Environmental Technology Verification Report

Removal of Precursors to Disinfection By-Products in Drinking Water

PCI Membrane Systems Fyne Process Model ROP 1434 With AFC-30 Nanofiltration Membranes

Prepared by

NSF

NSF International

Under a Cooperative Agreement with

⊕EPA U.S. Environmental Protection Agency

ET✔ ET✔ ET✔

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

ETV ✓

⊕EPA

U.S. Environmental Protection Agency

NSF.

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**NANOFILTRATION USED IN PACKAGED DRINKING WATER TREATMENT SYSTEMS**
APPLICATION:	**REMOVAL OF PRECURSORS TO DISINFECTION BY-PRODUCTS IN BARROW, ALASKA**
TECHNOLOGY NAME:	**FYNE PROCESS MODEL ROP 1434 WITH AFC-30 NANOFILTRATION MEMBRANES**
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

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

NSF International (NSF) in cooperation with the EPA operates the Drinking Water Treatment Systems (DWTS) Pilot, one of 12 technology areas under ETV. The DWTS Pilot recently evaluated the performance of a nanofiltration system used in package drinking water treatment system applications. This verification statement provides a summary of the test results for PCI Membrane Systems Inc.'s Fyne Process nanofiltration system equipped with a C10 module containing tubular polyamide AFC-30 membranes. The University of Alaska Anchorage in cooperation with the University of New Hampshire, a NSF-qualified field-testing organization (FTO), performed the verification testing.

ABSTRACT

Equipment testing and verification of PCI Membrane Systems Inc. Fyne Process nanofiltration systems Model ROP 1434 equipped with a C10 module containing AFC-30 tubular membranes was conducted from March 16 to May 11, 2000 in Barrow, Alaska. The source water was a moderate alkalinity, moderately turbid surface water with a pH near neutral and a total organic carbon (TOC) concentration of approximately 15 mg/l. The average feed water temperature was 14.4°C. The skid produced an average of 0.87 gpm of permeate when operated so that 80% of the raw water supplied to the test skid was recovered as permeate. The average transmembrane pressure and specific flux during the verification study were 88 psig, and 0.14 gfd/psi, respectively. The membrane removed more than 95% of TOC and reduced UV_{254} absorbance by an average of 97%. The test skid reduced the average total trihalomethane (TTHM) formation potential from 535 µg/l in the source water to 31 µg/l in the permeate. The average haloacetic acid (HAA5) formation potential was reduced from 398 µg/l in the source water to 6.2 µg/l in the permeate. All disinfection by-product formation potentials were evaluated using the U.S. EPA's Uniform Formation Conditions. The EPA Stage 1 Disinfectants/Disinfection By-Products (D/DBP) Rule requires TTHM and HAA5 concentrations not exceed 80 µg/l and 60 µg/l, respectively.

TECHNOLOGY DESCRIPTION

The Fyne Process refers to a family of treatment systems offered by PCI Membrane Systems that were originally developed in the United Kingdom to treat waters with high concentrations of organic materials. The Fyne Process is designed to remove both microbial contaminants and reduce the organic content as precursors to form disinfection byproducts. One unique aspect of the Fyne Process is the use of an automated foam ball cleaning process to remove accumulated organic and inorganic foulants. In this process, a small foam ball is forced through the tubular filter elements via water pressure flowing in the opposite direction of normal flow. The foam ball scrubs the tubular membrane surface removing the accumulated foulants. "Filter-catchers" (small, perforated plates installed in the module inlet and outlet lines) retain the foam-balls in the system. Cleaning frequency is adjustable and the entire process is fully automated.

The specific system verified in this study was equipped with a C10 module that contained 72 AFC-30 tubular polyamide nanofiltration membranes connected in series. The total membrane surface area available was 114 ft^2. The test skid contained two pumps: a raw water pump that supplied source water to the skid and a recirculation pump that introduced source water and recycled concentrate to the inside of the tubular membrane elements housed in the module. Permeate passing through the membranes was collected in the module shroud and discharged at atmospheric pressure.

VERIFICATION TESTING DESCRIPTION

Test Site

The verification test was conducted at a site owned and operated by Barrow Utilities Electric Cooperative Incorporated (BUECI) in Barrow, Alaska. Barrow is an Inupiat Eskimo village that draws raw water year round from Isatkoak Reservoir, a surface water source that has a moderate alkalinity, moderate turbidity and an elevated organic content.

Methods and Procedures

Water quality data were collected on all source water, permeate and concentrate streams produced by the PCI process and analyzed using *Standard Methods for the Examination of Water and Wastewater, 20th Edition* (1998) or EPA approved methods. The analysis of pH, turbidity, conductivity, color and temperature were conducted on-site using field instrumentation. Analysis for TOC, total suspended solids (TSS), total dissolved solids (TDS), chloride, bromide, sulfate, ortho-phosphate, total phosphate,

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magnesium, manganese, calcium, total hardness, alkalinity, iron, total silica and dissolved silica were performed by a state-certified laboratory. UV_{254} analysis was performed at the University of Alaska Anchorage. UV_{254}, pH, turbidity, conductivity and color analyses were conducted daily. The laboratory performed semiweekly (twice a week) analysis for TOC and biweekly (every two weeks) analysis for all other analytes. Flow rate and pressure data were obtained from skid instrumentation. All flow rate and pressure readings were manually verified during the verification study.

TTHM and HAA5 disinfection by-product formation potential for both the source water and the permeate was evaluated using the Uniform Formation Conditions (UFC) protocol specified EPA's Information Collection Rule (ICR). Biweekly feed and permeate samples were dosed with free chlorine and incubated for 24 hours at 20°C. All incubations were completed within 24 hours of sample collection. A sample with a free chlorine residual of 0.6 - 1.4 mg/l and final pH of 7.8 - 8.2 was quenched and sent to the laboratory for TTHM and HAA analysis.

VERIFICATION OF PERFORMANCE

System Operation

The test skid operated for 57 consecutive days from March 16 to May 11, 2000 with an average recovery of 80%. Feed and permeate flow rates averaged 1.08 gpm and 0.87 gpm, respectively, during the verification study. The test skid operated with an average transmembrane pressure 88 psig and the temperature corrected specific flux of 0.14 gfd/psi.

The system operated for the entire test period without requiring a chemical cleaning. A chemical cleaning was completed at the end of the verification test to evaluate cleaning efficiency using a caustic solution with an initial pH of approximately 10. The single high pH chemical cleaning recovered over 100% of the transmembrane pressure and specific flux values measured at the start of the verification study. Foam ball cleaning occurred at 5-hour intervals throughout the verification test.

Water Quality Results

The test skid effectively removed organic compounds and particulates from the source water during the verification study. The raw water TOC, which averaged 15 mg/l, was reduced by over 95%. As a result, the treatment system was able to reduce the source water TTHM and HAA5 concentration produced under the Uniform Formation Conditions by 94% and 98%, respectively, and produced a permeate that contained an average of 31 µg/l TTHM and 6.2 µg/l HAA5. Permeate turbidity was consistently less than 0.1 NTU.

The test skid also removed 47%-99% of iron, manganese, calcium and sulfate from solution. (Note: Iron can foul membranes and should be considered for all membrane installations. However, the specific flux data indicates that significant fouling did not occur during this verification study). Modest reductions in source water alkalinity (10%) and total dissolved solids concentration (34.5%) were also observed. The other water quality parameters monitored during the test were not significantly altered by membrane treatment.

	Turbidity (NTU)	UV$_{254}$ Absorbance	TOC (mg/l)	HAA5 (µg/l)	TTHM (µg/l)
		Feed Water Quality/Permeate Water Quality			
		PCI Membrane System Inc. Fyne Process Model # ROP 1434			
Average	3.4/0.056	0.52/0.012	15/0.7	405/6.7	544/31
Minimum	2.8/0.039	0.41/0	9.3/0.4	306/4	400/21
Maximum	4.5/0.165	1.53/0.032	16/1.2	480/11	605/46
Standard Deviation	0.5/0.019	0.19/0.0078	1.5/0.2	72/3.1	97/11
95% Confidence Interval	(3.3,3.6)/ (0.051,0.061)	(0.44,0.60)/ (0.009,0.016)	(14,15)/ (0.6,0.8)	(290,520)/ (1.7,12)	(389,699)/ (15,48)

Operation and Maintenance Results

The test system evaluated in this study was highly automated (with the exception of chemical cleaning) making day-to-day operation straightforward and simple. On most days (51 out of the 57 days of testing), test skid operators performed only the routine checks required for the verification study. The operators also made minor adjustments to the concentrate control valve to maintain target flow rates. When both routine operation and system repairs are considered, the average time required to operate the test system was 20 minutes per day. Power consumed by the test skid was 12.3 kW-hr per thousand gallons of permeate produced. The feed pump, which was external to the skid and not designed specifically for this project, consumed an additional 21.3 kW-hr per thousand gallons of permeate produced.

The operation and maintenance manual was well-written, effectively organized and contained appropriate information for most of the tasks required during the verification study. The information required to recalibrate the concentrate flow meter that was not in the original O&M manual supplied with the skid but was subsequently supplied by PCI.

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Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing for Removal of Precursors to Disinfection By-Products* dated August 9, 1999, the Verification Statement, and the Verification Report (NSF Report #00/19/EPADW395) are available from the following sources:

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

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

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

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

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September 2000

Environmental Technology Verification Report

Removal of Precursors to Disinfection By-products in Drinking Water

PCI Membrane Systems
Fyne Process Model ROP 1434 Equipped with a C10 Module and AFC-30 Nanofiltration Membranes

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Notice

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

Foreword

The following is the final report on an Environmental Technology Verification (ETV) test performed for NSF International (NSF) and the United States Environmental Protection Agency (EPA) by the University of Alaska Anchorage and the University of New Hampshire, in cooperation with PCI Membrane Systems. The test was conducted during March 16, 2000 through May 11, 2000 at Barrow Utilities and Electric Cooperative Incorporated in Barrow, Alaska.

Throughout its history, the EPA has evaluated the effectiveness of innovative technologies to protect human health and the environment. A new EPA program, the Environmental Technology Verification Program (ETV) has been instituted to verify the performance of innovative technical solutions to environmental pollution or human health threats. ETV was created to substantially accelerate the entrance of new environmental technologies into the domestic and international marketplace. Verifiable, high quality data on the performance of new technologies are made available to regulators, developers, consulting engineers, and those in the public health and environmental protection industries. This encourages more rapid availability of approaches to better protect the environment.

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

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

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Abbreviations and Acronyms

Avg.	Average
BUECI	Barrow Utilities and Electrical Cooperative Incorporated
CPU	Cobalt Platinum Unit
CT&E	Commercial Testing and Engineering Laboratory
D/DBP	Disinfectant/Disinfection By-product
DBP	Disinfection By-product
DPD	Diethyl-p-phenylenediamine Method
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
FOD	Field Operation Document
FTO	Field Testing Organization
gfd	Gallons per Square Foot per Day
gpm	Gallons per Minute
HAA	Haloacetic Acids
HAA5	The Five Haloacetic Acids Specified in EPA's Stage 1 D/DBP Rule
ICR	Information Collection Rule
kW	Kilowatts
LCL	Lower Confidence Interval
MCL	Maximum Contamination Level
Max.	Maximum
Min.	Minimum
MSDS	Material Safety Data Sheet
µg/l	Micrograms per Liter
µm	micron
µS/cm	Microsiemen per centimeters
mg/l	Milligrams per liter
NIST	National Institute of Standards and Technology
nm	Nanometers
NOM	Natural Organic Matter
NSF	NSF International (formerly National Sanitation Foundation)
NTU	Nephelometric Turbidity Units
O&M	Operations and Maintenance Manual
P&ID	Process and Instrumentation Diagram
PCI	PCI Membrane Systems (Manufacturer of Fyne Process)
DWTS	Drinking Water Treatment Systems
psig	Pounds per Square Inch Guage
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
RPD	Relative Percent Difference
SDI	Silt Density Index
TDS	Total Dissolved Solids
THM	Trihalomethane

TOC	Total Organic Carbon
TSS	Total Suspended Solids
TTHM	Total Trihalomethane
UAA	University of Alaska Anchorage
UCL	Upper Confidence Interval
UFC	Uniform Formation Conditions
UNH	University of New Hampshire
UV_{254}	Ultraviolet Absorbance at 254 nm

Chapter 1
Introduction

1.1 ETV Purpose and Program Operation

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

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

NSF International (NSF) in cooperation with the EPA operates the Drinking Water Treatment Systems (DWTS) ETV Pilot, one of 12 technology areas under ETV. The DWTS Pilot evaluated the performance the PCI's Fyne Process Model ROP 1434 equipped with a C10 membrane module containing AFC-30 polyamide nanofiltration tubular membranes. Any future reference to the "treatment system" or the "skid" refers to this combination of elements. The performance claim evaluated during field-testing of the system was that the system is capable achieving total trihalomethanes (TTHM) of less than 80 micrograms per liter (μg/l) and a haloacetic acid (HAA5) level of less than 60 μg/l. The EPA Stage 1 Disinfectants/Disinfection By-Products (D/DBP) Rule requires TTHM and HAA5 concentrations not exceed 80 μg/l and 60 μg/l, respectively. This document provides the verification test results for PCI's treatment system. All DBP formation potentials were assessed using EPA's Uniform Formation Conditions.

1.2 Testing Participants and Responsibilities

The ETV testing of the PCI's treatment system was a cooperative effort between the following participants:

- NSF International
- The University of New Hampshire (a NSF-qualified Field Testing Organization [FTO]) in cooperation with the University of Alaska Anchorage (UAA) and Barrow Utilities Electric Cooperative Incorporated (BUECI).
- PCI Membrane Systems Inc.
- U.S. Environmental Protection Agency

1.2.1 NSF International

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

NSF provided technical and primarily quality oversight of the verification testing. An on-site audit of the field analytical and data gathering and recording procedures was conducted. NSF also reviewed the Field Operations Document (FOD) to assure its conformance with the pertinent ETV protocol and test plan. NSF also conducted a review of this report and coordinated the EPA and technical reviews of this report.

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1.2.2 Field Testing Organization

UNH served as the NSF-qualified FTO and supervised the data collection and documentation efforts required for protocol verification. As part of their responsibilities, UNH:
- Provided guidance in the preparation of the FOD and a final review of the completed document.
- Reviewed all operational data collected from the test skid.
- Provided guidance in the preparation of the final verification report and a final review of the completed document.
- Provided a QA/QC review of the field-testing setup and laboratory analytical procedures.

The University of Alaska Anchorage functioned as the local project manager. As part of its duties, UAA:
- Prepared the FOD.
- Performed data management tasks.
- Prepared the final technology verification report.
- Provided all engineering and logistical support required by PCI to transport and install the package skid at the BUECI facility.

- Performed bi-weekly visits to the site to collect samples, calibrate instruments and collect operational data and debrief BUECI staff on any operational issues and implement any corrective actions that may be required.
- Provided regular updates to the project team members and NSF/EPA on the status of the project.

Barrow Utilities and Electric Cooperative Incorporated (BUECI) staff provided on-site support and operation. BUECI staff checked the treatment system daily basis and made notes on the general condition and performance of the skid and recorded any observations. BUECI staff also conducted routine on-site data collection and some sample collection.

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1.2.3 Manufacturer

PCI Membrane Systems, Inc. designed, manufactured and shipped the test skid and provided on-site startup support. As part of their startup services, PCI trained BUECI and UAA staff as necessary on the instrumentation setup, calibration, data collection and troubleshooting and procedures required for successful operation of the skid. PCI also established the numerical performance criteria verified in this study and specified the cleaning procedures used.

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1.2.4 Analytical Laboratory

Two analytical laboratories conducted off-site water quality analysis during the verification study. CT&E, a State of Alaska-certified contract laboratory in Anchorage, AK performed the first set of off-site water quality testing data. NSF's certified laboratory in Ann Arbor, MI performed all off-site analysis for the final three sampling events.

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1.2.5 U.S. Environmental Protection Agency

The EPA through its Office of Research and Development has financially supported and collaborated with NSF under Cooperative Agreement No. CR 824815. The Drinking Water Treatment Systems Pilot operating under the ETV Program supported this verification effort. The EPA reviewed this document for technical and quality content.

1.3 Verification Testing Site

The PCI treatment system was verified at the facility owned and operated by BUECI at 125 Agvik Road in Barrow, Alaska. Barrow is an Inupiat Eskimo village with a population of approximately 4,000 people. The utility draws its raw water year-round from Isatkoak Reservoir, a water source that can be characterized as cold, relatively soft with moderate turbidity and alkalinity. Due to high concentrations of naturally occurring organic material, the raw water is highly colored. TTHM and HAA5 formation potentials of three to five times the MCL's set by the EPA's Stage 1 D/DBP Rule have been reported (Lozier and Jones, *et al*., 1997).

A raw water tap was installed in the intake line for the existing facility to supply the test skid. Approximately 20 feet of flexible ¾ inch clear plastic hose ran from the tap to the test skid. The feed water tap was located downstream of an 1/32 inch stainless steel perforated basket strainer

and an 80 mesh stainless steel basket to remove gross and fine particles from the raw water. A shell and tube heat exchanger also preceded the sample tap that allowed for raw water with a temperature of 10-16°C to be supplied to the test skid. Power for the skid was delivered from a breakers on the main floor of the process building through drop cords wired into junction boxes located above the test area.

1.3.1 Source Water

The source water for the verification testing was Isatkoak Reservoir. Water quality data collected during the verification study for the reservoir are shown in Table 1-1. Isatkoak Reservoir water had an average total organic carbon (TOC) content of 15 milligrams per liter (mg/l). When incubated with chlorine, the raw water produced 400-600 µg/l of TTHM's and 300-480 µg/l of HAA5's. Turbidity of the water, which generally increased throughout the course of the verification test, ranged from 2.8 – 4.5 nephelometric turbidity units (NTU). The feed water had an average conductivity of 513 microseimens (µS/cm) and a moderate alkalinity.

Table 1-1. Summary Water Quality Data for Isatkoak Reservoir

	Total Alkalinity (mg/l)	Total Hardness (mg/l)	TDS (mg/l)	TSS (mg/l)	HAA5 (µg/l)	TTHM (µg/l)	TOC (mg/l)	UV_{254} Absorb. (cm^{-1})	Color (CPU)	Turbidity (NTU)
Average	56	75	298	1	405	544	15	0.52	124	3.4
Minimum	55	68.8	281	<2	306	400	9.3	0.41	97.4	2.8
Maximum	57	79	320	1.5	480	605	16	1.53	197	4.5
Std. Dev.	0.96	4.3	16.7	0.3	72	97	1.5	0.19	22.9	0.5
Number of Samples	4	4	4	4	4	4	18	55	17	57
95% Conf. Interval	(55,58)	(68,82)	(271, 324)	(0.7, 2)	(290, 520)	(389, 699)	(14, 15)	(0.44, 0.60)	(112, 136)	(3.3, 3.6)

Note: Standard deviation and confidence interval for TSS were calculated by using one-half of the detection limit (of 2 mg/l) as suggested in <u>Statistical Methods for Environmental Pollution Monitoring</u>, Richard O. Gilbert, Van Nostrand Reinhold (1987).

1.3.2 Package Effluent Discharge

The permeate of the package treatment unit was a colorless liquid with a TOC content of less than 1 mg/l and a turbidity of less 0.1 NTU. All permeate, as well as the concentrate and reject water generated during foam-ball cleaning, were discharged to a sump for ultimate disposal along with the backwash and concentrate from BUECI's existing microfiltration/nanofiltration treatment system to a local tundra pond. Discharge permits were not required.

Chapter 2
Equipment Description and Operating Processes

2.1 Equipment Description

The Fyne Process refers to a family of treatment systems offered by PCI Membrane Systems that were originally developed in the United Kingdom to treat waters with high concentrations of organic materials. The Fyne Process is designed to remove both microbial contaminants and reduce the organic content and potential to form disinfection byproducts. Its small footprint, modular construction and performance characteristics makes the Fyne Process well suited for small water systems (e.g., a several thousand gallons of treated water per day) that must treat water containing high concentrations of organic compounds.

One unique aspect of the Fyne Process is the use of an automated foam ball cleaning process to remove accumulated organic and inorganic foulants. In this process, a small foam ball is forced through the tubular filtration elements via water pressure flowing in the opposite direction of normal flow. The foam ball scours the tubular membrane surface removing the accumulated foulants. "Filter-catchers" (small, perforated plates installed in the module inlet and outlet lines) retain the foam-balls in the system. Cleaning frequency is adjustable and the entire process is fully automated.

The specific Fyne Process package skid (model number ROP 1434) verified in this performance evaluation study was equipped with a single C10 module constructed of ABS plastic that was 12 feet long and contained seventy-two AFC-30 polyamide tubular nanofiltration membranes. Each membrane tube is ½ inch in diameter and has a $CaCl_2$ salt rejection of 75%. The 72 membrane tubes are fed in series through the module. Maximum operating pressure of the C10 module is 175 pounds per square inch gauge (psig) at 70°F. Total active membrane surface area is 114.1 ft^2 (10.6 m^2). Test system specifications are summarized in Table 2-1. Figure 2-1 is a photo of the test skid with the C10 module installed.

Table 2-1.   PCI Test System Specifications

Parameter	Specification
Electrical Requirements	Skid Power = 1 x 460 V, 60 Hz, 1 hp, 3-phase power to run recirculation pump. 3-phase power is transformed to single phase to run instruments and actuated valves. Feed Pump Power = 1 x 110 V, 60 Hz, single phase. Feed pump on test skid in a ¾ horsepower centrifugal pump. Electrical equipment conforms to NEMA 4, IP55 standards
Crated Dimensions	Package Plant: 77" x 33" x 60", 790 lb. C10 Module: 155" x 13" x 22", 230 lb.
On-Skid Instrumentation	Feed flow meter and totalizer. Concentrate (effluent) flow meter. Permeate flow meter and totalizer. Meters for feed, inlet and concentrate pressure. Temperature sensor located in recycle line

Figure 2-1.   Photo of the PCI Model ROP 1434 Test Skid

Chemical cleaning is typically required once every 4 months or when feed pressure reaches 175 psig. Cleaning involves preparation of a caustic solution followed by acid cleaning solution, if necessary. Each solution is circulated for approximately one hour through the membrane module followed by a clean water rinse to remove residual cleaning solution. Total cleaning time is 3-4 hours.

2.2 Operating Process

A process and instrumentation diagram (P&ID) of the PCI test system is shown in Figure 2-2. Heated and screened raw water was supplied to a feed tank where it was pumped to the test skid using a small centrifugal pump (Note: the feed tank also serves and the clean in place (CIP) tank where cleaning chemicals are mixed for the package plant. This tank is labeled as the "FEED/CIP TANK" in Figure 2-2). A recirculation triplex piston pump was used to increase pressure and flow velocities through the membrane module and provide for internal recycle of concentrate. Permeate was collected in the membrane module housing and exited under atmospheric pressure to a sump which was periodically pumped to a local pond. The concentrate also exited to the sump.

Three types of operating cycles were used in the PCI system. These include: production, foam ball cleaning and chemical cleaning cycles. The unique flow characteristics of each cycle are described in detail in the following paragraphs.

2.2.1 Production Cycle

The production cycle is the normal operating mode used to generate potable drinking water. Raw water was supplied by to the skid at a pressure of approximately 38 psig by a centrifugal pump. Raw water flows through valves PV1 (a manual throttling valve) and through PV7 (a actuated valve) where it is combined with recycled concentrate. The mixture enters the recirculation pump that boosts the pressure and pumps the combined flow through an open 3-way valve PV5 and into the module. Flow passes through the 72 tubular nanofilter membranes housed in the module in series. Permeate passing through the membrane is collected in the shroud and discharged at atmospheric pressure. The concentrate exists the last membrane tube at a pressure of approximately 44 psig and flows through PV8. Concentrate flow is then split with a portion being rejected through PCV10 and the remainder recycled back to the recirculation pump. PCV10, a manual throttling valve, is used to control the balance of rejected and recycled concentrate flow and thus the recovery of the system.

2.2.2 Foam Ball Cleaning Cycle

The foam ball cycle is used to limit fouling of the membrane hence increasing the useful life of the system. During the study, the skid was operated in the automatic mode and a foam ball cleaning was performed every 5 hours. A manual foam ball cleaning can also be performed. During the foam ball cleaning cycle, the recirculation pump is off and PV7 is closed. Feed water is pumped through an open BPV4 and through the 3-way actuated valve PV6. This flow path introduces water into the module in the opposite direction of the production cycle. The foam ball, which rests against the foam ball catcher adjacent to PV6 at the start of the cleaning cycle,

is swept through all 72 membrane tubes to remove accumulated particles and foulants. The scoured material exits the module and flows through PV5 and out to reject through an open CV12. The catcher in line with PV5 prevents the foam ball from being lost when it exits from the last tubular element. The entire cleaning process requires 10-15 minutes with a flowrate of approximately 1 gpm provided by the feed pump only.

2.2.3   Chemical Cleaning

Chemical cleaning was accomplished by circulating cleaning fluid through the membrane module. For this process, the unit operates in the production cycle mode previously described with the exceptions that (a) the permeate line discharged back into the cleaning solution tank creating a closed loop and (b) PCV10 is fully open. A solution with a pH of approximately 10 is prepared by adding caustic to permeate produced by the skid and is circulated for 1-2 hours. If necessary, according to manufacturers instructions a low pH citric acid solution could be recirculated through the system. The module is then rinsed with permeate for approximately 15 minutes and the system put back on line. A manual foam ball cleaning is performed before initiating the chemical cleaning cycle.

Figure 2-2. Process and Instrumentation Diagram for the PCI Test System.
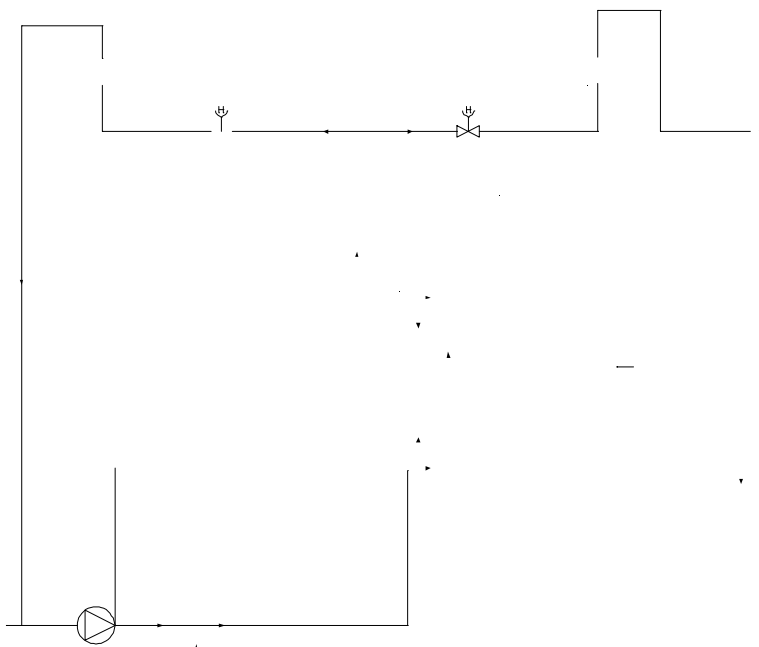
Chapter 3
Methods and Procedures

3.1   Introduction

Water quality and performance data were collected during the test period to verify that the PCI Membrane Systems Inc. Fyne Process treatment system equipped C10 module housing AFC-30 tubular nanofiltration membranes was capable of producing a permeate containing less than 80 µg/l of TTHM and less than 60 µg/l HAA5. The EPA Stage 1 D/DBP Rule requires TTHM and HAA5 concentrations not exceed 80 µg/l and 60 µg/l, respectively. A total of five tasks were accomplished as part of the verification study. These include:

- Task 1 - Membrane flux and operation. Membrane productivity, rate of flux decline and rejection capabilities were all evaluated in relation to feedwater quality.

- Task 2 – Cleaning efficiency. The efficiency of the membrane cleaning procedures recommended by the manufacturer were evaluated in this task by determining the fraction of specific flux that was restored following a cleaning.

- Task 3 – Finished Water Quality. The quality of the finished water produced by the membrane treatment system was evaluated by analyzing water samples collected throughout the study. A variety of organic and inorganic water quality parameters were measured.

- Task 4 – Data Management. Effective protocols for collecting, transferring and reducing data from the test skid were developed for the project and followed throughout the verification test.

- Task 5 – Quality Assurance/Quality Control. Protocols for assuring accurate measurement of operational and water quality parameters were developed and followed throughout the verification test.

In the following paragraphs, detailed descriptions of the materials and methods used to complete these five tasks are provided.

3.2   Treatment System Performance Calculations

3.2.1   Flux

Flux calculations for the PCI test skid were performed to quantify system performance. The temperature adjusted instantaneous flux was calculated using equation 1.

$$J_{i(at\,20^oC)} = \frac{Q_p * e^{-0.024(T-20^0C)}}{S} \tag{1}$$

Where:

J_i = instantaneous flux [gal/(ft^2 day) or gfd]

Q_p = permeate flowrate [gal/day]

T = permeate temperature [^{o}C]

S = membrane surface area [ft^2]. For the test system S = 114.1 ft^2

Specific flux, J_s, was calculated by normalizing the instantaneous flux for transmembrane pressure using equation 2.

$$J_{s(at\,20^o C)} = \frac{J_i}{TMP}$$ (2)

Where:

J_s = specific flux [gfd/psi]

TMP = transmembrane pressure [psig]

The transmembrane pressure, TMP, was calculated as the difference between the average module inlet (or feed) and module outlet (or concentrate) pressure and the permeate pressure as shown in equation 3.

$$TMP = \left[\frac{P_f + P_c}{2} - \Delta\pi\right] - P_p$$ (3)

Where:

TMP = transmembrane pressure [psig]

P_f = inlet or feed pressure [psig]

P_c = outlet or concentrate pressure [psig]

P_p = permeate pressure [psig]. For the test system the permeate pressure was atmospheric or 0 psig.

$\Delta\pi$ = change in osmotic pressure across the membrane [psig]

The change in osmotic pressure, $\Delta\pi$, was estimated using equation 4.

$$\Delta\pi = \frac{\pi_f + \pi_c}{2} - \pi_p$$ (4)

Where:

π_f = osmotic pressure of the raw water [psig]

π_c = osmotic pressure of the concentrate [psig]

π_p = osmotic pressure of the permeate [psig]

The average total dissolved solids (TDS) concentration of each flow stream was used to calculate an osmotic pressure by assuming that each 100 mg/l of TDS resulted in an osmotic pressure of

approximately 1 psi (AWWA, 1999). The average TDS concentrations measured for the feed and permeate streams were used to calculate the osmotic pressure of these flow streams. The osmotic pressure of the concentrate stream was determined using a TDS concentration (the actual TDS concentration of the concentrate was not measured) calculated by performing a simple mass balance on TDS for the test system using the average measured feed and permeate TDS concentrations.

3.2.2   Feedwater Recovery

Feedwater recovery, or the fraction of feedwater converted into permeate, was calculated using equation 5.

$$R = \frac{Q_p}{Q_f}(100) \qquad (5)$$

Where:

R= Recovery
Q_p = Permeate flow rate [gpm]
Q_f = Feed flow rate [gpm]

3.2.3   Power Consumption

Power consumption for the test skid was estimated by measuring the current draw using a handheld ammeter twice each week. Current draw to the 110-volt, single phase raw water pump was measured at the breaker. The current draw of each leg of the 460-volt skid power was measured at the motor starter bucket. The power requirements for the feed pump and the skid were calculated using equation 6 (WEF, 1997; WEF, 1984):

$$P = V \times I \times \sqrt{Ph} \times PF \qquad (6)$$

Where

P = Power [W]
V = line voltage (460 volts for skid; 115 volts for raw water pump)
I = average line current , or the average of actual meter readings made on all three legs
Ph = number of phases (3-phase for skid, single-phase for raw water pump)
PF = power factor. For the test skid a PF =0.80 was assumed based on literature values for similar pumps operating at full load.

3.3   Analytical Schedule and Methods

Table 3-1 lists the analysis schedule for the verification study. The water quality data were collected on-site by BUECI operators and UAA staff.   Off-site analysis was performed by the certified laboratories used for the study.

Table 3-1. Summary Analytical Testing Schedule for DBP Protocol Verification

Parameter	Feed	Permeate	Concentrate
pH	1 per day	1 per day	1 per day
Temperature	1 per day	1 per day	
Turbidity	1 per day	1 per day	1 per day
Total Alkalinity	2 per month	2 per month	
Total and Calcium Hardness	2 per month	2 per month	
Total Organic Carbon	2 per week	2 per week	1 per week
UV_{254} Absorbance	1 per day	1 per day	
Total Suspended Solids	2 per month	2 per month	2 per month
Total Dissolved Solids	2 per month	2 per month	
Ortho-phosphate	2 per month	2 per month	
Sulfate	2 per month	2 per month	
Iron	2 per month	2 per month	
Manganese	2 per month	2 per month	
Silica (total and dissolved)	2 per month	2 per month	
Chloride	2 per month	2 per month	
Bromide	2 per month	2 per month	
Conductivity	2 per month	2 per month	
SDI	2 per month		
Total THMs	2 per month	2 per month	
Haloacetic Acids (HAA5)	2 per month	2 per month	

3.3.1 On-Site Analytical Methods

On-site analytical methods describe the tests and readings performed in Barrow by BUECI staff or performed in the UAA lab. All on-site parameters were analyzed using the procedures specified in *Standard Methods for the Examination of Water and Wastewater, 20th Edition* (APHA *et al*., 1998) or by manufacturer calibrated and installed skid-mounted instrumentation.

3.3.1.1 pH

The pH was monitored using Standard Method 4500-H$^+$ B using a Sentron Model 1001 pH meter. Once each week, the meter was calibrated according to the manufacturer's instructions using a pH=7 and pH=10 Hach National Institute of Standards and Technology (NIST) traceable buffers. From March 16 through April 4, the pH calibration was checked against a single pH=7 standard and recalibrated if necessary. From April 5 through May 11, the pH meter calibration was checked against a pH=7 and a pH=10 standard and recalibrated if necessary.

3.3.1.2 Temperature

Permeate temperatures were recorded daily by the BUECI operators. The temperature was recorded using a NIST precision thermometer graduated in one-tenth of a °C, and range from -1° to + 51°C.

3.3.1.3 UV$_{254}$ Absorbance

All UV$_{254}$ samples were analyzed throughout the verification study. Samples were collected daily by BUECI staff and stored at 4°C. Each week the samples were either shipped to UAA via Alaska Airlines Goldstreak delivery service or collected by UAA staff during their sampling trips. All samples were analyzed using a Varian DMS 100 UV-Visible Spectrophotometer using Standard Method 5910 B. The instrument passed all tests for wavelength accuracy specified by in the manufacturer's instructions before initiating the verification test. However, due to the logistics and cost associated with shipping samples from Barrow on a daily basis, the 48 hour holding time was exceeded for most of these samples.

An experiment to verify the stability of the UV$_{254}$ absorbance readings over an extended holding period was conducted at UAA. Duplicate UV$_{254}$ samples of the feed and permeate were collected on March 18, 2000. Initial UV$_{254}$ absorbance readings for these samples were 0.420 and -0.003, respectively. The samples were then stored at 4°C until April 4, 2000 when the UV$_{254}$ absorbance was measured again. The absorbance values at this time were 0.442 and 0.027 for the feed and permeate, respectively. These results indicated that the extended holding time required for the UV$_{254}$ samples did not materially influence the absorbance readings and as a result, the data from all UV$_{254}$ analyses were included in the verification report.

3.3.1.4 Color

Color was measured in the field using a Milton Roy Model 401 Spectrophotometer set at 455 nanometers (nm). Cobalt Platinum Unit (CPU) color standards were purchased from Hach and used to develop a standard curve that related CPU to absorbance at 455 nm. In the field, the spectrophotometer was zeroed before each test using distilled and deionized water from the UAA lab. All samples were filtered through a 0.45 μm syringe filter into a disposable cuvette which was placed in the spectrophotometer. The absorbance readings were converted to CPU using the standard curve.

3.3.1.5 Turbidity

Grab samples were analyzed daily for turbidity using Standard Method 2130 and a Hach Model 2100 N turbidimeter. The meter was calibrated according to the manufacturer's specified procedure using a Hach Stabilcal Calibration Set as primary standards. From March 16 to April 16, 2000 secondary Hach Gelex standards were used to verify meter calibration according to the manufacturer's recommended procedure. (Note the secondary standard set included a stray light standard, and 0-2 NTU, 0-20 NTU, 0-200 NTU and 200-400 NTU standards. BUECI maintained calibration log with secondary standard readings starting on October 27, 1997 and running through the verification test period. The secondary standard measurements recorded

during the test period were within this historical range.) From April 16 through the end of the study, meter calibration was checked daily against a set of Hach Stabilcal standard with turbidities of 0.3, 0.5 and 1 NTU to ensure that the meter reading did not differ more than 10% in from the standard value.

Samples for permeate turbidity were collected from the end of the permeate line from March 16 to April 17, 2000 and then from a sample tap installed directly downstream of the membrane module from April 18 to May 11, 2000. The sample tap was installed to reduce the possibility of interference by the algal biofilm that had accumulated in the clear plastic permeate tubing. Prior to sample collection, each sample tap was allowed to run slowly and the beaker was rinsed with the sample water before collection. Samples for analysis were collected carefully to minimize air entrainment.

3.3.1.6 Conductivity

Conductivity was measured according to Standard Method 2510 B using a Myron L Company Ultrameter 4P. Meter calibration was checked before each analysis using Traceable One Shot 99.6 and 993 µS/cm standards.

3.3.1.7 Flow Rates

The raw water and concentrate flow rates were monitored continuously by skid instrumentation supplied by PCI. Permeate and concentrate flow rates were also manually verified using a volumetric cylinder and a stopwatch every two weeks and the meters recalibrated according to the manufactures instructions if necessary. If more than two consecutive comparisons of the meter reading and manually measured flow rates differed by more than 10%, the flow meters were cleaned and/or recalibrated.

3.3.1.8 Pressure

Pressure was monitored continuously by the skid instrumentation supplied by PCI. In-line pressure sensors were located in the raw water line, in the recycle line and in the concentrate line (a hand-operated valve was used to toggle between recycle and concentrate pressure meters). The accuracy of all pressure guages was verified by the manufacturer and also verified on-site by UAA staff using pressure meters before the start of verification project.

3.3.1.9 Silt Density Index

Silt density index (SDI) was performed according to ASTM method D 4189 using a Gelman P/N 66278 white, gridded sterile 47 µm, 0.45 millimeter (mm) filter. Tests were conducted on April 4, April 17, May 5 and May 11, 2000. The standard procedure was used on April 4 and April 17. However, an increase in raw water particle concentration required that the SDI values be calculated using a volume of 225 to 400 mL for the final two test because 500 mL of sample could not be passed through the filter after 5 minutes of operation on these dates.

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3.3.2   Off-Site (Chemical Samples Shipped Off-Site) Analyses

Samples for off-site water quality analysis were collected in Barrow March 19, April 4, April 17 and May 5 by UAA staff. All samples were collected for analysis according to the procedures specified in Standard Methods. The certified laboratory provided sample vials containing the appropriate preservative (if any). All sample vials were shipped with ice packs as checked baggage to and from Barrow by UAA staff. Full sample coolers were stored at 4°C in the UAA labs until delivery to CT&E (for the first set of samples) or overnight shipment to NSF (final three sets of samples) could be arranged. All samples were delivered to the contract laboratory within their required holding time. The methods used to analyze the samples are summarized in Table 3-2.

Table 3-2. Methods Used to Analyze Laboratory Samples

Parameter	CT&E Method Number		NSF Method Number	
	Standard Method	EPA Method	Standard Method	EPA Method
Total Alkalinity	2320 B		2320 B	
Total Hardness	2340 C		2340 C	
Total Organic Carbon		415.1	5310 C	
Iron		200.7		200.7
Manganese		200.7		200.7
Magnesium				200.7
Calcium Hardness	3500-Ca D			200.7
Total Dissolved Solids	2540 C		2540 C	
Total Suspended Solids		160.2		160.2
Ortho-phosphate		300.0		
Total Phosphate			4500-P-E	
Sulfate		300.0		300.0
Silica (dissolved)		200.7	4500-Si-E	
Silica (total)		200.7	4500-Si-E	
Chloride		300.0		300.0
Bromide		300.0		300.0
TTHMs		524.2		502.2
Haloacetic Acids (HAA5)	6251B			552.2

3.4   Disinfection By-Product (DBP) Incubation Protocol and Sample Collection

3.4.1   Incubation Conditions

The DBP formation potential was evaluated using the Uniform Formation Conditions (UFC) specified in the EPA's Information Collection Rule (ICR). All incubations were performed at UAA's lab on feed and permeate samples collected and shipped by UAA staff. In this procedure, water samples were incubated for 24 hours (±1 hour) at a temperature of 20°C (±1 ^{o}C). Samples were required to have a pH of 8 (±0.2) and a free chlorine residual of 1.0 mg/l (±0.4 mg/l) at the end of the incubation period.

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All water samples were incubated in one-liter amber glass bottles with Teflon lined caps. Prior to sample collection, the glassware was soaked in a 50 mg/l chlorine bath for at least 24 hr., rinsed three times with distilled and deionized water, and then dried at room temperature for at least 24 hr. Aluminum foil was placed over the bottles during drying to avoid contamination.

3.4.2   Solutions Used in the UFC Incubation Procedure

3.4.2.1 Reagent Water

UAA used distilled and deionized water for reagent water from the same source throughout the verification test to prepare all solutions used in the incubation procedure. The reagent water had no measurable chlorine demand.

3.4.2.2 Chlorine Dosing Solution

A dosing solution was prepared by diluting 10% reagent grade stock sodium hypochlorite solution (EM Science) with chlorine demand free water in a volumetric flask to produce a solution containing approximately 5 mg/ml chlorine. The solution was mixed and transferred to an amber bottle, sealed with a TFE lined-screw cap and stored in the refrigerator.   The concentration of the dosing solution was verified in UAA by diluting a sample of the chlorine dosing solution and then checking the free chlorine concentration using the Standard Method 4500-Cl G. (Note: a Hach free chlorine test kit with DPD reagent pillows were used in this verification test). A sample of the solution was sent to CT&E to verify the free chlorine content.

3.4.2.3 Mixed Buffer

A mixed phosphate-borate buffer solution was prepared according to Standard Methods 5710 B. The phosphate buffer was prepared by dissolving 68.1g of potassium dihydrogen phosphate (EM Science) and 11.7g of sodium hydroxide (EM Science) in reagent water to produce 1 L of solution. The borate buffer was prepared by to dissolving 30.9g H_3BO_3 (EM Science) and 10.8g NaOH (EM Science) in reagent water to give 1L of solution. 500 ml of each buffer were combined to produce 1L of mixed buffer that was added to the incubation bottles.

3.4.2.4 Sodium Sulfite Solution and Ascorbic Acid

Sodium sulfite solution was used to quench the TTHM samples sent to CT&E for analysis. The solution was prepared by dissolving 10g Na_2SO_3 in 100ml of reagent water. NSF provided vials containing ascorbic acid as the quenching agent.

3.4.2.5 Ammonium Chloride Solution

Ammonium chloride was used to dechlorinate the HAA5 sample after incubation. The solution was prepared by dissolving 5g NH_4Cl in 100ml of reagent.

3.4.2.6 Strong Acids and Bases

Adjustment to pH, if required, were accomplished using 1 N hydrochloric acid (HCl) (Fisher Scientific) or 1 N sodium hydroxide (NaOH) prepared in the UAA lab using reagent water and NaOH pellets (EM Science).

3.4.3   Incubation and Sampling Procedure

UAA collected a minimum of five (5) discrete samples of the raw water and permeate for each incubation. Samples were collected and transported in 1L chlorine demand free amber bottles prepared as previously described. All samples transported to UAA from Barrow were incubated within 24 hours of collection.

Twenty ml of a mixed buffer solution were added to an empty Cl_2 demand free amber bottle. At least 100 ml of the water sample were then transferred to a bottle containing the mixed buffer and each sample was spiked with an appropriate amount of the chlorine dosing solution. For the feed samples, a range of initial chlorine doses of 10-20 mg chlorine/l were targeted based on the results of trial incubations conducted before the verification test. Water from the sample was then added to almost fill the bottle and the pH checked and adjusted to 8±0.2 as necessary using strong acid or strong base. The bottle was then completely filled with water sample and incubated at 20±1°C.

After 24±1 hours of incubation, a 10 ml sample from each bottle was removed and analyzed for free chlorine residual using Standard Method 4500-Cl G. A Hach Free Chlorine Test Kit with DPD reagent pillows was used to perform this analysis in the UAA lab. (Free chlorine standards containing 0.0, 0.2, 0.8, 1.5mg chlorine/L purchased from Hach were analyzed prior to sample analysis). A second sample from the incubated bottle was used to determine the pH.   The incubated bottle with the required free chlorine residual and pH was then sampled for TTHM and HAA5.

3.4.4   TTHM Sample

TTHM samples were pipetted into 40 mL amber vials for transport to the contract laboratory. The samples sent to CT&E were quenched with 0.1ml of sodium sulfite (Na_2SO_3) solution. NSF provided amber vials containing ascorbic acid to quench the reaction. The pH of all samples was lowered to <2 using concentrated HCl (verified using pH paper) before shipment to the laboratory. All samples vials were headspace free.

3.4.5   HAA Sample

HAA5 samples were pipetted into 250 mL amber bottles that were sent to the contract laboratory, with 0.2 ml of ammonium chloride (NH_4Cl) solution added to each bottle to quench the reaction.

3.4.6 Reagent Blank

A blank to evaluate the presence of DBPs in the reagents used in the incubation was prepared by incubating a 50 mL sample of mixed buffer solution spiked with 1mL of dosing solution. The solution was mixed and used to a fill a 40 ml vial which was incubated at 20±1°C for 24±1 hours. 20 ml of incubated reagent blank was then diluted to 1 L with chlorine demand free water. Three 40 mL samples were then carefully transfered to a TTHM vial containing ascorbic acid. Three 250 mL samples for HAA analysis were also transferred to amber bottles and quenched with NH_4Cl. Both the TTHM and HAA reagent blank samples were sent to NSF for analysis.

3.4.7 Initial TTHM and HAA Blanks

Raw water and permeate samples were collected at Barrow and quenched without incubation or chlorine dosing to determine if any TTHM's or HAA's were present in the water before subjecting the samples to the UFC incubation procedure. The quenched samples were stored at 4^oC for 2 day before being shipped to NSF for analysis.

3.5 Cleaning Efficiency

The chemical cleaning solution was prepared by adding 0.2 lb of NaOH to approximately 28 gallons of permeate to give a cleaning solution with an initial pH of 10.3 and a conductivity of 494 µS/cm. Cleaning solution was pumped through the membrane unit as previously described. The high pH cleaning solution was recirculated through the membrane module for approximately 90 minutes. The pH at the end of this cycle was 9.0. The module was then rinsed with permeate for approximately 15 minutes until the pH had dropped to 7.6. The skid was then placed on line and the pressures, flow rates and flux values verified. Since over 90% of the initial flux was recovered with a single high pH cleaning, a second low pH cleaning was not required.

3.6 Quality Assurance/Quality Control

The quality of the operating equipment and analyses conducted for the verification project was maintained throughout the project by implementing a QA/QC plan that contained the elements described in the following sections.

3.6.1 QA/QC Verification Prior to the Testing Period

Before initiating the test run, the skid instrumentation was cleaned and calibrated and their accuracy verified. The pumps and valves were also cleaned and tested to verify that they were in good operating condition.

3.6.2 Daily QA/QC Verification

Daily QA/QC procedures were conducted by the operators to ensure that the equipment being verified remained in good operating condition order throughout the test period. Each day the operators verified that all tubing, connections, pumps and gauges were in good condition, and

replaced any failed equipment if necessary. The condition of each element was noted on the daily logs and reported to UAA. Any problems identified were immediately relayed to UAA and PCI for corrective action.

3.6.3   Quality Assurance Project Plan (QAPP)

The QAPP for the verification project specified procedures used by the operators and laboratory to ensure data quality and integrity. The data quality parameters established for the verification test included:

- Representativeness - the degree to which the data accurately and precisely represents the conditions being evaluated.
- Accuracy - the difference between the experimentally determined sample result and the accepted reference (or standard) value.
- Precision - a measure of the random error associated with individual measurements.
- Statistical uncertainty - the amount of variation around the mean.

The following policies and procedures were used to ensure that these data quality parameters were evaluated.

3.6.3.1 Data Representativeness

UAA established a sampling location for the feed, permeate and concentrate lines and all samples were taken from these specified locations. UAA established a sampling schedule prior to start up, the schedule laid out the daily, weekly and biweekly events. The sampling schedule was adhered to so that sufficient data for evaluating process performance were collected.

The CT&E and NSF laboratories provided all sampling bottles and chain of custody forms. CT&E sample bottles were collected prior to travel to Barrow, while NSF bottles were shipped to UAA and taken to Barrow as checked baggage. Both labs provided UAA with coolers and ice packs for sample preservation.

Daily operator data sheets included a sample time for each parameter, and a section for comments. The operators checked the operating condition of the test skid daily and recorded their observations on the daily checklist. The daily data sheet also included a comment section and it was used to record concerns regarding operation and data integrity. The chain of custody form that accompanies the samples for off-site analysis also included a sampling time. The time was also noted on the labeled bottles.

3.6.3.2 Data Accuracy

During the course of the study pH, conductivity, flow rate, pressure, temperature, color and turbidity were monitored daily. The accuracy of the data was ensured by routine calibration using high quality standards purchased from reputable manufacturers. BUECI operators checked and calibrated the on-site equipment at intervals specified on the daily data sheets and recorded the results. All on-skid instrumentation was calibrated by PCI and then manually verified before and during the testing period to ensure accuracy.

UAA staff evaluated the off-site laboratory reports for completeness and for any violations of the laboratories written QA/QC parameters. A full QA/QC package was provided by CT&E and reviewed by UAA's analytical chemist. NSF performed an internal QA/QC analysis of their laboratory data.

3.6.3.3 Data Precision

Data precision was evaluated by calculating the standard deviation and 95% confidence intervals for triplicate samples. All of the off-site water quality analyses had one set of samples taken in triplicate once during the study period.

3.6.3.4 Statistical Uncertainty

The statistical uncertainty of the water quality analyses were evaluated by calculating the 95% confidence interval of the triplicate water quality samples taken once during the 8-week study period. 95% confidence intervals were also calculated for all flow rate, pressure, flux and on-site water quality parameters evaluated during the verification study. Equation 7 is the general formula used to calculate confidence intervals.

$$\text{Confidence Interval} = X_{avg} \pm t_{n-1,1-\alpha/2} \, (S/\sqrt{n}) \qquad (7)$$

Where:

X_{avg} = sample mean;

S = sample standard deviation;

n = the number of independent measurements included in the data set

t = the Student's t distribution value with n-1 degrees of freedom;

α = the significance level, define for 95% confidence as: 1-0.95 = 0.05

Equation 8 is the formula used in this report to calculate the 95% confidence interval.

$$\text{95\% Confidence Interval} = X \pm t_{n-1,0.975} \, (S/\sqrt{n}) \qquad (8)$$

Chapter 4
Results and Discussion

4.1   Introduction

Testing of the PCI Fyne Process test skid was initiated on March 16, 2000 and ran for 57 consecutive days (1368 hours) until May 11, 2000.   Data on skid operation and performance were collected according to the methods and procedures outlined in Chapter 3.   The results of the verification test summarized in this chapter are presented according to the tasks specified in the Field Operations Document developed for the verification test. These tasks include:

- Task 1 - Membrane Flux and Operation
- Task 2 - Cleaning Efficiency
- Task 3 - Finished Water Quality
- Task 4 - Data Management
- Task 5 - Quality Assurance / Quality Control.

Copies of the data collected during the verification study and supporting documentation (daily data collection sheets, logbooks, laboratory reports, chain of custody forms, and O&M manual) are provided in the Appendices.

Verification testing was initiated after a 2-day startup period where various system flow rates and operating pressures were evaluated. Based on the results of the startup tests, PCI selected a target feed flow rate and recovery of 1.1 gpm and 80%, respectively.

4.2   Task 1 - Membrane Flux and Operation

4.2.1   Operation

Operation of the test skid was relatively simple and straightforward. On most days (51 out of the 57 test days), skid operators only performed routine checks to verify that all system components were functioning. Operators also made minor adjustment to the concentrate control valve (PCV-10) to maintain the target concentrate flow rate and recovery.

Solids present in the raw water resulted in several problems that required additional operator time beyond that required for routine operation. The concentrate flow meter, which measured flow using a floating disk type mechanism, occasionally accumulted solids within the meter body causing unstable flow readings. Operators removed, cleaned and recalibrated the concentrate flow meter twice during the test period. Each event required approximately 1.5-2.5 hours of operator time. On one occasion, solids in the raw water also lodged in the recirculation pump head check valves preventing them from completely seating resulting in unstable recycle pressure readings. BUECI operators removed and cleaned the check valves once during the test period. The skid also required additional operator time (approximately 5 hours) to replace the recycle pump (which had been in service since 1995) that began to leak oil after 192 hours of operation (day 8) and was eventually replaced after 384 hours of operation (on day 16). When both routine operation and system repairs are considered, the average time required to operate the test system was 20 minutes per day.

The operation and maintenance (O&M) manual (PCI, 1995) was well-written, effectively organized and contained appropriate information for most of the tasks required during the verification study. The information required to recalibrate the concentrate flow meter that was not in the original O&M manual supplied with the skid was promptly supplied by PCI.

4.2.2 Flow Rate

The daily raw water flow rate averaged 1.08 gpm and ranged from 0.97 - 1.16 gpm. Permeate flow rate averaged 0.87gpm and ranged from 0.75 – 0.94 gpm. The concentrate flow rate ranged from 0.19 - 0.25 gpm with an average of 0.22 gpm.

Variations in target flow rates did occur, especially during the first month of operation. Much of the variation appeared to be caused by operational difficulties with the flow meters. Accumulation of solids in the concentrate meter, and to a lesser degree the feed flow meter, resulted in unstable flow rate measurements. BUECI operators cleaned the feed and concentrate flow meters on day 27 that resulted in an improved feed meter stability for the remainder of the verification test. The concentrate meter, however, continued to experience fouling problems. BUECI operators cleaned and recalibrated this meter on day 36 and again on day 50 and 51 to ensure that accurate flow rate data were being collected. Solids, which were most likely algae growth dislodged from the clear plastic tubing used to supply source water to the skid, also accumulated on the needle valve regulating concentrate flow (PCV-10). As a result of this accumulation, concentrate flow rate dropped to zero on day 10 and 23. BUECI operators manipulated PCV-10 to dislodge accumulated solids and restore the target concentrate flow rate.

4.2.3 Pressure

Pressure data for the verification test is summarized in Table 4-1. The inlet pressure (i.e., the pressure provided by the raw water feed pump) averaged 37 psig and ranged from 25 - 48 psig. The feed pressure (i.e., the pressure of the combined raw water and concentrate streams fed to the C10 module) averaged 120 psig and ranged from 93 - 140 psig. The average concentrate pressure was 58 psig and ranged from 48 - 70 psig.

Table 4-1. Pressure and Transmembrane Pressure Summary Data

	Inlet (psig)	Feed (psig)	Concentrate (psig)	TMP (psig)
Average	37	120	58	88
Minimum	25	93	48	70
Maximum	48	140	70	102
Standard Deviation	3	8	5	6
Number of Samples	114	114	114	114
95% Confidence Interval	(37,38)	(120,120)	(58,59)	(87,89)

The minimum inlet pressure corresponded to the mechanical problems experienced with the recycle pump. On day 7, BUECI operators cleaned the pump valves and added oil to the skid pump. Within 10 minutes the pressure went from 92 psig to 115 psig indicating that the recycle

pump was unable to maintain the desired inlet pressure. The recycle pump was replaced on day 16. The highest inlet pressure of 137 psig was recorded on day 50. This elevated pressure corresponded to a concentrate flow meter calibration problem. When the concentrate flow meter was recalibrated, the inlet pressure dropped to 127 psig and remained near this value for the remainder of the verification test.

Figure 4-1 plots the transmembrane pressure (TMP) for the testing period. A general increase in the TMP from an initial value of 83 psig to a final value of 90 psig was observed during the verification test. The noticeable breaks in the data apparent in Figure 4-1 correspond to, and are likely the result of, the operational difficulties experienced with the recycle pump and concentrate flow meter. The local minimum observed after 119.5 hours of operation corresponded with a clogged recycle pump valve that reduced the inlet pressure. The local maximum observed after 649 hours of operation corresponded with cleaning of the concentrate and feed flow meters. The drop in TMP observed after 1175 hours of operation corresponded with the recalibration of the concentrate flow meter.
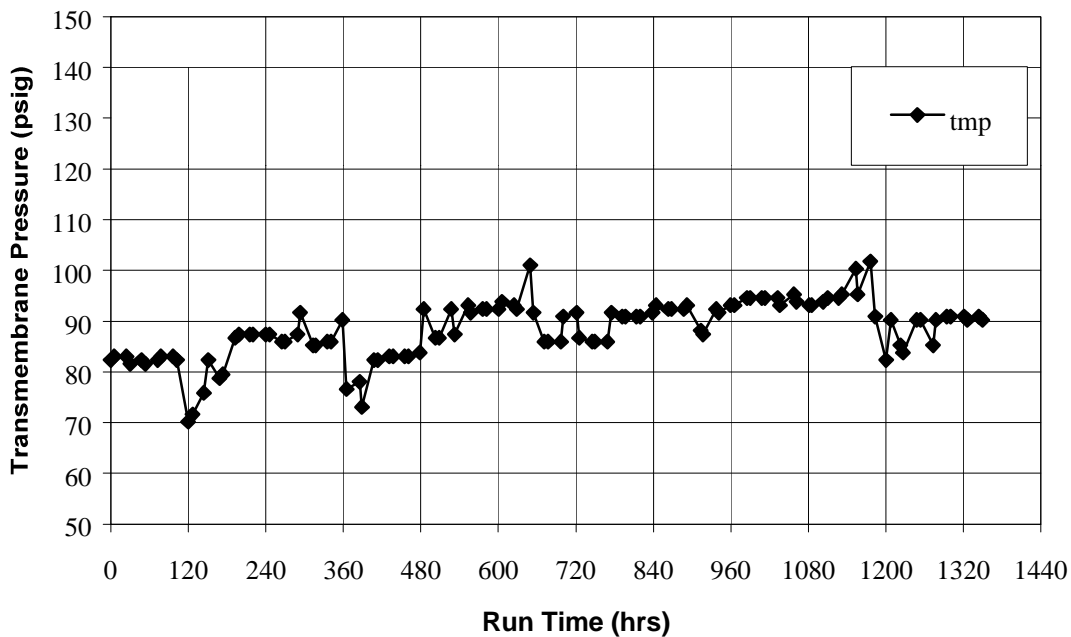
Figure 4-1. Transmembrane Pressure Data for the Verification Study

4.2.4   Temperature

The feed temperature ranged from 10 - 17.9 °C and averaged 14.4°C. The permeate temperature ranged from 12.6 - 18.6 °C and averaged 16.0 °C. The feed temperature was higher than the permeate temperature on 4 occasions. On these days the test skid was offline for a portion of the day allowing the raw water in the feed tank to increase in temperature.

4.2.5   Membrane Flux

The instantaneous flux for the verification test averaged 12.1 gfd and ranged from 10.6 – 13.4 gfd. In general, the instantaneous flux was more variable during the first month of testing when the mechanical problems with the recycle pump and concentrate flow meter were experienced. By the beginning of the second month of testing, instantaneous flux stabilized at approximately 12.4 gfd and remained stable throughout the remainder of the test period.

Figure 4-2 plots the specific flux data for the verification test period. The results of a linear regression of the data are also included in the figure. The specific flux value averaged 0.14 gfd/psi with minimum and maximum values of 0.11 and 0.16 gfd/psi, respectively. The scatter in the data is likely to due to day-to-day variations data collection time and the flow meter and pump problems previously described.   Despite this data variation, a slight decrease in specific flux during the study period is apparent. A rate of specific flux decline of 0.0002 gfd/psi/day was calculated by performing a linear regression on the specific flux data.
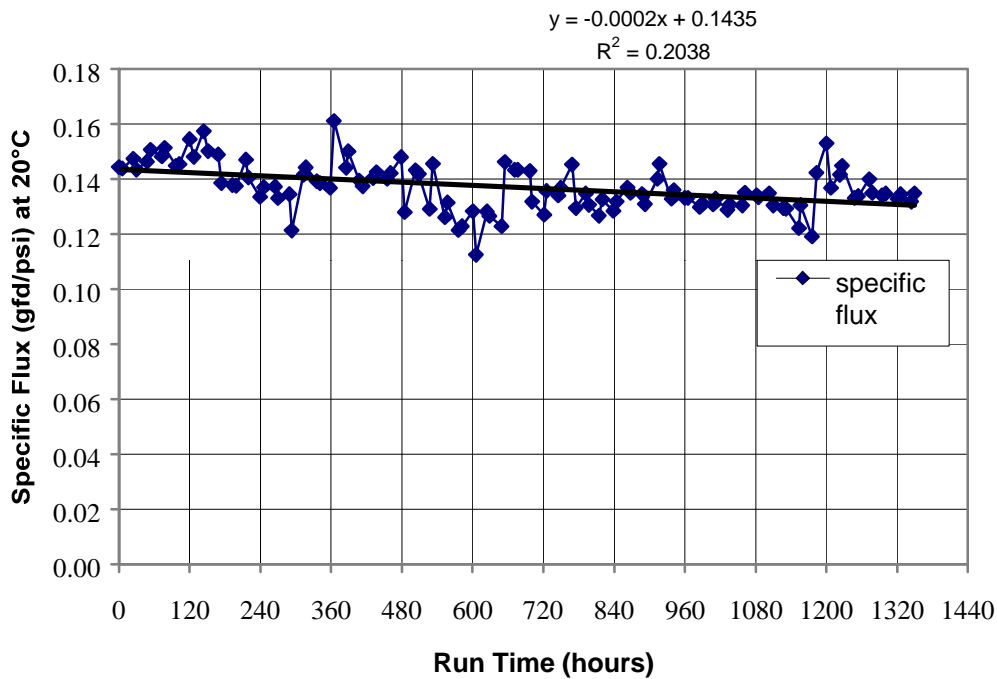
Figure 4-2. Test Skid Specific Flux Values

4.2.6   *Feedwater Recovery*

Figure 4-3 plots the feedwater recovery value for the verification testing period. The average recovery ranged from 77.1 - 82.4% and averaged 79.8%.
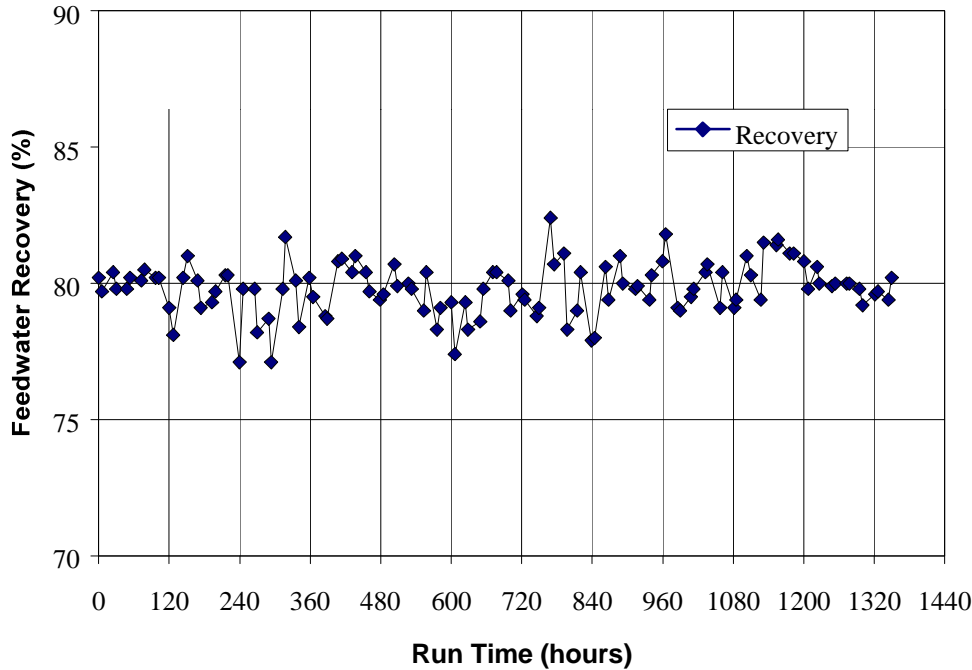
Figure 4-3. Test Skid Recovery

4.2.7   *Power Consumption*

The raw water pump had an average line current of 11.8 amps and an average power consumption for the study period of 1.09 kW. The skid 3-phase power average leg current was 1.0 amps and an average power consumption for the study period of 0.63 kW. The unit energy consumption rate was calculated by dividing the sum of the average feed pump and skid energy [(1.09 kW +0.63 kW) x 24 hr/day] by the average volume of permeate produced each day during the test period (1230 gallons/day). During the evaluation period, the test skid consumed 33.6 kW-hr of energy per 1000 gallons of permeate produced. However, it should be noted that 63% of the power was consumed by the raw water pump. Because this pump was not designed for this particular application, it operated at less than 2% efficiency. As a result, the power required to supply raw water to the skid were larger than would be expected for a full-scale system.

4.3 Task 2 - Cleaning Efficiency

4.3.1 Foam Ball Cleaning

The flux recovered due to foam ball cleaning was evaluated after 552 hours (23 days) of operation. The instantaneous and specific flux values at 20°C before cleaning were determined from the morning flow and pressure data. Afternoon flow and pressure data, which were collected 5 minutes after a foam ball cycle occurred, were used to determine the flux values after cleaning. The instantaneous and specific flux values at 20°C increased by 0.79 gfd and 0.011 gfd/psi, respectively, following the foam ball cleaning.

4.3.2 Chemical Cleaning

The test skid operated for the entire verification test without reaching a feed pressure of 175 psig, the criteria specified by PCI for chemical cleaning. A chemical cleaning was performed on the last day of operation to evaluate the effectiveness of the cleaning procedure. Approximately 0.28 lb. of NaOH was added to 28 gallons of permeate in the cleaning tank to produce a cleaning solution with an initial pH of 10.4. The solution was then circulated through the membrane module as described in Section 2.2.3 at a flow rate of 1.06 gpm. After approximately 1.5 hours of recirculation, the pH had dropped to 9 and the cleaning solution had a conductivity and TDS content of 494 µS and 260 mg/l, respectively. The turbidity of the cleaning solution was 9.66 NTU.

The cleaning solution was then discarded and permeate recirculated through the membrane module for approximately 15 minutes. The pH of the recirculated permeate was used to indicate when the cleaning solution had been effectively removed from the module. The test skid was then put back on line when the recirculated permeate reached 7.6. Flow rates and pressures were then measured to calculate a TMP and specific flux. Flow rates were also manually verified after the skid was placed back on line. The results of the chemical cleaning are summarized in Table 4-2. The single high pH chemical cleaning was able to recover 102.9% and 107.1% of the TMP and specific flux measured at the start of the verification study, respectively.

Table 4-2. Effect of Chemical Cleaning on TMP and Specific Flux

Parameter	Day 1*	Day 57*	After Cleaning	% of Day 1 Recovery
TMP (psig)	82.5	90.5	84.9	102.9%
Specific Flux at 20°C (gfd/psi)	0.14	0.13	0.15	107.1%

* data presented are the average of morning and afternoon readings

4.4 Task 3 – Finished Water Quality

The results of water quality analysis conducted on the source water, concentrate and permeate are presented in this section. In general, the test skid effectively removed organic DBP precursor compounds, iron, manganese and calcium, sulfate and particulates. Water quality data to support this statement are presented in the following sections. For convenience, the water quality data

have been separated into inorganic and organic parameters with a separate summary table created for each flow stream.

4.4.1   Inorganic Data

Tables 4-3, 4-4 and 4-5 summarize the feed, permeate and concentrate inorganic water quality parameters, respectively. Each table contains the average, minimum and maximum parameter values measured during the verification test along with the standard deviation and 95% confidence interval for each parameter.

Table 4-3. Feed Inorganic Water Quality Data Summary

Parameter *[number of samples]*	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
pH *[57]*	6.8	6.6	7.0	0.09	(6.8,6.8)
Turbidity (NTU) *[57]*	3.4	2.8	4.5	0.52	(3.3,3.6)
Conductivity (μS/cm) *[57]*	513	479	535	15.2	(509,517)
SDI *[4]*	9.49	0.17	17.9	7.97	(-3.19, 22.17)
Alkalinity (mg CaCO$_3$/l) *[4]*	56	55	57	0.96	(55,58)
Total Hardness (mg CaCO$_3$/l) *[4]*	75	68.8	79	4.3	(68,82)
Calcium Hardness (mg CaCO$_3$/l) *[4]*	35	31	37	2.6	(31,39)
Iron (mg/l) *[4]*	1.2	1.1	1.4	0.12	(1.1,1.4)
Manganese (mg/l) *[4]*	0.12	0.07	0.15	0.03	(0.06,0.17)
Bromide (mg/l) *[4]*	0.396	0.270	0.745	0.233	(0.0261,0.766)
Chloride (mg/l) *[4]*	93	82	110	12	(74,112)
Magnesium (mg/l) *[4]*	10	9	10	0.4	(9,11)
TDS (mg/l) *[4]*	298	281	320	16.7	(271,324)
TSS (mg/l) *[4]*	1.0	<2	1.5	0.3	(0.7,2)
Total Silica (mg/l) *[4]*	0.8	0.6	1.0	0.2	(0.6,1)
Dissolved Silica (mg/l) *[3]*	0.7	<0.5	1.0	0.30	(0.1,1)
Orthophosphate -P (mg/l) *[1]*	<0.5	<0.5	<0.5	NA*	NA*
Sulfate (mg/l) *[4]*	54	49	61.4	5.5	(45,62)
Total Phosphate (mg/l) *[3]*	<0.1	<0.1	<0.1	0	NA

NA = Not applicable because standard deviation = 0

NA* = Not applicable because sample size (n) was 1.

Note: Average, standard deviation and confidence intervals for TSS were calculated by assuming a value of one-half the reported laboratory detection limit as suggested in Gilbert (1987).

Table 4-4. Permeate Inorganic Water Quality Data Summary

Parameter *[number of samples]*	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
pH *[57]*	6.8	6.6	7.1	0.11	(6.8,6.9)
Turbidity (NTU) *[57]*	0.056	0.039	0.165	0.019	(0.051,0.061)
Conductivity (µS/cm) *[57]*	379	329	410	18.2	(374,384)
Alkalinity (mg CaCO$_3$/l) *[4]*	51	43	63	8.5	(37,65)
Total Hardness (mg CaCO$_3$/l) *[4]*	40	36	43	3.0	(36,45)
Calcium Hardness (mg CaCO$_3$/l) *[4]*	18	16	19	1.5	(16,20)
Iron (mg/l) *[4]*	0.007	<0.01	<0.025	0.004	(0.001,0.013)
Manganese (mg/l) *[4]*	0.05	0.03	0.06	0.02	(0.02,0.07)
Bromide (mg/l) *[4]*	0.394	0.270	0.726	0.222	(0.041,0.747)
Chloride (mg/l) *[4]*	96.5	85.8	100	7.1	(85.2,108)
Magnesium (mg/l) *[4]*	5.4	5.0	5.8	0.38	(4.6,6.3)
TDS (mg/l) *[4]*	195	180	200	10.0	(179,211)
TSS (mg/l) *[4]*	0.9	0.75	<2	0.1	(0.7,1)
Total Silica (mg/l) *[4]*	0.7	0.4	0.9	0.2	(0.3, 1)
Dissolved Silica (mg/l) *[3]*	0.6	<0.5	0.9	0.3	(0.1,1)
Orthophosphate - P (mg/l) *[1]*	<0.5	<0.5	<0.5	NA*	NA*
Sulfate (mg/l) *[4]*	5.2	3.5	6.5	1.4	(3,7.4)
Total Phosphate (mg/l) *[3]*	<0.1	<0.1	<0.1	0	NA

NA = Not applicable because standard deviation = 0

NA* = Not applicable because sample size (n) was 1.

Note: Average, standard deviation and confidence intervals for TSS and iron were calculated by assuming a value of one-half the reported laboratory detection limit as suggested in Gilbert (1987).

Table 4-5. Concentrate Inorganic Water Quality Data Summary

Parameter *[number of samples]*	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
pH *[57]*	7.0	6.8	7.3	0.1	(7,7)
Turbidity (NTU) *[57]*	6.8	0.21	15	2.5	(6.2,7.5)
TSS (mg/l) *[4]*	3	<2	7	3	(0.5,6)

Note: Average, standard deviation and confidence intervals for TSS were calculated by assuming a value of one-half the reported laboratory detection limit as suggested in Gilbert (1987).

4.4.1.1 TDS and Conductivity

The test skid reduced the raw water TDS by 34.5% from an average 298 mg/l in the raw water to an average of 195 mg/l in the permeate stream. Similarly, the feed conductivity was reduced from an average of 513 µS/cm to 379 µS/cm by membrane treatment.

4.4.1.2 TSS

TSS on all three flow streams was difficult to measure because most samples were at or near the detection limit of the method. TSS was detected in all three streams only during the first sampling event and based on these results, the membrane was able to remove 60% of the TSS present in the raw water. TSS was not detected in the concentrate on the second sampling event or in the feed and permeate for the remainder of the verification test.

4.4.1.3 Alkalinity

The skid removed 9% of the feed alkalinity reducing the raw water feed from an average of 56 mg $CaCO_3$/l to an average of averaged 51 mg $CaCO_3$/l in the permeate.

4.4.1.4 Bromide and Chloride

The feed and permeate concentrations of bromide and chloride indicated that the membrane was not effective at removing these anions.

4.4.1.5 Sulfate

The membrane rejected more than 80% of the sulfate present in the raw water reducing the feed concentration from an average of 54 mg/l to an average of 5.2 mg/l in the permeate.

4.4.1.6 Iron and Manganese

The membrane rejected more than 99% of the iron and 58% of the manganese present in the raw water. The iron concentration was reduced from an average of 1.2 mg/l to <0.01 mg/l by membrane treatment. (Note: Iron can foul membranes and should be considered for all membrane installations. However, the specific flux data indicates that significant fouling did not occur during this verification study). The manganese concentration was reduced from an average of 0.12 mg/l in the feed water to an average of 0.05 mg/l in the permeate.

4.4.1.7 Calcium Hardness, Total Hardness and Magnesium

The membrane removed approximately half of the magnesium, calcium and total hardness present in the feed water. Performance was consistent throughout the verification test. Calcium hardness was reduced by 47% from an average of 35 mg $CaCO_3$/l to an average of 18 mg $CaCO_3$/l. Similar results were observed for total hardness (a 46% reduction from 75 to 40 mg/l $CaCO_3$/l) and magnesium (a 46% reduction from 10 to 5.4 mg/l).

4.4.1.8 Total and Dissolved Silica

The results from April 4, 17 and May 5 sampling events indicated that that 80 - 100% of the total silica is dissolved. Dissolved and total silica concentrations greater than the detection limit were not reported for the first sampling event. The test skid removed an average of 12% of the total and 13% of the dissolved silica present in the raw water.

4.4.1.9 Turbidity

As shown in Figure 4-4, the test skid consistently produced a permeate turbidity of less than 0.1 NTU which corresponds to a 98.3% average removal. Only on one occasion (after 408 hours or 17 days of operation) did the permeate turbidity exceed 0.1 NTU with a value of 0.165 NTU. Feed turbidity values during the study increased from an initial value of 2.8 NTU to a final value of approximately 4.5 NTU. The concentrate contained a maximum turbidity of 15 NTU and the minimum was 0.2 NTU the average was 6.81 NTU.
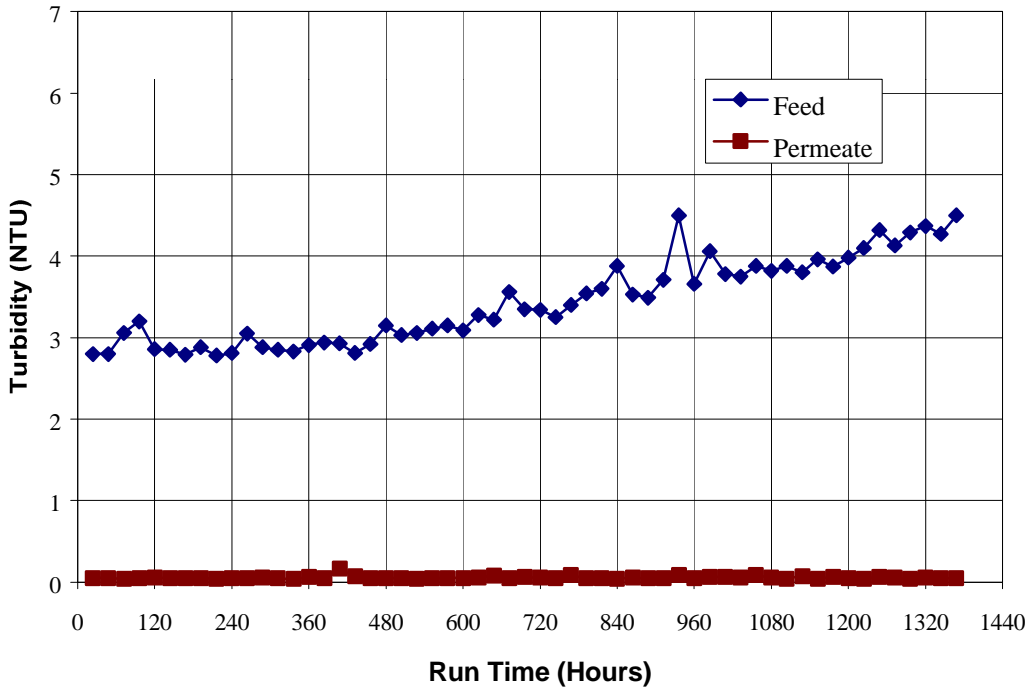
Figure 4-4. Raw Water and Permeate Turbidity

4.4.2 Organic Data

Tables 4-6, 4-7, and 4-8 summarize the results of the organic water quality analyses conducted on the feed, permeate and concentrate streams, respectively.

Table 4-6. Feed Organic Water Quality Data Summary

Parameter *[number of samples]*	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Color (CPU) *[17]*	124	97.4	197	22.9	(112,136)
TOC (mg/l) *[18]*	15	9.3	16	1.5	(14,15)
UV$_{254}$ Absorbance (cm^{-1}) *[55]*	0.52	0.41	1.53	0.19	(0.44,0.60)
TTHM (µg/l) *[4]*	544	400	605	97	(389,699)
HAA5 (µg/l) *[4]*	405	306	480	72	(290,520)

Table 4-7. Permeate Organic Water Quality Data Summary

Parameter *[number of samples]*	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Color (CPU) *[17]*	4.46	1.53	13.0	4.18	(2.31,6.62)
TOC (mg/l) *[18]*	0.7	0.4	1.2	0.2	(0.6, 0.8)
UV_{254} Absorbance (cm^{-1}) *[55]*	0.012	0.00	0.032	0.0078	(0.009,0.016)
TTHM (µg/l) *[4]*	31	21	46	11	(15, 48)
HAA5 (µg/l) *[4]*	6.7	4	11	3.1	(1.7, 12)

Table 4-8. Concentrate Organic Water Quality Data Summary

Parameter *[number of samples]*	Average	Minimum	Maximum	Standard Deviation	95% Confidence Interval
TOC *[11]*	83	59	100	13	(73, 92)

4.4.2.1 UV_{254} Absorbance and Color

Figure 4-5 plots the UV_{254} absorbance measured in the feed and permeate streams during the verification study and Figure 4-6 plots the percent removed by the test system. On average, the membrane removed 97% of the UV_{254} absorbing material present in the raw water, reducing the feed UV_{254} from an average of 0.517 cm^{-1} to 0.012 cm^{-1}. The maximum readings occurred in the feed water after 216, 312 and 336 hours of operation (day 9, 13, and 14). Although these values appear abnormally high, the analyses were duplicated to verify these results. Figure 4-7 plots the color of the feed and permeate. On average, the test skid reduced the raw water color by 96% producing a permeate that averaged less than 5 CPU.
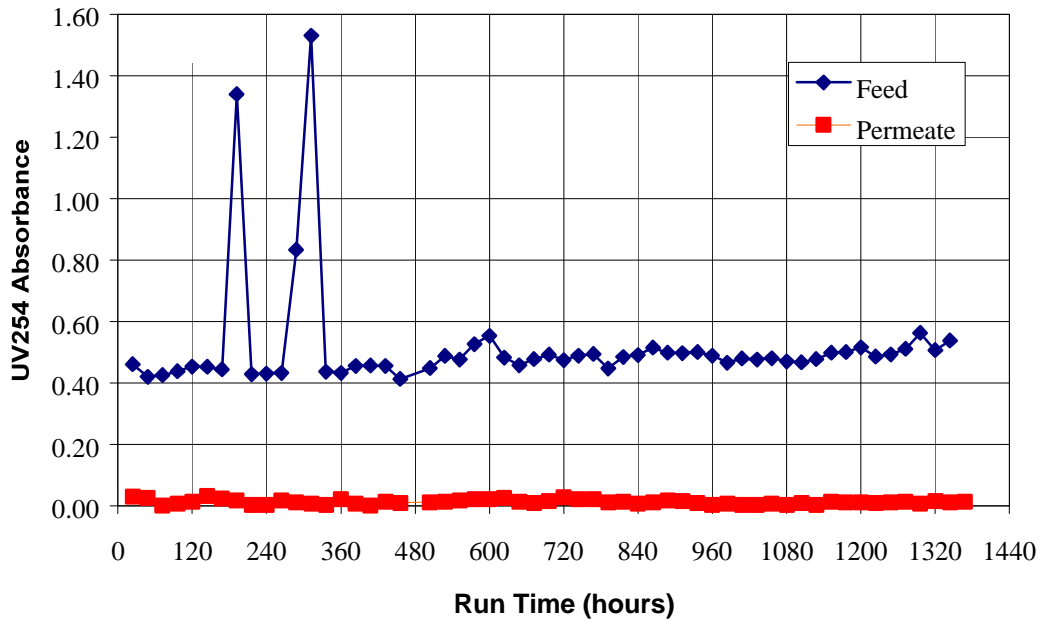
Figure 4-5. Raw Water and Permeate UV$_{254}$ Absorbance
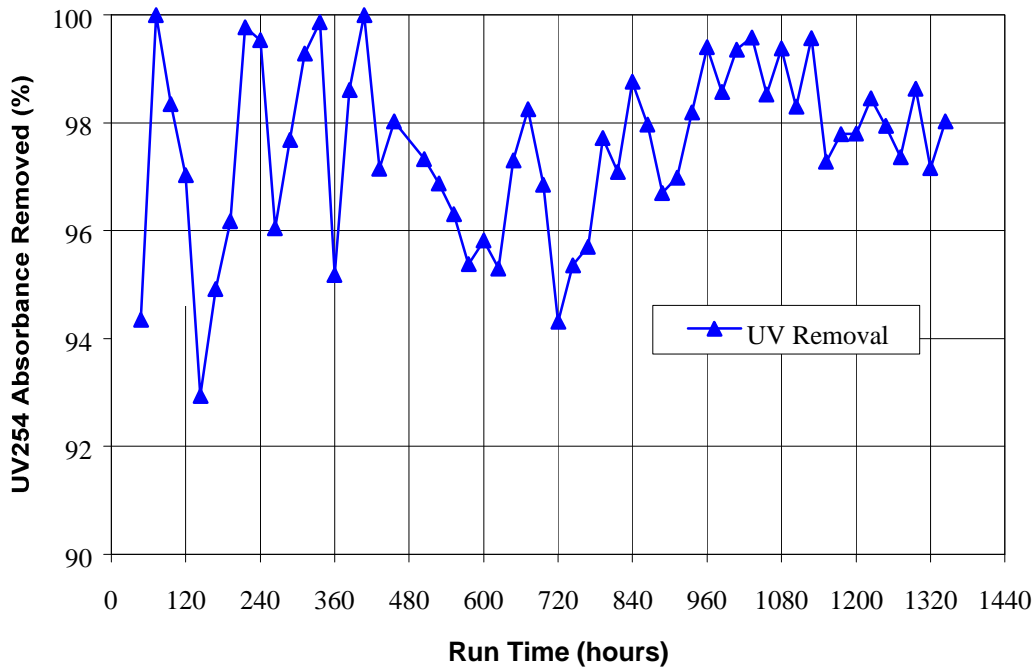
Figure 4-6. Percent of UV$_{254}$ Absorbance Removed
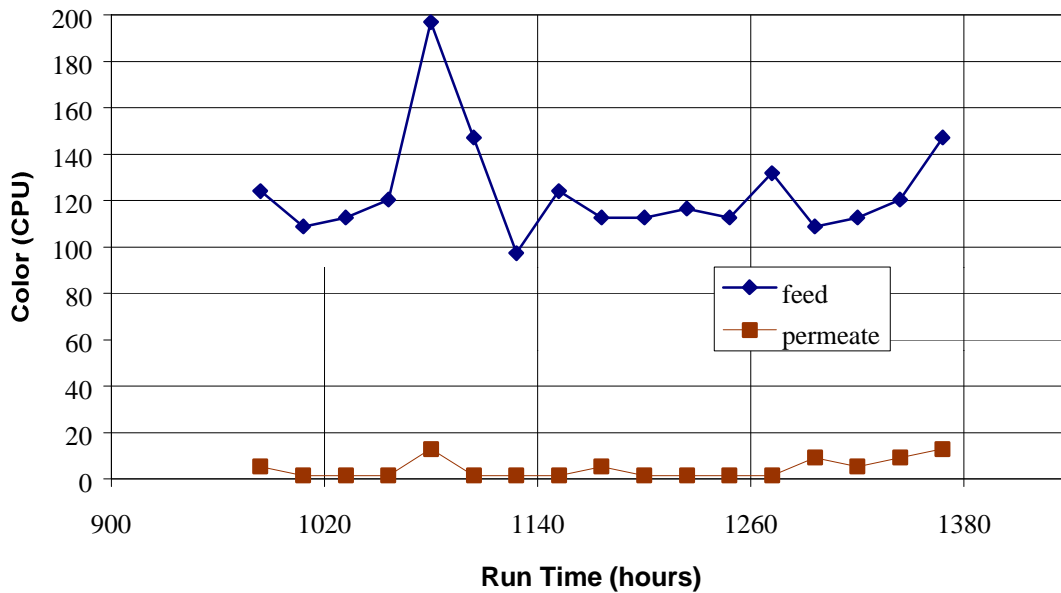
Figure 4-7. Raw Water and Permeate Color

4.4.2.2 TOC

TOC concentrations of the feed, permeate and concentrate are plotted in Figure 4-8. Minimum feed TOC (9.3 mg/l) was measured after 24 hours (1 day) of operation, but after 120 hours of operation (5 days) the concentration had increased to 15 mg/l. The feed TOC ranged from 14-16 mg/l for the remainder of the testing period. TOC in the permeate ranged from 0.4-1.2 mg/l and averaged 0.7 mg/l. On average, the test skid removed 95% of the TOC present in the raw water. The concentrate TOC, which was more variable than the feed and permeate concentrations, ranged from 59 mg/l – 100 mg/l. The percent TOC removed by the membrane treatment system is summarized in Figure 4-9
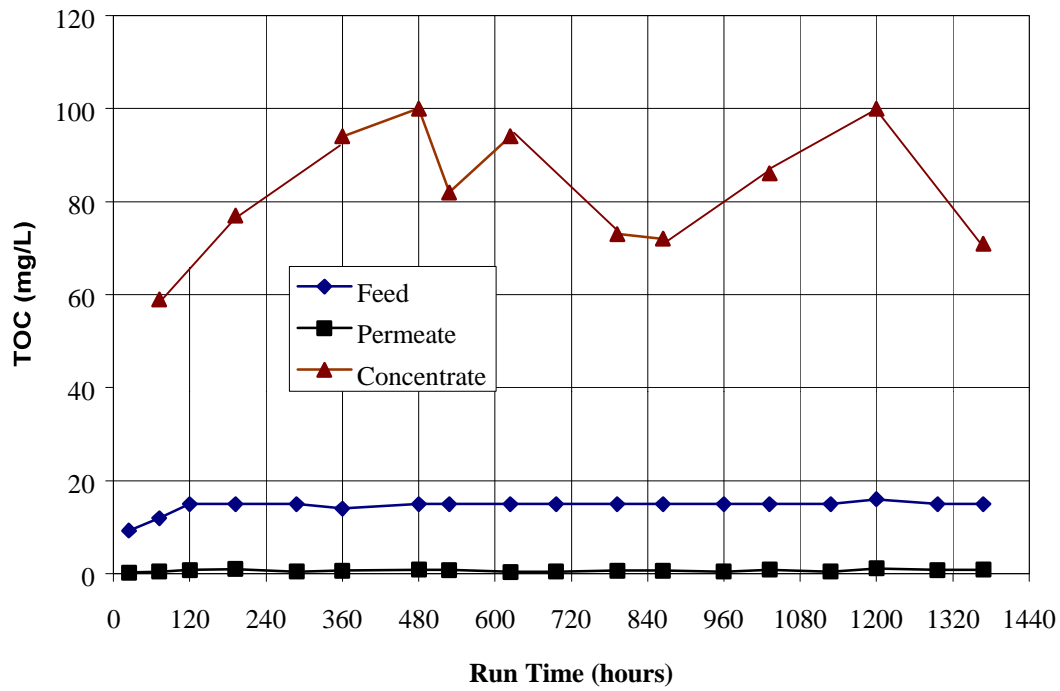
Figure 4-8. Raw Water, Permeate and Concentrate TOC Concentrations

Figure 4-9. Percent of TOC Removed

4.4.2.3 TTHM and HAA5

Table 4-9 summarizes the individual THMs and HAAs detected from the UFC incubation samples during the verification test. A general shift in the distribution of DBPs from chlorinated DBP's in the feed to brominated DBPs in the permeate was observed. For example, bromoform comprised less than 2% of the TTHMs in the feed but 40 - 65% of the TTHMs in the permeate. Chloroform, the major DBP species in the feed, typically accounted for less than 3% of the TTHMs in the permeate. A similar shift was observed with HAA's. Trichloroacetic and dichloroacetic acid comprise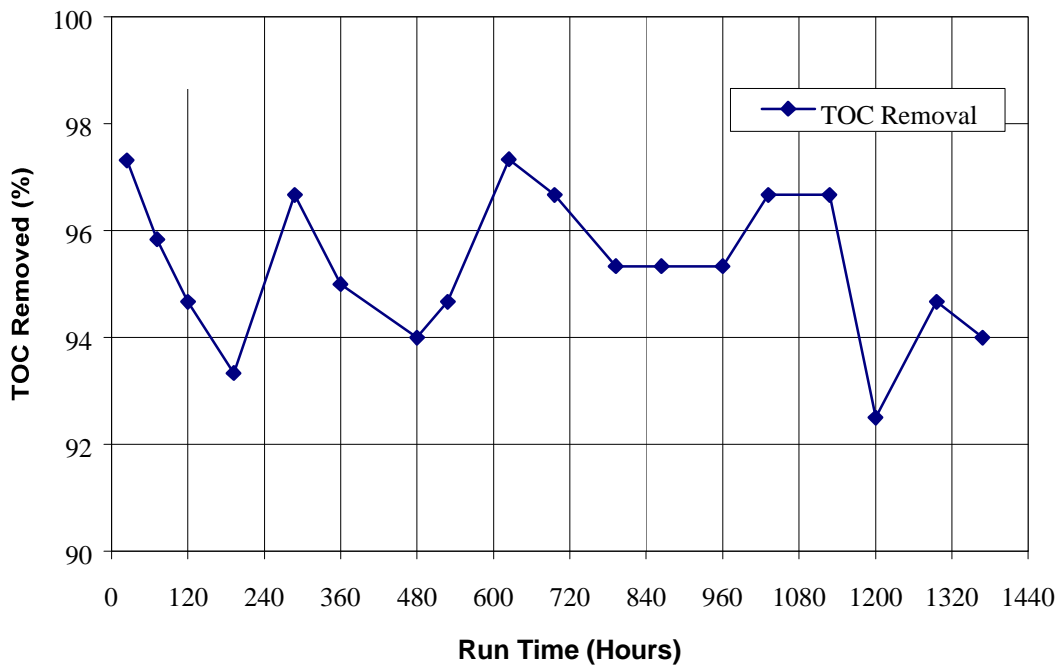d greater than 90% HAAs present in the feed but neither compound was detected in the permeate. Dibromoacetic acid, which accounted for less than 2% of the feed HAAs, comprised 80 - 100% of the permeate HAAs.

Table 4-9. Individual Trihalomethane and Haloacetic Acid Species

Compound	3/19/00		4/4/00		4/17/00		5/5/00	
	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate
Trihalomethanes								
Chloroform (μg/l)	430	0.51	290	1.5	420	0.7	367	<0.5
Bromodichloromethane (μg/l)	150	3.2	93	6.3	160	3.7	137	1.6
Chlorodibromomethane (μg/l)	25	11	16	12	22	11	24	6.6
Bromoform (μg/l)	<15	15	0.7	26	0.8	14	0.9	12
TTHM (μg/l) [+]	600	30	400	46	600	29	528	20
Haloaceteic Acids								
Monobromoacetic Acid (μg/l) *	2.3	<1.00	2	<1	2	<1	1	<1
Monochloroacetic Acid (μg/l) *	9	<1.00	12	1.7	9	<2	9	<2
Bromchloroacetic Acid (μg/l)	35	1.9	41.7	3.33	45	2	47.7	<1
Dibromoacetic Acid (μg/l) *	4.9	4.8	4	9	5	7	7	3
Dichloroacetic Acid (μg/l) *	120	<1.00	173	<1	180	<1	173	<1
Trichloroacetic Acid (μg/l) *	170	<1.00	243	<1	220	<1	243	<1
Chlorodibromoacetic Acid (μg/l)	8.6	3.1	NA	NA	NA	NA	NA	NA
Tribromoacetic Acid (μg/l)	<4.00	10	NA	NA	NA	NA	NA	NA
Bromodichloroacetic Acid (μg/l)	50	<1.00	NA	NA	NA	NA	NA	NA
HAA5 (μg/l)[+] (sum of *)	306	4.8	435	10	416	7	434	3

4/4/00 Individual HAA and HAA5 results are average of triplicate data
5/5/00 Individual THM and HAA and TTHM and HAA5 are average of triplicate data
+ HAA5 and TTHM values are the sum of individual species detected at concentrations above the detection limit.
NA= not analyzed

Figure 4-8 graphs the overall percent removal of TTHM and HAA5 formed during incubation under the Uniform Formation Conditions for each sampling event. The test skid removed 88.6 - 96.2% of TTHM and 97.6 - 99.4% of HAA5. The membrane produced a permeate with an average was 31.3 µg/l TTHM and 6.2 mg/l HAA5. The EPA Stage 1 D/DBP Rule requires TTHM and HAA5 concentrations not exceed 80 µg/l and 60 µg/l, respectively.
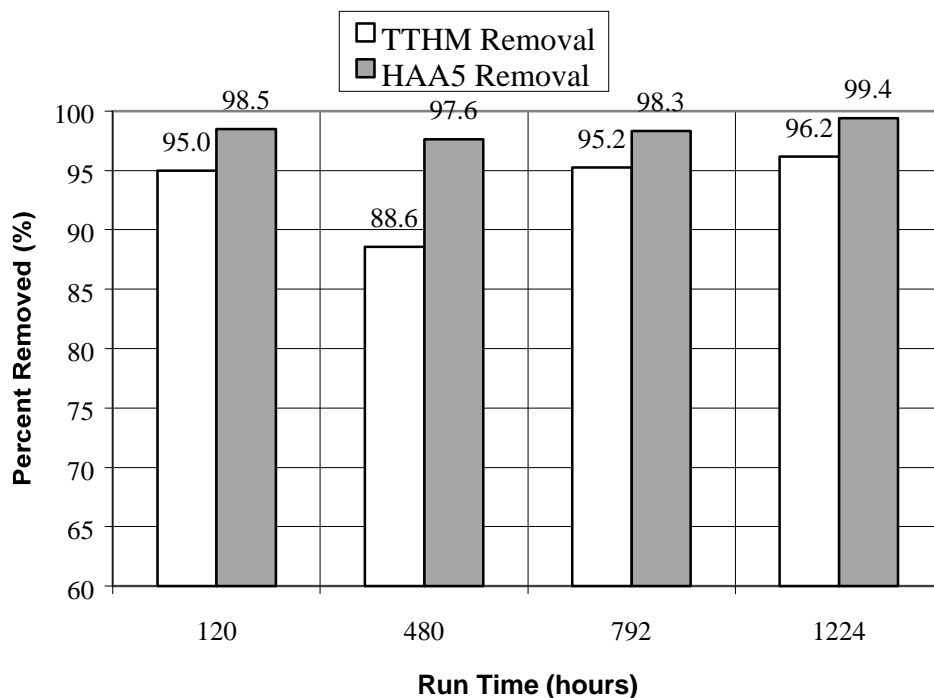

Figure 4-10. Percent TTHM and HAA5 Removal for each Sampling Event

4.5   Task 4 - Data Management

Data management for the verification test was accomplished using checklists, schedules, site visits and interim reports. BUECI operators completed data sheet provided in Appendix A each day of the verification test. For the first two weeks of operation, data sheets were emailed every second or third day to UAA for review. This procedure was discontinued after stable system operation had been demonstrated to UAA staff. The daily datasheets were then collected every two weeks when UAA staff traveled to Barrow for a sampling event. BUECI operators updated UAA staff if any change in operation occurs via email or telephone.

UAA staff verified the daily data sheets noting any errors, questions and corrections on the original sheets in pen along with the initials of the reviewer. The verified data was then entered into a spreadsheet and spot-checked for accuracy by a second member of the UAA staff.

Laboratory data was tracked through complete chain of custody reports. Checklists for samples analyzed in the UAA lab were also prepared. All lab reports were reviewed by UAA staff and any errors, questions and corrections noted in pen on the original lab reports. All lab data was entered into a spreadsheet and spot checked by a second member of the UAA staff.

4.6   Task 5 – Quality Assurance/Quality Control

In this section, the results of the quality assurance/quality control plan are provided. Quantification of data precision and statistical uncertainty, the results of control blanks, meter verifications, and a summary of relevant notes that qualify verification study data are provided.

4.6.1   Data Precision and Statistical Uncertainty

The results of the triplicate analysis conducted to determine data precision and statistical uncertainty are summarized in Table 4-10, which is divided into sections for feed, permeate and concentrate. Each section contains the average, minimum and maximum values obtained from the triplicate analysis conducted on the on-site and off-site water quality parameters during the verification study. Statistical analysis was performed on all parameters except color. Feed TSS and total phosphate and permeate iron, TSS, and total phosphate and concentrate TSS were below the method detection limit used by the laboratory so statistical analysis could not be performed on these parameters.

Two sets of triplicate analysis for HAA5 were conducted during the verification study. On April 4, tripilcate samples were collected from a single 1-L incubation bottle (for both feed and permeate) and analyzed for HAA. On May 5, a single sample was collected (for both the feed and permeate) from three replicate 1-L incubation bottles which were dosed with the identical chlorine and mixed buffer solutions.

Table 4-10. Statistical Analysis of Triplicate Samples

Feed							
Parameter	Date	Avg.	Min.	Max.	Std. Dev.	95% LCL	95% UCL
pH	4-Apr	6.8	6.8	6.8	0	NA	NA
Conductivity (μS/cm)	4-Apr	519	518	520	1.00	517	521
Turbidity (NTU)	4-Apr	3.54	3.52	3.57	0.03	3.48	3.61
Temperature (°C)	4-Apr	14.3	14.3	14.4	0.06	14.2	14.5
SDI	11-May	16.5	15.3	17.9	1.35	13.1	19.8
UV_{254} Absorbance (cm^{-1})	17-Apr	0.494	0.493	0.495	0.001	0.492	0.496
Total Alkalinity (mg $CaCO_3$/l)	4-Apr	55	55	56	0.58	54	57
Total Hardness (mg $CaCO_3$/l)	4-Apr	76	76	76	0	NA	NA
TOC (mg/l)	11-May	16	15	16	0.58	14	17
Iron (mg/l)	4-Apr	1.2	1.1	1.2	0.058	1.0	1.3
Manganese (mg/l)	4-Apr	0.09	0.07	0.10	0.02	0.05	0.13
Magnesium (mg/l)	4-Apr	10	10	10	0	NA	NA
Calcium Hardness (mg $CaCO_3$/l)	4-Apr	35	35	35	0	NA	NA
TSS (mg/l)	4-Apr	<2	<2	<2	0	NA	NA
TDS (mg/l)	4-Apr	290	290	290	0	NA	NA
Total Phosphate (mg/l)	4-Apr	<0.1	<0.1	<0.1	0	NA	NA
Sulfate (mg/l)	4-Apr	49	49	49	0	NA	NA
Silica (dissolved) (mg/l)	4-Apr	0.8	0.7	1.0	0.2	0.4	1
Silica (total) (mg/l)	4-Apr	0.9	0.8	1.0	0.1	0.7	1
Chloride (mg/l)	4-Apr	81	80	82	1.0	79	83
Bromide (mg/l)	4-Apr	0.210	0.090	0.270	0.104	-0.048	0.468
TTHM (μg/l)	5-May	530	500	570	36.1	440	620
HAA5 (μg/l)	4-Apr	435	418	468	28.6	364	506
HAA5 (μg/l)	5-May	434	397	480	42.3	328	539

NA= not applicable because the standard deviation is zero.

Table 4-10. Statistical Analysis of Triplicate Data- Continued

Permeate

Parameter	Date	Avg.	Min.	Max.	Std. Dev.	95% LCL	95% UCL
pH	4-Apr	6.63	6.60	6.65	0.0289	6.56	6.71
Conductivity (µS/cm)	4-Apr	359	358	359	0.577	357	360
Turbidity (NTU)	4-Apr	0.05	0.04	0.05	0.005	0.03	0.06
Temperature (°C)	4-Apr	15.6	15.5	15.6	0.0577	15.4	15.7
UV254 Absorbance (cm^{-1})	17-Apr	0.011	0.009	0.013	0.0021	0.0062	0.017
Total Alkalinity (mg CaCO$_3$/l	4-Apr	48	46	50	2.08	42	53
Total Hardness (mg CaCO$_3$/l)	4-Apr	43	43	43	0	NA	NA
TOC (mg/l)	11-May	0.8	0.8	0.9	0.06	0.7	1.0
Iron (mg/l)	4-Apr	<0.01	<0.01	<0.01	0	NA	NA
Manganese (mg/l)	4-Apr	0.03	0.03	0.03	0	NA	NA
Magnesium (mg/l)	4-Apr	5.8	5.8	5.8	0	NA	NA
Calcium Hardness (mg/l)	4-Apr	19	19	19	0	NA	NA
TSS (mg/l)	4-Apr	<2	<2	<2	0	NA	NA
TDS (mg/l)	4-Apr	200	200	200	0	NA	NA
Total Phosphate (mg/l)	4-Apr	<0.1	<0.1	<0.1	0	NA	NA
Sulfate (mg/l)	4-Apr	6.6	6.5	6.7	0.12	6.3	6.9
Silica (dissolved) (mg/l)	4-Apr	0.5	0.4	0.6	0.12	0.2	0.8
Silica (total) (mg/l)	4-Apr	0.6	0.6	0.7	0.06	0.5	0.8
Chloride (mg/l)	4-Apr	96	89	100	6.35	81	112
Bromide (mg/l)	4-Apr	0.267	0.260	0.270	0.010	0.252	0.281
TTHM (µg/l)	7-May	20	19	22	1.53	17	24
HAA5 (µg/l)	4-Apr	10	9	11	1.15	7	13
HAA5 (µg/l)*	7-May	4	3	4	0.87	1	6

* one half of the detection limit for the samples with HAA5 concentrations below the detection limit was assumed to calculate the standard deviation and confidence intervals.

NA = not applicable because the standard deviation is zero.

Concentrate

Parameter	Date	Avg.	Min.	Max.	Std. Dev.	95% LCL	95% UCL
pH	4-Apr	6.90	6.90	6.90	0	NA	NA
Turbidity (NTU)	4-Apr	6.56	6.50	6.63	0.07	6.40	6.72
TSS (mg/l)	4-Apr	<2	<2	<2	0	NA	NA
TOC (mg/l)	11-May	71	65	75	5.3	58	84

NA = not applicable because the standard deviation is zero.

4.6.2   Field Blank

A field blank was sent along with each sampling event. THMs were not detected in the field blanks.

4.6.3   Reagent Blank

THMs and HAAs were not detected in mixed buffer solution sent to the lab for analysis after incubation with free chlorine.

4.6.4   Initial TTHM and HAA Concentration

Samples of feed and permeate water were brought to UAA and quenched with the appropriate quenching agent (without chlorination). THMs and HAAs were not detected in either sample.

4.6.5   Flow Meter Verification

The permeate and concentrate flow rates were verified at least once per week using a stopwatch and volumetric container. The raw water (or feed) flow rate was verified by calculation from the manually measured concentrate and permeate flow rates. In addition, the permeate "meter" reading was actually a value calculated from the feed and concentrate meter readings because there was no flow meter on the permeate line.

All of the manually measured permeate and calculated raw water flow rates were within 10% meter values. The manually measured concentrate flow rates exceeded meter reading by more than 10% after 288, 624, 648 and 792 hours (12, 26, 27, and 33 days) of operation. The maximum difference (24.5%) was reported after 624 hours (26 days) of operation. In response, a flow meter verification was also performed after 648 hours (27 days) of operation. The value (23.1% difference) was similar to that measured after 624 hours (26 days) of operation.   The operators inspected the flow meters and found solids within the concentrate and feed flow meter. The cleaning helped to stabilize the reading after 792 hours of operation when the manual flow rate check resulted in a 16.5% difference. The meter was recalibrated again on after 864 hours (36 days) of operation and again after 1200 and 1224 hours (50 and 51 days) of operation.

4.6.6   Turbidity Calibration

The 0.3 NTU secondary standard meter reading differed from the standard value by greater than 10% (10.3%-16.3%) on 8 instances during the verification study. The 0.5 NTU secondary standard meter reading did not differ from the standard value by greater than 10% during the verification study. The 1.0 NTU secondary standard meter reading differed from the standard value by greater than 10% (10%-11%) on 3 instances during the verification study. The turbidimeter was recalibrated with primary standards before verification testing began and once after 792 hours of operation.

4.6.7 Conductivity Meter Calibration

The conductivity meter consistently read the standards within 2% difference.

4.6.8 Level 3 Data Review for CT&E Samples

A level 3 data report was provided by CT&E for the first sampling event (18 March 2000). UAA staff reviewed this documentation and noted the following data qualifiers:

- The feed sample analyzed by CT&E after incubation on 21 March 2000 reported surrogates outside of acceptable limits for TTHM's. CT&E used three surrogates in their analysis. The recovery of 1,2- dichloroethane-D4 was 135%, which exceeded the allowable recovery limit of 78-120%. The recovery of tolune-D8 was reported as 129%, which exceeded the allowable limit of 96-112%. Finally, the recovery of 4-bromofluorobenze was 132%, which exceeded the allowable limit of 93-107%. The data was properly footnoted regarding the surrogate failure. The footnote attributed the failed recoveries to sample dilution (the sample was diluted 30:1).
- The continuing calibration verification sample analyzed by CT&E on 20 March 2000 after incubation failed for chloroethane. Chloroethane was not detected in the permeate sample analyzed on that date.
- Total suspended solids analysis for the permeate sample submitted on 20 March 2000 exceeded the relative percent difference (RPD) limit of 21% between duplicate samples (actual RPD was 40%).

4.6.9 Additional Data Qualifiers and Notes

Over the course of the verification study there were several issues with sample labels and shipment. These include:

- Sample labels on the feed and permeate HAA samples analyzed on day 20 were switched. The data is properly reported in this report and noted on the laboratory data sheets.
- The March 16, 2000 feed sample for UV_{254} analysis was broken in transit. April 4, 2000 samples were not collected.
- The April 5, 2000 samples after incubation for 24 hours contained 1.6 mg Cl_2/l. This residual exceeded the 1.4 mg/l upper target concentration specified in the UFC protocol. The incubation procedure was not repeated due to lack of an available water sample.
- A review of the daily data sheets indicates that a pH check or calibration was not conducted on 6 instances when pH readings were collected. However, no more than two consecutive days were collected without a pH check/calibration being conducted.
- During the site visit on day 20 of the verification test, NSF raised some concerns regarding algae growth in the clear plastic tubing used to transfer the permeate to drain. In response, a sample tap was installed on day 33 at the module outlet that allowed permeate samples to be collected before entering the permeate tubing. On

the day 33 a UV_{254} sample was taken from the tap and the end of the tubing. The sample from the end of the tubing contained 150% more UV_{254} absorbance than the sample taken from the tap indicating that the biofilm present in the tubing was releasing organic material into the finished permeate.

Chapter 5
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