Information Collection Rule: Treatment Study Summary Report

Broward County Office of Environmental Services, Florida

District 1A WTP
BCOES Project No. 9520
July 1999

ICR TREATMENT STUDY SUMMARY REPORT

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

Conducted during the period: March 1998 – April 1999

Prepared by
Dr. Shankar Chellam
Montgomery Watson Americas Inc.
560 Herndon Parkway #300
Herndon, VA 20170

Prepared for
Broward County
PWSID # 4060167
2555 West Copans Road
Pompano Beach, FL 33069
Phone: (954) 960-3061
Fax: (954) 831-0842

Plant Name: Broward County District 1A Water Treatment Plant
Plant ICR #: 294

Section 1
Summary and Conclusions

Four quarters of nanofiltration (NF) testing using pretreated Biscayne Aquifer water were successfully completed at the District 1A Water Treatment Plant (WTP) in Broward County, Florida. Cartridge filtration was the only NF pretreatment employed. Three NF membranes were used to complete Information Collection Rule (ICR) treatment study requirements using the Rapid Bench Scale Membrane Test (RBSMT) methodology.

The Koch-Fluid Systems TFC-SR membrane achieved higher removals of total organic carbon (TOC), and precursor materials to trihalomethanes (THM) and haloacetic acids (HAA) compared to the Dow FilmTec NF-200B membrane. The Hydranautics NTR7450 membrane was more permeable to organic constituents than these two membranes. For example, the highest recorded TOC concentration in the permeate waters using the TFC-SR, NF-200B, and the NTR7450 membranes were 1.8, 2.8, and 7.2 mg/L respectively.

Under the simulated distribution system (SDS) conditions employed, the highest SDSTTHM and SDSHAA(5) concentrations in the TFC-SR membrane permeate were near 86 μg/L and 15 μg/L, respectively. Compared to the TFC-SR membrane, higher concentrations of organic constituents were observed in NF-200B and NTR7450 membrane permeate waters. SDSHAA(5) concentrations in TFC-SR and NF-200B membrane permeate waters were always below the placeholder set by Stage II of the D/DBP rule (30 μg/L for HAA(5)). However, maximum SDSTTHM concentrations in membrane permeate waters were above the placeholder under Stage II of the D/DBP rule (40 μg/L for TTHMs). Therefore, NF alone may not be sufficient to meet Stage II THM regulations if free chlorine is employed as the final disinfectant.

In addition, the TFC-SR membrane achieved higher removals of a variety of inorganic water quality parameters compared to the NF-200B and NTR7450 membranes. For example, the average TDS removal by TFC-SR, NF-200B, and NTR7450 membranes measured during routine monitoring were 44, 39, and 15% respectively.

Linear regression analysis suggests possible seasonal variations in fouling rates for both membranes. Using the RBSMT methodology, membrane chemical cleaning intervals ranged from approximately 55 hours to approximately 140 hours at 70% feed water recovery and an initial flux of approximately 15 gfd. However, more advanced NF membrane pretreatment may result in longer chemical cleaning intervals. In addition, more research may further establish the validity of the RBSMT methodology in terms of its ability to accurately predict membrane fouling rates (and cleaning intervals) observed in full-scale installations. Therefore, membrane fouling rates and cleaning intervals predicted by bench-scale experiments should be verified at the pilot-scale level.

Finally, because the concentrations of most water quality parameters in the TFC-SR, NF-200B, and NTR7450 permeates increased with feed water recovery (at constant flux), the transport of dissolved solutes across these polymeric membranes may be controlled by diffusion.

Section 2
Introduction

Objectives. The primary objective of this Information Collection Rule (ICR) treatment study was to evaluate the ability of two nanofiltration (NF) membranes to remove disinfection by-product (DBP) precursor materials and total organic carbon (TOC). Secondary objectives of this treatment study included the evaluation of inorganics rejection and membrane fouling. This report summarizes membrane operation and permeate water quality data from bench-scale experiments conducted using the rapid bench scale membrane test methodology as specified in the *ICR Manual for Bench- and Pilot-Scale Treatment Studies* (EPA 814-B-96-003).

Existing water treatment processes. A simple schematic of the existing water treatment processes for the Broward County Office of Environmental Services Water Treatment Plant 1A is given in the flow diagram in Appendix A. This figure also illustrates chemical dosing points as well as sampling points within the treatment train. The water for NF testing was obtained directly from the Biscayne Aquifer, prior to any chemical addition. Tables A.2 and A.3 of Appendix A summarize basic engineering and chemical feed data for each unit process.

Full-scale plant influent and finished water quality. Representative averages and ranges for various water quality parameters monitored regularly at the influent to Water Treatment Plant 1A are summarized in Table 1. All finished water quality parameters that are monitored at the full-scale plant have been summarized in Table 2. (No regular monitoring of THMs, HAAs, or UV_{254} are currently undertaken in the distribution system.)

Table 1. Full-scale influent water quality data.

Parameter	Units	Average	Minimum	Maximum
Temperature	ºC	26	25	27
pH	-	7.2	7.1	7.3
Turbidity	ntu	NA		
Alkalinity	mg/L as $CaCO_3$	200	180	220
Total Hardness	mg/L as $CaCO_3$	225	210	235
Calcium Hardness	mg/L as $CaCO_3$	215	200	225
TOC	mg/L	9	6	13

Table 2. Full-scale finished water quality data.

Parameter	Units	Average	Minimum	Maximum
Temperature	ºC	26	25	27
pH	unit	9	8.9	9.2
Turbidity	ntu	0.3	0.18	0.4
TOC	mg/L	7	6	8
UV_{254}	1/cm	NA	NA	NA
DS-THM4[a]	µg/L	NA	NA	NA
DS-HAA5	µg/L	NA	NA	NA

[a] DS represents distribution system

ICR bench-scale treatment study apparatus. All bench-scale ICR experiments were conducted using the Rapid Bench Scale Membrane Test (RBSMT) methodology. For these tests, a pressurized cell using a flat membrane sheet was employed. This cell utilized feed and permeate spacers that are also used in spiral-wound elements. The feed water was pumped tangential to the membrane to maintain a shear stress on the membrane surface; thereby limiting concentration polarization. A schematic of the apparatus used to conduct the ICR bench-scale NF experiments is shown in Figure 1. The use of positive displacement gear pumps for both feed water and recycle water minimized pressure fluctuations. The feed pump head (Cole-Palmer, Vernon Hills, IL, model #74011-11) was designed for use at high pressure and low flow. The recirculation pump head (Cole-Palmer, Vernon Hills, IL, model #07002-23) was designed for use at low pressure and high flow. These pumps used helical gears made of Teflon, a low friction material, to reduce potential friction loss on the gears. Tubing, connections, and the membrane cell were fabricated of stainless steel. Dual float rotameters increased the accuracy of flow measurements. In addition, permeate and waste flows were manually measured using a graduated cylinder and a stopwatch.

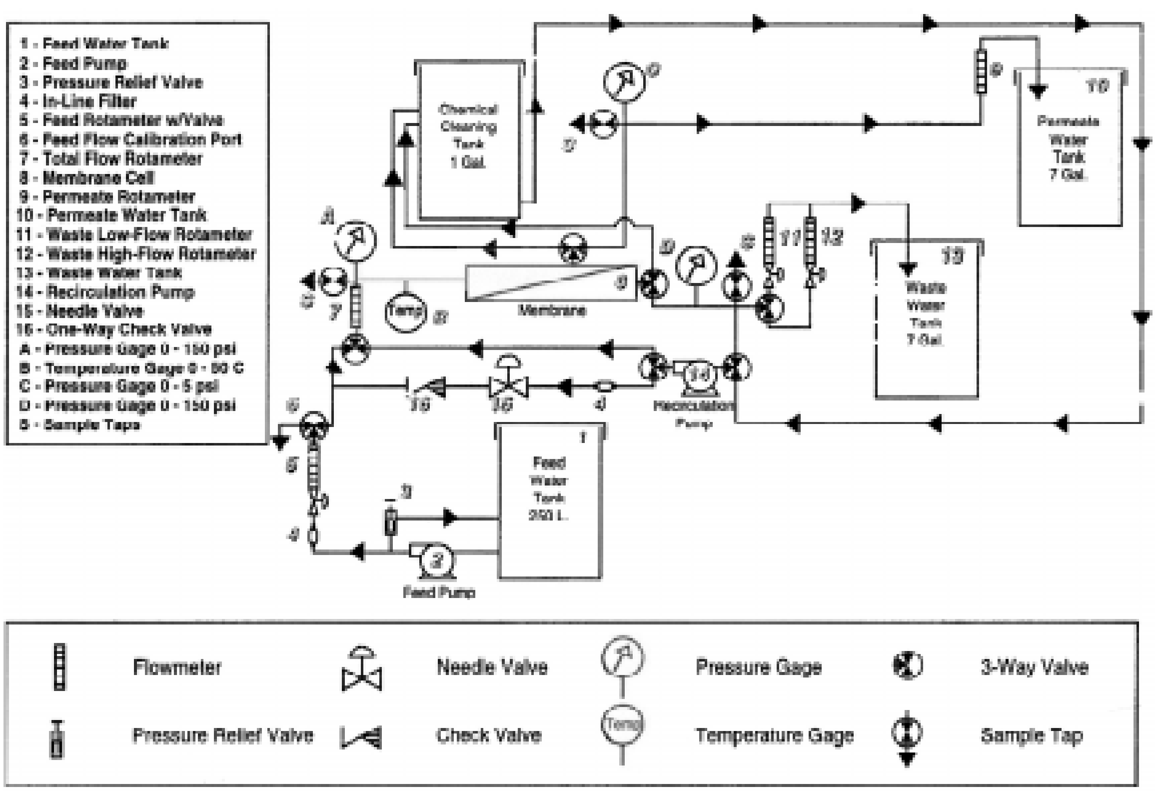

Figure 1. Schematic of the bench-scale NF apparatus

Membranes employed. ICR experiments were conducted using three NF membranes: FilmTec NF-200B (Dow Chemical Company, Midland, MI) and TFC-SR (Koch-Fluid Systems Corp., San Diego, CA), and NTR7450 (Hydranautics Corp., San Diego, CA). Important characteristics for each membrane (as specified by the manufacturers) are summarized in Table 3.

Table 3. Characteristics of membranes used during ICR testing.

Membrane designation	Manufacturer	Composition	MWCO [a] (Daltons)
NF-200B	FilmTec Corp.	polyamide	200-400
NTR7450	Hydranautics Corp.	polysulfone	~ 1,000
TFC-SR	Koch-Fluid Systems	polyamide	300

[a] Denotes Molecular Weight Cut-Off

Membrane cleaning. Membrane cleaning was accomplished through the circulation of a sodium hydroxide solution in deionized water at a pH near 12. In some cases, when base cleaning was ineffective, a sulfuric acid solution in deionized water at a pH of approximately (but not less than) 2.5 was also used. Cleaning was conducted at a temperature of approximately 40°C. The cleaning solution was initially circulated for 15 minutes at a transmembrane pressure of less than 5 pounds per square inch (psi). The membrane was then soaked for 30 minutes. Finally, the cleaning solution was circulated again for 10 minutes at a transmembrane pressure of less than 5 psi. The crossflow velocity was maintained near 1 foot per second (fps) during the circulation portion of the cleaning cycle. A pressure-flux profile was established for both membranes, following chemical cleaning with deionized water. After the base cleaning, the membrane cell was physically removed from the RBSMT apparatus, dismantled, and rinsed with deionized water.

NF feed water and pretreatment. Three, 30-gallon drums were sent to the District 1A WTP each quarter for feed water sampling. Prior to sending the drums, they were chemically cleaned. A high pH sodium hydroxide solution was used to remove organics and biological contaminants. Next, a low pH sulfuric acid solution was used to remove possible metallic deposits. The barrels were thoroughly rinsed with tap water and then dried for a minimum of 24 hours prior to shipment.

As required by the ICR, water was sampled prior to the first point of continuous oxidant addition. For the District 1A WTP, sample water was taken directly from the Biscayne Aquifer. Prior to the RBSMT experiments, the only pretreatment applied to this water was filtration using a 5 µm cartridge filter (RyanHerco, Burbank, CA, Model #6711-505). A simple schematic of the pretreatment processes employed is given in Figure 2.

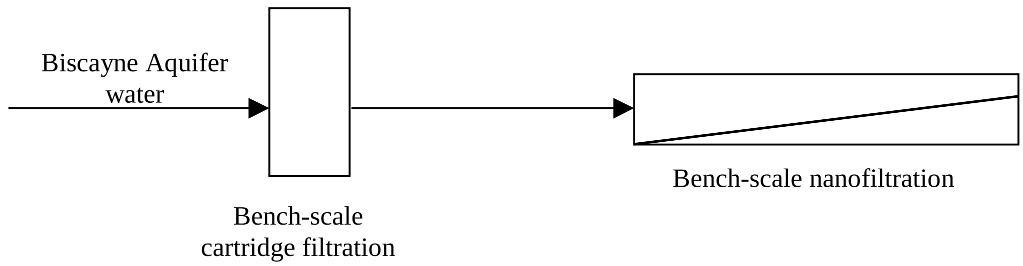

Figure 2. Simple schematic of the pretreatment used prior to bench-scale nanofiltration.

NF feed water samples were collected at the start of the first set of experiments and the end of the second set of RBSMT experiments. These samples were analyzed for a variety of physical, inorganic, and organic parameters. Table 4 summarizes membrane feed water quality for all four seasons of testing.

As shown in Table 4, after pretreatment, the NF feed water can be classified as a slightly alkaline hard water, having high concentrations of total organic carbon, simulated distribution system (SDS) haloacetic acid 5 (SDSHAA5[1]), SDS haloacetic acid 9 (SDSHAA9[2]), and SDS total trihalomethanes (SDSTTHM[3]).

Table 4. Summary of NF membrane feed water quality for all four seasons of testing.

Parameter	Units	Quarter I	Quarter II	Quarter III	Quarter IV
Alkalinity	mg/L as $CaCO_3$	191	205	421	348
Ca hardness	mg/L as $CaCO_3$	161	256	205	270
Total hardness	mg/L as $CaCO_3$	195	299	217	295
TDS	mg/L	297	317	280	293
Bromide	μg/L	140	150	140	140
Ammonia	mg NH_3-N/L	BMRL	0.30	BMRL	0.08
SDS Cl_2 demand	mg/L	18.77	16.52	12.51	16.05
TOC	mg/L	14.40	13.30	12.00	12.60
SDSTOX	μg/L	1,300	1,435	1,095	1,665
SDSTTHM	μg/L	566.1	538.9	462.9	539.5
SDSHAA5	μg/L	219.9	244.9	208.5	262.4
SDSHAA9	μg/L	247.9	273.4	237.2	300.0
UV_{254}	cm^{-1}	0.523	0.635	0.570	0.588
pH	-	8.34	7.85	7.98	8.10
Turbidity	NTU	0.96	1.26	0.62	0.26

[a] Denotes Below Minimum Reporting Level

[1] SDSHAA5 denotes the sum of monochloro, dichloro, trichloro, monobromo and dibromo acetic acids.
[2] SDSHAA9 denotes the sum of HAA(5) and tribromo, chlorobromo, dichlorobromo, and chlorodibromo acetic acids.
[3] SDSTTHM denotes the sum of chloroform, dichlorobromo methane, chlorodibromo methane and bromoform.

Membrane setting. Deionized water, characterized by a TDS concentration less than 1 mg/L, was filtered at the start of each set of RBSMT experiments for approximately 24 hours. This period is sometimes referred to as "membrane setting". All experiments were conducted at room temperature (~23°C). Therefore, any effects caused by seasonal variability in temperature were not reflected in the ICR experiments. A pressure-flux profile was conducted at the end of the first day or the beginning of the second day of testing, prior to switching to feed water. During these measurements, transmembrane pressure was changed in random order in the range of 0 to 80 psi to reduce systematic biases in calculating the membrane resistance. Results from pressure-flux profiles were modeled using Darcy's law (Equation 1) where J denotes the permeate flux (m/s), R_m (m^{-1}) denotes the membrane resistance, P_{tm} is the transmembrane pressure (Pa), and μ ($N\text{-}s/m^2$) denotes the absolute viscosity of water.

$$J = \frac{P_{tm}}{\mu R_m} \qquad (1)$$

NF experiments using pretreated Biscayne Aquifer water. Table 5 summarizes the sampling and membrane operational dates for RBSMT experiments that were conducted for all three membranes. The TFC-SR membrane was employed for all four quarters. However, the NF200B membrane was employed for the first two quarters and the NTR7450 membrane was used for the third and fourth quarters to satisfy ICR requirements.

Table 5. Quarterly dates of RBSMT experiments.

Quarter	Sampling date	Dates of membrane operation		
		NF-200B	NTR7450	TFC-SR
I	4/23/98	5/5/98-5/13/98	NA	4/28/98-5/5/98
II	7/1/98	7/15/98-7/22/98	NA	7/7/98-7/14/98
III	10/27/98	11/30/98-12/4/98	12/7/98-12/10/98	11/9/98-11/16/98
IV	3/9/98	NA	4/2/99-4/9/99	3/24/99-4/1/99

During each quarter, experiments using pretreated Biscayne Aquifer water were conducted continuously with each membrane for a period of approximately 150 hours. The feed water recovery, R_f, for the first experiment (approximately 78 hours in duration) was maintained near 70%. This was followed by experiments where R_f was maintained at values near 90%, 50%, and 30%. As required under the ICR, these experiments were run without any cleaning when changing the feed water recovery. In Table 6, average experimental conditions including net driving pressure, permeate flux, and water mass transfer coefficients used for the NF-200B membrane during the RBSMT are summarized. In Tables 7 and 8, this information is given for the NTR7450 and TFC-SR membranes.

Table 6. Summary of quarters I and II RBSMT experiments using NF-200B membrane.

Quarter	Recovery (%)	Net driving pressure (psi)	Permeate flux (gfd)	MTC_w [a] (gfd/psi)
I	69	62.5	11.6	0.18
I	89	61.5	9.9	0.16
I	52	62.0	11.1	0.18
I	31	63.0	10.3	0.16
II	67	57.1	16.8	0.18
II	91	57.2	14.1	0.25
II	50	56.8	13.5	0.24
II	30	54.2	13.6	0.25

[a] Denotes water mass transfer coefficient which is also referred to as the specific flux.

Table 7. Summary of quarters III and IV RBSMT experiments using NTR7450 membrane.

Quarter	Recovery (%)	Net driving pressure (psi)	Permeate flux (gfd)	MTC_w (gfd/psi)
III	72	67.8	10.3	0.15
III	50	67.8	10.0	0.15
IV	70	43.5	13.6	0.31
IV	87	43.1	11.6	0.27
IV	50	43.1	11.9	0.28
IV	30	43.2	11.8	0.27

Table 8. Summary of quarterly RBSMT experiments using TFC-SR membrane.

Quarter	Recovery (%)	Net driving pressure (psi)	Permeate flux (gfd)	MTC_w (gfd/psi)
I	70	47.3	14.4	0.30
I	82	47.1	12.4	0.26
I	50	48.6	13.1	0.27
I	29	49.2	12.8	0.26
II	68	52.7	15.1	0.29
II	91	52.6	12.1	0.23
II	51	51.6	12.9	0.25
II	30	50.9	11.9	0.23
III	72	46.2	13.7	0.30
III	90	45.9	11.4	0.25
III	54	48.1	12.7	0.25

Table 8 (Continued). Summary of quarterly RBSMT experiments using TFC-SR membrane.

Quarter	Recovery (%)	Net driving pressure (psi)	Permeate flux (gfd)	MTC_w (gfd/psi)
III	30	49.7	13.4	0.26
IV	71	47.0	10.5	0.27
IV	90	46.5	9.2	0.22
IV	51	47.4	10.9	0.20
IV	31	47.8	11.4	0.23

Membrane fouling analysis. Membrane fouling was analyzed using the 70% feed water recovery experiment for both membranes. This experiment was selected because of its extended operation time (approximately 78 hours) compared to the other three recoveries (approximately 24 hours). Since the rate of fouling appeared to be highly dependent on the feed water recovery, using data from all four recoveries in each quarter resulted in very low regression coefficients. In addition, full-scale plants would be operated at one fixed feed water recovery based either on pilot-scale tests or previous design experience. Therefore, fouling rates were calculated using linear regression of permeate flux data obtained at 70% recovery. Results from this analysis were modeled using the equation for a straight line (given in Equation 2).

$$J = -mt + b \tag{2}$$

where
J = permeate flux at room temperature (gfd)
m = fouling rate (gfd/h)
t = time (h)
b = initial permeate flux (gfd)

From Equation 3, cleaning intervals (t_{clean}) were calculated assuming a 20% drop in initial specific flux.

$$t_{clean} = \frac{0.2b}{m} \tag{3}$$

Similar calculations can be made for 10% and 15% initial flux declines based on manufacturer recommendations or pilot-scale results for full-scale operation.

Monitoring. Routine monitoring for membrane operation and water quality was conducted according to the recommended minimum EPA requirements described in Tables 9 and 10 respectively. Flow, pressure, and temperature measurements for feed, permeate, concentrate, and influent were recorded hourly during each recovery. TDS, pH, and UV_{254} were monitored at least three times per day for permeate, feed, and concentrate samples. For most analytes, ICR requirements were exceeded and TDS, UV_{254}, and pH were monitored hourly for permeate, feed, and concentrate samples.

Table 9. ICR recommended minimum monitoring frequencies for the RBSMT.

Routine RBSMT Study Monitoring Requirements					
Parameter	**Feed**	**Permeate**	**Concentrate**	**Influent**	**Recycle**
Flow	none	6xD	6xD	6xD	none
Pressure	none	None	6xD	6xD	none
Temperature	none	None	none	6xD	none
TDS	1xD	3xD	1xD	none	none
pH	1xD	3xD	1xD	none	none
UV_{254}	1xD	3xD	1xD	none	none

1xD – one time per 24 hours
3xD – three times per 24 hours
6xD – six times per 24 hours

Water quality parameters listed in Table 10 were analyzed on composite samples collected for each recovery.

Table 10. RBSMT water quality monitoring requirements established by the ICR.

Water Quality Parameters to be Evaluated at Each Recovery			
Parameter	**Feed**	**Permeate**	**Concentrate**
pH	TPR	FTPR	FTPR
Total Hardness	TPR	FTPR	FTPR
Calcium Hardness	TPR	FTPR	FTPR
Alkalinity	TPR	FTPR	FTPR
Total Dissolved Solids	TPR	FTPR	FTPR
Turbidity	TPR	FTPR	FTPR
Total Organic Carbon	TPR	FTPR	FTPR
UV_{254}	TPR	FTPR	FTPR
Bromide	TPR	FTPR	none
SDS-THM4	TPR	FTPR	none
SDS-HAA6	TPR	FTPR	none
SDS-TOX	TPR	FTPR	none
SDS-Cl_2 demand	TPR	FTPR	none

TPR – two times per run
FTPR – five times per run

Simulated distribution system tests. One of the important components of ICR treatment studies is the simulated distribution system (SDS) testing of NF feed and permeate waters. Backup permeate samples were collected overnight during the 70% recovery experiment. These samples were used to conduct a trial chlorine demand experiment with at least two different chlorine doses. Using the predetermined quarterly

SDS conditions of temperature, pH, and holding time, the samples were analyzed for chlorine concentrations using the DPD method. Based on these trial SDS experiments, appropriate chlorine dosages were determined for the actual SDS testing. During this test, the sample water was dosed with free chlorine after pH adjustment to obtain a free chlorine residual near 1 mg/L at the conclusion of the incubation period. The samples were then incubated under conditions that closely simulated "average" conditions of the existing distribution system. Following incubation, the chlorinated waters were sampled for THMs, HAAs, and TOX. The SDS conditions employed during the four quarters of testing are summarized in Table 11.

Table 11. Simulated distribution system test conditions used in this study.

Parameter	Quarter I	Quarter II	Quarter III	Quarter IV
Disinfectant	Free chlorine	Free chlorine	Free chlorine	Free chlorine
Temperature (°C)	25	25	25	24
pH	8.7	9.0	8.9	9.0
Holding time (hour)	24	24	24	24
Free chlorine residual (mg/L)	~1	~1	~1	~1

Analytical methods and laboratories involved. A list of analytical methods and their corresponding minimum reporting levels are given in Table 12. All analyses were performed using the methods and QA/QC procedures described in *DBP/ICR Analytical Methods Manual* (EPA 814-B-96-002, April 1996).

All analytical measurements were made by the operator conducting the RBSMT experiments, or by Montgomery Watson Laboratories, CA. Laboratory information is provided in Table 13.

Table 12. Summary of analytical methods and MRLs used in this study.

Analyte	Method	Units	Minimum Reporting Level
Alkalinity	SM 2320 B	mg/L as $CaCO_3$	2
Ammonia	EPA 350.1	mg/L	0.05
Bromide	EPA 300	μg/L	40
Calcium hardness	SM 3500 Ca D	mg/L as $CaCO_3$	5
Total hardness	SM 2340 C	mg/L as $CaCO_3$	5
Chlorine residual	SM 4500 Cl G	mg/L	0.5
pH	SM 4500 H^+ B	-	-
TDS	SM 2510 B (probe)	mg/L	10
Temperature	SM 2550 B	°C	-
Turbidity	SM 2130 B	NTU	0.05
TOC	SM 5310 C	mg/L	0.50

Table 12 (Continued). Summary of analytical methods and MRLs used in this study.

Analyte	Method	Units	Minimum Reporting Level
UV_{254}	SM 5910 B	cm^{-1}	0.009
$CHCl_3$, BDCM, DBCM, $CHBr_3$	EPA 524.2	µg/L	1 for each analyte
MCAA, DCAA, TCAA, MBAA, DBAA, TBAA, BCAA, BDCAA, DBCAA	SM 6251 B	µg/L	2, 1, 1, 1, 1, 4, 1, 1, and 2 respectively
TOX	SM 5320 B	µg Cl^-/L	25

Table 13. Laboratory information.

Laboratory	Service dates	Analyses performed	Contact information
Field site	April 1998 – April 1999	Alkalinity, calcium and total hardness, pH, Cl_2 residual, TDS, temperature, turbidity, UV_{254}	Dr. Shankar Chellam Montgomery Watson 560 Herndon Pkwy #300 Herndon, VA 20170
Montgomery Watson Laboratories	April 1998 – April 1999	Bromide, Ammonia, TOC, HAA, THM, TOX	ICR ID #: CA013 Dr. Andrew Eaton 555 E. Walnut St. Pasadena, CA 91101 Phone: (626) 568-6425 Fax: (626) 568-6324

MEMBRANE OPERATION

Clean membrane resistances and cleaning. Results from pressure-flux profiles conducted at the start of the experiments using new NTR7450 and NF-200B membranes are given in Figure 3. Corresponding data for the TFC-SR are provided in Figure 4. The linearity of the pressure-flux profiles suggests that compaction effects were negligible for these membranes in the range of pressures tested.

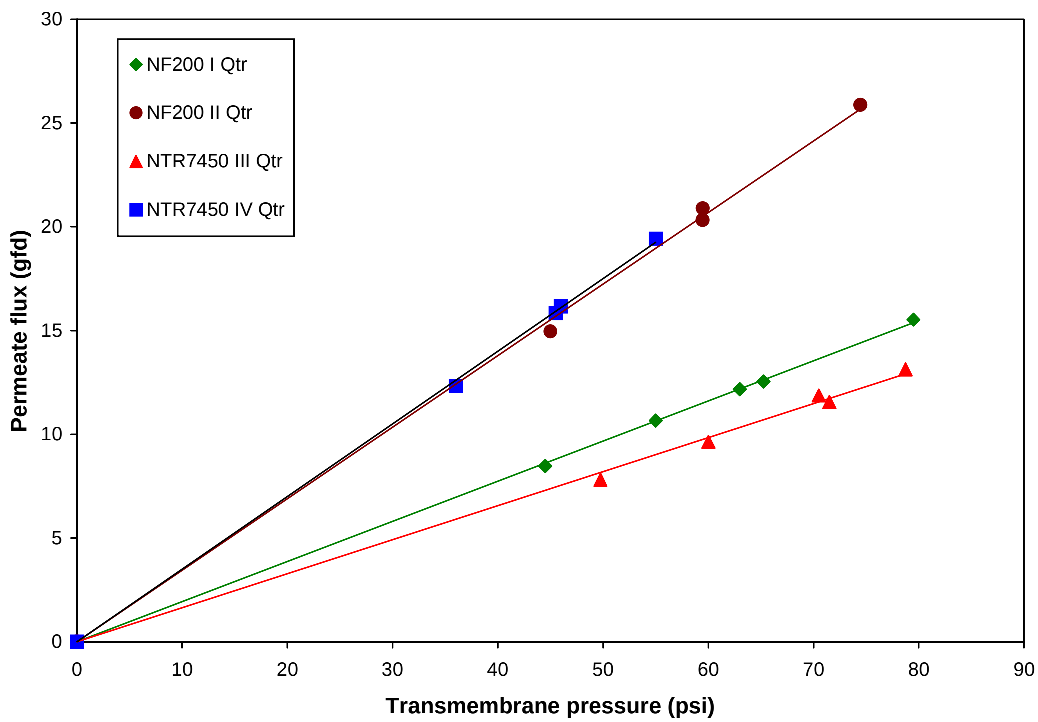

Figure 3. Resistances of new NTR7450 and NF200B membranes used for each quarter of testing.

These data were used in Equation 1 to calculate new membrane resistances and their 95% confidence intervals and are summarized in Table 14. Table 14 also summarizes membrane resistances calculated following chemical cleaning. The average resistance of new NTR7450 and NF200B membranes were equal to 5.9 x 10^{13} and 6.55 x $10^{13}m^{-1}$ respectively. Initial R_m values for the TFC-SR membrane ranged from 4.20 x 10^{13} to 4.76 x 10^{13} m^{-1} with an average value of 4.4 x 10^{13} m^{-1}. From Table 14, it is observed that the NF200B and TFC-SR membrane resistances before and after cleaning were very similar. However, a large increase in NTR7450 membrane resistance was observed following chemical cleaning during the fourth quarter of testing. These data suggest that the cleaning procedure employed was effective only in removing TFC-SR and NF-200B membrane foulants present in pretreated Biscayne Aquifer water. Different cleaning protocols may need to be developed for the NTR7450 membrane.

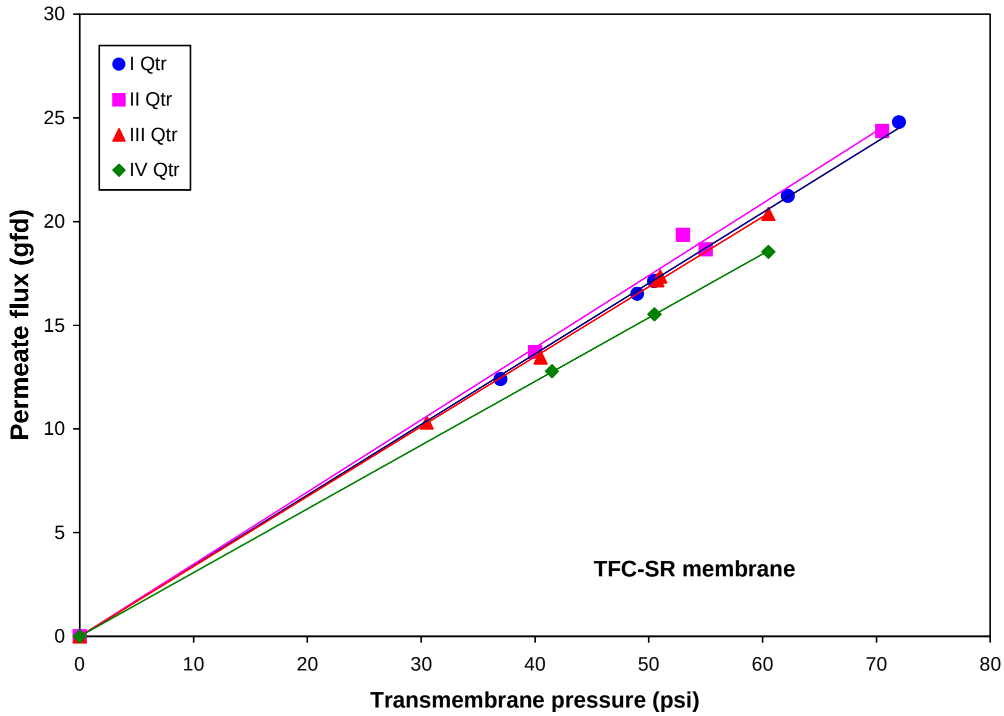

Figure 4. Resistances of the new TFC-SR membranes used for each quarter of testing.

Table 14. Summary of new membrane resistances and after membrane cleaning.[a]

Qtr	Membrane	Initial R_m (m^{-1})	R_m after base cleaning (m^{-1})	R_m after acid cleaning (m^{-1})	Change (%)	Cleaning solution
I	NF200	$7.56 \times 10^{13} \pm 7 \times 10^{11}$	$6.16 \times 10^{13} \pm 2.1 \times 10^{12}$	-	-18	NaOH
I	TFC-SR	$4.29 \times 10^{13} \pm 4 \times 10^{11}$	$4.08 \times 10^{13} \pm 1.2 \times 10^{12}$	-	-5	NaOH
II	NF200	$4.24 \times 10^{13} \pm 1 \times 10^{12}$	$4.29 \times 10^{13} \pm 5 \times 10^{11}$	-	1	NaOH & H_2SO_4
II	TFC-SR	$4.20 \times 10^{13} \pm 1.6 \times 10^{12}$	$3.73 \times 10^{13} \pm 9 \times 10^{11}$	-	-11	NaOH
III	NTR7450	$8.92 \times 10^{13} \pm 2.4 \times 10^{12}$	$1.06 \times 10^{14} \pm 3 \times 10^{12}$	$6.08 \times 10^{13} \pm 6 \times 10^{12}$	19,-32	NaOH
III	TFC-SR	$4.34 \times 10^{13} \pm 4 \times 10^{11}$	$4.11 \times 10^{13} \pm 3 \times 10^{11}$	-	-5	NaOH
IV	NTR7450	$4.18 \times 10^{13} \pm 6 \times 10^{11}$	$5.14 \times 10^{13} \pm 8 \times 10^{11}$	$6.61 \times 10^{13} \pm 2.5 \times 10^{12}$	23,58	NaOH & H_2SO_4
IV	TFC-SR	$4.76 \times 10^{13} \pm 1 \times 10^{11}$	$5.34 \times 10^{13} \pm 1.1 \times 10^{12}$	$5.09 \times 10^{13} \pm 6 \times 10^{12}$	14,7	NaOH

[a] All cleanings were conducted at a temperature of approximately 40°C.

Specific flux profiles. Normalized specific flux profiles for the duration of the experiments using the NTR7450 and NF-200B membranes are depicted in Figure 5. Corresponding data for the TFC-SR membrane are provided in Figure 6. It was observed that all membranes experienced an initial decline in flux and occasional declines during the 90% recovery experiment. However, the flux appeared to stabilize for the duration of the remaining experiments at 30% and 50% recoveries. Overall, the NTR7450, NF-200B and TFC-SR membranes experienced relatively stable operation throughout the duration of the experiment.

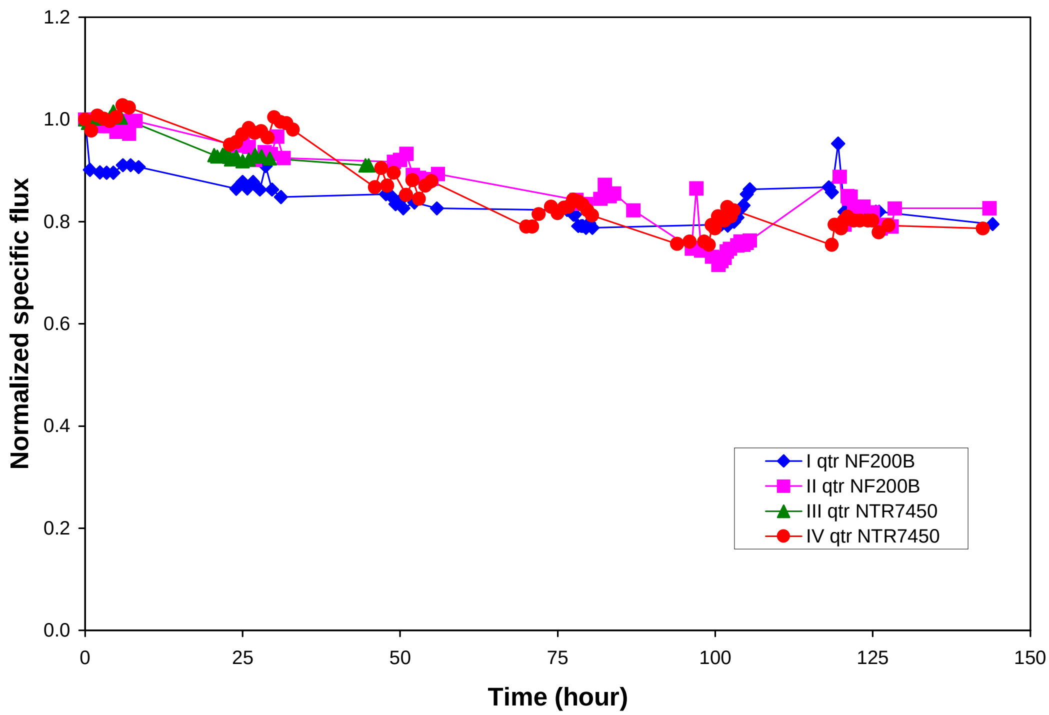

Figure 5. Normalized specific flux profiles for four quarters using the NTR7450 membrane.

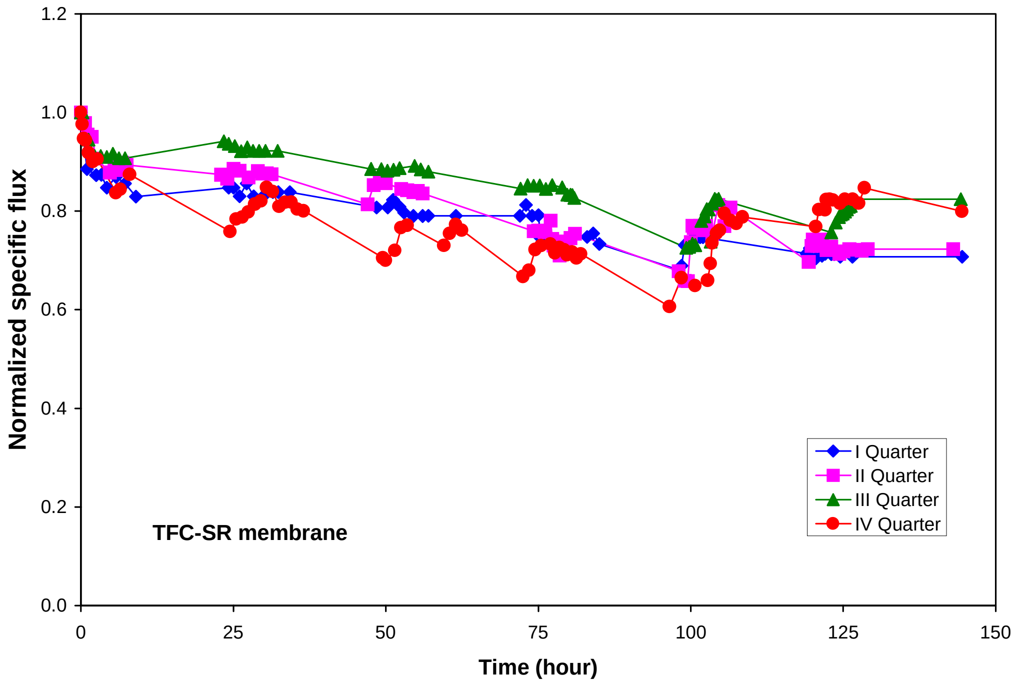

Figure 6. Normalized specific flux profiles for four quarters using the TFC-SR membrane.

Table 15 summarizes the average permeate flux during membrane setting as well as the lowest recorded permeate flux for each experiment. It was observed that the initial permeate flux ranged from 11.50 to 20.80 gfd with an average value of 15.28 gfd. The lowest recorded permeate flux ranged from 8.15 to 12.70 gfd with an average value of 10.64 gfd. This constituted a decrease of approximately 30% in flux from the membrane setting period to the lowest recorded permeate flux, which always occurred at 90% recovery.

Table 15. Summary of worst case permeate fluxes.

Quarter	Membrane	DI water permeate flux (gfd)	Lowest permeate flux [a] (gfd)
I	NF200	12.77	9.81
I	TFC-SR	15.81	11.66
II	NF200	20.79	12.78
II	TFC-SR	17.99	11.21
III	NF200	12.33	10.13
III	NTR7450	11.50	9.86
III	TFC-SR	16.01	10.96
IV	NTR7450	15.70	11.16
IV	TFC-SR	14.60	8.15

[a] The lowest recorded permeate flux always occurred at 90% recovery.

Fouling analysis and cleaning intervals. Fouling rate parameters obtained from Equation 2 for the RBSMT experiments conducted at 70% recovery are listed in Table 16. These data were obtained by linear regression analysis (the 95% confidence intervals are shown following the ± sign). The coefficient of regression ranged from 0.61 to 0.92, indicating a relatively close fit to the data. The corresponding cleaning intervals were obtained using Equation 3 and ranged from 55 to 140 hours with an average of 93 hours. Therefore, it appears that under the conditions employed, membrane cleaning needs to be conducted approximately every 4 days of operation at 70% recovery. However, it should be understood that no attempt was made to "optimize" membrane operation or to increase the duration between cleanings by pH adjustment, anti-scalent addition, or by incorporating more advanced pretreatment processes such as micro- or ultrafiltration. (It is not the intent of the ICR to determine optimum operating conditions for NF.)

Table 16. Summary of statistical fits to specific flux profiles at 70% recovery.

Quarter	Membrane	Fouling rate (gfd/h)	Initial flux (gfd)	r^2	Cleaning interval (h)*
I	TFC-SR	0.0283 ± 0.0089	15.45 ± 0.37	0.61	109
I	NF200	0.0206 ± 0.0058	11.56 ± 0.23	0.69	112
II	TFC-SR	0.0358 ± 0.0056	16.11 ± 0.23	0.85	90
II	NF200	0.0343 ± 0.0043	17.80 ± 0.16	0.92	104
III	TFC-SR	0.0208 ± 0.0049	14.59 ± 0.21	0.72	140
III	NTR7450	0.0400 ± 0.0197	10.93 ± 0.19	0.70	55
IV	TFC-SR	0.0410 ± 0.0075	12.52 ± 0.33	0.78	61
IV	NTR7450	0.0401 ± 0.0053	15.25 ± 0.24	0.88	76

* Cleaning interval was calculated assuming a 20% drop in initial flux.

PERMEATE WATER QUALITY

Composite sample collection. Permeate water quality was monitored frequently to establish a "steady-state" before collecting composite permeate and concentrate samples. Upon switching recoveries for each experiment, permeate water samples were collected every 20 minutes and analyzed for TDS and UV_{254}. Once consistent readings were achieved and the experiment reached "steady-state" conditions, composite samples were collected. These composite samples were analyzed for a variety of organic and inorganic water quality parameters. SDS testing was performed on the composite permeate samples and the feed water.

Table 17 provides a summary of all physical, organic and inorganic permeate water quality parameters obtained using the NTR7450 and NF-200B membranes at 70% feed water recovery for all four quarters of testing. Corresponding data for the TFC-SR membrane are provided in Table 18.

Table 17. Summary of NF-200B and NTR7450 permeate water quality at 70% recovery.[a]

Parameter	Units	NF200B membrane		NTR7450 membrane	
		Quarter I	Quarter II	Quarter III	Quarter IV
Alkalinity	mg/L as $CaCO_3$	177	114	364	319
Ca hardness	mg/L as $CaCO_3$	176	191	192	233
Total hardness	mg/L as $CaCO_3$	195	204	206	271
TDS	mg/L	223	257	264	279
Bromide	µg/L	120	150	140	140
Ammonia	mg NH_3-N/L	BMRL	BMRL	BMRL	BMRL
SDS Cl_2 demand	mg/L	1.86	1.10	1.86	4.40
TOC	mg/L	0.90	1.05	3.0	4.75
SDSTOX	µg/L	75	68	230	352
SDSTTHM	µg/L	57	51	107	155
SDSHAA(5)	µg/L	10.4	7.7	25.0	47.0
SDSHAA(9)	µg/L	19.5	11.1	40.2	70.5
UV_{254}	cm^{-1}	0.023	0.024	0.081	0.122
pH	-	8.32	7.68	8.23	8.00
Turbidity	NTU	0.15	0.09	0.12	0.09

[a] BMRL denotes Below Minimum Reporting Level.

Table 18. TFC-SR permeate water quality for all 4 quarters of testing at 70% recovery.[a]

Parameter	Units	Quarter I	Quarter II	Quarter III	Quarter IV
Alkalinity	mg/L as $CaCO_3$	161	193	321	155
Ca hardness	mg/L as $CaCO_3$	133	180	135	126
Total hardness	mg/L as $CaCO_3$	146	210	158	156
TDS	mg/L	225	238	232	204
Bromide	µg/L	130	120	130	100
Ammonia	mg NH_3-N/L	0.78	1.10	BMRL	BMRL
SDS Cl_2 demand	mg/L	4.36	4.32	2.82	2.26
TOC	mg/L	BMRL	0.70	0.85	0.75
SDSTOX	µg/L	BMRL	BMRL	62	65
SDSTTHM	µg/L	5.15	3.65	44.5	38.3
SDSHAA(5)	µg/L	1.9	3.8	6.7	5.8
SDSHAA(9)	µg/L	1.9	3.8	9.1	12.0
UV_{254}	cm^{-1}	BMRL	BMRL	0.021	0.020
pH	-	8.20	7.83	7.73	7.95
Turbidity	NTU	0.09	0.05	0.09	0.09

[a] BMRL denotes Below Minimum Reporting Level.

Total organic carbon removal. TOC removals measured at 70% feed water recovery by all three membranes are summarized in Figure 7. Of the three membranes tested at the bench-scale, the TFC-SR membrane achieved highest rejection of TOC. The NTR7450 was most permeable to TOC. As shown in Table 19, the highest permeate TOC concentration using the TFC-SR membrane was 1.8 mg/L. The highest recorded permeate TOC concentrations using NTR7450 and NF-200B membranes were 7.2 and 2.8 mg/L respectively (see Table 20). Thus, the lowest TOC removal percentage using the TFC-SR membrane was 85%. In contrast, the lowest TOC removal percentages using NTR7450 and NF-200B membranes were 43 and 79% respectively.

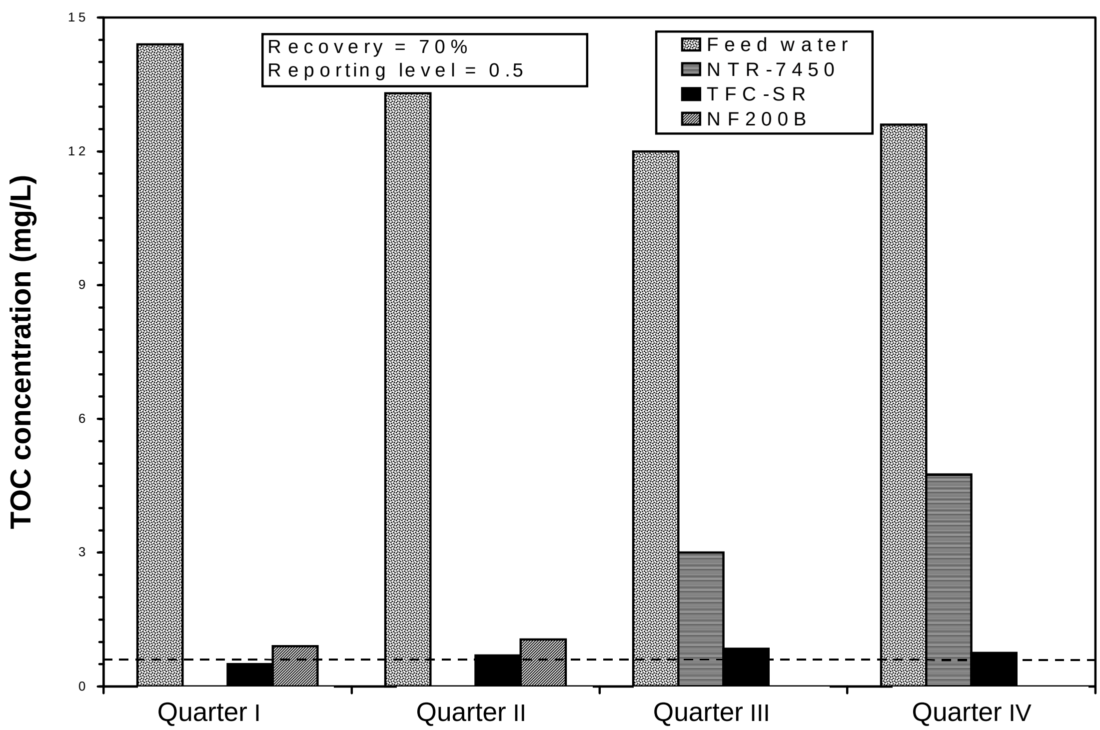

Figure 7. TOC removals by various membranes at 70% recovery.

Table 19. Summary of TOC concentrations in the permeate water using the TFC-SR membrane.

Recovery (%)	Quarter I		Quarter II		Quarter III		Quarter IV	
	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)
30	BMRL [a]	> 97	BMRL	> 96	0.8	93	0.7	94
50	0.60	96	0.90	93	1.0	92	1.0	92
70	BMRL	> 97	0.60	95	0.75	94	0.75	94
90	1.0	93	1.1	92	1.8	85	1.6	87

[a] Calculated using 0.5 mg/L as the TOC minimum reporting level

Table 20. Summary of TOC concentrations in the permeate water using the NTR7450 and NF-200B membranes.

Recovery (%)	NF200B membrane				NT7450 membrane			
	Quarter I		Quarter II		Quarter III		Quarter IV	
	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)
30	0.6	96	1.2	91	NA	NA	3.6	71
50	0.9	94	1.6	88	1.9	84	4.2	67
70	0.9	94	1.1	92	3.0	75	4.8	62
90	1.4	90	2.8	79	NA	NA	7.2	43

Disinfection by-product precursor removal. The highest SDSTTHM and SDSHAA(5) concentrations using the TFC-SR membrane were approximately 86 μg/L and 15 μg/L, respectively. Compared to the TFC-SR membrane, higher concentrations of organic constituents were observed in the NF-200B and NTR7450 membrane permeate waters. For example, the highest SDSTTHM and SDSHAA(5) concentrations using the NTR7450 membrane were 210 μg/L and 72 μg/L, respectively. The highest SDSTTHM and SDSHAA(5) concentrations using the NF-200B membrane were 118 μg/L and 24 μg/L, respectively.

Under the SDS conditions employed, SDSHAA(5) concentrations in TFC-SR and NF-200B membrane permeate waters were always below the place holder set by Stage II of the D/DBP rule (30 μg/L for HAA(5)). SDSTTHM concentrations in NTR7450 and NF-200B membrane permeate waters were above the place holder under Stage II of the D/DBP rule (40 μg/L for TTHMs). The TFC-SR membrane was sometimes able to decrease THM precursor materials to below 40 μg/L. Hence, NF alone may not be sufficient to meet proposed THM regulations if free chlorine is employed as the final disinfectant.

HAA(5) and TTHM precursor removals from pretreated Biscayne Aquifer water (at 70% recovery) are summarized in Figures 8 and 9, respectively.

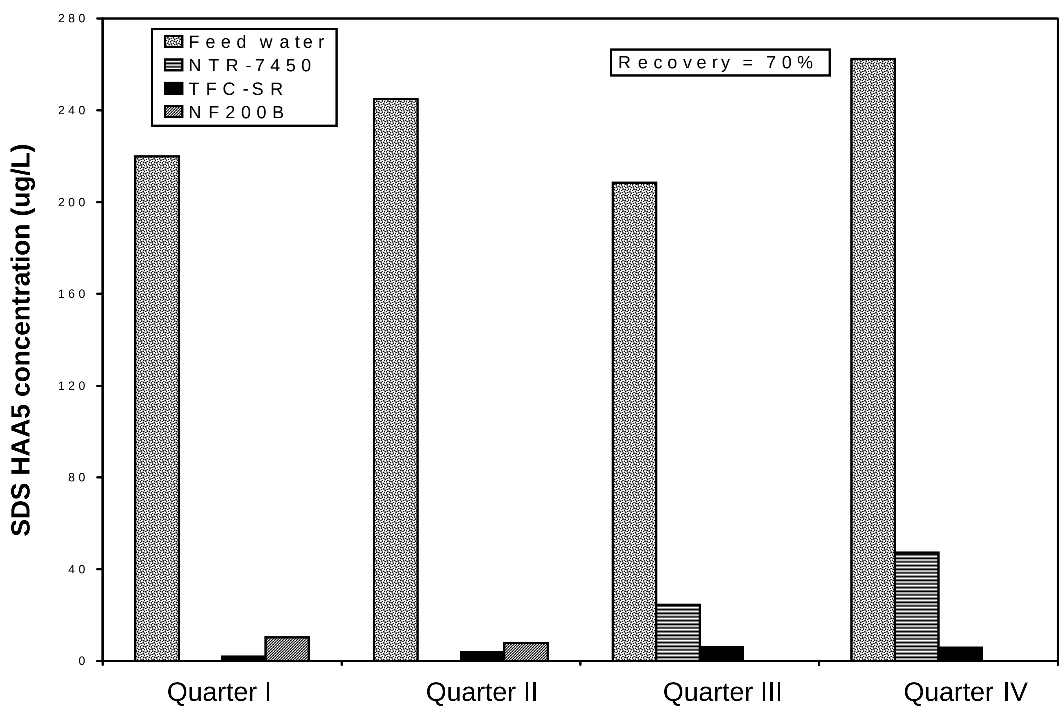

Figure 8. HAA5 precursor removals by various membranes at 70% recovery.

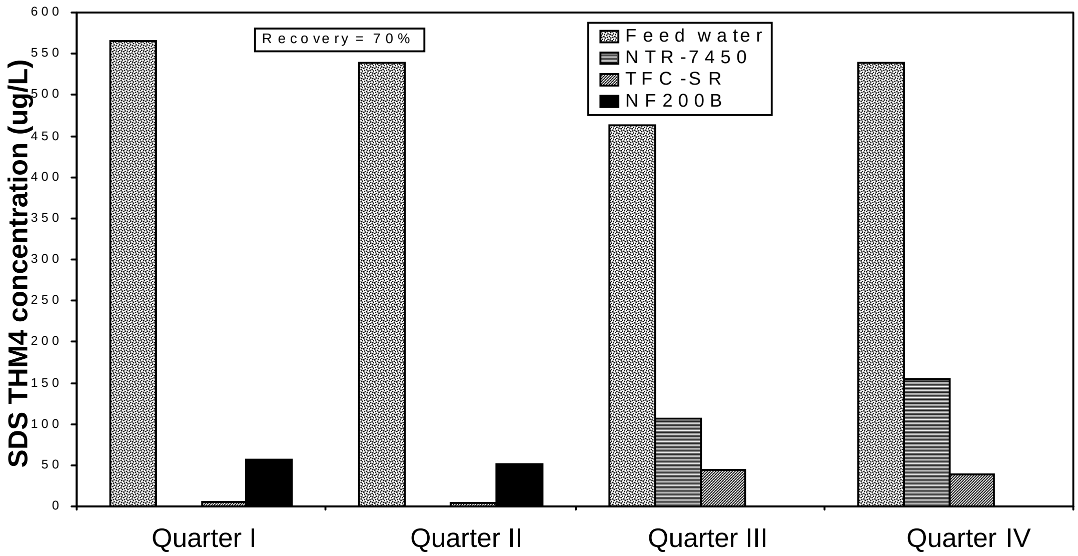

Figure 9. THM precursor removals by various membranes at 70% recovery.

Effect of nanofiltration on THM speciation. As described in previous sections, the NF membranes employed achieved high TOC removals. However, these membranes achieved essentially no bromide ion rejection. It appears these membranes were completely permeable to the bromide ion. Hence, the ratio of the bromide ion concentration to TOC concentration increased dramatically in the NF permeate water compared to the NF feed water. At the same time, SDS experiments were conducted by employing similar free chlorine concentration to TOC concentration ratios in the feed and permeate waters to achieve a similar free chlorine concentration (approximately 1 mg/L) at the end of the SDS incubation period.

Because of these SDS experimental conditions, large changes in the relative concentrations of the individual THM species were detected in the NF feed and permeate waters. This phenomenon is depicted in Figure 10 by expressing each THM specie as a mole fraction. As shown, chloroform was the dominant THM specie in the NF feed water. However, as the ratio of the concentration of bromide ion concentration to TOC concentration increased dramatically, dichloro bromomethane and chlorodibromo methane mole fractions increased in the NF permeate water.

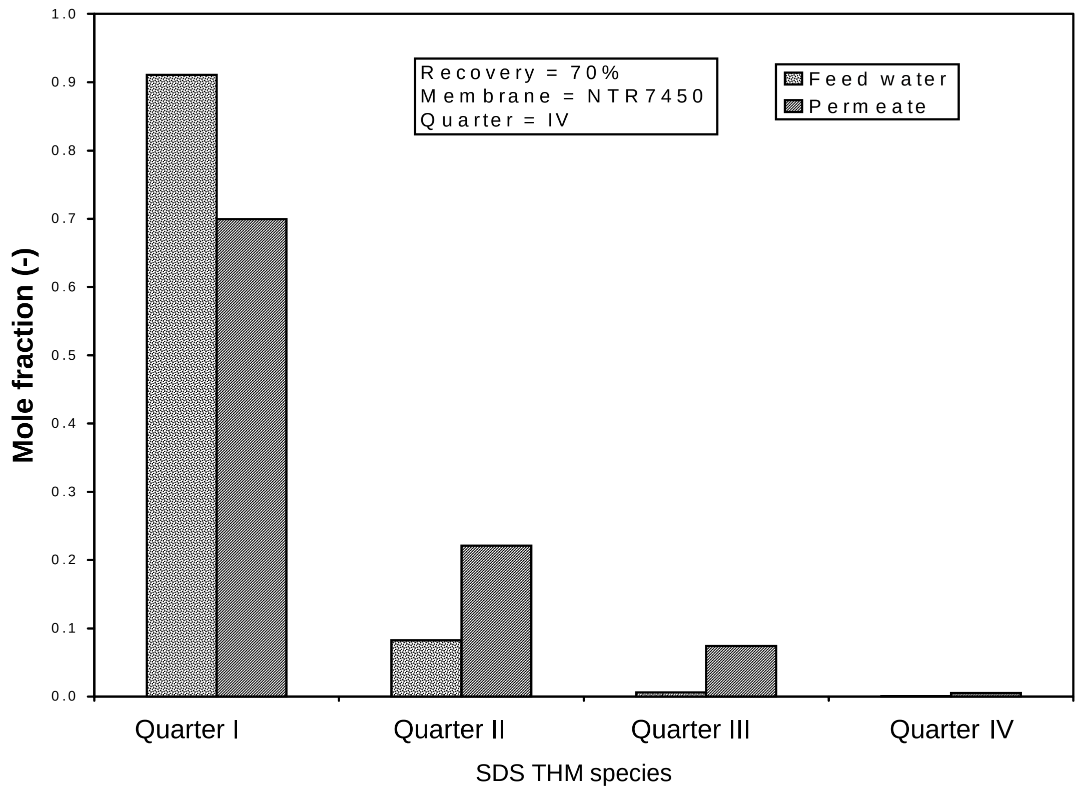

Figure 10. Changes in THM speciation expressed as a mole fraction upon nanofiltration (data from Quarter I experiments at 70% feed water recovery and NTR7450 membrane).

Inorganics removal. Although the NTR7450 membrane achieved only approximately 15% TDS rejection, the NF200B and TFC-SR membranes removed approximately 39% and 44% TDS from pretreated Biscayne Aquifer water. In addition, the TFC-SR and NF200B membranes removed approximately 35% and 32% of total hardness respectively (at 70% recovery). The NTR7450 membrane removed only 6% of total hardness from the membrane feed water (at 70% recovery). None of the membranes utilized in this study were able to achieve substantial removal of the bromide ion, resulting in large changes in trihalomethane and haloacetic acid speciation in the permeate water compared to the feed water.

Effect of feed water recovery on rejection. The concentrations of a variety of inorganic and organic permeate water quality parameters were dependent on feed water recovery for both membranes. Tables 21, 22, and 23 summarize the effects of recovery on the rejection of select water quality parameters by the NF-200B, NTR7450, and TRC-SR membranes. These data were obtained by employing data from all quarters of testing. The median and range for each parameter are also listed. In general, permeate concentrations increased with increasing feed water recovery.

Figure 11 depicts the effects of feed water recovery on permeate TDS concentrations using the NTR7450, NF200B and the TFC-SR membranes. Data obtained during the first and fourth quarters of testing have been used. It can be observed that permeate TDS concentrations increased exponentially with feed water recovery (R_f). The following empirical fits were obtained using these data:

TFC-SR membrane: Permeate TDS (mg/L) = 206 exp(0.0029R_f) (R^2 = 0.77)

NF200B membrane: Permeate TDS (mg/L) = 233 exp(0.0021R_f) (R^2 = 0.77)

NTR7450 membrane: Permeate TDS (mg/L) = 257 exp(0.0013R_f) (R^2 = 0.83)

Empirical correlations relating other organic and inorganic permeate water quality parameters to feed water recovery can be derived using linear regression techniques if necessary.

Table 21. Effect of feed water recovery on rejection of selected water quality parameters using the NF200B membrane.[a]

Parameter	Units	30% recovery		50% recovery		70% recovery		90% recovery	
		Median	Range	Median	Range	Median	Range	Median	Range
Ca hardness	mg/L as $CaCO_3$	158	144-272	175	154-196	180	161-198	199	182-216
Total hardness	mg/L as $CaCO_3$	175	163-186	196	184-208	201	188-208	213	176-230
Alkalinity	mg/L as $CaCO_3$	137	114-160	151	118-184	143	113-182	160	132-188
TDS	mg/L	232	214-250	242	223-260	238	222-263	256	223-288
Bromide	mg/L	130	120-140	135	120-150	135	120-150	135	120-150
Ammonia	mg NH_3-N/L	0.13	BMRL-0.13	BMRL	BMRL	BMRL	BMRL	BMRL	BMRL
SDS Cl_2 demand	mg/L	1.34	1.28-1.40	1.66	1.43-1.89	1.3	1.09-2.24	2.15	1.88-2.41
TOC	mg/L	0.90	0.6-1.2	1.25	0.9-1.6	0.95	0.9-1.1	2.1	1.4-2.8
TOX	µg/L	68.5	49-88	93.5	72-115	72.5	63-78	172.5	110-235
THM	µg/L	53.2	38.4-68	67.2	57.4-77	56.8	42.4-58.6	95.8	74-117.6
HAA(5)	µg/L	9.1	6.6-11.6	13.1	8.6-17.6	8.45	6.9-12.3	20.1	15.9-24.2
HAA(9)	µg/L	15.3	13.8-16.7	22.5	18.1-26.8	15.2	9.3-20.3	32.6	32.5-32.6
UV_{254}	cm^{-1}	0.029	0.016-0.042	0.039	0.026-0.051	0.023	0.019-0.028	0.072	0.038-0.106

[a] NF200B membrane employed only during the first two quarters of ICR testing.
Refer to Table 12 for minimum reporting levels of water quality parameters.

Table 22. Effect of feed water recovery on rejection of selected water quality parameters using the NTR7450 membrane.[a]

Parameter	Units	30% recovery		50% recovery		70% recovery		90% recovery	
		Median	Range	Median	Range	Median	Range	Median	Range
Ca hardness	mg/L as $CaCO_3$	212	-	196	174-218	230	192-236	268	-
Total hardness	mg/L as $CaCO_3$	240	-	225	204-246	270	206-272	294	-
Alkalinity	mg/L as $CaCO_3$	284	-	335	298-372	326	311-364	350	-
TDS	mg/L	271	-	266	262-270	272	264-286	293	-
Bromide	mg/L	140	-	140	140	140	140	140	-
Ammonia	mg NH_3-N/L	BMRL	-	BMRL	BMRL	BMRL	BMRL	BMRL	-
SDS Cl_2 demand	mg/L	3.6	-	2.54	1.18-3.90	4.35	1.86-4.40	5.70	-
TOC	mg/L	3.6	-	3.05	1.9-4.2	4.70	3.0-4.8	7.2	-
TOX	μg/L	300	-	235	135-335	345	230-360	530	-
THM	μg/L	130	-	108.5	77-140	150	110-160	210	-
HAA(5)	μg/L	37	-	28.5	14-43	45	25-49	72	-
HAA(9)	μg/L	58.4	-	45.1	24.2-65.9	68.6	40.2-72.4	95.4	-
UV_{254}	cm^{-1}	0.106	-	0.084	0.050-0.118	0.120	0.81-0.124	0.203	-

[a] The NTR7450 membrane was utilized during the last two quarters of ICR testing only. Quarter III testing only employed a 50% and 70% feed with recovery. All four recoveries (30, 50, 70, and 90) were employed during Quarter IV experiments. Refer to Table 12 for minimum reporting levels of water quality parameters.

Table 23. Effect of feed water recovery on rejection of selected water quality parameters using the TFC-SR membrane.

Parameter	Units	30% recovery		50% recovery		70% recovery		90% recovery	
		Median	Range	Median	Range	Median	Range	Median	Range
Ca hardness	mg/L as $CaCO_3$	124	102-146	154	116-158	135	124-184	180	158-206
Total hardness	mg/L as $CaCO_3$	142	118-162	174	140-182	157	138-212	210	186-270
Alkalinity	mg/L as $CaCO_3$	149	136-312	183	144-330	181	152-330	240	186-384
TDS	mg/L	214	184-225	247	198-247	232	201-240	263	259-273
Bromide	mg/L	110	83-130	120	96-130	125	100-130	135	130-140
Ammonia	mg NH_3-N/L	0.08	BMRL-0.08	0.22	BMRL-0.22	0.80	BMRL-1.10	0.30	BMRL-0.39
SDS Cl_2 demand	mg/L	2.13	1.09-2.51	1.94	1.12-3.50	3.81	1.78-4.39	2.63	1.66-4.42
TOC	mg/L	0.60	0.46-0.80	0.95	0.6-1.00	0.70	0.42-1.00	1.35	1.00-1.80
TOX	μg/L	44	41-72	60	52-85	62.5	BMRL-68	94	67-140
THM	μg/L	36.05	33.1-48.7	45.55	39.9-62	21.65	1.9-48.4	64.95	48.2-86.3
HAA(5)	μg/L	5.15	4.4-6.7	7.9	6-8.6	5.15	1.7-6.7	10.85	9.8-15
HAA(9)	μg/L	6.65	6.3-9.1	10.8	7.9-11.3	6.1	1.7-9.1	15.1	13-21
UV_{254}	cm^{-1}	0.017	BMRL-0.034	0.018	0.016-0.029	0.14	BMRL-0.022	0.037	0.024-0.065

Refer to Table 12 for minimum reporting levels of water quality parameters.

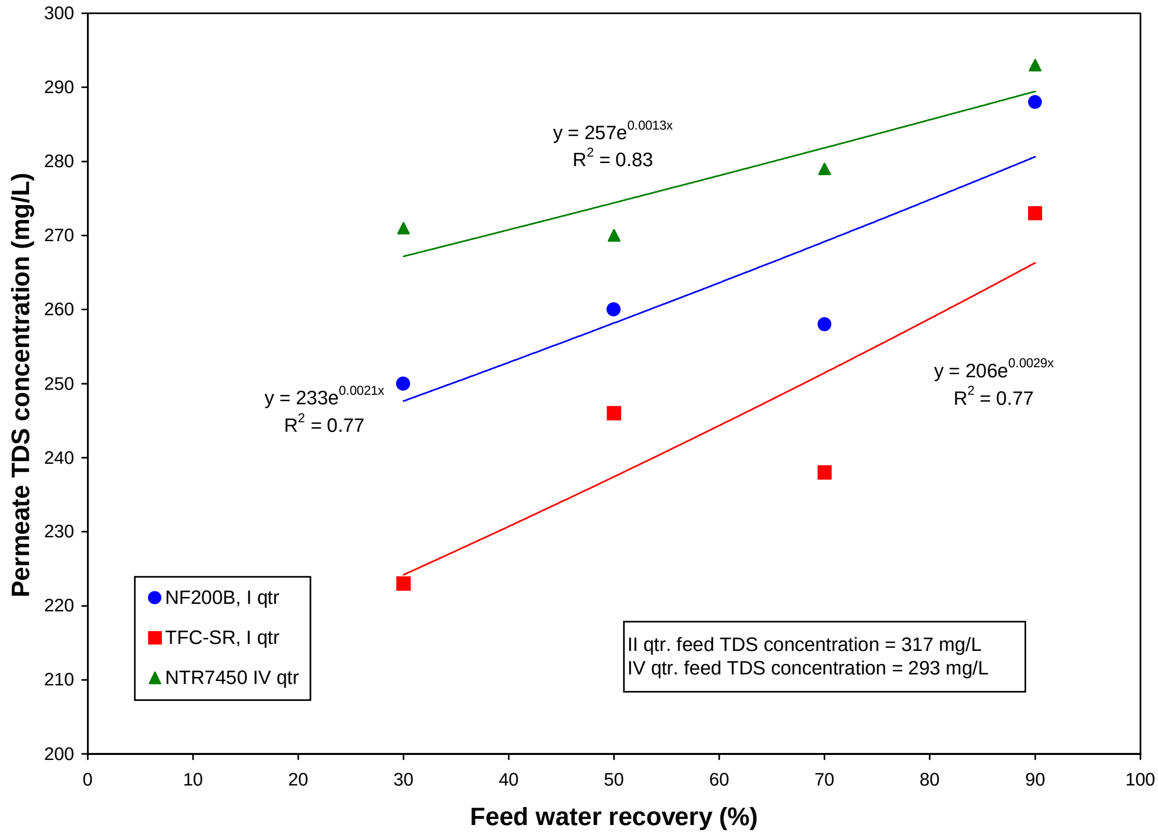

Figure 11. Effect of feed water recovery on permeate TDS concentration.

Permeate and feed water blending. Because of the high rejection capabilities of some nanofiltration membranes employed in water treatment, the concentrations of many water quality parameters in permeate waters are often much lower than regulatory maximum contaminant levels. This may allow the possibility of blending NF feed water with NF permeate, thereby reducing membrane area and/or energy requirements for the full-scale membrane plant.

It should be noted, however, that the concentrations of THM and HAA9 precursor materials in the NF feed water were relatively high (average feed water SDSTTHM concentration = 527 μg/L, average feed water SDSHAA9 concentration = 250 μg/L). When free chlorine is employed as the disinfectant, is not expected to be a feasible alternative if Stage II concentrations of the D/DBP Rule are considered.

Problems encountered. In general, ICR testing was conducted smoothly during Quarter I, Quarter II, and Quarter IV testing. During these experiments, waste flow rates occasionally dropped (particularly during the 90% feed water recovery) by approximately 2 to 8% when RBSMT apparatus was left unattended overnight.

Major operational and water quality problems occurred during the Quarter III testing using the NF-200B membrane. During the first run at 70% recovery, it was observed that the flux increased overnight, accompanied by increasing TDS and UV_{254} concentrations in the permeate. To address the problem, the membrane was replaced with a new NF-200B sample. The same experiment was continued using pretreated Biscayne Aquifer water. However, this experiment yielded the same results after two days. These observations are depicted in Figures 1a, 1b, and 1c. These operational and water quality problems were discussed with Mr. Steve Allegeier, ICR Technical Coordinator. Subsequent to these discussions, it was resolved to finish ICR requirements using the NTR7450 membrane. NTR7450 membrane performance was evaluated only at 70 and 50% recoveries.

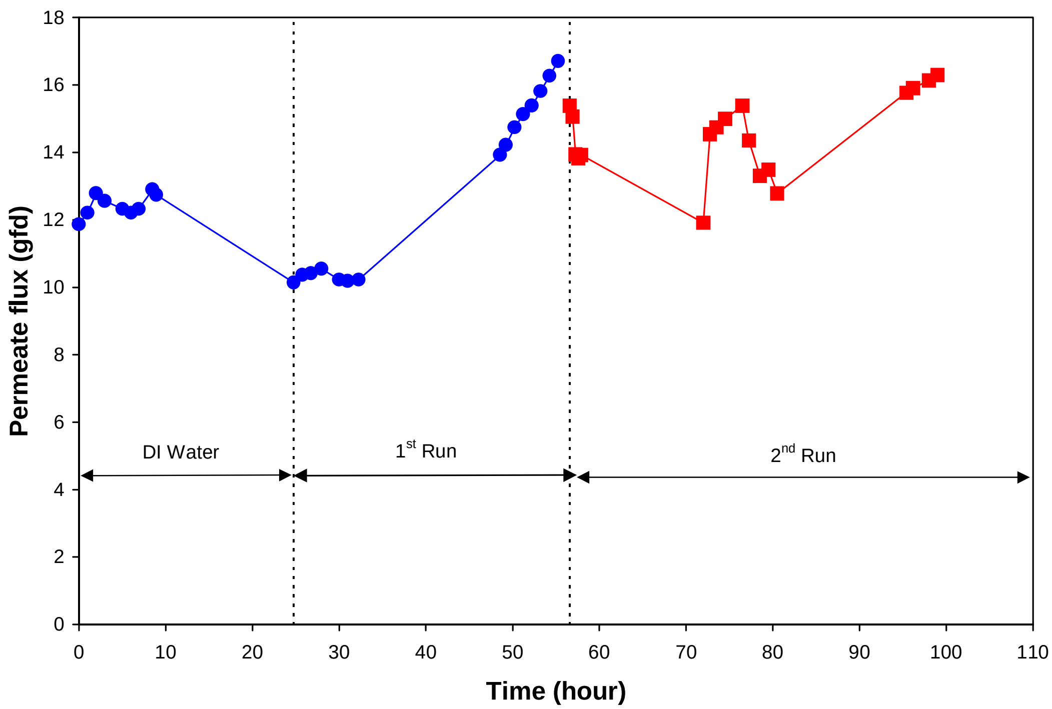

Figure 12a. Permeate flux profiles for Quarter III testing using the NF-200B membrane.

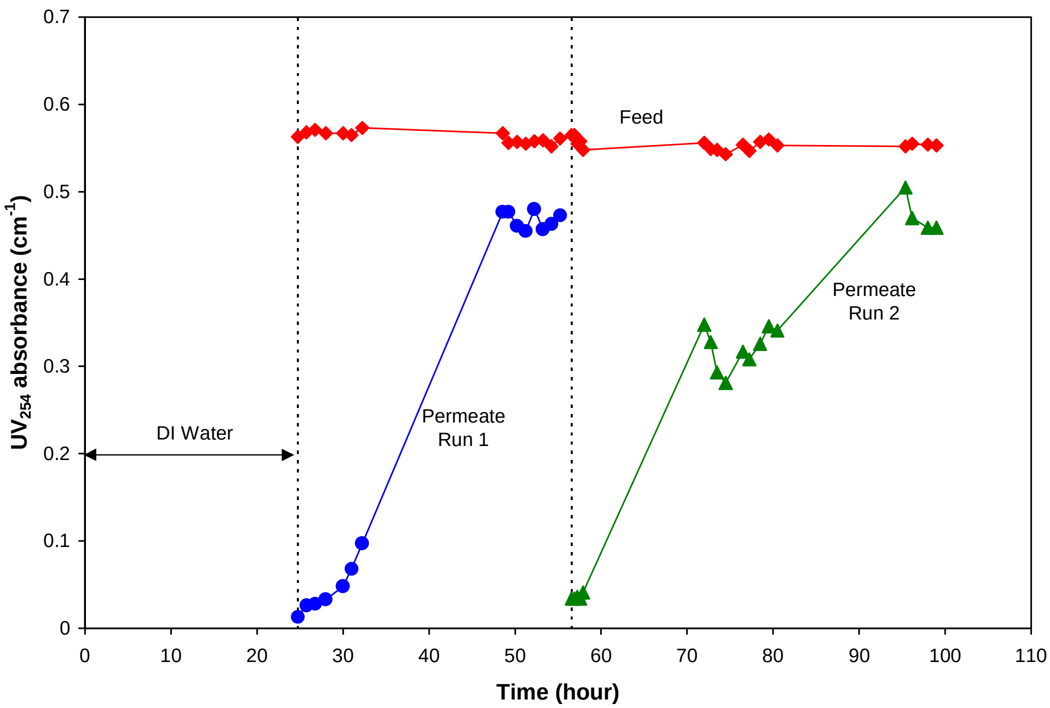

Figure 12b. UV_{254} profiles for Quarter III testing using the NF-200B membrane.

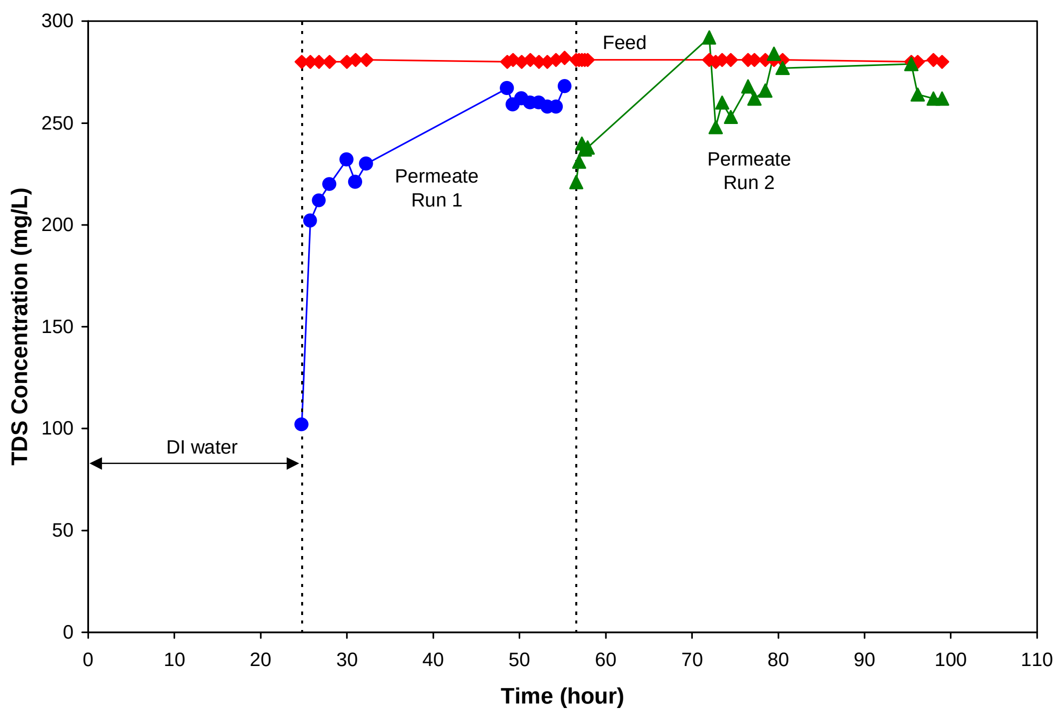

Figure 12c. TDS profiles for Quarter III testing using the NF-200B membrane.

Section 5
QA/QC Summary

Laboratory analyses. For this study, samples were shipped to Montgomery Watson Laboratories in Pasadena, California, an ICR certified laboratory. The tables presented in Section 5 summarize the QA/QC information provided by Montgomery Watson Laboratories in the format required by the ICR.

Quality assurance and quality control (QA/QC) summary data from Montgomery Watson Laboratories reflects ICR samples for Broward County and other bench-scale test utilities. These data are presented in support of an agreement with Mr. Steve Allegeir, ICR Technical Coordinator.

ICR RBSMT data collection spreadsheets. To ensure the integrity of the data collected and reported in this treatment study, we have already undergone one preliminary review of the ICR Treatment Study Data Collection Spreadsheets by the United States Environmental Protection Agency (USEPA). The comments generated by EPA during this preliminary review process are given in Appendix B. The Data Collection Spreadsheets reflect these comments. Detailed responses to these comments by EPA are described below:

<u>Global Comments Applicable to Both Membrane Worksheets:</u>

1. Missing information in Field 1 has been provided.
2. Cost of an 8x40 TFC-SR membrane element is not available from manufacturer.
3. No water quality parameters (including potential foulants) were measured prior to pretreatment because they were not required under the ICR.
4. Cartridge filtration was the only membrane pretreatment employed.
5. "-" has been removed from cell AP5 to facilitate the calculation of MTC_w.
6. Cost data have been provided.

<u>TFC-SR Membrane Quarter I:</u>

1. The recovery for the first run was changed from 0.07 to 0.70.
2. Alkalinity, total hardness, and calcium hardness values were verified and found to be correct. No changes were made.
3. All water quality parameters for the first run were verified and found to be correct. No changes made.

TFC-SR Membrane Quarter II:

1. Missing dates and operating times have been entered.
2. Formulas for UV_{254}, Cl_2 demand, THM4 and HAA5 have been entered.
3. TDS and UV_{254} values have been verified and found to be correct. No changes made.
4. All water quality parameters for the 70% recovery run including ammonia were verified and found to be correct. No changes made.

TFC-SR Membrane Quarter III:

1. Missing dates and operating times have been entered.
2. Formulas for UV_{254}, Cl_2 demand, THM4 and HAA5 have been entered.
3. Feed TOX and THM4 values were checked and found to be correct. No changes made.
4. All water quality parameters for the 70% recovery run including ammonia were verified and found to be correct. No changes made.

TFC-SR Membrane Quarter IV:

1. Missing dates and operating times have been entered.
2. Formulas for UV_{254}, Cl_2 demand, THM4 and HAA5 have been entered.
3. Alkalinity, total hardness, and calcium hardness values were verified and found to be correct. No changes were made.
4. Feed MCAA concentrations were verified and found to be correct. No changes made.

NF200B Membrane Quarter I:

1. Missing dates and operating times have been entered.
2. SUVA formula has been entered.
3. All operational parameters were verified and found to be correct. No changes made to alter the relatively high MTC_w.
4. Feed alkalinity concentrations were verified and found to be accurate. No changes made.
5. Alkalinity, TDS, total hardness, and calcium hardness values were verified and found to be correct. No changes were made.
6. All bromide concentrations were verified and found to be correct. No changes made.

NF200B Membrane Quarter II:

1. Formulas for UV_{254}, Cl_2 demand, THM4 and HAA5 have been entered.
2. All operational parameters were verified and found to be correct. No changes made to alter the relatively high MTC_w.
3. Feed ammonia concentrations were verified and found to be as reported by Montgomery Watson Laboratories. No changes made.
4. Alkalinity, total hardness, and calcium hardness values were verified and found to be correct. No changes were made.
5. Permeate TOC, UV_{254}, TOX and THM4 concentrations were verified and found to be correct. No changes made.

NF200B Membrane Quarter III:

1. Formulas for UV_{254}, Cl_2 demand, THM4 and HAA5 have been entered.
2. Increase in MTC_w and low TDS rejections were symptoms of a membrane problem. Hence, the NF200B membrane was replaced with a NTR7450 membrane.

NTR7450 Membrane Quarter III:

1. Missing dates and operating times have been entered.
2. Formulas for UV_{254}, Cl_2 demand, THM4 and HAA5 have been entered.
3. Erroneous influent pressure value changed to 67 psi.
4. All bromide concentrations were verified and found to be correct. Permeate TOC, UV_{254}, THM4 and HAA concentrations were also verified and found to be correct. No changes made.

NTR7450 Membrane Quarter IV:

1. Missing dates and operating times have been entered.
2. pH meter had malfunctioned during the beginning of these experiments. So, no pH data were collected initially.
3. Formulas for UV_{254}, Cl_2 demand, THM4 and HAA5 have been entered.
4. Feed MCAA concentrations were verified and found to be correct. No changes made.
5. All bromide concentrations were verified and found to be correct. Permeate TOC, UV_{254}, THM4 and HAA concentrations were also verified and found to be correct. No changes made.

Section 6
Acknowledgments

The laboratory testing and analysis component of this ICR treatment study would not have been completed without the assistance of Jennifer Abrajano, Dan Bush, Andy Eaton, Jim Hein, and Jason Radgowski. Dr. Dan Askenaizer and David Wilkes provided valuable comments during review of this summary report. Jennifer McMahon served as the project manager.

Jerry Baker of the Broward County Office of Environmental Services assisted in sampling efforts at the District 1A WTP. In addition, he provided background data required for the comparison of ICR Treatment Study spreadsheets.

Appendix A

Appendix B