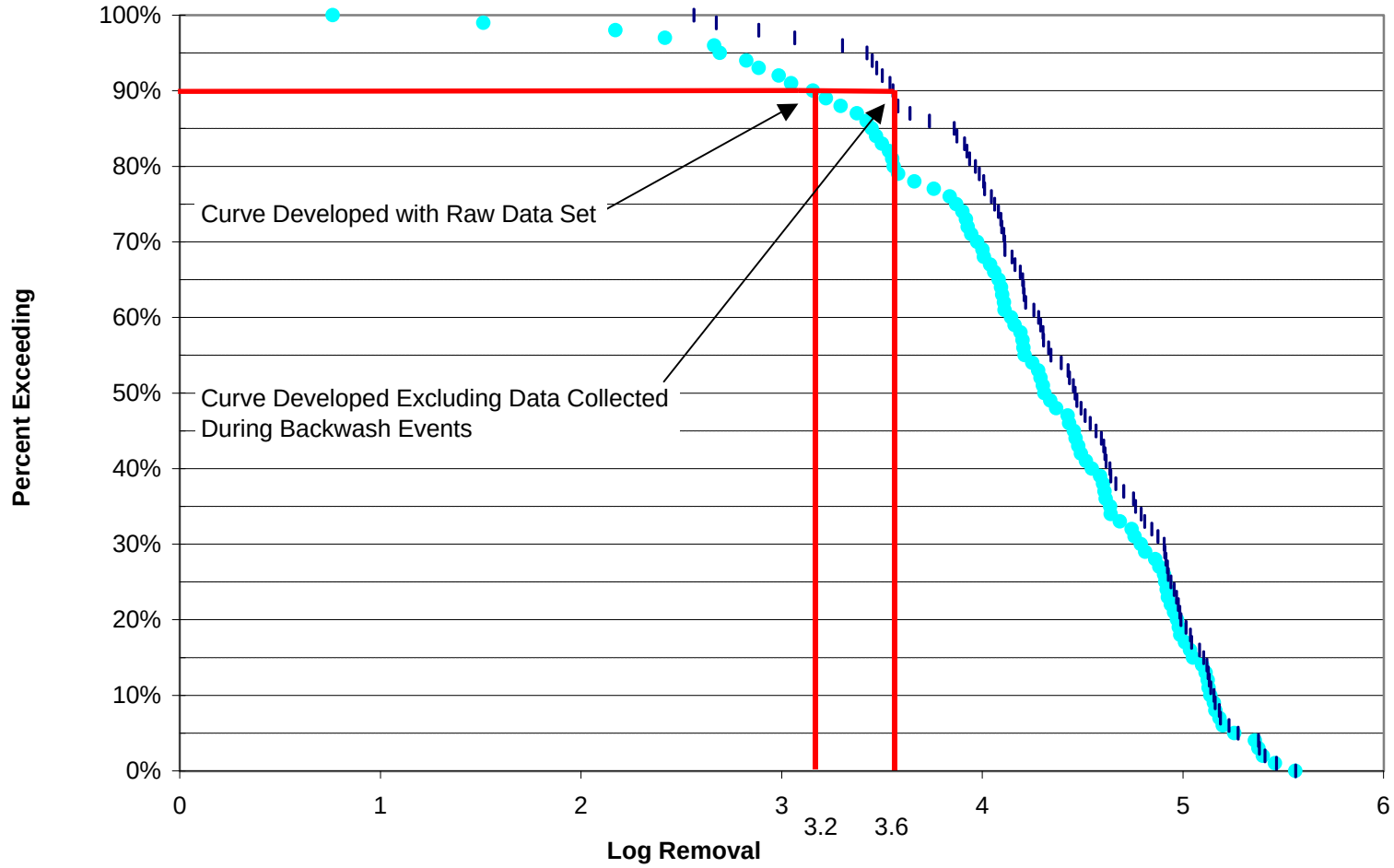


Figure 4-31
A Frequency Distribution of Log Removal for Particles >2 um
from 3/14/02 00:00 to 3/14/02 20:44 for the
Polymem UF Module UF120 S2 Membrane Module