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Environmental Technology Verification Report

Removal of Inorganic, Microbial, and Particulate Contaminants from a Fresh Surface Water

Village Marine Tec. Expeditionary Unit Water Purifier, Generation 1

Prepared by

NSF International

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

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THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**ULTRAFILTRATION AND REVERSE OSMOSIS**
APPLICATION:	**REMOVAL OF CHEMICAL AND MICROBIAL CONTAMINANTS FROM A SURFACE DRINKING WATER SOURCE**
PRODUCT NAME:	**EXPEDITIONARY UNIT WATER PURIFIER (EUWP), GENERATION 1**
VENDOR:	**VILLAGE MARINE TEC.**
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NSF International (NSF) manages the Drinking Water Systems (DWS) Center under the U.S. Environmental Protection Agency's (EPA) Environmental Technology Verification (ETV) Program. The DWS Center evaluated the performance of the Village Marine Tec. Generation 1 Expeditionary Unit Water Purifier (EUWP). The EUWP, designed under U.S. Military specifications for civilian use, employs ultrafiltration (UF) and reverse osmosis (RO) to produce drinking water from a variety of sources. This document provides the verification test results for the EUWP system evaluated at a fresh surface water site at Selfridge Air National Guard Base in Michigan.

EPA created the 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 accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations, stakeholder groups (consisting of buyers, vendor organizations, and permitters), and with the voluntary 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.

PRODUCT DESCRIPTION

The following technology description was provided by the manufacturer and has not been verified.

The EUWP was developed to treat challenging water sources with variable turbidity, chemical contamination, and very high total dissolved solids (TDS) including seawater, during emergency situations when other water treatment facilities are incapacitated. The EUWP components include feed pumps, a UF pretreatment system, a one or two pass RO desalination system with an energy recovery device, storage tanks, and product pumps. It has chemical feed systems for optional pretreatment coagulation and post treatment chlorination. Clean-in-place systems (CIP) are included with the UF and RO skids. During this verification test, coagulation pretreatment was employed, but chlorination was not evaluated.

Design specifications indicate that the UF system alone has a production capacity up to 250,000 gallons per day (gpd) from a fresh water source with up to 500 mg/L TDS and a temperature of 25°C. The combined UF and RO system is designed to produce from 98,000 gpd up to 162,000 gpd, depending on the TDS of the source water and the recovery settings of the RO process.

VERIFICATION TEST DESCRIPTION

Test Site

The testing site was Lake St. Clair at Selfridge Air National Guard Base in Michigan. The source water for testing was raw lake water. Initial characterization samples of raw lake water were collected in August 2006, and again in May 2007 for the second round of testing. Highlights of the source water characterization are presented in Table VS-i. The measured concentrations of regulated metals, phosphorus, nitrite, and nitrate are not shown here, but are presented in the final report, because they are either below the laboratory reporting limit or below the limit in the EPA National Primary Drinking Water Regulations (NPDWR) limit.

Table VS-i. Lake St. Clair Raw Water Characterization Data

Parameter	Sample Date 08/16/06	05/31/07
Total Organic Carbon (TOC, mg/L)	2.9	NM[1]
UV Light Absorbance at 254 nanometers (UV_{254}, Abs)	0.0668	NM
Total Suspended Solids (TSS, mg/L)	<5	<2
TDS (mg/L)	130	140
Alkalinity (mg/L as $CaCO_3$)	70	86
Total Hardness (mg/L as $CaCO_3$)	95	110
Total Silica (mg/L as SiO_2)	1.1	1.1
Specific Conductance (µmhos/cm)	NM	250
Cryptosporidium (oocysts/L)	<1	NM
Giardia (cysts/L)	<1	NM
Heterotrophic Plate Count (HPC, CFU/mL)	500	NM
Total Coliforms (CFU/100 mL)	291	NM
Bacillus Endospores (CFU/100 mL)	NM	689

(1) NM = not measured

Methods and Procedures

Initial testing of the EUWP was conducted in September and October of 2006 by the U.S Army Tank-Automotive Research, Development, and Engineering Center (TARDEC), with assistance from the U.S. Bureau of Reclamation (USBR). Immediately prior to the ETV test, the initial UF pressure decay tests indicated that pressure was being lost at a higher than desirable rate. The problem was investigated, and

was found to be the o-ring seals between the membrane modules and filtrate collection tubes. As a temporary fix, polytetrafluoroethylene (Teflon®) thread sealing tape was wrapped around the o-rings to increase the seal surface between the o-rings and membrane cartridges, and the test proceeded. After testing was complete, the UF performance data indicated that the temporary fix did not maintain sufficient membrane integrity. Therefore, a second test employing only the UF system was conducted in July and August of 2007 after permanent repairs were made. Issues concerning the seal problems and subsequent repairs are discussed in the ETV verification report.

The testing activities followed a test/quality assurance plan (TQAP) prepared specifically for the project. The TQAP was developed in accordance with the ETV Protocols *EPA/NSF Protocol for Equipment Verification Testing for Removal of Inorganic Constituents* – April 2002, and the *EPA/NSF Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants* – September 2005.

The 2006 verification test began on September 25, and ran for the planned 30 day test period, ending on October 25. The UF system was operated each day on semi-continuous basis, automatically shutting down when the RO feed tank was full. A typical operating day for the UF system was 15-17 hours (h) in duration. The RO system was setup to operate continuously, and typically ran 22 to 24 h per day. The RO system was shutdown periodically for various maintenance activities, or when alarms occurred and shut the system down. When alarms and shutdown occurred during unattended operation at night, the entire system would remain shutdown until an operator arrived in the morning.

The 2007 UF system retest was conducted from July 30 to August 24. The retest was stopped short of 30 days because the intent of the test as stated in the ETV test protocol – operation until a membrane cleaning was needed – was met. During the retest, the UF system was in operation an average of 14 h per day, not including down time for backwashes, cleanings, and other maintenance activities.

Flow, pressure, conductivity, and temperature recordings were collected twice per day when possible to quantify membrane flux, specific flux, flux decline, and recovery. Turbidity and pH readings were also recorded twice per day. The UF skid included in-line particle counters which recorded particle counts every five minutes. Pressure decay tests were conducted daily on the UF system to verify membrane integrity. Once per week samples were collected from the UF and RO process streams for analysis of alkalinity, hardness, total silica, TDS, TOC, TSS, UV_{254}, HPC (2006 test only), and total coliforms (2006 test only). For the 2007 test, *Bacillus* endospores were substituted for HPC and total coliforms.

VERIFICATION OF PERFORMANCE – 2006 TEST

Finished Water Quality

The UF system reduced the turbidity from a mean of 4.77 Nephelometric Turbidity Units (NTU) in the feed water to a mean of 0.14 NTU in the UF filtrate. The UF system reduced the turbidity of the feed water by a mean value of 95.9%. All filtrate turbidity measurements were below the NPDWR of 1 NTU. The second NPDWR criterion for turbidity is that 95% of the daily samples in any month must be ≤0.3 NTU. Only one filtrate turbidity measurement out of 58 was above 0.3 NTU: 0.47 NTU on October 5. Therefore, the EUWP UF system met the second NPDWR turbidity requirement, as 98% of the turbidity measurements were ≤0.3 NTU.

The RO membranes provided additional turbidity removal, resulting in a mean turbidity of 0.09 NTU from the permeate grab samples. The maximum measured RO permeate turbidity was 0.18 NTU. In general, the RO system provided an additional turbidity reduction in the range of 40% to 66%.

The UF system showed only a minor reduction in organic material as measured by the TOC data. The UF feed TOC concentrations ranged from 2.1 to 2.7 mg/L, and the UF filtrate levels were typically only 0.1 to 0.4 mg/L lower. These data indicate that most of the organic material, as measured by TOC, was dissolved in the feed water. The RO system reduced the permeate TOC to below the detection limit of 0.1 mg/L.

The RO system also reduced the dissolved ions in the water, as measured by conductivity, with a mean percent reduction of 99.4%. The mean conductivity of the RO permeate was 1.8 microSiemens per centimeter (μS/cm) compared to a mean RO feed conductivity of 287 μS/cm. The maximum measured permeate conductivity was 4.9 μS/cm. Hardness, alkalinity, TDS, and total silica were all removed to below the detection limit in the RO permeate.

UF and RO Membrane Integrity

Daily pressure decay tests were used to document UF membrane integrity, and HPC and total coliforms were measured in the UF feed and filtrate as a microbial membrane integrity indicator. The in-line particle counters provided an additional measurement of membrane integrity, and the capability of the system to remove particulate and microbial contaminants.

As discussed in the Methods and Procedures section, prior to the 2006 test TARDEC and USBR discovered that the seals between the UF elements and membrane module housings were not as tight as desired. After the problem was temporarily fixed, the pressure decay rate was measured as 0.37 pounds per square inch, gauge (psig) per minute (min). While this was higher than desired, there was no critical pressure decay rate to achieve, so the test proceeded. The mean daily pressure decay rate for the test was 0.29 psig/min, with a maximum observed decay rate of 0.43 psig/min.

While the turbidity data indicated that the UF system performed satisfactorily, the microbiological data showed higher than expected UF filtrate counts. The UF feed geometric mean HPC count was 2810 CFU/mL, and the filtrate geometric mean HPC count was 1670 CFU/mL. Mean total coliform counts were not calculated because only five sets of samples were collected. The UF feed total coliform counts ranged from 41 to 532 CFU/100 mL, while the filtrate counts ranged from 11 to 94 CFU/100 mL. High numbers of HPC and total coliforms were also found in the RO permeate. The mean RO permeate HPC count was 247 CFU/mL and the RO permeate total coliform counts ranged from <1 to 95 CFU/100 mL. This phenomenon has been observed in other published membrane studies, but it was beyond the scope of this study to determine whether the observed HPC and total coliform levels were breaching the membrane, or were a result of microbial contamination and growth downstream of the UF and RO membranes from previous field tests of the EUWP.

There is no reportable particle count data for the 2006 test because after the test was completed it was discovered that the particle counters had been improperly calibrated.

Direct integrity measurements of the RO system were performed prior to the start of the verification test, and again at the end of the test. A dye marker test was conducted, where a food-grade dye was added to the RO feed water, and UV absorbance levels were compared among the feed, permeate, and concentrate streams over a ten minute period. For the pre-verification test, the dye rejection rate was 99.6%, while that for the post-verification dye test was 99.8%. As with the UF pressure decay tests, there was no critical rejection level.

UF System Operation

UF process operations data for the 2006 test are presented in Table VS-ii. The intake flow is defined as the source water pumped into the UF feed water tank. The mean UF feed water flow rate of 246 gallons

per minute (gpm) was below the design feed flow rate of 259 gpm specified for the system. The UF water recovery was 89.5% based on the mean feed water and filtrate flow rates. The UF system only operated 15 h per day, on average, but the 220 gpm mean filtrate flow corresponds to a 24-h production rate of 316,800 gallons (gal). The UF system target production rate was 250,000 gpd (not including backwash water). The backwash process used about 900 gal of UF filtrate per event, and a backwash was conducted every 30 minutes. For 24 h of operation, a total of 43,200 gal of UF filtrate would be used for backwashes. Subtracting the backwash water from the calculated daily UF filtrate production results in 273,600 gpd of UF product water, which was above the performance goal of 250,000 gpd.

Table VS-ii. 2006 Test UF Operations Productivity Data

Parameter	Count	Mean	Median	Minimum	Maximum	Standard Deviation	95% Confidence Interval
UF Operation per day (h)	31	15.0	17.2	3.4	21.5	4.85	±1.71
Intake Flow (gpm)	58	298	299	278	302	3.34	±0.86
Feed Flow (gpm)	59	246	248	175	268	16.0	±4.07
Filtrate Flow (gpm)	59	220	222	149	243	16.1	±4.10
Retentate Flow (gpm)	59	26	26	21	31	1.81	±0.46
Backwash Flow (gpm)	Estimated at 900 gal per backwash cycle						
Feed Pressure (psig)	59	21	21	12	33	4.26	±1.09
Retentate Pressure (psig)	59	19	19	10	31	4.20	±1.07
Filtrate Temperature (°F[1])	59	52	52	43	60	5.16	±1.32

(1) °F = degrees Fahrenheit

A chemical coagulant (ferric chloride) was not used at the beginning of the verification test. At the start of the test on September 25, the trans-membrane pressure (TMP) was 11 psig. However, it quickly rose to 26 psig on September 29. As the TMP rose, the specific flux declined from 3.56 gallons per square foot per day (gfd)/psig on September 25 to 1.38 gfd/psig on September 29. It was evident that a coagulant should be used to attempt to lengthen the time between UF cleanings. The UF system was shut down on September 30 and cleaned. The CIP was successful as the specific flux rose to 3.52 gfd/psig. Ferric chloride was injected to the feed water upstream of the UF feed tank from September 29 through the end of the test. The addition of the coagulant improved performance, and the system was able to maintain filtrate production with the TMP below 20 psig until the last two days of the test. The specific flux varied between 3.0 and 4.5 gfd/psig from September 29 to October 18, and then it dropped down to 2.46 gfd/psig on October 19. From October 19 to the end of the test on October 25, it ranged from approximately 1.5 to 3.0 gfd/psig.

RO System Operation

The RO process operations data for the 2006 test are presented in Table VS-iii. The mean RO permeate flows of 53 gpm for Array 1 and 21 gpm for Array 2 yield a mean total permeate production of 74 gpm. The mean feed water flow of 107 gpm for Array 1 and 53 gpm for Array 2 were below the target feed rates of 116 gpm and 58 gpm, respectively. The recovery for Array 1 was 49.5%, (design target 50%) and the recovery for Array 2 was 39.6% (design target 48%).

Over the 30-day verification test, the RO feed water totalizer showed 5,382,670 gal of water fed to the RO unit. At an average recovery of 47% (prorated between Array 1 at 49.5% and Array 2 at 39.6%), the total volume of permeate produced was approximately 2,530,000 gal or an average of 84,330 gpd over the entire test period. The target flowrate fell short of the goal of producing 100,000 gpd of finished water.

The RO system maintained a steady permeate flow rate for both arrays throughout the verification test. The feed pressure was increased over the duration of the test to maintain feed water flow rates. The Array

1 feed pressure increased from 387 psig on September 25 to a maximum of 539 psig on October 24. The concentrate pressure from Array 1 was used by the energy recovery device to increase feed water pressure for Array 2. Based on the small pressure loss from the transfer of pressure between the Array 1 concentrate and the Array 2 feed water, the energy recovery device worked properly during the test.

Table VS-iii. RO System Operations Productivity Data for 2006 Test

Parameter	Count	Mean	Median	Minimum	Maximum	Standard Deviation	95% Confidence Interval
Array 1 Feed Flow (gpm)	59	107	107	104	110	1.38	± 0.35
Array 1 Permeate Flow (gpm)	59	53	53	44	56	2.0	± 0.50
Array 1 Concentrate Flow (gpm)	59	54	54	48	62	2.4	± 0.61
Array 2 Feed Flow (gpm)	59	53	52	49	59	2.3	± 0.60
Array 2 Permeate Flow (gpm)	59	21	21	19	24	1.1	± 0.27
Array 2 Concentrate Flow (gpm)	59	32	31	27	37	2.3	± 0.58
Array 1 Feed Pressure (psig)	59	444	428	374	539	45.9	± 11.7
Array 1 Concentrate Pressure (psig)	59	346	330	286	419	40.5	± 10.3
Array 2 Feed Pressure (psig)	59	345	327	284	436	42.5	± 10.8
Array 2 Concentrate Pressure (psig)	59	255	238	204	325	35.2	± 8.98
Array 1 and 2 Combined Permeate Pressure (psig)	59	28	27	15	39	4.6	± 1.2

The specific flux calculations show that the RO membranes were slowly being fouled during operation. Over the 30-day test, the specific flux dropped by approximately 31% for Array 1, from 0.050 to 0.035 gfd/psig and 26% for Array 2, from 0.054 to 0.040 gfd/psig. The RO system was chemically cleaned on October 6 using a citric acid low pH solution. The specific flux just before the start of the cleaning was 0.043 gfd/psig, and the cleaning increased the specific flux to 0.047 gfd/psig. Given the slow but steady trend of decreasing specific flux, an anti-scalant was fed to the RO system beginning on October 12. This chemical feed continued through the end of the verification test.

VERIFICATION OF PERFORMANCE – 2007 UF SYSTEM RETEST

The 2007 retest was conducted from July 31 to August 24. Prior to starting the retest, each membrane cartridge was individually integrity tested, and several were found to have broken fibers that required plugging. This is a typical practice prior to installation of hollow-fiber membrane modules. After plugging these fibers, each cartridge was again pressure tested. The results showed that 15 of the 16 modules were acceptable, so TARDEC and USBR decided to operate the UF system with only 15 membranes. After completion of the individual module pressure decay tests and repairs, the full system pressure decay rate was 0.025 psig/min. This value was more than ten times lower than the mean value of 0.29 psig/min obtained during the 2006 verification test. This indicated that the repairs made to the UF system following the 2006 test were providing better membrane module pressure-hold capability.

Finished Water Quality

For the 2007 retest, the UF system reduced the turbidity from a mean of 2.3 NTU in the feed water to a mean of 0.14 NTU in the UF filtrate. Despite the UF system integrity issues during the 2006 test, the 2006 mean filtrate turbidity was the same as for the 2007 test. Turbidity in the feed water was reduced by a mean value of 92.5%. There were two spikes in the feed water turbidity – on August 6, and from August 20 to 22. Both spikes were likely caused by rain events on these days. These feed water turbidity spikes did cause small increases in the filtrate turbidity, but only one measurement – 0.51 NTU on August 22 – was above 0.3 NTU. Therefore, the UF system also met the NPDWR turbidity requirements during the 2007 test.

UF Membrane Integrity

Pressure decay tests were again conducted daily for the 2007 UF system retest. The observed pressure decay rates were 5-10 times lower than those from the 2006 test, with a mean value of 0.025 psig/min. These direct integrity test results were indicative of membrane modules with no significant observable breaches.

The mean 2 to 3 µm particle count for the feed water was 13,376/10 mL. The range of 2 to 3 µm particle counts for the feed water was 1 to 39,418/10 mL. The filtrate had a mean particle count in the 2 to 3 µm size of 112/10 mL with a median of 55/10 mL and a range of 0 to 13,908/10 mL. However, the maximum particle count of 13,908 may not be indicative of typical performance. The UF system went through a backflush cycle every half-hour, and during these backflushes the particle counts were still being recorded. Consequently, the filtrate particle count data included numerous spikes. The backflushes were not time-stamped, so the spikes due to backflushes could not be identified with certainty and removed from the data set. As evidenced by the low mean and median filtrate counts, most of the counts were less than 200/10 mL. The UF system reduced the 2 to 3 µm particles by a mean value of 2.21 $\log_{10}$.

The mean 3 to 5 µm particle count for the feed water was 24,634/10 mL. The range of 3 to 5 µm particle counts for the feed water was 0 to 91,595/10 mL. The filtrate had a mean 3 to 5 µm particle count of 157/10 mL with a median of 77/10 mL and a range of 0 to 14,059/10 mL. As with the 2 to 3 µm maximum count, the 3 to 5 µm maximum count of 14,059 may not be indicative of UF performance due to particle count data being collected during the backflushes. The UF system reduced the 3 to 5 µm particles by a mean value of 2.33 $\log_{10}$.

The geometric mean UF feed *Bacillus* endospore count was 1,562 CFU/100 mL, with range of 862 to 7,420 CFU/100 mL. The mean filtrate endospore count was 203 CFU/100 mL, with a range of 78 to 996 CFU/100 mL. The mean log reduction was 0.88 $\log_{10}$ with a range of 0.07 to 1.74 $\log_{10}$ for the feed and filtrate sample pairs. This was a lower reduction than predicted based on the observed pressure decay rates and the particle count data. To explore the concern of membrane module integrity further, additional studies were conducted on selected modules from this UF skid. Results from these additional studies conducted at the NSF testing facility in Ann Arbor, MI, are not presented in this verification report. The following reference report provides separate ETV verification testing results for the laboratory challenge study of selected EUWP UF modules: "Removal of Microbial Contaminants in Drinking Water: Koch Membrane Systems, Inc. Targa® 10-48-35-PMC™ Ultrafiltration Membrane, as Used in the Village Marine Tec. Expeditionary Unit Water Purifier", EPA/600/R-09/075, http://www.epa.gov/etv.

UF System Operation

The 2007 UF system retest operations data are presented in Table VS-iv. With only 15 modules in operation, the mean feed and filtrate flow rates of 232 gpm and 206 gpm, respectively, were lower than those for the 2006 test. Based on the mean flow rates, the mean water recovery for the UF system was 88.8%. The 206 gpm mean filtrate flow corresponds to a 24-h production rate of 296,640 gpd. Subtracting the backwash water from the calculated daily filtrate production results in 253,440 gpd of UF product water, which is still above the design UF production of 250,000 gpd, despite being short one module.

Actual UF filtrate production was tracked using the RO feed totalizer. The total filtrate produced (not including backwash water) was 3,551,000 gal over 350.1 h of operation. This yields a mean useable UF filtrate production of 242,500 gpd. If the filtrate water used for backwashing the system is added (595,730 gal) to this production volume, then the mean total filtrate production is 283,200 gpd.

Table VS-iv. UF System Operations Productivity Data for 2007 Test

Parameter	Count	Mean	Median	Minimum	Maximum	Standard Deviation	95% Confidence Interval
UF Operation per day (h)	25	13.8	14.3	4.0	21.5	4.6	± 1.8
Intake Flow (gpm)	44	288	296	235	303	16.2	± 4.8
Feed Flow (gpm)	45	232	237	174	271	19.7	± 5.7
Filtrate Flow (gpm)	45	206	212	148	245	19.6	5.7
Retentate Flow (gpm)	44	26	26	25	28	0.7	± 0.2
Backwash Flow (gpm)	Not measured – approximately 900 gal per backwash						
Feed Pressure (psig)	45	24	25	13	32	5.9	± 1.7
Retentate Pressure (psig)	45	22	23	11	31	5.8	± 1.7
Filtrate Temperature (°F)	45	74	75	62	84	5.3	± 1.6

From August 2 through 7, the feed water pressure needed to be increased every day to maintain the target filtrate flow rate. During this time, TMP increased from 7 to 17 psig. On August 7, the UF system was shutdown for a chemical cleaning, and put back into service on August 9. The TMP did not drop as a result of the cleaning, but instead further increased up to 22 psig on August 12. Therefore, the feed pressure was increased to 30 psig in order to maintain water flow rates. The UF system was again shutdown and a second chemical cleaning performed on August 13. This cleaning dropped the TMP down to 16 psig. The feed water pressure was increased again to over 30 psig on August 14 and TMP increased accordingly. A decision was made to operate the UF system at the higher feed water pressure and TMP, since these pressures were still within the design specification and operating specification for the unit. The UF feed pressure remained steady for several days and was actually lower during the last week of the test. TMP remained fairly steady at around 20 psig for the duration of the test.

As the TMP increased, the specific flux declined. The CIP was successful in stabilizing the drop in specific flux, but did not result in returning the membrane to the specific flux attained at the beginning of the test. The specific flux at the start of the test on July 30 was 4.62 gfd/psig. The specific flux dropped to 1.78 gfd/psig on August 7, then remained between 1.12 and 2.18 gfd/psig for the remainder of the test.

Ferric chloride was also used as a coagulant during the retest. During the initial test runs for the retest, jar tests showed a ferric chloride dose of 1 mg/L as Fe should be the target feed rate. This feed rate was maintained until the rapid increase in TMP and drop in specific flux occurred. After the chemical cleaning on August 7 and 8, the ferric chloride feed rate was increased to 2 mg/L as Fe. Subsequent jar tests suggested that with the low source water turbidity, the ferric chloride feed should actually be decreased. The ferric chloride feed was shut off on August 10 and remained off until the CIP was required on August 13. The rapid loss of flux and rise in TMP indicated that the coagulant should be used in the system, but at a lower dose than used at the start of the test. The ferric chloride feed was set at 0.2 mL/min (0.02 mg/L as Fe) and continued at that rate for the remainder of the test.

QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

NSF provided technical and quality assurance oversight of the verification testing as described in the verification report, including a review of 100% of the data. NSF QA personnel also conducted a technical systems audit during testing to ensure the testing was in compliance with the test plan. One important finding was that the particle count data from the 2006 test was incorrect due to improper calibration of the particle counters. The particle counters were calibrated properly for the 2007 retest, so only the particle count data from the 2007 test is reported.

A complete description of the QA/QC procedures is provided in the verification report.

Original signed by Sally Gutierrez 11/24/09

Sally Gutierrez Date
Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original signed by Robert Ferguson 12/14/09

Robert Ferguson Date
Vice President
Water Systems
NSF International

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Availability of Supporting Documents

Copies of the test protocol, the verification statement, and the verification report (NSF report # NSF 09/28/EPADWCTR) are available from the following sources:

1. ETV Drinking Water Systems Center Manager (order hard copy)
   NSF International
   P.O. Box 130140
   Ann Arbor, Michigan 48113-0140
2. Electronic PDF copy
   NSF web site: http://www.nsf.org/info/etv
   EPA web site: http://www.epa.gov/etv

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October 2009

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Village Marine Tec.
Expeditionary Unit Water Purifier, Generation 1

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

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Foreword

The EPA is charged by Congress with protecting the nation's air, water, and land resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, the EPA's Office of Research and Development provides data and science support that can be used to solve environmental problems and to build the scientific knowledge base needed to manage our ecological resources wisely, to understand how pollutants affect our health, and to prevent or reduce environmental risks.

The Environmental Technology Verification (ETV) Program has been established by the EPA to verify the performance characteristics of innovative environmental technology across all media and to report this objective information to permitters, buyers, and users of the technology, thus substantially accelerating the entrance of new environmental technologies into the marketplace. Verification organizations oversee and report verification activities based on testing and quality assurance protocols developed with input from major stakeholders and customer groups associated with the technology area. ETV consists of six environmental technology centers. Information about each of these centers can be found on the internet at http://www.epa.gov/etv.

Under a cooperative agreement, NSF International has received EPA funding to plan, coordinate, and conduct technology verification studies for the ETV "Drinking Water Systems Center" and report the results to the community at large. The DWS Center has targeted drinking water concerns such as arsenic reduction, microbiological contaminants, particulate removal, disinfection by-products, radionuclides, and numerous chemical contaminants. Information concerning specific environmental technology areas can be found on the internet at http://www.epa.gov/nrmrl/std/etv/verifications.html.

Table of Contents

List of Figures

List of Tables

Appendices

Abbreviations and Acronyms

ANGB	Air National Guard Base
BOD	biochemical oxygen demand
°C	degrees Celcius
CFU	colony-forming unit
CI	Confidence Interval
CIP	clean-in-place
cm	centimeter
DF2	diesel fuel, grade 2
DFA	diesel fuel, arctic grade
DQO	data quality objectives
DWSC	Drinking Water Systems Center
EPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification
EUWP	Expeditionary Unit Water Purifier
°F	degrees Fahrenheit
FRP	fiberglass reinforced plastic
ft	foot (feet)
FTO	field testing organization
gal	gallons
gfd	gallons per foot per day
gpd	gallons per day
gpm	gallons per minute
h	hour
HPC	Heterotrophic plate count
in	inch
JP8	jet propellent 8 (jet fuel)
kgal	kilogallon
kW	kilowatt
kWh	kilowatt hour
L	liter
lb	pound
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
m	meter
mg	milligram
mL	milliliter
mS	millisiemens
NBC	nuclear, biological, and chemical
ND	not detectible
NDP	net driving pressure
NIST	National Institute of Standards and Technology
NM	not measured
NPDWR	National Primary Drinking Water Regulations
NRMRL	National Risk Management Research Laboratory
NSF	NSF International (previously known as the National Sanitation Foundation)

NSWCCD	United States Naval Surface Warfare Center – Carderock Division
NTU	Nephelometric turbidity units
O&M	operations and maintenance
ONR	Office of Naval Research
ORD	Office of Research and Development
P&ID	piping and instrumentation diagram
PE	performance evaluation
PLC	programmable logic controller
ppm	parts per million
psi	pounds per square inch
psig	pounds per square inch, gauge
PVC	polyvinyl chloride
PX	pressure exchanger
QA/QC	quality assurance/quality control
QAPP	quality assurance project plan
RO	reverse osmosis
RPD	relative percent difference
SDI	silt density index
SM	Standard Methods for the Examination of Water and Wastewater
SNL	Sandia National Laboratories
TARDEC	United States Army Tank-Automotive Research, Development, and Engineering Center
TDS	total dissolved solids
TOC	total organic carbon
TQAP	test/quality assurance plan
TQG	tactical quiet generator
TSS	total suspended solids
TMP	trans-membrane pressure
UF	ultrafiltration
USBR	United States Bureau of Reclamation
UV_{254}	ultra violet absorbance at 254 nanometers
VOC	volatile organic compounds
µm	micron
µS	microSiemens

Acknowledgements

The U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC) was the main field testing organization. TARDEC was supported by the U.S. Bureau of Reclamation (USBR). TARDEC and USBR were responsible for all elements of the tests, including operation of the equipment, collection of samples, instrument calibration, and data collection.

This verification report was authored by Mr. Michael Blumenstein and Mr. C. Bruce Bartley of the NSF International ETV Drinking Water Systems Center (DWSC), Mr. Dale Scherger of Scherger Associates (3017 Rumsey Drive, Ann Arbor, MI 48105), and Ms. Michelle Chapman of USBR. The verification report was based on the project test/quality assurance plan authored by DWSC, USBR, and TARDEC.

The laboratory selected for the analytical work was:

NSF International Chemistry Laboratory
789 N. Dixboro Road
Ann Arbor, Michigan 48105
Contact: Mr. Kurt Kneen

The manufacturer of the EUWP was:

Village Marine Tec.
2000 W. 135th St.
Gardena, CA 90249
Phone: 310-516-9911

The TARDEC engineers responsible for the field tests were Mr. Bob Shalewitz, Ms. Lori Bolster, and Mr. Jeremy Walker. The USBR support staff included Ms. Michelle Chapman, Mr. Daniel Gonzales, and Mr. Steve Dundorf.

The NSF DWSC project manager was Mr. Michael Blumenstein. The DWSC is managed by Mr. C. Bruce Bartley. Ms. Kristie Wilhelm of the DWSC provided valuable assistance with report preparation.

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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 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; with stakeholder groups consisting of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans responsive to the needs of stakeholders, conducting field demonstrations, collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The EPA has partnered with NSF International (NSF) under the ETV Drinking Water Systems Center (DWSC) to verify the performance of water supply technologies that serve both small and large communities. A goal of verification testing is to enhance and facilitate the acceptance of scalable 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 meets this goal by working with manufacturers and NSF-qualified Field Testing Organizations (FTO) to conduct verification testing under the approved protocols. It is important to note that verification of the equipment does not mean the equipment is "certified" by NSF or "accepted" by EPA. Rather, it recognizes that the performance of the equipment has been determined and verified by these organizations for those conditions tested by the FTO.

The DWSC recently evaluated the performance of the Village Marine Tec. Generation 1 Expeditionary Unit Water Purifier (EUWP). The EUWP, developed for the U.S. Military, uses ultrafiltration (UF) and reverse osmosis (RO) to produce drinking water from a variety of different sources. This document provides the verification test results for the EUWP system at a fresh surface water site in Selfridge Air National Guard Base (ANGB) in Michigan.

1.2 Testing Participants and Responsibilities

EUWP design, construction, and testing was overseen by a federal multi-agency team composed of representatives from Office of Naval Research (ONR); Army Tank-Automotive Research, Development, and Engineering Center (TARDEC); Naval Surface Warfare Command – Carderock Division (NSWCCD); United States Department of Interior Bureau of Reclamation (USBR); and Sandia National Laboratories (SNL). The manufacturer, Village Marine Tec., was

contracted to design and build the EUWP to the team's Generation 1 specifications using 2004 state-of-the-art technology.

The organizations involved in the verification testing project were:

- EPA
- NSF
- ONR
- TARDEC
- USBR
- Village Marine Tec.

The following is a brief description of all of the ETV participants and their roles and responsibilities.

1.2.1 EPA

EPA, through its Office of Research and Development (ORD), has financially supported and collaborated with NSF under Cooperative Agreements R-82833301 and CR833980. This verification effort was supported by the DWSC operating under the ETV Program. This document has been peer-reviewed, reviewed by EPA, and recommended for public release.

1.2.2 NSF International

NSF is an independent, not-for-profit testing and certification organization dedicated to public health and safety and to 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 products bearing the NSF Name, Logo and/or Mark meet those standards. The EPA partnered with NSF to verify the performance of drinking water treatment systems through the EPA's ETV Program.

NSF authored the test plan and test report. NSF also served as the analytical laboratory for all water quality parameters not measured in the field. NSF also provided technical oversight during testing and conducted an audit of the field testing activities.

Contact Information:

NSF International
789 N. Dixboro Road
Ann Arbor, Michigan 48105
Contact: Mr. Bruce Bartley, Project Manager
Phone: (734) 769-8010
Fax: (734) 769-0109
Email: bartley@nsf.org

1.2.3 ONR

The U.S. Navy ONR provided oversight of the EUWP development program which involved developing high productivity water treatment units for land and shipboard military and civilian emergency preparedness applications. ONR also provided funding for the EUWP ETV testing project.

Contact Information:

Office of Naval Research
Logistics Thrust Program
Operations Technology Division
800 N. Quincy St.
Arlington, VA 22217
Contact: Major Alan Stocks
Phone: 703-696-2561
Email: stocksa@onr.navy.mil

1.2.4 TARDEC

TARDEC served as the FTO for this verification. TARDEC was responsible for all on-site testing activities, including operation of the test equipment, collection of samples, measurement of water quality parameters, calibration and check of instrumentation, and operational data collection.

Contact Information:

U.S. Army TARDEC/RDECOM
AMSRD-TAR-D/210, MS 110
6501 E. Eleven Mile Road
Warren, MI 48397
Contact: Mr. Bob Shalewitz, TARDEC EUWP Program Manager
Phone: 586-574-4128
Email: bob.shalewitz@us.army.mil

1.2.5 USBR

USBR functioned as a co-FTO, providing field operations support, and technical support for equipment operation.

Contact Information:

U.S. Bureau of Reclamation
Denver Federal Center (D-8230)
P.O. Box 25007
Denver, CO 80225
Contact: Ms. Michelle Chapman
Phone: 303-445-2264
Email: mchapman@do.usbr.gov

1.2.6 Village Marine Tec.

The EUWP manufacturer was Village Marine Tec. The manufacturer was responsible for supplying a field-ready treatment system equipped with all necessary components, including instrumentation and controls, and an operation and maintenance (O&M) manual. The manufacturer was responsible for providing logistical and technical support, as needed, as well as technical assistance to the FTO during operation and monitoring of the equipment undergoing field verification testing.

Contact Information:

Village Marine Tec.
2000 W. 135th St.
Gardena, CA 90249
Phone: 310-516-9911
Email: sales@villagemarine.com

1.3 Verification Testing Site

The EUWP verification testing occurred at Selfridge ANGB at 127 Wing Public Affairs Office, 29423 George Avenue, Selfridge, MI 48045-5290. Selfridge ANGB is located in southeastern Michigan, 30 miles northeast of Detroit on the shore of Lake St. Clair, with an elevation of 580 feet (ft).

The EUWP was situated on a cement pad a few yards from Lake St. Clair (Figure 1-1). The raw water for testing was drawn from the inlet at the left in the photo.

Figure 1-1. Photo of concrete pad used for EUWP testing.

1.3.1 Source Water Description and Feed Water Quality

Raw water from Lake St. Clair was used for ETV testing. Approximately 430 square miles (mi^2) (1,114 square kilometers (km^2)) in area, the lake is part of the Great Lakes system. The lake, along with the St. Clair River and Detroit River, provides the connection between Lake Huron to the north and Lake Erie to the south. It is a shallow lake with an average depth of about 10 ft (3 m) and a maximum natural depth of 21 ft (6.4 m) (Wikipedia, 2006).

Chapter 2
Equipment Capabilities and Description

The EUWP was designed to meet purified water needs in areas with challenging water sources of very high total dissolved solids (TDS), turbidity, or hazardous contamination during emergency situations when other water treatment facilities are incapacitated. The system uses UF and RO to produce potable water. It is not intended to meet general municipal water treatment needs in a cost effective manner. The design requirements – to produce 100,000 gallons per day (gpd) and be C-130 transportable – forced the use of lightweight durable materials, such as titanium, that are more costly and would not usually be required for municipal water treatment. The requirements to treat source water with up to 60,000 milligrams per liter (mg/L) TDS and ensure removal of nuclear, biological, and chemical (NBC) contaminants to a safe limit, drove the design to two parallel arrays - with a 2nd permeate pass resulting in a maximum of 65% recovery. Most municipal water treatment systems can easily attain much higher recovery levels. The EUWP is also intended as a demonstration of the state-of-the-art of desalination for emergency situations.

Key innovations applied in the EUWP are:

- High flux UF membrane cartridges;
- Innovative staging of RO membrane modules; and
- Small system energy recovery to pressurize a parallel array.

The EUWP was developed to meet the following objectives:

- Develop a high capacity drinking water purification unit to provide strategic water production capability with a focus on peacekeeping, humanitarian aid, and disaster relief missions that the military frequently supports.
- Further the state of desalination technology with a view toward reduced operational costs, size, and weight; improved reliability; and verifying emerging technologies.

2.1 Equipment Capabilities

The objective of this verification test was to document the ability of the EUWP to meet the following performance criteria:

The EUWP is capable of producing 100,000 gpd of water meeting EPA's National Primary Drinking Water Regulations (NPDWR) from raw Lake St. Clair water based on contaminants found in the source water during the initial water characterization phase of ETV testing.

The EUWP is intended to meet purified water needs in areas with challenging water sources of very high TDS, turbidity, or hazardous contamination during emergency situations when other water treatment facilities are incapacitated. The unit was designed to meet or exceed Tri-Service Field Water Quality Standards for short-term consumption by healthy adults. However, the technology used is capable of exceeding the EPA NPDWR.

The EUWP, using the UF system only, can produce 250,000 gpd of potable water from a fresh water source with up to 500 mg/L TDS and a temperature of 77 Fahrenheit (°F) (25 Celsius, °C), provided that contaminants not removed by UF are not present in the source water. Using the UF and RO system, it is designed to produce from 98,000 gpd up to 162,000 gpd depending on the TDS of the source water and the recovery settings of the RO system. Production is decreased to 125,000 gpd (50% recovery) for higher TDS waters. It can also produce 98,000 gpd from a NBC contaminated source with up to 45,000 mg/L TDS. NBC contaminant removal and seawater desalination were not verified as part of this ETV testing at Selfridge ANGB.

2.2 General System Description

- Equipment name: Expeditionary Unit Water Purifier (EUWP)
- Model number: Generation 1
- Manufacturer: Village Marine Tec., 2000 W. 135th St., Gardena, CA 90249, (310) 324-4156.
- Power requirements: 480 volts, 250 Amp, 60 hertz, 3-phase electrical, or two 60 kilowatt (kW) diesel Tactical Quiet Generators (TQG).
  - UF Requirements – 125 amps maximum
  - RO Requirements – 125 amps maximum

The EUWP is composed of feed pumps, a UF pretreatment system, a 1 or 2 pass RO desalination system with energy recovery, storage tanks, and product pumps (Figure 2-1). It has chemical feed systems for pretreatment and post treatment. Clean-in-place systems (CIP) are included with the skids.

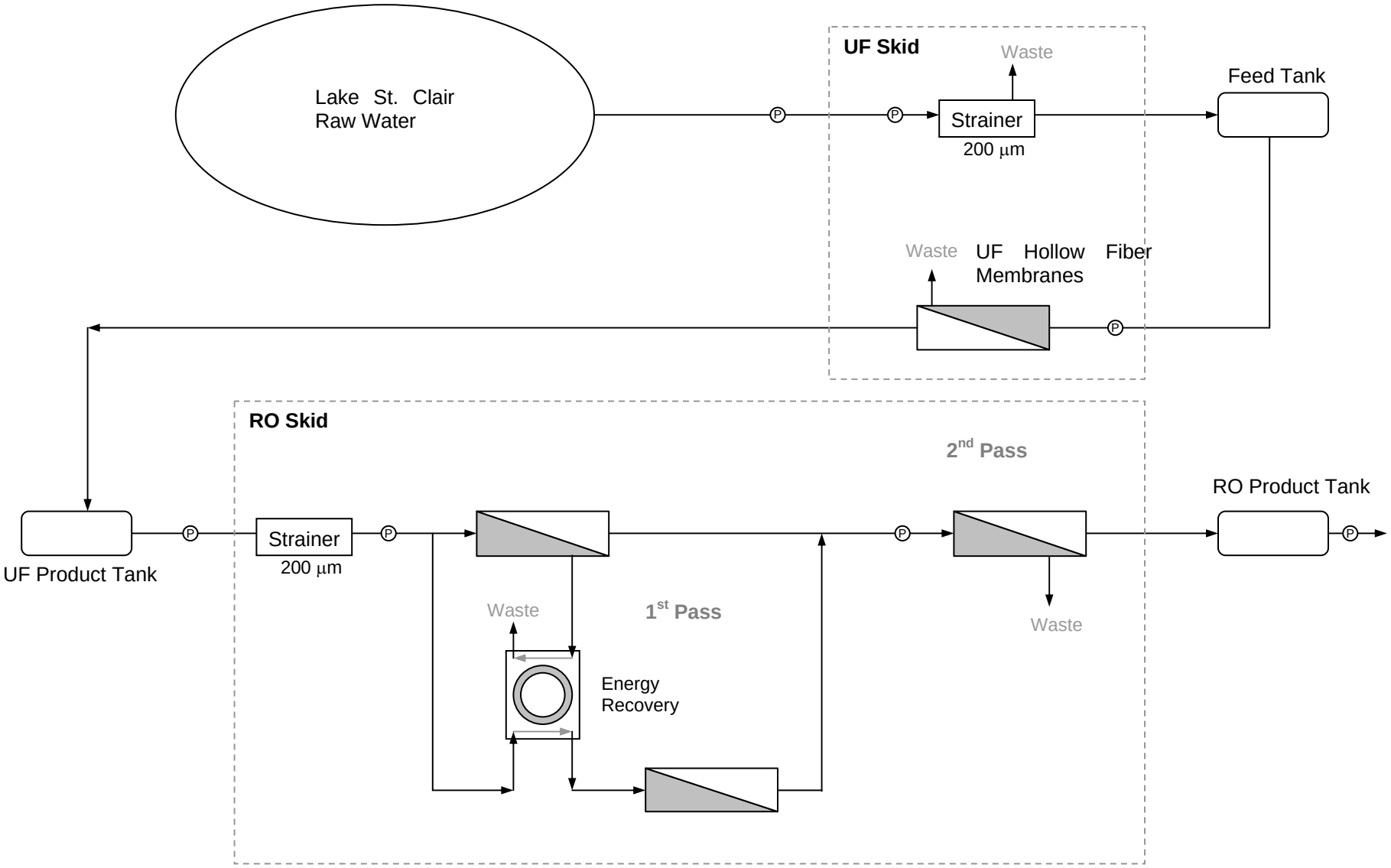


Figure 2-1. Process component diagram.

2.3 Concept of Treatment Processes

2.3.1 UF Pretreatment/Suspended Solids Filtration

UF is a low-pressure (5–90 pounds per square inch, gauge (psig)) membrane process that separates particulates based on size exclusion. The UF process retains oils, particulate matter, bacteria, and suspended solids that contribute to turbidity and a high silt density index (SDI). Feed water to RO systems should have turbidity less than 0.1 Nephelometric Turbidity Units (NTU) and a SDI less than 3. UF membranes pass water, dissolved salts, and most dissolved organic compounds. UF pore sizes range from 0.002 to 0.1 micron (μm), and the molecular weight cutoff ranges from 1,000 to 500,000. Koch Membrane Systems Targa-10 hollow fiber UF membranes are used in the EUWP. Water flows from the inside of the fiber to the outside causing suspended solids to collect on the inside of the fiber. Periodically, the system must be vigorously backwashed to remove this material from the system. Figure 2-2 shows example UF cartridges, a single fiber, and the flow pattern used in this system.

The key operating parameters for a UF system are the instantaneous flux and the overall productivity taking into account the volume required for backwash. Generally, the higher the instantaneous flux, the more often backwashing will be required. There is an optimum flux where overall productivity is maximized, called the critical flux. For municipal systems, it is economical to operate the system at the critical flux. The EUWP is an emergency supply system with extreme weight restrictions to enable transport. The weight restrictions drove design of the UF system to operate at a maximum flux with more frequent backwashes.

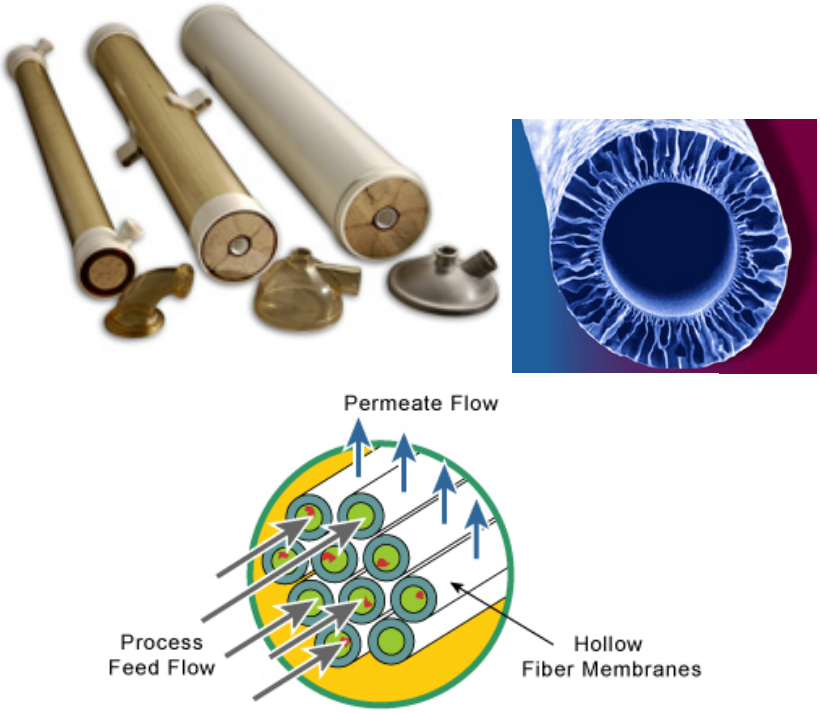


Figure 2-2. Koch UF hollow fiber modules, a single fiber, and the process flow through the module.

2.3.2 RO Desalination

Dissolved salts and larger molecular weight organic molecules can be removed by RO. Osmosis is a naturally occurring phenomenon in which pure water is transported down a chemical potential gradient across a semi-permeable membrane from a low concentration solution to a high concentration solution. One measure of the chemical potential is the osmotic pressure. Osmotic pressure is dependant on the concentration of ions and dissolved compounds. It can be measured by pressurizing the concentrated solution until osmotic induced flow stops. If this pressure is exceeded, then osmotic flow reverses from concentrated solution to the dilute solution.

RO is a moderate to high-pressure (80 – 1,200 psig) membrane separation process. The membranes in the EUWP are spiral wound with up to seven modules in a vessel. They are operated under cross-flow conditions at a pressure above the osmotic pressure of the bulk solution, plus additional pressure to overcome resistance of the modules. Water passing through the RO membrane is called permeate, and the concentrated discharge stream is called concentrate.

The separation model is of solution and diffusion of material through the polymer of the membrane. Dissolved salts are transported very slowly compared to water and other un-charged molecules. Uncharged molecules may be rejected based on size exclusion, depending on their mass and geometry.

2.4 Detailed System Description

This section provides a detailed system description. See the system operation manual in Appendix A for further details about the system and operation. Note that the system was designed and manufactured prior to promulgation of the final EPA Long Term 2 Enchanced Surface Water Treatment Rule (LT2ESWTR). The EUWP, as tested, was not designed to comply with the LT2ESWTR indirect integrity monitoring requirement that calls for the system to shut down pending a direct integrity test, if two consecutive turbidity readings exceed 0.15 NTU. The EUWP does have in-line turbidity meters to monitor the feed and filtrate streams for the UF skid, but the programmable logic controller (PLC) was not programmed to automatically shut down the system, if necessary. The RO system has an in-line turbidity meter for the RO permeate process stream. The RO system also includes in-line conductivity meters to monitor performance. The system process schematic and detailed layout are shown in Figures 2-3 and 2-4, respectively.

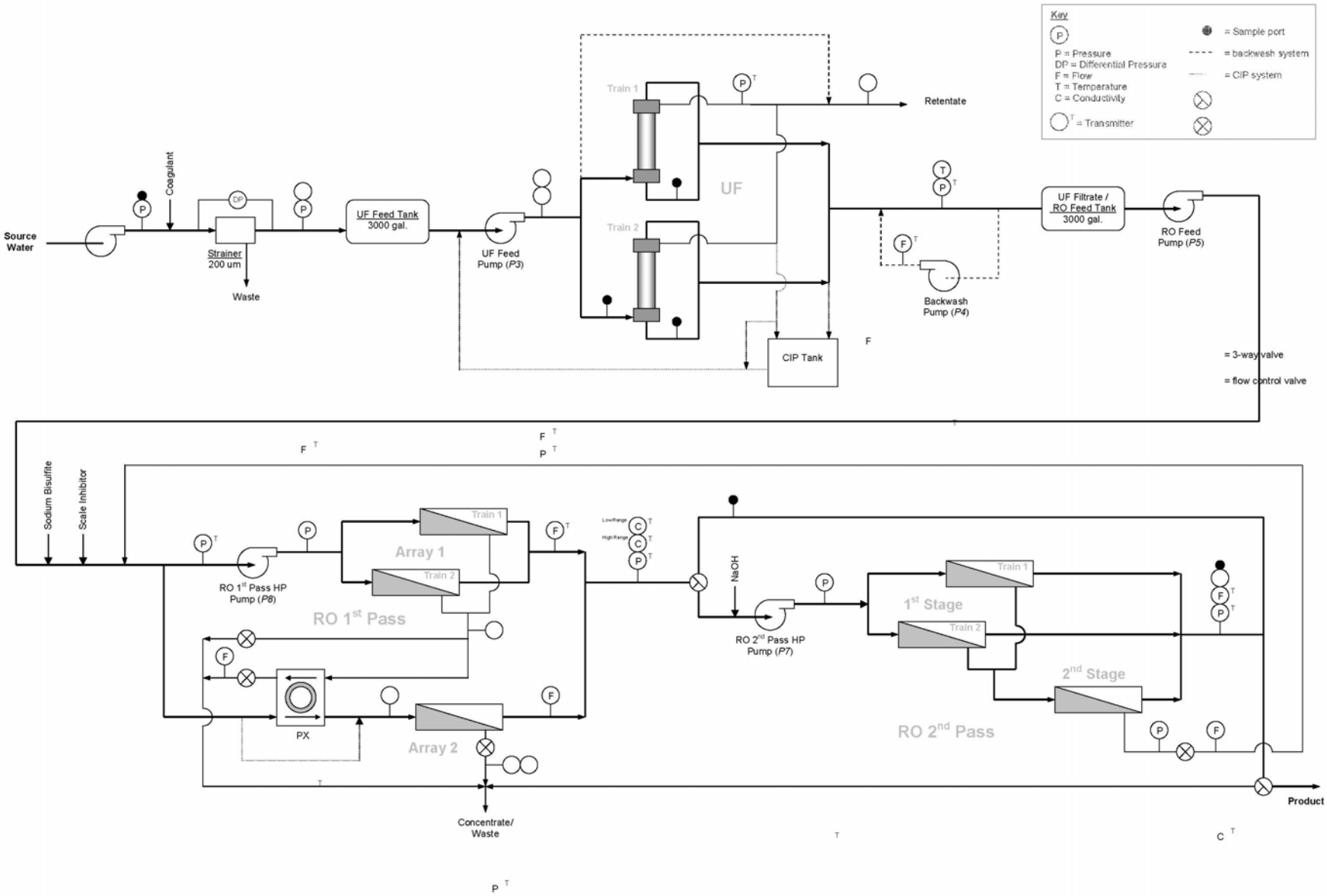


Figure 2-3. EUWP system process schematic.

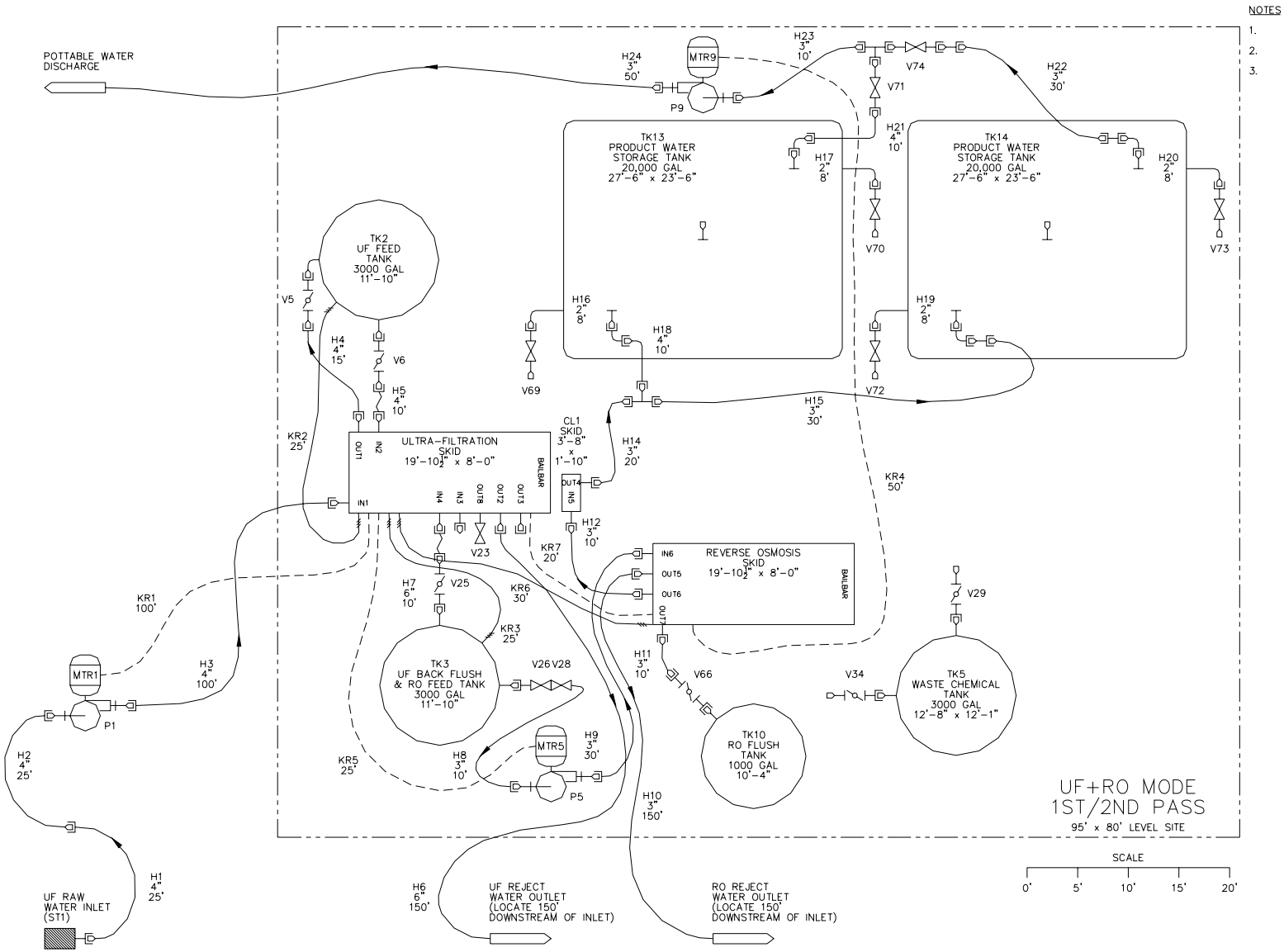


Figure 2-4. Schematic of typical EUWP layout.

2.4.1 Raw Water Intake

Raw Lake St. Clair water was drawn from the inlet shown at the left of Figure 1-2. An intake strainer was used to keep large pieces of debris from being drawn up. A close-up photo of the intake location and intake strainer is shown as Figure 2-5. Before the raw water reached the UF feed tank, ferric chloride was injected as a coagulant, and the water was strained again through two Amiad Filtrate Systems model TAF-750 filters operating in parallel. The filters are equipped with 200 μm weave wire screens. The strainers did not remove any ferric chloride floc, since there was not enough time for particles larger than 200 μm to form between the injection point and the strainer. The 3,000 gallon (gal) UF feed tank provides at least 12 minutes (min) of retention time for floc formation.

Figure 2-5. Photo of raw water intake and intake strainer.

2.4.2 UF System Description

The UF membranes used in the EUWP are model TARGA® 10-48-35-PMC, manufactured by Koch Membrane Systems. The UF cartridge specifications are presented in Table 2-1. The UF membranes are configured in two trains of eight cartridges each, all of which are operated in parallel. The membranes are operated such that 10% of the feed flow exits the cartridges as

retentate. Statistics of the UF skid are presented in Table 2-2. Photos of the UF skid are shown in Figure 2-6 and Figure 2-7.

Table 2-1. Koch Membrane Systems Targa 10-48-35-PMC Cartridge Specifications

Parameter	Value
Nominal molecular weight cut-off	100,000
Maximum recommended flow (per cartridge)	32.2 gpm(1)
Maximum pressure	45 psig
Maximum transmembrane pressure (TMP)	30 psig
Maximum backflush TMP	20 psig
Inner fiber diameter	0.035 in(2)
Membrane area	554 ft2(3)
Cartridge diameter	10.75 in
Cartridge length	48 in

(1) gallons per minute
(2) inch(es)
(2) square feet

Table 2-2. UF Skid Statistics

Parameter	Value
Production capacity	250,000 gpd
Maximum applied pressure	45 psig
Maximum TMP	30 psig
Water temperature range	34–104 °F
Turbidity range	0–150 NTU
Dimensions	20’ L x 8’ H x 8’ W
Weight	15,500 lbs dry, fully paced out for deployment, less fuel
Basic metals	UF System Piping: Fiberglass, Titanium, Nylon Air System Piping: Nylon Tubing
Operating ambient temperature range	32°F–120 °F
Storage and transport air temperature range	32°F–120 °F
Relative humidity:	3%–95%
Maximum slope of unit when deployed for operation	5 degrees side to side, 2 degrees end to end
Power source requirement	60 kW Generator (self contained) or power grid connection consisting of 480 volts, 125 amps. UF system and external pumping power requirements are 2.1 kWh/kgal(1)
Fuel type	DF2 (Diesel Fuel, Grade 2) DFA (Diesel Fuel, Arctic Grade) JP8 (jet propellent 8)
Fuel capacity (60 KW Generator)	43 gal

(1)Kilowatt-hours per kilogallon

Figure 2-6. Photo of the UF skid.

Figure 2-7. Photo of the UF cartridges mounted in the UF skid.

2.4.2.1 UF System Operation

The following is a basic description of the flow path and functional description of the UF system in normal operation for an open surface water source. The operation manual provides a full description of UF operation. Figure 2-8 is a piping and instrumentation diagram (P&ID) of the UF system.

1. Pump #1 (P1) brings water through the intake strainer #1 (ST1) (if an open intake is used) to the UF skid. Before entering the UF feed tank, water is strained (ST2) again to 200 microns on the UF skid. The strainers serve to eliminate debris that would clog the membrane fibers. Water exits strainer #2 and is stored in the UF feed tank (TK2) which serves as a break tank between the feed water supply and the UF feed.
2. If necessary, ferric chloride coagulant from Chemical Pump #1 (CP1) can be added to the feed stream before entering ST2 to enhance UF performance. The decision to use ferric chloride is site-specific, based on the raw water quality, if known, and/or the results of a jar test.
3. Pump #3 (P3) moves water from TK2 to the UF membranes.
4. The UF filtrate flows to tank #3 (TK3). TK3 acts as a break tank between the UF skid and the RO skid and a back flush reservoir for the UF skid.
5. Pump #5 (P5) pumps water from TK3 to the RO skid or directly through the disinfection system (CL1 – calcium hypochlorite) to the distribution system when RO is not required. The disinfection system will not be used for this verification.

2.4.2.2 UF CIP Procedure

The UF system must be cleaned when the TMP drop exceeds 35 psig after a normal backflush cycle. This cleaning cycle is required approximately every 30 days, depending on the water source. The CIP procedure typically uses citric acid as the low pH cleaning agent, and sodium hydroxide as the high pH cleaning agent. Note that different cleaning agents may need to be used for certain foulants.

If system operation requires the use of ferric chloride as a coagulant, then a low pH clean must be performed first, followed by a high pH clean. If ferric chloride is not being used, then a high pH clean must be performed first, then a low pH clean. Ferric chloride was used during testing at Selfridge ANGB. The following is a basic description of the flow path and functional description of the UF system in normal operation. The operation manual provides a full description of UF operation, including an operational summary described below.

1. Prior to CIP, perform a fresh back flush.
2. Following backwash, set up system for UF normal mode of operation. Activate UF drain mode on the screen.
3. Wait for the system to drain.
4. Connect the hose from the CIP tank to the system.
5. Touch the CIP button on the screen. Select CIP Mode ON. The PLC will automatically move the pneumatically operated valves to the correct positions.
6. Enable heaters to maintain CIP solution to between 96 and 100°F.
7. Turn tank mixer on using CIP display screen
8. Add the appropriate amount of chemical to achieve the desired pH.

9. Check the pH of the mixture in tank 4 at sample port V22 every 15 min. Use citric acid to lower the pH to 3 or use sodium hydroxide to raise the pH to 11.
10. With high pH only, add an appropriate amount of calcium hypochlorite.
11. Start CIP by touching the CIP button at the top left of the CIP screen then start to pump the solution using P3.
12. Allow the chemical to circulate through the selected array for 20 to 30 min.
13. Let the system soak for several hours after recirculation if needed to remove tough fouling.
14. Repeat recirculation with the desired chemicals.
15. Following chemical recirculation, rinse the system as necessary with clean water.

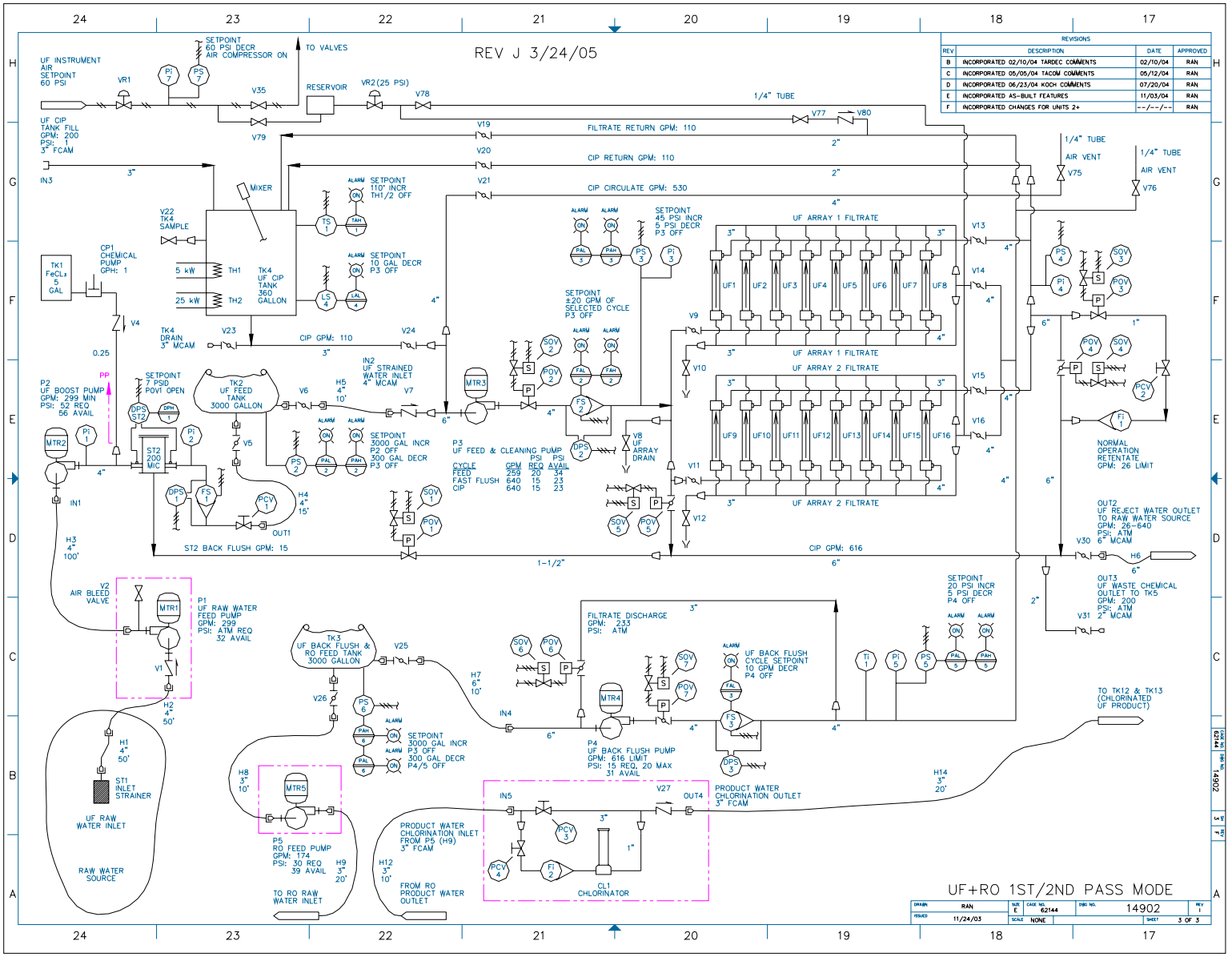


Figure 2-8. Piping and instrumentation diagram of UF skid.

2.4.3 RO System

The RO skid is shown below in Figures 2-9 and 2-10.

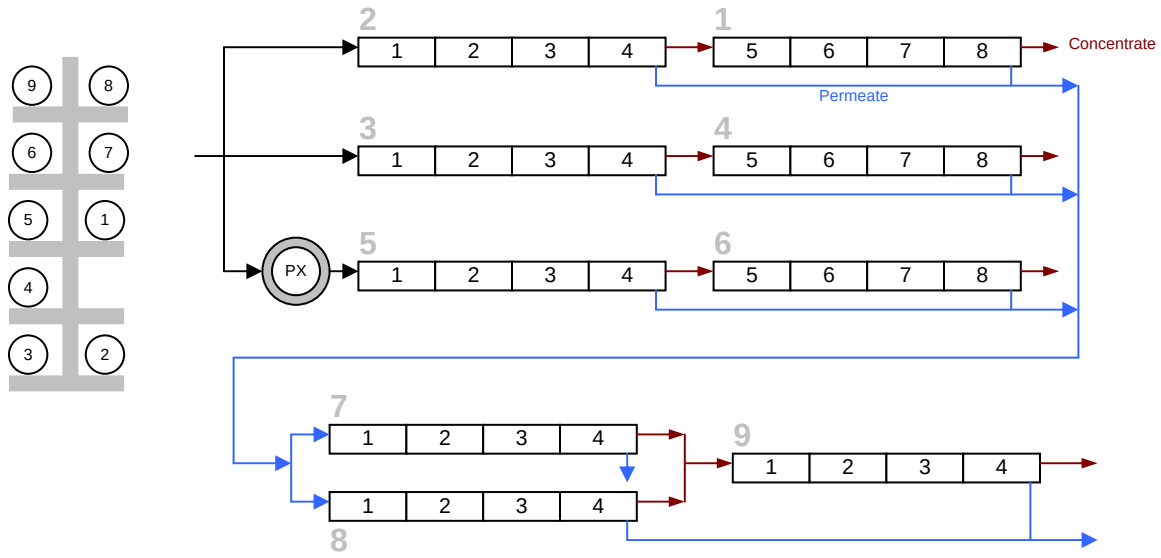
The RO system has the capability to operate in single-pass or double-pass mode if necessary (the double-pass mode was not used for this ETV test). The first pass of the RO system consists of a unique combination of moderate rejection/high productivity and high rejection/moderate productivity membranes. The first pass is composed of two parallel arrays (Figure 2-11). The first array is fed by the high-pressure pump and has two parallel trains with two four-element vessels each (Vessels 1, 2, 3, and 4 in Figure 2-11). The energy from the brine of this array is used to pressurize feed water via a pressure exchanger energy recovery device to feed a second array consisting of a single train of two four-element vessels (Vessels 5 and 6 in Figure 2-11).

The second pass RO system consists of a 2→1 array, where a second high-pressure pump boosts permeate pressure from the first pass feeding two parallel four-element vessels (Vessels 7 and 8 in Figure 2-11). The brine from these vessels then feeds one additional four-element vessel (Vessel 9 in Figure 2-11).

The RO design incorporates an internally staged RO element configuration on the first pass (Figure 2-12). This configuration consists of two Dow Chemical Company FILMTEC™ SW30-HR LE-400 elements, followed by two FILMTEC SW30-XLE400 elements, which are in turn followed by four FILMTEC SW30-HR-12000 ultra-low-energy experimental membranes. All membranes are polyamide thin-film composite type. The second pass RO system uses AquaPro LE-8040UP membrane elements. Table 2-3 provides performance data for the elements used in the system.

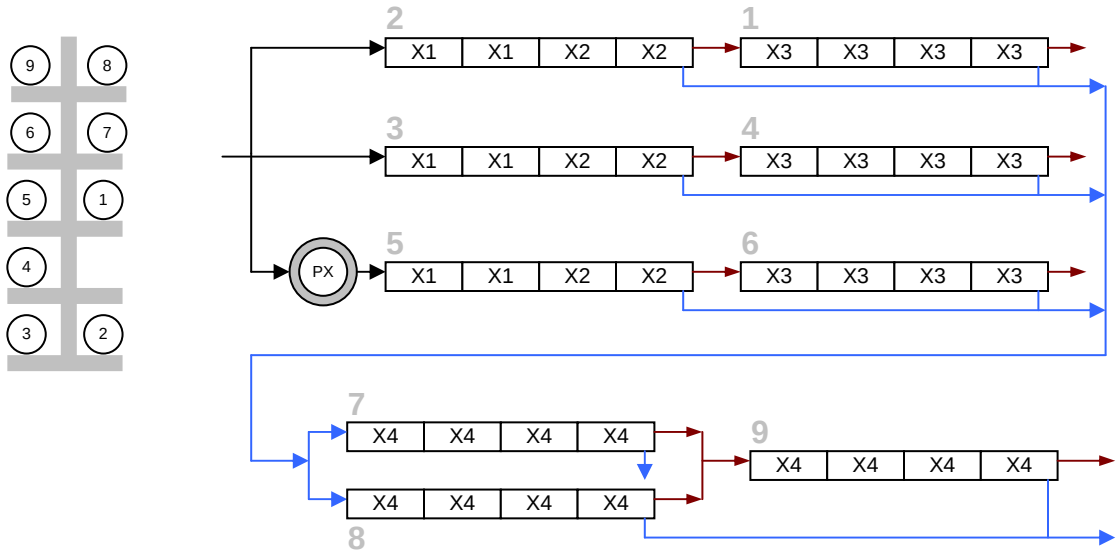
Figure 2-9. Photo of the RO skid.

Figure 2-10. Photo of the RO skid membrane vessels.



Numbers indicate pressure vessels

Figure 2-11. Vessel arrangement schematic.



Numbers indicate pressure vessels

Figure 2-12. Membrane arrangement schematic.

Table 2-3. RO System Membrane Element Characteristics

Vessel	Product	Designator	Nominal Active Surface Area ft^2 (m^2)	Permeate Flowrate gpd (m^3/d)	Stabilized Salt Rejection (%)
1st Pass 2, 3, 5	FILMTEC SW30-HR LE-400	X1	380 (35)	6000 (26)	99.8
1st Pass 2, 3, 5	FILMTEC SW30-XLE-400	X2	400 (37)	9000 (34)	99.7
1st Pass 1, 4, 6	FILMTEC SW30-HR -12000 (experimental)	X3	400 (37)	12,000 (45)	99.7
2nd Pass 7, 8, 9	AquaPro LE-8040UP *	X4	400 (37)	10,200 (38)	99.7

* Toray membrane assembled by AquaPro/Village Marine.

2.4.3.1 RO skid statistics

Table 2-4 presents statistics of the RO skid.

Table 2-4. RO Skid Statistics

Parameter	Value
Production capacity	~ 125,000 gpd for single pass on surface water above 25,000 mg/L TDS or groundwater above 2500 mg/L TDS ~162,000 gpd for other lower TDS waters ~98,000 gpd in double pass mode
Water temperature range	34–104 ^{o}F
Dimensions	20’ L x 8’ H x 8’ W
Weight	15,500 lbs dry, fully paced out for deployment, less fuel
Basic metals	High Pressure Piping: Titanium Production Piping: 316L Stainless Steel and fiberglass reinforced plastic (FRP)
Operating ambient temperature range	32°F–120 °F
Storage and transport air temperature Range	32°F–120 °F
Relative humidity	3%–95%
Maximum slope of unit when deployed for operation	No Restrictions
Power source requirement	Power for all but high-pressure pump is supplied from UF skid. HP pump requirements are 480 Volts and 125 Amps. The operational power use is 7.4 kWh/kgal for the RO system only.
Fuel type (if using RO pump engine)*	DF2, DFA, JP8
Fuel capacity (if using RO pump engine)*	60 gal

* Electric RO pump was used for ETV testing.

2.4.3.2 RO System Operation

The following is a basic description of the flow path and functional description of the RO system in normal operation. The RO system has the capacity to operate in either a one or two pass mode. The second pass is only used if sufficient treatment is not achieved with the first pass (especially for NBC contamination). The operation manual provides a full description of RO operation. Figure 2-13 is a P&ID of the RO system.

1. The UF filtrate is supplied to the RO 1st pass through P5 from TK3.
2. The RO 1st pass includes two arrays. The RO feed water (from the UF filtrate) flows into vessels 2 and 3 (PV2, PV3). The concentrate from vessels 2 and 3 flow into vessels 1 and 4 (PV1, PV4), respectively. The combined concentrate from vessels 1 and 4 flows through the energy recovery device, which boosts raw water pressure and feeds vessel 5 (PV5) of the second array. The concentrate from PV5 flows into vessel 6 (PV6). High pressure pump #6 (P6) supplies pressure for the 1st pass 1st and 2nd arrays and the pressure exchanger #8 (P8) supplies pressure for the 1st pass 3rd array.
3. Sodium metabisulfite from chemical pump #2 (CP2) and tank #7 (TK7) can be added after P5 to remove chlorine, if necessary. Free chlorine can damage RO membranes. The

maximum allowable chlorine level is membrane specific with the minimum chlorine tolerance being non-detect.

4. Anti-scalant from chemical pump #3 (CP3) and tank #8 (TK8) is added after P5 to minimize RO membrane scaling.
5. P6 increases the pressure to the required 1st pass 1st array operating pressure (800-1,200 psi depending on water conditions).
6. Concentrate from the 1st pass 1st array flows through the pressure exchanger P8. P8 exchanges energy from the high pressure, high salinity 1st pass concentrate to the lower pressure, lower salinity UF filtrate feed water. The UF filtrate pressurized by P8 flows into the 2nd array.
7. Pressure control valves #5, #6, and #7 (PCV5, PCV6, PCV7) are used to adjust pressure within the RO 1st pass piping. When PCV5 is fully open, P8 is bypassed. When restricted, PCV5 provides backpressure for P6.
8. As PCV6 is restricted, water is forced through P8.
9. When open, PCV7 prevents P8 overflow during start up. When restricted, it provides additional backpressure for P6.
10. Second pass operation is optional and will not be verified in this testing. During NBC operations or when the 1st pass permeate quality does not meet requirements, the 2nd pass is required.
11. The 2nd pass has one array with 12 membranes (PV7, PV8, PV9). The 1st pass permeate feeds the 2nd pass. If the raw water source does not contain NBC, concentrate from the 2nd pass (which is lower concentration because 2nd pass feed is 1st pass permeate) is recycled back to the raw water source to reduce the salinity of the inlet water.
12. Sodium hydroxide from chemical pump #4 (CP4) is added at the 2nd pass inlet to adjust pH to improve the rejection of certain contaminants that are ionized at high pH such as Boron.
13. Pump #7 (P7) pressurizes the 1st pass permeate. Pressure control valve #8 (PCV8) provides the backpressure for pump #7 (P7).
14. The 1st pass permeate is monitored by and displayed on conductivity sensors #1 and #2 (CS1, CS2), which determine if the permeate purity meets requirements. Permeate salinity is affected by temperature, TDS, and age of the RO membranes. If the permeate purity does not meet requirements, CS1 de-energizes solenoid valve #1, which then dumps the undesirable permeate back to the feed water source. If the permeate purity meets requirements, CS2 activates solenoid valve #1, allowing the handle on the dump valve to be latched, causing the high purity permeate to flow from the RO skid to the product water storage tanks. This diversion feature is disabled during 2nd pass operation.
15. Prior to distribution, RO permeate flows through the calcium hypochlorite disinfection system to the product water storage tanks. This system will not be operated during this test phase.

2.4.3.3 RO CIP Procedure

The RO elements should be cleaned whenever the temperature corrected product water output drops by 10 to 15% from the initial baseline established at the beginning of operation or from the expected output. The RO elements should also be cleaned when the TDS level of the product water exceeds 500 mg/L. Prior to cleaning the membranes, verify that any reduction in product output is not the result of a corresponding variation in raw water inlet temperature or salinity by

normalizing the data to a set of initial conditions. The following is a summarization of the operating instructions from the operations manual:

1. Set RO system in normal operation mode. Verify that valves are in the correct startup position. Make sure that the system output is being discharged to waste.
2. Select RO clean mode on main display screen.
3. Fill tank #4 with about 300 gal of fresh, un-chlorinated water to within 12 in of the top.
4. If ferric chloride is used in the system, perform the low pH adjustment first. If ferric chloride is not used, perform high pH adjustment first. (ETV note: ferric chloride was used during ETV test.)
5. Dissolve the appropriate amount of alkaline detergent or citric acid in a bucket of water.
6. Check the pH of the mixture in tank #4 and adjust as needed. Use citric acid to lower pH to 3 or use sodium hydroxide to raise the pH to 11.
7. Start P5 and allow chemical solution to circulate for three minutes. Check and adjust pH as needed.
8. Allow the cleaning solution to circulate for 15 min.
9. Touch “RO Clean” on the screen. Then touch “Enable RO Clean.”
10. Allow system to soak for 1 to 15 hours (h).
11. After soaking for the desired length of time, re-circulate the cleaning solution for 30 min.
12. Drain system and dispose of cleaning agents.
13. Repeat above steps for each desired chemical solution.
14. Rinse the RO system with fresh water.

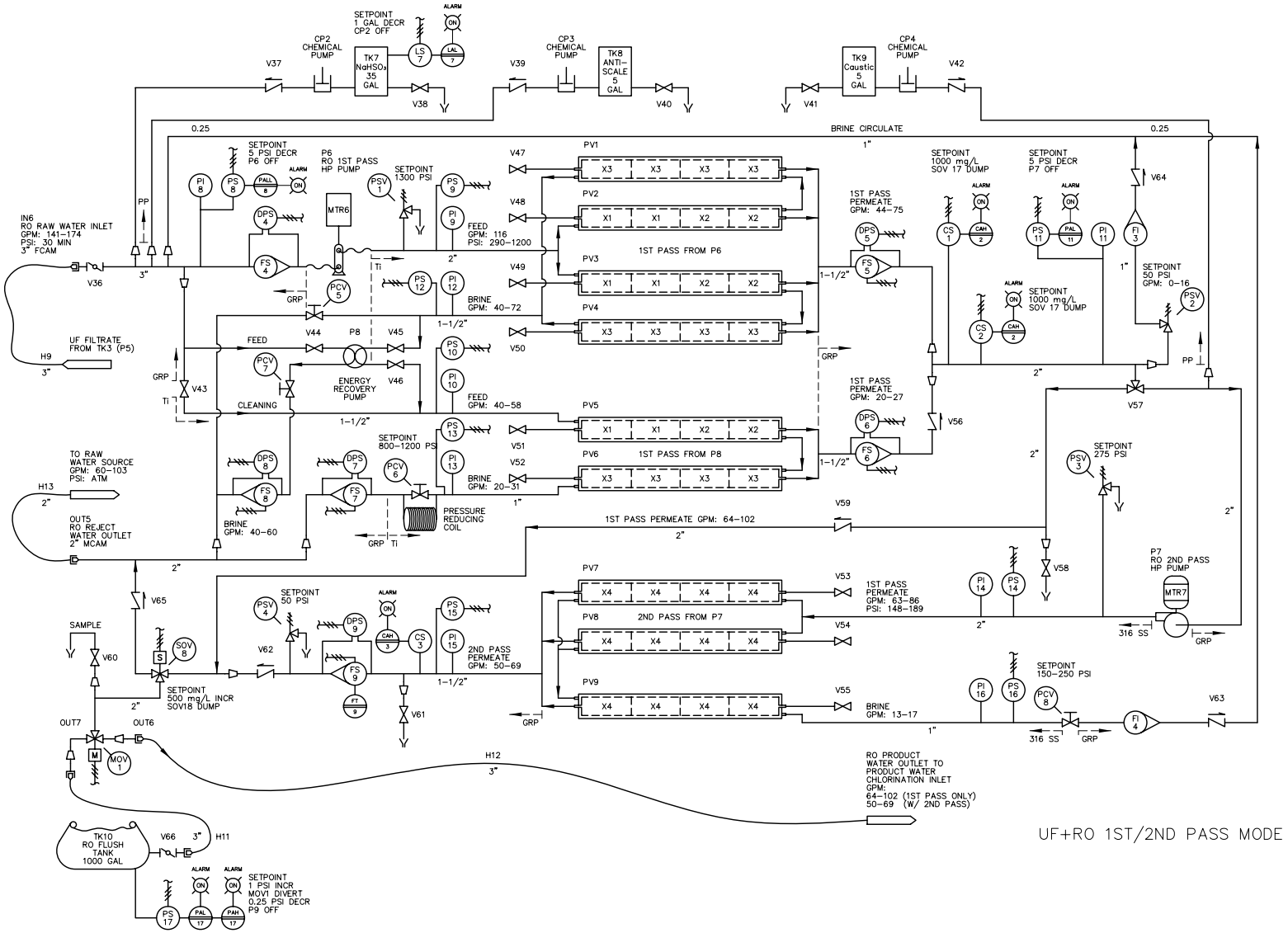


Figure 2-13. P&ID of RO skid.

2.4.3.4 Pressure Exchanger

RO is an inherently power intensive process. Historically, energy from the high-pressure brine was wasted through the utilization of a control valve to control the process. Today, several systems are available to recover the energy contained in the high-pressure brine to help offset the energy required. The EUWP uses the PX® Pressure Exchanger® (Model 90S) from Energy Recovery, Inc (Figure 2-14). The PX operates on the principle of positive displacement to allow incoming raw water to be pressurized by direct contact with the concentrate from a high-pressure membrane system. It uses a cylindrical rotor with longitudinal ducts parallel to its axis to transfer the pressure energy from the concentrate stream to the feed stream. The rotor fits into a ceramic sleeve between two ceramic end covers with precise clearances that, when filled with high-pressure water, create an almost frictionless hydrodynamic bearing. At any given time, half of the rotor ducts are exposed to the high-pressure stream and half of the ducts are exposed to the low-pressure stream. As the rotor turns, the energy is transferred to the low-pressure stream, pushing the feed water on to the booster pump. This type of energy device has been shown to be 90% efficient in transferring energy. During operation in Alamogordo, New Mexico, the average observed efficiency of the energy recovery device was 78 ± 8 %.

In a typical system, the pressurized feed water from the PX goes to a booster pump, which restores the pressure lost in the exchange and feeds a second RO vessel. However, the EUWP utilizes a parallel pass 1 train operation at approximately 10% lower pressure than the train operating directly off the high pressure pump. PX dimensions are 24 in long x 6.5 in diameter. Wetted materials are duplex stainless steel, ceramics, polyvinyl chloride (PVC), and fiberglass reinforced plastic (FRP).

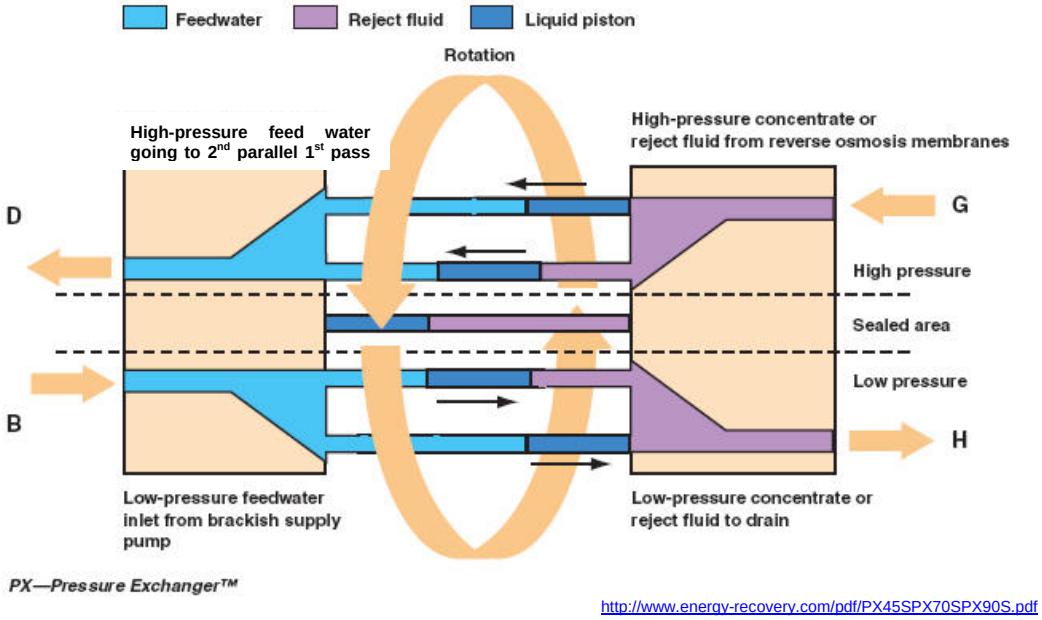


Figure 2-14. PX pressure exchanger.

2.5 General Requirements and Limitations

Table 2-5 lists the general environmental requirements for setup and operation of the EUWP.

Table 2-5. EUWP Site Considerations and Dimensions

Site Considerations	Site Dimensions
Drive-in access for on-road equipment	At least 10 ft wide
Work area required for equipment maneuvering and setup	At least 75 ft x 100 ft
Fairly smooth, level, and clear ground surface	Grade not to exceed 5° side to side and 2° end to end for UF configured platform or skid. No restriction for the RO skid. Ensure the elevation of tank #3 is equal to or higher than the UF skid (higher is better).
Cleared path to water source	Wide enough to move equipment
Work area elevation above pump #1	Maximum 25 feet vertical and 100 feet horizontal
Elevation/distance of pump #1 above the water source	Maximum 15 feet vertical and 50 feet horizontal
Distance of pump #1 from inlet strainer #1 in water source	Maximum 50 feet
Water depth from the inlet strainer #1 to the bottom of the raw water source	3 feet minimum; 5 feet or more preferred
Distance of distribution tanks from EUWP	Limited by hose length. Check hoses to determine distance.
Distance of distribution tanks from adjacent distribution tank	Limited by hose length. Check hoses to determine distance.
Distance of distribution pump #9 from tee adaptors	Limited by hose length. Check hoses to determine distance.
Cleaning waste storage tank	Less than 50 feet from the waste out connection

The EUWP was designed to be transported by air using a C-130 aircraft, or by land using any number of commercial and military haul transporters. The skids have forklift pockets that allow handling with an appropriately sized forklift.

Volume and type of consumables are site-specific depending on raw source water quality. As recommended by the membrane manufacturer, calcium hypochlorite, citric acid, or sodium hydroxide may be required to perform a CIP. Also as recommended by the membrane manufacturer, citric acid, sodium hydroxide, and/or a membrane detergent may be required to perform an RO cleaning. Depending on the raw water source quality, chemical additions may be needed for protection of the membranes during operation. Ferric chloride may be added at the UF skid to prevent clogging of the membranes by natural organic matter or high suspended solids in the feed water. Antiscalant and/or sodium meta-bisulphite may be added at the RO skid to prevent scaling and remove chlorine present in the feed water; and sodium hydroxide may be added to raise the pH to aid rejection of constituents during the 2nd pass. Calcium hypochlorite in granular or tablet form containing 65–70% free chlorine may be added prior to filtrate or permeate storage as a disinfectant (this did not occur as part of this ETV test). Table 2-6 covers equipment limitations and Table 2-7 presents membrane limitations.

Table 2-6. Equipment Limitations

System	Parameter	Value
Inlet Pump #1	Suction head (maximum)	25 ft
Strainer	Differential pressure (maximum) before manual backwash	7 psig
	Backpressure required for strainer auto flushing	35 psig
UF	Pretreatment requirements	200 µm strainer
	Feed pressure (maximum)	45 psig
	Ambient temperature range	32 – 120°F
	Water temperature range	34 – 104°F
	Control air pressure	60 psig
	Damaging chemicals	Grease, Oil, Silicon
	TMP (maximum) before CIP required	35 psig
	Pressure surges	Minimize by operating valves slowly
UF Membranes	Stagnation time (maximum) before preservation required with 1,000 – 5,000 mg/L sodium bisulfite (see operations manual for details) (see Table 2-1 for more details)	14 days (somewhat temperature dependent)
UF CIP Water	Turbidity	<1.0 NTU
	Iron	<0.05 mg/L
	Manganese	<0.05 mg/L
	Aluminum	<0.5 mg/L
	Reactive silica	ND(1)
	Colloidal silica	ND
	Total silica	<10 mg/L
	Calcium sulfate	< saturated at 50°C (122°F)
	Calcium carbonate	< saturated
	Microbiological	no living or dead material
	SDI	<3.0
	pH range	1.5 – 13
	Maximum feed pressure	45 psig
	Maximum air pressure	15 psig
	Temperature range	32°F to 120°F
	Filtered	500 µm prior to entering UF
	All water must be free of particulate matter	
RO	Water temperature range	34 – 104°F
	Maximum SDI	5 (membrane dependent)
	Operating ambient temperature range	32°F to 120°F
	Storage and transport air temperature range	32°F to 120°F
	Relative humidity	3% to 95%
	Pretreatment requirements	UF or 200 µm strainer on RO skid
	Maximum operating concentrate pressure after backpressure valve	200 psig
	Maximum operating permeate pressure (maximum)	100 psig
	2nd pass inlet pressure (maximum)	300 psig
	RO high pressure pump #6 maximum speed	600 revolutions per minute (RPM)
	RO high pressure pump #6 minimum inlet pressure	30 psig
	Stagnation time (maximum) before preservation required	1 week (somewhat temperature
RO Membranes	(see Table 2-7 for details)	

(1) Non-detect

Table 2-7. Membrane Limitations

Membrane	Maximum Pressure (psi)	Maximum Temperature(°F)	Maximum SDI	Maximum Chlorine Tolerance (mg/L)	pH range	pH range – feed, CIP	Maximum TMP per RO element (psi)	MaximumTMp per Vessel (psi)	Maximum Production TMP (psi)	Maximum Backwash TMP (psi)
TARGA® 10 - 48 - 35 – PMC	45	104		200					30	20
FILMTEC™ SW30HR LE-400	1,000[1]	113	5	<0.1	2-11	1-12	15	50		
FILMTEC™ SW30 XLE-400	1,200	113	5	<0.1	2-11	1-12	15			
FILMTEC™ SW30HR -12000 (experimental)	1,200	113	5	<0.1	2-11	1-12	15			
AquaPro LE-8040UP[2]	600	113	5	ND	2-11	1-12	20	60		

(1) May go up to 1,200 psi under certain conditions specified by Dow Chemical
(2) Toray membrane assembled by AquaPro/Village Marine

2.6 Waste Generation and Permits

The waste streams for the EUWP consist of the following:

- Cleaning waste from UF system (UF CIP);
- Cleaning waste from the RO system (RO CIP);
- Concentrate from the RO system; and
- Backwash waste and retentate from the UF system.

2.6.1 UF CIP

The UF system CIP cycle involves use of the 300-gallon CIP tank with the following chemical cleaning cycles: acid, rinse, base with chlorine, rinse. A second base cleaning may be required. The total volume generated with five cleaning cycles (worst case, assuming a second base cleaning) at 300 gal each, plus 200 gal for piping/membrane volume is approximately 2,500 gal. For this ETV verification, all cleaning solutions were captured in a storage tank. The contents of the storage tank were pumped into the sanitary sewer.

2.6.2 RO CIP

The CIP procedure for the RO system is similar to that of the UF and uses the same 300-gallon CIP tank to dispense the cleaning solutions. The cleaning cycles consist of an acid clean followed by a rinse, then a high pH clean with membrane cleaner followed by a final rinse. The approximate volume of waste generated from all of the cleaning cycles is 1,200 gal of cleaning solutions, plus 200 gal of piping/membrane volume for each cycle, for a total of approximately 2,000 gal.

2.6.3 RO Concentrate

The RO concentrate was blended with the RO permeate, UF backwash, and UF retentate, and the resulting mixture was discharged into Lake St. Clair.

2.6.4 UF Backwash and Retentate

The UF system automatically initiates a backwash every 30 min to remove captured material from the membrane surface. Each backwash cycle consists of backflushing the membranes with UF filtrate for a short period followed by a forward "fast flush" using feed water. In addition to the backwash, the UF system also discharges a continuous retentate stream.

Both waste streams exited the system using a common discharge line that was routed to a storage tank. The contents of the storage tank were discharged to Lake St. Clair when the tank was full.

2.6.5 Discharge Permits

TARDEC obtained a permit from the Michigan Department of Environmental Quality to discharge the mixture of UF backwash, UF retentate, RO concentrate, and RO permeate back into Lake St. Clair.

2.7 Discussion of the Operator Requirements

The following information on operator requirements is supplied by the manufacturer for informational purposes only. A team of four water treatment specialists, with proper site validation, layout planning and using a 10,000-lb forklift, should be able to have the EUWP setup and producing potable water within eight hours. Depending on the distribution connection requirements and availability of the connections, distribution of the produced potable water may take longer.

Except for periodic O&M and data collection, once set up and operational, the EUWP is capable of operating unattended. Staffing requirements are based on the O&M or data collection efforts being performed. Due to the use of high pressure, electricity or diesel, and chemicals, O&M on the equipment and piping should be performed by a minimum of two persons. Data collection requires only one person.

The EUWP requires a skilled operator familiar with water treatment processes, equipment, and concepts to perform O&M and collect data. A skilled operator could meet any of a variety of requirements as discussed below. Operation of the EUWP should be performed by an individual with similar experience, knowledge, or training as provided within these programs.

A U.S. military water treatment specialist (classified as skill level 4 through 1) supervises or performs installation, operation of water purification equipment, water storage, and distribution operations and activities.

The minimum skill level 4 requires the specialist to:

- Assist in water reconnaissance, site preparation, and setup of water treatment activity;
- Operate and maintain water treatment equipment;
- Receive, issue, and store potable water; and
- Perform water quality analysis testing and verification.

Although remote operation is not available, the EUWP can be monitored remotely 24 h per day by use of the water system management tool, WaterEye™ (www.watereye.com). WaterEye provides timely, critical operations monitoring information utilizing colored indicators to either confirm system status or alert potential problems. In addition, WaterEye can assist with managing daily, monthly, and yearly compliance requirements by monitoring compliance data and automatically creating reports. WaterEye maintains a database of monitored instrument readings, which are read every 15 min and uploaded to their server every 30 min. Alarm conditions are immediately uploaded for response. WaterEye can also display/store information calculated from uploaded instrument readings. Data must be either uploaded directly from the PLC on the EUWP or be able to be calculated from that data.

Chapter 3
Methods and Procedures

3.1 Introduction

The full EUWP system was tested at Selfridge ANGB during September and October of 2006. Immediately prior to the test, TARDEC and USBR discovered that the UF system seals between the housings and membrane modules were not as tight as desired. The problem was temporarily fixed, and NSF allowed the test to proceed because a future verification test at Port Hueneme, CA, would verify UF seal integrity after the problem was permanently fixed. After testing was complete, NSF reviewed the UF performance data and concluded that the temporary fix was not sufficient. Therefore, a second test of the UF system only was required, after permanent repairs were made. The UF system retest was conducted in July and August of 2007. See Section 4.3.1 for further discussion about the seal problem and how it was fixed.

3.2 Quantitative and Qualitative Evaluation Criteria

The objectives of the verification test were to evaluate equipment in the following areas:

- The actual results obtained by the equipment as operated under the conditions at the test site;
- The impacts on performance of any variations in feed water quality or process variation;
- The logistical, human, and other resources necessary to operate the equipment; and
- The reliability, ruggedness, ranges of usefulness, and ease of operation of the equipment.

There are three main components of the EUWP that were evaluated at the same time: the UF system, the RO system, and the energy recovery system. All three components must function successfully to meet the performance objectives.

To address these objectives, the verification test employed the quantitative and qualitative factors listed below.

Qualitative factor:

- Waste discharge requirements.

Quantitative factors:

- Water quality data;
- Physical operations data – flow, membrane flux, recovery, and pressure;
- Power usage;
- Chemical usage;
- Waste stream generation; and
- Operating cycle length.

3.3 Key Treated Water Quality and Operational Parameters

Treated product water must meet EPA NPDWR, and should meet EPA secondary Standards whenever possible. As discussed in Section 2.1, the objective of this ETV verification was to demonstrate that the EUWP can provide water that meets the requirements of the EPA NPDWR. As such, a list of key treated water parameters was developed based on the EPA regulations, and other water quality parameters of interest. Regulated contaminants not present in raw water samples analyzed during the characterization of feed water task were not included in the list. The final list is presented in Table 3-1.

Table 3-1. Key Treated Water Quality Parameters

Parameter	
pH	Total Silica
Temperature	TDS
Conductivity	Total Organic Carbon (TOC)
Turbidity	Total Suspended Solids (TSS)
Particle Counts	Ultraviolet Light Absorbance at 254 nm (UV_{254})
Alkalinity	Heterotrophic Plate Count (HPC) Bacteria (2006 test)
Hardness	Total Coliforms (2006 test)
	Bacillus Endospores (2007 test)

A portion of the water quality and operational parameters were measured continuously via online instrumentation, as listed in Table 3-2.

Table 3-2. Water Quality and Operational Parameters Measured Online

Membrane	UF Feed	UF Retentate	UF Filtrate	RO Feed	RO 1st Array Concentrate	RO 1st Array Permeate	RO 2nd Array Permeate	RO Permeate
Flow	X	X		X	X	X	X	
Pressure	X	X	X	X	X		X	
Conductivity							X	
Temperature			X					
Turbidity	X		X					X
Particle count	X		X					

3.4 Operations and Maintenance

Village Marine Tec. provided an operations and maintenance manual for the EUWP, which is included in Appendix A. The ETV test protocols call for review of the manual in regards to the ability of the user to successfully operate the system armed with only the information in the manual. An objective review of the manual by the field operators was not possible, because they already had intimate knowledge of the EUWP prior to the test. Therefore, a review is not included in this report.

The following aspects of operability are addressed in Chapters 2 and 4, and in the appendices:

- Fluctuation of flow rates and pressures through unit (the time interval at which resetting is needed);
- Presence of devices to aid the operator with flow control adjustment;
- Availability of pressure measurement;
- Measurement of raw water rate of flow;
- Pace of chemical feed with raw water; and
- Operation of the PLC control system.

3.5 Field Operations

Acting as the FTO, TARDEC conducted the testing of the EUWP as described below. TARDEC and USBR field personnel performed field analytical work using field laboratory equipment and procedures for pH, temperature, conductivity, and turbidity. NSF performed water quality analytical work for samples not analyzed on-site. Field staff were on site each day to operate the system and collect water quality data during the verification test.

The test plan called for the EUWP to be operated 24 hours per day, seven days per week, excluding regular backwashes and cleaning periods. However, this was not the case for much of the test period due to various alarms that shut the system down during the night when field personnel were not present.

3.6 Overview of ETV Testing Plan

A test/quality assurance plan (TQAP) was prepared for the EUWP verification test in accordance with the ETV Protocols *EPA/NSF Protocol for Equipment Verification Testing for Removal of Inorganic Constituents* – April 2002, and the *EPA/NSF Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants* – September 2005. The TQAP divided the work into three main tasks (A, B, C) with Task C, the verification test itself, divided into six subtasks.

These tasks are:

Task A: Characterization of Feed Water
Task B: Equipment Installation, Initial Test Runs, and Initial System Integrity Tests
Task C: Verification Test
- Task C1: Membrane Flux and Recovery
- Task C2: Cleaning Efficiency
- Task C3: Finished Water Quality

Task C4: Membrane Module Integrity
Task C5: Data Handling Protocol
Task C6: Quality Assurance/Quality Control (QA/QC)

The TQAP, which included a Quality Assurance Project Plan (QAPP), specified procedures to be used to ensure the accurate documentation of both water quality and equipment performance. An overview of each task is provided below with detailed information on testing procedures presented in later sections.

3.6.1 Task A: Characterization of Feed Water

The objective of this initial operations task was to obtain a chemical, biological, and physical characterization of the feed water prior to testing.

3.6.2 Task B: Equipment Installation, Initial Test Runs, and Initial System Integrity Tests

The objective of this initial operations task was to evaluate equipment operation and determine the treatment conditions that resulted in effective treatment of the feed water. This task was considered shakedown testing and was carried out prior to performing Task C.

3.6.3 Task C: Verification Test

The verification test itself consisted of six tasks described as follows:

3.6.3.1 Task C1: Membrane Flux and Recovery

Task C1 evaluated membrane operation and entailed quantification of membrane flux decline rates and product water recoveries. The rates of flux decline demonstrate membrane performance at the specific operating conditions established during Task B.

3.6.3.2 Task C2: Cleaning Efficiency

An important aspect of membrane operation is the restoration of membrane productivity after membrane flux decline has occurred. The objective of this task was to evaluate the efficiency of the membrane cleaning procedure. The fraction of specific flux restored following a chemical cleaning and after successive filter runs was determined.

3.6.3.3 Task C3: Finished Water Quality

The objective of this task was to evaluate the quality of water produced by the EUWP. Treated water quality was evaluated in relation to feed water quality and operational conditions. The monitored water quality parameters included the following: pH, temperature, conductivity, alkalinity, total hardness, total silica, TDS, turbidity, particle concentrations, TSS, TOC, and ultraviolet light absorbance at a 254 nm wavelength (UV_{254}). Also, total coliforms and HPC bacteria were measured during the 2006 test, and *Bacillus* endospores were measured during the 2007 test. The switch to *Bacillus* endospores was made because there were too many HPC and total coliforms present on the treated water sides of both the UF and RO skids, likely from the existing populations of bacteria. It was hoped that there would be fewer *Bacillus* endospores already present on the treated water sides of the skids, so that monitoring their populations would provide a better indicator of microbial removal.

3.6.3.4 Task C4: Membrane Module Integrity

The objective of this task was to demonstrate the methodology for monitoring membrane integrity and to verify the integrity of membrane modules.

3.6.3.5 Task C5: Data Handling Protocol

The objective of this task was to establish an effective field protocol for data management at the field operations site and for data transmission between TARDEC and NSF.

3.6.3.6 Task C6: Quality Assurance and Quality Control

An important aspect of verification testing is the protocol developed for QA/QC. The objective of this task was to assure accurate measurement of operational and water quality parameters during membrane equipment verification testing.

3.7 Task A: Characterization of Feed Water

The objective of this task was to determine the chemical, biological, and physical characteristics of the feed water. Grab samples were collected from Lake St. Clair at the test site in August 2006 for water quality analysis. To evaluate the Lake St. Clair water for organic chemicals, a sample was analyzed for the volatile organic compounds (VOC) included under EPA Method 502.2. It was assumed that any organic compounds present in the water column at significant levels would be VOCs. Any more hydrophobic organic chemicals, such as pesticides, would not be present dissolved in the water column in significant quantities, but rather would be adsorbed onto suspended organic particles.

3.8 Task B: Equipment Installation, Initial Test Runs, and Initial System Integrity Tests

The objective of this task was to properly install the equipment and begin equipment operation, then evaluate operation and determine whether the operating conditions resulted in effective treatment of the water. In this task, a preliminary assessment of the treatment performance of the equipment was made. This task was considered a shakedown testing period and was completed before Task C. This task also included pressure decay testing of the UF membranes, and dye removal testing of the RO system. See Section 3.9.4.1 for further discussion about these two tests.

3.9 Task C: Verification Testing

The verification test was started on September 25, 2006 and ran for the planned 30 day test period, ending on October 25, 2006. The UF system was operated each day on semi-continuous basis, automatically shutting down when the RO feed tank was full. A typical operating day for the UF system was 15 to 17 h in duration. The RO system was setup to operate continuously. After the first three days of the test, when the system was shutdown at night, the RO system typically ran 22 to 24 h each day. The RO system did shutdown periodically for various maintenance activities or when alarms occurred and shut the system down. When alarms and shutdown occurred during unattended operation at night, the entire system would remain shutdown until an operator arrived in the morning.

The UF system retest was conducted from July 30 to August 24, 2007. The retest was stopped short of 30 days because the intent of the test as stated in the ETV test protocol – operation to a membrane cleaning – was met. During the retest, the UF system was operated an average of 14 h per day, not including down time for backwashes, cleanings, and other maintenance activities.

The TQAP describes six tasks to be performed to achieve a successful verification test. Each of these tasks is described in detail in this section.

3.9.1 Task C1: Membrane Flux and Operation

The purpose of this task was to evaluate membrane flux during extended operation to demonstrate membrane performance. The objectives of this task were to demonstrate the feed water recovery achieved by the membrane equipment, and the rate of flux decline observed over extended membrane operation. Flow, pressure, conductivity, and temperature data were collected daily in order to quantify the loss of productivity in terms of specific flux decline.

3.9.1.1 Work Plan

Twice per day – in the morning and afternoon – the operator checked the flowrates and recovery and made adjustments as necessary to put the system on target. Thirty minutes after resetting target flow and recovery, the operator recorded the appropriate water quality and operational data, as outlined in Table 3-3. The set points for key operating parameters are listed in Table 3-4. Chemical usage was monitored by recording the concentration and tank level on a daily basis.

3.9.1.2 Evaluation Criteria

Completion of this task involved quantification of membrane flux decline rates and product water recoveries. Summaries of the data collected for Task 1 are presented in tabular format in Chapter 4 for both the RO and UF systems.

The plots listed in Table 3-5 are also presented in Chapter 4 to illustrate equipment operation for Task 1. Note that all plots are of the parameter over time.

Table 3-3. Operational Parameter Sampling Locations

Parameter	Raw	UF Feed	UF Filtrate	UF Retentate	UF Backwash	RO Feed	RO 1st Pass Permeate	RO 1st Pass Concentrate	UF Skid	RO Skid
Flow	X	X		X	X	X	X	X		
Pressure		X	X	X		X		X		
Conductivity						X	X	X		
Temperature		X	X			X	X	X		
Power usage									X	X
Operating hours									X	X

Table 3-4. Key Operating Parameters

Parameter	Set Point
UF feed flow (gpm)	259
UF recovery (%)	90
RO feed flow 1st pass array 1 (gpm)	116
RO feed flow 1st pass array 2 (gpm)	58
RO recovery levels (%)	50 (1st array) and 48 (2nd array)

Table 3-5. Operational Data Plots Appearing in Chapter 4

UF Skid	RO Skid
Filtrate Production	Flow Rates
Flow Rates	Percent Recovery
Operating Pressures	Operating Pressures
Trans-Membrane Pressures	Specific Flux
Specific Flux	Power Consumption
Loss of Specific Flux	
Power Consumption	

3.9.1.3 Equations

UF System

The following are the definitions and equations used for the verification report for the UF system:

Filtrate: Treated water produced by the UF process.

Retentate: The water rejected by the UF system

Feed water: The water introduced to the membrane elements after all chemical additions.

Raw water: The source water supply.

Membrane flux: The average flux across the UF membrane surface calculated by dividing the flow rate of filtrate by the surface area of the membrane. Membrane flux is calculated as follows:

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

where:

J_t = filtrate flux at time t (gallons per square foot per day (gfd))
Q_p = filtrate flow (gpd)
S = membrane surface area (ft^2)

Temperature Adjustment for Flux Calculation: Temperature corrections to 20°C for filtrate flux and specific flux are made to correct for the variation of water viscosity with temperature. The following empirically derived equation was used to provide temperature corrections for specific flux calculations:

$$J_t = \frac{Q_p \times e^{-0.0239(T-20)}}{S}$$

where:

J_t = filtrate flux at time t (gfd)
Q_p = filtrate flow (gpd)
S = membrane surface area (ft^2)
T = temperature of the feed water (°C)

Transmembrane Pressure: The pressure across the membrane, equal to the average feed water pressure on the membrane (average of inlet pressure and outlet pressure) minus the filtrate (permeate) pressure:

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

where:

TMP = transmembrane pressure (psig)
P_f = inlet pressure to the feed side of the membrane (psig)
P_c = outlet pressure on the retentate side of the membrane (psig)
P_p = filtrate pressure on the treated water side of the membrane (psig)

Specific flux: The filtrate flux that has been normalized for the TMP. The equation used for calculation of specific flux is given by the formula provided below. Specific flux is usually discussed with use of flux values that have been temperature-adjusted to 20°C per equation above:

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

where:

TMP = Transmembrane pressure across the membrane (psig)
J_t = filtrate flux at time t (gfd) (temperature-corrected flux values were employed)

J_{tm} = specific flux at time t (gfd/psig)

RO System

Permeate: Water produced by the RO membrane process.

Feed Water: Water introduced to the membrane element.

Concentrate: Water rejected by the RO membrane system.

Permeate Flux: The average permeate flux is the flow of permeate divided by the surface area of the membrane. Permeate flux is calculated according the following formula:

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

where:

J_t = permeate flux at time t (gpd))
Q_p = permeate flow (gpd)
S = membrane surface area (ft^2)

Temperature Adjustment for Flux Calculation: Temperature corrections to 25 °C for permeate flux and specific flux were made to correct for the variation of water viscosity with temperature. The following empirically-derived equation was used to provide temperature corrections for specific flux calculations:

$$J_t \text{ (at } 25^\circ \text{ C)} = \frac{Q_p \times e^{-0.0239 \cdot (T-25)}}{S}$$

where:

J_t = permeate flux at time t (gfd)
Q_p = permeate flow (gpd)
S = membrane surface area (ft^2)
T = temperature of the feed water (°C)

Net Driving Pressure: For this test, a temperature conversion chart provided by the manufacturer was used for all temperature correction. Net Driving Pressure (NDP) is the total average pressure available to force water through the membrane into the permeate stream. Net driving pressure is calculated according to the following formula:

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

where:

NDP = net driving pressure for solvent transport across the membrane (psig)
P_f = feed water pressure to the feed side of the membrane (psig)
P_c = concentrate pressure on the concentrate side of the membrane (psig)
P_p = permeate pressure on the treated water side of the membrane (psig)
$\Delta\pi$ = osmotic pressure (psig)

Osmotic Pressure Gradient: The term osmotic pressure gradient refers to the difference in osmotic pressure generated across the membrane barrier as a result of different concentrations of dissolved salts. The following equation provides an estimate of the osmotic pressure across the semi-permeable membrane through generic use of the difference in TDS concentrations on either side of the membrane:

$$\Delta\pi = \left[\left[\frac{\left(TDS_f + TDS_c\right)}{2}\right] - TDS_p\right]\left[\frac{0.6\ \ psi}{100\ \frac{mg}{L}}\right]$$

where:

$\Delta\pi$ = osmotic pressure (psig)
TDS_f = feed water TDS concentration (mg/L)
TDS_c = concentrate TDS concentration (mg/L)
TDS_p = permeate TDS concentration (mg/L)

Note that the different proportions of monovalent and multivalent ions composing the TDS will influence the actual osmotic pressure, with lower unit pressures resulting from multivalent species. The osmotic pressure ratio of 1 psig per 100 mg/L is based upon TDS largely composed of sodium chloride or other monovalent ions. In contrast, for TDS composed of multivalent ions, the ratio is closer to 0.5 psig per 100 mg/L TDS. Osmotic pressure was estimated using the ionic strength of the feed and concentrate based on the weekly data for cations and anions (Ca, Mg, Na, K, Li, Cl, SO_4, HCO_3). The ratio of 1 psig per 100 mg/L TDS gave a much higher osmotic pressure and the ratio of 0.5 psig per 100 mg/L TDS gave a lower osmotic pressure. It was determined that the equation for TDS using a factor 0.6 psig per 100 mg/L TDS most closely approximates the osmotic pressure calculated based on the ionic strength data available for this water.

Specific Flux: The term specific flux is used to refer to permeate flux that has been normalized for the net driving pressure. The equation used for calculation of specific flux is given by the formula provided below. Specific flux is usually calculated with use of flux values that have been temperature-adjusted to 25 °C:

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

where:

J_{tm} = specific flux (gfd/psig)
NDP = net driving pressure for solvent transport across the membrane (psig)
J_t = permeate flux at time t (gfd). Temperature-corrected flux values should be employed.

Water Recovery: The recovery of feed water as permeate water is given as the ratio of permeate flow to feed water flow:

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

where:

Q_f = feed water flow to the membrane (gpm)
Q_p = permeate flow (gpm)

Loss of Original Specific Flux:

$$\text{Percent Loss} = 100 \cdot \left(1 - \frac{J_s}{J_{so}} \right)$$

where:

J_{so} = specific flux (gfd/psig) at time zero point of membrane testing.
J_s = specific flux (gfd/psig) at time T of membrane testing.

Solute Rejection: Solute rejection is controlled by a number of operational variables that must be reported at the time of water sample collection. Bulk rejection of a targeted inorganic chemical contaminant may be calculated by the following equation:

$$\text{Percent Solute Rejection} = 100 \cdot \left(\frac{C_f - C_p}{C_f} \right)$$

where:

C_f = feed water concentration of specific constituent (mg/L)
C_p = permeate concentration of specific constituent (mg/L).

3.9.2 Task C2: Cleaning Efficiency

An important aspect of membrane operation is the restoration of membrane productivity after specific flux decline has occurred. The effectiveness of chemical cleaning to restore membrane productivity was evaluated.

3.9.2.1 Work Plan

The manufacturer specified that the UF cleaning procedure should be executed when the TMP drop exceeds 35 psig, even after a backwash. The manufacturer specified that the RO system be cleaned when there is a 10 to 15% decrease in normalized permeate flowrate, 15% increase in TMP drop or permeate TDS concentration.

Flow, pressure, and temperature data were recorded immediately before the system was shut down for cleaning and immediately upon return to membrane operation after cleaning procedure was complete.

Two primary indicators of cleaning efficiency and restoration of membrane productivity were examined in this task:

- Immediate recovery of membrane productivity (% recovery of specific flux); and
- Long term maintenance of specific flux over an equivalent time period.

The pH, temperature, conductivity, and TOC of each cleaning solution were measured after the cleaning. Flow, pressure, and temperature data were also collected during the cleaning procedure. Following the cleaning procedure, the specific membrane flux was calculated at the same operating conditions used prior to the cleaning. This value was compared to the pre-cleaning specific flux to determine the efficiency of the cleaning procedure. See Section 2.4.2.2 for the UF cleaning procedure, Section 2.4.3.3 for the RO cleaning procedure, and also the User's Manual (Appendix A) for details on the cleaning procedures employed.

3.9.2.2 Evaluation Criteria

The outputs for this task are post-cleaning flux recoveries, and the cleaning efficacy indicators described above (including flow, pressure, and temperature data).

3.9.3 Task C3: Finished Water Quality

The objective of this task was to assess the ability of the membrane equipment (both UF and RO) to meet the water quality goals specified by the manufacturer.

3.9.3.1 Work Plan

The water quality parameters in Table 3-6 were measured as indicated during the testing period. To the extent possible, scheduled on-site analyses for each sampling point were performed on water samples collected at the same time as the samples shipped off site.

In addition to manual sample collection for the water quality parameters listed in Table 3-6, in-line particle counters recorded particle counts for the UF feed and UF filtrate streams every five minutes. This data was only available for the 2007 UF test due to incorrect calibration of the particle counters for the 2006 test. Note that particle count data is not presented in the water quality discussion of Chapter 4, but rather in the membrane integrity section, since the primary purpose of the particle counters is to serve as a monitor of membrane integrity.

Table 3-6. Water Quality Sampling Schedule

Parameter	UF Feed	UF Filtrate	UF Retentate	UF Backwash	UF Cleaning Solution	RO Feed	RO 1st Pass Permeate	RO 1st Pass Concentrate
On-site Measurement								
pH	D	D			E	D	D	D
Temperature	D	D			E	D	D	D
Conductivity	D	D				D	D	D
Turbidity	D	D				D	D	D
Laboratory Measurements								
TOC	W	W	W		E	W	W	W
UV_{254}	W	W				W	W	W
TSS	W	W	W	W		W	W	W
TDS, dissolved (<0.45 μm)	W	W				W	W	W
Alkalinity, total (as $CaCO_3$)	W	W				W	W	W
Hardness, total (as $CaCO_3$)	W	W				W	W	W
Silica, total (as SiO_2)	W	W				W	W	W
HPC (2006 only)	D	D	D	D		D	D	D
Total Coliforms (2006 only)	W	W	W	W		W	W	W

D = twice daily; exception is HPC, which was collected once daily, Monday through Thursday.
E = at every cleaning event
W = weekly

3.9.3.2 Evaluation Criteria

All water quality data generated during the test periods is presented in a tabular format in Chapter 4. In addition, the UF feed and filtrate turbidity data, and the RO conductivity data is presented in a graphical format.

3.9.4 Task C4: Membrane Integrity Testing

The objective of this task is to demonstrate the methodology to be employed for direct integrity testing and indirect integrity monitoring of the RO and UF membrane elements. Direct testing and indirect monitoring methods were used together to provide consistent and sensitive evaluation of membrane system integrity.

3.9.4.1 Direct Integrity Testing:

The direct integrity testing method employed on the UF system was a pressure decay test, similar to that described in ASTM International Standard D6908 – *Standard Practice for Integrity Testing of Water Filtration Membrane Systems*. A pressure decay test was performed during Task B to establish a baseline pressure decay rate for the UF system. During testing, the pressure decay test was performed daily. The pressure decay test was also performed after each UF system cleaning.

The direct integrity test method employed on the RO system was a marker test with food-grade dye. The marker dye test was conducted prior to the start of the ETV test, and after the RO cleaning at the end of testing. The dye used was FD&C Food-grade Dye #40, Allura Red. The concentration of this dye was measured in the RO feed and RO permeate to determine the level of dye rejection by the RO system.

3.9.4.2 Continuous Indirect Integrity Monitoring:

Continuous indirect integrity monitoring methods were employed on both the UF and RO systems. Turbidity was monitored continuously on the UF feed, UF filtrate, and RO permeate. In addition to turbidity monitoring, particle counts were continuously monitored on the UF system, and specific conductance was continuously monitored on the RO membrane unit. Turbidity readings were recorded every fifteen minutes, while particle counts were recorded every five minutes, and conductivity readings were recorded hourly. Results of the direct integrity tests, and indirect integrity monitoring are presented in Chapter 4.

3.9.5 Task C5: Data Handling Protocol

The objectives of this task were to: 1) establish an effective structure for the recording and transmission of test field test data, such that TARDEC provided sufficient and reliable data; and 2) develop an effective and accurate statistical analysis of the data.

3.9.5.1 Work Plan

The EUWP test system was equipped with a computer monitoring system. Some of the required measurements (see Table 3-2) were recorded automatically by the automated system. The remaining required measurements were recorded by hand by the field operator on-site. The data was recorded onto specially prepared bench sheets. Miscellaneous operational notes were recorded in a data logbook with numbered pages (Appendix B). All errors were crossed out with one line, and the error was initialed and dated. Completed pages were signed, dated, and numbered by the individual responsible for the entries.

The database for the project was set up in the form of custom-designed spreadsheets. A spreadsheet containing the operational data, including calculations, was developed by USBR. A spreadsheet containing the water quality data was developed by NSF. Following data entry, 100% of the data in the spreadsheets was checked against the numbers on the field log sheets or laboratory analysis outputs.

3.9.6 Task C6: Quality Assurance Project Plan

QA/QC of the operation of the equipment and the measured water quality parameters was maintained through a QAPP, as described in this section.

3.9.6.1 Experimental Objectives

The objective of this task was to maintain strict QA/QC methods and procedures during the verification test. This included maintaining instrument calibration and operation within the ranges specified by the manufacturer.

The elements of the QAPP for this verification test included:

- work plan;
- QA/QC verifications;
- data correctness;
- calculation of indicators of data quality; and
- corrective action plan

3.9.6.2 Work Plan

A routine daily walk-through during testing was conducted to verify that each piece of equipment or instrumentation was operating properly. Chemical addition rates and receiving stream flowrates were checked to verify that they flowed at the expected rates. Values recorded by the automated data acquisition program were checked daily against those displayed on the instrument displays and those measured on-site.

3.9.6.3 QA/QC Verifications

Tables 3-7 and 3-8 give the on-site QA and on-site QC activities, respectively, for the verification test. NSF Laboratory analytical QA and QC activities followed those specified in the NSF Laboratory Quality Assurance Manual.

Table 3-7. On-Site Analytical Equpment QA Activities

	Equipment	Action Required
Initial	Flowmeters – electronic	Verified calibration volumetrically
	Turbidimeter – in-line (1720E)	Provided factory calibration certificate
	Turbidimeter – in-line (FilterTrak)	Provided factory calibration certificate
	Particle counter – in-line	Provided factory calibration certificate
	UV spectrophotometer	Provided factory calibration certificate
Daily	Chemical feed pump	Volumetrically checked flowrate
	Turbidimeter – in-line	Verified with portable turbidimeter
	pH meter – portable	3-point calibration (4,7,10)
	Turbidimeter – in-line	Volumetrically checked flowrate
	Particle counters – in-line	Volumetrically checked flowrate
Weekly	Rotameters	Inspected for buildup of algae, salt, etc.
	UF filtrate flow	Verified volumetrically
	Particle counter - in-line	Cleaned sensors
	Temperature – portable	Verified calibration with NIST-certified thermometer
	Turbidimeter – portable	Calibrated using <0.1, 20, 100, and 800 NTU standards
	Conductivity meter – portable	Calibrated at 2 points
Every Two Weeks	Flowmeters – electronic	Verified calibration volumetrically
Prior to Test	Tubing	Checked condition, checked for leaks
	Particle counter - in-line	Factory calibration
	Turbidimeter – in-line (1720E)	Cleaned and calibrated using 20 NTU standard
	Turbidimeter – in-line (FilterTrak)	Cleaned and calibrated using 0.8 NTU standard

Table 3-8. On-Site Data Generation QC Activities

Item		Action Required
Daily	Data	Reviewed system performance data since previous day
Weekly	Data	Compared field and lab water quality results when available

3.9.6.4 Data Correctness

There are five indicators of data quality that were used for this verification test:

- representativeness;
- statistical uncertainty;
- precision;
- accuracy; and
- completeness.

These five indicators are discussed in detail in the sections that follow.

3.9.6.4.1 Representativeness

Representativeness of the data for this verification was ensured by executing consistent sample collection and data collection procedures, including:

- Consistency of sample locations;
- Timing of sample collection;
- Analytical methods; and
- Sampling procedures, sample preservation, packaging, and transport.

3.9.6.4.1.1 On-Site Analytical Methods

The analytical methods for on-site monitoring of raw and treated water quality are described below.

pH

Analyses for pH were performed according to *Standard Method* 4500-H^+ B using a Myron L Ultrameter II Model 6P. Three-point calibration (using pH 4, 7, and 10 buffer solutions) was performed daily.

Temperature

Readings for temperature were conducted in accordance with *Standard Method* 2550 using a Myron L Ultrameter II Model 6P. A calibration check was performed weekly with a NIST-traceable thermometer.

Turbidity

Turbidity was measured at all sampling points using a hand-held turbidimeter. In addition, in-line turbidimeters were used for measurement of UF feed and filtrate. All measurements were conducted according to Standard Method 2130 B.

Hand-held Turbidimeters: A Hach 2100P Portable Turbidimeter (range 0 to 1000 NTU) was used to measure the turbidity of the appropriate grab samples. The turbidimeter was calibrated weekly using formazin turbidity standards of <0.1, 20, 100, and 800 NTU.

In-Line Turbidimeters: In-line Hach turbidimeters were used for measurement of turbidity in the feed (Hach 1720 E – Low Range) and UF filtrate water (Hach FilterTrak 660). The Hach 1720E has a range from 0 to 100 NTU and uses a 20 NTU calibration standard. The Hach FilterTrak has a range from 0.005 to 5.00 NTU and uses a 0.8 NTU calibration standard. These turbidimeters were calibrated at the start of the test. In-line readings were periodically compared to the readings from the hand-held turbidimeter. If the comparison suggested inaccurate readings, the in-line turbidimeter was recalibrated. A volumetric check on the sample flowrate was performed daily.

Conductivity

Analyses for conductivity were performed according to manufacturer's instructions using a Myron L Ultrameter II Model 6P. A two-point calibration was performed weekly.

Particle Count

In-line particle counters were employed for measurement of particle concentrations in UF membrane unit feed and filtrate waters. The Hach 2200 PCX in-line particle sensor is able to measure particles with a range of 2 μm to 750 μm in up to 32 user-defined bins. The particle counters were calibrated by the manufacturer prior to the ETV test.

3.9.6.4.1.2 Sample Collection, Shipment, and Storage for Laboratory Analyses

Samples were collected in bottles prepared by NSF and shipped to the test site. All samples were preserved, if required, according to the proper analytical method. Bottles for parameters requiring preservation were shipped to the test site containing the preservative. All samples were kept on ice in coolers and shipped overnight to NSF. Chain of custody forms accompanied all samples. No travel blanks were required during Task C testing because no organic chemical analyses were required. All samples were analyzed within the allowable hold time.

3.9.6.4.1.3 Laboratory Analytical Methods

A comprehensive list of laboratory analytical methods used can be found in Table 3-9. TDS from the lab analysis was correlated to conductivity for calculation of normalized permeate flow and rejection trends over time. TDS was used to calculate the osmotic pressure gradient needed for net driving pressure calculations.

Table 3-9. Analytical Methods for Laboratory Analyses

Parameter	Method	NSF Reporting Limit	Hold Time	Sample Container	Sample Preservation
TOC	SM[1] 5310C	0.1 mg/L	28 days	4-40 mL glass	H_2SO_4 to pH<2
UV_{254}	SM 5910B	0.000 Abs/cm[2]	2 days	1 L plastic	none
TSS	EPA 160.2	5 mg/L	7 days	1 L plastic	none
TDS	SM 2540C	5 mg/L	7 days	1 L plastic	none
Alkalinity, total (as $CaCO_3$)	EPA 310.2	5 mg/L	14 days	1 L plastic	none
Hardness, total (as $CaCO_3$)	SM 2340C	2 mg/L	180 days	125 mL plastic	HNO_3 to pH<2
Silica, total (as SiO_2)	EPA 200.7	0.1 mg/L	28 days	125 mL plastic	none
HPC	SM 9215B	1 CFU/mL	24 hours	125 mL plastic	none
Total coliforms	SM 9222B	1 CFU/100mL	24 hours	125 mL plastic	none

(1) SM=Standard Methods for the Examination of Water and Wastewater
(2) Abs/cm = UV absorbance per centimeter

3.9.6.4.2 Statistical Uncertainty

For the water quality parameters monitored, 95% confidence intervals were calculated for data sets of eight values or more. The following equation was used for confidence interval calculation:

$$\text{Confidence Interval} = \overline{X} \pm [t_{n-1,1-(\alpha/2)} \times (S/\sqrt{n})]$$

where:

$\overline{X}$ = sample mean
S = sample standard deviation
n = number of independent measurements included in the data set
t = Student's t distribution value with n-1 degrees of freedom
α = significance level, defined for 95% confidence as: 1 - 0.95 = 0.05

According to the 95% confidence interval approach, the α term is defined to have the value of 0.05, thus simplifying the equation for the 95% confidence interval in the following manner:

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

3.9.6.4.3 Accuracy

The accuracy of on-site analytical equipment was periodically verified according to the schedule in Table 3-7. The calibration records for the analytical equipment were recorded on bench sheets (Appendix B). All calibrations were performed at the frequency required. All calibration data were within the specified QC objectives on all days analyses were performed.

Accuracy for the laboratory analyses was quantified as the percent recovery of a parameter in a sample to which a known quantity of that parameter was added. The following equation was used to calculate accuracy:

$$\text{Percent Recovery} = 100 \times [(X_{known} - X_{measured}) \div X_{known}]$$

where:

X_{known} = known concentration of measured parameter
$X_{measured}$ = measured concentration of parameter

Accuracy also incorporates calibration procedures and use of certified standards to ensure the calibration curves and references for analysis are near the "true value." Accuracy of analytical readings was measured through the use of spiked samples and lab control samples.

The NSF Laboratory Quality Assurance Manual establishes the frequency of spike sample analyses at 10% of the samples analyzed. Laboratory control samples are also run at a frequency of 10%. The recovery limits specified for the parameters in this verification were 70-130% for laboratory-fortified samples and 85-115% for laboratory control samples. The NSF QA department reviewed the laboratory records and found all analyses for all sample groups were within the QC requirements for recovery. Calibration requirements were also achieved for all analyses.

As an additional check on accuracy, performance evaluation (PE) samples were purchased and sent to the field technicians for analysis.

3.9.6.4.4 Precision

Precision refers to the degree of mutual agreement among individual measurements and provides an estimate of random error. To quantify precision, the relative percent difference (RPD) of duplicate analyses was calculated. RPD was measured by use of the following equation:

$$RPD = \left| \frac{S_1 - S_2}{S_1 + S_2} \right| \times 200$$

where:

S_1 = sample analysis result; and

S_2 = sample duplicate analysis result.

Acceptable analytical precision for the verification test was set at an RPD of 30%. Field duplicates were collected at a frequency of 1 out of every 10 samples for each parameter, to incorporate both sampling and analytical variation to measure overall precision against this objective. In addition, the NSF Laboratory also conducted laboratory duplicate measurements at 10% frequency of samples analyzed. The laboratory precision for the methods selected was tighter than the 30% overall requirement, generally set at 20% based on the standard NSF Chemistry Laboratory method performance.

3.9.6.4.5 Completeness

Completeness refers to the amount of valid, acceptable data collected from a measurement process compared to the amount expected to be obtained. Completeness was quantified according to the following equation:

$$\%C = (V/T) \text{ X } 100$$

where:

%C = percent completeness

V = number of measurements judged valid

T = total number of measurements

The completeness objective for data generated during this verification test was based on the number of samples collected and analyzed for each parameter and/or method. Table 3-10 presents the completeness requirements based on the sampling frequency spelled out in the test/QA plan.

Table 3-10. Completeness Requirements

Number of Samples per Parameter and/or Method	Percent Completeness
0-10	80%
11-50	90%
> 50	95%

3.9.6.5 Operation and Maintenance

The EUWP was operated and maintained according to limits stated in Chapter 2 and the EUWP Operation and Maintenance Manual.

Chapter 4
Results and Discussion

This chapter presents a summary of the water quality and operating data collected during the ETV test. Operating data are presented to describe the flow rates, volume of treated water produced, backwash volumes and frequency, pressure differential across the UF and RO skids, and related operating information. Water quality data are presented for the key parameters listed in Table 3-1. Information on membrane integrity testing, pressure decay testing, and additional work performed during the 2007 retest of the UF membranes is also included in this Chapter. QA/QC information, as described by the QAPP (Section 3.9.6) for this verification test, is presented at the end of the chapter.

Two test events occurred: a test of the full EUWP system in 2006, and a retest of the UF skid in 2007. For the 2006 test, the EUWP system was delivered to Selfridge ANGB at the end of August 2006. Shakedown testing was conducted in September. The 30-day verification test began on September 25, 2006, and ended on October 25, 2006.

During the equipment installation and initial test runs phase of the 2006 verification test, TARDEC and USBR discovered that the UF system seals between the housings and membrane modules were not as tight as desired. The pressure decay tests indicated that system was not meeting the expected performance requirement and could allow leakage that would result in lower removals of biological agents. The problem was temporarily fixed with polytetrafluoroethylene (PTFE) tape, and a subsequent pressure decay test yielded a pressure decay rate that satisfied TARDEC and USBR. NSF allowed the test to proceed with the temporary fix because a future verification test of a second EUWP system at Port Hueneme, CA, would verify UF seal integrity after the problem was permanently fixed. See Sections 4.1.2 and 4.1.3.4 for the pressure decay test data and further discussion.

After reviewing the UF performance data from the 2006 test, NSF concluded that the temporary fix was not sufficient, and the UF system should be retested after the seal problem was permanently fixed. The cause was determined to be deformation of the nylon end caps and filtrate tube adapters, perhaps from contact with chlorine during cleaning, or from exposure to sunlight during operation. New filtrate tube adapters were fabricated, and the end caps were re-machined. Also, thicker o-rings were used between the filtrate tube adapters and end caps. The EUWP was shipped back to Selfridge ANGB from storage in Alamogordo, New Mexico in July of 2007 for the UF retest. The test of the repaired UF system was performed from July 30 to August 24, 2007.

The results of the 2006 ETV test and the additional 2007 retest, are presented herein. Both the UF and RO skids were operated for the 2007 retest, but ETV test data was only collected from the UF system. Note that the 2007 retest was stopped short of 30 days because the intent of the test as stated in the ETV test protocol – to operate until a membrane cleaning was conducted – was met.

4.1 2006 EUWP Test

4.1.1 Task A: Raw Water Characterization

Two sets of grab samples were collected in August 2006 to characterize the raw water supply, and to determine if any regulated metals or VOCs were present and should be included in the final sampling plan. The results of these analyses are presented in Table 4-1. Based on these results, no metals or VOCs were added to the sampling plan.

4.1.2 Task B: Equipment Installation and Initial Test Runs

The objective of this task was to evaluate equipment operation and determine whether the operating conditions result in effective treatment of the water. In this task, a preliminary assessment of the treatment performance of the equipment was made. This task is considered a shakedown testing period and was completed before the start of the verification test.

The unit plumbing, electrical hook-ups, and pumping of raw water to the UF feed tank were completed on September 12. The initial test runs and shakedown period took place between September 13 and the beginning of the official ETV test on September 25. During this period, all sensors were calibrated, communications were established with the particle counters and turbidimeters, and the PLC was operated to check that programming and data collection were operating properly. Inline turbidimeters were calibrated and, based on these results, the manufacturer was called to calibrate the filtrate inline unit. Handheld analyzers were calibrated and checked and colorimetric methods were tested. It was determined that ferric chloride coagulation would not be necessary to keep the UF system running smoothly. Subsequently, after the test started, UF membrane fouling issues resulted in ferric chloride being added as a coagulant to lengthen run times between chemical cleanings (CIP).

A pressure decay test for the UF system was an important part of the initial test runs to verify that the UF membranes and the connections were properly sealed. Pressure decay tests were performed on September 13, 14 and 15. These tests showed that pressure was being lost at a higher than desirable rate. An investigation of the problem revealed that the o-ring seals between the membrane modules and filtrate collection tubes were unsatisfactory. To confirm that only the o-rings were the cause of the high pressure decay rates, each membrane cartridge was integrity tested individually using an “air bubble” test. Each membrane cartridge was submerged in a trough of water and air pressure applied to check for bubbles emerging from the ends of individual UF fibers. These tests indicated that no fibers were compromised, based on the field logs noting each membrane as a “pass”. PTFE tape was wrapped around the o-rings in question to increase the seal surface between the o-rings and the membrane cartridges, and the cartridges were re-installed in the UF system. This reduced the pressure decay rate to 0.37 psig/min, and the permeate turbidity from 0.3 NTU to 0.08 NTU.

Table 4-1. Initial Characterization Sampling Results

Parameter	Sample Date 08/02/06	08/16/06	05/31/07	Parameter	Sample Date 08/16/06
TOC (mg/L)		2.9		Unregulated VOC's by EPA 502.2	
UV254 (Abs)		0.0668		(continued)	
TSS (mg/L)		ND(5)	ND(2)	1,2-Dichloroethane	ND(0.5)
TDS (mg/L)		130	140	Trichloroethylene	ND(0.5)
Alkalinity (mg/L $CaCO_3$)		70	86	1,2-Dichloropropane	ND(0.5)
Total Hardness (mg/L as $CaCO_3$)		95	110	Bromodichloromethane	ND(0.5)
Nitrate (mg/L of N)		ND(0.05)	0.25	Dibromomethane	ND(0.5)
Nitrite (mg/L of N)	ND(0.02)	ND(0.02)	ND(0.02)	cis-1,3-Dichloropropene	ND(0.5)
Total Silica (mg/L SiO_2)		1.1	1.1	trans-1,3-Dichloropropene	ND(0.5)
Orthophosphate (mg/L P)		ND(0.02)		1,1,2-Trichloroethane	ND(0.5)
Specific Conductance (µmhos/cm)			250	1,3-Dichloropropane	ND(0.5)
Cryptosporidium (oocysts/L)		<1		Tetrachloroethylene	ND(0.5)
Giardia (cysts/L)		<1		Chlorodibromomethane	ND(0.5)
HPC (CFU/mL)		500		Chlorobenzene	ND(0.5)
Total Coliforms (CFU/100 mL)		291		1,1,1,2-Tetrachloroethane	ND(0.5)
Bacillus Endospores			689	Bromoform	ND(0.5)
Regulated Metals by EPA 200.8 (all µg/L)				1,1,2,2-Tetrachloroethane	ND(0.5)
Antimony		ND(0.6)	ND(0.5)	1,2,3-Trichloropropane	ND(0.5)
Total Arsenic	ND(1)	1	ND(2)	1,3-Dichlorobenzene	ND(0.5)
Barium	18	20	17	1,4-Dichlorobenzene	ND(0.5)
Beryllium	ND(0.5)	ND(0.5)		1,2-Dichlorobenzene	ND(0.5)
Cadmium	ND(0.3)	ND(0.3)	ND(0.2)	Carbon Disulfide	ND(1)
Chromium	ND(1)	ND(1)	ND(1)	Methyl-tert-Butyl Ether	ND(0.5)
Copper	ND(2)	2	2	Methyl Ethyl Ketone	ND(0.5)
Lead	ND(1)	ND(1)	ND(1)	Methyl Isobutyl Ketone	ND(0.5)
Mercury	ND(0.2)	ND(0.2)	ND(0.2)	Toluene	ND(0.5)
Selenium	ND(4)	ND(4)	ND(2)	Ethyl Benzene	ND(0.5)
Thallium	ND(0.2)	ND(0.2)	ND(0.2)	m+p-Xylenes	ND(1)
Unregulated VOC's by EPA 502.2 (all µg/L)				o-Xylene	ND(0.5)
Dichlorodifluoromethane		ND(0.5)		Styrene	ND(0.5)
Chloromethane		ND(0.5)		Isopropylbenzene	ND(0.5)
Vinyl Chloride		ND(0.5)		n-Propylbenzene	ND(0.5)
Bromomethane		ND(0.5)		Bromobenzene	ND(0.5)
Chloroethane		ND(0.5)		2-Chlorotoluene	ND(0.5)
Trichlorofluoromethane		ND(0.5)		4-Chlorotoluene	ND(0.5)
Trichlorotrifluoroethane		ND(0.5)		1,3,5-Trimethylbenzene	ND(0.5)
1,1-Dichloroethylene		ND(0.5)		tert-Butylbenzene	ND(0.5)
Methylene Chloride		ND(0.5)		1,2,4-Trimethylbenzene	ND(0.5)
trans-1,2-Dichloroethylene		ND(0.5)		sec-Butylbenzene	ND(0.5)
1,1-Dichloroethane		ND(0.5)		p-Isopropyltoluene	ND(0.5)
2,2-Dichloropropane		ND(0.5)		1,2,3-Trimethylbenzene	ND(0.5)
cis-1,2-Dichloroethylene		ND(0.5)		n-Butylbenzene	ND(0.5)
Chloroform		ND(0.5)		1,2,4-Trichlorobenzene	ND(0.5)
Bromochloromethane		ND(0.5)		Hexachlorobutadiene	ND(0.5)
1,1,1-Trichloroethane		ND(0.5)		1,2,3-Trichlorobenzene	ND(0.5)
1,1-Dichloropropene		ND(0.5)		Napthalene	ND(0.5)
Carbon Tetrachloride		ND(0.5)		Benzene	ND(0.5)
				Total Trihalomethanes	ND(0.5)

The pressure decay rate was higher than TARDEC and USBR desired, but NSF and EPA deemed it acceptable to start the verification test because previous laboratory challenge tests on a smaller version of the Koch UF cartridge demonstrated bacteria removal of six $\log_{10}$ or greater, with a corresponding pressure decay rate of 0.29 psig/min (NSF 2006). Over the course of the test, the daily pressure decay test rates ranged from 0.20 to 0.43 psig/min, with a mean of 0.29 psig/min, so the daily pressure decay test results did not raise any alarms that there were continuing membrane integrity issues.

The RO system was dye tested on September 23, 2006. This test showed a rejection rate of 99.5%. The inline conductivity meters were also monitored at the start of operation to confirm the rejection rate of the RO membranes. See Section 4.1.3.4 for further discussion.

TARDEC and USBR were satisfied with the performance of the EUWP, as indicated by the outputs of the in-line particle counters and turbidimeters for the UF system, and the conductivity meters for the RO system (data not shown), so testing began on September 25.

4.1.3 Task C: Verification Test

The 2006 verification test was started on September 25 and ran for the planned 30 day test period, ending on October 25. The UF system was operated each day on a semi-continuous basis, automatically shutting down when the RO feed tank was full. A typical operating day for the UF system was 15 to 17 h in duration. The RO system was setup to operate continuously. After the first three days of the test, when the system was shutdown at night, the RO system typically ran 22-24 h each day. The RO system did shutdown periodically for various maintenance activities or when alarms occurred and shut the system down. When alarms and shutdown occurred during unattended operation at night, the entire system would remain shutdown until an operator arrived in the morning.

The on-site operators collected operating data and on-site water quality samples twice per day in accordance with the test plan schedule. The following sections present the operating data and water quality data.

4.1.3.1 Task C1: Membrane Flux and Operation

The purpose of this task was to evaluate system performance during operation. The objectives of this task were to demonstrate the appropriate operational conditions for the system, the feed water recovery achieved by the UF and RO membranes, and the rate of flux decline observed over the operation period.

Operational data were collected and on-site water quality measurements were made twice per day throughout both test periods, except for days when the UF was being cleaned and therefore not operating for a portion, or all, of the day. The complete data set can be found in Appendix B.

As discussed in Section 4.1.2, during the 2006 test the UF system experienced membrane seal integrity issues. The seal problems could affect the quality of the treated water, but as the data will show the microscopic leaks around the seals did not impact the collection of operational measurements, such as flow rates, pressure differentials, temperature, and calculated specific flux. Filtrate from the UF system was the feed water for the RO system during this first test.

4.1.3.1.1 UF System

The UF operational statistics for the 2006 test are presented in Table 4-2. The UF skid does not have a filtrate flow meter or filtrate pressure gauge. Therefore, the total filtrate flow rate was calculated as the UF feed water flow rate minus the UF retentate flow rate. The intake flow is the intake from the source water into the UF feed water tank. The intake pump is technically not part of the UF skid, but the intake flow is included here as part of the overall UF treatment process. The intake pump ran at a higher flow rate than the UF system to ensure that the UF feed water tank always contained sufficient water to operate the UF system.

Table 4-2. UF Operational Measurement Statistics for 2006 Test

Parameter	Count	Mean	Median	Minimum	Maximum	Standard Deviation	95% Confidence Interval (CI)
UF Operation per day (h)	31	15.0	17.2	3.4	21.5	4.85	±1.71
Intake Flow (gpm)	58	298	299	278[(1)]	302	3.34	±0.86
Feed Flow (gpm)	59	246	248	175	268	16.0	±4.07
Filtrate Flow (gpm)	59	220	222	149	243	16.1	±4.10
Retentate Flow (gpm)	59	26	26	21	31	1.81	±0.46
Backwash Flow (gpm)	Estimated at 900 gal per backwash cycle						
Feed Pressure (psig)	59	21	21	12	33	4.2.6	±1.09
Retentate Pressure (psig)	59	19	19	10	31	4.20	±1.07
Filtrate Temperature (°F)	59	52	52	43	60	5.16	±1.32

(1) Intake flow of 181 gpm recorded the morning of October 5. This reading is considered an outlier and has not been included in the statistics because the intake strainer was partially clogged. The afternoon reading on October 5 after the cleaning was 298 gpm.

The mean UF feed water flow rate of 246 gpm was somewhat below the design feed flow rate of 259 gpm specified for the system (See Table 3-2). The mean filtrate flow rate of 220 gpm corresponds to a flow rate of 13.8 gpm for each of the 16 UF membrane modules. Using these mean flow numbers, the UF water recovery was 89.5% based on the mean feed water and filtrate flow rates. While the UF system did not operate a full twenty four hours per day during this test, the 220 gpm mean filtrate flow would correspond to a 24-h production rate of 316,800 gal. This filtrate production volume includes water used for backwashes.

The stated UF production rate is 250,000 gpd (not including backwash water). The backwash process uses 900 gal of UF filtrate per event, and a backwash is conducted

every 30 min. For 24 h of operation, 48 backwashes would be conducted, using a total of 43,200 gal of UF filtrate. Subtracting this backwash volume from the calculated 24-h volume of 316,800 gal leaves 273,600 gal of UF product water, which is above the specified 250,000 gpd.

The EUWP included a totalizer to track the hours of UF system operation. The daily hours of operation varied widely, from 3.4 to 21.5, depending on the volume of filtrate required for the RO system and downtime for various maintenance activities. The UF system was operated an average of 15.0 h per day. There were six days of operation of less than 10 h. Excluding these days would increase the mean hours of operation to 17.1 h (range of 12.1 to 21.5 h).

UF filtrate production was also tracked using the RO feed totalizer. This production volume was the actual filtrate used for the RO feed water and thus does not include the filtrate used for backwash waste. Figure 4-1 shows the cumulative water production for the UF system for the duration of the 2006 verification test. The UF filtrate volume produced includes both the RO feed and the filtrate used for backwashes. Because of the wide range of operational hours per day, the UF production was also calculated based on gal produced per hour of operation. The mean UF production per hour was 11.8 kilogallons (kgal), with a range of 7.67 to 14.7 kgal/hr.

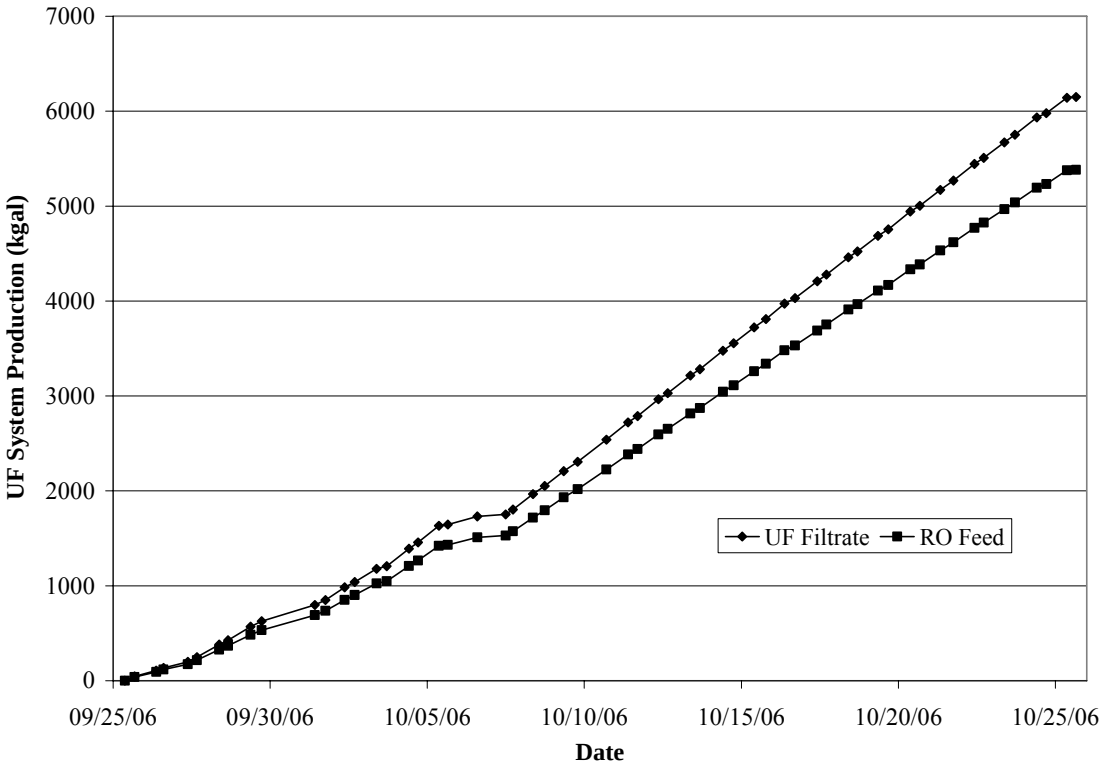


Figure 4-1. UF system filtrate production for 2006 test.

Figure 4-2 shows the UF system flow rates over the duration of the 2006 verification test. The retentate flow rate remained steady throughout the test. The feed water flow rate and filtrate flow rate dropped over time as the membrane became fouled with solids and TMP increased. Figure 4-3 shows the feed and retentate pressures during the test and Figure 4-4 shows the calculated TMP results. These three figures clearly depict the impact of solids build up on the UF membranes during the first few days of operation and again during the last week of operation.

The increase in TMP on September 30 coupled with the decrease in flow rate indicated that the membranes required a CIP, as the normal backwash cycle was not sufficiently cleaning the UF membranes. The system was shutdown on September 30 and a CIP initiated. After the cleaning was completed, flow rates and TMP returned to normal ranges and similar to the values measured at the beginning of the test.

A chemical coagulant (ferric chloride) was not used at the beginning of the verification test. However, after the fairly rapid increase of TMP occurred, it was evident that a coagulant should be used to attempt to lengthen the time between required CIP events. Ferric chloride was fed to the feed water upstream of the UF membranes beginning on September 29, 2006 and continued for the duration of the test. A purchased ferric chloride solution with a concentration of 33-36 % ferric chloride (12% as Fe) was fed to the intake water at a feed rate of 4 ml/min (0.06 gal/hr) to give an iron dose of 0.42 mg/L as Fe. The addition of the coagulant improved performance and the system was able to maintain filtrate production and TMP below 20 psig until the last two days of the test. If the verification test were to have continued beyond thirty days, a CIP would have been necessary to maintain flow rate and lower the TMP.

Figure 4-5 shows the specific flux calculated for the UF system during the test. The impact of solids buildup on the system is clear prior to the CIP performed on September 30. The CIP was successful as the specific flux was actually higher after the cleaning than at the beginning of the test. This may have been due to some solids buildup on the membranes during the shakedown and startup period.

Figure 4-6 shows the loss (or gain) of specific flux over the duration of the verification test. The change in specific flux is calculated by comparing the specific flux on a given day to the value calculated at the start of the test. This type of data shows the impact of cleaning and backwash by comparing any given days specific flux to the start of the test.

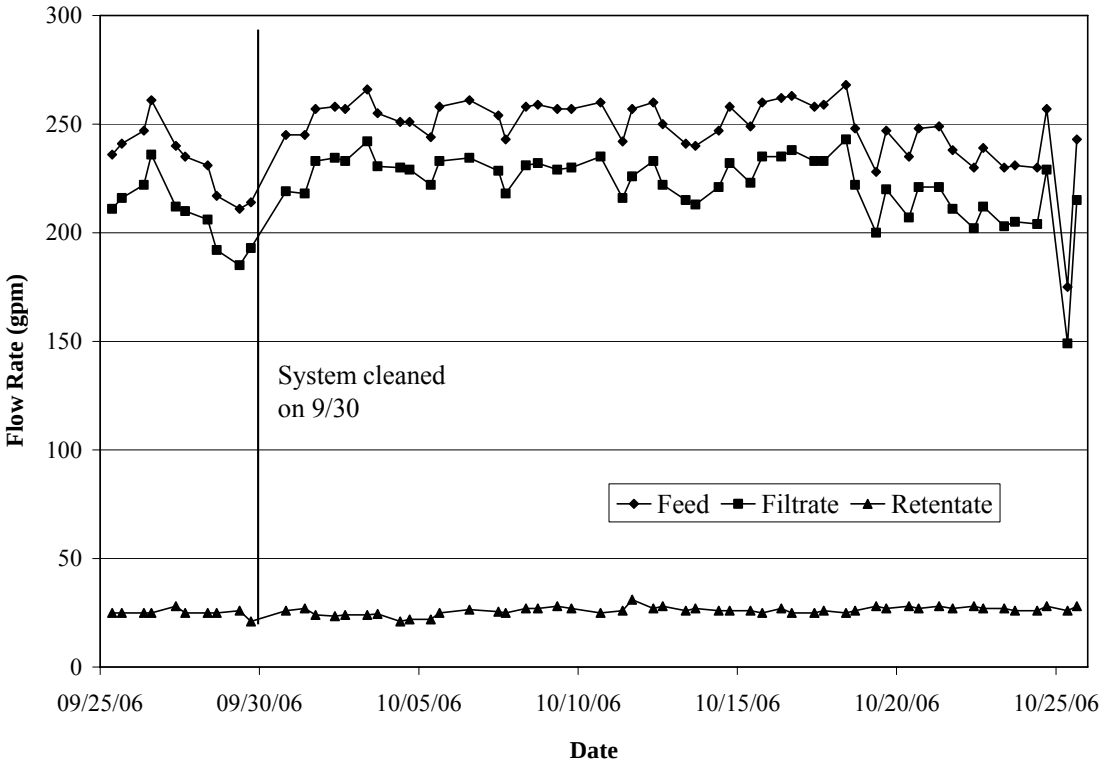


Figure 4-2. Plot of UF system flow rates for 2006 test.

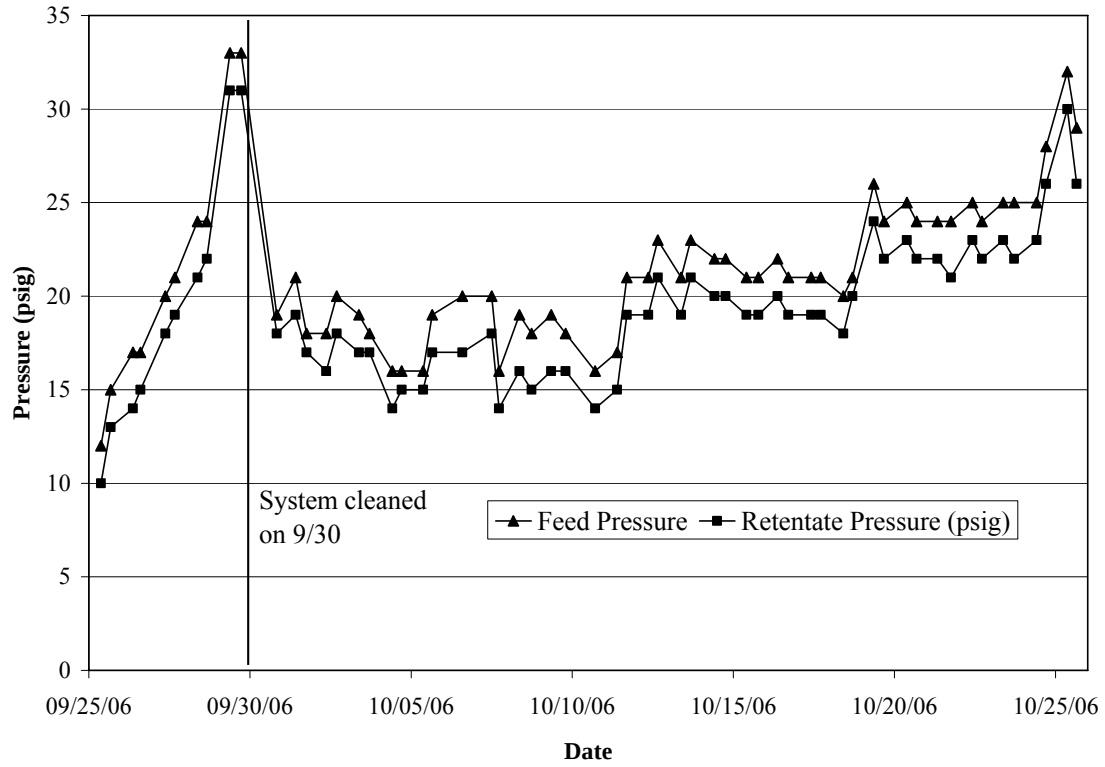


Figure 4-3. Plot of UF system feed and retentate pressures for 2006 test.

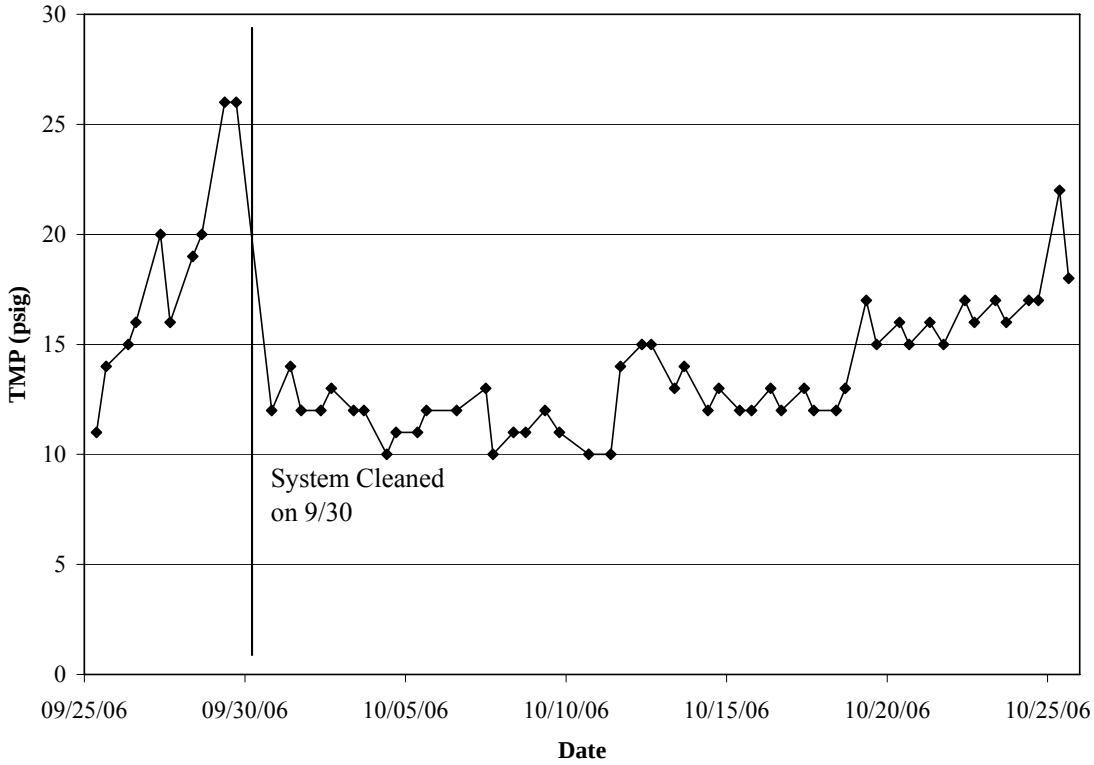


Figure 4-4. Plot of UF system TMP for 2006 test.

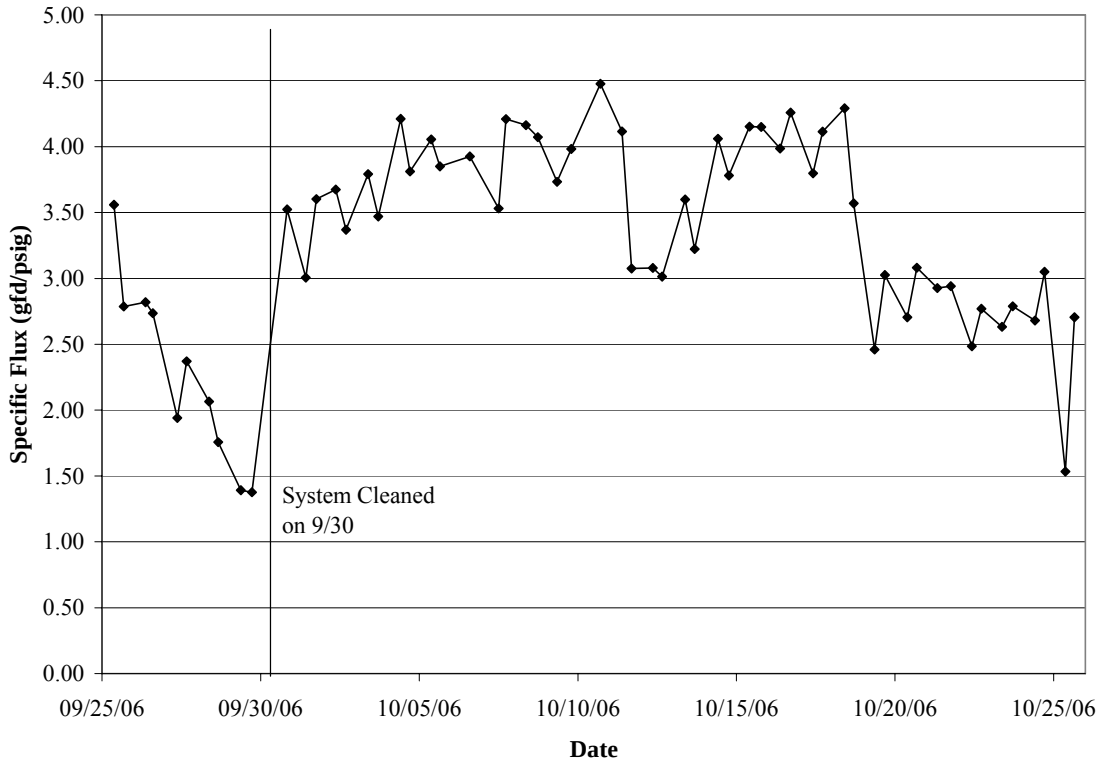


Figure 4-5. UF system specific flux calculations for 2006 test.

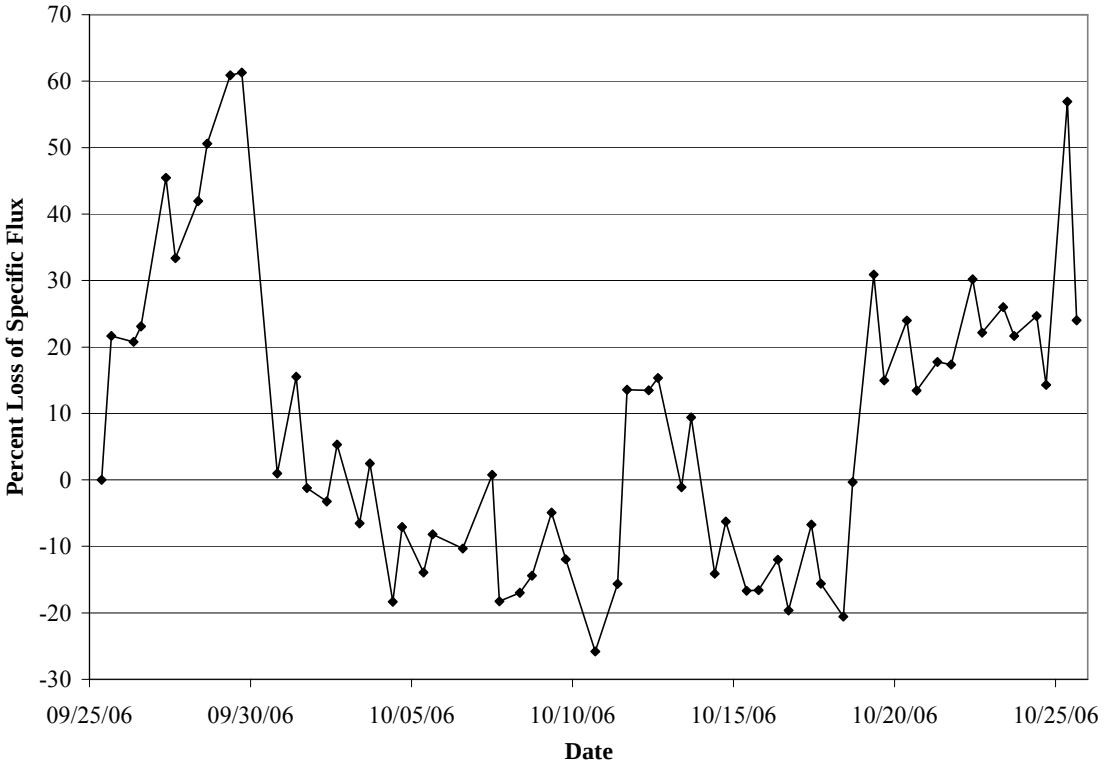


Figure 4-6. Loss of specific flux over time for 2006 test.

The power use for the UF system was monitored by a power meter that was separate from that for the RO high pressure pump. The UF power meter does include the power use by ancillary equipment on the RO skid. This meter provided power data for the UF system. The operators recorded power readings twice daily. The power data was then combined with the hours of UF system operation to calculate the power used per hour of operation. The mean power consumption was 39 kiloWatt-hours (kWh) per hour of operation with a median value of 39 kWh per hour of operation. Figure 4-7 shows the power consumption per hour of operation during the test. The spike in power use on October 6 and 7 occurred at the same time that the RO system was being cleaned and the RO power use dropped. It is not known why this occurred, but the UF power meter also includes the ancillary systems on the RO skid.

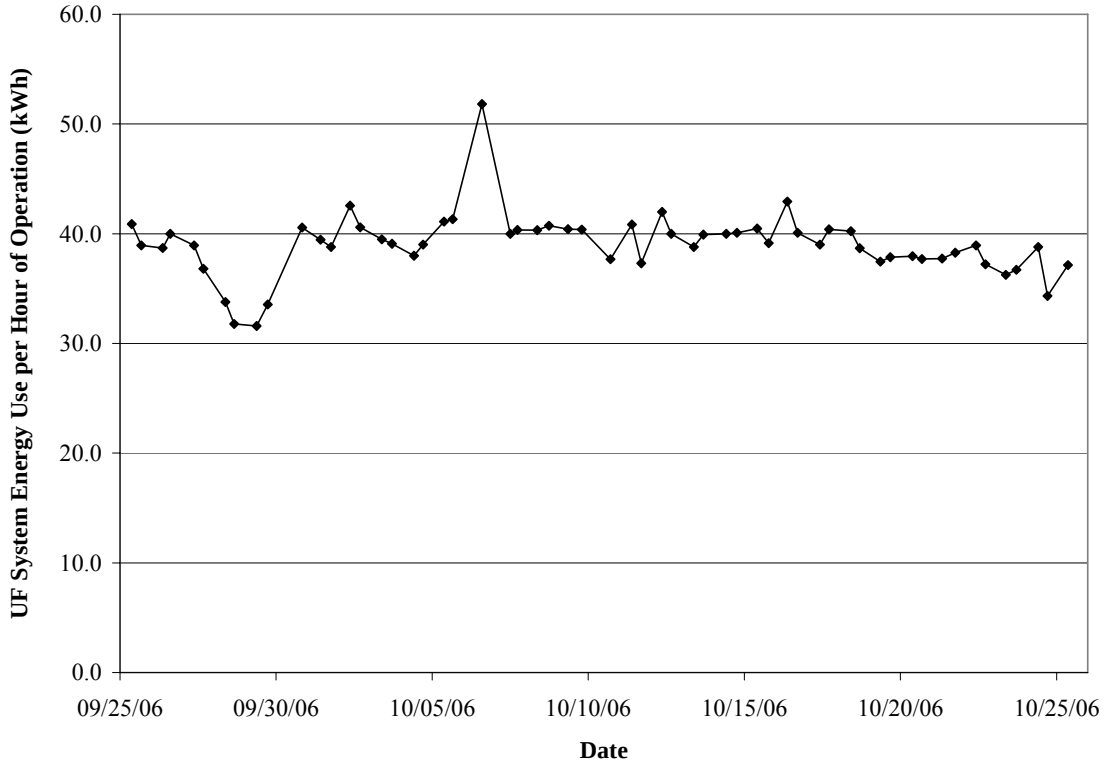


Figure 4-7. UF Power consumption per hour of operation for 2006 test.

4.1.3.1.2 RO System

The RO operational statistics for the 2006 test are presented in Table 4-3. The RO system has flow meters and pressure gauges to monitor the feed water, concentrate and permeate for Array 1. However, during the test the concentrate flow meter was not functioning properly. Therefore, the concentrate flow rate reported in Table 4-3 is calculated as the

difference between the feed water flow rate and the permeate flow rate. Array 2 has flow meters for the permeate and concentrate, and gauges to monitor pressure for the feed water, permeate, and concentrate. The feed flow rate for Array 2 was calculated by adding the permeate and concentrate flow rates. The UF system supplied all of the feed water for the RO system.

Table 4-3. RO System Operational Measurement Statistics for 2006 Test

Parameter	Count	Mean	Median	Minimum	Maximum	Standard Deviation	95% C I
Array 1 Feed Flow (gpm)	59	107	107	104	110	1.38	± 0.35
Array 1 Permeate Flow (gpm)	59	53	53	44	56	2.0	± 0.50
Array 1 Concentrate Flow (gpm)	59	54	54	48	62	2.4	± 0.61
Array 2 Feed Flow (gpm)	59	53	52	49	59	2.3	± 0.60
Array 2 Permeate Flow (gpm)	59	21	21	19	24	1.1	± 0.27
Array 2 Concentrate Flow (gpm)	59	32	31	27	37	2.3	± 0.58
Array 1 Feed Pressure (psig)	59	444	428	374	539	45.9	± 11.7
Array 1 Concentrate Pressure (psig)	59	346	330	286	419	40.5	± 10.3
Array 2 Feed Pressure (psig)	59	345	327	284	436	42.5	± 10.8
Array 2 Concentrate Pressure (psig)	59	255	238	204	325	35.2	± 8.98
Array 1 and 2 Combined Permeate Pressure (psig)	59	28	27	15	39	4.6	± 1.2

The RO system operated continuously during the verification test, except when alarms shut the unit down during unattended operation over night, or when maintenance was required on the system. During the first three days of testing the RO unit was shutdown overnight due to a miscommunication with the operators. The RO system operated greater than 20 h on 21 of the 31 test days (Day 0 through Day 30), and greater than 10 h on 27 days of the 31 test days. The mean operating hours were 19.4 h per day with a median of 22 h per day. The maximum operating hours were 24 h and the minimum was 6 h. The 95% confidence interval shows expected operating hours of 17-21 h per day. If the first three days of operation are removed from the calculations, the 95% confidence interval is 18-22 h of operation per day. These operating hours give a utilization rate of 75 to 92%.

The mean RO permeate flows of 53 gpm for Array 1 and 21 gpm for Array 2 yield a mean total permeate production of 74 gpm, which is below the design permeate rate of 112.5 gpm (162,000 gpd) specified in Table 2-4 for low TDS waters. The mean feed water flow of 107 gpm for Array 1 and 53 gpm for Array 2 were below the target feed rates specified in Table 3-2. However, the actual recovery for Array 1 was 49.5%, which is close to the design target of 50%. The recovery for Array 2 was 39.6%, which is lower than the target of 48% specified for the unit. Over the 30-day verification test, accounting for downtime for maintenance, alarms, and other shutdowns, the RO feed water totalizer showed that 5,382,670 gal of water was fed to the RO unit. At an average recovery of 47% (prorated between Array 1 at 49.5% and Array 2 at 39.6%), the total volume of permeate produced was approximately 2,530,000 gal or an average of 84,330 gpd over the entire test period. This falls short of the goal of demonstrating production of 100,000 gpd of finished water.

The RO system maintained a steady permeate flow rate for both arrays throughout the verification test. Figure 4-8 shows the daily flow rates for feed water, permeate, and concentrate for both arrays. Figure 4-9 shows the feed water and concentrate pressures for both arrays. Feed water pressure was increased over the duration of the test in order to maintain feed water flow rates. The concentrate pressure from Array 1 was used by the energy recovery device to increase feed water pressure for Array 2. These pressures were similar throughout the test. The Array 1 concentrate pressure had a mean value of 346 psi with a median value of 330 psi. The Array 2 feed pressure had a mean value of 345 psi with a median value of 327 psi. The 95% confidence interval for the Array 1 concentrate pressure was 336 to 357 psi, and the 95 % confidence interval for the Array 2 feed water pressure was 335 to 356 psi. Based on the small pressure loss from the transfer of pressure between the Array 1 concentrate and the Array 2 feed water, the energy recovery device worked properly during the test, and in an efficient manner.

Figure 4-10 shows the percent recoveries achieved by the RO system. Recoveries, as measured by the flow rate of the permeate divided by the feed water flow rate were consistent throughout the test. The recoveries for Array 2 were lower than for Array 1.

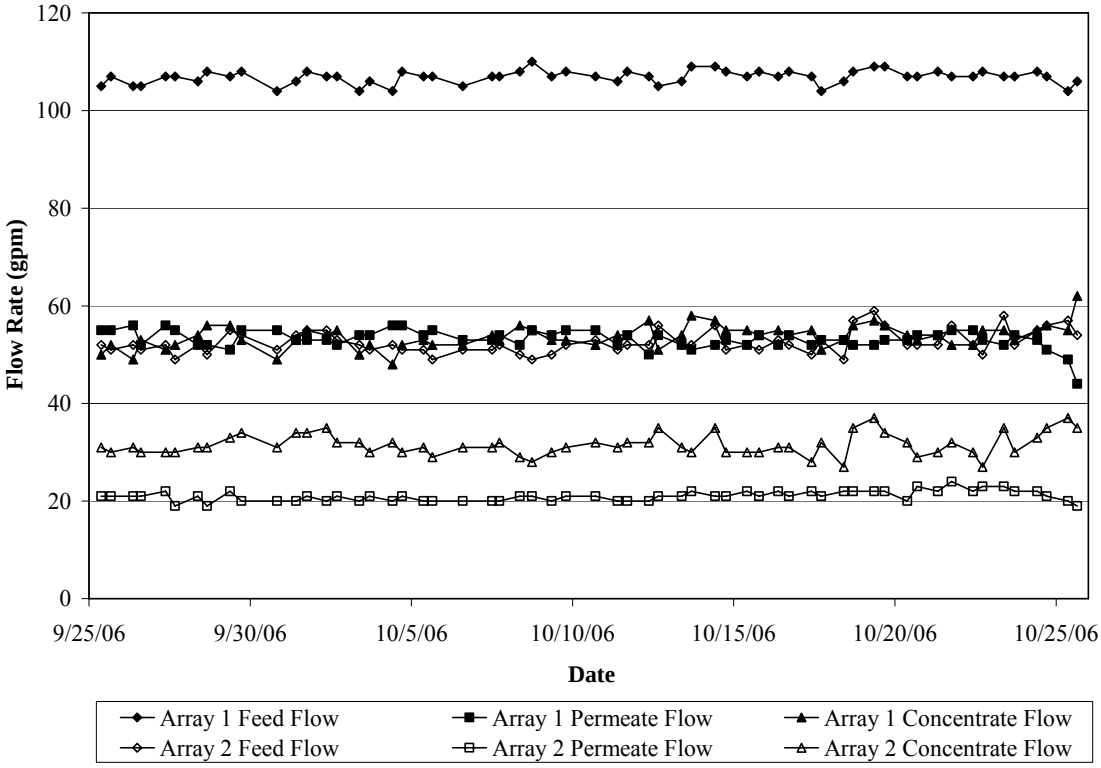


Figure 4-8. RO system flow rates for 2006 test.

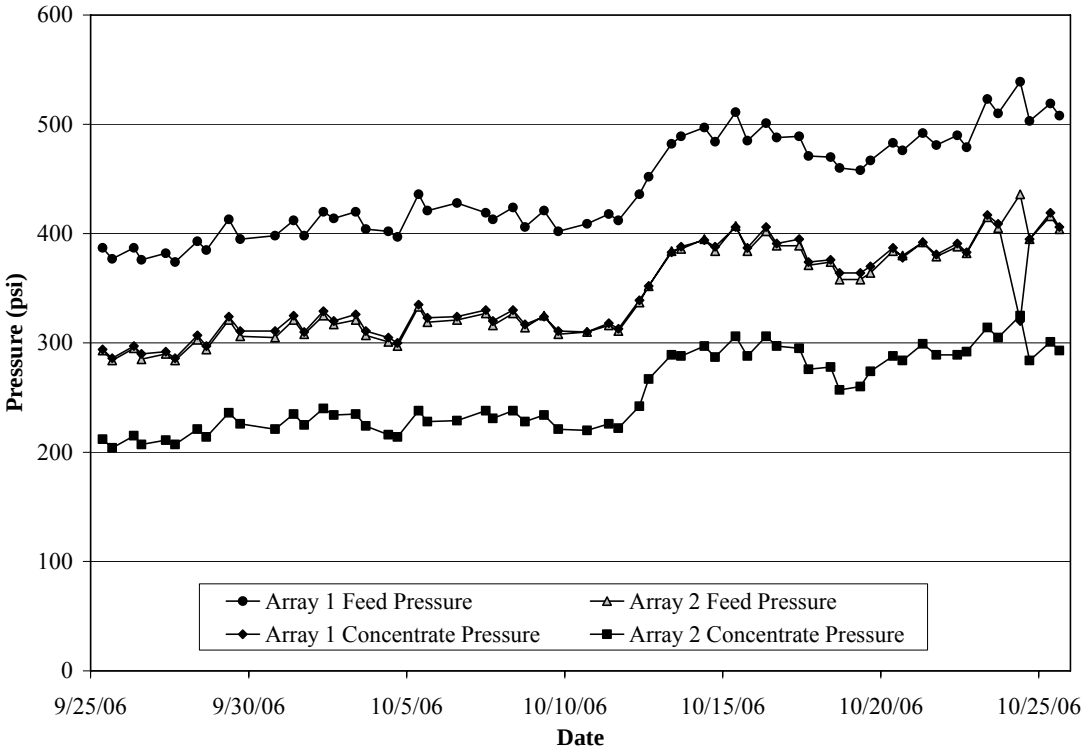


Figure 4-9. RO system operating pressures for 2006 test.

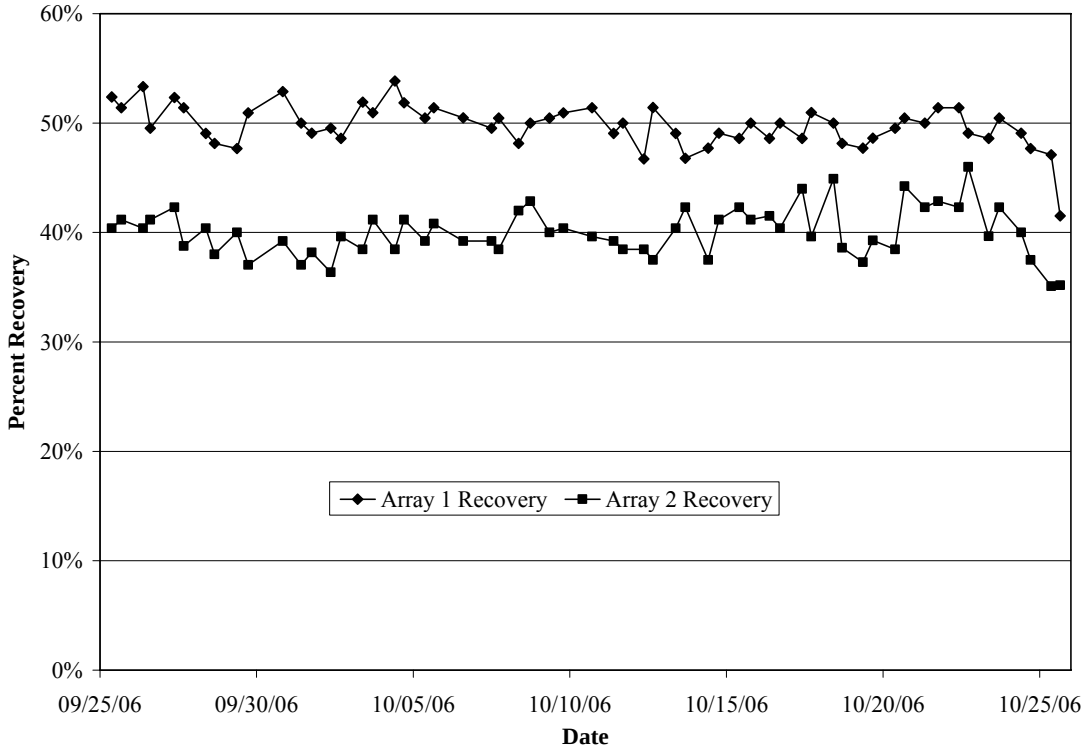


Figure 4-10. RO percent recoveries for 2006 test.

A common method of evaluating RO membrane performance is to calculate the specific flux, which adjusts the permeate flux based on NDP. The calculation of NDP that was used in the determination of specific flux included the calculation of osmotic pressure. A correlation between TDS and conductivity was calculated based on the weekly TDS data. This correlation was then used with the daily conductivity data to estimate TDS on a daily basis and calculate osmotic pressure. The equation for the line determined for this correlation is y(TDS) = 0.6014x(conductivity).

Figure 4-11 shows the specific flux for the two RO system arrays based on NDP and adjusted to a temperature of 25 ^{o}C. The trend shown by these data clearly indicate that the RO membranes were slowly being fouled as would be expected. The specific flux dropped by approximately 31% for Array 1 and 26% for Array 2 over the 30-day test. While the membranes were still functioning at the end of the test, it could be projected that the membranes would have required cleaning sometime in the next 30 to 60 days, based on the trend in the specific flux and the corresponding trend in increasing feed pressures (to maintain flow rate).

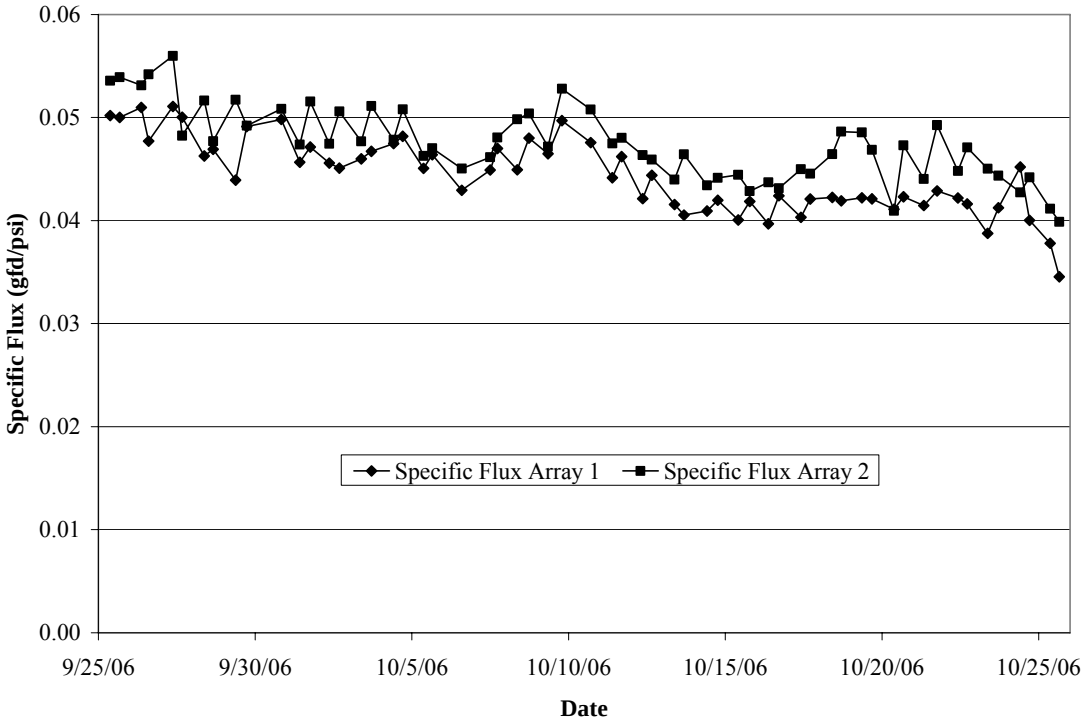


Figure 4-11. RO system specific flux for 2006 test.

The RO system was chemical cleaned on October 6 using a citric acid low pH solution. Two days earlier the RO system had been shutdown by the PLC due to a high pressure differential across the system. The next day the RO system was flushed for two hours with fresh water and then placed back into operation. The test plan requires that the RO membranes be cleaned at least once during, or at the end of the test period. Therefore, it was decided to clean the RO, even though the pressure differential appeared acceptable and the specific flux was only slightly lower than on the first day of operation (0.046 gfd/psi versus 0.050 gfd/psi). The specific flux just before the start of the cleaning was 0.0429 gfd/psi. The cleaning did increase the specific flux to 0.047 gfd/psi on the afternoon of the next day October 7.

Given the slow but steady trend of decreasing specific flux, see Figure 4-11, an anti-scalant was fed to the RO system beginning on October 12. Anti-scalants can help reduce surface buildup on RO membranes and slow the loss of flux across the membranes and the need for higher pressures to maintain permeate flow. The ONDEO (Nalco) PermaTreat® PC-191 anti-scalant was fed at a rate of approximately 7.5 mL/min to achieve an anti-scalant concentration in the RO feed water of 4 mg/L. This chemical feed continued through the end of the verification test.

The RO system power consumption was monitored twice daily during the verification test. The RO system had a separate power meter that was read by the operators and

recorded in the logbook. The power consumption in kWh per hour of RO operation was calculated by dividing the power use for each time period by the hours of RO operation, as monitored by the high pressure pump operating meter. The mean power consumption was 26 kWh per hour of operation with minimum of 15 kWh per hour of operation and a maximum of 31 kWh per hour of operation. The median power use was 26 kWh per hour of RO operation. Figure 4-12 shows the power use over the duration of the verification test.

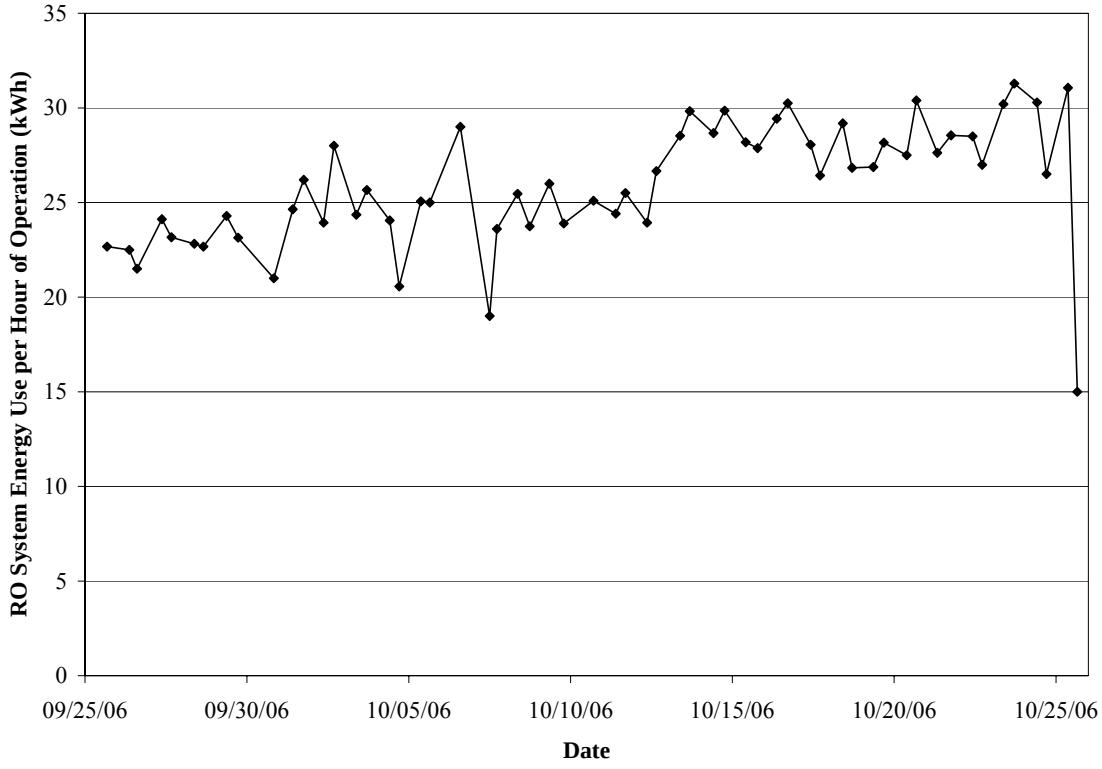


Figure 4-12. RO power use per hour of operation for 2006 test.

4.1.3.2 Task C2: Cleaning Efficiency

An important aspect of membrane operation is the ability to achieve long run times between chemical cleanings (maintain up time and minimize chemical use) and to restore membrane production after flux decline due to buildup of solids on the membrane and in the membrane pores. The objective of this task was to evaluate the membrane cleaning procedures and determine the fraction of specific flux restored following chemical cleaning.

4.1.3.2.1 UF Backwash and Cleaning Frequency and Performance

The UF system is designed to be backwashed automatically after every 30 min of operation. The backwash is designed to remove solids that have accumulated on and within the membrane. Frequent effective backwashes provide restoration of water

production and lengthen the time until chemical cleaning is required. The automatic backwash system reverses the flow through the membrane to remove material accumulated on the membrane surface, and then a fast forward flow flush is performed to clear the membrane. The system uses UF filtrate water for the backwash cycle.

The automatic backwash system functioned properly during the verification test. The automatic cycle initiated on schedule once every 30-min, as programmed, and the entire process was automated. The backwash cycle counter tracked the number of backwashes performed during the test. The backwash system used 900 gal of filtrate for each backwash cycle. Based on the number of backwashes performed and the flow rates achieved in the verification test, the backwash system used approximately 13-14% of the filtrate produced by the UF system.

Based on vendor experience it was expected that the UF system would require chemical cleaning about every 30 days. However, at the start of the verification test, the solids buildup occurred much quicker and the first CIP was performed on September 30, on the 6^{th} day of operation. At the time the unit was brought off line for cleaning, the TMP had increased to 25 psig from 11 psig at the start of the test. The specific flux had decreased to 1.38 gfd/psig from the starting value of 3.56 gfd/psig. The CIP was successful as the specific flux was 3.52 gfd/psig after the cleaning (99% recovery of specific flux) and the specific flux actually was somewhat higher after the cleaning than at the beginning of the test (see Figure 4-5).

The UF system ran for an additional 25 days and the automatic backwash system, in conjunction with the addition of ferric chloride as a coagulant (dose of 0.4 mg/L as Fe), was able to maintain the system at TMP below 20 psig and a specific flux in the 2 to 3 gfd/psig range. The UF was not chemically cleaned again during the test, but would probably have needed a CIP within the 30 days estimated in the system specification.

Figure 4-6 shows the loss (or gain) of specific flux over the duration of the verification test. The change in specific flux was calculated by comparing the specific flux on a given day to the value calculated at the start of the test. This type of data shows the impact of cleaning and backwash by comparing any given day's specific flux to the start of the test. As can be seen, there was a steady loss of specific flux at the beginning of the test, but the CIP on September 30 was successful and actually resulted in the UF system having a higher specific flux after the cleaning as compared to the start of the test.

The UF CIP procedure (Section 2.4.1.2) uses three chemicals, citric acid for the low pH cleaning and sodium hydroxide and calcium hypochlorite for the high pH cleaning. The amount of citric acid and sodium hydroxide needed to make a pH 3 or pH 11 cleaning solution will vary based on the water used for the making the cleaning solution and the concentration of acid or base used. For this test, 8 cups (64 ounces dry) of citric acid was added to the 300 gal of water in the CIP tank. At a density of 1.665 grams/mL, 8 cups is approximately 3144 grams or 6.9 lbs. This gave a cleaning solution pH of 2.98 to 3.08. For the high pH solution, 1.1 L of 0.5% by weight sodium hydroxide was added to the

300 gal of water in the CIP tank. This resulted in a cleaning solution pH of 11.00-11.63. In addition 300 gram of calcium hypochlorite was added to the high pH solution.

The UF cleaning solution was heated in the CIP tank with the low pH solution ranging from 35 to 39 ^{o}C and the high pH solution 32 to 37 ^{o}C. Each bank of modules was cleaned with each solution for 20 to 30 min.

4.1.3.2.2 RO Cleaning Frequency and Performance

The RO system was cleaned on October 6 using an acid solution. It is not clear that the RO required chemical cleaning at this point in the verification test. An increasing pressure differential and decreasing specific flux were the basis for the cleaning. There was only a slight increase in the specific flux after the cleaning. Figure 4-11 showed the specific flux for the two RO system arrays based on NDP and adjusted to a temperature of 25 ^{o}C. The trend shown by these data indicate that the RO membranes were slowly being fouled after the October 6, 2006 CIP, as would be expected. The specific flux dropped by approximately 31% for Array 1 and 26% for Array 2 over the 30-day test. While the membranes were still functioning at the end of the test, they probably would have required a chemical cleaning sometime in the next 30 to 60 days based on the trend in the specific flux and the corresponding trend in increasing feed pressures (to maintain flow rate).

The RO cleaning was performed with an acid solution. Citric acid was added to the 300-gallon CIP tank to achieve a pH in the range of 3.75 to 3.96. The specific amount of citric acid added was not recorded, but based on the UF CIP data, it can be estimated that approximately 4 to 6 lbs of citric acid was used to reach this pH. The system was circulated for approximately two hours and then allowed to soak overnight. The cleaning solution was circulated again for two hours and then the RO system was put back into normal operation.

4.1.3.2.3 Total Organic Carbon Results for UF Cleaning Solutions

Samples of the cleaning solution for the UF system CIP were collected from one cleaning period. These samples were analyzed for TOC as specified in the ETV Protocol and the Test Plan. The TOC results for the September 30, 2006 UF system cleaning solutions are presented in Table 4-4. The TOC was higher in the low pH solution. The used cleaning solution was acceptable for discharge to the sanitary sewer system at Selfridge ANB and was discharged to the sewer system after each cleaning cycle.

Table 4-4. UF Cleaning Solution TOC Results

Sample	Date	TOC (mg/L)
Low pH solution	9/30/06	400
High pH solution	9/30/06	64

4.1.3.3 Task C3: 2006 Water Quality Results

The primary objective of this task was to assess the ability of the membrane equipment to meet the water quality goals, which were established as producing water that meets EPA National Drinking Water Regulations. Several water quality parameters were selected as indicator parameters to demonstrate the performance of the UF and RO membranes. Turbidity and conductivity were selected as two key parameters, as turbidity removal by the system would indicate the ability to remove particulate related contaminants, and a reduction in conductivity (indicator of TDS content) would show the ability of the RO system to remove dissolved contaminants. Both turbidity and conductivity were measured with in-line meters in the EUWP, and were also measured with portable equipment on site, at least twice per day. In addition, pH and temperature were measured at least twice per day. Other water quality parameters were monitored by collecting samples on a weekly basis. These parameters included TOC, TDS, TSS, Alkalinity, Hardness, Silica, and UV_{254} absorbance. This section presents the water quality results for the 2006 verification test of both the UF and RO systems. Data on the bacteriological samples and integrity testing are presented later in a separate section of this report.

Figures 4-13 and 4-14 present the grab sample turbidity readings for the UF feed and UF filtrate over the duration of the test. Table 4-5 lists all of the grab sample turbidity readings and the summary statistics for the verification test. As can be seen, the UF system reduced the turbidity from a mean of 4.77 NTU in the feed water to a mean of 0.14 NTU in the UF filtrate. The 95% confidence level for the grab sample turbidity readings shows that filtrate turbidity can be expected to be in the range of 0.12 to 0.16 NTU. The UF system reduced the turbidity of the feed water by a mean value of 95.9%, with a median reduction of 96.4%

All filtrate turbidity measurements were below the NPDWR of 1 NTU. The second NPDWR criteria for turbidity is that 95% of the daily samples in any month must be ≤0.3 NTU. Only one filtrate turbidity measurement out of 58 was above 0.3 NTU: 0.47 NTU on October 5. Therefore, the EUWP UF system met the second NPDWR turbidity requirement, as 98% of the turbidity measurements were ≤0.3 NTU.

The feed water turbidity also spiked on October 5, up to 40.3 NTU. This was likely due to a rain event that occurred at the test site on October 3 and 4. The Lake St. Clair inlet from which the raw water was drawn has a stormwater runoff outfall, so discharge of the runoff into the inlet could have caused the spike in turbidity.

As discussed in Sections 2.4 and 3.9.4.2, the EUWP also includes in-line turbidity meters which measure the turbidity every 15 min as a means of monitoring membrane integrity. There were numerous instances where two or more consecutive turbidity measurements were above the LT2ESWTR action level of 0.15 NTU for shutting the system down and performing a direct integrity test. However, as discussed in Section 2.4, this did not occur because the EUWP is not compliant with the LT2ESWTR indirect integrity monitoring requirements. The in-line turbidity data was logged onto a laptop computer, but the

computer was not connected to the EUWP for the purpose of shutting down the system if necessary.

Also, the in-line turbidimeters were not shut off when the UF system was down for cleaning or other maintenance activities. This could give false high readings, as was the case when the system was shut down for a chemical cleaning. A second issue with the in-line turbidity data is that the date and time of the data logger were not reset prior to the start of the verification test. Therefore, it is not possible to correlate the turbidity data with the dates and times that the system was shut down for cleaning or maintenance. Because of incorrect date and time stamp for the turbidity readings, the data is not presented in this report.

The RO system had an additional impact on the turbidity levels with the RO permeate grab samples having a mean turbidity of 0.09 NTU. The maximum measured RO permeate turbidity was 0.18 NTU. This represents a further reduction in the range of 40% to 66% through the RO system.

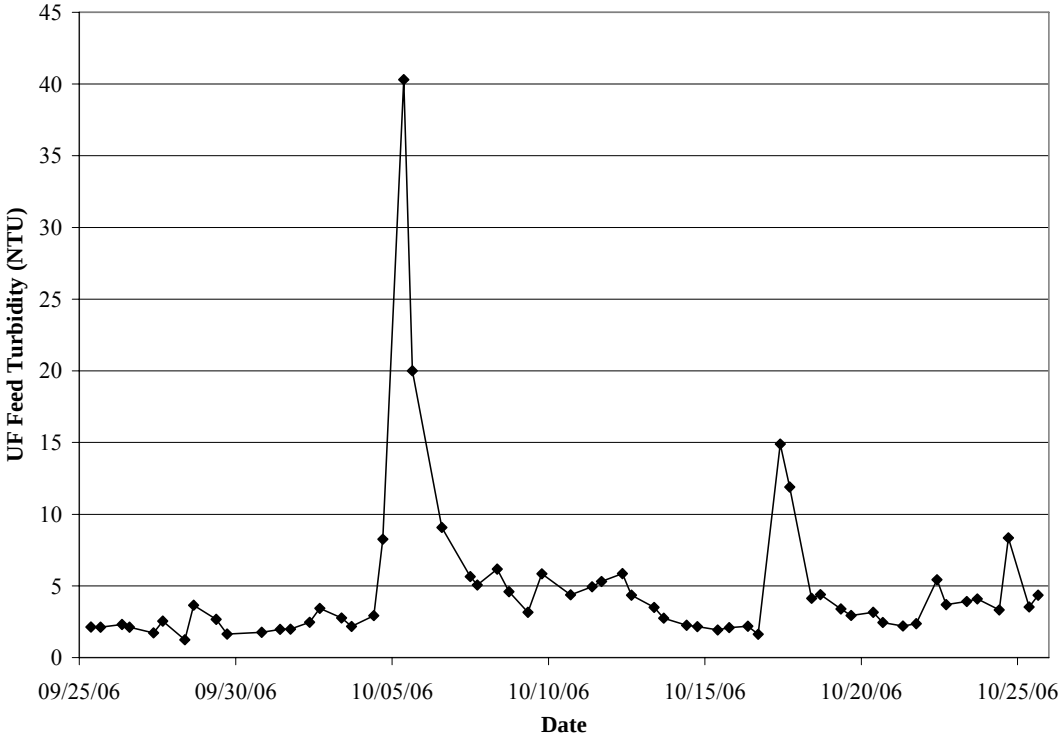


Figure 4-13. UF feed water turbidity for 2006 test.

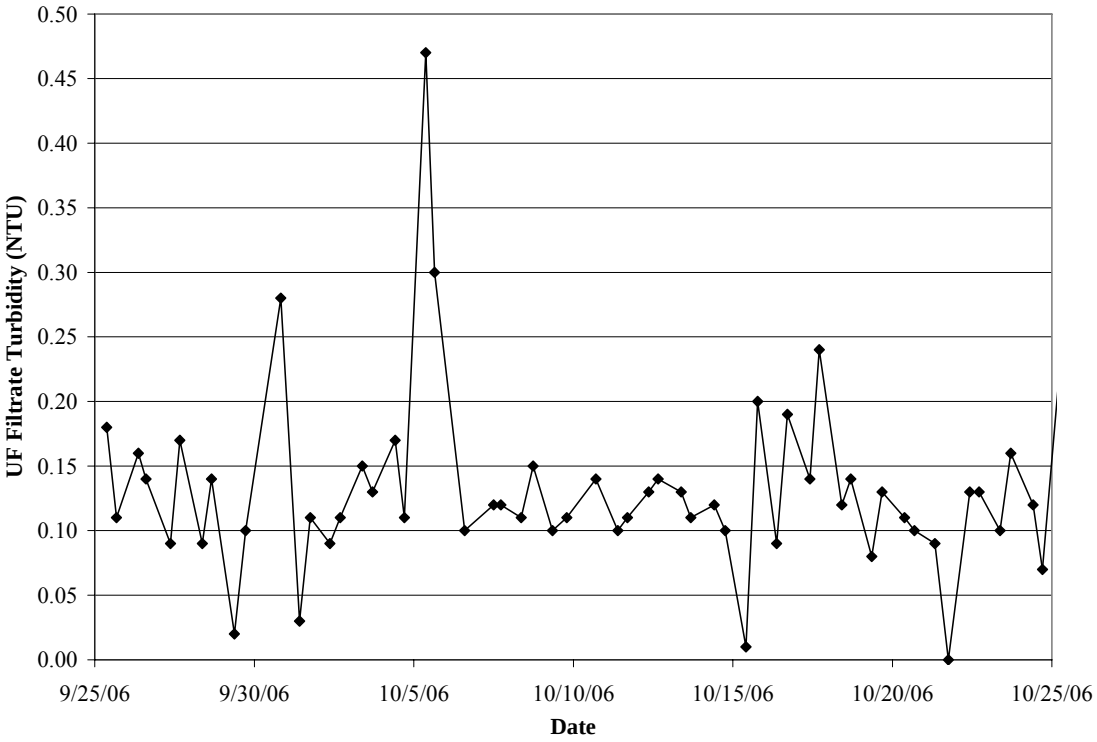


Figure 4-14. UF filtrate water turbidity for 2006 test.

Table 4-5. Turbidity Results for 2006 Test – Hand-Held Meter

	Turbidity (NTU)					
Date	UF Feed	UF Filtrate	RO Feed	RO 1st Pass Permeate	RO Concentrate	UF % Reduction
9/25/2006	2.13	0.18	0.16	0.08	0.22	91.5
9/25/2006	2.12	0.11	0.13	0.13	0.47	94.8
9/26/2006	2.31	0.16	0.10	0.08	0.20	93.1
9/26/2006	2.12	0.14	0.13	0.13	0.77	93.4
9/27/2006	1.73	0.09	0.11	0.09	0.30	94.8
9/27/2006	2.54	0.17	0.17	0.10	0.09	93.3
9/28/2006	1.24	0.09	0.10	0.07	0.16	92.7
9/28/2006	3.65	0.14	0.11	0.17	0.29	96.2
9/29/2006	2.67	0.02	0.05	0.07	0.14	99.3
9/29/2006	1.64	0.10	0.08	0.06	0.12	93.9
9/30/2006	1.76	0.28	0.54	0.07	0.58	84.1
10/1/2006	1.97	0.03	0.11	0.08	0.10	98.5
10/1/2006	1.99	0.11	0.15	0.09	0.12	94.5
10/2/2006	2.47	0.09	0.14	0.07	0.24	96.4
10/2/2006	3.43	0.11	0.12	0.18	0.25	96.8
10/3/2006	2.76	0.15	0.16	0.09	0.12	94.6
10/3/2006	2.17	0.13	0.11	0.12	0.12	94.0
10/4/2006	2.93	0.17	0.11	0.11	0.15	94.2
10/4/2006	8.25	0.11	0.14	0.14	0.14	98.7
10/5/2006	40.3	0.47	0.41	0.09	0.17	98.8
10/5/2006	20.0	0.30	0.19	0.12	0.16	98.5

Table 4-5. Turbidity Results for 2006 Test – Hand-Held Meter (continued)

	Turbidity (NTU)					
Date	UF Feed	UF Filtrate	RO Feed	RO 1st Pass Permeate	RO Concentrate	UF % Reduction
10/6/2006	9.08	0.10	0.15	0.10	0.09	98.9
10/7/2006	5.65	0.12	0.13	0.09	0.56	97.9
10/7/2006	5.06	0.12	0.10	0.10	0.29	97.6
10/8/2006	6.18	0.11	0.13	0.09	0.10	98.2
10/8/2006	4.60	0.15	0.11	0.12	0.38	96.7
10/9/2006	3.16	0.10	0.15	0.09	0.15	96.8
10/9/2006	5.85	0.11	0.13	0.08	0.09	98.1
10/10/2006	4.38	0.14	0.13	0.14	0.34	96.8
10/11/2006	4.94	0.10	0.11	0.10	0.13	98.0
10/11/2006	5.31	0.11	0.15	0.08	0.14	97.9
10/12/2006	5.86	0.13	0.10	0.09	0.13	97.8
10/12/2006	4.35	0.14	0.16	0.08	0.37	96.8
10/13/2006	3.5	0.13	0.12	0.13	0.16	96.3
10/13/2006	2.75	0.11	0.11	0.10	0.26	96.0
10/14/2006	2.26	0.12	0.12	0.08	0.13	94.7
10/14/2006	2.16	0.10	0.11	<0.01	0.14	95.4
10/15/2006	1.93	0.01	0.13	0.08	0.20	99.5
10/15/2006	2.09	0.20	0.14	0.10	0.22	90.4
10/16/2006	2.19	0.09	0.09	0.08	0.1	95.9
10/16/2006	1.63	0.19	0.11	0.13	0.31	88.3
10/17/2006	14.9	0.14	0.25	0.10	0.22	99.1
10/17/2006	11.9	0.24	0.30	0.06	0.54	98.0
10/18/2006	4.13	0.12	0.09	0.10	0.54	97.1
10/18/2006	4.39	0.14	0.24	0.08	0.21	96.8
10/19/2006	3.39	0.08	0.14	0.06	0.32	97.6
10/19/2006	2.94	0.13	0.08	0.09	0.28	95.6
10/20/2006	3.16	0.11	0.12	0.08	0.14	96.5
10/20/2006	2.45	0.1	0.09	0.04	0.13	95.9
10/21/2006	2.21	0.09	0.11	0.07	0.38	95.9
10/21/2006	2.37	NM(1)	0.12	0.09	0.61	—
10/22/2006	5.43	0.13	0.09	0.02	0.05	97.6
10/22/2006	3.69	0.13	0.16	0.1	0.33	96.5
10/23/2006	3.92	0.1	0.12	0.1	0.23	97.4
10/23/2006	4.09	0.16	0.13	0.05	0.12	96.1
10/24/2006	3.33	0.12	0.12	0.08	0.14	96.4
10/24/2006	8.35	0.07	0.63	0.07	0.70	99.2
10/25/2006	3.53	0.26	0.16	0.12	0.14	92.6
10/25/2006	4.35	0.19	0.17	0.09	0.3	95.6
Mean:	4.77	0.14	0.15	0.09	0.25	95.9
Median:	3.33	0.12	0.13	0.09	0.2	96.4
Minimum:	1.24	0.01	0.05	<0.01	0.05	84.1
Maximum:	40.3	0.47	0.63	0.18	0.77	99.5
Std. Dev.:	5.72	0.07	0.10	0.03	0.16	2.77
95% CI:	1.46	0.02	0.03	0.008	0.04	0.71

(1) not measured

Figure 4-15 presents the conductivity data for the RO system over the duration of the test. Table 4-6 shows the conductivity results for the UF and RO systems and the summary statistics for the verification test. The RO system reduced the dissolved ions in the water, as measured by conductivity. The mean conductivity in the RO permeate was 1.8 microSiemens per centimeter (µS/cm) compared to the mean conductivity in the RO feed water of 287 µS/cm. The median feed water conductivity was 289 µS/cm and the median RO permeate conductivity was 1.6 µS/cm. The RO unit reduced the conductivity (indicator of dissolved salts rejection) by a mean value of 99.4 %. The direct measurement of TDS, data shown later in Table 4-9, shows that the total dissolved solids concentration in the RO permeate was always below the detection limit of 5 mg/L.

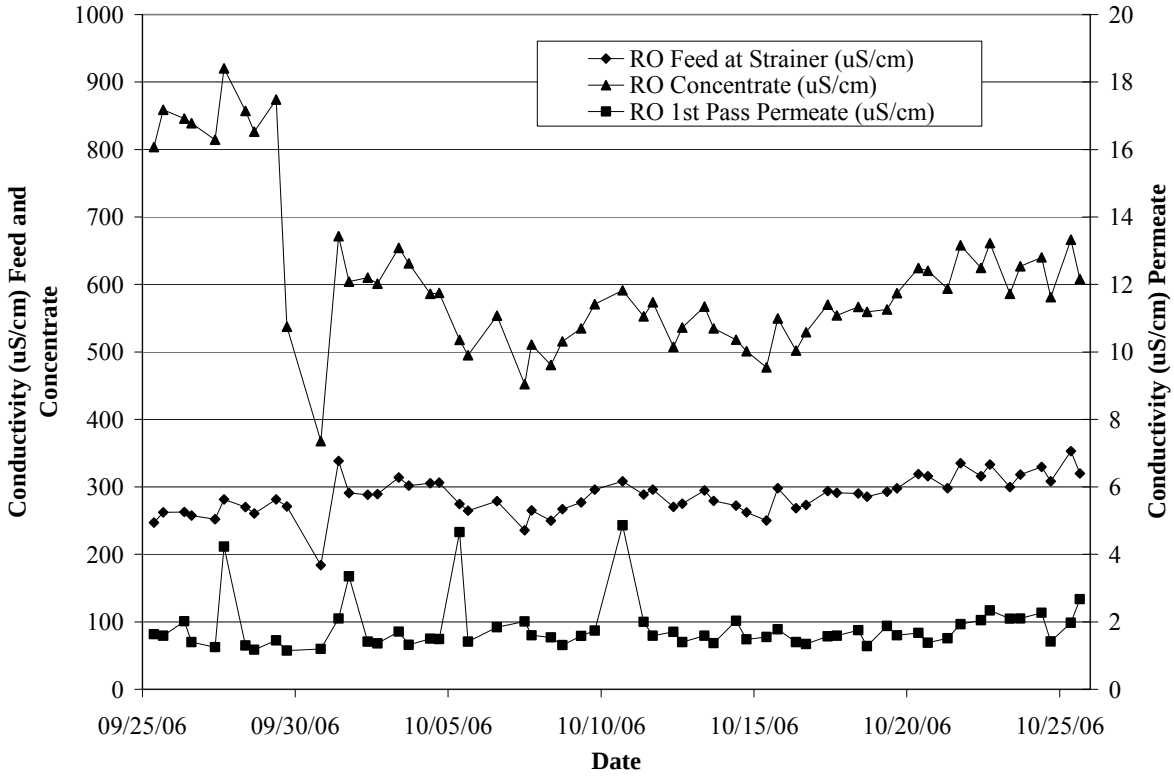


Figure 4-15. RO conductivity results for 2006 test.

Table 4-6. Conductivity Results for 2006 Test for In-Line Meter

	Conductivity (µS/cm)					
Date	UF Feed	UF Filtrate	RO Feed	RO 1st Pass Permeate	RO Concentrate	RO % Rejection
9/25/2006	252	248	247	1.6	804	99.3
9/25/2006	271	262	262	1.6	859	99.4
9/26/2006	262	267	263	2.0	846	99.2
9/26/2006	258	258	258	1.4	839	99.5
9/27/2006	253	253	252	1.3	815	99.5
9/27/2006	284	294	281	4.2	920	98.5
9/28/2006	270	269	270	1.3	857	99.5
9/28/2006	260	260	261	1.2	826	99.6
9/29/2006	289	282	282	1.5	874	99.5
9/29/2006	311	271	271	1.2	538	99.6
9/30/2006	265	264	184	1.2	368	99.3
10/1/2006	334	335	339	2.1	672	99.4
10/1/2006	291	291	291	3.4	604	98.8
10/2/2006	288	288	288	1.4	610	99.5
10/2/2006	310	289	289	1.4	601	99.5
10/3/2006	316	313	314	1.7	654	99.5
10/3/2006	304	301	302	1.3	631	99.6
10/4/2006	305	305	305	1.5	586	99.5
10/4/2006	306	306	306	1.5	588	99.5
10/5/2006	275	274	275	4.7	518	98.3
10/5/2006	265	265	265	1.4	495	99.5
10/6/2006	282	281	279	1.8	554	99.3
10/7/2006	238	237	236	2.0	452	99.1
10/7/2006	266	265	265	1.6	511	99.4
10/8/2006	250	250	250	1.5	481	99.4
10/8/2006	278	271	267	1.3	516	99.5
10/9/2006	277	277	277	1.6	535	99.4
10/9/2006	296	297	296	1.7	571	99.4
10/10/2006	306	306	308	4.9	591	98.4
10/11/2006	290	290	289	2.0	553	99.3
10/11/2006	295	296	296	1.6	574	99.5
10/12/2006	271	271	271	1.7	508	99.4
10/12/2006	275	274	275	1.4	536	99.5
10/13/2006	295	294	295	1.6	567	99.5
10/13/2006	277	279	279	1.4	535	99.5
10/14/2006	273	272	272	2.0	518	99.3
10/14/2006	264	265	262	1.5	501	99.4
10/15/2006	251	251	250	1.6	477	99.4
10/15/2006	305	298	298	1.8	550	99.4
10/16/2006	268	268	268	1.4	502	99.5
10/16/2006	353	273	273	1.3	529	99.5
10/17/2006	294	294	294	1.6	570	99.5
10/17/2006	293	293	291	1.6	554	99.5
10/18/2006	290	291	290	1.8	567	99.4
10/18/2006	283	284	285	1.3	559	99.6
10/19/2006	297	296	293	1.9	563	99.4
10/19/2006	297	296	298	1.6	587	99.5
10/20/2006	322	321	319	1.7	624	99.5
10/20/2006	324	323	316	1.4	620	99.6
10/21/2006	299	298	298	1.5	594	99.5

Table 4-6. Conductivity Results for 2006 Test for In-Line Meter (continued)

	Conductivity (µg/LS/cm)					
Date	UF Feed	UF Filtrate	RO Feed	RO 1st Pass Permeate	RO Concentrate	RO % Rejection
10/21/2006	335	335	335	1.9	658	99.4
10/22/2006	316	313	316	2.1	625	99.4
10/22/2006	338	338	333	2.3	661	99.3
10/23/2006	298	298	300	2.1	586	99.3
10/23/2006	320	318	318	2.1	627	99.3
10/24/2006	330	330	330	2.3	640	99.3
10/24/2006	305	307	308	1.4	581	99.5
10/25/2006	353	350	353	2.0	666	99.4
10/25/2006	316	315	320	2.7	608	99.2
Mean:	291	288	287	1.8	609	99.3
Median:	291	290	289	1.6	586	99.4
Minimum:	238	237	184	1.2	368	98.3
Maximum:	353	350	353	4.9	920	99.6
Std. Dev.:	26	25	29	0.8	117	0.25
95% CI:	6.7	6.4	7.3	0.2	29.9	0.065

Tables 4-7 and 4-8 present the pH and temperature data collected from the UF and RO systems. pH was steady over the test period and the UF system had little impact on the pH of the water. The RO system did lower the pH in the permeate. This is expected, as the constituents that contribute to hardness and alkalinity (dissolved species) are rejected by the membrane. The resultant permeate has less buffering capacity and will tend to have a lower pH. As shown later in Table 4-10, hardness was reduced to <2 mg/L as $CaCO_3$ and alkalinity was reduced to <5 mg/L as $CaCO_3$. The pH of the permeate ranged from 5.2 to 9.0.

The UF and RO systems had no effect on the temperature of the water as it passed through. Water temperature in the lake feed water at the beginning of the test was in the 16 ^oC to 18 ^oC range and dropped during the test to 8 to 9 ^oC by the end of the test in late October. This is typical in the northern climate. Temperature variation and impact on membrane operating production (flux and specific flux) were accounted for in the operating section by standardizing the data to either 20 ^oC or 25 ^oC, as described in Section 3.9.1.3. The temperature data in Table 4-8 served as the basis for the temperature adjustment calculations.

Table 4-7. pH results for 2006 Test – In line Meter

			pH		
Date	UF Feed	UF Filtrate	RO Feed	RO 1st Pass Permeate	RO Conc.
9/25/2006	7.9	7.5	8.1	6.3	8.0
9/25/2006	7.6	8.3	8.4	8.0	8.3
9/26/2006	7.2	7.8	8.0	6.2	8.1
9/26/2006	8.2	8.4	8.5	8.2	8.3
9/27/2006	8.6	8.5	8.4	7.6	8.3
9/27/2006	8.3	8.4	8.5	5.9	8.3
9/28/2006	8.4	8.5	8.5	7.8	8.3
9/28/2006	8.8	8.8	8.8	8.3	8.5
9/29/2006	7.4	7.7	8.0	6.6	8.2
9/29/2006	8.7	8.5	8.6	8.0	8.5
9/30/2006	8.3	8.4	8.5	9.0	8.5
10/1/2006	7.7	7.8	7.4	6.4	7.9
10/1/2006	8.8	8.8	8.6	5.7	8.7
10/2/2006	7.9	8.0	7.8	6.9	8.1
10/2/2006	8.0	8.4	8.1	8.3	8.2
10/3/2006	7.5	7.8	7.5	5.5	7.8
10/3/2006	8.2	8.5	7.8	8.0	8.2
10/4/2006	7.9	7.9	7.5	8.1	8.0
10/4/2006	8.1	8.1	7.9	7.3	8.1
10/5/2006	7.6	7.9	7.6	6.9	8.0
10/5/2006	7.8	8.1	8.0	8.4	8.2
10/6/2006	7.7	8.0	7.7	7.5	8.0
10/7/2006	7.9	7.9	7.7	5.8	7.9
10/7/2006	7.5	7.9	7.8	6.3	8.0
10/8/2006	7.7	7.9	7.8	6.6	8.0
10/8/2006	8.0	8.2	8.1	8.0	8.2
10/9/2006	8.0	8.1	7.7	6.2	8.0
10/9/2006	7.8	7.7	8.0	7.0	8.0
10/10/2006	7.9	8.0	7.8	7.8	8.1
10/11/2006	7.8	7.8	7.8	6.6	7.8
10/11/2006	8.0	8.1	8.1	8.3	8.0
10/12/2006	8.0	7.9	7.5	5.9	8.0
10/12/2006	8.2	8.1	8.1	5.4	8.1
10/13/2006	8.1	7.7	7.8	7.4	8.7
10/13/2006	7.8	8.1	7.9	8.7	8.3
10/14/2006	7.8	7.4	7.9	7.6	7.9
10/14/2006	8.1	8.1	8.2	5.4	8.1
10/15/2006	7.8	7.3	7.9	7.0	8.0
10/15/2006	7.4	8.2	8.1	6.3	8.1
10/16/2006	7.5	8.0	8.0	6.2	8.1
10/16/2006	7.6	7.8	8.2	8.1	8.2
10/17/2006	7.9	7.7	8.0	6.4	8.0
10/17/2006	7.8	8.0	8.0	6.6	8.1
10/18/2006	7.4	7.8	7.9	5.7	8.0
10/18/2006	8.1	8.3	8.3	5.7	8.3
10/19/2006	7.8	7.6	8.0	6.7	7.9
10/19/2006	7.9	7.6	7.9	6.8	8.0
10/20/2006	8.0	7.7	8.0	6.5	7.9
10/20/2006	8.4	8.3	8.3	7.5	8.2
10/21/2006	8.0	8.0	8.0	6.8	8.0

Table 4-7. pH results for 2006 Test – In line Meter

			pH		
Date	UF Feed	UF Filtrate	RO Feed	RO 1st Pass Permeate	RO Conc.
10/21/2006	7.6	7.8	7.8	5.9	7.8
10/22/2006	7.7	7.6	7.8	5.9	7.9
10/22/2006	7.9	7.8	7.3	5.2	7.9
10/23/2006	7.6	7.5	7.7	5.7	7.7
10/23/2006	7.6	7.3	7.7	5.5	7.7
10/24/2006	7.3	7.6	7.7	5.9	7.7
10/24/2006	8.2	8.1	8.1	7.3	8.3
10/25/2006	7.4	7.7	7.4	6.1	7.8
10/25/2006	7.3	7.2	7.4	5.7	7.5
Mean:	7.9	8.0	8.0	6.8	8.1
Median:	7.9	7.9	8.0	6.6	8.0
Minimum:	7.2	7.2	7.3	5.2	7.5
Maximum:	8.8	8.8	8.8	9.0	8.7
Std. Dev.:	0.36	0.36	0.33	0.99	0.23
95% CI:	0.09	0.09	0.09	0.25	0.06

Table 4-8. Temperature Data for 2006 Test – In line Meter

			Temperature (°C)		
Date	UF Feed	UF Filtrate	RO Feed	RO Permeate	RO Conc.
9/25/2006	16.4	16.3	16.1	16.6	17.2
9/25/2006	17.7	17.6	17.5	18.3	18.5
9/26/2006	16.4	16.3	16.0	16.7	17.0
9/26/2006	17.3	17.1	16.9	18.2	18.0
9/27/2006	17.1	17.0	16.6	17.0	17.6
9/27/2006	18.2	18.2	17.7	18.9	18.7
9/28/2006	15.4	15.7	15.9	16.2	17.0
9/28/2006	17.1	16.6	16.5	17.2	17.7
9/29/2006	15.2	15.2	14.9	15.4	15.9
9/29/2006	15.9	15.7	15.8	16.1	16.5
9/30/2006	14.5	14.7	15.1	15.3	15.9
10/1/2006	16.4	16.5	15.5	16.6	16.0
10/1/2006	16.0	15.9	16.0	16.7	16.6
10/2/2006	15.3	15.1	15.3	15.5	16.0
10/2/2006	16.4	16.0	15.9	16.6	16.6
10/3/2006	16.1	15.8	15.9	16.3	16.7
10/3/2006	17.4	17.1	17.1	17.9	17.7
10/4/2006	17.0	16.9	16.9	17.4	17.3
10/4/2006	16.6	16.5	16.8	16.7	17.4
10/5/2006	13.6	13.5	13.5	13.5	14.1
10/5/2006	14.5	14.1	14.3	14.7	14.7
10/6/2006	14.4	14.2	14.7	15.4	14.6
10/7/2006	15.7	15.1	14.4	17.1	14.7
10/7/2006	14.7	14.4	14.4	14.7	14.9
10/8/2006	13.5	13.3	13.4	13.5	14.0
10/8/2006	15.2	15.2	14.9	15.6	15.4

Table 4-8. Temperature Data for 2006 Test – In line Meter (continued)

	Temperature (°C)				
Date	**UF Feed**	**UF Filtrate**	**RO Feed**	**RO Permeate**	**RO Conc.**
10/9/2006	13.9	14.0	14.0	14.1	14.7
10/9/2006	14.0	13.8	14.1	14.1	14.9
10/10/2006	15.4	15.2	15.3	15.4	15.8
10/11/2006	14.9	14.8	15.0	15.6	15.6
10/11/2006	15.7	15.4	15.5	16.1	16.1
10/12/2006	12.4	12.3	13.1	12.5	13.8
10/12/2006	12.2	12.4	12.6	11.8	13.2
10/13/2006	10.4	10.8	10.3	10.1	10.9
10/13/2006	10.7	10.3	9.9	10.3	10.9
10/14/2006	9.5	10.0	9.7	9.9	10.3
10/14/2006	10.3	10.2	10.4	10.9	11.2
10/15/2006	10.1	10.1	9.3	10.3	10.2
10/15/2006	10.9	10.4	10.5	10.8	11.2
10/16/2006	9.7	9.7	9.8	10.2	10.5
10/16/2006	11.0	10.5	10.5	10.9	11.4
10/17/2006	10.5	10.5	10.7	11.0	11.4
10/17/2006	11.9	11.5	11.7	12.6	13.2
10/18/2006	11.6	11.5	11.4	11.9	12.2
10/18/2006	12.5	12.2	12.0	12.6	12.6
10/19/2006	11.6	11.5	11.7	11.8	12.5
10/19/2006	12.0	12.1	11.9	12.1	12.6
10/20/2006	11.2	11.3	11.2	11.3	11.9
10/20/2006	11.6	11.5	11.7	11.8	12.7
10/21/2006	10.8	10.7	11.0	11.0	11.9
10/21/2006	11.4	11.3	11.5	11.8	12.6
10/22/2006	11.2	11.4	11.2	11.4	12.0
10/22/2006	11.0	11.0	11.2	10.8	11.9
10/23/2006	9.1	9.1	9.5	9.3	10.5
10/23/2006	9.8	10.5	9.6	9.9	10.6
10/24/2006	8.0	7.9	7.9	8.1	8.8
10/24/2006	9.1	8.5	8.5	8.4	9.3
10/25/2006	8.6	8.1	8.2	8.1	8.9
10/25/2006	8.4	8.5	8.5	8.7	9.2
Mean:	13.3	13.2	13.2	13.6	13.9
Median:	13.6	13.5	13.5	13.5	14.1
Minimum:	8.0	7.9	7.9	8.1	8.8
Maximum:	18.2	18.2	17.7	18.9	18.7
Std. Dev.:	2.9	2.8	2.8	3.0	2.8
95% CI:	0.7	0.7	0.7	0.8	0.7

Tables 4-9 and 4-10 present the other water quality data collected on a weekly basis during the verification test. The UF system removed suspended material as shown by the TSS in the filtrate always being below the detection limit of 2 mg/L. These data support the daily turbidity results showing over 95% reduction in turbidity. The UF system did not change the other water quality parameters, as would be expected. These other parameters, such as hardness, alkalinity, TDS, etc. primarily represent dissolved inorganic constituents that are not removed by physical filtration.

The RO system did remove many of the inorganic dissolved species as shown by the results in Table 4-10 for the RO permeate. Hardness, alkalinity, TDS, and total silica were all removed to below the detection limit in the permeate water. The RO concentrate increased in concentration for these parameters above the feed water levels, as expected. These data support the daily conductivity measurements that showed a significant reduction in dissolved salts during the test. The RO membranes, at these operating conditions, rejected the dissolved salts present in the feed water throughout the test.

The UF system showed only a minor reduction in organic material as measured by the TOC data. The feed water, filtrate, and retentate all showed TOC concentrations within a range of 2.1 to 2.7 mg/L. The filtrate typically showed a 0.1 to 0.4 mg/L reduction in TOC compared to the feed water, and the retentate occasionally showed an increase in TOC of 0.1 mg/L compared to the feed water. These data would indicate that most of the organic material, as measured by TOC, was dissolved in the feed water. The RO system had a major impact on the TOC levels, reducing the TOC in the permeate to below the detection limit of 0.1 mg/L. As in the case of the dissolved salts, the RO membranes rejected dissolved organic material, as measured by TOC, and reduced the TOC concentration by greater than 95%.

Table 4-9 Other UF System Water Quality Data for 2006 Test

	TSS (mg/L)			
Date	**UF Feed**	**Filtrate**	**Retentate**	**Backwash**
9/26/06	<2	ND (2)	<2	5
10/03/06	3	ND (2)	NM	23
10/10/06	6	ND (2)	8	23
10/17/06	14	ND (2)	16	320
10/24/06	3	ND (2)	4	50

	TOC (mg/L)		
Date	**UF Feed**	**Filtrate**	**Retentate**
9/26/06	2.3	2.1	2.4
10/03/06	2.7	2.3	2.7
10/10/06	2.5	2.1	2.6
10/17/06	2.6	2.2	2.6
10/24/06	2.4	2.7	2.4

	Hardness (mg/L as $CaCO_3$)		Alkalinity (mg/L as $CaCO_3$)	
Date	**UF Feed**	**Filtrate**	**UF Feed**	**Filtrate**
9/26/06	110	110	86	90
10/03/06	120	120	93	92
10/10/06	130	120	97	96
10/17/06	120	120	94	95
10/24/06	140	140	100	100

	TDS (mg/L)	
Date	**UF Feed**	**Filtrate**
9/26/06	140	150
10/03/06	170	170
10/10/06	200	180
10/17/06	180	170
10/24/06	180	190

	Total Silica (mg/L)		UV_{254} (absorbance/cm)	
Date	**UF Feed**	**Filtrate**	**UF Feed**	**Filtrate**
9/26/06	0.45	<0.2	0.0617	0.0319
10/03/06	<0.2	<0.2	0.1063	0.0198
10/10/06	1.1	0.7	0.1169	0.0332
10/17/06	3.1	1.0	0.1542	0.0500
10/24/06	2.1	1.3	0.0760	0.0512

Table 4-10. Other RO System Water Quality Data for 2006 Test

	TSS (mg/L)			
Date	**RO Feed**	**Permeate**	**Concentrate**	**Discharge**
9/26/06	<2	<2	<5	<2
10/03/06	<2	<2	<2	<2
10/10/06	<2	<2	<2	6
10/17/06	<2	<2	<2	11
10/24/06	<2	<2	<2	3

	TOC (mg/L)		
Date	**RO Feed**	**Permeate**	**Concentrate**
9/26/06	2.1	<0.1	7.6
10/03/06	2.3	<0.1	5.2
10/10/06	2.1	<0.1	4.6
10/17/06	2.2	<0.1	4.2
10/24/06	2.4	<0.1	4.5

	Hardness (mg/L as $CaCO_3$)			Alkalinity (mg/L as $CaCO_3$)		
Date	**RO Feed**	**Permeate**	**Concentrate**	**RO Feed**	**Permeate**	**Concentrate**
9/26/06	110	<2	410	87	<5	310
10/03/06	120	<2	280	93	<5	200
10/10/06	120	<2	260	97	<5	200
10/17/06	120	<2	250	94	<5	180
10/24/06	140	<2	260	100	<5	190

	TDS (mg/L)		
Date	**RO Feed**	**Permeate**	**Concentrate**
9/26/06	150	<5	510
10/03/06	170	<5	370
10/10/06	180	<5	370
10/17/06	180	<5	330
10/24/06	180	<5	330

	Total Silica (mg/L)			UV_{254} (absorbance/cm)		
Date	**RO Feed**	**Permeate**	**Concentrate**	**RO Feed**	**Permeate**	**Concentrate**
9/26/06	<0.2	<0.2	0.98	0.0320	<0.0000	0.1462
10/03/06	<0.2	<0.2	<0.2	0.0534	<0.0000	0.0980
10/10/06	0.8	<0.2	1.4	0.0377	<0.0000	NM
10/17/06	0.7	<0.2	1.3	0.0459	NM	0.0858
10/24/06	1.3	<0.2	2.4	0.0432	<0.0000	0.0833

4.1.3.4 Task C4: 2006 Membrane Module Integrity

The objective of this task was to demonstrate methodology for direct integrity testing and indirect integrity monitoring of the UF and RO membranes. Pressure decay tests were used to document UF membrane integrity, and dye marker tests were used for the RO membrane system.

As discussed in Section 4, the initial UF pressure test on September 13, 2006 showed that pressure was being lost at a higher than desirable rate. The problem was investigated, and was found to be the o-ring seals between the membrane modules and filtrate collection tubes. As a temporary fix, PTFE tape was wrapped around the o-rings to increase the seal surface between the o-rings and membrane cartridges.

The pre-verification RO system dye reduction test was conducted on September 23. The dye test showed that based on absorbance readings the membranes were rejecting the dye as expected, and the dye was not leaking by any seals or through the membranes. RO feed water absorbance was 2.860, and RO permeate was in the range of 0.013 to 0.015 over a 10-min run, which equates to a rejection of 99.5%. This dye test is considered a direct measurement of RO membrane integrity. The in-line conductivity meters were also monitored at the start of the test to confirm the rejection rate of the RO membranes.

4.1.3.4.1 UF System Pressure Decay and Microbial Reduction Results

Pressure decay tests were performed each operating day during the verification test. Table 4-11 presents the pressure decay data, and Figure 4-16 shows the pressure decay data in a graphical format.

After the UF seal problem was temporarily fixed, a pressure decay test was conducted on September 22. The data for this test is also presented in Table 4-11. The pressure decay rate from this test was higher than desirable, but NSF and EPA allowed the test to proceed. The pressure decay on the first day of the official test period was 1.14 psig/min, which was almost four times higher than the 0.37 psig/min obtained on September 22. After the test was completed, the technician found that the air hose was leaking, so these initial data were not representative of the actual conditions. An air leak occurred again on October 9, when the UF Array 1 retentate valve was not completely closed. Excluding the pressure decay rates measured on September 25 and October 9, the pressure decay results were fairly consistent with a mean value of 0.29 psig/min and a median value of 0.28 psig/min. The highest pressure decay rate measured was 0.43 psig/min.

Table 4-11. Pressure Decay Data for the 2006 Test

Date	0 Min.	2 Min.	4 Min.	6 Min.	8 Min.	10 Min.	12 Min.	Decay (psig/min)
09/22/06	20.0	19.5	19.0	18.5	18.2	17.7	17.4	0.37
09/25/06	20.0	19.2	18.5	17.8	17.3	14.7	12.0	1.14
09/26/06	20.0	19.6	19.4	19.1	18.8	18.5	18.4	0.23
09/27/06	20.0	19.6	19.2	18.9	18.6	18.4	18.1	0.27
09/28/06	20.0	19.7	19.3	19.0	18.6	18.4	18.1	0.27
09/29/06	20.1	19.8	19.3	19.0	18.6	18.3	18.0	0.30
10/01/06	20.2	19.9	19.5	19.2	18.8	18.5	18.2	0.29
10/02/06	20.0	19.5	19.0	18.5	18.0	17.6	17.3	0.39
10/03/06	20.0	19.3	19.0	18.8	18.6	18.5	18.4	0.23
10/04/06	20.0	19.8	19.5	19.2	19.0	18.8	18.5	0.21
10/05/06	20.0	19.7	19.3	19.0	18.7	18.4	18.1	0.27
10/06/06	20.0	19.7	19.4	19.4	18.9	18.6	18.4	0.23
10/07/06	20.0	19.7	19.4	19.2	18.9	18.7	18.4	0.23
10/08/06	19.9	19.2	18.9	18.5	18.3	18.0	17.7	0.31
10/09/06	20.0	18.0	16.2	14.7	13.3	12.5	11.4	1.23
10/10/06	20.1	19.8	19.5	19.2	18.9	18.5	18.3	0.26
10/11/06	20.0	19.8	19.5	19.3	19.0	18.8	18.6	0.20
10/12/06	20.3	19.9	19.5	19.1	18.7	18.4	18.0	0.33
10/13/06	21.0	20.4	19.8	19.0	18.5	18.2	18.0	0.43
10/14/06	20.0	19.6	19.2	18.8	18.4	18.1	17.7	0.33
10/15/06	20.0	19.7	19.3	19.0	18.7	18.4	18.0	0.29
10/16/06	20.0	19.6	19.2	18.9	18.5	18.2	18.0	0.29
10/17/06	20.0	19.7	19.3	19.0	18.8	18.4	18.2	0.26
10/18/06	20.0	19.8	19.4	19.2	18.9	18.6	18.4	0.23
10/19/06	20.1	19.7	19.3	19.0	18.6	18.2	18.0	0.30
10/20/06	20.0	19.6	19.2	18.8	18.4	18.1	17.7	0.33
10/21/06	20.0	19.6	19.3	19.0	18.6	18.4	18.1	0.27
10/22/06	20.1	19.8	19.6	19.4	19.2	18.9	18.6	0.21
10/23/06	20.0	19.6	19.2	18.7	18.3	18.0	17.6	0.34
10/24/06	20.0	19.6	19.2	18.7	18.4	18.0	17.6	0.34
10/25/06	20.2	19.8	19.3	18.8	18.4	18.0	17.7	0.36
							Mean [1]	0.29
							Median [1]	0.28
							Maximum [1]	0.43
							Minimum [1]	0.20

(1) The statistics do not include the September 22, September 25, and October 9 data. See above for further discussion.

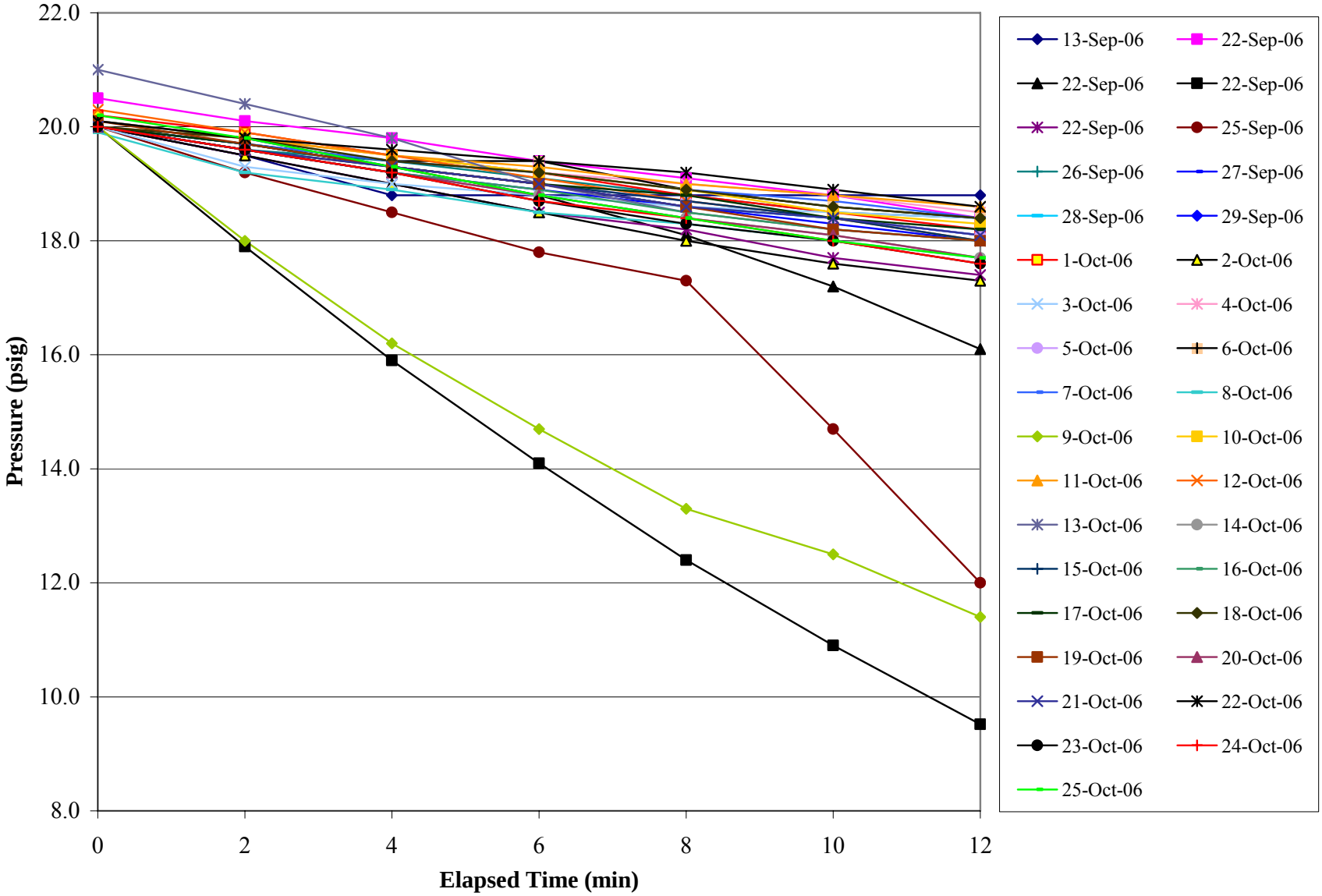


Figure 4-16. Pressure decay over time for the 2006 test.

The pressure decay tests showed that the integrity of the membranes and seals remained steady over the verification test. However, the mean value of 0.29 psig/min was on the high side of the values expected for this system and higher than desired for best removal and control of bacteria, virus, and other microbial agents. Previous ETV lab testing of the Koch UF membranes had shown pressure decay rates in the range of 0.11 to 0.29 psig/min. The ETV report, *Removal of Microbial Contaminants in Drinking Water Koch Membrane Systems, Inc. HF-82-35-PMPW™ Ultrafiltration Membrane, September 2006,* reported pressure decay test results from laboratory testing of the same UF fibers used in the EUWP, but not the same end cap design. The report stated: "The pressure decay rate for Cartridge 1 was measured to be 0.11 psig/min. The measured pressure decay rates for Cartridge 2 were 0.14 and 0.29 psig/min. Koch Membrane Systems provided an estimated severed fiber pressure decay rate of 2.1 psig/min for the HF-82-35-PMPW membrane, so the measured decay rates for Cartridge 2 are not indicative of a breach in membrane integrity. Also, the air bubble leak-check tests did not indicate that any membrane fibers were compromised during testing."

The verification statement for the HF-82-35-PMPW membrane reported: "The UF cartridges were challenged with approximately 5 $\log_{10}$ of the bacteriophage viruses fr and MS2, 7 to 8 $\log_{10}$ of the bacteria *Brevundimonas diminuta*, and 5.7 $\log_{10}$ of live *Cryptosporidium parvum* oocysts. The membranes removed a minimum of 4.8 $\log_{10}$ of the viruses, 6.0 $\log_{10}$ of *B. diminuta*, and 5.7 $\log_{10}$ of *C. parvum*." Therefore, it was expected that the UF system would achieve significant log reductions of microbial agents at the operating conditions found in the field test.

However, the HPC and total coliform data collected during the verification test did not show significant reduction. The data, shown in Tables 4-12 and 4-13 indicate that total coliform was reduced by at most 70% (0.7 $\log_{10}$) and HPC by at most 40% (0.4 $\log_{10}$) on a mean basis in the UF filtrate. In fact HPC and total coliform were actually higher in the filtrate compared to the feed water on occasions. The UF feed geometric mean HPC count was 2810 CFU/mL, and the filtrate geometric mean HPC count was 1670 CFU/mL. Mean total coliform counts were not calculated because only five sets of samples were collected. The UF feed total coliform counts ranged from 41 to 532 CFU/100 mL, while the filtrate counts ranged from 11 to 94 CFU/100 mL. High numbers of HPC and total coliforms were also found in the RO permeate. The mean RO permeate HPC count was 247 CFU/mL and the RO permeate total coliform counts ranged from <1 to 95 CFU/100 mL. This phenomenon has been observed in other published membrane studies, but it was beyond the scope of this study to determine whether the observed HPC and total coliform levels were breaching the membrane, or were a result of microbial contamination and growth downstream of the UF and RO membranes from previous field tests of the EUWP.

Table 4-12. HPC Results for the 2006 Test

	HPC (CFU/mL)						
Date	UF Feed	UF Filtrate	UF Retentate	UF Backwash	RO Feed	RO Permeate	RO Concentrate
09/25/06	14,400	7,800	8,900	17,500	15,600	314	24,700
09/26/06	14,800	78,000	1,230	15,600	9,500	99,000	67,000
09/27/06	6,700	7,400	7,700	23,700	9,500	131	15,700
09/28/06	8,200	14,100	283	8,900	6,900	3,800	33,200
10/02/06	7,300	905	1,250	5,300	3,500	346	5,300
10/03/06	8,200	1,840	1,460	10,300	1,430	13	4,000
10/04/06	10,900	1,160	1,150	8,200	1,400	9	911
10/05/06	13,600	5,200	4,700	8,500	8,700	270	7,800
10/09/06	1,470	2,380	520	9,500	3,100	10	5,000
10/10/06	2,220	810	3,200	12,000	1,920	260	2,370
10/11/06	10,200	13,9000	210,000	218,000	189,000	172,000	1,760
10/16/06	400	700	270	900	420	10	1,770
10/17/06	970	300	1,170	9,100	500	630	560
10/18/06	690	330	1,190	7,100	730	<10	800
10/19/06	530	260	280	980	500	<10	1,030
10/23/06	560	180	200	1,630	330	<10	760
10/24/06	680	70	440	3,100	210	54	290
10/25/06	640	260	590	430	630	30	930
Geometric Mean:	2,810	1,670	1,400	6,670	2,250	247	3,030
Maximum:	14,800	139,000	210,000	218,000	189,000	172,000	67,000
Minimum:	400	70	200	430	210	9	290

Table 4-13. Total Coliform Results for the 2006 Test

	Total Coliform (CFU/100mL)						
Date	UF Feed	UF Filtrate	UF Retentate	UF Backwash	RO Feed	RO Permeate	RO Concentrate
9/26/2006	67	75	78	240	93	95	247
10/3/2006	154	55	3	<1	29	<1	66
10/10/2006	173	94	9	16	71	35	97
10/17/2006	41	30	7	7	68	55	27
10/24/2006	532	11	540	724	13	<1	70

4.1.3.4.2 Particle Count Data

After completion of the 2006 ETV test, it was discovered that the particle counters had been improperly calibrated, so the particle count data from this test is not presented here.

4.1.3.4.3 RO System Dye Test Results

Direct integrity measurements of the RO system were performed prior to the start of the verification test and again at the end of the test. The test method was the dye marker test where a food grade dye is added to the RO feed water, and feed, permeate, and

concentrate UV absorbance values are measured. The RO permeate samples should have low absorbance if the membranes are in good condition and the seals are tight.

The dye test results are shown on Tables 4-14 and 4-15. As can be seen, the RO system showed good integrity at the beginning and end of the verification test. For the September 23, 2006 dye test prior to the start of the verification test, the RO feed water absorbance was 2.860, and the mean Array 1 RO permeate was 0.012 over a 10 min run, yielding a rejection rate of 99.6%. The Array 2 RO permeate absorbance was 0.011, also yielding a rejection rate of 99.6%. At the end of the verification test, the rejection was slightly better with an Array 1 rejection of 99.8% and an Array 2 rejection of 99.9%. These data show that the RO membrane and sealing system maintained integrity throughout the test.

Table 4-14. RO Dye Test Results – September 23, 2006

Time (min)	RO Feed Water (absorbance)	RO Permeate Array 1 (absorbance)	RO Permeate Array 2 (absorbance)	% RO Rejection Array 1	% RO Rejection Array 2
0	2.860 (only measured once at the start of the test)	0.013	0.007	99.5	99.8
1		0.014	0.005	99.5	99.8
2		0.014	0.014	99.5	99.5
3		0.014	0.013	99.5	99.5
4		0.012	0.013	99.6	99.5
5		0.010	NM	99.7	NM
6		0.003	NM	99.9	NM
7		0.013	NM	99.5	NM
8		0.015	0.013	99.5	99.5
9		0.014	0.013	99.5	99.5
10		0.015	0.013	99.5	99.5
Mean:	NA	0.012	0.011	99.6	99.6
Median:	NA	0.014	0.013	99.5	99.5
Maximum:	NA	0.015	0.014	99.9	99.8
Minimum:	NA	0.003	0.005	99.5	99.5

Table 4-15. RO Dye Test Results – October 24, 2006

Time (min)	RO Feed Water (absorbance)	RO Permeate Array 1 (absorbance)	RO Permeate Array 2 (absorbance)	% RO Rejection Array 1	% RO Rejection Array 2
0	2.921 (only measured once at the start of the test)	0.009	0.008	99.7	99.7
1		0.008	0.004	99.7	99.9
2		0.004	0.005	99.9	99.8
3		0.005	0.004	99.8	99.9
4		0.004	0.005	99.9	99.8
5		0.004	0.003	99.9	99.9
6		0.004	0.005	99.9	99.8
7		0.004	0.004	99.9	99.9
8		0.003	0.002	99.9	99.9
9		0.003	0.003	99.9	99.9
10		0.003	0.002	99.9	99.9
Mean:	3.169	0.005	0.004	99.8	99.9
Median:	3.19	0.004	0.004	99.9	99.9
Maximum:	3.041	0.009	0.008	99.9	99.9
Minimum:	0.998	0.003	0.002	99.7	99.7

4.1.3.4.4 Correlation of Membrane Integrity Indicators

For the 2006 test, the highest UF filtrate turbidity readings were associated with increased turbidity in the UF feed water due to rain events. The turbidity, particle count, bacteria, and pressure decay test data collected during these events can be compared to look for any correlations.

The rain event during the 2006 test occurred on October 3 and 4. As discussed in Section 4.1.3.3, the feed water turbidity increased up to approximately 40 NTU, and there was a corresponding spike in the filtrate turbidity up to 0.47 NTU. Table 4-16 presents the turbidity data from this time period, and the corresponding HPC, pressure decay test results, and recorded TMP readings. Also included for comparison are the averages for each parameter over the course of the test. Note that while the rain even occurred on October 3 and 4, the data is presented from the morning of October 4 to the afternoon of October 6 to encompass the rise and fall of the UF feed turbidity. The UF feed turbidity did not rise significantly above average until the October 4 afternoon measurement.

The feed water HPC for October 4 and 5 were higher than average, which is expected with turbid water. The October 4th filtrate HPC was actually below average, but the October 5th filtrate HPC was over three times above average. This high filtrate count correlates with the filtrate turbidity spike. The filtrate HPC and turbidity on October 5 indicate that the integrity of the UF system may have been compromised by the increased turbidity. The mechanism of action for turbidity compromising a membrane is expected to be through an increased pressure drop across the membrane stressing the seals or the membrane material itself, due to the build-up of suspended particles on the feed side. However, this is not apparent in the TMP readings or for October 5. The EUWP undergoes an automatic backflush every half-hour, so a TMP increase would only

become apparent over a longer time frame, as was observed during the month-long course of testing.

Table 4-16. UF Membrane Integrity Indicators for October 2006

Date	Time[1]	Feed Turbidity (NTU)	Filtrate Turbidity (NTU)	Feed HPC (CFU/mL)	Filtrate HPC (CFU/mL)	TMP (psig)	Pressure Decay (psig/min)
10/4	10:00	2.93	0.17	NM	NM	10	0.21
10/4	17:00	8.25	0.11	10,900	1,160	11	
10/5	09:00	40.3	0.47	13,600	5,200	11	0.27
10/5	15:40	20.0	0.30	NM	NM	12	
10/6	14:15[2]	9.08	0.10	NM	NM	12	0.23
Average ± 95% Confidence Interval[3]:		4.77 ± 1.46	0.14 ± 0.02	2,810	1,669	14 ± 1	0.29 ± 0.02

(1) Time of turbidity and TMP readings as part of the twice per day on-site data collection.
(2) Operational and water quality measurements were only recorded once on October 6.
(3) Averages are for all data over the course of the test, not just the data presented here.

4.1.4 2006 Chemical Consumption

The verification test in 2006 was started without the use of a coagulant. Following the fairly rapid decrease in UF specific flux, it was determined that the addition of ferric chloride as a coagulant aid could improve the UF operation. Beginning on October 2, ferric chloride was added to the intake water stream prior to the UF system. The ferric chloride solution had a concentration of 12 % as Fe. Feed rate varied from 0 to 1.46 gpd. The feed rate average was 4 mL/min or 0.063 gal of ferric chloride per operating hour. This represents a coagulant dosage of approximately 0.4 mg/L as Fe in the intake water. At this coagulant dose, the system would use 106 mg of Fe per 1000 gal of intake water or approximately 0.23 lbs of Fe per one million gal of intake water.

The RO system was designed to have a scale inhibitor added if needed. During the 2006 verification test it was determined after 19 days of operation that the addition of a scale inhibitor might improve and/or lengthen RO run time before chemical cleaning was needed. ONDEO (Nalco) PermaTreat® PC-191 anti-scalant was made by using 3.34 L of product to make 15 L of feed solution. The feed solution was fed at a rate of approximately 7.5 mL/min to achieve an anti-scalant concentration in the RO feed water of 4 mg/L or 0.11 gal per operating hour. This dose rate translates to approximately 1 gal of concentrated inhibitor per 36,000 gal of RO feed water.

The chemicals needed for the UF CIP were citric acid, sodium hydroxide, and calcium hypochlorite. Citric acid was used to lower the pH of the cleaning solution for the low pH cleaning cycle, and sodium hydroxide was used for the high pH cleaning cycle. The

calcium hypochlorite provided chlorine to help kill any biological growth on the membranes to help oxidize organic material.

The chemicals specified to be used for the RO chemical cleaning were citric acid and an alkaline detergent. Only the acid cleaning was performed during the ETV test. Citric acid was used to lower the pH of the cleaning solution for the low pH cleaning cycle, and the alkaline detergent if it had been used would have been used for the high pH cleaning cycle. The actual amount of acid or base needed to lower or raise the pH of the water used for the CIP solution will depend on the local water chemistry. For this test, tap water was used for the cleaning solution.

The first CIP for the UF system used 8 cups (64 ounces dry vol.) of citric acid added to the 300 gal of water in the CIP tank. This is approximately 6.9 lbs. of citric acid. This gave a cleaning solution pH of 2.98 to 3.08. For the high pH solution, 1.1 L of 0.5% sodium hydroxide was added to the 300 gal of water in the CIP tank. This resulted in a cleaning solution pH of 11.00-11.63. In addition 300 grams of calcium hypochlorite was added to the high pH solution.

For the RO cleaning, citric acid was added to the 300 gal CIP tank to achieve a pH in the range of 3.75 to 3.96. The specific volume of citric acid was not recorded, but based on the UF CIP data, it can be estimated that approximately 4 to 6 lbs. of citric acid was used in the 300 gal tank to reach this pH.

4.2 2007 EUWP Retest

4.2.1 Task A: Raw Water Characterization

Two sets of grab samples were collected in August 2006 to characterize the raw water supply, and to determine if any regulated metals or VOCs were present and should be included in the final sampling plan. The results of these analyses are presented in Table 4-1. Based on these results, no metals or VOCs were added to the sampling plan.

4.2.2 Task B: Equipment Install and Initial Test Runs

A retest of the UF system was scheduled for July and August 2007, due to the problems with the seals and integrity of the UF system during the initial ETV test in 2006. The EUWP unit was delivered to Selfridge ANGB in July 2007 and the unit was prepared for the retest. The emphasis during this start-up period was on UF membrane integrity as measured by pressure decay tests on individual membranes and on the system as a whole.

The unit plumbing, electrical hook-ups, and pumping of raw water to the UF feed tank were completed in the same manner as for the first test. The retest was designed to test the UF system only, so no monitoring was planned or performed for the RO system. However, due to the system design, the RO feed water flow meter was needed to monitor the UF filtrate production and the RO pump was needed to move the filtrate from the intermediate holding tank. Therefore, the RO system was operated during the retest, but only to obtain flow data for the UF filtrate and to discharge water from the skid.

It was determined during the first test that ferric chloride coagulation was necessary to keep the UF system running smoothly. Therefore, the ferric chloride feed system and tanks were setup and prepared for operation. For the 2007 test, ferric chloride was used right from the start of the retest.

On July 18, 2007, the integrity of each UF membrane was individually checked by the measurement of pressure decay over a 10-min period. Thirteen of the sixteen membranes showed pressure decay in the range of 0.01 psig/min to 0.1 psig/min. Two membranes had high decay rates. Inspection of the membranes determined that there was one broken fiber in each membrane. The fibers were plugged and the membranes retested with both now showing pressure decays of less than 0.15 psig/min. These membranes were determined to be useable. The third leaking membrane had eight broken fibers and an end cap seal problem. Because of the large number of broken fibers, this membrane was removed from the system and it was decided to run the test with 15 membranes instead of the normal 16 membranes.

Full UF system pressure decay tests were performed on six days between July 21 and July 27. The full system pressure decay ranged from 0.02 to 0.1 psi/min. These results showed that the seal problems encountered in the 2006 test had been resolved and that fiber plugging for the two membranes was successful.

The start-up operation particle count and turbidity data (not shown) demonstrated that the UF system was functioning properly, so testing proceeded.

4.2.3 Task C: 2007 Verification Retest

The 2007 verification retest of the repaired UF system was started on July 30 and ended on August 24, 2007. The 2007 retest was stopped short of 30 days because the intent of the test as stated in the ETV test protocol – to operate until a membrane cleaning was conducted – was met. Both the UF and RO skids were operated for the 2007 retest, but ETV test data was only collected from the UF system.

The on-site operators collected operating data and on-site water quality samples twice per day in accordance with the test plan schedule. The following sections present the 2007 retest operating data and water quality data.

4.2.3.1 Task C1: Membrane Flux and Operation

The purpose of this task was to evaluate system performance during operation. The objectives of this task were to demonstrate the appropriate operational conditions for the system, the feed water recovery achieved by the UF membrane, and the rate of flux decline observed over the operation period.

Operational data were collected and on-site water quality measurements were made twice per day throughout both test periods, except for days when the UF was being cleaned and therefore not operating for a portion, or all, of the day. The RO system was not monitored

during the retest. The data were summarized for presentation and discussion in this section. The complete data set can be found in Appendix B.

The UF retest operational statistics are presented in Table 4-17. Feed water flow rate and retentate flow rate were measured directly by flow meters. The filtrate flow rate was calculated as the UF feed water flow rate minus the UF retentate flow rate. The intake flow was the intake from the source water into the UF feed water tank. The intake pump ran at a higher flow rate than the UF system to ensure that the UF feed water tank always contained sufficient water to operate the UF system.

Table 4-17. UF System Operational Measurement Statistics for 2007 Retest

Parameter	Count	Mean	Median	Minimum	Maximum	Standard Deviation	95% CI
UF Operation per day (hr)	25	13.8	14.3	4.0	21.5	4.6	± 1.8
Intake Flow (gpm)	44	288	296	235	303	16.2	± 4.8
Feed Flow (gpm)	45	232	237	174	271	19.7	± 5.7
Filtrate Flow (gpm)	45	206	212	148	245	19.6	5.7
Retentate Flow (gpm)	44	26	26	25	28	0.7	± 0.2
Backwash Flow (gpm)	Not measured – approximately 900 gal per backwash						
Feed Pressure (psig)	45	24	25	13	32	5.9	± 1.7
Retentate Pressure (psig)	45	22	23	11	31	5.8	± 1.7
Filtrate Temperature (°F)	45	74	75	62	84	5.3	± 1.6

As discussed in Section 4.2.2, the UF system was operated with only 15 modules during the 2007 test. The mean feed water flow rate of 232 gpm was similar to the 2006 test (mean of 246 gpm), and was somewhat below the design feed flow rate of 259 gpm specified in Table 3-2. The mean filtrate flow of 206 gpm was also lower than the 2006 test (mean of 220 gpm). Based on the mean flow rates, the mean water recovery for the UF system was 88.8%, which is close to the 2006 recovery of 89.5%. The 206 gpm mean filtrate flow corresponds to a 24-h production rate of 296,640 gpd. This filtrate production rate includes water used for backwashes. The stated UF design production rate is 250,000 gpd (not including backwash water). The backwash process used 900 gal of UF filtrate per event, and a backwash is conducted every 30 min. Therefore, for 24 h of operation, 48 backwashes would be conducted using a total of 43,200 gal of UF filtrate. Subtracting this volume from the calculated daily filtrate production volume of 296,640 gal leaves 253,440 gal of UF product water, which is similar to the design production volume 250,000 gpd.

The EUWP includes a totalizer to monitor the hours of UF system operation. The hours of operation during the retest varied widely, from 4 to 21.5 h. The retest was designed for the UF system to operate for a similar number of hours as the 2006 test. Typically the unit was operated over a 16-h period with downtime due to maintenance and cleaning. The mean hours of operation for the 25-day test were 13.8 h (2006 test mean was 15 h) with a median of 14.3 h.

Total UF filtrate production was also tracked using the RO feed totalizer. The total filtrate produced was 3,551,000 gal over 350.1 h of operation. This yields a mean useable UF filtrate production per hour of operation of 10.1 kgal. If the filtrate water used for backwashing the system is added (595,730 gal) to this production volume, then the mean total filtrate production per hour of operation is approximately 11.8 kgal. Figure 4-17 shows the cumulative filtrate production over the duration of the 2007 retest.

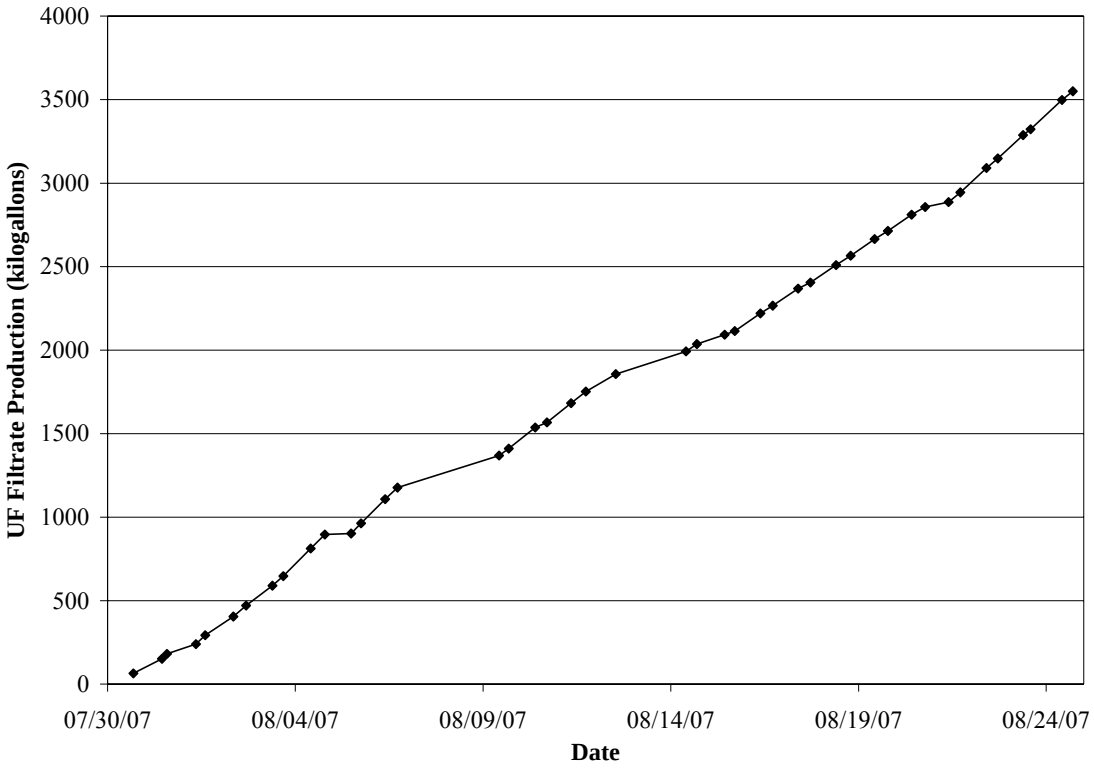


Figure 4-17. UF filtrate production for the 2007 retest.

Figure 4-18 shows the UF system flow rates over the duration of the retest. The retentate flow rate remained steady through the test. Figure 4-19 shows the feed and retentate pressures during the test and Figure 4-20 shows the calculated TMP results. After the first four days of operation (July 30 – August 2), the feed water pressure was increased in order to maintain the target flow rates for feed water and filtrate. TMP increased from <10 psig to 17 psig. Therefore, the UF system was shutdown for CIP. The system was cleaned on August 8 and put back into service. The TMP did not drop back to original operating conditions as expected, but did decrease slightly after several hours of operation from a high of 19 psig to a low of 16 psig.

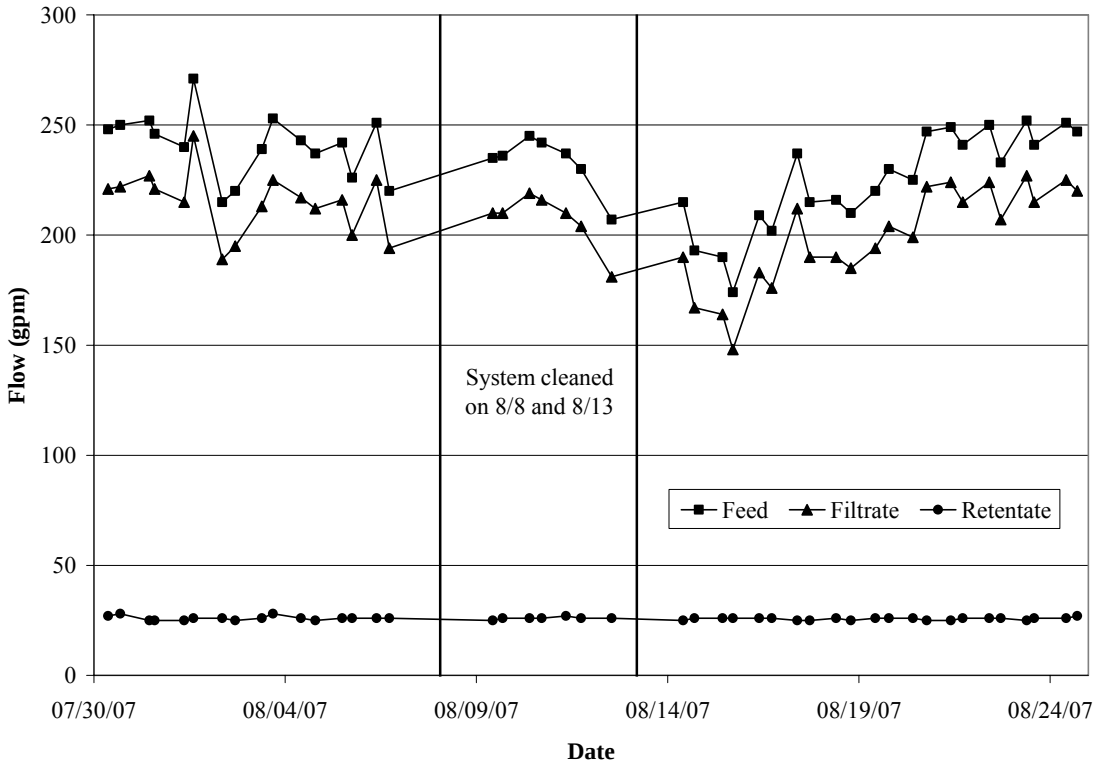


Figure 4-18. UF system flow rates for 2007 retest.

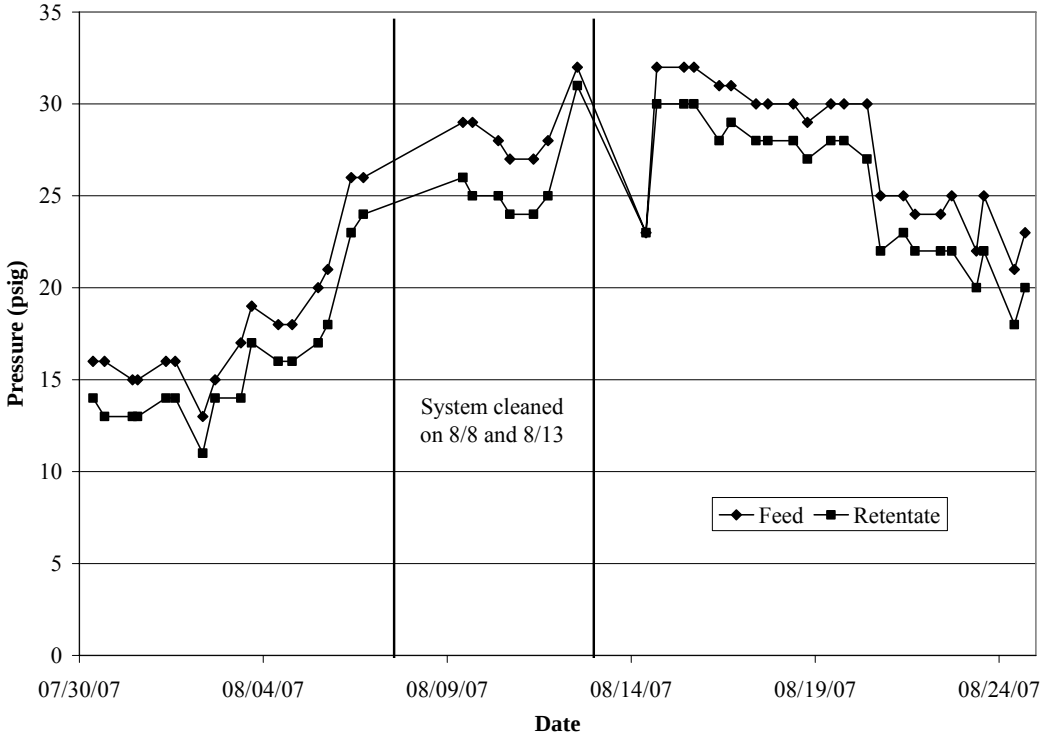


Figure 4-19. UF system feed and retentate pressures for 2007 retest.

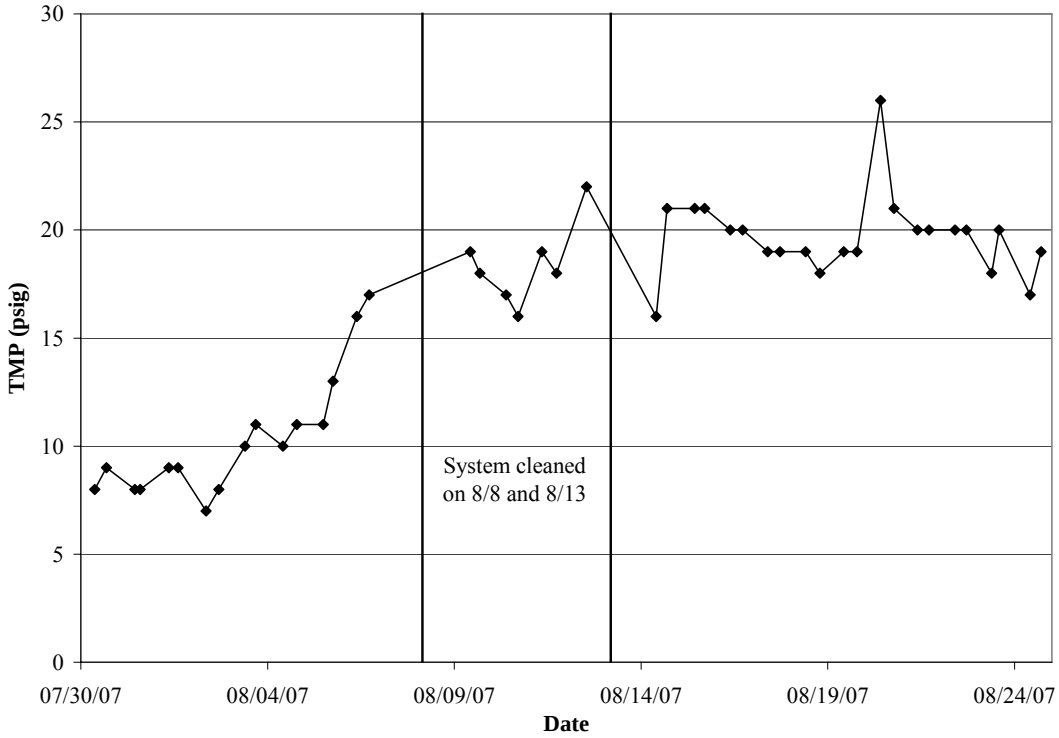


Figure 4-20. UF system TMP for 2007 retest.

The TMP increased again on August 12 to 19 psig and feed water pressure exceeded 30 psig to in order to maintain water flow rates. The UF was again shutdown and a chemical cleaning performed on August 13. This cleaning dropped the TMP back to 16 psig, but again the TMP was not as low as when the system was started on July 27. The feed water pressure increased again to over 30 psig on August 14 and TMP increased accordingly. It was decided to continue to operate the UF at the higher feed water pressure and TMP, as these pressures were still within the design specification and operating specification for the unit. As can be seen in Figure 4-19 and 4-20, the UF feed pressure remained steady for several days and was actually lower for the last week of the test. TMP remained fairly steady for the duration of the test.

Figure 4-21 shows the specific flux calculated for the UF system during the retest. The impact of solids buildup or some type of change in membrane filtrate capacity on the system is clear prior to the CIP performed on August 8. The CIP was successful in stabilizing the drop in specific flux (and increasing TMP discussed above), but did not result in returning the membrane to the specific flux attained at the beginning of the test. Following the second cleaning on August 13, the specific flux continued to drop for the next three days and then actually started to increase slightly over the remaining ten days of the test.

Figure 4-22 shows the loss of specific flux over the duration of the retest. The loss of specific flux is calculated by comparing the specific flux on a given day to the value

calculated at the start of the test. This type of data shows the impact of cleaning and backwash by comparing any given days specific flux to the start of the test. As can be seen, there was a steady loss of specific flux at the beginning of the test, but the CIP on August 8 and again in August 13 stabilized the loss of specific flux.

A chemical coagulant (ferric chloride) was used during the retest. During the initial test runs during the setup for the retest, jar tests showed a ferric chloride dose of 1 mg/L as Fe (a 12% Fe solution was fed at 10 mL/min for an intake flow rate of 300 gpm) should be the target feed rate. This feed rate was maintained until the rapid increase in TMP and drop in specific flux occurred. After the chemical cleaning on August 7 and 8, the ferric chloride feed rate was increased to 20 mL/min at the target intake flow rate of 300 gpm, yielding a dose rate of 2 mg/L as Fe. Subsequent jar test suggested that with the low turbidity in the source water the ferric chloride feed should actually be decreased. The ferric chloride feed was shut off on August 10 and remained off until the CIP was required on August 13. The rapid loss of flux and rise in TMP indicated that the coagulant should be used in the system, but at a lower dose than used at the start of the test. The ferric chloride feed was set at 0.2 mL/min (0.02 mg/L as Fe) and continued at that rate for the remainder of the test.

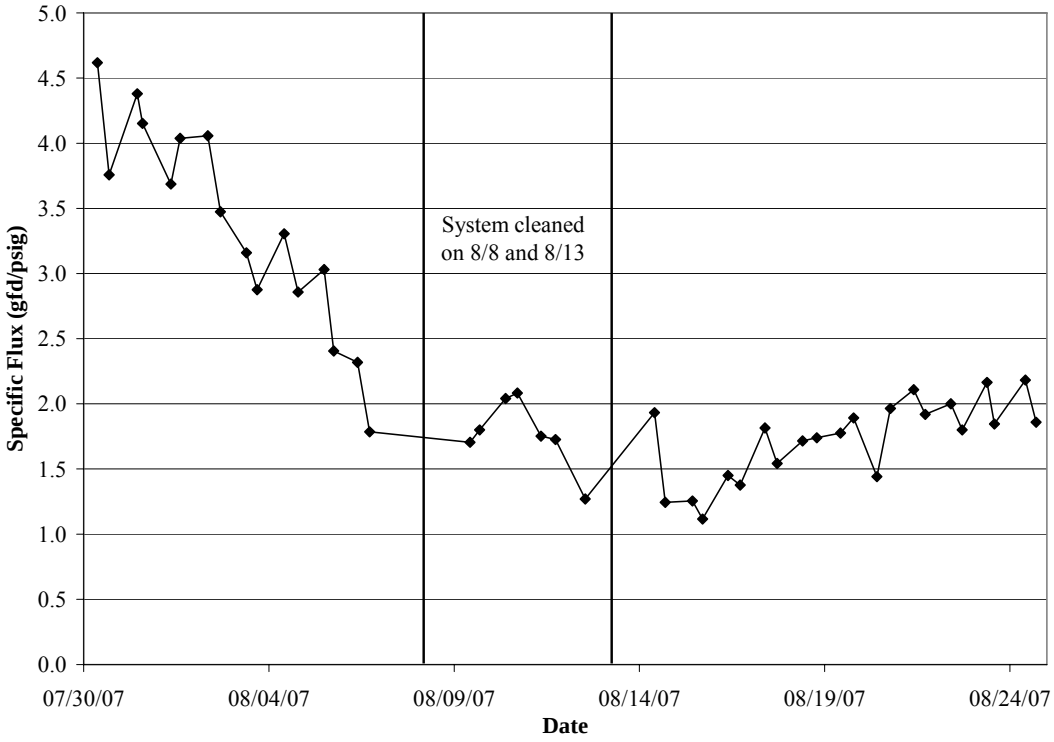


Figure 4-21. UF system specific flux for 2007 retest.

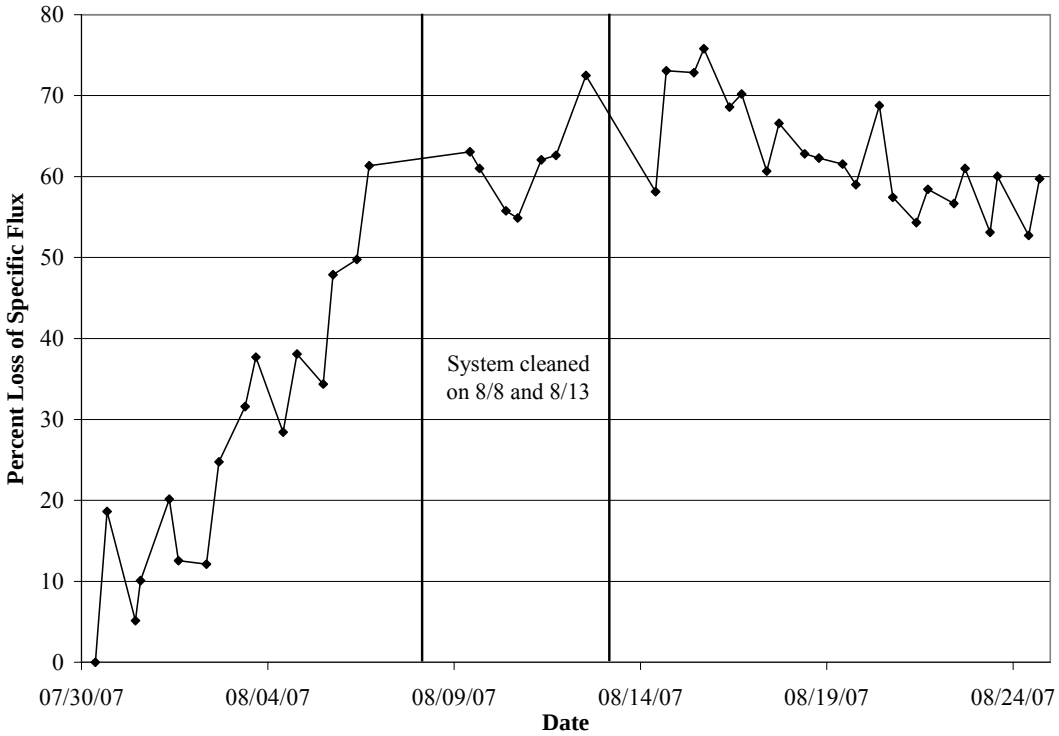


Figure 4-22. Loss of specific flux over time for 2007 retest.

The power use for the UF system was monitored by a power meter that was separate from the RO system. This provided power data specific to the UF system. Twice daily power readings were recorded by the operators. The power data was then combined with the hours of UF system operation to calculate the power used per hour of operation. The mean power consumption was 37 kWh per hour of operation with a median value of 37 kWh per hour of operation. The initial ETV test in 2006 had a mean power consumption of 39 kWh per hour of operation. Figure 4-23 shows the power consumption per hour of operation during the 2007 test.

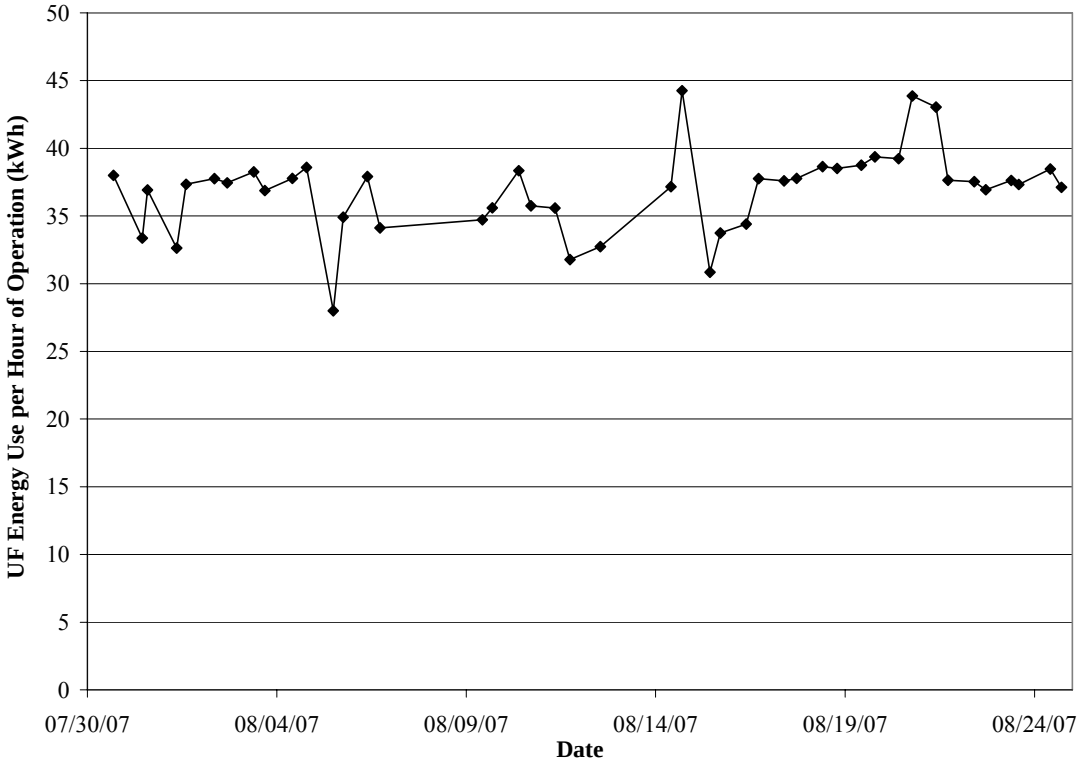


Figure 4-23. UF Power consumption per hour of operation for 2007 retest.

4.2.3.2 Task C2: Cleaning Efficiency

The objective of this task was to evaluate the membrane cleaning procedures and determine the fraction of specific flux restored following chemical cleaning.

4.2.3.2.1 UF Backwash and Cleaning Frequency and Performance

The automatic backwash system was operated on a 30-min cycle with 900 gal of filtrate used per backwash cycle, which was the same schedule and volume used for the initial verification test. The backwash volume represented approximately 15% of the filtrate produced during the 2007 retest, which was similar to the 2006 test when approximately 14% of the filtrate produced was used for backwash.
The TMP began to build quickly at the start of the retest and the specific flux dropped from 4.62 gfd/psig to 1.78 gfd/psig over the first seven days of the test.

A CIP was performed on August 8. Following the CIP, the measured specific flux was 1.71. and 1.78 gfd/psig on the next two readings. The CIP was not successful in restoring the membrane to the original specific flux of 4.62 gfd/psig. The TMP was in the range of 18-19 psig, which was just below the recommended 20 psig that would indicate a CIP was needed. The decision was made to continue operating and monitoring the change in TMP and specific flux. As discussed above, the ferric chloride feed was turned off on August 10.

On August 12, after four more days of operation, the TMP increased to 22 psig and the specific flux dropped to 1.27 gfd/psig. A second chemical cleaning was performed on August 13 in an attempt to restore the membrane productivity and lower the TMP. The CIP was only partially successful, as the specific flux after the cleaning was 1.93 gfd/psig and the TMP was lowered to 16 psig. This represents a minimal recovery of specific flux. After the August 13 cleaning, the ferric chloride feed was turned back on, but at a lower dose than used previously.

It is not known why the chemical cleaning was successful in the initial verification test, but was not able to restore the membranes to the original conditions during the retest. As shown in Figures 4-20, 4-21, and 4-22, the UF system did stabilize after the second cleaning and specific flux and TMP remained constant or actually increased slightly during operation after the second cleaning.

The amount of CIP chemical used, the pH of the solutions, and the temperatures were not recorded during this retest. Operators have indicated that the same procedures and chemicals were used, but this cannot be verified due to the lack of written records.

4.2.3.2.2 Total Organic Carbon Results for UF Cleaning Solutions

Samples of the cleaning solution for the UF system CIP were collected from two cleaning periods. These samples were analyzed for TOC as specified in the ETV Protocol and the Test Plan. The TOC results for the August 8, 2007 and August 13, 2007 UF system cleaning solutions are presented in Table 4-18. Note that no low pH solution sample was collected for the August 13, 2007 cleaning. The TOC was higher in the low pH solution. The used cleaning solution was acceptable for discharge to the sanitary sewer system at Selfridge ANB and was discharged to the sewer system after each cleaning cycle.

Table 4-18. UF Cleaning Solution TOC Results for 2007 Retest

Sample	Date	TOC (mg/L)
Low pH solution	8/08/07	750
High pH solution	8/08/07	160
High pH solution	8/13/07	48

4.2.3.3 Task C3: 2007 Water Quality Results

The primary objective of this task was to assess the ability of the membrane equipment to meet the water quality goals, which were established as producing water that meets EPA National Drinking Water Regulations. This section presents the water quality results for the 2007 verification retest. Data on the bacteriological samples and integrity testing are presented later in a separate section of this report.

Table 4-19 shows the daily turbidity results and the summary statistics for the verification test. Figures 4-24 and 4-25 present the grab sample turbidity readings for the UF feed and

Table 4-19. Turbidity Data for the 2007 Retest – Hand-Held Meter

	Turbidity (NTU)		
Date	**UF Feed**	**UF Filtrate**	**UF % Reduction**
07/30/07	0.7	<0.01	98.5
07/30/07	1.5	<0.01	99.3
07/31/07	1.6	<0.01	99.4
07/31/07	1.7	0.10	94.1
08/01/07	1.3	0.10	92.3
08/01/07	1.6	0.20	87.5
08/02/07	1.4	0.20	85.7
08/02/07	1.4	0.10	92.9
08/03/07	1.4	0.10	92.9
08/03/07	1.3	0.10	92.3
08/04/07	1.3	0.07	94.7
08/04/07	1.5	0.12	92.1
08/05/07	1.1	0.08	92.9
08/05/07	1.3	0.09	93.2
08/06/07	4.6	0.12	97.4
08/06/07	2.6	0.23	91.1
08/09/07	1.6	0.09	94.3
08/09/07	1.3	0.08	93.9
08/10/07	1.2	0.09	92.7
08/10/07	1.4	0.15	89.1
08/11/07	1.2	0.12	89.7
08/11/07	1.3	0.16	88.1
08/12/07	1.5	0.17	88.9
08/13/07	1.8	0.12	93.3
08/14/07	1.7	0.16	90.8
08/15/07	2.4	0.11	95.4
08/15/07	1.6	0.17	89.4
08/16/07	2.3	0.14	93.8
08/16/07	1.7	0.14	91.8
08/17/07	1.4	0.16	88.2
08/17/07	1.3	0.17	86.5
08/18/07	1.3	0.14	89.1
08/18/07	1.4	0.15	89.3
08/19/07	1.1	0.13	87.7
08/19/07	1.4	0.13	91.0
08/20/07	8.3	0.15	98.2
08/20/07	9.0	0.18	98.0
08/21/07	5.5	0.17	96.9
08/21/07	5.2	0.24	95.4
08/22/07	3.0	0.20	93.2
08/22/07	4.9	0.51	89.6
08/23/07	3.3	0.20	93.9
08/23/07	3.4	0.23	93.2
08/24/07	2.7	0.10	96.3
08/24/07	1.7	0.25	85.5
Mean:	2.3	0.14	92.5
Median:	1.5	0.14	92.9
Minimum:	0.7	<0.01	85.5
Maximum:	9.0	0.51	100
Std. Dev.:	1.8	0.08	3.8
95% CI:	±0.5	±0.02	±1.1

filtrate over the duration of the retest. Note that there is no data for August 7 and 8 because the UF system was shut down for cleaning. The UF system reduced the turbidity from a mean of 2.3 NTU in the feed water to a mean of 0.14 NTU in the UF filtrate. The filtrate turbidity 95% confidence interval is 0.12 NTU to 0.16 NTU. Note that despite the UF system integrity issues during the 2006 test, as discussed in Chapter 4, the 2006 mean filtrate turbidity and 95% confidence interval were the same as for the 2007 test. Turbidity in the feed water was reduced by a mean value of 92.5%, with a median reduction of 92.9% through the UF system. There were two spikes in the feed water turbidity – on August 6, and from August 20 to 22. Both spikes were likely caused by rain events on these days. These feed water turbidity spikes did cause small increases in the filtrate turbidity, but only one measurement – 0.51 NTU on August 22 – was above 0.3 NTU. Therefore, the UF system also met the NPDWR turbidity requirements during the 2007 retest.

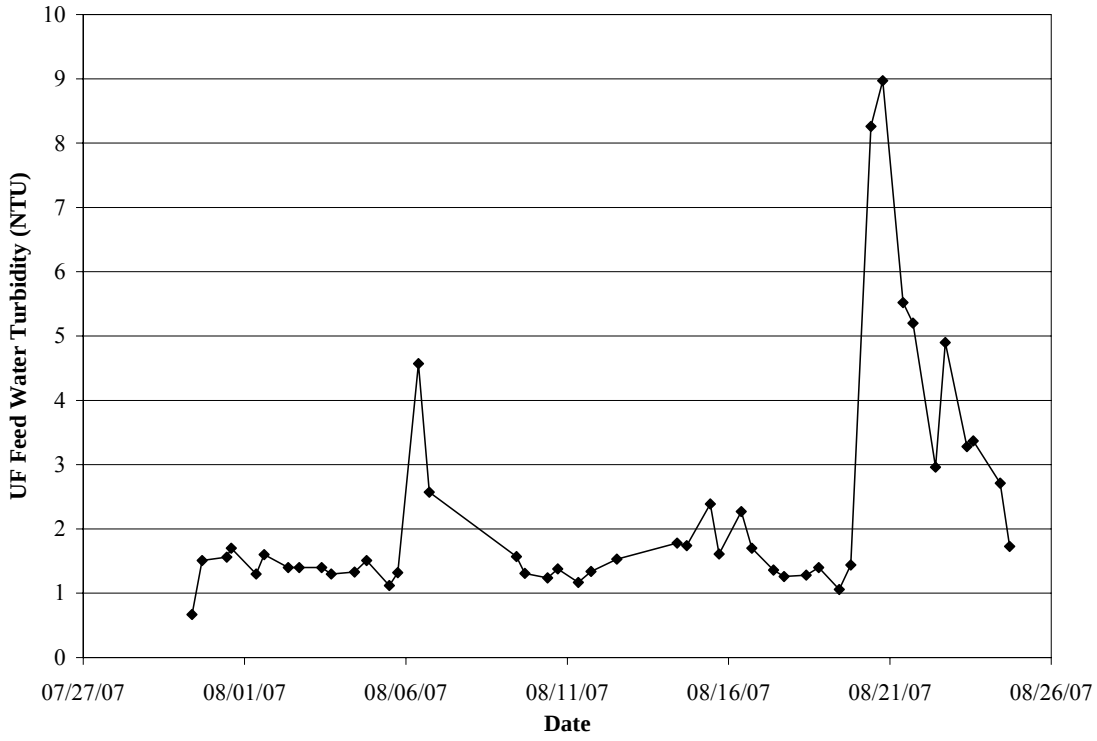


Figure 4-24. UF feed turbidity for the 2007 retest.

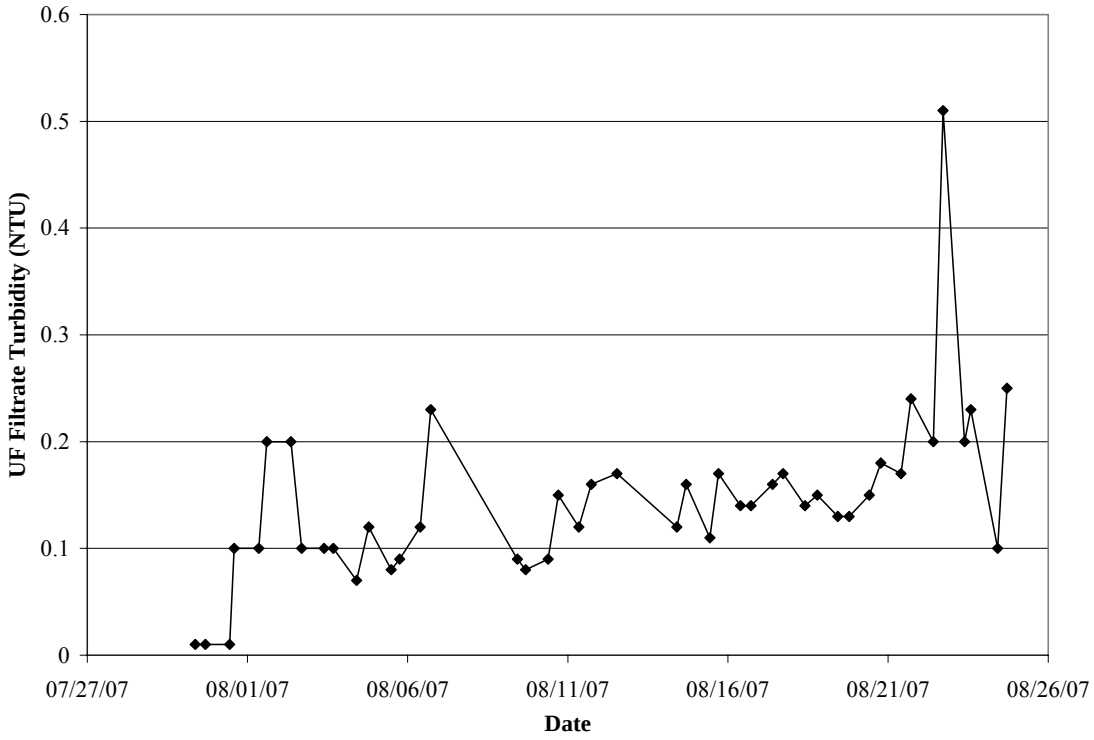


Figure 4-25. UF filtrate turbidity for the 2007 retest.

The in-line turbidimeter readings for the 2007 retest can be used to evaluate water quality because the date and time were properly set. However, the in-line turbidity readings only span from July 30 to August 21. The computer used to log the data crashed on August 21, and was not replaced for the last three days of the test. Figure 4-26 graphically shows the UF feed and filtrate in-line turbidity readings. Note that there are two y-axes in the graph, one for the feed and one for the filtrate. Also note that there are two large gaps in the data, corresponding to UF system cleanings, and a few smaller gaps when the system automatically shut down overnight. The first cleaning was on August 7 and 8, and the second cleaning was on August 13. The summary statistics for the UF feed and UF filtrate in-line turbidity measurements are shown in Table 4-20. The mean UF filtrate turbidity is 0.019 NTU, and the maximum recorded turbidity is 0.236 NTU. At no point did two consecutive measurements exceed the 0.15 NTU value that would have required the system to be taken off-line for a direct integrity test.

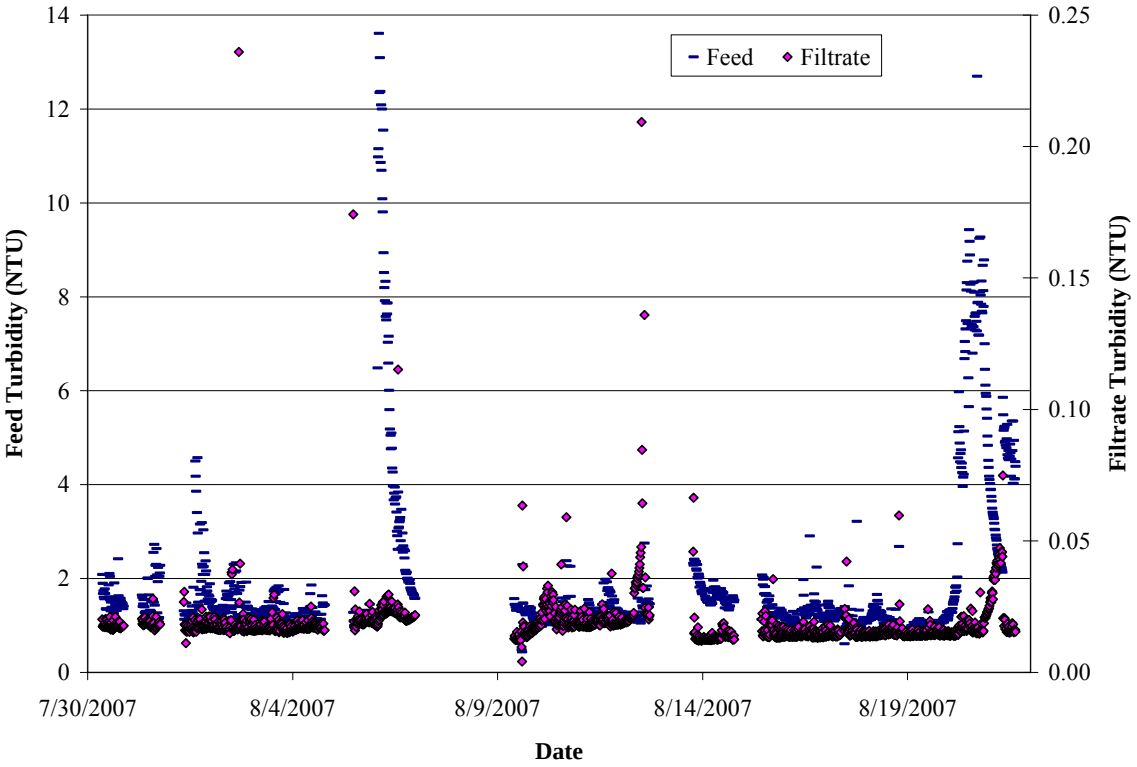


Figure 4-26. UF feed and filtrate in-line turbidity readings for the 2007 retest.

Table 4-20. In-Line Turbidity Measurement Statistics for the 2007 Retest

	UF Feed (NTU)	UF Filtrate (NTU)
Mean:	1.89	0.019
Median:	1.29	0.017
Minimum:	0.433	0.004
Maximum:	13.61	0.236
Count:	1568	1568
Std. Dev.:	1.75	0.011
95% CI:	±0.087	±0.001

Table 4-21 shows the conductivity results for the UF and the summary statistics for the retest. Because the RO system reduced the dissolved ions in the water in the 2006 test, it was not monitored during this retest. As expected, there was no change in conductivity levels in the UF treated water.

Table 4-21 also presents the pH and temperature data collected from the UF system. The pH in the filtrate ranged from 7.3 to 9.0 and was in the same range as the feed water.

Table 4-21. Conductivity, pH, and Temperature Data for the 2007 Retest

	pH		Conductivity (µS/cm)		Temperature (°C)	
Date	UF Feed	UF Filtrate	UF Feed	UF Filtrate	UF Feed	UF Filtrate
07/30/07	8.15	8.22	271	275	25.1	26.2
07/30/07	9.15	8.94	294	296	27.5	27.7
07/31/07	8.08	7.87	300	299	32.2	29.1
07/31/07	8.55	8.46	312	298	34.2	30.1
08/01/07	8.54	8.12	308	310	26.3	27.0
08/01/07	8.89	8.65	325	317	36.8	30.1
08/02/07	8.40	7.94	340	312	28.1	28.0
08/02/07	9.01	8.82	297	299	33.4	30.5
08/03/07	8.71	8.27	310	313	29.1	28.9
08/03/07	8.98	8.90	295	295	29.7	30.8
08/04/07	8.19	7.67	332	334	26.6	27.4
08/04/07	9.48	9.02	250	256	27.8	27.5
08/05/07	8.33	8.30	302	305	24.3	24.5
08/05/07	8.15	7.52	368	372	24.1	24.8
08/06/07	7.61	7.47	238	239	23.7	23.8
08/06/07	8.63	7.91	253	248	29.4	27.2
08/09/07	7.99	7.31	260	265	25.8	25.6
08/09/07	7.99	7.49	294	296	25.5	25.4
08/10/07	7.56	7.37	337	340	25.2	25.3
08/10/07	8.35	8.36	329	327	28.9	27.2
08/11/07	7.34	7.67	336	330	25.3	25.0
08/11/07	8.67	8.69	329	330	29.2	27.7
08/12/07	7.85	7.64	345	349	27.3	26.7
08/13/07	7.92	7.94	337	336	24.1	24.3
08/14/07	8.17	8.24	355	348	27.3	26.9
08/15/07	7.68	7.45	388	384	27.0	25.9
08/15/07	8.23	7.86	361	368	24.8	25.0
08/16/07	7.60	7.36	385	386	27.4	25.4
08/16/07	8.47	7.91	348	356	26.8	26.6
08/17/07	7.55	7.47	383	389	24.7	24.9
08/17/07	8.05	7.79	414	401	27.4	25.9
08/18/07	7.58	7.52	403	399	23.4	22.9
08/18/07	7.86	7.77	413	405	22.1	22.7
08/19/07	7.65	7.43	428	429	20.7	19.8
08/19/07	7.56	7.45	446	447	19.6	20.1
08/20/07	7.02	7.31	387	156	17.3	17.6
08/20/07	9.13	8.05	214	213	18.2	18.3
08/21/07	8.76	8.01	259	263	19.0	18.8
08/21/07	8.85	8.29	397	357	22.1	20.9
08/22/07	8.04	7.68	365	368	21.5	20.8
08/22/07	8.52	7.53	312	304	25.1	22.6
08/23/07	7.69	7.49	434	436	21.7	21.7
08/23/07	8.17	7.71	426	427	NM	27.8
08/24/07	7.85	7.53	296	299	25.3	24.6
08/24/07	8.76	7.79	285	290	27.3	25.7
Mean:	8.22	7.92	335	328	25.9	25.2
Median:	8.17	7.79	332	327	25.7	25.6
Minimum:	7.02	7.31	214	156	17.3	17.6
Maximum:	9.48	9.02	446	447	36.8	30.8
Std. Dev.:	0.55	0.48	57	61	4.0	3.3
95% CI:	0.16	0.14	17	18	1.2	1.0

The UF treatment had no effect on the temperature of the water as it passed through the system. Water temperature in the lake feed water at the beginning of the test was in the 25 to 30 ^{o}C range and dropped during the test to 20 to 25 ^{o}C by the end of the test in late August. Temperature variation and impact on membrane operating production (flux and specific flux) were accounted for in the operating section by standardizing the data to 20 ^{o}C, as described in Section 3.9.1.3. The temperature data in Table 4-21 served as the basis for the temperature adjustment calculations.

Table 4-22 presents the other water quality data collected on a weekly basis during the retest. The UF system removed suspended material as shown by the TSS concentration in the filtrate, which was always below the detection limit of 2 mg/L. These data support the daily turbidity results showing over 92% reduction in turbidity. The 2006 test results also showed the TSS in the filtrate was always less than 2 mg/L. The UF system did not change the other water quality parameters, as would be expected. These other parameters, such as hardness, alkalinity, TDS, etc. primarily represent dissolved inorganic constituents that are not removed by physical filtration.

The UF system showed minor reduction in organic material as measured by TOC. The feed water, filtrate, and retentate all showed TOC concentrations within a range of 2.0 to 3.4 mg/L. The filtrate typically showed a 0.0 to 0.8 mg/L reduction in TOC compared to the feed water, and the retentate occasionally showed an increase in TOC of 0.5 mg/L compared to the feed water. These data would indicate that most of the organic material, as measured by the TOC test, was dissolved in the feed water.

Table 4-22. Other Water Quality Data for the 2007 Retest

	TSS (mg/L)			
Date	**UF Feed**	**Filtrate**	**Retentate**	**Backwash**
7/30/07	3	ND (2)	6	20
8/10/07	ND (2)	ND (2)	10	50
8/15/07	ND (2)	ND (2)	ND (2)	ND (4)
8/22/07	3	ND (2)	10	40

	TOC (mg/L)			
Date	**UF Feed**	**Filtrate**	**Retentate**	**Backwash**
7/30/07	2.8	2.4	2.8	NM
8/10/07	2.8	2.0	3.3	NM
8/15/07	3.0	3.1	2.7	3.1
8/22/07	2.9	2.5	3.4	2.6

	Hardness (mg/L as $CaCO_3$)		Alkalinity (mg/L as $CaCO_3$)	
Date	**UF Feed**	**Filtrate**	**Feed Water**	**Filtrate**
7/30/07	95	95	69	66
8/10/07	88	87	150	140
8/15/07	110	110	210	210
8/22/07	74	72	70	63

Table 4-22. Other Water Quality Data for the 2007 Retest (continued)

Date	TDS (mg/L) UF Feed	Filtrate	Backwash
7/30/07	170	160	NM
8/10/07	150	140	NM
8/15/07	210	210	NM
8/22/07	200	170	190

Date	UV 254 (absorbance/mL) UF Feed	Filtrate
7/30/07	NM	0.051
8/10/07	0.08	0.0439
8/15/07	0.0904	0.0611
8/22/07	0.141	0.090

NM – not measured

4.2.3.4 Task C4: 2007 Membrane Module Integrity

The objective of this task was to demonstrate methodology for direct integrity testing and indirect integrity monitoring of the UF membranes. Pressure decay tests were used to document UF membrane integrity.

4.2.3.4.1 UF System Pressure Decay and Microbial Reduction Results – 2007 Retest

As discussed in Chapter 4, following the 2006 test, the UF seal integrity problem was addressed, and a retest was scheduled for 2007.

Prior to starting the retest, each membrane cartridge was individually tested as discussed in Section 4.2.2, and several were found to have broken fibers that required plugging. After plugging these fibers, each cartridge was again pressure tested. The results showed that 15 of the 16 modules were acceptable, so TARDEC and USBR decided to run the test with only 15 membranes. A full system pressure decay test was run on July 23, and the pressure decay rate was calculated as 0.025 psig/min. This value was more than ten times lower than the mean value of 0.29 psig/min obtained during the 2006 verification test.

For the 2007 test, pressure decay tests were again conducted daily. The results of these tests are shown in Table 4-23. The pressure decay rates were 5- 10 times lower than those from the 2006 test, with a mean value of 0.025 psig/min and a median value of 0.017 psig/min. These pressure decay rates were also lower than those measured during the laboratory tests. Figure 4-27 shows the pressure decay results graphically.

Table 4-23. Pressure Decay Results for UF System for the 2007 Retest

Date	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	Decay (psig/min)
7/30/2007	15.1	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	NM(1)	0.018
7/31/2007	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	NM	0.000
8/1/2007	15.2	15.1	15.0	14.9	14.9	14.8	14.7	14.7	14.6	14.5	14.5	14.4	14.4	14.4	14.3	14.3	14.3	0.075
8/2/2007	15.2	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	0.008
8/3/2007	15.2	15.1	15.1	15.1	15.1	15.1	15.0	15.0	15.0	14.9	14.9	14.9	14.8	14.7	14.7	14.7	14.7	0.042
8/4/2007	15.1	15.1	15.1	15.1	15.1	15.0	15.0	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.017
8/5/2007	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.008
8/6/2007	15.1	15.1	15.1	15.1	15.1	15.0	15.0	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.017
8/9/2007	15.1	15.1	15.1	15.1	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.8	14.8	0.025
8/10/2007	15.1	15.1	15.1	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.8	14.8	14.7	14.7	0.033
8/11/2007	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.8	14.8	14.7	14.7	14.7	14.7	14.7	14.7	0.025
8/12/2007	15.1	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.017
8/14/2007	15.1	15.1	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.8	14.7	14.7	14.7	14.7	14.7	14.6	0.033
8/15/2007	15.1	15.1	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.8	14.7	14.7	14.7	14.7	14.7	0.033
8/16/2007	15.1	15.0	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.017
8/17/2007	15.1	15.1	15.1	15.0	15.0	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.017
8/18/2007	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.008
8/19/2007	15.1	15.1	15.1	15.0	14.9	14.9	14.9	14.9	14.7	14.7	14.6	14.6	14.5	14.5	14.4	14.4	14.3	0.058
8/20/2007	15.1	15.0	15.0	14.9	14.9	14.8	14.7	14.7	14.7	14.6	14.5	14.5	14.5	14.4	14.4	14.4	14.3	0.058
8/21/2007	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.008
8/22/2007	15.1	15.1	15.1	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.8	14.8	14.7	14.7	14.7	14.7	14.6	0.033
8/23/2007	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	0.008
8/24/2007	15.1	15.1	15.0	15.0	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	0.017
																	Minimum	0.000
																	Maximum	0.075
																	Mean	0.025
																	Median	0.017
																	95% Confidence Interval	± 0.008

(1) NM = not measured

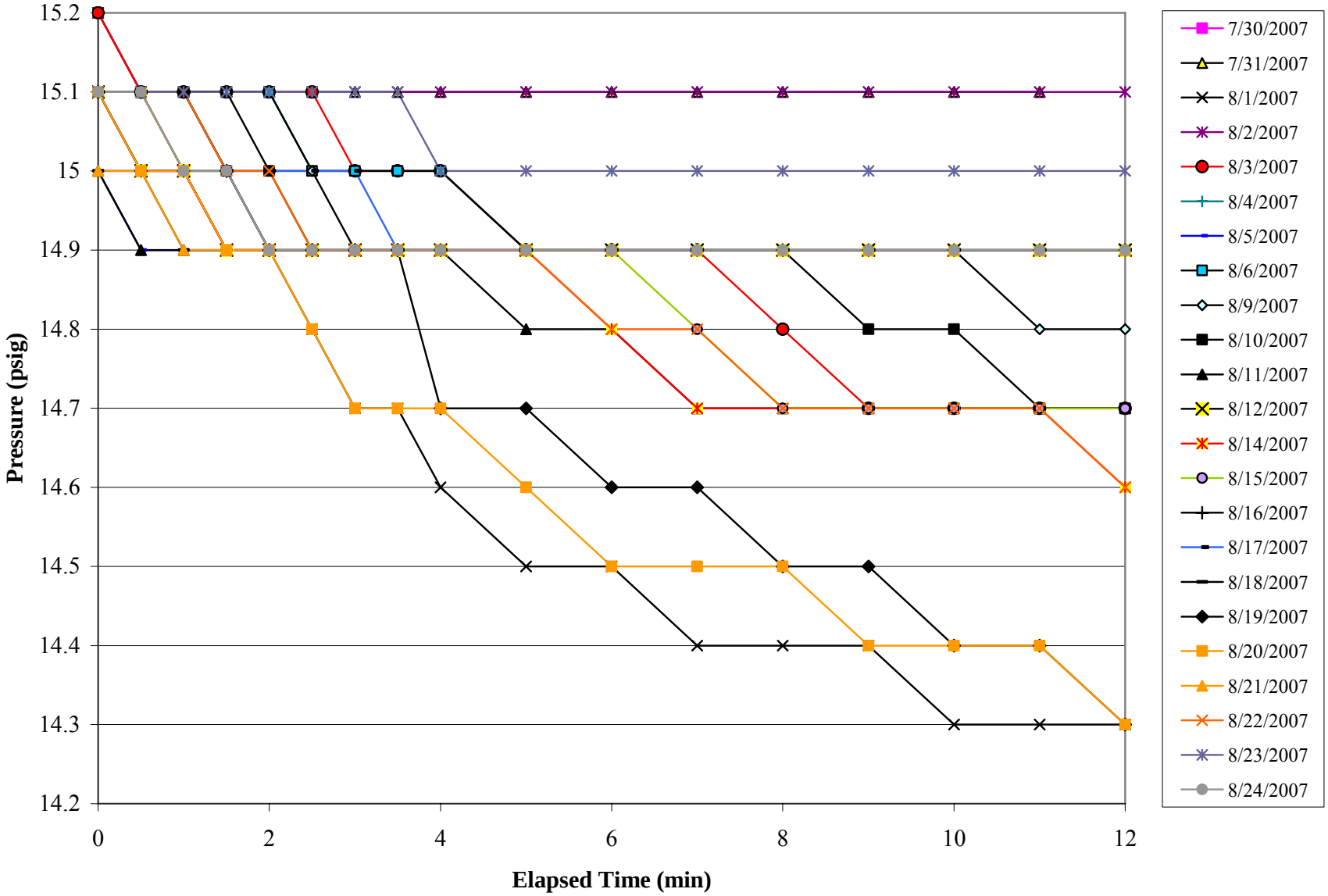


Figure 4-27. Pressure Decay Results for the 2007 Retest.

For the 2007 test, *Bacillus* endospores were substituted for HPC and total coliform. This change was made for the following reasons:

- Expected higher concentrations would allow better measurement for log reductions (note actual concentrations were not as high as expected);
- Good size range to represent bacteria and challenge the membrane (0.8 micron x 1.8 micron);
- Almost no potential for growth in piping and equipment as compared to HPC;
- Less sensitive to temperature during shipment to laboratory; and
- Can be easily used in laboratory tests for comparison.

The *Bacillus* endospores data are shown in Table 4-24. Figure 4-28 shows the results over the duration of the retest. The log reductions measured had a mean value of 0.88 log_{10} with a range of 0.07 to 1.74 log_{10}. These observed reductions were lower than predicted from an integral UF membrane, and the prior lab challenge data discussed in Section 4.1.3.4.1. It is possible that there was endospore contamination on the filtrate side of the membranes, given the previous membrane integrity problems, or that there were continuing membrane integrity issues.

Table 4-24. *Bacillus* Endospores – 2007 Retest

	***Bacillus* Endospores (CFU/100 mL)**				
Date	**Feed Water**	**UF Filtrate**	**Log Reduction**	**UF Retentate**	**UF Backwash**
7/30/2007	1,224	165	0.87	1,124	644
7/31/2007	874	217	0.61	769	NM
8/1/2007	880	206	0.63	1,021	NM
8/2/2007	862	142	0.78	833	NM
8/6/2007	1,262	184	0.84	1,704	NM
8/9/2007	1,276	134	0.98	2,024	NM
8/9/2007	1,540	144	1.03	1,725	6,954
8/14/2007	1,159	996	0.07	1,308	4,010
8/15/2007	1,504	413	0.56	1,690	NM
8/15/2007	1,063	231	0.66	1,106	NM
8/16/2007	1,269	323	0.59	1,787	NM
8/16/2008	1,258	228	0.74	1,700	NM
8/20/2008	6,360	359	1.25	7,820	NM
8/21/2008	7,420	134	1.74	9,120	10,660
8/22/2008	1,691	98	1.24	3,514	NM
8/23/2008	2,122	78	1.43	4,199	NM
Geometric Mean:	1,562	203	0.88	1,823	NA
Minimum:	862	78	0.07	769	NA
Maximum:	7,420	996	1.74	9,120	NA

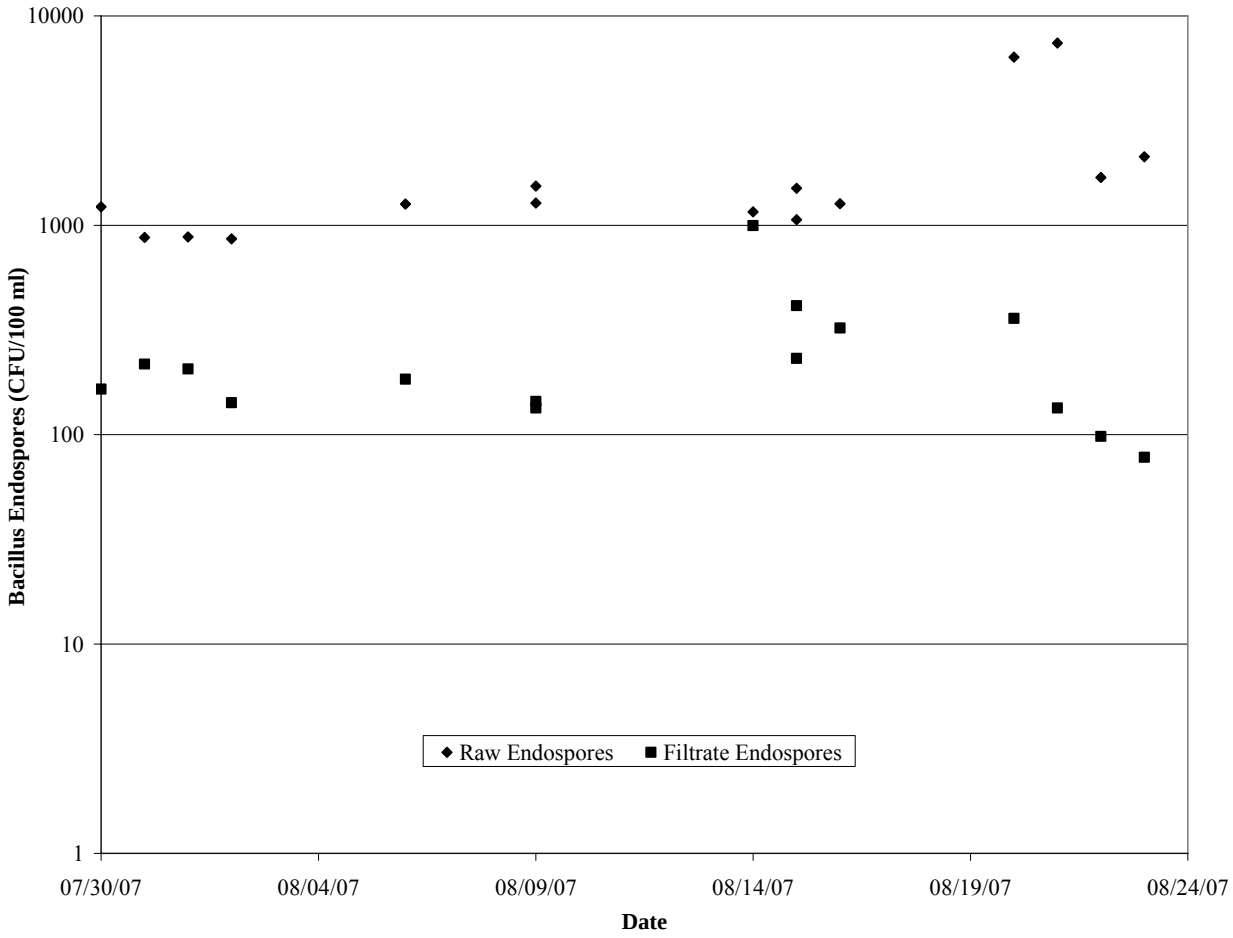


Figure 4-28. *Bacillus* endospores results for the 2007 retest.

4.2.3.4.2 *UF System Particle Count Data – 2007 Retest*

The in-line particle counters were calibrated properly for the 2007 retest, so the data is reported herein. These counters measured the particle counts in the UF feed and UF filtrate every five minutes, and stored the data for transfer to a personal computer. Particle count data can be helpful in evaluating the integrity and performance of membrane systems and in predicting the reduction/rejection of microbial contaminants.

The particle count data was condensed from five-minute increments to one-hour averages for graphical presentation. The data were separated to provide information on various size ranges (e.g. 2-3 µm, 3-5 µm), as these sizes correspond to the sizes of various microbial contaminants of interest in drinking water, such as *Cryptosporidium* (3 to 5 µm).

Figure 4-29 displays the feed and filtrate 2-3 µm particle counts, while Figure 4-30 shows the 3-5 µm particle counts.

Some notes about these figures and the particle count data presented:

- The y-axis of both graphs is in logarithmic scale.
- There is no particle count data for the first two days, and last three days of testing. The particle count data supplied by the field operators begins at 8:30 a.m. on August 1. The data ends at 3:35 p.m. on August 21 because the computer logging the data crashed.
- As with the 2007 turbidity data, there is no data for August 7 and 8, and from the afternoon of August 12 to the afternoon of August 13, because the UF system was shut down for cleaning.
- There were numerous other smaller gaps in the data, representing when the UF system was shut down for the daily pressure decay tests, or other reasons.
- There were numerous single time point spikes that were likely due to the automatic backwashes executed every half hour.

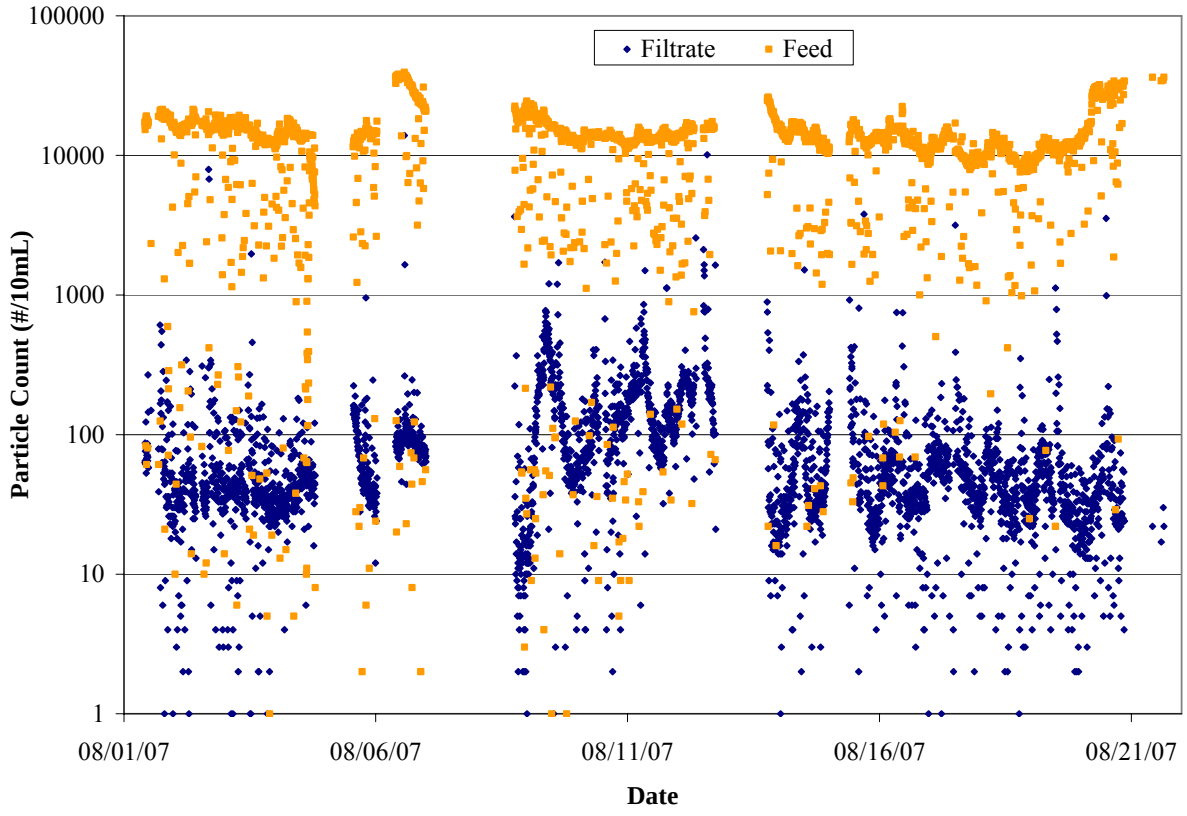


Figure 4-29. 2-3 µm particle counts for the 2007 retest.

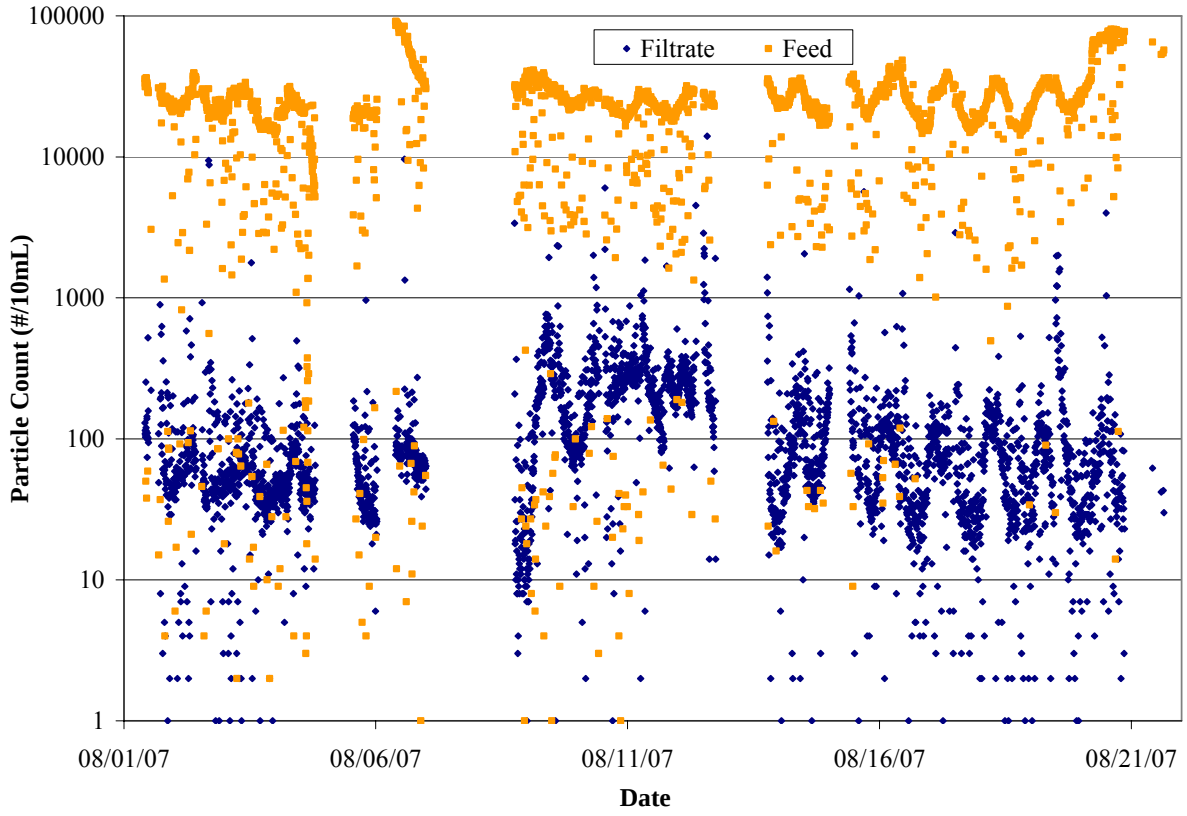


Figure 4-30. 3-5 µm particle counts for the 2007 retest.

The mean 2-3 µm particle count for the feed water was 13,376/10mL with a median value of 13,395/10mL. The range of particle counts for the feed water was 0-39,418/10mL. The filtrate had a mean particle count in the 2-3 µm size of 112/10mL with a median of 55/10mL and a range of 0-13,908/10mL. Note that these statistics are based on the individual counts, not the hourly averages calculated for the graphs.

The UF system goes through a backflush cycle every half-hour. During these backflushes, the particle counters are still working, so the raw particle count data includes numerous spikes in the counts, presumably because the counts were taken during backflushes. Therefore, the maximum filtrate particle count of 13,908 may not be indicative of the performance of the UF system under operation. As evidenced by the low mean filtrate count, the vast majority of the counts were less than 200/10mL. Of 3,408 2-3 µm counts used for this analysis, only 371 were >200/10mL, 67 were >500/10mL, and 25 were >1,000/10mL. The UF system reduced the 2-3 µm particles by a mean value of 2.21 log $_{10}$ with a median reduction value of 2.38 $\log_{10}$. However, there were many instances where the log reduction was negative because the feed count was lower than the filtrate count. If these negative log reductions are removed from the average log reduction calculations, the mean increases to 2.30 $\log_{10}$, and the median is 2.39 $\log_{10}$.

The mean 3-5 µm particle count for the feed water was 24,634/10mL with a median value of 23,605/10mL. The range of particle counts for the feed water was from 0-91,595/10mL. The

filtrate had a mean 3-5 µm particle count of 157/10mL with a median of 77/10mL and a range of 0-14,059/10mL. As with the 2-3 µm data, these statistics are based on the individual measurements, not the hourly averages. Of the 3,395 3-5 µm counts, 670 were >200/10mL, 127 were >500/10mL, and 45 were >1,000/10mL. As with the 2-3 µm maximum count, the 3-5 µm maximum count of 14,059 may not be indicative of UF performance due to particle count data being collected during the backflushes. The UF system reduced the 3-5 µm particles by a mean value of 2.33 $\log_{10}$ with a median reduction value of 2.52 $\log_{10}$. If the negative log reduction calculations are removed from the calculations, the mean is 2.45 $\log_{10}$, and the median is 2.54 $\log_{10}$

As can be seen, the UF system reduced the particle count in these size ranges. The observed reduction of particulate matter supports the pressure decay test data in showing that the UF system maintained integrity throughout the test. Further, a 2.4 $\log_{10}$ reduction would tend to predict a similar or larger reduction in equal and larger size microbial contaminants. Combined with the pressure decay test, these results would tend to support that the UF system should give 2-3 $\log_{10}$ control of these contaminants.

Unfortunately, the direct measurement of *Bacillus* endospores does not, and could not confirm these indicator tests of UF system performance for microbial contaminants.

4.2.3.4.3 Correlation of Membrane Integrity Indicators

As discussed with the presentation of the turbidity data for the 2007 retest in Section 4.2.3.3.1, although the UF system membrane integrity issues from the 2006 test were resolved, the 2007 hand-held turbidimeter data did not indicate improved membrane performance. Both the 2006 and 2007 tests had mean UF filtrate turbidities of 0.14 NTU, with 95% confidence intervals of ± 0.02. However, this may just be an issue of the sensitivity of the meter.

For both the 2006 and 2007 tests, the highest UF filtrate turbidity readings were associated with increased turbidity in the UF feed water due to rain events. The turbidity, particle count, bacteria, and pressure decay test data collected during these events can be compared to look for any correlations.

A rain event occurred during the 2007 retest on August 20 to 22. The feed water turbidity did not increase as high during this rain event, but examining this event is useful because there is particle count data and inline turbidity data, although this data is only available through the afternoon of August 21 due to the crash of the data logging computer.

Table 4-25 presents the turbidity data from this time period, and the corresponding Bacillus endospores data, pressure decay test results, and recorded transmembrane pressure readings. Also included for comparison are the averages for each parameter over the course of the test. The feedwater turbidity peaked at 9.0 NTU on August 20, but the filtrate turbidity peaked on the afternoon of August 22. Unfortunately the in-line turbidimeters were off-line by this point, so these readings cannot be correlated with the in-line turbidity readings at the same time. On August 20 and 21, the *Bacillus* endospore and 2-3 µm particle counts were also significantly above average. The August 20 filtrate endospore count was significantly higher than the average for the test, but on August 21, the filtrate endospore count was below average. The filtrate 2-3

µm particle counts on August 20 and 21 do not indicate any membrane integrity issues. The August 20 pressure decay rate was significantly above the average, but it was then significantly below average on the 21st. The TMP spiked up to 26 psig on the morning of August 20, but then it was back down to 21 psig in the early evening. The filtrate turbidity reading of 0.51 NTU on August 22 was significantly above the mean for the test. However, the *Bacillus* endospores and pressure decay test data for August 22 do not indicate any membrane integrity issues. The weekly water chemistry samples were collected on August 22, the results of which are displayed in Table 4-22. The filtrate TOC was 2.5 mg/L, which is in the middle of the range of filtrate values for the test. The feed and filtrate UV_{254} absorbance results were 0.141 and 0.090 respectively, both of which were the highest values measured during the test.

Table 4-25. UF Membrane Integrity Indicators for August 19, 2007 to August 23, 2007

		Benchtop Turbidity (NTU)		In-Line Turbidity[2] (NTU)		*Bacillus* Endospores (CFU/100 mL)		2-3 µm Particle Counts[2] (#/mL)		Pressure Decay	TMP
Date	**Time[1]**	**Feed**	**Filtrate**	**Feed**	**Filtrate**	**Feed**	**Filtrate**	**Feed**	**Filtrate**	**(psig/min)**	**(psig)**
8/19	18:50	1.4	0.13	1.04	0.015	NM	NM	1,192	2.1	0.058	19
8/20	09:54	8.3	0.15	6.97	0.017	6360	359	2,712	8.6	0.058	26
8/20	18:37	9.0	0.18	8.31	0.019			3,405	0.4		21
8/21	09:40	5.5	0.17	4.88	0.017	7420	134	3,633	2.2	0.008	20
8/21	17:07	5.2	0.24	4.39	0.016			3,627	2.2		20
8/22	09:50	3.0	0.20	NM	NM	1691	98	NM	NM	0.033	20
8/22	17:05	4.9	0.51	NM	NM			NM	NM		20
8/23	09:15	3.3	0.20	NM	NM	2122	78	NM	NM	0.008	18
Average ± 95% Confidence Interval[3]:		2.3 ± 0.5	0.14 ± 0.02	1.89 ± 0.087	0.019 ± 0.001	1,562 ± 1,113	203 ± 125	1,338 ± 25.3	11.2 ± 1.3	0.025 ± 0.008	16 ± 1.5

(1) Time of turbidity and TMP readings as part of the twice per day on-site data collection.
(2) Representative turbidity and particle count recordings from time closest to the time in column two.
(3) Averages are for all data over the course of the test, not just the data presented here.

4.2.4 2007 Chemical Consumption

During the 2007 retest, ferric chloride (12% Fe) was fed to the UF intake water at an initial rate of 10 ml/min or approximately 0.16 gal per operating hour. This dosing rate gave a coagulant concentration of approximately 1 mg/L as Fe in the intake water. After the August 6-9 period when TMP was increasing quickly, it was initially decided to double the feed rate and then, based on jar tests, to shutoff the ferric chloride feed. Subsequently, on August 15, after several jar tests, it was shown that a lower dose of ferric chloride would be effective. The ferric chloride was turned back on at a rate of 0.2 ml/min or 0.003 gal/h, which gave an iron dose rate of approximately 0.02 mg/L. The amount of iron used at the low dose rate would correspond to approximately 5 mg of Fe per 1000 gal of intake water and at the high dose rate to approximately 265 mg per 1000 gal of intake water.

The chemicals needed for the UF CIP were citric acid, sodium hydroxide, and calcium hypochlorite. Citric acid was used to lower the pH of the cleaning solution for the low pH

cleaning cycle, and sodium hydroxide was used for the high pH cleaning cycle. The calcium hypochlorite provided chlorine to help kill any biological growth on the membranes to help oxidize organic material.

The chemicals specified to be used for the RO chemical cleaning were citric acid and an alkaline detergent. Only the acid cleaning was performed during the ETV test. Citric acid was used to lower the pH of the cleaning solution for the low pH cleaning cycle, and the alkaline detergent if it had been used would have been used for the high pH cleaning cycle. The actual amount of acid or base needed to lower or raise the pH of the water used for the CIP solution will depend on the local water chemistry. For this test, tap water was used for the cleaning solution.

During the 2007 UF system retest, the membranes were cleaned twice using the same basic procedures and chemicals as for the 2006 chemical cleaning according to the operators. Unfortunately, the actual amount of citric acid added to the CIP tank was not recorded for either cleaning event in 2007, so the exact amount used is not known.

4.3 Quality Assurance/Quality Control

4.3.1 Introduction

An important aspect of verification testing is the QA/QC procedures and requirements. As described in Task C6 of the methods and procedures (Section 3.9.6), a structured QAPP was implemented to ensure the quality of collected data. Careful adherence to the procedures ensured that the data presented in this report were of sound quality, defensible, and representative of the equipment performance. The primary areas of evaluation were representativeness, accuracy, precision, and completeness.

4.3.2 Documentation

The field technicians recorded on-site data and calculations in a field logbook and on specially prepared field log sheets. The operating logbook included calibration records for the field equipment used for on-site analyses. Copies of the logbook, the daily data log sheets, and calibration log sheets are in Appendix B.

Data from the on-site laboratory and data log sheets were entered into Excel spreadsheets. These spreadsheets were used to calculate various statistics (average, mean, standard deviation, etc.). NSF DWSC staff checked 100% of the data entered into the spreadsheets to confirm the information was correct. The spreadsheets are presented in Appendix D.

Samples collected and delivered to the NSF Laboratory for analysis were tracked using chain-of-custody forms. Each sample was assigned a location name, date, and time of collection. The laboratory reported the analytical results using the NSF Chemistry Laboratory management system reports. These reports were received and reviewed by NSF DWSC staff. These laboratory data were entered into the data spreadsheets, corrected, and verified in the same manner as the field data. Lab reports and chain-of-custody records are included in Appendix C.

4.3.3 Quality Audits

The NSF QA officer performed an on-site audit on September 26, 2006, which was Day 2 of testing. The audit focused on review of the field procedures, including the collection of operating data and performance of on-site analytical methods. The TQAP requirements and QAPP were used as the basis for the audit. The NSF QA officer prepared an audit report. All deficiencies were corrected immediately. The QA officer did not conduct an audit for the 2007 test. Rather, DWSC staff visited the test site to verify continued compliance with the corrective action requests from the 2006 audit.

The NSF QA Department reviewed the Chemistry Laboratory analytical results for adherence to the QA requirements for calibration, precision, and accuracy detailed in the project QAPP and for compliance with the laboratory quality assurance requirements. The laboratory raw data records (run logs, bench sheets, calibrations records, etc.) are maintained at NSF and are available for review.

4.3.4 Test Procedure QA/QC

The USBR and TARDEC staff conducted the field monitoring, measurements, and sample collection and handling in accordance with the EPA-approved TQAP created specifically for this verification. NSF testing laboratory staff conducted the chemical and microbiological analyses by following the TQAP. NSF QA Department staff performed audits during testing to ensure the proper procedures were followed. The audit yielded no significant findings.

4.3.5 Sample Handling

All samples analyzed by the NSF Chemistry and Microbiology Laboratories were labeled with unique identification numbers. These identification numbers appear in the NSF laboratory reports for the tests. All samples were analyzed within allowable holding times.

However, some microbiological samples from the 2007 test did not meet the holding temperature established in the TQAP. All samples were refrigerated immediately after collection, then shipped in insulated shipping containers with ice or cold packs. At the beginning of the 2007 test, ice packs were used to cool the samples, and it was found that they were not sufficient to cool the samples properly. The starting temperature of the samples, and ambient air temperatures were sufficiently high that the samples did not reach the proper holding temperature by the time (within 24 h) they reached the NSF Laboratory. About halfway through the test, the field technicians switched to ice, and this sufficiently cooled the samples.

The potential effect of exceeding the holding temperature depends on whether the microorganisms were in a vegetative, spore or cyst state. For microorganisms in a vegetative state such as coliform and HPC, the warm temperatures could increase growth and potentially create a bias towards higher than expected counts. However, higher holding temperatures would not bias counts of microorganisms that are in a spore or cyst state such as *Bacillus* endospores, *Giardia* or *Cryptosporidium,* as other environmental conditions must be created to stimulate their growth. Since the only microbiological parameter for the 2007 test was *Bacillus* endospores, the high temperatures likely did not bias the endospore counts.

4.3.6 Physical and Chemical Analytical Methods QA/QC

The calibrations of all NSF laboratory analytical instruments and the analyses of all parameters complied with the QA/QC provisions of the NSF Laboratories Quality Assurance Manual.

Bench top field instruments that measured turbidity, pH meter, temperature and specific conductance (conductivity) were calibrated in accordance with the data quality objectives (DQO) in the TQAP during 2006 and 2007, with one exception. Temperature was not calibrated with a NIST-certified precision thermometer during the first week of sampling in 2006.

In-line field meters for particle counts and turbidity measurements were factory calibrated, and certificates were provided as required in the TQAP. However, in 2006, the incorrect calibration certificate data for bin voltages was entered into the software program for the particle counters. This resulted in rendering the particle count data inaccurate and not meeting the DQO. This was a critical parameter for the ETV test, as particle count data were used as a key indicator of membrane integrity, and to indicate real time removal of particles similar in size to pathogenic microorganisms. The NSF QA department and DWSC manager concluded that because of this, the UF system needed to be retested in 2007.

4.3.7 Microbiology Laboratory QA/QC

4.3.7.1 Growth Media Positive Controls

All media were checked for sterility and positive growth response when prepared and when used for microorganism enumeration. The media was discarded if growth occurred on the sterility check media, or if there was an absence of growth in the positive response check.

4.3.7.2 Negative Controls

For each sample batch processed, an unused membrane filter and a blank with 100 mL of sterile buffered deionized water filtered through the membrane were also placed onto the appropriate media and incubated with the samples as negative controls. No growth was observed on any blanks.

4.3.8 Documentation

All laboratory activities were documented using specially prepared laboratory bench sheets and NSF laboratory reports. Data from the bench sheets and laboratory reports were entered into Excel spreadsheets. These spreadsheets were used to calculate average feeds and filtrates, and $\log_{10}$ reductions for each challenge. One hundred percent of the data entered into the spreadsheets was checked by a reviewer to confirm all data and calculations were correct.

4.3.9 Data Review

NSF QA/QC staff reviewed the raw data records for compliance with QA/QC requirements. NSF ETV staff checked at least 10% of the data in the NSF laboratory reports against the lab bench sheets.

4.3.10 Data Quality Indicators

The quality of data generated for this ETV was established through four indicators of data quality: representativeness, accuracy, precision, and completeness.

4.3.10.1 Representativeness

Representativeness refers to the degree to which the data accurately and precisely represent the expected performance of the EUWP system under conditions expected for use in an emergency response situation, or theater of war. The EUWP was operated similar to conditions of deployment in an emergency. As stated in Chapter 2, the raw water source was a fresh surface water, representing a possible application for the EUWP during deployment. Two other ETV reports considered the EUWP performance when using sea water and secondary waste water as its feed.

Representativeness was ensured by consistent execution of the test protocol and TQAP for the test, including timing of sample collection, sampling procedures, and sample preservation. Representativeness was also ensured by using each analytical method at its optimum capability to provide results that represent the most accurate and precise measurement it is capable of achieving.

4.3.10.2 Accuracy

Accuracy was quantified as the percent recovery of the parameter in a sample of known quantity. Accuracy was measured through use of both matrix spikes of a known quantity and certified standards during calibration of an instrument. For chemical analyses performed by the NSF Laboratory, certified QC standards and/or matrix spikes were run with each batch of samples. The percent recoveries of all matrix spikes and standards were within the allowable limits for all analytical methods.

For physical and chemical analyses performed in the field, PE samples for pH and turbidity were run once during the testing period. The reported values for pH and turbidity were within the acceptable range for the PE samples.

4.3.10.3 Precision

Precision refers to the degree of mutual agreement among individual measurements and provides an estimate of random error. One sample per batch was analyzed in duplicate for the NSF Laboratory measurements. For field measurements, one process stream was analyzed in duplicate every day. Precision of duplicate analyses was measured through RPD.

All RPD were within the allowable limit of 30 percent for each parameter with the following exceptions:

- During the 2006 test, one conductivity measurement of RO permeate and four measurements of turbidity exceeded 30 percent RPD. In all cases the samples were measured very close to the instrument's limit of detection. Under such circumstances, RPD may be greater than 30 percent, which is expected and acceptable.
- During the 2007 retest, two measurements for turbidity exceeded 30 percent RPD, and again those measurements were at the limit of detection of the instrument.

4.3.10.4 Completeness

Completeness is the proportion of valid, acceptable data generated using each method as compared to the requirements of the test/QA plan. The completeness objective for data generated during verification testing is based on the number of samples collected and analyzed for each parameter and/or method, as presented in Table 3-10.

All planned water chemistry samples were collected and analyzed. All scheduled microbiological samples were collected and analyzed with acceptable results.

On three out of 31 days of testing in 2006, measurements for pH, temperature, conductivity, and turbidity were made only once per day rather than twice per day. This gave a completeness of 95% for these parameters, which met the goal of 90% in the TQAP.

During the 2007 test, measurements for pH, temperature, conductivity, and turbidity were collected once on one day, which resulted in a completeness of 98% for these parameters. The DQO of the TQAP was met for completeness.

References

EPA and NSF International (2002). *EPA/NSF Protocol for Equipment Verification Testing for Removal of Inorganic Constituents.* NSF International.

EPA and NSF International (2005). *EPA/NSF Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants.*

NSF International (2006). *Removal of Microbial Contaminants in Drinking Water, Koch Membrane Systems, Inc. HF-82-35-PMPW™ Ultrafiltration Membrane*. EPA/600/R-06/100.