

ICR Treatment Study Summary Report

Evaluation of Nanofiltration Technology
Using the Rapid Bench-Scale Membrane Test
for Compliance with the Information Collection Rule

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1 Conclusions and Recommendations

Source water for the City of Margate is high in TOC and has a high potential for disinfection byproduct formation. Raw water pretreated for feed to the nanofiltration membranes investigated in this study had an average TOC of 9.6 mg/L. This water formed an average of 207 µg/L of total trihalomethanes (THM4) and 132 µg/L of total haloacetic acids (HAA5) under simulated distribution system (SDS) conditions using free chlorine. These values do not meet the meet the Stage 1 Maximum Contaminant Levels (MCLs) under the Disinfection/Disinfection Byproducts Rule for THM4 and HAA5, which are 80 µg/L and 60 µg/L, respectively.

Four nanofiltration membranes were tested. Nanofiltration was effective at controlling SDS THM4 and HAA5, with product water concentrations of less than 10 µg/L for product water recoveries of 70 percent. The superior product water quality would allow bypass of feed water around the membrane for blending with the product water, while still meeting the Stage 1 and Stage 2 MCLs with a 10 percent factor of safety. The controlling parameter for blending in this manner is generally THM4. Depending on the membrane type used, raw water bypass on the order of 20-25 percent could meet the Stage 1 THM4 criteria. Raw water bypass would have to be reduced to 10-15 percent to meet the more stringent Stage 2 criteria.

While nanofiltration is an effective technology for controlling disinfection by-products (DBPs) in finished drinking water, alternate methods (e.g., alternative disinfectants and oxidants, granular activated carbon) also exist. It is recommended that the public water supplier develop WTP-specific water quality goals, and then consider all practical options for achieving those goals before choosing a treatment strategy.

2 Background Information

2.1 Treatment Plant Description

A schematic of the Margate Water Treatment Plant is presented as Figure 1. Design criteria for unit processes at the plant are summarized in Table 1.

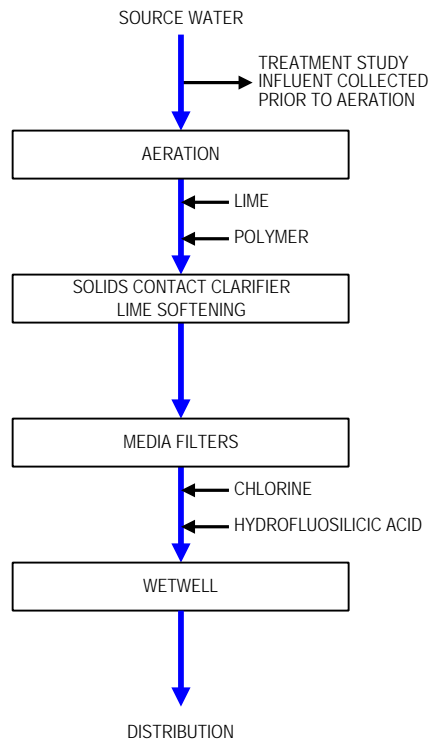


Figure 1 – WTP Schematic

Table 1
Margate Water Treatment Plant Design Criteria

Unit Process/Parameter	Value	
	West Train	East Train
Aeration		
Units	2	3
Steps	4	4
Trays/Step	6	6
Total Trays	48	72
Capacity	8 mgd	10 mgd
Softening		
Type	Accelerator NS	
Capacity	8 mgd	10 mgd
Tank Diameter	65 ft	70 ft
Draft Tube Diameter	27 ft	28.5 ft
Side Depth	17.75 ft	18.67 ft
Upflow Rate	2.0 gpm	2.2 gpm
Coagulant Addition	Lime	Lime
Coagulant Dose		
Filtration		
Filter Type	Greenleaf Self Backwash	
Media Type	Anthracite Sand	
Total Media Depth	30 inches	
Capacity	8 mgd	10 mgd
Tank Diameter	42 ft	44 ft
Side Depth	16.5 ft	16.5 ft
No. Filter Cells	4	4
Total Filter Area	1,271 SqFt	1,408 SqFt
Filtration Rate	4.4 gpm	4.9 gpm
Backwash Rate	15.2 gpm/SqFt	15.2 gpm/SqFt
Disinfection		
Chemical Type	Chlorine Gas	
Dosing Rate	6.0 mg/L as Cl ₂	
Clear Wells		
Liquid Volume	450,000 gal	
Corrosion Control Chemical	Poly ortho phosphate (Calciquest) 1.0 mg/L	
Ground Storage		
Liquid Volume	4.0 MG	

2.2 Water Quality

Tables 2 and 3 summarize source and finished water quality characteristics for the Margate WTP for the 1998 calendar year.

2.2.1 Source Water

Table 2 Margate Source Water Quality					
Parameter	Units	Average Annual Value	Standard Deviation	Maximum Annual Value	Minimum Annual Value
pH		7.11	0.03	7.20	7.10
Total Dissolved Solids	mg/L	NR	NR	NR	NR
Calcium Hardness	mg/L as CaCO ₃	280	2.3	284	276
Total Hardness	mg/L as CaCO ₃	291	2.3	295	287
Bromide	mg/L	NR	NR	NR	NR
Alkalinity	mg/L as CaCO ₃	249	2.3	254	246
Temperature	°C	NR	NR	NR	NR
Turbidity	Ntu	NR	NR	NR	NR
TOC	mg/L	8.26	5.41	21.0	0.0
UV254	cm ⁻¹	NR	NR	NR	NR
SUVA	L/(mg-m)	NR	NR	NR	NR
SUVA = UV254 * 100/TOC					
NR = Not Reported					

2.2.2 Finished Water

Table 3 Margate Finished Water Quality					
Parameter	Units	Average Annual Value	Standard Deviation	Maximum Annual Value	Minimum Annual Value
pH	pH units	9.13	0.05	9.20	9.10
Temperature	°C	NR	NR	NR	NR
Turbidity	Ntu	0.11	0.00	0.12	0.11
Total Dissolved Solids	mg/L	NR	NR	NR	NR
Total Hardness	mg/L as CaCO ₃	70.3	2.3	75.0	67.0
TOC	mg/L	6.83	1.33	9.00	3.50
UV254	cm ⁻¹	NR	NR	NR	NR
SUVA	L/(mg-m)	NR	NR	NR	NR
DS-THM4	µg/L	33.5	24.8	58.5	11.4
DS-HAA5	µg/L	NR	NR	NR	NR
DS-HAA6	µg/L	NR	NR	NR	NR
DS = distribution system; the DS data are averaged over four distribution system sampling locations					
SUVA = specific ultraviolet absorbance = UV254*100/TOC					
NR = Not Reported					

3 Materials and Methods

3.1 Sample Collection

Water for bench-scale testing was collected by CH2M HILL staff using 30-gallon polyethylene drums. Drums were shipped by 2-3 day air service to the CH2M HILL Applied Sciences Laboratory in Corvallis, Oregon for treatability testing. Pretreatment was performed on composited sample by mixing in a 200-gallon cone-bottomed polyethylene tank. Pretreated sample was stored in 30-gallon drums at 4 deg C until use.

3.2 Pretreatment

Water for testing was pretreated upon receipt at the laboratory. Pretreatment consisted of three steps, as illustrated in Figure 2:

- Acidification to the target pH values identified in Table 4 using reagent-grade hydrochloric acid.
- Acidified water was dosed with 3 parts per million by volume of a commercial antiscalant product (Pretreat Plus 0100, King Lee Technologies, San Diego).
- Filtration through a spun-wound cartridge filter with a 5 micron nominal pore size.

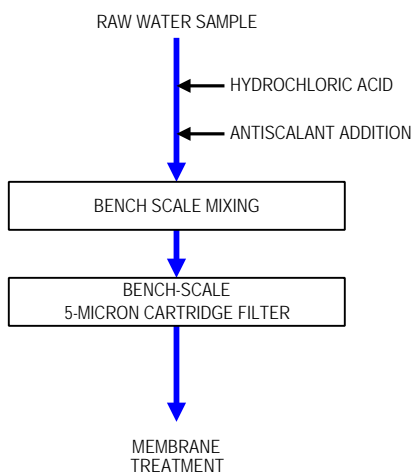


Figure 2 – Schematic of Membrane Pretreatment

3.3 Advanced Membrane Treatment Process

Nanofiltration treatment was performed using the Rapid Bench-Scale Membrane Test (RBSMT) procedures outlined in the *EPA ICR Manual for Bench and Pilot-Scale Treatment Studies*.

A schematic of the RBSMT system employed in this study is presented in Figure 3.

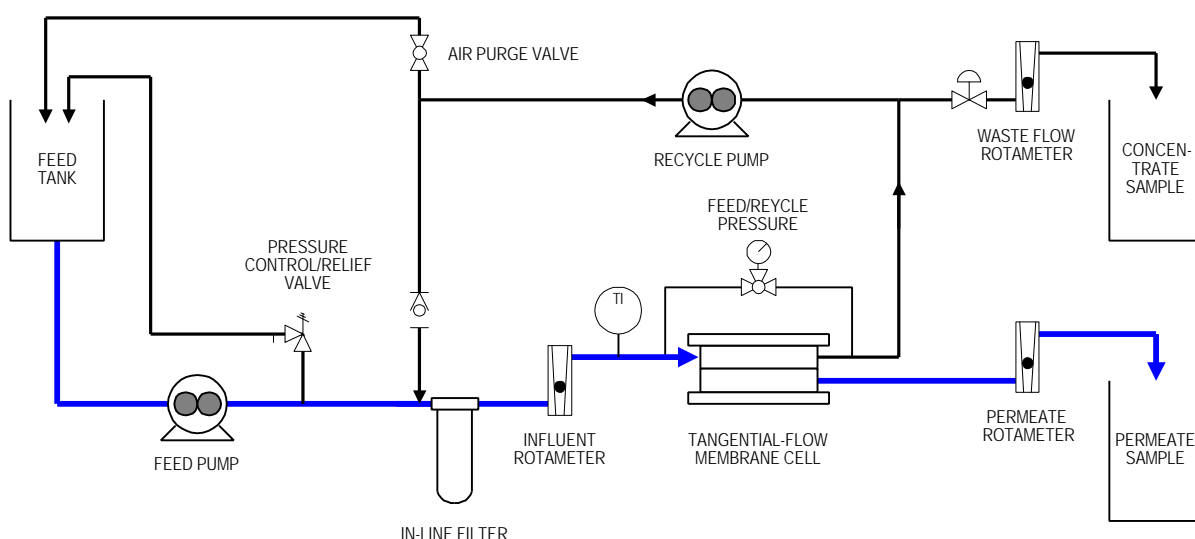


Figure 3 – Rapid Bench-Scale Membrane System Schematic

Two systems were constructed and operated in parallel to allow testing of two membranes simultaneously, using a common barrel of pretreated feed water.

3.4 Experimental Design

The City's groundwater source is not subject to seasonal variation in quality. As approved in a letter from EPA dated April 20, 1998, this study consisted of evaluating four membrane types in two separate rounds of testing. The timing and experimental design summary for this study is presented in Table 4.

Table 4 Experimental Design Summary							
Round	Membrane	Date Started	Date Completed	Pretreatment	Average Water Flux [gfd]	Actual Product Recoveries Sampled [%]	
1	A	11/17/98	12/16/98	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	24.6	69%	88% 49% 30%
1	B	11/17/98	12/16/98	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	20.7	71%	87% 48% 30%
1	C	2/12/99	3/5/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	22.2	70%	90% 50% 30%
1	D	2/12/99	3/5/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	14.3	70%	90% 50% 30%
2	A	5/1/99	5/8/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	25.1	68%	89% 52% 33%
2	B	4/24/99	4/30/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	21.0	69%	90% 52% 31%
2	C	4/24/99	4/30/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	26.3	68%	88% 49% 28%
2	D	5/1/99	5/8/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	15.2	69%	90% 79% 34%

3.4.1 Membranes Tested

Four membrane types were tested. Data from the Manufacturer for each type is summarized in Table 5.

Table 5 Characteristics of Membranes Used in This Study				
General Information				
Membrane Designation	Membrane A	Membrane B	Membrane C	Membrane D
Membrane manufacturer	Film Tec	Film Tec	Hydranautics	Fluid Systems
Membrane trade name	NF70	NF200B-400	ESNA1	TFC 8921S-400
Molecular weight cutoff (Daltons)	200	200-400	180	200
Membrane material (e.g., PVD, polyamide, etc.)	Polyamide	Polyamide	Polyamide	Polyamide
Membrane construction (e.g., thin-film composite)	Thin-Film Composite	Thin-Film Composite	Thin-Film Composite	Thin-Film Composite
Membrane hydrophobicity	Hydrophobic	Hydrophilic	Hydrophilic	Hydrophilic
Membrane charge (e.g., negative, highly negative, neutral, etc.)	Slightly negative charge	Highly Negative	Negative	Negative
Design Parameters				
Design flux, F_w (gfd)	25.0	21.1	27.0	15.0
Net driving pressure at the design flux, NDP (psi)	70.0	71.0	68.0	56.5
Water mass transfer coefficient, MTC_w (gfd/psi)	0.357	0.284	0.360	0.265
Temperature at which the MTC_w was determined, $T^\circ\text{C}$ ($^\circ\text{C}$)	25.0	25.0	25.0	25.0
Active membrane area of an equivalent 8" x 40" element (ft^2)	400.0	400.0	400.0	400.0
Purchase price for an equivalent 8" x 40" element (\$)	600.00	800.00	875.00	846.00
Maximum flow rate to the 8" x 40" element, $Q_{i, \max}$ (gpm)	75.0	70.0	75.0	70.0
Minimum flow rate to the 8" x 40" element, $Q_{i, \min}$ (gpm)	24.7	16.0	25.0	15.0
Total width of all membrane envelopes in the 8" x 40" element, w (ft)	2.9	1.1	76.7	63.2
Feed spacer thickness in the 8" x 40" element, T (ft)	28 mil	28 mil	28 mil	26 mil
Additional Information				
Design cross-flow velocity (fps)	Unknown	-	Unknown	.7 ft/sec @ 15 gfd, 10% rec.
Required influent flow to permeate flow rate ratio, $Q_i:Q_p$	1.54	-	5	6:1
Maximum element recovery (%)	15	19	20	17
Variability of design flux (%)	10	-10%, +25%	15	15
Rejection of reference solute and conditions of test (e.g., solute type and concentration)	95% 2000 ppm MgSO_4	>99% of 2,000 ppm MgSO_4 <50% 500 ppm CaCl_2	min 70% avg 80% 500 ppm NaCl	85.0% 500 mg/L NaCl @ 80 psi
Variability of rejection of reference solute (%)	3	-	10	5
Standard testing recovery (%)	15	15	15	10
Standard testing pH	7.0	6.7-7.3	6.5-7	8
Acceptable range of operating pressures	<250 psi	<105 psi	<400 psi	0-350
Acceptable range of operating pH values	3-9	3-10	3-10	4-11
Typical pressure drop across a single element (psi)	5	3	3-5	5
Maximum permissible SDI	5.0	5	5	5
Maximum permissible turbidity (ntu)	1.0	1	1	1
Chlorine/oxidant tolerance (e.g., < 0.1 mg/L for extended use, etc.)	1000 ppm-hr	1000 ppm-hr	<0.1 mg/L	<0.1 mg/L extended
Contact Information				
Contact	Terry Smith		John Wammes	Tom Stocker
Phone	619 481 2108		760 901 2565	619 653 3509
Fax	619 481 3874		760 901 2578	619 635 6218

3.5 Sampling and Analysis

All analyses associated with this treatment study were performed on-site by the CH2M HILL Applied Science Laboratory in Corvallis, Oregon. Required laboratory information is given below:

CH2M HILL
Applied Science Laboratory
2300 NW Walnut Blvd
Corvallis, Oregon 97330

ICR Lab ID Number: ICROR001

Lab contact: Kathy McKinley

Phone: 541/752-4271

Fax: 541/752-0276

Table 6 presents the RBSMT sampling plan. Table 7 summarizes the membrane operating conditions at the time of each set of permeate and concentrate samples.

Table 8 summarizes the analytical methods used during the treatment study, along with the minimum reporting levels (MRLs). Table 9 summarizes the conditions used during simulated distribution system testing for determination of disinfection byproducts.

Table 6 RBSMT Sampling Plan				
Parameter	Units	# of Samples per Run by Location		
		Feed	Permeate	Concentrate
pH	---	2	5	4
Temperature	deg C	2	5	4
Alkalinity	mg/L as CaCO ₃	2	5	4
Total dissolved solids	mg/L	2	5	4
Total hardness	mg/L as CaCO ₃	2	5	4
Calcium hardness	mg/L as CaCO ₃	2	5	4
Turbidity	ntu	2	5	4
Ammonia	mg NH ₃ -N / L	2	5	4
Total organic carbon	mg/L	2	5	4
UV254	cm ⁻¹	2	5	4
SUVA	L/(mg*m)	2	5	0
Bromide	mg/L	2	5	0
SDS-TOX	mg Cl ⁻ / L	2	5	0
SDS-THM4	mg/L	2	5	0
SDS-HAA5	mg/L	2	5	0
SDS-HAA6	mg/L	2	5	0

Table 7
RBSMT Water Quality Sample Conditions

Round	Membrane	Run	Target Recovery	Permeate Flow [mL/min]	Waste Flow [mL/min]	Actual Recovery	Feed Rate during Sample [mL/min]	Influent Flow during Sample [mL/min]
1	A	1	70%	10.9	4.9	69%	15.8	600
1	A	2	90%	10.9	1.5	88%	12.3	600
1	A	3	50%	9.9	11.3	47%	21.2	600
1	A	4	30%	10.9	25.6	30%	36.5	600
1	B	1	70%	9.0	3.7	71%	12.8	600
1	B	2	90%	9.0	1.3	87%	10.4	600
1	B	3	50%	9.0	9.8	48%	18.9	600
1	B	4	30%	9.0	21.3	30%	30.3	600
1	C	1	70%	13.2	6.6	67%	19.8	410
1	C	2	90%	10.5	2.2	83%	12.7	410
1	C	3	50%	10.7	10.5	50%	21.2	410
1	C	4	30%	9.9	26.7	27%	36.6	410
1	D	1	70%	5.8	2.0	74%	7.8	300
1	D	2	90%	5.6	0.8	87%	6.5	300
1	D	3	50%	6.5	5.5	54%	12.0	300
1	D	4	30%	6.6	14.4	31%	21.0	300
2	A	1	70%	11.0	4.8	70%	15.8	531
2	A	2	90%	11.1	1.3	90%	12.4	531
2	A	3	50%	10.9	11.1	50%	22.0	531
2	A	4	30%	11.2	25.8	30%	37.0	531
2	B	1	70%	9.0	3.9	70%	12.9	344
2	B	2	90%	9.2	1.0	90%	10.2	344
2	B	3	50%	9.1	9.1	50%	18.2	344
2	B	4	30%	9.3	21.7	30%	31.0	344
2	C	1	70%	11.6	5.3	69%	16.9	411
2	C	2	90%	11.7	1.4	89%	13.1	411
2	C	3	50%	11.2	11.8	49%	23.0	411
2	C	4	30%	11.0	27.7	28%	38.7	411
2	D	1	70%	6.6	2.8	70%	9.4	299
2	D	2	90%	6.4	0.7	90%	7.1	299
2	D	3	50%	6.7	6.5	51%	13.2	299
2	D	4	30%	7.0	15.3	31%	22.3	299

Table 8
RBSMT Analytical Methods and Minimum Reporting Levels

Parameter	Analytical Method	Minimum Reporting Level
pH	SM 4500-H+	Not Applicable
Ammonia	SM 4500-NH ₃ D	0.10 mg/L as NH ₃ -N
Calcium Hardness	EPA 200.7	5 mg/L as CaCO ₃
Total Hardness	SM 2340 D	5 mg/L as CaCO ₃
Bromide	EPA 300.0	10 mg/L
Alkalinity	SM 2320 B	5 mg/L as CaCO ₃
Temperature	Thermometer	Not Applicable
Turbidity	SM 2130 B	0.05 ntu
TOC	SM 5310 D	0.50 mg/L
TOX	SM 5320 B	25 mg/L as Cl ⁻
UV254	SM 5910	0.009 cm ⁻¹
THMs: CHCl ₃ , BDCM, DBCM, CHBr ₃	EPA 551.1	0.5 mg/L for each analyte
HAAs: BCAA, DBAA, DCAA, MBAA, MCAA, TCAA	SM 6251 B	1.0 mg/L for each analyte, except 2.0 mg/L for MCAA
Free Chlorine Residual	SM 4500-Cl G	0.05 mg/L

Table 9
Simulated Distribution System Sample Conditions

Sample	Cl ₂ dose mg/L	Free Cl ₂ residual mg/L	Cl ₂ demand mg/L	Temper- ature deg C	pH ---	Incubation time hours
Feed Water (Average of 2 samples)						
Membrane A Round 1	12.0	1.3	10.7	23.0	7.53	23.6
Membrane B Round 1	12.0	1.3	10.7	23.0	7.53	23.6
Membrane C Round 1	13.0	0.7	12.3	22.0	7.52	23.3
Membrane D Round 1	13.0	0.7	12.3	22.0	7.52	23.3
Membrane A Round 2	12.2	0.9	11.4	22.0	7.50	24.2
Membrane B Round 2	12.6	1.1	11.5	22.0	7.44	24.1
Membrane C Round 2	12.6	1.1	11.5	22.0	7.44	24.1
Membrane D Round 2	12.2	0.9	11.4	22.0	7.50	24.2
Permeate (average of 5 samples at 4 recoveries)						
Membrane A Round 1	3.7	0.8	2.9	23.0	7.50	23.6
Membrane B Round 1	5.2	1.4	3.8	23.0	7.48	23.7
Membrane C Round 1	3.6	1.1	2.4	22.0	7.52	23.5
Membrane D Round 1	4.6	1.1	3.5	22.0	7.53	23.4
Membrane A Round 2	3.0	0.6	2.5	22.0	7.53	23.9
Membrane B Round 2	5.5	0.9	4.6	22.0	7.55	23.6
Membrane C Round 2	5.3	1.0	4.3	22.0	7.54	28.8
Membrane D Round 2	4.2	0.9	3.3	22.0	7.52	24.2

4 Results and Discussion

4.1 Problems Encountered

Several refinements were needed to the basic configuration and operation of the test set up used in this study:

- The initial flow control valve for the concentrate line could not achieve the required range in flows. The valve was particularly hard to control during high recovery operation (70 percent and 90 percent), where the waste flow was the lowest. This resulted in inconsistent waste flows. This was particularly problematic with respect to taking composite samples for analysis at high recovery. The low waste flow required compositing of sample overnight, and the reduction in actual waste flow during the sampling resulted in errors in actual product recovery value. These errors are reflected in the mass balance closure data (Table 17).
- During round 2, a positive-displacement pump was substituted for the waste flow control valve for use in high recovery operation (70 percent and 90 percent). This pump could be calibrated to deliver a consistent, known waste flow rate, providing better control of product recovery. The particular pump used was suited to operation at low flows, and was found to not provide a benefit at lower recovery operation. Consequently, the original flow control valve was used on the waste line during 30 percent and 50 percent recovery.

The feed pump selected for use was a gear-type pump as recommended in the *ICR Manual for Bench- and Pilot-Scale Treatment Studies*. The pump proved to be a high maintenance item, requiring frequent speed adjustment to maintain the desired set point. As the pump speed increases, wear on the gear seals increases rapidly. This problem proved to be manageable by maintaining an inventory of replacement seals for the pump and proactively replacing the parts before wear became a problem.

- To provide better documentation of actual recoveries and flow rates during composite sampling, these samples were measured either volumetrically or by weighing the sample container at the end of the sampling period.
- Membrane samples received from the manufacturer did not meet specifications several times, requiring a test to be terminated and rerun. In one case, further discussions with the manufacturer revealed that the initial sample sent for use was from an old inventory of flat sheet material.
- For Round 1 membranes A and B, the feed water ran out overnight on December 4, 1998. An additional barrel of pretreated water had to be warmed to room temperature before the system could be restarted.
- For Round 1 membranes A&B, the test period extended over two weekends. The test system and feed water were stored in a walk-in cooler at 4 deg C over each weekend.

4.2 Influent Water Quality

Water quality for the membrane feed is summarized in Table 10. In each round of testing, two membranes were tested simultaneously using a common batch of feed water. As required by the ICR protocol, feed water quality was sampled twice during each test.

Table 10
Average Pretreated (Membrane Feed) Water Quality

Parameter	Units	Round 1				Round 2				All	
		Membranes A&B		Membranes C&D		Membranes A&D		Membranes B&C		Samples	
		Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
pH	---	6.69	0.14	6.35	0.03	6.76	0.30	6.87	0.10	6.67	0.25
Temperature	°C	21.5	0.0	20.1	0.1	#DIV/0!	0.0	#DIV/0!	0.0	10.4	11.1
Alkalinity	mg/L as CaCO ₃	148	1	70	5	145	0	95	9	114	36
Total dissolved solids	mg/L	474	7	587	22	511	34	514	177	521	81
Total hardness	mg/L as CaCO ₃	295	0	285	1	311	15	328	13	305	19
Calcium hardness	mg/L as CaCO ₃	279	0	268	1	292	14	308	13	287	18
Turbidity	ntu	0.38	0.03	0.87	0.53	0.28	0.10	0.86	0.91	0.60	0.49
Ammonia	mg NH ₃ -N / L	0.64	0.01	0.35	0.07	0.61	0.01	0.72	0.13	0.58	0.16
Total organic carbon	mg/L	9.7	0.0	11.0	0.6	9.3	0.5	8.5	0.1	9.6	1.0
UV ₂₅₄	cm ⁻¹	0.28	0.00	0.37	0.02	0.23	0.13	0.21	0.12	0.27	0.10
SUVA	L/(mg*m)	2.9	0.0	3.4	0.4	2.4	1.3	2.4	1.5	2.8	0.9
Bromide	mg/L	185	1	177	3	179	2	194	24	183	12
SDS-Cl ₂ demand	mg/L	10.7	0.0	12.3	0.2	11.4	0.0	11.5	0.1	11.5	0.6
SDS-TOX	mg Cl ⁻ /L	722	13	924	46	791	16	618	70	764	123
SDS-THM4	mg/L	227	5	210	7	183	3	207	1	207	17
SDS-HAA5	mg/L	117	2	161	9	122	13	126	4	132	20
SDS-HAA6	mg/L	125	2	175	10	134	13	138	6	143	21

4.3 RBSMT Results

4.3.1 Membrane Setting

Table 11 summarizes data from the setting period used at the start of each membrane test. During this study, setting was performed using deionized laboratory water with total dissolved solids of less than 20 ppm. The mass transfer coefficient for water (MTC_w) for each membrane at 12 hours and at the end of the setting period is compared to the manufacturer's reported MTC_w at the test temperature.

Table 11
Membrane Setting Data Summary

Round	Membrane	Setting Period Duration [hours]	Mfr Reported MTC _w [gfd/psi]	MTC _w @ 12 hrs [gfd/psi]	MTC _w Final [gfd/psi]
1	A	118	0.33	0.35	0.35
1	B	118	0.26	0.35	0.35
1	C	186	0.33	0.28	0.22
1	D	186	0.24	0.19	0.15
2	A	27	0.33	0.26	0.28
2	B	31	0.26	0.21	0.20
2	C	31	0.33	0.26	0.25
2	D	27	0.24	0.19	0.20

4.3.2 Product Water Quality

Product water quality for key parameters at the recoveries investigated are summarized in Table 12.

Table 12A
Effect of Recovery on Product Quality
Membrane A

Water Quality Parameter		Product Quality at Listed Recovery							
		Round 1				Round 2			
		30%	47%	69%	88%	30%	50%	70%	90%
TDS	mg/L	52	87	338	260	63	63	115	158
Ca Hardness	mg/L as CaCO ₃	22	46	218	121	27	28	47	82
Total Hardness	mg/L as CaCO ₃	20	43	210	115	27	28	44	78
Bromide	mg/L	38	50	171	137	25	28	45	83
TOC	mg/L	0.6	0.5	0.8	1.1	BMRL	BMRL	0.3	0.4
UV254	cm ⁻¹	BMRL	0.012	0.010	0.025	BMRL	BMRL	BRML	0.014
SDS-THM4	µg/L	7.3	12.3	18.4	32.9	6.0	3.0	8.5	15.4
SDS-HAA5	µg/L	0.0	3.7	2.3	6.6	0.0	0.0	0.6	1.8
SDS-HAA6	µg/L	0.0	5.3	3.8	9.2	0.0	0.0	1.2	3.1
SDS-TOX	mg/L as Cl	BMRL	30	32	69	BMRL	BMRL	BRML	37

Table 12B
Effect of Recovery on Product Quality
Membrane B

Water Quality Parameter		Product Quality at Listed Recovery							
		Round 1				Round 2			
		30%	48%	71%	87%	30%	50%	70%	90%
TDS	mg/L	200	414	122	374	374	469	350	432
Ca Hardness	mg/L as CaCO ₃	102	215	76	238	211	232	253	274
Total Hardness	mg/L as CaCO ₃	99	206	72	227	201	220	239	259
Bromide	mg/L	174	175	78	181	155	175	170	174
TOC	mg/L	0.9	1.2	0.8	1.9	3.1	0.9	0.4	0.7
UV254	cm ⁻¹	0.016	0.018	0.018	0.038	0.018	0.026	0.010	0.020
SDS-THM4	µg/L	23.5	29.3	20.2	52.7	27.4	38.5	20.2	34.2
SDS-HAA5	µg/L	5.2	6.9	7.3	12.5	4.2	7.9	2.4	7.4
SDS-HAA6	µg/L	7.6	9.8	9.9	17.7	6.5	11.3	3.9	10.5
SDS-TOX	mg/L as Cl ⁻	41	62	51	110	45	60	33	89

Table 12C
Effect of Recovery on Product Quality
Membrane C

Water Quality Parameter		Product Quality at Listed Recovery							
		Round 1				Round 2			
		27%	50%	67%	83%	28%	49%	69%	89%
TDS	mg/L	58	54	81	198	210	297	332	438
Ca Hardness	mg/L as CaCO ₃	18	23	33	68	115	143	209	254
Total Hardness	mg/L as CaCO ₃	18	23	33	64	107	134	196	239
Bromide	mg/L	24	32	52	77	82	91	127	146
TOC	mg/L	0.3	0.3	0.4	0.5	0.6	1.0	1.7	2.2
UV254	cm ⁻¹	0.003	0.003	0.005	0.007	0.021	0.028	0.048	0.062
SDS-THM4	µg/L	1.0	3.6	5.7	9.5	20.9	34.0	51.5	59.5
SDS-HAA5	µg/L	0.0	0.0	0.0	2.2	5.7	8.9	13.9	22.2
SDS-HAA6	µg/L	0.0	0.0	0.0	3.5	7.9	13.0	20.0	29.0
SDS-TOX	mg/L as Cl ⁻	BMRL	BMRL	BRML	32	55	73	109	140

Table 12D
Effect of Recovery on Product Quality
Membrane D

Water Quality Parameter		Product Quality at Listed Recovery							
		Round 1				Round 2			
		31%	50%	74%	87%	31%	51%	70%	90%
TDS	mg/L	94	112	267	392	89	201	153	214
Ca Hardness	mg/L as CaCO ₃	37	51	111	180	23	84	69	123
Total Hardness	mg/L as CaCO ₃	35	48	104	171	23	79	64	116
Bromide	mg/L	42	53	132	134	24	78	64	120
TOC	mg/L	0.4	0.5	1.1	2.0	0.3	0.7	0.8	1.1
UV254	cm ⁻¹	0.009	0.012	0.032	0.053	BMRL	0.022	0.020	0.033
SDS-THM4	µg/L	8.9	13.3	30.5	49.6	6.9	24.3	20.7	31.4
SDS-HAA5	µg/L	3.0	4.0	9.6	15.4	0.0	6.7	6.3	8.7
SDS-HAA6	µg/L	4.5	5.7	13.7	21.8	0.0	9.4	8.7	12.2
SDS-TOX	mg/L as Cl ⁻	29	35	86	147	BMRL	68	57	83

4.3.3 Feed Rejection as a Function of Recovery

Data for feed rejection as a function of recovery is presented in Figures 4 through 6. Results for each of the two rounds of testing are presented.

Figure 4A

Membrane A Round 1 Rejection Summary by Recovery

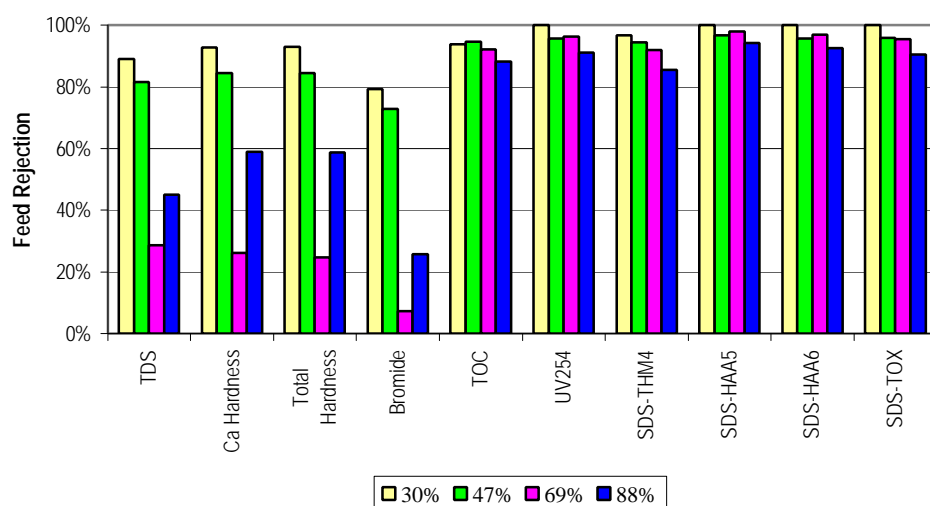


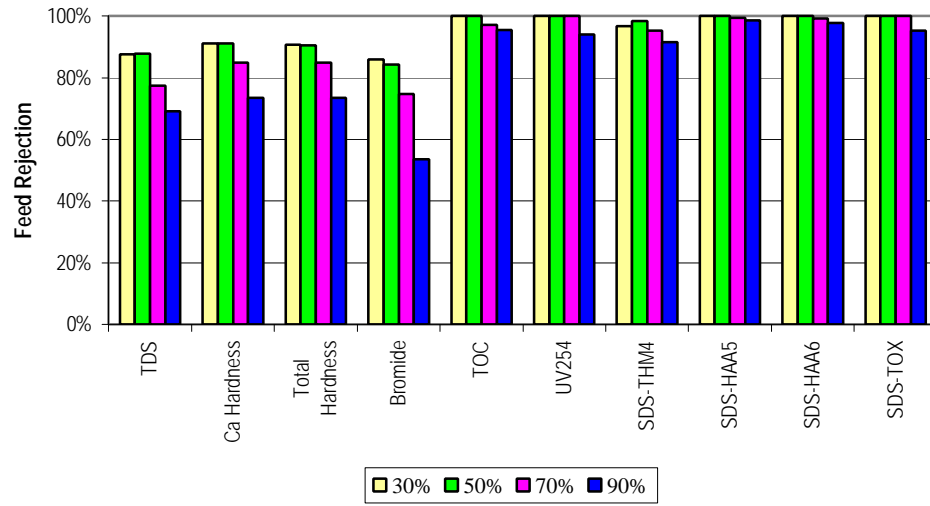
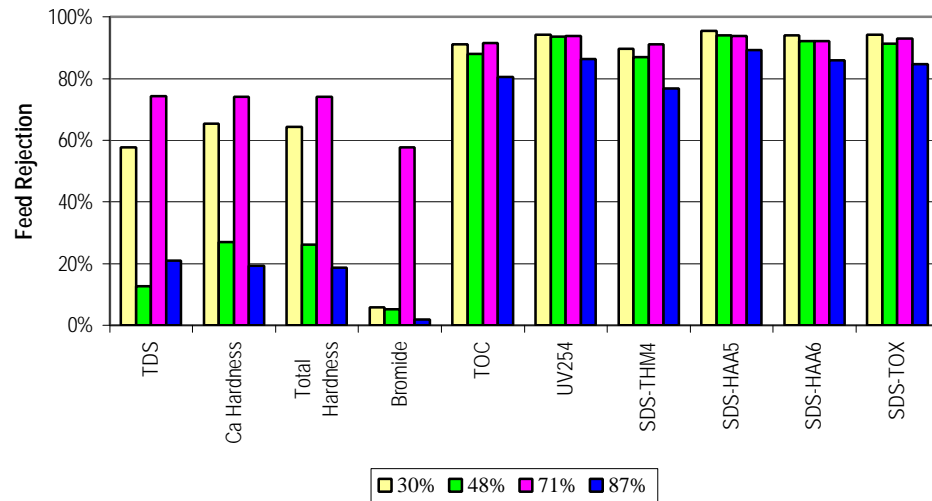
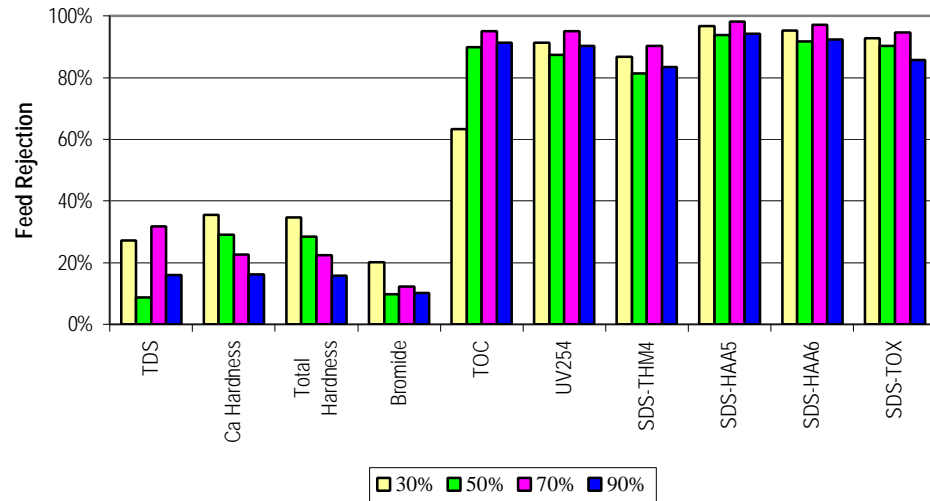
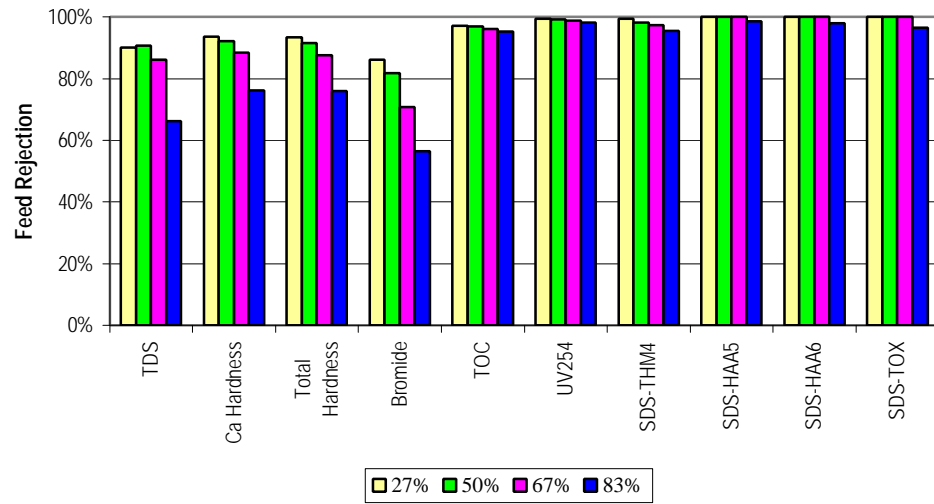
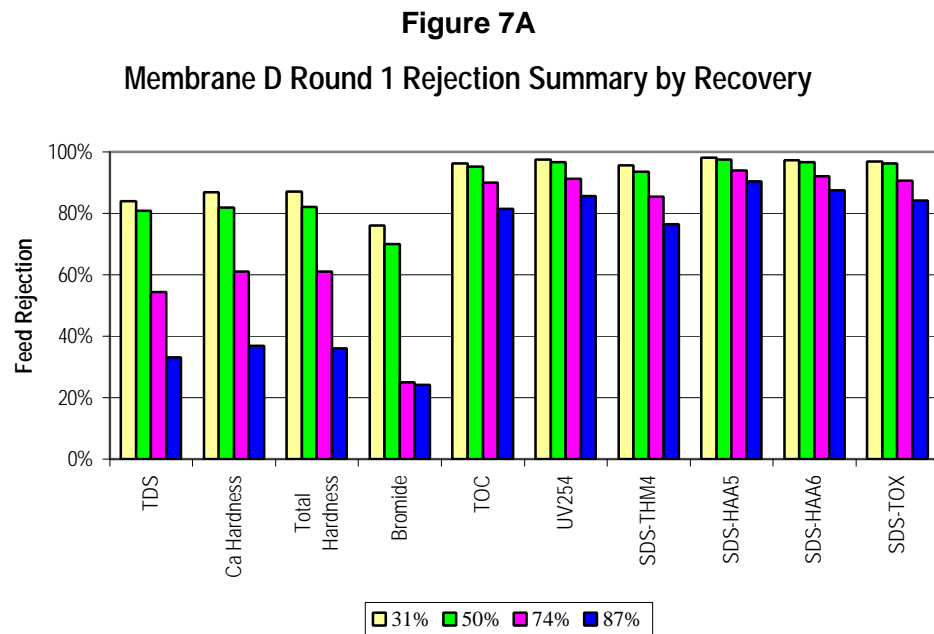
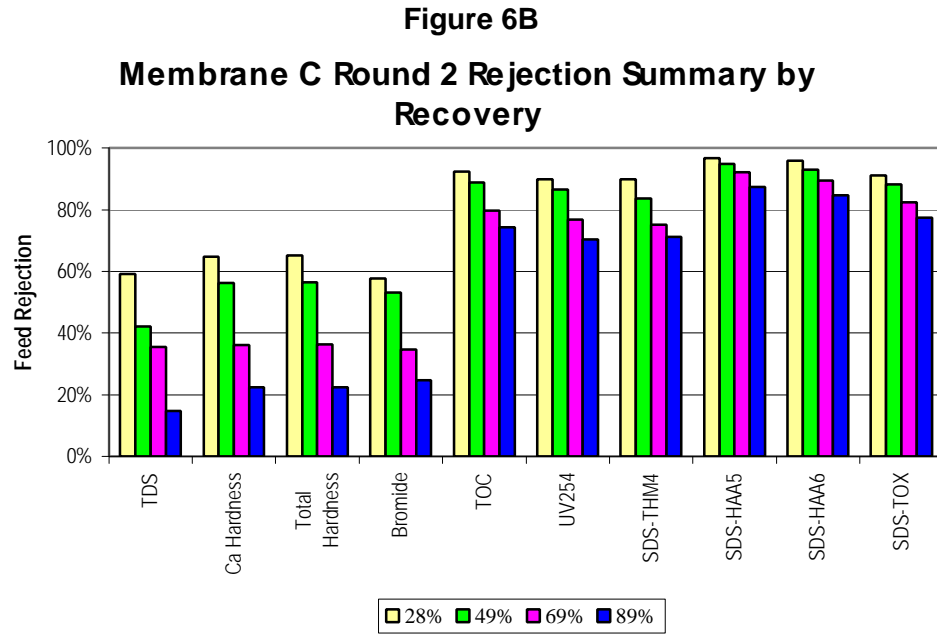
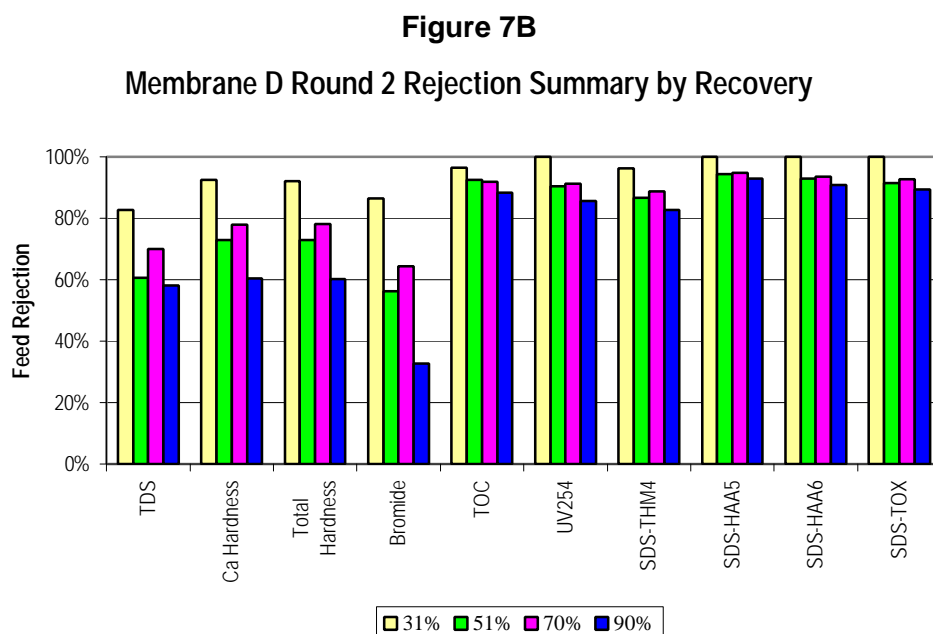
Figure 4B**Membrane A Round 2 Rejection Summary by Recovery****Figure 5A****Membrane B Round 1 Rejection Summary by Recovery**

Figure 5B**Membrane B Round 2 Rejection Summary by Recovery****Figure 6A****Membrane C Round 1 Rejection Summary by Recovery**





4.3.4 Permeate Blending Scenarios

The high rejection of disinfection byproduct precursors by nanofiltration produces product water that in most cases greatly exceeds target DBP concentrations. This offers an opportunity for blending of bypassed feed water with the product water to meet treatment objectives. Raw water bypass can reduce the required membrane area and energy requirements for operating the treatment system.

The *ICR Treatment Studies Data Collection Spreadsheets* contain calculations of the acceptable ratio of permeate flow to total product flow to achieve Stage 1 and proposed Stage 2 DBP MCLs with a 10 percent factor of safety (THM4 = 54 µg/L for Stage 1, 36 µg/L for stage 2; HAA5 = 54 µg/L for Stage 1, 27 µg/L for Stage 2). These ratios, plus the projected quality of the blended water for key parameters, are summarized in Table 14. In most cases for the waters tested in this study, THM4 is the controlling parameter that dictates the allowable blend ratio. In other cases, it is HAA5. The controlling parameter is highlighted under each condition in Table 14. In some cases, the treatment objective can not be met with nanofiltration as tested in this study.

Table 13-A1 Blend Ratios to Achieve Target DBP Goals Membrane A Round 1						
Controlling Treatment Objective	Permeate: Total Flow Blend Ratio	Value at Blend Ratio				
		TOC mg/L	SDS THM4 µg/L	SDS HAA5 µg/L	SDS TOX µg/L	
Stage 1 TTHM = 72 mg/L						
Recovery = 30%	70%	3.3	72	34	NA	
Recovery = 47%	72%	3.1	72	35	223	
Recovery = 69%	74%	3.1	72	32	210	
Recovery = 88%	80%	2.9	72	29	201	
Stage 2 TTHM = 36 mg/L						
Recovery = 30%	87%	1.8	36	15	NA	
Recovery = 47%	89%	1.5	36	16	106	
Recovery = 69%	92%	1.5	36	12	90	
Recovery = 88%	98%	1.3	36	8	79	

Table 13-A2 Blend Ratios to Achieve Target DBP Goals Membrane A Round 2						
Controlling Treatment Objective	Permeate: Total Flow Blend Ratio	Value at Blend Ratio				
		TOC mg/L	SDS THM4 µg/L	SDS HAA5 µg/L	SDS TOX µg/L	
Stage 1 TTHM = 72 mg/L						
Recovery = 30%	63%	NA	72	46	NA	
Recovery = 50%	62%	NA	72	47	NA	
Recovery = 70%	64%	3.6	72	45	NA	
Recovery = 90%	66%	3.4	72	42	292	
Stage 2 TTHM = 36 mg/L						
Recovery = 30%	83%	NA	36	21	NA	
Recovery = 50%	82%	NA	36	22	NA	
Recovery = 70%	84%	1.7	36	20	NA	
Recovery = 90%	88%	1.5	36	17	129	

Table 13-B1 Blend Ratios to Achieve Target DBP Goals Membrane B Round 1						
Controlling Treatment Objective	Permeate: Total Flow Blend Ratio	Value at Blend Ratio				
		TOC mg/L	SDS THM4 µg/L	SDS HAA5 µg/L	SDS TOX µg/L	
Stage 1 TTHM = 72 mg/L						
Recovery = 30%	76%	3.0	72	32	204	
Recovery = 48%	78%	3.0	72	31	205	
Recovery = 71%	75%	3.1	72	35	220	
Recovery = 87%	89%	2.7	72	24	178	
Stage 2 TTHM = 36 mg/L						
Recovery = 30%	94%	1.4	36	12	83	
Recovery = 48%	97%	1.4	36	11	85	
Recovery = 71%	92%	1.5	36	16	103	
Recovery = 87%	Permeate Exceeded Treatment Objective					

Table 13-B2 Blend Ratios to Achieve Target DBP Goals Membrane B Round 2						
Controlling Treatment Objective	Permeate: Total Flow Blend Ratio	Value at Blend Ratio				
		TOC mg/L	SDS THM4 µg/L	SDS HAA5 µg/L	SDS TOX µg/L	
Stage 1 TTHM = 72 mg/L						
Recovery = 30%	75%	4.5	72	35	188	
Recovery = 50%	80%	2.4	72	31	171	
Recovery = 70%	72%	2.7	72	37	195	
Recovery = 90%	78%	2.4	72	33	205	
Stage 2 TTHM = 36 mg/L						
Recovery = 30%	95%	3.4	36	10	73	
Recovery = 50%	Permeate Exceeded Treatment Objective					
Recovery = 70%	92%	1.1	36	13	83	
Recovery = 90%	99%	0.8	36	9	94	

Table 13-C1 Blend Ratios to Achieve Target DBP Goals Membrane C Round 1						
Controlling Treatment Objective	Permeate: Total Flow Blend Ratio	Value at Blend Ratio				
		TOC mg/L	SDS THM4 µg/L	SDS HAA5 µg/L	SDS TOX µg/L	
Stage 1 TTHM = 72 mg/L						
Recovery = 27%	66%	3.9	72	55	NA	
Recovery = 50%	67%	3.9	72	53	NA	
Recovery = 67%	68%	3.9	72	52	NA	
Recovery = 83%	69%	3.8	72	52	310	
Stage 2 TTHM = 36 mg/L						
Recovery = 27%	83%	2.1	36	27	NA	
Recovery = 50%	84%	2.0	36	25	NA	
Recovery = 67%	85%	2.0	36	24	NA	
Recovery = 83%	87%	1.9	36	23	150	

Table 13-C2 Blend Ratios to Achieve Target DBP Goals Membrane C Round 2						
Controlling Treatment Objective	Permeate: Total Flow Blend Ratio	Value at Blend Ratio				
		TOC mg/L	SDS THM4 µg/L	SDS HAA5 µg/L	SDS TOX µg/L	
Stage 1 TTHM = 72 mg/L						
Recovery = 28%	73%	2.8	72	53	210	
Recovery = 49%	78%	2.6	72	46	193	
Recovery = 69%	87%	2.6	72	35	176	
Recovery = 89%	92%	2.7	72	35	181	
Stage 2 TTHM = 36 mg/L						
Recovery = 28%	92%	1.3	36	20	101	
Recovery = 49%	99%	1.0	36	11	79	
Recovery = 69%	Permeate Exceeded Treatment Objective					
Recovery = 89%	Permeate Exceeded Treatment Objective					

Table 13-D1 Blend Ratios to Achieve Target DBP Goals Membrane D Round 1						
Controlling Treatment Objective	Permeate: Total Flow Blend Ratio	Value at Blend Ratio				
		TOC mg/L	SDS THM4 µg/L	SDS HAA5 µg/L	SDS TOX µg/L	
Stage 1 TTHM = 72 mg/L						
Recovery = 31%	69%	3.7	72	53	309	
Recovery = 50%	70%	3.7	72	51	300	
Recovery = 74%	77%	3.4	72	45	279	
Recovery = 87%	86%	3.3	72	36	255	
Stage 2 TTHM = 36 mg/L						
Recovery = 31%	87%	1.8	36	24	149	
Recovery = 50%	88%	1.7	36	22	137	
Recovery = 74%	97%	1.4	36	14	111	
Recovery = 87%	Permeate Exceeded Treatment Objective					

Table 13-D2 Blend Ratios to Achieve Target DBP Goals Membrane D Round 2						
Controlling Treatment Objective	Permeate: Total Flow Blend Ratio	Value at Blend Ratio				
		TOC mg/L	SDS THM4 µg/L	SDS HAA5 µg/L	SDS TOX µg/L	
Stage 1 TTHM = 72 mg/L						
Recovery = 31%	63%	3.6	72	45	NA	
Recovery = 51%	70%	3.3	72	41	285	
Recovery = 70%	68%	3.5	72	43	289	
Recovery = 90%	73%	3.3	72	39	273	
Stage 2 TTHM = 36 mg/L						
Recovery = 31%	83%	1.8	36	20	NA	
Recovery = 51%	93%	1.3	36	15	121	
Recovery = 70%	91%	1.6	36	17	127	
Recovery = 90%	97%	1.3	36	12	105	

4.3.5 Membrane Productivity and Cleaning Efficiency

Membrane productivity can be expressed as the mass transfer coefficient for water (MTC_w), which is the flux at a reference temperature normalized to the net driving pressure across the membrane. This parameter is expressed in units of gfd/psi. Membrane cleaning is usually indicated when the MTC_w drops by a specified percentage. The rate of decrease in the calculated MTC_w can be used to project a cleaning interval for the membranes. In this study, a cleaning criteria of 15 percent was used.

MTC_w values as the start of each run, and before and after the cleaning procedure prescribed by the *ICR Manual for Bench- and Pilot-Scale Treatment Studies* are summarized in Table 14, along with projected cleaning intervals using the 15 percent MTC_w decrease criteria.

In this study, cleaning procedures used for each membrane were as follows:

1st Clean:

- Citric acid in warm (30-35 deg C) DI water, 2% by weight (40 grams in 2 Liters).
- Check and record pH of cleaning solution. Must be above 2.0.
- Recirculate for 30 minutes
- Soak for 2 hours
- Recirculate for 30 minutes

2nd Clean:

- Sodium Hydroxide/Surfactant in warm DI water (30-35 deg C).
- 0.5% sodium hydroxide by weight (10 grams in 2 L)
- 0.1% Calsoft L-40 by volume (2 mL in 2 L)
- Check and record pH of cleaning solution. Must be below pH 11
- Recirculate for 30 minutes
- Allow to Soak for 2 hours
- Recirculate for 30 minutes

Table 14 Membrane Productivity and Cleaning Efficiency					
Operating Conditions	Initial MTC_w	Final MTC_w	Average Rate of MTC_w Decline	Projected Cleaning Interval (Note 1)	MTC_w After Cleaning
	gfd/psi	gfd/psi	gfd/psi/day	days	gfd/psi
Membrane A Round 1	0.305	0.183	-0.026	1.7	0.204
Membrane B Round 1	0.204	0.159	-0.020	1.5	0.158
Membrane C Round 1	0.225	0.142	-0.019	1.8	0.143
Membrane D Round 1	0.135	0.136	0.003	Note 2	0.151
Membrane A Round 2	0.268	0.212	-0.008	5.2	0.214
Membrane B Round 2	0.177	0.171	0.000	Note 2	0.247
Membrane C Round 2	0.211	0.183	-0.003	10.8	0.183
Membrane D Round 2	0.178	0.148	-0.006	4.5	0.175
Note 1: Based on a 15% reduction in MTC _w					
Note 2: Calculation not valid because MTC _w increased during test run.					

5 Quality Assurance/Quality Control

The QA/QC data for laboratory duplicates, laboratory fortified matrix samples, and independent QC checks (Performance Evaluation, or PE samples) are summarized in the *Treatment Study Summary Report Spreadsheets*, submitted in conjunction with this report. The data in the *Treatment Study Summary Report* reflect laboratory operation during the entire period when RBSMT studies were being performed, including this study and a study performed for another utility in Florida.

Calibration procedures used for bromide, TOC, TOX, UV254, THMs, and HAAs are summarized in Table 15. Calibration frequencies, calibration check standard concentrations, and calibration acceptance criteria specified in the *DPB/ICR Analytical Methods Manual* (EPA, 1996b) were followed.

Table 15 Calibration Procedures Summary			
Parameter	Analytical Method	Initial Calibration	Continuing Calibration
Bromide	EPA 300.0	4-point calibration with point-to-point interpolation	Low-, mid-, and high-level calibration checks each analysis day; LCS
TOC	SM 5310 D	5-point calibration with linear fit	Low-, mid-, and high-level calibration checks each analysis day; LCS
TOX	SM 5320 B	Test titrations; cell checks within 3% of injected mass	Low-, mid-, and high-level calibration checks each analysis day
UV254	SM 5910	Blank; LCS	Low-, mid-, and high-level calibration checks each analysis day
THMs: CHCl ₃ , BDCM, DBCM, CHBr ₃	EPA 551.1	8-point calibration with point-to-point interpolation	Low-, mid-, and high-level calibration checks each analysis day; LCS
HAAs: BCAA, DBAA, DCAA, MBAA, MCAA, TCAA	SM 6251 B	5-point calibration with point-to-point interpolation	Low-, mid-, and high-level calibration checks each analysis day; LCS
LCS = lab control sample (secondary source standard)			

The RBSMT protocol required duplicate samples of permeate for each membrane run at 70% recovery. Values for relative percent difference of these duplicate samples as calculated by the *RBSMT Data Collection Spreadsheets* are summarized in Table 16.

Table 16
Permeate Duplicate Samples @ 70% Target Recovery
Relative Percent Difference

Parameter	Round 1				Round 2				Overall Average
	A	B	C	D	A	B	C	D	
pH	2.0	0.4	1.2	0.2	0.3	1.2	0.6	1.5	0.9
Temperature	0.0	0.0	0.0	0.0					0.0
Alkalinity	0.8	2.2	12.2	4.3	0.8	4.7	1.0	9.1	4.4
Total dissolved solids	0.6	9.1	31.1	20.0	0.4	78.9	10.6	1.3	19.0
Total hardness	4.1	0.5	1.5	0.0	0.2	0.0	1.0	1.5	1.1
Calcium hardness	3.8	0.4	1.5	0.0	0.0	0.0	1.0	1.3	1.0
Turbidity	50.0	133.3	0.0	0.0					45.8
Ammonia	15.1	13.3	4.7	10.2	9.0	6.6	2.4	21.6	10.3
Total organic carbon	67.5	25.5	65.1	3.7	7.4	7.2	1.7	6.6	23.1
UV254	0.0	5.7	7.8	0.0		4.9	0.0	0.0	2.6
SUVA	67.5	31.1	72.0	3.7		2.4	1.7	6.6	26.4
Bromide	4.7	2.4	25.8	51.1	13.3	2.4	0.8	1.6	12.7
SDS-Cl ₂ dose	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SDS-Free Cl ₂ residual	18.8	1.9	2.8	0.9	4.8	4.8	9.5	2.1	5.7
SDS-Cl ₂ demand	3.1	0.9	1.6	0.3	1.5	0.9	1.5	0.6	1.3
SDS-Chlorination temp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SDS-Chlorination pH	0.8	0.3	0.1	1.7	0.4	1.6	0.4	0.4	0.7
SDS-Incubation time	0.1	0.4	0.3	0.4	0.3	8.6	0.1	0.1	1.3
SDS-TOX	7.2	5.0		0.3		9.4	3.2	0.7	4.3
SDS-CHCl ₃	1.0	7.3	12.1	0.9	19.0	6.1	3.0	1.9	6.4
SDS-BDCM	0.3	4.1	11.8	1.5	12.9	2.5	7.9	1.4	5.3
SDS-DBCM	8.4	2.0	6.9	1.6	9.2	5.8	8.3	1.4	5.5
SDS-CHBr ₃	25.0			11.9		15.1	5.4	0.0	11.5
SDS-THM ₄	10.2	4.3	10.3	0.4	13.0	5.9	6.6	0.5	6.4
SDS-MCAA*									
SDS-DCAA*		3.7		3.5			7.3	3.9	4.6
SDS-TCAA*		3.6		7.5			2.4	4.4	4.5
SDS-MBAA*									
SDS-DBAA*	13.0	1.7		2.6		8.3	14.6	6.9	7.9
SDS-BCAA*	0.8	1.7		0.3		0.0	16.4	0.0	3.2
SDS-TBAA									
SDS-CDBAA									
SDS-DCBAA									
SDS-HAA ₅	13.0	3.2		3.2		8.3	6.5	1.6	6.0
SDS-HAA ₆	8.3	2.8		2.2		5.1	9.5	1.2	4.8

5.1 Mass Balance Closure Errors

For each membrane test run the observed flow rates and analytical results for feed, permeate, and concentrate samples can be used to calculate a mass balance across the membrane. For a given constituent, the feed concentration multiplied by the feed flow rate should equal the sum of the flow rate times the concentration for the permeate plus the

concentrate. The *Treatment Study Summary Report Spreadsheets* calculate the closure error for the mass balance on several water quality parameters. A summary of these calculated values is presented in Table 17.

Table 17 Mass Balance Closure Error Summary										
Round	Membrane	Run	Target Recovery	Alkalinity	TDS	Total Hardness	Ca Hardness	Ammonia	TOC	UV254
1	A	1	70%	68%	58%	54%	55%	40%	19%	22%
1	A	2	90%	30%	NA	26%	26%	NA	-38%	35%
1	A	3	50%	4%	NA	-1%	-1%	NA	9%	8%
1	A	4	30%	-3%	-227%	-9%	-9%	-87%	-6%	NA
1	B	1	70%	1%	-7%	-5%	-9%	-44%	49%	47%
1	B	2	90%	25%	NA	17%	15%	NA	-20%	40%
1	B	3	50%	15%	NA	12%	12%	NA	25%	23%
1	B	4	30%	3%	-151%	-3%	-3%	NA	-8%	4%
1	C	1	70%	5%	-3%	1%	1%	7%	7%	7%
1	C	2	90%	23%	38%	31%	30%	-25%	33%	31%
1	C	3	50%	6%	0%	-7%	-7%	21%	-3%	-2%
1	C	4	30%	8%	-3%	0%	0%	13%	0%	-5%
1	D	1	70%	24%	25%	18%	18%	37%	23%	25%
1	D	2	90%	31%	44%	41%	42%	17%	30%	25%
1	D	3	50%	14%	-4%	1%	0%	20%	5%	-97%
1	D	4	30%	-12%	-15%	-0%	-0%	16%	-4%	-6%
2	A	1	70%	46%	-7%	-9%	-9%	-16%	-6%	NA
2	A	2	90%	-10%	-32%	-32%	-32%	0%	-13%	14%
2	A	3	50%	6%	9%	2%	3%	10%	NA	NA
2	A	4	30%	0%	-2%	-2%	-2%	-7%	NA	NA
2	B	1	70%	9%	-58%	-6%	-7%	-3%	5%	30%
2	B	2	90%	38%	-11%	-24%	-25%	6%	0%	27%
2	B	3	50%	-88%	20%	-12%	-13%	-15%	5%	31%
2	B	4	30%	-6%	2%	-8%	-8%	-24%	11%	33%
2	C	1	70%	11%	-15%	3%	3%	-48%	-25%	-22%
2	C	2	90%	17%	27%	-7%	-7%	-3%	-1%	33%
2	C	3	50%	-81%	10%	-13%	-14%	-8%	3%	38%
2	C	4	30%	-5%	3%	-9%	-9%	-24%	2%	35%
2	D	1	70%	46%	-0%	-10%	-10%	-16%	-7%	27%
2	D	2	90%	-3%	-21%	-25%	-25%	-28%	-9%	20%
2	D	3	50%	46%	49%	44%	44%	40%	47%	60%
2	D	4	30%	3%	7%	-1%	-1%	-5%	99%	NA

6 References

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