ICR Treatment Study Summary Report

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

Prepared by:

CH2MHILL

2300 NW Walnut Blvd.
Corvallis, OR 97330-3538

July 13, 1999

For:

City of Delray Beach, Florida
PSWID #FL4500351

200 SW 6th Street
Delray Beach, FL 33444

Phone (407) 243-7318
Fax (407) 243-7316

ICR # 1086

Contents

Figures

Tables

1 Conclusions and Recommendations

Source water for the City of Delray Beach 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 10.4 mg/L. This water formed an average of 205 μg/L of total trihalomethanes (THM4) and 172 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, with product water concentrations generally between 20-40 μg/L for product water recoveries of 70 percent. HAA5 was also effectively removed, with product water concentrations generally in the 10-20 μg/L range at 70 percent recovery. Stage 1 and Stage DBP criteria were not met in all cases, however.

In many cases. the high-quality product water would allow a blend of bypassed feed water and membrane product water, to meet the Stage 1 MCLs with a 10 percent factor of safety. The controlling parameter for blending in this manner is THM4 under some conditions and HAA5 under other conditions. Depending on the membrane type used, raw water bypass on the order of 15 to 25 percent could be used while still meeting the Stage 1 DBP criteria. Raw water bypass of less than 10 percent would be allowable for meeting 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 Delray Beach Water Treatment Plant is presented as Figure 1. Design criteria for unit processes at the plant are summarized in Table 1.

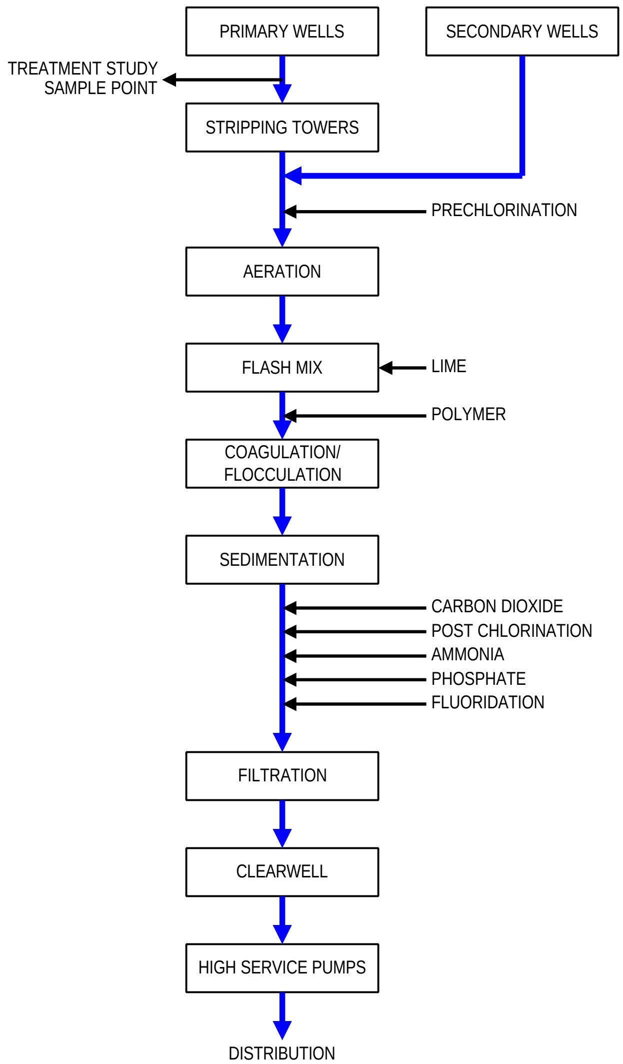


Figure 1 – Delray Beach WTP Schematic

Table 1
Delray Beach Water Treatment Plant Design Criteria

Unit Process/Parameter		Criteria
Aeration		
	Type	Cascade Tray
	No. of Units	6
	Nop. Of Steps/Unit	4
	No. of Trays/Step	6
	Total Trays/Unit	24
	Capacity	21.5 mgd
Softening		
	Type	Solids Contact Upflow Clarifier
	# of units	4
	Tank Diameter	65 ft
	Side Depth	2 @ 16 ft, 2@ 18 ft
	Coagulant Addition	Lime, 125 mg/L
		Polymer, 0.12 mg/L
Disinfection		
	Chemical Type	Chlorine Gas
		Anhydrous NH_3
	Dosing Rate	12 mg/L as Cl_2
Filtration		
	Media Type	Mixed Media
	Total Media Depth	52 inches
	# of Filters	8
	Total Filter Area	5,664 SqFt
	Filtration Rate	4 gpm/SqFt
	Backwash Rate	20 gpm/SqFt
Clear Wells		
	Liquid Volume	1 mil gal
	Corrosion Control Chemical	Polyphosphate
	Corrosion Inhibitor Dose	2 mg/L

2.2 Water Quality

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

2.2.1 Source Water

Table 2 Delray Beach Source Water Quality					
Parameter	**Units**	**Average Annual Value**	**Standard Deviation**	**Maximum Annual Value**	**Minimum Annual Value**
pH		7.51	0.05	7.60	7.40
Calcium Hardness	mg/L as $CaCO_3$	230	3.1	236	226
Total Hardness	mg/L as $CaCO_3$	242	3.4	248	237
Bromide	mg/L	NR	NR	NR	NR
Alkalinity	mg/L as $CaCO_3$	200	6.9	210	185
Temperature	°C	NR	NR	NR	NR
Turbidity	Ntu	NR	NR	NR	NR
TOC	mg/L	NR	NR	NR	NR
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 Delray Beach Finished Water Quality					
Parameter	**Units**	**Average Annual Value**	**Standard Deviation**	**Maximum Annual Value**	**Minimum Annual Value**
pH	pH units	7.68	0.11	7.80	7.50
Temperature	°C	NR	NR	NR	NR
Turbidity	Ntu	0.21	0.02	0.24	0.18
Total Dissolved Solids	mg/L	NR	NR	NR	NR
Total Hardness	mg/L as $CaCO_3$	102	5.4	116	93
TOC	mg/L	7.96	1.02	10.10	6.00
UV254	cm^{-1}	NR	NR	NR	NR
SUVA	L/(mg-m)	NR	NR	NR	NR
DS-THM4	mg/L	0.032	0.013	0.054	0.017
DS-HAA5	mg/L	NR	NR	NR	NR
DS-HAA6	mg/L	NR	NR	NR	NR

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 for the first round of testing consisted of three steps, as illustrated in Figure 2:

- Aeration by applying air to each barrel through a fine bubble diffuser overnight to oxidize iron.
- Acidification to the target pH noted 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).
- Microfiltration using a bench-scale hollow fiber cartridge with a 1-micron nominal pore size.

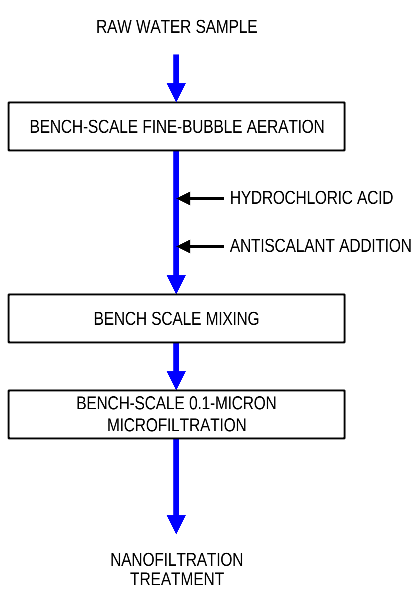


Figure 2 – Schematic of Pretreatment used in This Study

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.

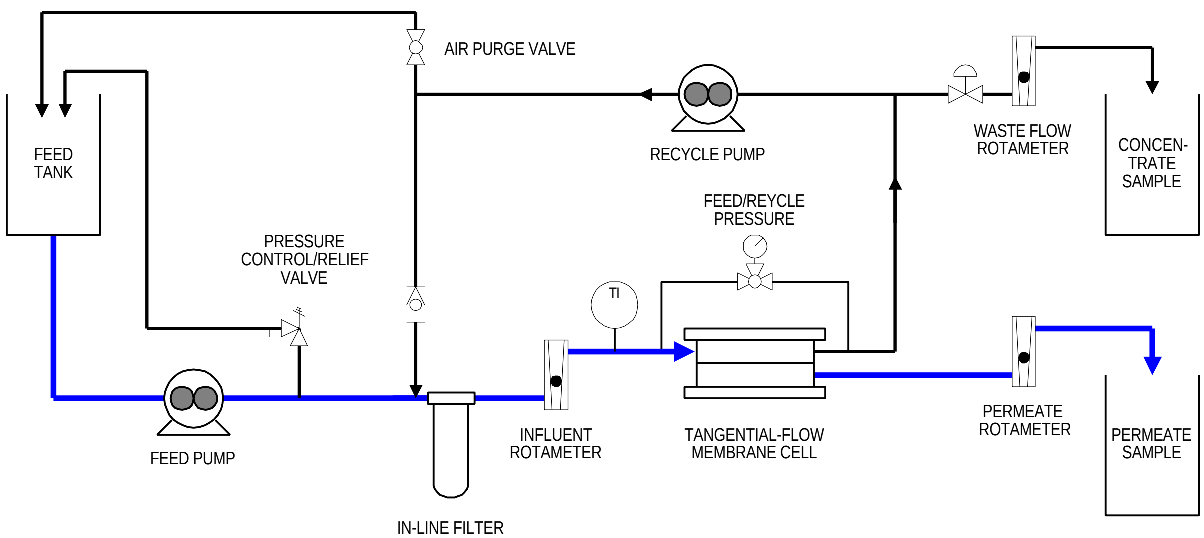


Figure 3 – Rapid Bench-Scale Membrane System Schematic

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. 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	Mem-brane	Date Started	Date Com-pleted	Pretreatment	Average Water Flux [gfd]	Actual Product Recoveries Sampled [%]
1	A	3/15/99	3/27/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	25.0	69% 91% 57% 31%
1	B	4/16/99	4/23/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	21.1	68% 90% 50% 27%
1	C	4/16/99	4/23/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	25.6	66% NA 49% 30%
1	D	3/16/99	3/27/99	Acidify to pH 6.5, 3 ppm antiscalant, 5 µm cartridge filter	15.3	69% 91% 79% 38%
2	A	5/8/99	5/15/99	Aerate, Acidify to pH 6.0, 3 ppm antiscalant, 0.1 µm membrane filter	15.1	68% 90% 50% 30%
2	B	5/15/99	5/22/99	Aerate, Acidify to pH 6.0, 3 ppm antiscalant, 0.1 µm membrane filter	15.0	70% 90% 50% 30%
2	C	5/22/99	5/29/99	Aerate, Acidify to pH 6.0, 3 ppm antiscalant, 0.1 µm membrane filter	15.1	76% 90% 50% 35%
2	D	5/8/99	5/15/99	Aerate, Acidify to pH 6.0, 3 ppm antiscalant, 0.1 µm membrane filter	14.8	69% 89% 50% 32%

3.4.1 Membranes Tested

Four membrane types were tested. Data on 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^oC (^oC)	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	95%	>99% of 2,000 ppm MgSO4	min 70% avg 80%	85.0%
(e.g., solute type and concentration)	2000 ppm MgSO4	<50% 500 ppm CaCl2	500 ppm NaCl	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%	10.6	4.7	69%	15.3	530
1	A	2	90%	10.8	1.1	91%	11.9	530
1	A	3	50%	11.0	10.6	51%	21.6	530
1	A	4	30%	11.0	25.3	30%	36.3	530
1	B	1	70%	9.1	4.1	69%	13.2	344
1	B	2	90%	9.1	1.0	90%	10.1	344
1	B	3	50%	9.5	9.5	50%	19.0	344
1	B	4	30%	9.5	19.9	32%	29.4	344
1	C	1	70%	11.3	5.3	68%	16.6	411
1	C	2	90%	Not Available				
1	C	3	50%	11.5	12.1	49%	23.6	411
1	C	4	30%	11.6	25.5	31%	37.1	411
1	D	1	70%	6.5	2.9	69%	9.4	300
1	D	2	90%	6.5	0.6	91%	7.1	300
1	D	3	50%	6.5	6.6	50%	13.1	300
1	D	4	30%	7.0	15.8	31%	22.8	300
2	A	1	70%	6.5	3.0	68%	9.5	299
2	A	2	90%	6.5	0.7	90%	7.2	299
2	A	3	50%	6.6	6.5	50%	13.1	299
2	A	4	30%	6.5	15.4	30%	21.9	299
2	B	1	70%	6.7	2.8	71%	9.5	299
2	B	2	90%	6.6	0.7	90%	7.3	299
2	B	3	50%	6.8	6.8	50%	13.6	299
2	B	4	30%	6.4	15.0	30%	21.4	299
2	C	1	70%	6.3	2.9	68%	9.2	299
2	C	2	90%	6.6	0.7	90%	7.3	299
2	C	3	50%	6.5	6.5	50%	13.0	299
2	C	4	30%	6.9	15.4	31%	22.3	299
2	D	1	70%	6.4	2.7	70%	9.1	299
2	D	2	90%	6.5	0.7	90%	7.2	299
2	D	3	50%	6.5	6.5	50%	13.0	299
2	D	4	30%	6.4	15.4	29%	21.8	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-NH3 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: CHCl3, BDCM, DBCM, CHBr3	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	Free Cl_2 residual	Cl_2 demand	Temper-ature	pH	Incubation time
	mg/L	mg/L	mg/L	deg C	---	hours
Feed Water (Average of 2 samples)						
Membrane A Round 1	13.7	2.5	11.2	20.0	7.47	22.3
Membrane B Round 1	11.6	1.2	10.4	20.0	7.49	12.4
Membrane C Round 1	11.6	1.2	10.4	20.0	7.49	24.4
Membrane D Round 1	13.7	2.5	11.2	20.0	7.47	22.3
Membrane A Round 2	12.7	0.7	12.0	20.0	7.51	23.9
Membrane B Round 2	12.7	0.8	11.9	20.0	7.52	23.8
Membrane C Round 2	12.7	0.8	11.9	20.0	7.52	23.8
Membrane D Round 2	12.7	0.7	12.0	20.0	7.51	23.9
Permeate (average of 5 samples at 4 recoveries)						
Membrane A Round 1	3.7	1.0	2.7	20.0	7.50	25.1
Membrane B Round 1	5.6	1.5	4.1	20.0	7.46	24.1
Membrane C Round 1	3.5	0.8	2.1	20.0	7.49	24.1
Membrane D Round 1	4.1	0.9	3.2	20.0	7.52	24.3
Membrane A Round 2	3.9	0.8	3.1	20.0	7.54	24.1
Membrane B Round 2	4.7	0.8	4.0	20.0	7.52	24.6
Membrane C Round 2	5.0	1.0	4.0	20.0	7.51	24.3
Membrane D Round 2	3.7	1.1	2.6	20.0	7.51	24.3

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).
- 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 Membrane B in Round 1, the 90 percent recovery condition could not be attained without pressures in excess of those for which components of the test system were rated (150 psi). This condition was therefore not evaluated.

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 Samples	
		Membranes A&D		Membranes B&C		Membranes A&D		Membranes B&C			
		Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
pH	---	6.55	0.49	6.37	0.49	6.17	0.04	6.16	0.22	6.31	0.33
Temperature	^oC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Alkalinity	mg/L as $CaCO_3$	7.4	3.4	3.3	0.3	25.1	0.6	19.2	9.9	13.8	10.2
Total dissolved solids	mg/L	468	26	530	107	471	23	480	83	487	59
Total hardness	mg/L as $CaCO_3$	222	5	256	18	245	9	233	19	239	18
Calcium hardness	mg/L as $CaCO_3$	211	5	245	18	232	8	221	18	227	17
Turbidity	ntu	0.28	0.16	0.25	0.04	0.05	0.01	0.26	0.06	0.21	0.12
Ammonia	mg NH_3-N / L	0.42	0.04	0.47	0.13	0.58	0.01	0.48	0.16	0.49	0.10
Total organic carbon	mg/L	10.7	0.5	10.2	0.5	11.1	0.6	5.8	5.5	9.5	3.1
UV_{254}	cm^{-1}	0.334	0.006	0.332	0.030	0.359	0.012	0.021	0.000	0.261	0.149
SUVA	L/(mg*m)	3.1	0.2	3.3	0.5	3.2	0.1	0.7	0.6	2.6	1.2
Bromide	mg/L	117	16	109	2	130	11	191	74	136	45
SDS-Cl_2 demand	mg/L	11.2	0.3	10.4	0.1	12.0	0.0	11.9	0.0	11.4	0.7
SDS-TOX	mg Cl^-/L	940	43	854	320	1,059	1	1,001	161	963	159
SDS-THM4	mg/L	174	16	166	11	234	24	246	18	205	40
SDS-HAA5	mg/L	197	26	129	173	182	3	180	16	172	72
SDS-HAA6	mg/L	205	26	137	174	190	2	189	18	180	72

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 (MTCw) 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	70	0.33	0.31	0.29
1	B	2	0.26	0.00	0.00
1	C	67	0.33	0.27	0.22
1	D	41	0.24	0.20	0.20
2	A	31	0.33	0.27	0.28
2	B	27	0.26	0.13	0.13
2	C	28	0.33	0.19	0.18
2	D	31	0.24	0.00	0.16

4.3.2 Product Water Quality

Table 12A
Effect of Recovery on Product Quality
Membrane A

Water Quality Parameter		Product Quality at Listed Recovery							
		Round 1				Round 2			
		31%	57%	69%	91%	30%	50%	68%	90%
TDS	mg/L	100	126	202	364	66	66	76	297
Ca Hardness	mg/L as $CaCO_3$	45	68	96	168	17	21	29	107
Total Hardness	mg/L as $CaCO_3$	43	65	91	160	17	21	29	102
Bromide	mg/L	26	48	61	100	BMRL	BMRL	26	71
TOC	mg/L	0.5	0.8	1.1	2.9	BMRL	BMRL	BRML	1.2
UV254	cm^{-1}	0.016	0.025	0.030	0.082	BMRL	BMRL	BRML	0.042
SDS-THM4	μg/L	12.8	20.7	27.4	64.6	0.0	0.0	3.8	5.5
SDS-HAA5	μg/L	5.9	8.0	9.9	35.6	0.0	0.0	0.0	0.0
SDS-HAA6	μg/L	7.6	10.4	13.0	41.5	0.0	0.0	0.0	0.0
SDS-TOX	mg/L as Cl^-	41	113	83	217	BMRL	BMRL	BRML	BMRL

Table 12B
Effect of Recovery on Product Quality
Membrane B

Water Quality Parameter		Product Quality at Listed Recovery							
		Round 1				Round 2			
		27%	50%	68%	90%	30%	50%	70%	90%
TDS	mg/L	358	306	350	414	378	293	417	430
Ca Hardness	mg/L as $CaCO_3$	160	154	172	201	149	176	199	213
Total Hardness	mg/L as $CaCO_3$	155	149	166	193	143	168	191	203
Bromide	mg/L	85	87	100	106	113	118	119	124
TOC	mg/L	1.1	1.3	1.2	1.8	0.8	1.2	0.7	1.0
UV254	cm^{-1}	0.038	0.041	0.038	0.056	0.021	0.034	0.021	0.032
SDS-THM4	μg/L	37.8	26.8	37.3	45.1	27.7	42.1	32.9	37.5
SDS-HAA5	μg/L	12.5	16.2	13.8	23.9	6.8	10.4	8.0	12.7
SDS-HAA6	μg/L	17.6	20.7	18.5	30.1	9.6	15.0	11.4	17.9
SDS-TOX	mg/L as Cl^-	97	149	115	168	54	101	67	98

Table 12C
Effect of Recovery on Product Quality
Membrane C

Water Quality Parameter		Product Quality at Listed Recovery							
		Round 1				Round 2			
		30%	49%	66%	90%	35%	50%	76%	90%
TDS	mg/L	177	222	280	Not Availalble	250	296	401	454
Ca Hardness	mg/L as $CaCO_3$	101	109	138		109	117	145	199
Total Hardness	mg/L as $CaCO_3$	96	103	131		104	110	137	189
Bromide	mg/L	56	61	89		75	77	114	112
TOC	mg/L	0.4	0.7	0.9		1.1	1.0	1.3	2.9
UV254	cm^{-1}	0.019	0.023	0.027		0.036	0.037	0.048	0.102
SDS-THM4	μg/L	16.4	17.0	26.6		32.0	35.0	43.5	67.7
SDS-HAA5	μg/L	7.1	7.8	11.1		14.0	13.2	20.0	40.5
SDS-HAA6	μg/L	9.7	10.5	14.6		18.1	17.7	25.5	48.0
SDS-TOX	mg/L as Cl^-	48	62	89		117	108	119	298

Table 12D
Effect of Recovery on Product Quality
Membrane D

Water Quality Parameter		Product Quality at Listed Recovery							
		Round 1				Round 2			
		38%	79%	69%	91%	32%	50%	69%	89%
TDS	mg/L	102	197	241	402	95	122	168	142
Ca Hardness	mg/L as $CaCO_3$	33	75	104	162	29	42	72	46
Total Hardness	mg/L as $CaCO_3$	33	72	99	155	29	39	69	46
Bromide	mg/L	22	54	74	91	20	27	49	43
TOC	mg/L	0.6	1.1	1.7	2.8	BMRL	0.4	0.8	BMRL
UV254	cm^{-1}	0.018	0.037	0.052	0.081	0.011	0.016	0.028	0.041
SDS-THM4	µg/L	14.3	22.9	39.1	62.8	8.4	12.4	23.6	33.7
SDS-HAA5	µg/L	7.0	10.0	17.7	37.6	2.5	4.0	8.8	15.7
SDS-HAA6	µg/L	8.6	12.9	21.8	43.7	3.6	5.4	11.5	19.6
SDS-TOX	mg/L as Cl^-	47	104	134	211	28	53	74	140

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

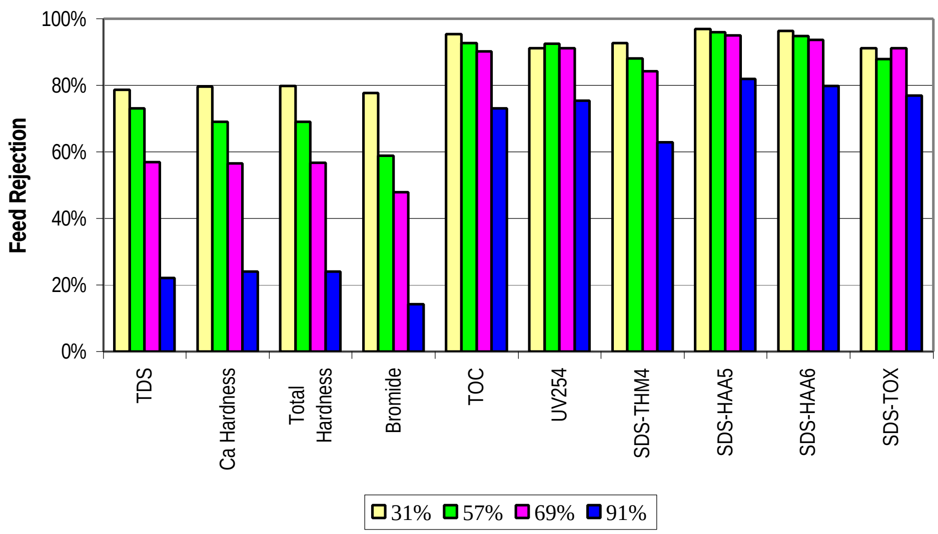


Figure 4B

Membrane A Round 2 Rejection Summary by Recovery

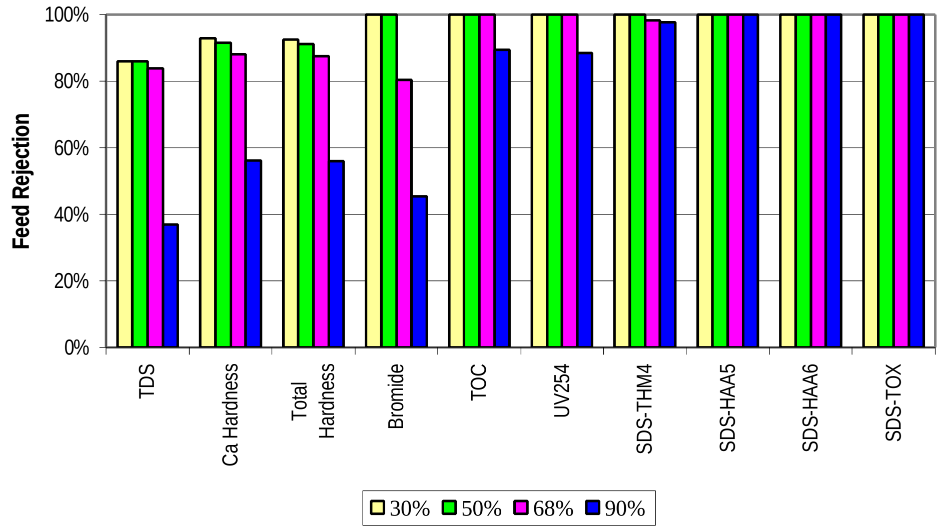


Figure 5A

Membrane B Round 1 Rejection Summary by Recovery

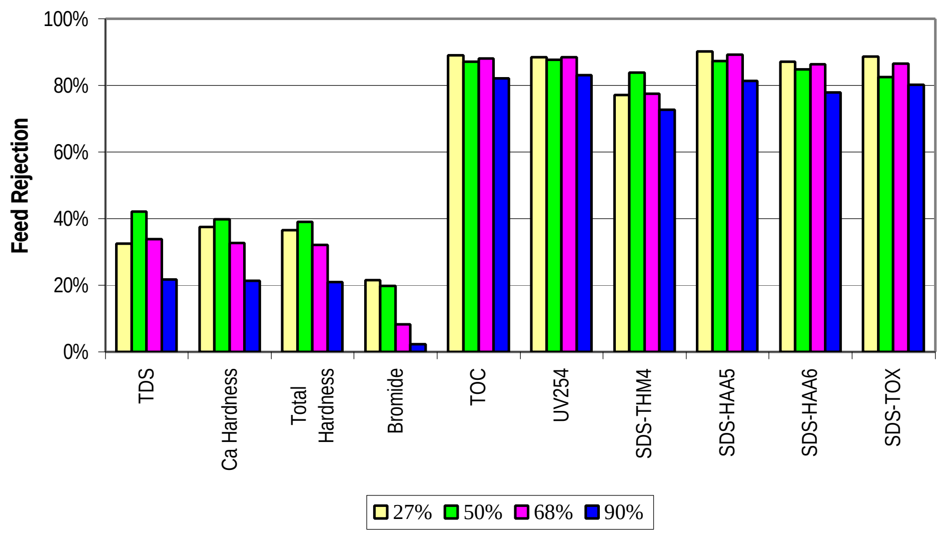


Figure 5B

Membrane B Round 2 Rejection Summary by Recovery

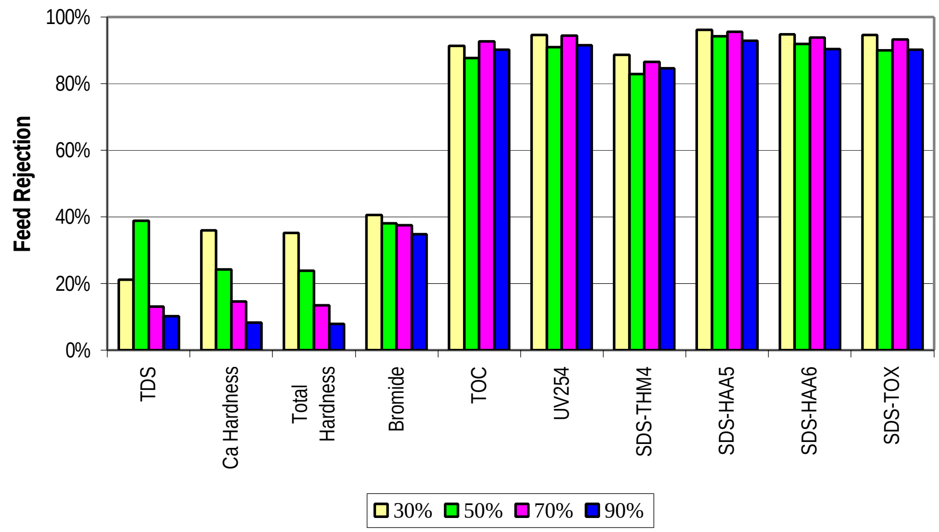


Figure 6A

Membrane C Round 1 Rejection Summary by Recovery

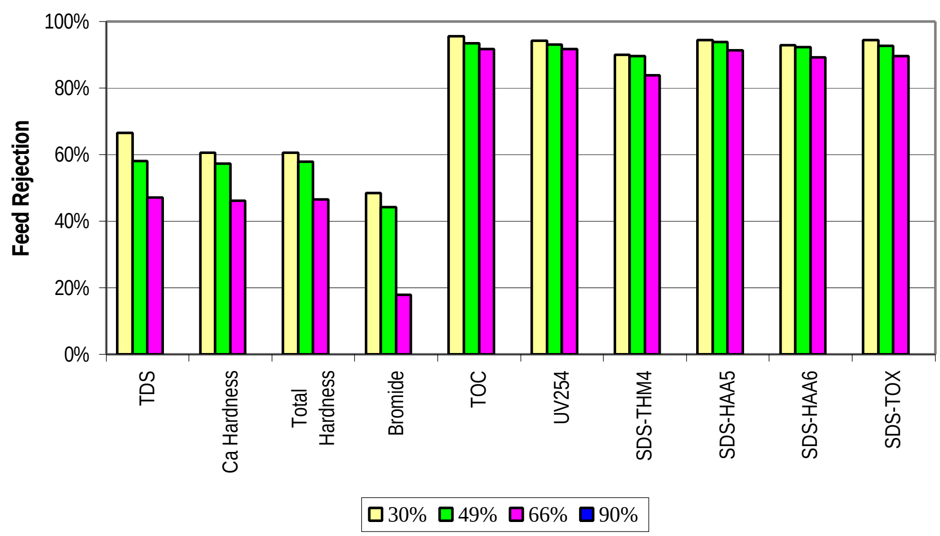


Figure 6B

Membrane C Round 2 Rejection Summary by Recovery

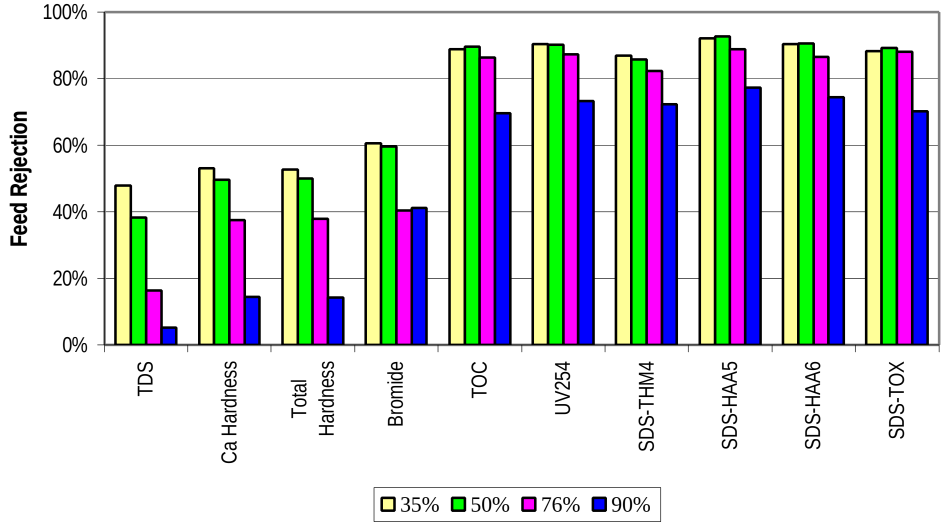


Figure 7A

Membrane D Round 1 Rejection Summary by Recovery

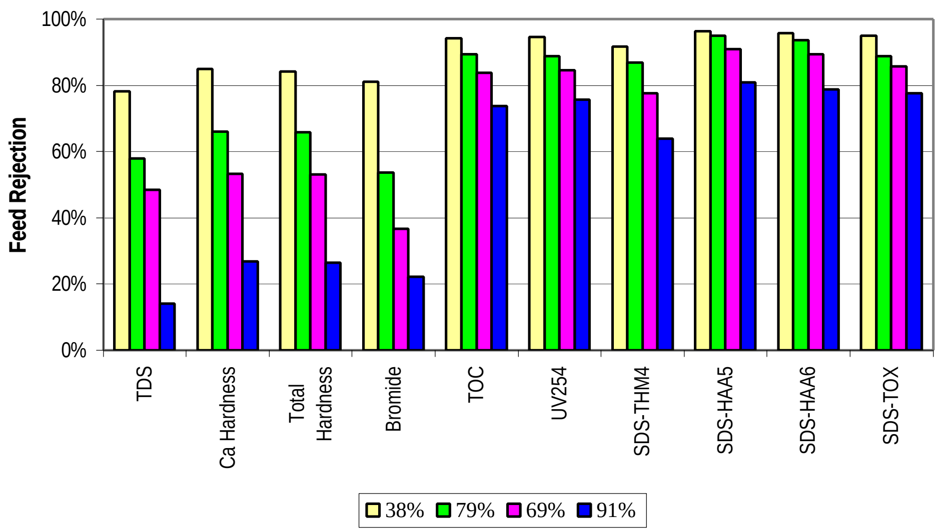
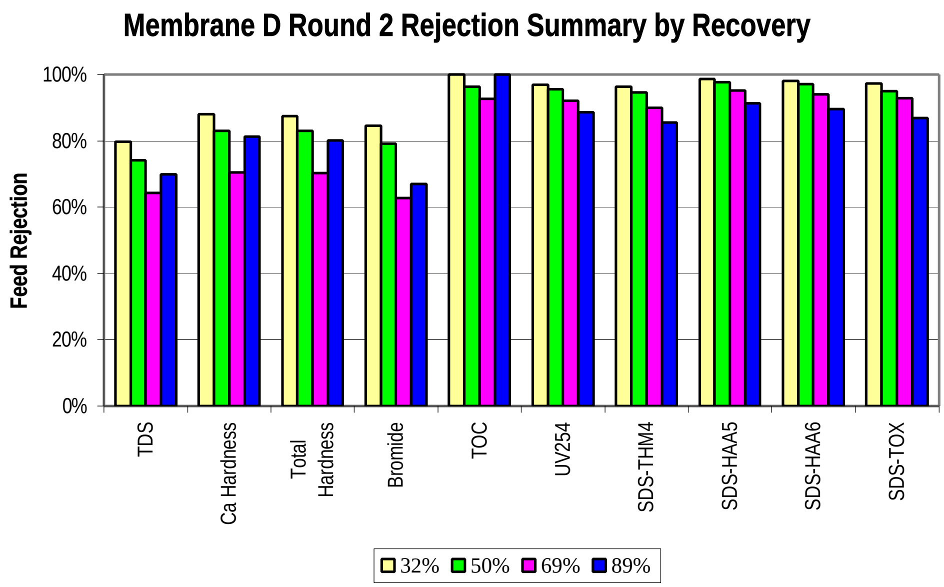


Figure 7B



4.3.4 Permeate Blending Scenarios

The high rejection of disinfection byproduct precursors by nanofiltration produces product water that in many 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 13. In some cases, 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 (as noted), 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						
Recovery =	31%	63%	3.1	53	54	267
Recovery =	57%	67%	3.2	58	54	314
Recovery =	69%	70%	3.3	62	54	284
Recovery =	91%	93%	3.4	72	46	266
Stage 2						
Recovery =	31%	86%	1.6	31	27	140
Recovery =	57%	90%	1.8	36	27	195
Recovery =	69%	94%	1.6	36	21	133
Recovery =	91%	Does not Meet Treatment Objective				

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						
Recovery =	30%	69%	######	69	54	######
Recovery =	50%	69%	######	69	54	######
Recovery =	68%	70%	#DIV/0!	72	54	#DIV/0!
Recovery =	90%	71%	4.0	72	53	######
Stage 2						
Recovery =	30%	85%	######	35	27	######
Recovery =	50%	85%	######	35	27	######
Recovery =	68%	86%	#DIV/0!	36	26	#DIV/0!
Recovery =	90%	87%	2.5	36	24	######

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						
Recovery =	27%	73%	3.6	72	44	299
Recovery =	50%	67%	4.2	72	53	379
Recovery =	68%	73%	3.7	72	45	315
Recovery =	90%	78%	3.7	72	47	321
Stage 2						
Recovery =	27%	Does not Meet Treatment Objective				
Recovery =	50%	93%	1.9	36	24	196
Recovery =	68%	Does not Meet Treatment Objective				
Recovery =	90%	Does not Meet 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						
Recovery =	30%	80%	2.6	72	42	247
Recovery =	50%	85%	2.4	72	35	233
Recovery =	70%	82%	2.3	72	40	239
Recovery =	90%	83%	2.4	72	40	248
Stage 2						
Recovery =	30%	96%	1.2	36	13	90
Recovery =	50%	Does not Meet Treatment Objective				
Recovery =	70%	99%	0.8	36	10	81
Recovery =	90%	Does not Meet Treatment Objective				

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						
Recovery =	30%	63%	4.1	72	53	348
Recovery =	49%	63%	4.2	72	53	356
Recovery =	66%	67%	3.9	72	50	339
Recovery =	0%	Not Available				
Stage 2						
Recovery =	30%	87%	1.7	36	23	154
Recovery =	49%	87%	1.9	36	23	164
Recovery =	66%	93%	1.5	36	19	141
Recovery =	90%	Not Available				

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						
Recovery =	35%	81%	2.7	72	45	282
Recovery =	50%	82%	2.5	72	42	265
Recovery =	76%	86%	2.5	72	42	244
Recovery =	90%	98%	3.1	72	44	315
Stage 2						
Recovery =	35%	98%	1.2	36	17	133
Recovery =	50%	100%	1.0	36	14	112
Recovery =	76%	Does not Meet Treatment Objective				
Recovery =	90%	Does not Meet 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						
Recovery =	38%	64%	3.1	54	54	267
Recovery =	79%	68%	3.4	58	54	300
Recovery =	69%	76%	3.6	66	54	297
Recovery =	91%	92%	3.5	72	51	271
Stage 2						
Recovery =	38%	86%	1.7	31	27	141
Recovery =	79%	91%	2.0	36	26	176
Recovery =	69%	Does not Meet Treatment Objective				
Recovery =	91%	Does not Meet 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						
Recovery =	32%	72%	######	72	53	318
Recovery =	50%	73%	3.3	72	52	323
Recovery =	69%	77%	3.2	72	49	301
Recovery =	89%	81%	######	72	48	315
Stage 2						
Recovery =	32%	88%	######	36	24	154
Recovery =	50%	89%	1.5	36	23	160
Recovery =	69%	94%	1.4	36	19	133
Recovery =	89%	99%	######	36	18	150

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 gfd/psi	Final MTC_w gfd/psi	Average Rate of MTC_w Decline gfd/psi/day	Projected Cleaning Interval (Note 1) days	MTC_w After Cleaning gfd/psi
Membrane A Round 1	0.262	0.190	-0.009	4.5	0.212
Membrane B Round 1	0.183	0.183	0.001	Note 2	0.283
Membrane C Round 1	0.194	0.157	-0.006	4.5	0.153
Membrane D Round 1	0.197	0.132	-0.021	1.4	0.144
Membrane A Round 2	0.329	0.248	-0.008	5.9	0.228
Membrane B Round 2	0.122	0.120	0.000	246.8	0.242
Membrane C Round 2	0.183	0.165	-0.004	7.0	0.187
Membrane D Round 2	0.158	0.123	-0.007	3.2	0.155

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: CHCl3, BDCM, DBCM, CHBr3	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 A	Round 1 B	Round 1 C	Round 1 D	Round 2 A	Round 2 B	Round 2 C	Round 2 D	Overall Average
pH	0.2	0.5	0.9	2.2	1.6	0.8	2.6	0.2	1.1
Temperature									
Alkalinity	4.0	0.0	77.4	3.9	13.1	2.1	6.5	3.6	13.8
Total dissolved solids	3.5	100.0	27.1	2.5	1.3	8.9	2.5	7.5	19.2
Total hardness	1.0	1.2	0.7	1.0	0.7	1.5	5.5	1.4	1.6
Calcium hardness	0.5	1.2	0.8	0.5	0.7	1.6	5.8	1.5	1.6
Turbidity						18.2			18.2
Ammonia	6.1	0.0	0.0	4.1	9.3	0.0	6.9	32.9	7.4
Total organic carbon	0.0	5.8	2.4	1.7		1.4	18.9	14.8	6.4
UV254	3.4	0.0	0.0	1.9		0.0	1.0	1.8	1.2
SUVA	3.4	5.8	2.4	3.7		1.4	19.9	13.1	7.1
Bromide	3.5	1.0	24.7	9.5	3.9	1.7	23.8	2.1	8.8
SDS-Cl2 dose	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.3
SDS-Free Cl2 residual	3.4	62.8	1.2	5.8	100.9	11.9	1.4	1.8	23.6
SDS-Cl2 demand	1.7	14.8	0.3	2.0	15.9	2.8	0.5	0.7	4.8
SDS-TOX	9.9	11.4	14.2	7.5		10.7	11.8	5.2	10.1
SDS-CHCl3	6.1	35.3	20.6	7.2	8.7	4.2	3.3	1.1	10.8
SDS-BDCM	5.0	34.7	24.9	5.9	8.0	0.0	0.6	1.1	10.0
SDS-DBCM	5.6	29.8	38.0	1.7	7.4	1.4	0.9	5.2	11.3
SDS-CHBr3		24.0	8.7			6.9	0.0		9.9
SDS-THM4	9.5	33.0	26.7	5.9	8.0	0.9	0.7	1.3	10.8
SDS-MCAA*									
SDS-DCAA*	0.0	10.9	6.9	2.6		4.3	2.7	8.2	5.1
SDS-TCAA*	17.4	44.1	20.0	27.3		4.4	7.1	12.3	18.9
SDS-MBAA*									
SDS-DBAA*	7.4	21.3	23.5	0.0		3.0	0.0	0.0	7.9
SDS-BCAA*	6.5	6.3	5.7	4.9		0.0	0.0	3.8	3.9
SDS-TBAA									
SDS-CDBAA									
SDS-DCBAA									
SDS-HAA5	7.1	19.6	8.1	14.7		1.3	4.5	9.1	9.2
SDS-HAA6	3.9	13.0	4.8	11.0		0.9	3.5	7.9	6.4

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%	40%	-7%	3%	3%	-73%	8%	9%
1	A	2	90%	NA	34%	26%	26%	33%	16%	10%
1	A	3	50%	-135%	-8%	0%	1%	-15%	1%	2%
1	A	4	30%	-18%	7%	3%	3%	-2%	-2%	0%
1	B	1	70%	-17%	-29%	-16%	-17%	42%	-5%	-7%
1	B	2	90%	-34%	-68%	-41%	-43%	97%	-30%	-33%
1	B	3	50%	35%	-27%	-12%	-13%	38%	-1%	-6%
1	B	4	30%	10%	3%	1%	1%	32%	4%	4%
1	C	1	70%	41%	-12%	-9%	-9%	-6%	10%	10%
1	C	2	90%	Not Tested						
1	C	3	50%	-10%	-9%	-12%	-12%	26%	-2%	0%
1	C	4	30%	12%	-6%	-1%	-1%	27%	-4%	1%
1	D	1	70%	58%	41%	37%	37%	-17%	36%	36%
1	D	2	90%	NA	60%	41%	42%	NA	26%	20%
1	D	3	50%	-168%	-16%	-18%	-18%	-6%	-5%	-13%
1	D	4	30%	-481%	-5%	-1%	-1%	11%	-4%	-2%
2	A	1	70%	3%	-6%	-2%	-1%	-36%	NA	NA
2	A	2	90%	-7%	7%	-34%	-34%	-62%	-22%	-1%
2	A	3	50%	3%	-7%	4%	4%	-3%	NA	NA
2	A	4	30%	1%	14%	-2%	-2%	-4%	NA	NA
2	B	1	70%	54%	12%	12%	13%	39%	-3%	-213%
2	B	2	90%	-465%	-2%	8%	9%	55%	-28%	-49%
2	B	3	50%	437%	-19%	7%	7%	26%	14%	-5%
2	B	4	30%	28%	-15%	-6%	-6%	-53%	4%	10%
2	C	1	70%	-384%	17%	-47%	-47%	-108%	-26%	-37%
2	C	2	90%	-580%	39%	-3%	-3%	-733%	-13%	-19%
2	C	3	50%	NA	7%	4%	5%	-176%	0%	-6%
2	C	4	30%	-64%	13%	-5%	-4%	-146%	-0%	-2%
2	D	1	70%	-1%	-12%	-3%	-3%	-0%	-13%	-11%
2	D	2	90%	4%	11%	-10%	-9%	34%	NA	-0%
2	D	3	50%	4%	10%	-1%	-1%	2%	-10%	-403%
2	D	4	30%	4%	-0%	-5%	-5%	1%	NA	9%

6 References

EPA. 1996. *ICR Manual for Bench- and Pilot-Scale Treatment Studies*. EPA 814-B-96-003, April 1996a.

EPA. 1996. *DBP/ICR Analytical Methods Manual*. EPA 814-B-96-002, April 1996b.

EPA. 1997. *ICR Treatment Studies Data Collection Spreadsheet User's Guide*. EPA 815-B-97-002, April 1997.