STRENGTH IN NUMBERS – FOUR MUNICIPALITIES SHARE COSTS FOR A MAJOR LOW PRESSURE MEMBRANE PILOT STUDY

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ABSTRACT

Pilot testing can be an expensive and time-consuming project. An innovative approach to pilot studies that minimizes costs is for entities to come together and share the expenses. This benefits the utilities from a financial perspective and provides information for the enhanced water treatment possibilities at multiple facilities.

The City of Mansfield, along with several other municipalities in the Dallas/Fort Worth Metroplex, obtains raw water from Cedar Creek, Richland-Chambers, and Benbrook Lakes, which are operated by the Tarrant Regional Water District (TRWD). The Cities of Waxahachie, Midlothian and Fort Worth will also use water from these sources for the new water treatment plants (WTPs) proposed for their cities. Since the four Cities will use the same raw water from TRWD, they have decided to work together and share the results of a membrane filtration pilot study.

The City of Mansfield volunteered to host the pilot study using the TRWD raw water at their existing WTP. G.E. Ionics, Siemens Memcor, G.E. Zenon Environmental, Pall Corporation, and Koch Membrane Systems provided pilot units for the study. The pilot study commenced early February 2006 and the initial runs were completed by December 2006. Settled water was piloted first, followed by direct filtration using both aluminum sulfate (alum) and polyaluminum chloride (PACl) coagulated water.

Due to drought conditions in the Dallas/Fort Worth Metroplex, raw water from Lake Benbrook was not pumped to the Mansfield WTP during the pilot study in 2006. As such, a pilot study using raw water from Lake Benbrook is being conducted at the Benbrook Water and Sewer Authority (BWSA) WTP, just north of Lake Benbrook, for the City of Fort Worth. Direct filtration using ferric sulfate coagulated water will be piloted at Benbrook. The data collected from the Benbrook pilot will be presented along with the data from the Mansfield WTP in a single pilot report for the TRWD water.

Testing results from the pilot studies at the Mansfield and Benbrook WTPs will be used in conjunction with the experience of the engineer, owner, regulatory agencies and membrane manufacturers to determine appropriate operation and design criteria for the full-scale WTPs. This paper provides a description of membrane technology and terminology, a comparison of the water quality data for the three TRWD raw water sources, coordination details for conducting a low-pressure pilot study, and the results collected to date from the pilot studies at the Mansfield and Benbrook WTPs.

KEYWORDS

Water treatment, membranes, ultrafiltration, microfiltration, pilot testing.

BACKGROUND

TRWD pumps raw water from Cedar Creek Lake, Richland Chambers Lake or a combination of the two lakes into the Dallas/Fort Worth Metroplex. Occasionally, raw water from Benbrook Lake is pumped through the line in the opposite direction to supply TRWD customers. Figure 1 is a map of the TRWD lakes and raw water pipeline routes as published in the 2005 TRWD Water Conservation and Drought Contingency Plan.

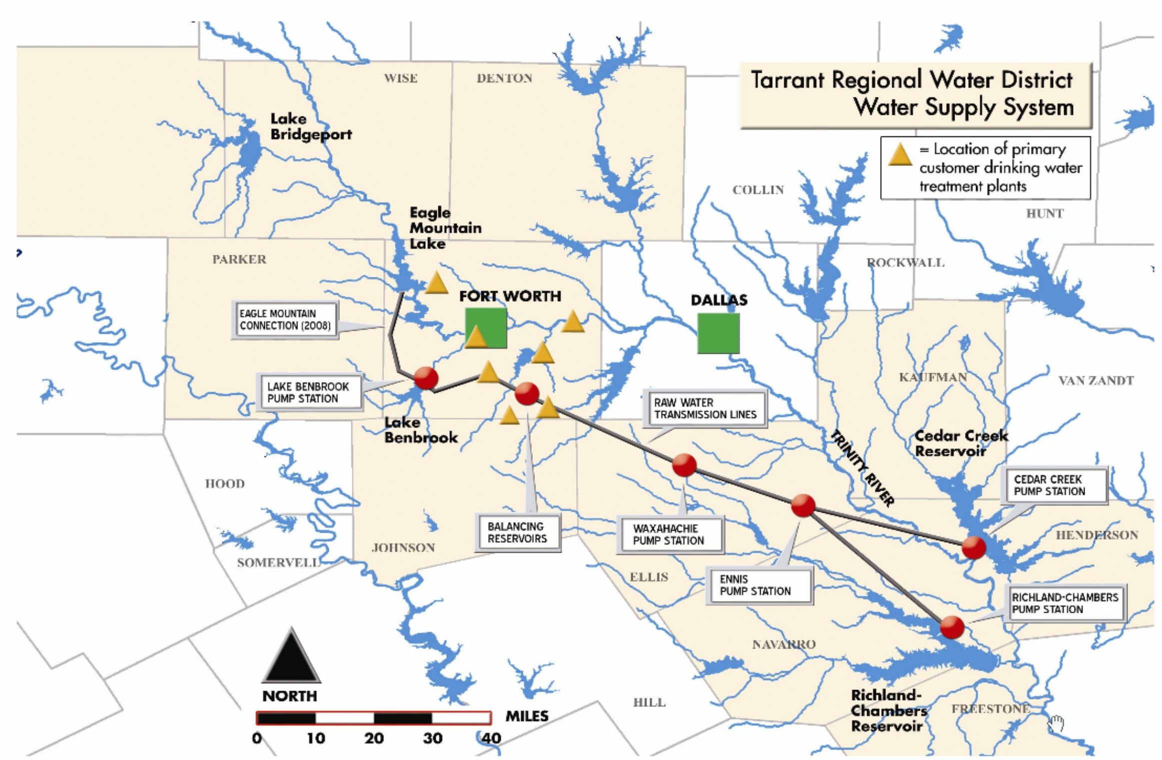

Figure 1: Tarrant Regional Water District Supply System

When an innovative treatment system is proposed for a water treatment plant, a licensed professional engineer must provide to the State either pilot test data or data collected at a similar full-scale facility which demonstrates that the innovative treatment system will meet drinking water standards. Due to the scale of the four proposed WTP projects, a membrane filtration pilot study was preferred to adapting pilot data collected at other water treatment plants. The membrane pilot studies are being conducted in accordance with the Texas Commission on Environmental Quality (TCEQ) Guidance Document for low-pressure membrane pilot studies. The guidance documents for membrane filtration pilot studies are available on the Internet along with other Public Drinking Water Staff

Guidance Documents for Public Water Systems at www.tceq.state.tx.us/permitting/water_supply/pdw/technical_guidance/staff_guidance/.

MEMBRANE FILTRATION

Membrane filtration is as a pressure or vacuum driven separation process in which particulate matter larger than the membrane pore size is rejected by an engineered barrier through a size exclusion mechanism. Membrane filters have highly uniform pore sizes and are therefore capable of very high or "absolute" removal of a targeted particle size or microorganism.

Membrane systems are generally classified by the pore size of the membrane element. Microfiltration (MF) (pore sizes 0.005 to 3.0 um) and ultrafiltration (UF) (pore sizes 0.003 to 0.03 um) are referred to as low-pressure systems. Nanofiltration (NF) (0.001 to 0.008 um) and reverse osmosis (RO) (0.0001 to 0.0015 um) membranes require higher operating pressures and are most often used for the removal of dissolved contaminants, as in the case of softening or desalination. Neither NF nor RO treatment is not required for this source water. Low-pressure membrane systems are being piloted for the four municipalities.

Low-pressure membrane systems (MF/UF) are available in two configurations, pressurized and vacuum. Pressurized systems utilize feed pumps and membranes installed in containers with sealed ends. The containers or modules are mounted to pipe headers or manifolds which make up a rack or skid. Typical operating pressures range from 3 to 40 psi. Figure 2 is a photo of the San Patricio Pall installation in Ingleside, Texas.

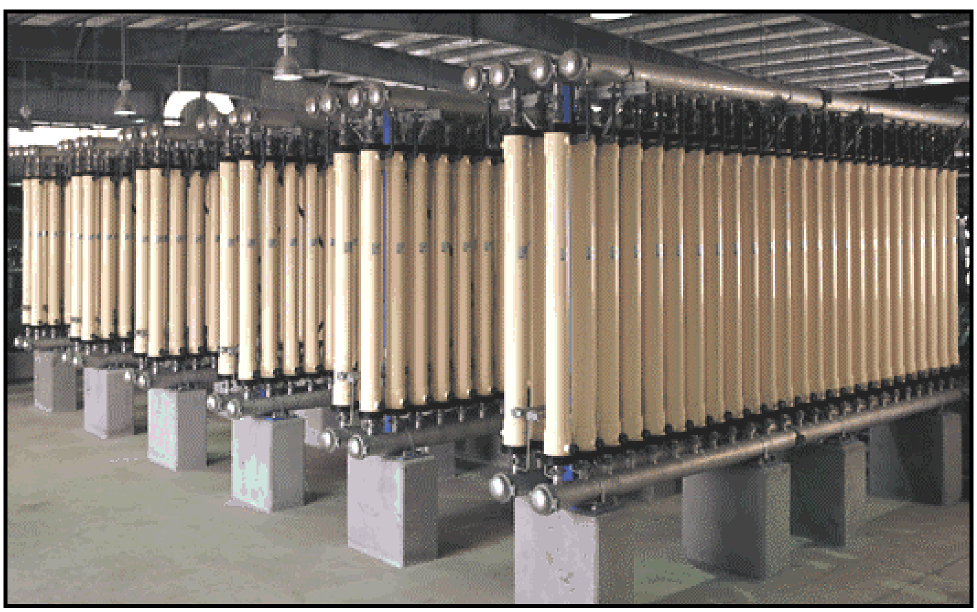

Figure 2: Pall Pressurized Membrane Installation

Vacuum type membrane systems are usually immersed in a basin and filtrate is drawn into the membrane by pump suction. An immersed membrane system operates under a vacuum ranging from -12 to -3 psi. Figure 3 is a photo of a Siemens Memcor vacuum installation in Albany/Millersburg, Oregon. The immersion basin is drained and one of the racks is being removed with Memcor's Service Access Platform (MEMSAP).

Figure 3: Siemens Vacuum Membrane Installation

Both pressurized and vacuum membranes are modular. This allows additional capacity to be installed in small increments, reducing the initial investment. In both configurations, strainers to protect the membranes precede the membrane skids. The diameter and length of membrane modules vary by manufacturer, as does the configuration of the modules and headers.

The TCEQ credits UF/MF membranes with a 3-log removal of *Giardia* and 2-log removal of *Cryptosporidium*. However, currently no credit is given by the TCEQ for UF/MF membranes for virus removal, unless pretreatment is provided. With coagulation and flocculation pre-treatment, the TCEQ credits UF/MF membranes with a 1-log removal of viruses. With coagulation, flocculation and sedimentation pre-treatment, the TCEQ credits UF/MF membranes with a 2-log removal of viruses (as with conventional treatment). Low-pressure membranes are capable of consistently achieving turbidities below 0.1 NTU, regardless of the feed water quality.

Membrane Terminology

Membrane terminology and design criteria are different than for filters. Transmembrane pressure (TMP) refers to the pressure that is required to force water through the membrane. It is the pressure difference between the feed side of the membrane and the filtered side, also known as the filtrate or product side. The TMP will increase over an operating cycle.

The equation used to calculate TMP is provided below.

$$TMP = P_f - P_p$$

Where: TMP = Transmembrane pressure (psi)
P_f = feed pressure (psi)
P_p = filtrate pressure, i.e. backpressure (psi)

Flux rate is the flow rate of the filtered water per unit area of membrane. It is similar to the hydraulic loading rate of a filter. The flux rate may change over time. If flux rates are too high, the membrane surface will accumulate particles too rapidly causing the TMP to increase prematurely. An increase in TMP results in shorter filter runs and increased cleaning requirements, which reduces the recovery of the membranes. The equation used to calculate instantaneous flux is provided below.

$$J = Q_p / A_m$$

Where: J = Instantaneous flux (gfd)
Q_p = Filtrate flow (gpd)
A_m = Membrane surface area (sf)

The effect of temperature on membrane filtration is related to the viscosity of water. As the water temperature decreases, the viscosity of the water increases. As the viscosity of the water increases, more pressure is required to overcome the resistance across the membrane module. If the pressure or TMP is held constant, the capacity of the membrane module decreases with decreasing temperature. The equation used by the TCEQ to calculate temperature's effect on membrane filtration is provided below.

$$J_{20\,°C} = J_t * e^{[-0.0239*(\text{actual water temperature } -20)]}$$

Where: $J_{20\,°C}$ = Instantaneous flux at 20 °C (gfd)
J_t = Instantaneous flux at actual water temperature (gfd)

The effect of viscosity on water production is considered complementary, as the new WTP will have lower production demands when the water temperatures are lower. Using the TCEQ temperature correction equation, a membrane plant with a capacity of 20 MGD at 20 °C would have a capacity of 14.7 MGD at a minimum water temperature of 7 °C and a capacity of 26.6 MGD at a maximum water temperature of 32 °C.

The recovery is the percent of treated water that is obtained as a ratio to the feed water. The recovery is affected by the backwashing frequency and chemical cleaning frequency, which as stated are a function of the raw and feed water quality, pretreatment, membrane type, and flow pattern.

The equation used to calculate percent recovery is provided below.

$$R = Q_p / Q_f$$

Where: R = Recovery of the membrane (%)
Q_p = Filtrate flow (gpd)
Q_f = Feed flow (gpd)

Membrane fouling occurs when particles, organic matter, and microorganisms accumulate on the membrane surface as water passes through the membrane or when chemicals deposit or absorb into the membrane. This accumulation may be due to physical size or surface charge of the particles. Fouling may be irreversible or reversible. Backwashing is done to remove accumulated material from the membrane surface, similar to a filter, and return the membrane to an operating level close to its original TMP. The backwash cycle is a function of the water quality, membrane type, and flow pattern in the membrane. Backwash intervals determined through piloting at the Mansfield and Benbrook WTPs range from 15 to 45 minutes and lasts 90 seconds to 4.5 minutes.

Most manufactures also suggest a chemically enhanced backwash using sodium hypochlorite and/or citric acid to improve membrane performance. The frequency of chemically enhanced backwashing ranged from daily to once every two weeks when piloting settled water and from every third backwash to daily when piloting direct membrane filtration.

Backwashing may not return the membrane to the original flux and TMP conditions. Over time, the membrane permeability will be reduced. Some of the reduction can be reclaimed by clean-in-place (CIP) chemical cleaning. CIP chemical cleans include a low pH cycle with citric or phosphoric acid and then a high pH cycle with caustic and chlorine. The low pH cycle is commonly used to dissolve mineral scaling. The high pH cycle is typically employed to dissolve organic material and control biofouling. The cleaning cycle lasts several hours and the module or skid is taken offline from service during cleaning. CIP cleaning intervals vary from 25 days to six months.

Integrity of the membrane system was checked daily via an air integrity test (AIT). In hollow-fiber systems, typically the inside of the fiber lumen is drained and pressurized with air. The applied pressure is lower than the bubble point pressure of the membrane but high enough to detect a 3-micron defect. A significant decrease in the held pressure indicates a failed test. The integrity of the membrane should be monitored continuously using Hach Filtertrak 660 laser turbidimeters on the filtrate of each skid.

TRWD RAW WATER

Table 1 provides raw water data collected from the Mansfield WTP. The turbidity and alkalinity data was collected every two hours from January 2002 to November 2006. The TOC data was collected monthly from January 2001 through April 2006. The WTP raw water source for the Mansfield WTP is typically a two-thirds Richland Chambers Lake and one-third Cedar Creek Lake blend. TRWD varies the raw water blend to the Mansfield WTP between Lakes Richland Chambers, Cedar Creek and Benbrook depending on lake levels and maintenance needs.

Table 1: Raw Water Quality Data Collected at the Mansfield WTP

Parameter	Units	Average	Median	Minimum	Maximum	Std. Dev.
Turbidity	NTU	5.00	4.02	0.06	39.5	3.94
Alkalinity	mg/L	93.9	93.0	47.0	153	13.7
TOC	mg/L	4.51	4.40	2.90	9.30	0.87

Table 2 provides raw water data from the Benbrook WTP. The turbidity and alkalinity data was collected daily from January 2002 through November 2006. The TOC data was collected monthly from January 2002 through October 2006. The WTP raw water source for the time period was Lake Benbrook.

Table 2: Raw Water Quality Data Collected at the Benbrook WTP

Parameter	Units	Average	Median	Minimum	Maximum	Std. Dev.
Turbidity	NTU	7.79	6.00	1.44	33.3	5.55
Alkalinity	mg/L	110	111	75.0	155	14.9
TOC	mg/L	4.72	4.70	3.00	6.00	0.52

The average turbidity, alkalinity and TOC values measured at the two plants are similar.

Table 3 lists the average values and one standard deviation of the water quality values measured at the top and middle monitoring locations of the TRWD reservoirs. Samples were collected quarterly between January 2003 and November 2005.

Table 3: Comparison of Water Quality Data Collected at TRWD Reservoirs

Constituent	Units	Cedar Creek		Benbrook		Richland-Chambers	
		Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
TOC	mg/L	6.46	0.93	5.04	0.45	4.87	0.68
DOC	mg/L	5.89	0.74	4.51	0.45	2.23	0.57
TSS	mg/L	8.18	2.48	8.10	2.11	10.1	8.48
TDS	mg/L	129	17.0	191	18.8	171	18.2
NH3-N	mg/L	0.06	0.06	0.10	0.10	0.04	0.02
NOx-N	mg/L	0.10	0.09	0.12	0.13	0.24	0.31
TKN	mg/L	1.10	0.33	0.90	0.24	0.92	0.22
TP-P	mg/L	0.09	0.09	0.06	0.01	0.01	0.01
DOPO4-P	mg/L	0.02	0.01	0.01	0.01	5.22	0.79
Alkalinity	mg/L	56	11	108	14	92	14
Sulfate	mg/L	21.8	2.85	30.8	8.71	29.5	3.42
Chloride	mg/L	13.5	2.89	19.7	4.20	10.8	1.36
T-Fe	ug/L	220	142	152	182	264	131
T-Mn	ug/L	68.5	41.0	17.3	12.8	21.8	10.8
Calcium	mg/L	19	4	39	7	35	5
Magnesium	mg/L	3.55	0.48	5.22	1.02	3.24	0.30
Sodium	mg/L	13.5	1.91	17.2	3.13	14.4	1.04
Potassium	mg/L	4.46	0.41	4.07	0.48	4.33	0.43
Total As	ug/L	2.26	1.34	2.54	1.33	3.47	2.67
Chl-a	ug/L	25.3	13.2	19.9	11.8	17.1	8.83
Algae	cells/mL	10131	10404	12644	10128	6244	6035
TTHMFP	umoles/L	2.39	0.71	1.66	0.54	1.92	0.62
Bromide	mg/L	0.52	0.16	0.77	0.25	0.66	0.88
E. coli	MPN	3.95	6.07	8.46	9.77	2.61	5.32

Geosmin concentrations in excess of the threshold taste and odor value of 10 ng/L have been measured at Richland-Chambers, Cedar Creek and Benbrook Lakes. The highest geosmin concentrations have typically been found at Lake Benbrook. Geosmin is a secondary metabolic products of algae (actinomycetes and cyanobacteria). The higher chlorophyll A and algae counts measured in Lake Benbrook correlate with the higher geosmin concentrations.

The pilot study at the Benbrook WTP will be considered an extension of the pilot the Mansfield WTP. The data collected from the Benbrook WTP pilot will be presented along with the data from Mansfield in a single pilot report for the TRWD water.

PILOT TESTING EQUIPMENT

The five different membrane products piloted on the TRWD water are G.E. Ionics, Pall, Siemens Memcor, G.E Zenon, and Koch Membrane Systems. All of the pilot units are self-contained systems including the membrane, backwash and CIP systems and the operation and monitoring instrumentation. Details about the membranes piloted are given in Table 4.

Table 4: Membrane Manufactures in the Pilot Study

Parameter	**Ionics**	**Pall**	**Memcor**	**Zenon**	**Koch**
Model No.	Norit S225	Microza USV1	CMF-S S10V	ZeeWeed 1000	KPAK 10-inch
Type	Pressure	Pressure	Vacuum	Vacuum	Pressure
Classification	UF	MF	MF	UF	UF
Membrane Material	Polyethersulfone /Polyvinyl-pyrolidone blend	Polyvinylidene-flouride	Polyvinylidene-flouride	Polyvinylidene-flouride	Polysulfone
Length of Membrane Fiber	60 inches	80 inches	41.3 inches	25.6 inches	72 inches
Surface Area of the Feed Water Side	425 ft^2	538 ft^2	300 ft^2/272 ft^2	600 ft^2/500 ft^2	871 ft^2
Flow Direction	Inside Out	Outside in	Outside in	Outside in	Inside Out
Nominal Pore Size	0.03 micron	0.1 micron	0.1 micron	0.02 micron	0.01 micron
Maximum Pore Size	0.035 micron	0.2 micron	0.1 micron	0.1 micron	0.05 micron
Oxidant Resistance	Chlorine (500 ppm), Sodium hypochlorite (250 ppm)	Chlorine (5,000 ppm), Ozone, Chlorine dioxide	Chlorine (1,000 ppm)	Chlorine (1,000 ppm) and other typical WTP oxidants	Instantaneous chlorine tolerance up to 200 ppm at pH > 10
Temperature Operating Range	1 to 40 °C	1 to 40 °C	1 to 40 °C	1 to 35 °C	1 to 35 °C
Feed Water Turbidity Operating Limit	50 NTU on a constant basis	500 NTU	100 NTU	Less than 250 NTU for less than 72 hours	Site dependant
Method of Operation	Dead end	Dead end/ Cross-flow	Dead end	Dead end	Dead end/ Cross-flow
Maximum Recommended Flux at 20 °C	50 to 60 gfd	100 gfd (treated water) 65 gfd (raw water)	50-55 gfd, but may vary depending on water quality	To be determined by water quality	100 gfd

Both settled and coagulated water was piloted. For the settled water portion of the piloting, membrane feed water was diverted from the settled water pipe prior to the filters. For the coagulated water portion of the piloting, raw water was diverted to the membrane skids after chlorine dioxide and before coagulant injection.

Separate coagulant dosing equipment was used to dose the appropriate amount of alum, PACl, or ferric sulfate into the membrane feed water prior to a common 1,000-gallon break tank. The City of Waxahachie donated the coagulant pump for the Mansfield WTP and Watson-Marlow, through Environmental Improvements, Inc. (EI2), donated the coagulant pump for the Benbrook WTP. From the common 1,000-gallon break tank, each pilot unit had a booster pump to push feed water through the individual prescreens.

At the Mansfield WTP pilot, permeate water and the pilot unit drain line containing spent cleaning chemicals and membrane backwash water was discharged to a common 8-inch drain line routed to the wastewater recovery basin. At the Benbrook WTP pilot, the permeate water and the pilot unit drain lines were kept separate. The permeate water was routed in a common 3-inch line to the backwash recovery basin and the pilot drain lines were discharged to a common 6-inch header routed to a nearby sewer manhole.

All of the membrane pilot units required an air compressor for the air scour and/or backwash. The manufacturers will supply air compressors for their membrane pilot units at no additional charge. See Table 5 for electrical requirements, pilot unit size and weight, CIP chemicals and other requirements.

Table 5: Requirements of the Pilot Units

Parameter	Ionics	Pall	Memcor	Zenon	Koch
Electrical Requirement	480V/60Hz/3 Phase, 10 Amps	Either 1 or 3 phase, 230VAC/60Hz 15 amp; Plus air compressor single phase 115V, 15 amps	3 phase, either 240V/60Hz 30 amp or 480V/60Hz 15 amp; Plus air compressor 480V/60Hz 15 amp	3 phase, 480 V, 60 Hz, 30 amps or 230 V, 60 Hz, 50 amps	480V/3 Phase, 30 Amps, Plus air compressor 110V, 20 amps
Pilot Unit Footprint	16’L x 9’W x 7’H	9.1’L x 3.8’W x 10.7’H	7.1’L x 3.8’W x 6.9’H	Two components 6’L x 2’W x 10’H & 6’L x 10’W x 6’H	13.8’L x 6.7’W x 10.6’H
Maximum Feed Water Flow	35 gpm	40 gpm	50 gpm	50 gpm	45 gpm
Maximum Drain Line Flow	77 gpm	60 gpm	50 gpm	50 gpm	50 gpm
Pilot Unit Weight (as operating with water)	3,300 lbs.	1,700 lbs.	1,600 lbs.	2,900 lbs.	2,600 lbs.
CIP Chemicals	Provided by Ionics: 12.5% NaOCl (typ. 3 gal/wk) 32% HCl (typ. 2 gal/wk)	Provided by Pall: 100% citric acid 40% solution NaOH 12% solution NaOCl	Provided by Memcor: Citric acid 40% solution NaOH Memclean C	Provided by Zenon: Dilute solution NaOCl Citric acid cleaner	Provided by Koch: 25-50% Caustic Soda, 5.25-12.5% NaOCl, Citric Acid
Other Requirements	Dedicated telephone line	Dedicated telephone line	Dedicated telephone line	Dedicated telephone line	Dedicated telephone line

PILOT STUDY COSTS

The pilot unit equipment rental fees for the 10-month pilot study at the Mansfield WTP were approximately $100,000. The pilot unit equipment rental fees for the two-month pilot study at the Benbrook WTP will be approximately $30,000. The Cities furnished their sales tax exemption numbers as necessary.

Underwriter's Laboratory provided the bulk of the off-site laboratory testing. San Antonio Testing Laboratory provided the chlorophyll A testing. Appendices A and B list the recommended laboratory and frequency of the analytical procedures for the settled water and direct filtration portions of the pilot study, respectively. Sample bottles were provided as part of the test fee. The total laboratory costs for the membrane pilot studies at the Mansfield and Benbrook WTPs are anticipated to be about $11,000 and $5,000, respectively.

Additional costs of the membrane pilot study include forklift rental, piping and electrical connections and telephone expenses. The City of Mansfield donated the raw water and power for the pilot study at their site. The City of Fort Worth purchased a tent enclosure for freeze protection for the pilot units at the Benbrook WTP and will reimburse the City of Benbrook for the raw water and power usage.

PILOT UNIT OPERATION

Each pre-treatment scenario tested was conducted in three stages, in accordance with TCEQ guidelines. A description of the three stages is given in the paragraphs below.

Stage 1. The first stage of testing is used to establish site-specific and full-scale operating parameters for each of the membrane pilot units. Stage 1 typically lasts between three and six weeks. The pilot units start up at low flux rates and increase flux rates slowly to find optimum values. If the TMP escalates to unacceptable values, the pilot unit will undergo a CIP procedure and the flux rate will be reduced. Stage 1 testing may reveal site-specific conditions that require modifications to the pilot study schedule.

Stage 2. The membrane pilots undergo a CIP procedure and physical integrity test at the beginning of each stage of testing. Stage 2 will include testing each membrane module under its optimum set of simulated full-scale water treatment plant design conditions as determined during Stage 1. Each membrane module will be operated continuously for multiple periods of not less than 30 days each during Stage 2 to simulate acceptable periods between CIP procedures.

For any unscheduled downtime greater than 24 hours, the Stage 2 test period should be restarted. Unfortunately, minor equipment malfunctions such as air compressor problems or loss of prime on the chemical feed pump (for the chemically enhanced backwash), will likely result in unscheduled downtimes greater than 24 hours with one or more of the manufacturers participating in the pilot. It may not be feasible to restart Stage 2 due to pilot equipment issues that are unrelated to the membrane treatment capacity. Any unscheduled downtimes greater than 24 hours should be evaluated closely in conjunction with the TCEQ to determine if restarting Stage 2 is the right course of action.

If the specific flux rate or TMP of a membrane pilot unit reaches unacceptable levels before the end of the 30-day test period, the membrane pilot unit will need to restart Stage 2 at a more conservative flux rate or could be eliminated from further consideration and testing.

Stage 3. The third stage of testing is conducted to determine the percent loss of the original specific flux for each membrane module and whether irreversible fouling has occurred. Stage 3 includes a CIP and physical integrity test followed by operating the membrane modules at simulated full-scale water treatment plant design conditions for at least 10 days.

Figure 4 is a graph of the pilot operating data for the Stage 2 design settled water run for one of the participants in the pilot study. The figure illustrates the TMP recovery after each daily chemically enhanced backwash.

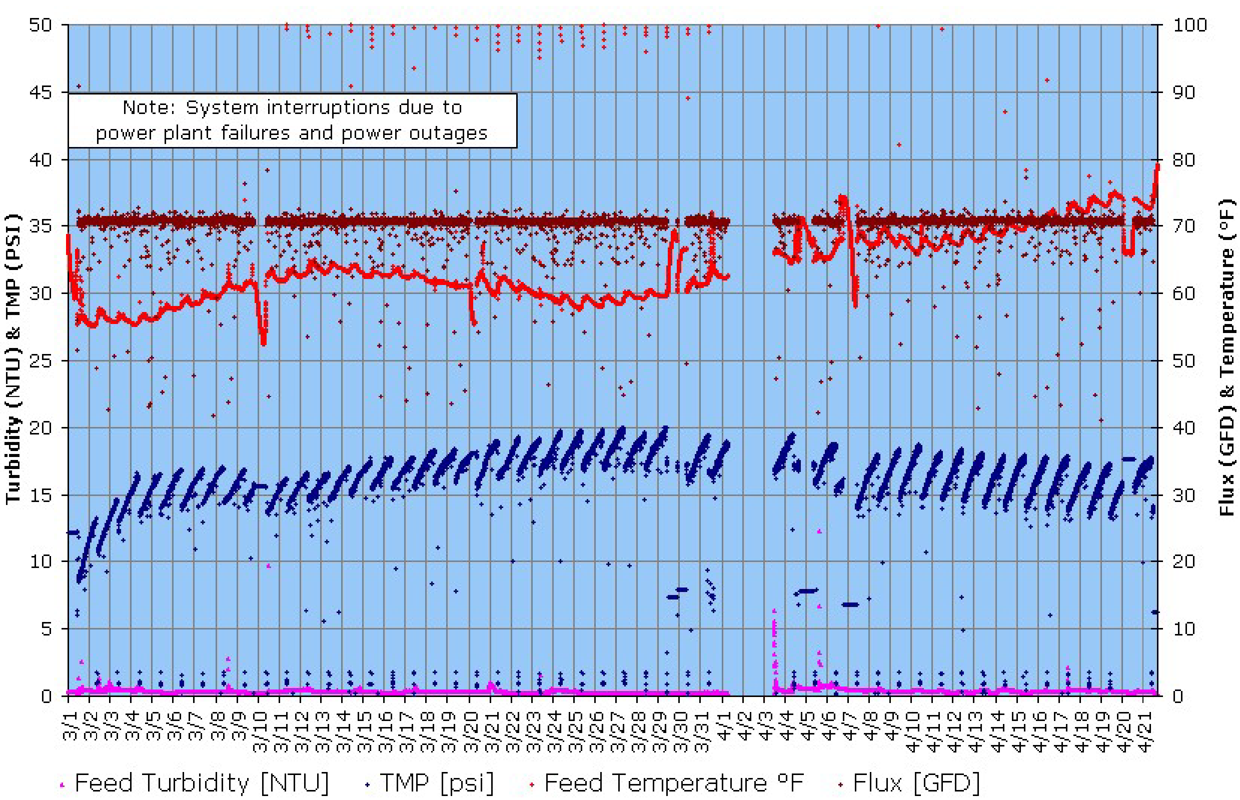

Figure 4: Settled Water Design Run

SUMMARY

When used in conjunction with chemical disinfectants, membranes provide an additional barrier from disease-bearing microbes to the public. Full-scale membrane facilities can be highly automated. Membranes are not susceptible to breakthrough of microorganisms or other suspended contaminants unless membrane fibers or skid equipment is compromised. Low-pressure membrane systems (UF/MF) are less prone to fouling than the historically more well-known reverse osmosis membrane systems, yet still provide superior water treatment when compared to gravity media filters. The benefits of low-pressure membrane filtration will have to outweigh the additional capital costs of the equipment for each membrane application.

The goal of the pilot study was to evaluate the effectiveness of membranes on the TRWD water sources for both direct filtration and settled water filtration. Standard backwash, chemically-enhanced backwash and CIP procedures were found to be effective in controlling membrane fouling and maintaining the TMP within acceptable ranges for the majority of the suppliers participating in the study.

ACKNOWLEDGEMENTS

The authors would like to thank all those who took part in the low-pressure membrane pilot studies and contributed to the success of the project. The Pilot Engineers with the five membrane manufacturers brought experience, expertise and energy to the project. Lynsy Nagle with APAI applied her exceptional enthusiasm to sample collection and operation of the pilot units at the Benbrook WTP. Special thanks to Robert Galbraith and the City of Mansfield staff for their dedication and efforts in operating and maintaining the membrane pilot units at the Mansfield WTP.

Appendix A - Settled Water Portion of Pilot Study
Pilot Study Sampling Schedule and Analytical Methods

ANALYTE	UNITS	SOURCE	STANDARD METHOD	RAW WATER	MF/UF FEED	FILTRATE
Water Characteristics						
Temperature	^{o}C	Pilot unit analytical equipment	N/A	Monitored daily	Every 4 hours	
pH	std. units	OWNER	SM 4500 H^+	Monitored daily	Monitored daily	Once a day
Turbidity	NTU	Pilot unit analytical equipment	N/A	Monitored daily	Every 5 minutes	Every 5 minutes
Total Particle Counts	No./mL	Pilot unit analytical equipment	N/A			
Total Hardness	mg/L $CaCO_3$	OWNER	EPA 130.2	Monitored daily	Every 30 days	
Alkalinity	mg/L	OWNER	SM 2320 B	Monitored daily	Every 30 days	
TOC	mg/L	Underwriter's Laboratory	EPA 415.1	Once a week	Once a week	Once a week
UV_{254}	cm^{-1}	Underwriter's Laboratory	EPA 415.1		Once a week	
DOC	mg/L	Underwriter's Laboratory	SM 19^{th} 5910 B		Once a week	
TSS	mg/L	Underwriter's Laboratory	SM 2540 D	Monitored monthly	Every 30 days	
TDS	mg/L	Underwriter's Laboratory	SM 2540 C	Monitored monthly	Every 30 days	
ClO_2 Disinfection Residual	mg/L	OWNER	SM 4500 ClO_2 E		Monitored daily	Once a week
Silica	mg/L	Underwriter's Laboratory	EPA 370.1		Every 30 days	
Chlorophyll A	mg/L	San Antonio Testing Laboratory	SM 10200 F	Every 30 days	Every 30 days	
Elements						
Aluminum	mg/L	Underwriter's Laboratory	SM 3500 Al B	Monitored monthly	Every 30 days	
Manganese	mg/L	Underwriter's Laboratory	SM 3500 Mn B	Monitored monthly	Every 30 days	
Iron	mg/L	Underwriter's Laboratory	SM 3500 Fe B	Monitored monthly	Every 30 days	
Barium	mg/L	Underwriter's Laboratory	SM 3500 Ba B	Monitored monthly	Every 30 days	
Strontium	mg/L	Underwriter's Laboratory	STDM 17-3500B		Every 30 days	
If disinfectant is applied during the second stage of testing						
Total Trihalomethanes	mg/L	Underwriter's Laboratory	SM 6232 B			Each 30-day Run
Haloacetic Acids	mg/L	Underwriter's Laboratory	EPA 552			Each 30-day Run
Chlorite	mg/L	Underwriter's Laboratory	EPA 300.4			Each 30-day Run

Darkly shaded areas do not require reported analyses. Lightly shaded areas are analytes already monitored by OWNER.

Appendix B - Direct Filtration Portions of Pilot Study
Pilot Study Sampling Schedule and Analytical Methods

ANALYTE	UNITS	SOURCE	STANDARD METHOD	RAW WATER	MF/UF FEED	FILTRATE
Water Characteristics						
Temperature	^{o}C	Pilot unit analytical equipment	N/A		Every 4 hours	
pH	std. units	OWNER	SM 4500 H^{+}	Monitored daily	Twice a week	Twice a week
Turbidity	NTU	Pilot unit analytical equipment	N/A	Monitored daily	Every 5 minutes	Every 5 minutes
Total Particle Counts	No./mL	Pilot unit analytical equipment	N/A			
Total Hardness	mg/L $CaCO_3$	OWNER	EPA 130.2		Every 30 days	
Alkalinity	mg/L	OWNER	SM 2320 B	Monitored daily	Once a week	
TOC	mg/L	Underwriter's Laboratory	EPA 415.1		Once a week	Once a week
UV_{254}	cm^{-1}	Underwriter's Laboratory	EPA 415.1		Once a week	
DOC	mg/L	Underwriter's Laboratory	SM 19^{th} 5910 B		Once a week	
TSS	mg/L	Underwriter's Laboratory	SM 2540 D		Every 30 days	
TDS	mg/L	Underwriter's Laboratory	SM 2540 C		Every 30 days	
ClO_2 Disinfection Residual	mg/L	Palintest Kit	SM 4500 ClO_2 E		Twice a week	Twice a week
Silica	mg/L	Underwriter's Laboratory	EPA 370.1		Every 30 days	
Chlorophyll A	mg/L	San Antonio Testing Laboratory	SM 10200 F		Every 30 days	
Elements						
Aluminum	mg/L	Underwriter's Laboratory	SM 3500 Al B		Every 30 days	
Manganese	mg/L	Underwriter's Laboratory	SM 3500 Mn B		Every 30 days	
Iron	mg/L	Underwriter's Laboratory	SM 3500 Fe B		Every 30 days	
Barium	mg/L	Underwriter's Laboratory	SM 3500 Ba B		Every 30 days	
Strontium	mg/L	Underwriter's Laboratory	STDM 17-3500B		Every 30 days	
If disinfectant is applied during the second stage of testing						
Total Trihalomethanes	mg/L	Underwriter's Laboratory	SM 6232 B			Each 30-day Run
Haloacetic Acids	mg/L	Underwriter's Laboratory	EPA 552			Each 30-day Run
Chlorite	mg/L	Underwriter's Laboratory	EPA 300.4			Each 30-day Run

Darkly shaded areas do not require reported analyses. Lightly shaded areas are analytes already monitored by OWNER.