2012

Groundwater Reliability Improvement Program (GRIP): Evaluation of a High Recovery NF/RO Integrated Treatment System

Cooperative Agreement No. R11AC35293

Groundwater Reliability Improvement Program (GRIP): Evaluation of a High Recovery NF/RO Integrated Treatment System

Final Report

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United States Department of the Interior
Bureau of Reclamation

Prepared by:

Sanitation Districts of Los Angeles County

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Abbreviations

ADI	Acceptable daily intake
AOP	Advanced oxidation process
AWTP	Advanced water treatment plant
CDPH	California Department of Public Health
CECs	Chemicals of emerging concern
CIP	Clean-in-place
CWCGB	Central and West Coast Groundwater Basins
DEET	N,N-diethyl-meta-toluamide
DGRRR	Draft Groundwater Recharge Reuse Regulations
DWEL	Drinking water equivalent level
EDX	Energy Dispersive X-Ray
FTIR	Fourier-Transform Infra Red
GRIP	Groundwater Reliability Improvement Program
IPR	Indirect Potable Reuse
LOI	Loss on ignition
MCL	Maximum contaminant level
MF	Microfiltration
MGD	Million gallons per day
MW	Molecular weight
MWCO	Molecular weight cutoff
NDMA	N-Nitrosodimethylamine
NF	Nanofiltration
NSF	Normalized specific flux
RO	Reverse Osmosis
SAT	Soil aquifer treatment
SEM	Scanning Electron Microscopy
SJC	San Jose Creek
TCEP	Tris(2-chloroethyl)phosphate
TDS	Total dissolved solids
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon
UF	Ultrafiltration
UV	Ultraviolet light
WRD	Water Replenishment District of Southern California
WRP	Water Reclamation Plant

Acknowledgements

The project team (consisting of Bruce Mansell, Phil Ackman, Chi-Chung Tang, and Ray Tremblay from the Sanitation Districts, as well as Paul Fu from WRD) would like to acknowledge and thank Dow Water and Process Solutions for providing the NF-270 membrane elements as well as the UF membranes used during this study. We would also like to acknowledge the many Sanitation Districts' staff members who contributed to the successful completion of this project. Special thanks are extended to Charles Harris (Engineering Technician, Wastewater Research Section), Cheng Yao Tsai (Engineering Intern, Wastewater Research Section), Leo Mariscal (Laboratory Technician), Brenda Bell-Whitebear (Senior Laboratory Technician), and Maria Pang (Assistant Manager of Laboratories).

Project Summary

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Technical Summary:

The Sanitation Districts of Los Angeles County (Sanitation Districts), in collaboration with the Water Replenishment District of Southern California (WRD), are currently exploring the feasibility of the Groundwater Reliability Improvement Program, or GRIP. The goal for implementation of GRIP is to improve reliability and reduce dependency on imported water for replenishment of the Central and West Coast Groundwater Basins (CWCGB). To achieve this goal, a significant portion of the imported replenishment water would be replaced with locally produced, high-quality recycled water. The preliminary plan is to construct an advanced water treatment plant (AWTP) to treat secondary or final effluent produced from the Sanitation Districts' San Jose Creek (SJC) West Water Reclamation Plant (WRP). The process train would include microfiltration (MF) or ultrafiltration (UF) as the low-pressure membrane component, acid and antiscalant addition for high-pressure membrane scaling control, reverse osmosis (RO) as the high-pressure membrane component, hydrogen peroxide addition coupled with ultraviolet light to achieve advanced oxidation (UV/AOP), and product water stabilization processes. The AWTP would be designed and constructed to produce 10,000 acre-feet per year (~ 9 million gallons per day). Effluent produced by the AWTP would be recharged into the CWCGB at or near the Montebello Forebay.

The overall objective of this project was to evaluate the viability and potential application of an alternative high-pressure membrane system concept, High Recovery NF/RO Integrated Treatment System, that could potentially be employed for the GRIP project. Compared to typically designed and operated high-pressure membrane systems that incorporate RO membranes, implementation of the NF/RO integrated system could reduce the volume of concentrate that needs to be disposed of by approximately one half. The integrated system concept includes a primary nanofiltration (NF) system and a secondary RO system that is used to treat concentrate produced by the primary NF system. Permeate produced by each system is blended to achieve an overall recovery greater than 90%.

To demonstrate the viability and potential application of the NF/RO integrated system concept, pilot-scale testing was conducted over approximately 7 months, from August 2011 to March 2012, at the Sanitation Districts' SJC West WRP using UF filtered final effluent as feedwater. Specific pilot testing objectives included: (1) evaluate the operational performance of the NF/RO integrated system with respect to feed pressure, fouling, and related cleaning requirements; (2) evaluate the rejection performance of the NF/RO integrated system with respect to constituents that are relevant for indirect potable reuse projects including nitrogen, total organic carbon (TOC), and chemicals of emerging concern (CECs) (e.g., NDMA, 1,4-dioxane, hormones, pharmaceuticals and personal care products).

The results from this study demonstrated that the NF/RO integrated treatment system concept is a viable alternative to a standard RO system and can potentially be employed for the GRIP project. The main advantages of this system that were demonstrated during this study include the following: (1) the ability to operate at an overall recovery of approximately 93%, which would reduce the volume of concentrate that needs to be disposed of; (2) the ability to achieve a high degree of rejection for many of the constituents that are relevant for indirect potable reuse projects including TOC and select CECs. A potential additional advantage is that the product water produced by the integrated system would have a higher total dissolved solids (TDS) concentration, when compared to that produced by RO systems, and would thus be less corrosive. This would lead to a reduction in costs associated with post treatment stabilization processes that are typically employed with RO systems.

Key findings of this study are summarized below.

<u>Operational Performance</u>

The NF/RO integrated system was operated for over 3,000 hours in two distinct phases, with the major difference being the antiscalant product used for membrane scale control. During Phase One, the antiscalant product that was employed was SpectraGuard (Professional Water Technologies). This product was initially selected because of its unique molecular structure (dendrimer based chemistry) and reported ability to be concentrated, in high-recovery applications, to relatively high levels without contributing to membrane fouling. However, this product was not effective for scale control and significant membrane fouling was observed in both the primary NF and secondary RO systems. During Phase Two, the antiscalant was changed to Y2K (King Lee Technologies). This antiscalant product, which is a proprietary formulation of phosphonic acids, was effective for controlling membrane scale formation. The pilot system was operated for approximately 3 months (~ 2,000 hours), with significantly less fouling compared to Phase One operation. Over the 3-month operating period, the normalized specific flux for the primary NF and secondary RO systems decreased 16% and 28%, respectively.

Membrane Autopsy

At the conclusion of testing, sample NF and RO membrane elements were sent to Avista Technologies for autopsy analyses to (1) compare the performance of the elements to manufacturer specifications for new membrane elements, and (2) characterize the foulant material on the membrane surface. The results of the autopsy analyses confirmed the operational performance results and indicated that significant membrane fouling in general, and scaling in particular, did not occur during Phase Two operation. Membrane fouling was identified to be primarily organic in nature. However, biofouling, colloidal, as well as inorganic fouling were also identified.

Rejection Performance

The NF/RO integrated system achieved a high degree of rejection for some of the constituents that are relevant for indirect potable reuse projects including TOC (89%) and select CECs. Of 30 target CECs, 19 were detected in the feed stream to the system. Most of the detected CECs were rejected to a high degree (> 80%) and/or to below their respective reporting limits. Significantly lower rejection was achieved for total nitrogen (14%), NDMA (7%), and 1,4-dioxane (25%). Despite the low rejection for these constituents, application of the NF/RO integrated system for the GRIP project would still be feasible because (1) nitrogen removal could be achieved by the existing nitrification-denitrification activated sludge treatment process at the SJC West WRP, and (2) NDMA and 1,4-dioxane could be removed to below regulatory limits by downstream UV/AOP.

Financial Summary (SF-425):

FEDERAL FINANCIAL REPORT

(Follow form instructions)

1. Federal Agency and Organizational Element to Which Report is Submitted Bureau of Reclamation	2. Federal Grant or Other Identifying Number Assigned by Federal Agency (To report multiple grants, use FFR Attachment) R11AC35293	Page 1 of pages

3. Recipient Organization (Name and complete address including Zip code)

County Sanitation Districts of Los Angeles County

4a. DUNS Number	4b. EIN	5. Recipient Account Number or Identifying Number (To report multiple grants, use FFR Attachment)	6. Report Type	7. Basis of Accounting
06-776-1700	95-3755190		□ Quarterly □ Semi-Annual □ Annual ■ Final	■ Cash □ Accrual

8. Project/Grant Period From: (Month, Day, Year)	To: (Month, Day, Year)	9. Reporting Period End Date (Month, Day, Year)
4/1/2011	3/31/2012	3/31/2012

10. **Transactions**	Cumulative
(Use lines a-c for single or multiple grant reporting)	
Federal Cash (To report multiple grants, also use FFR Attachment):	
a. Cash Receipts	$50,000
b. Cash Disbursements	$50,000
c. Cash on Hand (line a minus b)	0
(Use lines d-o for single grant reporting)	
Federal Expenditures and Unobligated Balance:	
d. Total Federal funds authorized	$50,000
e. Federal share of expenditures	$50,000
f. Federal share of unliquidated obligations	0
g. Total Federal share (sum of lines e and f)	$50,000
h. Unobligated balance of Federal funds (line d minus g)	0
Recipient Share:	
i. Total recipient share required	$90,000
j. Recipient share of expenditures	$90,000
k. Remaining recipient share to be provided (line i minus j)	0
Program Income:	
l. Total Federal program income earned	0
m. Program income expended in accordance with the deduction alternative	0
n. Program income expended in accordance with the addition alternative	0
o. Unexpended program income (line l minus line m or line n)	0

11. Indirect Expense	a. Type	b. Rate	c. Period From	Period To	d. Base	e. Amount Charged	f. Federal Share
	N/A	N/A	N/A	N/A	N/A	N/A	N/A
				g. Totals:			

12. *Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation:*

13. Certification: By signing this report, I certify that it is true, complete, and accurate to the best of my knowledge. I am aware that any false, fictitious, or fraudulent information may subject me to criminal, civil, or administrative penalities. (U.S. Code, Title 18, Section 1001)

a. Typed or Printed Name and Title of Authorized Certifying Official Phil Ackman, Supervising Engineer, Wastewater Research Section, Technical Services Department	c. Telephone (Area code, number and extension) 562-908-4288, ext. 2833 d. Email address packman@lacsd.org
b. Signature of Authorized Certifying Official	e. Date Report Submitted (Month, Day, Year) 06/29/2012
	14. Agency use only:

Standard Form 425
OMB Approval Number: 0348-0061
Expiration Date: 10/31/2011

1. Introduction

1.1 Groundwater Reliability Improvement Program

1.1.1 Collaborating Agencies

The Water Replenishment District of Southern California (WRD) is a special district that was formed, under the Water Replenishment District Act in 1959, to manage the groundwater in the Central and West Coast Groundwater Basins (CWCGB). These basins supply nearly 40% of the water demand for about 4 million people in 43 cities, covering a service area of approximately 420 square miles (Figure 1-1). WRD is responsible for maintaining adequate groundwater supplies, preventing seawater intrusion into the groundwater aquifers, and protecting groundwater quality against contamination. There are approximately 350 drinking water wells operated by 40 active groundwater pumpers within the WRD service area.

The Sanitation Districts of Los Angeles County (Sanitation Districts) are a confederation of 23 independent special districts serving approximately 5.7 million people in Los Angeles County. The Sanitation Districts' service area covers approximately 800 square miles and encompasses 78 cities and unincorporated territory within the county (Figure 1-2). Formed in 1923 under the County Sanitation District Act, the Sanitation Districts construct, operate, and maintain facilities to convey, treat, recycle, and dispose of sewage and industrial wastes. In addition, the Sanitation Districts provide for the management of solid wastes, including disposal, transfer operations, energy conversion, and materials recovery.

Figure 1-1. WRD Service Area

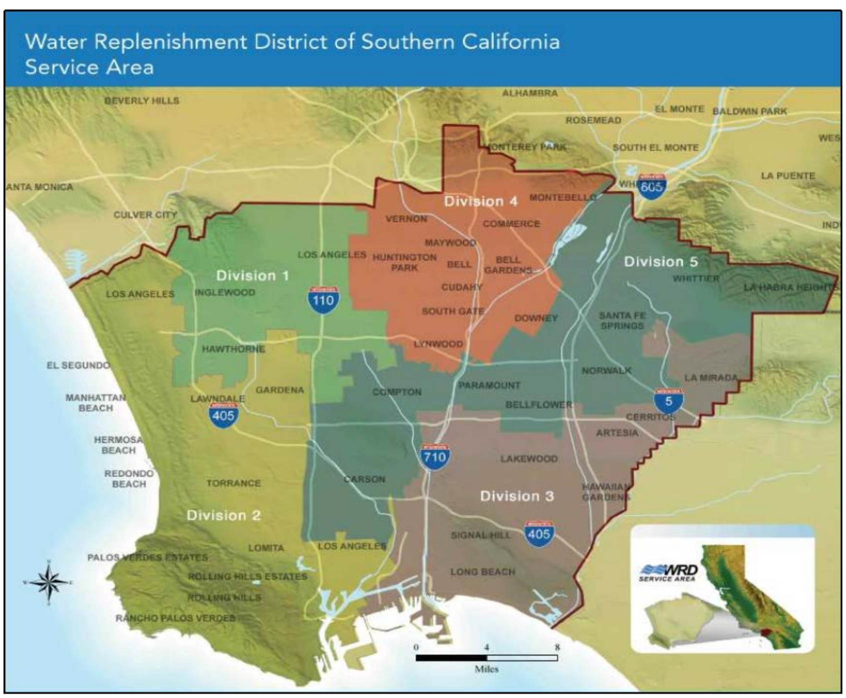


Figure 1-2. Sanitation Districts' Service Area

1.1.2 Project Background

To preserve and protect groundwater supplies in the CWCGB, various sources of water are used for replenishment via surface spreading at the Rio Hondo and San Gabriel River Spreading Grounds in the Montebello Forebay section of the Central Basin (Figures 1-3 and 1-4). Historically, three types of water have been used; storm water (since 1923), imported river water (since 1953), and recycled water (since 1962). Imported water has typically comprised a significant fraction of the total replenishment volume. For example, since 1938, 7.3 million acre-feet of water have been recharged. Of this total, 2.9 million acre-feet (40%) of imported water have been recharged (Ly and Johnson, 2011). However, the availability of imported water for recharge has become more limited due to drought, increasing water demands, and judicial constraints.

To improve reliability and reduce dependency on imported water for replenishment, WRD and the Sanitation Districts are currently exploring the feasibility of the Groundwater Reliability Improvement Program, or GRIP. The goal for implementation of GRIP is to replace a significant portion of the imported replenishment water with locally produced, high-quality recycled water. The preliminary plan is to construct an advanced water treatment plant (AWTP) to treat secondary or final effluent produced at the Sanitation Districts' San Jose Creek (SJC) West Water Reclamation Plant (WRP). A description of the SJC WRP is included in Appendix A. The AWTP process train would include microfiltration (MF) or ultrafiltration (UF) as the low-pressure membrane component, acid and antiscalant addition for high-pressure membrane scaling control, reverse osmosis (RO) as the high-pressure membrane component, hydrogen peroxide addition coupled with ultraviolet light to achieve advanced oxidation (UV/AOP), and product water stabilization processes (Figure 1-5). The AWTP would be designed and constructed to produce 10,000 acre-feet per year (~ 9 million gallons per day, or MGD). Effluent produced by the AWTP would be recharged into the CWCGB at or near the Montebello Forebay.

Figure 1-3. Vicinity Map of Rio Hondo and San Gabriel River Spreading Basins

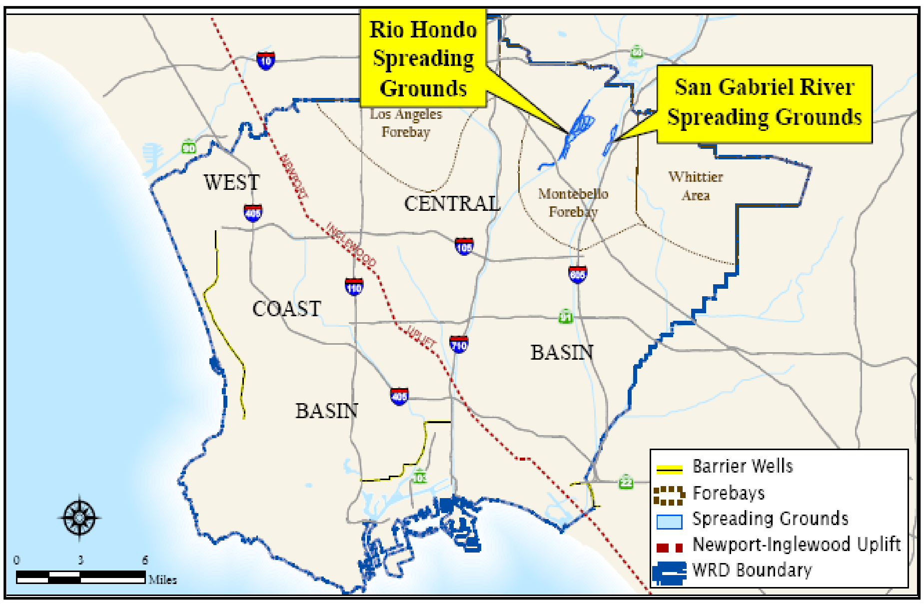
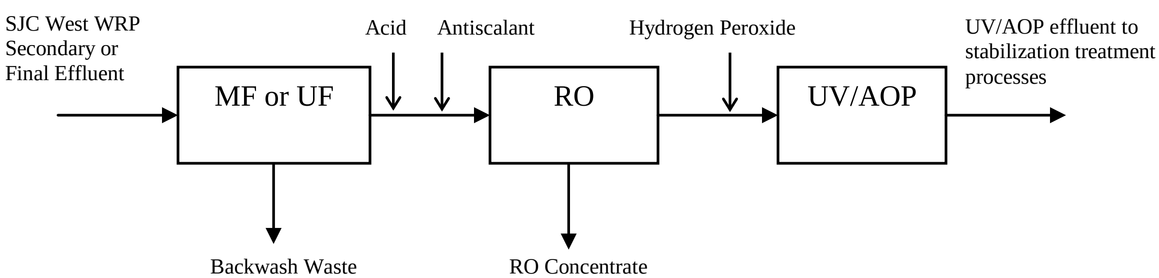


Figure 1-4. Rio Hondo and San Gabriel River Spreading Basins

Rio Hondo Spreading Basins

San Gabriel River Spreading Basins

Figure 1-5. Proposed AWTP Process Train for GRIP



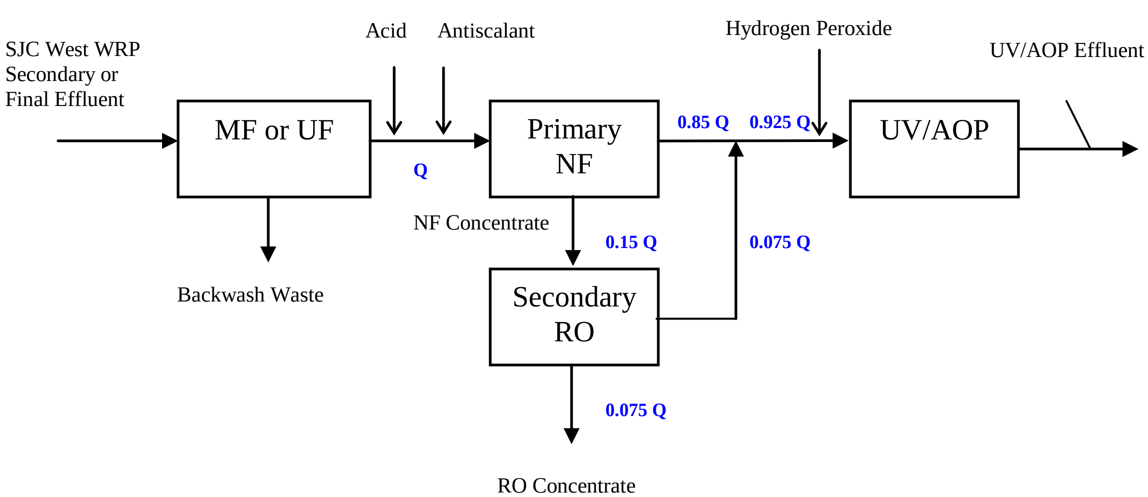
1.2 High Recovery NF/RO Integrated Treatment System

One of the main drawbacks of using RO membranes is that these systems are typically limited to a maximum recovery of 85%. This limitation in recovery is due to the potential precipitation of sparingly soluble salts onto the membrane surface, which is also known as membrane scaling. To overcome this limitation in recovery, an alternative high-pressure membrane system concept was recently developed and tested by the Sanitation Districts (Mansell et al., 2011). The alternative system, High Recovery NF/RO Integrated Treatment System, includes a primary nanofiltration (NF) system and a secondary RO system that is used to treat the concentrate produced by the primary NF system (Figure 1-6). The primary NF system is operated at a typical recovery of 85%, while the secondary RO system is operated at the minimum recovery required to achieve the target overall system recovery following blending of the two permeate streams.

For example, as shown in Figure 1-6, if the target overall system recovery is 92.5%, the secondary RO system would be operated at 50% recovery. The maximum secondary RO system recovery, and thus overall system recovery, that can be achieved will depend on the specific water quality being treated, operating flux, and related membrane fouling.

The key component of the integrated system is the NF membrane. NF membranes differ from RO membranes primarily because they are designed to selectively remove compounds such as multivalent ions (e.g., hardness) or organic contaminants, while allowing other compounds to pass (Bellona et al., 2004). For this study, the NF-270 membrane (manufactured by Dow/FilmTec) was used. This membrane is designed to achieve a high degree of rejection of organics, but only moderate TDS rejection. Because the NF-270 membrane achieves relatively low rejection of ions that have high scale-formation potential, the concentrate stream produced by this membrane has a relatively reduced scale-formation potential compared to concentrate produced by an RO membrane. This allows for further treatment of the concentrate stream by the secondary RO system, thus increasing overall system recovery. An additional advantage of the NF-270 membrane is that it can be operated at lower feed pressures compared to RO membranes. Based on previous bench and pilot-scale testing, the NF-270 membrane feed pressure requirements are 40 - 50% lower than RO membranes (Yu et al., 2010; Mansell et al., 2011). As a result, the overall NF/RO integrated system feed pressure requirements are lower than typical high-pressure membrane systems that employ only RO membranes.

Figure 1-6. Alternative GRIP AWTP Process Train with High Recovery NF/RO Integrated Treatment System



1.3 Project Objectives

The overall objective of this project was to evaluate the alternative High Recovery NF/RO Integrated Treatment System. Specific objectives included the following:

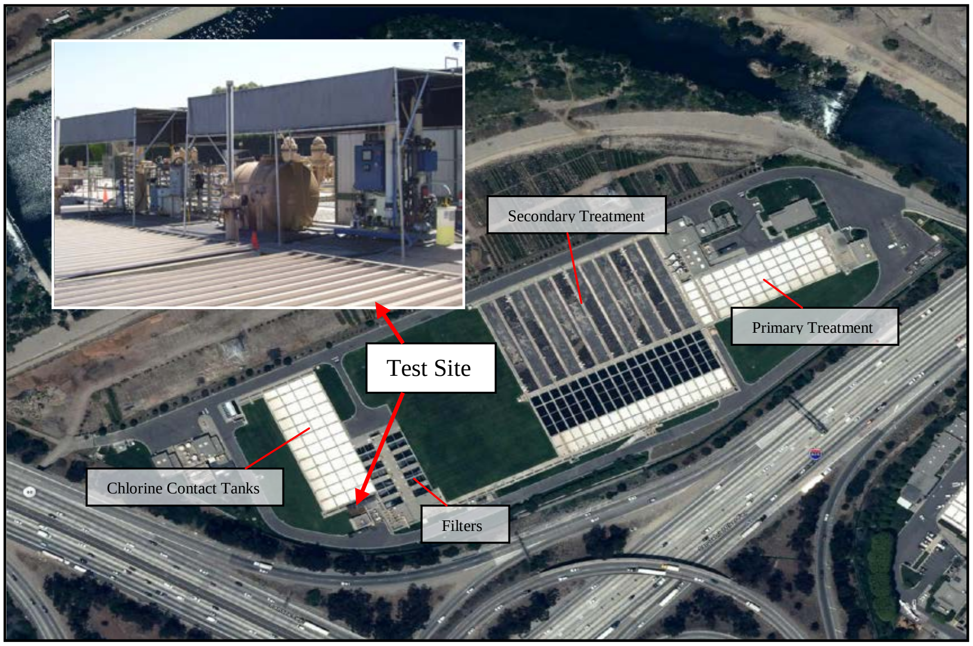
1. Evaluate the operational performance of the NF/RO integrated system with respect to feed pressure, fouling, and cleaning requirements.
2. Evaluate the rejection performance of the NF/RO integrated system with respect to constituents that are relevant for indirect potable reuse (IPR). The constituents include nitrogen, TOC, and chemicals of emerging concern (CECs) such as NDMA, 1,4-dioxane, hormones, pharmaceuticals and personal care products.

2. Technical Approach

2.1 Test Site

The study was conducted at the SJC West WRP near the chlorine contact tank feed channel (Figure 2-1). Although secondary or chlorinated final effluent are both being considered as feedwater sources for the full-scale AWTP, a final decision has not been made to date. For the pilot study, final effluent obtained from the plant wash-water system was used as feedwater because of its availability near the test site. The intake for the wash-water system pump station is located in the outfall structure after the chlorine contact tanks. Effluent from the pilot system was discharged to the chlorine contact tank feed channel, while all waste streams were discharged to the tertiary filters.

Figure 2-1. Pilot Study Test Site



2.2 Pilot System

A schematic diagram of the pilot-scale system that was tested in this study is shown in Figure 2-2. The system consisted of three skid mounted pilot plants. The first component of the integrated process was the Dow SFP 2880 UF System (Figure 2-3), which was used to provide feedwater to the NF/RO integrated system. This system was fed final effluent from the SJC West WRP, which typically has a total chlorine residual of 2-4 mg/L. The feedwater was first pumped through a 130 µm strainer and then through two SFP 2880 UF modules. Each module consisted of a PVC shell, or pressure vessel, containing approximately 10,000 polyvinylidene fluoride (PVDF) hollow fibers with a total active membrane surface area of 829 ft^2. The hollow fibers have an outside-in flow configuration, outside diameter of 1.3 mm, inside diameter of 0.7 mm, and a nominal pore size of 0.03 µm. Additional details for the UF system are shown in Table 2-1. The UF product water, or filtrate, was stored in a tank before being pumped to the primary NF system, or used for backwashing. The UF system was operated at a flux of 37 gallons/ft^2-day (gfd) and backwash frequency of 30 minutes. Throughout the pilot study, the UF system produced high quality filtrate with turbidity < 0.1 NTU and silt density index (SDI) < 3. A presentation summarizing UF system performance over approximately 5 months of operation is located in Appendix B.

The basic components of the primary NF system (Figure 2-4) included chemical tanks and metering pumps for acid and antiscalant addition to control scale formation, a 5µm cartridge filter, a high-pressure pump, and a two-stage pressure vessel array. The pressure vessels were configured in a 2:2:1:1 array and contained twenty-one NF-270 spiral wound membrane elements that were 4-inches in diameter by 40-inches long. The Stage 1 vessels contained fourteen elements while the Stage 2 vessels contained seven elements to achieve a 2:1 element array commonly employed in full-scale systems. Additional details for the primary NF system are shown in Table 2-2. Specifications for the NF-270 elements are shown in Table 2-3.

The basic components of the secondary RO system (Figure 2-5) included a 10 µm cartridge filter, a high-pressure pump, and seven single-element pressure vessels. Each pressure vessel was loaded with one 2.5-inch diameter by 40-inch long TFC-HR RO element (Koch Membrane Systems). The pressure vessels were plumbed to operate in series to simulate one seven-element vessel. Specifications for the TFC-HR elements are shown in Table 2-3. Additional details for the secondary RO system are shown in Table 2-4.

Figure 2-2. Schematic Diagram of the Pilot System

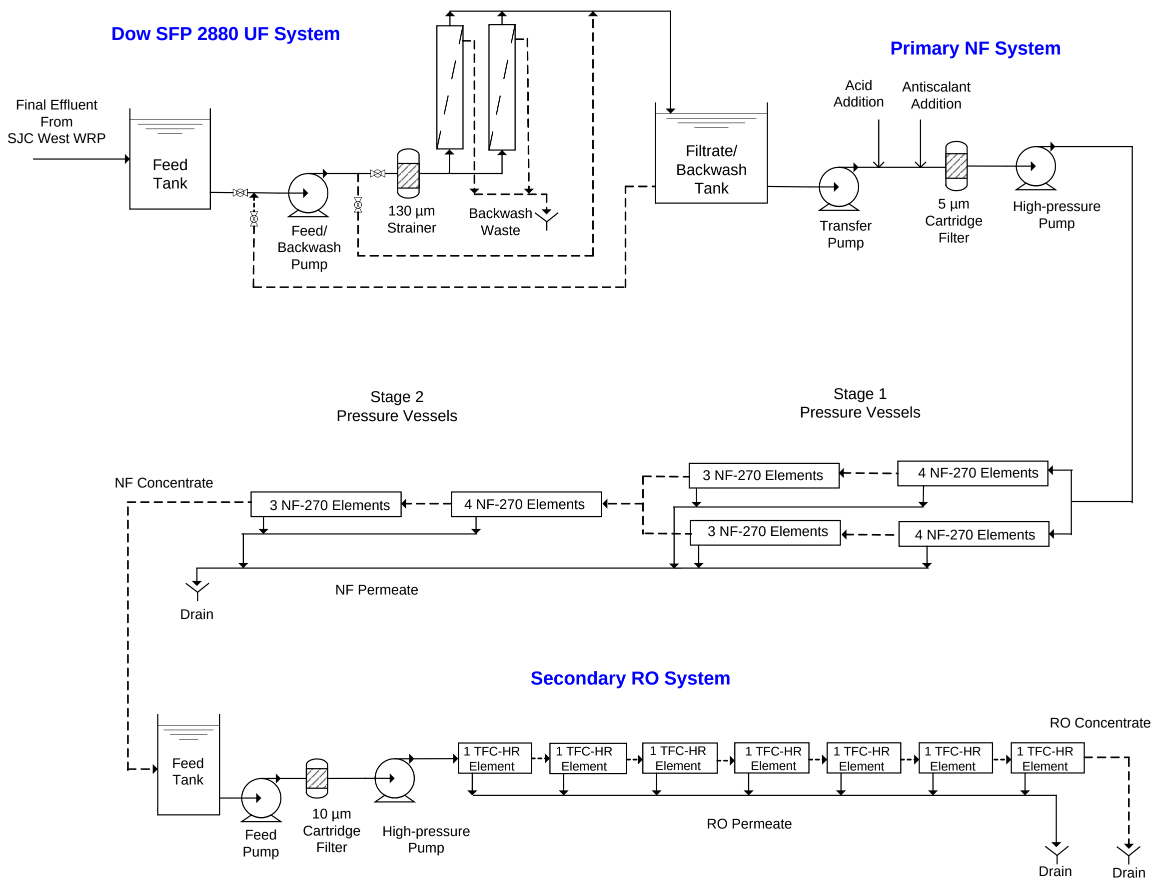


Figure 2-3. Dow SFP 2880 UF System

Table 2-1. Dow SFP 2880 UF System Components

Item	Number	Description
Feed/Backwash Pump	1	Goulds, 2 HP
Strainer	1	Arkal Disk Filter, 130µm
SFP 2880 UF Modules	2	Length = 92.9 inches, Diameter = 8.9 inches, Surface Area = 829 ft^2, Max Feed Pressure = 87 psi, Hollow Fibers (PVDF, 10,000 per module, 1.3 mm OD, 0.7 mm ID, 0.03 µm nominal pore size)
Control System	1	ICS Healy-Ruff, icontrol™ solutions
Instrumentation		
Pressure Sensors	3	Dwyer
Flowmeters	2	George Fisher
Feed Turbidimeter	1	Hach 1720E Low Range
Filtrate Turbidimeter	1	Hach Filter Track 660SC™ Laser Nephelometer
Temperature Sensor	1	George Fischer
Pressure Gauges	3	Wika
Filtrate/Backwash Tank	1	100 Gallons
Chemical Feed Systems		
Chlorine	1	25 gph LMI Dosing Pump, 15 Gallon Storage Tank
Air Compressor	1	Gast, Oil-less, 1/3 HP, 100 psi
Power Requirements	--	120/1PH/60Hz

Figure 2-4. Primary NF System

Table 2-2. Primary NF System Components

Item	Number	Description
High-Pressure Feed Pump	1	Grundfos, 7.5HP
Cartridge Filter	1	Pentek®, Dual Gradient, 50µm Pre-filter, 5µm Post-filter
Chemical Feed Systems		
Acid	1	30 gpd Pulsafeeder Dosing Pump, 25 Gallon Storage Tank
Antiscalant	1	12 gpd Pulsafeeder Dosing Pump, 25 Gallon Storage Tank
Pressure Vessels	6	PROTEC™ Bekaert, 4-inch, FRP, 300 psi
NF-270 Membranes	21	See Table 2-4 for Specifications
Control System	1	R&D Specialties, Series 250
Instrumentation		
Pressure Sensors	4	Measurement Specialties
Flowmeters	4	Burkert
Conductivity Sensors	4	R&D Specialties
Temperature Sensor	1	R&D Specialties
Pressure Gauges	1	Ashcroft
pH Sensor	1	Omega Engineering
Power Requirements	--	480V/3PH/60Hz

Figure 2-5. Secondary RO System

Table 2-3. NF-270 and TFC-HR Membrane Element Specifications

Membrane (Manufacturer)	Material	Element Area (ft^2)	Nominal NaCl Rejection (%)	Nominal $MgSO_4$ Rejection (%)	Molecular Weight Cutoff (Daltons)	pH Range	Max Temp. (°C)	Max Free Cl_2 (mg/L)	Max Operating Pressure (psi)
NF-270 4040 (Dow/FilmTec)	Polyamide TFC[1]	82	--	> 97.0	~ 200	2 -11	45	< 0.1	600
TFC-HR 2540 (Koch)	Polyamide TFC	26	99.6	--	~ 100	4 -11	45	< 0.1	600

1. Thin-Film Composite.

Table 2-4. Secondary RO System Components

Item	Number	Description
High-Pressure Feed Pump	1	STA-RITE, 1HP
Cartridge Filter	1	Applied Membranes, 10 μm
Pressure Vessels	7	Applied Membranes, 2.5-inch, 316SS, 300 psi
TFC-HR Membranes	7	See Table 2-4 for Specifications
Control System	1	R&D Specialties, Series 150
Instrumentation		
Pressure Gauges	3	REO-TEMP
Flowmeters	2	King Instrument Company
Conductivity Sensors	2	R&D Specialties
Temperature Sensor	1	R&D Specialties
Power Requirements	--	120V/1PH/60Hz

2.3 Testing Conditions

Average operating conditions for the NF/RO integrated system are shown in Table 2-5. The primary NF system was operated for a total of 3,690 hours, while the secondary RO system was operated for a total of 3,021 hours. The system was operated in two phases, with the major difference being the antiscalant product used for membrane scale control. Each antiscalant was dosed at approximately 2 mg/L in the feed to the primary NF system, resulting in a dose of approximately 13 mg/L in the feed to the secondary RO system. During Phase One, the antiscalant product employed was SpectraGuard (Professional Water Technologies). This product was selected because of its unique molecular structure (dendrimer based chemistry) and reported ability to be concentrated, in high-recovery applications, to relatively high levels without contributing to membrane fouling.

During Phase Two, the antiscalant was changed to Y2K (King Lee Technologies). This antiscalant is a proprietary formulation of phosphonic acids, which are known to be effective chelating agents and scale inhibitors. However, phosphonic acids are sparingly soluble and can precipitate with the multivalent cations that are bound to them (Nowack, 2003). To control potential antiscalant precipitation and fouling, an operations strategy was employed in which the feed pH was periodically lowered to approximately 4-5 since Y2K is easily dissolved at this pH.

In addition to antiscalant, sulfuric acid was dosed in the feed to the primary NF system to control membrane scaling. Approximate feedwater pH set points were selected based on preliminary scaling projections using membrane manufacturer design software. During Phase One, the average feedwater pH was 6.26, resulting in an average pH of 6.54 in the feed to the secondary RO system. During Phase Two, the average feedwater pH was 6.23, resulting in an average pH of 6.39 in the feed to the secondary RO system. These averages do not include the low pH from the periodic flushes described above.

The primary NF system was operated at an overall flux of approximately 12 gallons/ft^2-day (gfd) and 85% recovery during both phases. However, as will be discussed in Section 3, the first stage and second stage fluxes of the system were varied during Phase One in an attempt to reduce the significant membrane fouling that was observed during this phase. The secondary RO system was initially operated at the target flux of approximately 10 gfd and 50% recovery during Phase One. As with the primary NF system, however, the system was also operated under varied hydraulic conditions (reduced flux, reduced recovery, and with a concentrate recycle loop) to reduce membrane fouling observed during this phase. The secondary RO system was operated at the target flux and recovery throughout Phase Two.

Throughout the pilot study, pertinent operations data including flow, pressure, conductivity, temperature, and pH were recorded daily (Tables 2-6 and 2-7). The data were used to calculate and monitor operations parameters including recovery, flux, net driving pressure, differential pressure, and normalized specific flux. Net driving pressure is the feed pressure required to produce the desired permeate flux minus the differential pressure, permeate pressure, and osmotic pressure. This value was used to calculate normalized specific flux (i.e., flux divided by the net driving pressure, gfd/psi), which was used to evaluate the pressure or energy requirements of the membranes as well as fouling. A higher specific flux indicates that a lower feed pressure and thus lower energy is required. As membranes foul during operation, the net driving pressure increases in order to maintain permeate flux causing the normalized specific flux to decline over time. The rate of decline was used to assess the relative fouling propensity of the membranes. Normalized specific flux values were calculated per ASTM D 4516 (Standard Practice for Standardizing Reverse Osmosis Performance Data).

Table 2-5. NF/RO Integrated System Average Operating Conditions

Parameter	Primary NF System	Secondary RO System			
Phase One (8/15/11 – 11/21/11)					
Net Operating Time (hours)	1,654	987			
Feed Flow (gpm)	17.0	2.4	1.7	1.7	1.5
Permeate Flow (gpm)	14.4	1.2	0.6	0.6	0.6
Concentrate Flow (gpm)	2.6	1.2	1.1	1.1	0.9
Concentrate Recycle Flow (gpm)	--	--	--	2.0	2.0
Flux (gfd)	12.0	9.5	4.7	4.7	4.7
Recovery (%)	84.7	50.0	35.3	35.3	40.0
Feed pH	6.26	6.54			
Antiscalant	**SpectraGuard**[1]	**SpectraGuard**			
Antiscalant Dose (mg/L)	**2**	**13.1 mg/L**[2]			
Phase Two (12/5/11 – 3/22/12)					
Net Operating Time (hours)	2,036	2,035			
Feed Flow (gpm)	17.1	2.4			
Permeate Flow (gpm)	14.5	1.2			
Concentrate Flow (gpm)	2.6	1.2			
Flux (gfd)	12.1	9.5			
Recovery (%)	84.8	50.0			
Feed pH	6.23	6.39			
Antiscalant	**Y2K**[3]	**Y2K**			
Antiscalant Dose (mg/L)	**2**	**13.2 mg/L**[4]			

1. Manufactured by Professional Water Technologies.
2. Estimated based on average Primary NF System recovery of 84.7% and related concentration factor of 6.54.
3. Manufactured by King Lee Technologies.
4. Estimated based on average Primary NF System recovery of 84.8% and related concentration factor of 6.58.

Table 2-6. Primary NF System Operations Parameters

Location	Parameter				
	Flow	Pressure	Conductivity	Temperature	pH
Feed (after acid addition)	√		√	√	√
Feed (membrane feed, just before stage 1 vessels)		√			
Stage 1 Permeate	√		√		
Stage 2 Permeate	√		√		
Total Permeate	√	√	√		
Stage 1 Concentrate		√			
Total Concentrate	√	√			

Table 2-7. Secondary RO System Operations Parameters

Location	Parameter				
	Flow	Pressure	Conductivity	Temperature	pH
Feed	√	√	√	√	√
Permeate	√	√	√		
Concentrate	√	√			

2.4 Water Quality Sampling and Analysis Plan

To evaluate the rejection performance of the NF/RO integrated system, a sampling and analysis program was implemented. Grab samples were collected from the feed, permeate, and concentrate streams of the pilot system (Figure 2-2) and analyzed for the water quality parameters shown in Tables 2-8 and 2-9 by the Sanitation Districts' San Jose Creek Water Quality Laboratory. Table 2-8 includes general water quality parameters, while Table 2-9 includes chemicals of emerging concern (CECs). Analytical methods for all of the parameters are listed in Appendix C. The list of CECs includes constituents with California Department of Public Health (CDPH) Notification Levels as well as unregulated chemicals such as selected pharmaceuticals, personal care products, and hormones. Several of these CECs, in bold font, are specifically recommended for monitoring in recycled water for groundwater recharge/reuse projects by the California State Water Resources Control Board (State Water Board, 2010).

Ten sampling events were conducted for TDS, TOC, nitrogen, UVT, 1,4-dioxane, and NDMA, while only three sampling events were conducted for all other parameters. TDS results were used to evaluate the general salt rejection capabilities of the system. TOC and nitrogen are of particular importance because these constituents are specifically addressed in the most recent revision of the CDPH Draft Groundwater Recharge Reuse Regulations (November 21, 2011). UVT measurements were only conducted on permeate samples to assess the treatability of constituents (e.g., NDMA, 1,4-dioxane) in the system's product water by UV/AOP. In addition to having CDPH Notification Levels, NDMA and 1,4-dioxane are of particular importance because these constituents are typically used to establish minimum design requirements for UV/AOP systems.

Table 2-8. General Water Quality Parameters Monitored in this Study

Parameters	Sample Location						Number of Samples
	NF Feed	NF Permeate	NF Concentrate	RO Permeate	RO Concentrate	Blended Permeate	
TDS (Total dissolved solids)	√	√	√	√	√	√	10
TOC (Total organic carbon)	√	√	√	√	√	√	10
Nitrate	√	√	√	√	√	√	10
Nitrite	√	√	√	√	√	√	10
Ammonia	√	√	√	√	√	√	10
TKN (Total Kjeldahl nitrogen)	√	√	√	√	√	√	10
UVT (UV Transmittance, 254 nm)		√		√		√	10
pH	√	√	√	√	√	√	3
Total Alkalinity	√	√	√	√	√	√	3
Bicarbonate Alkalinity	√	√	√	√	√	√	3
Carbonate Alkalinity	√	√	√	√	√	√	3
Calcium	√	√	√	√	√	√	3
Chloride	√	√	√	√	√	√	3
Magnesium	√	√	√	√	√	√	3
Sulfate	√	√	√	√	√	√	3
Total Phosphate	√	√	√	√	√	√	3
Silica	√	√	√	√	√	√	3
Barium	√	√	√	√	√	√	3
Strontium	√	√	√	√	√	√	3
Fluoride	√	√	√	√	√	√	3
Iron	√	√	√	√	√	√	3
Aluminum	√	√	√	√	√	√	3
Potassium	√	√	√	√	√	√	3
Sodium	√	√	√	√	√	√	3

Table 2-9. Chemicals of Emerging Concern Monitored in this Study

Parameters	Description	Sample Location					Number of Samples
		NF Feed	NF Permeate	NF Concentrate	RO Permeate	Blended Permeate	
Acetaminophen	Analgesic	√	√	√	√	√	3
Atenolol	Beta Blocker	√	√	√	√	√	3
Azithromycin	Antibiotic	√	√	√	√	√	3
Bisphenol A[1]	Plasticizer	√	√	√	√	√	3
Caffeine	Stimulant	√	√	√	√	√	3
Carbamazepine	Antiepileptic	√	√	√	√	√	3
DEET[2]	Insecticide	√	√	√	√	√	3
1,4 - dioxane[3]	Solvent	√	√	√	√	√	10
Diclofenac	Analgesic	√	√	√	√	√	3
Estrone	Hormone	√	√	√	√	√	3
17β - Estradiol	Hormone	√	√	√	√	√	3
17α - Ethynylestradiol	Synthetic Hormone	√	√	√	√	√	3
Erythromycin	Antibiotic	√	√	√	√	√	3
Fluoxetine	Antidepressant	√	√	√	√	√	3
Furosemide	Diuretic	√	√	√	√	√	3
Gemfibrozil	Lipid Regulator	√	√	√	√	√	3
Ibuprofen	Analgesic	√	√	√	√	√	3
Iopromide	Contrast Media	√	√	√	√	√	3
Meprobamate	Antianxiety	√	√	√	√	√	3
Naproxen	Analgesic	√	√	√	√	√	3
NDMA[4]	Disinfection by-product, Industrial	√	√	√	√	√	10
4-Nonylphenol	Surfactant	√	√	√	√	√	3
4-Octylphenol	Surfactant	√	√	√	√	√	3
Primidone	Antiepileptic	√	√	√	√	√	3
Phenytoin (Dilantin)	Anticonvulsant	√	√	√	√	√	3
Sucralose	Artificial Sweetener	√	√	√	√	√	3
Sulfamethoxazole	Antibiotic	√	√	√	√	√	3
TCEP[5]	Flame Retardant	√	√	√	√	√	3
Triclosan	Antimicrobial	√	√	√	√	√	3
Trimethoprim	Antibiotic	√	√	√	√	√	3

1. Chemicals of emerging concern in bold font are specifically recommended for monitoring in recycled water for groundwater recharge/reuse projects by the California State Water Resources Control Board (State Water Board, 2010).
2. DEET (N,N-diethyl-meta-toluamide).
3. 1,4-dioxane CDPH Notification Level = 1 µg/L.
4. NDMA (N-Nitrosodimethylamine) CDPH Notification Level = 10 ng/L.
5. TCEP (Tris (2-chloroethyl) phosphate).

2.5 Membrane Autopsy Analyses

At the conclusion of testing, sample NF and RO membrane elements were sent to Avista Technologies for autopsy analyses to (1) compare the performance of the elements to manufacturer specifications for new membrane elements, and (2) characterize the foulant material on the membrane surface. A total of four elements were analyzed, including two NF-270 and two TFC-HR elements (one lead and one tail end element each from the primary NF and secondary RO systems). The analyses that were conducted and their descriptions are listed in Table 2-10.

Table 2-10. Membrane Autopsy Analyses

Analysis	Description
External Visual Exam	Thorough examination of the exterior of the elements with a focus on damage or defects in the outer wrappings, anti-telescope devices, permeate tubes, brine seals, and the general condition of the feed and concentrate ends.
Wet Test	The elements are placed in a single element vessel and operated under laboratory conditions. Flow, pressure, and salt rejection are measured and these data are compared to manufacturer specifications.
Internal Visual Exam	The outer wrappings are removed and the membranes are cut open. Glue lines are examined and notes are made of any color and/or odors emanating from the membrane leaves. Foulant material is collected for analysis.
Foulant Analyses	*Loss on Ignition*: Thermogravimetric test used to determine the amount of organic foulants relative to inorganic foulants on the membrane surface. *Foulant Density:* Membrane foulant density is determined as the weight of dry foulant per cm^2 of membrane surface. *Acid Test*: Used to determine the presence of carbonates on the membrane surface. Several drops of dilute hydrochloric acid are placed on the foulant surfaces. Effervescing indicates a positive test result. *Gram Staining*: Foulant samples are stained and examined with a light microscope at 1000x using an oil immersion lens. Gram positive bacteria are stained blue, while Gram negative bacteria are stained red. *FTIR (Fourier-Transform Infra Red) Spectroscopy Analysis*: Used to determine the nature of any organic foulants on membrane surface. *EDX (Energy Dispersive X-Ray)/ SEM (Scanning Electron Microscopy)*: EDX analyses are used to identify inorganic foulants and SEM analyses are used to produce high magnification images of the membrane surface.

3. Results

3.1 Operational Performance Results

The primary NF system was operated for a total of 3,690 hours, while the secondary RO system was operated for a total of 3,021 hours. Each of the systems was operated in two phases, with the major difference being the antiscalant product used for membrane scale control. During Phase One, the antiscalant product that employed was SpectraGuard, which is manufactured by Professional Water Technologies. This antiscalant product was not effective for scale control and relatively significant membrane fouling was observed in both the primary NF and secondary RO systems. During Phase Two, the antiscalant was changed to Y2K, which is manufactured by King Lee Technologies. This antiscalant product was effective for controlling membrane scale formation. Results from each phase of testing are discussed below.

3.1.1 Phase One – Primary NF System

The primary NF system was operated for 1,654 hours during Phase One. The system was operated at an average overall flux, recovery, and feedwater pH of 12 gfd, 84.7%, and 6.26, respectively. At start-up, the normalized specific flux (NSF) was approximately 0.35 gfd/psi (Figure 3-1, Run 1). After only 1,119 hours of operation, the NSF decreased 30% to 0.25 gfd/psi at the end of Run 1. The system was subsequently shut down and a clean-in-place (CIP) was conducted using a high pH (pH ~10) cleaning solution followed by a low pH (pH ~ 2) cleaning solution. The high pH solution consisted of 2.0% sodium tripolyphosphate (STPP) and 0.8% sodium ethylaminediaminetetraacetic acid (EDTA), while the low pH solution consisted of 2% citric acid. Each of the cleaning solutions was recirculated for approximately 30 minutes through Stage 1 of the system first, followed by Stage 2. The temperature of the solutions was maintained between 32 and 35ºC.

To verify the effectiveness of the CIP, the system was started up (Run 2) and operated for approximately five hours under the same hydraulic conditions as Run 1. As shown in Figure 3-1, complete recovery of the start-up NSF was achieved. After verifying the effectiveness of the CIP, the hydraulic operating conditions of the system were changed as described below.

During Run 1, a significant (from 0.25 to 0.14) decrease in the permeate flow ratio was observed (Table 3-1). The permeate flow ratio is defined as the stage 2 permeate flow divided by the stage one permeate flow. This indicates that the majority of fouling occurred in Stage 2 of the system, most likely due to membrane scaling. Further evidence of this is the start-up and final fluxes for Stages 1 and 2 of the system (Table 3-2); the Stage 1 flux increased from 14.7 to 15.1 gfd, but the Stage 2 flux decreased from 7.3 to 6.5 gfd.

In an attempt to reduce the rate of fouling that was observed in Stage 2 during Run 1, Stage 1 permeate throttling was used (backpressure ~ 10 psi) during Run 2 to improve the balance of fluxes between the stages. As shown in Figure 3-1, even with the hydraulic changes, relatively significant fouling was still observed. After only 530 hours of operation, the NSF decreased from 0.28 gfd/psi to 0.19 gfd/psi. As observed during Run 1, the permeate flow ratio decreased (from 0.38 to 0.22), the Stage 1 flux increased (from 13.0 to 13.4 gfd), and the Stage 2 flux decreased (from 10.0 to 8.3 gfd). The system was subsequently shut down and a CIP was conducted as described above with the exception that the cleaning solutions were recirculated through the system for 1 hour as opposed to 30 minutes.

Figure 3-1. Phase One Primary NF System Normalized Specific Flux

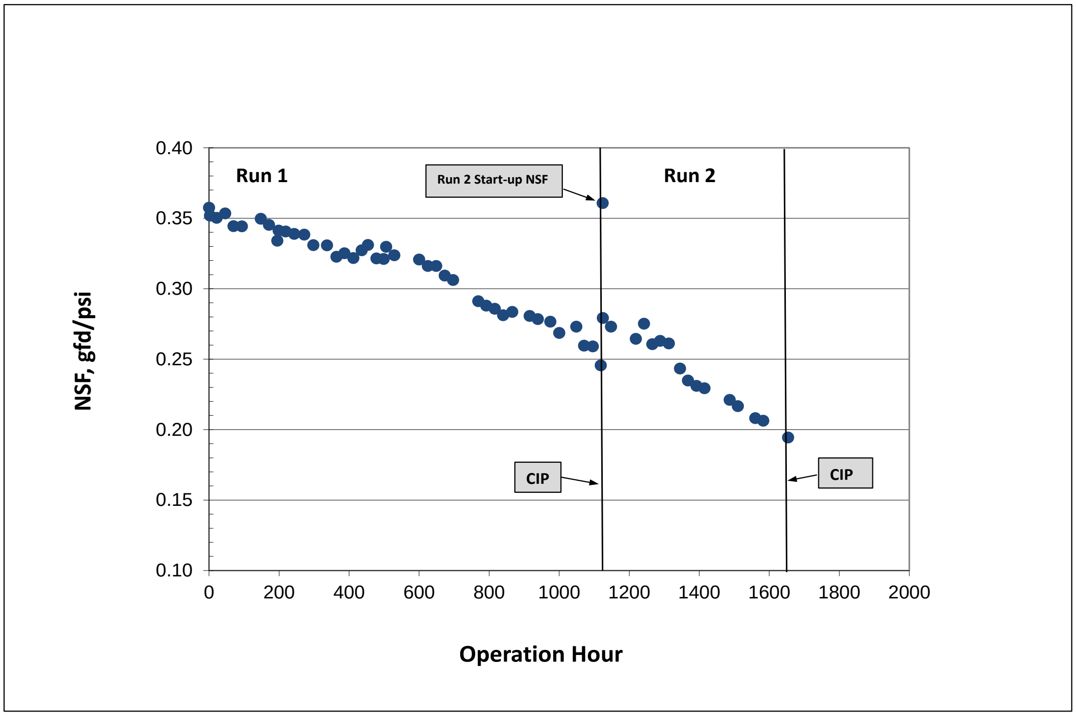


Table 3-1. Primary NF System Phase One and Two Permeate Flow Ratios[1]

Phase	Run	Operating Time (hours)	Start-up Permeate Flow Ratio	Final Permeate Flow Ratio
One	1	1,119	0.25	0.14
	2	530	0.38	0.22
Two	--	2,036	0.38	0.41

1. Permeate flow ratio = Stage 2 permeate flow divided by the Stage 1 permeate flow.

Table 3-2. Primary NF System Phase One and Two Fluxes

Phase	Run	Operating Time (hours)	Overall System Flux (gfd)	Stage 1 Flux (gfd)	Stage 2 Flux (gfd)
One	1	1,119	12.2	Start-up = 14.7 Final = 15.1	Start-up = 7.3 Final = 6.5
	2	530	11.8	Start-up = 13.0 Final = 13.4	Start-up = 10.0 Final = 8.3
Two	--	2,036	12.1	Start-up = 13.0 Final = 12.8	Start-up = 10.0 Final = 10.8

3.1.2 Phase One – Secondary RO System

The secondary RO system was operated for 987 hours during Phase One. Similar to the primary NF system, significant fouling, most likely due to membrane scaling, was initially observed and therefore changes were subsequently made to the hydraulic operating conditions of the system in an attempt to improve performance (Table 3-3). These changes included reducing the flux and recovery as well as adding a concentrate recycle loop. The average feedwater pH was 6.54 throughout Phase One.

The secondary RO system was initially operated at the target flux of approximately 10 gfd and 50% recovery. Under these operating conditions, the NSF decreased from 0.20 gfd/psi to 0.11 gfd/psi after only 70 hours of operation (Figure 3-2, Run 1). The system was subsequently shutdown and a CIP was conducted using the same high and low pH solutions as described above.

After conducting the CIP, the system was started up at a reduced flux of approximately 5 gfd and recovery of 35% (Run 2). Under these operating conditions, significant membrane fouling was again observed, but after a longer operating period of 268 hours. The NSF decreased 48%, from 0.25 gfd/psi to 0.13 gfd/psi. The system was subsequently shutdown and a CIP was conducted. To verify the effectiveness of the CIP, the system was started up (Run 3) and operated for approximately one hour under the same hydraulic conditions as Run 2. As shown in Figure 3-2, complete recovery of the Run 2 start-up NSF was achieved.

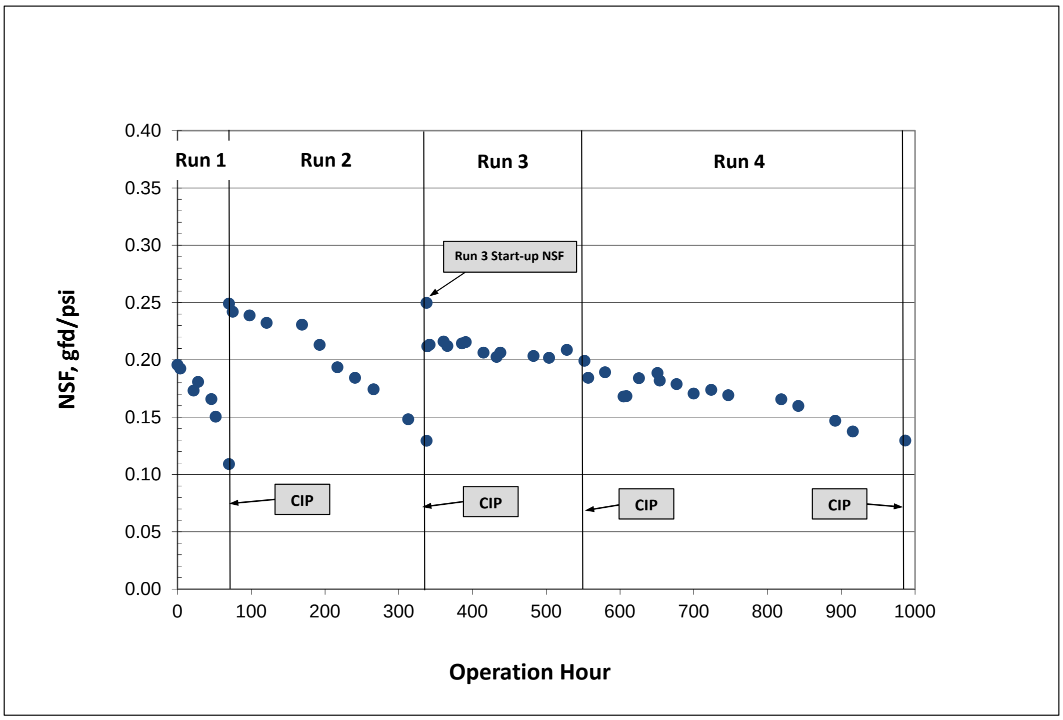
For the remainder of Run 3, the system was operated with a concentrate recycle loop so that a higher cross-flow velocity (~ 3 times higher) through the RO elements could be achieved (Table 3-3). The corresponding feed, permeate, concentrate, and concentrate recycle flows are shown in Table 2.5. Increasing the cross-flow velocity through the elements significantly reduced the rate of membrane fouling. The NSF only decreased from 0.21 gfd/psi to 0.20 gfd/psi, over 214 hours of operation. However, the system had to be shutdown at this point to conduct a CIP for the primary NF system (end of Run 1 for primary NF system).

During Run 4, the system was again operated with a concentrate recycle loop. However, based on the Run 3 results, the recovery was increased to 40%. Improved performance was again observed, relative to operation without the concentrate recycle loop. The NSF decreased from 0.18 gfd/psi to 0.13 gfd/psi, over 435 hours of operation.

Table 3-3. Secondary RO System Phase One and Two Flux, Recovery, and Cross Flow Velocity

Phase	Run	Operating Time (hours)	Flux (gfd)	Recovery (%)	Concentrate Recycle Loop	Cross Flow Velocity (ft/s)
One	1	70	9.5	50	--	0.23
	2	268	4.7	35	--	0.21
	3	214	4.7	35	√	0.59
	4	435	4.7	40	√	0.55
Two	--	2,035	9.5	50	--	0.23

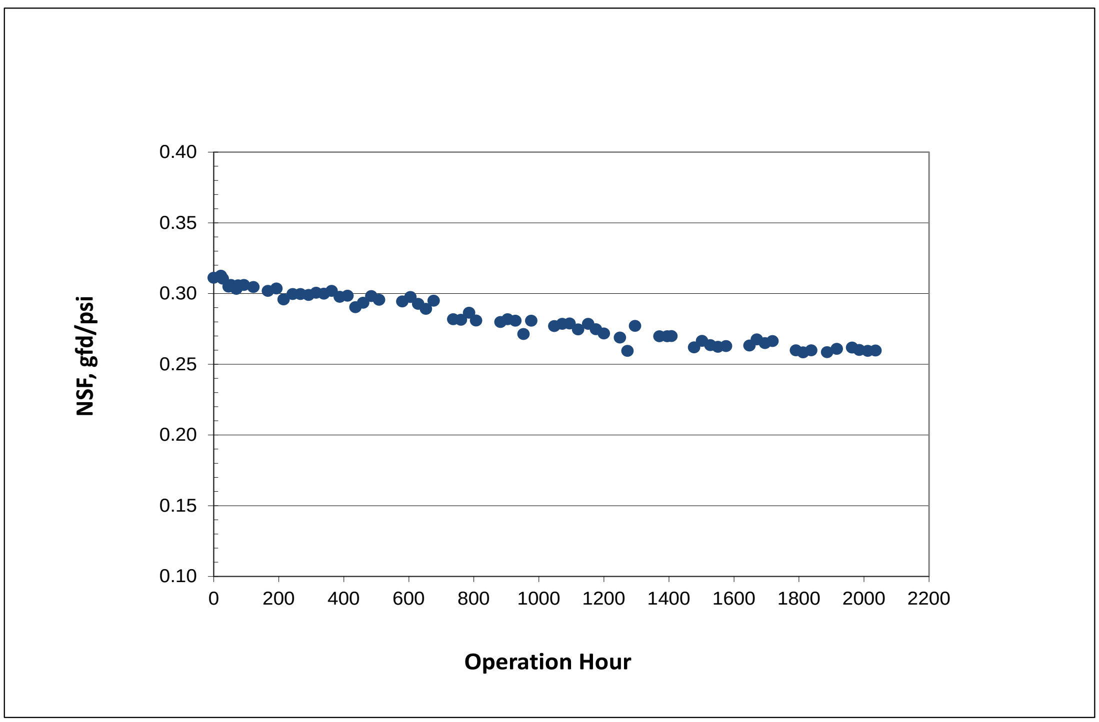
Figure 3-2. Phase One Secondary RO System Normalized Specific Flux



3.1.3 Phase Two – Primary NF System

During Phase Two, the primary NF system was operated at an average overall flux, recovery, and feedwater pH of 12.1 gfd, 84.8%, and 6.23, respectively. Similar to Phase One (Run 2), Stage 1 permeate throttling was used to balance the fluxes between the stages of the system. Under these conditions, the system was operated for 2,036 hours, or approximately 3 months, with significantly less fouling compared to Phase One operation. The NSF decreased from 0.31 gfd/psi at start-up to 0.26 gfd/psi at the end of Phase Two (Figure 3-3). The permeate flow ratio increased (from 0.38 to 0.41), the Stage 1 flux decreased (from 13.0 to 12.8 gfd), and the Stage 2 flux increased (from 10.0 to 10.8 gfd) (Tables 3-1 and 3-2). These results indicate that there was insignificant scaling in Stage 2 of the system. This was confirmed by the results of membrane autopsy analyses, discussed in Section 3.2.

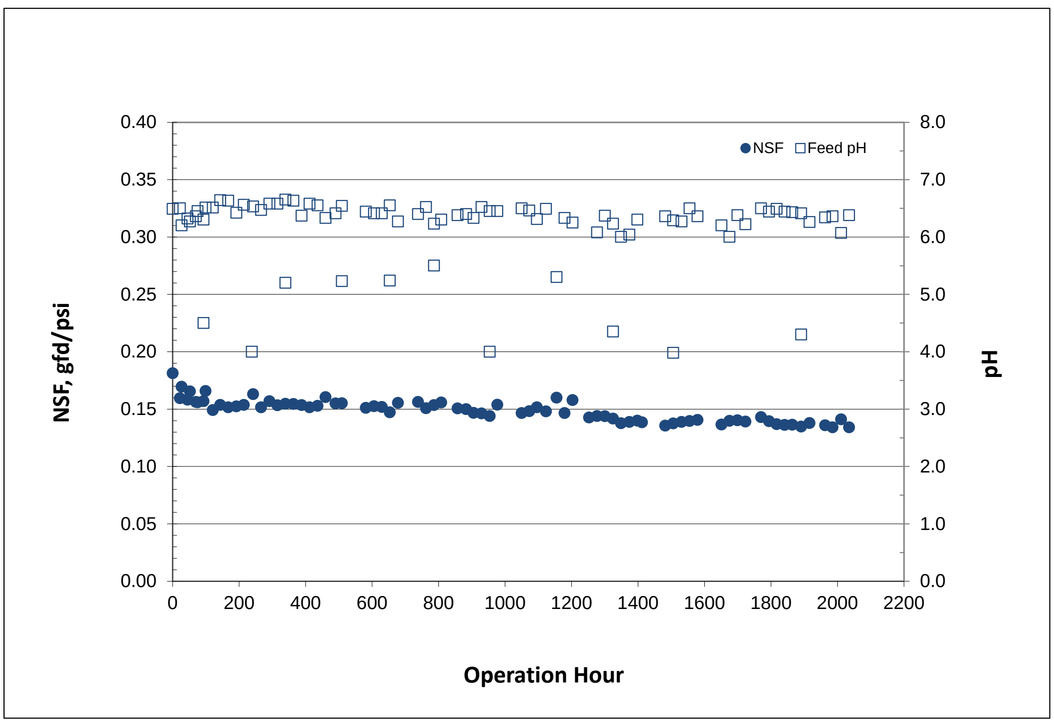
Figure 3-3. Phase Two Primary NF System Normalized Specific Flux



3.1.4 Phase Two – Secondary RO System

During Phase Two, the secondary RO system was operated at an average flux, recovery, and feedwater pH of approximately 10 gfd, 50%, and 6.39, respectively. The antiscalant product used during this phase (Y2K) is a proprietary formulation of phosphonic acids. Phosphonic acids are sparingly soluble and can precipitate with the multivalent cations that they bind to. Therefore, to control potential antiscalant precipitation and fouling, an operational strategy was employed in which the feed pH was periodically lowered to approximately 4-5 (Figure 3-4) since the Y2K product is easily dissolved at this pH. The pH was lowered approximately once per week by simply increasing the acid feed rate for 30 minutes. Under these conditions, the system was operated for 2,035 hours, or approximately 3 months. Significantly less fouling was observed compared to Phase One operation. The NSF decreased from 0.18 gfd/psi at start-up to 0.13 gfd/psi at the end of Phase Two. As with the primary NF system, results of membrane autopsy analyses confirm that there was insignificant scaling during Phase Two operation.

Figure 3-4. Phase Two Secondary RO System Normalized Specific Flux and Feed pH



3.2 Membrane Autopsy Results

At the conclusion of testing, sample NF and RO membrane elements were sent to Avista Technologies for autopsy analyses to (1) compare the performance of the elements to manufacturer specifications for new membrane elements, and (2) characterize the foulant material on the membrane surface. A total of four elements were analyzed, including two NF-270 and two TFC-HR elements (one lead and one tail end element each from the primary NF and secondary RO systems).

The results of the autopsy analyses confirm the operational performance results and indicate that significant membrane fouling in general, and scaling in particular, did not occur during Phase Two operation. Membrane fouling was identified to be primarily organic in nature, with some biofouling, colloidal, as well as inorganic fouling. Results of autopsy analyses for the primary NF and secondary RO systems are summarized below.

3.2.1 Primary NF System

3.2.1.1 External Visual Exam

Based on the external exam of the lead and tail end NF elements, the outer fiberglass wrappings, anti-telescope devices, permeate tubes, brine seals, and feed and concentrate ends were all in good condition.

3.2.1.2 Wet Test

Wet test results for the lead and tail end NF elements are shown in Table 3-4. The tail element normalized permeate flow was within the manufacturer specified range for a new, clean membrane. However, membrane fouling was observed for the lead element; the normalized permeate flow was slightly lower than the specified minimum. The differential pressure for both elements was within the manufacturer specified range. This indicates that there was no significant blockage of the feed/concentrate channel due to deposition of particulate matter, biofilm formation, or scaling, during operation.

Table 3-4. Wet Test Results for Lead and Tail NF Elements[1]

Parameter	Lead Element	Tail Element	Manufacturer Specification
Normalized Permeate Flow (gpm)	1.3	1.7	1.5 - 1.7
Differential Pressure (psi)	3	3	3 - 5
$MgSO_4$ Rejection (%)	99.5	96.9	≥ 97

1. Test conditions: 2,000 mg/L $MgSO_4$, 70 psi feed pressure, pH = 7.7

3.2.1.3 Internal Visual Exam

Based on the internal exam of the lead and tail end NF elements, the feed spacers, permeate spacers, and glue lines were in good condition. The active membrane surfaces of the elements were coated with a thin tan colored organic foulant layer (Figures 3-5 and 3-6).

Figure 3-5. Lead NF Element Active Membrane Surface

Figure 3-6. Tail NF Element Active Membrane Surface

3.2.1.4 Foulant Analyses

Results of the foulant analyses for the lead and tail end NF elements are summarized below. Based on the analyses that were conducted, in conjunction with visual observations of the active membrane surfaces, membrane fouling was identified to be primarily organic in nature. However, biofouling, colloidal, as well as inorganic fouling were also identified.

Loss on Ignition: loss on ignition could not be determined due to insufficient foulant material on the membrane surfaces.

Foulant Density: foulant density could not be determined due to insufficient foulant material on the membrane surfaces.

Acid Test: no effervescing was observed when acid was applied on the surfaces of the membranes indicating that carbonates were not present.

Gram Staining: microscope analysis of foulant scraped from the membrane surface identified Gram negative and Gram positive bacteria, algae, and amorphous organic material on the lead element. Insufficient foulant material was present on the tail element to perform the analysis.

FTIR: FTIR analyses identified absorbance bands associated with organic material, including carbohydrates and proteins.

EDX/SEM: EDX analyses identified negligible inorganic fouling on the membrane surfaces. Trace amounts of silica were identified on the lead element, while trace amounts of silica, aluminum, and magnesium were identified on the tail element. SEM images for both elements did not identify the presence of a significant amount of fouling. Images of the lead element identified a thin layer of organic material and colloidal solids (Figure 3-7). Images of the tail element identified very few particles on the membrane surface (Figure 3-8).

Figure 3-7. Lead NF Element SEM Image

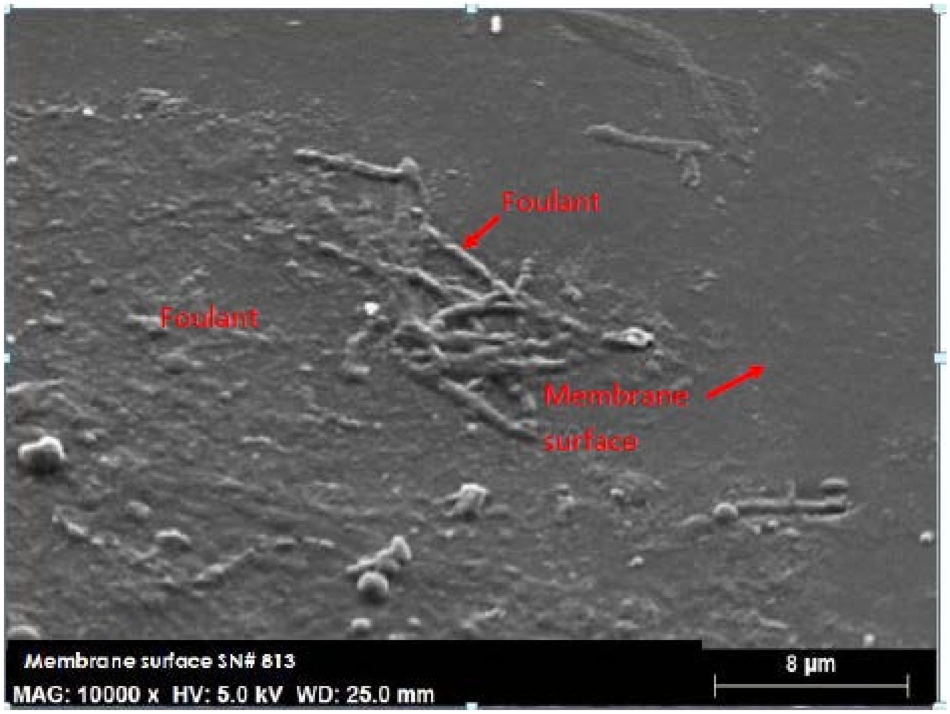
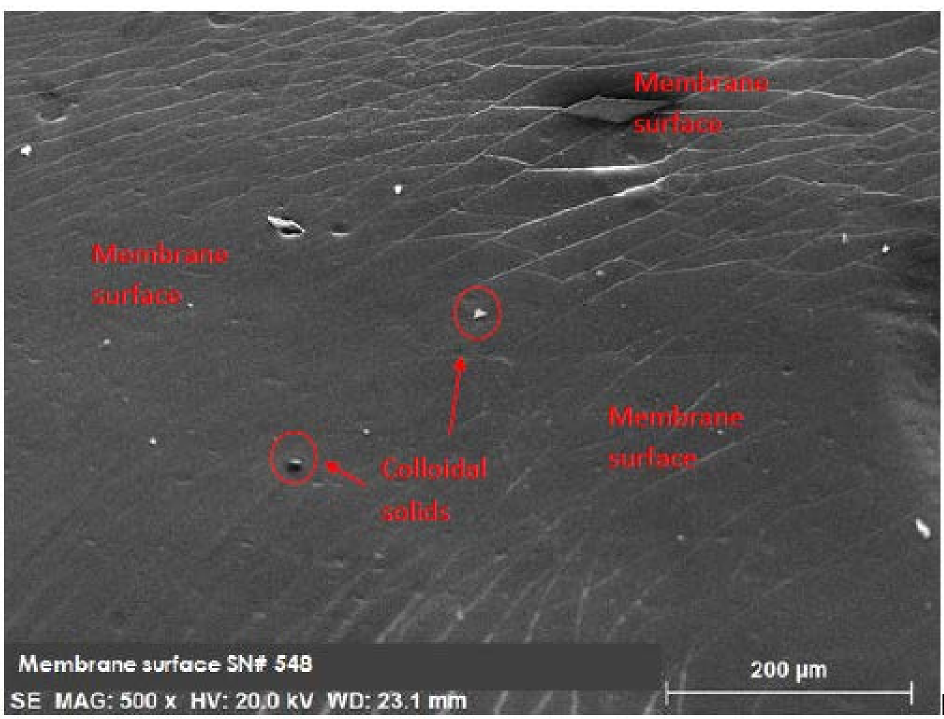


Figure 3-8. Tail NF Element SEM Image



3.2.2 Secondary RO System

3.2.2.1 External Visual Exam

Based on the external exam of the lead and tail end RO elements, the outer tape wrappings, anti-telescope devices, permeate tubes, brine seals, and feed and concentrate ends were all in good condition.

3.2.2.2 Wet Test

Wet test results for the lead and tail end RO elements are shown in Table 3-5. The lead element normalized permeate flow was within the manufacturer specified range for a new, clean membrane. However, membrane fouling was observed for the tail element; the normalized permeate flow was 20% lower than the specified minimum. The differential pressure for both elements was within the manufacturer specified range. This indicates that there was no significant blockage of the feed/concentrate channel due to deposition of particulate matter, biofilm formation, or scaling, during operation.

Table 3-5. Wet Test Results for Lead and Tail RO Elements[1]

Parameter	Lead Element	Tail Element	Manufacturer Specification
Normalized Permeate Flow (gpm)	0.46	0.35	0.44 - 0.62
Differential Pressure (psi)	3	3	3 - 5
TDS Rejection (%)	99.1	99.1	98.8 - 99.4

1. Test conditions: Dechlorinated City of San Diego Tap Water, 225 psi feed pressure, pH = 7.2

3.2.2.3 Internal Visual Exam

Based on the internal exam of the lead and tail end RO elements, the feed spacers, permeate spacers, and glue lines were in good condition. The active membrane surfaces of the elements were coated with a thin tan colored organic foulant layer (Figures 3-9 and 3-10). As expected, the foulant layer was more pronounced on the RO membrane surfaces when compared to the NF membranes.

Figure 3-9. Lead RO Element Active Membrane Surface

Figure 3-10. Tail RO Element Active Membrane Surface

3.2.2.4 Foulant Analysis

Results of the foulant analyses for the lead and tail end RO elements are summarized below. Based on the analyses that were conducted, in conjunction with visual observations of the active membrane surfaces, membrane fouling was identified to be primarily organic in nature. However, biofouling, colloidal, as well as inorganic fouling were also identified.

Loss on Ignition: loss on ignition could not be determined due to insufficient foulant material on the membrane surfaces.

Foulant Density: foulant density could not be determined due to insufficient foulant material on the membrane surfaces.

Acid Test: no effervescing was observed when acid was applied on the surfaces of the membranes indicating that carbonates were not present.

Gram Staining: microscope analysis of foulant scraped from the membrane surface identified Gram negative and Gram positive bacteria as well as colloidal solids on the lead and tail elements.

FTIR: FTIR analyses identified absorbance bands associated with organic material, including carbohydrates and proteins.

EDX/SEM: EDX analyses identified negligible inorganic fouling on the membrane surfaces. Silica, aluminum, calcium, and phosphorus were identified on the lead element, while silica, aluminum, and phosphorus were identified on the tail element. SEM images for both elements did not identify the presence of a significant amount of fouling. Images of the lead and tail elements identified a few colloidal solids as well as isolated patches of a smooth foulant layer (Figures 3-11 and 3-12).

Figure 3-11. Lead RO Element SEM Image

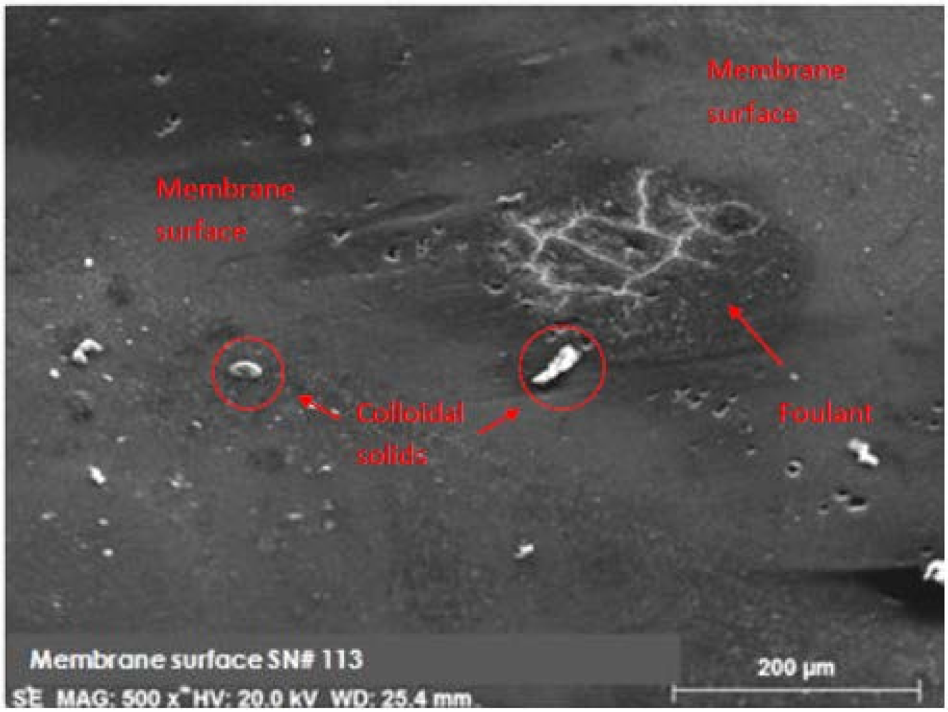
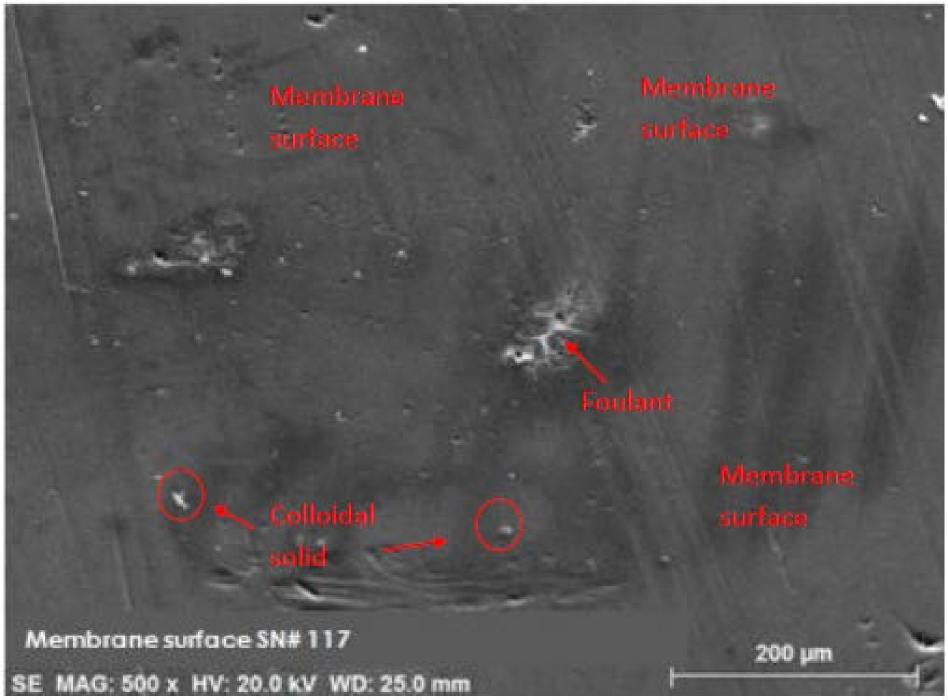


Figure 3-12. Tail RO Element SEM Image



3.3 Rejection Performance Results

To evaluate the rejection performance of the NF/RO integrated system, a sampling and analysis program was implemented during the study. Grab samples were collected from the feed, permeate, and concentrate streams of the membrane pilot system (Figure 2-2) and analyzed for general water quality parameters (Table 2-8) and CECs (Table 2-9). The results are discussed below.

3.3.1 General Water Quality Parameters

Rejection results for general water quality parameters are shown in Tables 3-6, 3-7, and 3-8, for the primary NF system, secondary RO system, and overall NF/RO integrated system, respectively. As designed, the primary NF system achieved moderate overall TDS rejection (52.8%), a high degree of TOC rejection (87.3%), and varying degrees of rejection for specific constituents, ranging from - 7.5% for nitrate to 98.6% for sulfate. Negative nitrate rejection by NF membranes has been observed in previous studies and is related to ion mobility and the need to maintain pore and permeate electroneutrality during operation (Drewes et al., 2008; Yu et al., 2010). The highly mobile and negatively charged nitrate ion is forced to freely permeate through the membrane to balance the charge of less mobile but more concentrated cations.

The secondary RO system achieved a high degree of rejection for TDS (98.5%), TOC (97.9%), as well as all other specific constituents. Blending RO permeate with NF permeate slightly improved the overall product water quality (see Blended Permeate, Table 3-8).

The concentrations of those constituents in the blended permeate that have State of California Primary or Secondary MCLs (Maximum Contaminant Levels) were below their respective MCLs. Other blended permeate parameters of interest include total nitrogen, TOC, and UVT. Total nitrogen and TOC are of interest because each of these parameters is specifically addressed in the CDPH Draft Groundwater Recharge Reuse Regulations (DGRRR). UVT is of importance because it has a significant impact on the design and performance of UV/AOP, which is typically downstream of high-pressure membrane systems.

For nitrogen control, the DGRRR require that a total nitrogen concentration of 10 mg/L be met for surface spreading projects such as GRIP. Although the NF/RO integrated system does not provide a significant barrier for nitrogen removal (14.3% total nitrogen rejection), application of this system for the proposed GRIP AWTP would still be feasible because the nitrification-denitrification activated sludge treatment process at the SJC West WRP typically produces effluent with total nitrogen concentration < 10 mg N/L.

The TOC limit that needs to be met for surface spreading projects is equal to 0.5 mg/L divided by the recycled water contribution. This limit does not have to be met until after infiltration, at the point where the recycled water meets the groundwater, thus receiving credit for removal that may occur within the vadose zone. Therefore, the acceptability of the blended permeate water quality will ultimately depend on (1) the approved recycled water contribution for the GRIP project and, (2) the expected degree of additional TOC removal within the vadose zone of the spreading basins. This analysis is beyond the scope of this project.

The blended permeate UVT ranged from 95.7 - 97.4%, with an average of 96.8%. These results indicate that the blended permeate produced by the NF/RO integrated system would be suitable for treatment by UV/AOP since these systems are typically designed for a minimum UVT of 95% (Trojan Technologies, Inc., 2002).

3.3.2 Chemicals of Emerging Concern

Rejection results for target CECs are shown in Tables 3-9, 3-10, and 3-11, for the primary NF system, secondary RO system, and overall NF/RO integrated system, respectively. Average rejection results for the primary NF and secondary RO systems are also shown in Figures 3-13 and 3-14, along with the molecular weights (MW) of the detected CECs. Of the 30 target CECs, 19 of them were detected in the feed stream to the primary NF system. The primary NF system achieved a high degree of rejection and/or rejection to below the respective reporting limits for all of the CECs, with the exception of NDMA (8.4%) and 1,4-dioxane (18.3%). The relatively poor rejection of NDMA and 1,4-dioxane is related to membrane rejection mechanisms as well as the physicochemical properties of the compounds. Based on a comprehensive literature review conducted by Bellona et al. (2004), the dominant rejection mechanisms for the removal of CECs by high-pressure membranes include: (1) size exclusion (i.e., removal of compounds with a MW greater than the molecular weight cutoff (MWCO) of the membrane); (2) electrostatic exclusion (i.e., removal of negatively charged compounds by electrostatic repulsion at the net negatively charged membrane surface); and (3) adsorption (i.e., adsorption of relatively hydrophobic compounds onto the membrane surface). Both NDMA and 1,4-dioxane are relatively small (MW NDMA = 74 g/mol, MW 1,4-dioxane = 88 g/mol), uncharged, and hydrophilic (i.e., log $K_{ow} < 2$) compounds. Therefore, rejection by high-pressure membranes is due to size exclusion only. Since the reported MWCO of the NF-270 membrane used in the primary NF system is approximately 200 Daltons (Yu et al., 2010), poor rejection is expected.

For the secondary RO system, 26 of the 30 target CECs were detected in the feed stream (NF concentrate). Seven of these CECs were not detected in the feed to the primary NF system, including acetaminophen, caffeine, estrone, 17ß - estradiol, furosemide, ibuprofen, and trimethoprim. This indicates that although these CECs were not detected in the NF feed, they were present and were concentrated by the NF-270 membrane. All of the detected CECs were rejected to a high degree and/or to below their respective reporting limits, with the exception of NDMA (39.8%). Poor NDMA rejection is expected, however, since the reported MWCO of the TFC-HR membrane used in the secondary RO system is approximately 100 Daltons (Drewes et al., 2008).

Rejection results for the overall NF/RO integrated system were essentially the same as the results for the primary NF system (Figure 3-15). These results illustrate that the permeate produced by the secondary RO system has a negligible effect on the overall product water quality.

Eleven CECs were detected above their respective reporting limits in the blended permeate, including atenolol, azithromycin, carbamazepine, DEET, 1,4-dioxane, meprobamate, NDMA, primidone, phenytoin, sucralose, and TCEP. Currently, of these 11 CECs, only 1,4-dioxane and NDMA have regulatory limits. The CDPH Notification Levels for 1,4-dioxane and NDMA are 1 µg/L and 10 ng/L, respectively. The average 1,4-dioxane concentration of the blended permeate (0.9 µg/L) was lower than the 1 µg/L Notification Level. However, the Notification Level was not consistently met (concentrations ranged from 0.75 - 1.2 µg/L). NDMA levels were significantly higher than the 10 ng/L Notification Level, ranging from 110 - 260 ng/L, with an average of 176 ng/L. These results indicate that in order to reliably meet the Notification Levels for 1,4-dioxane and NDMA, downstream UV/AOP would be needed after the NF/RO integrated system.

For the remaining CECs that were detected in the blended permeate, there are currently no regulatory levels. However, risk assessment studies have been conducted in which acceptable daily intakes (ADI) have been established for some of them (Snyder et al., 2008; Nellor et al., 2010). An ADI is commonly defined as the amount of chemical to which a person can be exposed to on a daily basis over an extended period of time, usually a lifetime, without suffering a deleterious effect. These ADI can be converted to drinking water equivalent levels (DWELs) by making assumptions about the daily water intake by a person. DWELs have been established for 7 of the CECs detected in the blended permeate including atenolol, carbamazepine, DEET, meprobamate, phenytoin, primidone, and TCEP. As shown in Table 3-12, the DWELs for these CECs are significantly higher than the maximum concentrations detected in the blended permeate. It should also be noted that, with the exception of TCEP, all of these CECs have been demonstrated to be efficiently removed by advanced oxidation processes. In addition, varying degrees of removal have been observed during soil aquifer treatment. Therefore, the detection of these CECs in the blended permeate may not be a concern with respect to causing deleterious health effects.

Table 3-6. Primary NF System
Rejection Results for General Water Quality Parameters

Parameters	Sample Location						
	Feed		Permeate		Concentrate		Average % Rejection
	Range	Average[1]	Range	Average[1]	Range	Average	
TDS (mg/L)	529 - 565	545	236 - 286	257	1,900 - 2,200	2,077	52.8
pH (field)	6.0 - 6.6	6.3	5.7 - 6.2	5.9	6.3 - 6.6	6.5	--
Total Alkalinity (mg/L $CaCO_3$)	75 - 77	76	42 - 52	47	181 - 219	200	38.2
Calcium (mg/L)	49 - 52	50	13 - 16	15	237 - 259	249	70.0
Chloride (mg/L)	99 - 109	103	91 - 98	95	121 - 179	154	7.8
Magnesium (mg/L)	13 - 14	14	3.4 - 4.1	3.7	68 - 75	73	73.6
Sulfate (mg/L)	146 - 183	159	1.5 - 3.6	2.3	904 - 1,110	989	98.6
Total Phosphate (mg/L PO_4^{3-})	2.1 - 5.1	3.3	0.14 - 0.40	0.23	13 - 32	20	93.0
Silica (mg/L SiO_2)	22 - 24	23	21 - 23	21	34 - 39	35	8.7
Barium (µg/L)	29 - 36	32	7.8 - 9.7	8.9	142 - 176	156	72.2
Strontium (µg/L)	333 - 351	339	88 - 115	99	1,610 - 1,760	1,690	70.8
Fluoride (mg/L)	0.75 - 0.79	0.78	0.47 - 0.58	0.53	2.0 - 2.5	2.2	32.1
Iron (mg/L)	0.026 - 0.060	0.040	< 0.020	< 0.020	0.16 - 0.22	0.19	≥ 50.0
Aluminum (µg/L)	< 10 - 12	11	< 10	< 10	33 - 77	52	≥ 9.1
Potassium (mg/L)	14	14	9.0 - 10	9.5	38 - 41	39	32.1
Sodium (mg/L)	99 - 102	101	66 - 70	67	270 - 286	278	33.7
Nitrogen							
Nitrate (mg N/L)	5.6 - 9.2	6.7	5.8 - 9.7	7.2	3.5 - 6.0	4.2	- 7.5
Nitrite (mg N/L)	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	--
Ammonia (mg N/L)	0.80 - 1.0	0.87	0.52 - 0.83	0.68	1.6 - 2.0	1.8	21.8
TKN (mg N/L)	1.2 - 2.3	1.7	0.23 - 1.6	1.0	5.1 - 7.1	5.8	41.2
Total Nitrogen (mg N/L)	7.5 - 11	8.4	7.1 - 11	8.2	8.8 - 11	10	2.4
TOC							
TOC (mg/L)	4.5 - 5.9	4.8	< 0.5 - 0.87	0.61	25 - 32	27	87.3
Transmittance							
UVT (%)	--	--	95.9 - 97.4	96.8	--	--	--

1. Average values calculated assuming reporting limit for results < reporting limit.

Table 3-7. Secondary RO System
Rejection Results for General Water Quality Parameters

Parameters	Sample Location						
	Feed		Permeate		Concentrate		Average % Rejection
	Range	Average	Range	Average[1]	Range	Average[1]	
TDS (mg/L)	1,900 - 2,200	2,077	< 25 - 47	32	3,130 - 4,430	3,914	98.5
pH (field)	6.3 - 6.6	6.5	5.4 - 5.8	5.6	6.4 - 6.8	6.6	--
Total Alkalinity (mg/L $CaCO_3$)	181 - 219	200	14 - 25	18	288 - 434	362	91.0
Calcium (mg/L)	237 - 259	249	0.24 - 0.98	0.51	364 - 505	458	99.8
Chloride (mg/L)	121 - 179	154	2.6 - 3.1	2.9	242 - 371	290	98.1
Magnesium (mg/L)	68 - 75	73	0.07 - 0.28	0.15	111 - 141	127	99.8
Sulfate (mg/L)	904 - 1,110	989	2.2 - 9.1	5.2	1,320 - 2,280	1,850	99.5
Total Phosphate (mg/L PO_4^{3-})	13 - 32	20	< 0.10 - 0.27	0.16	26 - 49	38	99.2
Silica (mg/L SiO_2)	34 - 39	35	0.58 - 1.2	0.81	51 - 77	64	97.7
Barium (µg/L)	142 - 176	156	< 0.50 - 0.57	0.52	228 - 357	291	99.7
Strontium (µg/L)	1,610 - 1,760	1,690	1.5 - 7.0	3.5	2,610 - 3,460	3,120	99.8
Fluoride (mg/L)	2.0 - 2.5	2.2	0.12 - 0.23	0.16	3.0 - 4.8	3.9	92.7
Iron (mg/L)	0.16 - 0.22	0.19	< 0.020	< 0.020	0.30 - 0.41	0.34	≥ 89.5
Aluminum (µg/L)	33 - 77	52	< 10	< 10	49 - 135	94	≥ 80.8
Potassium (mg/L)	38 - 41	39	1.1 - 2.6	1.6	63 - 82	75	95.9
Sodium (mg/L)	270 - 286	278	8.1 - 16	11	397 - 543	491	96.0
Nitrogen							
Nitrate (mg N/L)	3.5 - 6.0	4.2	0.26 - 0.53	0.36	5.0 - 12	7.9	91.4
Nitrite (mg N/L)	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03 - 0.04	0.03	--
Ammonia (mg N/L)	1.6 - 2.0	1.8	0.20 - 0.57	0.41	2.3 - 3.6	3.0	77.2
TKN (mg N/L)	5.1 - 7.1	5.8	0.40 - 0.84	0.52	7.7 - 13	11	91.0
Total Nitrogen (mg N/L)	8.8 - 11	10	0.65 - 1.3	0.87	13 - 23	19	91.3
TOC							
TOC (mg/L)	25 - 32	27	< 0.5 - 0.71	0.57	41 - 61	50	97.9
Transmittance							
UVT (%)	--	--	97.4 - 99.3	98.3	--	--	--

1. Average values calculated assuming reporting limit for results < reporting limit.

Table 3-8. Overall NF/RO Integrated System Rejection Results for General Water Quality Parameters

Parameters	Sample Location						
	Feed		Blended Permeate		Concentrate		Average % Rejection
	Range	Average[10]	Range	Average[10]	Range	Average[10]	
TDS[1] (mg/L)	529 - 565	545	209 - 260	227	3,130 - 4,430	3,914	58.3
pH (field)	6.0 - 6.6	6.3	--	--	6.4 - 6.8	6.6	--
Total Alkalinity (mg/L $CaCO_3$)	75 - 77	76	37 - 48	43	288 - 434	362	43.4
Calcium (mg/L)	49 - 52	50	12 - 14	13	364 - 505	458	74.0
Chloride[2] (mg/L)	99 - 109	103	77 - 87	82	242 - 371	290	20.4
Magnesium (mg/L)	13 - 14	14	3.0 - 3.5	3.2	111 - 141	127	77.1
Sulfate[3] (mg/L)	146 - 183	159	2.6 - 4.7	3.6	1,320 - 2,280	1,850	97.7
Total Phosphate (mg/L PO_4^{3-})	2.1 - 5.1	3.3	0.11 - 0.33	0.21	26 - 49	38	93.6
Silica (mg/L SiO_2)	22 - 24	23	18 - 19	18	51 - 77	64	21.7
Barium[4] (µg/L)	29 - 36	32	6.8 - 8.2	7.7	228 - 357	291	75.9
Strontium (µg/L)	333 - 351	339	79 - 96	85	2,610 - 3,460	3,120	74.9
Fluoride[5] (mg/L)	0.75 - 0.79	0.78	0.43 - 0.57	0.49	3.0 - 4.8	3.9	37.2
Iron[6] (mg/L)	0.026 - 0.060	0.040	< 0.020	< 0.020	0.30 - 0.41	0.34	≥ 50.0
Aluminum[7] (µg/L)	< 10 - 12	11	< 10	< 10	49 - 135	94	≥ 9.1
Potassium (mg/L)	14	14	8.2 - 8.9	8.5	63 - 82	75	39.3
Sodium (mg/L)	99 - 102	101	59 - 62	60	397 - 543	491	40.6
Nitrogen							
Nitrate[8] (mg N/L)	5.6 - 9.2	6.7	4.7 - 8.0	6.2	5.0 - 12	7.9	7.5
Nitrite[9] (mg N/L)	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03 - 0.04	0.03	--
Ammonia (mg N/L)	0.80 - 1.0	0.87	0.49 - 0.78	0.64	2.3 - 3.6	3.0	26.4
TKN (mg N/L)	1.2 - 2.3	1.7	0.24 - 1.5	0.96	7.7 - 13	11	43.5
Total Nitrogen (mg N/L)	7.5 - 11	8.4	6.0 - 8.8	7.2	13 - 23	19	14.3
TOC							
TOC (mg/L)	4.5 - 5.9	4.8	< 0.5 - 0.79	0.54	41 - 61	50	88.8
Transmittance							
UVT (%)	--	--	95.7 - 97.4	96.8	--	--	--

1. TDS: Secondary MCL = 500 mg/L recommended, 1,000 mg/L upper limit; **2.** Chloride: Secondary MCL = 250 mg/L recommended, 500 mg/L upper limit; **3.** Sulfate: Secondary MCL = 250 mg/L recommended, 500 mg/L upper limit; **4.** Barium: Primary MCL = 1 mg/L; **5.** Fluoride: Primary MCL = 2 mg/L; **6.** Iron: Secondary MCL = 0.3 mg/L; **7.** Aluminum: Primary MCL = 1 mg/L, Secondary MCL = 0.2 mg/L; **8.** Nitrate: Primary MCL = 10 mg N/L; **9.** Nitrite: Primary MCL = 1 mg N/L; **10.** Average values calculated assuming reporting limit for results < reporting limit.

Table 3-9. Primary NF System Rejection Results for CECs

Parameters	Number of Detections[2]	Sample Location				
		Feed		Permeate		Average % Rejection
		Range	Average[3]	Range	Average[3]	
Acetaminophen (ng/L)	0	< 10	< 10	< 10	< 10	--
Atenolol (ng/L)	3	201 - 344	282	< 30 - 49	40	85.8
Azithromycin (ng/L)	3	29 - 236	160	< 10 - 14	12	92.5
Bisphenol A[1] (ng/L)	0	< 10	< 10	< 10	< 10	--
Caffeine (ng/L)	0	< 10	< 10	< 10	< 10	--
Carbamazepine (ng/L)	3	191 - 212	200	10 - 24	17	91.5
DEET (ng/L)	3	63 - 139	106	< 10 - 15	12	88.7
1,4 – dioxane (µg/L)	10	1.0 - 1.5	1.2	0.77 - 1.4	0.98	18.3
Diclofenac (ng/L)	2	< 10 - 11	11	< 10	< 10	≥ 9.1
Estrone (ng/L)	0	< 2	< 2	< 2	< 2	--
17β – Estradiol (ng/L)	0	< 2	< 2	< 2	< 2	--
17α – Ethynylestradiol (ng/L)	0	< 2	< 2	< 2	< 2	--
Erythromycin (ng/L)	2	< 10 - 54	33	< 10	< 10	≥ 69.7
Fluoxetine (ng/L)	3	25 - 33	30	< 10	< 10	≥ 66.7
Furosemide (ng/L)	0	< 10	< 10	< 10	< 10	--
Gemfibrozil (ng/L)	3	41 - 198	113	< 10	< 10	≥ 91.2
Ibuprofen (ng/L)	0	< 10	< 10	< 10	< 10	--
Iopromide (ng/L)	3	175 - 542	313	< 30	< 30	≥ 90.4
Meprobamate (ng/L)	3	360 - 411	387	17 - 43	31	92.0
Naproxen (ng/L)	0	< 10	< 10	< 10	< 10	--
NDMA (ng/L)	10	120 - 270	190	120 - 260	174	8.4
4-Nonylphenol (ng/L)	3	35 - 62	49	< 25	< 25	≥ 49.0
4-Octylphenol (ng/L)	3	6.6 - 9.8	7.8	< 5	< 5	≥ 35.9
Primidone (ng/L)	3	178 - 191	186	< 10 - 11	10	94.6
Phenytoin (ng/L)	3	168 - 202	186	< 10 - 18	15	91.9
Sucralose (µg/L)	3	27 - 32	29	0.24 - 0.35	0.31	98.9
Sulfamethoxazole (ng/L)	3	23 - 34	27	< 10	< 10	≥ 63.0
TCEP (ng/L)	3	318 - 349	334	39 - 92	62	81.4
Triclosan (ng/L)	0	< 10	< 10	< 10	< 10	--
Trimethoprim (ng/L)	0	< 10	< 10	< 10	< 10	--

1. Chemicals of emerging concern in bold font are specifically recommended for monitoring in recycled water for groundwater recharge/reuse projects by the California State Water Resources Control Board (State Water Board, 2010).
2. Number of detections of compound in feed stream during 3 sampling events (10 sampling events for 1,4-dioxane and NDMA).
3. Average values calculated assuming reporting limit for results < reporting limit.

Table 3-10. Secondary RO System Rejection Results for CECs

Parameters	Number of Detections[2]	Sample Location				
		Feed		Permeate		Average % Rejection
		Range	Average[3]	Range	Average[3]	
Acetaminophen (ng/L)	1	< 10 -13	11	< 10	< 10	≥ 9.1
Atenolol (ng/L)	3	1,100 - 1,886	1,502	< 30	< 30	≥ 98.0
Azithromycin (ng/L)	3	89 - 1,444	954	< 10 -14	11	98.8
Bisphenol A[1] (ng/L)	0	< 10	< 10	< 10	< 10	--
Caffeine (ng/L)	2	< 10 - 38	22	< 10	< 10	≥ 54.5
Carbamazepine (ng/L)	3	804 - 1,076	970	< 10	< 10	≥ 99.0
DEET (ng/L)	3	316 - 718	541	< 10	< 10	≥ 98.2
1,4 – dioxane (µg/L)	10	2.4 - 3.1	2.8	< 0.40	< 0.40	≥ 85.7
Diclofenac (ng/L)	2	< 10 - 89	55	< 10	< 10	≥ 81.8
Estrone (ng/L)	2	< 2 - 7.6	4.4	< 2	< 2	≥ 54.5
17β – Estradiol (ng/L)	1	< 2 - 8.5	4.2	< 2	< 2	≥ 52.4
17α – Ethynylestradiol (ng/L)	0	< 2	< 2	< 2	< 2	--
Erythromycin (ng/L)	3	34 - 304	198	< 10	< 10	≥ 94.9
Fluoxetine (ng/L)	3	149 - 226	180	< 10	< 10	≥ 94.4
Furosemide (ng/L)	1	< 10 - 33	18	< 10	< 10	≥ 44.4
Gemfibrozil (ng/L)	3	198 - 1,120	607	< 10	< 10	≥ 98.4
Ibuprofen (ng/L)	2	< 10 - 75	35	< 10	< 10	≥ 71.4
Iopromide (ng/L)	3	864 - 2,640	1,545	< 30	< 30	≥ 98.1
Meprobamate (ng/L)	3	1,990 - 2,480	2,293	< 30	< 30	≥ 98.7
Naproxen (ng/L)	0	< 10	< 10	< 10	< 10	--
NDMA (ng/L)	10	140 - 350	221	80 - 170	133	39.8
4-Nonylphenol (ng/L)	3	239 - 524	360	< 25	< 25	≥ 93.1
4-Octylphenol (ng/L)	3	39 - 63	48	< 5	< 5	≥ 89.6
Primidone (ng/L)	3	1,010 - 1,070	1,043	< 10	< 10	≥ 99.0
Phenytoin (ng/L)	3	840 - 1,200	1,020	< 10	< 10	≥ 99.0
Sucralose (µg/L)	3	126 - 146	137	< 0.04 - 0.30	0.20	99.9
Sulfamethoxazole (ng/L)	3	113 - 174	142	< 10	< 10	≥ 93.0
TCEP (ng/L)	3	1,480 - 1,690	1,603	< 10	< 10	≥ 99.4
Triclosan (ng/L)	0	< 10	< 10	< 10	< 10	--
Trimethoprim (ng/L)	3	24 - 35	31	< 10	< 10	≥ 67.7

1. Chemicals of emerging concern in bold font are specifically recommended for monitoring in recycled water for groundwater recharge/reuse projects by the California State Water Resources Control Board (State Water Board, 2010).
2. Number of detections of compound in feed stream during 3 sampling events (10 sampling events for 1,4-dioxane and NDMA).
3. Average values calculated assuming reporting limit for results < reporting limit.

Table 3-11. Overall NF/RO Integrated System Rejection Results for CECs

Parameters	Number of Detections[2]	Sample Location				
		Feed		Blended Permeate		Average % Rejection
		Range	Average[5]	Range	Average[5]	
Acetaminophen (ng/L)	0	< 10	< 10	< 10	< 10	--
Atenolol (ng/L)	3	201 - 344	282	< 30 - 41	37	86.9
Azithromycin (ng/L)	3	29 - 236	160	< 10 - 15	12	92.5
Bisphenol A[1] (ng/L)	0	< 10	< 10	< 10	< 10	--
Caffeine (ng/L)	0	< 10	< 10	< 10	< 10	--
Carbamazepine (ng/L)	3	191 - 212	200	< 10 - 19	15	92.5
DEET (ng/L)	3	63 - 139	106	< 10 - 13	11	89.6
1,4 – dioxane[3] (µg/L)	10	1.0 - 1.5	1.2	0.75 - 1.2	0.90	25.0
Diclofenac (ng/L)	2	< 10 - 11	11	< 10	< 10	≥ 9.1
Estrone (ng/L)	0	< 2	< 2	< 2	< 2	--
17β – Estradiol (ng/L)	0	< 2	< 2	< 2	< 2	--
17α – Ethynylestradiol (ng/L)	0	< 2	< 2	< 2	< 2	--
Erythromycin (ng/L)	2	< 10 - 54	33	< 10	< 10	≥ 69.7
Fluoxetine (ng/L)	3	25 - 33	30	< 10	< 10	≥ 66.7
Furosemide (ng/L)	0	< 10	< 10	< 10	< 10	--
Gemfibrozil (ng/L)	3	41 - 198	113	< 10	< 10	≥ 91.2
Ibuprofen (ng/L)	0	< 10	< 10	< 10	< 10	--
Iopromide (ng/L)	3	175 - 542	313	< 30	< 30	≥ 90.4
Meprobamate (ng/L)	3	360 - 411	387	15 - 38	28	92.8
Naproxen (ng/L)	0	< 10	< 10	< 10	< 10	--
NDMA[4] (ng/L)	10	120 - 270	190	110 - 260	176	7.4
4-Nonylphenol (ng/L)	3	35 - 62	49	< 25	< 25	≥ 49.0
4-Octylphenol (ng/L)	3	6.6 - 9.8	7.8	< 5	< 5	≥ 35.9
Primidone (ng/L)	3	178 - 191	186	< 10 - 11	10	94.6
Phenytoin (ng/L)	3	168 - 202	186	< 10 - 17	14	92.5
Sucralose (µg/L)	3	27 - 32	29	0.25 - 0.36	0.32	98.9
Sulfamethoxazole (ng/L)	3	23 - 34	27	< 10	< 10	≥ 63.0
TCEP (ng/L)	3	318 - 349	334	36 - 76	56	83.2
Triclosan (ng/L)	0	< 10	< 10	< 10	< 10	--
Trimethoprim (ng/L)	0	< 10	< 10	< 10	< 10	--

1. Chemicals of emerging concern in bold font are specifically recommended for monitoring in recycled water for groundwater recharge/reuse projects by the California State Water Resources Control Board (State Water Board, 2010).
2. Number of detections of compound in feed stream during 3 sampling events (10 sampling events for 1,4-dioxane and NDMA).
3. 1,4-dioxane CDPH Notification Level = 1 µg/L.
4. NDMA CDPH Notification Level = 10 ng/L.
5. Average values calculated assuming reporting limit for results < reporting limit.

Table 3-12. Drinking Water Equivalent Levels and Observed Removals by AOP and SAT for Select CECs

CEC	Max Blended Permeate Concentration (ng/L)	DWEL[1] (ng/L)	Observed AOP Removal[4]	Observed SAT Removal[5]
Atenolol	41	70,000[2]	> 90%	≥ 99.9%
Carbamazepine	19	12,000[2]	> 90%	Negligible
DEET	13	81,000[3]	> 90%	75%
Meprobamate	38	260,000[2]	> 90%	50%
Phenytoin	17	1,700[2]	> 90%	Negligible
Primidone	11	850[3]	> 90%	Negligible
TCEP	76	4,400[3]	< 25%	49%

1. DWEL = Drinking Water Equivalent Level.
2. Snyder et al., 2008.
3. Nellor et al., 2010.
4. Observed AOP (Advanced Oxidation Process) removal from Drewes et al. (2008b).
5. Observed SAT (Soil Aquifer Treatment) removal from Laws et al. (2011).

Figure 3-13. Average Rejection Results for CECs Detected in Primary NF System Feed

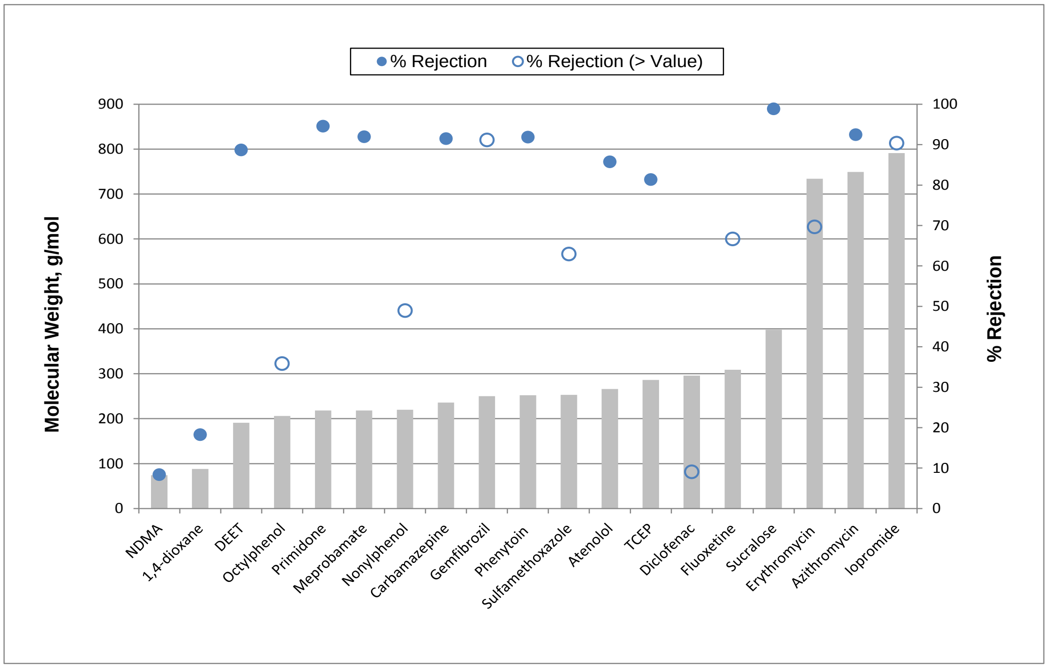


Figure 3-14. Average Rejection Results for CECs Detected in Secondary RO System Feed

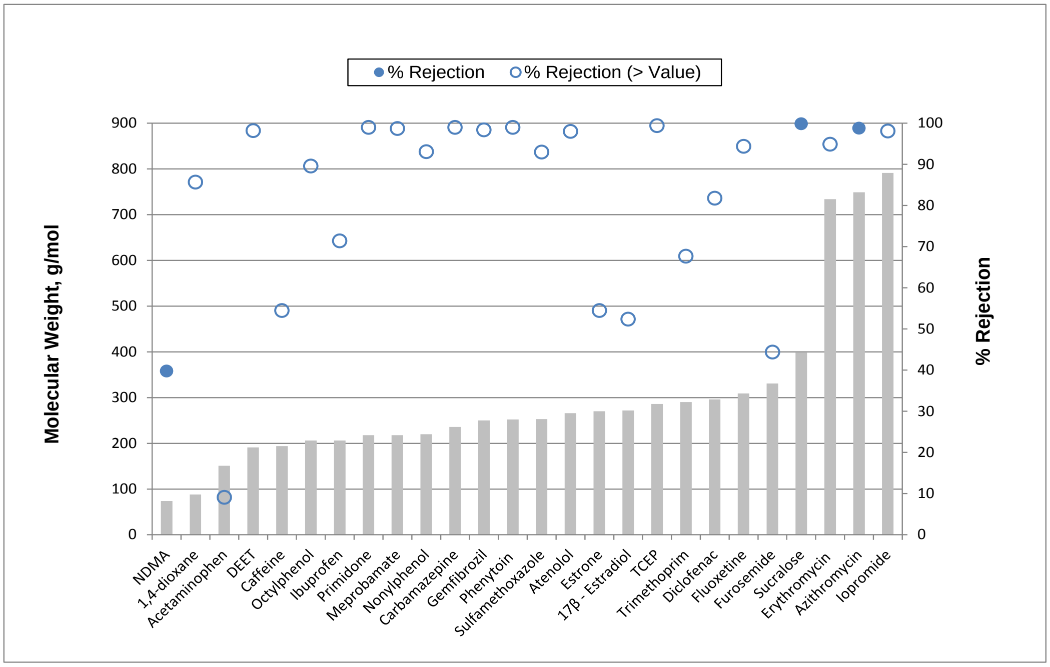
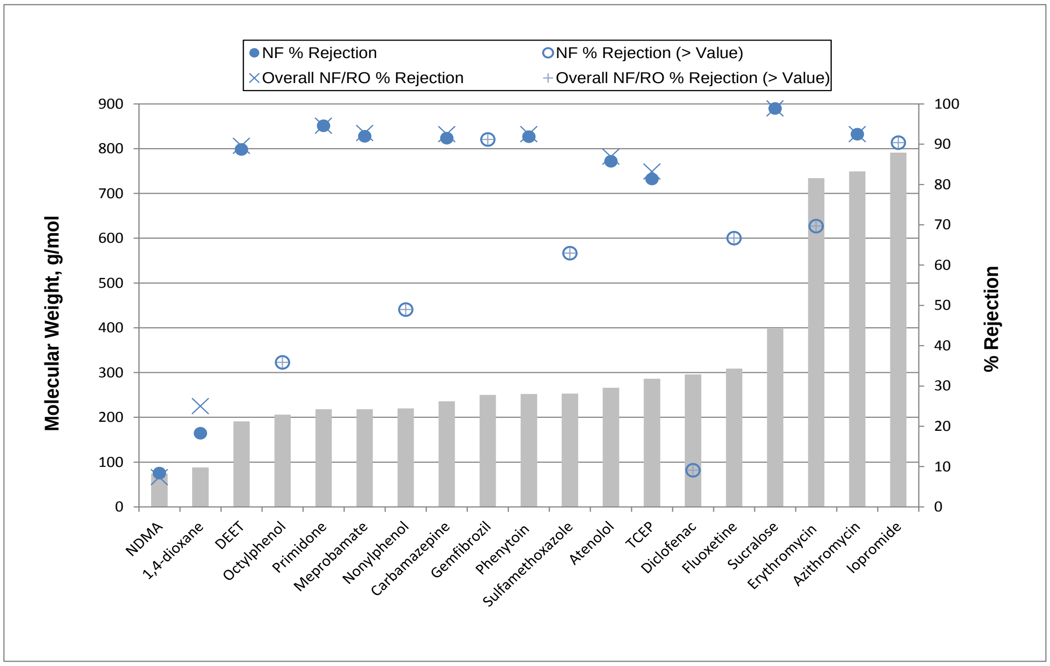


Figure 3-15. Primary NF System and Overall NF/RO Integrated System Average Rejection Results for CECs



4. Summary and Conclusions

Key findings of this study are summarized below.

Operational Performance

The NF/RO integrated system was operated for over 3,000 hours in two distinct phases, with the major difference being the antiscalant product used for membrane scale control. During Phase One, the antiscalant product employed was SpectraGuard (Professional Water Technologies). This product was not effective for scale control and relatively significant membrane fouling was observed in both the primary NF and secondary RO systems. During Phase Two, the antiscalant was changed to Y2K (King Lee Technologies). This antiscalant product was effective for controlling membrane scale formation. The pilot system was operated for approximately 3 months (~ 2,000 hours), with significantly less fouling compared to Phase One operation. Over the 3-month operating period, the normalized specific flux for the primary NF and secondary RO systems decreased 16% and 28%, respectively.

Membrane Autopsy

At the conclusion of testing, sample NF and RO membrane elements were sent to Avista Technologies for autopsy analyses to (1) compare the performance of the elements to manufacturer specifications for new membrane elements, and (2) characterize the foulant material on the membrane surface. The results of the autopsy analyses confirmed the operational performance results and indicated that significant membrane fouling in general, and scaling in particular, did not occur during Phase Two operation. Membrane fouling was identified to be primarily organic in nature. However, biofouling, colloidal, as well as inorganic fouling were also identified.

Rejection Performance

The NF/RO integrated system achieved a high degree of rejection for some of the constituents that are relevant for indirect potable reuse projects including TOC (89%) and select CECs. Of 30 target CECs, 19 were detected in the feed stream to the system. Most of the detected CECs were rejected to a high degree (> 80%) and/or to below their respective reporting limits. Significantly lower rejection was achieved for total nitrogen (14%), NDMA (7%), and 1,4-dioxane (25%). Despite the low rejection for these constituents, application of the NF/RO integrated system for the GRIP project would still be feasible because (1) nitrogen removal could be achieved by the existing nitrification-denitrification activated sludge treatment process at the SJC West WRP, and (2) NDMA and 1,4-dioxane could be removed to below regulatory limits by downstream UV/AOP.

The results from this study demonstrated that the NF/RO integrated treatment system concept is a viable alternative to a standard RO system and can potentially be employed for the GRIP project. The main advantages of this system, that were demonstrated during this study, include the following: (1) the ability to operate at an overall recovery of approximately 93%, which would reduce the volume of concentrate that needs to be disposed of; (2) the ability to achieve a high degree of rejection for many of the constituents that are relevant for indirect potable reuse projects including TOC and select CECs. A potential additional advantage is that the product water produced by the integrated system would have a higher TDS concentration, when compared to that produced by RO systems, and would thus be less corrosive. This would lead to a reduction in costs associated with post treatment stabilization processes that are typically employed with RO systems.

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Appendix A - San Jose Creek Water Reclamation Plant

The San Jose Creek (SJC) Water Reclamation Plant (WRP), located in Whittier, CA, was first built in 1971 with a design capacity of 37.5 MGD (Stage I). The 25 MGD Stage II expansion was completed in 1982 and the 37.5 MGD Stage III expansion was completed and fully operational in 1993, bringing the total plant capacity to 100 MGD. Stages I and II (SJC East WRP) are located on the east side of the 605 Freeway, while Stage III (SJC West WRP) is located on the west side of the 605 Freeway (Figure A-1). Enough space exists at SJC West for a future 25 MGD Stage IV expansion, however, there is no set schedule for this project. In 2010, the SJC WRP produced 69.5 MGD of recycled water. Of this, 39.9 MGD was reused by several entities at 94 individual sites including 37.6 MGD for groundwater replenishment.

Figure A-1. San Jose Creek WRP

SJC East and West WRPs are operated independently. However, influent flows to the plants can be diverted from one facility to the other. SJC East WRP typically receives raw sewage from the Joint Outfall (JO) "H" trunk sewer, but can also receive flow from the San Jose Creek Interceptor. SJC West WRP typically receives raw sewage from the San Jose Creek Interceptor, but can also receive flow from the JO "H" trunk sewer. Both plants use the same treatment process train including primary sedimentation, step-feed activated sludge process with biological nitrogen removal, secondary sedimentation, coagulation, inert media filtration, chlorination, and dechlorination. Recycled water delivered for groundwater recharge or discharged to lined channels is dechlorinated, while recycled water delivered for reuse is not dechlorinated. SJC WRP effluent discharge points are summarized in Table A-1 and are also shown in Figure A-2. Process flow diagrams for SJC East and West are shown in Figures A-3 and A-4, respectively.

Table A-1. San Jose Creek WRP Effluent Discharge Points

Discharge Serial No.	Description	Discharge Location
001	Effluent from SJC East and West WRP is conveyed through an outfall pipeline approximately eight miles south of the plant to the discharge point on the west side of the San Gabriel River near Firestone Blvd. The river is lined with concrete from the discharge point to the tidal prism.	San Gabriel River (lined)
001A	Effluent from Discharge Serial No. 001A is allowed to recharge groundwater underneath the unlined San Gabriel River when the headworks of the San Gabriel River Spreading Grounds are unavailable due to maintenance or other constraints.	San Gabriel River (unlined)
001B	Not yet constructed. Once constructed, recycled water from this outfall will increase groundwater recharge in the vicinity through the unlined San Gabriel River.	San Gabriel River (unlined)
002	Effluent from SJC East WRP is discharged to an unlined section of the San Jose Creek adjacent to the plant. This outfall allows the use of recycled water for groundwater recharge. After discharge, the recycled water is conveyed via various channels and diversion structures to either the San Gabriel River Spreading Grounds or the Rio Hondo Spreading Grounds.	San Jose Creek (unlined)
003	Effluent from SJC West WRP is discharged to an unlined section of the San Gabriel River. This outfall allows the use of recycled water for groundwater recharge. After discharge, the recycled water is conveyed via various channels and diversion structures to either the San Gabriel River Spreading Grounds or the Rio Hondo Spreading Grounds.	San Gabriel River (unlined)

Figure A-2. Map of San Jose Creek WRP Effluent Discharge Points

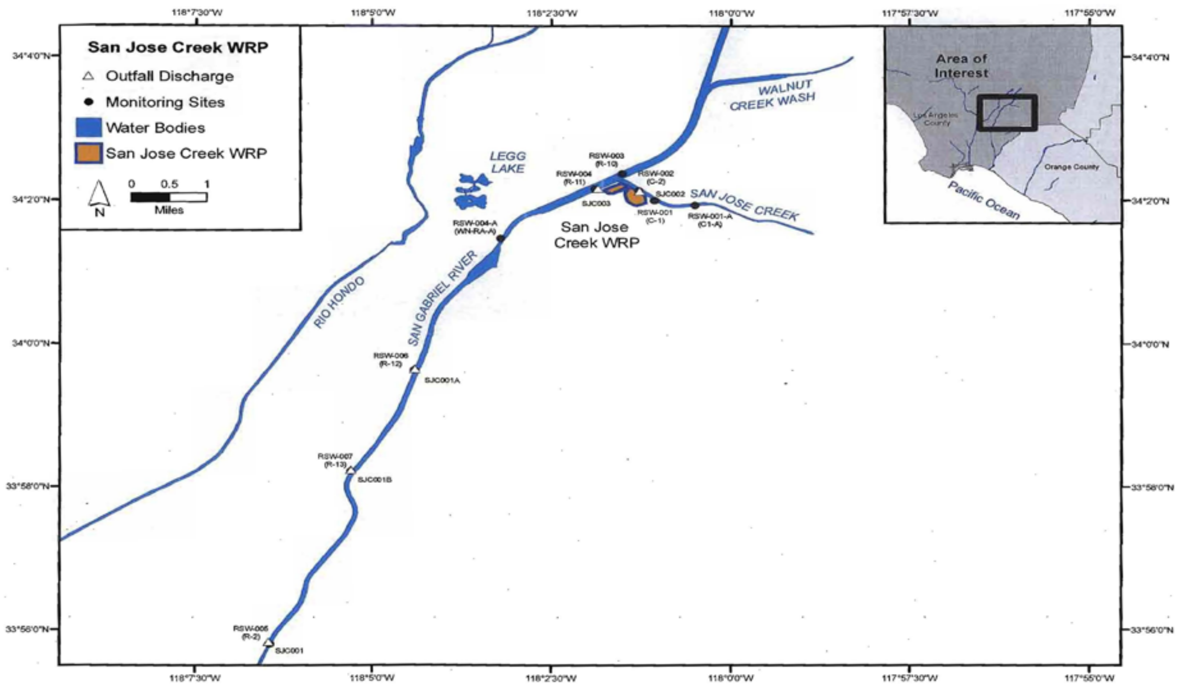


Figure A-3. San Jose Creek East WRP Process Flow Diagram

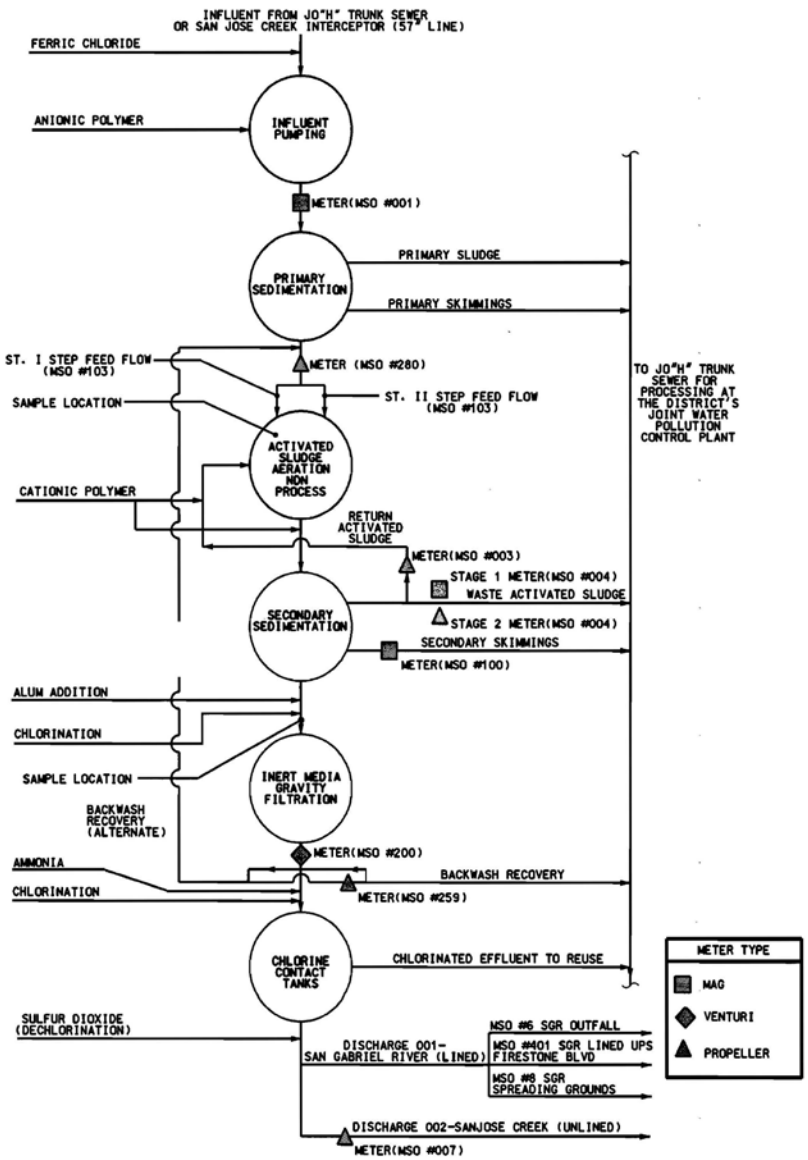
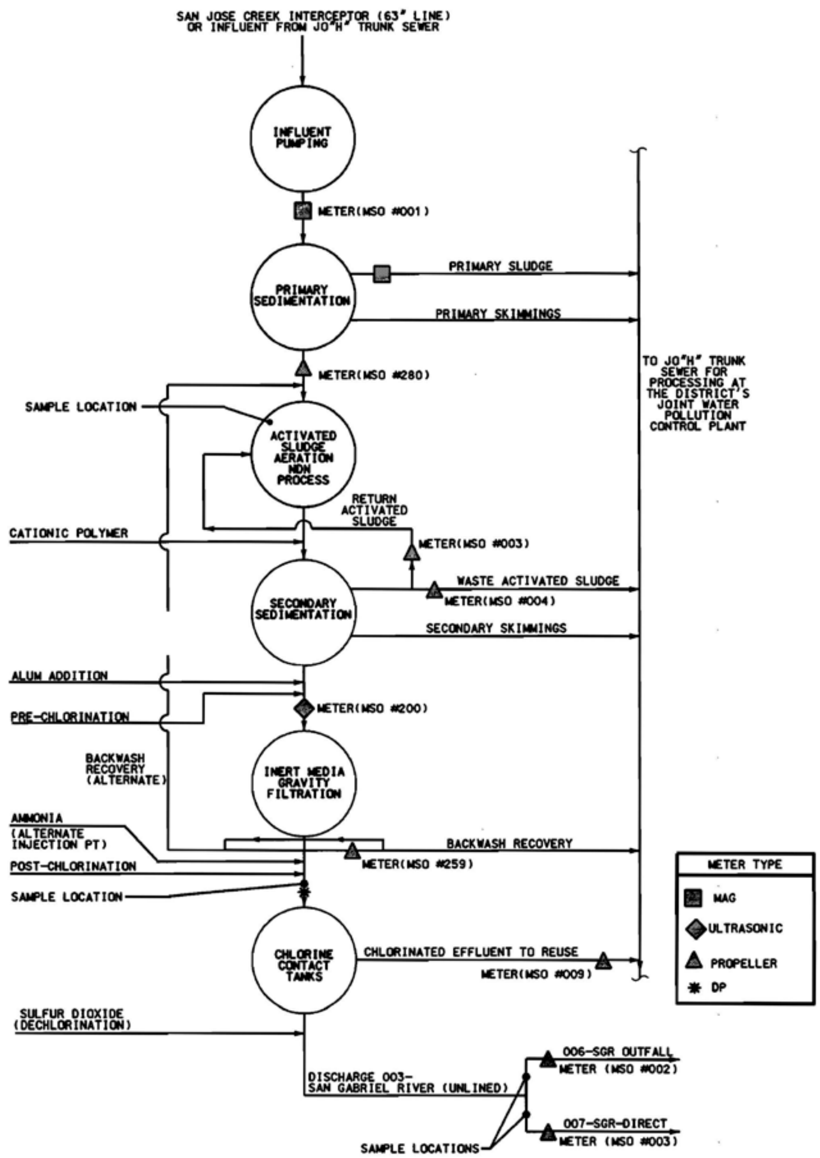
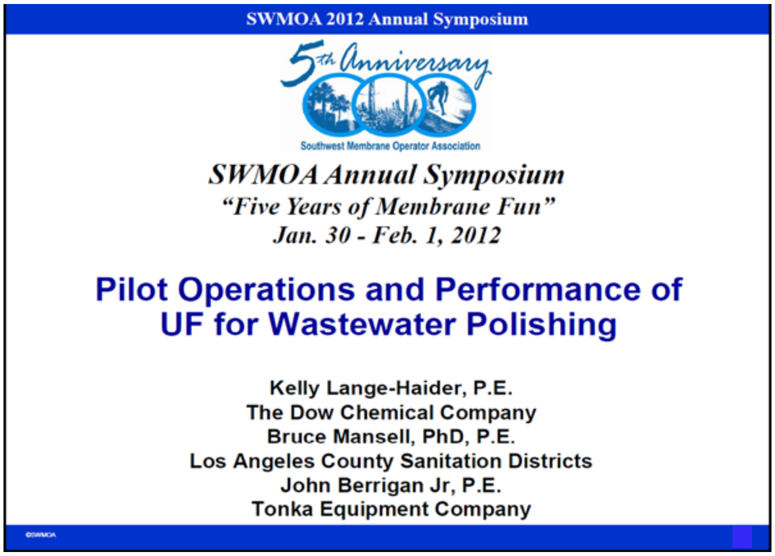
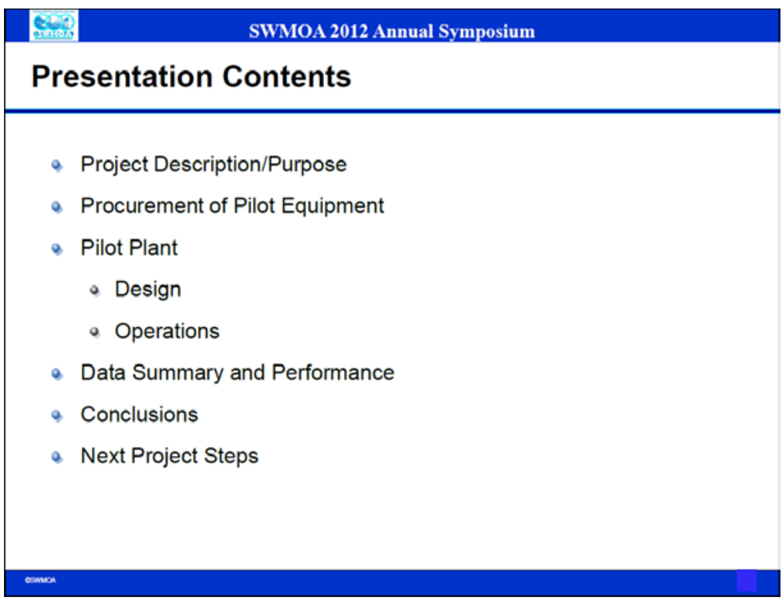


Figure A-4. San Jose Creek West WRP Process Flow Diagram



Appendix B – Dow Ultrafiltration System Presentation





Project Description/Purpose

- Los Angeles County Sanitation Districts (LACSD) is conducting pilot scale testing for the treatment of tertiary effluent using low pressure ultrafiltration membranes followed by a high recovery NF/RO integrated treatment system.
- Determine if product water meets water quality goals for future indirect potable reuse consideration using surface spreading
- Evaluate operation of NF/RO integrated system at recoveries greater than 90%

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Procurement of Pilot Equipment

- Funding
  - US Bureau of Reclamation - Partial funding for pilot scale testing through cooperative agreement number R11AC35293
  - The Dow Chemical Company provided Membranes
  - LACSD, WRD, and USGVMWD remaining funding support

Schedule

- Initiated October 2010
- Tonka Quote November 2010
- USBR/LACSD Agreement February 2011
- LACSD Board Approval March 2011
- Pilot Unit Delivered June 2011
- Startup June 2011
- Pilot Completion March 2012

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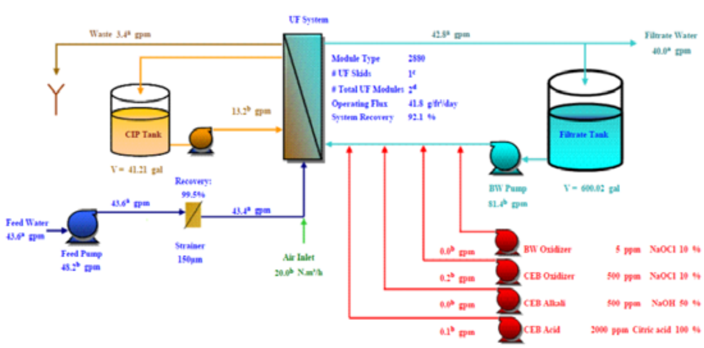
Pilot Plant Design Projection

UF SYSTEM FLOW DIAGRAM



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UF Pilot Feed Water

Water Quality Parameter	Average	Minimum	Maximum
Turbidity, NTU	0.6	0.3	2.5
TSS, mg/L	<2.5	<2.5	4.2
TOC, mg/L	5.0	4.5	5.7
pH	7.1	6.6	7.3
Temperature, °F	79	68	86
Chloramines, mg/L	3	2	4
TDS, mg/L	530	490	568

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Module Anatomy and Specifications

2880 Module	Specifications
Membrane Area	829 ft2/77 m2
Weight	135/220 lbs
Diameter	~ 8 in
Length	~ 80 in

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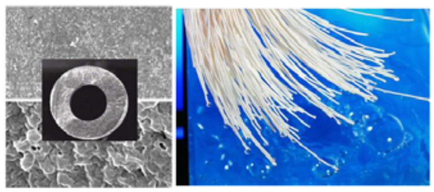
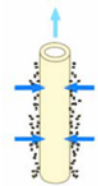
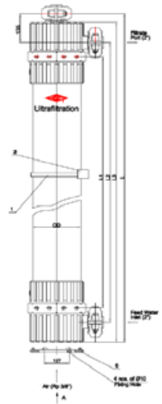
UF Product Features

- ✓ Pressurized Outside/In Membrane Modules
- ✓ H-PVDF Hollow Fibers - 1.3 mm x 0.7 mm
- ✓ UF Pore Size - 0.03 µm Nominal Pore Size







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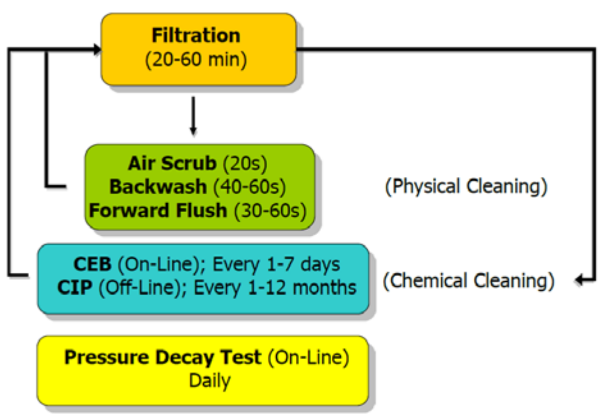
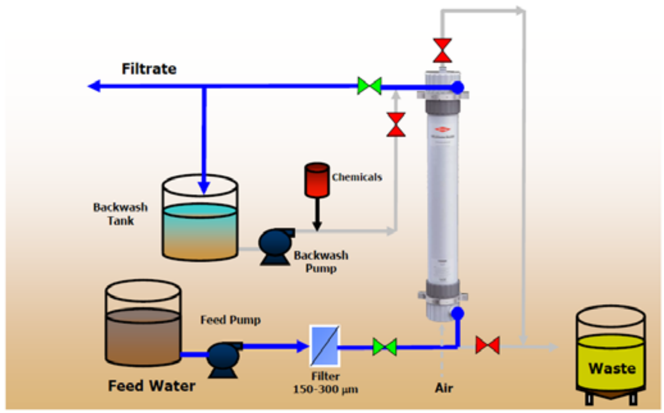
System Operations - Overview



UF Operations - Filtration

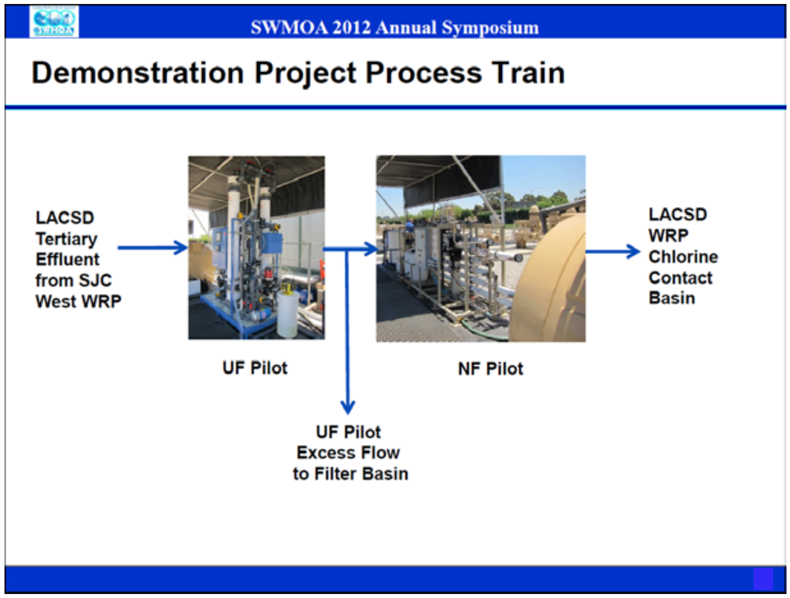


Certifications for Reuse

- LRV certification
- California Water Recycle Criteria (Title 22)
- NSF/ANSI 61

Table VS-i. LRV_{C-TEST} for Each Organism

Challenge Organism	Mean LRV	Lowest LRV
C. parvum	6.20	5.97
B. atrophaeus	5.90	5.77
MS2	2.54	2.37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Demonstration Project Process Train
LACSD Tertiary Effluent from SJC West WRP
UF Pilot
NF Pilot
LACSD WRP Chlorine Contact Basin
UF Pilot Excess Flow to Filter Basin


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UF Pilot
TONKA

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UF Pilot

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UF Pilot

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UF Pilot Instrumentation

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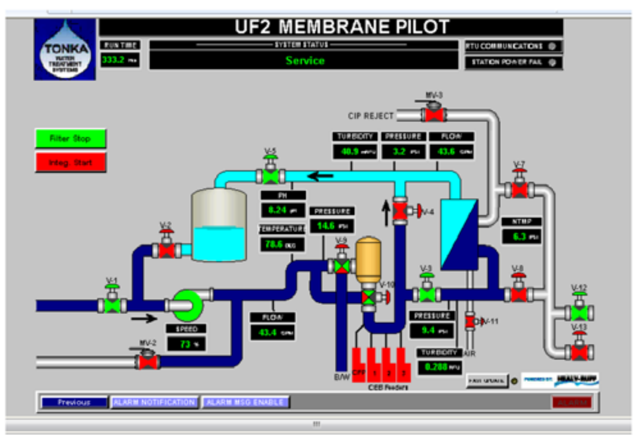
Remote Monitoring Screen Shot



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Cleaning Sequence and Duration

Cleaning Sequence	Projection (seconds)	Pilot Operations (seconds)
Air Scour	20	20
Drain Down	20	40
Backwash Top	30	25
Backwash Bottom	30	10
CEB Soak	10	5
Forward Flush	60	90

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Operating Conditions

- Started up the system and gradually increased the flux
- Operating at 37 gfd without change
- CEB every 24 hrs (hypochlorite)
- Backwash frequency 30 min

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Data Collection, Summary, and Performance

- Turbidity
- Flow/Flux
- Temperature
- TMP/Permeability

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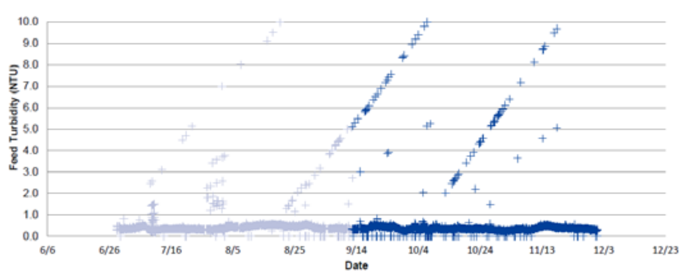
UF Pilot Feed Turbidity



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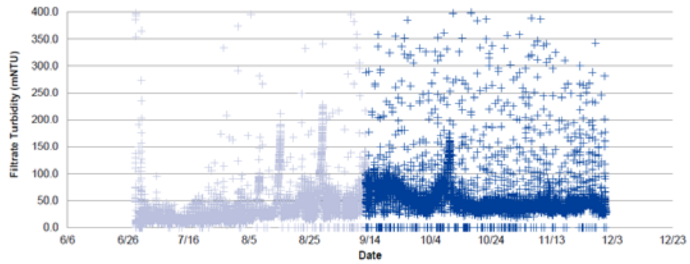
UF Pilot Filtrate Turbidity



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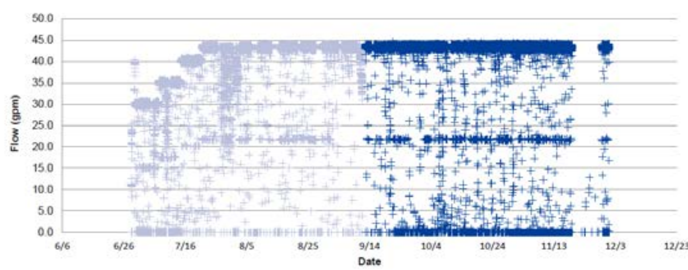
UF Pilot Filtrate Flow



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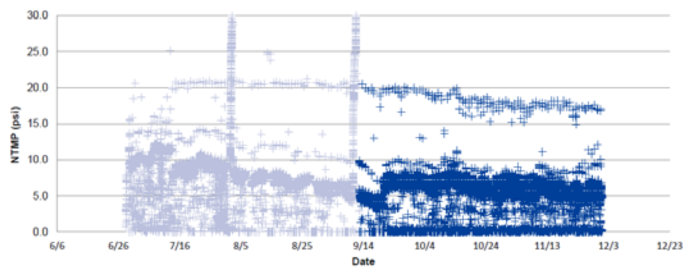
UF Pilot Normalized Transmembrane Pressure



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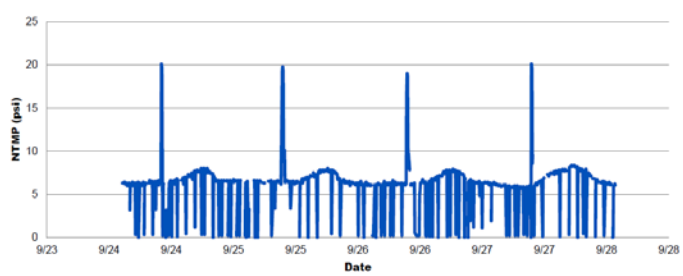
UF Pilot NTMP Pattern



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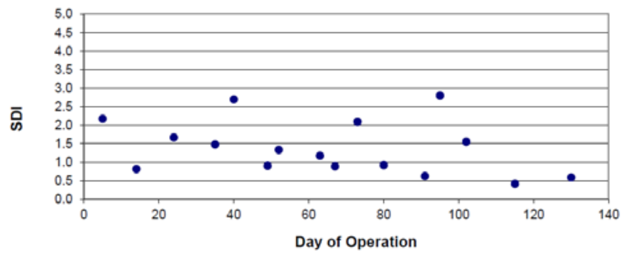
UF Pilot Filtrate SDI Performance



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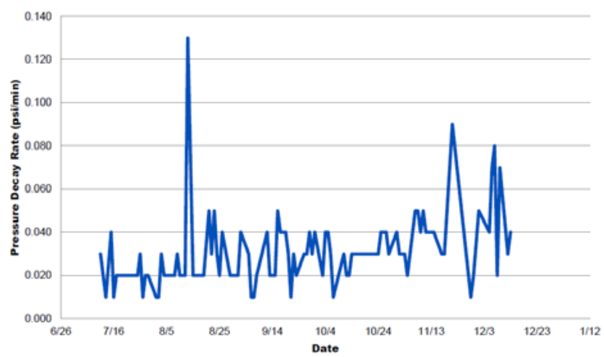
Integrity Test Results



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Conclusions

- CIP not required during testing period
- Operating flux 37 gfd
- Recovery ~94%
- 30 min. filtration cycle and daily hypochlorite CEB produced stable operations
- No integrity issues – 100% passing

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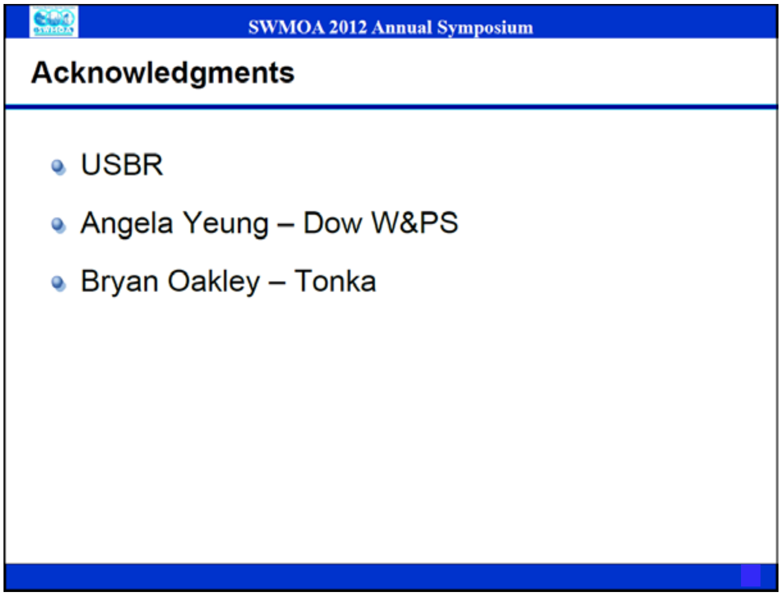
Next Project Steps

- Optimize UF pilot
  - Increase Flux
  - Filtration Cycle Duration
  - CEB Frequency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Acknowledgments
USBR
Angela Yeung – Dow W&PS
Bryan Oakley – Tonka

Appendix C – Analytical Methods

Parameters	Analytical Methods
General Parameters	
TOC (Total organic carbon)	SM[1] 5310 C
TDS (Total dissolved solids)	SM 2540 C
Nitrate	SM 4500 NO3 F
Nitrite	SM 4500 NO3 F
Ammonia	SM 4500 NH3 G
TKN (Total Kjeldahl nitrogen)	EPA[2] 351.2
UVT (UV Transmittance, 254 nm)	SM 5910 B
pH	SM 4500 H+ B
Total Alkalinity	SM 2320 B
Bicarbonate Alkalinity	SM 2320 B
Carbonate Alkalinity	SM 2320 B
Calcium	EPA 200.8
Chloride	EPA 300.0
Magnesium	EPA 200.8
Sulfate	EPA 300.0
Total Phosphate	EPA 365.1
Silica	EPA 200.8
Barium	EPA 200.8
Strontium	EPA 200.8
Fluoride	SM 4500 F C
Iron	EPA 200.8
Aluminum	EPA 200.8
Potassium	EPA 200.8
Sodium	EPA 200.8
Chemicals of Emerging Concern	
Acetaminophen	LC/MS/MS[3]
Atenolol	LC/MS/MS
Azithromycin	LC/MS/MS
Bisphenol A	LC/MS/MS
Caffeine	LC/MS/MS
Carbamazepine	LC/MS/MS
DEET (N,N-diethyl-meta-toluamide)	LC/MS/MS
1,4 – dioxane	SW[4]-846 8270MOD
Diclofenac	LC/MS/MS
Estrone	LC/MS/MS
17β - Estradiol	LC/MS/MS
17α - Ethynylestradiol	LC/MS/MS
Erythromycin	LC/MS/MS
Fluoxetine	LC/MS/MS
Furosemide	LC/MS/MS
Gemfibrozil	LC/MS/MS
Ibuprofen	LC/MS/MS
Iopromide	LC/MS/MS
Meprobamate	LC/MS/MS
Naproxen	LC/MS/MS
NDMA (N-Nitrosodimethylamine)	EPA 1625
4-Nonylphenol	LC/MS/MS
4-Octylphenol	LC/MS/MS
Primidone	LC/MS/MS
Phenytoin (Dilantin)	LC/MS/MS
Sucralose	LC/MS/MS
Sulfamethoxazole	LC/MS/MS
TCEP (Tris (2-chloroethyl) phosphate)	LC/MS/MS
Triclosan	LC/MS/MS
Trimethoprim	LC/MS/MS

1. SM: Standard Methods for the Examination of Water and Wastewater.
2. EPA: U.S. Environmental Protection Agency.
3. LC/MS/MS – Liquid chromatography mass spectrometry method as described in Nelson et al., 2011.
4. SW-846: U.S. Environmental Protection Agency - Test Methods for Evaluating Solid Waste, Physical/Chemical Methods.