Demineralization of High Salinity Brackish Groundwater Using Seawater Technology

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Abstract

Collier County's North County Regional Water Treatment Plant (NCRWTP) is a combined nanofiltration (NF)/reverse osmosis (RO) treatment facility, with design production capacity of 20-mgd (12-mgd NF, 8-mgd RO). The RO portion of the NCRWTP treats brackish water from 11 wells in the Lower Hawthorne Aquifer. Since their construction in 1998, 4 of the 11 wells have experienced increased total dissolved solids (TDS). The chloride concentrations in these four wells increased from a range of 2,000-3,000 mg/L to 6,000-10,000 mg/L by 2002, rendering them useless to the existing low pressure RO system.

The production loss from these wells allows the NCRWTP to marginally meet the 11-mgd raw water required for the RO portion of the treatment system by eliminating available redundancy. Additional wells are planned for the future to improve the raw water supply capability; however, the prospect of abandoning four highly productive, permitted, and relatively new wells is not favorable. Instead, the concept of independently treating the raw water from the high salinity wells was investigated.

Treating high salinity groundwater using seawater RO (SWRO) technology is a new concept in Florida. In theory, this scenario presents an ideal application for SWRO technology because of the high quality of the groundwater with respect to silt density index (SDI) and turbidity and the history of successful treatment of water from the Lower Hawthorne Aquifer by RO. However, the absence of past experience with SWRO technology and the potential for unforeseeable treatment challenges warranted demonstration testing.

The objectives for this RO demonstration study were three-fold:

- Verify treatability of high salinity Lower Hawthorne groundwater with SWRO technology and minimal pretreatment (5-micron filtration and scale inhibitor only)
- Develop energy use, chemical consumption, and cleaning interval data to estimate operational costs and establish full-scale design criteria
- Familiarize Collier County operations staff with isobaric energy recovery technology.

This paper discusses the application of the latest seawater technology for the treatment of highly brackish groundwater in Florida. Included is information on the development of the demonstration testing protocol, establishment of the most economical design recovery and flux rates, and the performance of the low energy seawater membranes and isobaric energy recovery devices. Operational data from the demonstration study will be presented, including

operating pressures, water quality, and energy usage. This paper serves as a roadmap to other utilities who are suffering from a reduction in potable water supply due to salt water intrusion and provides concrete evidence that the latest seawater technology and design concepts significantly lower the cost of treating high salinity water.

1. INTRODUCTION

1.1. Background

The North County Regional Water Treatment Plant (NCRWTP) is a combined nanofiltration (NF)/reverse osmosis (RO) treatment facility, with design production capacity of 20-mgd (12-mgd NF, 8-mgd RO). The RO portion of the NCRWTP treats brackish water from 11 wells that tap the Lower Hawthorne Aquifer. Since their construction in 1998, 4 of the 11 wells (RO-1N through RO-4N) have experienced increases in the total dissolved solids (TDS). The chloride concentrations in these four wells increased from a range of 2,000-3,000 mg/L to 6,000 to 10,000 mg/L by 2002, rendering them useless to the existing low pressure RO systems at the NCRWTP.

The production loss from these wells allows the NCRWTP to marginally meet the 11-mgd raw water requirement for the RO portion of the treatment system at the cost of eliminating any available redundancy. Additional wells are planned for the future to improve the raw water supply capability; however, the prospect of abandoning four highly productive, permitted, and relatively new wells is not favorable. Instead, the concept of independently treating the raw water from wells RO-1N through RO-4N was being investigated.

1.2. Demonstration Study Objectives

Treating high salinity groundwater using seawater RO (SWRO) technology is a new concept in the state of Florida. In theory, this scenario presents an ideal application for SWRO technology because of the high quality of the groundwater with respect to silt density index (SDI), suspended solids, and turbidity and the history of successful treatment of water from the Lower Hawthorne Aquifer by RO. However, the absence of past experience with SWRO technology and the potential for unforeseeable treatment challenges warranted demonstration testing.

The objectives for the high pressure reverse osmosis (HPRO) demonstration study were three-fold:

- Verify treatability of high salinity Lower Hawthorne groundwater with SWRO technology and minimal pretreatment (5-micron filtration and the option for scale inhibitor)
- Develop energy use, chemical consumption, and cleaning interval data to estimate operational costs and establish full-scale design criteria

- Familiarize Collier County operations staff with isobaric energy recovery technology, which is currently being proposed for the Northeast Regional Water Treatment Plant.

1.3. Water quality

A summary of the raw water quality is presented in Table 1.3. The raw water quality data is derived from information presented in the *North County Regional Water Treatment Plant - High Pressure Reverse Osmosis Feasibility Study* (March 2005) for wells RO-1N through RO-3N (water quality data for RO-4N was not presented in the aforementioned study). Average values for most major ions were used to develop the design water. However, maximum values for critical parameters, specifically barium, strontium, and silica, were used as a conservative measure to evaluate scaling potential.

Table 1.3 Demonstration Scale Test Design Water Quality
HPRO DEMONSTRATION STUDY
Collier County Utilities Department

Parameter[1]	Minimum	Average	Maximum	Design
Calcium (Ca^{2+})	330	417	460	**417**
Magnesium (Mg^{2+})	510	763	900	**763**
Sodium (Na^{+})	3,400	5,200	6,100	**6068**
Potassium (K^{+})	130	213	260	**213**
Barium (Ba^{2+})	0.046	0.051	0.055	**0.055**
Strontium (Sr^{2+})	18.00	19.00	20.00	**20.0**
Iron (Fe^{2+})	0.00	0.13	0.29	**0.13**
Manganese (Mn^{2+})	0.001	0.002	0.003	**0.003**
Ammonium (NH_4^{+})	0.78	0.90	0.96	**0.90**
Bicarbonate (HCO_3^{-})	232	281	305	**281**
Sulfate (SO_4^{2-})	1,400	2,033	2,400	**2033**
Chloride (Cl^{-})	8,600	10,867	12,000	**10867**
Fluoride (F^{-})	0.0	0.1	0.2	**0.2**
Silica (SiO_2)	17.0	18.7	20.0	**20.0**
Color (units)	5.0	8.3	10.0	**10.0**
Hydrogen Sulfide	5.0	0.0	5.0	**5.0**
pH (units)	7.12	7.14	7.15	**7.14**
Alkalinity (mg/l as $CaCO_3$)	190	230	249	**230**
Hardness (mg/l as $CaCO_3$)	2,926	4,187	4,858	**4,186**
TOTAL IONS + SiO_2	14,638	19,813	22,467	**20,683**
TDS (SUM)	14,519	19,670	22,311	**20,540**
Temperature (^{o}F)	88	88	88	**88**
Temperature (^{o}C)	31	31	31	**31**
Total Ions	14,638	19,813	22,467	**20,714**
TDS by Evaporation	13,000	20,666	25,000.	**20,559**
TDS by Ion Summation	14,519	19,669	22,311	**20,547**
Evaporation/Summation Ratio	0.9	1.1	1.1	**1.00**
Ion Balance Deviation (%)	-13.5	-5.6	-3.1	**0.0**

Notes:
1. Units are in mg/L unless otherwise noted.
2. Water quality derived from *North County Regional Water Treatment Plant - High Pressure Reverse Osmosis Feasibility Study* (March 2005) for wells RO-1N through RO-3N (water quality data for RO-4N was not presented in the aforementioned study).

During the demonstration test, water quality samples were taken at regular intervals to confirm the assumed design water, which is presented in Table 1.3. Table 1.4 shows a comparison of the design water used for test protocol development versus the actual water quality experienced during the demonstration study.

Table 1.4	Demonstration Scale Test Water Quality Comparison HPRO DEMONSTRATION STUDY Collier County Utilities Department		
Parameter[1]	**Design**	**9/13/06 Sample**	**12/11/06 Sample**
Calcium (Ca^{2+})	417	410	390
Magnesium (Mg^{2+})	763	590	790
Sodium (Na^{+})	6,068	5,700	5900
Potassium (K^{+})	213	300	260
Barium (Ba^{2+})	0.055	0.050	Not Detected
Strontium (Sr^{2+})	20.0	17	18
Iron (Fe^{2+})	0.13	Not Detected	Not Detected
Manganese (Mn^{2+})	0.003	0.0029	Not Detected
Bicarbonate (HCO_3^{-})	281	293	317
Sulfate (SO_4^{2-})	2033	2100	2,800
Chloride (Cl^{-})	10,867	11,000	11,000
Fluoride (F^{-})	0.2	2.10	5.8
Silica (SiO_2)	20.0	24	24
pH (units)	7.14	6.83	6.97
Alkalinity (mg/l as $CaCO_3$)	230	240	260
Hardness (mg/l as $CaCO_3$)	4,186	3,456	4,230
TOTAL IONS + SiO_2	20,683	20,469	21,556
TDS (SUM)	20,540	20,320	21,394
TDS by Evaporation		23,100	22,800
Temperature (^oC)	31	31	31
Conductivity (μmhos/cm)		33,000	34,000
Empirical Factor (TDS/Conductivity)		0.62	0.63

Notes:
1. Units are in mg/L unless otherwise noted.
2. Water quality derived from *North County Regional Water Treatment Plant - High Pressure Reverse Osmosis Feasibility Study* (March 2005) for wells RO-1N through RO-3N (water quality data for RO-4N was not presented in the aforementioned study).

2. DEMONSTRATION TESTING

2.1. Process Description

Figure 2.1.1 defines the general process for the demonstration test. The equipment used consisted of full-scale components, including 8-in diameter pressure vessels and membrane elements. The demonstration skid was leased from the Affordable Desalination Collaboration.

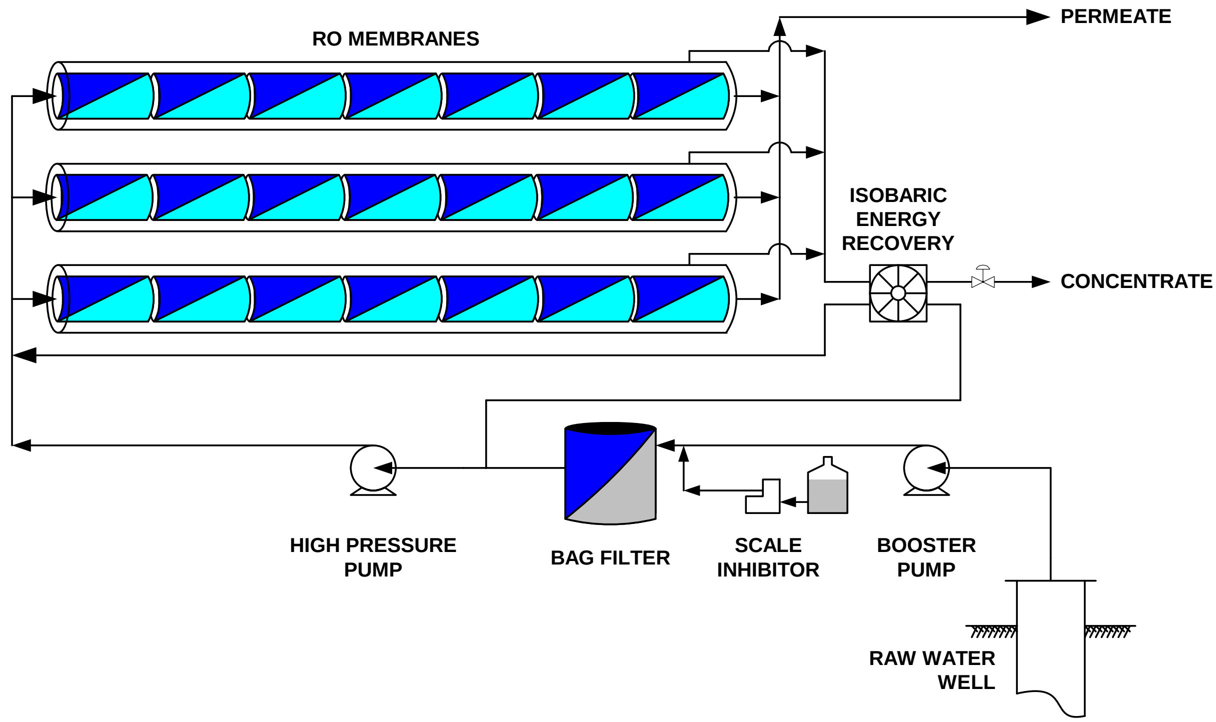

Figure 2.1.1: Demonstration Test Process Flow Diagram

2.2. Determining Operational Parameters

Prior to the demonstration study, a relative present worth value analysis was conducted to establish the most desirable operating flux and recovery parameters. The analysis included both relative capital and relative operations costs. The relative cost comparison only evaluated components that varied based on flux and recovery. The costs were developed based on the following assumptions:

- No capital cost for well construction or well pumps
- Items included in the analysis because they vary based on flux and recovery parameters
  - Capital Costs
    - Cartridge filters
    - Membrane feed pumps
    - Pressure exchangers
    - PX booster pumps
    - Pressure vessels

    - Membrane Elements
  - Operating Costs
    - Power usage
    - Chemical usage
    - Membrane Replacement
    - Cartridge Filter Replacement
- Items excluded from the analysis because they were deemed equal for all scenarios
  - Capital Costs
    - Installation and other costs (excluding equipment or material costs) for cartridge filters, feed pumps, chemical storage and feed systems, electrical system components, instrumentation components, and structural modifications (if applicable).
    - Degasification, product transfer, and high service pumping
    - Chemical storage and feed modifications
    - Instrumentation and programming modifications
    - Electrical system components and modifications
  - Operating Costs
    - Staffing and administrative costs
    - Equipment maintenance
    - Degasification and odorous air treatment
    - Product transfer and high service pumping
    - Disinfection

The criteria presented in Table 2.2.1 were the basis for the relative present value analysis. When establishing operation and maintenance costs for membrane replacements, the membrane lifespan shown in Table 2.2.2 was used to estimate yearly replacement quantities. Membrane replacement resulting from warranty maintenance by the manufacturers is not part of the replacement cost. Costs resulting from the Cumulative Annual Replacement Rates (CARR) are built into the membrane element cost by the manufacturers.

Table 2.2.1	Present Value Analysis Criteria HPRO DEMONSTRATION STUDY Collier County Utilities Department
Criteria	**Value**
Project Size	2 MGD
Capital Cost	
Pretreatment[1]	Feasibility Report
Desalination Plant[2]	Unit Costs for Pressure Vessels and Elements Used for Relative Comparison
Project Life	30 years
Bond Payment Period	30 years
Interest[3]	5%
Power Cost	$0.08 per kWh
Well Pump TDH	275 ft H_2O
Well Pump Efficiency	75%
Well Pump Motor Efficiency	93%
RO Feed Pump TDH	Based on Flux and Recovery
RO Feed Pump Efficiency	95%
RO Feed Pump Motor Efficiency	93%
PX Booster Pump TDH	Based on Flux and Recovery
PX Booster Pump Efficiency	75%
PX Booster Pump Motor Efficiency	93%
Membrane Life	See Table 2.2.2
Membrane Element Cost	$500 per element
Scale Inhibitor Cost	$0.53 per pound
Scale Inhibitor Dose	Dosage based on recovery
Sodium Hydroxide Cost (50% Solution)	$0.23 per pound
Sodium Hydroxide Dose	Dosage based on permeate quality
Cartridge Filter Loading Rate	4 gpm per 10-inches
Cartridge Filter Cost	$5 per 10-inches
Cartridge Filter Life	2000 hours

Notes:
1. Based upon 5-micron cartridge filtration pretreatment.
2. Includes costs for feed pumps, RO elements, pressure vessels, pressure exchangers and PX booster pumps.
3. Assumed interest rate.

Table 2.2.2 Membrane Replacement Schedule
HPRO DEMONSTRATION STUDY
Collier County Utilities Department

	Flux					
	6 GFD		7.5 GFD		9 GFD	
Recovery	CARR[1]	Membrane Life	CARR[1]	Membrane Life	CARR[1]	Membrane Life
35%	7%	6.5 yrs	8%	6.25 yrs	9%	6 yrs
42.5%	9%	6 yrs	10%	5.75 yrs	11%	5.5 yrs
50%	11%	5.5 yrs	12%	5.25 yrs	13%	5 yrs

Notes:
1. Cumulative Annual Replacement Rate (CARR). The percentage of membrane elements that would be replaced to maintain a performance requirement (i.e., permeate quality and energy) for a 5-year warranty.

Based on the relative present value analysis, the optimum operating condition for the demonstration study was 50 percent recovery at a flux rate of 6 gallons per day per square foot of membrane area (gfd). Pressures were based on membrane performance projections for the proposed manufacturers. The results of the present value analysis are presented in Figures 2.2.1 and 2.2.2

Figure 2.2.1 demonstrates that the optimum operating condition based on RO power usage alone is 42.5% recovery at 6 gfd. However, when raw water pumping, membrane replacement, cartridge filter replacement, and chemical usage are considered, the high recovery/low flux option becomes the most economical based on relative operations costs.

The difference in *relative* capital costs for the options evaluated was somewhat insignificant compared to the operational costs and thus did not alter the recommendation for high recovery/low flux operation. As shown in Figure 2.2.2, the addition of the relative capital cost components to the overall present value analysis reduces the difference between the relative present value costs at each recovery, but doesn't change the downward cost trend as recovery increases.

Since power costs drive the relative present worth analysis for the project, a sensitivity analysis was performed to verify that increased power costs would not impact the selected operating parameters. The relative present worth analysis was performed using power costs of $0.10, $0.12, $0.15, and $0.20 per kilowatt-hour and compared to the relative present worth results at $0.08/ per kilowatt-hour. Figure 2.2.3 shows that the selected high recovery/low flux option remains the most cost effective even if power costs increase.

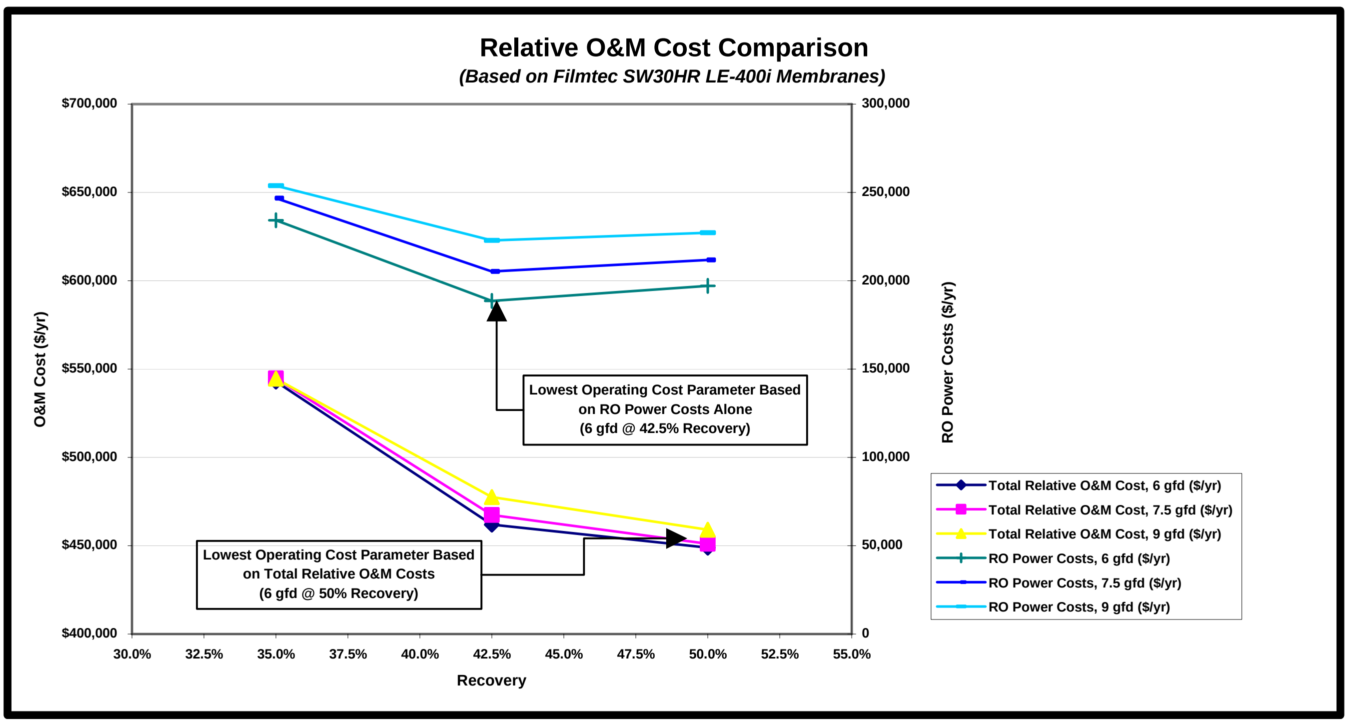

Figure 2.2.1 Relative O&M Cost Comparison

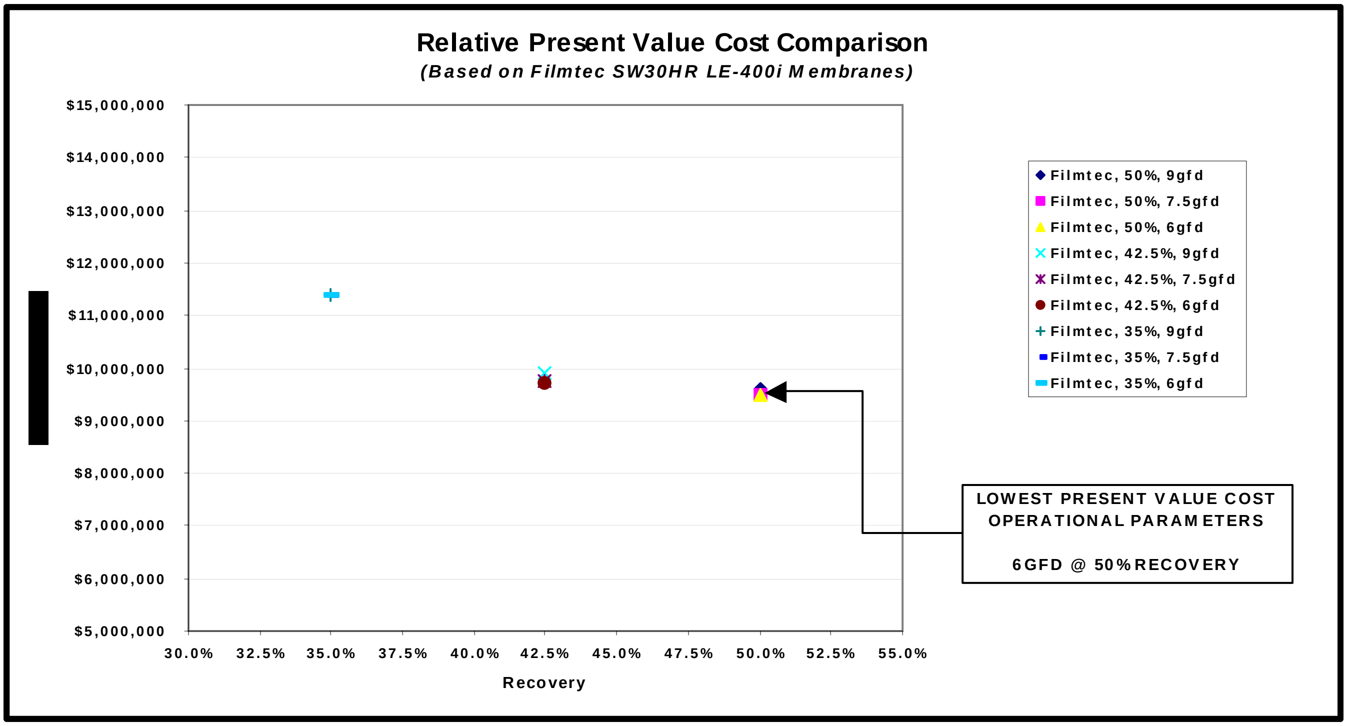

Figure 2.2.2 Relative Present Worth Cost Comparison

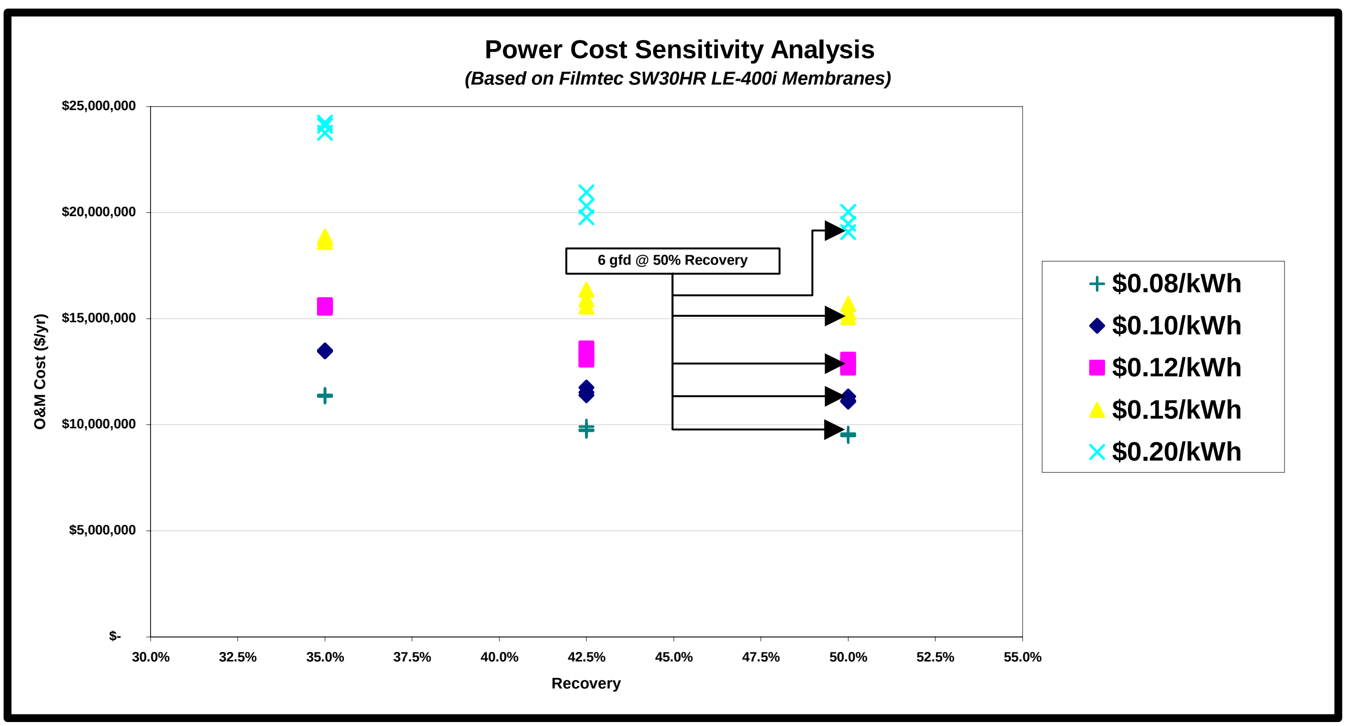

Figure 2.2.3 Power Cost Sensitivity Analysis

In addition to being the lowest cost alternatives, the selected operating parameters have other benefits, which are:

- Reduced raw water usage
- Reduced concentrate volumes for disposal
- Reduced fouling potential due to low flux operation

As a result of the low flux proposed, the possibility existed that the permeate quality would suffer relative to the high flux alternatives. Therefore, permeate quality was to be monitored during the first six weeks of the test phase and changes, such as increasing the flux, were to be made in the second part of the test phase, if required.

2.3. SWRO Demonstration Scale Testing

Three months of demonstration scale testing of the HPRO system occurred over a 6-month period (June 2006 to January 2007). The membrane tested was a Filmtec SW30HR-400*i*. Testing proceeded under the following criteria:

- Operating parameters were set based on the relative present value analysis. Testing proceeded under these operating conditions for 6 weeks.
- During the first six weeks, if excessive fouling or permeate quality becomes problematic, the membranes were to be cleaned and the flux and recovery modified to improve performance. If fouling of the membranes was not problematic and water quality acceptable, no changes were to be made for the second six weeks of testing.

3. DEMONSTRATION TEST RESULTS

3.1. Operational Data

The operational data gathered from the demonstration test, specifically pressures, water quality, and power consumption, are presented in the following sections. Power consumption rate was measured and included the following electrical loads:

- HPRO High Pressure Positive Displacement Pump
- HPRO PX Booster Pump

The following was not included in the power consumption rate measurements:

- Well Water Pump (artesian pressure was sufficient to supply the demonstration system feed boost pump during the demonstration study)
- Chemical Metering Pumps
- Instrumentation and Controls

While the feed/flush/cleaning pump was used to provide suction side pressure to the High Pressure Positive Displacement pump, thereby reducing the overall TDH, it was not be included in the power monitoring. For the recovery and flux economic analysis, the existing well pumps' horsepower was assumed based upon actual flowrates and an overall TDH of 275-ft.

Hydraulic conditions for the demonstration scale HPRO equipment at each test condition are presented in Table 3.1.1.

Table 3.1.1 Schedule of Hydraulic Testing Conditions
HPRO DEMONSTRATION STUDY
Collier County Utilities Department

Parameter	Weeks 1-6	Weeks 7-12
<u>SW30HR LE-400*i* Conditions</u>		
Flux, gfd	6	9
Recovery	50%	50%
RO Pump, gpm	35	52.5
PX Booster Pump, gpm	34	53.5[1]
Total Product, gpm	35	52.5
Concentrate, gpm	35	52.5

NOTE.
1. PX Booster Pump Flowrate set at 1 gpm above concentrate flowrate to minimize TDS increase in the feedwater due to mixing in the energy recovery device.

3.1.1. Permeate Quality

Permeate conductivity is presented in Figure 3.1.1.1. The normalized salt rejection and salt passage data, shown in Figure 3.1.1.2, is relatively flat throughout the duration of the study (with the exception of the last few days of the study when a clogged bag filter caused concentrate recirculation through the PX unit).

Table 3.1.1.1 shows how the permeate sampled and tested during the demonstration study compares to the quality estimated using the membrane supplier's projection software. In general, the permeate TDS measured during the demonstration study was higher than that predicted by the membrane manufacturer's projection software. Based on the quality of the permeate during the first phase of the testing, the flux rate was increased to 9 gfd for the second phase of the test. The improvement in quality was sufficient to assure that the addition of post treatment chemicals would not cause in increase in TDS beyond the 500 mg/L secondary standard and would be more compatible (with respect to TDS) with the product from the existing facility's nanofiltration and low pressure RO systems.

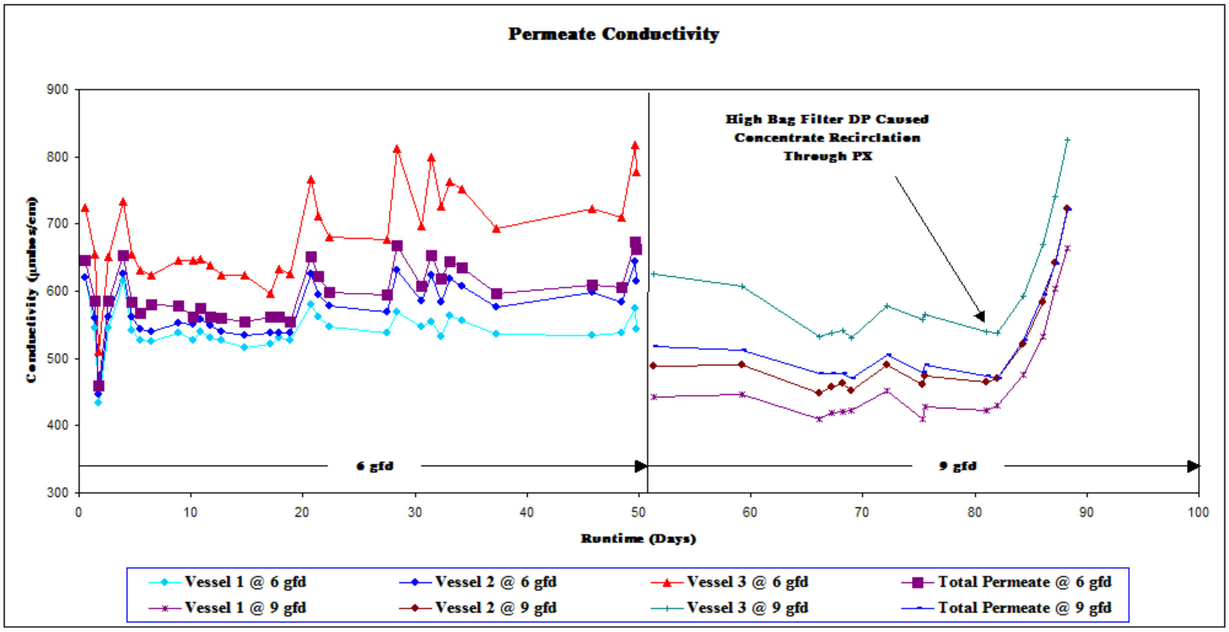

Figure 3.1.1.1: Permeate Conductivity

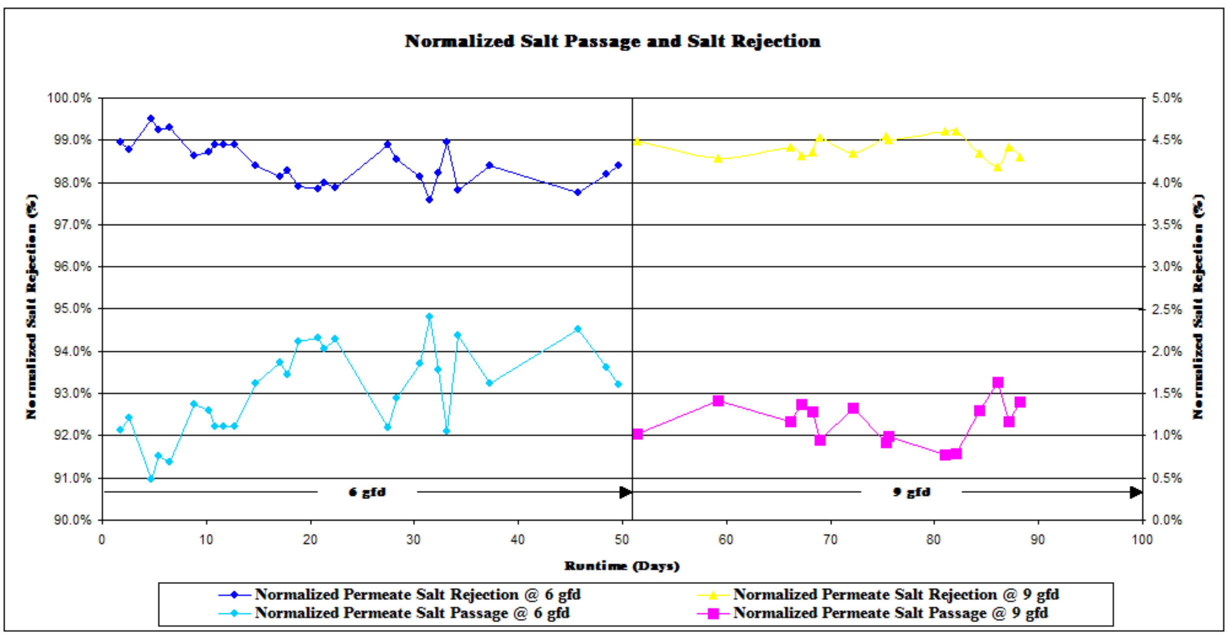

Figure 3.1.1.2: Normalized Salt Passage Data

Table 3.1.1.1 Demonstration Scale Test Permeate Water Quality Comparison
HPRO DEMONSTRATION STUDY
Collier County Utilities Department

Parameter[1]	Permeate, 6 gfd[2]			Permeate, 9 gfd[2]		
	Actual	Projected	% Difference	Actual	Projected	% Difference
Calcium (Ca^{2+})	1.5	1.2	25%	0.8	0.8	0%
Magnesium (Mg^{2+})	2.5	1.8	43%	1.2	1.6	-23%
Sodium (Na^{+})	130.0	111.4	17%	78.0	73.0	7%
Potassium (K^{+})	6.3	5.6	13%	3.5	3.2	10%
Strontium (Sr^{2+})	0.06	0.05	26%	0.0	0.0	0%
Bicarbonate (HCO_3^{-})	19.5	4.9	302%	17.1	3.7	368%
Sulfate (SO_4^{2-})	6.0	3.1	94%	3.2	2.5	26%

Table 3.1.1.1 Demonstration Scale Test Permeate Water Quality Comparison HPRO DEMONSTRATION STUDY Collier County Utilities Department						
Parameter[1]	**Permeate, 6 gfd**[2]			**Permeate, 9 gfd**[2]		
	Actual	**Projected**	**% Difference**	**Actual**	**Projected**	**% Difference**
Chloride (Cl^-)	200.0	179.0	12%	130.0	117.0	11%
Fluoride (F^-)	0.08	0.04	98%	0.1	0.1	33%
pH (units)	6.2	5.5	13%	6.2	5.5	14%
TOTAL IONS + SiO_2	367.3	307.6	19%	234.7	202.2	16%
TDS (SUM)	357.3	305.1	17%	226.0	200.3	13%

Notes:
1. Units are in mg/L unless otherwise noted.
2. Permeate quality estimated using ROSA v6.1 projection software (Filmtec®)

3.1.2. Pressures

Pressures observed during the demonstration test were consistent with the anticipated pressures from the manufacturer's projection software. Limitations on instrumentation did not allow for a look at the change in normalized differential pressure for the duration of the study, However, since temperature, recovery, and feedwater quality were very consistent throughout the study, a review of the recorded pressure data provides some insight into the fouling potential of the water.

Based on the recorded (non-normalized) data, no significant change in pressure was observed over time, which indicates that the water does not have a strong tendency to foul the membranes. The exception to this was observed during the end of the testing, when the artesian flow from the well proved inadequate to maintain positive gauge pressure on the raw water line. As a result, negative pressure was being drawn on the suction line and a slow accumulation of air in the raw water line resulted. This air caused the oxidation of hydrogen sulfide to colloidal sulfur, which subsequently fouled the bag filter. With high pressure drop across the bag filter, there was insufficient raw water pressure to maintain flushing flows through the PX unit. Since the concentrate was not completely pushed out of the chambers of the PX unit, it recycled back into the feedwater, causing a progressive increase in the feedwater TDS. This increase in TDS corresponded with the increase in feed pressure, which is illustrated Figures 3.1.2.1 and 3.1.2.2.

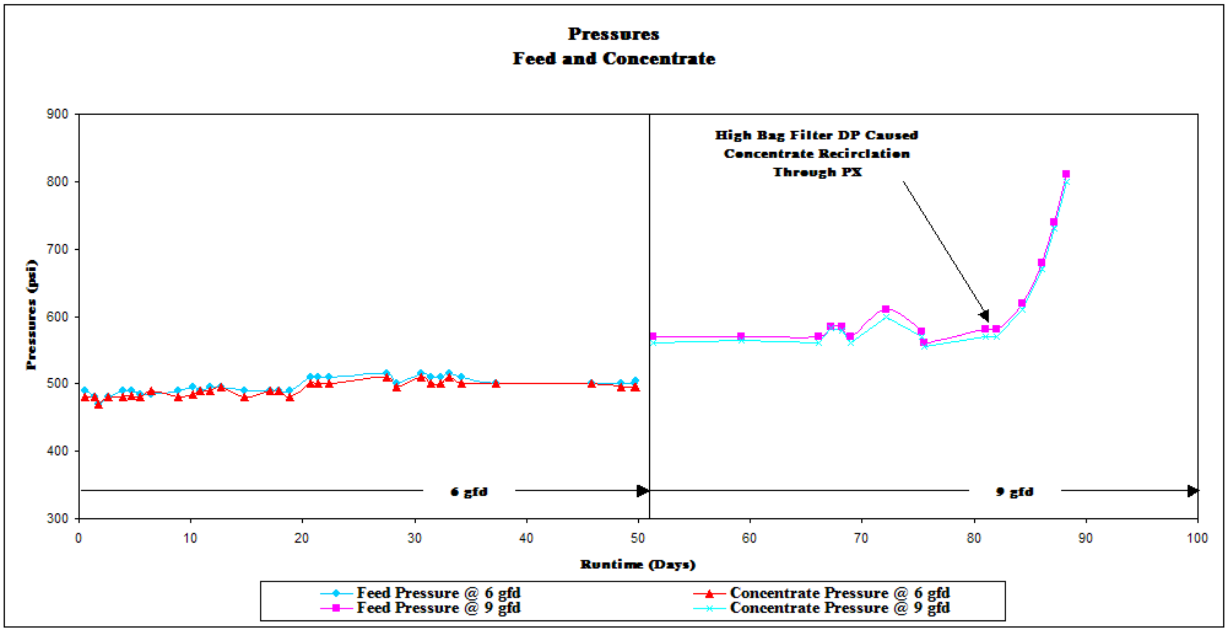

Figure 3.1.2.1 - Feed and Concentrate Pressures

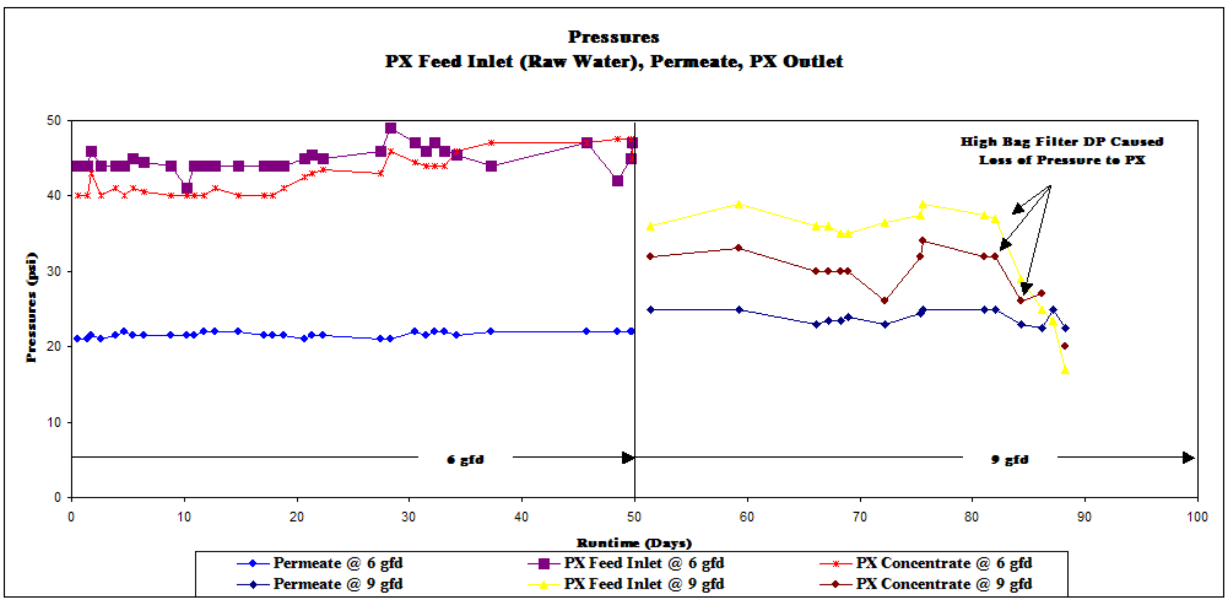

Figure 3.1.2.2 - Permeate, PX Inlet, and PX Concentrate Outlet Pressures

3.1.3. Energy Usage

Energy usage was monitored using power meters on the high pressure pump and PX boost pump. The RO power and specific energy are presented in Figure 3.1.3.1. In general, the measured specific energy was in the range of 4 to 5 kWh/kgal. In comparison, the specific energy from previous Affordable Desalination Collaboration was in the 6 to 7 kWh/kgal range. The lower energy consumption observed was expected, since the Hawthorne Aquifer groundwater is warmer and the TDS lower than the Pacific Ocean water tested during Phase I of the ADC demonstration program.

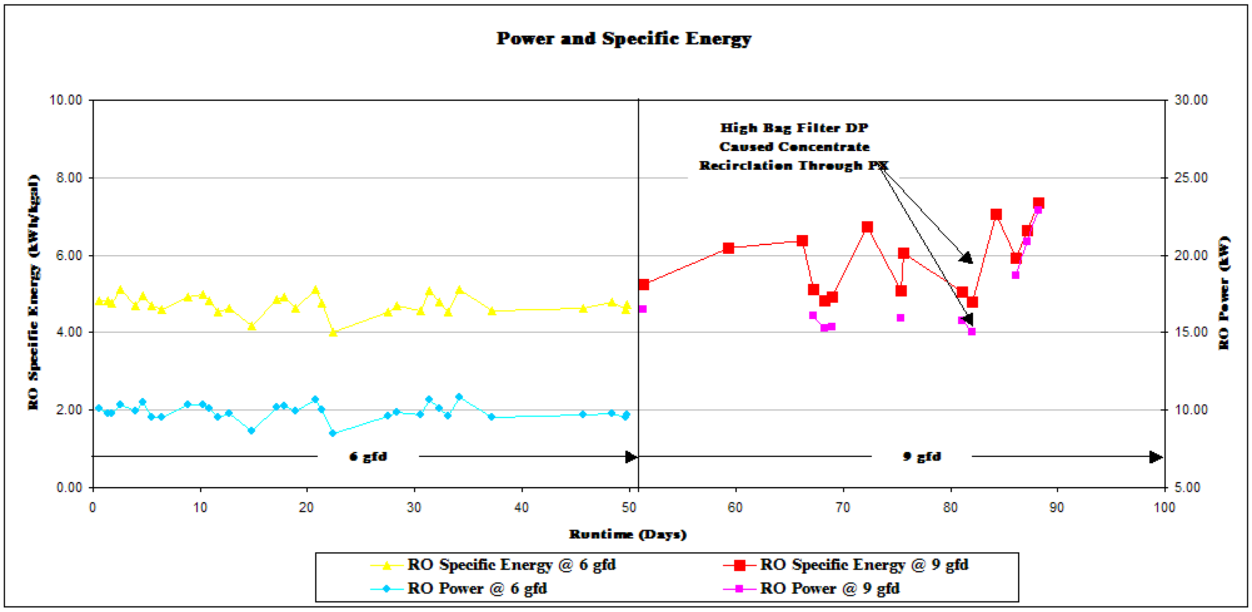

Figure 3.1.3.1 - Permeate, PX Inlet, and PX Concentrate Outlet Pressures

4. CONCLUSIONS

The results of the demonstration test confirmed that the high TDS water from the Hawthorne Aquifer is treatable using seawater RO technology. Although the preliminary economic comparison determined that low flux, high recovery operation was the most economical, the results of the demonstration test proved that higher flux rates are required to achieve the minimum permeate quality desired.

Using the data presented herein, design criteria will be developed for a 2-mgd full-scale reverse osmosis system to be installed in parallel with the existing 12-mgd membrane softening treatment system and the 8-mgd low-pressure reverse osmosis system at the North County Regional Water Treatment Plant. The lessons learned during operation, specifically the intricacies of positive displacement pumps and isobaric energy recovery devices, will be considered and incorporated into the final design.