Demonstration of a High Recovery and Energy Efficient RO System for Small-Scale Brackish Water Desalination

Report

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Acronyms and Abbreviations Used in this Report

CCC	closed concentrate circulation
gpd	gallons per day
gfd	gallons per square foot per day
gpm	gallons per minute
kWh/m^3	kilowatt-hours per cubic meter
m/s	meters per second
µS/cm	microSiemens per centimeter
mg/L	milligrams per liter
psi	pounds per square inch
RO	reverse osmosis
NaCl	sodium chloride
TWDB	Texas Water Development Board
TDS	total dissolved solids

Executive summary

A brackish water reverse osmosis (RO) system was tested for energy efficient operation at high recovery for small-scale desalination applications. Both high recovery and energy efficiency are achieved by the system through closed concentrate circulation. In this system, concentrate is recycled under pressure and combined with raw feed water in ratios specified by the operator. Once a target recovery has been achieved, the concentrate is discharged as waste. In contrast to conventional large-scale RO systems that typically employ pressure vessels containing six to eight membranes connected in series and arranged in stages in "Christmas Tree" configurations, the small-scale system described in this report uses two single membranes arranged in parallel.

Testing of the system consisted of three phases. In the first phase, energy consumption was measured for production of permeate from solutions of sodium chloride with concentrations of 1000, 2500 and 5000 mg/L at several feed and concentrate circulation flowrates. Tests were conducted up to 90% recovery. For all phases of testing, energy consumption was measured as specific energy, defined as the energy required to produce a given volume of permeate. Specific energies obtained for the small-scale system were then compared to values published for conventional large-scale RO systems. Published values of specific energy for large-scale brackish RO systems range from about 0.4 to 1.0 kWh/m^3. Tests indicated that specific energies of the small-scale system are comparable to those of large-scale systems for permeate flux up to 15.4 gallons per square foot per day (gfd) in laboratory tests at 1000, 2500 and 5000 mg/L sodium chloride. At permeate flux of approximately 20.6 and 25.7 gfd, specific energies for the pilot system exceed published vales for large-scale systems at all salinities, with specific energies of the pilot system at approximately 150% of published large-scale values at feed flowrates of 1.0 gpm. However, these permeate fluxes are outside of the range of permeate flux generally encountered in RO systems.

In the second phase of testing, the benefits of using closed concentrate circulation and variable crossflow velocity to control membrane fouling were assessed. The impact of crossflow velocity on the time required to observe membrane fouling was investigated using inlet crossflow velocities of approximately 0.1 m/s and 0.2 m/s. Tests used raw feedwaters containing 2500 mg/L sodium chloride and several concentrations of a commercially available foulant. The time required for onset of membrane fouling was estimated for each foulant concentration and crossflow velocity by comparing feed pump pressure versus operating time at these conditions with the feed pump pressure versus operating time for baseline conditions using raw feedwater containing only 2500 mg/L sodium chloride. Test results showed that crossflow velocity had a small but measurable effect on the time required for membrane fouling at the crossflow velocities and foulant concentrations studied. Increasing crossflow velocity generally increased the time required for onset of membrane fouling, indicating potential benefits of variable closed concentrate circulation for raw feedwaters with the potential to foul membranes.

In the third phase of testing, the energy consumption and overall performance of the system were assessed under "real-world" conditions, using brackish groundwater of varying scaling potential from three on-site wells at the Brackish Groundwater National Desalination Research Facility in Alamogordo, New Mexico. Tests were conducted at several feed and circulation flowrates and

were also conducted with and without anti-scalant. Test results indicated that specific energy values for brackish groundwater with moderate to high scaling potential are comparable to specific energy values for raw feed containing only sodium chloride. However, tests also indicate that the addition of anti-scalant lowers energy consumption for groundwaters with moderate and high scaling potential. The feed flowrate in tests using brackish groundwater continues to have a much stronger impact on energy consumption by the RO process than salinity or scaling potential.

A fourth phase of this study consisted of a cost estimate for desalination using the small-scale RO design, and a comparison with energy costs for conventional large-scale RO systems. The cost comparison/analysis demonstrated potential marketability of this technology for small towns located in arid or semi-areas where the only reliable source of water is brackish groundwater.

1 Introduction

The project "Demonstration of a High Recovery and Energy Efficient RO System for Small-Scale Brackish Water Desalination", supported by the Texas Water Development Board (TWDB), commenced in August 2010 and has recently been completed. The main goal of the project is to demonstrate that a RO system of new configuration can work for small-scale brackish water desalination at recovery and energy efficiency comparable to those for large-scale RO desalinations.

1.1 Background

1.1.1 Conventional RO systems

Conventional RO systems are typically designed to produce permeate at rates from tens of thousands of gallons per day (gpd) to several million gpd. Any system that produces permeate (desalinated water) from raw feed in quantities of at least 25,000 gpd can be considered a "large-scale" system. The water and salts rejected by the membrane are referred to as "concentrate" or "retentate". Systems that treat brackish water operate at recoveries in excess of 80%. The recovery or "recovery ratio" is the ratio of the volume of permeate produced to the volume of raw feed required to produce that permeate volume. For a conventional RO system, the recovery is calculated using Eq. 1 below.

$$R = \frac{\int_0^t Q_P\,dt}{\int_0^t Q_F\,dt} \qquad (1)$$

where R is the recovery or recovery ratio for the RO process, Q_P is the permeate flowrate over a specified time increment, Q_F is the corresponding feed flowrate and dt is the length of the time increment.

Additionally, in a conventional RO system, recovery may be defined as the ratio of the permeate flowrate to the of raw feed flowrate. As will be demonstrated later, the former definition (volume:volume basis) must be used in a closed concentrate circulation configuration. Conventional systems achieve high recovery by linking up to eight membranes within a pressure vessel. The concentrate from one membrane becomes the feed to the next membrane in series within the pressure vessel. The pressure vessels are then staged in “Christmas-Tree” structures in which the number of membranes in succeeding stages are reduced in proportion to the reduction of total flow caused by the removal of permeate. This enables the maintenance of an acceptable crossflow velocity. Booster pumps are often employed to maintain adequate pressure between stages since frictional head losses and “minor” head losses are inevitable.

Another important operating parameter is the salt rejection, which is expressed as a decimal number between 0 and 1 or as a percent and represents the relative ability of the process to remove TDS from the feed. Salt passage by the RO membrane increases as the rejection decreases. Salt rejection is determined using Eq. 2 below:

$$r = 1 - \frac{C_P}{C_F} \qquad (2)$$

where r is the salt rejection, C_P is the TDS or salt concentration in the permeate and C_F is the concentration of TDS or salt in the raw feed.

Salt rejection generally decreases as RO membranes age.

Energy efficiency is maximized through the use of energy recovery devices such as isobaric pressure exchangers that extract energy from the pressurized concentrate.

The operating pressure of the RO process is governed by several factors. Major factors include: (1) the hydraulic resistance of the membrane and water flux across the membrane; (2) the osmotic pressure gradient between the membrane channel (feed side) and the permeate; (3) enhancement of the osmotic pressure gradient by the occurrence of concentration polarization on the feed side of the membrane; and (4) additional resistance to flow created by fouled membranes. Membrane fouling occurs when pores and channels on the surface of the membrane are narrowed or blocked by sparingly soluble salts and bacterial growth. There is evidence that concentration polarization and membrane fouling can be reduced or prevented by increasing the crossflow velocity in the membrane channel. Crossflow velocity is the velocity of the fluid flowing parallel to the membrane surface.

One major drawback of conventional RO designs is the fact that system operating pressure is based on the maximum osmotic pressure occurring in the process. The maximum operating pressure occurs where the feed to the membranes is most concentrated, i.e., at the latest membranes in the process. This pressure is in large excess to the relatively unconcentrated feed at the earlier membranes. Since energy consumption is a function of operating pressure, this results in a large amount of wasted energy. A typical conventional RO configuration ("Christmas tree") is presented below in Figure 1-1. Each rectangle represents a pressure vessel in which (typically) up to eight membranes are connected in series.

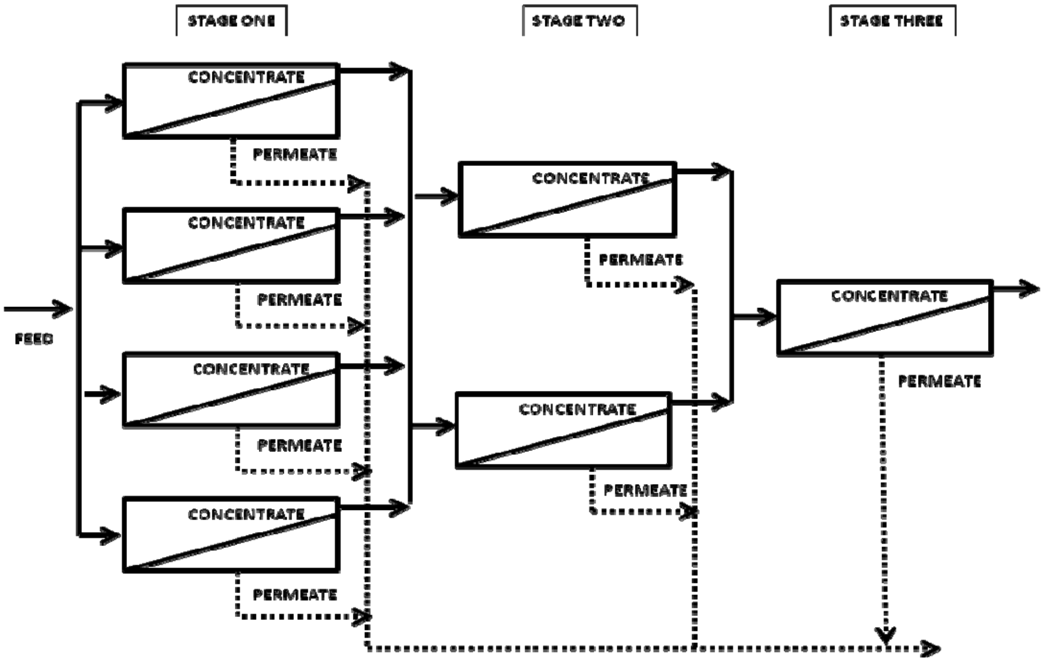

Figure 1- 1. Conventional large-scale "Christmas tree" RO configuration.

1.1.2 Major limitations of conventional RO design in small-scale applications

Conventional RO designs are not well adapted to small-scale applications due to the low flowrates involved. Small-scale RO systems may be defined as systems that produce less than 25,000 gpd of permeate. The low flowrates generated in these systems are not sufficient to maintain adequate crossflow velocities and shear rates to prevent fouling and concentration polarization in the long membrane channels and multiple stages used to achieve satisfactory recovery in conventional large-scale designs. In addition, the relatively small amount of energy remaining in the concentrate stream of small-scale brackish desalination processes, while significant for long-term operation, would not be sufficient to be economically extracted by energy recovery devices currently available. Because of the limited number of membrane elements in the typical small-scale RO desalination system, the feedwater is discharged from the RO system before a desirable recovery has been achieved. The discharge of pressurized concentrate at low recovery from the RO system results in the waste of large amounts of energy.

1.1.3 Closed concentrate circulation desalination

In closed concentrate circulation (CCC), the raw feed is combined with the circulating (pressurized) concentrate in ratios specified by the operator. At some pre-determined operating pressure or recovery, whichever occurs first, the circulating concentrate is discharged from the system as waste. In this type of system, there are three parameters related to flowrate that impact performance of the system: the feed flowrate, the concentrate circulation flowrate and the flowrate of the combined feed and circulating concentrate stream. The flowrate for the combined stream determines the crossflow velocity, the shear rate at the membrane surface and its impact on concentration polarization and membrane fouling. Since the system cannot have either a negative or positive mass accumulation over time, the average feed flowrate and average permeate flowrate must be balanced (equal one another).

In addition to a high-pressure pump to supply the driving pressure to generate permeate from raw feed, a system employing closed concentrate circulation may include an additional pump to compensate for head losses in the concentrate circulation piping and to equalize the pressure between the circulating concentrate and the incoming raw feed with which it is blended. Head losses in the concentrate circulation piping may be either frictional head losses or “minor” head losses due to valves, contractions, expansions and tees. The system may also include a mixing tank to dampen the effects of rapidly rising osmotic pressure, a bypass line for removing accumulated salt for continuous operation of the system and valves that allow the switching between “normal” mode and “cleanout” mode. To enable the system to operate the system for extended periods of time, these additional features are essential; without them, salts would accumulate and the operating pressure could theoretically rise indefinitely.

There are two types of recovery for a CCC system: the overall recovery and the recovery **per pass** through the membrane module. The overall recovery is the net ratio of permeate volume to raw feed volume over the entire system operating time. The recovery per pass is the ratio of the permeate flowrate to the combined raw feed and circulating concentrate flowrate. The overall recovery of a CCC system is also determined using Eq. 1, unless the system contains a mixing tank, a separate “cleanout” mode of operation and a flushing operation for the mixing tank during “cleanout” mode to rid the system of accumulated salts. In this case, the volume of water, typically raw feed, used to flush out the holding tank must be accounted for in the calculation of recovery and the recovery is determined using Eq. 3 below.

$$R = \frac{\int_0^t Q_P \, dt}{\int_0^t Q_F \, dt + V_{Flush}} \tag{3}$$

where R is the recovery or recovery ratio for the RO process, Q_P is the permeate flowrate over a specified time increment, Q_F is the corresponding feed flowrate, V_{Flush} is the amount of raw feed used to flush the system (including mixing tank) of accumulated salt during "cleanout" mode and dt is the length of the time increment. In contrast to conventional RO, recovery in CCC systems with a separate flushing cycle is a function of operating time due to the extra flushing volume in the denominator in Eq. 3.

In the testing described in this report, ratios of circulating concentrate flow to raw feed flow from 4:1 to 6:1 were used. These correspond to recoveries per pass from approximately 20% to approximately 14%. Most tests were conducted using ratios of 4:1 and 5:1. These ratios were selected based on two criteria.

- A typical recovery range for RO processes is 10% to 15%. Tests were designed to maintain per pass recoveries as close to this range as possible.

- Ratios of circulation flowrate to feed flowrate greater than 6:1 would result in more desirable recoveries (below 15%). However, the circulation pump cannot operate at ratios greater than 6:1, especially at higher feed flowrates.

Based on these constraints, ratios of 4:1 to 6:1 were selected for all tests.

A sample CCC system is represented below in Figure 1-2.

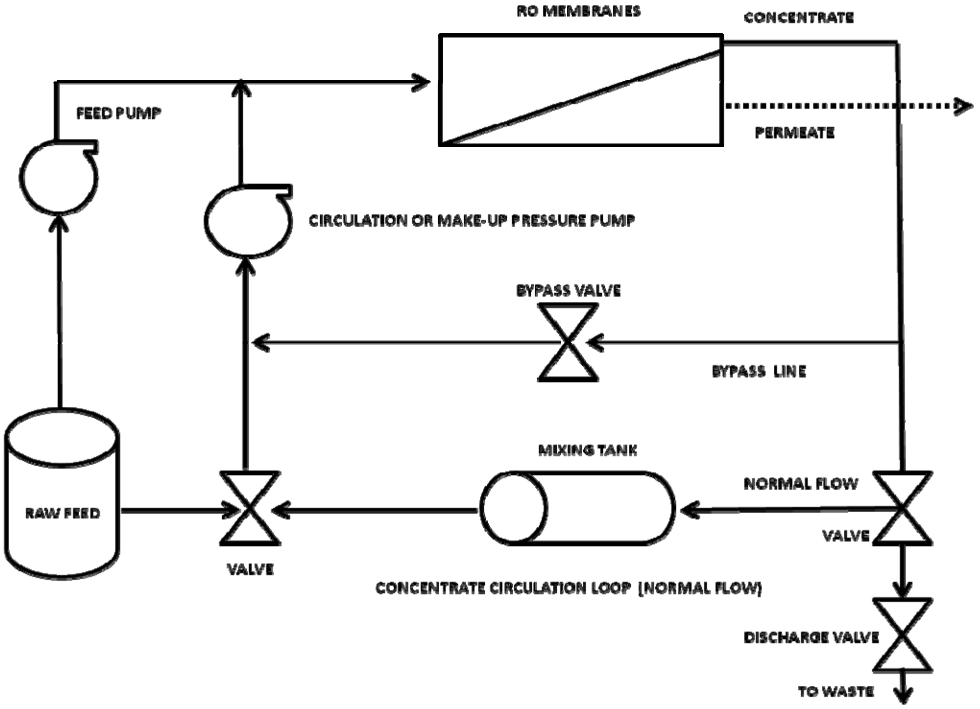

Figure 1- 2. Example of a CCC desalination system.

1.1.4 Closed concentrate circulation in small-scale RO

Designs using CCC are much better suited to small-scale RO applications than the conventional design. As addressed previously, the small flowrates in small-scale applications are not sufficiently large to maintain the needed crossflow velocity in the membrane channel to prevent fouling and concentration polarization in the long membrane channels in conventional designs. Without the long membrane channels created by linking several membranes in series, satisfactory recoveries are not possible with conventional one-pass systems. The only way to achieve the desired recoveries in small-scale applications is through multiple passes of the fluid being desalinated, in other words, through circulation of concentrate. Concentrate circulation also enables the operator to control crossflow velocity, especially important for raw feed of high fouling potential. In addition, the circulation of concentrate under pressure is also necessary to achieve satisfactory energy efficiency. Closed (pressurized) circulation of concentrate actually serves three main functions in small-scale brackish desalination: (1) to achieve the desired recovery without increasing the number of membrane elements, (2) to conserve the energy in the pressurized concentrate, and (3) to be able to control the crossflow velocity without changing the raw feed flowrate.

Recovery for the pilot RO small-scale system describerd here is a function of operating time and is determined using Equation 4 below.

$$R = \frac{\int_0^t Q_P \, dt}{\int_0^t Q_F \, dt + V_{HT}} \tag{4}$$

where Q_f is the feed flowrate, V_{HT} is the holding tank volume and dt is the time increment over which flow measurements are made.

1.1.5 Impact of fouling and concentration polarization on closed concentrate desalination

Fouling is the process by which the surface of the membrane is altered in such a way that the openings and channels by which water passes through the membrane become more restricted and narrower, causing increases in the operating pressure required to maintain permeate flux and in energy consumption. Fouling may be caused by sparingly soluble salts, organics, the growth of microscopic organisms and the formation of colloids large enough to settle out.

In the second phase of this project, the effect of crossflow velocity on colloidal fouling was investigated due to (1) the availability of a well-characterized, commercially available colloidal foulant and (2) numerous data and studies available on colloidal foulants.

Concentration polarization is the formation of a thickening layer of charged species on the membrane surface. This phenomenon cause an effective increase in the osmotic pressure gradient between feed and permeate and an increase in operating pressure and energy consumption. Normally, particles diffuse from the membrane surface back into the bulk solution. However, the thickening of the concentration polarization layer over time reduces the ability of species to diffuse away from the membrane surface.

There is evidence that increasing the crossflow velocity can reduce fouling and concentration polarization or slow their occurrence by increasing the shear rate and turbulence at the membrane surface.

1.2 Study objectives

In this project, a pilot RO system has been demonstrated for improved water recovery and energy efficiency for small-scale brackish water desalination. The pilot RO system features a parallel arrangement of RO elements and closed circulation of concentrate. With these features, high recovery and high energy efficiency can be achieved even with a small number of membrane elements.

Project phases include 1) an evaluation of the energy efficiency of small-scale system with NaCl solutions; 2) assessment of colloidal fouling mitigation; 3) demonstration of the small-scale RO system with real brackish water; and 4) cost estimate for small-scale RO using the design and marketability assessment of the process. All the proposed tests and demonstrations have been completed. Results and findings are summarized in this report.

2 Experimental

Tests have been designed specifically to determine whether or not closed concentrate circulation can effectively increase recovery and energy efficiency of small-scale brackish desalination under a wide range of operating conditions and raw feedwater chemistries. The assessment has been based on comparisons of specific energies determined for the small-scale system with reported specific energy values for large-scale RO systems. Tests have been conducted using NaCl solutions at three concentrations (1,000 mg/L, 2,500 mg/L and 5,000 mg/L) and using brackish groundwater from three wells at the Brackish Groundwater National Desalination Research Facillity having moderate to high potential for scaling of membrane elements. These tests have also examined anti-scalant concentration as a variable affecting specific energy.

Tests were also conducted to assess the impact of crossflow velocity on the rate of membrane fouling at a salt concentration of 2,500 mg/L and at foulant concentrations ranging from 50 mg/L to 1,500 mg/L. Tests were conducted at two inlet crossflow velocities: 0.1 m/s and 0.2 m/s. Inlet crossflow velocity was controlled by varying the raw feed flowrate and the concentrate circulation flowrate. In RO systems, the crossflow velocity is reduced between the inlet and outlet of the membrane channel by the removal of permeate; therefore, the difference between inlet and outlet crossflow velocity is a function of the recovery of the RO process. In conventional RO systems, typically up to eight membranes are linked within staged pressure vessels. This design can provide recoveries exceeding 50% within a single stage. This translates into an equal reduction in crossflow velocity in the membrane channel. Unlike conventional RO systems, the pilot small-scale RO system uses two single membranes in a parallel configuration. Although the overall recovery of the small-scale process is achieved through multiple passes of circulating concentrate and is a function of operating time, the recovery **for a single pass** is equal to the ratio of the raw feed flowrate to the combined flowrates for raw feed and circulating concentrate. The percentage difference between inlet and outlet crossflow velocity is equal to the recovery and is approximately 17% for a 5:1 ratio of raw feed flowrate to total flowrate and approximately 20% for a 4:1 ratio.

Results have been divided into three phases. In the first phase, specific energies determined for a range of feed and circulation flowrates and recoveries (up to 90%) under laboratory conditions using NaCl solutions are presented. In the second phase, the results of tests to determine the impact of crossflow velocity on membrane fouling rate are presented. In the third phase, specific energies determined for raw feed from three groundwater wells for a range of feed and circulation flowrates and recoveries (to 90%) have been presented. Groundwater was obtained from wells at the Brackish Groundwater National Desalination Research Facility in Alamogordo, New Mexico

2.1 Pilot RO system with closed concentrate circulation

The pilot small-scale system uses only single membranes in a parallel configuration, eliminating the long channels seen in conventional large-scale RO systems. Since the small-scale system uses only single membranes, the reduction in crossflow velocity for the small-scale system is only a fraction of the reduction seen in large-scale RO systems where up to eight membranes are connected in a single pressure vessel, forming long membrane channels. A diagram of the pilot RO system is presented below in Figure 2-1.

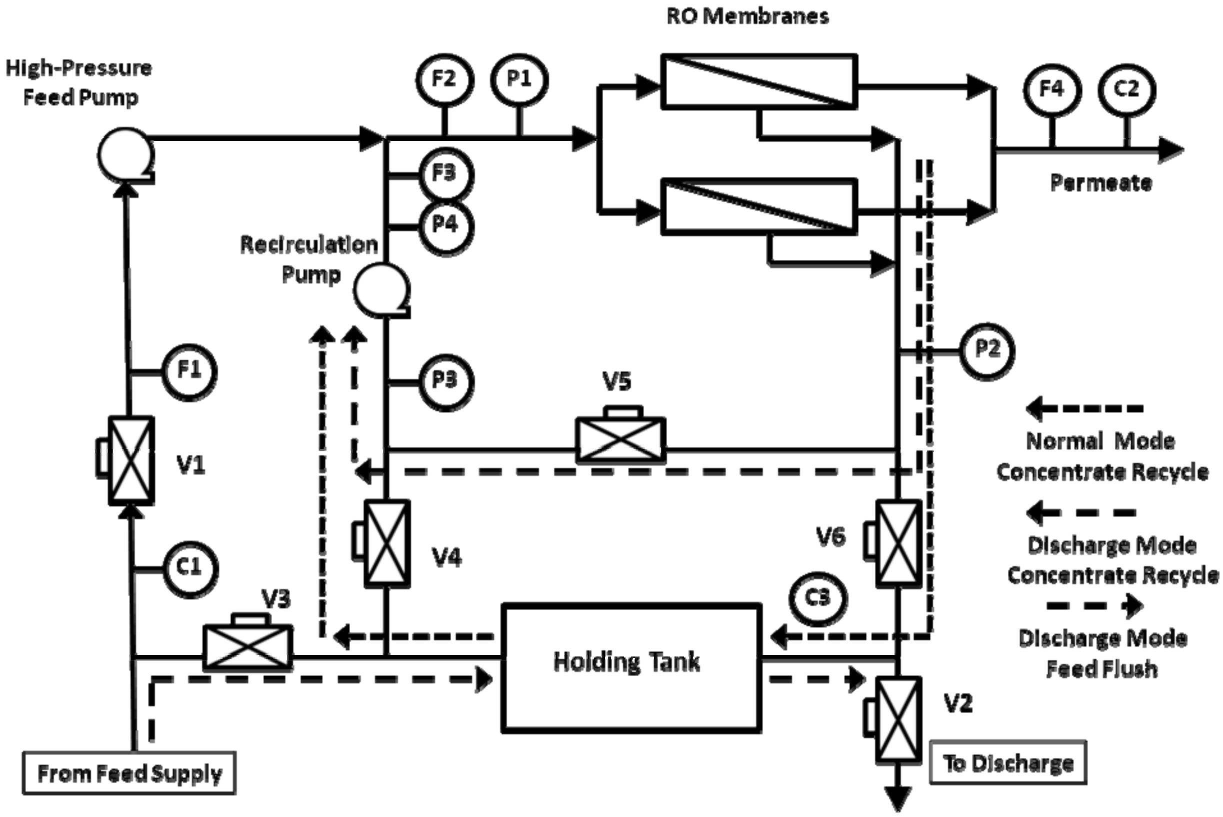

Figure 2-1. Schematic of the pilot small-scale RO system.

Operating parameters, such as feed flowrate, concentrate circulation flowrate and length of discharge cycle are set by manual numeric entry using the control panel and the associated keypad. Other parameters, such as system shutdown pressure and shutdown temperature are set in the same manner. System is therefore a constant flux system and operating pressure is governed by the flux.

The feed pump supplies the driving pressure required to produce permeate from the raw feed. The circulation pump ("recirculation pump") equalizes the pressure between the circulating concentrate stream and the raw feed stream with which circulating concentrate is blended prior to entry in the membrane channels. In addition to these two pumps, the system also requires an auxiliary pump to supply raw feed at at least 20 psi. Without this auxiliary pressure, the system remains "off" and cannot be started.

The nodes identified as "F1", "F2", "F3" and "F4" are flowmeters. "F1" measures the flow of raw feed into the system, while "F2" measures the combined raw feed/circulating concentrate stream. The meter labeled "F3" measures the flowrate for circulating concentrate, while "F4" measures the permeate flowrate.

Because there can be no net positive or negative accumulation of water in the system, the feed flowrate equals the permeate flowrate.

Nodes identified as “C1”, “C2” and “C3” are conductivity meters. “C1” measures the conductivity of the incoming raw feed, while “C2” measures the conductivity of the permeate..“C3” measures the conductivity of the circulating concentrate prior to entry into the holding tank and the resulting mixing.

Nodes identified as “P1”, “P2”, “P3” and “P4” are pressure sensors. “P1” measures the pressure of the combined raw feed/circulating concentrate stream and the operating pressure of the feed pump. “P2” measures the pressure of the circulating concentrate stream prior to entry into the holding tank. “P3” measures the pressure of the circulating concentrate stream after exiting the holding tank and prior to passage through the circulation pump. “P4” measures the pressure of the circulating concentrate stream following flow through the circulation pump and prior to combining with incoming raw feed.

Nodes identified as “V1” through “V6” are valves that control the flow of feed, circulating concentrate and discharge waste during system operation. The system operates in two modes: “normal” and “discharge” mode. During “discharge” mode, accumulated salts are flushed from the holding tank with raw feed and discarded as waste at atmospheric pressure. This occurs only after a target recovery has been reached. The switch from “normal” mode to “discharge” mode, is accomplished manually by pushing the appropriate button on the control panel keypad. The length of time for “normal” mode is determined by the time needed to reach the target recovery, according to Eq. 4. For a feed flowrate of 0.4 gpm and a recovery of 90%, this is approximately four hours and 15 minutes. The length of “discharge” mode is determined by the time required to flow a given volume of raw feed through the holding tank. For Eq. 4 to be valid, one one holding tank volume is used to flush the tank. Since the flush flowrate was approximately 2 gpm, the time for discharge mode was approximately 5.5 minutes. Once “discharge” mode had ended, the system switched back to “normal” mode.

In “normal” mode, raw feed enters the system through “V1”, while concentrate is circulated through “V2” and“V6”, the holding tank, “V4” and the recirculation pump prior to combining with incoming raw feed. Valves “V2”, “V3” and “V5” are closed in “normal” mode.

In “discharge” mode, “V6” and “V4” are closed, while “V5”, “V3” and “V2” are open. The holding tank is flushed with raw feed through “V3” and its contents discharged as waste through “V2”. During discharge, concentrate circulates through “V5” and the recirculation pump prior to blending with raw feed. Discharge continues for sufficient time to flush the holding tank with one volume of raw feed, based upon the flowrate of feed through “V3”. The function of “V1” during “discharge” does not change. The valve is used to control the flow of raw feed as in “normal” mode. The flow through “V3” is driven by an auxiliary pump external to the system (see photo in Fig. 1-3). Flow through “V1” during discharge mode is driven by the auxiliary pump and by the feed pump and is set by the target feed flowrate that controls the feed pump. Flow through “V3” during “discharge” mode usually ranges from 1.8 to 2.2 gpm and reflects the sum of competing effects from the feed and auxiliary pumps and hydraulic effects created by the piping, valves and holding tank.

In the transition from "normal" mode to "discharge" mode, "V2", "V3" and "V5" open, but not simultaneously. After giving the system the "command" to commence "discharge" mode, "V5" opens at approximately five seconds. Valves "V4" and "V6" close simultaneously at 10 seconds. Valve "V3" opens at 20 seconds. When "discharge" ends, the order of valve closing and opening is the exact reverse. Valve "V3" is the first to close, "V4" and "V6" open 20 seconds later and "V5" closes 10 seconds following the opening of "V4" and "V6".

Certain valves have a greater effect on system pressure once "discharge" has ended. The opening of "V4" and "V6" causes an abrupt drop in system pressure. However, there is a five second delay in the occurrence of this drop.

The holding tank has a volume of approximately 11.5 gallons and functions as a pressure damping device by eliminating abrupt rises in the osmotic pressure of the circulating concentrate. Adequate mixing of holding tank contents is essential to this damping effect. Effective flushing of the holding tank during "discharge", however, depends upon significant "plug-flow" within the holding tank. Without adequate flushing of the tank, system pressure is not reduced adequately at the start of each "normal" cycle and the possibility for salt accumulation over time exists. The competing processes of pressure damping and holding tank flushing are important to optimal functioning of the pilot small-scale RO system. Increasing the circulation flowrate has the potential to increase mixing of tank contents, which may be beneficial. However, increasing the circulation flowrate also increases head losses in the circulation pipe, which results in higher energy consumption.

Flow within the two membrane elements was assumed to be equal. No testing was conducted to ascertain the validity of this assumption.

Data are logged by the system at 60-second intervals. Data from various meters and sensors is logged by the system using an AS400 data acquisition system, manufactured by ABB of Zurich, Switzerland. System software uses data averaging within the logged intervals to provide a more representative value in situations where the data are "noisy" and display a great deal of short-term variation. Data logged include feed pump operating pressure ("P1" on Figure 2-1), pressure downstream from the RO membranes and upstream from the holding tank ("P2"), pressures upstream and downstream from the circulation pump ("P3" and "P4"), feed flowrate ("F1"), flowrate for the combined raw feed/circulating concentrate stream ("F2"), circulation flowrate ("F3"), permeate flowrate ("F4"), raw feed conductivity ("C1"), permeate conductivity ("C2") and concentrate conductivity ("C3").

Photographs of the system control panel and the pilot RO system membrane pressure vessels and holding tank are provided below in Figures 2-2 and 2-3.

Figure 2-2. Pilot RO system control panel and batch feed tank.

Figure 2-3. Pilot RO system membrane housing pressure vessels and holding tank.

2.1.1 Operating parameters

Parameters identified as experimental variables differed in the three experimental phases of the research presented in this report.

In phase one, the laboratory assessment of energy consumption with NaCl solutions, test variables included: feed flowrate, circulation flowrate and level of TDS in the raw feed. In phase three, the field assessment of system performance and energy consumption using actual brackish groundwater, test variables included feed flowrate, circulation flowrate and groundwater source. Since each groundwater source possessed its own unique chemical composition, TDS level and scaling potential, these characteristics were additional variables investigated in that portion of the research.

The only TDS levels monitored were those of the raw feed and the permeate. The TDS level of the raw feed in phase one was based on weighed amounts of sodium chloride in a known volume of water (225-gallon feed tank). The concentration of the NaCl solutions was checked after solution preparation by measuring the conductivity with an Orion Three-Star hand-held conductivity probe and applying a conversion factor (conductivity in μS/cm to TDS in mg/L) of 0.54 for 5,000 mg/L solutions and 0.5 for 2,500 and 1,000 mg/L solutions. The TDS level of the permeate was estimated based on the system-measured conductivity of the permeate and a conversion factor of 0.5. The assumed TDS of the raw feed from Wells 1, 2 and 3 in the field studies was based on the most recent analytical data.

In phase two, the fouling mitigation assessment, experimental variables were crossflow velocity and colloidal foulant concentration. TDS levels were constant at 2,500 mg/L as sodium chloride. Crossflow velocity was controlled by varying the combined feed and concentrate circulation flowrates. Two crossflow velocities were used: 0.1 and 0.2 m/s. The crossflow velocity is equal to the volumetric flowrate divided by the appropriate feed channel spacer cross section area.

In all phases of the research, the feed and circulation flowrates were controlled via the RO system control panel by entering the appropriate flowrate in gpm on the control panel keypad (see Figure 2-2).

2.2 Test Protocols

Phases one and two were conducted in a laboratory setting, while phase three was a field-conducted study performed at the Brackish Groundwater National Desalination Research Facililty in Alamogordo, New Mexico.

2.2.1 Verification of system performance

Tests were conducted from June through October 2010 to estimate energy consumption of the system, to assess basic functioning of the system and to ensure that system flow meters and pressure sensors were functioning properly. During this phase of testing, Dow model TW30-25-40 (tap water) membranes were used. Membrane element length was 40 inches, element diameter was 2.5 inches and active surface area was 28 square feet. Each element contained two "leaves". Energy consumption for the pilot RO system was estimated at feed and permeate flowrates ranging from 0.6 to 1.0 gpm and concentrate circulation flowrates ranging from 3.0 to 5.0 gpm. The ratio of circulation flowrate to feed flowrate was 5:1 for tests conducted during this period. Raw feed salinities of 1,000 mg/L, 2,000 mg/L, and 5,000 mg/L sodium chloride were used. Energy consumption was measured as specific energy, defined as the energy required to produce a given volume of permeate. Twenty-one total tests were conducted during this phase. Test duration ranged from one to two hours and covered only one operating cycle.

Water softener salt, with a guaranteed purity of 99.5% , was used as the source of sodium chloride. Raw feed solutions for each test were created by dissolving sufficient salt in 225 gallons of purified water to provide the desired concentration. Purified water was supplied by a two-pass RO system maintained by Texas Tech University Physical Plant. (Permeate from the first stage is passed through second stage.) Prior to use, the temperature of the water was allowed to cool to room temperature (65 to 70 ^{o}F) overnight. Salt was added to the water once it had cooled. This step was necessary due to the heat transferred to the supply water by the purification equipment.

Duplicate measurements of permeate flow were made with a graduated cylinder and a stopwatch to ensure that the permeate flowmeter was functioning properly.

Based on calculations of the hydraulic resistance of the membranes and projected osmotic pressures of the combined feed/circulation concentrate stream at various recoveries, observed feed pump pressures were judged to be high for the feed salinities used. In an effort to reduce feed pump pressure and associated energy consumption, membranes were removed and examined for evidence of fouling or scaling. . The presence of reddish deposits was interpreted as indicative of membrane fouling, possibly by iron compounds, such as iron oxide. The basis for this reasoning included the following:

- Certain grades of stainless steel can be corroded by high levels of chloride. These levels might be reached in the circulating concentrate.
- In this phase of the study, the form of salt used was water softener salt, which might contain sufficient iron (as an impurity) in the concentrate stream to deposit on the membranes.

The tape-wrapped membranes were replaced with Dow model BW30-2540 brackish water membranes and duplicate tests were run with the new membranes. (The specifications for the brackish membranes are: length of 40 inches, diameter of 2.5 inches, and active surface area of 28 square feet. Each membrane element contained two leaves.)

2.2.2 Evaluation of energy efficiency using NaCl solutions

Tests were conducted to determine the energy consumption of the pilot RO system using NaCl solutions with concentrations of 1,000 mg/L, 2,500 mg/L and 5,000 mg/L. Thirteen tests were conducted using water softener salt as the source of sodium chloride and 13 tests were conducted using reagent grade sodium chloride for a total of 26 tests. Tests were run using a range of feed and permeate flowrates from 0.4 gpm to 1.0 gpm and a range of circulation flowrates from 2.0 gpm to 5.0 gpm. The circulation flowrates corresponded to a ratio of circulation flow to feed flow of either 4:1 or 5:1.

The purpose and scope of this phase of testing was limited to providing an initial assessment of CCC RO as a technology for energy-efficient small-scale desalination without introducing complicating factors such as membrane fouling. This phase was designed to demonstrate whether or not CCC configurations have potential to achieve comparable energy efficiency to conventional designs under laboratory conditions.

Test durations ranged from three to six hours, not including test preparation time. Tests were run up to 90% recovery during the first cycle or until feed pump pressures exceeded 400 to 425 psi, whichever occurred first. Tests were continued, following discharge, into the second cycle to recoveries of 85% to 90% or when feed pump pressures exceeded 400 psi. For tests using salinities of 2,500 mg/L and 5,000 mg/L, tests conducted at flowrates above 0.6 gpm were run to recoveries less than 90% due to high operating pressures. During these tests, the number of operating cycles was increased since operating time within a cycle was reduced due to high pressures.

Additional tests were conducted to determine the reason for high pressure drops within the concentrate circulation pipe. Pressure measurements within the circulation pipe were made using only pure water for pipe diameters of one inch and one-quarter inch. One set of measurements was made bypassing the membranes and one set was made using normal flow through the membranes.

Prior to each test, purified water used to make the feed solutions was allowed to cool overnight to room temperature in order to maintain a feed temperature between 75 and 85^{o}F.

2.2.3 Quality assurance and quality control for evaluation of system using NaCl solutions

In order to provide quality assurance, duplicate tests were conducted for a feed sodium chloride concentration of 2,500 mg/L at feed and circulation flowrates of 1.0 gpm and 4.0 gpm and triplicate tests were conducted for a feed concentration of 5,000 mg/L at feed and circulation flowrates of 0.6 gpm and 3.0 gpm. During each test, duplicate measurements were collected at various regular intervals for feed pump pressure , pressures upstream and downstream from the circulation pump and permeate conductivity. Duplicate pressure measurements were made with Ashcroft digital pressure gauges. Permeate conductivity measurements were made with an Orion Three-Star hand-held conductivity meter, manufactured by Thermo Scientific Corporation. Permeate flow measurements were verified by timing the filling of a 2-liter graduated cylinder with a stopwatch. A total of 26 tests, not counting tests to determine source of pressure drops, were conducted during this phase of the research.

In addition, the system and holing tank were flushed prior to each test for three minutes with the feed solution to be used in the test. The flow rate during the holding tank flushing was over 13 gpm, ensuring that at least two holding tank volumes were used to prepare the tank for each test. (The holding tank volume is approximately 11.5 gallons.)

2.2.4 Laboratory assessment of colloidal fouling mitigation

In this phase of the study, testing focused on the assessment of crossflow velocity as a means to reduce membrane fouling and the increased energy consumption associated with fouling. To solutions containing 2,500 mg/L of sodium chloride dissolved in water, known concentrations of a commercially available foulant were added. The foulant used was Snowtex ST-ZL colloidal silica, manufactured by Nissan Chemical.

A total of 15 tests were conducted at several foulant concentrations ranging from 50 mg/L to 1,500 mg/L and inlet crossflow velocities of 0.1 m/s and 0.2 m/s. The crossflow velocity was varied by varying the circulation flowrate and not the feed flowrate. Increasing the feed flowrate would also increase feed pump pressure by increasing permeate flow, potentially exaggerating the true impact of fouling on feed pump pressure and resulting in invalid conclusions regarding the degree of fouling reduction through control of crossflow velocity.

The impact of crossflow velocity was measured as time required to observe the onset of membrane fouling. The onset of membrane fouling was determined by comparing the rate of feed pump pressure increase for each foulant concentration and inlet crossflow velocity to the baseline (no foulant added) rate of feed pump pressure increase at that crossflow velocity. The first occurrence of membrane fouling was assumed to occur at the point where the rate of pressure increase (slope of curve) for a given foulant concentration and inlet crossflow velocity became greater (steeper) than the baseline case. Tests were run through one operating cycle to the point at which the deviation of the pressure versus time curve deviated significantly from the baseline curve and the onset of membrane fouling could be observed. Tests were allowed to continue through discharge and for several minutes into cycle two in order to assess the efficiency of discharge in flushing foulant from the system. Test durations ranged from two to five hours.

2.2.5 Quality assurance and quality control for fouling mitigation study

One duplicate test was completed at a inlet crossflow velocity of 0.2 m/s and a foulant concentration of 100 mg/L . Duplicate pressure measurements were made with Ashcroft digital pressure gauges at locations corresponding to the feed pump pressure and pressures upstream and downstream from the circulation pump. Duplicate permeate conductivity measurements were made with an Orion “Three-Star” hand-held conductivity meter. Permeate flow measurements were verified by timing the filling of a 2-liter graduated cylinder with a stopwatch

Between each test, membranes were cleaned by washing with permeate at a feed flowrate of 1.0 gpm and a circulation flowrate of 5.0 gpm. Discharge cycles were begun at various intervals to facilitate cleaning by flushing the system of any foulant removed from the membranes. The washing process was continued until system pressure had been reduced to a baseline value and the discharge appeared free from visible turbidity.

2.2.6 Field demonstration of RO system with real brackish waters

In the final phase of the study, testing focused on assessment of energy consumption and basic functioning of the pilot small-scale system under field conditions with real brackish groundwater. This phase was initially proposed to be conducted in the exploratory RO plant in the City of Seminole. With the approval by TWDB, the tests were moved to the Brackish Groundwater National Desalination Research Facility in Alamogordo, New Mexico, for better facilities and brackish water sources. Instead of only one type of brackish water at the Seminole RO plant, brackish waters of three different salinities (Well 1, Well 2 and Well 3) are available for the tests at Alamogordo site. As in phase one testing, key variables also included feed flowrate and concentrate circulation flowrate. In addition, tests were run with and without anti-scalant and using different anti-scalant dosings. TriPol 3150, a commercially available anti-scalant manufactured by TriSep Corporation, was used in this phase of the study. Anti-scalant dosing recommendations were supplied by Ms. Malynda Cappelle of University of Texas, El Paso and were based on analyses using Dow Rosa software and performed by TriSep Corporation.

The concentration of total dissolved solids (TDS) in groundwater from Well 1 was 1,240 mg/L, the concentration in groundwater from Well 2 was 5,900 mg/L and the concentration in groundwater from Well 3 was 4,200 mg/L. The concentration of sulfate in Well 1 groundwater was 730 mg/L, the concentration in Well 2 groundwater was 3,400 mg/L and the concentration in Well 3 groundwater was 2,200 mg/L. The concentration of carbonate hardness was 230 mg/L in Well 1 groundwater, 2,600 mg/L in Well 2 groundwater and 2,200 mg/L in Well 3 groundwater. Groundwater data were obtained during a sampling event on August 22, 2011 (TetraTech, 2011). A summary of water quality data and anti-scalant concentrations is provided below in Table 2-1.

Recommended anti-scalant dosings for raw feed from groundwater Wells 1, 2 and 3 were provided by the anti-scalant manufacturer, Tri-Sep Corporation, and were based on analyses of scaling potential performed using the ROSA RO modeling software provided by Dow Chemical Corporation. Scaling potential was determined for (1) raw feed and (2) for the mixed feed to the membranes consisting of raw feed and circulating concentrate. Scaling potential for the mixed feed was determined for an assumed recovery of 75% for RO desalination of Well 1 groundwater, 45% for desalination of Well 2 groundwater and 60% for desalination of Well 3 groundwater. These recoveries were selected based on the scaling potential of the raw feed. Based on these recoveries, the recommended dosing for Well 1 groundwater was 2.0 mg/L, the recommended dosing for Well 2 groundwater was 5.5 mg/L and the recommended dosing for Well 3 groundwater was 3.6 mg/L.

According to the analysis, raw feed from Well 1 contained the following species in excess of 100% saturation: barium sulfate (437%). At 75% recovery, the analysis predicted the following species in excess of 100% saturation in the concentrate: barium sulfate (2381%) and calcium fluoride (1250%). Strontium sulfate was predicted to be at a concentration 95% of saturation in the concentrate.

Raw feed from Well 2 contained the following species in excess of 100% saturation, based on the analysis: calcium sulfate (121%) and barium sulfate (183%). The analysis also identified concentrations of strontium sulfate at 87% of saturation in raw feed from Well 2. At 45% recovery, the analysis predicted the following species in excess of 100% saturation in the concentrate: calcium sulfate (262%), strontium sulfate (147%) and barium sulfate (348%).

Based on the analysis, raw feed from Well 3 contained the following species in excess of 100% saturation: barium sulfate (157%). In addition, Well 3 groundwater contained calcium sulfate at 80% of saturation. At 60% recovery, the analysis predicted the following species to be in excess of 100% saturation: calcium sulfate (266%), strontium sulfate (161%) and barium sulfate (434%).

A major goal of the testing was to achieve recoveries as close to 90% as possible; therefore, the recommended dosings were increased based on an assumption that concentrations of all species in the raw feed/concentrate mixture would be increased approximately 10-fold over their concentrations in the raw feed alone at 90% recovery. To determine final dosings, TDS concentrations in the raw feed were multiplied by 10 and divided by the TDS concentration in the raw feed/concentrate mixture predicted by the Tri-Sep analysis at the assumed recovery for the individual groundwater source. The following equation was used in the calculation:

$$\mathrm{Dose}_{\mathrm{Final}} = \mathrm{Dose}_{\mathrm{Tri\text{-}Sep}} \times \frac{(10 \times \mathrm{TDS}_{\mathrm{RawFeed}})}{(\mathrm{TDS}_{\mathrm{Tri\text{-}Sep,\,Predicted}})}$$

where $\mathrm{Dose}_{\mathrm{Final}}$ is the actual dosing used in the testing, $\mathrm{Dose}_{\mathrm{TriSep}}$ is the dosing recommended by the manufacturer, $\mathrm{TDS}_{\mathrm{RawFeed}}$ is the TDS concentration in the raw feed and $\mathrm{TDSTriSep}_{\mathrm{,\,Predicted}}$ is the concentration of TDS in the raw feed/concentrate mixture predicted by the scaling analysis at the assumed recovery.

Eighteen tests were conducted using groundwater from Well 1, 10 tests were conducted using groundwater from Well 2 and eight tests were conducted using groundwater from Well 3, for a total of 36 tests. Two concentrations of anti-scalant were added to groundwater from Well 1: 5.4 mg/L and 10.0 mg/L. For tests using Well 2 groundwater, the anti-scalant concentration was 30.6 mg/L since this groundwater had the highest scaling potential. Two additional tests were run using Well 2 groundwater with no anti-scalant added. The concentration of anti-scalant added to groundwater from Well 3 was 15.3 mg/L.

Table 2- 1. Groundwater sources, concentrations of selected constituents and anti-scalant concentrations.

Total dissolved solids, sulfate, carbonate hardness and anti-scalant concentrations (milligrams per liter)

Source	Total dissolved solids	Sulfate	Hardness as calcium carbonate	Anti-scalant dosing[1]
Well 1	1,240	730	230	5.4 and 10.1
Well 2	5,900	3,400	2,600	0 and 30.7
Well 3	4,290	2,200	2,200	15.3

[1] TriPol 3150 is certified by NSF International as a drinking water chemical up to a maximum concentration of 10 mg/L.

For each groundwater source and anti-scalant concentration, specific energies were determined at three feed flowrates and at two circulation flowrates for each feed flowrate. Two duplicate tests were also conducted for each set of six tests. Tests were run, whenever possible to 90% recovery in the first operating cycle and to 85% in the second operating cycle. For wells with higher TDS and scaling potential, discharge was commenced prior to achieving 90% recovery due to feed pump pressures above 400 psi. In addition, some duplicate tests only lasted one operating cycle, since the sharpest rise in specific energy as a function of recovery is during the first cycle and the assessment of energy efficiency therefore has focused on primarily on the first cycle. Test durations ranged from three to six hours.

2.2.7 Quality assurance/quality control for field demonstration of RO system

Duplicate tests were conducted for each groundwater source. Two duplicate tests at different feed and circulation flowrates were conducted for groundwater from Wells 2 and 3. For groundwater from Well 1, four duplicate tests were conducted, since two anti-scalant dosings were used. Two duplicate tests for each anti-scalant concentration were conducted.

Duplicate permeate conductivity measurements were made at various time intervals during the tests using an Orion "Three-Star" hand-held conductivity meter. Duplicate pressure measurements were made at various time intervals using three digital Ashcroft pressure gauges at locations corresponding to feed pump pressure and pressures upstream and downstream from the circulation pump. Permeate flow measurements were verified by timing the filling of a 2-liter graduated cylinder with a stopwatch.

Due to the scaling potential from each groundwater source, prior to each test, the system was flushed with permeate from a separate on-site RO system operated by the Bureau of Reclamation. The flushing continued until a stable pure water baseline was reached at a feed flowrate of 1.0 gpm and a circulation flowrate of 4.0 gpm.

3 Results and Discussion

Results have been presented and analyzed separately for each phase of the research in sections 3.1 and 3.2 below. Results of laboratory tests, including verification of system performance, have been presented in Section 3.1, while results of field tests have been presented in Section 3.2.

3.1 Results of laboratory tests

3.1.1 Verification of system performance

From June to October 2010, tests were conducted to verify that system flowmeters were providing reliable data. Tests indicated that the "paddlewheel" permeate flowmeter was providing flowrates far below the actual permeate flowrates. The "paddlewheel" meter was replaced with a magnetic flowmeter. Subsequent tests conducted since October 2010 indicated that the magnetic permeate flowmeter readings were between 100% and 110% of flow measurements made with a stopwatch and graduated cylinder. The error is greatest for low flowrates. At a flowrate of approximately 0.4 gpm, the error ranges from 7% to 10%, while at a flowrate of approximately 1.0 gpm, the error ranges from 0% to 5%.

In November 2010, NIST-certified digital pressure gages were installed at "P1", "P3" and "P4" for duplicate pressure measurements to confirm the accuracy of logged system pressure readings. Errors in pressure measurements have generally been between 0% and 5%.

In all testing since January 2011, duplicate measurements of permeate conductivity have been made with an Orion "Three-Star" conductivity meter, made by Thermo-Scientific to confirm the accuracy of logged system permeate conductivity readings. Generally the discrepancy between the two sets of readings have ranged from 0% to 10%.

3.1.2 Results of laboratory assessment of energy consumption using NaCl solutions

The assessment of closed concentrate circulation as a means of increasing recovery and maximizing energy efficiency of small-scale brackish RO must address the following issues:

1. Does the process operate as designed? Does the pressure rise gradually in response to rising salinity of the combined feed/concentrate stream, thereby reducing the large excesses of net driving pressure seen in large-scale RO? During discharge cycles, is the flushing of accumulated salt from the holding tank efficient enough that the system returns to its original state at the commencement of each “normal” cycle?

2. How does the energy efficiency, measured as specific energy, of the pilot small-scale system, compare to recently published values for conventional large-scale RO systems?

Results of laboratory testing conducted at Texas Tech University have been analyzed in response to these issues and are presented below.

Key indicators of system performance have been analyzed and are presented below in Figures 3-1 through 3-3. In Figure 3-1, feed pump pressure has been plotted for first cycle operating times of approximately 80 minutes. If the system operates as designed, the pressure will rise gradually in response to increasing salinity of the combined stream entering the membrane channels.

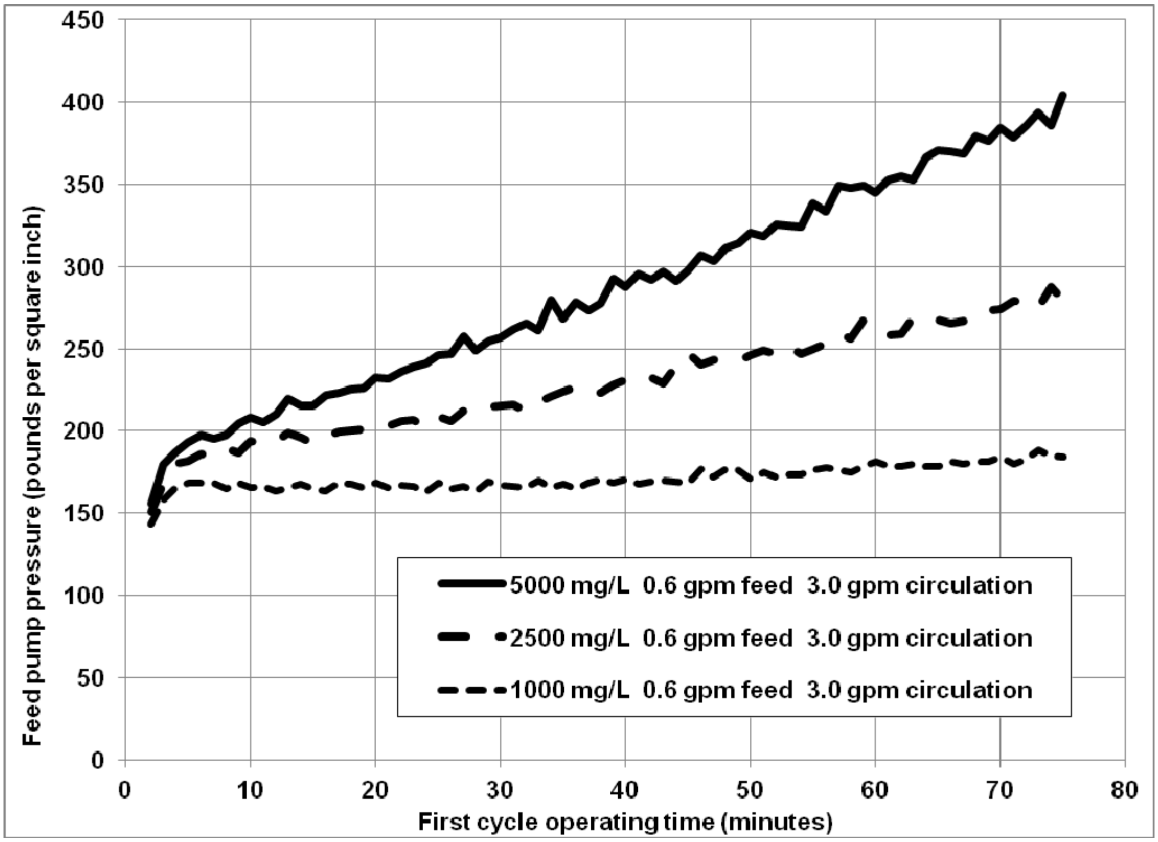

Figure 3-1. Feed pump operating pressure versus first cycle operating time.

Results presented in Figure 3-1 indicate that feed pump pressure does rise gradually over time within the first operating cycle and that this feature of the system functions as designed. Except for the first few minutes of operation, the pressure increase is gradual and essentially linear at all feed TDS concentrations. Feed pump pressure rises gradually during the experiment due to the increase in the osmotic pressure difference between fluid in the membrane channel and the permeate as the TDS concentration in the circulating concentrate rises. Since the rise is essentially linear and is a function of the osmotic pressure of the concentrate, the slopes of the lines are determined by the feed concentrations. The slope of the line for feed TDS of 5,000 mg/L would be expected to be roughly five times the slope of the line for feed TDS of 1,000 mg/L and roughly two times the slope of the line for feed TDS of 2,500 mg/L.

Potential reasons for the sharp initial increase in feed pump pressure include the following:

- Salts adhering to membrane surfaces become loosened or begin to dissolve as the crossflow velocity increases during the first few minutes of operating pressure, resulting in reduced resistance to flow and lower operating pressures.

In order to assess the effectiveness of the discharge cycle, feed pump pressure and concentrate conductivity have been plotted versus operating time for multiple operating cycles in Figures 3-2 and 3-3.

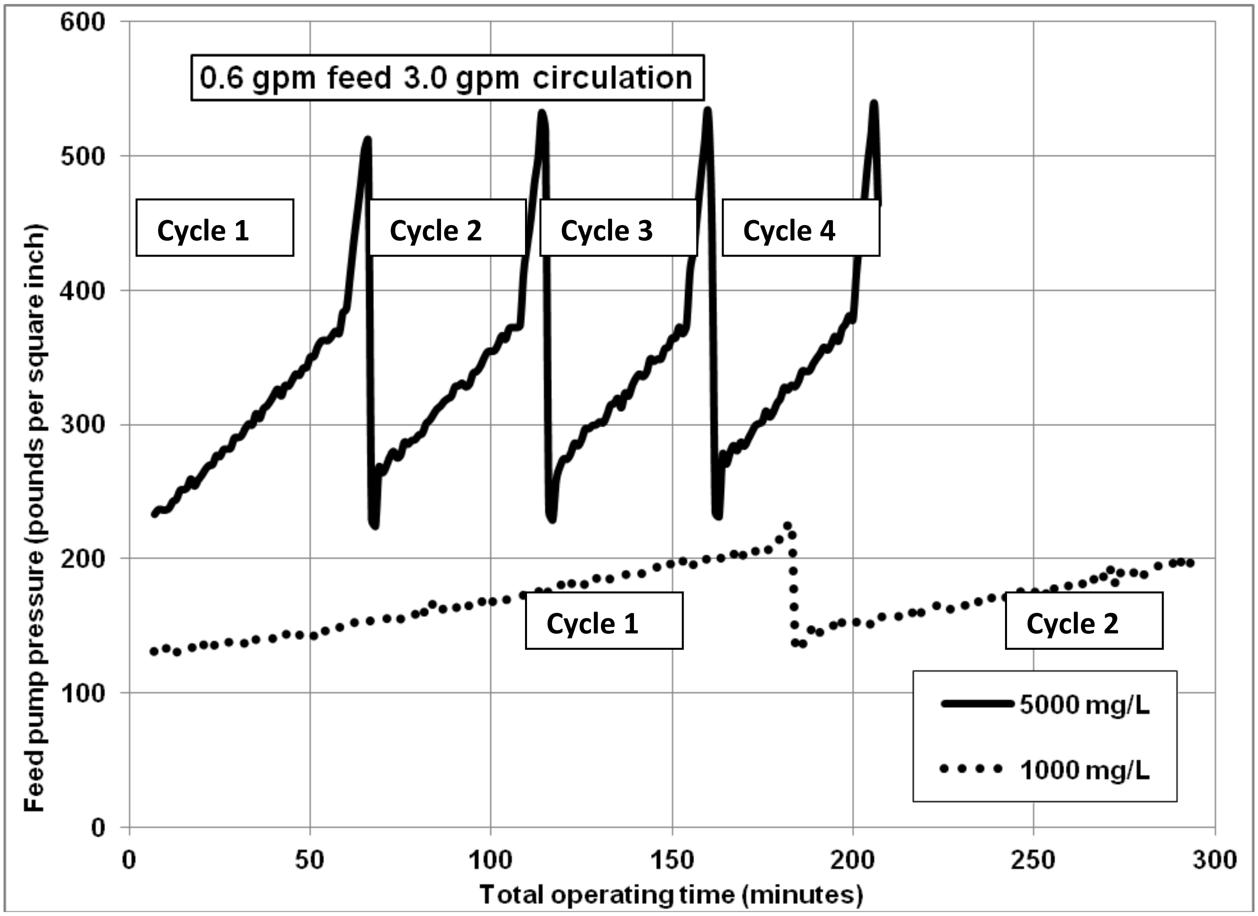

Figure 3-2. Feed pump operating pressure versus total operating time (multiple cycles).

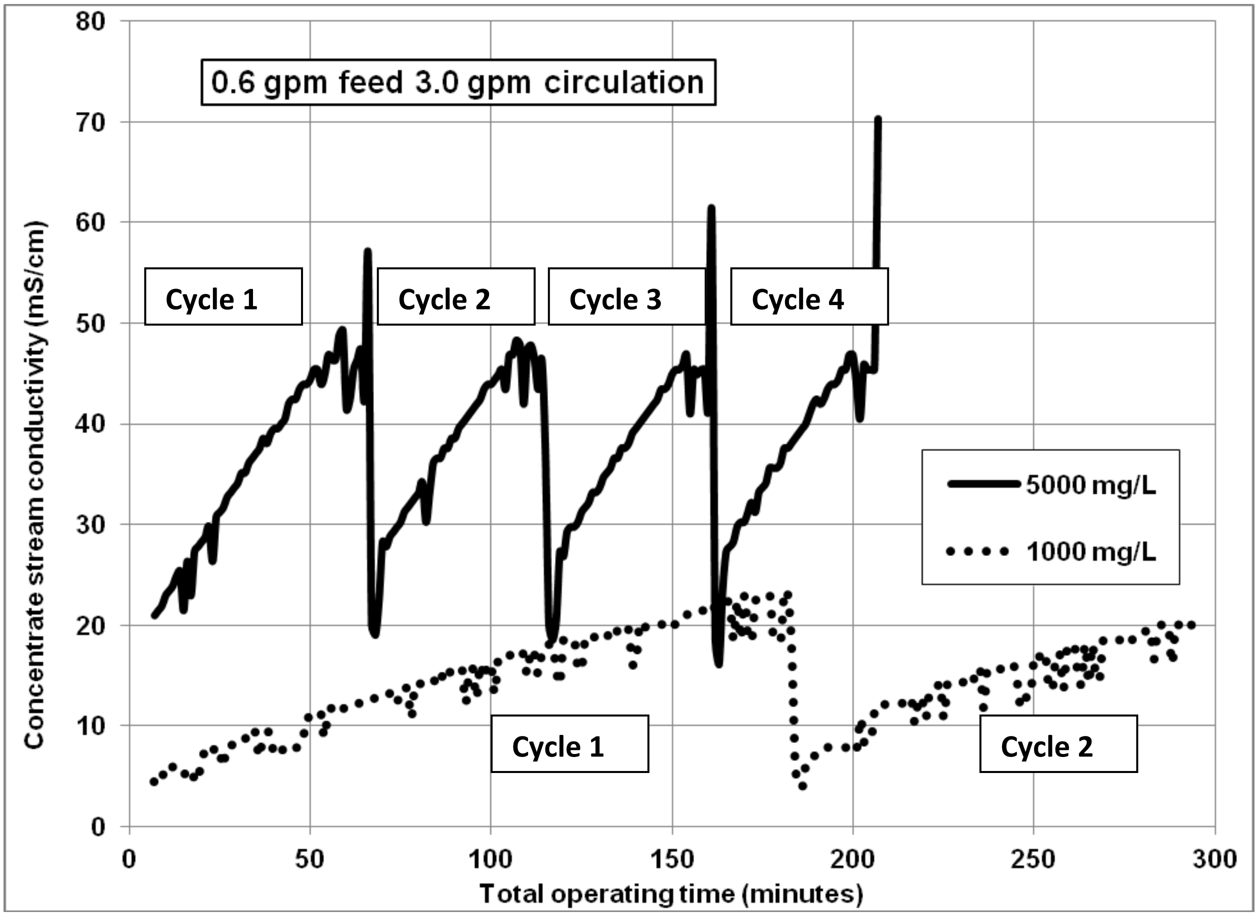

Figure 3-3. Concentrate stream conductivity versus total operating time (multiple cycles).

In the above graphs, discharge cycles correspond to the downward spikes in pressure and conductivity. Efficient flushing of the system is reflected in the return of the system to its original state at start-up. Graphs of feed pump operating pressure and concentrate stream conductivity indicate that the flushing of the holding tank during the discharge cycle is quite effective in removing accumulated salts and preparing the system for the commencement of the next operating cycle.

Due to residual salt remaining in the system from the previous operating cycle, there is a small memory effect indicated by the pressure spikes immediately following discharge, beginning in operating cycle 2. This effect is also evident in the shorter times between required discharge operations (greater than 60 minutes in cycle 1 versus 50 minutes in subsequent cycles). Visible effects of residual salt in the system are much less apparent when concentrate conductivity is examined as a variable.

In order to assess the energy efficiency of the pilot small-scale system and determine the effectiveness of closed concentrate circulation, specific energies were determined for the pilot RO system for feed sodium chloride concentrations of 1,000, 2,500, and 5,000 mg/L at several feed and concentrate circulation flowrates. Specific energy values were then compared to published values for large-scale systems.

A value of 0.61 kWh/m^3 has been reported for the Kay Bailey Hutchinson facility in El Paso operating at a recovery of 81%, Texas (McHarg, 2010), while a reduction of that value to 0.45 kWh/m^3 by employing isobaric pressure exchangers and inter-stage booster pumps has also been reported (McHarg, 2011). One recent source has provided a theoretical energy requirement for conventional single stage brackish RO of 0.54 kWh/m^3 without energy recovery devices and a corresponding theoretical energy requirement of 0.26 kWh/m^3 for closed circuit desalination (Qiu and Davies, 2012). Lenntech Corporation provided a specific energy value of 1.5 kWh/m^3 at a recovery of 65% to 80% for its brackish water RO plants on its product website in 2011. A range of 0.6 to 0.9 kWh/m^3 was provided by Veolia at the 3rd Conference on Life Cycle Management, based on an "optimal" recovery of 80% (Vince and others, 2007). Other reported values include 1.29 kWh cubic meter without energy recovery devices and 0.86 kWh/m^3 with isobaric energy recovery devices both at a recovery of 60% (Stover, 2007). Based on values provided by several recent sources, a range of 0.4 to 1.0 kWh/m^3 has been assumed when performing the comparison.

Values of specific energy determined for the pilot small-scale system are presented below in Figures 3-4 through 3-11 (below) for feed and permeate flowrates from 0.4 to 1.0 gpm. A permeate flowrate of 1.0 gpm corresponds to a permeate flux of 25.7 gallons per square foot per day (gfd), a permeate flowrate of 0.8 gpm corresponds to a permeate flux of 20.6 gfd, a permeate flowrate of 0.6 gpm corresponds to permeate flux of 15.4 gfd and a permeate flowrate of 0.4 gpm corresponds to a permeate flux of 10.3 gfd. The ratio of circulation flowrate to feed flowrate was five to one in each test presented. In each test, the target recovery in the first operating cycle was initially 90%. In addition, tests were designed to run for at least two operating cycles. Due to the high pressures observed during testing, however, no test using a feed sodium chloride concentration of 5,000 mg/L achieved the target recovery. In addition, tests using a feed concentration of 2,500 mg/L were unable to achieve 90% recovery at feed flowrates of 0.8 gpm and 1.0 gpm.

The total specific energy is the sum of the specific energy for the feed pump and the specific energy for the circulation pump. Only the total specific energy and the feed pump component of the specific energy are presented. In addition, the form of sodium chloride used in testing has been specified in parentheses.

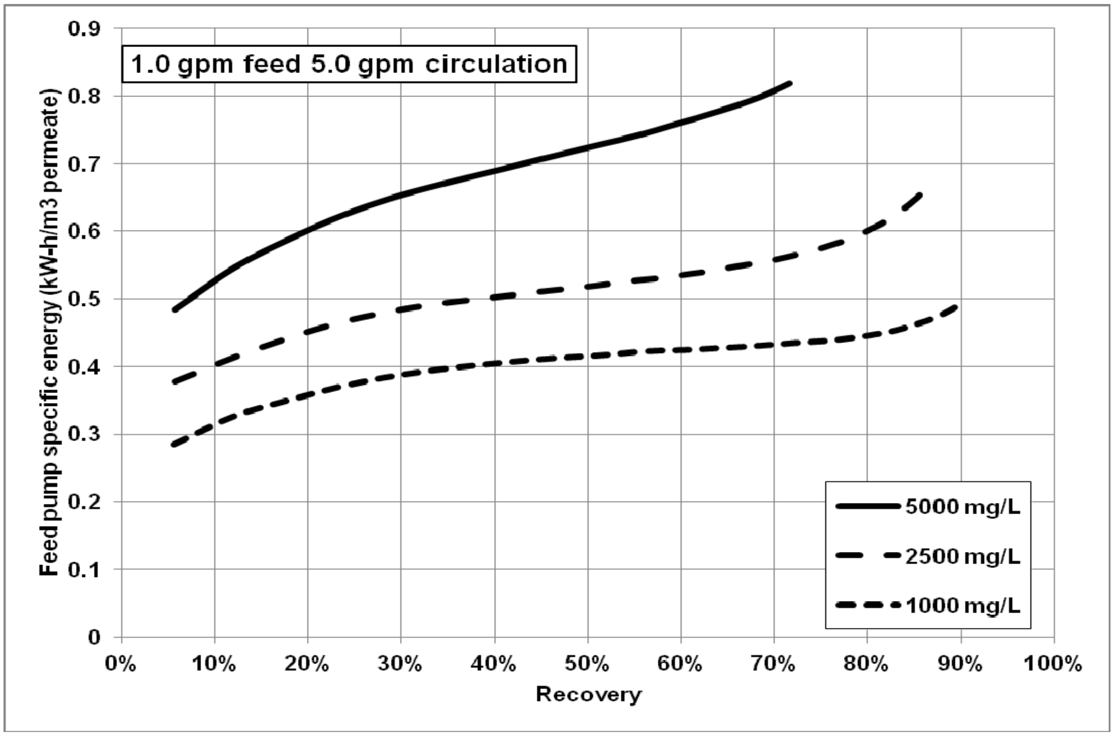

Figure 3-4. **Feed pump specific energy versus recovery**

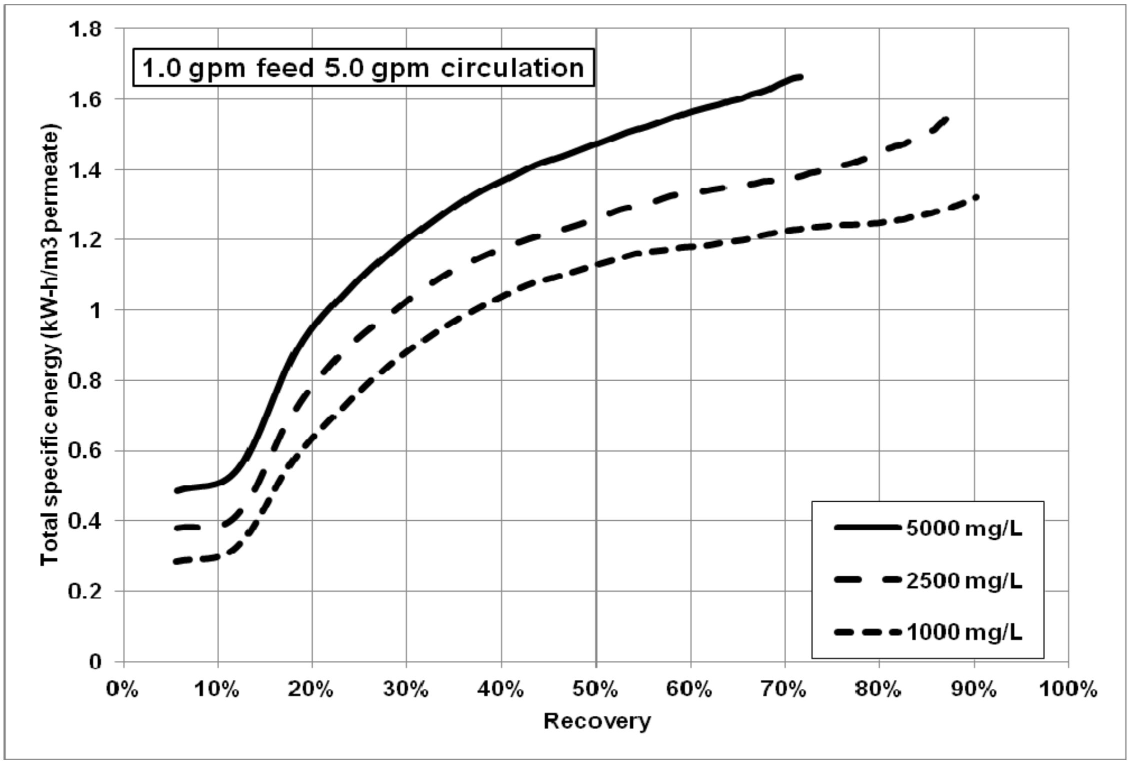

Figure 3-5. **Total specific energy versus recovery**

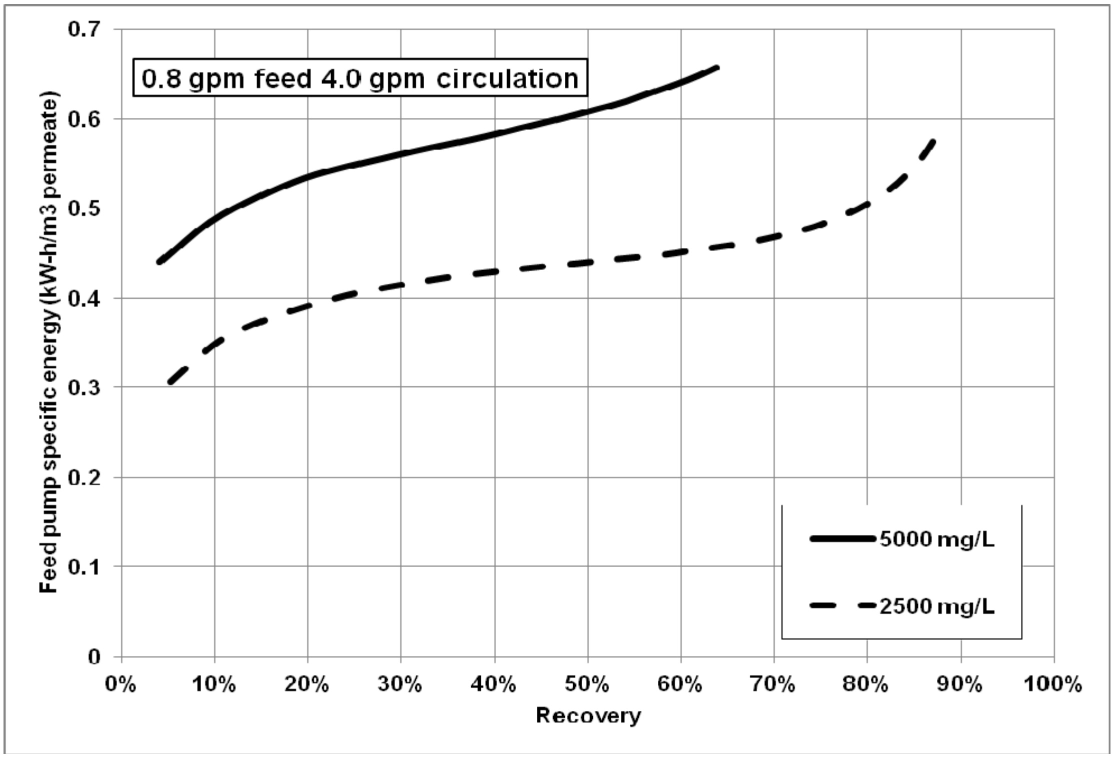

Figure 3-6. **Feed pump specific energy versus recovery**

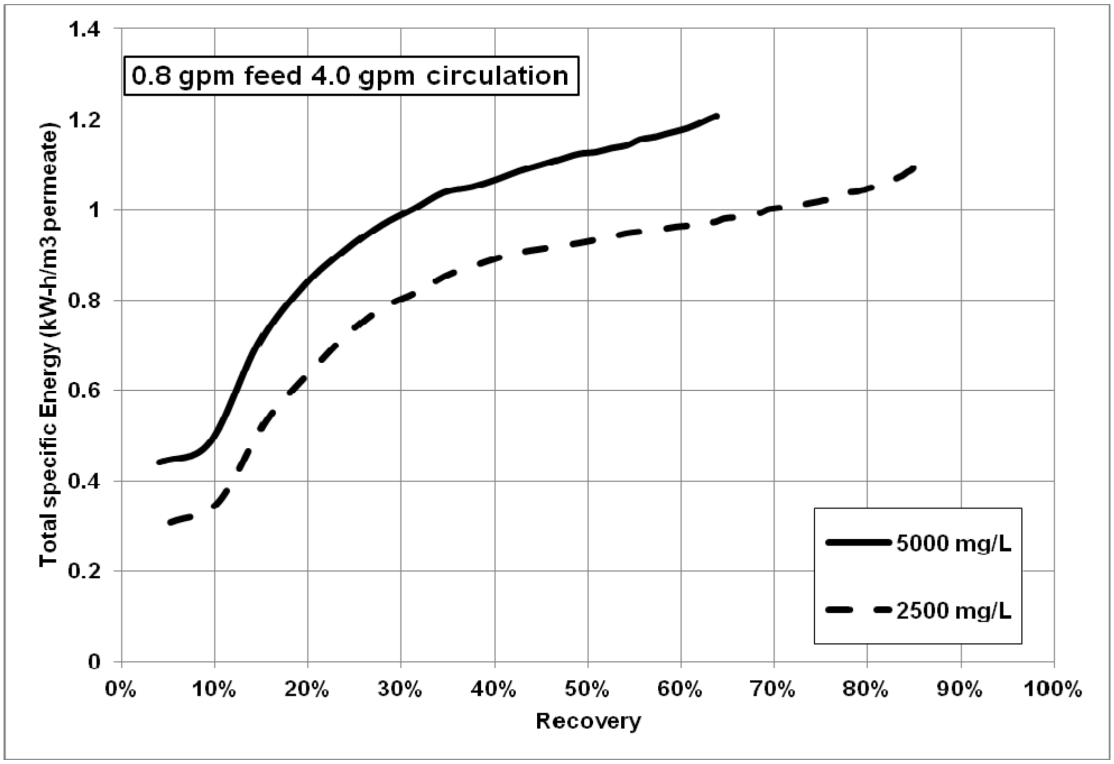

Figure 3-7. **Total specific energy versus recovery**

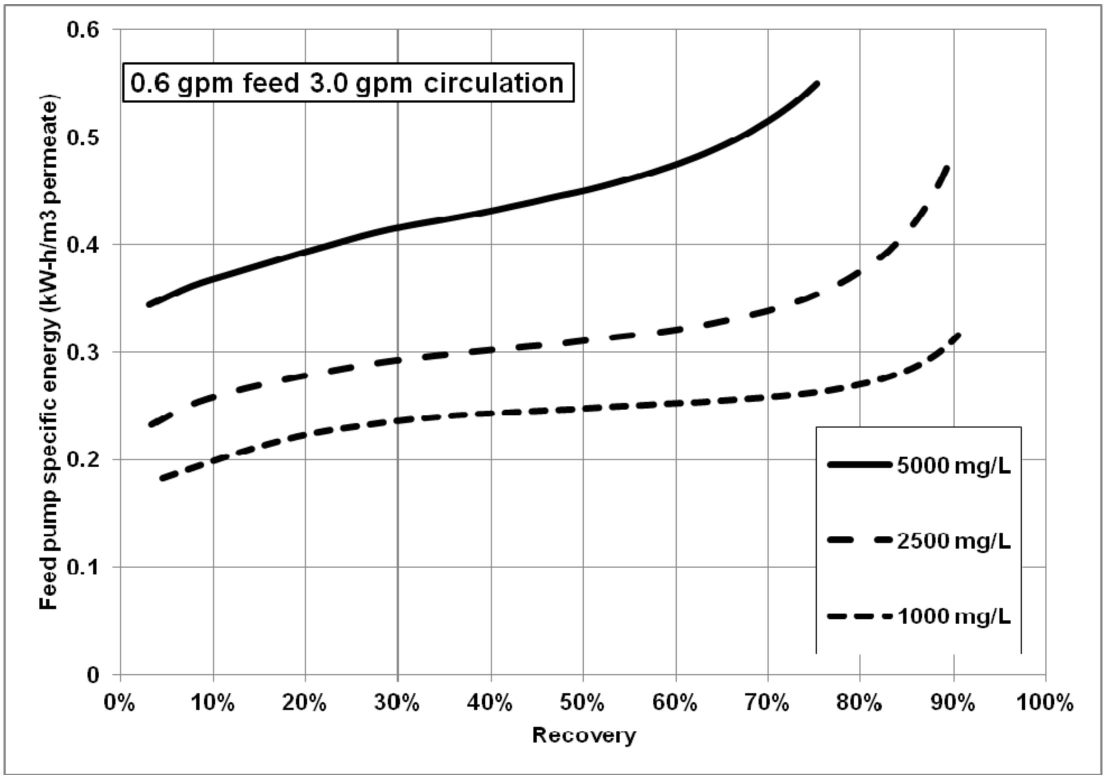

Figure 3-8. **Feed pump specific energy versus recovery**

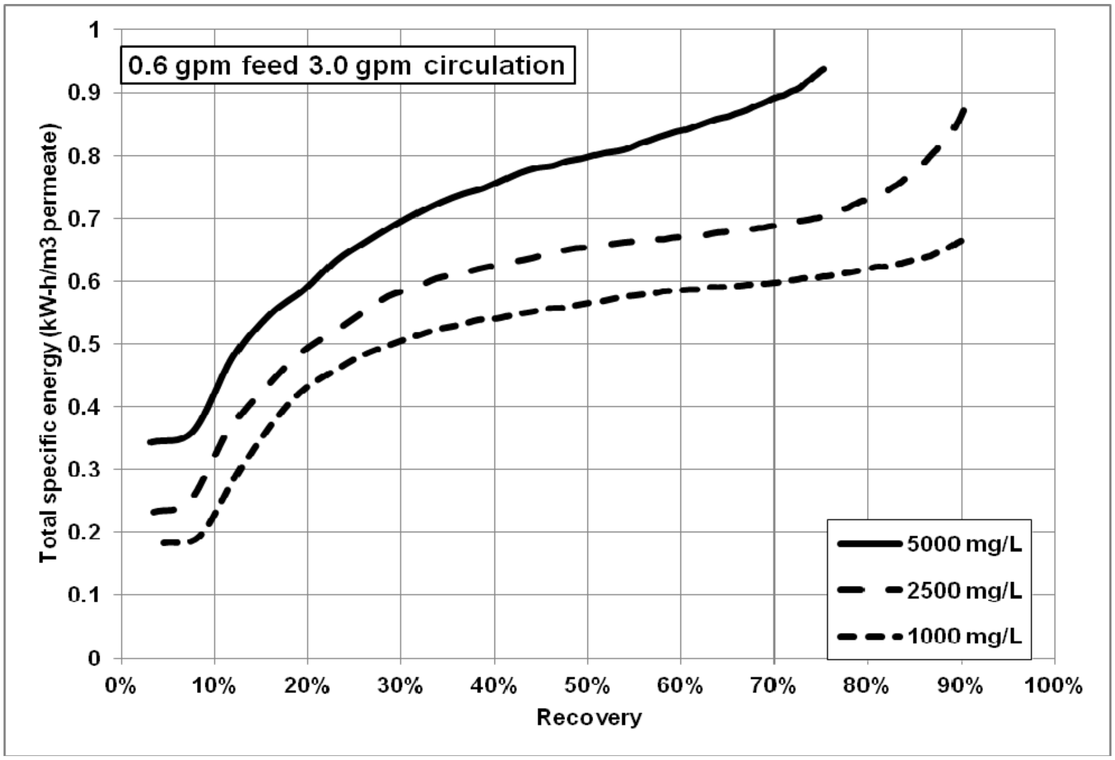

Figure 3-9. **Total specific energy versus recovery**

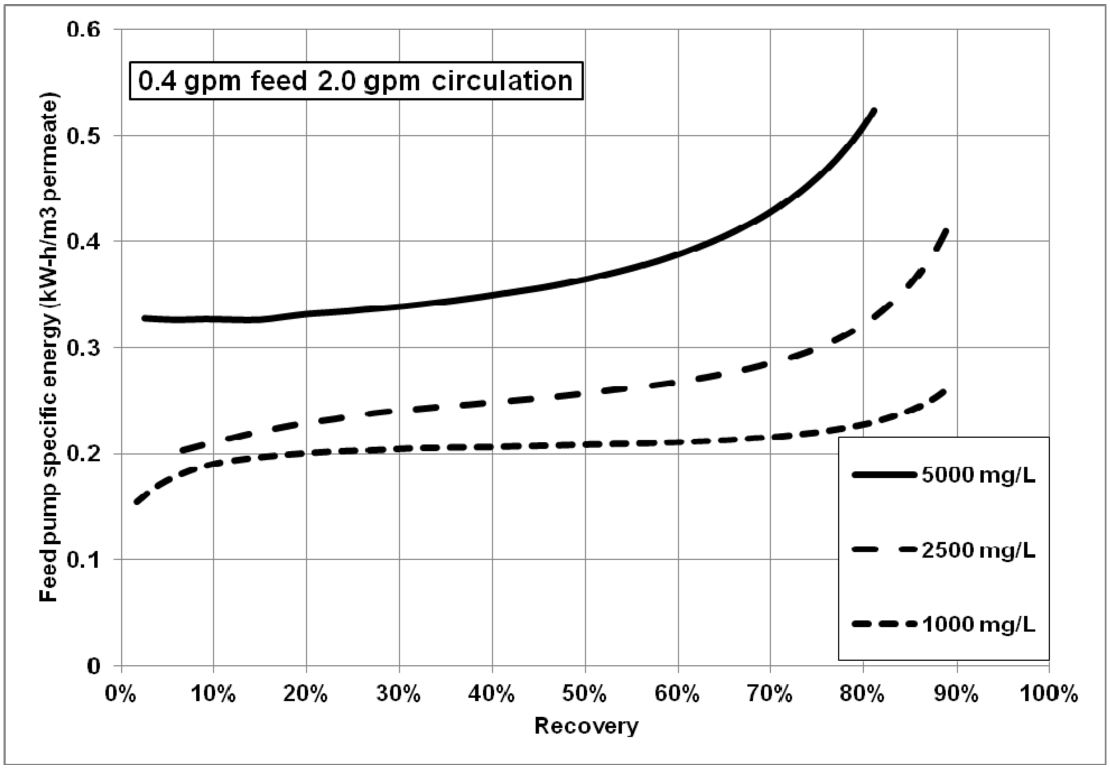

Figure 3-10. **Feed pump specific energy versus recovery**

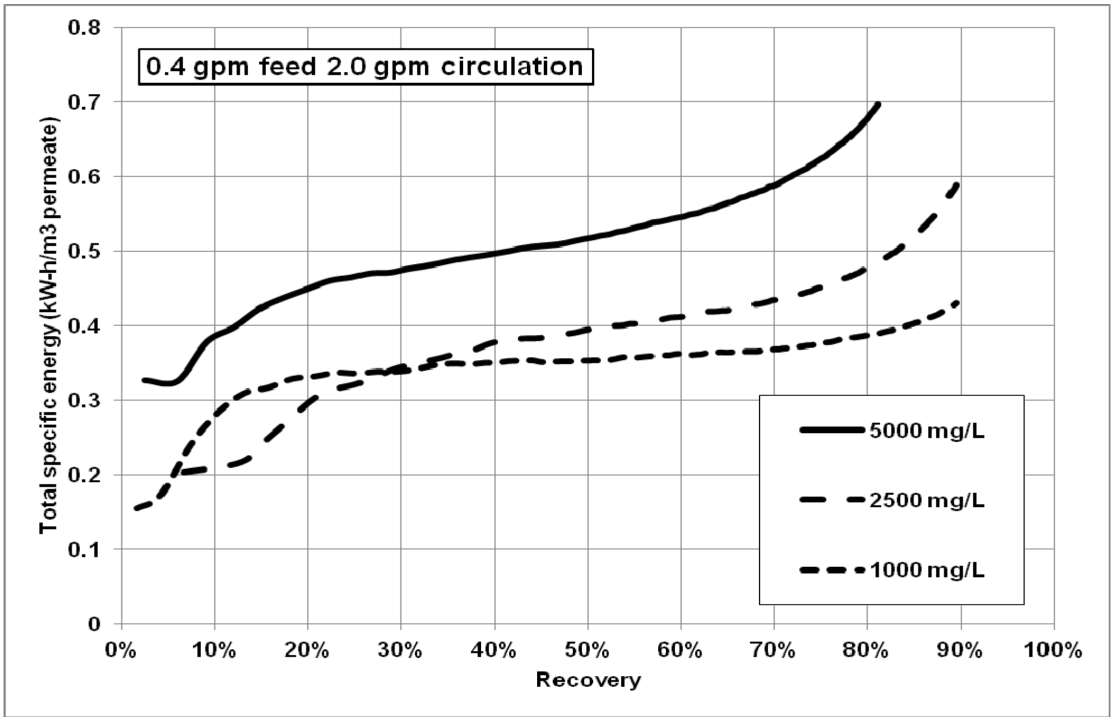

Figure 3-11. **Total specific energy versus recovery.**

At a feed flowrate of 1.0 gpm, total specific energy exceeded 1.0 kWh/m^3 for all feed salinities at recoveries greater than 40%. For a feed flowrate of 0.8 gpm, total specific energy exceeded the 1.0 kWh limit for recoveries greater than 30% for a feed salinity of 5,000 mg/L and exceeded the 1.0 kWh limit for recoveries greater than 70% for a feed salinity of 2,500 mg/L. For a feed flowrate of 0.6 gpm, total specific energy was below the 1.0 kWh/m^3 threshold for the maximum recoveries achieved at each feed salinity: 75% at 5,000 mg/L and 90% at 1,000 and 2,500 mg/L. For all feed flowrates and feed salinities tested, the feed pump specific energy component was below the 1.0 kWh threshold at the maximum recoveries achieved.

The energy consumption by the circulation pump represents the difference between total energy consumption and feed pump energy consumption. The circulation pump is required to equalize the pressure between the incoming feed which is pressurized by the feed pump and the circulating concentrate which suffers head losses, manifested as pressure drops, not only within the membrane channels, but within the piping that conveys the concentrate away from the membranes, through the holding tank and circulation pump, prior to its combining with incoming feed. Test data indicate that pressure drops within the membrane channel, or crossflow pressure drops, and pressure drops within the holding tank are between two to five psi. Most of the head losses that cause these pressure drops are due to flow within the pipe itself, are functions of the flow velocity and consist mainly of frictional head losses and losses within pipe bends, tees, expansions and contractions. Preliminary calculations indicate that total specific energy could be reduced below the 1.0 kWh/m^3 limit if the pressure drops within the concentrate circulation pipe could be limited to 15 to 20 psi.

Significant reductions in pressure drops within the concentrate circulation loop can be achieved by reducing sources of head loss within this portion of the system wherever possible. Potential sources of head loss include: small diameter pipe, 90-degree tees, abrupt transitions from small diameter pipe to large diameter pipe, small radius elbows and valves. In many cases it is not possible to completely remove the source of the head loss, but to substitute a component of more suitable size and radius for the less desirable component. For example, head loss could be reduced by substituting 45-degree lateral tees for 90-degree tees. Other reductions in head loss could be realized by increasing the radius of elbows, selecting a different type of valve, increasing the diameter of pipe or by eliminating pipe diameter changes and using, for example, pipe of a single diameter. Replacement of valves, tees and other components could be accomplished by comparing the head loss coefficients of components currently in use with head loss coefficients of potential substitutions. These head loss coefficients may be found in reference works such as Perry's Chemical Engineer's Handbook or other reference works on pipe flow.

It should be noted, however, that specific energy appears to plateau following the first operating cycle. In Figure 3-12 below, specific energy has been plotted as a function of operating time for four operating cycles at a feed salinity of 5,000 mg/L and for two operating cycles at feed salinities of 1,000 and 2,500 mg/L. The flattening of the curve and the achievement of a relatively constant specific energy is most evident at the highest salinity.

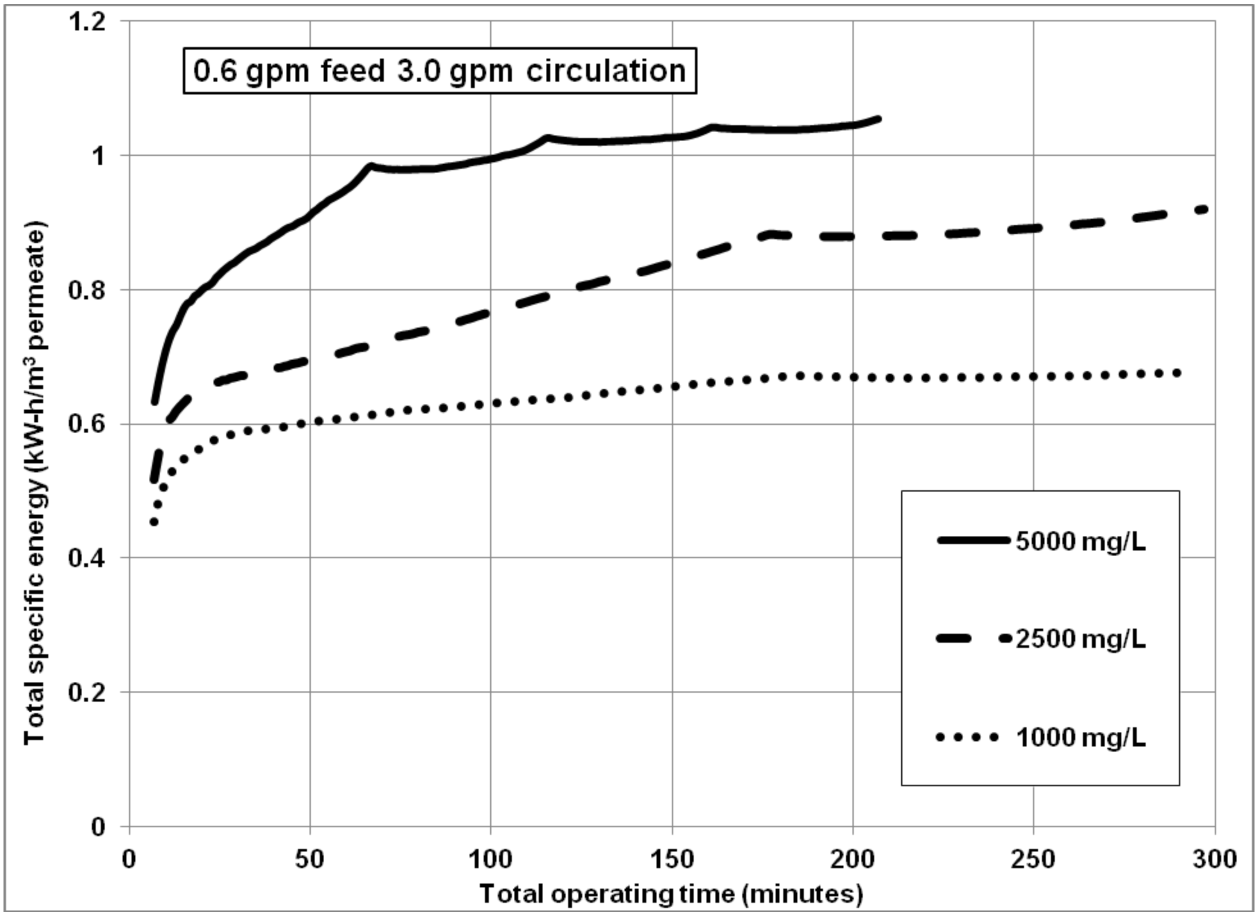

Figure 3-12. Total specific energy as a function of operating time over multiple cycles.

3.1.3 Results of fouling mitigation study with variable inlet crossflow velocity)

Results of tests to determine the impact of inlet crossflow velocity on membrane fouling are presented below in Figures 3-13 through 3-16

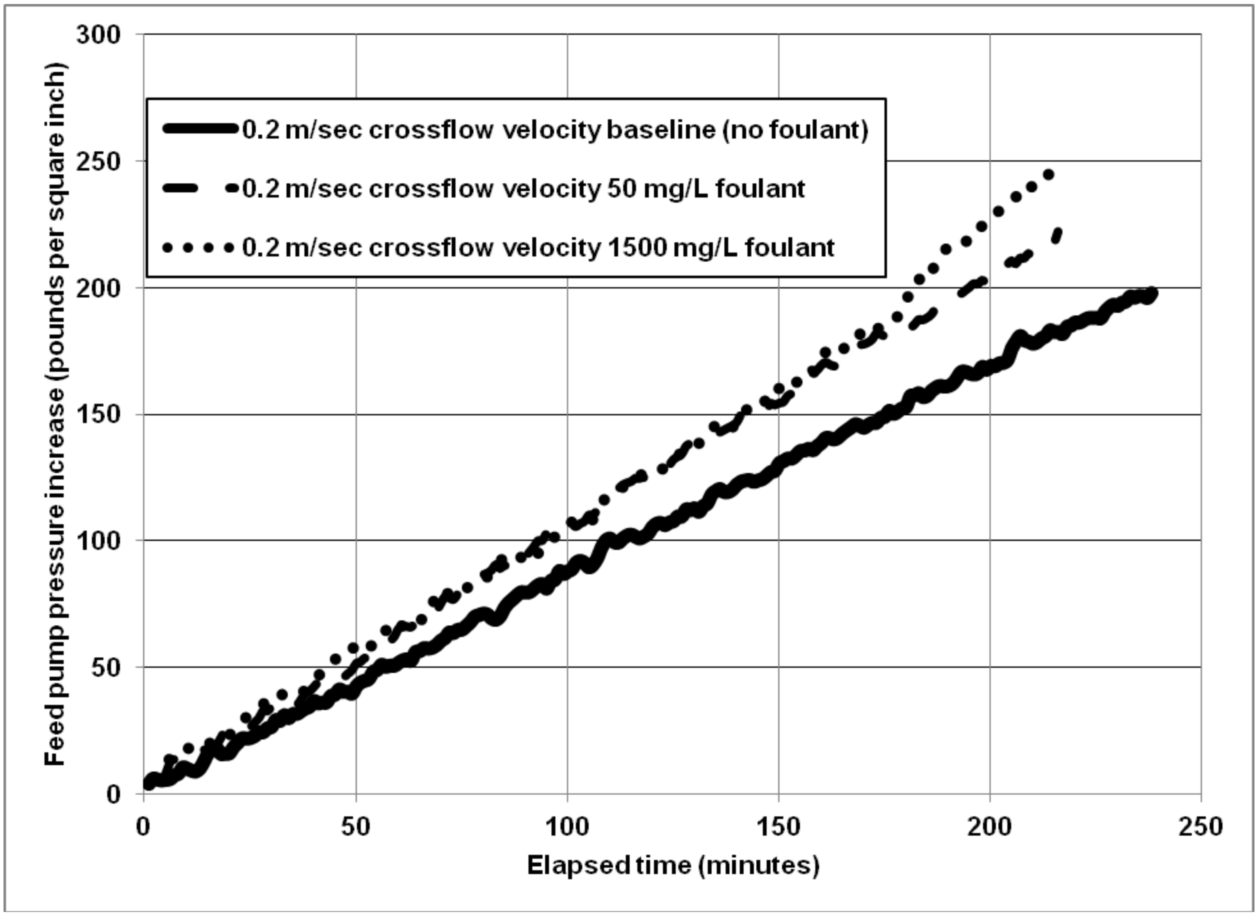

Figure 3-13. Impact of foulant concentration on time required for onset of fouling

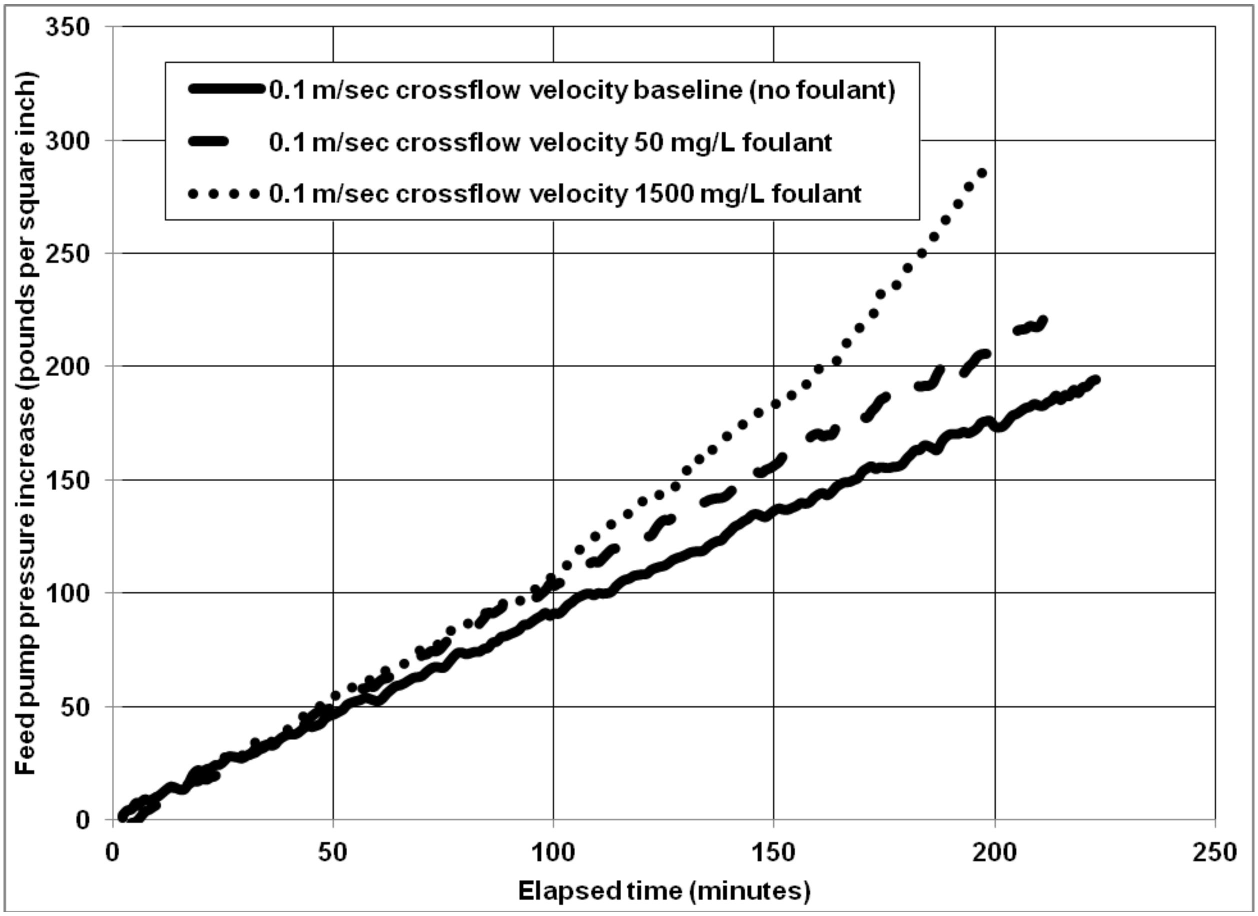

Figure 3-14. **Impact of foulant concentration on time required for onset of fouling**

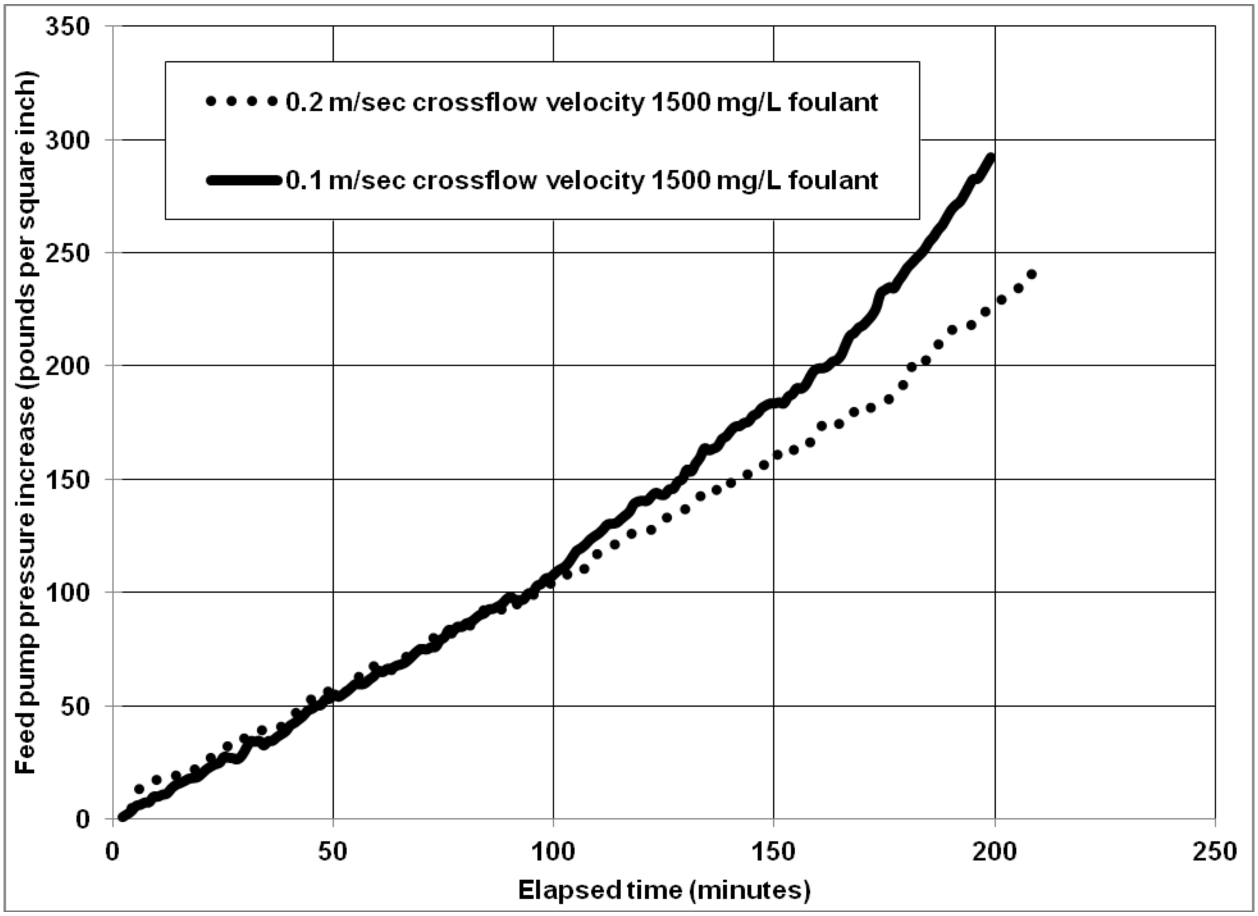

Figure 3-15. Impact of crossflow velocity on membrane fouling.

The severity of membrane fouling, as evidenced by the feed pump pressure increase, is far greater for an inlet crossflow velocity of 0.1 m/s.

In order to correctly analyze these results, it should be noted that the foulant concentrations shown in the figures are the foulant concentrations in the raw feed and not the concentrations actually entering the membrane channels. The fluid entering the membrane channels contains both raw feed and recycled concentrate and is several times as concentrated as the raw feed in terms of salinity and foulant concentration. Even at these high foulant concentrations, significant membrane fouling occurs fairly slowly, requiring in some cases several hours.

The greater severity of fouling at an inlet crossflow velocity of 0.1 m/s provides some indication that increasing crossflow velocity can reduce membrane fouling.

3.2 Results of field testing at the Brackish Groundwater National Desalination Research Facility

Total specific energy and feed pump specific energy were determined for permeate production from groundwater supplied by Wells 1, 2 and 3 at the Brackish Groundwater National

Desalination Research Facility. Testing was conducted at several feed flowrates for each well using circulation flow to feed flow ratios of five to one and six to one.

Pre-treatment of the well water included passage through a 25-micron filter, followed by passage through a 5-micron filter, prior to entry of the raw feed into the RO system.

As an additional test variable, for tests using feed from Wells 1 and 2, the amount of anti-scalant was varied, in order to assess the impact of anti-scalant on energy consumption.

Results for tests conducted at feed flowrates of 0.5, 0.6 and 0.8 gpm and a circulation to feed flow ratio of five to one are presented for each of the groundwater sources in Figures 3-16 through 3-21 below. Results are for operating cycle one and recoveries to 90%.

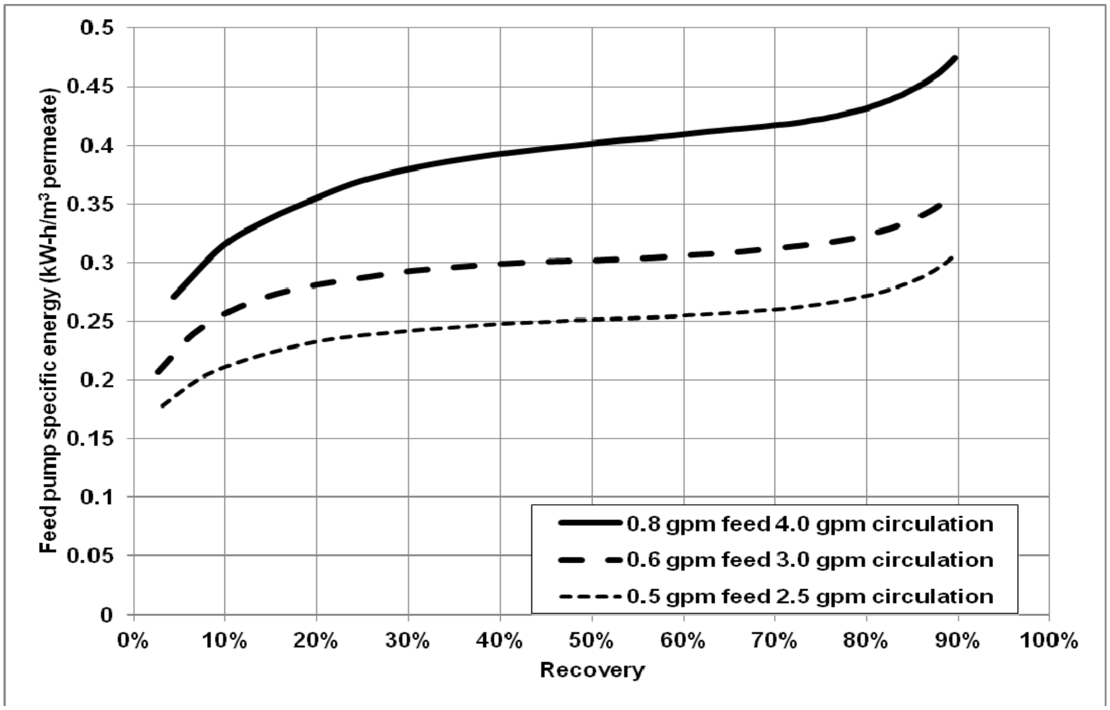

Figure 3-16. Feed pump specific energy versus recovery at various feed and circulation flowrates. Well 1

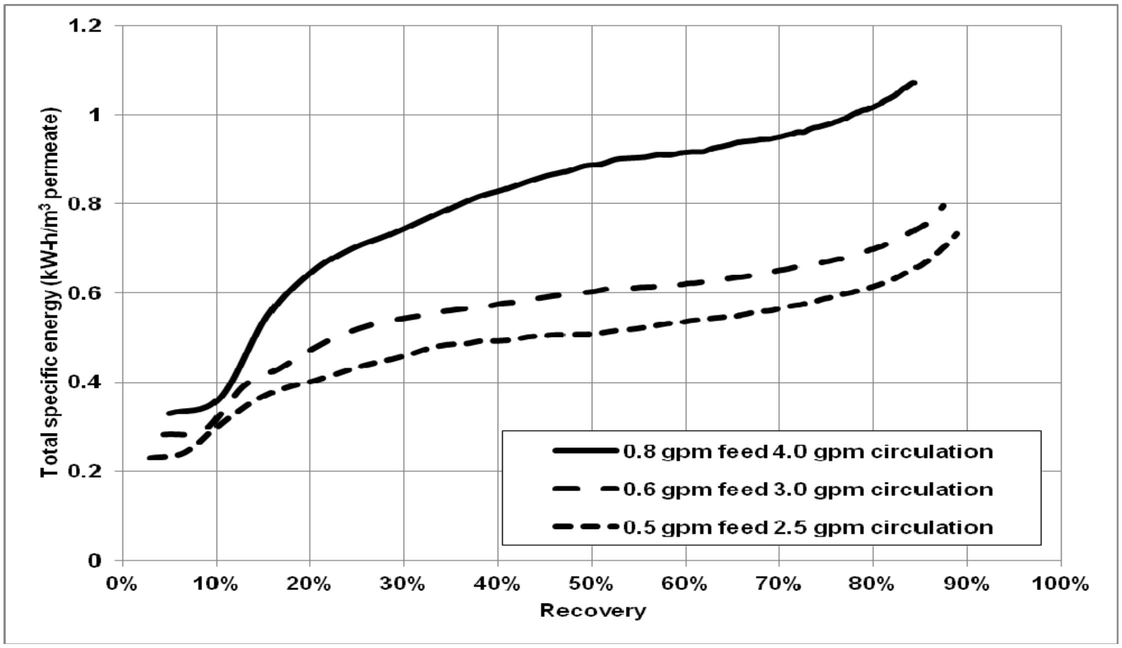

Figure 3- 17 Total specific energy versus recovery at various feed and circulation flowrates. Well 1.

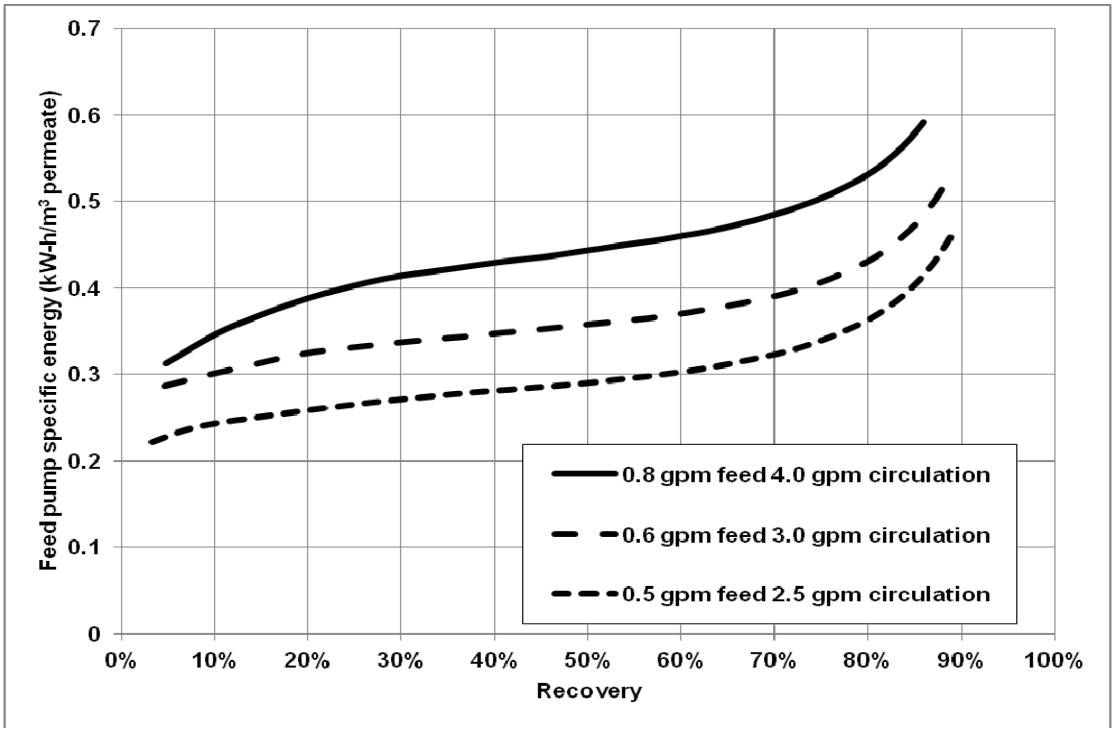

Figure 3-18. Feed pump specific energy versus recovery at various feed and circulation flowrates. Well 3.

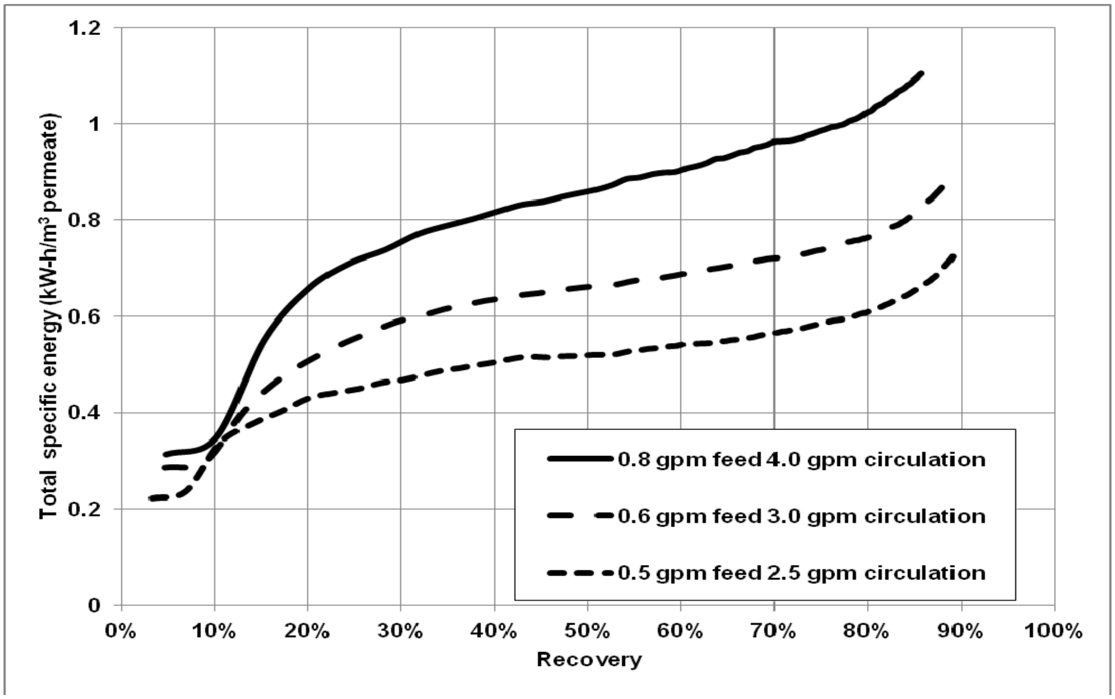

Figure 3-19. Total specific energy versus recovery at various feed and circulation flowrates. Well 3.

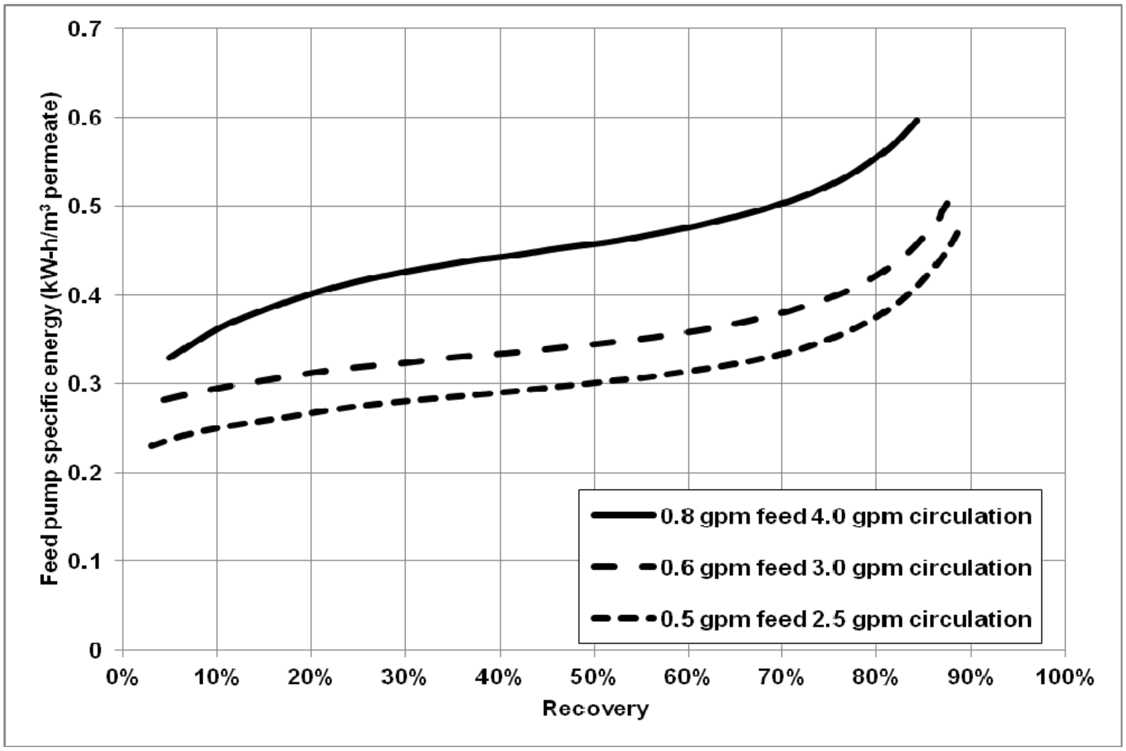

Figure 3-20. Feed pump specific energy versus recovery at various feed and circulation flowrates. Well 2.

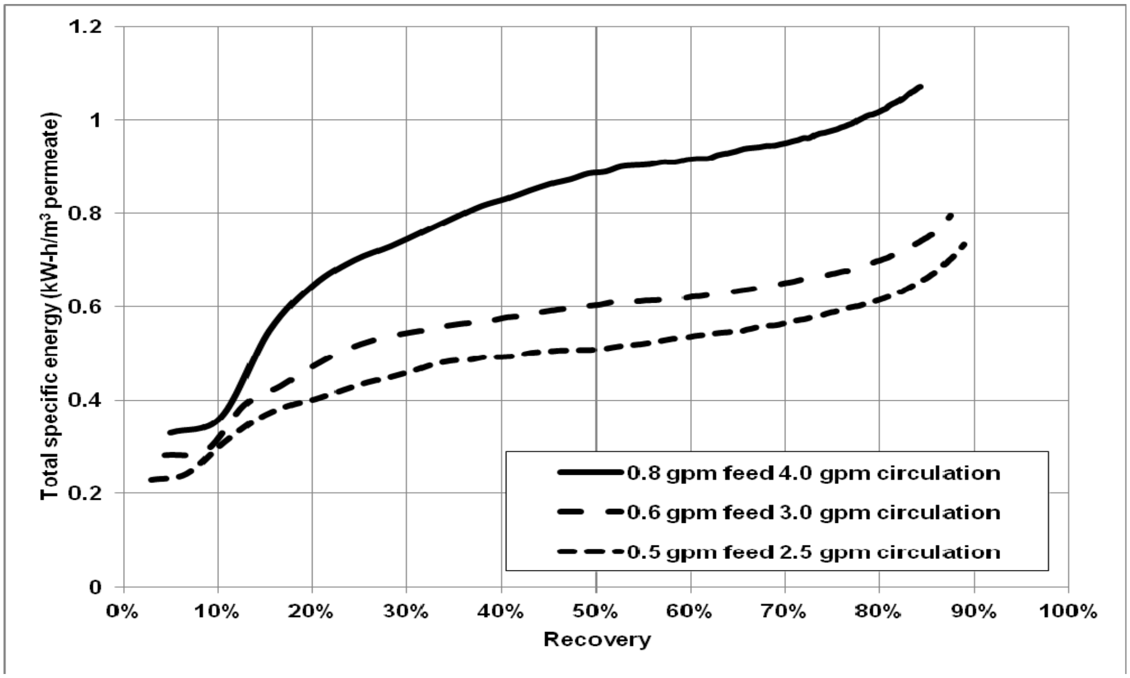

Figure 3-21. Total specific energy versus recovery at various feed and circulation flowrates. Well 2.

Feed pump specific energy for tests using water from Well 1 was slightly lower than feed pump specific energy for tests using water from Wells 2 and 3. Feed pump specific energies for tests using water from Well 3 were nearly equal to values determined for groundwater from Well 2, although Well 2 has a TDS concentration over 30% higher than the concentration in water from Well 3 and much greater scaling potential, indicating that anti-scalant addition may be able to significantly reduce energy consumption in waters with high scaling potential.

Feed pump specific energies for permeate production from all three wells were very similar to feed pump specific energies for feed containing 2,500 mg/L sodium chloride. Although the concentration of TDS in water from Well 1 is approximately 50% of this concentration, water from Well 1 has a much higher scaling potential than a solution of essentially pure sodium chloride. Groundwaters from Well 2 and Well 3 have TDS concentrations of approximately 5,900 mg/L and 4,200 mg/L and much greater scaling potential than water from Well 1. These results indicate that the addition of anti-scalant to groundwaters with moderate to high scaling potential may be able to significantly lower RO energy consumption.

Although the amount of anti-scalant added to water from Well 2 was several times the amount added to water from Well 1, the dose represents a very small amount, only several grams in approximately 230 gallons (or 1,900 pounds) of water. This represents a large potential energy savings from such a small amount of chemical.

The energy-saving potential of anti-scalant was directly measured in tests using different concentrations of anti-scalant in Well 1 water and in tests using water from Well 2 with and without anti-scalant. Specific energy values as a function of recovery for these tests are presented below in Figures 3-22 through 3-24.

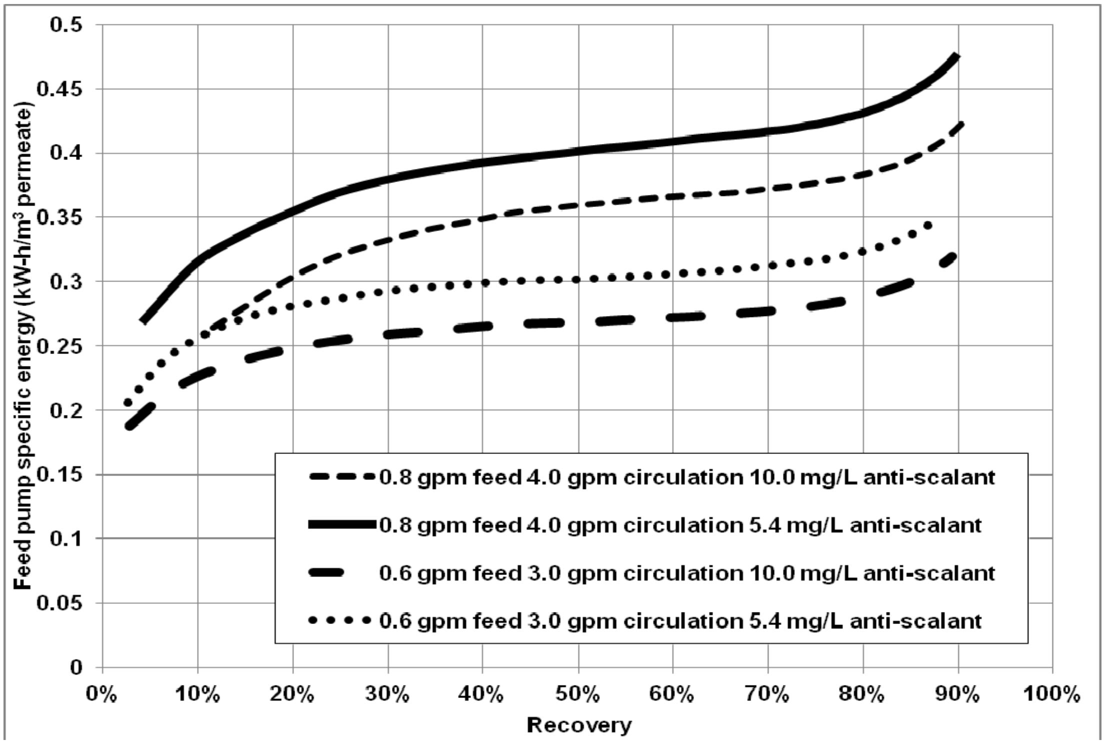

Figure 3-22. **Feed pump specific energy versus recovery, effect of anti-scalant. Well 1.**

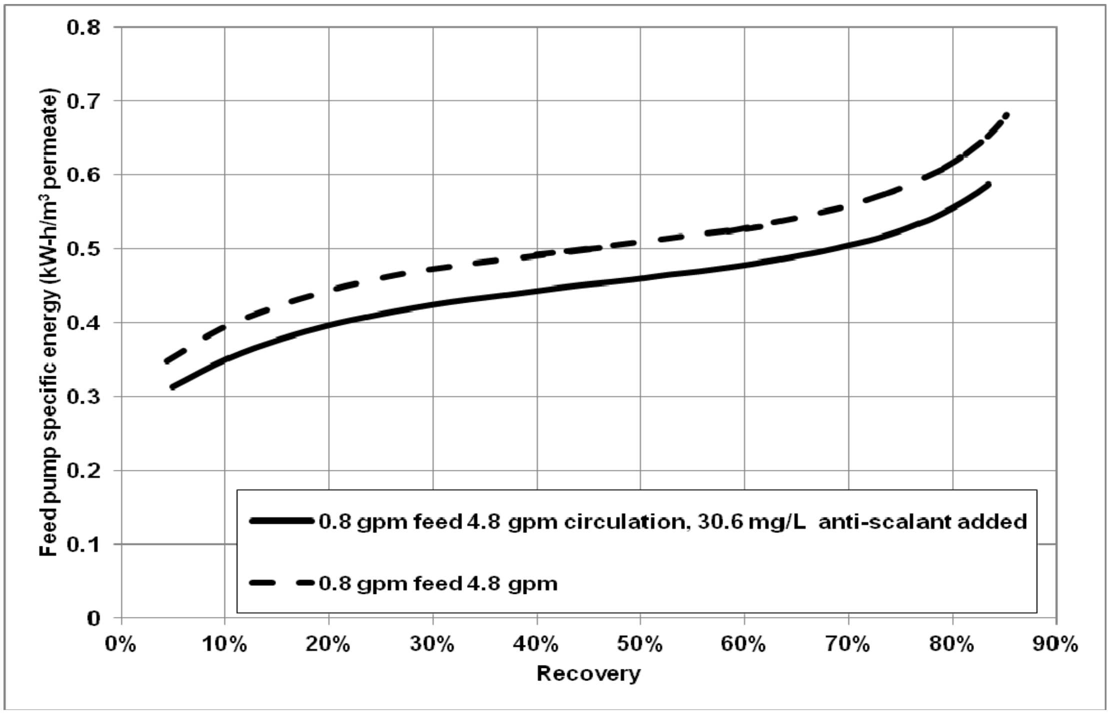

Figure 3-23. **Feed pump specific energy versus recovery, effect of anti-scalant. Well 2.**

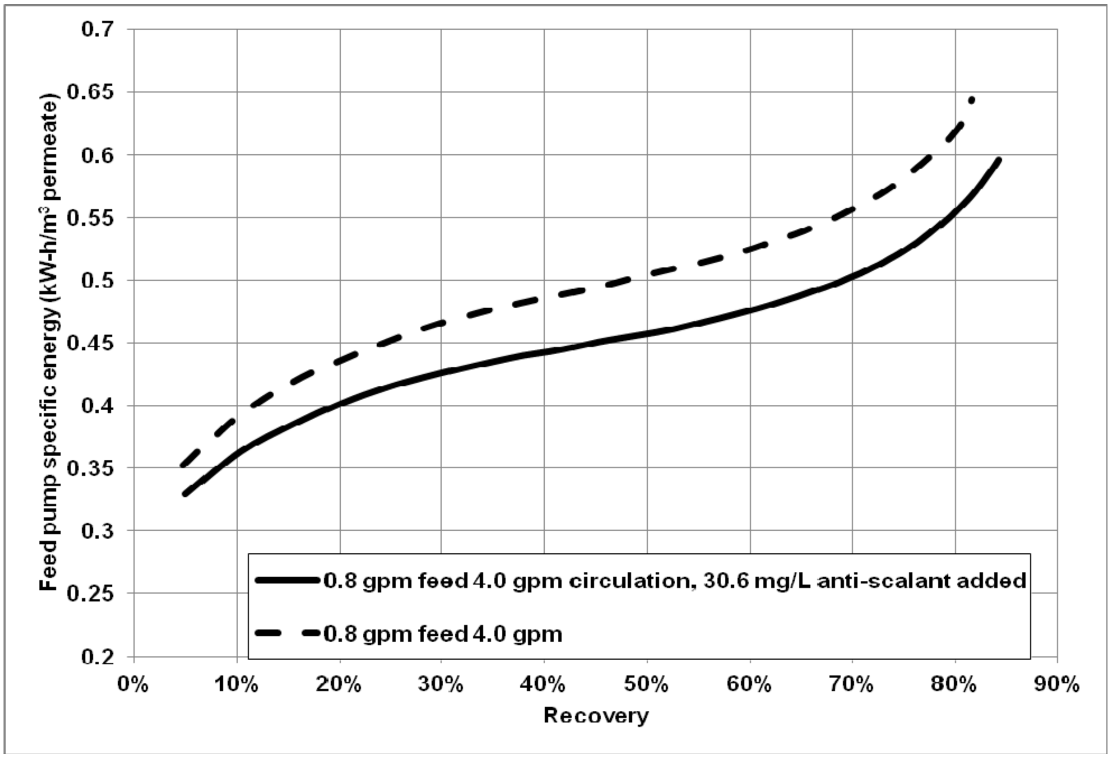

Figure 3-24. Feed pump specific energy versus recovery, effect of anti-scalant. Well 2.

A doubling of the anti-scalant concentration added to water from Well 1 resulted in a reduction in feed pump specific energy of approximately 15% at feed flowrates of 0.6 and 0.8 gpm.

The effect of anti-scalant on specific energy was less pronounced, although significant, in tests using Well 2 groundwater. Although water from Well 2 has much greater scaling potential and tests were conducted (1) without anti-scalant and (2) with an anti-scalant concentration several times the concentrations added to Well 1 water, the addition of anti-scalant to water from Well 2 resulted in a decrease in specific energy of only 10% at a feed flowrate of 0.8 gpm.

In order to assess the effect of waters with high scaling potential on the effectiveness of the discharge cycle and the flushing of the holding tank, feed pump pressure and concentrate conductivity have been plotted as a function of operating time through multiple cycles for water from Well 2 in Figures 3-25 and 3-26 below.

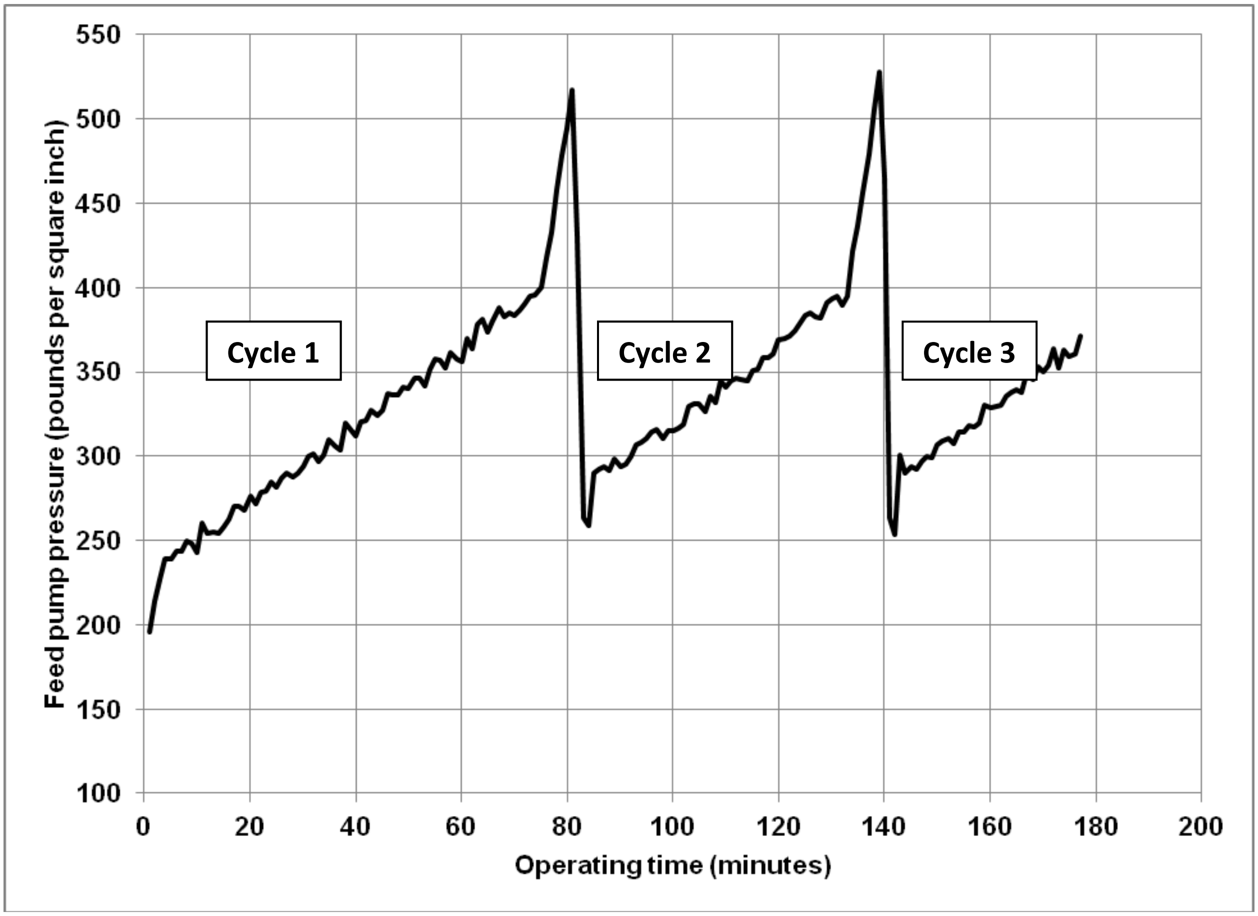

Figure 3-25. Feed pump pressure versus operating time. Well 2.

Feed pump pressure fails to drop to its original concentration, indicating either that flushing of the holding tank is incomplete or that salts are accumulating in the system. However, this effect is only evident between cycles one and two. The post-discharge pressure appears to stabilize and the efficiency of tank flushing appears to improve between cycles two and three.

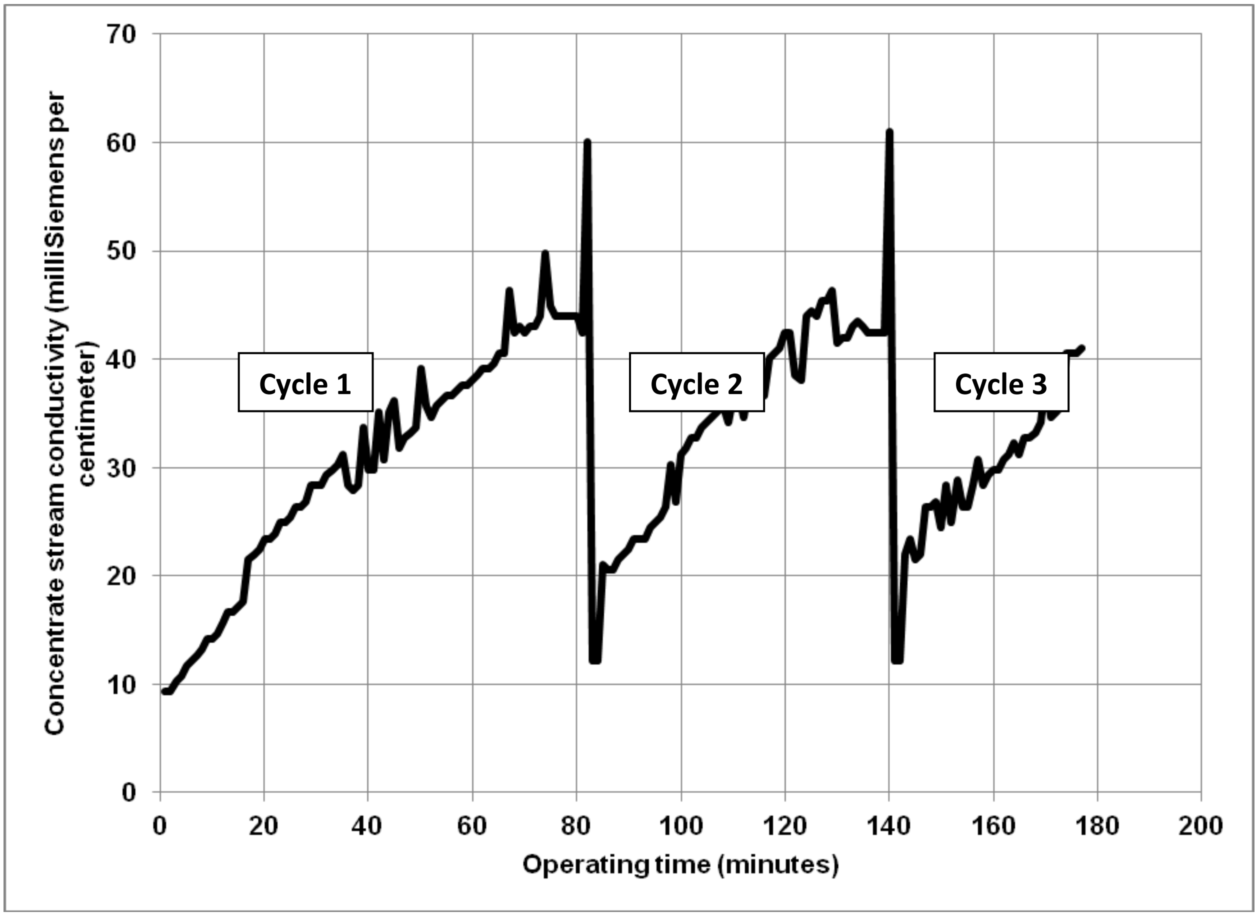

Figure 3-26. **Concentrate stream conductivity versus operating time. Source: Well 2. Feed flowrate: 0.8 gpm. Circulation flowrate: 4.0 gpm.**

The apparent efficiency of holding tank flushing is much greater when concentrate conductivity is examined as a variable. Conductivity returns to a concentration near its original concentration and maintains this pattern into operating cycle three.

Results of field tests conducted at the Brackish Groundwater National Desalination Research Facility indicate that the design of the pilot small-scale RO system, incorporating closed concentrate circulation, is a viable means to increase recovery and energy efficiency not only in well controlled laboratory conditions, but also in the much harsher field conditions to be found in areas where groundwater chemistry presents the greatest challenges to desalination.

4 Cost estimate of small-scale RO system

An estimate of the cost of desalinated water using the small-scale RO design presented here has been performed as specified in the project scope of work. Results of that assessment are presented below.

4.1 Cost of desalination for pilot small-scale RO system

The costs associated with producing desalinated water include (1) energy costs, (2) maintenance costs, including replacement equipment, (3) initial capital costs and (4) the costs associated with depreciation of capital equipment. Costs associated with post-treatment of RO permeate for special uses have not been considered in this report.

4.1.1 Energy cost determination

Energy costs have been estimated using specific energy data obtained from brackish groundwater desalination performed from June through July 2012 at the Brackish Groundwater National Desalination Research Facility in Alamogordo, New Mexico. Energy consumption for desalination of groundwater from Wells 1, 2 and 3 is determined largely by the flux. Although TDS concentration and scaling potential have some effect, the impact of flux is the largest impact by far. A nominal permeate flowrate of 0.6 gpm using two parallel membranes corresponds to a flux of approximately 16 gfd which is within the recommended range for brackish membranes provided on the Dow Filmtec product website (Dow, 2011). At this flux, the specific energy at 90% recovery for desalination of groundwater from Well 2, which has the highest TDS and scaling potential, is approximately 0.8 kW-h/m^3 permeate. In Figure 4-1 below, specific energy as a function of operating time is presented for desalination of groundwater from Well 2.

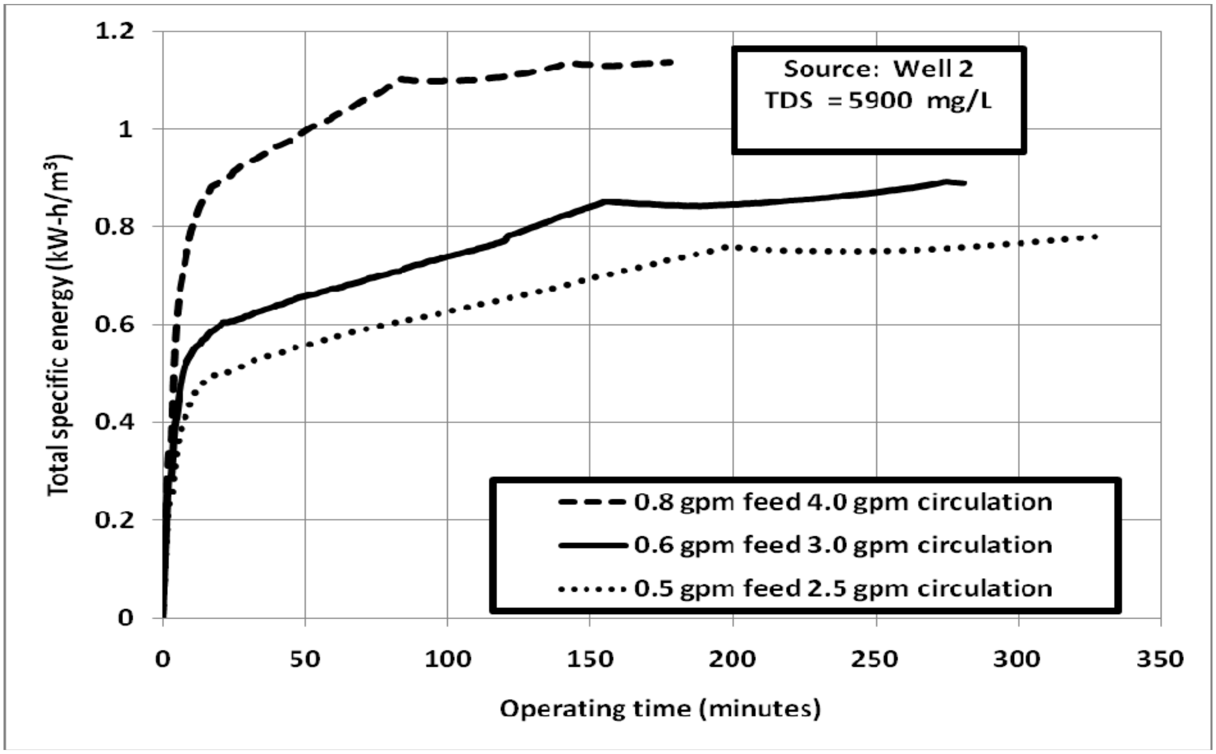

Figure 4- 1. Specific energy as a function of operating time at various flowrates. Well 2.

At a feed flowrate of 0.6 gpm and a circulation flowrate of 3.0 gpm, specific energy appears to plateau at approximately 0.9 kW-h/m^3, which is within the assumed range for conventional large-scale RO systems. At this specific energy and assuming a cost of $0.15/kW-h, the energy cost is $0.135/$m^3$ permeate. Energy costs of the small-scale RO system are comparable to energy costs of conventional large-scale plants, based on information gathered from various sources.

4.1.2 Equipment costs

The cost of the small-scale parallel RO system with closed concentrate circulation is estimated based on the available information of the small scale conventional RO systems, with adjust for the additional cost for the circulation pump and holding tank, which are the major addition of the proposed RO system over the conventional systems. The listed price for a GE conventional RO skid (E8-86K-ECN-6) of capacity of 336m^3/d is about $60,000. The system uses 12 standard 8"×40" membrane elements. The system also includes feed pump and motor, clean-in-place systems, and anti-scalant storage tank and pump. Because of the same parts can be used in the proposed parallel RO system with closed concentrate circulation, it is reasonable to assume the same cost for the same part plus 50% increase for the additional circulation pump and holding tank. Then the cost for the proposed RO system of the capacity of 336m^3/d is estimated at $90,000. Considering the savings from the lower energy cost and high recovery of the feed water, there should be niches for the small-scale parallel RO system with closed concentration circulation in the desalination market.

5 Conclusions

The pilot RO system with closed concentration circulation described in this report is designed to improve the recovery and energy efficiency for small-scale desalination applications. Since the circulation flowrate is selected by the operator, the feature also permits the adjustment of inlet crossflow velocity based on the scaling potential and/or fouling potential of the feed.

The research presented in this report has focused upon (1) assessment of closed concentrate circulation as a means to improve energy efficiency and recovery for small-scale brackish RO under a wide range of operating conditions and (2) assessment of variable crossflow velocity as a means to control membrane fouling..

Based upon the results of these studies, closed concentrate circulation can be an effective design feature for increasing recovery and reducing energy consumption at the same time. Based on a range reported in the literature of 0.4 to 1.0 kWh/m^3 for conventional large-scale RO processes, the energy consumption of the pilot system compares favorably the specific energy of large-scale systems for permeate flux up to 15.4 gfd. At a permeate flux of approximately 20.6 gfd, specific energy of the small-scale system rises above 1.0 kWh/m^3, with values as high as 1.5 kWh/m^3 for fluxes of 25.7 gfd. Product technical guidance provided on the Dow Filmtec website suggests a range from 11 to 18 gfd, depending upon the water quality of the raw feed (Dow, 2010).

This limitation, however, does not preclude the use of this technology for a wider range of permeate flux. Much of the energy consumption is due to head losses within the concentrate circulation loop. These head losses are flowrate-dependent and could potentially be significantly reduced by design changes in the piping configuration. The feed pump component of the specific energy, which is a much more integral part of the process, was within the range of published values for large-scale RO systems for the full range of permeate flux tested, indicating that the technology itself is sound and has great potential for improving the energy efficiency of small-scale RO systems. Results of tests using brackish groundwater with moderate to high scaling potential indicate that the design of the pilot system incorporating closed concentrate circulation can achieve energy efficiency comparable to large-scale systems for permeate flux up to 15 gfd, with the addition of small amounts of anti-scalant.

Results also indicate that increasing inlet crossflow velocity can reduce the severity of membrane fouling. Although the observed effects are significant only for the highest foulant concentrations for the test durations in this study, tests run for longer periods of time may provide more dramatic evidence of the benefits of concentrate circulation in controlling crossflow velocity.

6 Acknowledgments

We would like to thank Ms. Malynda Cappelle of University of Texas, El Paso, for her technical expertise in support of the research conducted at the Brackish Groundwater National Desalination Research Facility in Alamogordo, New Mexico, and facility staff members Mr. Randy Shaw, Mr. Steve Holland and Mr. Bobby Granados for their generous technical and logistical assistance at the Alamogordo facility.

7 References

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8 Appendix: Reviewers' Comments on the Draft Report

Reviewers' Comments on the Draft Report "Demonstration of a High Recovery and Energy Efficient Reverse Osmosis System for Small-Scale Brackish Water Desalination"
TWDB Contract #1004831107

The TWDB reviewers have completed their reviews of the draft report for the project. Please address the following comments in the report.

General Comments:

1.0 The draft report does not include Task 4 (cost estimation) of the scope of work. Please add a separate section in the report that provides the cost of brackish water desalination using the parallel reverse osmosis (RO) system.

2.0 Please update information on page iii of the report. Current information about TWDB Board members and the Executive Administrator is available at
http://www.twdb.texas.gov/about/board_members.asp;
http://www.twdb.texas.gov/about/exec_admin.asp

3.0 To help readers understand the terms used in the report, please add an acronym section at the front of the report.

4.0 The report uses the term 'cross-flow velocity.' The report should clearly mention whether the cross-flow velocity is inlet or outlet. There is a modest difference between the two types of cross-flow velocities.

5.0 The draft report does not provide sufficient information on the advantages of the "closed concentrate circulation" (CCC) desalination system over the conventional desalination system for small-scale processes. Additionally, the report does not include a detailed description on the operation of a CCC desalination system. Please consider dividing the "Introduction" section into the following sub-sections to explain the need as well as the operation of a CCC desalination system for small-scale processes:

- Description of a conventional reverse osmosis system for water treatment: In this sub-section, please describe how the conventional system is arranged including how membranes are configured in a pressure vessel, and how pressure vessels are connected with each other in different stages of a conventional reverse osmosis desalination system. Please add appropriate figures to explain a conventional RO system.

  Additionally, please discuss various operational parameters that are widely used in membrane filtration systems such as feed stream, permeate stream, concentrate stream, feed water recovery, salt rejection, osmotic pressure, feed pressure, operating pressure, specific energy, cross-flow velocity, concentration polarization, and different types of fouling. Please provide appropriate equations where necessary (such as equations for feed water recovery and salt rejection).

- Major limitations of a conventional RO system in a small-scale operation: In this sub-section, please clearly define a small-scale system, and explain the major limitations of using a conventional RO configuration in a small-scale system.

- A closed concentrate circulation desalination system: In this sub-section please discuss the following issues:

    - Please provide a detailed description (with appropriate schematics) of the operation of a CCC desalination system.
    - Please describe the terms that are unique for the CCC desalination system (such as concentrate circulation rate, and the equation for recovery in a CCC desalination system. If possible, please explain the recovery rate equation in a CCC desalination system with an appropriate example).
    - Please explain why feed flow = permeate flow in a CCC desalination system (if possible, please provide an appropriate example).
    - Please discuss the effect of the "ratio of circulation flow to feed flow" on the performance of a CCC desalination system. Additionally, please describe the significance of selecting 5:1 ratio of circulation flow to feed flow for the experiments of the study.
    - Please explain with an appropriate example how recovery of a CCC desalination system changes with time.

- CCC desalination system for small-scale operations: Describe why a CCC desalination system is better than a conventional RO system for small-scale operations.

- Impact of fouling on a CCC desalination system: In this sub-section, please describe the impact of fouling on a CCC desalination system. Because the draft report studied the effect of colloidal fouling on a CCC desalination system, please describe why the effect of colloidal fouling is more important than other types of fouling on a CCC desalination system.

- Study Objectives: In this sub-section, please identify various objectives of the study. The study objectives should match the scope of work for the project.

6.0 To help readers understand the experimental protocols of the study clearly, please consider dividing the 'Experimental Setup' section into the following sub-sections:

- Please consider moving the fifth, sixth, and last paragraphs of page 2 as the first paragraph of 'Experimental Setup.'

- Pilot CCC RO system setup: Please show figure 2-1 in this sub-section, and explain the figure clearly. In the figure, please define various nodes such as F1, F2, V1, V2, etc.
  In this sub-section, please describe the functions of different valves, pressure gauges, and flow meters in the system. If possible, please provide a photograph of the experimental setup.
- Operational parameters: Please describe what parameters (such as cross-flow velocity and anti-scalant dosage) were varied during the experiments. Please describe how cross-flow velocity and other operational parameters (such as feed flow rate, feed pressure, and operating pressure) were controlled in the experimental setup.
- Test Protocols: Please mention that the tests were conducted in two different setups; in a laboratory setup, and in a field demonstration.
  - Tests performed in a laboratory setup: Please include descriptions of various experiments performed in this setup:
    (a) Verification of system performance
    (b) Evaluation of energy efficiency using NaCl solution
    (c) Laboratory assessment of colloidal fouling mitigation
    (d) QA/QC of laboratory setup
  - Field demonstration of the CCC desalination system with real brackish water: In this section please describe how field demonstration of the CCC desalination system was conducted using real brackish water.
    (a) Add a QA/QC section for the field demonstration system.

7.0 The ‘Results’ section of the report should follow the outline delineated in the ‘Test Protocol’ section of the ‘Experimental Setup.’ Therefore, the results of the entire study should be divided into the following sub-sections:

- Results from the tests performed in a laboratory setup
  (a) Results of the verification of system performance
  (b) Results of the evaluation of energy efficiency using NaCl solution
  (c) Results of the laboratory assessment of colloidal fouling mitigation
- Results from the field demonstration of the CCC desalination system with real brackish water

Specific Comments

Page 1, second paragraph: “Tests were conducted to 90% recovery” might be more clearly phrased “Tests were conducted up to 90% recovery” or “from 10% to 90% recovery”. The phrase “conducted to 90% recovery” is too easily read “conducted at 90% recovery” which misses the point.

Page 2, fifth, sixth, and last paragraphs: Please consider moving the paragraphs to the beginning of the ‘Experimental’ section.

Page 3, section 2.1, paragraph 1: In “normal mode”, the two supposedly identical elements travel as it were from the base of the “Christmas tree,” to use the simile on page 1, to the peak. In “discharge mode” with concentrate recycle, the elements are like the last element in the last stage in a nonrecycling unit run at the same exit velocity and pressure. This element is the peak of the “Christmas tree”. This is the worst performing element in the unit and is the element most susceptible to fouling since it has the highest feed concentration and the lowest driving pressure and fluid velocity. With the recycle pump and holding tank, however, the fluid velocity of the elements in the test unit can be varied widely, unlike those in a multi-stage unit where the velocity is tightly constrained, particularly at high recovery. Please clarify the issue.

Page 3, section 2.1, first, second, and fourth paragraphs (along with the equation): Please consider merging the discussions of these paragraphs with the discussion of ‘a closed concentrate circulation desalination system’ in the “Introduction” section (please see general comments).

Page 3, section 2.1, third paragraph: Please consider merging the discussions of these paragraphs with the discussion of the ‘CCC desalination system for small-scale operations’ in the “Introduction” section (please see general comments).

Page 3, paragraph 2.1: It is not clear if the unit is manually controlled or if there is some automatic control over the operation of the unit. Additionally, the report does not provide information on the set points that were used to establish the operating conditions. Please address the issues in the report.

Page 4 and pages 11-12, figures 3-2 and 3-3: The text over figure 2-1 says that the system operates in two modes. The changeover from one mode to the other is apparently caused by closing and opening of certain valves. Please mention clearly if closing and opening the valves occur simultaneously. Please clarify if abrupt changes in the slope of the curves occur due to particular valves. If so, the operation of the system should be shown on one of the figures by indicating what operation of which valve produced the change. It is also not clear how much time was spent in each mode. Please address the issues in the report.

Additionally, please describe clearly if the valves ‘V3’, ‘V2’, and ‘V5’ are closed in “normal mode”. Please describe the function of V1 valve in discharge mode. If V1 valve is kept open in discharge mode, please explain how flow between V1 and V3 valves is controlled.

Page 4, figure 2-1: Running two elements in parallel carries the assumption that flow through the two elements is identical. Please address if any test, such as a preliminary wet test, was performed to confirm that this assumption is correct.

Page 4, figure 2-1 and page 9, paragraph 3.1.1: Information provided in the draft report permits no estimate of how mixing occurs in the holding tank. Theoretically, it could range from well-stirred to slug flow; however, practically, the flow was probably somewhere in between. The flow in the holding tank might have changed as the recirculation flow varied, moving more toward well-stirred with higher flow rates. A well-stirred flow will help desalination, and slug flow would be best during tank flush. Please address the issues in the report.

Page 5, second paragraph: Please mention the name of the software that was used for data logging.

Page 5, section 2.2.1: Please mention the conversion factor that was used to convert conductivity to TDS.

Page 5, section 2.2.1, first paragraph: Please mention the physical properties of the membrane (diameter, length, and active surface area) used for the study. Please mention if the elements contained one leaf or multiple leaves. Additionally, please provide the volume of the holding tank.

Page 5, section 2.2.1, first paragraph: The sequence of testing is not described. Ideally, 21 tests would be done in a random sequence to prevent the results from being confounded by some external factor like membrane degradation. It would be a major effort to vary feed concentration randomly, but the recovery could be changed in an arbitrary sequence. Please address the issues in the report.

Page 5, section 2.2.1, second paragraph, third sentence: The term "**two-pass, permeate staged** RO system" is confusing. Reverse osmosis systems are either configured as a two-pass mode (where permeate from the first stage is allowed to pass through the membranes of the second stage again), or as a two-stage mode (where concentrate from the first stage is passed through the membranes of the second stage). Please clarify the issue.

Page 5, section 2.2.1, second paragraph, last sentence: The statement, "Prior to use, **the temperature of the water was allowed to cool to room temperature** ----" leads the reader to think that hot water was used to prepare NaCl solution. Please clarify if hot water from Texas Tech university's physical plant was used to prepare the solutions.

Page 5, last paragraph, first sentence: Please explain the issue with appropriate reference why feed pump pressures were believed to be high for the feed salinities used in the study.

Page 5, last paragraph, third sentence: Please provide further clarification of the statement, "The presence of reddish deposits was interpreted as indicative of membrane fouling."

- Are NaCl deposits reddish in color?
- Please provide an explanation that eliminates the possibility of depositing iron salts on the membrane surface from the system's connections.
- Because the experiment was conducted using NaCl solution only, please evaluate the above-mentioned statement in the light of the following discussions:
    - NaCl deposits on the membrane surface only when the salt concentration near the membrane surface exceeds the saturation index of the salt. Please clearly mention the saturation index of NaCl at room temperature. Additionally, please estimate the concentration of NaCl near the membrane surface for the experiment.
    - Please describe the techniques that can be used to identify NaCl scaling on the membrane surface.

Page 6, section 2.2.2: The heading of this section uses the term ‘synthetic brackish water.’ Because the solutions were prepared by dissolving NaCl in pure water, it would be more appropriate to identify the section as ‘Evaluation of energy efficiency using NaCl solution’ instead of ‘synthetic brackish water.’

Additionally, use of sodium chloride as a salinity surrogate is good for initial studies, but it conceals the probable difficulties due to scaling at high recoveries. It also permits operation at much higher recoveries than would be obtained with natural water. Please address the issue in the report.

Page 6, fourth paragraph: The statement, “Prior to each test, purified water was used to make the feed solutions **was allowed to cool overnight to room temperature**----,“ leads the reader to think that hot water was used to prepare NaCl solution. Please clarify if hot water from Texas Tech university’s physical plant was used to prepare the solutions.

Page 6, fifth paragraph: Please add a ‘Quality Assurance and Quality Control’ sub-section for the ‘laboratory evaluation’ section, and move the contents of this paragraph into that sub-section.

Page 7, section 2.4 and page 8, table 2-1: Please mention that TriPol 3150 is certified by NSF International as a drinking water chemical up to a maximum concentration of 10 mg/L. Considerably, higher concentrations were used for some tests.

Page 7, third and fourth paragraphs: Please add a ‘Quality Assurance and Quality Control’ sub-section for the ‘laboratory assessment of colloidal fouling mitigation’ section, and move the contents of these paragraphs into that sub-section.

Page 7, last paragraph: Please mention the key criteria that were used to determine an anti-scalant dose in a water sample.

Page 8, second paragraph: The word, ‘level’ should be replaced with the word ‘concentration’ to indicate various concentrations of contaminants in wells 1, 2, and 3.

Page 8, last two paragraphs: Please add a ‘Quality Assurance and Quality Control’ sub-section for the ‘field demonstration of RO system’ section, and move the contents of these paragraphs into that sub-section.

Page 9, section 3 (the entire ‘Results and Discussions’ section): To compare the specific energy between conventional and CCC desalination plants, both plants should operate at similar recoveries and should treat waters that produce similar osmotic pressures. Failing these two similarities, the comparison may not be meaningful. Please address the issue in the report.

Page 10, first paragraph: Please consider adding following discussions in this paragraph:

- Figure 3-1 shows that the feed pressure increment rate was much sharper than the rest of the experiment for the first five minutes of the experiment. Please provide an explanation for this behavior.
- Please discuss the reasons for the gradual increase of feed pump pressure over time (after the first 5 minutes to the end of the experiment).
- Please explain why the slope of the line for 5,000 mg/L NaCl is greater than the slopes of the lines for 2,500 mg/L and 1,000 mg/L NaCl.

Page 11: Inside the figure, please show clearly (by pointing an arrow) how many operating cycles were performed.

Page 12, figure 3-3: In the figure, please show clearly how many operating cycles were performed.

Page 12, second paragraph: Please define the term 'small memory effect.'

Page 12, section 3.1.2 and page 21, section 3.1.2: It appears that a considerable fraction of the specific energy for circulation was used in the external piping. The report does not include any photographs of the 'test unit', so it is not possible to see what kind of plumbing connections were used for the tests. However, in a low pressure drop system, like the recirculation system, significant pressure drop reductions can be obtained by careful attention to details like pipe routing, using larger diameter pipe, minimizing fittings, using long radius elbows, and avoiding tees or at least using 45° lateral tees. Valves, depending on type, can be a particularly high pressure drop item. The effect of appropriate substitutions can be calculated fairly accurately from existing correlations of pressure drop through fittings like those in Perry's Handbook. Please address the issue in the report.

Pages 14 to 35, figures 3-4 to 3-25: The ordinate scale values vary from graph to graph, which makes visual comparison of the results for different conditions almost impossible. Please show the 'pump specific' and 'total energy' graphs on the same page. Additionally, please make the title of each graph appear below that graph.

Page 22, last line: Please correct the figure numbers in the text.

Page 23 to 26, figure 3-13 to 3-16: Please delete the words, 'Rise of' from the y-axes of the figures.

Page 25, figure 3-15, and the second paragraph of page 26: The result of the experiment is confusing. Please consider removing the description as well as the assocaited figure related to the experiment from the report.

Page 26, figure 3-16: To determine the effect of cross-flow velocity on membrane fouling, please plot a graph showing 'elapsed time' vs. 'feed pump pressure' at a constant foulant concentration.

Page 27, last paragraph, first sentence: Please correct the figure numbers in the text.

Page 27, section 3.3: The data from BGNDRF show that the unit can be operated with real brackish water. Please mention clearly if any pretreatment (including conventional filtration, and sedimentation) other than the addition of an antiscalant, was conducted on this water.

Page 32, first, second, and third paragraphs: The descriptions in these paragraphs include scaling potential for the raw water from wells #1, 2, and 3. To help readers understand clearly the significance of scaling potential, please include a discussion of the process that was used to identify scaling potential for various sources of water ("moderate" or "high scaling potential" are very general terms). Since data on well water compositions is available, sufficient information could be included to indicate potential scaling compounds in the water and the degrees of supersaturation of each scaling compound at various recoveries.

Page 34, figure 3-24, and page 35, figure 3-25: In the "legend boxes" of the figures, please show the concentration of the anti-scalants that were used for the experiments.