# Information Collection Rule Treatment Study Summary Report

City of Brownsville, Texas

July, 1999

MONTGOMERY WATSON

# 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: January 1998 – March 1999

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Plant Name: Brownsville PUB Water Treatment Plant #1
Plant ICR #: 614

# Section 1
# Summary and Conclusions

Four quarters of nanofiltration (NF) testing using pretreated Rio Grande River water were successfully completed for the City of Brownsville's Public Utilities Board Water Treatment Plant No. 1. Pretreatment included coagulation, flocculation, sedimentation, and cartridge filtration. Two 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. For example, the highest recorded TOC concentration in the TFC-SR membrane permeate was 0.6 mg/L. The highest TOC concentration measured in the NF-200B membrane permeate was 1 mg/L.

Under the simulated distribution system (SDS) conditions employed, the highest SDSTTHM and SDSHAA(5) concentrations in the TFC-SR membrane permeate were 30 µg/L and 6.8 µg/L, respectively. The highest SDSTTHM and SDSHAA(5) concentrations in the NF200B membrane permeate were less than 74.4 µg/L and 13.0 µg/L, respectively. Therefore, when free chlorine was employed as the final disinfectant, SDSTTHM and SDSHAA(5) concentrations in the TFC-SR membrane permeate waters were below the placeholders set by Stage II of the D/DBP rule (40 µg/L for TTHMs and 30 µg/L for HAA(5)). However, only SDSHAA(5) concentrations in the NF-200B membrane permeate waters were below the placeholder set by Stage II of the D/DBP rule when free chlorine was 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 membrane. For example, the TFC-SR membrane achieved greater than 90% removal of sulfate while operating at 70% feed water recovery (corresponding to a permeate sulfate concentration of less than 8 mg/L). Higher sulfate concentrations were measured in the NF-200B membrane permeate (approximately 40 mg/L) corresponding to only 75% removal at 70% recovery.

Linear regression analysis suggests possible seasonal variations in fouling rates for both membranes. Using the RBSMT methodology, membrane chemical cleaning intervals ranged from approximately 70 hours to 200 hours at 70% feed water recovery and an initial flux of 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, bench-scale measurements and calculations should be verified at the pilot-scale level.

Finally, since the concentrations of most water quality parameters in the TFC-SR and NF-200B 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. 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 schematic of the existing water treatment processes for the City of Brownsville Public Utilities Board Water Treatment Plant No. 1 is given in the flow diagram in Appendix A. This schematic was generated during the development of the initial sampling plan for the 18-month monitoring plan of DBP/microbiological. The water for NF testing was obtained directly from the Rio Grande River.

Basic engineering and chemical feed data for each unit process are summarized in Tables A.2 and A.3 of Appendix A. These tables were also generated using the *ICR Water Utility Database System* (EPA 814-B-96-004) under the ICR.

**Full-scale plant influent and finished water quality.** Under the 18 months of water quality monitoring for the ICR, quarterly samples were collected from July 1997 through December 1998 at Water Treatment Plant No. 1. Table 1 summarizes these data from the influent water of the full-scale plant. In Table 2, these data are summarized for the plant's finished water.

**Table 1.** Full-scale influent water quality data.

| Parameter | Units | Average | Standard Deviation | Minimum | Maximum | Count |
|---|---|---|---|---|---|---|
| Temperature | ºC | 25.9 | 4.1 | 21 | 31 | 6 |
| pH | - | 8.1 | 0.3 | 7.6 | 8.4 | 6 |
| Turbidity | ntu | 12.9 | 6.7 | 1.5 | 20 | 6 |
| Alkalinity | mg/L as $CaCO_3$ | 178.3 | 34.9 | 130 | 230 | 6 |
| Total Hardness | mg/L as $CaCO_3$ | 315 | 38.9 | 260 | 360 | 6 |
| Calcium Hardness | mg/L as $CaCO_3$ | 230.2 | 49.3 | 170 | 312 | 6 |
| TOC | mg/L | 3.6 | 0.8 | 2.9 | 4.9 | 6 |
| $UV_{254}$ | 1/cm | 0.082 | 0.019 | 0.058 | 0.114 | 6 |
| Bromide | µg/L | 363.3 | 85.5 | 290 | 530 | 6 |
| TSUVA* | L/(mg-m) | 2.3 | 0.4 | 1.81 | 3 | 6 |

*TSUVA = [$UV_{254}$ (1/m)] / [TOC (mg/L)] and was calculated using matched-pair data.

**Table 2.** Full-scale finished water quality data.

| Parameter | Units | Average | Standard Deviation | Minimum | Maximum | Count |
|---|---|---|---|---|---|---|
| Temperature | ºC | 25.4 | 4.03 | 21 | 30.6 | 6 |
| pH | unit | 8.06 | 0.25 | 7.78 | 8.5 | 6 |
| Turbidity | ntu | 0.07 | 0.01 | 0.06 | 0.08 | 6 |
| TOC | mg/L | 2.95 | 0.43 | 2.6 | 3.7 | 6 |
| $UV_{254}$ | 1/cm | 0.086 | 0.008 | 0.074 | 0.098 | 6 |
| DS-THM4 [a] | µg/L | 19.2 | 8.1 | 12.5 | 42.3 | 24 |
| DS-HAA5 | µg/L | 15.6 | 3.7 | 9.5 | 21.7 | 24 |
| DS-HAA6 | µg/L | 21.9 | 4.9 | 14 | 30.8 | 24 |

[a] DS represents distribution system

# Section 3
# Materials and Methods

**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.

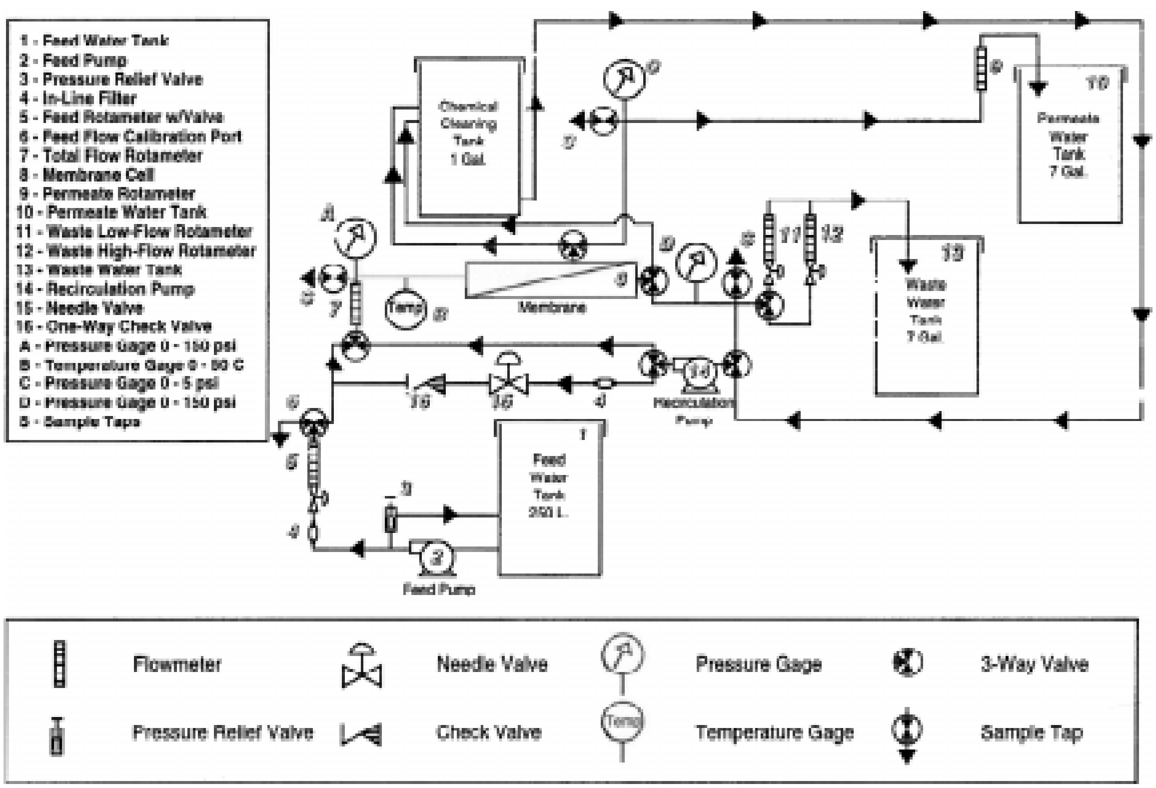


**Figure 1. Schematic of the bench-scale NF apparatus**

**Membranes employed.** ICR experiments were conducted using two NF membranes: FilmTec NF-200B (Dow Chemical Company, Midland, MI) and TFC-SR (Koch-Fluid Systems 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 |
| 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 one case, when base cleaning was ineffective (NF-200B membrane, Quarter IV), 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 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, thirty gallon drums were sent to Brownsville 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. A low pH sulfuric acid solution was then used to remove metallic deposits. These 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. Because chlorine dioxide is added in the full-scale plant prior to rapid mixing, sample water was taken directly from the Rio Grande River. Upon receipt of the raw Rio Grande River water in Montgomery Watson's labs in Herndon VA, pretreatment was conducted by using chemical dosages and hydraulic parameters adjusted to simulate those employed at the full-scale plant. Therefore, prior to the RBSMT experiments, raw water from the Rio Grande River was coagulated using 30 mg/L alum ($Al_2(SO_4)_3$ $14H_2O$), allowed to settle for 24 hours and then filtered using an electronics grade 5 μm cartridge filter (RyanHerco, Burbank, CA, Model #6711-505). A simple schematic of the pretreatment processes employed is given in Figure 2.

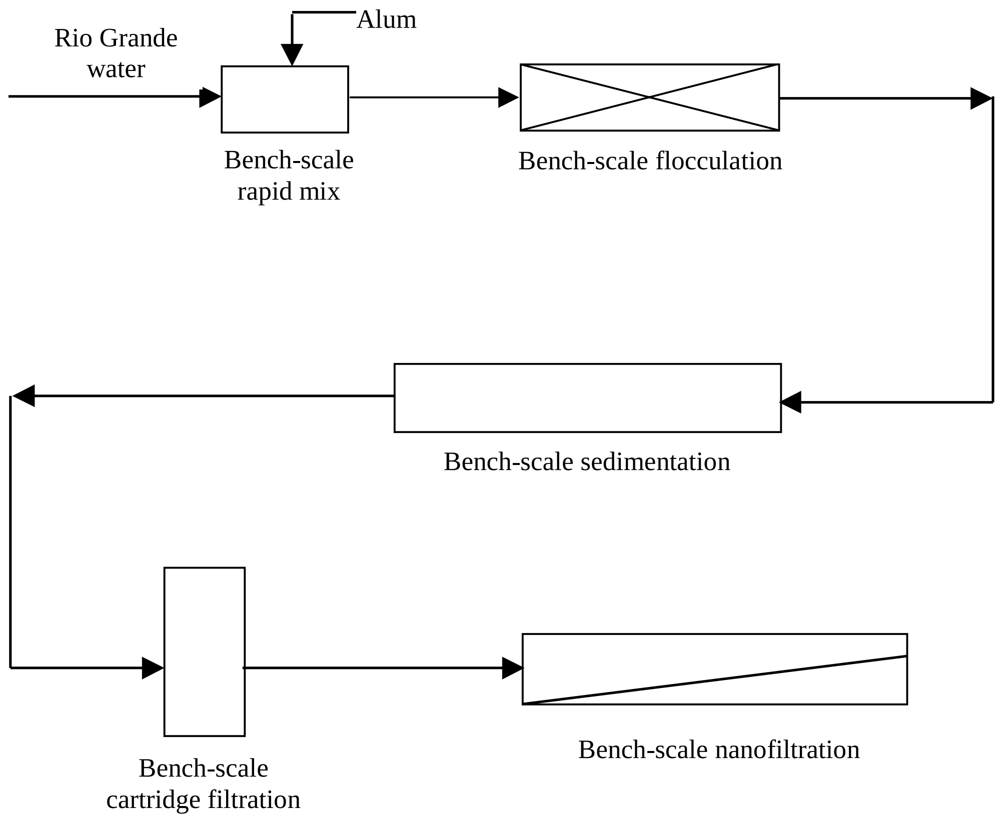


**Figure 2.** Simple schematic of the pretreatment used prior to bench-scale nanofiltration.

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 moderate concentrations of total organic carbon (TOC) and simulated distribution system (SDS) haloacetic acid 5 (SDSHAA5[1]). Concentrations of total dissolved solids (TDS), bromide ion, SDS total trihalomethanes (SDSTTHM[2]) and SDS haloacetic acid 9 (SDSHAA9[3]) were high.

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

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

| Parameter | Units | Quarter I | Quarter II | Quarter III | Quarter IV |
|---|---|---|---|---|---|
| Alkalinity | mg/L as $CaCO_3$ | 136 | 105 | 210 | 167 |
| Ca hardness | mg/L as $CaCO_3$ | 247 | 193 | 216 | 293 |
| Total hardness | mg/L as $CaCO_3$ | 369 | 311 | 329 | 409 |
| TDS | mg/L | 741 | 571 | 638 | 789 |
| Bromide | μg/L | 475 | 190 | 355 | 630 |
| Ammonia | mg $NH_3$-N/L | 0.06 | BMRL[a] | BMRL | BMRL |
| SDS $Cl_2$ demand | mg/L | 5.80 | 3.95 | 3.23 | 5.30 |
| TOC | mg/L | 3.05 | 2.65 | 2.50 | 3.50 |
| SDS TOX | μg/L | 325 | 274 | 270 | 348 |
| SDS TTHM | μg/L | 236 | 151 | 170 | 298 |
| SDS HAA5 | μg/L | 50.7 | 42.5 | 28.0 | 45.0 |
| SDS HAA9 | μg/L | 131.7 | 100.2 | 66.5 | 112.8 |
| $UV_{254}$ | $cm^{-1}$ | 0.071 | 0.060 | 0.060 | 0.075 |
| pH | - | 8.25 | 7.91 | 8.13 | 8.19 |
| Turbidity | NTU | 0.24 | 0.17 | 0.14 | 0.14 |

[a] Denotes Below Minimum Reporting Level

**Sulfate sampling.** At the request of the City of Brownsville, sulfate samples were also collected from the feed, permeate, and concentrate waters and shipped to Brownsville for analysis. These analyses are not required by the ICR. The NF feed water sulfate concentrations have been summarized in Table 5.

**Table 5.** Summary of sulfate concentrations in the NF feed water.

| Quarter | Sulfate concentration (mg/L) |
|---|---|
| I | NA[a] |
| II | 255 |
| III | 288 |
| IV | 167 |

[a] Denotes sample not collected

**Membrane setting.** Deionized water (TDS concentration less than approximately 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 (approximately 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 $\mu$ ($N\text{-}s/m^2$) denotes the absolute viscosity of water.

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

**NF experiments using pretreated Rio Grande River water.** Table 6 summarizes the sampling and membrane operational dates for RBSMT experiments that were conducted for both membranes.

**Table 6.** Quarterly dates of RBSMT experiments.

| Quarter | Sampling date | Dates of membrane operation | |
|---|---|---|---|
| | | NF-200B | TFC-SR |
| I | 1/22/98 | 2/16/98 – 2/23/98 | 2/3/98 – 2/10/98 |
| II | 5/7/98 | 6/3/98 – 6/10 /98 | 5/26/98 – 6/2/98 |
| III | 7/23/98 | 8/31/98 – 9/8/98 | 8/17/98 – 8/24/98 |
| IV | 1/12/99 | 2/5/99 – 2/12/99 | 2/13/99 – 2/20/99 |

During each quarter, experiments using pretreated Rio Grande River 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 7, average experimental conditions including net driving pressure, permeate flux, and water mass transfer coefficient for the NF-200B during the RBSMT are summarized. These data are summarized in Table 8 for the TFC-SR membrane.

**Table 7.** Summary of quarterly RBSMT experiments using NF-200B membrane.

| Quarter | Recovery (%) | Net driving pressure (psi) | Permeate flux (gfd) | $MTC_w$ [a] (gfd/psi) |
|---|---|---|---|---|
| I | 71 | 74 | 12.2 | 0.167 |
| I | 89 | 72 | 10.6 | 0.141 |
| I | 51 | 77 | 11.1 | 0.149 |
| I | 30 | 77 | 11.5 | 0.151 |
| II | 70 | 58 | 11.3 | 0.203 |
| II | 88 | 56 | 10.0 | 0.179 |
| II | 51 | 61 | 11.3 | 0.189 |
| II | 32 | 59 | 10.9 | 0.188 |
| III | 72 | 40 | 10.9 | 0.132 |
| III | 90 | 38 | 8.6 | 0.109 |

**Table 7 (Continued).** Summary of quarterly RBSMT experiments using NF-200B membrane.

| Quarter | Recovery (%) | Net driving pressure (psi) | Permeate flux (gfd) | $MTC_w$ [a] (gfd/psi) |
|---|---|---|---|---|
| III | 51 | 41 | 11.3 | 0.134 |
| III | 29 | 43 | 11.9 | 0.137 |
| IV | 70 | 43 | 10.5 | 0.250 |
| IV | 90 | 41 | 8.6 | 0.220 |
| IV | 52 | 44 | 10.6 | 0.250 |
| IV | 34 | 43 | 10.5 | 0.250 |

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

**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 | 69 | 73 | 10.6 | 0.153 |
| I | 90 | 65 | 8.7 | 0.128 |
| I | 51 | 75 | 10.3 | 0.137 |
| I | 31 | 76 | 10.6 | 0.142 |
| II | 69 | 54 | 13.3 | 0.251 |
| II | 88 | 52 | 10.6 | 0.209 |
| II | 49 | 54 | 12.4 | 0.236 |
| II | 32 | 53 | 11.7 | 0.226 |
| III | 71 | 73 | 11.2 | 0.162 |
| III | 91 | 72 | 9.0 | 0.128 |
| III | 51 | 76 | 11.9 | 0.155 |
| III | 32 | 77 | 12.2 | 0.150 |
| IV | 70 | 42 | 11.8 | 0.290 |
| IV | 88 | 40 | 9.4 | 0.240 |
| IV | 52 | 43 | 11.4 | 0.270 |
| IV | 30 | 43 | 11.7 | 0.280 |

**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 then 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.** Target simulated distribution system 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 | 21 | 25 | 24 |
| pH | 8.2 | 8.2 | 8.2 | 8.2 |
| Holding time (hour) | 72 | 48 | 24 | 48 |
| 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, by Montgomery Watson Laboratories, or by Summers and Hooper, Inc. The analyses performed as well as some information regarding these different laboratory sites are 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 |
| $UV_{254}$ | 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 | Feb. 3, 1998 – March 2, 1999 | Alkalinity, calcium and total hardness, pH, $Cl_2$ residual, TDS, temperature, turbidity, $UV_{254}$ | Dr. Shankar Chellam<br>Montgomery Watson<br>560 Herndon Pkwy #300<br>Herndon, VA 20170 |
| Montgomery Watson Laboratories | Feb. 3, 1998 – March 2, 1999 | Bromide, Ammonia, TOC, HAA, THM, TOX | ICR ID #: CA013<br>Dr. Andrew Eaton<br>555 E. Walnut St.<br>Pasadena, CA 91101<br>Phone: (626) 568-6425<br>Fax: (626) 568-6324 |
| Summers and Hooper Inc. | Mar. 2, 1999 – Mar. 4, 1999 | HAA | ICR ID#: OH033<br>Mr. Stuart Hooper<br>6 Knollcrest Drive<br>Cincinnati, OH 45237<br>Phone: (513) 679-2200<br>Fax: (513) 679-2201 |

# Section 4
# Results and Discussion

## MEMBRANE OPERATION

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

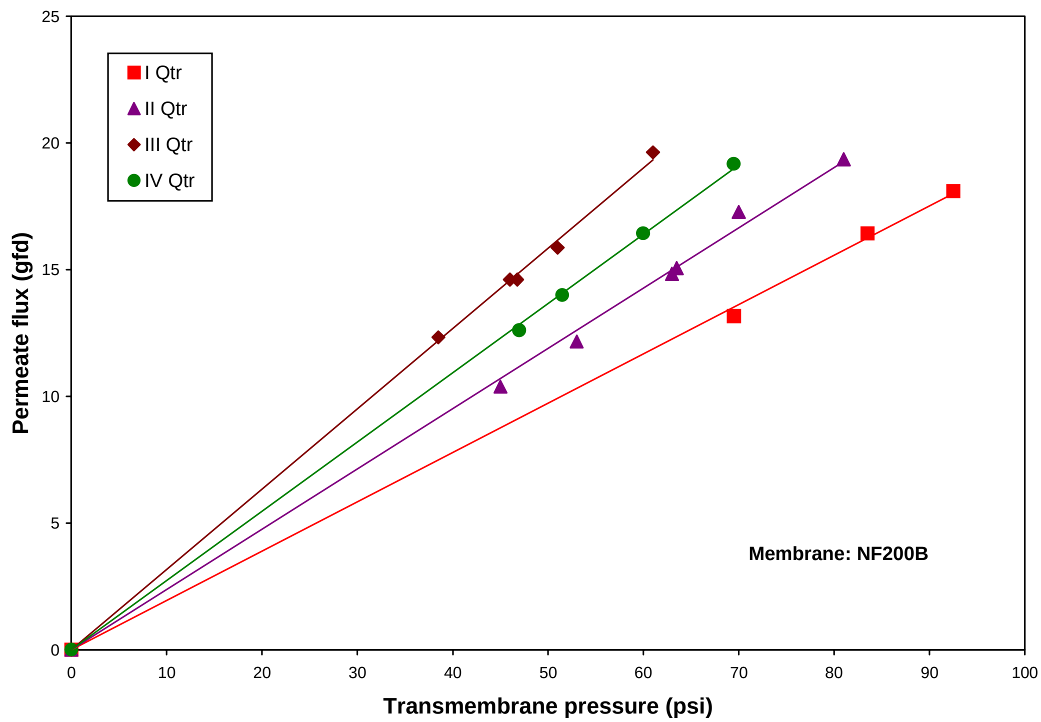


**Figure 3.** Resistances of the new NF-200B membranes used for each quarter of testing.

These data were used in Equation 1 to calculate new membrane resistances and are summarized in Table 14. Table 14 also summarizes membrane resistances calculated following chemical cleaning. New NF-200B membrane resistance values were in the range of 4.61 x $10^{13}$ to 7.51 x $10^{13}$ $m^{-1}$ with an average value of 5.90 x $10^{13}$ $m^{-1}$. Initial $R_m$ values for the TFC-SR membrane ranged from 5.32 x $10^{13}$ to 1.04 x $10^{14}$ $m^{-1}$ with an average value of 7.68 x $10^{13}$ $m^{-1}$. In general, it was observed that the difference in membrane resistances before and after cleaning were less than 10%. These data suggest that the cleaning procedure employed was effective in removing NF foulants present in the Rio Grande River water.

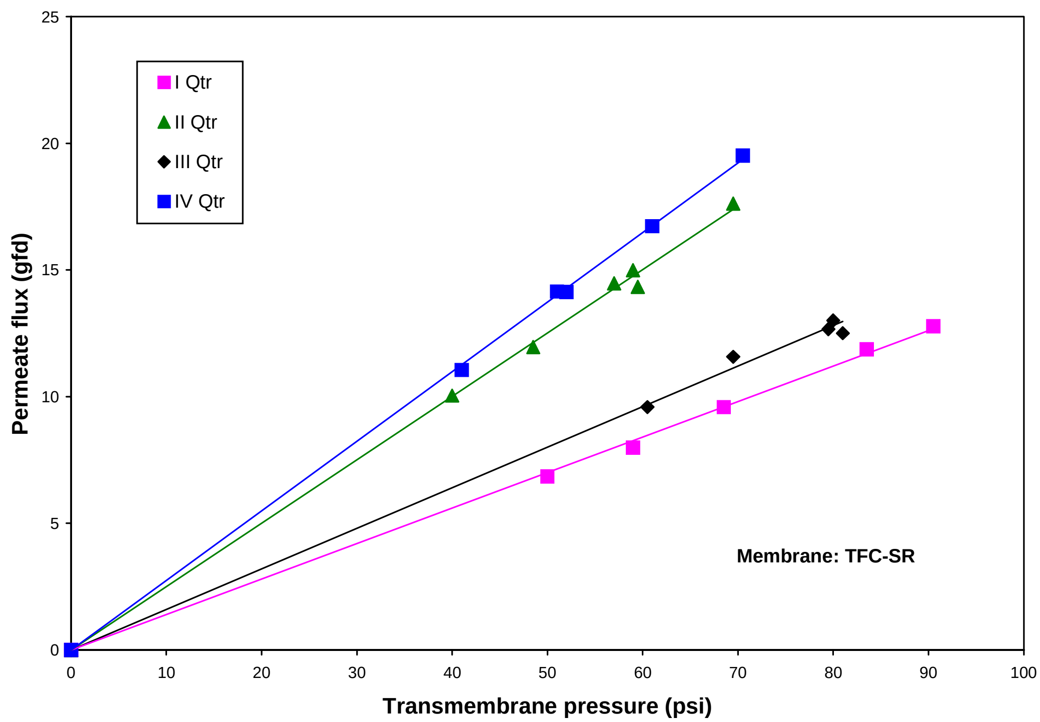


**Figure 4.** Resistances of the new TFC-SR membranes used in each quarter.

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

| Quarter | Membrane designation | Initial $R_m$ ($m^{-1}$) | $R_m$ after cleaning ($m^{-1}$) | Change (%) | Cleaning solution |
|---|---|---|---|---|---|
| I | TFC-SR | $1.04 \times 10^{14} \pm 2 \times 10^{12}$ | $1.10 \times 10^{14} \pm 6 \times 10^{12}$ | +6 | NaOH |
| I | NF-200B | $7.51 \times 10^{13} \pm 3.4 \times 10^{12}$ | $8.18 \times 10^{13} \pm 1.4 \times 10^{12}$ | +8 | NaOH |
| II | TFC-SR | $5.84 \times 10^{13} \pm 1.2 \times 10^{12}$ | $5.06 \times 10^{14} \pm 1.3 \times 10^{12}$ | -15 | NaOH |
| II | NF-200B | $6.14 \times 10^{13} \pm 1.4 \times 10^{12}$ | $5.50 \times 10^{13} \pm 5 \times 10^{11}$ | -12 | NaOH |
| III | TFC-SR | $9.13 \times 10^{13} \pm 2.7 \times 10^{12}$ | $8.94 \times 10^{13} \pm 1.5 \times 10^{12}$ | -2 | NaOH |
| III | NF-200B | $4.61 \times 10^{13} \pm 7 \times 10^{11}$ | $5.42 \times 10^{13} \pm 1.5 \times 10^{12}$ | +15 | NaOH |
| IV | TFC-SR | $5.32 \times 10^{13} \pm 6 \times 10^{11}$ | $4.96 \times 10^{13} \pm 8 \times 10^{11}$ | -7 | NaOH |
| IV | NF-200B | $5.35 \times 10^{13} \pm 7 \times 10^{11}$ | $5.67 \times 10^{13} \pm 3.5 \times 10^{12}$ | +6 | NaOH, $H_2SO_4$ |

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

**Specific flux profiles.** Normalized specific flux profiles for the duration of the experiments using NF-200B and TFC-SR membranes are depicted in Figures 5 and 6, respectively. Both membranes experienced an initial decline in flux and during the 90% recovery experiment. However, the flux appeared to stabilize for the duration of the remaining experiments at 30% and 50% recoveries. Overall, both membranes experienced relatively stable operation throughout the duration of the experiment.

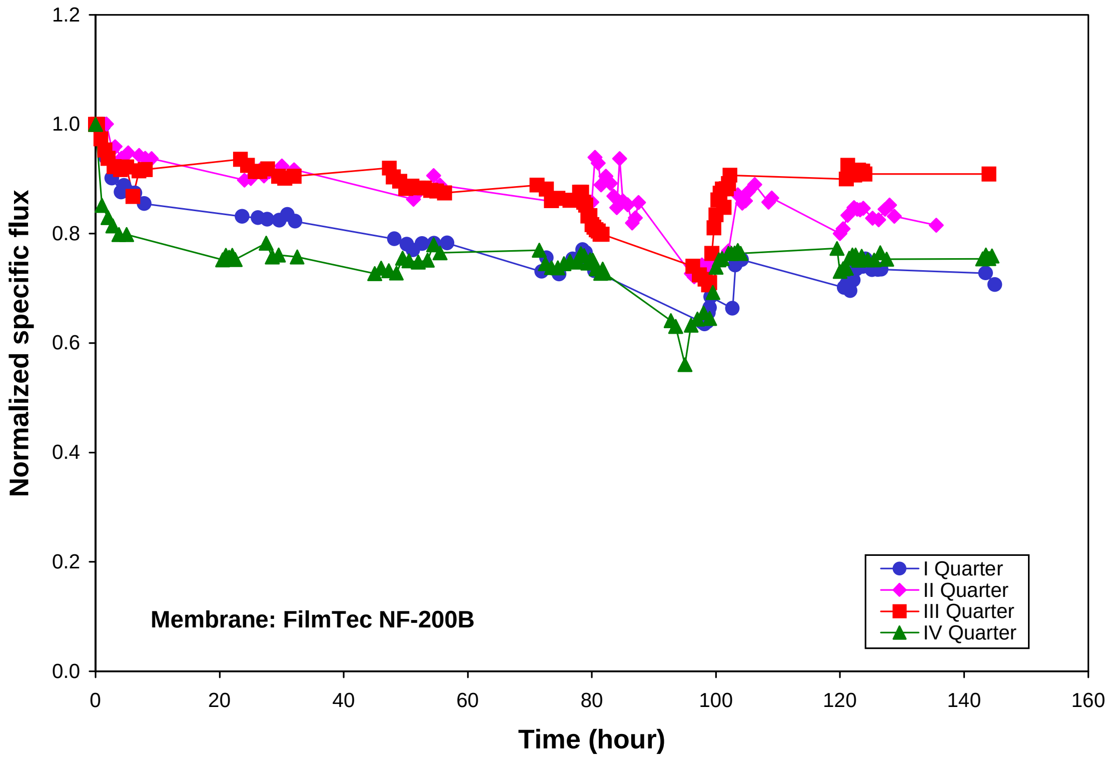


**Figure 5.** Normalized specific flux profiles for four quarters using the NF-200B membrane.

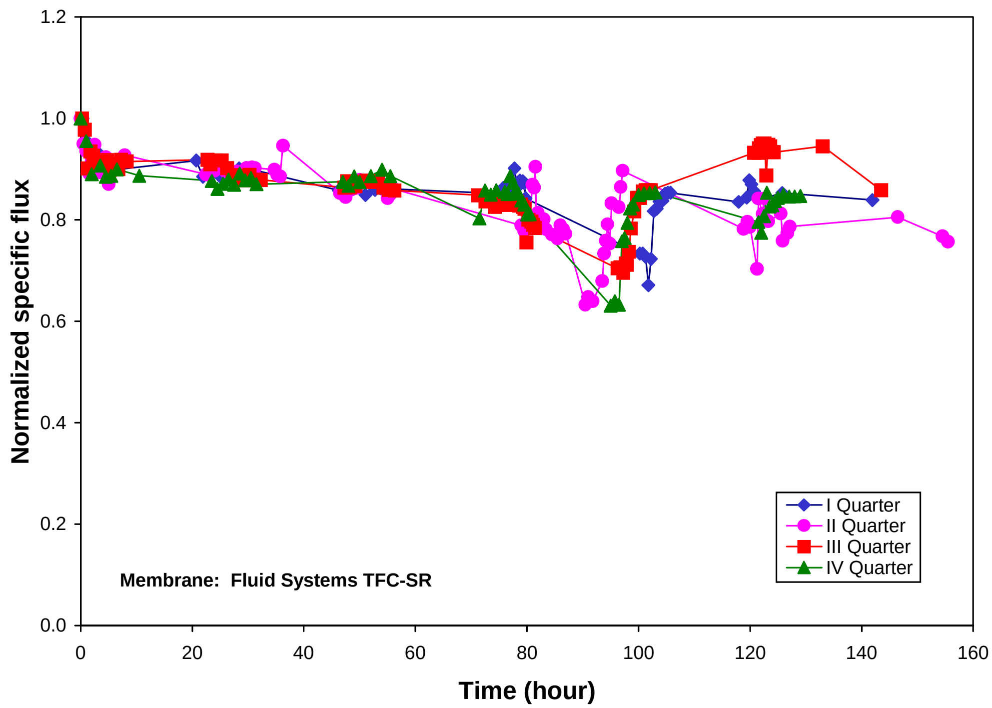


**Figure 6.** Normalized specific flux profiles for four quarters using the TFC-SR membrane.

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 11.3 to 15.4 gfd with an average value of 13.0 gfd. The lowest recorded permeate flux ranged from 7.3 to 9.3 gfd with an average value of 8.7 gfd. This constituted a decrease of approximately 33% 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 | NF-200B | 15.2 | 9.3 |
| I | TFC-SR | 11.6 | 7.7 |
| II | NF-200B | 15.0 | 8.8 |
| II | TFC-SR | 14.3 | 9.1 |
| III | NF-200B | 14.0 | 8.3 |
| III | TFC-SR | 13.5 | 8.7 |
| IV | NF-200B | 14.0 | 7.5 |
| IV | TFC-SR | 14.2 | 8.1 |

[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 0.47 to 0.82. The corresponding cleaning intervals were obtained using Equation 3 and ranged from 69 to 192 hours with an average of 132 hours. Therefore, it appears that under the conditions employed, membrane cleaning needs to be conducted approximately every 6 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 | NF-200B | 0.0411 ± 0.0079 | 14.08 ± 0.36 | 0.82 | 68.5 |
| II | NF-200B | 0.0192 ± 0.0047 | 12.25 ± 0.19 | 0.74 | 127.9 |
| III | NF-200B | 0.0140 ± 0.0038 | 11.50 ± 0.16 | 0.64 | 164.4 |
| IV | NF-200B | 0.0204 ± 0.0081 | 11.48 ± 0.38 | 0.47 | 112.1 |
| I | TFC-SR | 0.0216 ± 0.0048 | 11.47 ± 0.20 | 0.77 | 106.3 |
| II | TFC-SR | 0.0206± 0.0049 | 13.93 ± 0.18 | 0.64 | 135.6 |
| III | TFC-SR | 0.0161± 0.0028 | 11.88 ± 0.12 | 0.77 | 147.9 |
| IV | TFC-SR | 0.0129 ± 0.0048 | 12.41 ± 0.21 | 0.52 | 192.4 |

*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 or organic and inorganic water quality parameters. SDS testing was performed on the composite permeate samples and the feed water.

Tables 17 and 18 provides a summary of all physical, organic and inorganic permeate water quality parameters obtained using the NF-200B and TFC-SR membranes, respectively, at 70% feed water recovery for all four quarters of testing.

**Table 17.** NF-200B permeate water quality for all four quarters of testing at 70% recovery.

| Parameter | Units | Quarter I | Quarter II | Quarter III | Quarter IV |
|---|---|---|---|---|---|
| Alkalinity | mg/L as $CaCO_3$ | 113 | 97 | 196 | 143 |
| Ca hardness | mg/L as $CaCO_3$ | 115 | 89 | 96 | 148 |
| Total hardness | mg/L as $CaCO_3$ | 167 | 173 | 144 | 212 |
| TDS | mg/L | 495 | 360 | 441 | 556 |
| Bromide | μg/L | 510 | 280 | 380 | 655 |
| Ammonia | mg $NH_3$-N/L | BMRL | 0.08 | BMRL | BMRL |
| SDS $Cl_2$ demand | mg/L | 1.46 | 0.69 | 0.51 | 1.44 |
| TOC | mg/L | BMRL | BMRL | 0.65 | 0.5 |
| SDSTOX | μg/L | 35.5 | 37.5 | 36.5 | 44 |
| SDSTHM | μg/L | 30.6 | 30.5 | 17.2 | 43 |
| SDSHAA(5) | μg/L | 8.45 | 12.6 | 3.5 | 5.5 |
| SDSHAA(9) | μg/L | 19.4 | 12.6 | 8.3 | 6.0 |
| $UV_{254}$ | $cm^{-1}$ | BMRL [a] | BMRL | BMRL | BMRL |
| pH | - | 8.20 | 8.26 | 8.34 | 8.10 |
| Turbidity | NTU | 0.05 | 0.06 | 0.09 | 0.07 |

[a] BMRL denotes below minimum reporting level

**Table 18.** TFC-SR permeate water quality for all four quarters of testing at 70% recovery.

| Parameter | Units | Quarter I | Quarter II | Quarter III | Quarter IV |
|---|---|---|---|---|---|
| Alkalinity | mg/L as $CaCO_3$ | 107 | 100 | 199 | 140 |
| Ca hardness | mg/L as $CaCO_3$ | 54 | 59 | 52 | 106 |
| Total hardness | mg/L as $CaCO_3$ | 65 | 80 | 78 | 138 |
| TDS | mg/L | 439 | 377 | 441 | 511 |
| Bromide | μg/L | 425 | 280 | 350 | 655 |
| Ammonia | mg $NH_3$-N/L | 0.07 | 0.13 | 0.06 | BMRL |
| SDS $Cl_2$ demand | mg/L | 1.18 | 0.60 | 0.38 | 0.77 |
| TOC | mg/L | BMRL | BMRL | 0.5 | BMRL |
| SDSTOX | μg/L | 40 | 36.5 | 27 | 29 |
| SDSTHM | μg/L | 17.2 | 19.0 | 15 | 21 |
| SDSHAA(5) | μg/L | 2.4 | 4.7 | 4.1 | 3.3 |
| SDSHAA(9) | μg/L | 2.4 | 10.3 | 4.1 | 3.3 |
| $UV_{254}$ | $cm^{-1}$ | BMRL | BMRL | BMRL | BMRL |
| pH | - | 8.00 | 7.92 | 8.21 | 7.93 |
| Turbidity | NTU | 0.22 | 0.07 | 0.11 | 0.07 |

[a] BMRL denotes below minimum reporting level

**Total organic carbon removal.** TOC removals measured at 70% feed water recovery by both membranes are summarized in Figure 7. Of the two membranes tested at the bench-scale, the TFC-SR membrane achieved higher rejections of total organic carbon. As shown in Table 19, permeate TOC concentrations using the TFC-SR membrane were all below the minimum reporting level of 0.5 mg/L (except for three measurements). The highest recorded permeate TOC concentration using this membrane was 0.6 mg/L. Thus, the lowest TOC removal percentage using the TFC-SR membrane was 77%. In contrast, the NF-200B membrane achieved lower TOC removal (see Table 20). The highest recorded permeate TOC concentration using this membrane was 1.0 mg/L. Thus, the lowest TOC removal percentage using the NF-200B membrane was 71%.

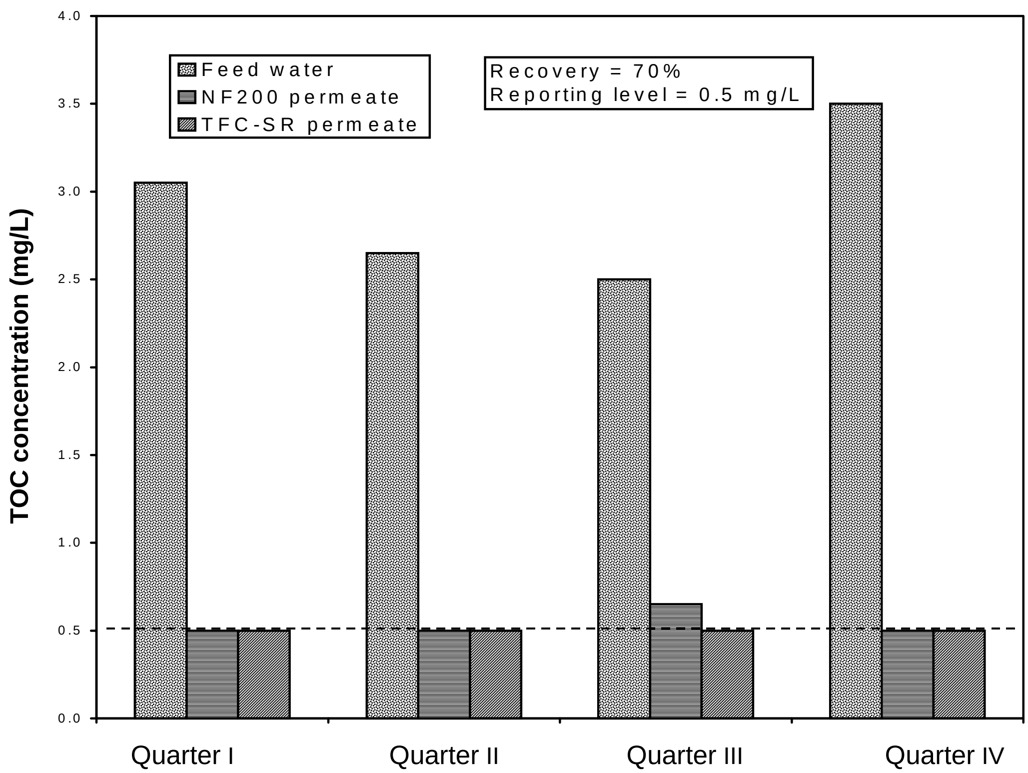


**Figure 7.** TOC removal by TFC-SR and NF200B membranes at 70% recovery.

**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 | > 84 [a] | BMRL | > 81 | BMRL | > 80 | BMRL | > 86 |
| 50 | BMRL | > 84 | 0.60 | 77 | BMRL | > 80 | BMRL | > 86 |
| 70 | BMRL | > 84 | BMRL | > 81 | 0.50 | 80 | BMRL | > 86 |
| 90 | BMRL | > 84 | 0.60 | 77 | BMRL | > 80 | BMRL | > 86 |

[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 NF-200B 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 | > 84 [a] | BMRL | > 81 | BMRL | > 80 | BMRL | > 86 |
| 50 | BMRL | > 84 | BMRL | > 81 | BMRL | > 80 | 1.0 | 71 |
| 70 | BMRL | > 84 | BMRL | > 81 | 0.65 | 74 | 0.5 | 86 |
| 90 | 0.80 | 74 | 0.80 | 70 | 0.50 | 80 | 0.9 | 74 |

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

**Disinfection by-product precursor removal.** The highest SDSTTHM and SDSHAA(5) concentrations using the TFC-SR membrane were approximately 21 μg/L and 4.7 μg/L, respectively. Compared to the TFC-SR membrane, higher concentrations of organic constituents were observed in the NF-200B membrane permeate water. For example, the highest SDSTTHM and SDSHAA(5) concentrations using the NF200B membrane were 31 μg/L and 20 μg/L, respectively.

Both membranes achieved high TOC removals, but the TFC-SR membrane achieved higher removals of SDSTTHM and SDSHAA(5) precursors (see Tables 17 and 18). Under the SDS conditions employed, SDSTTHM and SDSHAA(5) concentrations in both membrane permeate waters (except for NF-200B membrane during Quarter IV) were below the place holders set by Stage II of the D/DBP rule (40 μg/L for TTHMs and 30 μg/L for HAA(5)).

HAA(5) and TTHM precursor removals from pretreated Rio Grande River water by TFC-SR and NF200B membranes (at 70% recovery) are summarized in Figures 8 and 9, respectively.

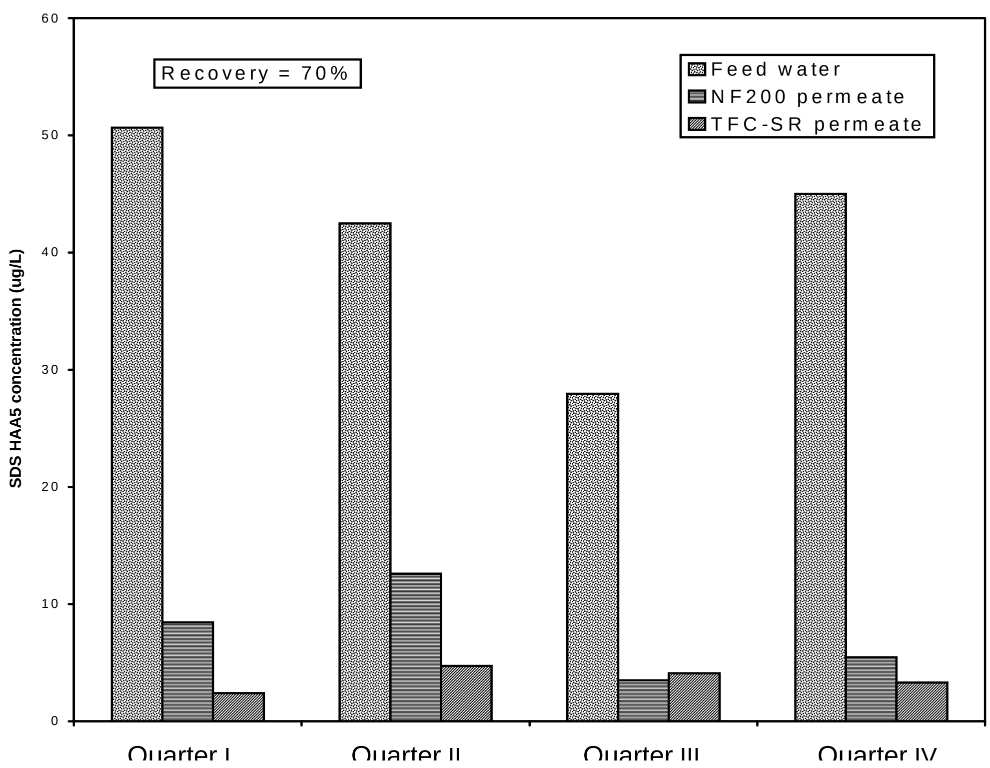


**Figure 8.** HAA5 precursor removals by TFC-SR and NF200B membranes at 70% recovery.

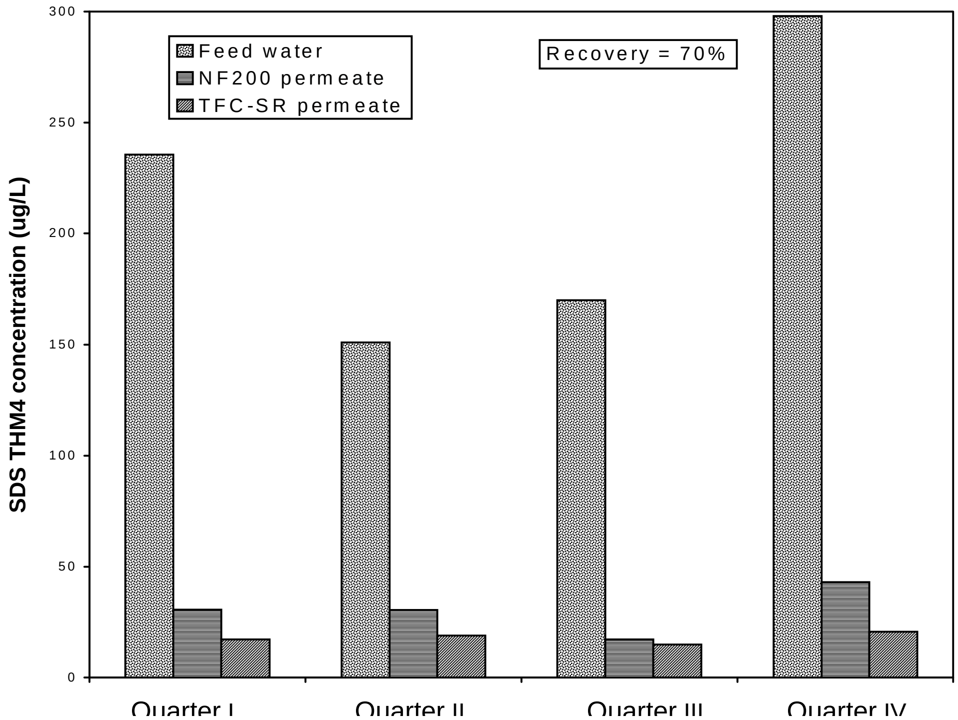


**Figure 9.** THM precursor removals by TFC-SR and NF200B membranes at 70% recovery.

**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 concentration of 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 the 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, the mixed chloro-bromo species were dominant in the NF feed water. However, as the ratio of the concentration of bromide ion concentration to TOC concentration increased dramatically, bromoform and chlorodibromo methane were the dominant THM species in the NF permeate water.

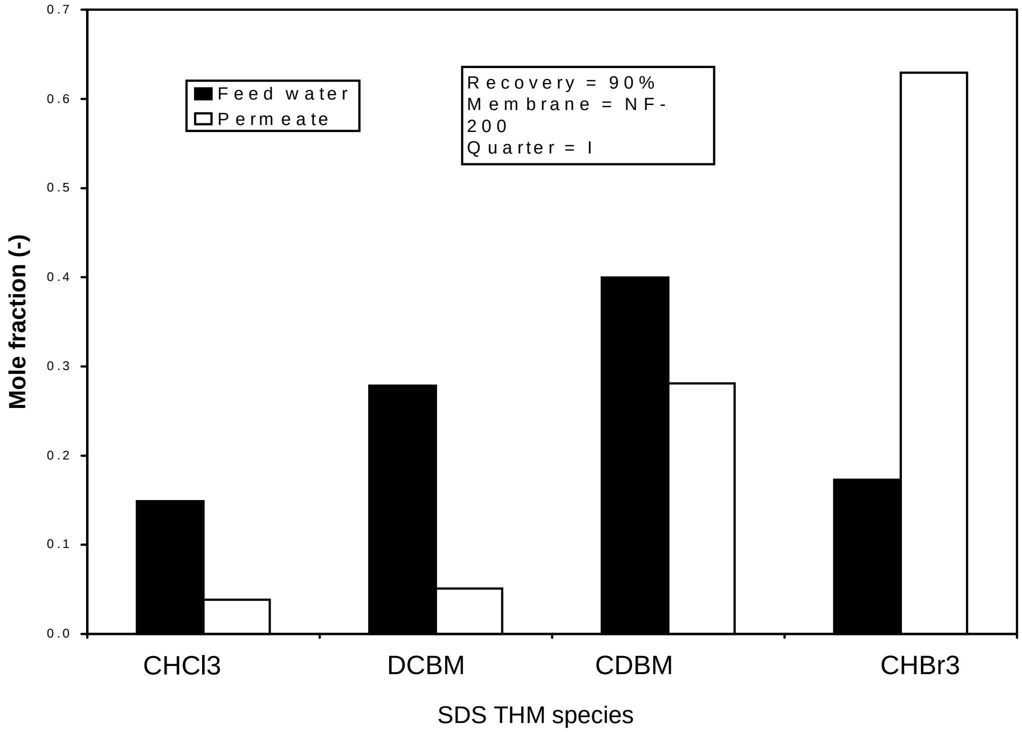


**Figure 10.** Changes in THM speciation expressed as mole fraction after nanofiltration (data from Quarter I experiments at 90% feed water recovery using NF-200B membrane).

**Inorganics removal.** Both membranes employed in this study achieved approximately 63% TDS rejection. In addition, the TFC-SR membrane removed approximately 75% of total hardness. However, the NF-200B membrane removed only 51% of total hardness from the membrane feed water. Neither membrane employed in this study was able to achieve any measurable removal of the bromide ion, resulting in large changes in trihalomethane and haloacetic acid speciation in the permeate water compared to the feed water.

**Sulfate removal.** Results from sulfate sampling of the permeate waters for the NF-200B and TFC-SR membranes are summarized in Tables 21 and 22, respectively. Samples were taken only during the last three quarters of testing. The effects of feed water recovery on permeate sulfate concentrations measured during the second quarter of testing are depicted in Figure 11. As with other water quality parameters, the TFC-SR membrane achieved higher removals of sulfate compared to the NF-200B membrane.

**Table 21.** Summary of sulfate concentrations in NF-200B membrane permeate.

| Recovery (%) | Quarter I | Quarter II | | Quarter III | | Quarter IV | |
|---|---|---|---|---|---|---|---|
| | | Conc. (mg/L) | Removal (%) | Conc. (mg/L) | Removal (%) | Conc. (mg/L) | Removal (%) |
| 30 | NA[a] | 9.7 | 96 | 9.8 | 97 | 19.1 | 89 |
| 50 | NA | 15.4 | 94 | 14.6 | 95 | 27.7 | 83 |
| 70 | NA | 25.0 | 90 | 29.9 | 90 | 39.5 | 76 |
| 90 | NA | 58.1 | 77 | 59.8 | 79 | 93.2 | 44 |

[a] Denotes sample not collected

**Table 22.** Summary of sulfate concentrations in NF-200B membrane permeate.

| Recovery (%) | Quarter I | Quarter II | | Quarter III | | Quarter IV | |
|---|---|---|---|---|---|---|---|
| | | Conc. (mg/L) | Removal (%) | Conc. (mg/L) | Removal (%) | Conc. (mg/L) | Removal (%) |
| 30 | NA[a] | 5.3 | 98 | 2.0 | 99 | 3.8 | 98 |
| 50 | NA | 6.7 | 97 | 2.9 | 99 | 5.3 | 97 |
| 70 | NA | 7.2 | 97 | 5.2 | 98 | 7.6 | 95 |
| 90 | NA | 22.3 | 91 | 17.0 | 94 | 18.2 | 89 |

[a] Denotes sample not collected

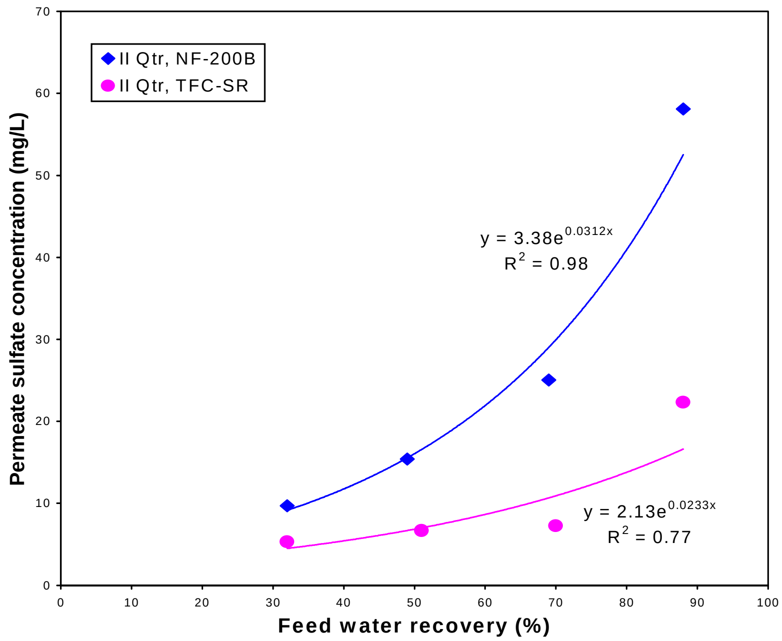


**Figure 11.** Effect of feed water recovery on sulfate concentrations.

**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 23 and 24 summarize the effects of recovery on the rejection of select water quality parameters by the NF-200B and TRC-SR membranes. These data were obtained by averaging 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 12 depicts the effects of feed water recovery on permeate TDS concentrations and TDS removal using the NF200B and the TFC-SR membranes for the first quarter of testing. Permeate TDS concentrations increased exponentially with feed water recovery ($R_f$) for both membranes. The following empirical fits were obtained using the first quarter data:

TFC-SR membrane: Permeate TDS (mg/L) = 386 exp(0.0024$R_f$) ($R^2$ = 0.83)

NF200B membrane: Permeate TDS (mg/L) = 403 exp(0.0032$R_f$) ($R^2$ = 0.93)

The effects of feed water recovery on permeate $SO_4$ concentrations using the NF200B and the TFC-SR membranes were depicted graphically in Figure 8 for the second quarter of testing. Permeate TDS concentrations increased exponentially with feed water recovery for both membranes. The following empirical fits were obtained using the second quarter data:

TFC-SR membrane: Permeate $SO_4$ (mg/L) = 3.38 exp(0.0312$R_f$) ($R^2$ = 0.98)

NF200B membrane: Permeate $SO_4$ (mg/L) = 2.13 exp(0.0233$R_f$) ($R^2$ = 0.77)

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 23.** Effect of feed water recovery on rejection of selected water quality parameters using the NF-200B membrane.

| Parameter | Units | 30% recovery | | 50% recovery | | 70% recovery | | 90% recovery | |
|---|---|---|---|---|---|---|---|---|---|
| | | Median | Range | Median | Range | Median | Range | Median | Range |
| Ca hardness | mg/L as $CaCO_3$ | 92 | 76-138 | 98 | 84-148 | 104 | 88-150 | 118 | 102-198 |
| Total hardness | mg/L as $CaCO_3$ | 139 | 114-198 | 145 | 130-206 | 169 | 144-212 | 184 | 140-256 |
| TDS | mg/L | 422 | 339-525 | 436 | 321-537 | 467 | 355-567 | 515 | 396-630 |
| Bromide | μg/L | 445 | 230-640 | 450 | 280-660 | 445 | 380-660 | 445 | 270-630 |
| Ammonia | mg $NH_3$-N/L | 0.05 | BMRL-0.05 | BMRL | BMRL | 0.08 | BMRL-0.08 | 0.18 | BMRL-0.18 |
| SDS $Cl_2$ demand | mg/L | 0.61 | 1.32-0.33 | 0.73 | 1.27-0.46 | 0.91 | 1.81-0.48 | 1.32 | 1.70-0.67 |
| TOC | mg/L | BMRL | BMRL | 1.0 | BMRL-1.0 | 0.6 | 0.5-0.9 | 0.8 | BMRL-0.7 |
| SDSTOX | μg/L | 32 | BMRL-35 | 28 | BMRL-34 | 37 | 34-50 | 58 | 53-71 |
| SDSTTHM | μg/L | 16.27 | 11-20.7 | 20.5 | 12.9-26.4 | 30.5 | 16.6-45.6 | 53.70 | 29.5-74.4 |
| SDSHAA(5) | μg/L | 3.30 | 1.7-4.8 | 5.10 | 1.6-8.5 | 5.45 | BMRL-12.6 | 8.95 | 1.7-13.0 |
| SDSHAA(9) | μg/L | 3.30 | 1.7-4.8 | 6.2 | 1.6-9.5 | 5.95 | BMRL-21.2 | 17.55 | 1.7-27.2 |
| $UV_{254}$ | $cm^{-1}$ | BMRL | BMRL | BMRL | BMRL | BMRL | BMRL | 0.011 | BMRL-0.013 |

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

**Table 24.** 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 $CaCO_3$ | 57 | 46-116 | 60 | 50-120 | 56 | 52-108 | 72 | 60-138 |
| Total hardness | mg/L as $CaCO_3$ | 78 | 64-148 | 78 | 66-152 | 80 | 66-142 | 105 | 88-170 |
| TDS | mg/L | 400 | 371-498 | 423 | 374-517 | 441 | 370-518 | 474 | 450-545 |
| Bromide | μg/L | 410 | 300-650 | 395 | 290-640 | 385 | 280-670 | 415 | 280-620 |
| Ammonia | mg $NH_3$-N/L | 0.06 | BMRL-0.06 | 0.06 | 0.14-BMRL | 0.07 | 0.2-BMRL | 0.06 | 0.06-BMRL |
| SDS $Cl_2$ demand | mg/L | 0.56 | 1.2-0.39 | 0.62 | 1.23-0.44 | 0.68 | 1.26-0.41 | 0.75 | 1.4-0.56 |
| TOC | mg/L | BMRL | BMRL | 0.6 | BMRL-0.6 | 0.5 | BMRL-0.5 | 0.6 | BMRL-0.6 |
| SDSTOX | μg/L | 30 | BMRL-33 | 27 | 25-92 | 31 | 27-41 | 36 | 31-58 |
| SDSTTHM | μg/L | 12.6 | 11.0-15.8 | 16.3 | 13.3-18.8 | 17.9 | 14.8-23.0 | 28.2 | 26.3-30.1 |
| SDSHAA(5) | μg/L | 2.20 | 1.6-3.0 | 2.60 | 1.9-2.9 | 3.45 | 2.3-6.9 | 5.40 | 3.1-6.8 |
| SDSHAA(9) | μg/L | 2.45 | 1.9-3.5 | 2.60 | 1.9-4.1 | 3.45 | 2.3-11.0 | 5.40 | 3.1-8.6 |
| $UV_{254}$ | $cm^{-1}$ | BMRL | BMRL | BMRL | BMRL | BMRL | BMRL | BMRL | BMRL |

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

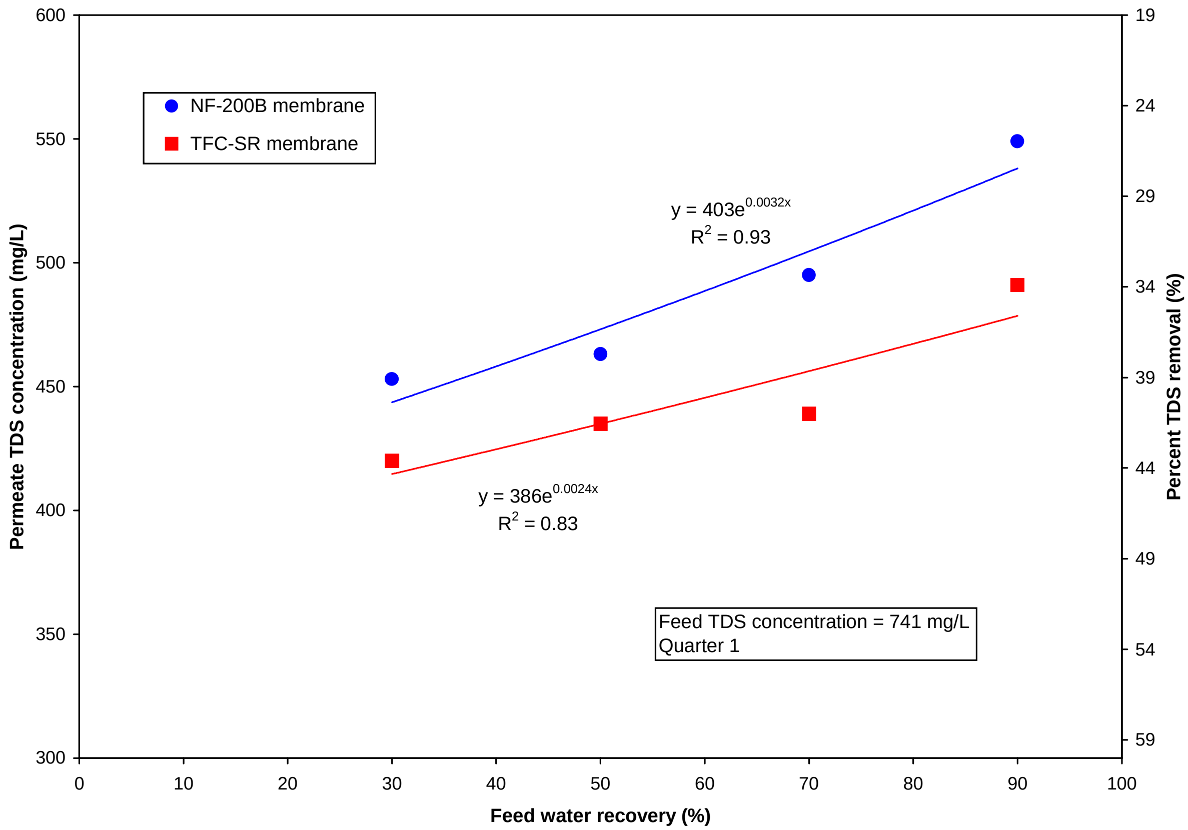


**Figure 12.** Effect of feed water recovery on permeate TDS concentration.

**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 water 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 = 214 μg/L, average feed water SDSHAA9 concentration = 103 μg/L). When free chlorine is employed as the disinfectant, blending is not expected to be a feasible alternative if Stage II concentrations of the D/DBP Rule are considered.

**Problems encountered.** In general, ICR experiments were conducted smoothly. Occasionally, the feed water recovery dropped by approximately 2 to 8% when the ICR RBSMT apparatus was left unattended during overnight operation, especially during experiments at 90% feed water recovery.

# Section 5
# QA/QC Summary

**Laboratory analyses.** For this study, samples were shipped to two ICR certified laboratories: Montgomery Watson Laboratories, CA and Summers and Hooper Inc., OH. The tables presented in this section summarize the QA/QC information provided by these two commercial laboratories in the format required under the ICR.

Quality assurance and quality control (QA/QC) summary data from Montgomery Watson Laboratories reflects ICR samples for the City of Brownsville and other bench-scale test utilities, as per agreement with Mr. Steve Allegeier, ICR Technical Coordinator.

Summers and Hooper provided HAA9 analyses only.

**ICR RBSMT data collection spreadsheets.** To ensure the integrity of the data collected and reported in this treatment study, EPA has previously provided one preliminary review of the ICR Treatment Study Data Collection Spreadsheets for the City of Brownsville. The comments generated during this preliminary review process are in Appendix B. The Data Collection Spreadsheets reflect these comments. Detailed responses to these comments are described below:

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

1. Cost of an 8x40 TFC-SR membrane element is not available from manufacturer.
2. No water quality parameters (including potential foulants) were measured prior to pretreatment because they were not required under the ICR.
3. The chemical formula for the alum employed in bench-scale pretreatment is provided.
4. A value of 0 has been entered for $\Delta\pi$.
5. Cost data have been provided.
6. Quarterly changes in SDS incubation times represent seasonal variations in the City of Brownsville's distribution system.

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

1. The rapid drop in $MTC_w$ was because we had inadvertently switched $Q_p$ and $Q_c$. Appropriate changes were made.
2. BDCM and $CHBr_3$ concentrations are as reported by the lab. No changes made.
3. The permeate bromide concentrations are as reported by the lab. No changes made.
4. The measured SDS conditions have been entered.

TFC-SR Membrane Quarter II:

1. Missing dates have been entered.
2. Duplicate HAA concentrations are reported as NR.
3. The permeate bromide concentrations are as reported by the lab. No changes made.

TFC-SR Membrane Quarter III:

1. SUVA formula has been entered.
2. The overall TDS rejection measured in all TFC-SR RBSMT experiments during 3rd quarter RBSMT experiments was 59%. It is only slightly (not substantially) lower than the TDS rejections measured in other quarters (62%, 63% and 69%). Further, the overall rejection should be calculated as a volume or time weighted average. A simple arithmetic average will depend on the number of measurements at different recoveries. Additionally, a complete water quality analysis needs to be performed to determine the ionic composition of the NF feed water to further understand the rejection of individual ions (and therefore the TDS).
3. Permeate TOX concentration at 50% recovery is as reported by the lab. No change made.

TFC-SR Membrane Quarter IV:

1. Missing dates have been entered.
2. $MTC_w$ values are as measured in the laboratory. No changes made.

NF-200B Membrane Quarter I:

1. Missing dates have been entered.
2. Dates and times of sampling have been entered.
3. BDCM and $CHBr_3$ concentrations are as reported by the lab. No changes made.

NF-200B Membrane Quarter II:

1. “-“ has been deleted from cell AP5.
2. Missing dates have been entered.
3. Duplicate HAA concentrations are reported as NR.
4. Alkalinity concentrations are as measured in the lab. No changes made.
5. Bromide concentrations at 30% recovery are as reported by the lab. No changes made.

NF-200B Membrane Quarter III:

1. "-" has been deleted from cell AP5.
2. Missing dates have been entered.
3. All water quality parameters reported for the run at 90% recovery are as measured in the lab. No changes made.
4. TOC concentrations and $UV_{254}$ values are as reported in the lab data sheets. No changes made.

NF-200B Membrane Quarter IV:

1. Missing dates have been entered.
2. TOC concentrations are as reported by the labs. No changes made.

# Section 6
# Acknowledgments

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# Appendix A

# Appendix B