WATER REUSE TECHNOLOGY DEMONSTRATION PROJECT

Demonstration Facility Pilot Study
Reverse Osmosis Membrane
Advanced Treatment Application
Final Draft Report

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By

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BLACK & VEATCH

King County

Department of Natural Resources and Parks
Wastewater Treatment Division
Technology Assessment Program

Contents

Tables

Figures

Appendices

Executive Summary

This report summarizes the findings of the reverse osmosis (RO) membrane process pilot tests. The testing facilities were designed to supply the RO unit with two feed streams, each of which was designated as a specific test stage:

- Stage 1 – Membrane Bioreactor (MBR) Effluent.
- Stage 2 – Microfiltration Membrane (MF) Effluent.

The focus of these tests was to evaluate the RO membrane process as an advanced treatment step to achieve the highest level of nutrient and total organic carbon (TOC) removal, i.e. to meet established water quality goals for a number of potential effluent end uses including discharge to wetlands, streams, lakes, and groundwater recharge. As summarized below, the performance goals were:

- Effluent TDS <100 mg/L, 95th percentile (for discharge to lakes and groundwater).
- Effluent turbidity < 0.1 NTU, 95th percentile (for discharge to wetlands, streams and lakes, and for non-potable groundwater recharge).
- Effluent TOC <1 mg/L, 90th percentile (for groundwater recharge, potable).
- Effluent total phosphorous (TP) <0.02 mg/L, 90th percentile (for discharge to lakes).
- Less than 2 percent long-term flux decline per year.

Table 1 summarizes the RO unit's ability to meet these performance goals.

Table 1. Effectiveness of RO Membrane to Meet Performance Goals

Goal Description	Reliability Percentile	Target	Measured Performance	
			Stage 1	Stage 2
TDS Removal	95th	<100 mg/L	109 mg/L	62.6 mg/L
Turbidity Removal	95th	<0.1 NTU	Not measured[a]	Not measured[a]
TOC Removal	90th	<1 mg/L	1.56 mg/L	1.38 mg/L
TP Removal	90th	<0.02 mg/L	0.014 mg/L	0.0067 mg/L
Long-Term Flux Decline		<2% per year	Not measrued[b]	Not measrued[b]

[a] no reliable turbidity measurement, little if any solids in the RO permeate
[b] Unable to measure during the pilot test duration

The performance of the RO for specific parameters is discussed below.

TDS Removal

The RO membrane achieved the performance goal of <100 mg/L TDS at the 95th percentile for Stage 2. However, for Stage 1, TDS removal was 109 mg/L at the 95th percentile. The data set had only five data points for each test stage. With the caveat that the number of data points was small, it is anticipated that the RO membrane can meet the performance goal when treating MF effluent.

Turbidity Removal

This performance goal was not evaluated because turbidity could not be reliably measured in the RO permeate. The permeate turbidity levels were below the measuring accuracy of the turbidimeter.

TOC Removal

The RO membrane did not achieve the 90^{th} percentile performance goal of <1 mg/L TOC. The actual 90^{th} percentile values were 1.56 and 1.38 mg/L for Stage 1 and 2, respectively.

TP Removal

The RO membranes achieved the TP 90^{th} percentile performance goal of <0.02 mg/L. Most of the permeate samples analyzed were below the detection limit of 0.005 mg/L.

Long-Term Flux Decline

The clean-water performance data for both membranes were similar and indicated a good recovery of membrane performance after one chemical clean. However, to fully assess long-term flux decline, additional filtration/cleaning cycles need to be tested.

This technology would be suitable for use in a full-scale facility with the following design criteria (for the RO membrane tested):

- Operating Pressure: 100 to 400 psi.
- Average Flux at 20 ºC: 9 gfd.
- System Recovery: 70 to 85 percent.

Introduction

The King County Department of Natural Resources (King County) conducted a nine-month demonstration pilot-testing project to assess the performance of eight emerging wastewater treatment technologies. The focus of this project is to assess technologies capable of producing effluent meeting either State of Washington Class A Reuse Standards or more stringent water quality standards.

This report summarizes the findings of the reverse osmosis (RO) membrane filtration pilot tests. The RO pilot unit, supplied by Black & Veatch, was configured to receive effluent from the membrane bioreactor (MBR) pilot unit and the microfiltration (MF) pilot unit. The focus of these particular pilot tests was to evaluate an RO membrane process for advanced treatment, specifically additional nutrient reduction.

Description of the Technology

The RO membrane process removes dissolved impurities from water. A semi-permeable membrane selectively allows water to pass through the membrane under pressure at a much greater rate than dissolved material. Water and a small amount of the dissolved material diffuse through the semi-permeable membrane. The purified RO water is called "permeate" or "product." The remaining water that flows out of the membrane pressure vessel contains higher concentrations of impurities than the influent (because water has been removed from this flow but most of the impurities are still in it); this outflow is called the "concentrate" or "brine".

In addition to removing ions (such as sodium and chloride), RO also removes uncharged compounds, such as cysts, silica, and many organics. The removal percentage of dissolved components depends on the size and charge of those components, and on operating conditions (pressure, temperature, membrane material). To prevent rapid fouling or plugging of the RO membrane's spiral-wound configurations, pretreatment of the influent with a low-pressure membrane (e.g., microfiltration) is required.

Figure 1. RO Pilot System Schematic

is a process schematic for the RO pilot system. The unit is equipped with a feed tank, a low-pressure supply pump, two cartridge filters, a high-pressure supply pump, an RO membrane housed in a pressure vessel, and a downstream collection tank. The feed to the RO system is supplied to the feed tank, which typically overflows to the collection tank to maintain a constant pressure to the cartridge filter pump. The overflow from the collection tank goes to drain. There are two chemical injection points just upstream of the cartridge filters. The cartridge filters, typically with a pore size between 5 and 10-micron, prevent debris from clogging the spiral-wound membrane element. The chemical injection points allow for the addition of anti scalant and acid addition. Acid is added to prevent calcium carbonate scaling. Anti scalant is added to control scaling of other sparingly soluble salts in the feed stream.

Flow from the cartridge filters is routed to the high-pressure supply pump. This pump includes a variable frequency drive to control flow rate and pressure to the RO membrane. The portion of the feed stream that passes through the membrane (permeate) is sent to the downstream collection tank. The portion not passed through the membrane (concentrate) can be recirculated to the suction side of the high-pressure pump and/or sent to drain.

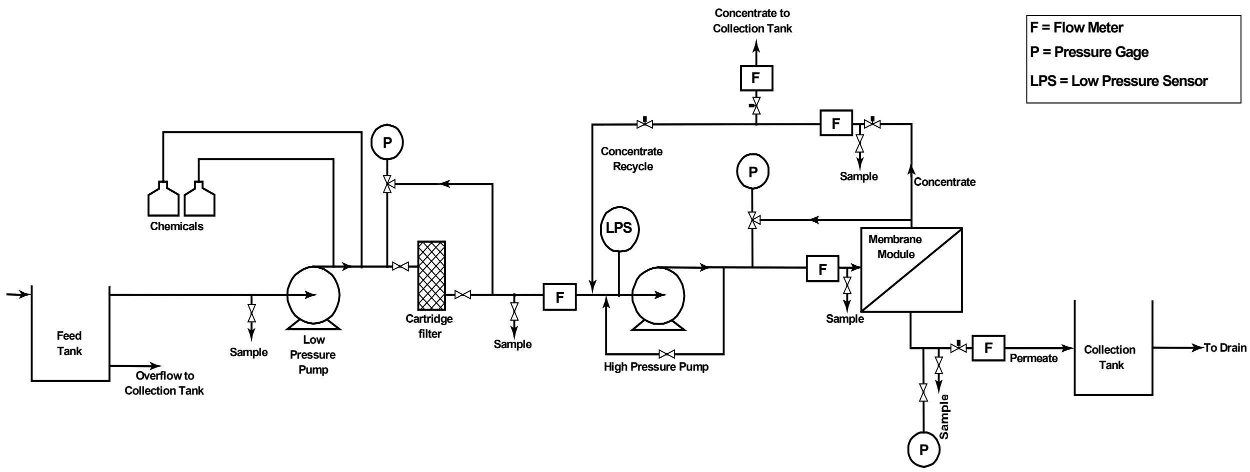

Figure 1. RO Pilot System Schematic

The single membrane module is placed in a horizontal housing. Filtration occurs in cross-flow mode (i.e., flow direction is parallel to the membrane surface), and only a portion of the feed passes through the membrane. The concentrate stream continuously carries away concentrated impurities to minimize membrane fouling. However, over time, impurities will build up on the membrane and restrict the permeate flow. To maintain a constant permeate flow rate, the feed pressure is automatically increased as needed. When the feed pressure becomes excessive, the module is taken off-line and is chemically cleaned.

The membrane manufacturer will specify the cleaning protocol. Typically, it includes low-velocity recirculation followed by high-velocity recirculation with the cleaning solution. Then the system is flushed using de-ionized or RO permeate water. In some cases, a chemical soaking step is implemented between the recirculation steps.

System recovery is defined as the ratio of permeate flow to feed flow. Since RO membranes are designed for cross-flow filtration, a single multi-module pressure vessel will typically be operated at about 50 percent recovery. A full-scale plant usually includes multiple membrane stages operated in series. The concentrate from the upstream stages becomes the feed for the downstream stages, which increases the system recovery for the overall plant. The typical recovery of a full-scale 3-stage system is 85 percent. Since the RO pilot system has just one module and therefore one stage, it can be operated at 50 percent recovery if brine recirculation is used to maintain cross-flow velocity. This represents the operating conditions of a membrane element in the middle-stage of a full-scale plant.

Full-Scale Facilities

Reverse osmosis has been widely used in wastewater reuse projects in the recent years. Following is a list of full-scale RO membrane water reuse system installations in the United States that treat secondary effluent from municipal wastewater plants.

- Chandler, AZ (2mgd): MF + RO
- Scottsdale, AZ (19 mgd): MF + RO
- Alamitos, CA (3.5 mgd): MF + RO
- Carlsbad, CA (1 mgd): MF + RO
- Dublin/San Ramon, CA (3 mgd): MF + RO
- Livermore, CA (1 mgd): MF + RO
- Terminal Island, Los Angeles, CA (6.2 mgd): MF + RO
- Water Factory 21, Fountain Valley, CA (5 mgd): RO
- Groundwater Replenishment Project (in design), Water Factory 21, Fountain Valley, CA (86 mgd): MF + RO
- West Basin/Carson, CA (5.9 mgd): MF + RO
- West Basin/El Segundo, CA (2.7 mgd): MF + RO
- West Basin/El Segundo Phase 3, CA (5.9 mgd): MF + RO
- Honolulu, HA (3.4 mgd): MF + RO
- East Coast Power, NJ (3 mgd): MF + RO
- State College, PA (1 mgd): MF + RO

Pilot Testing

Goals and Objectives

The goal of the pilot study was to use the reverse osmosis membrane process to treat MBR effluent and MF effluent and determine its effectiveness to meet effluent water quality goals more stringent than Class A Reuse requirements. The pilot study was designed to address the following major goals:

- Determine nutrient and total dissolved solids (TDS) removal.
- Target the following performance goals for the specified potential end uses:
  - Effluent TDS<100 mg/L, 95th percentile (for discharge to lakes and groundwater recharge).

- Effluent turbidity < 0.1 NTU, 95th percentile (for discharge to wetlands, streams and lakes, and for non-potable groundwater recharge).
- Effluent TOC <1 mg/L, 90th percentile (groundwater recharge, potable).
- Effluent total phosphorous (TP) <0.02 mg/L, 90th percentile (for discharge to lakes).
- Less than 2 percent long-term flux decline per year.

Also, the following were considered secondary goals for the project.

- Monitor head loss across the membrane for a constant flux rate and system recovery.
- Evaluate the potential for long-term membrane fouling.

Demonstration Setup

The RO pilot unit arrived at the West Point WWTP on August 29, 2001 and was on site for a total of five months. The Black & Veatch startup engineer was on site in mid-September to conduct the system startup and train County staff to operate the unit. County staff operated the unit for the entire testing duration. The consultant team coordinated the pilot testing and provided data analysis.

The pilot unit was located inside the Technology Assessment Facility at the West Point WWTP, as shown in Figure 2. Table 2 describes the physical attributes of the pilot unit.

Figure 2. Black & Veatch RO Membrane Pilot Unit.

Table 2. Summary of RO Pilot System Parameters

Parameter [a]	Unit	Value
Membrane Module[b]		
Filtration Surface Area	Square Feet	78
Module Length	Inches	40
Module Diameter	Inches	4
Membrane Material	-	polyamide
Membrane Structure	-	thin-film composite
Feed Tank Volume	Gallon	45
Collection Tank Volume	Gallon	15
Low-Pressure Pump		
Flow Rate	gpm	20
Discharge Pressure (at 20 gpm)	psi	20
High-Pressure Pump		
Flow Rate	gpm	20
Discharge Pressure (at 20 gpm)	psi	300
Cartridge Filter Pore Size	μm	10

[a] (Black & Veatch, 2001)

[b] Koch/Fluid Systems Model TFC 4820 HR

The system does not include a programmable logic controller, data logger, or SCADA system; the operator records the instrument readings manually. Instrumentation includes:

- Inlet and outlet cartridge filter pressure gage.
- Low-pressure sensor on the suction side of the high-pressure pump.
- Inlet and outlet RO membrane pressure gages.
- Flow meters (rotameters) to measure RO membrane feed flow, permeate flow, recycled concentrate flow and concentrate flow to drain.
- Feed water temperature probe.

The system includes two chemical feed pumps, each with chemical solution tanks, to supply antiscalant and/or acid to the feed.

Testing Plan

A testing plan was prepared at the beginning of the pilot study and is contained in Appendix A. Also included in Appendix A is a copy of the *Model RO-2001 Pilot Unit Operations Manual, Black & Veatch, 2001*. This manual provides a good summary of reverse osmosis membrane technology as well as a detailed description of the pilot unit configuration, including process, instrumentation, and layout drawings.

The test plan includes a detailed description of the pilot unit operating conditions, test stages, sampling, and special testing. As the testing progressed, there were deviations from this test plan, which are summarized in the beginning of Appendix A.

The system performance was checked two to four times per day. Pressure and flow measurements were manually recorded on operator data sheets two to four times per day. If needed, manual valves or pump speed were adjusted to maintain permeate and concentrate flow-rate set points. Inlet and outlet cartridge filter pressure was recorded to determine the pressure drop. The antiscalant feed pump rate was checked along with the level in the antiscalant supply tank.

Following is a summary of key features of the original test plan:

- The focus of the testing was to evaluate permeate water quality when treating MBR and MF effluent. Operating parameters such as permeate flow rate, system recovery, and antiscalant dose were not optimized. Instead, these parameters remained constant to provide a stable operation.
- For each feed stream, grab samples were collected and analyzed for scaling indices to assess the need for antiscalant and/or acid addition.
- Particulate and organic material in the feed stream will accumulate on the membrane surface and cause membrane fouling. The silt density index (SDI) is used as a fouling indicator. SDI is calculated based on the time required to filter a 100 mL feed sample through a 0.45 µm filter. In general, an SDI value less than three indicates that the feed stream is not likely to foul the membrane. For each feed stream, the SDI was calculated to assess fouling potential.
- Feed and permeate conductivity were measured to monitor salt rejection. A sudden salt passage increase would indicate the membrane had been damaged or that there had been a failure in one of the physical sealing systems, such as the o-rings. Conductivity passage, one way to assess salt rejection, is the ratio of permeate to feed conductivity. A low percent conductivity passage represents high salt rejection.
- Two new membrane modules were used, one for each stage of testing. The membrane manufacturer performed clean water performance tests prior to supplying the modules. At the conclusion of each test stage, the membrane module was shipped to a membrane testing company to perform a chemical clean and determine the post-clean water performance. Chemical cleaning was not done onsite.
- The polyamide membrane is not resistant to free chlorine.
- The pilot test consisted of the following testing stages:
  - **Stage 1 – MBR Effluent Feed.** Effluent from the Zenon MBR was supplied to the RO unit during this stage. The MBR was treating West Point WWTP primary influent to demonstrate compliance with Class A reuse standards. It was also

operated to nitrify. This system includes a low-pressure ultrafiltration membrane that produced effluent turbidity consistently below 0.1 NTU.

- **Stage 2 – MF Effluent Feed.** Effluent from the MF pilot unit was supplied to the RO unit during this stage. The entire treatment train included West Point WWTP primary effluent supplied to the biological aerated filter (BAF) #1 unit for biochemical oxygen demand (BOD) oxidation followed by the BAF #2 unit for nitrification, which then supplied the MF unit. The focus of Stage 2 was enhanced nutrient removal on West Point primary effluent. Similar to the MBR, the MF effluent turbidity was consistently below 0.1 NTU.

Results

Operating Data Considerations

Trans Membrane Pressure

The trans membrane pressure (TMP) is the head loss across the membrane and represents the driving force needed to achieve a given permeate flow condition. Membrane fouling and scaling will cause the TMP to rise. TMP is a calculated value using feed pressure, concentrate pressure and permeate pressure values.

Membrane Flux

Membrane flux is evaluated during a pilot study to determine the design flux for a full-scale application. The flux is a measure of the membrane permeate flow rate divided by the active surface area of the membrane. It is calculated as follows:

- Flux (gfd) = filtrate flow (gallons per day) / membrane surface area (sq ft)

In the United States, the units for flux are gallons per day per square foot, which is abbreviated as gfd.

Membrane flux is a parameter used for evaluating the system performance. The flux is directly affected by the feed water temperature. As the temperature decreases, the liquid viscosity increases, requiring a higher feed pressure to maintain the same flux for a colder feed stream.

A temperature of 20 °C was used as the standard temperature. The temperature-corrected flux (flux at 20 °C) is calculated by multiplying the actual flux by the temperature correction factor. The correction factor is calculated as follows:

- Temperature correction factor = $1.03^{(20\,^{\circ}\text{C} - \text{actual feed temperature }^{\circ}\text{C})}$

However, the system can produce a constant flux even when the temperature drops. A higher feed pressure is required which, in turn, increases the TMP. To account for this variable, the flux is normalized with respect to TMP, and is referred to as the specific flux. To account for both temperature and TMP, the temperature-corrected specific flux is used and calculated as follows:

- Temperature-Corrected Specific Flux (gfd/psi) = Temperature-Corrected Flux (gfd)/TMP (psi)

In the results section below, the operating data presented include the feed temperature, TMP, temperature-corrected flux and temperature-corrected specific flux.

Stage 1 – MBR Effluent Feed

The RO unit was supplied with MBR effluent from September 20, 2001, to January 20, 2002.

RO Element Clean Water Performance

Table 3 is a summary of the clean water flux data for the Stage 1 membrane module. Testing results were corrected to standard conditions of: 2000 mg/L NaCl feed concentration, 225 psi, 15% recovery, 77 ºF, and pH 7.5. Cleaning was performed by Betz-Dearborn/Argo Scientific using their standard acid (Kleen MCT103) and caustic-detergent (Kleen MCT411) cleaning agents. A standard acid and caustic-detergent cleaning brought the permeate flow performance to within 5% of the initial clean water performance. The post-cleaning rejection and pressure drop was essentially the same as the initial clean water test results. It is not unusual to observe a small amount of flux loss during early operations. A properly designed full-scale plant would take this into account.

Table 3. Stage 1 Membrane Clean Water Performance

Description	Before Pilot Test	After Pilot Test	
		Before CIP	After CIP
Permeate Flow, gpd	2010	1730	1940
Flux, gfd	25.8	22.2	24.9
Chloride Rejection, %	99.6	98.8	99.0
Feed-Brine Pressure Drop, psid	4.1	5	3

Overall, these results indicate the scaling/fouling was not irreversible; however, longer-term testing would be needed to fully quantify the fouling potential, to observe multiple fouling-cleaning cycles and verify that this initial loss would not worsen over time.

Scaling Characteristics

The MBR effluent was sampled on October 23, 2001. The County laboratories performed the analyses for various inorganic species. These species, if concentrated at the membrane surface, can reach saturation causing precipitates to form. Depending on the cross-flow hydraulic conditions at the membrane surface, these particulates can deposit on the membrane and increase membrane fouling.

The following parameters and their concentrations found in the MBR effluent are summarized in Table 4.

Table 4. Scaling Constituents in MBR Effluent[a]

Parameter	Value
Alkalinity, mg/L $CaCO_3$	52.7
TDS, mg/L	578
Chloride, mg/L	211
Sulfate, mg/L	45.2
Fluoride, mg/L	0.644
$NO_2 + NO_3$, mg/L	12
Silica, mg/L	16.3
Total Barium, mg/L	0.0025
Total Calcium, mg/L	19.7
Total Iron, mg/L	0.053
Total Magnesium, mg/L	15.9
Total Manganese, mg/L	0.0049
Total Potassium, mg/L	12.6
Total Sodium, mg/L	137
Total Aluminum, mg/L	0.0227

[a] sample without anti scalant.

Equilibrium calculations showed little potential for precipitating calcium carbonate and other sparingly soluble salts for this feed stream as long as the unit continued to operate at less than or equal to 50 percent recovery. If the feed water concentrations were to increase, the most likely precipitant would be calcium carbonate. In turn, if this precipitation occurred, it would result in a high membrane feed pressure and a significant increase in the feed-brine pressure drop.

Antiscalant feed (Bet_3Dearborn, Inc. Hyperspace AF 150 UF at a target dose of 2 to 2.5 mg/L) was implemented at the beginning of Stage 1. For the last month of testing, beginning on January 8, 2002, the antiscalant feed was shut off to determine the impact on TMP. Acid addition was not implemented because high levels of calcium carbonate were not anticipated in the feed. This was confirmed with the data analysis (Table 4).

Fouling Characteristics

The County measured the SDI twice and this data is summarized in Table 5. Both values were less than 3, suggesting a low potential for fouling with MBR effluent. This was the anticipated outcome due to the pore size of the membrane in the MBR.

Table 5. MBR Effluent SDI Values

Date	SDI Value
November 9, 2001	2.5
November 14, 2001	0.8

The MBR effluent TOC measured during Stage 1 ranged from 4 to 8.4 mg/L.

Stage 1 Operating Data

The RO membrane temperature-corrected specific flux, TMP and temperature-corrected flux are plotted in Figure 3 for the Stage 1 testing duration. Feed temperature is also included.

The TMP pressure was initially 104 psi and gradually increased to 184 psi by the end of the testing. There was no noticeable change in the TMP increase once the antiscalant feed was discontinued. The feed temperature was initially 20 ºC and decreased to as low as 15 ºC.

The temperature-corrected flux ranged from 8.3 to 13.7 gfd, with an average of 11.2 gfd. The fluctuation was primarily due to the manually controlled permeate flow rate.

The temperature-corrected specific flux was initially 0.11 gfd/psi and gradually decreased to 0.05 gfd/psi by the end of the test. A 50 percent reduction in specific flux indicates membrane fouling/scaling occurred for the MBR effluent. The element clean in place (CIP) appeared to be successful but more fouling/cleaning cycles are recommended before the long-term fouling behavior can be fully assessed.

Figure 4 shows the feed and permeate conductivity data. The average permeate conductivity was 9 µmho/cm compared to the average feed conductivity of 816 µmho/cm. The RO system provided a 2-log reduction of conductivity and the conductivity passage ranged between 0.5 and 1.9 %. Overall these data show low conductivity passage and therefore, a high salt rejection.

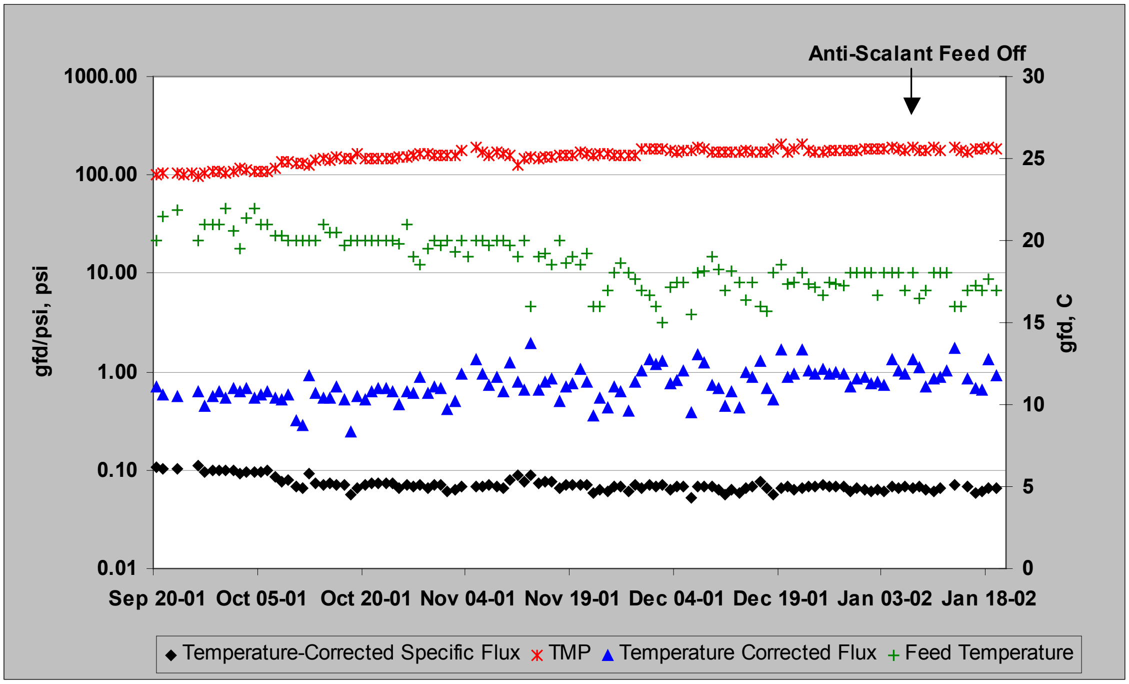

Figure 3. Stage 1 Operating Data

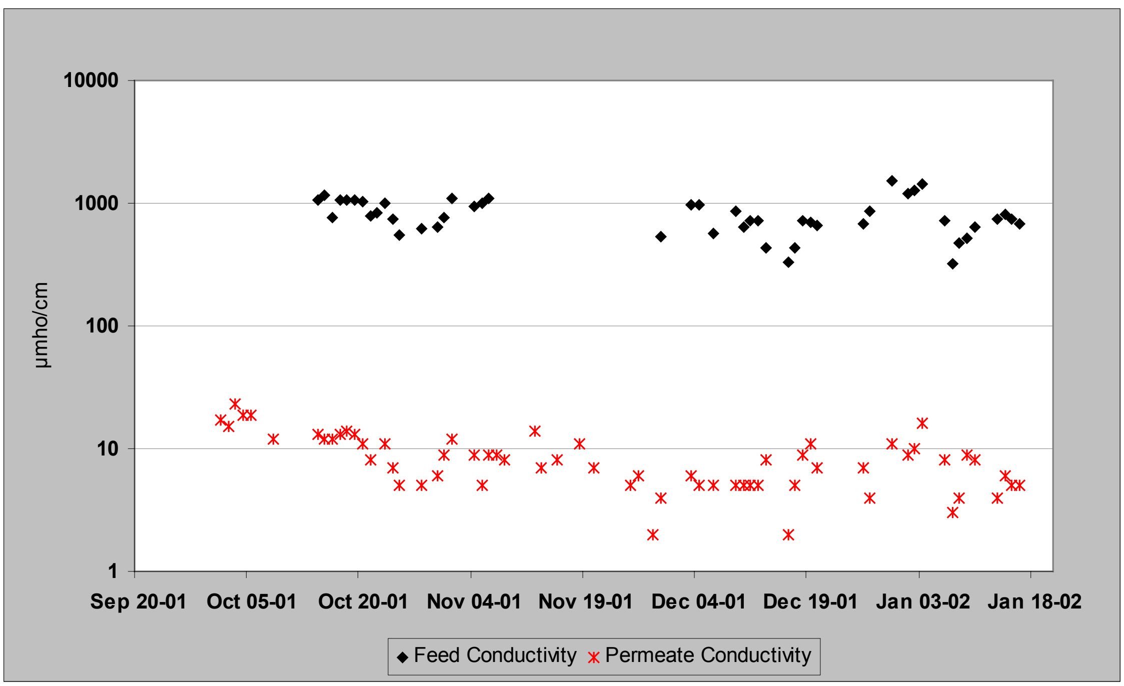

Figure 4. Stage 1 Feed and Permeate Conductivity

Water Quality

TDS, TOC and nutrients were measured in the feed and permeate. Automatic samplers were used to collect 24-hour composites for a measurement of conductivity, TDS and TKN by the

West Point WWTP Process Laboratory. Grab samples were also collected for analysis of TOC and other nutrients by the King County Environmental Laboratory. On one occasion, feed and permeate grab samples were collected and analyzed for metals and organics.

Table 6 summarizes the TDS, TOC and nutrient data, including percent removal. All data collected were used to calculate the feed and permeate concentration statistics presented. For many parameters, the permeate concentrations were less than the laboratory method detection limit (MDL). These data were assigned the MDL value for the statistics calculations. Percent removal was calculated using the average feed and permeate concentrations.

The following subsections present the feed and permeate concentrations for each water quality parameter. Special sampling results for metals and organics are presented in the last subsection.

TDS

Feed and permeate TDS are shown in Figure 5. The data was collected from January 13 to January 17. These limited data indicate the RO membrane provided a high rejection of TDS. The average removal was 93.8%.

Figure 6 shows a lognormal distribution of the permeate TDS data. At the 95^{th} percentile, the TDS concentration was 109 mg/L, which did not quite meet the permeate TDS performance goal of <100 mg/L 95^{th} percentile.

Table 6. Stage 1 Water Quality Summary

Parameter	Average	Minimum	Maximum	MDL
TDS				
Feed, mg/L	579	472	936	na
Permeate, mg/L	39	6	96	na
Removal, percent	93.8	-	-	
TOC				
Feed, mg/L	6.515	3.950	8.390	0.5
Permeate, mg/L	1.114	0.770	1.770	0.5
Removal, percent	82.6	-	-	
NITROGEN COMPOUNDS				
TKN				
Feed, mg/L	0.472	0.103	1.050	0.01
Permeate, mg/L	0.054	<0.01	0.090	0.01
Removal, percent	>88.6[a]	-	-	
NH4-N				
Feed, mg/L	0.146	0.010	3.570	0.01
Permeate, mg/L	0.014	0.010	0.107	0.01
Removal, percent	90.4	-	-	
NO3-N				
Feed, mg/L	6.786	0.4000	14.600	0.02
Permeate, mg/L	0.169	0.035	0.452	0.02
Removal, percent	>97.5 [a]	-	-	
PHOSPHOROUS COMPOUNDS				
TP				
Feed, mg/L	0.99	0.05	3.66	0.005
Permeate, mg/L	0.006	0.005	0.012	0.005
Removal, percent	>99.4 [a]	-	-	
PO4-P				
Feed, mg/L	1.39	0.045	5.87	0.002
Permeate, mg/L	0.002	0.002	0.004	0.002
Removal, percent	>99.9[a]	-	-	

na not applicable
- = percent removal only calculated for average feed and permeate data
[a] shown as greater than calculated value because the average permeate includes values <MDL

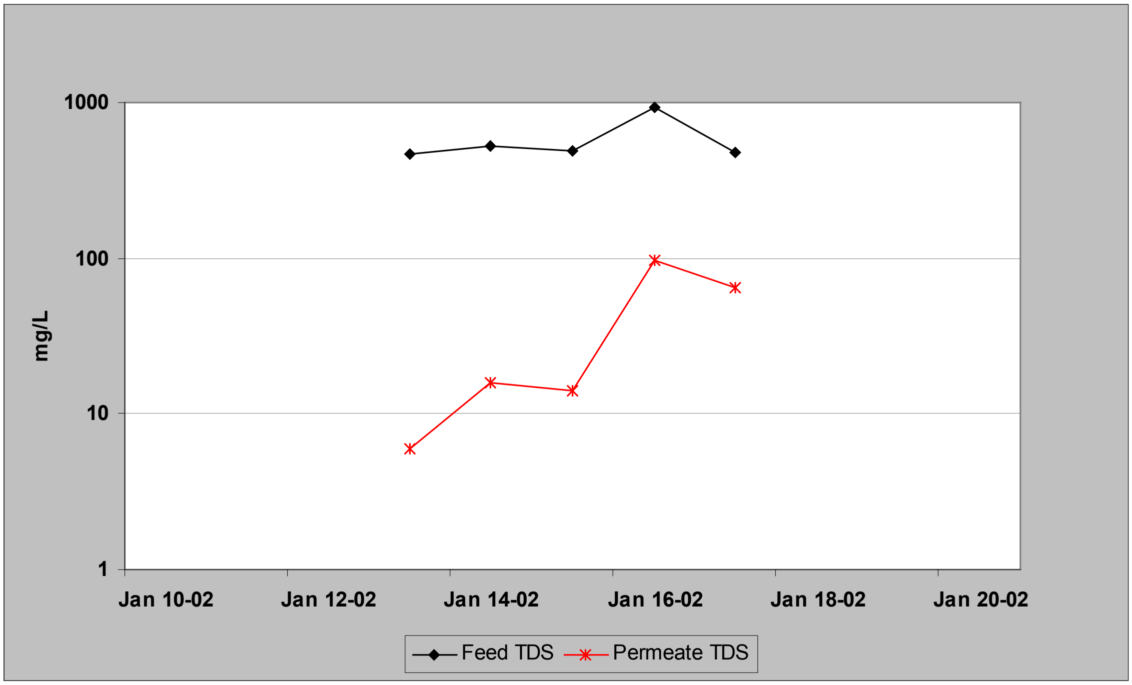

Figure 5. Stage 1 - Feed and Filtrate TDS

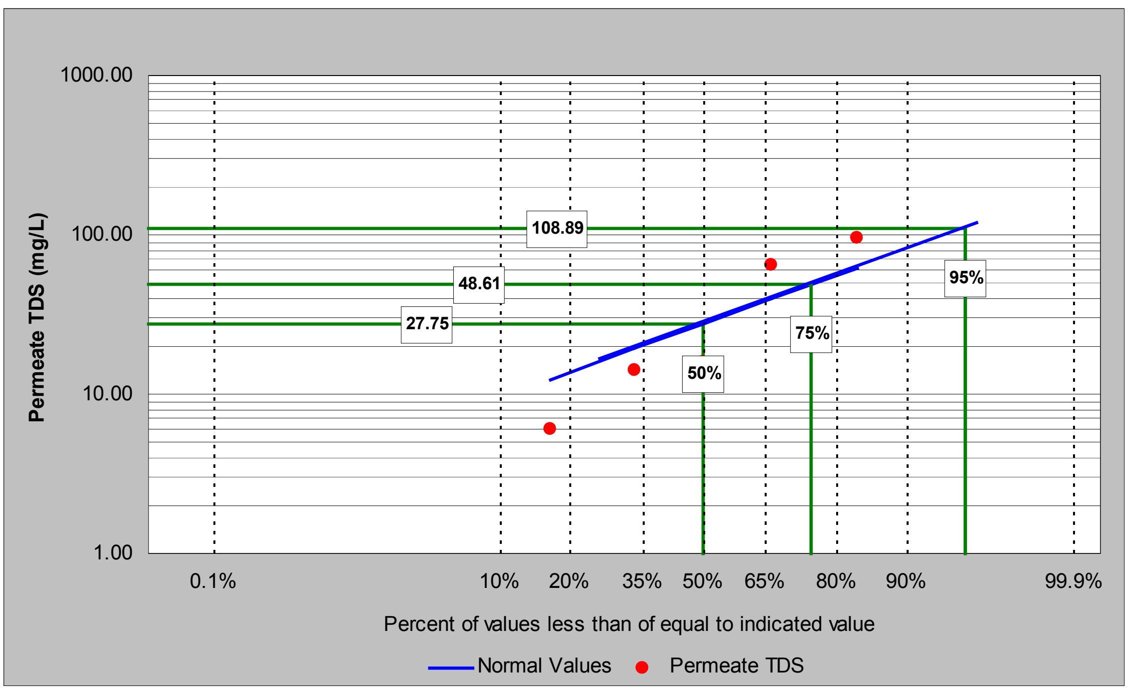

Figure 6. Stage 1 - Permeate TDS Log Normal Distribution

TOC

Figure 7 shows feed and permeate TOC. The average removal was 82.8%. The RO membrane effectively removed TOC from the MBR effluent.

Figure 8 shows a log normal distribution of the permeate TOC. The 90th percentile value is 1.56 mg/L. These data indicate the RO membrane did not achieve the permeate TOC 90th percentile performance goal of <1 mg/L.

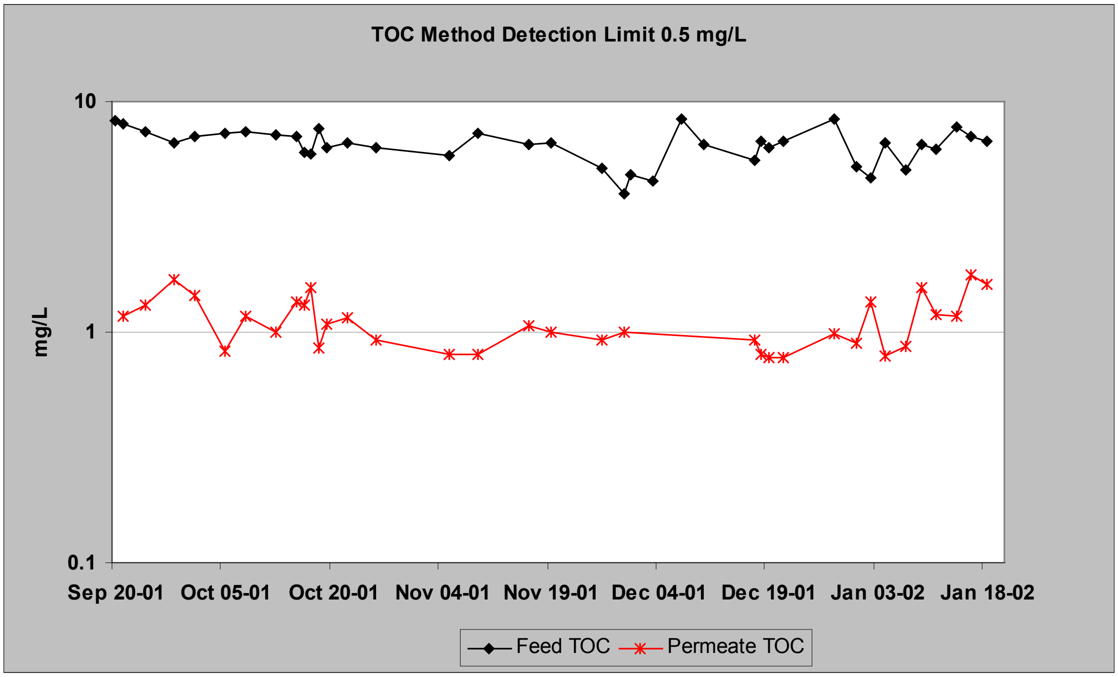

Figure 7. Stage 1 - Feed and Permeate TOC

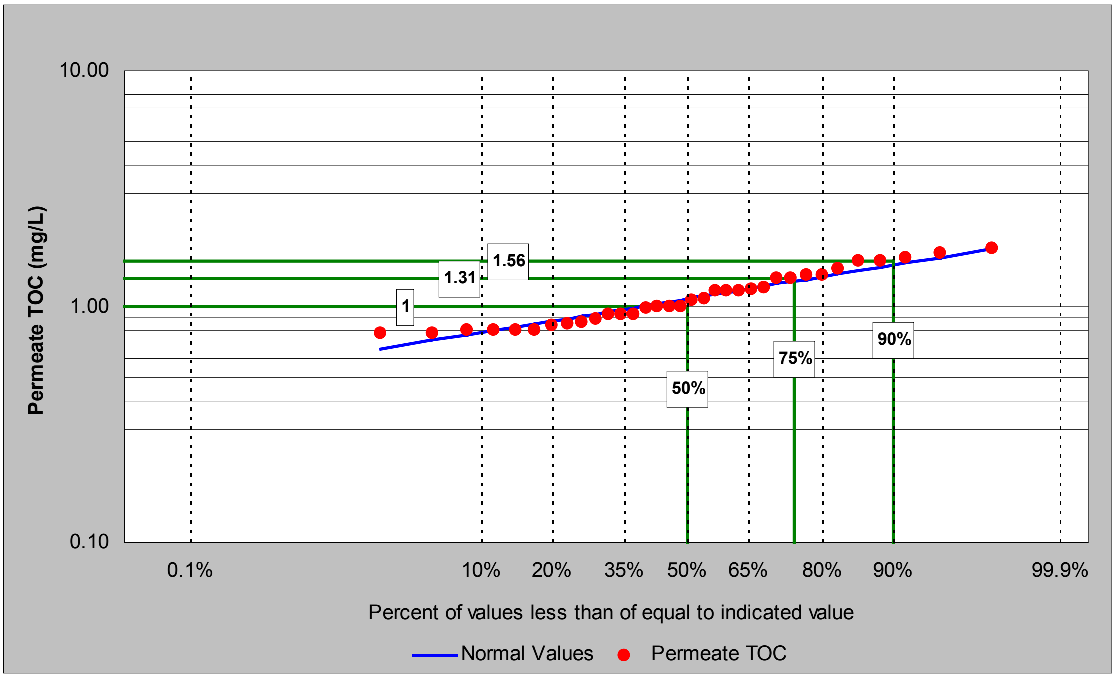

Figure 8. Stage 1 - Permeate TOC Log Normal Distribution

Nitrogen Compounds

Figure 9 includes feed and permeate TKN concentrations. The average removal was >88.6%.

Figure 10 shows NH4-N feed and permeate concentrations. With the exception of four days in December, feed NH4-N ranged from 0.02 to 0.17 mg/L. The permeate NH4-N was consistently <0.01 mg/L, the lab method detection limit. The average removal was >90.4%.

During Stage 1, the MBR unit was operating in nitrification mode. However, on the following days the MBR effluent ammonia increased and there was a corresponding increase in RO permeate ammonia. In all cases, RO reduced ammonia by more than 90%, providing a protection against a potential upstream MBR upset.

- December 7: MBR effluent ammonia, 3.57 mg/L; RO permeate ammonia (not measured)
- December 18: MBR effluent ammonia, 2.09 mg/L; RO permeate ammonia, 0.107 mg/L
- December 19: MBR effluent ammonia, 1.4 mg/L; RO permeate ammonia, 0.071 mg/L
- December 20: MBR effluent ammonia, 1.94 mg/L; RO permeate ammonia, 0.067 mg/L

There were two days in early October when the MBR effluent ammonia peaked above 0.1 mg/L. However, the permeate ammonia remained < 0.01 mg/L.

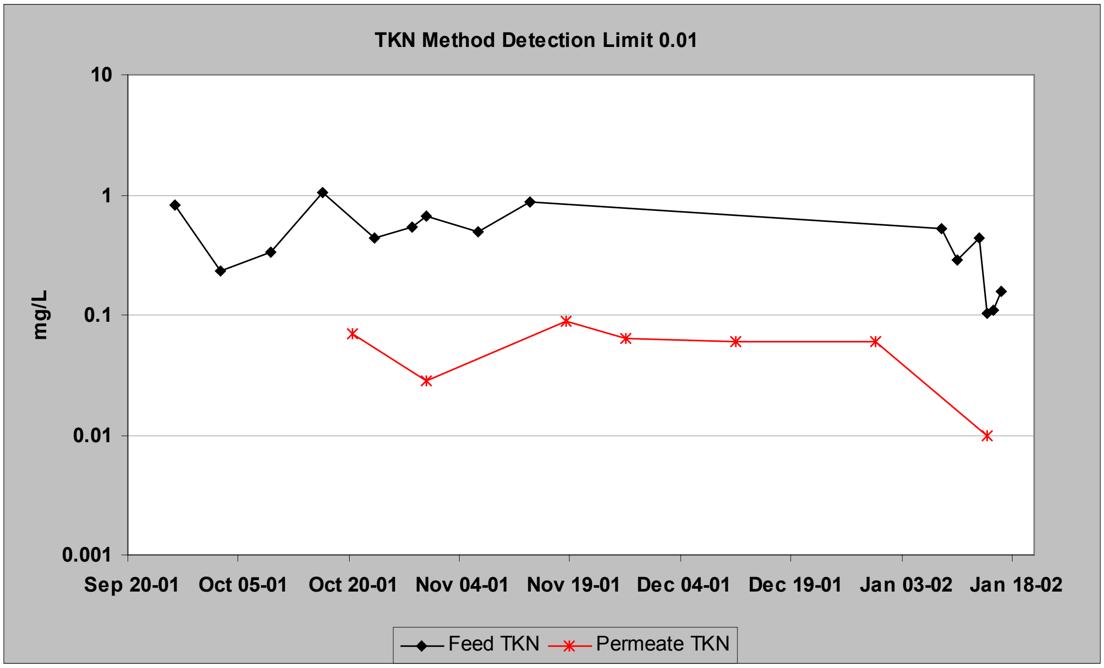

Figure 9. Stage 1 - Feed and Permeate TKN

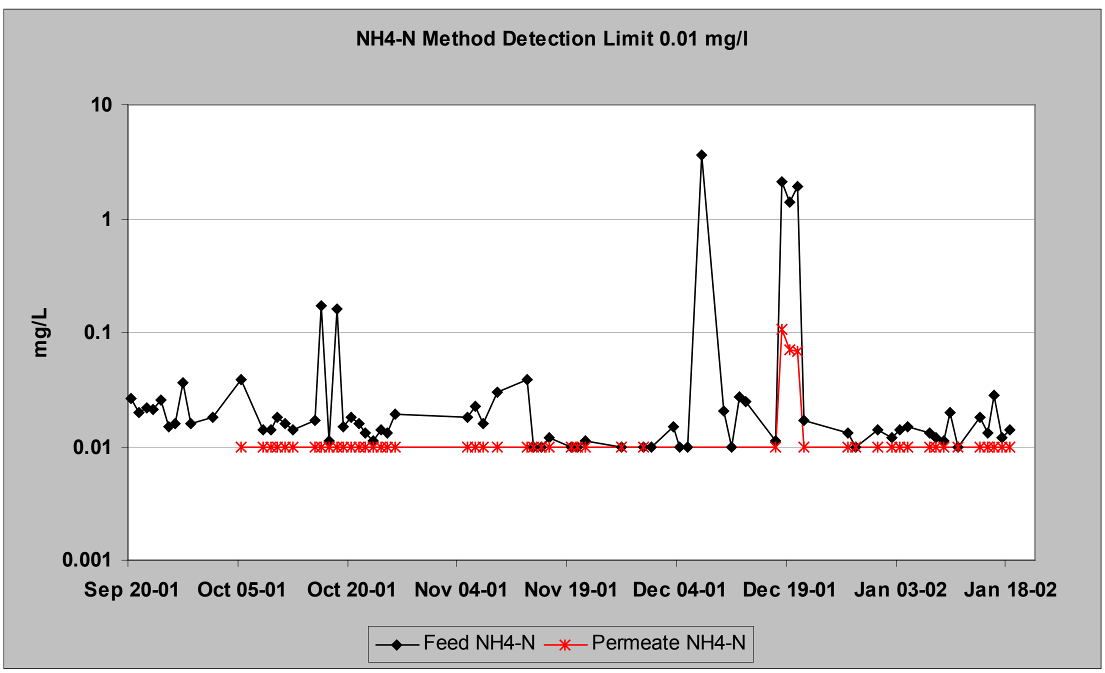

Figure 10. Stage1 Feed and Permeate NH4-N

Figure 11 shows NO3-N feed and permeate concentrations and percent removal. The RO membrane consistently rejected nitrate at a high rate, with an average removal >97.5%.

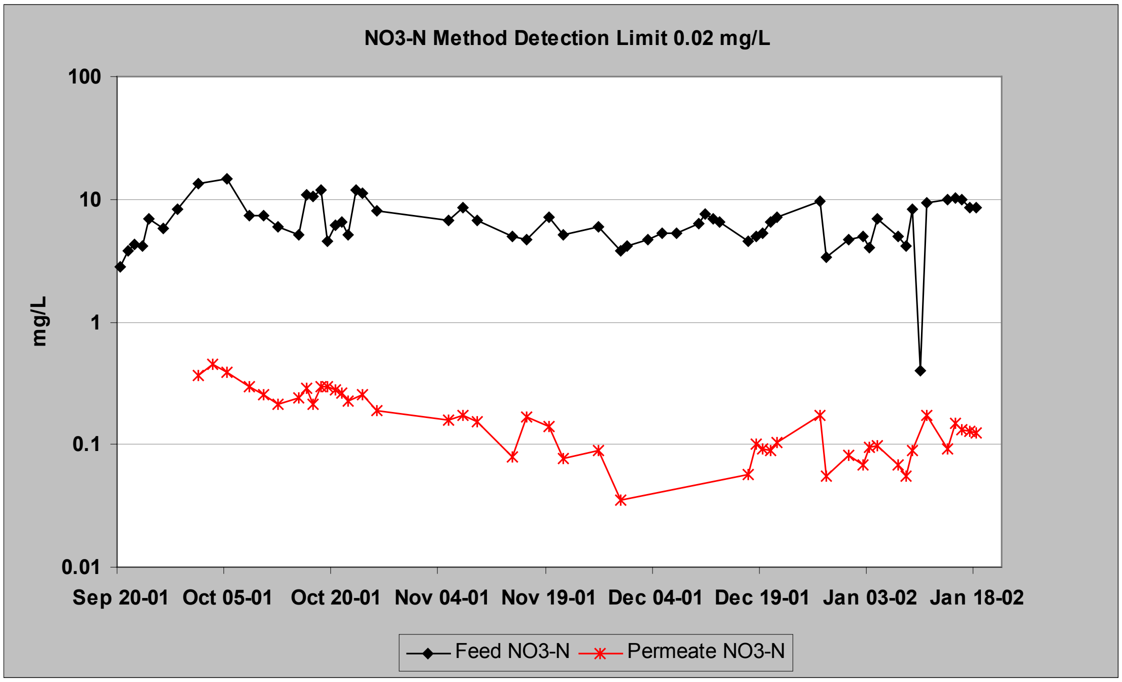

Figure 11. Stage 1 Feed and Permeate NO3-N

Phosphorous Compounds

Figure 12 shows the feed and permeate TP concentrations. The average removal was >99.4%.

A log normal distribution of the permeate TP is shown in Figure 13. The 90th percentile was 0.014 mg/L, which met the 90th percentile performance goal of <0.02 mg/L. The RO membrane effectively removed TP from the MBR effluent.

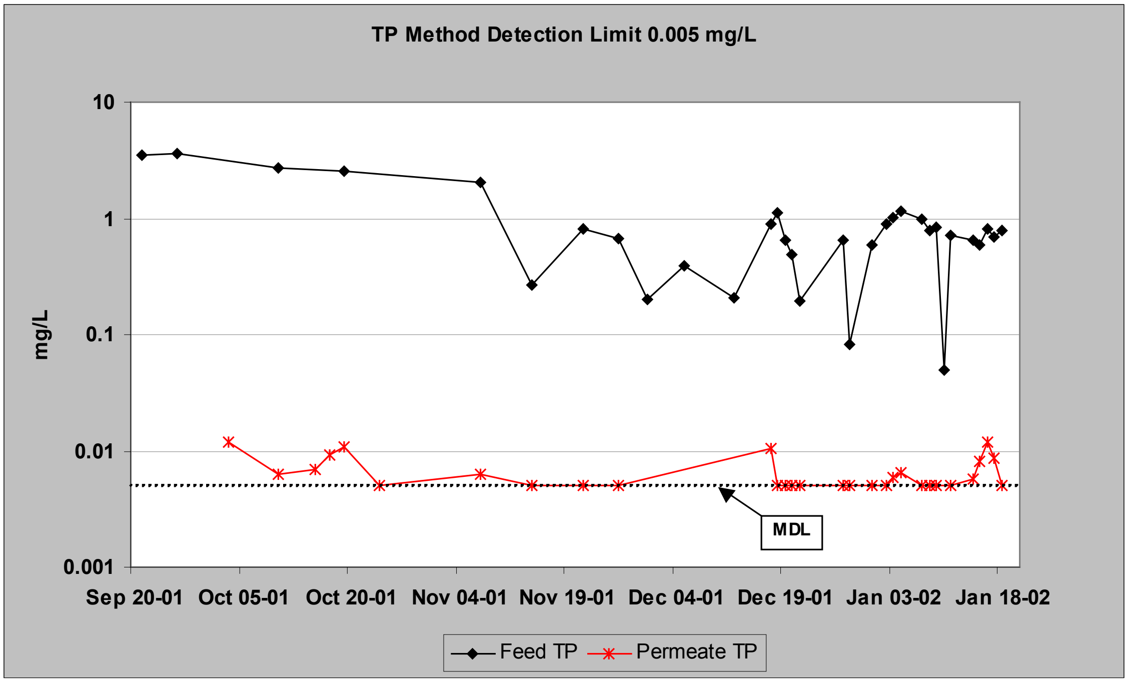

Figure 12. Stage 1 Feed and Permeate TP

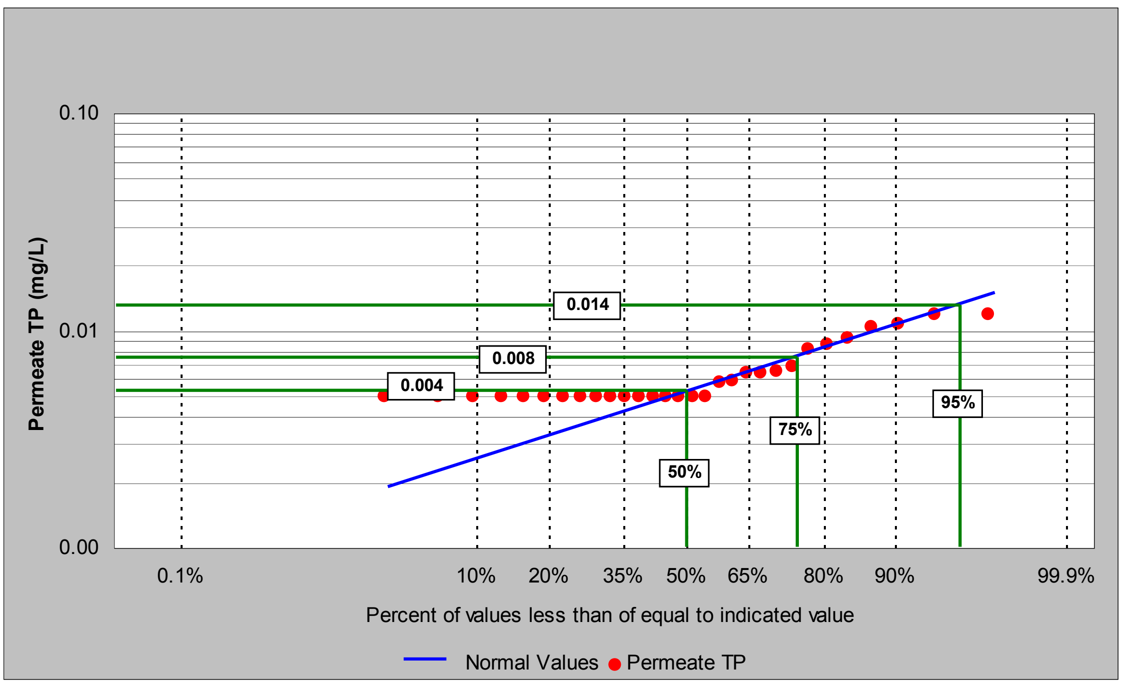

Figure 13. Stage 1 Permeate TP Log Normal Distribution

Feed and permeate ortho phosphate (PO4-P) concentrations are shown in Figure 14. With the exception of three data points, all of the permeate PO4-P results were <0.005 mg/L, the MDL. The RO membrane effectively removed PO4-P from the MBR effluent with an average removal >99.9%.

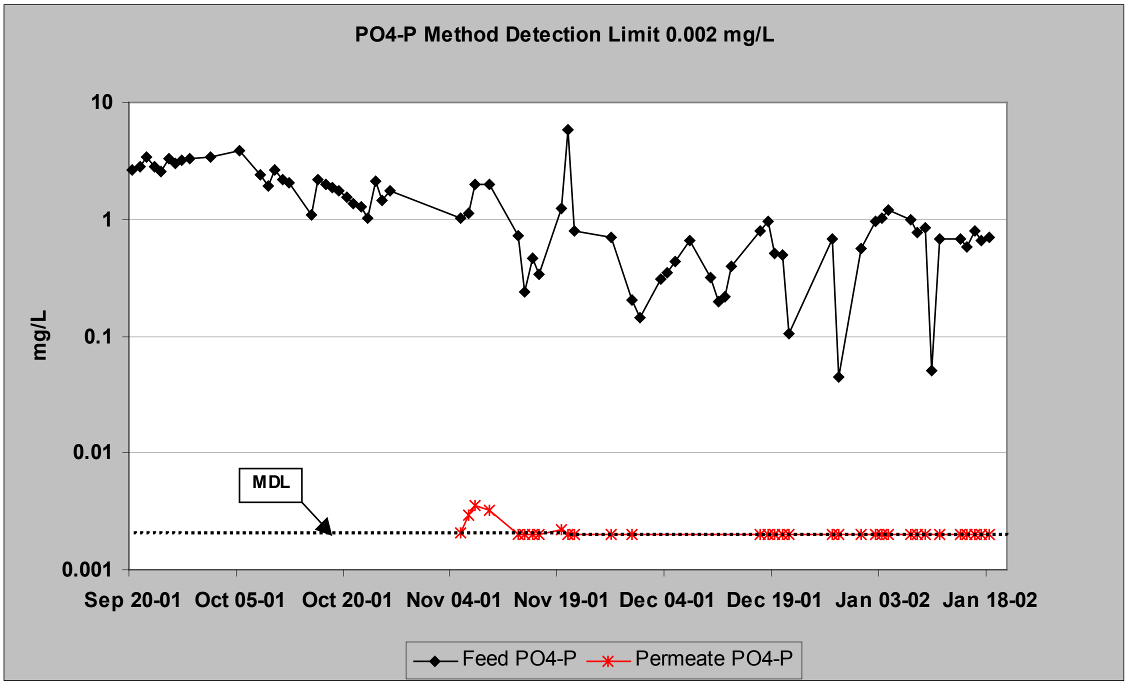

Figure 14. Stage 1 Feed and Permeate PO4-P

Metals and Organics

On September 25, 2001 grab samples of the MBR effluent and RO permeate were analyzed for metals and organics. Table 7 summarizes the metals data. With the exception of aluminum, barium, copper, iron, molybdenum, and zinc, all feed concentrations were non-detectable (i.e., <MDL). There were no detectable levels of metals in the RO permeate.

Table 7. Stage 1 Feed and Permeate Metals

Parameter	Feed Concentration (mg/L)	Permeate Concentration (mg/L)	MDL (mg/L)
Aluminum	0.0133	<0.002	0.002
Antimony	<0.0005	<0.0005	0.005
Arsenic	0.0017	<0.0005	0.005
Barium	0.00342	<0.0002	0.0002
Beryllium	<0.0002	<0.0002	0.0002
Cadmium	<0.0001	<0.0001	0.0001
Chromium	0.0006	<0.0004	0.0004
Cobalt	0.002	<0.0002	0.0002
Copper	0.00953	<0.0004	0.0004
Iron	0.071	<0.05	0.05
Lead	0.00074	<0.0002	0.0002
Molybdenum	0.00917	<0.0005	0.0005
Nickel	0.00325	<0.0003	0.0003
Selenium	<0.0015	<0.0015	0.0015
Silver	<0.0002	<0.0002	0.0002
Thallium	<0.0002	0.00024	0.0002
Vanadium	0.001	<0.0003	0.0003
Zinc	0.0332	<0.0005	0.0005
Mercury	<0.00005	<0.00005	0.00005

The organics data are summarized in Table 8. For all parameters measured, none of the feed or permeate concentrations exceeded the method detection limit. With no detectable organics in the feed, these data cannot be used to evaluate the ability of the RO membrane to remove these organic compounds from the MBR effluent.

Table 8. Stage 1 Feed and Permeate Organics

Parameter	Feed Concentration (µg/l)	Permeate Concentration (µg/l)	MDL (µg/l)
1,1,1-Trichloroethane	<1	<1	1
1,1,2,2-Tetrachloroethane	<1	<1	1
1,1,2-Trichloroethane	<1	<1	1
1,1,2-Trichloroethylene	<1	<1	1
1,1-Dichloroethane	<1	<1	1
1,1-Dichloroethylene	<1	<1	1
1,2-Dichloroethane	<1	<1	1
1,2-Dichloropropane	<1	<1	1
2-Butanone (MEK)	<5	<5	5
2-Chloroethylvinyl ether	<1	<1	1
2-Hexanone	<5	<5	5
4-Methyl-2-Petanone (MIBK)	<5	<5	5
Acetone	<2.5	<2.5	2.5
Acrolein	<5	<5	5
Acrylonitrile	<5	<5	5
Benzene	<1	<1	1
Bromodichloromethane	<1	<1	1
Bromoform	<1	<1	1
Bromoethane	<1	<1	1
Carbon Disulfide	<1	<1	1
Carbon Tetrachloride	<1	<1	1
Chlorobenzene	<1	<1	1
Chlorodibromoethane	<1	<1	1
Chloroethane	<1	<1	1
Chloroform	<1	<1	1
Chloromethane	<1	<1	1
Cis-1,3-Dichloropropene	<1	<1	1
Ethylbenzene	<1	<1	1
Methylene Chloride	<1	<1	1
Styrene	<1	<1	1
Tetrachloroethylene	<1	<1	1
Toluene	<1	<1	1
Total Xylenes	<1	<1	1
Trans-1,2-Dichloroethylene	<1	<1	1
Trans-1,3-Dichloropropene	<1	<1	1
Trichloroflouromethane	<1	<1	1
Vinyl Acetate	<5	<5	5
Vinyl Chloride	<1	<1	1

Stage 2 – MF Effluent Feed

The RO unit received MF effluent from February 3, 2002 to February 27, 2002. Antiscalant was not used during Stage 2, because equilibrium calculations (see Scaling Characteristics section) did not indicate the need, and because the results from Stage 1 did not indicate any benefit was realized from adding antiscalant. From February 20 to 27, alum (50 mg/L) was added to the MF unit feed to enhance phosphorous removal, and this addition reduced the RO feed TP and PO4-P levels.

RO Element Clean Water Performance

The clean water performance data is shown in Table 9 for the Stage 2 membrane module. Testing results were corrected to standard conditions of: 2000 mg/L NaCl feed concentration, 225 psi, 15% recovery, 77 ºF, and pH 7.5. Cleaning was performed by Betz-Dearborn/Argo Scientific using their standard acid (Kleen MCT103) and caustic-detergent (Kleen MCT411).

Table 9. Stage 2 Membrane Clean Water Performance

Description	Before Pilot Test	After Pilot Test	
		Before CIP	After CIP
Permeate Flow, gpd	2,340	920	2260
Flux, gfd	30.0	11.8	29.0
Chloride Rejection, %	99.7	98.8	99.0
Feed-Brine Pressure Drop, psid	3.1	5	3

As with the first element, the permeability of the membrane element was almost completely restored after chemical cleaning. There was some decline in performance, but it is not unusual to observe a small amount of performance loss during the first few operation-cleaning cycles.

Overall, the results indicate the flux loss was not irreversible. Longer-term testing is recommended to fully understand the fouling potential by observing multiple fouling-cleaning cycles to verify that this initial loss would not worsen over time.

Scaling Characteristics

The RO membrane feed was sampled on January 29, 2002 before Stage 2 testing started. At that time, the MF unit was treating BAF #2 effluent. Since the MF membrane does not reject inorganic salts, it was assumed that the target scaling species in the MF unit feed (BAF #2 effluent) would represent the scaling characteristics of the feed to the RO unit.

Table 10 summarizes the parameters and their concentrations measured in the BAF #2 effluent.

Table 10. Scaling Constituents in BAF #2 Effluent[a]

Parameter	Value
Alkalinity, mg/L $CaCO_3$	62.6
TDS, mg/L	nm
Chloride, mg/L	211
Sulfate, mg/L	45.2
Fluoride, mg/L	0.644
NO_2 + NO_3, mg/L	12
Silica, mg/L	16.3
Total Barium, mg/L	0.0025
Total Calcium, mg/L	19.7
Total Iron, mg/L	0.053
Total Magnesium, mg/L	15.9
Total Manganese, mg/L	0.0049
Total Potassium, mg/L	12.6
Total Sodium, mg/L	137
Total Aluminum, mg/L	0.0227

nm = not measured

[a] sample without antiscalant.

Similar to Stage 1, operating at the pilot testing condition of 50 percent recovery, the risk of inorganic scaling is low. Generally, calcium carbonate scaling would not occur at this condition; however, it might occur if conditions worsened beyond what was measured (Table 10).

Fouling Characteristics

Three SDI tests were conducted and the results are shown in Table 11. All values were less than 3, suggesting a low fouling potential with MF effluent, as anticipated based on experience with this technology at other sites.

Table 11. BAF #2 Effluent SDI Values

Date	SDI Value
February 4, 2002	1.4
February 21, 2002	0.9
February 25, 2002	1.1

Stage 2 Operating Data

The membrane temperature-corrected specific flux, TMP, temperature-corrected flux and feed temperature are plotted in Figure 15 for Stage 2.

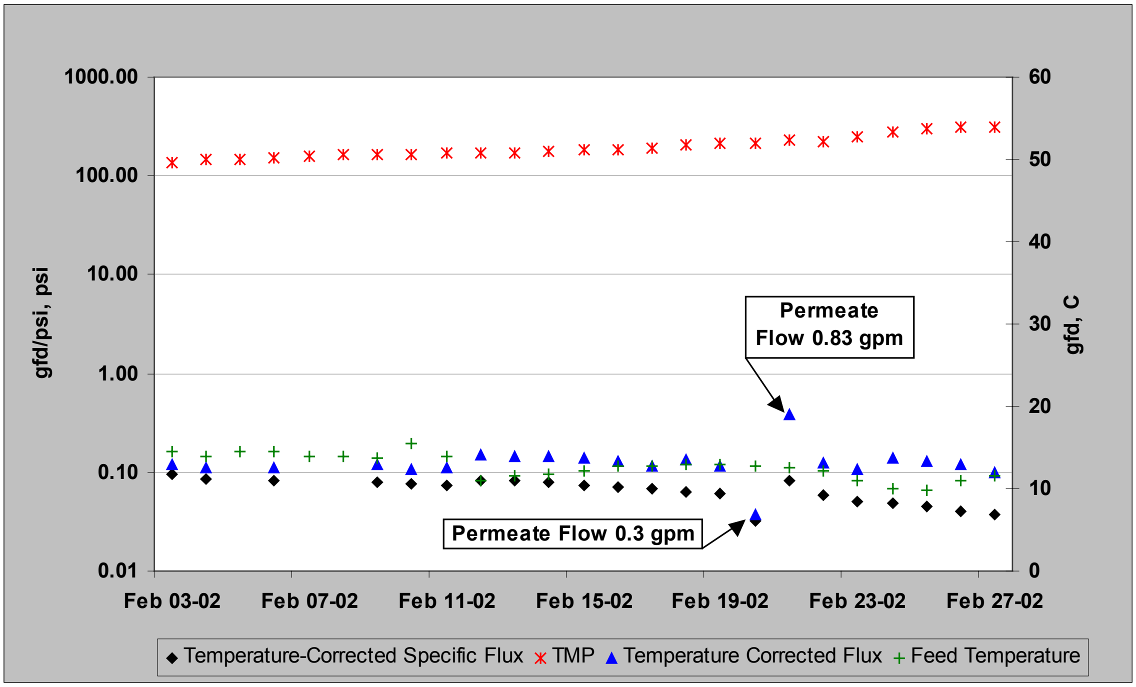

Figure 15. Stage 2 Operating Data

The TMP was initially 137 psi and increased to 314 psi by the end of the 3-week testing. This was a much faster TMP increase than the increase observed during Stage 1.

Except for two days, the temperature-corrected flux remained between 12 and 14 gfd. On February 20, the observed permeate flow rate was 0.3 gpm. The operator adjusted the valves, and the next day permeate flow was 0.83 gpm, which exceeded the 0.6 gpm set point. The valves were adjusted again and the permeate flow rate remained at 0.5 to 0.6 gpm for the rest of the testing.

The temperature-corrected specific flux was initially 0.09 gfd/psi and decreased to 0.04 gfd/psi by the end of the test. A 55% reduction in specific flux indicates the membrane fouled under constant permeate flow rate conditions for the MF effluent. The feed temperature was initially 15.5 ºC and decreased to as low as 9.7 ºC.

The decline in temperature-corrected specific flux increased right after the increase in permeate flow from 0.3 to 0.83 gpm. This could have caused some scale formation. Under these conditions, the system recovery increased above 50%, which increases the concentration of rejected species at the membrane surface. This can cause inorganic species to exceed their precipitation limit. Once precipitation takes place, the crystals will provide nuclei for subsequent precipitation, causing more scaling.

Figure 16 shows the feed and permeate conductivity data. The average permeate conductivity was 6 µmho/cm compared to the average feed conductivity of 621 µmho/cm. The conductivity passage ranged between 0.6 and 1.4%. Overall these data show low conductivity passage and therefore, a high salt rejection.

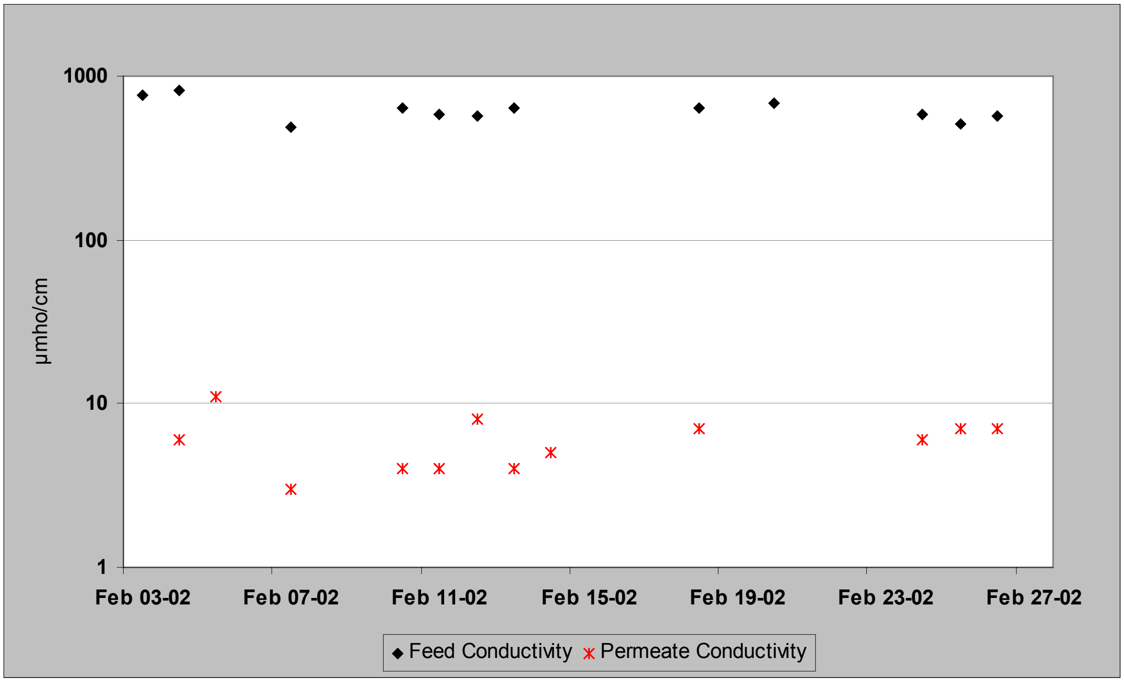

Figure 16. Stage 2 Feed and Permeate Conductivity

Water Quality

TDS, TOC, and nutrients were measured in the feed and permeate. Automatic samplers were used to collected 24-hour composites for measurement of conductivity, TDS and TKN by the West Point WWTP Process Laboratory. Grab samples were also collected for analysis of TOC and other nutrients by the King County Environmental Laboratory. On January 29, 2002 feed and permeate grab samples were collected and analyzed for metals, organics, and microorganisms. A few microbiological parameters, along with Total Suspended Solids (TSS) were also measured in the feed and permeate and are discussed at the end of this section.

Table 12 summarizes TDS, TOC, and nutrients data including percent removal. Since the alum pre-treatment for the MF unit decreased the RO feed TP and PO4-P concentrations, the phosphorous data is presented with the alum-pretreatment data separate from the no alum pretreatment data.

All data collected were used to calculate the feed and permeate concentration statistics presented. For many parameters, the permeate concentrations were less than the laboratory method detection limit (MDL). These data were assigned the MDL value for the statistical calculations. Percent removal was calculated using the average feed and permeate concentrations.

Table 12. Stage 2 Water Quality Summary

Parameter	Average	Minimum	Maximum	Lab MDL
TDS				
Feed, mg/L	386	280	496	na
Permeate, mg/L	30	10	54	na
Removal, percent	92.2	-	-	
TOC				
Feed, mg/L	7.365	4.390	9.560	0.5
Permeate, mg/L	1.208	0.950	1.390	0.5
Removal, percent	83.6	-	-	
NITROGEN COMPOUNDS				
TKN				
Feed, mg/L	0.890	0.340	1.940	0.01
Permeate, mg/L	0.08	0.05	0.14	0.01
Removal, percent	>91.0[a]	-	-	
NH4-N				
Feed, mg/L	0.610	0.033	2.350	0.01
Permeate, mg/L	0.015	0.010	0.040	0.01
Removal, percent	97.5	-	-	
NO3-N				
Feed, mg/L	9.877	5.550	12.90	0.02
Permeate, mg/L	0.1666	0.102	0.219	0.02
Removal, percent	>98.0[a]	-	-	
PHOSPHOROUS COMPOUNDS				
TP (no alum in MF feed)				
Feed, mg/L	1.6	1.0	2.5	0.005
Permeate, mg/L	<0.005	<0.005	0.007	0.005
Removal, percent	>99.7[a]	-	-	
TP (alum in MF feed)				
Feed, mg/L	0.033	0.015	0.056	0.005
Permeate, mg/L	<0.005	<0.005	<0.005	0.005
Removal, percent	>84.9[a]	-	-	
PO4-P (no alum in MF feed)				
Feed, mg/L	1.483	0.900	2.260	0.002
Permeate, mg/L	<0.002	<0.002	0.003	0.002
Removal, percent	>99.9	-	-	
PO4-P (alum in MF feed)				
Feed, mg/L	0.004	0.002	0.009	0.002
Permeate, mg/L	<0.002	<0.002	<0.002	0.002
Removal, percent	>50.0[a]	-	-	

na not applicable
- percent removal calculated only for average feed and permeate data
[a] shown as greater than calculated value because the average permeate includes values <MDL

The following subsections present the feed and permeate concentrations for each water quality parameter. Special sampling results for metals and organics are presented in the last subsection., followed by the TSS and microbial data.

TDS

Figure 17 shows feed and permeate TDS. These data indicate the RO membrane provided a high rejection of TDS. The average removal rate was 92.2%.

Figure 18 shows a log normal distribution of the permeate TDS data. The 95^{th} percentile was 62.6 mg/L and the RO membrane achieved the performance goal of < 100 mg/L at the 95^{th} percentile.

TOC

Figure 19 shows feed and filtrate TOC. The average removal was 83.6%.

Figure 20 shows log normal distribution of the permeate TOC. The 90^{th} percentile value is 1.38 mg/L. These data indicate the RO membrane did not achieve the performance goal of permeate TOC <1 mg/L at the 90^{th} percentile when treating the MF filtrate.

Nitrogen Compound

Figure 21 includes feed and permeate TKN concentrations. The average removal was >91%.

NH4-N feed and permeate concentrations are shown in Figure 22. The average removal was 97.5%.

Figure 23 shows NO3-N feed and permeate concentrations. The RO membrane achieved a consistently high nitrate rejection rate. Only three permeate NO3-N values were above the method detection limit. The average removal was 98%.

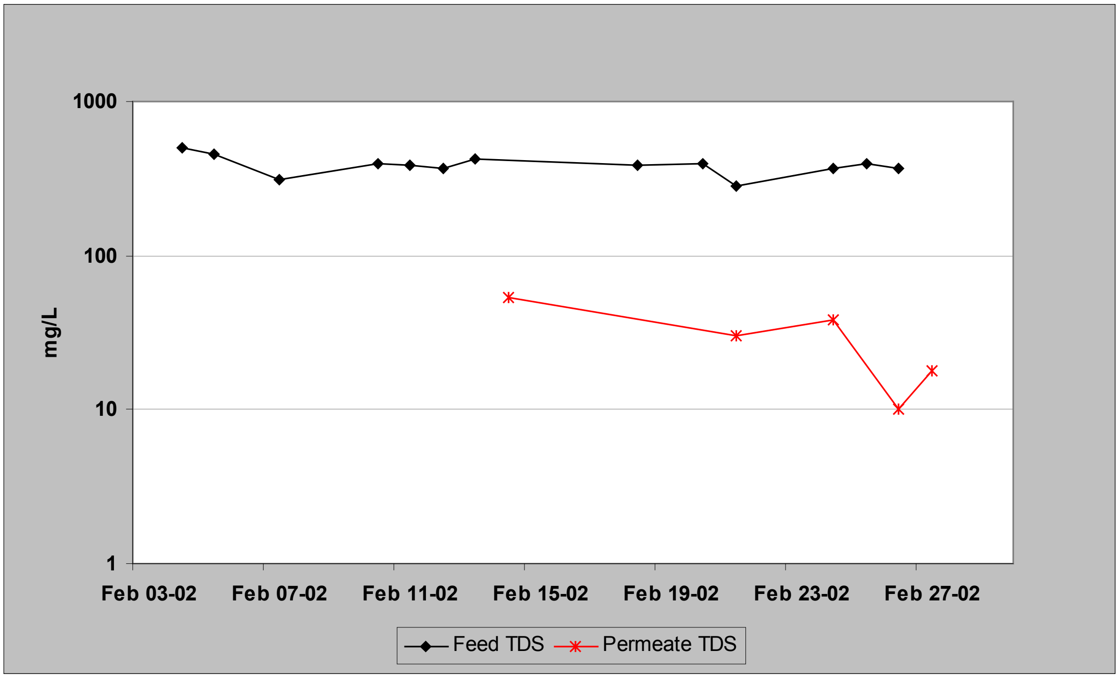

Figure 17. Stage 2 - Feed and Permeate TDS

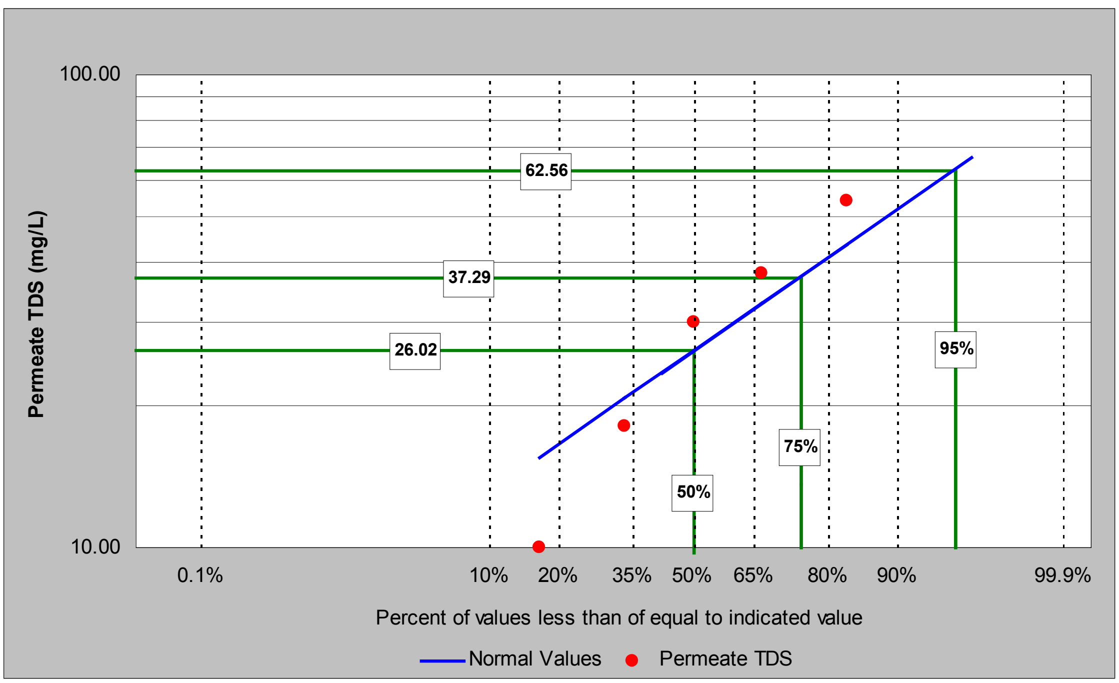

Figure 18. Stage 2 - Permeate TDS Log Normal Distribution

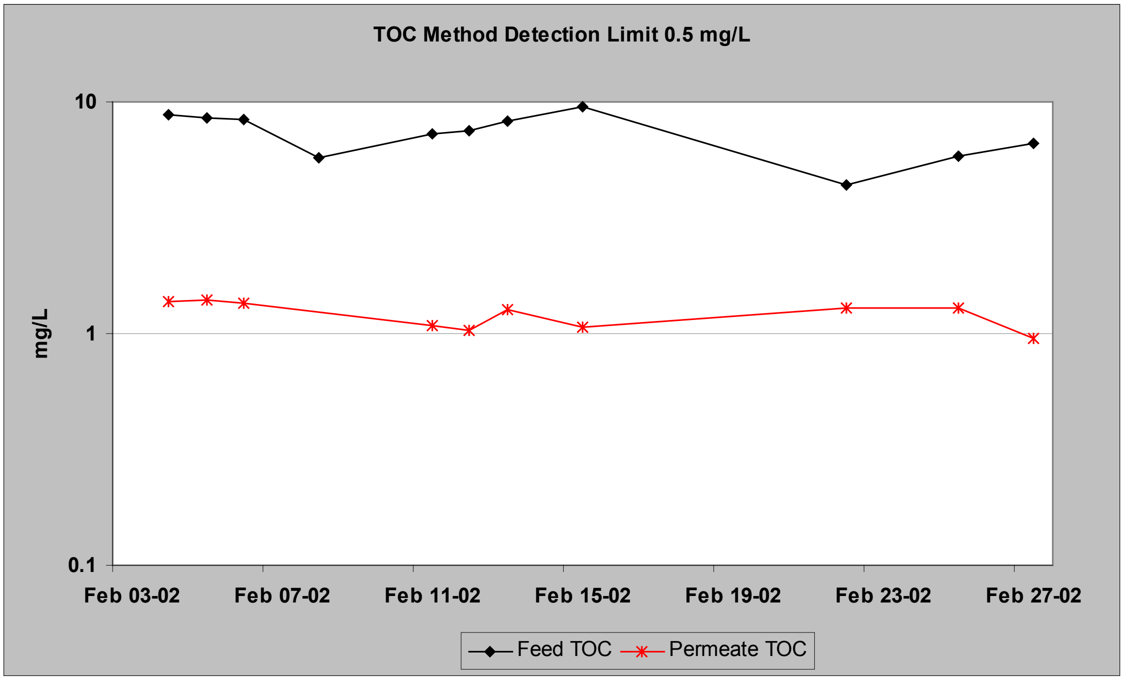

Figure 19. Stage 2 - Feed and Filtrate TOC

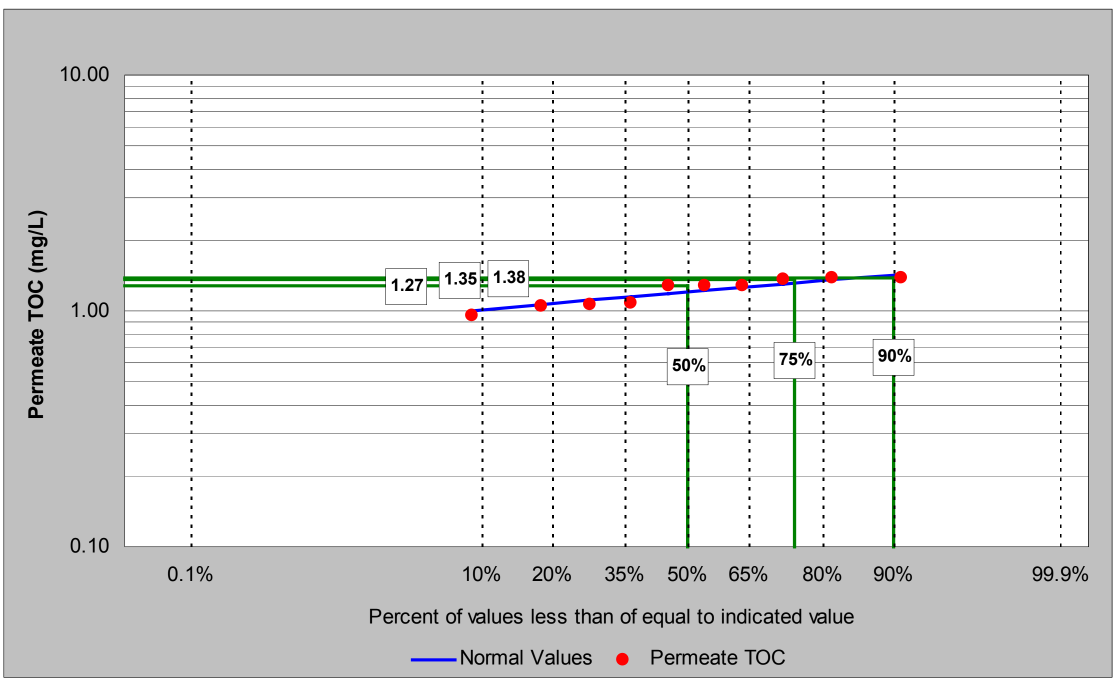

Figure 20. Stage 2 Permeate TOC Log Normal Distribution

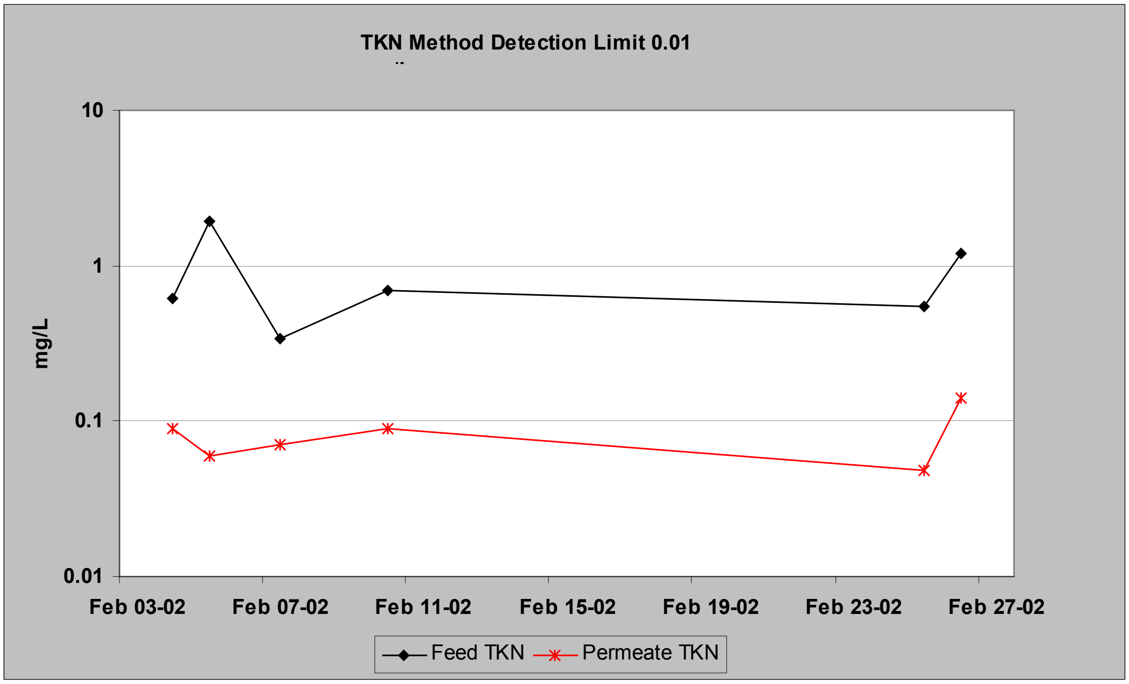

Figure 21. Stage 2 - Feed and Permeate TKN

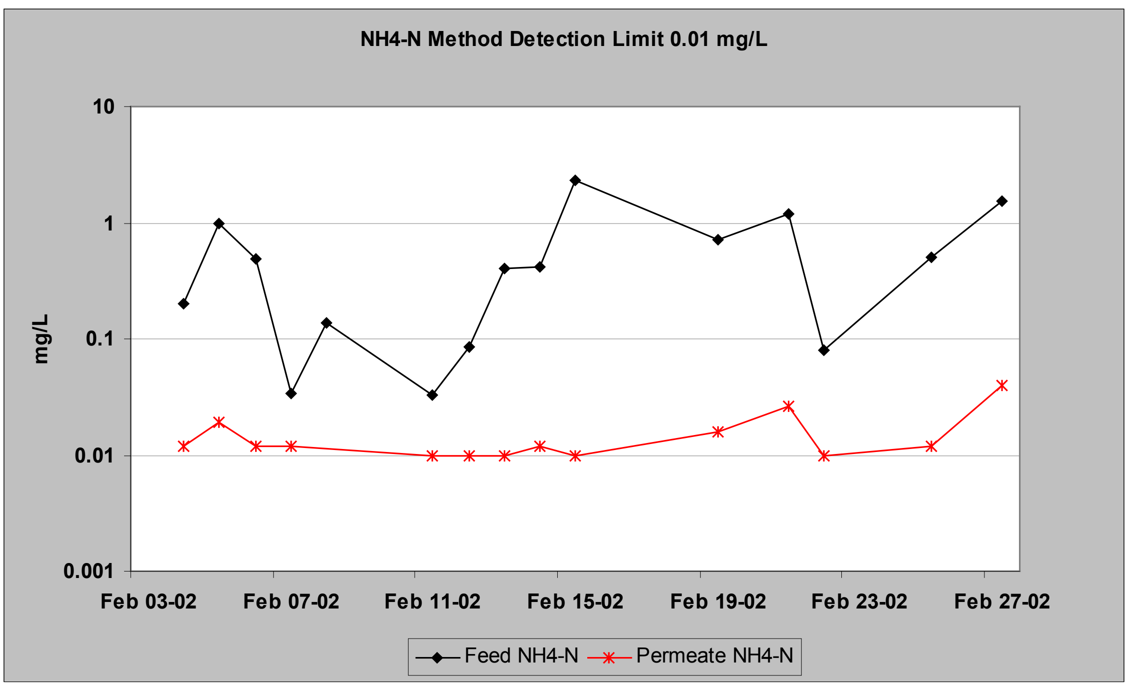

Figure 22. Stage2 Feed and Permeate NH4-N

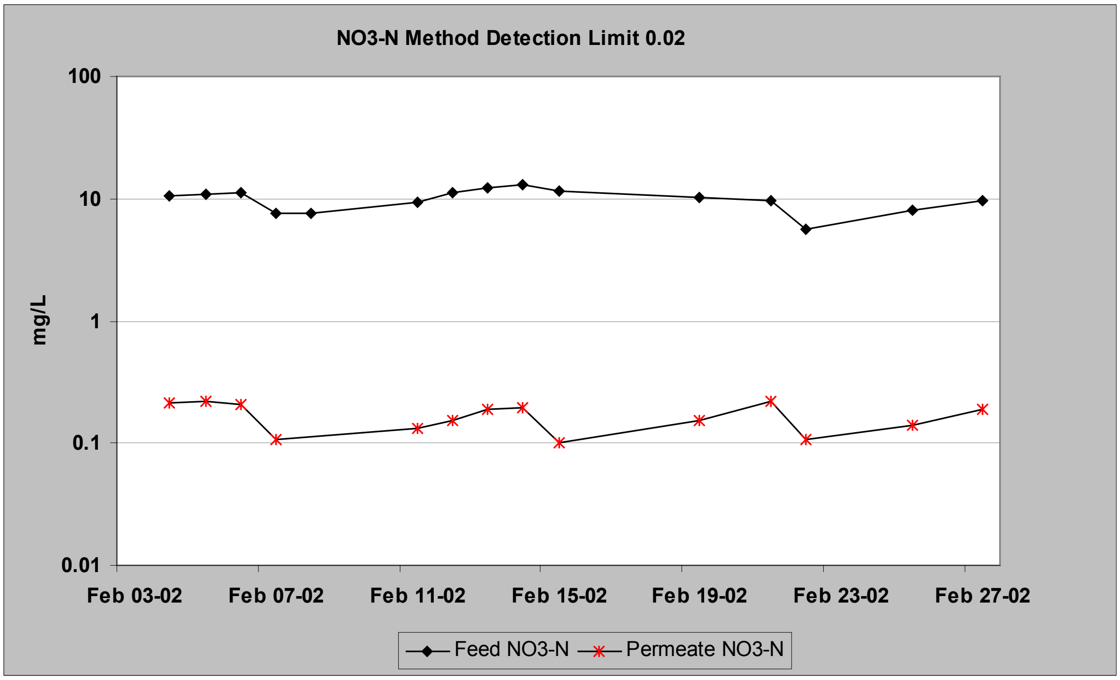

Figure 23. Stage 2 Feed and Permeate NO3-N

Phosphorous Compounds

Figure 24 shows the feed and permeate TP concentrations. On February 20, 2002 the feed TP decreased because alum pre-treatment was initiated on the MF unit feed. The addition of alum enhanced the MF unit's ability to remove TP, which reduced the MF filtrate (RO feed) TP levels. Before alum pre-treatment, the RO membrane achieved an average TP removal >99.7%. With alum pre-treatment, the average TP removal was >84.9% (lower than with no alum pre-treatment due to the lower feed TP concentration). The permeate TP levels were just above the MDL or non-detectable.

A log normal distribution of the permeate TP is shown in Figure 25. The entire permeate TP data set is included in this analysis. Permeate TP was 0.0067 mg/L at the 90^{th} percentile, which met the performance goal of <0.02 mg/L at the 90^{th} percentile. Note that the MDL for TP is 0.005 mg/L.

Figure 26 shows feed and permeate PO4-P concentrations. Alum pre-treatment for the MF unit feed had a similar impact on the RO unit PO4-P feed concentrations. Before alum pre-treatment, the RO membrane achieved an average PO4-P removal >99.9%. With alum pre-treatment, the average removal was >50%. This lower removal rate with alum pre-treatment is due to a lower feed TP level in the RO feed. The permeate PO4-P concentration was just above the MDL or non-detectable.

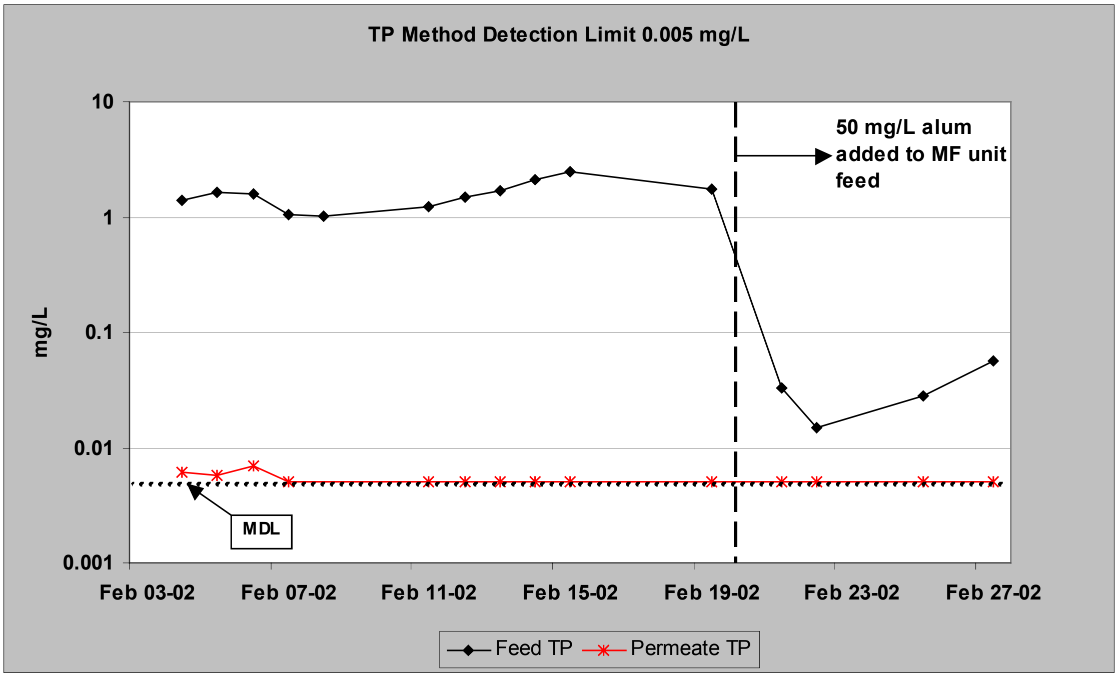

Figure 24. Stage 2 Feed and Permeate TP

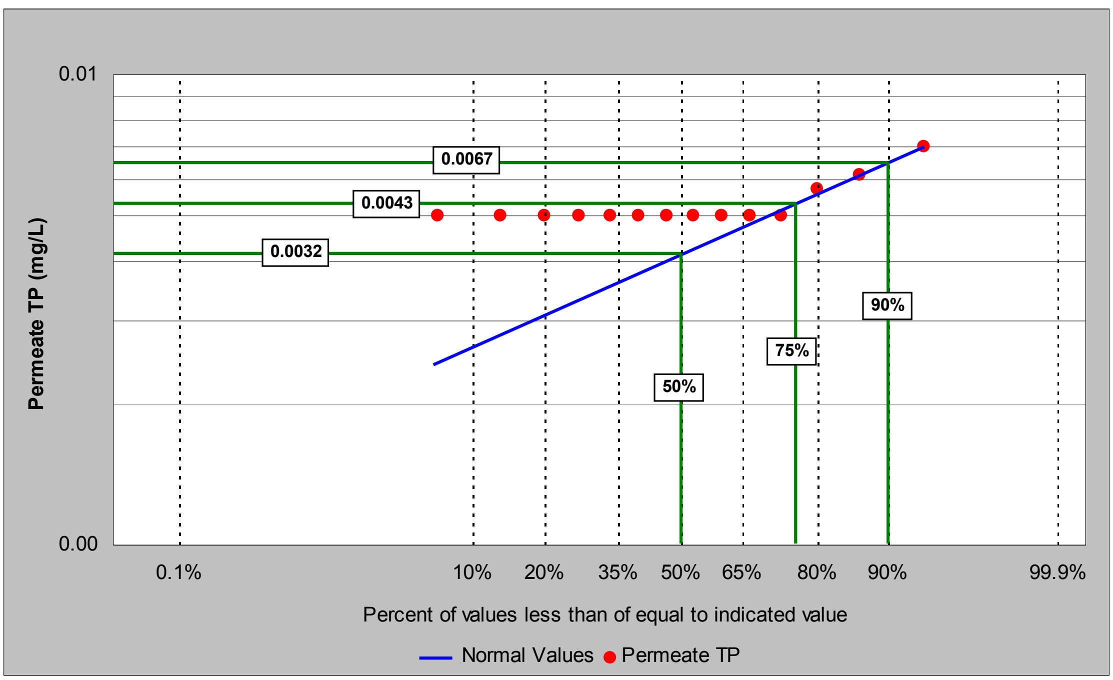

Figure 25. Stage 2 Permeate TP Log Normal Distribution

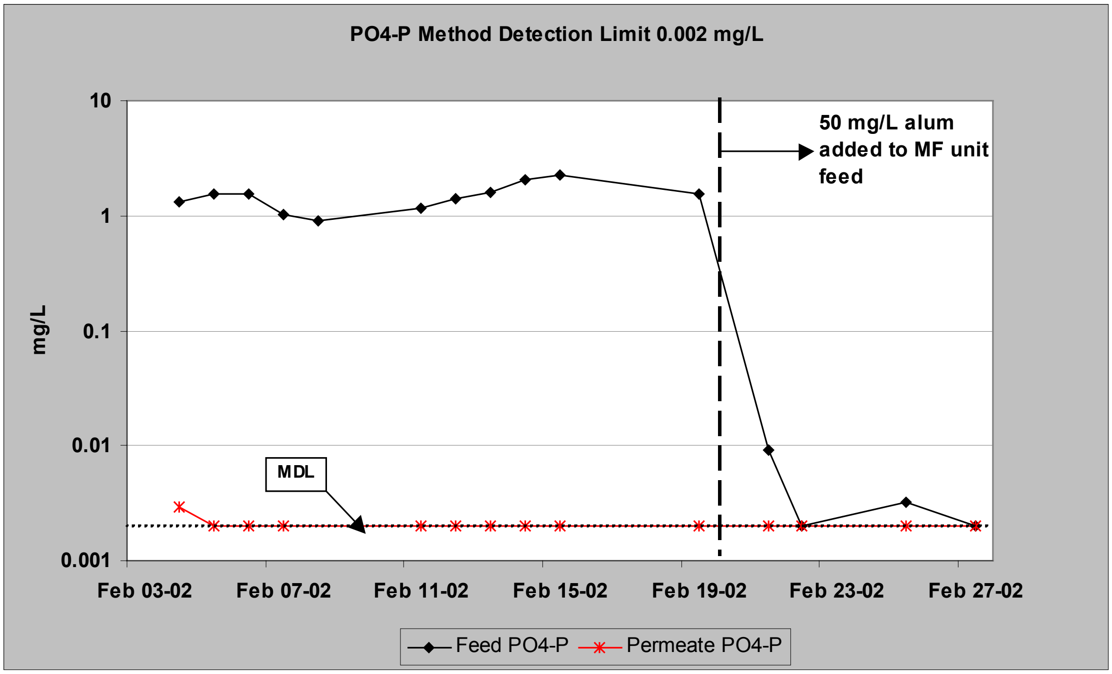

Figure 26. Stage 2 Feed and Permeate PO4-P

Metals and Organics

On January 29, 2002 grab samples of the BAF #2 effluent and RO permeate were analyzed for metals and organics. This was before the RO unit began continuous operation for Stage 2. However, to accommodate this special sampling, the RO unit was turned on for several hours on January 29, 2002 to collect the permeate sample.

Table 13 summarizes the metals data. The following metals were detected in the RO feed at concentrations above the MDL: aluminum, barium, chromium, cobalt, copper, iron, lead, molybdenum, nickel, vanadium and zinc. The remaining metals analyzed in the feed were below the MDL. There were no detectable levels of metals in the RO permeate.

Total Suspended Solids

Total suspended solids were measured on the feed and permeate. The average feed and permeate levels were 2 mg/L and 1.5 mg/L, respectively.

Microbiological

Heterotrophic plate counts (HPC) and total Coliform (TC) levels were measured in grab samples of the feed and permeate three days during Stage 2; one sample each day. The average feed and permeate HPC counts were 38,600 CFU/100 mL and 1,500 CFU/100 mL, respectively. The average feed TC level was only 16 CFU/100 mL. There was no evidence of TC measured in the three permeate grab samples. The values reported by the county Environmental Laboratory were 0 CFU/100 mL.

Table 13. Stage 2 Feed and Permeate Metals

Parameter	Feed Concentration (mg/L)	Permeate Concentration (mg/L)	MDL (mg/L)
Aluminum	0.0133	<0.002	0.002
Antimony	<0.0005	<0.0005	0.005
Arsenic	0.0017	<0.0005	0.005
Barium	0.00342	<0.0002	0.0002
Beryllium	<0.0002	<0.0002	0.0002
Cadmium	<0.0001	<0.0001	0.0001
Chromium	0.0006	<0.0004	0.0004
Cobalt	0.002	<0.0002	0.0002
Copper	0.00953	<0.0004	0.0004
Iron	0.071	<0.05	0.05
Lead	0.00074	<0.0002	0.0002
Molybdenum	0.00917	<0.0005	0.0005
Nickel	0.00325	<0.0003	0.0003
Selenium	<0.0015	<0.0015	0.0015
Silver	<0.0002	<0.0002	0.0002
Thallium	<0.0002	0.00024	0.0002
Vanadium	0.001	<0.0003	0.0003
Zinc	0.0332	<0.0005	0.0005
Mercury	<0.00005	<0.00005	0.00005

Table 14 shows that of all the organic compounds analyzed, both the feed and permeate samples had non-detectable levels except methylene chloride.

Table 14. Stage 2 Feed and Permeate Organics

Parameter	Feed Concentration (µg/l)	Permeate Concentration (µg/l)	MDL (µg/l)
1,1,1-Trichloroethane	<1	<1	1
1,1,2,2-Tetrachloroethane	<1	<1	1
1,1,2-Trichloroethane	<1	<1	1
1,1,2-Trichloroethylene	<1	<1	1
1,1-Dichloroethane	<1	<1	1
1,1-Dichloroethylene	<1	<1	1
1,2-Dichloroethane	<1	<1	1
1,2-Dichloropropane	<1	<1	1
2-Butanone (MEK)	<5	<5	5
2-Chloroethylvinyl ether	<1	<1	1
2-Hexanone	<5	<5	5
4-Methyl-2-Petanone (MIBK)	<5	<5	5
Acetone	<2.5	<2.5	2.5
Acrolein	<5	<5	5
Acrylonitrile	<5	<5	5
Benzene	<1	<1	1
Bromodichloromethane	<1	<1	1
Bromoform	<1	<1	1
Bromoethane	<1	<1	1
Carbon Disulfide	<1	<1	1
Carbon Tetrachloride	<1	<1	1
Chlorobenzene	<1	<1	1
Chlorodibromoethane	<1	<1	1
Chloroethane	<1	<1	1
Chloroform	<1	<1	1
Chloromethane	<1	<1	1
Cis-1,3-Dichloropropene	<1	<1	1
Ethylbenzene	<1	<1	1
Methylene Chloride	1.2	<1	1
Styrene	<1	<1	1
Tetrachloroethylene	<1	<1	1
Toluene	<1	<1	1
Total Xylenes	<1	<1	1
Trans-1,2-Dichloroethylene	<1	<1	1
Trans-1,3-Dichloropropene	<1	<1	1
Trichloroflouromethane	<1	<1	1
Vinyl Acetate	<5	<5	5
Vinyl Chloride	<1	<1	1

Evaluation of Pilot Results

Effectiveness of Technology to Achieve Performance Goals

Table 15 summarizes performance goals and Stage 1 and Stage 2 results.

Table 15. Effectiveness of Process to Achieve Performance Goals

Goal Description	Reliability Percentile	Target	Measured Performance	
			Stage 1	Stage 2
TDS Removal	95th	<100 mg/L	109 mg/L	62.6 mg/L
Turbidity Removal	95th	<0.1 NTU	Not Measured[a]	Not Measured[a]
TOC Removal	90th	<1 mg/L	1.56 mg/L	1.38 mg/L
TP Removal	90th	<0.02 mg/L	0.014 mg/L	0.0067 mg/L
Long-Term Flux Decline		<2% per year	Not Measured[b]	Not Measured[b]

[a] no reliable turbidity measurement, little if any solids in the RO permeate
[b] Unable to measure due to the pilot test duration

The performance of the RO for specific parameters is discussed below.

TDS Removal

The RO membrane achieved the performance goal of <100 mg/L TDS at the 95th percentile for Stage 2. However, for Stage 1, TDS removal was 109 mg/L at the 95th percentile. The data set had only five data points for each test stage. With the caveat that the number of data points was small, it is anticipated that the RO membrane can the performance goal when treating MF effluent.

Turbidity Removal

This performance goal was not evaluated because turbidity could not be reliably measured in the RO permeate. The permeate turbidity levels were below the measuring accuracy of the turbidimeter.

TOC Removal

The RO membrane did not achieve the 90th percentile performance goal of <1 mg/L TOC. The actual 90th percentile values were 1.56 and 1.38 mg/L for Stage 1 and 2, respectively.

TP Removal

The RO membranes achieved the TP 90th percentile performance goal of <0.02 mg/L. Most of the permeate samples analyzed were below the detection limit of 0.005 mg/L.

Long-Term Flux Decline

The clean-water performance data for both membranes were similar and indicated a good recovery of membrane performance after one chemical clean. However, to fully assess long-term flux decline, additional filtration/cleaning cycles need to be tested.

Long-term flux decline would be evaluated in a pilot test by comparing the new membrane clean water flux to the post chemical cleaning clean water flux. Post-clean flux data from at least two to three chemical cleans is recommended. A chemical clean is conducted when the system inlet pressure exceeds a specified set point (for the membrane used in this pilot study, a typical set point would be 400 psi).

Reliability Considerations

The reliability of the RO membrane process to achieve the performance goals is described in detail in the previous results sections. The RO membrane reliably achieved the TDS and TP performance goals. However, it did not achieve the TOC goal, for either test stage.

Pilot Unit Observations

The RO pilot unit system was simple and easy to operate. Throughout the testing, the County operators recorded detailed comments on the pilot unit operation. These comments are included in Appendix B. The following summarizes the main observations recorded by the operators.

- The manual flow control required daily operator attention to maintain the target set points.
- Because the RO membrane was not resistant to free chlorine, the operators had to shut down the RO unit during Stage 1 when a maintenance clean was conducted on the MBR unit. The MBR maintenance clean included a backwash with chlorine solution.

Implementation

Design Criteria

The intent of this pilot test was to demonstrate the ability of the RO membrane to remove specific pollutants from the feed stream while operating under "typical" plant conditions. Using only one brand of RO membrane, albeit one that is commonly used in reuse applications, flux, chemical addition and chemical cleaning were not optimized. Therefore, full-scale implementation of the RO membrane process will have to be based on previous experience and other pilot testing information. In general, for treating a feed stream similar to the MBR effluent or MF filtrate, a single module operating at 50 percent recovery would meet the permeate water quality goals. A full-scale plant would likely be designed for an 85% recovery using a multi-stage design.

Full-scale design criteria for the RO membrane tested includes:

- Operating Pressure: 100 to 400 psi.
- Average Flux at 20 ºC: 9 gfd.

- System Recovery: 70 to 85 percent.

Design Features

The following features would be included in a full-scale RO membrane application for enhanced nutrient removal of MBR or MF effluent.

- **Chemical Addition Facilities.** Chemical feed facilities with automatic dosing control for antiscalant and acid addition and for chemical cleans.
- **Monitoring and Process Control.** Provide on-line instrumentation to monitor pressure, flow and post acid-feed pH. Flow control will be automated to maintain a permeate flow rate design point.
- **Dechlorination.** Because the RO membrane is not resistant to free chlorine, dechlorination facilities will be required for treating MF effluent, if chlorine is added to the MF feed.
- **Residuals.** The concentrated brine stream will require disposal. The stream can be toxic to receiving waters. Also, spent cleaning chemicals will require disposal. For a full-scale installation, it is anticipated that the brine and spent chemicals will be discharged to the local sewer.
- **Effluent Blending.** The RO permeate could be corrosive because most of the inorganic species will be removed by the membrane. If this is the case, blending the RO permeate with a non-RO treated reuse stream may be considered to minimize the corrosive nature of the permeate.

Issues Not Resolved By Pilot Test Program

- The impact on permeate water quality by increasing the system recovery.
- The impact on scaling using antiscalant and acid addition when treating MF effluent.
- Operator experience with chemical cleaning an RO membrane.
- The determination of nutrient removal was somewhat limited because many of the permeate data points were below detection levels.
- The determination of TDS removal was limited because there were only five data points collected for each test stage.
- Long-term fouling could not be measured.

References

Black & Veatch, Inc., 2001 Model RO-2001 Pilot Unit Operations Manual.

Appendix A - Test Plan Revisions, Test Plan and RO Unit Operation Manual

Appendix B - Pilot Unit Photos and Operator Comments

Reverse Osmosis Test Plan Revisions Summary

Introduction

This memorandum is a brief summary of the actual test conditions for the reverse osmosis membrane pilot unit. It focuses on changes and modifications from the last version of the microfiltration membrane pilot test plan, *Procedure H-08 Reverse Osmosis Operation Rev. 1 Draft, October 16, 2001*. This memorandum does not replace the test plan. The intent is for the reader to reference it in conjunction with the test plan, which is also included in Appendix A.

The changes and modifications are summarized below. Each major heading corresponds to a section of the test plan affected.

Pilot Unit Description

Operating Conditions

The percent recovery remained at 50% for all of the testing. Testing at 85% recovery was dropped (see below).

Pilot Testing Objectives

Full-Scale Considerations

Testing at 85% recovery was not conducted because optimizing the system recovery was not a main objective of the pilot testing. Operating a single-element system at 50% recovery provided a permeate water quality similar to a full-scale system operated at 85% recovery.

Pilot Test Plan

Overview

Phase 1 and 2 are referred to as Stage 1 and 2 in the *Reverse Osmosis Membrane Advanced Treatment Memorandum* (RO Report).

Schedule

Table 1 summarized the anticipated test phases and individual test runs to be conducted. Each run was to address treating either MBR effluent or MF unit effluent. For the MBR effluent testing, the MBR feed stream would always be West Point WWTP primary influent. However, the feed to the MF unit could have included BAF #1 effluent or BAF #2 effluent. Due to changes in the anticipated schedule for operating the upstream unit processes, many of the anticipated runs were not conducted. Also, the runs designated for 15% system recovery were dropped. The conditions actually tested are listed below.

- Phase 1 (Stage 1): MBR effluent, Run 1.
- Phase 2 (Stage 2): BAF #2, Run 7.

Sampling

Operational

The County operators measured the SDI on each feed twice for each test stage, instead of twice per week.

To limit the number of special tests conducted by the County Environmental Laboratory, special testing on the recycle stream was not conducted.

Sampling Plan

The sampling plan included in the test plan was an estimation of the schedule and timing for various parameters measured. However, the actual test schedule changed from week to week. Beginning in December 2001, the actual sampling plan for all of the pilot units was updated by the County weekly and reviewed by the consultant team.

Appendices

The appendices included in the original test plan are no longer provided in this Appendix. The sampling plan was updated regularly as noted above. The data management system RO Operation Data Sheet can be found in the County's data management system files.

Reverse Osmosis Test Plan

RO Test Plan Rev. 1b Draft

October 16, 2001

Background and Purpose

The reverse osmosis (RO) unit, supplied by Black & Veatch (B&V), is one of eight unit processes to be tested during the King County Water Reuse Demonstration Project. It is being tested as an advanced treatment step (i.e., post tertiary filtration) and will treat various sources of tertiary effluent during the overall testing program. The unit arrived on site the week of August 27. The B&V startup engineer started it up the week of September 17. This unit will be on site for six months: months 4 through 9 of the overall testing program.

The *Water Reuse Demonstration Project, Test Plan, Rev. 2, August 15, 2001* depicts the "big picture" testing program for all eight pilots units and the entire nine-month testing program. It summarizes the performance goals for each test unit. This unit-specific test plan provides a detailed road map for operating the RO unit to meet the objectives of the overall testing program.

Pilot Unit Description

The Model RO-2001 Pilot Unit Operations Manual, Black & Veatch, August 2001 provides a detailed description of the pilot unit.

Modes of Operation

The unit operates in the follow modes:

- Normal Operation: Normal operation occurs when water is passed through the membrane. With a spiral-wound membrane cartridge configuration, backwashing is not done. To minimize fouling, acid and an anti-scalant is added to the feed stream.

- Membrane Cleaning: When the pressure drop across the membrane increases by 15 percent, the membrane is taken off line and cleaned. The cleaning protocol includes a low-flow recirculation step followed by high-flow recirculation.

Membrane Characteristics

Black & Veatch selected a reverse osmosis membrane that has performed well on other reuse projects. Only one membrane type will be used throughout the testing. The membrane selected is manufactured by Koch/Fluid Systems. The membrane characteristics are listed below:

- Model No.: TFC 4820 HR
- Material: polyamide, thin-film composite
- Active filter area: 78 square feet (sf)

- Module size: 4 inches wide by 40 inches long

The RO unit was shipped with one spare RO membrane.

It should be noted that this membrane is not resistant to free chlorine. Based on recent experience at other plants, this membrane can handle chloramine concentrations up to 5 ppm.

For this project, the feed streams to the RO unit must not contain any free chlorine. Feed chloramine concentrations should be below 5 ppm.

Instrumentation and Control

Refer to the PI&D in the back of the O&M manual for details on the RO unit instrumentation. All valves and instruments are controlled manually. The County operators will record all instrument readings manually.

Operating Conditions

Based on the startup data collected the week of September 17, the RO unit operating conditions will be as follows:

- Permeate flow: 0.6 gpm
- Membrane flux: 11 gfd
- Recirculation Flow: 6.5 gpm
- Concentrate Flow: 0.6 gpm
- System Recovery: 50%
- Anti-scalant Feed: 2.25 gpm
- Anti-scalant: Argo Scientific/Betz Dearborn AF 150 UL, 7,000 mg/l stock solution
- Anti-scalant chemical feed pump: Feed stock solution at 90 ml/min into the 1.2 gpm feed stream.

With the exception of system recovery, it is not anticipated that these operating conditions will change for the six months of testing. The system recovery may be increased to 85% for full-scale considerations, which are discussed in a subsequent section of this Plan.

Under these conditions, the RO unit will be able to demonstrate that this technology can provide a permeate water quality that meets the water quality goals for groundwater, stream and lake discharge.

In order to maintain these operating conditions, the County operators will need to adjust the following about every other day:

- Permeate flow: controlled by the booster pump speed on the electrical panel
- Recycle (recirculation) flow: controlled by valve MV-5.
- Concentrate flow: controlled by valve MV-4 with MV-3 (high flow range) valve closed.
- Anti-scalant feed rate: check the feed pump output and adjust as needed to maintain 90 ml/min.

Pilot Testing Objectives

The pilot testing objective will be to determine the ability of the RO unit to meet nutrient removal requirements focused on permeate nitrogen and phosphorous limits.

Key performance questions for the RO unit are:

- What nutrient and TDS removal rates can be achieved?
- What is the head loss across membrane, transmembrane pressure (TMP)?
- What is the achievable flux rate?
- What recovery rate can be achieved?
- What are the long-term fouling characteristics?

The specific performance goals are listed below.

- Effluent TDS < 100 mg/L, 95th percentile
- Effluent turbidity < 0.5 NTU, 95^{th} percentile
- Effluent total phosphorous (TP) concentration <0.02 mg/L, 90^{th} percentile
- Effluent TOC <1 mg/L, 90^{th} percentile
- Less than 2% long-term flux decline per year.

Full-Scale Considerations

The results from this testing will provide reliable flux- and recovery-rates for consistent treatment performance. With the recovery at only 50% and only using a single module, the results from other full-scale systems and pilot studies will be used in conjunction with the data from this project to determine the recovery for a full-scale treatment train.

Since full-scale plants typically operate at a total plant recovery of 85%, the pilot unit will be operated at 85% recovery for a seven-day period during several of the test runs. This will provide some additional information on the permeate water quality at 85% recovery conditions.

Pilot Test Plan

Overview

The RO unit pilot testing will include the two phases listed below. Each phase is based on the feed stream to the unit, which will come either from the MBR or the MF unit.

- Startup – This was completed the week of September 17. The system is operating as expected and the operating conditions have been established for the remainder of the testing. It is not expected that the operating conditions will change between test phases.

- Phase 1 – Nutrient removal demonstration with MBR filtrate.

- Phase 2 – Nutrient removal demonstration with MF filtrate.

Test Conditions

Startup has been completed and the system will run per the aforementioned operating conditions while treating both feed streams. The unit will be operated in a constant flow condition while monitoring an increase in TMP as the membrane fouls.

Schedule

Table 1 depicts the testing schedule for the RO unit. It is based on 23 weeks of testing to be completed at the end of Month 9, February 2002. There are four runs for treating the MBR filtrate and six runs for treating the MF filtrate.

Table 1. Test Phases and Schedule

Phase	Run	Expected Duration	Weekly Schedule[1]
1 - MBR Effluent Nutrient Removal	1 - MBR treating WP PE & WP PI, Nit/Denit Mode, 50% REC	5 weeks	Weeks 1 - 5: 9/24 to 10/28
	2 - MBR treating WP PE & WP PI, Nit/Denit Mode 15% REC	1 week	Week 6: 10/29 to 11/4
2 - MF Effluent Nutrient Removal	3 - MF Filtrate from treating BAF 1 effluent. BAF 1 treating WP PE [2] 50% REC	3 weeks	Weeks 7 - 9: 11/5 to 11/25
	4 - MF Filtrate from treating BAF 1 effluent. BAF 1 treating WP PE [2] 15% REC	1 week	Week 10: 11/26 to 12/2
	5 - MF Filtrate from treating BAF 1 effluent. BAF 1 treating DND PE 50% REC	2 weeks	Weeks 11 - 12: 12/3 to 12/16
	6- MF Filtrate from treating BAF 2 effluent. BAF 1 treating DND PE. 50% REC	9 days	Weeks 13 - 14: 12/17 to 12/27
	7 - MF Filtrate from treating BAF 2 effluent. BAF 1 treating WP PE. 50% REC	4 weeks	Weeks 15 - 18: 12/31 to 1/27
	8 - MF Filtrate from treating BAF 2 effluent. BAF 1 treating WP PE. 15% REC	1week	Week 19: 1/28 to 2/3
1 - MBR Effluent Nutrient Removal	9 - MBR treating WP PI, Bio P mode 50% REC	3 weeks	Weeks 20 - 22: 2/4 to 2/24
	10 - MBR treating WP PI, Bio P mode 15% REC	4 days	Week 23: 2/25 to 2/28

Notes:
(1) Week 1 starts on September 24th. Startup was completed on September 21st.
(2) Assumes FF1 will not be supplying PE to BAF 1. Still using WP PE to supply BAF 1. BAF 2 will not be ready to supply the MF unit until December.
WP PE: West Point Primary Effluent
WP PI: West Point Primary Influent
DND PE Densadeg Unit Primary Effluent

Sampling

Sampling and analysis to track the RO unit performance is presented herein. The sampling efforts include operational sampling, special tests and water quality goals sampling.

Operational

Parameters to be measured to address the operating performance of the RO unit include pH, temperature, conductivity, flow and pressure. The values will be recorded the by operators daily using the daily operator log included in the O&M Manual. The operators will also measure the silt density index (SDI) on the feed twice a week.

The following parameters will also be measured with analyses to be done by the King County Environmental Lab:

- TOC
- TDS
- Fouling Indices/Recovery Limitations
  - Alkalinity
  - Nitrate

- pH
- Special Test

It is expected that TOC will be measured twice a week and TDS will be measured once a week on the feed and permeate. The alkalinity, nitrate, pH and special tests will be conducted once for each of the ten test runs to characterize the fouling characteristics of the feed, the concentrate and, when recycling the concentrate (50% recovery mode) the raw/recycle blend. A permeate sample will also be included so a mass balance on fouling constituents can be determined.

The special test will include the following parameters:

- Calcium
- Magnesium
- Sodium
- Potassium
- Iron (total and dissolved)
- Manganese
- Barium (with a detection limit down to 0.01 mg/L)
- Strontium
- Aluminum
- Chloride
- Sulfate
- Fluoride
- Silica (total and dissolved)

Water Quality

The following parameters will be measured, with analysis done by the King County Environmental Lab, to assess the ability of the RO unit to meet water quality goals:

- NH_4
- TKN
- $NO_2 + NO_3$
- Ortho P
- Metals
- Organics (including SOCs and VOCs)

With the exception of metals and organics, the water quality parameters will be measured three times a week on the feed and permeate. Metals and organics will be measured on the feed and permeate, but only once during a given test run. The schedule for collecting and performing the analyses for all of the samples handled by the Environmental Lab is discussed in the following section.

Sampling Plan

The sampling plan for the Environmental Lab is detailed in Table 1 of the Appendix. The table identifies the number of samples for each parameter collected each day.

The sample location labels are as follows:

- RO Influent from MF, auto sampler S10
- RO Influent from MBR, auto sampler S12
- RO permeate auto sampler: S13
- RO concentrate grab sample 13g
- RO blend (feed plus recycled concentrate) grab sample 13b

ROLES AND RESPONSIBILITIES

The County will operate the RO unit, maintain the daily data collection, conduct the SDI test twice per week, and collect all samples for analysis by the Environmental Lab.

The County will also maintain the project data management system to include the data obtained for the RO unit. The consultant team (HDR and Black & Veatch) will evaluate the data and distribute the information to the project team. It is anticipated that two conference calls per month will be held to discuss the overall testing program. These calls will include the status and data review for the RO unit. On an as-needed basis, the County will coordinate a conference call with Scott Freeman of Black & Veatch. If possible, these calls will include all project team members listed in the subsequent contacts section. However, since it is difficult to coordinate calls for a large group of people, the level of participation may vary to reduce the coordination effort. At a minimum, Bob Bucher and J. B. Neethling or Michael Norton will participate in these calls.

DATA MANAGEMENT

County operators will fill out the daily log sheet to record specified operating parameters. The data from the Environmental Lab will be logged into standard excel spreadsheets that will be kept on the County's network servers for access by County staff. This data will also be transferred into the project data management system (DMS) by County staff.

Data collected by the County operators will be entered in the RO operation data sheet by County staff. In this way lab data and manually recorded operating conditions will be maintained in the DMS and accessed via the RO operation data sheet.

CONTACTS

Since this testing is expected to require midstream adjustments, it is important to maintain frequent communications between King County, the consultant team (HDR and Black & Veatch) and the vendor. The following is a list of the project team members.

King County

Bob Bucher

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HDR

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Black & Veatch (Consultant Team)

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Black & Veatch (Vendor)

Scott Freeman, Kansas City
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APPENDIX

Table 1. Sampling Plan
(see separate Excel workbook “RO sampling plan_Oct1Feb v1.xls”
worksheet “RO all” emailed with this file)

DMS RO Operation Data Sheet
(to be provided in the next version of the Test Plan)

Date	Comments (Operator Data Sheet)	Comments (Log Book)
8/29/2001		Black and Veatch RO skid arrived.
8/30/2001		Skid uncrated and set in place. Electrical contractor noted problem with feed power connection. Primary neutral included - transformer not providing secondary side neutral. Transformer will have to be replaced. Mechanical connections (hoses) ordered.
8/31/2001		
9/6/2001		
9/7/2001		
9/8/2001		
9/9/2001		
9/10/2001		Resolved problem with transformer. Con reconfigured existing transformer to provide secondary side neutral. Black & Veatch (Scott Freeman) provided necessary documentation to perform work.
9/11/2001		Resolved problem with transformer. Con reconfigured existing transformer to provide secondary side neutral. Black & Veatch (Scott Freeman) provided necessary documentation to perform work.
9/12/2001		Resolved problem with transformer. Con reconfigured existing transformer to provide secondary side neutral. Black & Veatch (Scott Freeman) provided necessary documentation to perform work.
9/13/2001		Resolved problem with transformer. Con reconfigured existing transformer to provide secondary side neutral. Black & Veatch (Scott Freeman) provided necessary documentation to perform work.
9/14/2001		Resolved problem with transformer. Con reconfigured existing transformer to provide secondary side neutral. Black & Veatch (Scott Freeman) provided necessary documentation to perform work.
9/15/2001		
9/16/2001		
9/17/2001		Electrical contractor completed reconfiguration of transformer by late afternoon. Black & Veatch onsite (Scott Freeman and Patty Buchanan) for skid startup. Mechanical hoses to and from skid installed.
9/18/2001		Performed water checkouts on skid with "dummy" RO module. Both Scott and Patty onsite during day. At the end of the day, discovered that emergency stop button does not shutdown pumps when they are in the "manual" operating mode. Black & Veatch investigating

Date	Comments (Operator Data Sheet)	Comments (Log Book)
9/19/2001		Black & Veatch onsite (Patty and Scott) to continue startup. Switched feed water source from potable water (used during checkouts) to MBR effluent. RO module was installed. Provided with wiring revision to allow Emergency stop to secure feed and booster
9/20/2001	RO feed is from MBR (treated effluent). RO element is Koch/Fluid Systems TFC 4820 hr (s/n KM809720-1088). [MBR EFFLUENT OFFICIAL START]	Arranged for Electrical contractor to perform emergency stop switch wiring. Will not be performed until 0730 hrs tomorrow (9/21). Operated unit throughout day on MBR effluent. Plan to run overnight. Modified feed tank to provide additional overflow cap
9/21/2001	At 1920 hrs united secured during MBR maintenance clean. Allowed MBR feed to drain for 15 minutes.	
9/22/2001		No changes
9/23/2001		No changes. Working on install of S11/S13 sampler. Plan to use 2L overflow container and standard autosampler.
9/24/2001	At 1530 hrs disconnected to perform MBR maintenance clean, returned feed at 1621 hrs.	No comments.
9/25/2001		No comments.
9/26/2001		No comments.
9/27/2001	At 1702 hrs adjusted booster pump speed (permeate flow) and MV-4 (concentrate flow) to setpoint targets.	No comments.
9/28/2001		No comments.
9/29/2001		No comments.
9/30/2001	Composite sampler will be started on 10/1 (grab sample on 10/1 for process lab).	No comments.
10/1/2001	Unit secured from 1226 hrs to 1330 hrs for MBR maintenance clean.	At 1226 hrs secured skid per planned shutdown process. Secured during maintenance clean on the MBR unit. Plan restart at 1330 hrs. Process lab conductivity measurement: S12 (feed from MBR) = 956 ps/cm, S13 (RO effluent) = 17 ps/cm. At 1635 hrs confirm
10/2/2001	At 1033 hrs suspect previous problem with dosing pump (air in supply line).	At 1033 hrs noted antiscalant tank level has dropped from 6.75 gal - 6 gal. Expect that over the last 10 days, flow has not been delivered to feed water due to bubbles in dosing pump line. To confirm. Checks of dosing. At 1245 hrs discovered unit had
10/3/2001	At 1515 hrs following flow adjustments to match targets.	At 1575 hrs adjusted process flows. Recycle flow: 7.4 to 6.5 gpm. Low range concentration flow: 0.55 to 0.6 gpm.
10/4/2001		No comments.
10/5/2001		No comments.

Date	Comments (Operator Data Sheet)	Comments (Log Book)
10/6/2001		No comments.
10/7/2001	At 1030 hrs adjusted recycle flow from 7 to 6.5 gpm. At 1031 hrs adjusted concentrate flow from 0.58 to 0.6 gpm. At 1032 hrs adjusted permeate flow from 0.55 to 0.6 gpm.	Setup S11/S13 sampler and overflow container. Ready to start except for power to sampler. Will purchase power cord pigtail and install tomorrow. At 1330 hrs refilled antiscalant tank (used 120 mL).
10/8/2001	At 1612 hrs adjusted flows. System secured due to MBR effluent at loss.	At 1615 hrs unit shutdown due to loss of MBR effluent feed flow. MBR permeate off due to drop in aerobic tank level - primary effluent feed OFF for LEL detector calibration. At 1640 hrs unit started back up. MBR in production.
10/9/2001		No comments.
10/10/2001		No comments.
10/11/2001	At 1530 hrs adjusted permeate flow back to 0.6 gpm. MV-2 opened slightly to decrease permeate pressure. Booster pump speed increased to increase permeate flow.	No comments.
10/12/2001	At 0932 hrs no permeate flow to sampler.	No comments.
10/13/2001		No comments.
10/14/2001	At 0630 hrs filled antiscalant tank with 5 gallons of DI water and 120 mL antiscalant.	At 0630 hrs refilled antiscalant tank. 5 gal DI water and 120 mL antiscalant.
10/15/2001		At 1235 hrs secured RO skid in support of MBR cleaning. At 1625 hrs restarted RO skid following MBR maintenance.
10/16/2001		No comments.
10/17/2001	At 0923 hrs unit shutdown for MC1 clean of MBR; followed panel shutdown procedures. Back online at 1030 hrs.	No comments.
10/18/2001		At 1025 hrs - secured RO skid to support MBR cleaning restarted at 1135 hrs. At 1137 hrs adjusted permeate flow to achieve 0.6 gpm.
10/19/2001	At 1136 hrs adjusted permeate flow to 0.6 gpm. At 1450 hrs adjusted permeate flow to 0.6 gpm.	No comments.
10/20/2001	At 0847 hrs adjusted permeate flow.	No comments.
10/21/2001	At 1001 planned shutdown to facilitate MBR maintenance clean. At 1124 hrs back online.	Refilled antiscalant tank.
10/22/2001		At 1001 hrs planned shutdown to facilitate MBR maintenance clean; back online at 1124 hrs.
10/23/2001		No comments.
10/24/2001		Planned shutdown of skid to facilitate MBR maintenance clean; back online at 1124 hrs.
10/25/2001		Antiscalant level not dropping - need to check into. Low permeate flux and high permeate psi, need to check.

Date	Comments (Operator Data Sheet)	Comments (Log Book)
10/26/2001		No comments.
10/27/2001	At 0856 hrs adjusted permeate flow up to 0.6 gpm from 0.52 gpm.	No comments.
10/28/2001		At 0832 hrs filled antiscalant tank with 5 gal of RO quality water (from process lab) and 120 mL antiscalant. Pre-fill reading of 2 gallons. Post-fill reading of 7 gallons.
10/29/2001		Secured unit to facilitate MBR cleaning at 0907 hrs. Back online at 1017 hrs.
10/30/2001		No comments.
10/31/2001	Secured unit for MBR maint clean at 1113 hrs. Back online at 1215 hrs.	Unit offline during MBR Citric acid clean (approximately 1 hr).
11/1/2001	At 0945 hrs adjusted flows (recycle flow, low range concentrate flow, and permeate flow) after recording data. At 0941 hrs secured unit for MBR work. At 1018 hrs restarted unit.	No comments.
11/2/2001	At 0115 hrs unit not running. At 0835 hrs adjusted permeate flow after taking reading.	Unit offline during following periods: from 0100 to 0200 hrs (MBR permeate off due to PI feed pump tripped out on overload), 1010hrs to 1110 hrs (MBR unit clean with HOCl). Setup for SDI measurement of feed water (MBR permeate). Plant to perform SDI on
11/3/2001		No comments.
11/4/2001		No comments.
11/5/2001	Secured unit for MBR maintenance clean at 0933 hrs. Back online at 1110 hrs.	Filled antiscalant tank (initial tank level was 0.1 gals, final tank level of 7 gals) added 6 gals of H_2O and 137 mL antiscalant. Planned shutdown for MBR maintenance clean at 0935 hrs.
11/6/2001	At 1000 hrs adjusted flows after readings taken.	No comments.
11/7/2001	Planned shutdown to facilitate MBR maintenance clean at 1028 hrs. Back online at 1120 hrs.	No comments.
11/8/2001	At 1356 hrs adjusted flows after readings.	No comments.
11/9/2001	Planned shutdown to facilitate MBR maintenance clean at 0930 hrs. Back online at 1044 hrs.	Performed SDI test on RO feed using feed 2 sample tap.
11/10/2001	At 0835 hrs discovered offline - no MBR feed (most likely since last evening at approximately 1900 hrs). At 0935 hrs restarted unit.	No comments.
11/11/2001		No comments.
11/12/2001		No comments.

Date	Comments (Operator Data Sheet)	Comments (Log Book)
11/13/2001	At 1025 hrs added 5 gal DI and 120 mL antiscalant.	At 0840 hrs unit secured due to loss of MBR permeate flow (WS1/3 empty). Back online by 0930 hrs. At 1020 hrs added 5 gal RO quality water and 120 mL antiscalant to antiscalant feed tank. Now at 7 gal level.
11/14/2001	At 1149 hrs secured unit for MBR chlorination clean. At 1545 hrs unit back online.	At 1149 hrs unit secured for MBR chlorination clean. At 1545 hrs restarted unit following MBR clean.
11/15/2001		No comments.
11/16/2001		No comments.
11/17/2001		No comments.
11/18/2001		No comments.
11/19/2001	Shutdown process to facilitate MBR maintenance clean at 0914 hrs. Back in service at 1110 hrs.	No comments.
11/20/2001		No comments.
11/21/2001	At 0911 hrs shutdown process to facilitate MBR maintenance clean, back online at 1008 hrs.	No comments.
11/22/2001		No comments.
11/23/2001		No comments.
11/24/2001		No comments.
11/25/2001	Adjusted permeate flow at 0910 hrs.	No comments.
11/26/2001	Planned shutdown for MBR maintenance clean, started at 0834 hrs, back online at 0954 hrs.	No comments.
11/27/2001	At 0910 hrs, adjusted flows after recording values.	No comments.
11/28/2001	At 0938 hours planned shutdown for MBR maintenance clean.	Added 5 gallons of RO quality H2O + 120 mL antiscalant. Final level was 7 gallons.
11/29/2001		No comments.
11/30/2001		No comments.
12/1/2001		No comments.
12/2/2001		No comments.
12/3/2001	At 08?? Hours unit down for MBR maintenance work and maintenance clean. Back online at 1117 hrs. At 1132 hrs adjusted permeate flow.	No comments.
12/4/2001	At 0700 hrs increased permeate flow.	No comments.
12/5/2001	At 1042 hrs planned shutdown to facilitate MBR maintenance clean. Back online at 1147 hrs.	At 1040 hrs added 5 gallons of RO PH2O plus 120 mL antiscalant, final level of 7 gallons.

Date	Comments (Operator Data Sheet)	Comments (Log Book)
12/6/2001	Offline due to MBR being down. RO back online at 1217 hrs. Adjusted recycle flow to 6.5 at 1227 hrs. Adjusted permeate flow to 0.6 at 1228 hrs.	No comments.
12/7/2001	S13 grab. Adjusted permeate flow to 0.6 at 0717 hrs and recycle flow to 6.5. Adjusted permeate flow to 0.60 and 6.5 for recycle flow at 1714 hrs.	No comments.
12/8/2001	Adjusted permeate flow to 0.6 at 0916 hrs. Adjusted permeate flow to 0.6 and recycle flow to 6.5 at 2245 hrs.	No comments.
12/9/2001	Adjusted permeate flow to 0.6 and recycle flow to 6.5 at 0450 hrs. Started sampler at 0900 hrs. Adjusted permeate flow to 0.6 at 1850 hrs.	No comments.
12/10/2001	S13 sample grab. At 0747 hrs adjust MV4 (concentrate flow) to 0.6 gpm. Planned shutdown to facilitate MBR maint clean at 1008 hrs. Back online at 1110 hrs.	No comments.
12/11/2001	Adjusted flows following data record at 0940 hrs.	No comments.
12/12/2001	Planned shutdown for MBR clean at 1102 hrs. Back online at 1212 hrs.	No comments.
12/13/2001	Adjusted flows following data record at 1001 hrs. 1450 hrs - Filled antiscalant tank	At 1450 hrs added 5 gallons of RO PH2O plus 120 mL antiscalant, final level of 7 gallons.
12/14/2001	Adjusted flows following data record at 0927 hrs. 1430 hrs - Secured unit for MBR Maint Clean.	No comments.
12/15/2001	1440 hrs - Adjusted Permeate flow to 0.6; Recycle flow to 6.5	No comments.
12/16/2001	Adjusted concentrate flow to 0.6 following data record at 0936hrs.	No comments.
12/17/2001	Planned shutdown for MBR clean at 0902 hrs. Back online at 1026hrs.	No comments.
12/18/2001		No comments.
12/19/2001	Planned shutdown for MBR clean at 1452 hrs. Back online at 1605 hrs.	No comments.
12/20/2001	Adjusted permeate flow @ 1515 hrs.	At 0920 hrs added 5 gallons of RO PH2O plus 120 mL antiscalant, final level of 7 gallons.
12/21/2001	Planned shutdown for MBR clean at 1206 hrs. Back online at 1323 hrs. Adjusted flows @ 1151 hrs & 1750 hrs	No comments.
12/22/2001	1445 Hrs - Adjusted permeate flow to 0.6; Recycle flow dropped to 6.5	No comments.
12/23/2001		No comments.

Date	Comments (Operator Data Sheet)	Comments (Log Book)
12/24/2001		No comments.
12/25/2001		No comments.
12/26/2001		No comments.
12/27/2001		Added 5 gallons of RO PH2O plus 120 mL antiscalant, final level of 7 gallons.
12/28/2001		No comments.
12/29/2001		No comments.
12/30/2001		No comments.
12/31/2001	0724 - Adjusted permeate flow to 0.6; raised recycle flow to 6.5; 1340 hrs - 1500 hrs Unit secured for MBR Maint Clean.	Secured unit to facilitate MBR cleaning from 1340 - 1500 hrs.
1/1/2002	1840 hrs - Adjusted Permeate, Recycle, and Concentrate flow	No comments.
1/2/2002	1007 - Planned shutdown for MBR Maint Clean; BIS 2 1110 hrs; 0030 hrs - Adjusted Permeate, Recycle, and concentrate flows	Added 5 gallons of RO PH2O plus 120 mL antiscalant, final level of 7 gallons.
1/3/2002	1620 hrs - Adjusted concentrate flow	No comments.
1/4/2002	0948 hrs - Planned shutdown to facilitate MBR Maint Clean; BIS 1051 hrs; RO shutdown due to high vacuum alarm on MBR	No comments.
1/5/2002		No comments.
1/6/2002		No comments.
1/7/2002		No comments.
1/8/2002	0830 hrs - Antiscalant turned OFF.	0835 hrs - Secured antiscalant dosing pump. Conference call with consultants led to decision not to operate with antiscalant for remainder of testing with MBR effluent
1/9/2002	0847 hrs - Planned shutdown to facilitate MBR Maint Clean; BIS @ 1054 hrs.	
1/10/2002		0200 -1030 hrs - Unit shutdown due to MBR permeate pump failure. ~1045 hrs- Unit back on line with MBR effluent feed.
1/11/2002		
1/12/2002		~0100 hrs - Unit shutdown due to MBR failure.
1/13/2002	1145 hrs - Adjusted flows following readings logged- concentrate flow and permeate	0940 hrs - Shut OFF RO unit (still not restarted from MBR failure) and plan to restart midday after MBR has a chance to operate for several hours; 1050 hrs - Started unit with HIGH RANGE concentrate valve open to 8 gpm (for 1 min)
1/14/2002	1034 hrs - Planned shutdown to facilitate MBR Maint Clean; BIS @ 1230 hrs; Adjusted flows at 1230 hrs.	[restart unit]

Date	Comments (Operator Data Sheet)	Comments (Log Book)
1/15/2002	1455 hrs - Adjusted flows	
1/16/2002	0625 - Adjusted flows; 1205 - 1344 hrs - Planned shutdown for MBR Maint Clean &plant power outage. 1640 hrs & 1722 - Adjusted flows	
1/17/2002	0153 hrs- Adjusted flows; antiscalant pump unplugged	
1/18/2002	Planned shutdown for MBR Maint clean - 0919 hrs; 0115 hrs - adjusted Recycle to 6.5	
1/19/2002		
1/20/2002	Unit Secured while MBR troubleshooting underway (permeate	1040 hrs - Unit shutdown due to MBR permeate pump failure. 1640 hrs -
1/21/2002		
1/22/2002		
1/23/2002		
1/24/2002		
1/25/2002		
1/26/2002		
1/27/2002		
1/28/2002		1400 hrs- New RO unit element installed; 1530 hrs - Serial # KM80972 - 1052; 1605 hrs - Completed leak check of unit - several tries to fix VIC fitting leak.
1/29/2002		1115 hrs - Started unit with plant to run for 2 hours (data collection every .5 hrs)
1/30/2002		No comments
1/31/2002		No comments
2/1/2002		No comments
2/2/2002		N
2/3/2002	At 12:30 hrs, started the unit. Increased permeate pressure to 1 psi by closing mv2 slightly. New feed source = MF>	At 12:30 hrs, started unit wit new feed source (MF effluent). No antiscalant addition
2/4/2002		At 13:30 hrs, SDI test = 1.37
2/5/2002	Around 10:00 to 12:45 hrs, the unit was offline for cleaning of MF	No comments
2/6/2002	Adjusted permeate flow to 0.6	No comments
2/7/2002	At 9:16 hrs, adjusted permeate flow	No comments
2/8/2002		No comments
2/9/2002		No comments
2/10/2002		No comments
2/11/2002		No comments

Date	Comments (Operator Data Sheet)	Comments (Log Book)
2/12/2002		AT 13:30 hrs, SDI test = 1.6. From 14:00 to 15:55 hrs, secured unit for MF maintenance clean.
2/13/2002		No comments
2/14/2002		No comments
2/15/2002		No comments
2/16/2002		No comments
2/17/2002		No comments
2/18/2002		No comments
2/19/2002		At 15:15, secured unit for MF maintenance clean.
2/20/2002	At 18:30, performed adjustments, decrease permeate pressure to 1 psi and increase permeate flow 0.6	At 14:30, started the unit back up.
2/21/2002	At 8:32 hrs, reduced permeate flow to 0.6	No comments
2/22/2002		No comments
2/23/2002		No comments
2/24/2002		No comments
2/25/2002		No comments
2/26/2002		No comments
2/27/2002		At 11:45, shut down the unit--finished testing

Reverse Osmosis Pilot Unit Photos

Introduction

The following is a series of photos of the reverse osmosis membrane pilot unit system taken during the pilot testing. Each photo includes a caption and text boxes to point out key pieces of equipment.

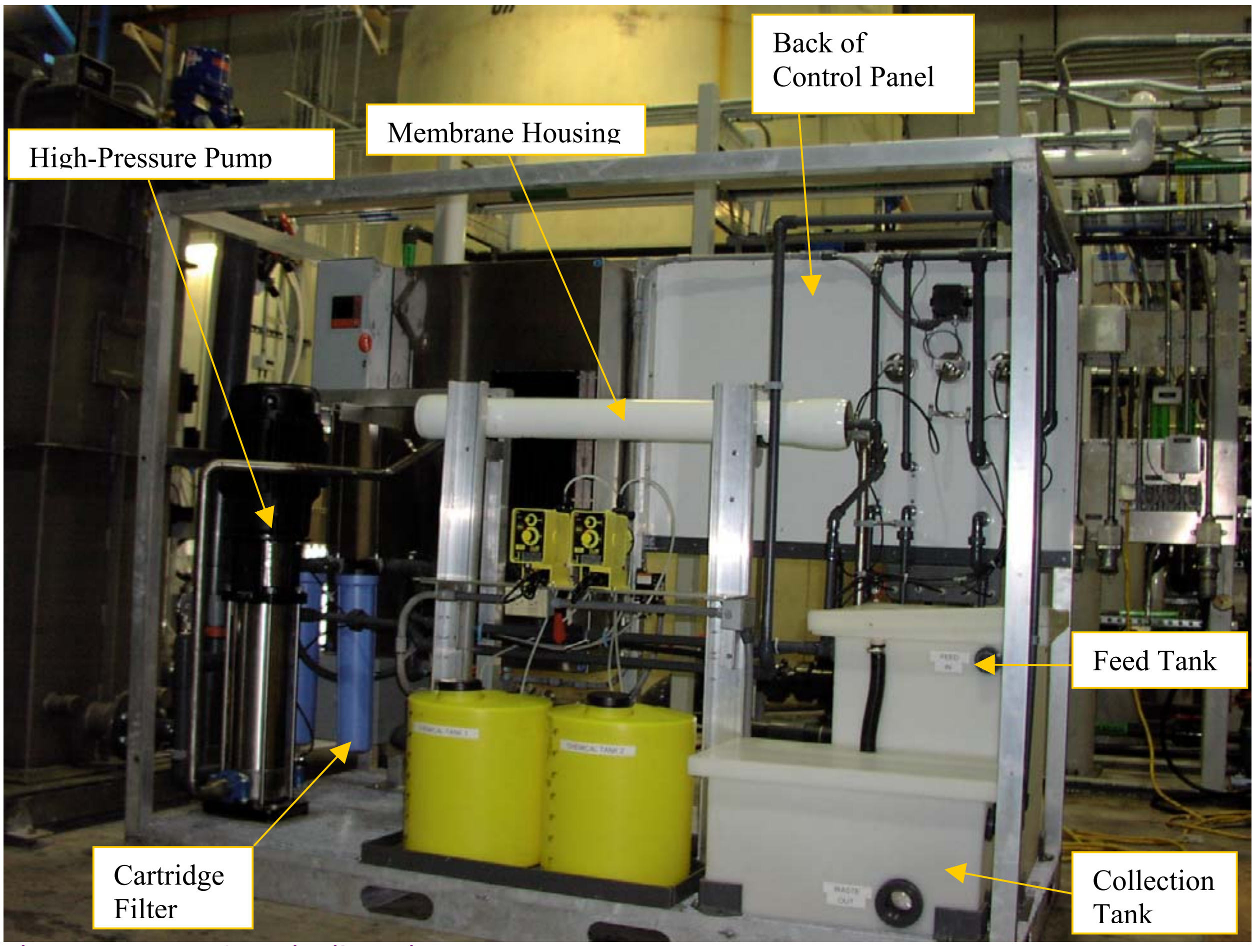

Figure 1. Reverse Osmosis Pilot Unit

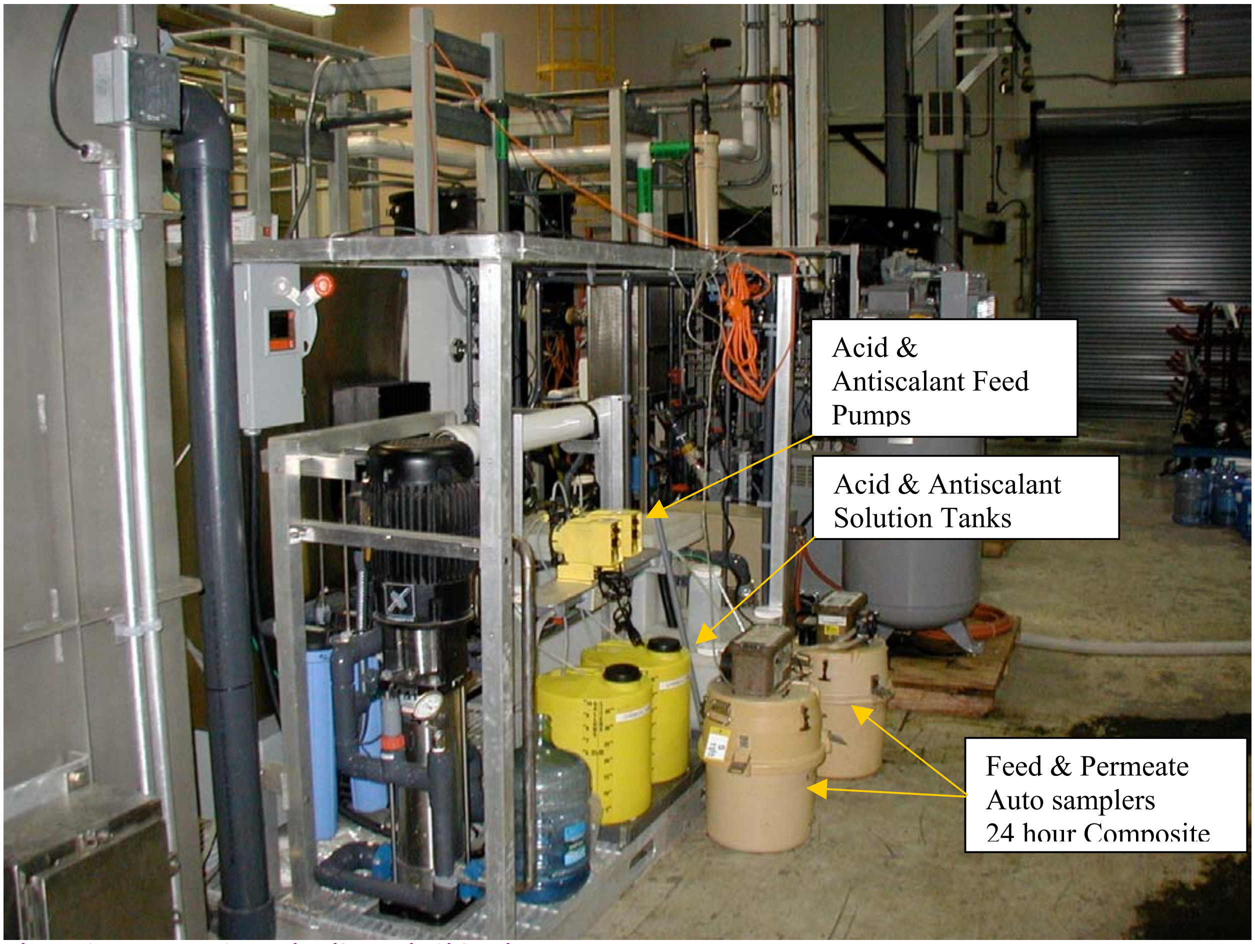

Figure 2. Reverse Osmosis Pilot Unit Side View

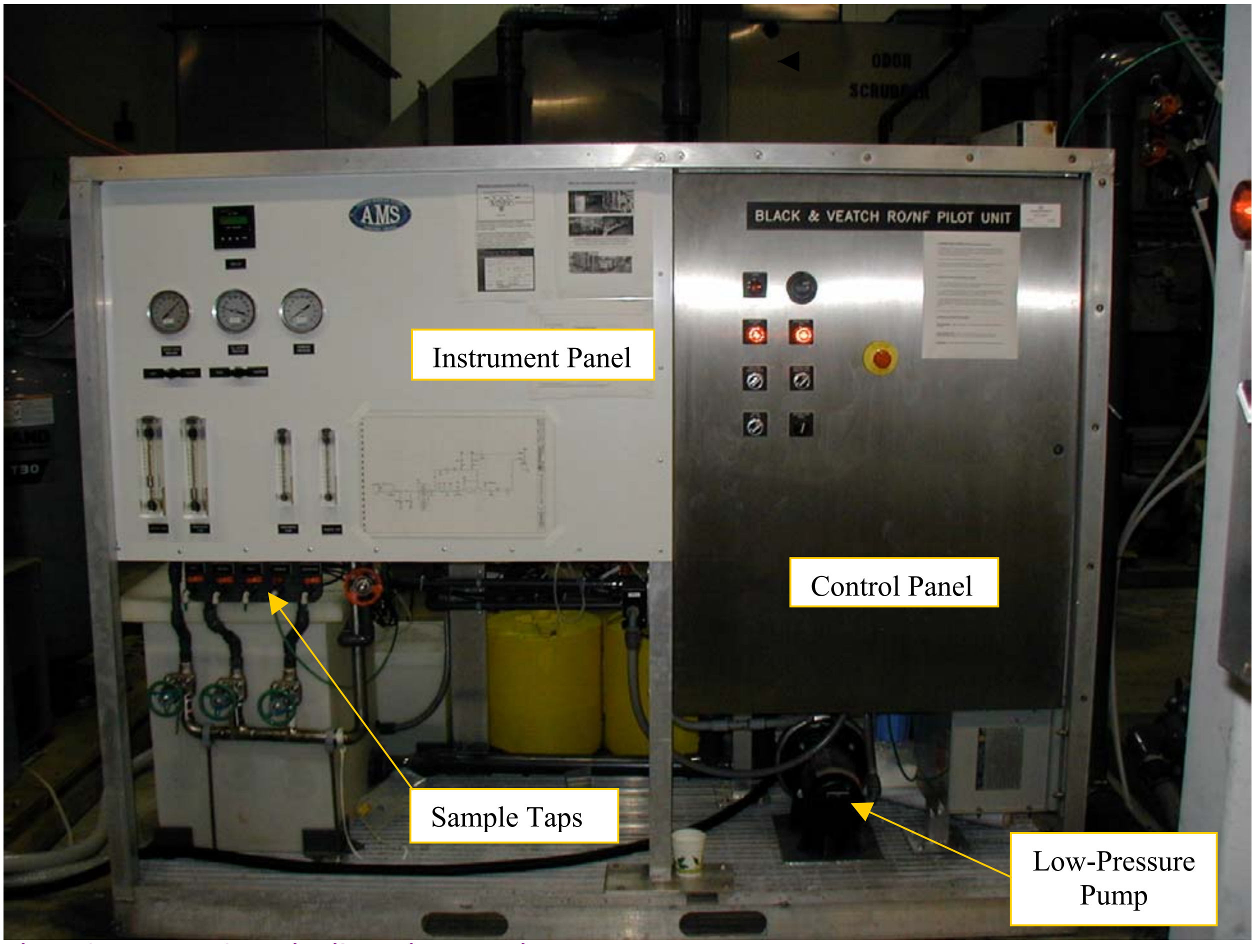

Figure 3. Reverse Osmosis Pilot Unit Front View

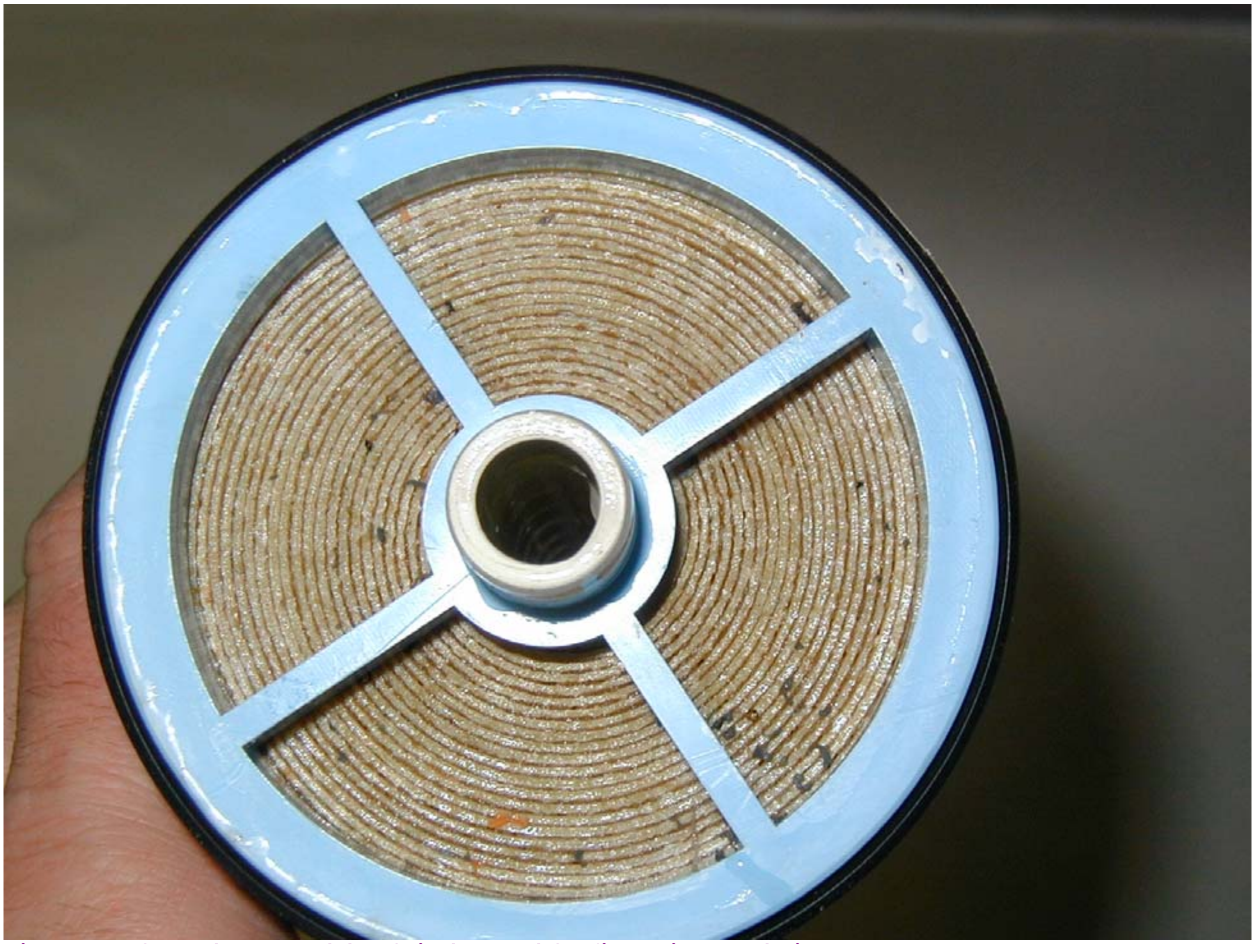

Figure 4. RO Membrane Module – Spiral Wound Configuration – End View