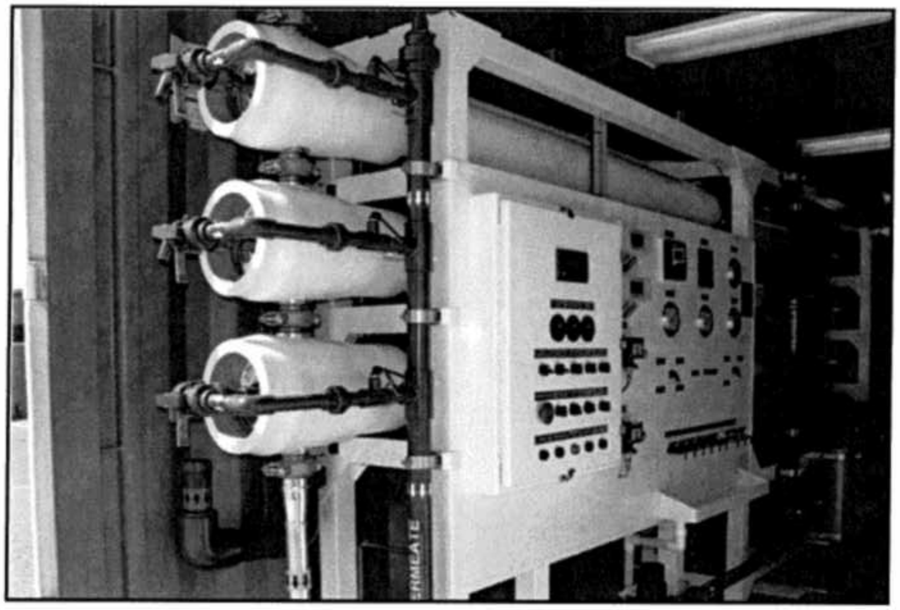
Energy Optimization of Brackish Groundwater Reverse Osmosis Desalination



Final Report for Contract Number 0804830845

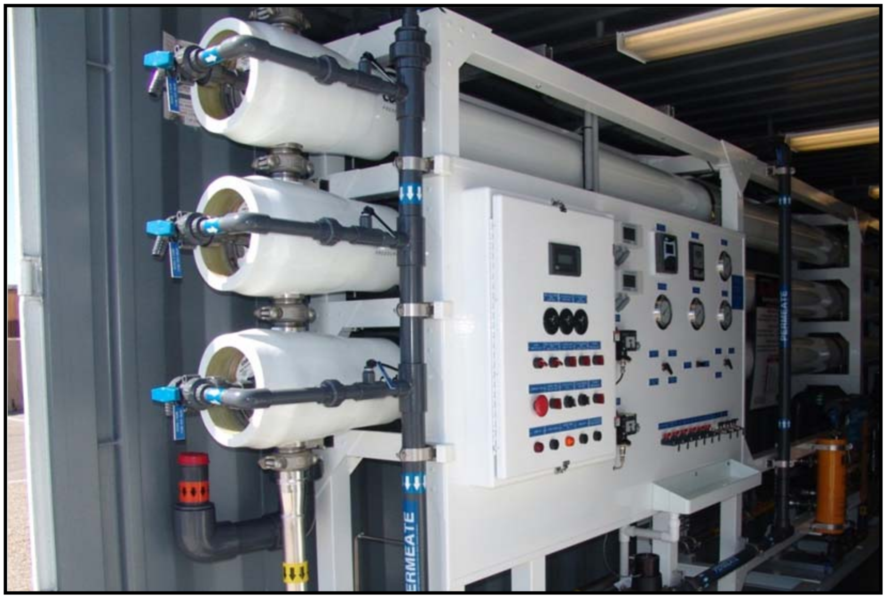
by
Principal Investigator: John P. MacHarg

Texas Water Development Board

P.O. Box 13231, Capital Station
Austin, Texas 78711-3231

September 2011

Energy Optimization of Brackish Groundwater Reverse Osmosis Desalination



Final Report for Contract Number 0804830845

by
Principal Investigator: John P. MacHarg

Texas Water Development Board

P.O. Box 13231, Capital Station
Austin, Texas 78711-3231

September 2011

This page is intentionally blank.

Texas Water Development Board

Contract Report Number 0804830845

Energy Optimization of Brackish Groundwater Reverse Osmosis Desalination

by
John P. MacHarg
Affordable Desalination Collaboration

September 2011

Table of Contents

List of Figures

List of Tables

Executive Summary

A key challenge facing inland desalination today is to develop a new generation of reverse osmosis plants that deliver high quality, fresh water at reduced economic and environmental cost. Texas has a large reserve of brackish groundwater in its aquifers, approximately 125 million acre-feet in the Far West Texas region, where the Kay Bailey Hutchison Desalination plant is located. As the salinity level of the groundwater increases, the feed pressure required to desalt this water also increases in the reverse osmosis process. Membrane desalination is an energy intensive process, whereby energy is a major contribution to facility operation and maintenance cost. To reduce the cost of desalination, the key is to minimize energy consumption.

Two key areas of focus in this Texas Water Development Board study are minimizing energy consumption for brackish groundwater desalination through energy recovery and optimizing the achievable reverse osmosis recoveries of inland brackish water systems. The Affordable Desalination Collaboration was awarded a contract from the TWDB to pursue the following tasks.

1. Test and demonstrate state of the art isobaric energy recovery technology in an optimized brackish water reverse osmosis design. The Affordable Desalination Collaboration-TWDB project achieved a 14 percent energy savings compared to a similar system but without energy recovery, and 24 percent compared to a traditional design without energy recovery or interstage boost.
2. Develop and demonstrate process designs that are possible as a result of the isobaric energy recovery technologies.

Galvanized by Affordable Desalination Collaboration's successful demonstration of incorporating isobaric energy devices in seawater reverse osmosis to reduce the energy consumption of the membrane desalination process, it is anticipated that the energy recovery technology can also be applicable to the brackish groundwater desalination market. However, traditional seawater reverse osmosis consists of single stage membrane processes, whereas brackish groundwater reverse osmosis can have two- or even three- stages. Given this difference in membrane configuration, the isobaric energy device will have to be configured differently as well. It is the purpose of this study to validate that the isobaric energy recovery device can be incorporated in brackish groundwater desalination plants and still save energy. To achieve this goal, different process configurations at different recovery points were tested.

The Affordable Desalination Collaboration Demonstration Pilot unit initially tested an optimized flow configuration. In traditional seawater designs where pressure exchangers have been primarily used the pressure exchanger booster pump is applied at outlet of the pressure exchanger unit, which is the feed to the reverse osmosis membranes. However, in a brackish water system there is an opportunity to optimize the location of the pressure exchanger booster pump by applying it in between the first and second reverse osmosis stages. In this position the pressure exchanger booster pump also acts as an interstage booster pump to help balance the flux between the first and second stages, thereby creating and optimized pressure exchanger design for brackish water applications. The optimum operating point was at 80 percent reverse osmosis Recovery. Full-scale model extrapolations to 3-million gallons per day reverse osmosis train

determined a 1.59 kilowatt hours per 1000 gallon reverse osmosis specific energy, which includes the pressure exchanger and pressure exchanger/interstage boost pump. This configuration minimizes energy consumption as compared to a similar 3-million gallons per day reverse osmosis train with permeate throttling, where the reverse osmosis specific energy was calculated to be 2.26 kilowatt hours per 1000 gallon.

The Affordable Desalination Collaboration-TWDB project also tested a brine recirculation process that is achievable by underflushing of the pressure exchanger unit. Flux decline occurred in the second stage of the reverse osmosis train during experiment runs at system recoveries over 85 percent, and repeated chemical cleaning cycles were not able to re-establish original flux conditions. The lag membrane element was sent for membrane autopsy and the results revealed presence of amorphous structures that were determined to be silicates, even though silica antiscalant was consistently dosed to prevent silica fouling.

A payback period of 5.05 years was calculated by dividing the initial capital investment over the annual energy savings for a 3-million gallon per day reverse osmosis train. A present worth analysis determined an energy savings over 20 years for $891,415 for a 3 million gallons per day reverse osmosis train with an isobaric pressure exchanger system 80 percent reverse osmosis recovery, with a total capital cost (including debt service of 5 percent) for $479,127. Compared to a reverse osmosis train without energy recovery, the present worth savings approximated $412, 551.

1 Project Background

1.1 Introduction

A key challenge facing inland desalination today is to develop a new generation of reverse osmosis plants that deliver high quality, fresh water at reduced economic and environmental cost. Texas has a large reserve of brackish groundwater in its aquifers, approximately 125 million acre-feet in the Far West Texas region, where the Kay Bailey Hutchison Desalination plant is located. As the salinity level of the groundwater increases, the feed pressure required to desalt this water also increases in the reverse osmosis process. Membrane desalination is an energy intensive process, whereby energy costs makes up to 40 percent of the operating cost. To reduce the cost of desalination, the key is to minimize energy consumption.

Isobaric Pressure Exchanger energy recovery for seawater desalination is a technology that has been proven worldwide in the last decade. In United States, the Affordable Desalination Collaboration was formed in 2004 to fund and execute the first part (Affordable Desalination Collaboration I) of what has become a multiple phase Affordable Desalination Demonstration Project. The Affordable Desalination Collaboration built and operated a demonstration plant at the United States Navy’s Seawater Desalination Test Facility in Pt. Hueneme, California and achieved remarkable results by desalinating seawater at energy levels between 6.0-6.9 kilowatt-hours per thousand gallons (1960-2250 kilowatt-hours per acre-foot). However, isobaric energy recovery for brackish groundwater systems has not been demonstrated in municipalities previously and the goal for this study is to incorporate isobaric pressure exchanger energy recovery devices in brackish groundwater reverse osmosis desalination.

The Affordable Desalination Collaboration represents a unique collaboration leading government agencies, municipalities, reverse osmosis manufacturers, consultants and professionals that are working together to improve the designs and technology applied in state of the art desalination systems. Our demonstration plant, processes, and personnel have proven to meet project goals and produce valid data on the operation of desalination systems. A partial list of member/participants that contributed in the Affordable Desalination Collaboration-TWDB project includes:

- Carollo Engineers, Inc.
- Energy Recovery Inc.
- Hydranautics Membrane
- FilmTec Corporation
- Koch Membrane Systems
- Zenon
- Professional Water Technologies
- Toray Membrane America
- California Department of Water Resources
- City of Santa Cruz Water Department
- United States Bureau of Reclamation
- West Basin Water District
- Marin Municipal Water District
- San Diego County Water Authority
- California Energy Commission
- Municipal Water District of Orange County
- Naval Facilities Engineering Service Center
- New Water Supply Coalition (US Desal Coalition)

1.2 Purpose of the study

The objectives of the Affordable Desalination Collaboration are to demonstrate affordable, reliable, and environmentally responsible reverse osmosis desalination technologies and to provide a platform by which cutting edge technologies can be tested and measured for their ability to reduce the overall cost of the reverse osmosis treatment process. Affordable Desalination Collaboration-TWDB funded work included testing the following brackish water reverse osmosis process alternatives:

1. Test and demonstrate state of the art isobaric energy recovery technology in an optimized brackish water design in order to demonstrate energy savings over traditional designs.
2. Develop and demonstrate new process designs that are possible as a result of the isobaric energy recovery technologies. The project should use the Affordable Desalination Collaboration demonstration scale system to test and demonstrate these new flow schemes in order to push the recoveries beyond what has been traditionally achievable.

1.3 Organization of the report

This report contains five sections. Section 1 describes the background of the Affordable Desalination Collaboration and its experience on energy recovery technology, and relates how the technology will be applied for brackish water desalination in Texas. A technology review for isobaric energy recovery is included in Section 2, where an isobaric pressure exchanger will be incorporated in a brackish water reverse osmosis system to optimize energy consumption. In this section, the project approach and criteria are outlined. Section 3 consists of the pilot setup and experimentation protocols. Results and discussions for the pilot study, including a cost analysis for a full-scale (3 million gallons per day train) system are included in Section 4. Final conclusions and recommendations are summarized in Section 5.

2 Methodology

2.1 Problem statement

Brackish groundwater desalination via reverse osmosis is an energy intensive process. Encouraged by the success of reducing energy consumption for seawater reverse osmosis with isobaric energy recovery, it is anticipated that the energy recovery technology could be applied in brackish groundwater desalination. However, isobaric energy recovery has limited use in the brackish groundwater reverse osmosis market whereby the water recovery is maximized via different process configurations. In traditional isobaric energy recovery with seawater applications, the reverse osmosis process is usually a one-stage system with a water recovery of 40 to 50 percent. In brackish groundwater desalination processes, to meet the product water goals and maximize the water recovery, the reverse osmosis process is usually a two-stage system with a water recovery of 70 to 85 percent. Due to the different configurations of the brackish groundwater reverse osmosis process and the seawater reverse osmosis process, the incorporation of the isobaric energy recovery devices in the seawater to brackish groundwater systems will also differ.

Pressure exchanger isobaric energy recovery is a technology that has been used in the seawater reverse osmosis industry since 1997 (Hauge and Ludvigsen, 1999). It is currently the market leader amongst other energy recovery technologies in the seawater desalination market with over 7,000 installations in service worldwide. However, the pressure exchanger has only been applied to a relatively few brackish water systems providing little opportunity to demonstrate and optimize the technology in brackish water applications.

Pressure exchangers as energy recovery devices have been installed in brackish water treatment facilities worldwide to reduce energy consumption of desalinating water. Table 1 is a list of project references obtained from the manufacturer for the types of pressure exchangers installed.

Further follow-up indicated that while these membrane facilities mainly treat high TDS brackish water, the majority of the membrane trains are not two-stage systems like Kay Bailey Hutchison Desalination Plant. However, it is evident that the concept of energy recovery in brackish water desalination is a viable option for both single stage and two stage systems.

Table 1. Energy recovery devices in brackish water installations project reference.

Quantity Installed	Type	Location
1	PX-45SB	Mayan Desalination Services S.A.
2	PX-45SB	
2	PX-220B	St Water Purification Inc
6	PX-140SB	
7	PX-90SB	The Shores at Kohanaiki – Single Stage
3	PX-180B	Aramco Dahran Reverse Osmosis- Two Stage
3	PX-180B	Upgrade Drinking Water Production, Damman, Dahran
2	PX-70SB	DSD Shatin 1000 CMD Project
3	PX-220B	Altona – Two Stage

2.2 Project approach and optimization criteria

2.2.1 Pressure Exchanger Isobaric Energy Recovery

The pressure exchanger unit utilizes the principle of positive displacement to pressurize filtered reverse osmosis feed water by direct contact with the concentrated high-pressure brine/reject stream from a brackish water reverse osmosis system. Pressure transfer occurs in longitudinal ducts in a ceramic rotor, which rotates inside a ceramic sleeve. Each duct operates as an individual isobaric vessel or chamber. The rotor-sleeve assembly is held between two ceramic end covers. At any given instant, half of the ducts are exposed to high pressure flow and half the ducts are exposed to the low pressure flow. As the rotor turns, ducts pass a sealing area that separates the high pressure flow from the low pressure flow. This separation allows the high and low pressure flows to operate independently at different pressures, rates and even in opposite directions. Figure 1 illustrates pressure exchanger operation, when the high and low-pressure flows are balanced i.e. B=D and I = H.

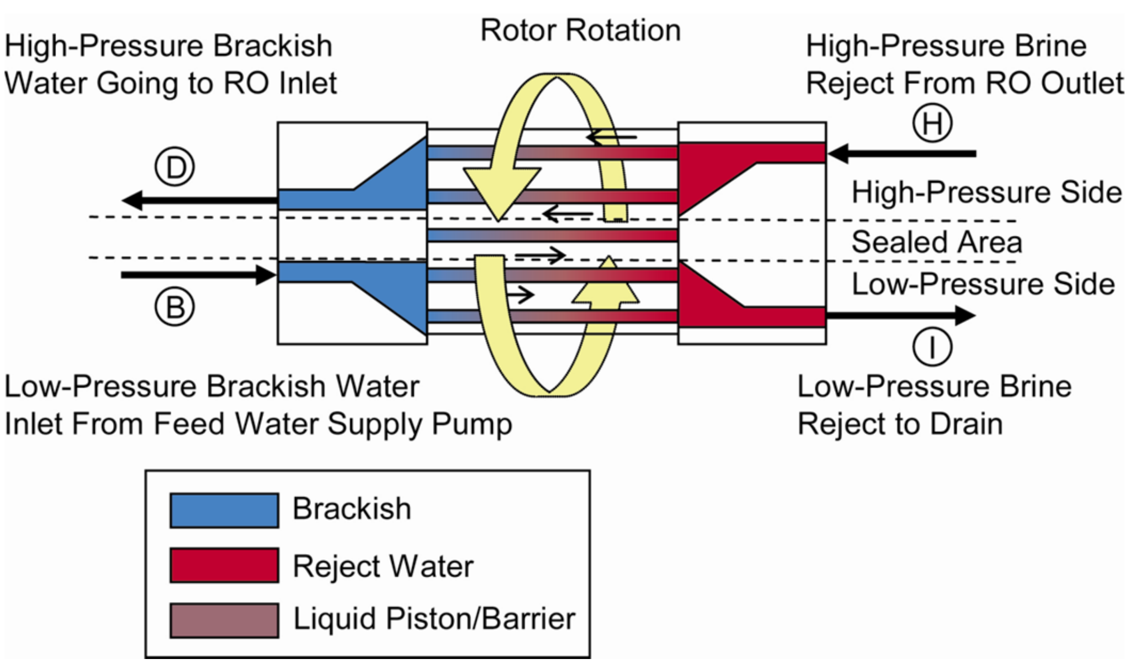


Figure 1. Pressure exchanger internal flow path.

Feed water from the supply pump flows into the low-pressure ducts on the left (B). This flow expels brine from the low-pressure ducts at the right (I). Similarly, after the rotor ducts rotate past a sealing area, high pressure brine flows into the high pressure ducts at the right (H) exposing the feed water to high pressure and expelling the feed water from the high pressure ducts on the left side (D). This two-stroke exchange process is repeated for each duct with every rotation of the rotor such that the ducts are continuously filling and discharging. At 1,200 revolutions per minute, one revolution is completed every one-twentieth seconds limiting the amount of mixing that can occur.

During each cycle the brine and reverse osmosis feed water are separated by a liquid piston barrier composed of a mixture of brine and feed water. The reverse osmosis feed is in direct contact with the liquid piston resulting in a small amount of contamination or mixing of brine and feed water and there are two ways that this mixing effect can be considered.

Considering a mass balance approach to the pressure exchanger, volumetric mixing is the ratio of the volume of brine that transfers into a volume feed water and can be calculated with the following equation independent of pressure exchanger high and low pressure flow balance:

$$\text{Volumetric Mixing} = \frac{\text{Brine out Salinity } - \text{Feed in Salinity}}{\text{Brine in Salinity} - \text{Feed in Salinity}}$$

where salinity is measured at the inlet and outlet connections of the pressure exchanger device or array of pressure exchanger devices. Volumetric mixing is a function of the ratio of the high and low-pressure flow rates, but it is independent of the membrane recovery rate. Volumetric mixing in a pressure exchanger device is about 6 percent when the high and low-pressure flow rates are equal.

Practically, this volumetric mixing must be accounted for during the reverse osmosis process modeling to determine the impact to the feed pressure and permeate total dissolved solids, which both will increase as a result of the increase in feed water salinity. The percent increase in salinity at the feed to the reverse osmosis membranes can be approximated by the empirically arrived at equation below:

$SI \cong R \times M \times 1.04$ (ERI Doc. No. 80088-01)

where:

- SI = salinity increase
- R = membrane recovery (affects concentration difference between feed and brine)
- M = volumetric mixing (approximately 6 percent @ balanced flows)

It is important to distinguish between lubrication flow (or leakage) and mixing in isobaric energy recovery devices. Lubrication flow occurs primarily at the seals, which are located at the ends of rotor ducts. High-pressure flow leaks to low pressure flow resulting in a slight loss from the high pressure inlet flow (H) to the high pressure outlet flow (D) and a corresponding gain from the low pressure inlet flow (B) to the low pressure outlet flow (I). Mixing occurs within the rotor ducts and does not change the lubrication flow rates. The lubrication flow rate may change if the seals become damaged, however, mixing will not increase with time or wear. Mixing and lubrication flow are independent and unrelated (ERI Doc. No. 80088-01)

2.2.2 Pressure exchanger system design and operation

Figure 2 shows the flow path of a typical BWRO system. A feed water supply pump provides sufficient feed flow and pressure to the inlet of the main high pressure pump and pressure exchanger. The main high-pressure pump flow (C) is equal to the permeate flow (J) plus a small amount equal to the lubrication/leakage flow in the pressure exchanger. The pressurized feed stream (D) exiting the pressure exchanger combines with the main high-pressure pump flow to feed the reverse osmosis membranes. The reject brine from the reverse osmosis membranes (H) passes into the pressure exchanger, where its pressure and flow are transferred directly to a portion of the feed water. The pressure exchanger/Interstage boost pump (not the main high-pressure pump) is required to circulate the flow through the high-pressure circuit composed of flows, D, E, F/G and H. In traditional single stage seawater designs the pressure exchanger boost pump is applied at the outlet of the pressure exchanger (D). However, there is an opportunity for optimization in a 2-stage brackish water design by applying the pressure exchanger boost pump in between the first and second stages (MacHarg and McClellan, 2004). In this position, the pressure exchanger/Interstage boost pump also acts as an reverse osmosis interstage boost pump to help balance flux between the first and second stages. This booster pump location provides for an optimized isobaric energy recovery configuration for the brackish water desalination process.

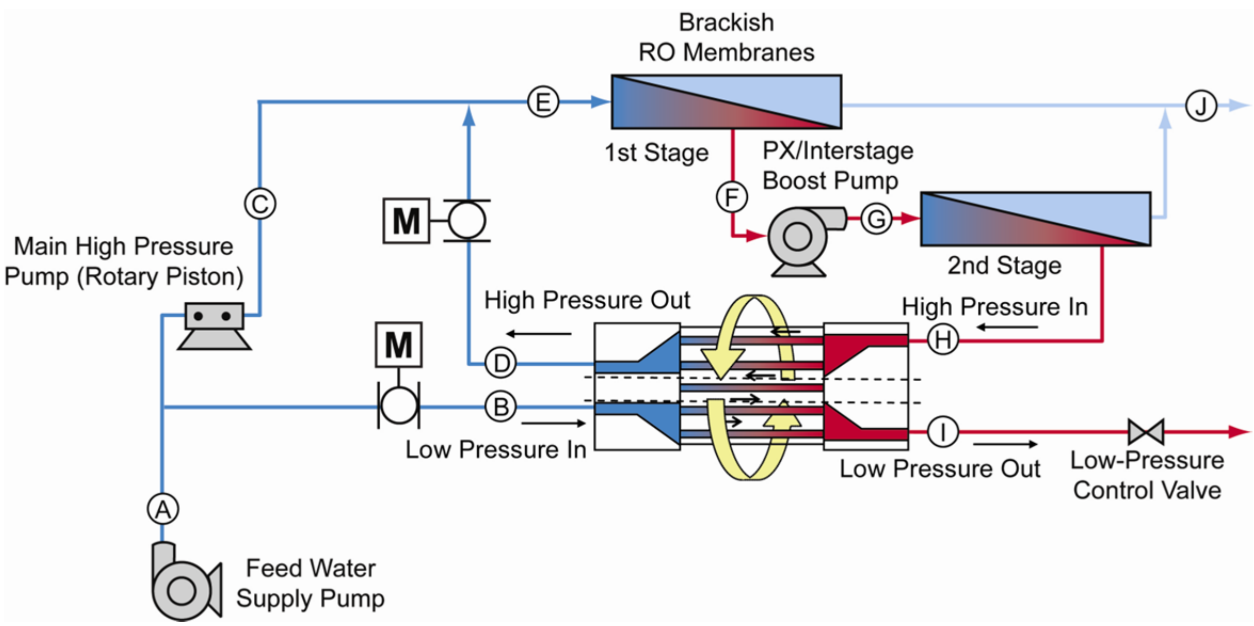


Figure 2. Optimized brackish water reverse osmosis system design.

In a brackish water reverse osmosis system with isobaric energy recovery, the main high-pressure pump is sized to equal the reverse osmosis permeate flow plus the small amount of pressure exchanger lubrication/leakage flow, not the full feed flow. Therefore, the pressure exchanger significantly reduces flow through the main high-pressure pump. This point is significant because a reduction in the size of the main high-pressure pump results in lower capital and energy costs.

Because of the pressure exchange process inherent in the pressure exchanger, the high and low pressure flows are independent and must be controlled separately. In Figure 2, the high pressure flow is controlled through variable frequency drive operation of the boost pump and a high pressure flow meter and the low pressure flow is controlled via the low pressure control valve and a separate flow meter. It is traditional to maintain the high pressure and low pressure flows at approximately equal rates, but in some cases, it can be desirable to create an imbalance in these flows.

2.2.3 Balanced flow, over-flush and under-flush

There are several ways in which the low and high-pressure flows can be adjusted during pressure exchanger operation.

- Balanced pressure exchanger Flows – Low pressure inlet flow equals the high pressure outlet flow or B = D and H = I. At balanced flows the membrane recovery (J/E) and system recovery (J/A) are equal.
- Over-flush – The ratio of low-pressure inlet flow divided by high-pressure outlet flow is greater than 1. Over-flush occurs when B > D, I > H and decreases system recovery (J/A).
- Under-flush – The ratio of low-pressure inlet flow divided by high-pressure outlet flow is less than 1. Under-flush flow occurs when D > B, H > I and can be used to increase system recovery (J/A) while maintaining or decreasing reverse osmosis recovery (J/E).

Flows B and I are controlled using the low pressure control valve and are independent from flows D and H. Flows D and H are controlled by a variable frequency drive on the pressure exchanger/interstage booster pump.

To reduce mixing in isobaric devices excess feed water is supplied to over-flush the chambers of any residual brine. Over-flushing reduces mixing in the energy recovery device as illustrated in Figure 3. However, this over-flush condition will require increased feed flow, reducing system recovery. Under-flushing can be used to create a brine recirculation process to decrease reverse osmosis recovery while maintaining or increasing system recovery.

2.2.4 Brine recirculation process for higher system recovery

By incorporating the pressure exchanger into a reverse osmosis system, brine recirculation to yield an increased overall system recovery can be achieved by unbalancing the flows through the pressure exchanger device. Under-flushing can reduce reverse osmosis recovery while maintaining or increasing system recovery. Recirculation of the reverse osmosis brine with the source water will occur to produce the increase in reverse osmosis feed flow i.e. lower reverse osmosis recovery. Under-flushing the pressure exchanger to induce brine recirculation is part of the test conditions outlined for this study. The advantages of this mode of operation include:

- Improved membrane boundary layer condition by maintaining “high” velocity flows
- Maintain brine flow requirements within manufacturers’ specifications
- Maximum allowable recoveries within manufacturer’s specifications

Table 2 provides a matrix of system recovery to reverse osmosis recovery points that were tested at 14.9 gallons per foot per day. When under-flushing the pressure exchanger for higher system recovery, the procedure was to set the system recovery equal to the reverse osmosis recovery and then increase the system recovery in 5 percent increments. X's represent points that were successfully tested and O's represent points that were tested but rapid scaling prevented data collection.

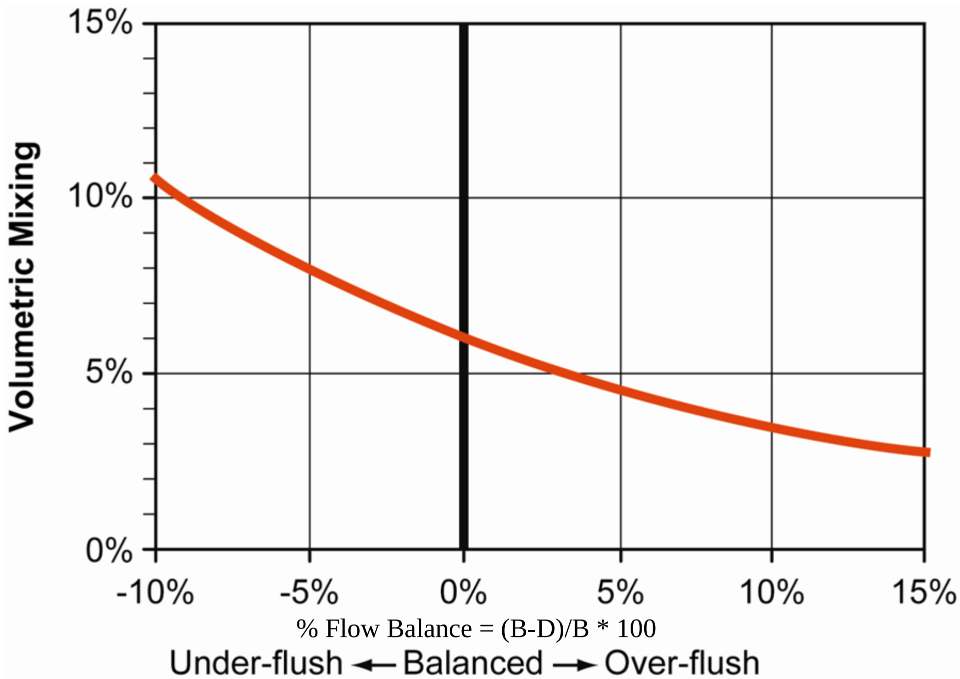


Figure 3. **Balanced flow, over and under-flushing versus pressure exchanger mixing (ERI Doc No. 80088-01).**

Table 2. **Affordable Desalination Collaboration study under-flush experiment matrix.**

		Percent reverse osmosis recovery	
		75	80
Percent System Recovery	75	x	
	80	x	x
	85	x	x
	90	x	o

3 Project implementation

The Affordable Desalination Collaboration operated at the Kay Bailey Hutchison Desalination Plant and used the same feed water as the full-scale plant diverted following sand removal. The desalination plant draws feed water from a number of brackish groundwater wells from the Hueco-Mesilla Bolson (Basin) in El Paso, Texas. Figure 4 shows the location of the Affordable Desalination Collaboration demonstration pilot unit at the Kay Bailey Hutchison Desalination Plant. The demonstration system was designed to closely mimic the full-scale plant so that comparisons could be made between the pilot system performance and the full-scale plant performance. While evaluating these brackish water process alternatives, it is important that product water quality met primary and secondary standards. Potable water quality goals for this Affordable Desalination Collaboration-TWDB study are summarized in Table 3.

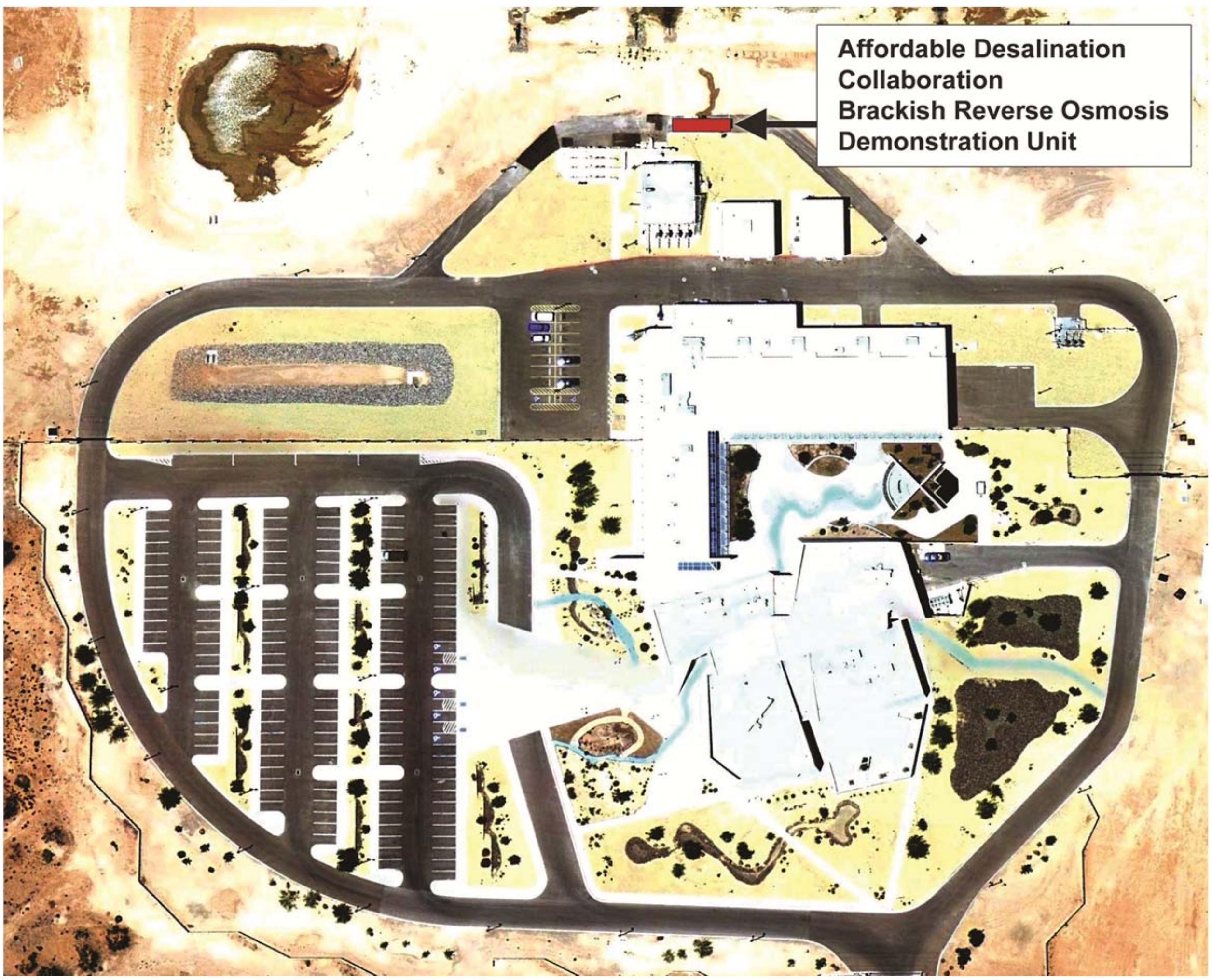


Figure 4. Aerial view of the Kay Bailey Hutchison Desalination Plant and Affordable Desalination Collaboration demonstration pilot location.

Table 3. Demonstration scale test potable water quality goals.

Parameter	Value
Total dissolved solids[1]	< 500 milligrams per liter
Chloride[1]	< 250 milligrams per liter
Nitrate[2]	< 10 milligrams per liter as nitrate^{-}
Nitrite[2]	< 1 milligrams per liter as nitrogen dioxide
Fluoride[2]	< 4 milligrams per liter
Sulfate[1]	< 250 milligrams per liter
pH[1]	6.5-8.5

1. U.S. Environmental Protection Agency Secondary Standard
2. U.S. Environmental Protection Agency Primary Standard

Source: EPA 816-F-09-0004, May 2009

3.1 Pilot plant set-up

In January of 2010, the Affordable Desalination Collaboration demonstration unit was reconfigured to a two-stage brackish water system and was mobilized to the Kay Bailey Hutchison Desalination Plant in El Paso, Texas (Figure 5). The startup testing initiated in February 2010, and testing continued through December 2010.

Figure 5. Affordable Desalination Collaboration pilot demonstration unit (Single Stage left view, Two Stage right view).

The Kay Bailey Hutchison Desalination Plant uses the same pretreatment and membranes (Hydranautics ESPA 1) as the Affordable Desalination Collaboration system (Figure 6). The two stage 2:1 array with seven 8-inch elements configuration in each vessel is also identical. At the Kay Bailey Hutchison Desalination Plant, the permeate flux between the reverse osmosis stages is balanced by permeate throttling. In the demonstration unit, permeate flux balance is achieved via an inter-stage boost pump. Balancing the permeate flux between membrane stages has the advantages of minimizing the rate of foulant deposition over the greatest membrane area and improving the permeate quality when the flux is increased in the later stages. To maintain the flux balance between stages, first stage permeate can be throttled to generate sufficient permeate back-pressure to balance the feed flow entering the second stage. When using first stage permeate throttling to balance flux, the rule of thumb is not to exceed 30 pressure per square inch permeate back-pressure. At permeate back-pressures beyond 30 pressure per square inch, operating cost savings can be realized by investing capital costs into an inter-stage boost pump or an energy recovery device.

The significant differences in the pilot unit are the pump type for the feed water into the reverse osmosis, inter-stage boost pump, energy recovery system, and motor and pump efficiency. Recovery for the Affordable Desalination Collaboration system included the identical 80 percent recovery operating point as Kay Bailey Hutchison Desalination Plant.

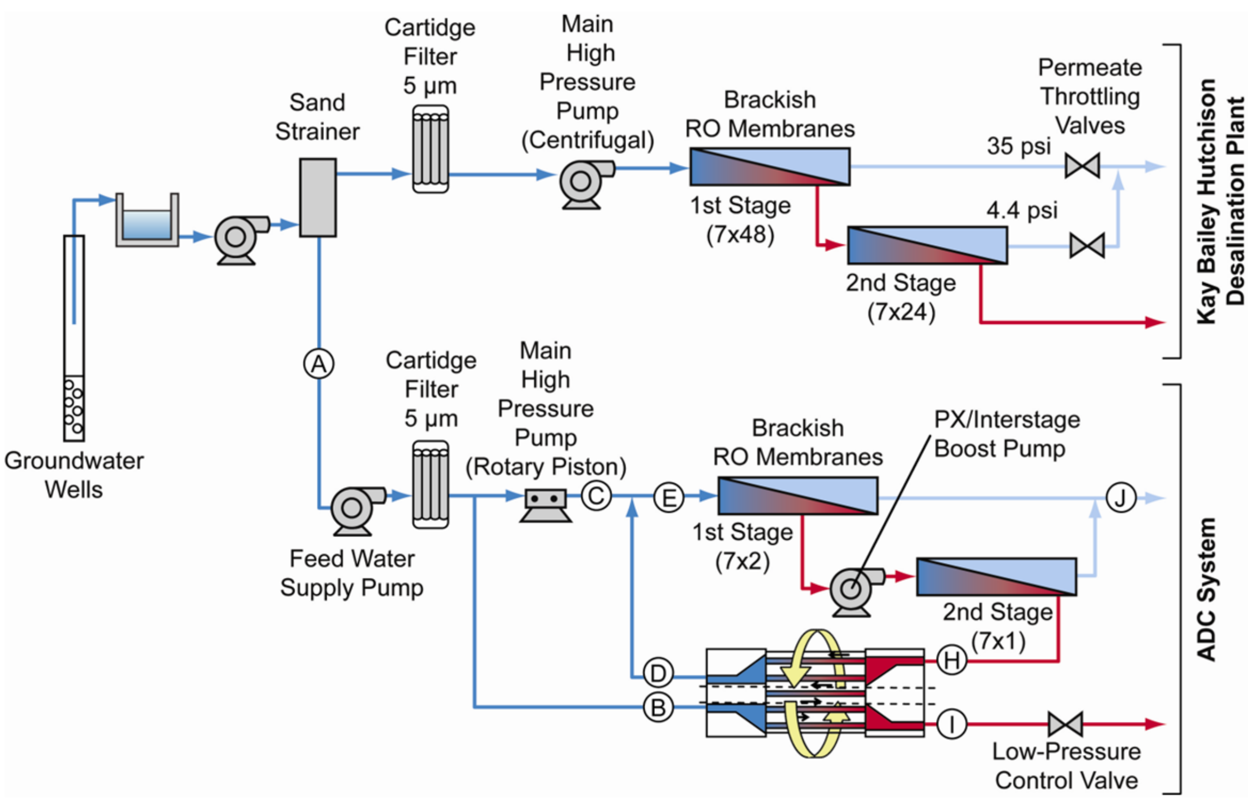


Figure 6. Process schematic with the Kay Bailey Hutchison Desalination Plant and Affordable Desalination Collaboration systems.

3.2 Source water characterization

The Kay Bailey Hutchison Desalination Plant is supplied by brackish groundwater wells from the Hueco-Mesilla Basin, where the total dissolved solids of the combined feed into the plant averages a total dissolved solids of approximately 2,000 milligrams per liter. Table 4 lists the water quality constituents in the design feed water for the demonstration testing.

Table 4. Design feed water quality.

Constituent	Unit	Concentration
Calcium	milligrams per liter	135
Magnesium	milligrams per liter	35
Sodium	milligrams per liter	609
Potassium	milligrams per liter	19
Barium	milligrams per liter	0.11
Strontium	milligrams per liter	2
Carbonate	milligrams per liter as Calcium Carbonate	0.2
Bicarbonate	milligrams per liter as Calcium Carbonate	57
Sulfate	milligrams per liter	187
Chloride	milligrams per liter	1093
Fluoride	milligrams per liter	0.6
Nitrate	milligrams per liter	0.1
Silica	milligrams per liter	32
Temperature	degrees Celsius	26
pH	pH unit	7.2
TDS	milligrams per liter	2183
Turbidity	Nephelometric Turbidity Unit	< 1

3.3 Equipment

This section will describe the major equipment that make up the demonstration test unit. The criteria used to size the demonstration scale brackish water reverse osmosis and cartridge pretreatment equipment are presented in Table 5.

3.4 Project monitoring and reporting

Deliverables for the Affordable Desalination Collaboration-TWDB project were provided in the form of monthly reports. According to TWDB Contract Number 0804830845 Sect II, Art III.5, “The contractor will submit progress reports with submittal of payments according to the payment submission schedule. Progress reports shall be in written form and shall include a brief statement of the overall progress made since the last status report; a brief description of any problems that have been encountered during the previous reporting period that will affect the study, delay the timely completion of any portion of this contract, inhibit the completion of or cause a change in any of the study's products or objectives; and a description of any action the contractor plans to take to correct any problems that have been encountered.”

Table 5. BWRO demonstration scale test equipment criteria.

Parameter	Value
Feed, flush, cleaning pump	
Manufacturer/model	AMPCO, ZC2 2.5 x 2
Duty range	170 gallons per minute @ 80 feet Total Dynamic Head
Cartridge filter	
Manufacturer/model	Eden Excel, 88EFCT4-4C150
Quantity	22
String wound cartridge specs	#XL1-EP050-PLC40, 5 micron
Pressure vessels	
Manufacturer/model	Codeline, 80A100-7
Quantity	3
No. of membrane elements per vessel	7
Membrane elements	
Manufacturer/model	Hydranautics ESPA1-7
Quantity	21
Diameter	8 inches
Surface area	400 square feet
Total membrane area (A_{sys})	8,400 square feet
Permeate Flow	12,000 gpd
Salt Rejection	99.3%
Maximum Operating Temperature	113 ^{o}F (45 ^{o}C)
pH Tolerance	2-10
The stated performance is initial (data taken after 30 minutes of operation), based on the following conditions:	1500 PPM NaCl solution 150 psi (1.05 MPa) Applied Pressure 77 ^{o}F (25 ^{o}C) Operating Temperature 15% Permeate Recovery 6.5 - 7.0 pH Range
	Reference
High pressure pump	
Pump type	Positive Displacement, Variable Frequency Drive
Manufacturer/model	Danfoss 2 x APP-10.2
High pressure pump flow	40-90 gallons per minute (7-15 gallons per square foot of membrane per day)
High pressure pump total dynamic head	349 – 2,698 feet water (150 – 1,160 pounds per square inch)
pressure exchanger boost pump	
Pump type	Multi-stage centrifugal, VFD
Manufacturer/model	Energy Recovery, Inc. HP-8504
pressure exchanger boost pump total dynamic head	70– 115 feet water (30 – 50 pounds per square inch)
Energy recovery device	
Type	Pressure Exchanger
Manufacturer/model	Energy Recovery, Inc. PX-45S BW
Quantity	1

4 Results

4.1 Optimized isobaric energy configuration

To achieve and mimic the 80 percent reverse osmosis recovery at the Kay Bailey Hutchison Desalination Plant, the resulting reverse osmosis brine flow was below the normal operating range of the energy recovery (PX-45S) unit. To simulate full-scale pressure exchanger operation and maintain the manufacturer recommended of less than 5 percent salinity increase at the reverse osmosis feed, over flushing of the pressure exchanger system was performed. Figure 7 illustrates the results of the reverse osmosis, overall system recovery, and the normalized permeate flows from each stage of the demonstration pilot unit in the optimized pressure exchanger/interstage booster configuration. Relative stable operation was observed during the demonstration period. Optimization experiments were conducted from February 2010 to August 2010. Due to over flushing of the pressure exchanger, the reverse osmosis recovery is greater than the system recovery. The 80 percent reverse osmosis recovery was established as baseline for the system during optimization experiments. Periodically the system would be operated at 80 percent recovery to ensure that the system was maintaining stable performance between operating points.

Figure 8 shows how the reverse osmosis specific energy consumption and water quality vary with varying recovery and flux at balanced pressure exchanger flows i.e., System recovery = reverse osmosis recovery. The following points of interest can be observed from the graphs:

- There is an optimum point or low energy point that occurs around 80 percent recovery as shown in Figure 8. This appears to be analogous to a similar optimum point that occurs in single stage seawater systems at around 35-40 percent recovery (MacHarg, 2003).
- Energy consumption appears to increase proportionally with increasing flux between 12-16 gallons feet per day.
- As expected, water quality improved with increasing flux according to membrane solubility laws and decreased with increasing recovery due to the increase in brine concentration.

New membranes were tested and therefore produced the best possible results in terms of energy consumption. Extended testing could be conducted to determine the effect of membrane aging on energy consumption between cleaning cycles, however, membrane projections can provide designers with a good understanding of system performance over time if long-term experiments cannot be executed due to time constraints.

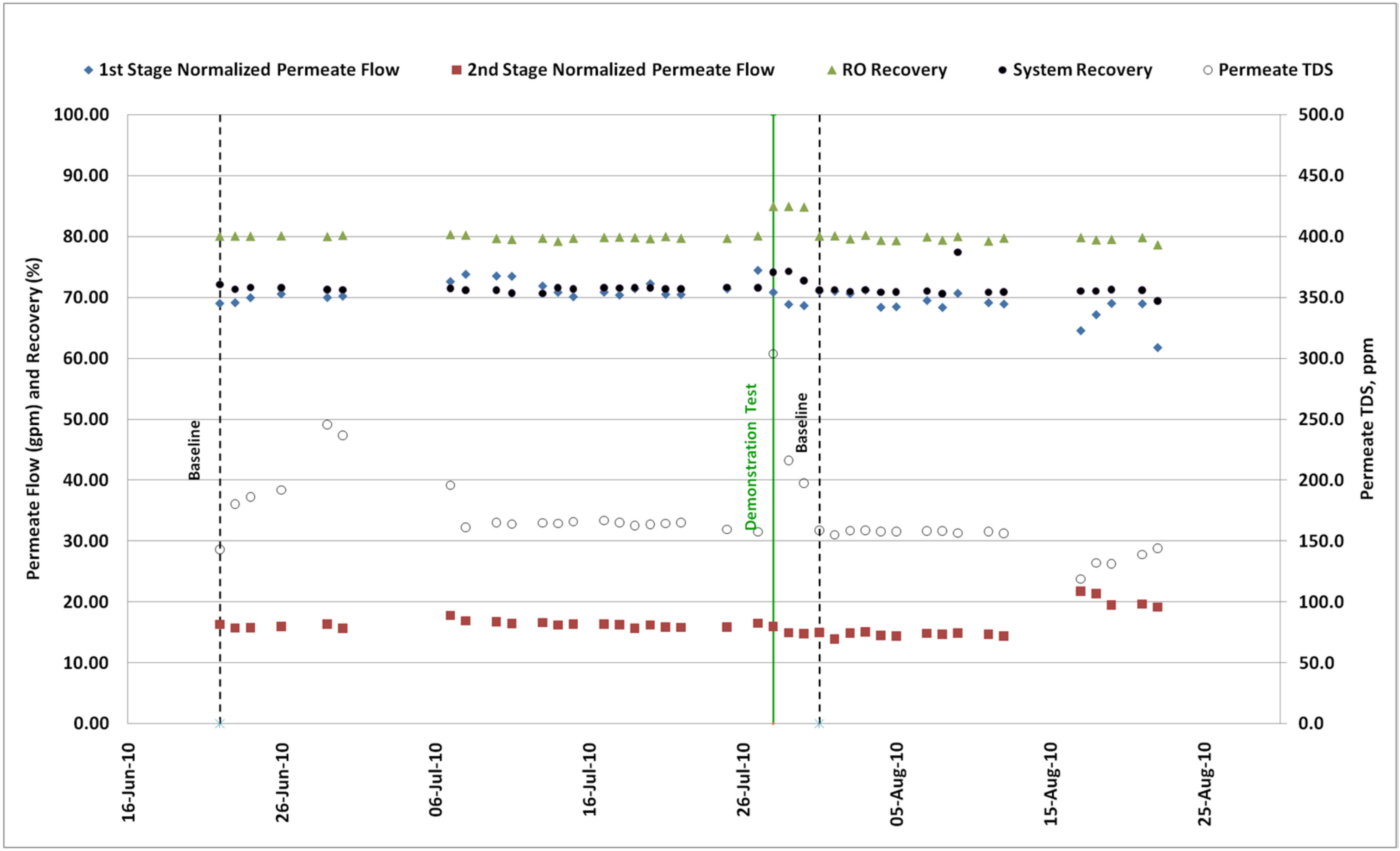


Figure 7. **Recovery and normalized permeate flow for the optimized configuration.**

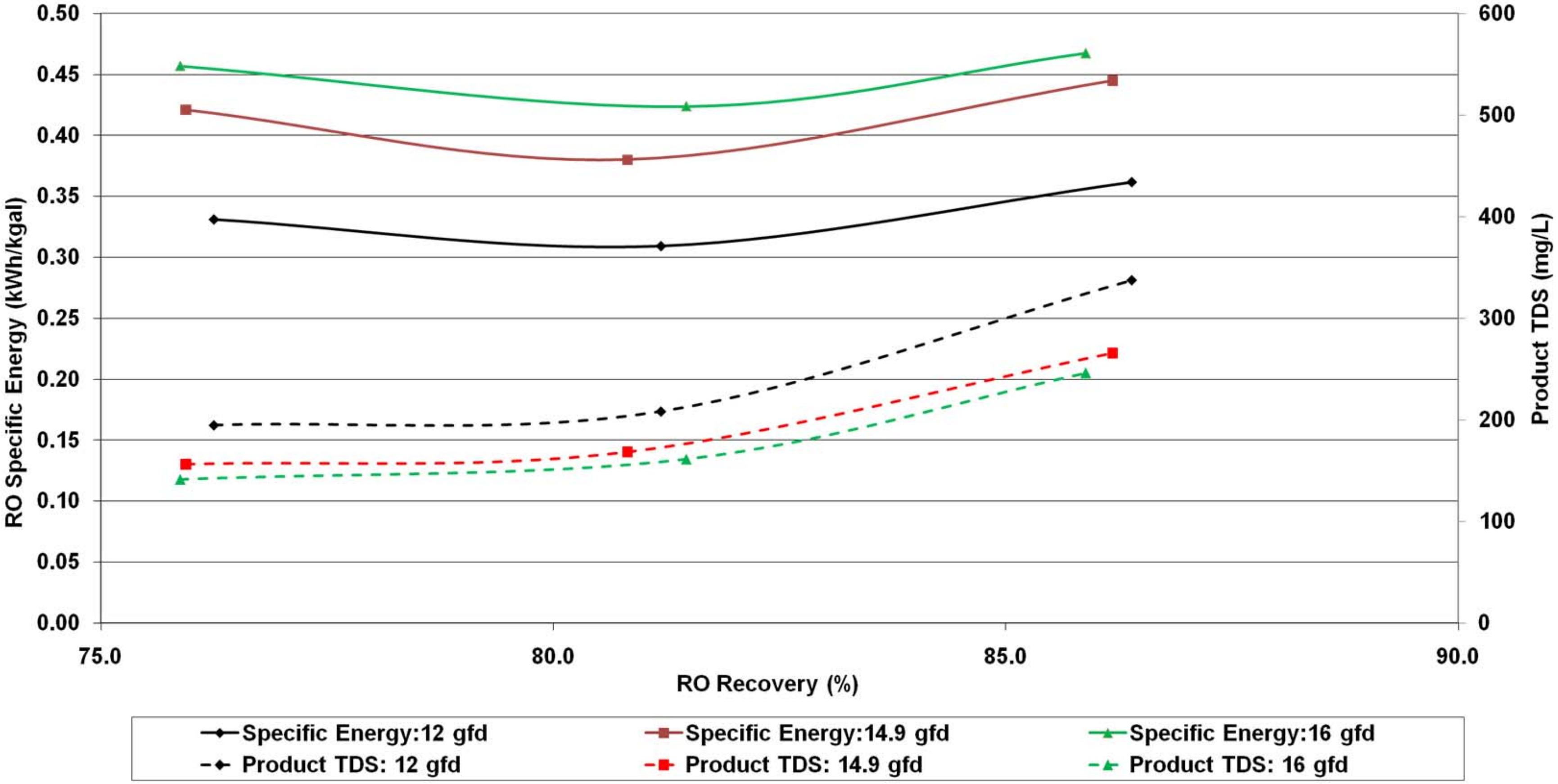


Figure 8. **Balanced flow curve for reverse osmosis specific energy and water quality at various flux rates.**

4.2 Brine recirculation configuration (under-flush)

To exceed the 80 percent system recovery, a 2-month long-term test was carried out that included brine recirculation by under-flushing. The resulting reverse osmosis recovery in this configuration will be lower than the system recovery, and in this unbalanced flow scheme, the system is synonymous to brine recycling where the reverse osmosis unit produces more reject flow to feed the pressure exchanger unit. Figure 9 illustrates the results of the reverse osmosis and overall system recovery, and the normalized permeate flows from each stage in the pilot unit for the under-flushing configuration. Under-flush flow testing was conducted from August 2010 to December 2010.

Second stage flux decline was continually observed despite several cycles of high pH cleaning to remove possible organic foulants. Although the reverse osmosis recovery was returned to baseline conditions after each clean, flux decline continued to affect the optimal operation of the pilot. In September, the lag membrane element in the second stage was sent for membrane autopsy to determine the cause for flux decline and new second stage membranes were installed in the reverse osmosis unit. Membrane autopsy results were received in November 2010, and revealed no visible foulants or mineral scalants on the membrane surface. Energy dispersive X-ray analysis showed a high concentration of silica presence (45.8 percent). Even with silica-specific anti-scalant dosing, fouling in the second stage was persistent at system recoveries of 85 percent due to super-saturation of silica in the brine concentrate.

Figure 10 shows how the energy consumption and water quality vary as the system recovery increased, while maintaining a constant reverse osmosis recovery with brine recirculation through under-flushing the pressure exchanger. A flux of 14.9 gallons per feet per day was maintained for the 75 percent and 80 percent reverse osmosis recovery regimes. The following points of interest can be observed from the graphs:

- At 75 percent reverse osmosis recovery increasing system recovery resulted in a steady increase in energy use, compared to the balanced flow conditions where their appeared to be a low energy inflection point around 80 percent recovery.
- Between 80-85 percent system recovery, there was minimal difference in performance between the 75 percent and 80 percent reverse osmosis recovery points. However, with 75 percent reverse osmosis recovery we were able to achieve 90 percent system recovery, while at 80 percent reverse osmosis recovery the system recovery could not exceed 85 percent without rapid scaling.
- Permeate water quality decreased significantly with increasing system recovery due to increasing brine salinity.

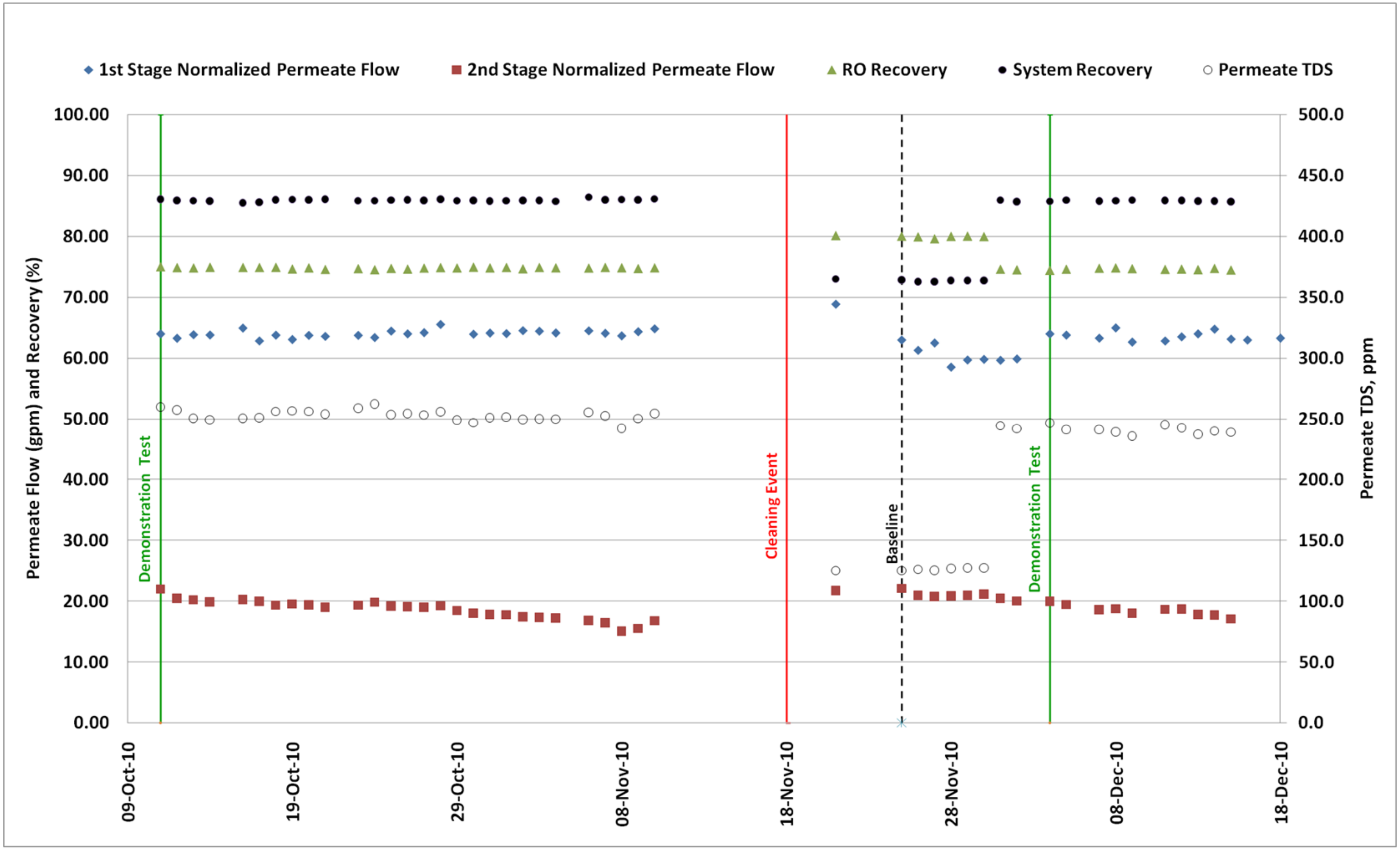


Figure 9. **Recovery and normalized permeate flow for the underflush configuration.**

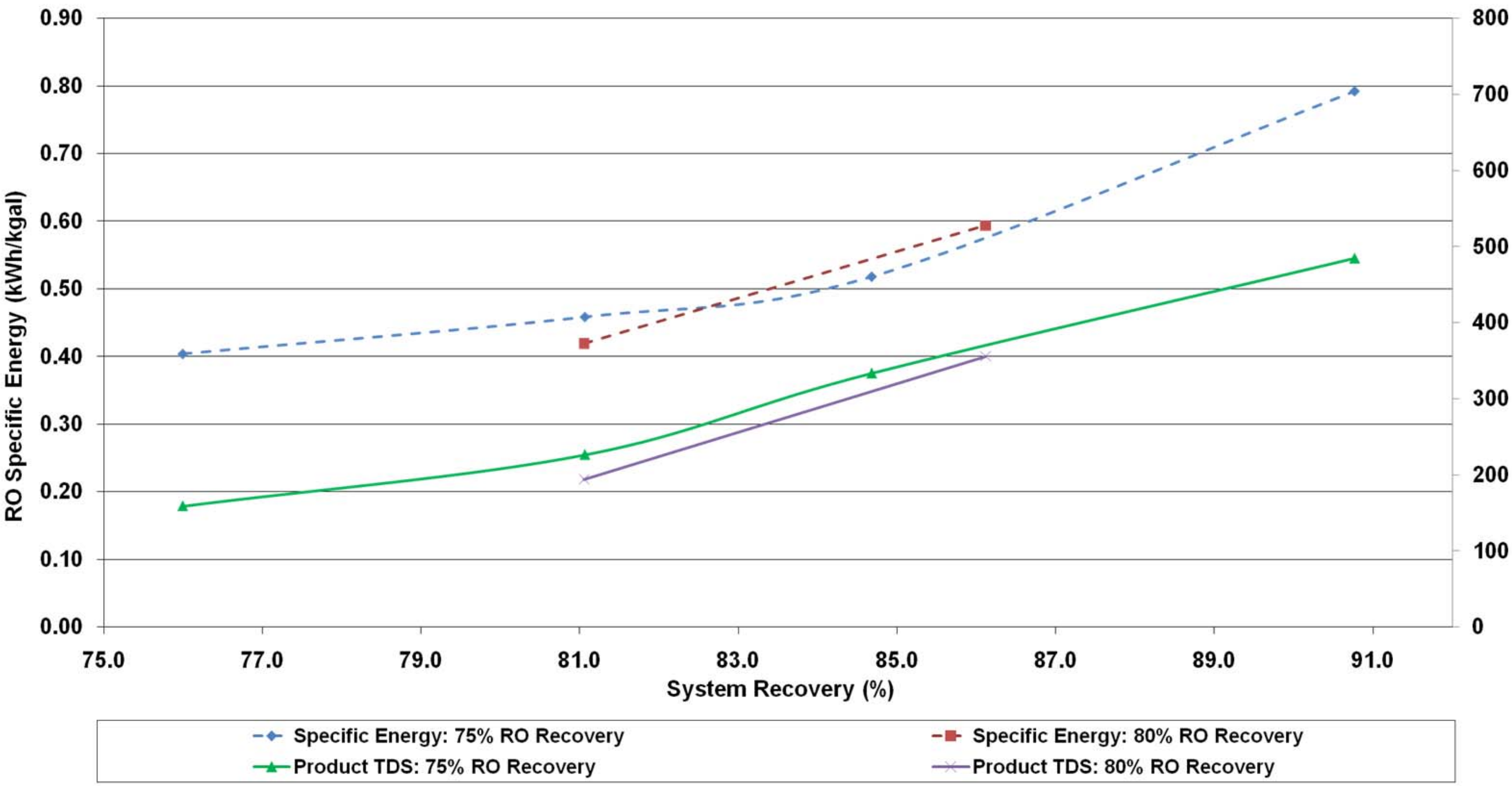


Figure 10. **Unbalanced flow curve for reverse osmosis process power and water quality at 14.9 gallons feet per day.**

4.3 Reverse osmosis membrane scanning electron microscopy and elemental analysis

Experiments conducted between February 2010 and August 2010 to determine the optimum operating points for the Affordable Desalination Collaboration Demonstration Unit included higher reverse osmosis recovery runs up to 90 percent. During this testing period, a continuous permeate flux decline in the second stage of the reverse osmosis train was observed as reverse osmosis recovery was increased. The reduction in the permeate production in the second stage membranes was compensated by an increased permeate production in the first stage membranes at the set reverse osmosis recovery. Despite several cleaning cycles to remove organic foulants, the gradual decline in the second stage flux could not recovered completely. In September 2010, the lag membrane element in the second stage reverse osmosis train was removed for Scanning Electron Microscopy and elemental analysis for membrane autopsy.

No visible foulants, mineral scalants, or membrane discoloration was observed when the membrane sheets were dissembled from the element casing. Under 1050X magnification on the Scanning Electron Microscopy, amorphous structures on the membrane surface were detected as seen in Figure 11. Further elemental analysis conducted for the membrane surface revealed a high presence of silica and sulfur, as shown in Figure 12.

The antiscalant dosed in the pilot is reported to be effective for silica concentrations up to 300 milligrams per liter, and the manufacturer has cited other cases where stable reverse osmosis operation was observed for silica concentrations up to 340 milligrams per liter. At 80 percent and 85 percent reverse osmosis recoveries, the silica concentrations in the reject were 156 and 208 milligrams per liter, respectively. Once the reverse osmosis recovery approached 90 percent, the silica concentration in the reject stream increased to 312 milligrams per liter. However, trivalent ions in the water, such as iron and aluminum can effectively bind with silica in the water and form silica-metal complexes even before silica reaches its supersaturation level in the presence of antiscalants, as seen from the presence of iron and silica on the membrane surface in Figure 12. Sulfur presence can be attributed to the polysulfone support layer of the membranes.

4.4 Energy requirements of an optimized brackish groundwater desalination system

4.4.1 Model assumptions

During the testing period from February 2010 to December 2010, feed water quality fluctuated from the projected design water quality due to the activation of higher salinity brackish wells to supply feed water into the plant. A separate feed water analysis was conducted in July 2010 and the results indicated that the feed water TDS increased by 1,000 milligrams per liter compared to the design water quality data (Shown in Table 4). The updated feed water analysis is presented in Table 6.

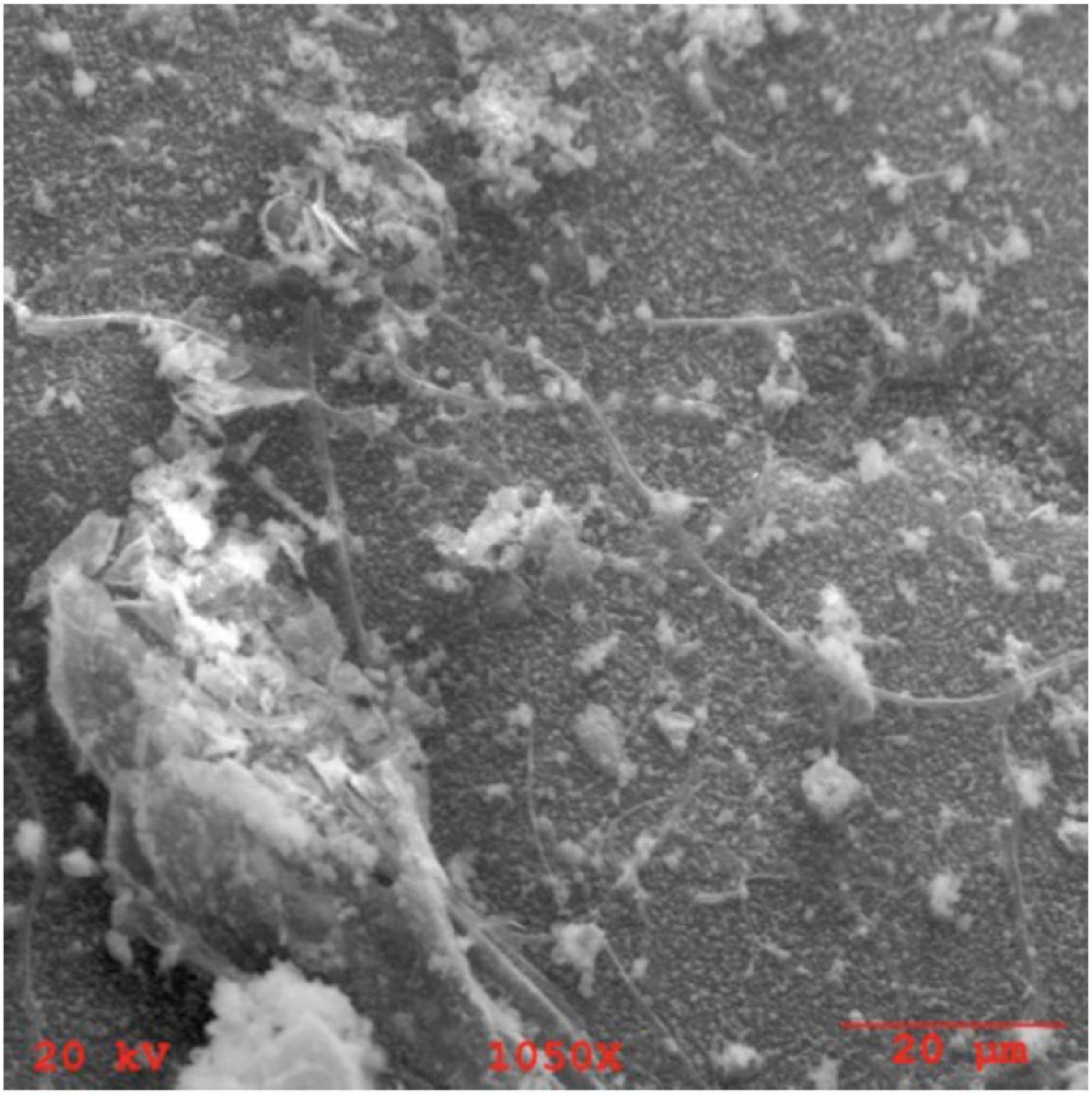


Figure 11. Scanning Electron Microscope image of the foulant on the membrane surface.

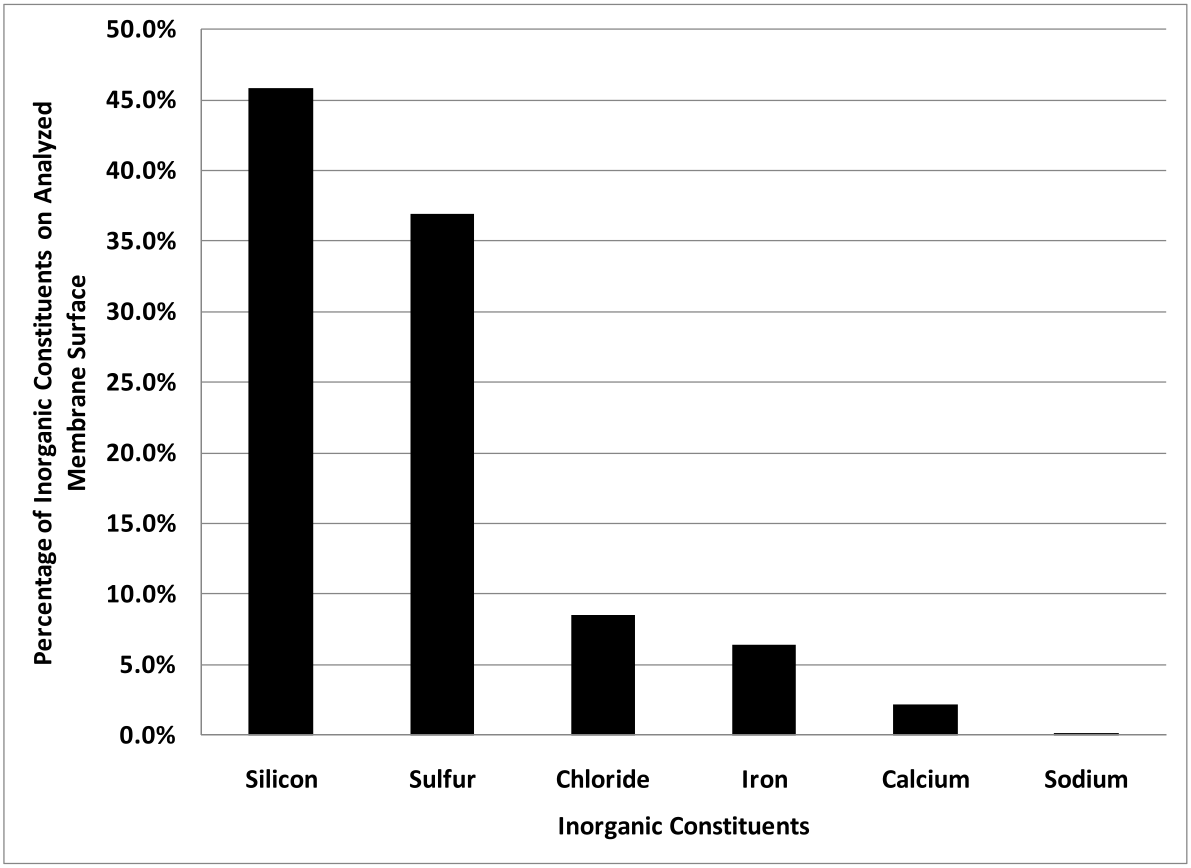


Figure 12. Graphical representation of the inorganic constituents found on the membrane surface.

Table 6. Updated feed water quality.

Constituent	Unit	Updated Concentration	Original Concentration
Calcium	milligrams per liter	147	135
Magnesium	milligrams per liter	38	35
Sodium	milligrams per liter	963.6	609
Potassium	milligrams per liter	34	19
Barium	milligrams per liter	0.05	0.11
Aluminum	micrograms per liter	70	-
Strontium	milligrams per liter	4.45	2
Iron	micrograms per liter	679	-
Carbonate	milligrams per liter as Calcium Carbonate	0.6	0.2
Bicarbonate	milligrams per liter as Calcium Carbonate	89.6	57
Sulfate	milligrams per liter	320	187
Chloride	milligrams per liter	1600	1093
Fluoride	milligrams per liter	0.5	0.6
Nitrate	milligrams per liter	2.0	0.1
Silica	milligrams per liter	31.2	32
Temperature	degrees Celsius	26.5	26
pH	pH unit	7.8	7.2
TDS	milligrams per liter	3231	2183
Turbidity	Nephelometric Turbidity Unit	< 1	< 1

Reverse osmosis membrane modeling simulations for the demonstration unit operations was calibrated against the actual demonstration data at the 80 percent recovery baseline condition. The predicted feed pressure for the projected high-pressure pump and reject/brine pressure were within 1-5 percent of the actual operating data. Given the level of accuracy of our model predictions, full-scale extrapolation was simulated for the 80 percent reverse osmosis Recovery with and without pressure exchanger.

The energy required to produce fresh water from brackish water is defined by the specific power consumption of the desalination system, (i.e., the power per unit of time required to produce a unit of water.) The specific energy for the reverse osmosis process includes the main horsepower pump power and pressure exchanger interstage/booster pump power divided by the permeate flow rate. The power required for brackish raw water supply, pretreatment, post treatment and distribution is not included. We have chosen to isolate the reverse osmosis process specific energy for the following reasons:

- The reverse osmosis process specific energy is the least understood and most over estimated energy number in the total treatment process.
- The pre-treatment, concentrate disposal and post treatment energy requirements varies from site to site for brackish water treatment.

In Figure 13, the reverse osmosis process specific energies were compared. The actual Affordable Desalination Collaboration test results are presented on the left, while the extrapolations to a full-scale 3 million gallons per day system are presented on the right. Several scenarios were considered:

- <u>Affordable Desalination Collaboration Actual</u>:
    - "80 percent reverse osmosis Recovery Baseline (pressure exchanger + Boost Pump)":

      Actual demonstration test results from the Affordable Desalination Collaboration demonstration unit for the overflush configuration with pilot pump and motor efficiencies.
    - "75 percent reverse osmosis-85 percent System Recovery (pressure exchanger + Boost Pump):

      Actual demonstration test results from the Affordable Desalination Collaboration demonstration unit for the underflush configuration with pilot pump and motor efficiencies.

- <u>Affordable Desalination Collaboration Calculated:</u>
    - "Full-Scale 80 percent reverse osmosis Recovery (pressure exchanger + Boost Pump)":

      3 million gallons per day full-scale reverse osmosis train projection using pump energy requirements from the pilot 80 percent reverse osmosis Recovery Baseline (pressure exchanger) test data, accounting for additional 5 percent salinity increase of the reverse osmosis feed due to mixing in the pressure exchanger. Pump and motor efficiencies for the high pressure feed pumps were obtained from Kay Bailey Hutchison Desalination Plant's pump data, whereas assumptions for the interstage boost pump and motor efficiencies were obtained from manufacturer pump curves.

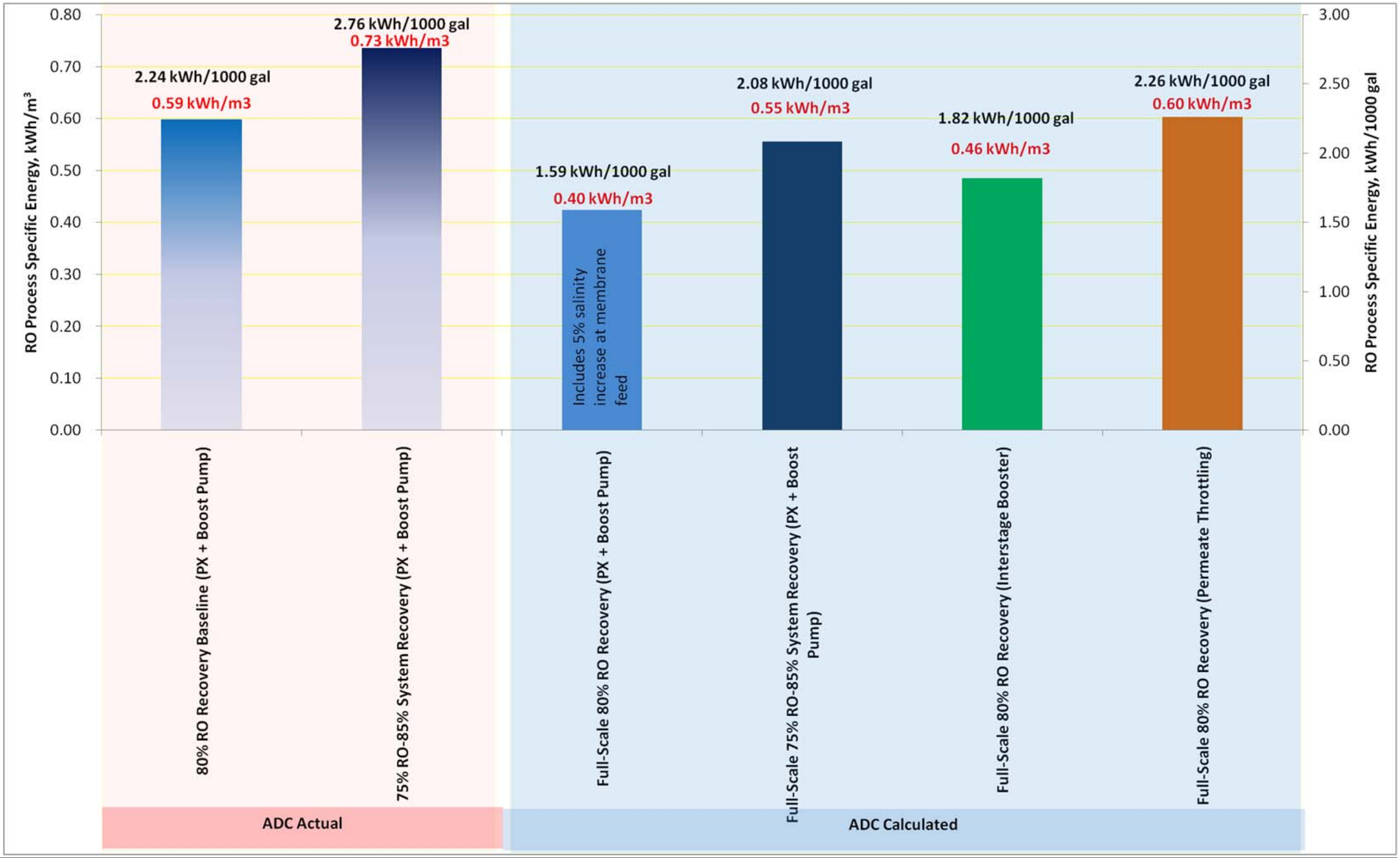


Figure 13. **Reverse osmosis process specific energy comparison.**

- "Full-Scale 75 percent reverse osmosis-95 percent System Recovery (pressure exchanger + Boost Pump)":

  3 million gallons per day full-scale reverse osmosis train projection using pump energy requirements from the pilot 75 percent reverse osmosis-85 percent system Recovery (pressure exchanger) test data. Pump and motor efficiencies for the high pressure feed pumps were obtained from Kay Bailey Hutchison Desalination Plant's pump data, whereas assumptions for the interstage boost pump and motor efficiencies were obtained from manufacturer pump curves.

- "Full-Scale 80 percent reverse osmosis Recovery with Interstage Boost":

  3 million gallons per day full-scale reverse osmosis train projection for a reverse osmosis recovery of 80 percent without pressure exchanger, but with an interstage boost pump to achieve flux balance in between two stages. Pump and motor efficiencies for the high pressure feed pumps were obtained from Kay Bailey Hutchison Desalination Plant's pump data, whereas assumptions for the interstage boost pump and motor efficiencies were obtained from manufacturer pump curves.

- "Full-Scale 80 percent reverse osmosis Recovery with Permeate Throttling":

  3 million gallons per day full-scale reverse osmosis train projection for a reverse osmosis recovery of 80 percent without either pressure exchanger or an interstage boost pump. Permeate throttling was modeled here to simulate Kay Bailey Hutchison reverse osmosis process conditions. Pump and motor efficiencies for the high pressure feed pumps were obtained from Kay Bailey Hutchison Desalination Plant's pump data.

The assumed pump efficiencies are presented in Table 7. At the same feed total dissolved solids and system pump efficiency into the system, in decreasing specific energy ranking:

- Full-Scale 80 percent reverse osmosis Recovery with Permeate Throttling
- Full-Scale 75 percent reverse osmosis-85 percent System Recovery with pressure exchanger + Boost Pump
- Full-Scale 80 percent reverse osmosis Recovery with Interstage Boost
- Full-Scale 80 percent reverse osmosis Recovery with pressure exchanger + Boost Pump

An energy savings comparison was performed for the full-scale 3 million gallons per day flow scenario using the Full-Scale 80 percent reverse osmosis Recovery with pressure exchanger + Boost Pump as a baseline. At full-scale flows, the Full-Scale 80 percent reverse osmosis Recovery with pressure exchanger + Boost Pump configuration will save 13 percent energy consumed compared to the Full-Scale 80 percent reverse osmosis Recovery with Interstage Boost configuration, 24 percent compared to Full-Scale 75 percent reverse osmosis-85 percent System Recovery with pressure exchanger + Boost Pump configuration, and 30 percent compared to the Full-Scale 80 percent reverse osmosis Recovery with Permeate Throttling configuration.

Table 7. Pump efficiencies for reverse osmosis specific energy calculations.

	High Pressure / Feed Pump			Boost Pump		
VFD Efficiency 95%	**Flow (gpm)**	**Pressure (psi)**	**Assumed Pump/Motor Efficiencies (%)**	**Flow (gpm)**	**Pressure (psi)**	**Assumed Pump/Motor Efficiencies (%)**
80% reverse osmosis Recovery (pressure exchanger + Boost Pump)	2088	133	81/94.5	809	40	77/95
80% reverse osmosis Recovery (Interstage Boost)	2604	109	81/94.5	1159	90	77/95
80% reverse osmosis Recovery (Permeate Throttling)	2604	187	81/94.5	-	-	-
75% reverse osmosis-85% System Recovery (pressure exchanger + Boost Pump)	2090	177	81/94.5	1180	46	77/95

4.5 Life-cycle cost analysis

Incorporating isobaric energy recovery to an existing brackish water desalination facility provides the opportunity to reduce power consumption and power cost over the life of the facility. Cost savings associated with a reduction in specific energy in a desalination system with an integrated energy recovery device may offset the additional capital cost when compared to a brackish water desalination system with permeate thottling. Figure 14 provides a specific energy modeled comparison at year 0 and year 5 membrane life for a 3 million gallon per day brackish desalination train. The specific energy data was calculated based on the same water quality conditions as outlined in Table 6. In order to evaluate the life-cycle cost, year 0 and year 5 specific energy were averaged for both the Full Scale 80 percent recovery with Energy Recovery and the Full Scale 80 percent recovery with permeate thottling as shown in Figure 13.

One must consider the additional capital cost associated with implementing energy recovery technology to an existing system and the debt service associated with the cost of the capital. Table 10 provides a conceptual cost to implement energy recovery into a 3 million gallon per day train (Similar to the Kay Bailey Hutchison Desalination Plant’s train configuration)

Factors that affect the capital and energy cost include the facilities on-line use, energy cost, rebate incentive from power suppliers, interest/ bond rate for capital improvement, and inflation rate.

The following assumptions are made for this conceptual life-cycle cost analysis:

- On-line use factor = 90 percent
- Energy Cost = $0.095 per kilowatt hour (United States Energy Information Administration).
- Annual energy inflation rate of 3 percent used based on Texas average annual energy inflation from 1990 to 2009 (United States Energy Information Administration).
- No utility rebate incentive used in cost analysis.
- 5 percent annual interest rate for interest rate for energy recovery device capital improvement.
- 20 year project life cycle
- Membrane life of 5 years (Used to determine the Average Specific Energy)
- 5 year average Reverse Osmosis specific energy for 3 million gallon per day train at 80 percent recovery with Energy Recovery Device is 1.70 kilowatt hour per 1000 gallons
- 5 year average Reverse Osmosis specific energy for 3 million gallon per day train at 80 percent recovery with Permeate Thottling for Stage flux balance is 2.34 kilowatt hour per 1000 gallons

The following calculation shows the specific energy savings of a 3 million gallons per day train with Energy Recovery when compared with a 3 million gallons per day train with Permeate Thottling using the assumptions above:

Average reverse osmosis specific energy savings=

=2.34 kilowatt hours per 1000 gallons – 1.70 kilowatt hour per 1000 gallons

= 0.64 kilowatt hour per 1000 gallons

Payback period is defined as the length of time for the cumulative net annual profit to equal the initial investment. Therefore:

$$\text{Payback} = \frac{\text{initial investment}}{\text{Net annual profit}}$$

To determine the payback period in implementing energy recovery a conceptual capital cost is use as the initial investment and the net annual profit is the energy saving realized by energy recovery technology. Therefore:

Initial investment = $302,500.00 (Refer to Table 10 for breakdown of conceptual cost)

3 million gallons per day Train Permeate Production with 90 percent online use factor = 112,500 gallons per hour.

Table 8 below outlines the reverse osmosis power cost associated with a permeate thottled train configurations and train with energy recovery. The table provides a resulting annual power cost savings using energy recovery of ($219,077 - $159,158)= $59,919.

Table 8. Reverse osmosis power and reverse osmosis power cost comparison.

Configuration for 3 MGD train at 80% recovery	Specific Energy Kwh/1000 gallons	reverse osmosis Power Consumed (based on 5 year Average Specific Energy and 90% online use)	reverse osmosis Power Cost per year (based on Energy cost of $0.095/KWh)
Train with Permeate Thottling	2.34	263.25 kw	$ 219,077
Train with Energy Recovery	1.70	191.25 kw	$ 159,158

MGD = million gallons per day
% = percent
kw = kilowatt

$$\textit{Payback} = \frac{\textit{initial investment}}{\textit{Net annual profit (Energy Savings)}} = \frac{\$302{,}500.00}{\$59{,}934.81} = 5.05 \textit{ year}$$

In addition to determining the simple payback, a 20 year life cycle analysis is important to determine the anticipated 20 year present worth of the investment. This conceptual project cost analysis accounts for energy inflation over time as well as the cost to finance the capital investment. The same 90 percent on-line use factor is used for the life cycle analysis.

The uniform series present worth calculation is used to determine the impact of inflation over time and is shown as present worth reverse osmosis power cost for a 20 year life cycle. An annual energy inflation rate of 3 percent is used based on Texas average annual energy inflation from 1990 to 2009.

In Table 9, a present worth comparison reveals an energy saving over 20 year of $891,415. The present worth total capital cost (from Table 10 below), including debt service (5 percent, 20 year loan) is $479,127.

The 20 year present worth life cycle savings for a 3 million gallons per day Train with energy recovery when comparing to a 3 million gallons per day train with permeate thottling will be approximately $412,288.00

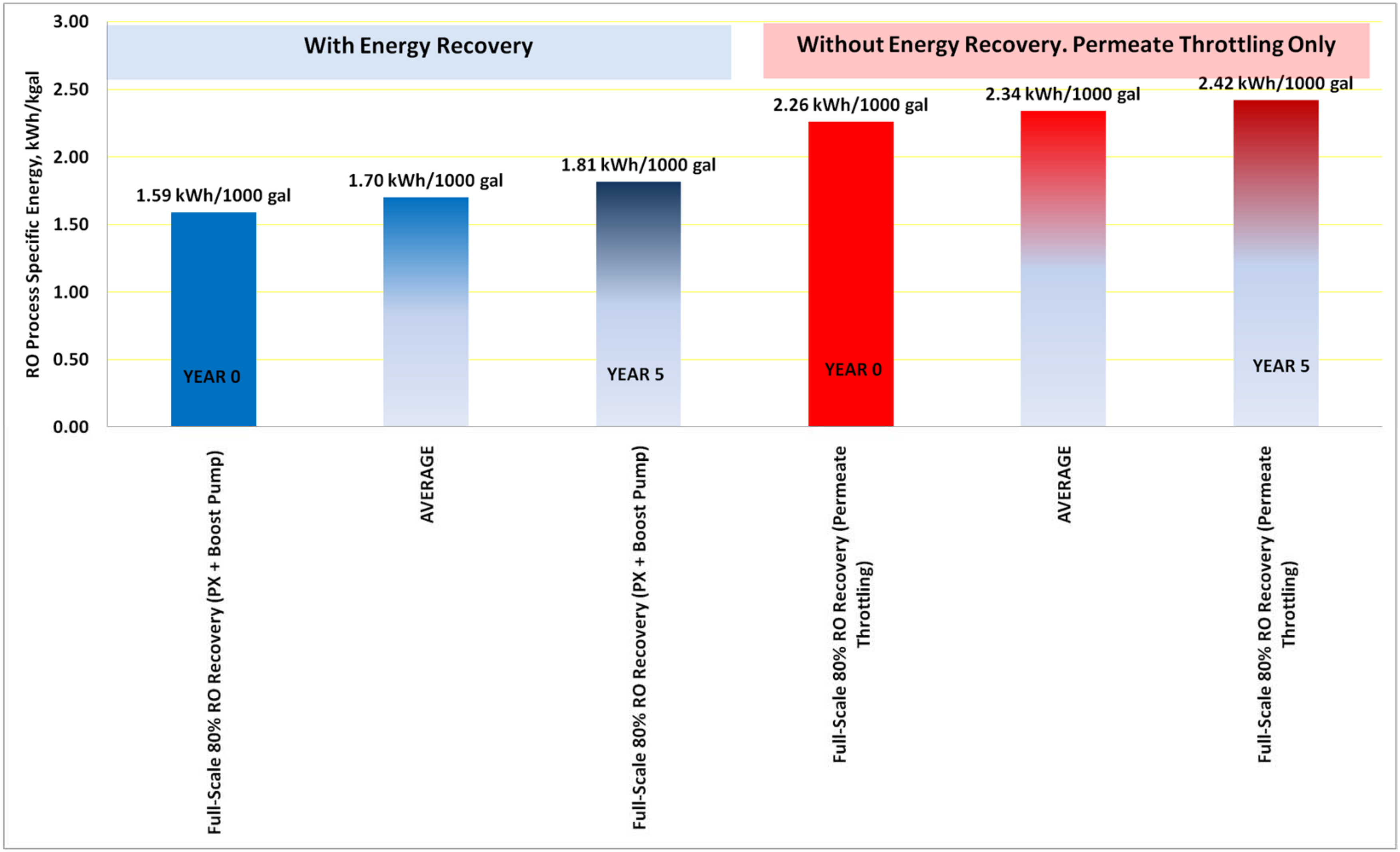


Figure 14. **Reverse osmosis process specific energy comparison for Year 0 to 5.**

Table 9. Reverse osmosis power cost comparison.

Train Configuration	Power Cost annual amount	Present Worth reverse osmosis Power Cost (P/A, 3% Energy Inflation, Discount rate of 6%,20 years)	Capital Cost including debt service with 5% interest, 20 year payback
3MGD, 80% recovery with Permeate Throttling	$ 219,077	$3,259,208	$0
3MGD,80% recovery with Energy Recovery	$ 159,158	$2,367,793	Capital Cost $302,500.00 Debt Service $176,627.00 **Total Cost $479,127.00**

Table 10. Conceptual capital cost to implement energy recovery for a full-scale 3-million gallons per day reverse osmosis train

Quantity	Description	Unit budgetary price	Final price/ train
2	BPX-300 device	32,000	64,000
1	Interstage/Boost pump	55,000	55,000
1	Instrumentation	15,000	15,000
1	Boost pump variable frequency drive	7,500	7,500
1	316 SS Fittings	3,500	3,500
1	Piping Manifolds	20,000	20,000
1	Miscellaneous Valving	15,000	15,000
1	Programming	7,000	7,000
1	Engineering	25,000	25,000
1	Construction Installation	60,000	60,000
1	Start-up and Commissioning	3,000	3,000
		Subtotal	$ 275,000.00
		10% Contingency	$ 27,500.00
		Total ERD Capital Cost	$ 302,500.00

5 Conclusions and recommendations

- 80 percent reverse osmosis recovery was determined to be the optimum operating point for the isobaric energy recovery with brackish groundwater reverse osmosis process to give the lowest reverse osmosis specific energy. Projected energy savings are 23 percent.
- Under flush (concentrate recycle) may improve boundary layer conditions at the reverse osmosis; however, high concentrations of silica in the presence of heavy metals limited recovery.

- Feed water quality challenges with respect to silica supersaturation prevented system recovery from exceeding 80 percent, despite antiscalant dosing.
- At the optimum 80 percent reverse osmosis Recovery, a 3 million gallons per day full-scale simulation revealed significant energy savings for incorporating pressure exchanger with brackish water reverse osmosis system
- Isobaric Energy Recovery can provide significant energy savings when compared to traditional two stage brackish groundwater reverse osmosis using permeate throttling to balance flux between stages.
- Optimizing the position of the pressure exchanger booster between the first and second reverse osmosis stages successfully provided interstage boost pressure and flux balance while simultaneously circulating flow through the pressure exchanger system.

6 Dissemination/Outreach Activities

During the Affordable Desalination Collaboration -TWDB contract period of performance the Affordable Desalination Collaboration provided the papers, presentation and/or articles as listed in Table 11 and Appendix C for copies of the papers, articles, and press releases.

Table 11. Dissemination and outreach activities.

Trade show/conference/publication	Date(s)	Author(s)	Presenter	TWDB submittal
Innovative Designs to Be Tested in Affordable Desalination Collaboration , D&WR	Sept/Nov 2007	John P. MacHarg	n/a	Q2-09
Joint Affordable Desalination Collaboration -AMTA workshop, Annual Conference, Austin, Texas	July 2009	n/a	Various	Q2-09
IDA Annual Conference, Dubai-2009, Optimizing Low Energy Seawater Desalination	Aug-2009	S. Dundorf, J. MacHarg, B. Sessions, T. Seacord	S. Dundorf	Final Report
Texas Water Innovation Presentation	Sept-2010	John MacHarg	n/a	Oct-2010
Multi-State Salinity Coalition	March 2011	Sessions, Shih, MacHarg	n/a	Final Report
Joint Affordable Desalination Collaboration -AMTA workshop, Annual Conference, Miami, FL	July-2011	n/a	Various	Final Report
Optimizing Brackish Water Reverse Osmosis for Affordable Desalination, AMTA-SEDA Annual Conference	July-2011	Sessions, Shih, MacHarg, Dundorf and Arroyo	Sessions	Final Report

7 References

ERI Technical Bulletin Isobaric Device Mixing, Doc. No. 80088-01

Hauge, L. J. and F. Ludvigsen. 1999. "Field Installation of Pressure Exchanger in an 80 m3/D SWRO Plant" Costa Teguise, Lanzarote, Canary Islands, 1999 IDA San Diego

Hauge, L. J. and F. Ludvigsen. 1999. "Field Installation of Pressure Exchanger in an 80 m3/D SWRO Plant" Costa Teguise, Lanzarote, Canary Islands, 1999 IDA San Diego

MacHarg, J.P. 2003. Exchanger Test Verifies 2.0 kWh/m3 SWRO Energy Use. *Desalination and Water Reuse* Vol 11/1, June-2003

MacHarg, J.P.and S.A. McClellan, 2004, Pressure Exchanger Helps Reduce Energy Consumption in Brackish Water Design, *Journal AWWA*, November 2004

USEPA, 2009, U.S. Environmental Protection Agency Primary Standard 816-F-09-0004, May 2009

USEPA, 2009, U.S. Environmental Protection Agency Secondary Standard 816-F-09-0004, May 2009

U.S. Energy Information Administration, Form EIA-861, "Annual Electric Power Industry Report.

Appendix A: Validation Protocol

AFFORDABLE DESALINATION COLLABORATION

TEXAS WATER DEVELOPMENT BOARD

BRACKISH GROUNDWATER RO DEMONSTRATION STUDY

LOCATION: EL PASO DESALINATION PLANT

VALIDATION PROTOCOL

ADC Demonstration Pilot System

ADC

Affordable Desalination Collaboration

Affordable Desalination Collaboration, 2419 E. Harbor Blvd, #173, Ventura, CA 93001
Tel: 650-283-7976 – Fax: 805-658-8060 – www.affordabledesal.com – jmacharg@affordabledesal.com

TABLE OF CONTENTS

Affordable Desalination Collaboration

ADC-TWDB BRACKISH GROUNDWATER RO DEMONSTRATION STUDY

1.0 INTRODUCTION

1.1 Background

The Affordable Desalination Collaboration (ADC) is a California non - profit organization comprised of state and federal government agencies, water districts, and industry leaders working together to demonstrate seawater desalination as a reliable, affordable, an environmentally sound source of potable water. The original objective of the ADC was to design, build and test a scalable SWRO plant using commercially available technology that can demonstrate efficient energy consumption. The ADC's demonstration scale SWRO plant (rated seawater capacity of 48,000 gpd to 75,600 gpd) was tested at the U.S. Navy's Desalination Research Center, located in Port Hueneme, California, and operated from May 2005 through July 2009. Key achievements of our initial seawater testing included:

- Demonstrating that SWRO is a viable water supply alternative for Southern California, as shown in Figure 1.1.
- Setting a world record low SWRO process energy consumption of 6.0 kWh/kgal of permeate produced.
- Test and demonstrate 7 membrane models from four manufacturers providing performance comparison under similar feed water conditions.
- Test and demonstrate Dow Filmtec's "hybrid membrane" design, by staging membranes of various performance in a single seven element vessel
- Test and demonstrate Dow Filmtec's high boron rejection membrane for seawater

- Demonstrate new process design configurations to achieve higher system recoveries in seawater (i.e., over 50%)
- Test and demonstrate the performance of GE/Zenon ZeeWeed® 1000 ultrafiltration (UF) membrane technology as a reliable method of pretreatment for SWRO systems for feed water conditions at the Port Hueneme Test Facility.

By testing and demonstrating these new technologies and designs and sharing the results, the ADC has been able to provide information to SWRO designers and industry stake holders that seawater desalination is an affordable, viable and reliable source of potable water for the future. The ADC website: www.affordabledesal.com details the goals, previous publications and information related to the ADC.

1.2 TWDB-ADC Demonstration Study Objectives

The objectives of this Texas Water Development Board Brackish (TWDB) Ground Water Demonstration Projects are as follows:

1. Develop and demonstrate new process designs that are possible as a result of the isobaric energy recovery technologies. As a natural result of the pressure exchanger (PX) technology in particular, there are new kinds of flow schemes that can improve the performance of higher recovery brackish water systems. We will use the ADC pilot system to test and demonstrate these new flow schemes in order to push the recoveries beyond what has been traditionally achievable.
2. Test and demonstrate state of the art isobaric energy recovery technology in an optimized brackish water design. The ADC expects to achieve 15-30% energy savings over traditional brackish water systems even where energy recovery turbines are applied.

The ADC will operate at the El Paso Brackish Water Desalination facility and use the same feed water as the full scale plant. In so far as possible, the pilot system design will mimic the full scale plant so that comparisons may be made between the pilot system performance and the full scale plant performance.

While evaluating these brackish water process alternatives, it is important that potable water quality meets primary and secondary standards. Potable water quality goals for this ADC TWDB study are summarized in Table 1.2.

Table 1.2 Demonstration Scale Test Potable Water Quality Goals
Brackish RO Demonstration Study
Affordable Desalination Collaboration Part II

Parameter	Unit	Value	Basis
TDS	mg/L	< 500	Federal Secondary Standard
Chloride	mg/L	< 250	Federal Secondary Standard

2.0 VALIDATION PROTOCOL

This section describes the materials and methods used to validate that the following process design concepts and their potential to reduce either or both capital costs or energy consumption while meeting potable water quality goals.

- Optimized brackish water design with isobaric energy recovery
- Higher recovery operation through isobaric brine recirculation

2.1 Demonstration Scale Brackish RO Equipment

Criteria used to size the demonstration scale Brackish RO and UF Pretreatment equipment are presented in Table 2.1. A process flow diagrams are presented in Figures 2.1, 2.2, and 2.3.

Table 2.1 BWRO Demonstration Scale Test Equipment Criteria
Brackish water RO Demonstration Study
ADC-TWDB Brackish Water Demonstration Project

Parameter	Unit	Value
Feed, Flush, Cleaning Pump		
Manufacture/Model		AMPCO, ZC2 2.5x2
Duty Range	gpm @ ft H_2O	170gpm @ 80 ft TDH
Media Filter		
Manufacturer		ALAMO
Quantity	No.	2
Diameter	Inch	48
Height	Inch	72
Loading Rate	gpm/ft^2	3 to 6
Cartridge Filter		
Manufacturer/Model		Eden Excel, 88EFCT4-4C150
Quantity	No.	22
String Wound Cartridge Specs		#XL1-EP050-PLC40, 5 micron
Pressure Vessels		
Manufacturer/Model		Codeline, 80A100-7
Quantity	No.	3
No. of Membrane Elements per Vessel	No.	7
Membrane Element		

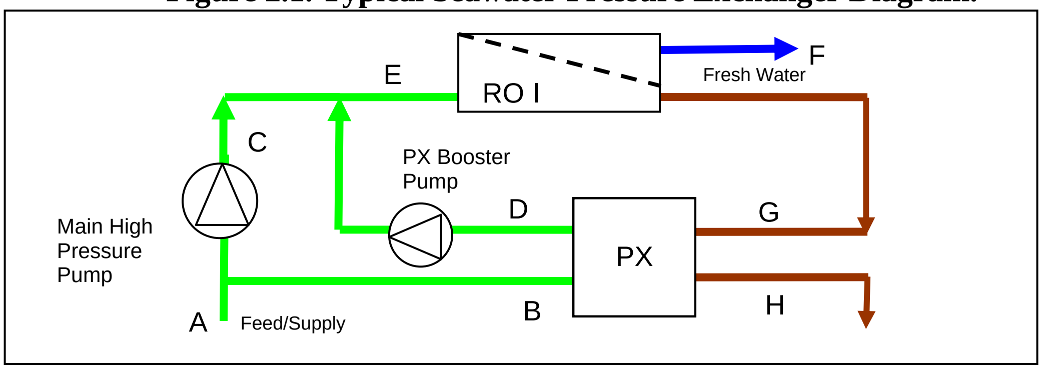
Table 2.1 BWRO Demonstration Scale Test Equipment Criteria
Brackish water RO Demonstration Study
ADC-TWDB Brackish Water Demonstration Project

Parameter	Unit	Value
Manufacturers/ Models		Hydranautics ESPA1-7
Quantity	No.	21
Diameter	inch	8
Surface Area	ft^2	400
Total Membrane Area (A_{SYS})	ft^2	8400
High Pressure Pump		
High Pressure Feed Pump Type		Positive Displacement
Manufacturer		Danfoss
Model		2 x APP-10.2
Driver		VFD
High Pressure Pump flow	gpm	40-90 (7-15 gfd)
High Pressure Pump TDH	ft H_2O (psi)	349 to 2698 (150 to 1160)
PX Booster Pump		
PX Booster Pump Type		Multi-stage Centrifugal
Manufacturer		Energy Recovery, Inc.
Model		HP-8504
Driver		VFD
PX Booster Pump TDH		70 to 115 (30 to 50)
Energy Recovery		
Energy Recovery Devise Type		Pressure Exchanger
Manufacturer		Energy Recovery, Inc.
Model		PX-70S SW / PX-?? BW
Quantity	No.	2
Notes:		

2.1.1 Optimized Isobaric Energy Recovery Demonstration

An isobaric energy recovery system utilizes the principle of positive displacement to pressurize filtered feed water by direct contact with the high-pressure concentrate (waste) stream or reject from an RO system. Within a pressure exchanger (PX) pressure transfer occurs in the longitudinal ducts of a ceramic rotor that spins inside a ceramic sleeve. The rotor-sleeve assembly is held between two ceramic end covers. At any given instant, half of the ducts are exposed to the high pressure fluid side and half the ducts are exposed to the low pressure fluid side. Figure 2.1 shows the flow path of a typical seawater reverse osmosis (SWRO) PX system. The concentrate from the RO membranes (G) passes through the PX, where its pressure is transferred directly to a portion of the incoming feed water at up to 97% efficiency. This pressurized feed water stream (D), which is approximately equal in volume and pressure to the reject stream, passes through a PX auxiliary pump (not the main high-pressure pump) to add the small amount of pressure lost due to the differential pressure across the membranes and to friction in the associated piping and the PX. The PX booster pump drives the flow through the high-pressure side (G and D) of the PX. Fully pressurized feed water then merges with the main feed water line of the RO system after the main high-pressure pump. In an RO-PX system, the main pump is sized to equal the RO permeate flow plus a small amount of rotor lubrication flow, not the full RO feed flow. Therefore, the PX significantly reduces flow through the main pump. This point is significant because a reduction in the size of the main pump results in lower power consumption and operating costs.

Figure 2.1. Typical Seawater Pressure Exchanger Diagram.



The RO-PX system requires a booster pump to make up the small amount of pressure losses through the membranes, PX, and the associated piping circuit. In the standard single stage seawater system this pump is applied at the outlet of the PX. However, in a 2 stage brackish water system the PX booster pump can serve 2 purposes by being installed in between stages 1 and 2 as shown in Figure 2-2. In this configuration the PX booster pump also acts as an interstage booster pump helping to reduce the required pressure from the main high pressure feed pump, by balancing the flux between the 1st and 2nd stages

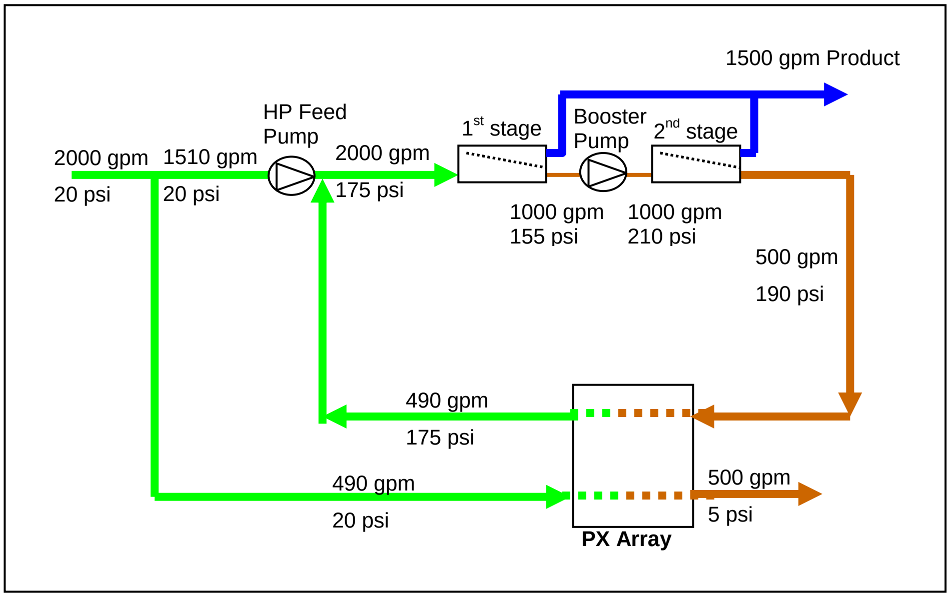


Figure 2-2. Example Interstage Booster PX Design @ 75% RO Recovery

The example in figure 2-2 (see Appendix A for detail P&ID) shows that while the PX booster is supplying the energy to drive the water around the PX circuit it is also conveniently providing 55 psi of interstage boost pressure. In addition to improving the flux balance, it also results in significant savings by both the PX reducing the main HP pump size and the lower 1st stage feed pressure inherent to an interstage booster design. Table 1 shows the PX power savings verses a standard interstage booster design.

Table 2-2. Projected PX Savings in Interstage Booster system

	Std	ERI
Feed pump efficiency	83%	83%
Feed pump motor efficiency	94%	94%
Feed pump power, kW	172.9	130.3
Booster pump efficiency	80%	80%
Booster pump motor efficiency	94%	94%
Booster pump power, kW	23.2	31.8
RO Feed Pressure, PSI	175	175
RO Recovery, %	75%	75%
KWh/kgal	**2.19**	**1.82**
17% savings yields $17,500/year @ $0.06/kWh		

In conclusion, an optimally designed brackish water PX system can provide many benefits including energy savings and flux balance. These concepts could save operators of brackish water systems as much 10-30% of the operating energy compared to traditional systems while simultaneously improving the performance of the RO membranes.

2.1.1.1 - Procedure for testing Brine Recirculation Process

Demonstration scale tests of the Optimized Isobaric Energy Recovery system will occur over an approximate 6 month period. As presented in Table 2-3, each phase of testing consists of the following:

- Two weeks (weeks 1-2) of “ripening” at a typical flux and recovery rate. This “ripening” period has been included based upon past experience operating new membranes. Experience has indicated that approximately two and one half weeks are required before some new membrane’s performance (e.g., pressure and salt rejection) reaches a steady state condition. It is possible that pre-ripened membranes will be used in this test and this period may be shortened or omitted accordingly.
- Four weeks (weeks 3-6) of testing at different system flux and RO recovery points. Each flux and recovery point will be operated for 1 day to obtain the approximate energy and water quality performance at a given point.
- 2 month demonstration at a single flux and recovery point.

Tables 2-3 indicates the desired flux and recovery that will be set for this test. The applicable equations are as follows:

$$R = \frac{Q_{P-SYS}}{Q_{F-SYS}} * 100$$ **Equation 2.4**

$$Q_{F-SYS} = Q_{P-SYS} + Q_{REJECT}$$ **Equation 2.5**

$$Q_{PX\text{- }HP\text{-}out} == Q_{REJECT} + 1.5gpm\_leakage$$ **Equation 2.6**

$$Q_{P-SYS} = Q_{F-HP-Pump} - 1.5gpm\_leakage$$ **Equation 2.7**

Where:
R = Recovery, %
$Q_{F\text{-}SYS}$ = RO system feed flow, gpm
$Q_{F\text{-}HP\text{-}Pump}$ = High pressure positive displacement pump flow, gpm
$Q_{PX\text{-}HP\text{-}out}$ = $Q_{PX\text{-}Pump}$ = PX High Pressure Outlet, gpm

Q_{Reject} = RO membrane reject flow, gpm

Between each system flux and recovery matrix, the original/ripening flux and recovery (i.e., the flux and recovery tested during weeks 1-2) will be retested to confirm membrane performance at baseline conditions.

Approximately 8 weeks of operating at the RO-System recovery point determined, *through testing*, to 1) meet water quality goals for TDS and 2) results in the most affordable operation, as determined by a net present value analysis, or 3) and operating point that best matches the current operating conditions of full scale El Paso plant.

The data gathered from these tests shall be used to develop graphs that show the power consumption rate and water quality that can be achieved at each condition. Power consumption rate shall be measured to include the following electrical loads:

- High Pressure RO Pump (P2)

- PX Booster Pump (P3)

The following will not be included in the power consumption rate measurements

- Intake Lift Pump (P1)
- Chemical Metering Pumps
- Instrumentation and Controls
- Product water pumping
- Pretreatment pumping

While the intake lift pump may provide suction side pressure to the High Pressure Positive Displacement pump, thereby reducing the overall TDH, it will not be included in the power monitoring. For the affordability analysis, an intake pump's horsepower will be assumed based upon flow and overall lift TDH of 200 ft of H_2O.

Table 2-3 **Schedule of Testing Conditions**
Optimized Isobaric Energy Recovery Demonstration
ADC TWDB Desalination Demonstration Project

Parameter	**1-2 Weeks Ripening**	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**
Membrane sq-ft	400				Base Line				Base Line
Flux, gfd	14.9	12	12	12	14.9	14.9	14.9	14.9	14.9
RO recovery	80.0%	75.0%	80.0%	85.0%	80.0%	75.0%	80.0%	85.0%	80.0%
System Recovery	80.0%	75.0%	80.0%	85.0%	80.0%	75.0%	80.0%	85.0%	80.0%
High Pressure RO Pump ($Q_{F\text{-}HP\ Pump}$), gpm	88.4	71.5	71.5	71.5	88.4	88.4	88.4	88.4	88.4
PX HP Outlet, ($Q_{PX\text{-}HP\text{-}Out}$), gpm	20.2	21.8	16.0	10.9	20.2	27.5	20.2	13.8	20.2
Permeate ($Q_{P\text{-}SYS}$), gpm	86.9	70.0	70.0	70.0	86.9	86.9	86.9	86.9	86.9
PX Low Pressure Inlet, gpm	20.2	21.8	16.0	10.9	20.2	27.5	20.2	13.8	20.2
Concentrate, gpm	21.7	23.3	17.5	12.4	21.7	29.0	21.7	15.3	21.7

				Base Line	
	Day 9	**Day 10**	**Day 11**	**Day 12**	**2 Month Demo Point**
Flux, gfd	16	16	16	14.9	TBD
RO recovery	75.0%	80.0%	85.0%	80.0%	TBD
System Recovery	75.0%	80.0%	85.0%	80.0%	TBD
High Pressure RO Pump ($Q_{F\text{-}HP\ Pump}$), gpm	94.8	94.8	94.8	88.4	TBD
PX HP Outlet, ($Q_{PX\text{-}HP\text{-}Out}$), gpm	29.6	21.8	15.0	20.2	TBD
Permeate ($Q_{P\text{-}SYS}$), gpm	93.3	93.3	93.3	86.9	TBD
PX Low Pressure Inlet, gpm	29.6	21.8	15.0	20.2	TBD
Concentrate, gpm	31.1	23.3	16.5	21.7	TBD

Notes:

1. Maximum system pressure is 600 psi. If any point exceeds 600 psi system will shutdown and point will need to be skipped.
2. Flows assume 400 sq-ft membrane
3. $Q_{F\text{-}HP\ Pump}$ = High pressure positive displacement pump flow = Product flow +1.5 gpm (PX leakage).
4. $Q_{PX\text{-}HP\text{-}Out}$ = PX booster pump flow= Concentrate flow gpm - 1.5 gpm (PX leakage).
5. $Q_{P\text{-}SYS}$ = SWRO system permeate flow.

2.1.2 Brine Recirculation Process for Higher Recovery in Single Stage Array

The brine recirculation process is achieved through unbalancing the flows through an isobaric energy recovery device. As a natural result of isobaric energy recovery systems there are new kinds of flow schemes that may improve the performance of higher recovery seawater and brackish water systems. One example is shown in Figure 2-3 below where a PX is intentionally unbalanced yielding an overall system recovery (F divided by A) of 85% and 2000 tds feed water, but the membrane recovery (F divided by E) is at 65% and 4,886 tds feed water.

Figure 2-3 The Unbalanced Pressure Exchanger Diagram Single Stage Array

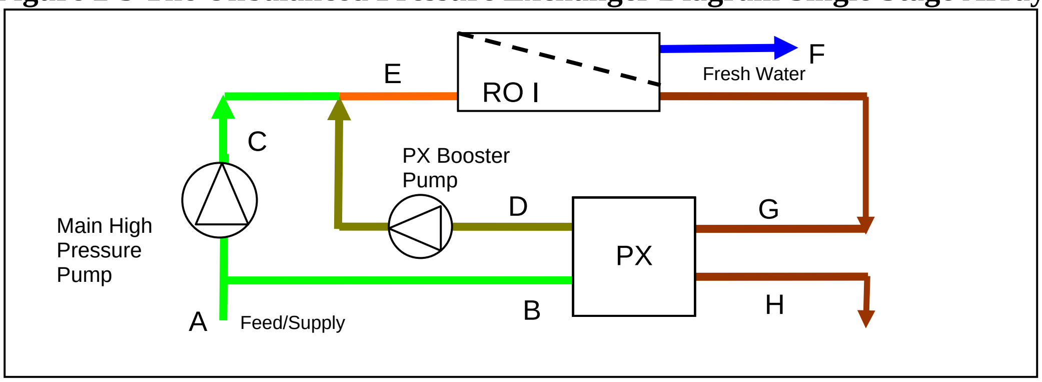


Table 2-4 Unbalanced PX 65/85% Recovery Projection Single Stage Array

		A	B	C	D	E	F	G	H
Flow	gpm	1774	250	1524	775	2299	1500	799	274
	gpd	2,554,560	360,000	2,194,560	1,116,000	3,310,560	2,160,000	1,150,560	394,560
Pressure	PSI	25	25	241	221	241	5	231	10
Quality	mg/l TDS	2,000	2,000	2,000	10,563	4,886	92.0	14,000	14,000
					PX Brine cross flow =		549	gpm	
PX-70		QTY	**4**		Temperature = 25ºC				
PX UNIT FLOW		GPM	200		Flux ~ 13 gfd				
PX Internal Bypass		GPM	24						
Membrane Differential		PSI	10						
RO Recovery		%	65%						
System Recovery		%	85%						
HIGH PRESS. PUMP									
Feed Pump eff		%	90%						
Motor eff		%	93%						
VFD eff		%	97%		Total RO Process (kW)			189.1	
Power		kW	176.2						
BOOSTER PUMP					kWh/m3 Permeate			0.55	
Boost Pump Eff		%	60%		kWh/1000 gal Permeate			2.10	
Motor Eff		%	90%		kWh/acre-ft Permeate			684	
VFD eff		%	97%						
Power		kW	12.9						
Supply/Feed Pump kW			0.0						

Mechanisms associated with this novel mode of operation that might lead to improved performance at higher recoveries include:

- Improved boundary layer conditions by maintaining “high” velocities/flow

- Balanced membrane flux through increased lead element velocities
- Balanced membrane flux through increased lead element salinity
- Minimum brine flow requirements within manufacturers specifications
- Maximum allowable recoveries within manufacturers specifications

Testing this brine recirculation process is straight forward and will be achieved with the ADC Demonstration system in its Optimized Isobaric Energy Recovery Configuration as shown in Figure 2-2 and the detailed P&ID in Appendix A.

2.1.2.1 - Procedure for testing Brine Recirculation Process

Demonstration scale tests of the unbalance PX system will occur over an approximate 6 month period. As presented in Table 2-5, each phase of testing consists of the following:

- Two weeks (weeks 1-2) of "ripening" at a typical flux and recovery rate. This "ripening" period has been included based upon past experience operating new membranes. Experience has indicated that approximately two and one half weeks are required before some new membrane's performance (e.g., pressure and salt rejection) reaches a steady state condition. It is possible that pre-ripened membranes will be used in this test and this period may be shortened or omitted accordingly.
- Four weeks (weeks 3-6) of testing at different system and RO recovery points. Each recovery point will be operated for 1 day. The flux rates will be maintained at a constant 14.9 gallons per square foot of membrane area per day (gfd).
- 2 month demonstration at a single flux and recovery point

As indicated in Tables 2.6, two separate recovery rates will need to be determined and set for this test. These are the RO membrane recovery, which is determined by the PX booster pump flow and the total system recovery, which is determined by the PX LP inlet flow. The applicable equations are as follows:

RO R = $Q_{P\text{-}SYS}$ / $Q_{RO\ feed\ flow}$

System $R = \dfrac{Q_{P-SYS}}{Q_{F-SYS}} * 100$ **Equation 2.4**

$Q_{F-SYS} = Q_{P-SYS} + Q_{REJECT}$ **Equation 2.5**

$Q_{PX-Pump} = Q_{REJECT} + 1.5 gpm\_leakage$ **Equation 2.6**

$Q_{P-SYS} = Q_{F-HP-Pump} - 1.5 gpm\_leakage$ **Equation 2.7**

Where:
R = Recovery, %
$Q_{F\text{-}SYS}$ = RO system feed flow, gpm

$Q_{F\text{-}SYS}$ = $Q_{PX\text{-}HP\text{-}out} + Q_{F\text{-}HP\text{-}Pump}$
$Q_{F\text{-}HP\text{-}Pump}$ = High pressure positive displacement pump flow, gpm
$Q_{PX\text{-}HP\text{-}out}$ = PX High Pressure Outlet, gpm
Q_{Reject} = RO membrane reject flow, gpm

Between each system recovery matrix, the original/ripening flux and recovery (i.e., the flux and recovery tested during weeks 1-2) will be retested to confirm membrane performance at baseline conditions.

Approximately 8 weeks of operating at the RO-System recovery point determined, *through testing*, to 1) meet water quality goals for TDS and 2) results in the most affordable operation, as determined by a net present value analysis or 3) an operating point that best matches the current operating conditions of full scale El Paso plant.

The data gathered from these tests shall be used to develop graphs that show the power consumption rate and water quality that can be achieved at each condition. Power consumption rate shall be measured to include the following electrical loads:

- High Pressure RO Pump (P2)
- PX Booster Pump (P3)

The following will not be included in the power consumption rate measurements

- Intake Lift Pump (P1)
- Chemical Metering Pumps
- Instrumentation and Controls
- Product water pumping
- Pretreatment pumping

While the intake lift pump may provide suction side pressure to the High Pressure Positive Displacement pump, thereby reducing the overall TDH, it will not be included in the power monitoring. For the affordability analysis, an intake pump's horsepower will be assumed based upon flow and a overall lift TDH of 200 ft of H_2O.

Table 2.5 — **Schedule of Testing Conditions**
Brine Recirculation Process for Higher Recovery in two Stage Array
ADC TWDB Desalination Demonstration Project

Parameter	**1-2 Weeks Ripening**	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**
Membrane sq-ft	400						Base Line			
Flux, gfd	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9
RO recovery	80.0%	75.0%	75.0%	75.0%	75.0%	75.0%	80.0%	80.0%	80.0%	80.0%
System Recovery	80.0%	75.0%	80.0%	85.0%	90.0%	95.0%	80.0%	80.0%	85.0%	90.0%
High Pressure RO Pump ($Q_{F\text{-}HP\ Pump}$), gpm	88.4	88.4	88.4	88.4	88.4	88.4	88.4	88.4	88.4	88.4
PX HP Outlet, ($Q_{PX\text{-}HP\text{-}Out}$), gpm	20.2	27.5	27.5	27.5	27.5	27.5	20.2	20.2	20.2	20.2
Permeate ($Q_{P\text{-}SYS}$), gpm	86.9	86.9	86.9	86.9	86.9	86.9	86.9	86.9	86.9	86.9
PX Low Pressure Inlet, gpm	20.2	27.5	20.2	13.8	8.2	3.1	20.2	20.2	13.8	8.2
Concentrate, gpm	21.7	29.0	21.7	15.3	9.7	4.6	21.7	21.7	15.3	9.7
		Base Line				Base Line			Base Line	
-	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**	**Day 15**	**Day 16**	**Day 17**	**Day 18**	**2 Month Demo Point**
Flux, gfd	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	TBD
RO recovery	80.0%	80.0%	85.0%	85.0%	85.0%	80.0%	90.0%	95.0%	80.0%	TBD
System Recovery	95.0%	80.0%	85.0%	90.0%	95.0%	80.0%	90.0%	90.0%	80.0%	TBD
High Pressure RO Pump ($Q_{F\text{-}HP\ Pump}$), gpm	88.4	88.4	88.4	88.4	88.4	88.4	88.4	88.4	88.4	TBD
PX HP Outlet, ($Q_{PX\text{-}HP\text{-}Out}$), gpm	20.2	20.2	13.8	13.8	13.8	20.2	8.2	3.1	20.2	TBD
Permeate ($Q_{P\text{-}SYS}$), gpm	86.9	86.9	86.9	86.9	86.9	86.9	86.9	86.9	86.9	TBD
PX Low Pressure Inlet, gpm	3.1	20.2	13.8	8.2	3.1	20.2	8.2	8.2	20.2	TBD
Concentrate, gpm	4.6	21.7	15.3	9.7	4.6	21.7	9.7	9.7	21.7	TBD

Notes:
1. Maximum system pressure is 600 psi. If any point exceeds 600 psi system will shutdown and point will need to be skipped.
2. Flows assume 400 sq-ft membrane
3. $Q_{F\text{-}HP\ Pump}$ = High pressure positive displacement pump flow = Product flow +1.5 gpm (PX leakage).
4. $Q_{PX\text{-}HP\text{-}Out}$ = PX booster pump flow= Concentrate flow gpm - 1.5 gpm (PX leakage).
5. $Q_{P\text{-}SYS}$ = SWRO system permeate flow.

2.2 Testing Operation and Monitoring

Hydraulic and water quality data will be collected to evaluate the operation of the demonstration scale equipment relative to the project goals for power consumption and treated water quality. These data shall be collected and evaluated by Carollo Engineers, P.C.

Tables 2.6-2.7 presents a matrix for monitoring hydraulic data from the demonstration scale brackish water RO equipment. Hydraulic data collected from this equipment consists of both pressure and flow data. The frequency of monitoring for each type of data is presented based upon the type/phase of operation. In general, data shall be collected once daily or at each individual flux and recovery during the 18 point data matrixes and 3 times per week during the 2 month demonstration phases. When applicable, flow meter calibration shall be checked at least weekly using a graduated bucket and a stop watch.

Hydraulic data shall be recorded in the data spreadsheet presented in Appendix B. The data spreadsheet shall be emailed weekly (i.e., Friday) to Carollo Engineers, P.C. Bradley Sessions (bsessions@carollo.com) and the ADC's, P.C. John MacHarg (johnmacharg@gmail.com) for data evaluation.

Water quality data shall be collected at the locations and frequencies presented in Tables 2.7 and analyzed by the methods presented in Table 2.8. These data shall then be recorded in the the spreadsheet in Appendix B. The data spreadsheet shall be emailed weekly (i.e., Friday) to Carollo Engineers, P.C. Bradley Sessions (bsessions@carollo.com) and the ADC's, P.C. John MacHarg (johnmacharg@gmail.com). One sampling for TOC, iron, manganese, and aluminum from location SC-1 every nine weeks will also be provided.

Table 2.6 Hydraulic Monitoring – Brackish water RO System
ADC TWDB Desalination Demonstration Project

Parameter	Unit	Each Flux/recovery point	Demonstration and Ripening Periods					Data Logger
			Monday	Tuesday	Wednesday	Thursday	Friday	
Pressure								
$P_{MF\text{-}in}$ (PI1)	psig	1x	1x	-	1x	-	1x	
$P_{MF\text{-}out}$ / $P_{CF\text{-}in}$ (PI1)	psig	1x	1x	-	1x	-	1x	
$P_{CF\text{-}out}$ (PI1)	psig	1x	1x	-	1x	-	1x	
$P_{PX\text{-}HP\text{-}out}$ (PI2)	psig	1x	1x	-	1x	-	1x	PT1
$P_{Stage1\text{-}out}$ (PI4)	psig	1x	1x	-	1x	-	1x	PT2
$P_{Stage2\text{-}In}$ (PI4)	psig	1x	1x	-	1x	-	1x	PT2
$P_{Stage2\text{-}out}$ (PI2)	psig	1x	1x	-	1x	-	1x	PT2
$P_{P\text{-}SYS}$ (PI3)	psig	1x	1x	-	1x	-	1x	
Flow								
$Q_{F\text{-}HP\ Pump}$ (FI3)	gpm	1x	1x	-	1x	-	1x	
$Q_{PX\text{-}LP\text{-}IN}$ (FI2)	gpm	1x	1x	-	1x	-	1x	FT2
$Q_{PX\text{-}HP\text{-}Out}$ (FI5)	gpm	1x	1x	-	1x	-	1x	FT5
$Q_{P\text{-}stage1}$ (FI6)	gpm	1x	1x	-	1x	-	1x	FT4
$Q_{P\text{-}stage2}$ (FI7)	kWh	1x	1x	-	1x	-	1x	AM1
$Q_{P\text{-}SYS}$ (FI4)	kWh	1x	1x	-	1x	-	1x	AM1
Power Consumption	kWh	1x	1x	-	1x	-	1x	AM1

Table 2.6 Hydraulic Monitoring – Brackish water RO System
ADC TWDB Desalination Demonstration Project

Parameter	Unit	Each Flux/recovery point	Demonstration and Ripening Periods					Data Logger
			Monday	Tuesday	Wednesday	Thursday	Friday	

Notes:
1. $P_{MF\text{-}in}$ = Pressure on the influent side of the media filters (PI1a)
2. $P_{MF\text{-}out}$ / $P_{CF\text{-}in}$ = Pressure on the effluent side of the media filters / Pressure on the inlet side of the cartridge filters (PI1b)
3. $P_{CF\text{-}out}$ = Pressure on the effluent side of the cartridge filters (PI1c)
4. $P_{PX\text{-}HP\text{-}out}$ = Feed water pressure at the PX high pressure outlet and inlet to Stage 1 membranes (PI2).
5. $P_{Stage1\text{-}out}$ = Stage 1 outlet pressure and PX booster pump inlet pressure (PI2)
6. $P_{Stage2\text{-}in}$ = Stage 2 inlet pressure and PX booster pump outlet pressure (PI2)
7. $P_{Stage2\text{-}out}$ = Stage 2 outlet pressure (PI2)
8. $P_{PX\text{-}LP\text{-}out}$ = Discharge pressure at the PX low pressure outlet, before the system recovery control valve (PI3b)
9. $P_{P\text{-}SYS}$ = RO system permeate pressure
10. $Q_{F\text{-}HP\ Pump}$ = High pressure positive displacement pump flow (FI3)
11. $Q_{PX\text{-}LP\text{-}IN}$ = Low pressure flow into the PX (FI2)
12. $Q_{PX\text{-}HP\text{-}Out}$= High pressure flow out of PX (FI5)
13. $Q_{P\text{-}Stage1}$ = Product flow from stage 1 array
14. $Q_{P\text{-}Stage2}$ = Product flow from stage 2 array
15. $Q_{P\text{-}SYS}$ = RO system permeate flow (FI4)
16. Power consumption will be calculated based on hydraulic data collected. On line measurements are taken from the Amp Meter.
17. Facility monitoring during weeks 3-6 will be required once per day.

Table 2.7 Water Quality Monitoring Brackish Water RO System
ADC TWDB Desalination Demonstration Project

		Each Flux and Recovery Point		Demonstration and Ripening Periods										Data Logger
				Monday		Tuesday		Wednesday		Thursday		Friday		
Parameter	**Unit**	**Location**	**No. of Times**	**Location**	**No. of Times**	**Location**	**No. of Times**	**Location**	**No. of Times**	**Location**	**No. of Times**	**Location**	**No. of Times**	
Temperature	^{o}C (^{o}F)	SC5, SC6, SC11	1x	SC5, SC6, SC11	1x	-	-	SC5, SC6, SC11	1x	-	-	SC5, SC6, SC11	1x	
pH		SC3, SC4, SC5, SC6, SC7, SC11	1x	SC3, SC4, SC5, SC6, SC7, SC11	1x	-	-	SC3, SC4, SC5, SC6, SC7, SC11	1x	-	-	SC3, SC4, SC5, SC6, SC7, SC11	1x	
Conductivity	mS/cm	SC3, SC5, SC6, SC7, SC11, SC12, SC13	1x	SC3, SC5, SC6, SC7, SC11, SC12, SC13	1x	-	-	SC3, SC5, SC6, SC7, SC11, SC12, SC13	1x	-	-	SC3, SC5, SC6, SC7, SC11, SC12, SC13	1x	
Total Dissolved Solids	mg/L	SC3, SC5, SC6, SC7, SC11, SC12, SC13	1x	SC3, SC5, SC6, SC7, SC11, SC12, SC13	1x	-	-	SC3, SC5, SC6, SC7, SC11, SC12, SC13	1x	-	-	SC3, SC5, SC6, SC7, SC11, SC12, SC13	1x	
Turbidity	NTU	Meter	1x	Meter	1x	-	-	Meter	1x	-	-	Meter	1x	NTU1
Silt Density Index		SC3	1x	SC3	1x	-	-	SC3	1x	-	-	SC3	1x	

Notes:
1. NS = No Sample
2. NA = Not applicable (e.g., value calculated)
3. Sample connection numbers per Harn P&ID revision 2, 4-19-05.

Table 2.8 Water Quality Testing Methods
Brackish water RO Demonstration Study
Affordable Desalination Collaboration

Parameter	Method: Seawater	Method: RO Permeate
Temperature, °C	SM 2550	N/A
pH	SM 4500-H^+	SM 4500-H^+
Conductivity, µS/cm	SM 2510	SM 2510
TDS, mg/L	SM 2540C	SM 2540C
Turbidity, NTU	SM 2130	N/A
Silt Density Index	ASTM D4189-95	N/A
Boron, mg/L	EPA 200.7	EPA 200.7
Bromide, mg/L	EPA 300.0	EPA 300.0
Total Organic Carbon, mg/L	SM 5310C	SM 5310C
Iron, mg/L	EPA 200.7	EPA 200.7
Manganese, mg/L	EPA 200.7	EPA 200.7
Aluminum, mg/L	EPA 200.7	EPA 200.7
Calcium, mg/L	EPA 200.7	EPA 200.7
Magnesium, mg/L	EPA 200.7	EPA 200.7
Sodium, mg/L	EPA 200.7	EPA 200.7
Potassium, mg/L	EPA 200.7	EPA 200.7
Alkalinity, mg/L as $CaCO_3$	SM 2320B/EPA 310.1	SM 2320B/EPA 310.1
Carbon Dioxide, mg/L	SM4500-CO2-D	SM4500-CO2-D
Carbonate, mg/L	SM 2320B/EPA 310.1	SM 2320B/EPA 310.1
Bicarbonate, mg/L	SM 2320B/EPA 310.1	SM 2320B/EPA 310.1
Sulfate, mg/L	EPA 300.0	EPA 300.0
Chloride, mg/L	EPA 300	EPA 300.0
Fluoride, mg/L	SM4500F-C	SM4500F-C/EPA 300.0

Notes:
SM = *Standard Methods* for the Examination of Water and Wastewater, 20th Edition
ASTM = American Society for Testing and Materials
N/A = Not applicable

Water quality samples requiring analysis by a local, outside lab shall be shipped to a certified testing laboratory (to be determined).

Samples should be collected in a 125 ml polypropylene bottle, filled to the top with no head space. Preserve samples in accordance with the standards reference in Table 2.16, bubble rapped and shipped in a cooler overnight to the address above. Label sample bottles using a permanent marker with the:

- Location they were collected (e.g., “Raw”, “Feed”, “Permeate”, “PX Booster Pump Discharge”),
- Date collected
- Return authorization number (RA #) provided by lab.

Standard laboratory quality assurance and quality control procedures shall be practiced. Laboratory instruments shall be calibrated in a manner consistent with the Standard or EPA method procedure. Duplicate and blank samples shall be analyzed as required by the testing method. On-line instruments shall be calibrated as recommended by the instrument manufacturer’s specifications.

2.3 Membrane Cleaning & Storage

2.3.1 RO Membranes

Membrane cleaning will be performed if bench-mark testing (i.e., conducted between test during weeks 3-5) indicates a higher differential pressure across the RO system when compared to the initial (Weeks1 through 3) test performance. Membrane cleaning procedures will be per the recommendations of the respective membrane supplier. A summary of cleaning procedures provided by each membrane supplier is provided in Appendix C.

The ADC may conduct more testing at other sites in the future. Membranes shall be stored to ensure that they will be able to perform for these future studies. The following procedures shall be followed for membrane storage:

- Unless the elements have experienced significant performance decline it should not be necessary to clean the elements prior to storage. However, elements will be flushed with stored permeate (in the CIP/suck back tank) until a TDS less than 800 mg/L is recorded from sample location SC5 (Refer to Appendix B).
- If enough stored permeate remains, the CIP tank will be used to flush the membrane elements with a 1 to 1.5% bisulfite solution. If there is not enough stored permeate remaining, upon removal from the pressure vessels, the elements should be drained of excess water by standing on end after removal from the pressure vessel. The elements should then be submerged in a small tank or barrel of 1 to 1.5% sodium bisulfite/permeate solution for a minimum of 1 hour. Distribution of the preservative solution is enhanced if the element is lifted, drained, and re-submerged 2-3 times during the soak time.

- The elements will arrive sealed in oxygen barrier bags that can be reused to store the elements. As much excess air as possible should be removed from the bag prior to sealing it with tape. If possible, bags should be vacuum-sealed.
- For optimal storage conditions the bagged elements should be stored out of direct sunlight at a temperature <25°C.
- For long-term storage, 2 elements should be opened and the pH determined of the residual preservative solution every 2-3 months. If the pH drops below 3, the elements should be re-preserved.

2.4 Determining Affordability

After completion of the variable flux and recovery tests, a present value analysis will be conducted to establish the most affordable operating condition, which accounts for both capital and operations costs.

The criteria presented in Table 2-9 shall be the basis for the present value analysis.

Table 2-9 Present Value Analysis Criteria
Brackish Water RO Demonstration Study
Affordable Desalination Collaboration

Criteria		Value
Project Size		25 MGD
Capital Cost		
	Pretreatment	Media followed by cartridge
	Desalination Plant	To be developed using WTCOST based upon demonstration test condition
Project Life		20 years
Bond Payment Period		20 years
Interest		3.5%
Inflation		3%
Construction Contingencies		15% of capital cost
Contractor OH&P		10% of capital cost
Engineering & Const. Mgmt.		25% of capital cost
Annual Maintenance Costs		1.5% of the capital cost
Power Cost		$0.12 per kWhr
Intake Lift Pump TDH		200 ft H_2O
High Service Pump TDH		200 ft H_2O
Intake/High Service Pump Efficiency		TBD
Intake/High Service Lift Pump Motor Efficiency		TBD

Table 2-9 Present Value Analysis Criteria
Brackish Water RO Demonstration Study
Affordable Desalination Collaboration

Criteria	Value
Membrane Life	5 years
Membrane Element Cost	TBD
No. of Plant Staff and Salary	TBD
Labor overhead multiplier	x 1.75
Cartridge Filter Loading Rate	3 gpm per 10-inches
Cartridge Filter Cost	$3 per 10-inches
Cartridge Filter Life	Determined during demonstration test
Carbon Dioxide Dose	16 mg/L
Carbon Dioxide Cost	$0.04 per pound
Lime Dose	44 mg/L
Lime Cost	$0.05 per pound
Sodium Hypochlorite Dose (post treatment)	1.5 mg/L

NOTES:
1. Includes costs for RO equipment, CIP equipment, building, process electrical and instrumentation, yard piping, post treatment chemical facilities, 5-MG of ground storage and high service pumping.
3. Inflation based upon historic ENR cost index inflation over 50 years. Inflation will be applied annually.
4. Assumes no chlorine demand. 4.6 mg/L of SBS will quench 2 mg/L of Cl_2.

Appendix A

PROCESS AND INSTRUMENTATION DIAGRAMS

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL RELEASE	5-1-09	

P1 SUPPLY PUMP
QTY: 1
FLOW: 70-170 GPM
PRESSURE: 30 PSI MIN.
POWER: 460VAC/60/3PHASE
MOTOR: 10 HP

P2 HP PUMP
QTY: 1
FLOW: 35-90GPM
PRESSURE: 100-1140 PSI
POWER: 460VAC/60/3PHASE
MOTOR: 50 HP

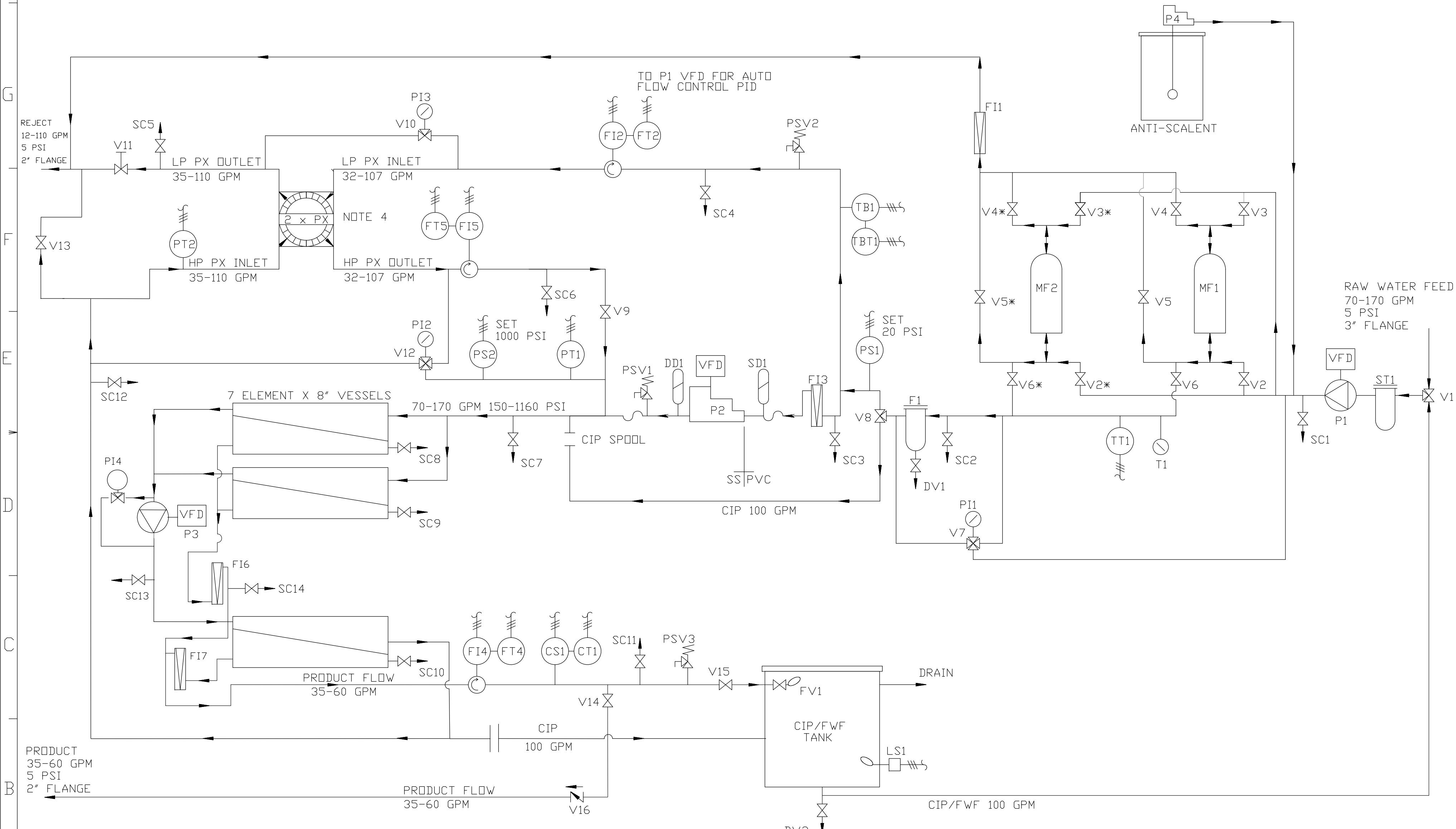
P3 HP PUMP
QTY: 1
30-110 GPM
PRESSURE: 30-50 DELTA PSI
POWER: 460VAC/60/3PHASE
MOTOR: 5 HP

P4 CHEMICAL INJ PUMP
QTY: 1
TBD
PRESSURE: 100 PSI
POWER: 110VAC/60/1PHASE
MOTOR: TBD

MF1/MF2 MEDIA FILTER
QTY: 2
OPERATION: MANUAL
DIA x HIGH: 36" x 72"
M.O.C.: GRP

CARTRIDGE FILTER
QTY: 1
CAPACITY: 200 GPM
M.O.C.: GRP
MFGR: EXCEL

RO VESSELS
QTY: 3
TYPE: 8" X 7 ELEMENT
ARRAY: 2-1



NOTES:

1. MAIN HP PUMP AND PRODUCT FLOW RATE WILL BE ADJUSTABLE USING A VFD DRIVE TO CONTROL THE MAIN HP PUMP. APPROX. HP PUMP FLOW RANGE WILL BE 80-90 GPM.
2. FRESH WATER FLUSH (FWF) IS REQUIRED TO KEEP PRESSURE EXCHANGER AND MEMBRANES FREE OF BIOLOGICAL GROWTH DURING SHUTDOWN. SEE START AND STOP PROCEDURES IN O&M MANUAL.
3. CIP CONNECTION ARE TWO BLIND FLANGES WITH A REMOVABLE PIPE SPOOL.
4. PX MANIFOLD WILL HOLD 2EA, PX-UNITS.

SYSTEM FLOW PARAMETERS (GPM)

	% REC	GFD	FEED	PERM	REJECT
MIN FLOW	85	12	82	70	12
MAX FLOW	75	16	124	93	31
DESIGN FLOW	85	149	102	87	15

ADC
2419 E. Harbor Blvd, Ventura, CA 93001

ADC PILOT PLANT
P&ID DIAGRAM

DRAWN A. BENNETT DATE 5-1-09
CHECKED DATE
APPROVED DATE
ISSUE DATE
CONTRACT NO.
? NEXT HIGHER ASSEMBLY
APPLICATION
SIZE E CAGE NO N/A DWG NO AKB-5109-12 REV 1
SCALE N/A SHEET 1

1 SH REVISION STATUS OF SHEETS
- REV

Appendix B: Data

TIME				CALCULATED PARAMETERS					TEMP	PRESSRE									FLOWS						MAIN PANEL KW METER				VFD KW METER			
		Operation	System	RO	Ave. Sys. Flux	1st Stage Flux	2nd Stage Flux	Power	Influent	P_{CF-in}	P_{CF-out}	$P_{PX-Feed\ In}$	$P_{PX-conc\ out}$	PX-HP out RO 1 fe	$P_{RO\ 2\ feed}$	$P_{C-RO1\ PX\ Booster\ inlet}$	P_{C-RO2}	P_{P-SYS}	$Q_{F-HP\ Pump}$	$Q_{PX\ HP-out}$	$Q_{Feed\ PX-In}$	$Q_{P-Stage\ 1}$	$Q_{P-Stage\ 2}$	Q_{P-SYS}	A_{sys}	P HP/PX	P booster	Power	PX power	HP Power	Feed Pump	
Date	Time	Time	Recovery %	Recovery %	Gfd	Gfd	Gfd	kWh/m3	Temp F	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	amp	(kw)	(kw)	Factor	(kw)	(kw)	(kw)	Notes
MM/DD/YY	hh:mm	hh.hh							17	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**Membrane Ripening Period (BASELINE)**														1							
02/11/10	13:00	12335.8	69.0%	79.7%	14.14	14.91	12.60	0.69	70.0	32.5	30.5	29.0	23.8	175	200	150	178	21.3	80.0	21.00	37.02	58.00	24.50	82.50	19.50	12.90	4.1	0.700	1.70	10.1	3.4	
02/11/10	17:06	12339	74.4%	80.0%	12.09	13.37	9.51	0.59	71.0	31.5	29.7	29.0	26.5	155	170	133.7	158	14.5	70.5	17.62	24.26	52.00	18.50	70.50	14.50	9.48	3.3	0.753	1.10	7.5	2.2	
02/12/10	9:01	12355.1	73.2%	79.9%	14.06	14.91	12.34	0.67	70.5	32.5	30.0	29.2	25.5	175	195	150	178	20.5	80.0	20.64	30.01	58.00	24.00	82.00	19.40	12.54	4.3	0.775	1.60	9.9	3.6	
02/18/10	15:41	12357.5	76.1%	80.5%	14.14	14.91	12.60	0.67	71.0	32.5	30.0	29.2	26.5	170	190	148	172	17.2	80.0	20.02	25.97	58.00	24.50	82.50	19.15	12.49	3.86	0.771	1.60	9.8	2.6	Total product data is calculated.
02/25/10	13:10	12375.3	76.0%	80.2%	14.14	15.04	12.34	0.66	70.0	32.3	30.0	29.3	26.5	171	190	149	172	17.2	81.0	20.40	26.02	58.50	24.00	82.50	18.77	12.40	3.12	0.779	1.60	9.7	2.4	
02/26/10	15:41	124000	76.3%	80.2%	14.23	15.17	12.34	0.66	70.5	32.5	30.0	29.2	26.3	172	190	150	172.5	17.3	80.5	20.50	25.78	59.00	24.00	83.00	18.94	12.52	3.36	0.777	1.60	9.8	1.9	Plant was shut off when arrived due to lo
02/27/10	12:27	12420.7	76.0%	80.0%	14.13	15.04	12.29	0.66	72.0	32.3	30.0	29.3	26.2	172	191	150	175	17.2	81.0	20.66	26.03	58.50	23.90	82.40	19.30	12.29	3.19	0.778	1.60	9.7	1.9	
02/28/10	12:00	12444.2	76.1%	79.9%	14.23	15.17	12.34	0.65	71.5	32.5	30.2	29.3	26.5	172	191	150	175	17.3	80.0	20.93	26.03	59.00	24.00	83.00	19.23	12.27	3.27	0.776	1.50	9.6	2	
03/01/10	14:04	12470.4	76.1%	80.1%	14.13	15.04	12.29	0.65	71.0	32.5	30.0	29.5	26.3	172	191	150	175	17.2	80.0	20.48	25.89	58.50	23.90	82.40	18.86	12.21	3.147	0.787	1.50	9.6	1.8	
03/02/10	12:05	12492.4	76.1%	80.3%	14.23	15.30	12.09	0.65	71.0	32.2	31.0	29.4	26.5	172	191	150	175	17.0	81.0	20.37	26.05	59.50	23.50	83.00	18.76	12.24	3.43	0.784	1.40	9.7	2.2	
03/03/10	15:06	12519.4	75.8%	80.0%	14.09	15.17	11.93	0.65	73.0	32.2	30.1	29.3	26.2	173	191	150	175	17.3	80.0	20.56	26.22	59.00	23.20	82.20	19.44	12.19	3.33	0.780	1.50	9.7	2.1	Vessel 1 is leaking water from end cap
03/04/10	12:21	12540.6	76.0%	79.9%	14.19	15.30	11.98	0.65	73.0	32.5	30.2	29.3	26.3	172	191	150	176	17.2	81.0	20.84	26.12	59.50	23.30	82.80	19.28	12.27	3.44	0.784	1.50	9.7	2.3	
03/05/10	14:25	12563.8	75.8%	79.9%	14.23	15.38	11.93	0.66	73.0	32.5	30.0	29.2	29.2	172	191	150	177	17.3	80.0	20.94	26.54	59.80	23.20	83.00	18.88	12.37	3.14	0.790	1.50	9.8	1.6	Plant was shut off when arrived due to lo
03/06/10	11:20	12584.8	76.1%	80.1%	14.14	15.17	12.09	0.65	73.0	32.3	29.9	29.4	26.3	174	192	151	178	17.4	80.0	20.51	25.95	59.00	23.50	82.50	18.60	12.22	3.11	0.783	1.50	9.7	1.8	
03/07/10	13:42	12611.1	75.7%	79.7%	14.09	15.17	11.93	0.65	74.0	32.5	30.1	29.3	26.2	174	192	150	178	17.3	80.0	20.97	26.34	59.00	23.20	82.20	18.89	12.21	3.15	0.782	1.50	9.7	1.7	
03/08/10	15:20	12636.8	76.0%	80.2%	14.40	15.43	12.34	0.64	73.0	32.5	30.0	29.2	26.3	175	193	151	179	17.2	79.0	20.74	26.49	60.00	24.00	84.00	18.44	12.28	3.36	0.784	1.40	9.8	1.9	
03/09/10	14:02	12659.5	76.2%	80.4%	14.38	15.43	12.29	0.64	73.0	33.0	30.1	29.4	26.2	175	193	151	179	17.1	80.0	20.48	26.23	60.00	23.90	83.90	18.66	12.25	3.25	0.784	1.50	9.7	1.8	
03/10/10	12:55	12681.7	76.5%	80.3%	14.57	15.69	12.34	0.64	71.0	32.5	29.9	29.3	26.1	176	194	152	178	17.1	80.0	20.90	26.04	61.00	24.00	85.00	18.95	12.30	3.36	0.773	1.50	9.7	1.9	
03/16/10	15:50	12705.8	76.3%	80.6%	14.71	16.71	10.70	0.67	70.0	32.8	30.1	29.2	26.5	179	196	158	180	18.0	88.0	20.66	26.60	65.00	20.80	85.80	19.89	13.07	2.7	0.775	1.40	10.6	1	Plant start up after replacing old rotor an
03/26/10	16:18	12718.1	75.8%	79.7%	14.43	16.51	10.29	0.70	74.0	32.2	30.0	29.5	26.5	186	207	162	190	17.6	87.0	21.45	26.88	64.20	20.00	84.20	20.06	13.47	2.722	0.782	1.50	10.8	0.8	plant start up after new filters, cleaned o
03/27/10	16:20	12720.45	72.2%	79.7%	13.89	16.20	9.26	0.67	72.0	31.0	28.0	29.2	25.8	182	200	165	188	17.5	85.0	20.68	31.13	63.00	18.00	81.00	18.85	12.27	2.566	0.773	1.20	10.1	1	Cartridge Filget Pressure Gause has a cra
04/02/10	15:26	12726	67.1%	71.3%	12.17	12.86	10.80	0.62	72.0	32.2	30.0	29.3	25.0	142	171	120	149	15.0	73.0	28.64	34.88	50.00	21.00	71.00	15.41	9.92	2.7	0.765	2.00	6.9	1.1	
04/02/10	17:50	12728.4	61.2%	71.0%	12.17	12.86	10.80	0.61	72.0	33.0	30.2	29.0	22.0	141	170	119	145	15.0	73.0	28.93	45.04	50.00	21.00	71.00	15.32	9.81	2.723	0.765	2.00	6.8	1.2	
04/08/10	14:43	12731.8	62.0%	71.8%	12.17	12.86	10.80	0.60	73.0	32.9	30.2	29.3	22.5	135	165	111	140	10.7	74.0	27.88	43.53	50.00	21.00	71.00	15.14	9.64	2.69	0.768	2.10	6.6	1.1	
04/09/10	15:00	12740.1	62.1%	72.4%	12.26	12.86	11.06	0.60	75.0	32.9	30.1	29.2	22.5	135	165	111	139	11.0	73.0	27.23	43.61	50.00	21.50	71.50	15.50	9.70	3.921	0.752	2.00	6.6	3.2	
04/10/10	12:00	12761.2	62.1%	71.6%	12.26	12.86	11.06	0.60	75.0	32.8	30.2	29.3	22.7	136	165	111	139	10.9	74.0	28.42	43.61	50.00	21.50	71.50	15.32	9.68	3.709	0.754	2.10	6.6	2.9	
04/11/10	13:11	12786.3	62.0%	71.7%	12.27	12.86	11.11	0.60	76.0	32.9	30.3	29.2	23.3	135	165	111	139	11.0	73.0	28.21	43.85	50.00	21.60	71.60	16.19	9.71	3.14	0.753	2.10	6.6	2.8	
04/12/10	17:07	12814.3	62.1%	71.5%	12.26	12.86	11.06	0.60	77.0	32.9	30.3	29.2	22.5	135	165	111	140	11.1	73.0	28.49	43.68	50.00	21.50	71.50	14.90	9.78	3.649	0.751	2.20	6.7	2.9	
04/21/10	15:33	12833	62.2%	71.7%	12.26	12.86	11.06	0.59	76.0	32.9	30.3	29.3	22.6	130	160	108	135	11.2	73.0	28.17	43.37	50.00	21.50	71.50	14.85	9.55	3.344	0.756	2.10	6.4	2.5	
04/23/10	15:50	12853.3	62.6%	70.6%	12.31	12.86	11.21	0.60	70.0	33.0	30.3	29.5	22.8	131	161	109	136	11.3	73.0	29.94	42.98	50.00	21.80	71.80	15.59	9.74	3.915	0.750	2.20	6.6	2.7	
04/24/10	11:38	12873.1	62.5%	71.1%	12.31	12.93	11.06	0.59	73.0	32.9	30.2	29.4	22.6	131	161	109	136	11.2	73.0	29.16	43.11	50.30	21.50	71.80	15.64	9.65	3.883	0.750	2.10	6.5	2.7	
04/25/10	10:55	12896.4	62.5%	71.4%	12.34	13.11	10.80	0.59	74.0	33.0	30.2	29.3	22.6	131	161	109	138	11.0	73.0	28.84	43.22	51.00	21.00	72.00	15.47	9.60	3.808	0.750	2.20	6.5	2.7	
04/26/10	17:11	12926.2	62.1%	71.6%	12.17	12.86	10.80	0.59	78.0	32.9	30.3	29.5	22.7	131	161	109	138	11.0	73.0	28.13	43.41	50.00	21.00	71.00	15.15	9.56	3.768	0.746	2.10	6.5	2.6	
04/27/10	13:32	12946.5	62.8%	72.0%	12.53	13.11	10.75	0.57	75.0	32.9	30.3	29.4	22.5	132	162	109	138	11.3	74.0	28.37	43.26	51.00	20.90	73.10	14.94	9.46	3.254	0.755	2.10	6.4	1.7	New flow rate/totalizer fixed and registe
04/28/10	16:24	12973.4	71.4%	79.8%	14.18	15.69	10.18	0.60	78.0	32.9	30.2	29.5	25.1	159.0	178.0	137.0	161.0	14.3	85.0	20.87	33.16	61.0	19.8	82.70	18.10	11.24	3.513	0.765	1.40	8.8	2.4	Adjusted flows to baseline 80% recovery
04/29/10	12:25	12993.4	71.3%	80.0%	14.21	15.94	9.93	0.60	76.0	33.0	30.2	29.4	25.3	160.1	180	138	163	13.8	84.5	20.68	33.29	62.00	19.30	82.90	17.75	11.31	3.457	0.769	1.40	8.9	2.3	
04/30/10	17:02	13017.5	71.3%	79.8%	14.16	16.20	9.51	0.60	72.0	33.0	30.3	29.4	25.2	162.0	180.0	141.0	165.0	11.5	84.5	20.88	33.20	63.00	18.5	82.60	17.10	11.28	2.814	0.769	1.30	9.0	1.1	
05/01/10	12:09	13036.6	71.4%	79.8%	14.14	16.25	9.41	0.60	73.0	32.8	30.1	29.5	25.2	167.0	183.0	144.0	170.0	13.8	84.5	20.86	33.10	63.20	18.3	82.50	16.85	11.27	2.524	0.772	1.30	8.9	0.8	
05/02/10	13:07	13061.6	71.2%	79.4%	14.09	16.28	9.21	0.60	74.0	32.9	30.0	28.8	24.5	168.0	185.0	145.0	170.0	13.8	84.5	21.33	33.18	63.30	17.9	82.20	17.66	11.27	2.94	0.770	1.30	9.0	1.6	
05/03/10	17:06	13089.6	71.2%	79.6%	14.18	16.35	9.05	0.60	76.0	33.0	30.0	29.4	25.0	168.0	186.0	145.0	170.0	13.6	84.5	21.22	33.38	63.60	17.6	82.70	17.26	11.25	2.487	0.772	1.30	9.8	0.8	
05/05/10	16:00	13112.6	70.9%	79.8%	14.14	16.38	9.15	0.60	77.0	34.5	32.0	31.0	27.0	168.0	185.0	145.0	170.0	13.8	84.0	20.86	33.91	63.70	17.8	82.50	16.50	11.28	2.52	0.781	1.30	9.1	1.2	
05/06/10	16:32	13137.2	70.3%	79.6%	14.07	16.41	8.85	0.60	78.0	35.0	32.2	31.0	26.8	169.0	186.0	145.0	171.0	14.0	84.0	21.10	34.74	63.80	17.2	82.10	17.42	11.27	2.473	0.781	1.30	8.9	0.9	
05/07/10	15:03	13155.8	71.2%	79.6%	14.14	16.46	8.85	0.59	79.0	33.2	30.1	29.5	25.1	161.0	180.0	139.0	165.0	6.1	84.5	21.17	33.38	64.00	17.2	82.50	16.34	11.02	2.537	0.785	1.30	8.7	1	Pressures reflect permeate deflection to p
05/08/10	13:15	13178	71.2%	79.7%	14.09	16.71	8.74	0.59	76.0	33.0	30.2	29.5	25.3	162.0	181.0	140.0	165.0	5.7	85.0	20.98	33.19	65.00	17.0	82.20	16.92	11.06	2.598	0.774	1.20	8.8	1.1	
05/09/10	14:06	13202.8	71.1%	79.1%	14.13	16.53	8.69	0.59	79.0	33.1	30.1	29.4	25.2	161.0	181.0	140.0	166.0	5.8	85.0	21.76	33.44	64.30	16.9	82.40	15.61	11.02	2.45	0.776	1.30	8.7	0.9	
05/10/10	17:44	13230.5	71.2%	79.2%	14.09	16.66	8.38	0.59	79.0	33.2	30.1	29.6	25.2	162.0	181.0	141.0	167.0	5.9	84.5	21.64	33.29	64.80	16.3	82.20	15.53	11.06	2.508	0.776	1.30	8.8	0.9	
05/11/10	14:52	13251.6	71.2%	79.1%	14.11	16.71	8.33	0.59	79.0	33.3	30.2	29.4	25.2	163.0	182.0	141.0	168.0	5.7	84.0	21.68	33.21	65.00	16.2	82.30	16.10	11.04	2.597	0.779	1.20	8.9	1.1	
05/12/10	16:00	13276.7	71.3%	79.4%	14.13	16.84	8.28	0.59	77.0	33.5	30.3	29.5	25.2	165.0	182.0	142.0	168.0	5.8	84.3	21.42	33.20	65.50	16.1	82.40	17.17	11.10	2.62	0.778	1.20	8.8	1.1	
05/13/10	14:20	13299.2	71.1%	79.2%	14.09	16.92	8.18	0.60	78.0	33.7	30.2	29.5	25.1	165.0	183.0	142.0	169.0	5.7	84.0	21.55	33.41	65.80	15.9	82.20	17.28	11.13	2.971	0.773	1.20	8.8	1.6	
05/20/10	12:18	13327	70.8%	79.6%	14.11	15.22	11.31	0.58	78.0	32.8	30.2	29.3	25.0	151.0	171.0	129.0	154.0	5.8	85.0	21.05	33.96	59.20	22.0	82.30	17.01	10.92	2.922	0.773	1.50	8.4	2.1	Data reflects 19 hrs running after cleanin
05/22/10	12:49	13360.4	72.4%	80.8%	14.85	16.41	11.52	0.61	79.0	33.0	30.2	29.3	25.2	160.0	179.0	138.0	162.0	6.8	88.0	20.53	33.03	63.80	22.4	86.60	17.90	11.91	2.905	0.774	1.40	9.3	2	
05/23/10	13:39	13385.2	72.2%	81.0%	14.86	16.38	11.42	0.60	79.0	33.1	30.2	29.2	25.1	161.0	180.0	138.0	163.0	6.7	88.0	20.32	33.31	63.70	22.2	86.70	18.02	11.88	2.513	0.781	1.50	9.4	1.4	
05/24/10	12:32	13408.1	72.4%	81.1%	14.85	16.46	11.42	0.61	78.0	33.1	30.2	29.4	25.0	161.0	180.0	138.0	164.0	6.8	88.0	20.20	33.01	64.00	22.2	86.60	17.71	11.93	2.593	0.781	1.40	9.4	1.3	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**12 gfd flux**																					
05/25/10	12:40	13432.2	70.9%	81.2%	12.10	13.89	8.23	0.50	78.0	32.0	29.9	29.3	26.0	138	151	120	139	3.5	71.7	16.36	28.92	54.00	16.00	70.6	11.08	7.96	2.105	0.740	0.80	6.1	0.9	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**BASELINE**																					
05/26/10	12:00	13455.5	72.0%	80.8%	14.88	16.46	11.31	0.61	79.0	33.1	30.2	29.5	25.1	162	181	139	165	6.9	88.1	20.60	33.75	64.00	22.00	86.8	17.67	12.05	2.612	0.786	1.50	9.5	1.4	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux**																					

TIME				CALCULATED PARAMETERS					TEMP	PRESSRE									FLOWS						MAIN PANEL KW METER				VFD KW METER			
		Operation	System	RO	Ave. Sys. Flux	1st Stage Flux	2nd Stage Flux	Power	Influent	P_{CF-in}	P_{CF-out}	$P_{PX-Feed\ In}$	$P_{PX-conc\ out}$	$P_{X-HP\ out\ RO\ 1\ fe}$	$P_{RO\ 2\ feed}$	$P_{C-RO1\ PX\ Booster\ inlet}$	P_{C-RO2}	P_{P-SYS}	$Q_{F-HP\ Pump}$	$Q_{PX\ HP-out}$	$Q_{Feed\ PX-In}$	$Q_{P-Stage\ 1}$	$Q_{P-Stage\ 2}$	Q_{P-SYS}	A_{sys}	P HP/PX	P booster	Power	PX power	HP Power	Feed Pump	
Date	Time	Time	Recovery %	Recovery %	Gfd	Gfd	Gfd	kWh/m3	Temp F	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	amp	(kw)	(kw)	Factor	(kw)	(kw)	(kw)	Notes
MM/DD/YY	hh:mm	hh.hh							17	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**BASELINE**																					
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**16 gfd flux**																					
05/27/10	9:19	13476.8	72.9%	81.5%	15.98	20.47	12.34	0.66	78.0	33.5	30.2	29.5	24.9	177	197	150	180	8.5	95.0	21.20	34.56	79.60	24.00	93.2	20.65	13.98	3.374	0.793	1.70	11.2	2.6	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**BASELINE**																					
05/27/10	19:05	13486.6	72.4%	80.8%	14.88	16.46	10.95	0.61	79.0	33.1	30.2	29.5	25.1	163	182	140	168	6.7	88.1	20.57	33.09	64.00	21.30	86.8	15.39	11.98	2.984	0.765	1.40	9.5	2	
05/29/10	11:37	13508.1	72.5%	80.8%	14.90	16.59	10.90	0.61	80.0	33.0	0.2	29.4	25.2	164	183	141	178	7.0	88.3	20.64	32.90	64.50	21.20	86.9	16.89	12.03	2.779	0.776	1.40	9.4	1.7	
05/30/10	11:40	13532.2	72.4%	80.8%	14.86	16.51	10.80	0.61	80.0	33.1	30.2	29.6	25.1	165	184	141	178	6.9	88.2	20.55	33.04	64.20	21.00	86.7	17.38	12.10	2.882	0.776	1.40	9.5	1.9	
05/31/10	11:00	13555.5	72.4%	81.2%	14.86	16.71	10.75	0.61	79.0	33.0	30.1	29.4	25.1	166	185	141	170	7.0	88.0	20.13	33.07	65.00	20.90	86.7	17.97	12.09	2.997	0.777	1.40	9.6	2.1	
06/01/10	12:01	13580.5	72.4%	80.8%	14.85	16.84	10.59	0.62	79.0	33.0	30.2	29.3	25.0	168	185	142	171	6.9	88.0	20.64	33.08	65.50	20.60	86.6	20.90	12.15	2.762	0.770	1.40	9.6	1.7	
06/02/10	13:00	13605.5	72.4%	81.1%	14.86	16.92	10.39	0.62	80.0	33.2	30.1	29.3	25.0	168	187	143	171	7.2	88.2	20.23	33.13	65.80	20.20	86.7	20.07	12.19	3.092	0.776	1.40	9.6	2.2	
06/03/10	12:25	13628.9	72.4%	80.8%	14.90	16.97	10.29	0.62	79.5	33.1	30.2	29.3	25.1	168	187	142	172	7.0	88.0	20.67	33.15	66.00	20.00	86.9	20.49	12.20	2.761	0.777	1.40	9.7	1.7	
06/05/10	13:24	13653.6	72.0%	80.5%	14.86	16.97	10.23	0.62	81.0	33.1	30.2	29.5	25.1	168	186	142	171	6.9	88.1	20.95	33.68	66.00	19.90	86.7	15.89	12.13	3.41	0.777	1.40	9.7	2.6	
06/06/10	13:24	13677.6	72.1%	80.3%	14.81	16.97	10.13	0.62	81.0	33.2	30.1	29.3	25.0	169	187	143	171	7.0	88.0	21.19	33.49	66.00	19.70	86.4	17.18	12.15	2.941	0.786	1.40	9.7	2.1	
06/07/10	12:32	13700.7	72.3%	80.8%	14.85	17.10	9.87	0.62	80.0	33.1	30.1	29.4	25.0	170	188	145	172	7.2	88.0	20.54	33.25	66.50	19.20	86.6	19.95	12.19	3.196	0.784	1.40	9.6	2.6	
06/08/10	12:00	13724.2	72.2%	80.6%	14.81	17.13	9.77	0.62	80.0	33.2	30.1	29.4	25.1	170	189	146	172	7.2	88.0	20.73	33.34	66.60	19.00	86.4	18.97	12.26	3.376	0.788	1.30	9.8	2.7	
06/09/10	11:03	13747.2	72.2%	80.6%	14.85	17.23	9.67	0.62	80.5	33.3	30.2	29.2	25.0	171	189	147	175	7.0	88.1	20.89	33.40	67.00	18.80	86.6	18.77	12.27	3.363	0.784	1.30	9.8	2.7	
06/10/10	11:00	13771.2	72.0%	80.8%	14.88	17.31	9.46	0.62	80.0	33.5	30.3	29.4	25.1	172	190	148	175	7.2	88.1	20.69	33.74	67.30	18.40	86.8	18.91	12.32	3.442	0.780	1.40	9.8	2.6	
06/12/10	12:30	13796.5	72.2%	81.2%	14.88	17.33	9.41	0.62	80.0	33.5	30.3	29.5	25.0	172	190	148	175	7.0	88.0	20.09	33.50	67.40	18.30	86.8	19.48	12.27	3.527	0.783	1.30	9.8	2.8	
06/13/10	16:07	13824.2	72.1%	80.2%	14.81	17.49	9.26	0.63	80.0	33.8	30.1	29.5	25.0	173	191	149	176	7.0	88.0	21.30	33.39	68.00	18.00	86.4	18.66	12.34	3.538	0.781	1.30	9.9	2.7	
06/15/10	12:16	13862.6	71.9%	80.5%	14.79	17.54	8.85	0.62	80.0	34.0	30.1	29.3	25.2	174	191	150	178	7.0	88.0	20.84	33.78	68.20	17.20	86.3	19.78	12.22	3.373	0.782	1.30	9.9	2.8	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**12 gfd flux 75% Recovery**																					
06/16/10	11:40	13886	67.4%	76.2%	12.05	14.27	7.30	0.53	80.0	33.0	30.5	29.4	25.0	141	160	121	145	3.5	71.8	21.90	33.94	55.50	14.20	70.3	12.82	8.38	2.795	0.756	1.10	6.3	2.1	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 75% Recovery**																					
06/17/10	12:18	13910.7	67.5%	75.9%	14.90	17.23	9.82	0.66	80.0	35.0	30.6	29.4	24.0	171	196	143	176	7.0	88.0	27.53	41.76	67.00	19.10	86.9	19.35	12.95	4.169	0.787	1.90	9.8	3.8	Raw water feed pressure very low about
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**16 gfd flux 75% Recovery**																					
06/18/10	8:39	13931	66.7%	75.9%	16.03	18.46	11.26	0.72	79.5	36.0	30.8	29.3	21.0	182	212	150	189	8.1	94.5	29.73	46.66	71.80	21.90	93.5	22.70	15.26	4.615	0.809	2.50	11.7	4.8	Raw water feed pressure very low about
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**BASELINE**																					
06/22/10	11:38	13972.7	72.5%	81.1%	14.88	17.74	8.38	0.63	81.0	35.2	30.1	29.3	25.0	178	195	154	180	7.1	88.2	20.21	32.94	69.00	16.30	86.8	19.41	12.45	3.07	0.782	1.30	10.1	2.5	
06/23/10	12:32	13997.6	71.5%	81.0%	14.86	18.26	7.66	0.64	81.0	35.3	30.2	29.4	25.1	188	203	165	190	7.0	88.3	20.34	34.50	71.00	14.90	86.7	19.23	12.64	2.474	0.787	1.10	10.3	1.6	Main plant switched one well 97 to 512,
06/24/10	22:48	14019.3	71.6%	80.8%	14.81	18.44	7.66	0.65	80.0	35.3	30.1	29.5	25.0	190	208	169	192	7.0	88.1	20.54	34.27	71.70	14.90	86.4	19.25	12.85	2.748	0.785	1.20	10.6	1.9	
06/26/10	12:17	14042.0	71.5%	80.9%	14.85	18.49	7.66	0.65	80.0	35.5	30.2	29.2	24.8	190	208	169	192	6.9	88.3	20.50	34.48	71.90	14.90	86.6	20.25	12.84	2.483	0.783	1.10	10.7	1.7	
06/29/10	11:46	14073.6	71.4%	80.9%	14.85	18.51	7.20	0.67	79.0	35.1	30.1	29.3	24.8	200	215	179	202	7.0	88.4	20.48	34.65	72.00	14.00	86.6	19.94	13.12	3.135	0.778	1.10	10.9	2.6	
06/30/10	11:32	14096.1	71.4%	81.1%	14.86	18.62	7.10	0.67	79.0	35.2	30.1	29.4	24.9	200	217	180	203	7.1	88.2	20.25	34.78	72.40	13.80	86.7	20.39	13.15	2.889	0.778	1.00	11.1	2.6	
07/07/10	11:34	14119.9	71.4%	81.1%	14.83	18.51	7.61	0.66	79.0	35.1	30.2	29.2	24.7	195	211	173	198	7.0	88.2	20.22	34.60	72.00	14.80	86.5	20.02	13.03	3.18	0.782	1.10	10.8	2.5	
07/08/10	10:47	14143.2	71.3%	81.1%	14.90	18.21	7.97	0.63	78.0	34.9	30.2	29.4	24.8	181	198	160	183	7.1	88.1	20.23	34.92	70.80	15.50	86.9	18.91	12.45	2.918	0.791	1.20	10.2	2.2	
07/10/10	15:00	14182.8	71.4%	80.6%	14.85	18.08	7.97	0.64	78.0	34.8	30.2	29.3	24.9	181	199	160	185	7.1	88.0	20.84	34.72	70.30	15.50	86.6	19.36	12.53	3.132	0.780	1.20	10.2	2.6	
07/11/10	10:26	14202.3	71.0%	80.6%	14.86	18.00	7.87	0.63	78.0	34.8	30.2	29.2	24.7	181	199	159	184	7.0	88.0	20.93	35.34	70.00	15.30	86.7	18.90	12.46	3.106	0.784	1.20	10.3	2.6	
07/13/10	12:17	14252.1	71.0%	80.8%	14.90	18.00	7.97	0.63	79.0	34.8	30.2	29.2	24.5	180	198	159	182	5.9	88.1	20.71	35.53	70.00	15.50	86.9	19.28	12.44	3.111	0.786	1.20	10.2	2.7	
07/14/10	12:12	14276.0	71.9%	80.2%	14.86	18.00	7.97	0.63	80.0	34.8	30.1	29.2	25.0	180	198	158	182	5.8	88.0	21.41	33.95	70.00	15.50	86.7	19.04	12.40	3.084	0.784	1.10	10.1	2.4	
07/15/10	12:14	14300.1	71.6%	80.7%	14.85	18.00	8.02	0.63	80.0	34.8	30.3	29.2	25.0	181	198	159	182	5.5	88.0	20.77	34.30	70.00	15.60	86.6	18.74	12.43	2.984	0.786	1.10	10.1	2.4	
07/17/10	12:10	14324.6	71.9%	80.8%	14.85	18.00	7.97	0.63	80.0	34.7	30.2	29.4	25.0	180	198	158	182	5.7	88.4	20.53	33.92	70.00	15.50	86.6	18.74	12.44	3.125	0.782	1.10	10.3	2.6	
07/18/10	12:32	14348.9	71.8%	80.9%	14.83	18.00	7.97	0.63	80.0	34.5	30.2	29.6	25.0	180	198	159	182	5.5	88.2	20.48	34.00	70.00	15.50	86.5	20.15	12.43	3.112	0.782	1.20	10.2	2.5	
07/19/10	12:02	14372.5	71.7%	80.6%	14.81	18.26	7.77	0.63	80.0	34.8	30.1	29.3	25.0	180	197	159	183	5.5	88.2	20.73	34.16	71.00	15.10	86.4	18.93	12.40	3.193	0.784	1.10	10.1	2.6	
07/20/10	12:00	14396.4	71.7%	80.5%	14.81	18.13	7.87	0.63	79.0	34.7	30.2	29.3	25.0	180	198	159	182	5.8	88.3	20.90	34.08	70.50	15.30	86.4	18.54	12.41	2.934	0.786	1.20	10.2	2.3	
07/21/10	12:26	14420.8	71.7%	81.0%	14.83	18.00	7.82	0.63	80.0	34.6	30.3	29.3	24.9	180	198	159	183	5.7	88.4	20.27	34.16	70.00	15.20	86.5	18.59	12.39	3.06	0.785	1.20	10.2	2.5	
07/22/10	12:30	14444.9	71.7%	80.7%	14.83	18.00	7.82	0.63	80.0	34.9	30.2	29.4	25.0	180	198	159	184	5.8	88.3	20.63	34.10	70.00	15.20	86.5	18.95	12.35	3.857	0.789	1.10	10.2	2.6	
07/25/10	13:30	14492.0	72.0%	80.7%	14.85	18.00	7.82	0.63	79.0	34.7	30.2	29.3	24.9	180	197	158	182	5.6	88.4	20.68	33.72	70.00	15.20	86.6	18.76	12.37	3.915	0.776	1.10	10.1	3.5	
07/27/10	12:10	14537.9	71.8%	81.0%	14.85	18.13	7.87	0.63	77.0	34.8	30.2	29.5	24.9	180	197	158	182	5.8	88.2	20.30	34.02	70.50	15.30	86.6	19.40	12.41	3.838	0.780	1.20	10.1	3.4	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**12 gfd flux 85% Recovery**																					
07/28/10	12:44	14560.6	74.7%	86.4%	12.00	15.38	4.27	0.52	80.0	33.0	29.9	29.5	27.0	161	170	148	162	3.0	71.3	11.03	23.76	59.80	8.30	70	12.77	8.20	2.896	0.754	0.40	6.9	1.9	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 85% Recovery**																					
07/29/10	13:48	14584.9	74.8%	86.2%	14.88	18.57	6.27	0.63	80.0	34.3	30.2	29.2	26.0	190	201	171	192	6.8	89.0	13.92	29.22	72.20	12.20	86.8	19.05	12.37	3.21	0.780	0.70	10.6	2.8	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**16 gfd flux 85% Recovery**																					
07/30/10	12:15	14607.4	73.1%	85.9%	16.01	20.06	7.10	0.67	80.0	35.0	30.5	29.3	24.8	201	213	181	204	7.5	94.2	15.35	34.31	78.00	13.80	93.4	21.93	14.23	3.691	0.789	0.90	12.3	3.5	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**BASELINE**																					
07/31/10	14:07	14633.3	71.3%	81.0%	14.85	18.26	7.71	0.63	78.0	34.9	**30.3**	29.5	24.8	181	198	160	185	5.8	88.2	20.36	34.80	71.00	15.00	86.6	19.29	12.42	2.723	0.786	1.20	10.2	1.8	
08/01/10	14:10	14657.3	71.5%	81.1%	14.95	18.26	7.71	0.63	78.0	35.0	**30.2**	29.3	24.9	181	199	160	187	5.8	88.2	20.30	34.73	71.00	15.00	87.2	19.34	12.49	2.684	0.785	1.20	10.3	1.8	
08/02/10	11:48	14678.9	71.3%	80.6%	14.88	18.13	7.71	0.63	78.0	34.9	**30.2**	29.4	24.9	181	199	160	185	6.0	88.0	20.89	34.98	70.50	15.00	86.8	19.19	12.46	2.554	0.785	1.20	10.2	1.7	
08/03/10	12:55	14704.0	71.5%	81.1%	14.91	18.26	7.77	0.63	78.0	35.0	**30.1**	29.2	24.8	181	199	160	185	6.0	88.0	20.21	34.75	71.00	15.10	87	19.51	12.43	2.546	0.784	1.20	10.2	1.8	
08/04/10	12:06	14727.2	71.4%	80.5%	14.93	18.00	7.71	0.63	79.0	34.9	**30.1**	29.3	24.8	182	199	160	186	5.9	88.2	21.05	34.97	70.00	15.00	87.1	18.74	12.48	2.853	0.787	1.20	10.2	1.8	
08/05/10	12:23	14751.5	71.4%	80.5%	14.90	18.00	7.66	0.63	79.0	35.0	**30.2**	29.1	24.8	182	199	160	185	6.0	88.0	21.10	34.85	70.00	14.90	86.9	18.92	12.49	2.698	0.786	1.20	10.2	1.5	
08/07/10	14:13	14775.2	71.4%	81.0%	14.85	18.00	7.71	0.62	79.0	34.9	**30.1**	29.3	25.0	180	198	158	181	5.7	88.1	20.30	34.66	70.00	15.00	86.6	18.57	12.24	2.858	0.786	1.10	10.0	1.9	
08/08/10	12:57	14798.0	71.1%	80.6%	14.78	17.74	7.71	0.63	79.0	34.9	**30.2**	29.3	24.9	180	198	158	182	5.9	88.2	20.75	34.96	69.00	15.00	86.2	18.73	12.28	3.062	0.781	1.20	10.0	2.3	

TIME				CALCULATED PARAMETERS					TEMP	PRESSRE									FLOWS						MAIN PANEL KW METER				VFD KW METER			
					Ave. Sys.	1st Stage	2nd Stage																							HP	Feed	
		Operation	System	RO	Flux	Flux	Flux	Power	Influent	P_{CF-in}	P_{CF-out}	$P_{PX-Feed\ In}$	$P_{PX-conc\ out}$	$P_{X-HP\ out\ RO\ 1}$	$P_{RO\ 2\ feed}$	$P_{C-RO1\ PX\ Booster\ inlet}$	P_{C-RO2}	P_{P-SYS}	$Q_{F-HP\ Pump}$	$Q_{PX\ HP-out}$	$Q_{Feed\ PX-In}$	$Q_{P-Stage\ 1}$	$Q_{P-Stage\ 2}$	Q_{P-SYS}	A_{sys}	P HP/PX	P booster	Power	PX power	Power	Pump	
Date	Time	Time	Recovery %	Recovery %	Gfd	Gfd	Gfd	kWh/m3	Temp F	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	amp	(kw)	(kw)	Factor	(kw)	(kw)	(kw)	Notes
MM/DD/YY	hh:mm	hh.hh							17	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
08/09/10	10:45	14819.8	77.7%	81.1%	14.81	18.00	7.66	0.62	78.0	35.0	**30.1**	29.4	24.9	180	198	158	182	5.7	88.0	20.20	24.74	70.00	14.90	86.4	18.78	12.26	3.007	0.783	1.10	10.1	2	
08/11/10	12:27	14868.9	71.3%	80.4%	14.88	18.00	7.71	0.63	79.0	35.1	**30.3**	29.3	25.0	180	199	159	181	5.8	89.0	21.22	34.95	70.00	15.00	86.8	19.07	12.38	3.034	0.780	1.20	10.1	2.1	
08/12/10	12:58	14893.4	71.3%	80.9%	14.86	18.00	7.66	0.63	79.0	35.2	**30.1**	29.5	25.0	181	199	159	185	5.9	88.0	20.51	34.82	70.00	14.90	86.7	18.79	12.36	2.631	0.788	1.10	10.2	1.8	
08/17/10	16:57	14894.6	71.5%	81.0%	14.85	16.20	11.06	0.62	82.0	33.1	**30.1**	29.5	25.0	169	189	145	171	5.8	88.2	20.31	34.44	63.00	21.50	86.6	18.07	12.15	2.792	0.783	1.40	9.6	1.6	
08/18/10	12:09	14913.9	71.5%	80.6%	14.85	16.46	10.70	0.61	81.0	33.5	**30.2**	29.6	25.0	169	188	143	171	5.5	88.2	20.90	34.56	64.00	20.80	86.6	18.57	12.09	2.95	0.785	1.40	9.5	1.1	
08/19/10	12:40	14938.4	71.6%	80.5%	14.85	16.97	10.03	0.62	80.0	33.3	**30.1**	29.5	25.0	170	190	148	175	5.8	89.0	20.97	34.40	66.00	19.50	86.6	18.60	12.14	3.042	0.785	1.40	9.6	1.4	
08/21/10	19:19	14969.8	71.6%	80.9%	14.85	16.97	9.77	0.61	80.0	33.5	**30.2**	29.3	25.0	170	189	148	172	5.8	88.0	20.45	34.35	66.00	19.00	86.6	18.39	12.01	3.135	0.778	1.30	9.7	1.5	
08/22/10	18:54	14993.4	71.5%	81.0%	14.86	15.43	9.51	0.62	80.0	33.2	**30.2**	29.3	25.0	171	189	148	173	5.9	89.0	20.30	34.52	60.00	18.50	86.7	18.23	12.14	3.382	0.778	1.30	9.7	1.9	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 75-75% Recovery**																					
08/24/10	17:10	15031.8	66.1%	76.0%	14.88	16.46	11.31	0.64	78.0	34.0	**30.5**	29.3	22.5	165	191	140	170	6.5	88.0	27.42	44.42	64.00	22.00	86.8	19.54	12.66	3.226	0.789	2.10	9.5	1.8	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 75-80% Recovery**																					
08/25/10	12:21	15051.0	81.1%	75.7%	14.90	16.97	10.29	0.68	77.0	32.0	**29.9**	29.0	27.0	183	210	159	189	6.5	89.0	27.88	20.30	66.00	20.00	86.9	19.90	13.49	2.556	0.795	2.00	10.2	0.9	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 75-85% Recovery**																					
08/26/10	12:10	15073.4	84.7%	75.5%	14.91	17.74	8.23	0.71	78.0	36.0	**34.5**	35.0	34.0	210	235	185	212	6.5	89.0	28.25	15.74	69.00	16.00	87	20.69	13.97	2.507	0.802	1.80	11.2	0.9	Main plant is experirencing problems wi
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**BASELINE 14.9 gfd flux 80-80% Recovery**																					
08/26/10	21:41	15082.9	71.7%	81.1%	14.90	17.74	8.74	0.62	78.0	33.8	**30.2**	29.3	25.0	179	195	158	181	7.0	89.0	20.31	34.25	69.00	17.00	86.9	18.28	12.31	2.736	0.784	1.20	10.1	0.9	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 80-80% Recovery**																					
08/28/10	12:06	15108.0	71.3%	81.1%	14.90	17.74	8.74	0.62	79.0	33.8	**30.1**	29.2	25.0	178	192	154	180	5.8	88.0	20.31	34.91	69.00	17.00	86.9	18.25	12.25	3.28	0.778	1.20	9.9	1.8	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 80-85% Recovery**																					
08/29/10	12:34	15132.2	86.1%	79.1%	14.90	18.51	7.10	0.70	79.0	32.0	29.3	29.0	27.9	212	231	93	218	6.5	89.0	22.90	14.01	72.00	13.80	86.9	20.11	13.87	2.558	0.792	1.20	11.5	0.9	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 75-90% Recovery**																					
08/30/10	12:00	15155.7	90.8%	75.4%	14.88	21.09	2.06	0.90	79.0	33.2	**31.0**	30.5	30.0	310	332	290	317	6.0	89.0	28.37	8.83	82.00	4.00	86.8	25.10	17.72	2.457	0.822	1.10	15.6	0.9	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**BASELINE 14.9 gfd flux 80-80% Recovery**																					
09/02/10	13:12	15159.2	68.0%	80.6%	14.81	18.51	5.40	0.65	80.0	33.6	**30.5**	29.3	23.5	191	210	175	198	7.0	88.0	20.85	40.60	72.00	10.50	86.4	18.88	12.68	3.481	0.780	1.00	10.9	2.5	
09/03/10	13:00	15183.0	68.1%	79.8%	14.88	19.80	4.47	0.65	79.0	33.7	**30.5**	29.2	23.0	200	218	180	205	7.0	88.0	21.95	40.58	77.00	8.70	86.8	19.07	12.82	3.222	0.784	1.00	10.8	2.4	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**BASELINE 14.9 gfd flux 80-80% Recovery**																					
10/01/10	14:44	15185.7	69.9%	81.1%	14.88	15.94	12.34	0.61	77.0	33.2	**30.0**	29.5	25.0	162	180	140	168	7.0	88.0	20.21	37.39	62.00	24.00	86.8	18.19	12.03	3.602	0.781	1.50	9.3	3	
10/02/10	12:19	15207.4	69.8%	80.7%	14.86	15.94	12.34	0.60	78.0	33.0	**30.2**	29.5	24.5	162	181	140	168	6.9	89.0	20.75	37.54	62.00	24.00	86.7	18.02	11.90	3.526	0.777	1.50	9.5	2.9	
10/03/10	11:35	15230.6	69.9%	80.8%	14.88	15.69	12.45	0.60	77.0	33.1	**30.0**	29.5	24.4	162	181	140	168	7.0	88.0	20.58	37.36	61.00	24.20	86.8	19.01	11.91	3.325	0.779	1.50	9.4	3	
10/04/10	12:14	15255.2	69.5%	80.7%	14.90	15.69	12.45	0.60	78.0	33.1	**30.5**	29.5	24.0	161	180	139	165	6.5	88.0	20.76	38.10	61.00	24.20	86.9	19.18	11.88	3.361	0.775	1.50	9.3	3	
10/05/10	12:29	15279.5	70.0%	80.8%	14.90	15.94	12.60	0.60	77.0	33.0	**30.2**	29.3	24.5	163	182	140	68	6.9	88.1	20.69	37.17	62.00	24.50	86.9	18.64	11.92	3.347	0.774	1.50	9.3	3	
10/06/10	12:25	15303.4	69.4%	80.5%	14.85	15.69	12.50	0.60	78.0	33.2	**30.3**	29.5	24.0	161	180	138	165	6.0	89.0	20.96	38.23	61.00	24.30	86.6	18.43	11.86	3.374	0.777	1.50	9.3	3.1	
10/07/10	11:09	15326.2	69.7%	80.7%	14.90	15.94	12.60	0.60	78.0	33.2	**30.1**	29.5	24.0	162	181	140	166	6.8	88.0	20.84	37.80	62.00	24.50	86.9	18.59	11.91	3.304	0.778	1.60	9.3	3.1	
10/09/10	14:04	15351.4	69.6%	80.6%	14.85	15.69	12.34	0.61	78.0	33.3	**30.5**	29.5	24.3	162	181	140	168	7.0	89.0	20.81	37.86	61.00	24.00	86.6	18.87	11.93	3.792	0.775	1.40	9.6	3.3	
10/10/10	12:49	15374.1	69.7%	81.0%	14.90	15.94	12.34	0.61	77.0	33.2	**30.1**	29.5	24.1	163	182	140	168	7.0	88.0	20.32	37.79	62.00	24.00	86.9	19.15	11.95	3.789	0.779	1.50	9.3	3.3	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 75-85% Recovery 2 month Demo Point**																					
10/11/10	12:57	15398.3	86.2%	75.9%	14.90	16.46	11.31	0.70	77.0	32.0	30	29.5	27.8	200	222	179	208	6.5	89.0	27.66	13.89	64.00	22.00	86.9	21.34	13.85	3.024	0.789	1.80	11.0	2.1	
10/12/10	12:05	15421.4	86.2%	75.9%	14.88	16.46	10.80	0.70	78.0	32.0	**30.0**	29.5	28.5	200	222	178	208	6.3	90.0	27.53	13.94	64.00	21.00	86.8	21.03	13.76	2.889	0.782	1.80	10.9	1.9	
10/13/10	12:08	15445.5	86.1%	75.9%	14.88	16.46	10.80	0.70	77.0	32.0	**30.0**	29.7	28.5	201	224	179	207	6.5	89.0	27.61	13.99	64.00	21.00	86.8	20.35	13.82	2.758	0.795	1.80	11.0	1.7	
10/14/10	12:07	15469.5	86.1%	76.0%	14.88	16.46	10.75	0.70	77.0	32.0	**29.9**	29.7	28.5	201	224	179	208	6.3	89.0	27.42	14.01	64.00	20.90	86.8	20.27	13.76	3.021	0.793	1.80	11.0	2	
10/16/10	12:24	15494.9	85.8%	76.0%	14.91	16.46	10.80	0.70	76.0	32.0	**30.0**	29.5	28.6	201	224	179	208	6.5	90.0	27.50	14.36	64.00	21.00	87	21.35	13.91	2.979	0.787	1.80	11.0	1.9	
10/17/10	12:55	15519.5	85.9%	76.0%	14.90	16.46	10.80	0.71	78.0	32.1	**30.0**	29.5	28.5	201	222	179	208	6.5	89.0	27.51	14.26	64.00	21.00	86.9	21.47	13.92	2.94	0.785	1.90	11.1	1.8	
10/18/10	12:20	15542.9	86.2%	75.8%	14.85	16.71	10.54	0.71	77.0	32.2	**30.1**	29.7	28.6	205	227	180	210	6.4	89.0	27.64	13.90	65.00	20.50	86.6	21.45	13.90	2.915	0.790	1.80	11.0	1.9	
10/19/10	12:34	15567.1	86.3%	75.7%	14.88	16.46	10.75	0.71	77.0	32.2	30	29.5	28.6	203	228	180	210	6.3	89.0	27.85	13.75	64.00	20.90	86.8	20.91	13.97	2.935	0.789	1.80	11.1	1.8	
10/20/10	12:33	15591.1	86.2%	75.8%	14.88	16.71	10.54	0.71	77.0	32.0	30.0	29.5	28.7	205	228	180	209	6.3	90.0	27.76	13.91	65.00	20.50	86.8	21.49	13.96	2.947	0.785	1.80	11.2	1.9	
10/21/10	14:19	15616.8	86.3%	75.5%	14.88	16.71	10.54	0.71	77.0	32.0	29.9	29.5	28.7	205	228	180	210	6.0	89.0	28.15	13.80	65.00	20.50	86.8	21.47	13.96	3.079	0.860	1.80	11.1	2	
10/23/10	14:35	15649.7	86.2%	75.9%	14.91	16.46	10.54	0.71	76.0	32.0	30.0	29.5	28.7	205	229	180	210	6.3	89.0	27.62	13.90	64.00	20.50	87	21.37	13.96	3.415	0.784	1.80	11.2	2.4	
10/24/10	13:03	15672.2	86.2%	75.7%	14.88	16.46	10.54	0.71	76.0	32.1	30.0	29.7	28.8	207	228	180	210	6.5	89.0	27.88	13.90	64.00	20.50	86.8	21.63	13.99	2.995	0.787	1.80	11.2	1.9	
10/25/10	12:00	15695.1	86.2%	75.7%	14.90	16.71	10.54	0.71	76.0	32.0	30.0	29.5	28.8	207	228	180	210	6.5	89.0	27.89	13.93	65.00	20.50	86.9	21.87	14.02	3.056	0.788	1.80	11.2	2	
10/26/10	11:21	15718.5	86.3%	75.7%	14.88	16.71	10.34	0.71	76.0	32.0	29.9	29.7	28.5	208	229	181	211	6.4	90.0	27.93	13.82	65.00	20.10	86.8	21.40	14.03	3.029	0.850	1.90	11.3	2.1	
10/27/10	12:19	15743.4	86.2%	75.8%	14.88	16.71	10.29	0.71	76.0	32.1	30.0	29.5	28.8	207	229	181	211	6.3	89.0	27.66	13.92	65.00	20.00	86.8	21.49	13.97	3.047	0.788	1.70	11.3	2	
10/28/10	11:17	15766.4	86.3%	75.8%	14.91	16.97	10.23	0.71	75.0	31.9	29.9	29.3	28.5	209	230	183	212	6.5	90.0	27.83	13.83	66.00	19.90	87	20.95	14.05	3.077	0.786	1.80	11.3	2.1	
10/30/10	12:57	15802.5	86.1%	75.9%	14.88	16.71	10.18	0.71	76.0	32.0	30.0	29.6	28.7	208	229	181	210	6.0	90.0	27.55	13.96	65.00	19.80	86.8	20.80	13.90	2.511	0.798	1.70	11.0	1.3	
10/31/10	12:36	15826.2	86.1%	75.9%	14.88	16.97	10.03	0.71	76.0	32.0	30.0	29.5	28.8	209	230	185	212	6.5	89.0	27.58	14.01	66.00	19.50	86.8	21.59	13.93	2.939	0.793	1.70	11.2	1.8	
11/01/10	12:59	15850.6	86.0%	75.8%	14.86	16.97	9.87	0.71	76.0	32.0	30.0	29.5	28.7	209	231	185	212	6.3	89.0	27.67	14.07	66.00	19.20	86.7	21.23	13.99	2.802	0.792	1.70	11.1	1.6	
11/02/10	11:36	15873.2	86.2%	76.0%	14.91	16.97	9.77	0.71	75.0	32.0	30.0	29.5	28.8	210	231	187	215	6.5	89.0	27.51	13.98	66.00	19.00	87	21.12	14.04	2.618	0.792	1.70	11.3	1.4	
11/03/10	11:43	15897.3	86.2%	75.8%	14.93	16.97	9.77	0.71	75.0	32.0	29.9	29.5	28.8	210	232	187	216	6.3	89.0	27.84	13.95	66.00	19.00	87.1	21.95	14.06	2.791	0.793	1.70	11.2	1.5	
11/04/10	12:06	15921.7	86.2%	76.0%	14.86	16.97	9.67	0.71	75.0	32.1	29.9	29.6	28.8	211	232	188	218	6.5	89.0	27.44	13.90	66.00	18.80	86.7	21.05	13.95	2.779	0.792	1.70	11.2	1.6	
11/06/10	11:29	15946.6	86.1%	76.0%	14.86	16.97	9.51	0.71	75.0	32.0	29.9	29.5	28.8	210	231	187	213	6.3	89.0	27.42	14.03	66.00	18.50	86.7	21.68	13.89	3.037	0.787	1.70	11.3	1.9	
11/07/10	12:01	15972.2	86.6%	75.8%	14.85	17.23	9.31	0.71	76.0	32.0	30.0	29.5	28.8	211	231	188	215	6.3	89.0	27.68	13.35	67.00	18.10	86.6	21.45	14.00	3.049	0.787	1.60	11.3	2	
11/08/10	12:09	15996.3	86.3%	75.9%	14.85	17.23	9.21	0.71	76.0	32.0	30.0	29.6	28.8	212	231	189	218	6.2	89.0	27.46	13.78	67.00	17.90	86.6	20.94	13.93	2.995	0.786	1.60	11.3	1.9	
11/09/10	12:21	16020.5	86.3%	75.8%	14.86	17.49	8.90	0.71	76.0	31.9	29.9	29.8	28.8	213	235	190	220	6.3	89.0	27.66	13.79	68.00	17.30	86.7	20.96	14.03	3.026	0.791	1.60	11.4	1.9	
11/10/10	11:03	16043.2	86.2%	75.7%	14.85	17.49	8.74	0.71	75.0	32.0	29.9	29.5	28.8	215	235	191	220	6.5	89.0	27.77	13.83	68.00	17.00	86.6	21.73	14.00	3.01	0.794	1.60	11.4	1.9	
11/21/10	10:51	16044.1	86.4%	75.9%	14.88	17.23	9.21	0.71	71.0	32.0	30.0	29.5	28.8	212	231	190	219	6.0	89.0	27.54	13.65	67.00	17.90	86.8	21.23	14.07	3.257	0.786	1.60	11.4	2.2	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 80-80% Recovery Baseline**																					
11/25/10	15:03	16070.1	73.1%	81.0%	14.86	16.20	11.57	0.60	69.0	33.0	30.3	29.5	25.3	170	185	147	172	6.8	88.0	20.30	31.98	63.00	22.50	86.7	18.11	11.83	3.576	0.768	1.30	9.6	2.7	Data Reflects silica CIP
11/26/10	13:29	16092.5	73.3%	81.1%	14.86	16.20	11.57	0.60	72.0	32.9	30.2	29.4	25.5	169	183	143	171	6.8	88.0	20.22	31.59	63.00	22.50	86.7	18.02	11.75	3.485	0.768	1.30	9.4	2.7	

TIME				CALCULATED PARAMETERS					TEMP	PRESSRE									FLOWS						MAIN PANEL KW METER				VFD KW METER			
		Operation	System	RO	Ave. Sys. Flux	1st Stage Flux	2nd Stage Flux	Power	Influent	P_{CF-in}	P_{CF-out}	$P_{PX-Feed\ In}$	$P_{PX-conc\ out}$	PX-HP out RO 1 fe	$P_{RO\ 2\ feed}$	$P_{C-RO1\ PX\ Booster\ inlet}$	P_{C-RO2}	P_{P-SYS}	$Q_{F-HP\ Pump}$	$Q_{PX\ HP-out}$	$Q_{Feed\ PX-In}$	$Q_{P-Stage\ 1}$	$Q_{P-Stage\ 2}$	Q_{P-SYS}	A_{sys}	P HP/PX	P booster	Power	PX power	HP Power	Feed Pump	
Date	Time	Time	Recovery %	Recovery %	Gfd	Gfd	Gfd	kWh/m3	Temp F	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	amp	(kw)	(kw)	Factor	(kw)	(kw)	(kw)	Notes
MM/DD/YY	hh:mm	hh.hh							17	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
11/27/10	12:03	16115.1	73.2%	81.0%	14.88	16.20	11.57	0.60	71.0	33.0	30.1	29.5	25.2	169	183	142	170	6.6	89.0	20.36	31.86	63.00	22.50	86.8	18.62	11.87	3.522	0.770	1.40	9.5	2.6	
11/28/10	13:23	16140.5	73.1%	81.1%	14.86	15.94	11.47	0.61	73.0	33.0	30.2	29.4	25.3	170	185	145	171	6.9	88.0	20.21	31.83	62.00	22.30	86.7	18.29	11.92	3.481	0.769	1.30	9.6	2.7	
11/29/10	13:13	16164.3	73.0%	80.7%	14.88	16.20	11.31	0.60	72.0	33.0	30.3	29.3	25.4	170	186	148	171	7.0	88.0	20.82	32.12	63.00	22.00	86.8	18.65	11.90	3.506	0.770	1.40	9.6	2.8	
11/30/10	12:41	16187.8	73.2%	81.1%	14.90	16.20	11.31	0.60	72.0	33.0	30.2	29.4	25.3	170	185	148	172	7.0	88.0	20.28	31.83	63.00	22.00	86.9	18.28	11.87	3.489	0.771	1.30	9.6	2.7	
12/01/10	12:05	16211.2	73.1%	81.1%	14.86	16.20	11.37	0.60	72.0	33.0	30.1	29.2	25.3	170	185	148	172	6.8	88.0	20.24	31.88	63.00	22.10	86.7	18.46	11.88	3.517	0.769	1.30	9.5	2.8	
12/02/10	12:54	16236	73.2%	81.0%	14.90	16.20	11.42	0.60	72.0	22.9	30.2	29.5	25.3	170	184	147	171	6.8	89.0	20.38	31.88	63.00	22.20	86.9	18.30	11.93	3.558	0.770	1.40	9.6	2.7	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 75-85% Recovery 2 month Demo Point**																					
12/04/10	12:24	16257.5	86.3%	75.8%	14.88	16.46	10.54	0.71	73.0	32.0	29.9	29.5	28.8	205	228	180	210	6.3	90.0	27.78	13.82	64.00	20.50	86.8	20.87	13.90	2.573	0.790	1.80	11.1	1.2	
12/05/10	11:47	16280.9	86.1%	75.7%	14.88	16.46	10.39	0.71	73.0	32.0	30.0	29.4	28.9	206	229	180	210	6.4	89.0	27.81	14.05	64.00	20.20	86.8	21.03	13.91	2.658	0.792	1.80	11.0	1.4	
12/07/10	13:55	16330.5	86.2%	75.7%	14.90	16.46	10.29	0.70	73.0	32.0	30.0	29.3	28.8	208	229	181	211	6.5	90.0	27.88	13.96	64.00	20.00	86.9	21.26	13.90	3.011	0.783	1.70	11.3	1.9	
12/08/10	12:48	16353.4	86.3%	75.8%	14.88	16.71	10.03	0.71	72.0	32.0	30.0	29.5	28.7	209	230	182	211	6.4	89	27.77	13.78	65	19.5	86.8	21.13	14.02	3.018	0.783	1.8	11.2	1.9	
12/09/10	14:18	16378.9	86.2%	76.0%	14.88	16.71	9.87	0.71	74.0	32.0	30.0	29.5	28.9	209	230	183	211	6.4	89	27.41	13.9	65	19.2	86.8	21.25	13.93	2.99	0.785	1.8	11.2	1.9	
12/11/10	12:10	16403	86.2%	76.0%	14.91	16.71	10.03	0.70	74.0	32.0	30.0	29.5	28.7	209	230	182	211	6.3	89	27.43	13.91	65	19.5	87	20.82	13.91	2.375	0.795	1.7	11.2	1.7	
12/12/10	14:15	16429.1	86.2%	75.7%	14.88	16.97	9.77	0.71	74.0	31.7	29.9	29.4	28.8	210	230	183	213	6.5	88	27.81	13.86	66	19	86.8	20.36	14.05	2.504	0.794	1.8	11.3	1.2	
12/13/10	13:09	16452.03	86.2%	75.7%	14.90	16.97	9.72	0.71	73.0	32.0	29.9	29.6	28.8	210	231	185	214	6.3	90	27.93	13.89	66	18.9	86.9	20.87	14.02	2.656	0.789	1.7	11.3	1.4	
12/14/10	11:16	16474.1	86.2%	75.7%	14.86	16.97	9.62	0.70	73.0	32.0	30.1	29.5	28.8	209	230	183	212	6.4	89	27.8	13.87	66	18.7	86.7	21.1	13.81	2.569	0.79	1.7	11.3	1.3	
12/15/10	12:10	16499	86.2%	75.7%	14.90	16.97	9.51	0.70	74.0	32.0	30.0	29.2	28.5	210	230	185	212	6.4	90	27.87	13.94	66	18.5	86.9	21.08	13.89	2.391	0.79	1.7	11.2	1.2	
12/16/10	12:00	16522.8	86.1%	75.9%	14.85	16.97	9.36	0.70	74.0	32.0	30.0	29.5	28.8	210	230	186	214	6.5	89	27.45	13.94	66	18.2	86.6	20.59	13.84	2.284	0.793	1.7	11.2	1	
12/18/10	12:24	16548.2	86.1%	75.8%	14.88	16.97	9.21	0.70	73.0	32.0	29.9	29.5	28.8	211	231	188	217	6.3	89	27.76	13.99	66	17.9	86.8	20.77	13.86	2.769	0.79	1.6	11.3	1.7	
12/23/10	20:24	16676.2	86.1%	76.0%	14.90	18.00	7.97	0.70	73.0	32.0	30.0	29.5	28.7	219	237	195	222	6.5	89	27.47	13.98	70	15.5	86.9	20.37	13.8	2.762	0.794	1.3	11.6	1.8	
12/25/10	16:00	16677.2	86.2%	76.0%	14.90	16.71	10.44	0.71	70.0	32.0	30.0	29.5	28.8	210	230	187	215	6.3	89	27.44	13.88	65	20.3	86.9	20.36	13.97	2.428	0.788	1.8	11.2	1.2	Data Reflects silica CIP
12/26/10	13:20	16698.6	86.3%	75.7%	14.88	16.97	10.39	0.70	72.0	32.0	30.0	29.5	28.9	208	229	182	210	6	89	27.9	13.74	66	20.2	86.8	20.91	13.78	2.495	0.788	1.8	11	1.4	
12/27/10	13:01	16722.2	86.3%	75.8%	14.86	16.97	10.29	0.70	72.0	32.0	30.0	29.4	28.8	209	230	183	11	6	89	27.72	13.76	66	20	86.7	20.7	13.74	2.101	0.793	1.7	11.2	0.8	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 85-85% Recovery**																					
12/28/10	16:21	16745.2	76.5%	86.2%	14.88	17.49	9.00	0.60	72.0	33.0	30.0	29.5	26.5	180	190	162	182	6.8	89	13.9	26.59	68	17.5	86.8	18.16	11.77	2.941	0.768	0.8	10	1.9	
12/29/10	13:09	16766.05	76.7%	86.1%	14.90	17.49	9.00	0.60	73.0	32.8	30.1	29.5	26.3	180	190	162	181	6.7	89	14.08	26.4	68	17.5	86.9	18.11	11.75	2.963	0.771	0.8	10.1	2.3	
12/31/10	13:01	16812.9	76.8%	86.1%	14.88	18.00	8.38	0.59	70.0	33.0	30.2	29.3	26.0	183	191	168	185	6.5	89	13.96	26.21	70	16.3	86.8	17.98	11.7	2.887	0.77	0.8	10.1	2	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes											**14.9 gfd flux 80-80% Recovery Baseline**																					
01/01/11	14:27	16838.3	73.7%	80.9%	14.88	16.46	11.31	0.60	70.0	33.0	30.1	29.3	25.5	170	187	148	172	6.5	88	20.45	31.03	64	22	86.8	17.76	11.75	3.032	0.766	1.3	9.5	2.3	

TIME			pH			CONDUCTIVITY										TDS											TURBIDITY		SDI	OTHER					
Date MM/DD/YY	Time hh:mm	Operation Time hh.hh	pH_{F-sys} SC5	pH pH_{P-sys} SC11	pH_{C-sys} SC7	C_{CF-out} SC3	$C_{F-PX-out}$ SC6	C_{F-sys} SC5	$C_{P-total\ sys}$ SC11	Conductivity (mS/cm) $C_{P-1st\ stage\ 1}$ SC14	$C_{P-1st\ stage\ 2}$	$C_{P-2nd\ stage}$ SC10	$C_{-Interstage}$ SC 13	C_{C-sys} SC12	$C_{C-PX-out}$ SC7	TDS_{CF-out} SC3	$TDS_{F-PX-out}$ SC6	% Inc @ memb in	TDS_{F-sys} SC5	TDS_{P-sys} SC11	TDS (mg/L) $TDS_{P-1st\ stage}$ SC14	$TDS_{P-1st\ stage}$	$TDS_{P-2nd\ stage}$ SC10	$TDS_{Interstage}$ SC 13	TDS_{C-sys} SC12	$TDS_{C-PX-out}$ SC7	Turbidity (NTU) NTU_{MF-in} SC1	NTU_{CF-out} meter	Density Index SDI_{CF-out} CART	V_{TANK} (gallons)	Inhibitor Pump Speed (gph)	HP VFD Speed (Hertz)	PX VFD Speed (Hertz)	FEED VFD Speed (Hertz)	Notes
			25	26	27	28	29	30	31	32	33	34	35	36	37	28	29		30	31	32	33	34	35	36	37	30	38		39	40	41-02	42-02	43-02	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes																**Membrane Ripening Period**																			
02/11/10	16:15	12338.00	7.90	6.50	7.99	4490	nd	4529	237.2	139.6	135.4	473.5	9470	18.26	13.45		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.037	nd	20	20/30	53.35	42.51	51.32	
02/11/10	17:16	12339.00	7.98	6.50	8.12	4514	nd	4626	294	166.3	160.8	659.7	10.11	18.52	15.5		nd	nd		192.10	106.60	102.80	447.40	8487.00	16.98	13.85	nd	0.032	nd	20	20/30	45.79	35.86	45.07	
02/12/10	9:11	12355.30	7.86	6.88	6.86	4477	nd	4505	274.1	158.1	155	559.2	9539	18.62	15.04	3461.00	nd	0.8%	3487.00	177.90	101.00	98.84	376.50	7958.00	17.11	13.33	nd	0.029	nd	20	20/30	53.50	41.54	52.58	
02/18/10	15:52	12357.60	7.77	6.60	7.99	4464	nd	4617	293.7	170.6	167.8	597.7	9633	18.53	16.27	3446.00	nd	3.9%	3581.00	191.80	109.20	107.10	404.20	802.00	17.09	14.53	nd	0.035	nd	20	20/30	53.58	41.72	47.18	
02/25/10	13:22	12375.40	7.88	6.50	8.14	4490	nd	4651	304.6	178.5	175.1	625.4	9679	18.62	16.22	3477.00	nd	4.4%	3629.00	201.30	114.70	112.40	423.80	8085.00	17.05	14.51	nd	0.037	nd	20	20/30	53.67	41.46	40.60	
02/26/10	15:54	12400.20	7.84	6.51	7.99	4499	nd	4622	300	176.7	174.1	613.1	9680	18.65	16.3	3463.00	nd	3.2%	3573.00	196.20	113.30	111.70	414.80	8046.00	17.09	14.59	nd	0.055	nd	19.5	20/30	53.70	41.54	42.60	
02/27/10	12:35	12420.90	7.85	6.52	7.95	4492	nd	4649	299.9	176.8	174.1	612.7	9727	18.67	16.32	3482.00	nd	3.9%	3619.00	196.00	113.50	111.60	415.70	8090.00	17.16	14.59	nd	0.029	nd	19.5	20/30	53.64	41.42	41.10	
02/28/10	12:04	12444.30	7.87	6.53	7.97	4495	nd	4650	296.1	175.9	173.1	598.2	9707	18.55	16.22	3478.00	nd	4.2%	3624.00	193.70	113.30	111.00	405.30	8095.00	17.04	14.52	nd	0.029	nd	19	20/30	53.70	41.57	42.51	
03/01/10	14:20	12470.60	7.85	6.54	8.09	4488	nd	4655	297.5	177.5	173.9	604.1	9714	18.19	16.21	3464.00	nd	4.1%	3605.00	194.70	113.90	111.50	409.10	8089.00	16.61	14.51	nd	0.028	nd	19	20/30	53.64	41.46	40.61	
03/02/10	12:18	12492.60	7.87	6.56	8.05	4478	nd	4603	301.5	178.1	175.2	622.2	9813	18.71	16.21	3452.00	nd	3.2%	3563.00	197.20	114.30	112.40	421.40	8176.00	17.18	14.49	nd	0.026	nd	19	20/30	53.64	41.04	44.27	
03/03/10	15:14	12519.50	7.78	6.47	7.88	4479	nd	4615	299.8	179.1	176	614.5	9759	18.48	16.19	3449.00	nd	4.0%	3588.00	197.30	114.90	112.80	415.70	8124.00	16.89	14.48	nd	0.026	nd	18.5	20/30	53.58	41.25	43.07	
03/04/10	12:40	12540.90	7.76	6.46	7.99	4472	nd	4597	298.6	179.2	176	612.7	9768	18.44	16.18	3443.00	nd	3.0%	3548.00	195.00	115.00	112.90	414.10	8116.00	16.82	14.42	nd	0.027	nd	18.5	20/30	53.58	41.34	43.00	
03/05/10	14:39	12564.10	7.75	6.46	7.82	4472	nd	4605	299.6	179.9	176.3	611.2	9737	18.36	16.09	3444.00	nd	3.1%	3551.00	195.60	115.60	113.00	413.90	8120.00	16.74	14.35	nd	0.027	nd	18.5	20/30	53.67	41.46	40.86	
03/06/10	11:33	12585.00	7.83	6.50	7.92	4510	nd	4631	298.4	180	176.4	606.8	9728	17.96	16.02	3481.00	nd	3.0%	3586.00	195.10	115.60	113.40	410.90	8084.00	15.64	14.28	nd	0.027	nd	18	20/30	53.64	41.48	39.36	
03/07/10	13:55	12611.30	7.77	6.47	7.86	4470	nd	4622	297.8	180.4	177.5	608.6	9747	18.21	15.98	3441.00	nd	3.6%	3566.00	194.80	115.80	113.90	411.50	8105.00	16.57	14.26	nd	0.028	nd	17.8	20/30	53.58	41.46	37.80	
03/08/10	15:33	12637.00	7.86	6.36	7.85	4476	nd	4613	299.1	180.1	176	615.4	9828	18.37	16.07	3454.00	nd	3.2%	3566.00	196.50	115.80	112.90	417.80	8181.00	16.76	14.10	nd	0.028	nd	17.8	20/30	53.67	41.13	40.79	
03/09/10	14:14	12659.70	7.76	6.15	7.97	4612	nd	4789	311.1	-	-	-	-	-	-	3579.00	nd	4.0%	3721.00	204.30	-	-	-	-	-	-	nd	-	nd	-	-	-	-	-	Plant shut down during data collection due to
03/10/10	13:07	12681.90	7.77	6.33	7.96	4481	nd	4649	298.6	180.8	177.2	611.3	9849	18.27	16.1	3440.00	nd	5.1%	3614.00	195.40	116.00	113.70	414.20	8254.00	16.68	14.37	nd	0.028	nd	17.8	20/30	53.70	41.37	41.23	
03/16/10	16:04	12706.10	7.79	6.53	7.91	4487	5038	4510	332.8	195.7	192.3	768.4	10.64	18.84	16.33	3470.00	3920.00	13.0%	3477.00	219.20	126.30	124.20	524.50	8954.00	17.27	14.61	nd		nd	17.8	20/30	55.34	40.08	35.04	
03/26/10	16:29	12718.20	7.80	6.60	7.85	5250	6456	5419	388.2	235.7	232	870.7	12.19	20.28	18.22	4103.00	5166.00	25.9%	4245.00	257.20	152.90	150.50	598.80	10.43	18.84	16.60	nd	0.034	nd	17.8	20/30	54.80	41.95	30.00	
03/27/10	16:28	12720.58	7.80	6.69	7.75	5274	5705	5286	407.1	242.9	237.9	978.4	12.4	20.56	16.71	4140.00	4510.00	8.9%	4133.00	270.50	157.60	154.50	677.30	10.62	19.20	15.01	nd	0.030	nd	17.8	20/30	52.62	38.79	30.00	
04/02/10	15:35	12726.22	7.79	6.78	7.80	4134	4787	4197	255.9	182.4	178.7	444.6	8147	12.96	11.48	3168.00	3709.00	17.1%	3206.00	165.90	117.30	114.60	297.50	6647.00	11.16	9740.00	nd	0.033	nd	17.6	50/90	46.28	45.73	35.73	
04/02/10	17:57	12728.58	7.65	6.69	7.77	4072	4247	4098	232.6	166.1	163.3	396.4	7633	12.2	9857	3118.00	3282.00	5.3%	3125.00	151.10	106.20	104.40	263.00	6183.00	10.43	8204.00	nd	0.033	nd	17.5	50/90	46.26	46.20	33.38	
04/08/10	14:50	12731.97	7.60	6.60	7.66	4060	4242	4092	240.3	169.6	167	409.9	7705	12.4	10.01	3071.00	3215.00	4.7%	3075.00	154.40	107.40	105.70	269.80	6205.00	10.51	8265.00	nd	0.029	nd	17	50/90	46.29	46.11	33.26	
04/09/10	15:10	12740.34	7.70	6.38	7.73	4003	4175	4035	235	166.7	164.1	401.3	7545	12.22	9887	3017.00	3171.00	5.1%	3029.00	151.00	105.50	103.70	263.70	6054.00	10.33	8143.00	nd	0.033	nd	16.1	50/90	46.26	46.14	48.02	
04/10/10	12:11	12761.37	7.66	6.41	7.64	4011	4187	4040	230.8	164.9	162.5	388.6	7499	12.12	9845	3021.00	3165.00	4.8%	3044.00	148.40	104.30	102.70	255.00	5997.00	10.25	8115.00	nd	0.027	nd	14.2	50/90	46.25	46.55	46.67	
04/11/10	13:17	12786.47	7.65	6.43	7.65	4009	4169	4054	231	165.2	162.4	386.9	7510	12.1	9836	3026.00	3149.00	4.1%	3051.00	148.50	104.50	102.60	253.80	6007.00	10.22	8097.00	nd	0.032	nd	12	50/90	46.20	46.88	50.79	
04/12/10	17:15	12814.43	7.73	6.46	7.75	4053	4222	4088	232.8	167.1	164.4	389.6	7562	12.13	9951	3053.00	3193.00	4.6%	3079.00	149.70	105.70	103.90	255.60	6047.00	10.24	8200.00	nd	0.028	nd	23	50/90	46.23	46.96	43.79	Filled up anti-scallent tank with 10:1 dilution
04/21/10	15:44	12833.22	7.49	6.21	7.65	4065	4249	4121	241.2	172.1	169.6	406.8	7598	12.26	10.01	3063.00	3216.00	5.0%	3107.00	155.00	109.10	107.40	267.40	6079.00	10.37	8253.00	nd	0.032	nd	21.3	50/90	46.26	46.73	46.90	
04/23/10	16:00	12853.47	7.62	6.31	7.72	4035	4148	4051	234.2	168.1	165.5	391.8	7522	12.09	10.04	3033.00	3141.00	3.6%	3062.00	150.70	106.40	104.80	257.60	6039.00	10.22	8266.00	nd	0.035	nd	19.3	50/90	46.41	47.29	46.65	
04/24/10	11:46	12873.25	7.54	6.33	7.65	4059	4274	4131	238.7	171.2	168.2	400.6	7607	12.15	9979	3068.00	3248.00	5.9%	3120.00	153.50	108.50	106.50	263.30	6091.00	10.27	8231.00	nd	0.033	nd	17.4	50/90	46.32	46.99	46.77	
04/25/10	11:03	12896.51	7.53	6.30	7.63	4055	4196	4091	238.1	171.4	168.4	402.4	7614	12.11	9916	3058.00	3171.00	3.7%	3084.00	153.10	108.60	106.60	264.50	6096.00	10.23	8172.00	nd	0.037	nd	15.5	50/90	46.29	46.99	46.86	
04/26/10	17:16	12926.28	7.37	6.22	7.37	4044	4212	4081	238.4	171.5	168.7	408.5	7650	12.14	9929	3040.00	3184.00	4.7%	3073.00	153.10	108.60	106.70	268.50	6125.00	10.25	8179.00	nd	0.035	nd	12.2	50/90	46.26	46.85	46.97	
04/27/10	13:39	12946.67	7.55	6.33	7.66	3880	4037	3915	219.6	156.3	153.7	378.7	7495	11.77	9598	2913.00	3047.00	4.6%	2938.00	141.10	98.72	97.02	248.40	5902.00	9920.00	7891.00	nd	0.032	nd	20.2	50/90	46.32	46.49	37.58	Filled up anti-scallent tank with 10:1 dilution
04/28/10	16:40	12973.68	7.39	6.13	7.41	4024	4223	4032	268	164.9	162.9	594.3	9134	15.74	12.33	3021.00	3138.00	3.9%	3032.00	171.90	104.30	102.30	397.60	7489.00	13.83	10.43	nd	0.032	nd	17.6	50/90	52.53	41.07	44.58	
04/29/10	12:43	12993.73	7.55	6.21	7.57	4131	4275	4141	277	171.5	168.5	620.4	9452	16.07	12.63	3118.00	3238.00	3.8%	3124.00	178.10	108.70	106.60	415.60	7746.00	14.18	10.72	nd	0.030	nd	15.5	50/90	52.59	41.16	44.17	
04/30/10	5:09	13017.66	7.68	6.29	7.59	4280	4438	4287	298.2	181.6	178.1	696.9	10.06	17.01	13.14	3253.00	3375.00	3.8%	3250.00	192.90	115.50	113.10	470.60	8308.00	15.13	11.22	nd	0.029	nd	13.2	50/90	52.57	40.08	30.77	Had to adjust % salinity, main plant had swit
05/01/10	12:17	13036.81	7.59	6.26	7.63	4329	4442	4343	301	185.6	182.1	711.6	10.17	17.05	13.17	3288.00	3354.00	2.0%	3297.00	194.80	118.20	115.90	478.80	8418.00	15.18	11.26	nd	0.030	nd	11.6	50/90	52.45	40.05	32.22	During data collection 5 salinity was low. 5
05/02/10	13:14	13061.76	7.65	6.36	7.65	4366	4505	4372	301.6	186.9	183	721.4	10.32	17.07	13.4	3320.00	3431.00	3.3%	3320.00	195.20	119.10	116.50	485.40	8555.00	15.24	11.47	nd	0.030	nd	9.2	50/90	52.44	40.16	30.73	After data collection, filled up anti-scallent ta
05/03/10	17:25	13089.94	7.55	6.34	7.61	4377	4581	4387	303.1	188.1	184.3	721.4	10.33	16.98	13.32	3325.00	3495.00	5.1%	3331.00	196.10	120.00	117.30	485.80	8560.00	15.08	11.39	nd	0.031	nd	21.5	50/90	52.41	40.31	33.44	
05/05/10	16:14	13112.90	7.52	6.36	7.52	4391	4585	4418	309.2	191.5	187.5	742.8	10.35	16.97	12.83	3342.00	3488.00	4.4%	3352.00	200.20	122.00	119.40	500.10	8552.00	15.06	10.91	nd	0.032	nd	19	50/90	52.38	40.32	30.00	
05/06/10	16:39	13137.32	7.35	6.30	7.35	4390	4512	4407	306	190.8	187.1	739.6	10.41	16.94	13.34	3318.00	3433.00	3.5%	3343.00	198.00	121.60	119.10	497.60	8622.00	15.03	11.42	nd	0.032	nd	16.8	50/90	52.32	40.17	34.96	
05/07/10	15:09	13155.95	7.62	6.38	7.52	4405	4587	4428	309.8	192.8	188.8	755.2	10.55	17.1	13.44	3342.00	3497.00	4.6%	3361.00	200.60	122.90	120.20	508.80	8758.00	15.20	11.53	nd	0.029	nd	15	50/90	52.38	40.17	31.56	
05/08/10	13:21	13178.14	7.67	7.39	7.52	4397	4591	4408	305.7	190.2	186.3	748.2	10.56	17.01	13.4	3343.00	3501.00	4.7%	3349.00	198.00	121.30	118.60	504.20	8774.00	15.13	11.48	nd	0.031	nd	12.8	50/90	52.38	40.02	38.78	
05/09/10	14:12	13203.00	7.48	6.22	7.42	4396	4549	4423	304.3	191.2	187.2	749.3	10.59	16.96	13.45	3335.00	3464.00	3.9%	3357.00	196.80	121.80	119.10	504.60	8785.00	15.08	11.51	nd	0.031	nd	10.3	50/90	52.32	40.11	35.45	
05/10/10	17:50	13230.63	7.53	6.32	7.46	4389	4576	4421	302.2	190.6	186.6	750.6	10.65	16.94	13.48	3329.00	3487.00	4.7%	3350.00	195.40	121.40	118.80	505.70	8849.00	15.08	11.54	nd	0.031	1.22	22	50/90	52.35	40.11	31.42	Filled up anti-scallent tank with 10:1 dilution
05/11/10	14:58	13251.77	7.54	6.29	7.42	4400	4575	4431	302.8	191.5	187.7	758.3	10.7	16.93	13.47	3336.00	3486.00	4.5%	3364.00	195.80	122.00	119.50	511.10	8895.00	15.07	11.54	nd	0.026	1.33	20.1	50/90	52.35	40.05	32.02	
05/12/10	16:03	13276.85	7.54	6.31	7.50	4402	4585	4417	300.8	190.5	186.7	757.7	10.76	16.94	13.4	3347.00	3507.00	4.8%	3355.00	194.50	121.50	118.90	511.20	8961.00	15.05	11.47	nd	0.026		17.5	50/90	52.38	39.99	33.03	
05/13/10	14:25	13299.21	7.55	6.29	7.56	4401	4546	4423	302.6	192.3	188.2	767.3	10.78	16.86	13.36	3342.00	3473.00	3.9%	3362.00	195.70	122.60	119.80	517.70	8998.00	15.01	11.47	nd	0.026	1.68	15.6	50/90	52.35	39.81	38.08	
05/20/10	12:25	13327.52	7.44	6.39	7.59	4342	4450	4352	241.2	146.6	142.4	500.3	9385	17.09	13.31	3293.00	3383.00	2.7%	3300.00	155.00	92.44	89.72	331.60	7690.00	15.18	11.37	nd	0.031	nd	12.5	50/90	52.32	41.72	43.42	
05/22/10	12:55	13360.50	7.50	6.27	7.42	4304	4462	4320	257.6	152.5	147.5	560.2	9708	18.02	13.77	3252.00	3394.00	4.4%	3270.00	165.20	96.04	92.82	372.50	7980.00	16.17	11.91	nd	0.032	nd	9.3	50/90	55.02	41.40	34.15	After data collection, filled up anti-scallent ta
05/23/10	13:44	13385.34	7.50	6.29	7.45	4321	4473	4345	262.6	155.5	151.2	575.6	9797	18.06	13.79	3274.00	3403.00	3.9%	3291.00	168.50	98.06	95.23	383.00	8057.00	16.20	11.94	nd	0.029	nd	22	50/90	55.02	41.40	41.31	
05/24/10	12:37	13408.19	7.61	6.33	7.56	4330	4505	4358	264.2	156.9	152.3	580.5	9813	18.08	13.83	3286.00	3434.00	4.5%	3306.00	169.60	99.04	96.10	386.60	8077.00	16.26	11.98	nd	0.029	1.12	19.7	50/90	55.08	41.43	42.56	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**12 gfd flux**																				
05/25/10	12:46	13432.34	7.56	6.32	7.59	4310	4446	4351	321.1	189.8	184.7	771.5	10.16	17.41	12.95	3265.00	3391.00	3.9%	3300.00	208.40	120.90	117.40	520.90	8403.00	15.54	11.03	nd	0.028	1.13	17.3	50/90	44.93	34.63	30.00	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**BASELINE**																				
05/26/10	12:03	13455.64	7.57	6.33	7.55	4293	4446	4318	262.6	157.5	153.1	576.9	9742	17.78	13.69	3246.00	3379.00	4.1%	3270.00	168.40	99.34	96.51	382.90	8022.00	15.66	11.84	nd	0.027	0.998	15	50/90	55.28	41.92	41.55	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**16 gfd flux**																				
05/27/10	9:27	13477.02	7.53	6.26	7.54	4289	4441	4296	251.8	147.9	143.7	558.1	9826	18.39	14.02	3248.00	3376.00	3.9%	3253.00	161.50	93.18	90.50	371.10	8089.00	16.59	12.16	nd	0.025	0.922	12.7	50/90	59.56	43.62	43.10	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**BASELINE**																				
05/27/10	19:11	13486.77	7.46	6.27	7.42	4303	4418	4324	269.6	159.8	155.4	608.2	9929	17.99	13.75	3247.00	3351.00	3.2%	3273.00	172.70	100.80	97.96	406.80	8161.00	16.14	11.89	nd	0.027	nd	11.8	50/90	55.14	41.25	35.20	
05/29/10	11:41	13508.21	7.52	6.30	7.45	4359	4498	4391	280.8	166.5	161.7	637.5	10.1	18.17	13.98	3298.00	3428.00	3.9%	3332.00	180.60	105.20	102.10	427.20	8379.00	16.33	12.12	nd	0.027	nd	24.8	50/90	55.17	41.31	42.70	
05/30/10	11:45	13532.27	7.51	6.33	7.46	4359	4509	4381	280.7	166.6	161.9	637.7	10.07	18.05	13.87	3303.00	3432.00	3.9%	3323.00	180.50	105.30	102.30	427.20	8282.00	16.19	12.01	nd	0.024	nd	22.4	50/90	55.20	41.31	41.25	
05/31/10	11:05	13555.60	7.50	6.25	7.45	4368	4496	4397	280.9	167.6	162.7	642.5	10.11	17.95	13.84	3309.00	3418.00	3.3%	3336.00	180.60	106.00	102.80	430.50	8348.00	16.10	11.98	nd	0.025	nd	20.2	50/90	55.20	41.31	41.06	
06/01/10	12:08	13580.65	7.59	6.36	7.58	4383	4533	4402	280.9	168.2	163.2	649	10.18	17.92	13.87	3323.00	3450.00	3.8%	3344.00	180.70	106.50	103.10	435.10	8409.00	16.07	12.00	nd	0.024	nd	17.8	50/90	55.20	41.28	42.33	
06/02/10	13:07	13605.53	7.55	6.39	7.48	4391	4503	4405	283.7	169.2	164.2	660.4	10.21	17.88	13.78	3322.00	3428.00	3.2%	3342.00	182.60	107.10	103.70	442.70	8436.00	16.00	11.92	nd	0.028	1.17	15.1	50/90	55.20	41.25	43.46	
06/03/10	12:30	13629.03	7.68	6.43	7.74	4431	4589	4450	282.1	168.9	163.9	664.8	10.45	18.07	14.14	3363.00	3498.00	4.0%	3379.00	181.50	106.80	103.50	445.80	8639.00	16.41	12.27	nd	0.026	nd	12.8	50/90	55.17	41.25	43.61	New Myron L meter readings
06/05/10	13:29	13653.70	7.58	6.44	7.66	4259	4374	4298	279.2	164	159.2	651.5	10.11	17.47	13.55	3308.00	3422.00	3.4%	3351.00	184.60	106.50	103.30	448.90	8659.00	16.05	12.06	nd	0.027	nd	25.3	50/90	55.14	41.16	45.95	Filled up anti scallent tank with 15 gallons of
06/06/10	13:30	13677.71	7.60	6.43	7.66	4274	4413	4295	276.4	164.7	159.6	658.4	10.17	17.63	13.31	3317.00	3447.00	3.9%	3344.00	182.70	106.90	103.60	453.50	8638.00	16.24	11.72	nd	0.032	nd	22.8	50/90	55.11	41.16	47.63	
06/07/10	12:38	13700.85	7.58	6.39	7.68	4256	4425	4268	272.4	143.2	158.7	657.1	10.24	17.52	13.57	3313.00	3458.00	4.4%	3324.00	179.90	106.00	103.10	453.00	8726.00	16.14	12.08	nd	0.026	nd	20.6	50/90	55.17	41.16	46.58	
06/08/10	12:05	13724.30	7.72	6.56	7.64	4269	4412	4301	272.6	164.7	159.8	663.5	10.26	17.43	13.49	3317.00	3449.00	4.0%	3352.00	180.10	107.20	103.70	457.40	8754.00	16.04	12.00	nd	0.027	nd	18	50/90	55.20	41.16	47.17	
06/09/10	11:08	13747.35	7.63	6.48	7.63	4262	4410	4280	271.8	164.6	159.8	668.2	10.3	17.42	13.57	3319.00	3454.00	4.1%	3336.00	179.60	107.00	103.80	460.80	8790.00	16.02	12.80	nd	0.029	1.43	15.9	50/90	55.17	41.16	47.46	
06/10/10	11:08	13771.35	7.51	6.42	7.60	4257	4385	4296	274.8	165.3	160	671.5	10.35	17.17	13.53	3310.00	3427.00	3.5%	3351.00	181.70	107.40	103.90	463.20	8840.00	15.75	12.04	nd	0.028	nd	13.3	50/90	55.22	41.13	47.61	
06/12/10	12:32	13796.64	7.56	6.44	7.59	4242	4410	4263	273.6	166.3	160.3	677.2	10.27	17.14	13.33	3303.00	3450.00	4.5%	3320.00	180.80	108.00	104.10	467.10	8768.00	15.74	11.84	nd	0.029	nd	10.2	50/90	55.20	41.10	47.21	
06/13/10	16:12	13824.30	7.67	6.55	7.63	4239	4343	4263	263.4	165.7	160.6	682.8	10.39	17.39	13.3	3298.00	3393.00	2.9%	3321.00	173.60	107.70	104.30	471.20	8872.00	16.00	11.82	nd	0.029	nd	22.8	50/90	55.20	41.13	47.77	Filled up anti scallent tank with 15 gallons of
06/15/10	12:21	13862.77	7.51	6.42	7.64	4241	4359	4248	275.1	167.7	162.5	710.9	10.58	17.33	13.06	3301.00	3405.00	3.2%	3310.00	181.90	109.10	105.50	491.30	9061.00	15.92	11.48	nd	0.026	nd	18.6	50/90	55.05	40.46	48.50	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**12 gfd flux 75% Recovery**																				
06/16/10	11:46	13886.18	7.57	6.47	7.63	4235	4343	4261	293.6	187.3	182	676	9697	14.64	**11.97**	3293.00	3391.00	3.0%	3318.00	194.90	122.60	119.00	466.40	8206.00	13.16	10.41	nd	0.026	.74, .71	16.3	50/90	45.06	38.47	43.88	SDI was done twice to comfirm first value
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 75% Recovery**																				
06/17/10	12:23	13910.80	7.54	6.44	7.66	4235	4358	4265	237	155.6	151	531.4	9554	15.09	**11.9**	3290.00	3404.00	3.5%	3321.00	156.40	100.90	97.83	362.70	8069.00	13.60	10.34	nd	0.026	0.935	13.8	50/90	55.55	45.79	53.88	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**16 gfd flux 75% Recovery**																				
06/18/10	8:46	13931.18	7.47	6.37	7.61	4236	4376	4264	214.6	143.1	138.9	457.7	9287	14.75	**11.74**	3304.00	3422.00	3.6%	3324.00	141.50	92.66	89.93	311.00	7831.00	13.26	10.19	nd	0.025	0.896	11.7	50/90	59.85	50.24	58.27	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**BASELINE**																				
06/22/10	11:42	13972.79	7.55	6.40	7.65	4276	4460	4312	285.4	174.8	169.4	768.9	10.97	17.56	**13.64**	3323.00	3492.00	5.1%	3363.00	189.10	114.00	110.30	532.20	9402.00	16.17	12.14	nd	0.027	nd	17.9	50/90	55.15	40.17	46.66	
06/23/10	12:39	13997.74	7.48	6.42	7.59	4914	5074	4937	352.6	215.9	209.3	1012	12.93	19.92	**15.14**	3874.00	4017.00	3.7%	3899.00	236.60	142.40	137.80	710.70	11.35	18.82	13.66	nd	0.026	nd	15.6	50/90	55.14	39.15	39.43	

Water Quality Data

TIME			pH			CONDUCTIVITY										TDS											TURBIDITY		SDI	OTHER					
Date MM/DD/YY	Time hh:mm	Operation Time hh.hh	$pH_{F\text{-}sys}$ SC5	pH $pH_{P\text{-}sys}$ SC11	$pH_{C\text{-}sys}$ SC7	$C_{CF\text{-}out}$ SC3	$C_{F\text{-}PX\text{-}out}$ SC6	$C_{F\text{-}sys}$ SC5	$C_{P\text{-}total\ sys}$ SC11	Conductivity (mS/cm) $C_{P\text{-}1st\ stage\ 1}$ SC14	$C_{P\text{-}1st\ stage\ 2}$	$C_{P\text{-}2nd\ stage}$ SC10	$C_{interstage}$ SC 13	$C_{C\text{-}sys}$ SC12	$C_{C\text{-}PX\text{-}out}$ SC7	$TDS_{CF\text{-}out}$ SC3	$TDS_{F\text{-}PX\text{-}out}$ SC6	% Inc @ memb in	$TDS_{F\text{-}sys}$ SC5	$TDS_{P\text{-}sys}$ SC11	TDS (mg/L) $TDS_{P\text{-}1st\ stage}$ SC14	$TDS_{P\text{-}1st\ stage}$	$TDS_{P\text{-}2nd\ stage}$ SC10	$TDS_{Interstage}$ SC 13	$TDS_{C\text{-}sys}$ SC12	$TDS_{C\text{-}PX\text{-}out}$ SC7	Turbidity (NTU) $NTU_{MF\text{-}in}$ SC1	$NTU_{CF\text{-}out}$ meter	Density Index $SDI_{CF\text{-}out}$ CART	V_{TANK} (gallons)	Inhibitor Pump Speed (gph)	HP VFD Speed (Hertz)	PX VFD Speed (Hertz)	FEED VFD Speed (Hertz)	Notes
06/24/10	22:53	14019.47	7.52	6.47	7.59	5037	5239	5057	365.2	223.6	216.7	1050	13.27	20.4	**15.71**	3991.00	4170.00	4.5%	4009.00	245.70	147.80	143.00	741.20	11.70	19.35	14.24	nd	0.026	nd	12.9	50/90	55.20	39.29	38.70	
06/26/10	12:22	14042.20	7.48	6.47	7.61	5108	5247	5134	374.3	229.9	223	1080	13.41	20.52	**15.94**	4050.00	4173.00	3.0%	4077.00	252.10	151.80	147.20	762.10	11.92	19.49	14.47	nd	0.026	nd	10.4	50/90	55.20	39.23	40.63	
06/29/10	11:52	14073.72	7.47	6.48	7.56	5721	5927	5742	458.5	281.3	272.6	1405	15.5	23.22	**17.54**	4597.00	4771.00	3.8%	4609.00	311.70	186.40	180.20	1004.00	14.03	22.55	16.18	nd	0.027	nd	7.5	50/90	55.25	38.20	49.92	
06/30/10	11:38	14096.30	7.50	6.49	7.57	5703	5893	5733	451.2	277.6	269.5	1369	15.38	23.02	**17.44**	4577.00	4741.00	3.6%	4600.00	306.50	183.70	178.00	977.10	13.92	22.28	16.07	nd	0.026	nd	19.9	50/90	55.25	38.53	45.94	
07/07/10	11:40	14120.08	7.48	6.50	7.58	5636	5832	5667	438.2	268.4	260.6	910.1	14.75	22.31	**17.04**	4524.00	4689.00	3.6%	4546.00	297.70	177.50	171.90	909.90	13.27	21.51	15.65	nd	0.029	nd	17.5	50/90	55.28	39.23	45.32	
07/08/10	10:53	14143.29	7.49	6.53	7.66	4575	4720	4598	318.5	192.9	187.2	900.6	11.94	18.81	**14.18**	3599.00	3721.00	3.4%	3614.00	212.80	126.60	122.70	630.60	10.38	17.57	12.71	nd	0.029	nd	15.2	50/90	55.25	39.35	42.70	
07/10/10	15:03	14182.90	7.54	6.50	7.68	4642	4764	4655	327.3	198.1	192.2	923.2	12.09	18.93	**14.39**	3650.00	3760.00	3.0%	3665.00	219.00	130.20	126.10	647.00	10.53	17.71	12.92	nd	0.030	nd	11	50/90	55.25	39.38	47.23	
07/11/10	10:30	14202.39	7.51	6.50	7.68	4645	4757	4656	327.2	198.2	192.1	919.4	12.06	18.89	**14.2**	3650.00	3756.00	2.9%	3663.00	218.90	130.20	126.00	644.40	10.50	17.66	12.72	nd	0.031	nd	9	50/90	55.22	39.40	47.05	
07/13/10	12:22	14252.26	7.63	6.53	7.65	4639	4779	4661	324.8	198.2	192.1	914.5	12.04	18.78	**14.71**	3648.00	3769.00	3.3%	3666.00	217.20	130.20	126.00	640.70	10.47	17.52	13.24	nd	0.029	0.46	24	50/90	55.20	39.46	44.82	Filled Antiscallent tank with 20 gals of 10:1 d
07/14/10	12:19	14276.22	7.54	6.52	7.65	4638	4829	4656	323.8	198	192.2	912.5	12.04	18.76	**14.5**	3644.00	3811.00	4.6%	3661.00	216.40	130.10	126.10	639.20	10.47	17.51	13.02	nd	0.028	nd	21.8	50/90	55.20	39.52	43.91	
07/15/10	12:18	14300.16	7.46	6.55	7.66	4632	4787	4663	324	198.3	192.2	916.1	12.04	18.78	**13.7**	3635.00	3774.00	3.8%	3667.00	216.50	130.20	126.10	641.50	10.48	17.53	13.35	nd	0.029	nd	19	50/90	55.17	39.46	41.31	
07/17/10	12:14	14324.69	7.50	6.56	7.66	4624	4798	4647	329.6	199.2	193.2	929.6	12.07	18.83	**14.48**	3633.00	3785.00	4.2%	3656.00	220.60	130.90	126.80	651.90	10.51	17.60	13.01	nd	0.028	nd	16.7	50/90	55.20	33.35	46.16	
07/18/10	12:37	14349.07	7.52	6.54	7.66	4615	4809	4625	324.3	197.7	191.9	917.5	12.01	18.71	**14.43**	3629.00	3795.00	4.6%	3636.00	216.90	129.90	125.90	642.80	10.44	17.47	12.96	nd	0.028	nd	14	50/90	55.23	39.40	46.25	
07/19/10	12:07	14372.57	7.54	6.52	7.65	4596	4725	4631	325.1	197.9	191.8	921.3	11.98	18.65	**14.29**	3606.00	3721.00	3.2%	3637.00	217.30	130.00	125.80	645.00	10.42	17.40	12.82	nd	0.027	nd	11.8	50/90	55.19	39.35	46.47	
07/20/10	12:03	14396.51	7.51	6.52	7.70	4617	4810	4640	324.9	197.5	192	919.3	12	18.63	**14.37**	3629.00	3796.00	4.6%	3646.00	217.20	129.80	125.80	643.60	10.44	17.38	12.90	nd	0.026	nd	9.2	50/90	55.22	39.40	43.45	Added 5 gallons of antiscallent 10:1 dilutions
07/21/10	12:30	14420.97	7.50	6.54	7.68	4598	4720	4622	324.9	197.9	191.9	924.6	12.02	18.69	**14.35**	3610.00	3717.00	3.0%	3631.00	217.20	130.00	125.90	648.00	10.46	17.45	12.87	nd	0.026	0.697	11.3	50/90	55.17	39.29	43.27	
07/22/10	12:33	14445.01	7.55	6.59	7.69	4595	4717	4610	326.7	198	191.9	932.1	12.09	18.76	**14.51**	3606.00	3716.00	3.1%	3622.00	218.70	130.10	126.00	654.10	10.52	17.54	13.04	nd	0.028	nd	9	50/90	55.20	39.17	46.19	main plant switch wells to 515. Added 5 gal
07/25/10	13:34	14492.08	7.61	6.56	7.70	4536	4673	4553	316.7	193.6	187.7	895.5	11.8	18.34	**14.23**	3560.00	3678.00	3.3%	3573.00	211.50	127.10	123.00	627.10	10.25	17.03	12.76	nd	0.031	nd	9.1	50/90	55.20	39.52	52.10	
07/27/10	12:12	14537.99	7.49	6.55	7.72	4524	4711	4537	313.6	192.5	186.6	882.9	11.73	18.17	**14.14**	3553.00	3715.00	4.6%	3561.00	209.50	126.40	122.30	617.60	10.18	16.89	12.67	nd	0.027	nd	4.7	50/90	55.22	39.64	51.89	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**12 gfd flux 85% Recovery**																				
07/28/10	12:57	14560.86	7.52	6.65	7.68	4527	4654	4539	495.2	283.4	274.8	2064	14.98	22.06	**14.67**	3548.00	3661.00	3.2%	3561.00	337.60	187.90	181.80	1526.00	13.51	21.23	13.20	nd	0.028	0.324	25	20/45	44.62	27.71	42.79	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 85% Recovery**																				
07/29/10	13:55	14585.09	7.56	6.57	7.71	4495	4643	4496	393.2	220.2	212.9	1428	14.04	22.58	**15.22**	3520.00	3651.00	3.7%	3523.00	265.50	145.40	140.30	1022.00	12.55	21.82	13.75	nd	0.037	0.381	24.6	23/45	55.37	33.75	48.49	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**16 gfd flux 85% Recovery**																				
07/30/10	12:20	14607.52	7.61	6.59	7.71	4489	4665	4501	365.7	204.4	197.6	1296	13.95	22.68	**14.55**	3520.00	3670.00	4.3%	3531.00	246.20	134.50	129.80	923.30	12.47	21.90	13.08	nd	0.028	0.394	24	25/45	59.53	35.83	52.10	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**BASELINE**																				
07/31/10	14:15	14633.42	7.57	6.58	7.62	4575	4778	4585	317.7	195.7	189.7	909.5	12.01	18.39	**14.22**	3596.00	3769.00	4.8%	3602.00	212.30	128.50	124.40	637.50	10.45	17.10	12.74	nd	0.028	nd	23.7	24/45	55.43	39.52	40.41	
08/01/10	14:14	14657.41	7.51	6.55	7.67	4570	4754	4592	317.2	195.6	190	909.5	11.37	18.38	**14.1**	3590.00	3749.00	4.4%	3608.00	211.80	128.50	124.60	637.20	9823.00	17.10	12.62	nd	0.031	nd	23	24/45	55.43	39.46	40.75	
08/02/10	11:54	14679.08	7.59	6.56	7.52	4595	4743	4584	316.6	195.4	189.5	907.8	12.02	18.42	**14.2**	3611.00	3738.00	3.5%	3600.00	211.40	128.30	124.30	635.90	10.46	17.12	12.72	nd	0.028	nd	22.4	24/45	55.41	39.58	38.78	
08/03/10	13:00	14704.18	7.62	6.54	7.69	4578	4706	4591	316.9	195.4	189.7	907.2	12	18.27	**14.16**	3597.00	3708.00	3.1%	3607.00	211.90	128.40	124.50	635.60	10.44	16.99	12.68	nd	0.028	nd	22	24/45	55.43	39.61	40.51	
08/04/10	12:14	14727.42	7.57	6.51	7.76	4570	4697	4592	312.6	195	189.3	899.9	11.96	17.86	**14.09**	3589.00	3698.00	3.0%	3606.00	208.60	128.10	124.20	630.50	10.40	16.52	12.61	ns	0.027	nd	21.7	24/45	55.40	39.67	39.78	
08/05/10	12:27	14751.64	7.50	6.50	7.72	4571	4713	4585	315.7	195.4	189.4	900.7	11.91	18.15	**13.97**	3590.00	3716.00	3.5%	3600.00	210.80	128.30	124.20	630.70	10.35	16.80	12.48	nd	0.027	nd	21.2	24/45	55.43	39.67	40.50	
08/07/10	14:18	14775.38	7.53	6.54	7.65	4551	4686	4546	318.1	195.1	188.7	902.3	11.8	18.25	**13.74**	3569.00	3690.00	3.4%	3567.00	212.60	128.20	123.70	631.60	10.25	16.86	12.26	nd	0.037	nd	20.7	24/45	55.11	39.64	38.14	
08/08/10	13:02	14798.11	7.49	6.56	7.61	4542	4691	4556	316.2	194.5	188.4	898.4	11.79	18.26	**14.05**	3565.00	3694.00	3.6%	3575.00	211.10	127.80	123.50	628.80	10.23	16.97	12.57	nd	0.037	nd	20	24/45	55.10	39.61	41.60	
08/09/10	10:50	14819.90	7.58	6.58	7.73	4551	4710	4566	314.8	193.5	187.8	895.1	11.81	18.17	**14.07**	3575.00	3711.00	3.8%	3585.00	210.30	127.10	123.20	626.70	10.26	16.88	12.60	nd	0.038	nd	19.7	24/45	55.11	39.67	41.68	
08/11/10	12:33	14869.06	7.59	6.60	7.67	4563	4697	4570	315.2	194.2	188.4	900.6	11.86	18.2	**14.07**	3582.00	3699.00	3.3%	3586.00	210.40	127.50	123.50	630.40	10.31	16.87	12.59	nd	0.038	nd	18.3	24/45	55.37	39.61	39.89	
08/12/10	13:03	14893.53	7.57	6.61	7.62	4539	4657	4567	314.1	193.7	187.4	899.3	11.85	18.2	**14.1**	3557.00	3665.00	3.0%	3583.00	209.60	127.20	122.80	629.60	10.29	16.87	12.63	nd	0.039	nd	18	24/45	55.40	39.64	42.86	
08/17/10	17:05	14894.82	7.48	6.58	7.62	4529	4649	4568	236.4	142.6	137.6	526.2	10.32	18.57	**14.31**	3544.00	3659.00	3.2%	3580.00	156.00	92.31	89.15	359.20	8808.00	17.31	12.82	nd	0.043	nd	17.9	24/45	55.08	41.60	39.05	
08/18/10	12:14	14913.98	7.48	6.59	7.67	4533	4661	4549	264	158.3	153.2	605.2	10.49	18.34	**14.26**	3549.00	3665.00	3.3%	3567.00	174.10	102.80	99.34	416.50	8976.00	17.02	12.78	nd	0.039	nd	17.7	24/45	55.05	41.31	39.28	
08/19/10	12:46	14938.52	7.47	6.57	7.65	4525	4672	4550	267	161.1	156.1	631.3	10.57	17.94	**14.23**	3553.00	3678.00	3.5%	3573.00	176.30	104.70	101.30	435.20	9064.00	16.63	12.76	nd	0.034	nd	17.2	24/45	55.13	41.31	37.07	
08/21/10	19:25	14969.95	7.53	6.68	7.65	4489	4606	4509	277.7	165.6	160.3	680.4	10.7	18.13	**14.04**	3511.00	3619.00	3.1%	3533.00	183.80	107.70	104.10	469.70	9186.00	16.85	12.56	nd	0.042	nd	16.4	24/45	55.05	40.45	31.86	
08/22/10	19:00	14993.54	7.40	6.66	7.67	4464	4581	4489	279.8	165.9	160.6	691.9	10.8	18.24	**14.09**	3480.00	3608.00	3.7%	3516.00	185.20	107.90	104.30	477.80	9274.00	16.95	12.61	nd	0.039	nd	16	24/45	55.37	40.31	39.56	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 75-75% Recovery**																				
08/24/10	17:16	15031.98	7.47	6.59	7.64	4471	4613	4505	240.6	155.4	150.9	503.7	9571	15.66	**12.58**	3505.00	3629.00	3.5%	3536.00	158.80	100.80	97.89	343.40	8097.00	14.20	11.02	nd	0.032	0.638	15.5	24/45	55.28	47.48	42.05	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 75-80% Recovery**																				
08/25/10	12:26	15051.15	7.77	6.56	7.63	4478	9531	5487	337.4	218.8	217.3	732.4	12.32	19.01	**19.04**	3511.00	8072.00	129.9%	4389.00	226.30	144.70	143.70	508.40	10.77	17.81	17.84	nd	0.028	0.6	15	24/45	55.55	46.67	31.60	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 75-85% Recovery**																				
08/26/10	12:16	15073.50	7.72	6.60	7.75	4484	15410	6556	489.2	308.5	307.1	1205	16.3	23.62	**23.74**	3514.00	13960.00	297.3%	5321.00	333.40	205.70	204.70	854.80	14.84	22.99	23.11	nd	0.036	nd	14.5	23/45	55.49	44.56	30.00	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**BASELINE 14.9 gfd flux 80-80% Recovery**																				
08/26/10	21:45	15082.99	7.60	6.62	7.68	4488	4685	4512	284.8	169.9	164.4	759.4	11.3	18.41	**14.12**	3522.00	3689.00	4.7%	3542.00	189.00	110.80	106.90	527.50	9769.00	17.09	12.65	nd	0.030	nd	14	24/45	55.60	39.35	31.82	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 80-80% Recovery**																				
08/28/10	12:12	15108.11	7.52	6.58	7.66	4525	4715	4546	292	173.5	168.3	778.3	11.36	18.46	**14.2**	3550.00	3714.00	4.6%	3569.00	194.00	113.20	109.60	540.60	9831.00	17.20	12.73	nd	0.030	nd	13.8	24/45	55.61	39.40	41.88	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 80-85% Recovery**																				
08/29/10	12:40	15132.58	7.73	6.66	7.70	4523	15160	5645	521.2	323.2	321.2	1542	17.76	25.65	25.66	3545.00	13690.00	286.2%	4607.00	355.70	216.00	214.60	1113.00	16.42	25.26	25.24	nd	0.037	0.711	13.2	23/45	55.60	39.40	30.48	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 75-90% Recovery**																				
08/30/10	12:03	15155.80	7.92	6.76	7.66	4536	26,670	9114	701.9	608.1	659	3500	31.84	33.6	**33.47**	3557.00	26450.00	643.6%	7666.00	484.50	418.60	454.50	2679.00	32.46	34.60	34.51	nd	0.037	nd	12.3	29/45	55.58	38.96	30.00	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**BASELINE 14.9 gfd flux 80-80% Recovery**																				
09/02/10	13:16	15159.30	7.49	6.68	7.67	4520	4725	4535	300	170.3	164.8	1202	13.04	18.05	**12.85**	3540.00	3717.00	5.0%	3556.00	199.60	110.90	107.10	852.60	11.47	16.73	11.28	nd	0.039	nd	12.2	24/45	55.14	37.68	45.20	
09/03/10	13:05	15183.12	7.53	6.53	7.64	4514	4795	4553	300	176.9	171.2	1404	13.67	17.65	**12.64**	3542.00	3784.00	6.8%	3575.00	199.70	115.60	111.60	1005.00	12.19	16.30	11.09	nd	0.030	nd	12	24/45	55.20	36.68	45.44	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**BASELINE 14.9 gfd flux 80-80% Recovery**																				
10/01/10	14:49	15185.85	7.58	6.58	7.66	4562	4682	4572	270.8	160.8	155.8	558.7	9901	18.58	**13.56**	3585.00	3687.00	2.8%	3592.00	179.00	104.50	101.10	382.30	8409.00	17.34	12.09	nd	0.039	nd	12	24/45	55.52	41.45	49.47	
10/02/10	12:24	15207.42	7.55	6.64	7.68	4565	4702	4588	267.3	162.2	157.3	548.1	9950	18.58	**13.61**	3581.00	3703.00	3.4%	3604.00	176.60	105.50	102.10	374.80	8456.00	17.34	12.14	nd	0.040	nd	11.3	24/45	55.46	41.51	48.89	
10/03/10	11:40	15230.69	7.50	6.59	7.70	4570	4747	4597	264	162.3	157.6	531.2	9896	18.39	**13.7**	3591.00	3745.00	4.3%	3614.00	174.20	105.60	102.40	362.10	8407.00	17.13	12.23	nd	0.040	nd	10.6	24/45	55.37	42.01	49.24	
10/04/10	12:20	15255.36	7.62	6.56	7.69	4565	4724	4579	261.3	161.8	157.3	519.5	9810	18.28	**13.48**	3588.00	3723.00	3.8%	3602.00	172.40	105.30	102.20	355.00	8324.00	17.03	12.01	nd	0.040	nd	10	24/45	55.37	42.19	49.33	
10/05/10	12:34	15279.61	7.61	6.58	7.67	4560	4773	4584	260.4	161.9	157.4	517.3	9826	18.33	**13.71**	3587.00	3766.00	5.0%	3604.00	171.80	105.30	102.30	353.50	8341.00	17.07	12.26	nd	0.032	nd	9.5	24/45	55.40	42.45	49.05	
10/06/10	12:29	15303.52	7.55	6.59	7.69	4564	4716	4603	260.8	162.2	157.7	517.7	9800	18.27	**13.45**	3584.00	3717.00	3.7%	3617.00	172.00	105.50	102.40	353.40	8309.00	17.05	12.00	nd	0.041	nd	9	24/45	55.37	42.22	49.59	
10/07/10	11:14	15326.28	7.62	6.62	7.69	4577	4768	4605	259.9	162.5	158	514.5	9840	18.31	**13.56**	3598.00	3763.00	4.6%	3621.00	171.50	105.70	102.70	351.40	8353.00	17.05	12.08	nd	0.042	nd	8.5	24/45	55.40	42.45	49.31	
10/09/10	14:04	15351.53	7.56	6.61	7.66	4558	4727	4582	267.1	164.3	159.8	538.1	9894	18.36	**13.48**	3580.00	3727.00	4.1%	3600.00	176.40	106.80	103.80	367.80	8412.00	17.09	12.01	nd	0.040	nd	17.8	24/45	55.53	41.66	51.31	Added 10 gals to to anti-scalent tant 1:4 Dilu
10/10/10	13:00	15374.36	7.53	6.60	7.69	4550	4727	4579	262.7	163.2	158.9	526.5	9866	18.39	**13.46**	3577.00	3727.00	4.2%	3599.00	173.30	106.20	103.20	359.70	8378.00	17.15	12.03	nd	0.040	nd	17.3	24/45	55.58	41.89	51.46	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 75-85% Recovery 2 Motnth Demo Point**																				
10/11/10	13:02	15398.40	7.74	6.66	7.71	4554	16790	6917	514.7	328.9	329.3	1075	16.16	25.66	25.6	3577.00	15380.00	330.0%	5642.00	351.20	219.90	220.60	759.50	14.70	25.31	25.26	nd	0.040	0.41	16.8	23/45	55.55	44.36	43.68	
10/12/10	12:09	15421.52	7.75	6.65	7.70	4573	16720	7042	516.4	331.9	331.1	1081	16.21	25.74	25.65	3595.00	15300.00	325.6%	5760.00	352.60	222.20	221.50	764.60	14.76	25.37	25.31	nd	0.040	nd	16.2	23/45	55.34	44.30	41.97	
10/13/10	12:12	15445.56	7.78	6.61	7.71	4552	16480	6084	506.9	326.2	327.3	1052	16.01	25.44	25.39	3577.00	15040.00	320.5%	4912.00	345.80	218.30	219.00	744.30	14.56	25.07	25.01	nd	0.040	nd	15.9	23/45	55.37	44.41	43.12	
10/14/10	12:11	15469.55	7.79	6.69	7.71	4554	16540	6245	510.4	325.6	326.5	1053	15.97	25.33	25.25	3581.00	15090.00	321.4%	5050.00	348.40	217.80	218.50	744.20	14.52	24.94	24.87	nd	0.039	nd	15.3	23/45	55.37	44.30	43.21	
10/16/10	12:29	15495.05	7.76	6.64	7.55	4556	16410	5893	506.7	327.6	325.4	1061	15.96	25.42	25.37	3581.00	14990.00	318.6%	4759.00	345.90	219.30	217.80	749.80	14.52	25.07	24.98	nd	0.042	nd	14.8	23/45	55.72	44.36	41.51	
10/17/10	13:00	15519.56	7.60	6.62	7.70	4552	16420	6080	507.6	325.9	326.8	1056	15.95	25.37	25.26	3573.00	14970.00	319.0%	4904.00	346.40	218.40	218.80	745.50	14.49	24.94	24.86	nd	0.042	nd	14.3	23/45	55.72	44.44	41.50	
10/18/10	12:25	15542.98	7.79	6.62	7.69	4550	16850	7104	521.4	334	335.6	1098	16.29	25.7	25.66	3577.00	15430.00	331.4%	5816.00	356.30	223.90	225.10	778.80	14.84	25.34	25.29	nd	0.041	0.68	13.8	23/45	55.52	44.09	41.63	
10/19/10	12:41	15567.26	7.75	6.67	7.71	4554	16930	6218	521	336.6	336.9	1083	16.23	25.61	25.42	3579.00	15510.00	333.4%	5028.00	355.90	225.70	225.90	765.70	14.77	25.23	25.05	nd	0.042	nd	13.5	23/45	55.52	44.44	41.54	
10/20/10	12:38	15591.21	7.82	6.66	7.70	4556	16920	6612	520.2	336.1	334.8	1093	16.34	25.77	25.69	3580.00	15510.00	333.2%	5371.00	355.30	225.30	224.50	773.60	14.89	25.46	25.35	nd	0.042	0.46	13	23/45	55.55	44.18	42.06	
10/21/10	14:22	15616.95	7.77	6.66	7.68	4558	16850	7247	520.7	336.7	337.6	1081	16.27	25.57	25.57	3584.00	15430.00	330.5%	5948.00	355.70	225.70	226.40	764.10	14.82	25.19	25.22	nd	0.042	nd	12.5	23/45	55.55	44.53	43.54	
10/23/10	14:42	15649.86	7.77	6.69	7.69	4561	16890	6458	526.2	339.9	338.9	1105	16.3	25.5	25.53	3590.00	15510.00	332.0%	5240.00	359.70	228.10	227.40	781.40	14.85	25.14	25.16	nd	0.043	nd	11.9	23/45	55.58	44.36	42.36	
10/24/10	13:09	15672.32	7.80	6.69	7.72	4566	17050	7353	529.1	341.2	342.8	1109	16.48	25.66	25.61	3594.00	15660.00	335.7%	6048.00	358.90	229.10	230.10	785.40	15.05	25.31	25.26	nd	0.043	nd	11.3	23/45	55.58	44.33	42.39	
10/25/10	12:02	15695.17	7.82	6.71	7.72	4562	16810	7310	518.5	337.1	336.9	1077	16.15	25.45	25.38	3590.00	15380.00	328.4%	6009.00	354.30	226.10	226.00	761.90	14.70	25.07	25.01	nd	0.042	nd	11	23/45	55.61	44.38	42.77	
10/26/10	11:26	15718.60	7.77	6.63	7.74	4562	17010	6607	517.9	338.6	339.2	1079	16.48	25.6	25.55	3593.00	15640.00	335.3%	5368.00	353.80	227.10	227.60	763.80	15.05	25.24	25.19	nd	0.042	nd	12.3	23/45	55.61	44.50	43.02	
10/27/10	12:26	15743.60	7.83	6.66	7.65	4559	16850	6611	514.5	336.1	337.1	1081	16.47	25.61	25.56	3590.00	15510.00	332.0%	5372.00	351.50	225.40	226.10	764.30	15.03	25.25	25.20	nd	0.042	0.561	11.9	24/45	55.52	44.09	43.10	
10/28/10	11:23	15766.54	7.83	6.67	7.74	4565	17150	6913	520.6	339.2	341.7	1095	16.66	25.83	25.78	3596.00	15780.00	338.8%	5642.00	355.80	227.60	229.30	775.60	15.25	25.55	25.45	nd	0.042	nd	11.3	24/45	55.61	44.12	43.49	
10/30/10	13:12	15802.84	7.74	6.63	7.64	4572	16380	6415	505.3	333.2	335.9	1064	16.29	25.33	25.23	3594.00	14940.00	315.7%	5198.00	344.90	223.30	225.20	750.70	14.84	24.92	24.85	nd	0.042	nd	8.8	24/45	55.55	44.18	39.29	
10/31/10	12:41	15826.32	7.66	6.69	7.71	4568	16580	6895	505	333.9	335.8	1059	16.37	25.3	25.28	3588.00	15220.00	324.2%	5624.00	344.80	223.80	225.20	748.80	14.93	24.93	24.88	nd	0.042	nd	8	24/45	55.58	44.30	39.53	

TIME			pH			CONDUCTIVITY										TDS											TURBIDITY		SDI	OTHER					
Date MM/DD/YY	Time hh:mm	Operation Time hh.hh	$pH_{F\text{-}sys}$ SC5	pH $pH_{P\text{-}sys}$ SC11	$pH_{C\text{-}sys}$ SC7	$C_{CF\text{-}out}$ SC3	$C_{F\text{-}PX\text{-}out}$ SC6	$C_{F\text{-}sys}$ SC5	$C_{P\text{-}total\ sys}$ SC11	Conductivity (mS/cm) $C_{P\text{-}1st\ stage\ 1}$ SC14	$C_{P\text{-}1st\ stage\ 2}$	$C_{P\text{-}2nd\ stage}$ SC10	$C\text{-}_{Interstage}$ SC 13	$C_{C\text{-}sys}$ SC12	$C_{C\text{-}PX\text{-}out}$ SC7	$TDS_{CF\text{-}out}$ SC3	$TDS_{F\text{-}PX\text{-}out}$ SC6	% Inc @ memb in	$TDS_{F\text{-}sys}$ SC5	$TDS_{P\text{-}sys}$ SC11	TDS (mg/L) $TDS_{P\text{-}1st\ stage}$ SC14	$TDS_{P\text{-}1st\ stage}$	$TDS_{P\text{-}2nd\ stage}$ SC10	$TDS_{Interstage}$ SC 13	$TDS_{C\text{-}sys}$ SC12	$TDS_{C\text{-}PX\text{-}out}$ SC7	Turbidity (NTU) $NTU_{MF\text{-}in}$ SC1	$NTU_{CF\text{-}out}$ meter	Density Index $SDI_{CF\text{-}out}$ CART	V_{TANK} (gallons)	Inhibitor Pump Speed (gph)	HP VFD Speed (Hertz)	PX VFD Speed (Hertz)	FEED VFD Speed (Hertz)	Notes
11/01/10	13:05	15850.72	7.74	6.68	7.72	4565	16780	6620	511.4	338.1	338.3	1089	16.58	25.52	25.57	3595.00	15380.00	327.8%	5380.00	349.30	226.90	227.00	770.50	15.16	25.13	25.20	nd	0.034	0.528	23	24/45	55.61	43.77	39.56	Added 15 gals to to anti-scalent tant 1:4 Dilu
11/02/10	11:40	15873.33	7.66	6.70	7.70	4554	16880	6632	511.8	338.1	340.9	1097	16.68	25.61	25.56	3588.00	15480.00	331.4%	5405.00	349.70	226.90	228.80	775.80	15.27	25.26	25.20	nd	0.032	nd	22.3	24/45	55.61	43.62	33.47	
11/03/10	11:46	15897.41	7.79	6.66	7.69	4561	16810	6735	506.8	338.4	340.3	1088	16.67	25.44	25.37	3589.00	15410.00	329.4%	5481.00	346.10	227.00	228.40	769.50	15.25	25.06	24.99	nd	0.039	nd	21.8	24/45	55.61	43.59	39.56	
11/04/10	12:10	15921.81	7.73	6.64	7.71	4560	16770	6307	505.8	340.1	340.1	1092	16.8	25.58	25.48	3589.00	15400.00	329.1%	5107.00	345.40	228.10	228.50	772.80	15.40	25.21	25.12	nd	0.039	0.396	21.3	24/45	55.40	43.38	39.17	
11/06/10	11:34	15946.78	7.80	6.67	7.74	4552	16540	6748	508.7	337.1	338.8	1106	16.61	25.24	25.18	3584.00	15130.00	322.2%	5494.00	347.50	226.10	227.30	782.60	15.20	24.81	24.75	nd	0.043	nd	20.8	24/45	55.40	43.21	42.55	
11/07/10	12:05	15972.29	7.75	6.69	7.71	4564	17020	6714	519.7	346.8	349.3	1131	16.99	25.48	25.38	3590.00	15630.00	335.4%	5461.00	355.00	233.00	234.70	801.10	15.59	25.10	25.01	nd	0.043	nd	20.2	24/45	55.37	43.27	42.69	
11/08/10	12:13	15996.42	7.79	6.70	7.71	4565	17010	6591	511.7	347.5	347.8	1113	17.05	25.43	25.39	3595.00	15610.00	334.2%	5355.00	349.60	233.40	233.60	787.20	15.67	25.08	25.01	nd	0.043	nd	19.8	24/45	55.37	43.27	42.18	
11/09/10	12:25	16020.62	7.80	6.70	7.68	4560	16690	6746	499.5	338.7	339.7	1103	16.98	25.35	25.3	3589.00	15270.00	325.5%	5490.00	341.50	227.20	228.00	780.70	15.58	24.93	24.89	nd	0.043	0.451	18.9	24/45	55.40	42.71	42.34	
11/10/10	11:06	16043.31	7.81	6.66	7.69	4552	17070	7177	510.8	348.7	347.5	1137	17.37	25.58	25.49	3583.00	15690.00	337.9%	5888.00	348.90	234.30	233.40	805.50	16.01	25.21	25.13	nd	0.043	nd	18.3	24/45	55.43	42.51	42.34	
11/21/10	10:57	16044.23	7.72	6.71	7.61	4564	17270	5580	521.9	338.5	339.8	1204	17.41	25.85	25.75	3618.00	15910.00	339.7%	4477.00	357.10	227.90	228.20	855.40	16.07	25.51	25.45	nd	nd	nd	18.3	24/45	55.40	42.69	44.95	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 80-80% Recovery Baseline**																				
11/25/10	15:07	16070.23	7.58	6.51	7.79	4530	4674	4553	237.8	145.1	142.3	505.9	10.26	18.82	14.89	3578.00	3691.00	3.2%	3585.00	157.50	94.20	92.25	345.70	8772.00	17.61	13.45	nd	0.044	nd	18	25/45	55.22	39.96	47.01	Data reflect silica clean
11/26/10	13:34	16092.68	7.74	6.68	7.81	4523	4735	4569	250.3	154.8	151.8	524.8	10.19	18.52	14.96	3569.00	3736.00	4.7%	3595.00	165.40	100.50	98.54	358.90	8695.00	17.57	13.51	nd	0.043	nd	17.5	25/45	55.11	40.31	47.06	
11/27/10	12:08	16115.24	7.74	6.69	7.84	4529	4726	4543	250	155.4	152.5	522.5	10.19	18.61	14.94	3569.00	3731.00	4.5%	3574.00	165.20	101.00	99.06	357.30	8709.00	17.39	13.50	nd	0.040	nd	16.8	25/45	55.52	40.40	47.30	
11/28/10	13:28	16140.58	7.67	6.70	7.78	4531	4691	4575	251	157.2	153.9	523	10.21	18.51	14.93	3570.00	3716.00	4.1%	3599.00	165.80	102.10	99.98	357.90	8726.00	17.24	13.47	nd	0.042	nd	16	25/45	55.49	40.43	47.51	
11/29/10	13:17	16164.39	7.73	6.69	7.83	4525	4746	4550	252.1	156.3	153.6	527	10.25	18.57	14.94	3580.00	3751.00	4.8%	3582.00	166.60	101.70	99.79	360.50	8772.00	17.34	13.50	nd	0.043	nd	15.5	25/45	55.55	40.25	47.21	
11/30/10	12:45	16187.87	7.75	6.67	7.81	4531	4691	4545	253.5	157.9	154.8	533.3	10.25	18.58	14.82	3571.00	3705.00	3.8%	3576.00	167.50	102.60	100.50	364.90	8777.00	17.32	13.38	nd	0.042	nd	14.5	25/45	55.52	40.17	47.15	
12/01/10	12:12	16211.31	7.79	6.69	7.82	4525	4708	4550	254.1	158.1	154.9	534.5	10.25	18.53	14.89	3571.00	3710.00	3.9%	3581.00	167.80	102.70	101.00	365.90	8768.00	17.36	13.45	nd	0.042	nd	14	25/45	55.52	40.22	47.56	
12/02/10	12:59	16236.10	7.75	6.69	7.80	4522	4700	4535	253.7	159	156	529.8	10.18	18.43	14.87	3563.00	3705.00	4.0%	3563.00	167.50	103.30	101.30	362.40	8688.00	17.13	13.42	nd	0.043	0.574	13.2	25/45	55.47	40.46	47.39	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 75-85% Recovery 2 Motnth Demo Point**																				
12/04/10	12:30	16257.62	7.93	6.71	7.77	4487	16670	6422	487.6	318.6	322.2	1015	16.17	25.14	25.05	3526.00	15250.00	332.5%	5206.00	332.80	213.10	215.70	716.20	14.71	24.72	24.64	nd	0.041	nd	12.5	24/45	55.61	44.33	36.23	
12/05/10	11:52	16280.99	7.86	6.68	7.80	4475	16670	6026	483.5	315.8	321.9	1009	16.19	25.13	25.17	3520.00	15260.00	333.5%	4864.00	329.80	211.20	215.60	711.90	14.75	24.75	24.77	nd	0.042	nd	11.8	24/45	55.61	44.36	36.77	
12/07/10	14:00	16330.61	7.84	6.68	7.79	4499	16720	6657	485.9	319.2	324.6	1025	16.35	25.29	25.21	3546.00	15320.00	332.0%	5418	331.40	213.60	217.30	722.90	14.91	24.88	24.82	nd	0.045	nd	10.3	24/45	55.61	44.03	41.95	
12/08/10	12:54	16353.51	7.84	6.75	7.8	4494	16770	6804	486.5	321	324	1018	16.32	25.17	25.09	3535.00	15370.00	334.8%	5546	332.00	214.90	216.90	718.10	14.89	24.75	24.69	nd	0.045	0.609	9.8	24/45	55.63	44.09	41.13	
12/09/10	14:22	16378.98	7.89	6.75	7.8	4481	16720	6426	485.2	319.7	325.2	1020	16.34	25.14	25.07	3521.00	15320.00	335.1%	5216	331.10	213.90	217.70	719.40	14.89	24.73	24.66	nd	0.044	nd	9	24/45	55.63	44.06	42.06	
12/11/10	12:14	16403.11	7.83	6.69	7.8	4489	16410	6669	480.1	318.3	322.1	1010	16.21	24.99	24.94	3529.00	14970.00	324.2%	5425	327.10	212.90	215.50	712.40	14.79	24.54	24.5	nd	0.043	nd	8.3	24/45	55.66	43.95	34.14	
12/12/10	14:20	16429.22	7.86	6.67	7.76	4484	16570	6307	478.9	317.4	321.9	1008	16.29	25.06	25.1	3525.00	15170.00	330.4%	5110	326.60	212.30	215.40	710.40	14.85	24.64	24.69	nd	0.045	nd	7.8	24/45	55.72	43.97	34.93	
12/13/10	13:16	16452.14	7.78	6.71	7.79	4475	16990	6218	490.3	325.1	332.6	1044	16.74	25.51	25.42	3533.00	15580.00	341.0%	5032	334.70	217.70	223.00	738.30	15.34	25.15	25.08	nd	0.044	nd	22.7	24/45	55.69	43.68	33.46	
12/14/10	11:16	16474.22	7.78	6.72	7.79	4484	16780	6522	483.4	323.2	328.1	1038	16.68	25.5	25.37	3532.00	15410.00	336.3%	5299	329.90	216.30	219.90	731.40	15.27	25.07	25.02	nd	0.044	nd	21.9	24/45	55.4	43.45	34.85	
12/15/10	12:15	16499.13	7.82	6.69	7.75	4496	16660	6256	476.1	320.6	324.8	1012	16.5	25.04	24.94	3536.00	15280.00	332.1%	5064	324.50	214.40	217.50	714.10	15.08	24.61	24.53	nd	0.043	0.503	21.2	24/45	55.4	43.48	36.15	
12/16/10	12:04	16522.94	7.83	6.71	7.8	4485	16720	6698	479.7	325.9	328.5	1023	16.7	25.26	25.22	3529.00	15330.00	334.4%	5450	327.10	218.30	220.10	722.60	15.29	24.86	24.84	nd	0.045	nd	20.5	24/45	55.37	43.51	30	
12/18/10	12:28	16548.33	7.85	6.64	7.69	4478	16610	6636	477.9	323.4	325.6	1047	16.72	25.08	25.03	3523.00	15200.00	331.5%	5392	325.90	216.40	218.10	736.40	15.32	24.67	24.61	nd	0.044	nd	19.8	24/45	55.58	43.04	40.83	
12/23/10	20:30	16676.37	7.81	6.68	7.73	4475	16650	6389	462.5	325.2	329.1	1050	17.42	25.12	25.03	3523.00	15270.00	333.4%	5185	315.30	217.90	220.80	741.80	16.08	24.72	24.65	nd	0.046	nd	16	24/45	55.72	41.95	40.37	
12/25/10	16:07	16677.38	7.73	6.6	7.57	4459	17370	6752	469	306	309.9	976.7	16.52	25.62	25.55	3516.00	15930.00	353.1%	5504	319.00	204.10	207.00	688.00	15.11	25.27	25.22	nd	0.045	nd	16	24/45	55.28	44.44	35.4	Data reflect silica CIP
12/26/10	13:26	16698.69	7.75	6.69	7.81	4481	17000	6644	487.1	319.1	323.4	1009	16.33	25.17	25.09	3524.00	15750.00	346.9%	5408	332.60	213.40	216.50	711.60	14.9	24.78	24.68	nd	0.045	nd	15.7	24/45	55.47	44.31	36.81	
12/27/10	13:04	16722.33	7.8	6.69	7.79	4457	16860	6889	483.5	317.1	321.6	1009	16.23	25.2	25.12	3505.00	15490.00	341.9%	5627	330.00	212.10	215.30	712.10	14.79	24.81	24.72	nd	0.046	nd	15	24/45	55.49	43.97	38.64	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**14.9 gfd flux 85-85% Recovery**																				
12/28/10	16:26	16745.33	7.57	6.66	7.79	4478	4631	4472	324.7	176.5	172.1	893.1	12.06	22.43	16.04	3526.00	3649.00	3.5%	3511	217.60	115.40	112.40	626.10	10.52	21.68	14.61	nd	0.045	nd	14	24/45	55.61	33.9	43.45	
12/29/10	13:13	16766.12	7.58	6.72	7.79	4461	4602	4469	322.1	176.2	171.8	887.6	12.08	22.56	16.16	3513.00	3623.00	3.1%	3508	215.80	115.30	112.20	621.90	10.54	21.83	14.73	nd	0.045	0.654	13.3	24/45	55.58	33.9	39.43	
12/31/10	13:07	16813.04	7.62	6.69	7.81	4474	4608	4473	341.5	181.7	176.6	1002	12.64	23.42	16.24	3537.00	3632.00	2.7%	3518	229.80	119.10	115.60	707.30	11.09	22.83	14.83	nd	0.044	nd	12	24/45	55.43	32.75	42.61	
Optimized Isobaric Energy Recovery Demonstration - Hydranautics ESPA 1 Membranes															**BASELINE**																				
01/01/11	2:36 PM	16838.43	7.55	6.63	7.82	4467	4650	4480	251.8	158.1	154.8	525.7	10.09	18.42	14.68	3515	3665	4.3%	3522	166.40	102.80	100.60	359.90	8609	17.22	13.23	nd	0.045	nd	11	25/45	55.43	40.11	44.64	

Appendix C: White Papers

From 2005-2009 the Affordable Desalination Collaboration operated at Port Hueneme, California using a surface seawater feed source. Many of the ideas and concepts that were developed during this initial seawater testing provided a foundation for this TWDB brackish ground water study. For example, the high recovery under-flush process was first developed and tested at Port Hueneme to achieve seawater recoveries up to 65 percent. Therefore, we are also including in this section the white papers from the earlier testing that provide context to both seawater and brackish water applications.

MacHarg

Pressure Exchanger Helps Reduce Energy Costs

in Brackish Water RO System

By John P. MacHarg and Stuart A. McClellan

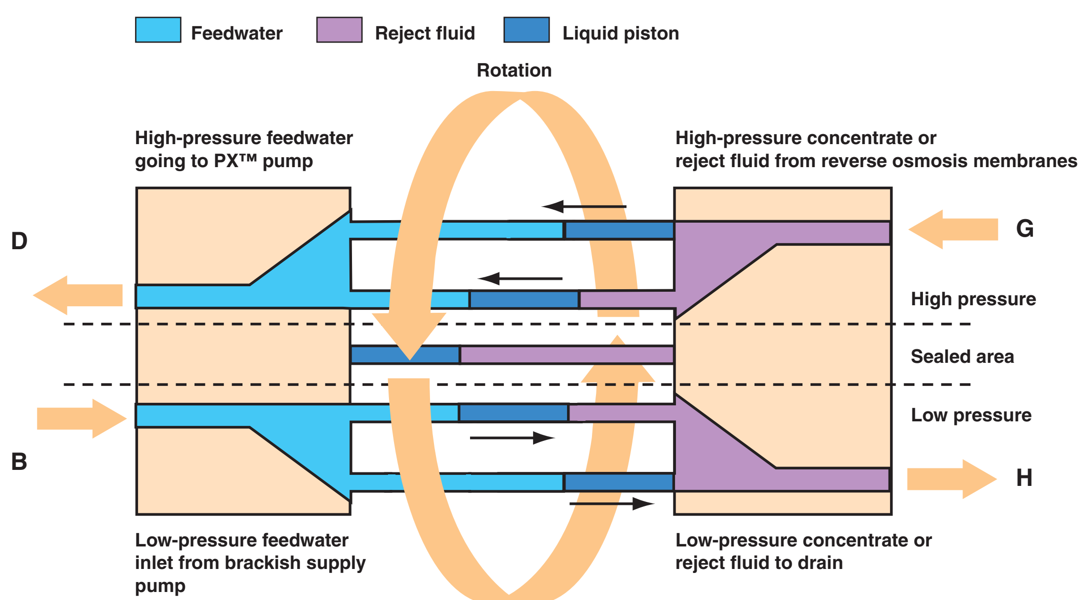
A device from Energy Recovery Inc. (ERI), which has been proven effective in hundreds of seawater reverse osmosis (RO) applications, has now been shown to save money in brackish RO plants as well. In the seawater desalination industry, ERI's Pressure Exchanger^{TM} (PX^{TM}) is well known as a reliable energy-recovery device that dramatically lowers operating costs. Until recently it was unknown whether the PX could achieve similar results in brackish water applications, but in February 2004 this question was answered at the Card Sound Golf Club desalination facility at the Ocean Reef Club in Key Largo, Fla. An ERI retrofit project at the Florida facility has shown that the PX can significantly lower the costs of brackish water RO applications—it is saving the Ocean Reef desalination facility an estimated $15,000 per year.

HOW THE PX WORKS

The PX unit uses the principle of positive displacement to pressurize filtered feedwater by direct contact with the high-pressure concentrate (waste) stream or the reject fluid from an RO system. Pressure transfer occurs in the longitudinal ducts of a ceramic rotor that spins inside a ceramic sleeve. The rotor-sleeve assembly is held between two ceramic end covers. At any given instant, half of the ducts are exposed to the side with high-pressure fluid and half are exposed to the side with low-pressure fluid. As the rotor turns, ducts pass a sealing area that separates the high-pressure side from the low-pressure side. This process is illustrated in Figure 1.

Feedwater pumped from the brackish water supply at low pressure flows into a duct on the left side of the figure. This flow expels concentrate from the duct on the right side of the figure. After the rotor turns past a sealed area, high-pressure

FIGURE 1 PX^{TM} sectional view



PX—Pressure Exchanger™

concentrate flows into the right side of the duct, pressurizing the feedwater. Pressurized feedwater then flows into the high-pressure feed line going to the PX pump. This pressure-exchange process is repeated for every duct with each revolution of the rotor such that the ducts are alternately filling and discharging. At a speed of 1,200 rpm, one revolution is completed every 1/20 of a second.

Figure 2 and Table 1 show the flow path of a typical RO–PX system. The concentrate from the RO membranes (G) passes through the PX, where its pressure is transferred directly to a portion of the incoming feedwater at up to 91% efficiency. This pressurized stream of feedwater (D), which is approximately equal in volume and pressure to the reject stream, passes through a PX auxiliary pump (not the main high-pressure pump) to add back the small amount of pressure lost from the differential pressure across the membranes and from friction in the piping and the PX. The PX booster pump drives the flow through the high-pressure side (G and D) of the PX. Fully pressurized feedwater then merges with the main feedwater line of the RO system after the main high-pressure pump.

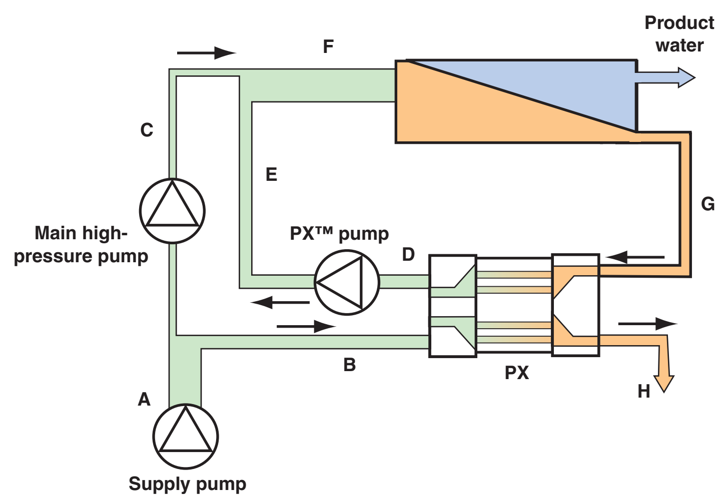
In an RO–PX system, the main pump is sized to equal the RO permeate flow plus a small amount of rotor lubrication flow, not the full RO feed flow. Therefore, the PX significantly reduces flow through the main pump. This point is significant because a reduction in the size of the main pump results in lower power consumption and operating costs.

TABLE 1 Flow rates and pressures at the Ocean Reef Club desalination facility

Diagram Location	Description	Flow Rate *gpm (L/s)*	Pressure *psi (kPa)*
A	Feed supply	495 (31.2)	28 (190)
B	PX™ low-pressure inlet	171 (10.8)	28 (190)
C	Main pump outlet	324 (20.4)	200 (1,380)
D	PX high-pressure outlet	171 (10.8)	184 (1,270)
E	PX pump outlet	171 (10.8)	200 (1,380)
F	Reverse osmosis feed stream	495 (31.2)	200 (1,380)
G	PX high-pressure inlet/reject	175 (11.0)	190 (1,310)
H	PX low-pressure outlet/reject	175 (11.0)	17 (120)
I	Product water	320 (20.2)	3 (20)

PX—Pressure Exchanger™

FIGURE 2 Typical PX™ system



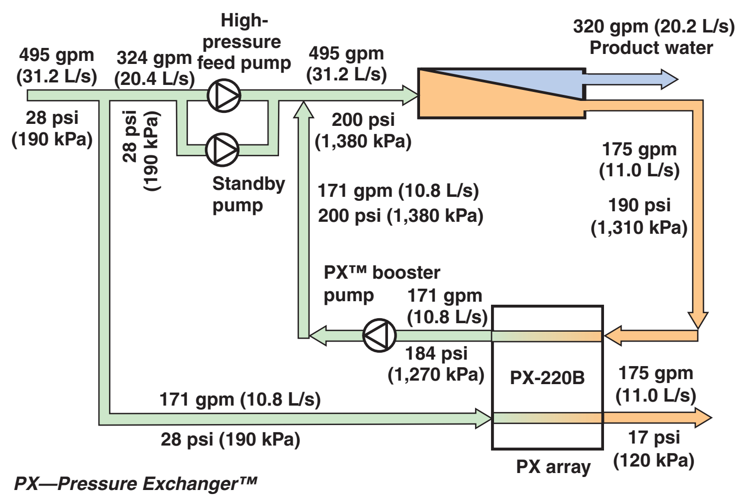
PX—Pressure Exchanger™

PX RETROFIT AT THE OCEAN REEF CLUB

ERI first learned of the Ocean Reef PX retrofit project in mid-2001. It was reported that the golf resort paid as much as \$6/1,000 gal (\$1.59/1,000 L) from the local water authority, which made onsite desalination an attractive cost-saving option. Because of its high efficiency, the ERI PX promised a capacity expansion with the lowest possible capital and operations and maintenance costs when compared with other energy-recovery technologies. However, many issues had to be overcome, including the installation of new raw water wells. There was also a question of whether the PX could produce adequate savings in this low-pressure brackish RO system.

Although the PX had proven itself in hundreds of seawater and several brackish water applications around the world, it had not yet been used in a brackish water plant in the United States. There was concern that the PX might not be a viable solution for the brackish treatment market because of the relatively low operating pressures. However, when the PX–220B was put online, the resulting power savings of 37% put these concerns to rest. The 0.46-mgd (1.74-ML/d) plant at the Ocean Reef Club saves 25 kW at \$0.09/kW·h—which results in a projected savings of nearly \$15,000 per year. Running with the PX, electricity costs are now around \$0.20/1,000 gal (\$0.05/1,000 L) at the facility.

FIGURE 3 The Ocean Reef Club's reverse osmosis plant



PX—Pressure Exchanger™

The entire project included expanding the original plant by replacing and adding new membranes (12 pressure vessels with six elements[1]), replacing the old pumps with two new high-pressure pumps[2], and installing a booster pump[3] for the PX–220B

THE PX SIGNIFICANTLY REDUCES FLOW THROUGH THE MAIN PUMP. THIS POINT IS SIGNIFICANT BECAUSE A REDUCTION IN THE SIZE OF THE MAIN PUMP RESULTS IN LOWER POWER CONSUMPTION AND OPERATING COSTS.

energy recovery unit. The design included redundancy with two main pumps as shown in Figure 3. The high-pressure pumps can supply the total feed flow to the RO membranes, or one pump can be taken off-line and replaced with the PX system.

The design offered an excellent platform to compare a standard brackish RO system with no energy recovery to a system with a PX (Table 2). The Ocean Reef retrofit demonstrates that the PX can provide significant savings in brackish water RO applications.

INTERSTAGE BOOSTER DESIGN

In some applications, even more savings are possible by applying the PX booster pump as an interstage booster pump in multistaged arrays. The PX system requires a booster pump to make up the small amount of pressure loss that occurs through the membranes, the friction in the PX, and the piping circuit. In single-stage systems, this pump is applied at the outlet of the PX (Figures 2 and 3). However, in a two-stage brackish water system, the PX booster pump can serve two purposes by being installed between stages 1 and 2 (Figure 4). In this configuration, the PX booster pump also acts as an interstage booster pump that helps reduce the required pressure from the main high-pressure feed pump and balance the flux between stages 1 and 2.

Figure 4 (page 48) shows that while the PX booster is supplying the energy to drive the water around the PX circuit, it is also providing 55 psi (380 kPa) of

TABLE 2 Power comparison at the Ocean Reef Club reverse osmosis plant

Project Stage	Feed Pressure *psi (kPa)*	Total Power *kW*	Product Water Flow Rate *gpm (L/s)*	Power Consumption/ Volume *kW·h/1,000 gal (3,785 L)*
Original system	300 (2,070)	60.8	200 (12.6)	5.06
Two new high-pressure pumps	200 (1,380)	63.3	340 (21.5)	3.10
One high-pressure pump and Pressure Exchanger™	200 (1,380)	37.8	320 (20.2)	1.96

TABLE 3 PX™ savings comparison in an interstage booster system for brackish water

Parameter	Standard Reverse Osmosis	Energy Recovery Inc.
Feed pump efficiency—%	83	83
Feed pump motor efficiency—%	94	94
Feed pump power—*kW*	172.9	130.3
Booster pump efficiency—%	80	80
Booster pump motor efficiency—%	94	94
Booster pump power—*kW*	23.2	31.8
Power consumption/volume—*kW·h/1,000 gal (3,785 L)*	2.19	1.82

PX—Pressure Exchanger™

interstage boost pressure. In addition to improving the flux balance, the PX also results in significant savings by reducing the size of the main high-pressure pump and lowering the first-stage feed pressure inherent to an interstage booster design. Table 3 shows the power savings in a PX system versus a standard interstage booster system.

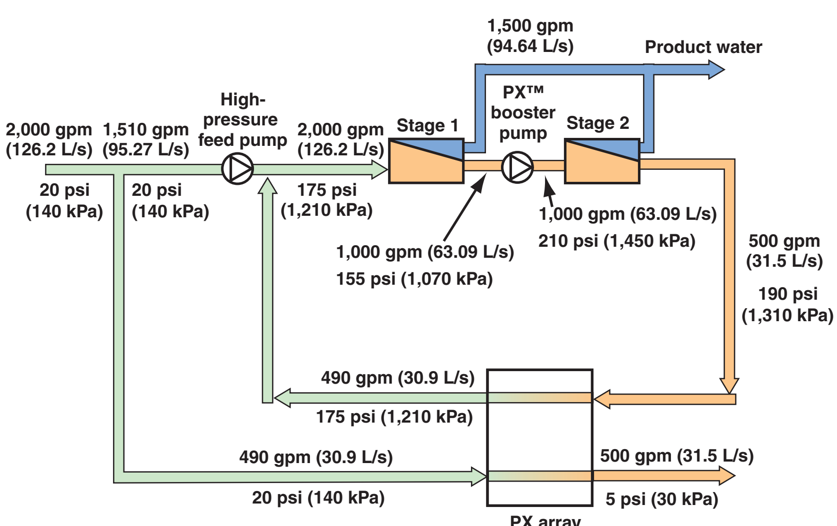
As Table 3 indicates, the PX results in savings of 17% when applied to a typical 75% recovery brackish water RO system. In this example of a 2.1 mgd (7.9 ML/d) system (and with a power cost of \$0.06/kW·h), the PX will save approximately \$17,500 per year.

The PX has been proven in hundreds of seawater applications around the world, and it has now been shown effective in providing similar power savings in lower-pressure, higher-recovery brackish water plants. With savings typically ranging between 10 and 30% in lower-pressure, higher-recovery systems, the PX may become as common in the brackish RO market as it is in seawater markets.

PHOTO: ERI

Energy Recovery Inc.'s retrofit installation at the Ocean Reef Club in Key Largo, Fla., shows (from left to right) the PX220-B, the reverse osmosis rack, the booster pump, and the high-pressure pumps.

FIGURE 4 **Interstage booster PX™ design for a two-stage system**



PX—Pressure Exchanger™

—John P. MacHarg is general manager of Energy Recovery Inc. Previously he was a vice-president at Village Marine Technology, where he was involved in the design, manufacture, and sales of packaged seawater desalination equipment. He has been working in the desalination industry for 15 years. He can be reached at the ERI offices in San Leandro, Calif., at (510) 483-7370 or by e-mail at jmacharg@energy-recovery.com. Stuart A. McClellan is a director emeritus on the board of directors of the American Membrane Technology Association and is president of Successfully Applied Membranes. Since 1986 McClellan has developed technical information for the use of FILMTEC® Membrane Products. A co-founder of Basic Technologies Inc., McClellan pioneered the successful application of RO technology in potable and industrial water treatment, introducing the concept of membrane softening (nanofiltration) in 1976. He has been working with RO membranes for more than 30 years. He can be reached at his offices in Palm Beach Gardens, Fla., at (561) 625-0031 or by e-mail stuartamcclellan@hotmail.com.

FOOTNOTES

[1]BW30-440, FILMTEC Products, The Dow Chemical Co., Midland, Mich.
[2]4×6–9 MPV, Afton Pumps Inc., Houston, Texas
[3]2×3–7 ILVS, Afton Pumps Inc., Houston, Texas

Optimizing Lower Energy Seawater Desalination, The Affordable Desalination Collaboration

Authors: Stephen Dundorf, John MacHarg, Bradley Sessions, Thomas F. Seacord
Presenter: Stephen Dundorf
Environmental Engineer - Bureau of Reclamation - USA

Abstract

Increasing demand for freshwater resources, drought, and the need for a diverse water supply portfolio are among the many reasons that people across the United States and the world are looking to the sea as a potential source. However, in the United States, the high cost of desalination relative to other sources has historically hindered interest in seawater as a possible fresh water supply. Sensitive to the issue of cost as a limitation to realizing large-scale implementation of seawater desalination, engineers, scientists, and the manufacturing industry have worked to reduce both the capital and operating cost associated with desalinated water.

The Affordable Desalination Collaboration (ADC) is a California non-profit organization composed of leading companies and agencies in the desalination industry that have agreed to pool their resources and share their expertise in the mission to realize the affordable desalination of seawater. Using a combination of energy efficient, commercially available RO technologies including pumps, membranes and energy recovery equipment, the ADC has demonstrated that seawater reverse osmosis can produce water at a cost and energy consumption rate comparable to other supply alternatives. The ADC's demonstration scale seawater reverse osmosis treatment plant uses an isobaric energy recovery technology (Pressure Exchanger (PX)) and has a one-pass RO array consisting of three 7-element 8" diameter pressure vessels in parallel. The flux and recovery can be varied from 6-9 gfd and 35-60% respectively. The product capacity of the system can be varied from approximately 50,000-80,000 gpd (200-300 m^3/day). The treatment system has been in use for the past three years at the Navy's Seawater Desalination Test Facility in Port Hueneme, California.

The research to be presented concerns development and testing of innovative process designs that utilize isobaric energy recovery technology. As a result of the PX in particular, there are flow schemes that can increase the recovery of seawater and brackish water systems. The PX operates with the high pressure concentrate boosting the pressure of a portion of the feed flow in an energy recycling process. Under normal operating conditions, there is minimal mixing from the concentrate to the feed flow streams. The unbalanced PX involves decreasing the low pressure system feed flow while maintaining the high pressure concentrate flow through the pressure exchanger. The result is an increased system recovery while the membranes operate at a lower recovery, but at the expense of a higher feed water salinity due to concentrate flow recirculating through the PX (i.e., unbalanced flow). The flow scheme of the "unbalanced PX" has been used to demonstrate recoveries of seawater systems above 50%, while still producing acceptable quality water at low energy consumption and maintaining membrane manufacturer's standard warranties.

Results have shown that at least a 10% increase in system recovery (over 50%) can be achieved with a proportional increase in energy consumption, but at lower overall total treatment costs due to the decrease in pretreatment and capital costs. Optimum operating points for minimum overall cost (capital and O&M) were found at system recovery/RO membrane recovery values of 50/45 and 55/50, along

with other nearby operating points. This resulted in a projected total water cost of \$3.00/kgal (\$0.79/m^3) for a 50 MGD (189,000 m^3/day) seawater desalination plant using media filtration pretreatment. Continuous testing of the unbalanced PX was completed for a period of 1 month to demonstrate the feasibility and reliability of operation with a 60/45 flow regime. Pretreatment using a UF membrane system took the place of media filtration in July 2008 and was used for these high recovery tests.   .

The ADC is helping to confirm that as an industry we have achieved the monumental accomplishment of making fresh water from seawater affordable and at acceptable levels of energy consumption when compared to many traditional sources. The challenge that lies before us is to effectively communicate our accomplishment to the appropriate decision makers and applicable stakeholders in our various regions of the world.

DISCLAIMER

Information contained in this report regarding commercial products or firms was supplied by those firms. It may not be used for advertising or promotional purposes and is not to be construed as an endorsement of any product or firm by the Bureau of Reclamation. The information contained in this report was developed for the Bureau of Reclamation; no warranty as to the accuracy, usefulness, or completeness is expressed or implied.

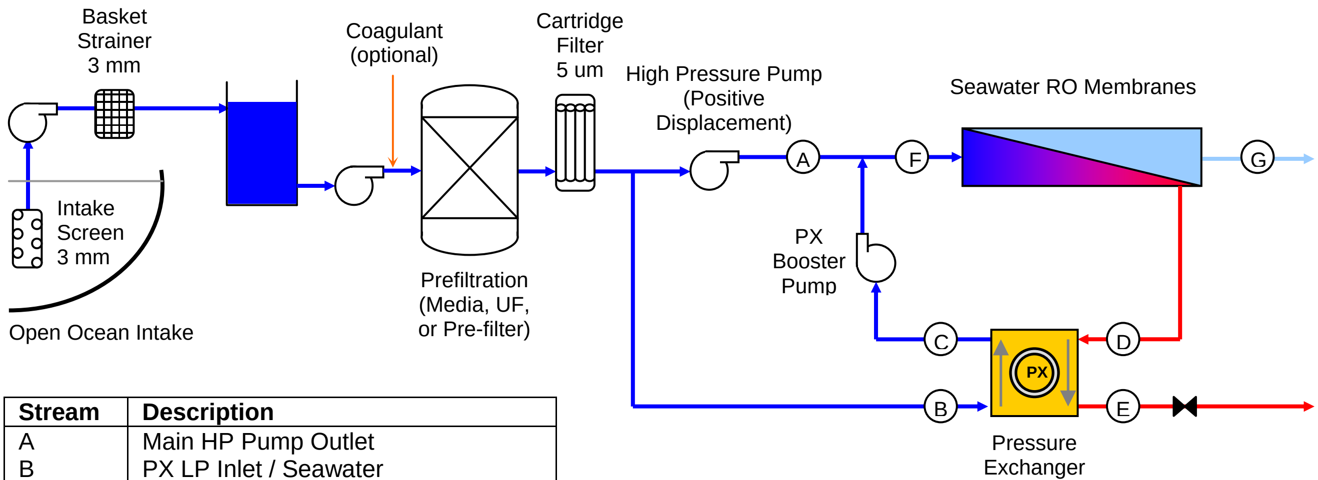
I. INTRODUCTION

Increasing demand for allocated freshwater resources, drought, and the need for a diverse water supply portfolio are among the many reasons that people across the United States and the world are looking to the sea as a potential water supply. Many arid locations around the world, and especially those with lower energy costs, have a substantial history of seawater desalination. However, in the United States where many water source options have been prevalent, the high cost of desalination has hindered interest in seawater as a possible fresh water supply. Sensitive to the issue of cost as a limitation to realizing large scale implementation of seawater desalination, engineers, scientists, and the manufacturing industry have worked over the last fifty years to reduce both the capital and operating cost associated with desalinated water.

The Affordable Desalination Collaboration (ADC) is a California non-profit organization composed of a group of leading companies and agencies in the desalination industry that have agreed to pool their resources and share their expertise in the mission to realize the affordable desalination of seawater. Using a combination of energy efficient, commercially available RO technologies including pumps, membranes and energy recovery equipment, the ADC has demonstrated that seawater reverse osmosis can be used to produce water at an affordable cost and energy consumption rate comparable to other supply alternatives. The research approach and results are made possible through the collaboration of members and participants that include:

- Amiad Filtration Systems
- Bureau of Reclamation
- California Department of Water Resources
- California Energy Commission
- Carollo Engineers
- City of Santa Cruz / Soquel Creek Water District
- FilmTec Corporation
- Hydranautics – Nitto Denko
- Koch Membrane Systems
- Marin Municipal Water District
- Metropolitan Municipal Water District of Southern California
- Municipal Water District of Orange County
- Naval Facilities Engineering Service Center
- New Water Supply Coalition
- Pentair - CodeLine Pressure Vessels
- Poseidon Resources
- San Diego County Water Authority
- Toray Membrane USA
- West Basin Municipal Water District
- Zenon - GE

The ADC's demonstration scale seawater reverse osmosis (SWRO) treatment system uses pressure exchanger technology for energy recovery (**Figure 1.1**). The RO array consists of 3 each x 7 element 8" diameter CodeLine pressure vessel. The flux and recovery can be varied from 6-9 gfd (244-367 L/m^2/d) and 35-60%, respectively. The overall capacity of the system can be varied from approximately 200-300 m^3/day (50,000-80,000 gpd) by changing the recovery and pump speed. The demonstration scale testing is located at the US Navy's Seawater Desalination Test Facility in Port Hueneme, California.



Stream	Description
A	Main HP Pump Outlet
B	PX LP Inlet / Seawater
C	PX HP Outlet / PX Booster pump In
D	PX HP Inlet / RO Concentrate
E	PX LP Outlet / System Concentrate
F	RO Feed Stream
G	RO Permeate

HP = high pressure, LP = low pressure

Figure 1.1 Process flow schematic

The objective of this project is to test a state-of-the-art, energy efficient, demonstration scale SWRO process, designed and built using scalable, commercially available and/or new technologies, in a manner that would provide preliminary information necessary for estimating both capital and operating costs for a 50-MGD seawater desalination plant to supply potable water.

The overall goal of this project is to:

- Improve seawater desalination treatment technologies in terms of cost, energy use, and environmental considerations
- Use the estimated costs generated as a result of this work to further refine the paradigm for engineers, planners, OEMs, membrane manufacturers, and policy makers related to the costs of seawater desalination.

1.1 Phase I

The first phase of testing began in May 2005 and was completed in April 2006. Phase I focused on demonstrating the cost of optimized desalination using a combination of state-of-the-art, commercially available technologies that minimize energy consumption and are typically scalable to 50 MGD (189,000 m^3/day). The positive displacement main high pressure pump is not scalable to 50 MGD, but there are pumps that operate at similar efficiencies that would be used in a 50 MGD facility. Testing included three membrane sets and varying flux and recovery to seek the most cost effective operating point. The most cost effective operating point was estimated by calculating the net present value for each tested condition, accounting for both capital and operating costs. The RO specific energy consumption using the ADC's SWRO process design was demonstrated to range from 6.81 to 8.90 kW-hr/kgal (1.80 to 2.00 kW-hr/m^3) at the most cost effective operating point (i.e., 9 gfd, 50% recovery for the HR membrane and XLE membrane, and 6 gfd, 50% recovery for the HR membrane). The lowest RO process energy consumption, 5.98 kW-hr/kgal (1.58 kW-hr/m^3), was demonstrated using the XLE membrane at 6 gfd (244 $L/m^2/d$), 42.5% recovery. Results were presented at the 2006 AMTA biennial conference in Los Angeles, CA [1].

1.2 Phase II

Phase II incorporates Phase I recommendations along with objectives from the California Department of Water Resources (DWR) Proposition 50, a major funding source.

Phase I recommendations incorporated in Phase II include:

- Pretreatment
- System configuration
- Increased recovery research

Relevant California DWR Proposition 50 goals include:

- Opportunities for energy efficiency
- Improved membranes with high salt rejection and less susceptibility to scaling and fouling
- Strategies for brine/concentrate management
- Better feed water pretreatment processes and strategies

Based on Phase I recommendations and Proposition 50 goals, pretreatment specific objectives are as follows:

- Determine optimal design parameters for the system that will generate stable membrane performance.
- Demonstrate that the UF membrane pre-treatment system will produce high quality effluent and meet applicable standards.
- Develop effective cleaning regimes, including type of chemicals and minimum time between cleanings.

The second phase began in August 2007 and includes 3 stages as follows:

1.2.1 Stage 1: Low Energy Membrane Tes*ting & Demonstration* **–** This included testing and demonstrating three additional manufacturers' membranes using a similar protocol as Phase I. The Phase II typical test protocol included the addition of a 10 gfd flux test (flux rates tested were: 6.0, 7.5, 9.0, 10.0 gfd), elimination of the 35% recovery point, and addition of a 46% recovery point (recoveries test were: 42%, 46%, 50%). Each set of membranes were run through a 12 point approximate eight week test protocol.

In testing membranes from three additional manufacturers the ADC expands the Phase I work and validates that overall low energy numbers can be achieved with elements from more than one commercial membrane supplier. Furthermore, the ADC is able to provide a general matrix of performance, using natural Southern California seawater in a full scale configuration, showing energy consumption, salt rejection, and boron rejection from four leading membrane manufacturers. It should be noted that membrane testing was not performed "side by side" and that there were variations in feed water quality between membrane tests.

Figure 1.2 shows some results from the various membranes tested in Phase I & II. Demonstrating additional membranes has validated our results from Phase I and shown that similar results can be achieved with all four leading membrane manufactures products. However, raw water quality was not exactly the same between tests so data can not be compared in an absolute fashion.

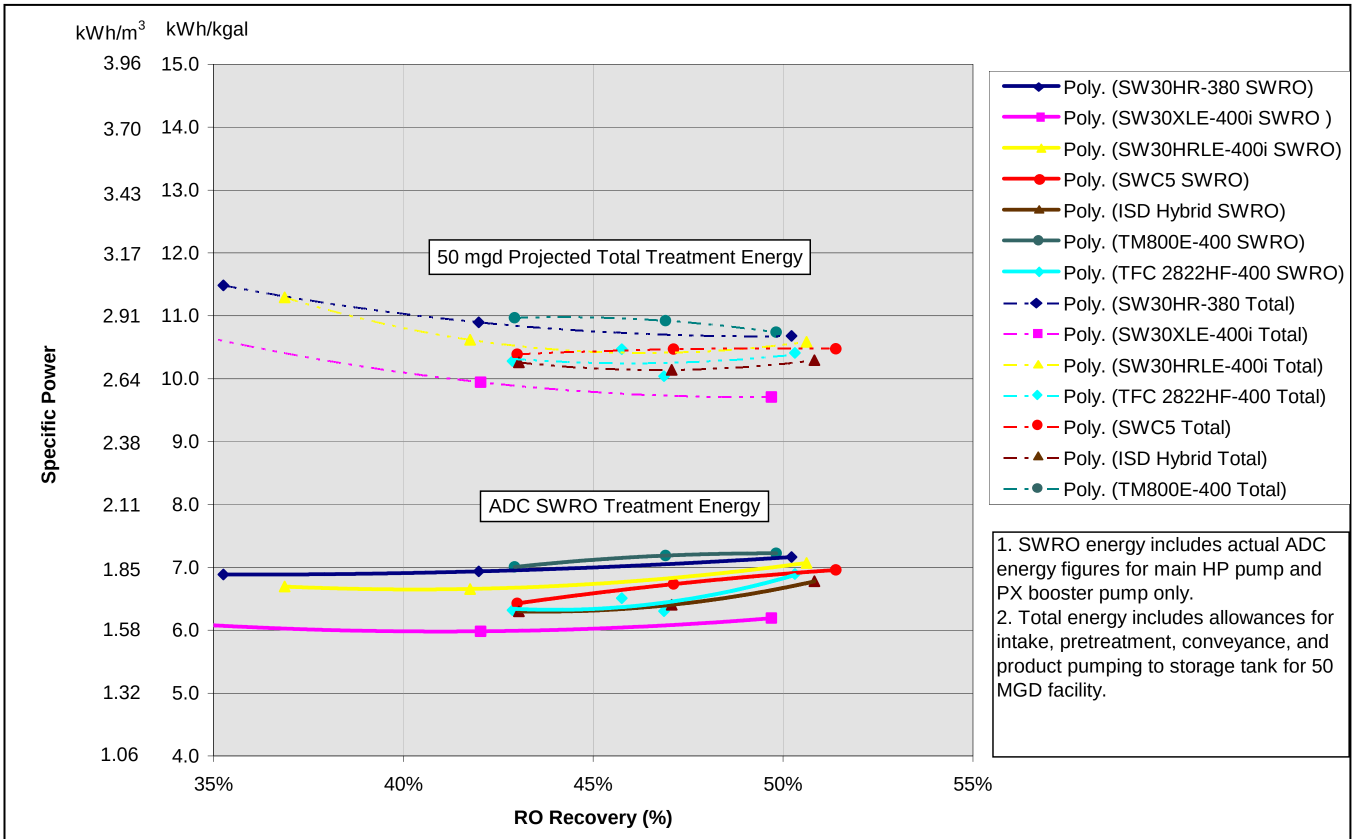


Figure 1.2 Energy vs recovery at 6 gfd (244 L/m^2/d) flux

1.2.2 Stage 2: Staged Membrane Testing - In addition to demonstrating the new commercially available and proven membrane technology described above, we tested a design from one manufacturer, which they are calling their hybrid approach. This concept internally stages membranes of different performance down a single 7 element pressure vessel and seeks to balance the feed water distribution and flux rate from the lead element to the end element. These membranes include both low energy and high rejection membranes with the membranes operated at a higher 55% recovery per manufacturer request. The results show that the extra low energy only membrane tests out perform the hybrid approach except for boron removal which is very close to the absolute 1.45 mg/L California action level limit (**Figure 1.3 & Figure 1.4**) . Both membranes are above the 1.045 ADC most affordable point goal. The hybrid membrane setup does offer some energy savings over higher rejection models and lower total treatment costs at 55% recovery vs. lower recoveries.

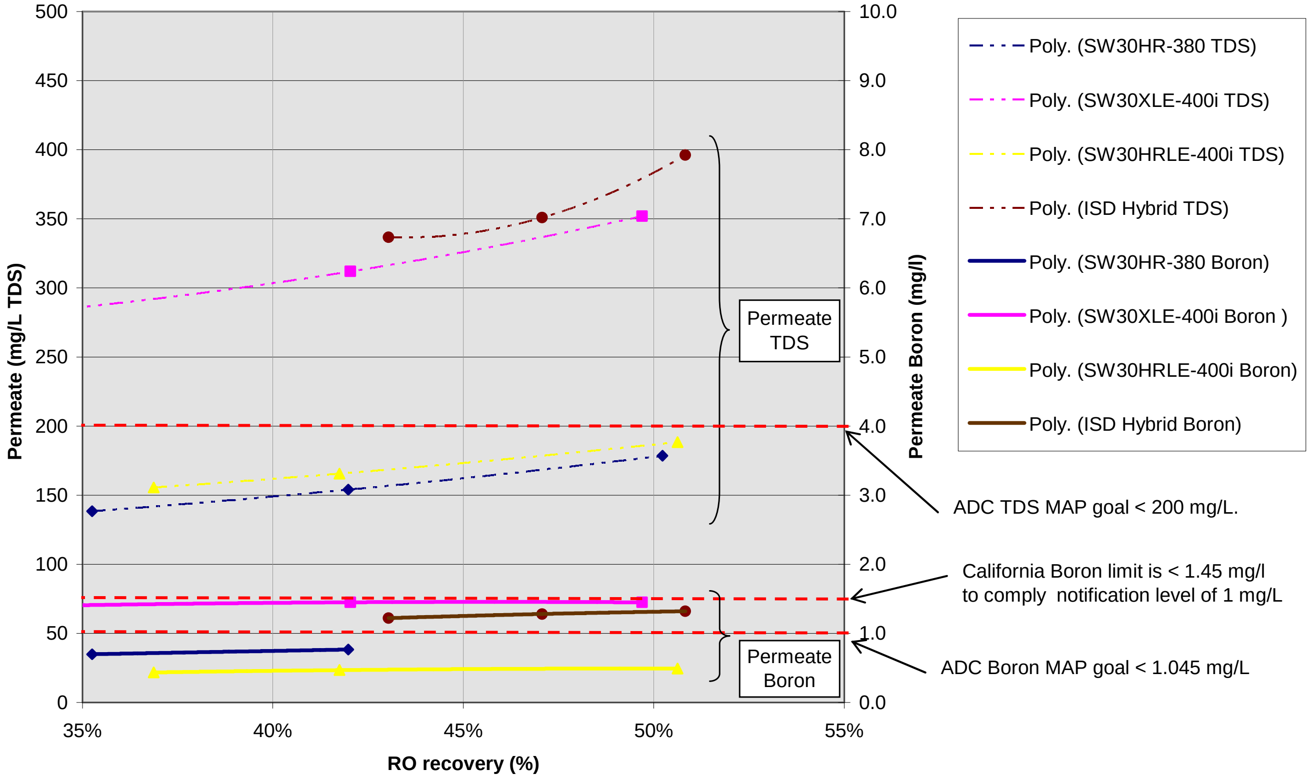


Figure 1.3 Water quality for standard vs hybrid membrane setup at 6 gfd (244 L/m^2/d) flux

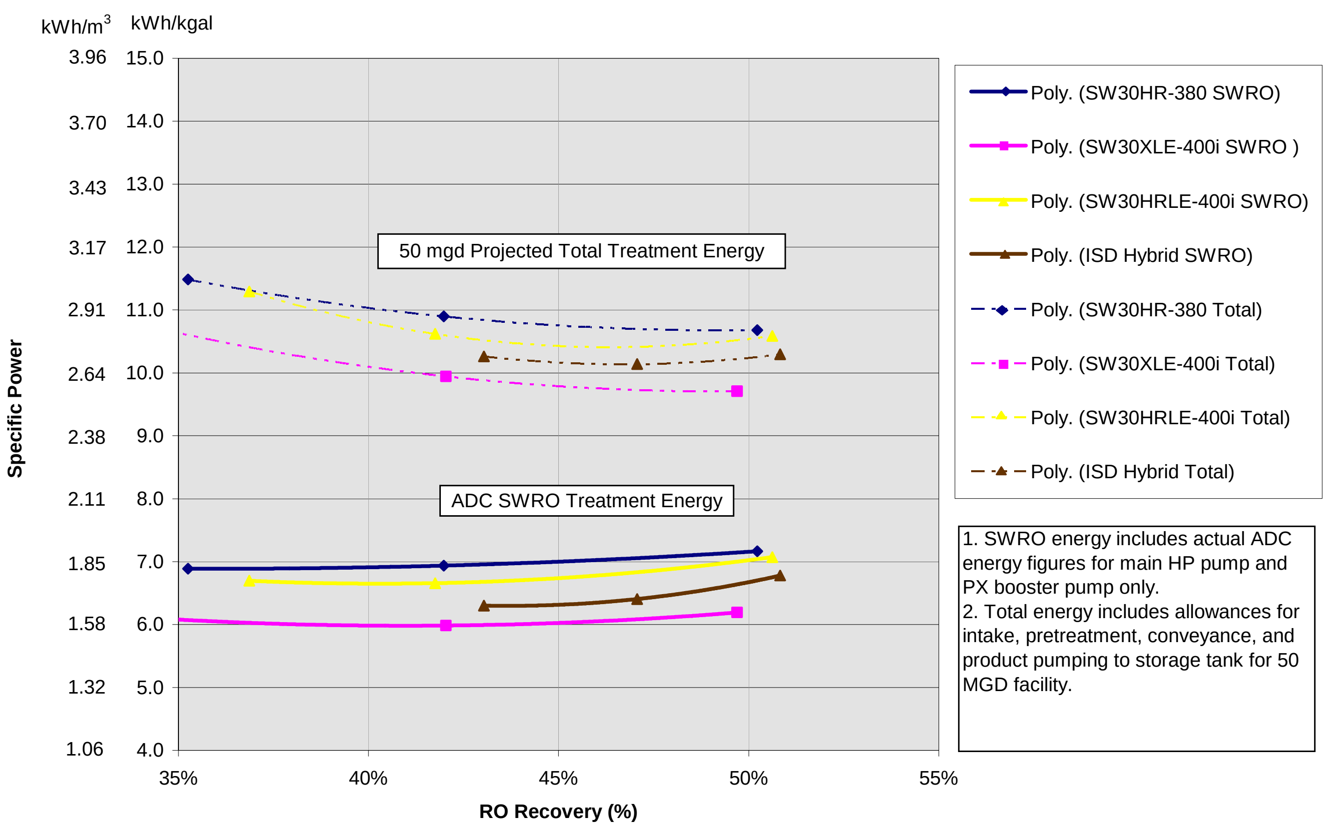


Figure 1.4 Energy use for standard vs hybrid membrane setup at 6 gfd (244 L/m^2/d) flux

1.2.3 Stage 3: Innovative Flow Regimes - As a natural result of isobaric energy recovery technology in particular, there are flow schemes that can improve the performance of higher recovery seawater and brackish water systems. These new flow schemes were used to demonstrate recoveries of seawater systems above 50%, while still maintaining acceptable water quality and low energy consumption. Test were conducted at a variety of test conditions to determine the range of possible operating conditions and the optimum operating point. Finally, the ADC continues to test and demonstrate advanced prefiltration technologies including an ultrafiltration system. In general, use of membranes for seawater pretreatment is limited and this work provides valuable information for the U.S. and world.

II MATERIALS AND METHODS

The ADC's SWRO plant is being tested at the U.S. Navy's Desalination Research Center, located in Port Hueneme, California. This facility was chosen based upon the availability of experienced staff familiar with the operation of SWRO process equipment and the availability of an existing ocean intake and outfall.

The ADC's demonstration scale system design and testing protocols were developed by Carollo Engineers and reviewed by the ADC's members. The design and testing protocols established the basis for the study, how the equipment is to be tested, how the data is to be interpreted, and the cost estimating procedures. This process helps to ensure that the data and results developed during the study will not be influenced by a desired result. A detailed testing protocol including manufacturer specific information is available on the ADC's website: www.affordabledesalination.com, and is summarized below.

2.1 Equipment

The ADC's demonstration scale SWRO plant is designed to produce between 48,100 to 75,600 gallons per day (182 to 286 m^3/day) of permeate. The configuration is similar to Phase I presented in **Figure 1.1**. As indicated, the process uses an open intake, pretreatment filter, cartridge filter, high efficiency positive displacement pump, and high efficiency isobaric energy recovery device. The media filter used for pretreatment in Phase I was replaced by ultrafiltration membranes after stage 1 was complete. The design criteria for these components are presented in **Table 2.1**.

Parameter	Unit	Value
Filter (Media)		
Loading Rate	3 to 6 120 to 240	gpm/ft^2 lpm/m^2
Depth/Grain Size/U.C. of Anthracite	18 / 0.85-0.95 / <1.4	in/mm/-
Depth/Grain Size/U.C. of Sand	10 / 0.45-0.55 / <1.4	in/mm/-
Depth/Grain Size/U.C. of Gravel	6 / 0.3 / <1.4	in/mm/-
Filter (Membrane)		
Size	UF (0.01 micron)	
Flux	20 815	gfd L/m^2/day
Cartridge Filter		
Cartridge Specs	#2, 5-micron	
Loading Rate	~1 ~10	gpm/10-in. lpm/m
Membrane System		
Models	Various	
Diameter	8	Inch
Elements per Vessel	7	No.
Vessels	3	No.
High Pressure Pump		

	Type	Positive Displacement	
	TDH	1385 to 2790 (600 to 1200) 422 to 844 (4137 to 8274)	ft (psig) m (kPa)
Energy Recovery			
	Type	Pressure Exchanger™ (PX™)	
PX Booster Pump			
	Type	Multi-stage Centrifugal	
	TDH	70 to 115 (20 to 50) 21 to 35 (138 to 345)	ft (psig) m (kPa)

Table 2.1 Equipment design criteria

2.2 Operation and Monitoring

2.2.1 Schedule The system is being operated for approximately 32 months with work divided into 3 stages (**Table 2.2**).

		Months																															
	Year	2005						2006				2007					2008									2009							
Stage	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	Low Energy Membranes																																
2	Staged Membranes																																
3	Innovative Flow Regimes																																
Pre-treatment	Media Filtration																																
	Ultrafiltration																																
	Prefilter																																

Table 2.2 Project timeline

2.2.2 Innovative Flow Regimes - This involves the development and testing of process flows that are possible in conjuction with isobaric energy recovery technologies. As a natural result of PX technology in particular there are flow schemes that may improve the overall system performance of higher recovery seawater and brackish water systems. The intentionally unbalanced PX concept developed by John MacHarg in **Figure 2.1** yields a higher overall system recovery of “F” divided by “A” (i.e. 54%), but a lower membrane recovery of “F” divided by “E” (i.e. 44%). In addition, there are other flow regimens discussed at the end of the paper under next steps.

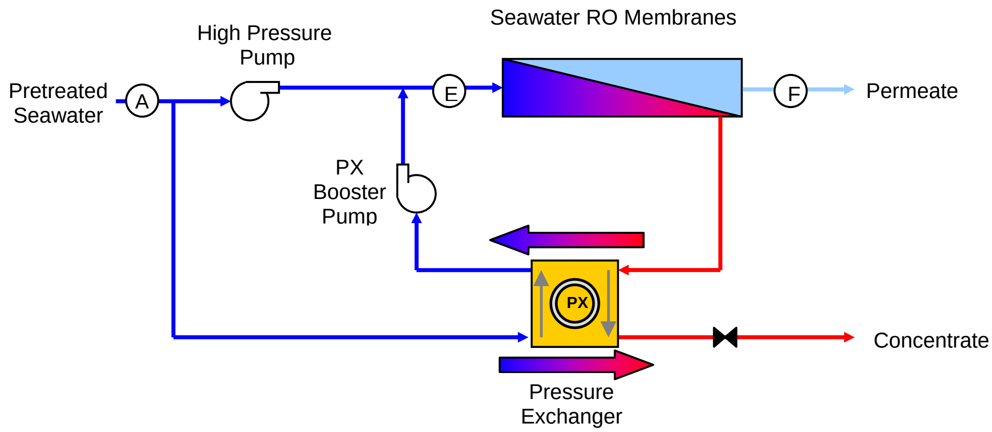


Figure 2.1 Unbalanced pressure exchanger diagram

2.2.3 Test Protocol The unbalanced testing uses a further revised set of test operating conditions due to the unique combinations of membrane and system recoveries, shown below at 9 gfd (**Table 2.3**).

	Goal		Actual							
	RO Recovery %	**System Recovery %**	**RO Recovery %**	**System Recovery %**	**Flux (gfd)**	**HP pump Flow (gpm)**	**PX Booster Pump Flow (gpm)**	**Permeate Flow (gpm)**	**PX Inlet Flow (gpm)**	**Concentrate Flow (gpm)**
Ripening	42.5	42.5	42.0	41.9	8.97	72.5	72.2	52.3	52.3	72.2
Multi-Point Testing	40	40	40.2	40.3	8.97	77.7	77.3	52.3	52.3	77.3
		45	40.4	45.6	8.98	77.2	62.5	52.4	52.4	62.5
		50	40.4	50.7	8.98	77.3	50.9	52.4	52.4	50.9
		55	40.4	55.8	8.95	77.1	41.3	52.2	52.2	41.3
		60	40.4	61.1	9.00	77.3	33.5	52.5	52.5	33.5
	45	45	45.6	45.6	9.02	62.8	62.7	52.6	52.6	62.7
		50	45.4	50.7	8.98	62.9	51.0	52.4	52.4	51.0
		55	45.4	55.7	8.97	63.0	41.6	52.3	52.3	41.6
		60	45.5	61.1	9.00	63.0	33.4	52.5	52.5	33.4
	50	50	50.5	50.6	8.97	51.2	51.0	52.3	52.3	51.0
		55	50.6	56.0	9.00	51.3	41.2	52.5	52.5	41.2
		60	50.5	61.1	9.00	51.4	33.5	52.5	52.5	33.5
	55	55	55.7	55.9	8.98	41.6	41.4	52.4	52.4	41.4
		60	55.7	60.9	9.00	41.7	33.7	52.5	52.5	33.7
Balanced RO & System Recovery Points (shown for reference)	40	40	40.2	40.3	8.97	77.7	77.3	52.3	52.3	77.3
	45	45	45.6	45.6	9.02	62.8	62.7	52.6	52.6	62.7
	50	50	50.5	50.6	8.97	51.2	51.0	52.3	52.3	51.0
	55	55	55.7	55.9	8.98	41.6	41.4	52.4	52.4	41.4

Table 2.3 Test operating conditions at 9 gfd

Testing begins with a 2 week ripening period to ensure the membranes have reached steady state operation before the flux or recovery is modified. The multi-point testing involves changing the RO and system recovery approximately daily to collect data over the range of recoveries. The multi-point testing is performed at a flux of 7.5 and 9.0 gfd (306 and 367 L/m^2/d). Upon completion of the tests, data are analyzed and a net present value analysis is conducted (described below) to determine which test condition(s) is the most cost effective operating point(s) known as the most affordable point (MAP). The system was finally operated at 45% RO recovery and 60% system recovery at 7.5 gfd for a period of 1 month.

2.2.4 Water Quality and Operation Data Collection During each testing condition, hydraulic, water quality and energy data are collected at periodic intervals. **Table 2.4** presents the type and frequency of manually collected data.

	Parameter	Weeks 1-2 and 6-8	Weeks 3-5
Flow	Permeate, Raw Water (PD Pump), Raw Water (into PX), Raw Water (out of PX)	1x per day	3x per week
Pressure	Filter Inlet, Filter Outlet, Cartridge Filter Outlet, PX Booster Pump Suction, PX Brine Outlet, RO Feed, RO Brine, RO Permeate	1x per day	3x per week
Energy	PD Pump & PX Booster Pump	1x per day	3x per week
Water Quality	Temperature, Turbidity, SDI	Raw: 1x per day	3x per week
	pH, Conductivity, TDS,	Raw: 1x per day RO Feed: 1x per day Permeate: 1x per day	Raw: 3x per week RO Feed: 3x per week Permeate: 3x per week
	Boron, Bromide, Iron, Manganese, Aluminum, Calcium, Magnesium, Sodium, Potassium, Bicarbonate, Carbonate, Sulfate, Chloride, Fluoride	Raw: 2x per week RO Feed: 2x per week Permeate: 2x per week	Raw: 3x per week RO Feed: 3x per week Permeate: 3x per week

Table 2.4 Type and frequency of manual data collection

Water quality parameters sampled daily are analyzed using field kits and those parameters monitored weekly are analyzed using EPA or *Standard Methods* [2]. Key water quality parameters are shown below (**Table 2.5**).

Parameter	Location	Mean	Range
TDS (mg/L)	Raw	34,000	31,400 – 36,300
Temperature (^{o}C)	Raw	15	12 – 20
Boron (mg/L)	Raw	4.8	3.9 – 6.1
Turbidity (NTU)	Raw	1.6	0.25 - 12
Turbidity (NTU)	RO Feed	0.06	0.02 – 0.25
SDI – from Media Filter	RO Feed	4.0	1.8 – 11.4
SDI – from UF	RO Feed	2.6	1.2-4.3

Table 2.5 Key raw water quality parameters

2.2.5 Advanced Pretreatment Advanced filtration system(s) were added in the later part of the testing to replace the conventional media filtration system. The first advanced filtration system to be tested is a 0.01 micron UF membrane demonstration scale system. This is a low energy immersed membrane process that consists of outside-in, hollow-fiber modules immersed directly in the feed-water. The small pore size of the membranes ensures that no particulate matter, including Cryptosporidium oocysts, Giardia cysts, or suspended solids pass into the treated water stream. If needed, oxidation and/or coagulation can be added to remove colloidal and dissolved components such as iron and natural organic matter. These features and advantages will help the ADC and other full scale seawater desalination systems operate more reliably through the California summer water conditions that include green algae blooms and red tide events.

2.3 Cost Estimating Procedures

A present value analysis model, which accounts for both capital and operating costs, was developed and used to establish the MAP. The present value analysis model is operated at the completion of the membrane/system recovery variation tests, presented previously in **Table 2.3**. The conditions for the present value analysis model were established as part of the testing protocol and are presented below (**Table 2.6**).

Plant Capacity	50 MGD	**High Service Pump TDH**	200 ft H_2O (61 m)
Plant Average Demand	95% of Plant Capacity	**Intake/High Service Pump Eff.**	80%
Plant Utilization Factor	95%	**Intake/High Service Pump Motor Eff.**	95%
Capital Cost [1]	Determined with WTCOST Model and Manufacturer Quotes	**RO Process Energy Demand**	Study data[2]
		RO Membrane Life	Refer to **Table 2.7**
		RO Membrane Element Cost	$550
Electrical Systems	12% of Capital Cost	**RO Pressure Vessel** [3]	$8547
Instrumentation & Control	10% of Capital Cost	**Sodium Hypochlorite Dose (pretreatment)**	2 mg/L
Project Life	30 years	**Sodium Hypochlorite Cost**	$1.2/lb ($0.54/kg)
Bond Payment Period	30 years	**Sodium Bisulfite Dose**	4.6 mg/L
Interest	5%	**Sodium Bisulfite Cost**	$0.3/lb ($0.14/kg)
Construction Contingencies	15% of capital cost	**Cartridge Filter Loading Rate**	3 gpm/10-in (31 lpm/m)
Contractor OH&P	10% of capital cost	**Cartridge Filter Cost**	$5/10-in
Engineering & Const. Mgmt.	25% of capital cost	**Cartridge Filter Life**	1000 hours
Permitting Cost	$10-million	**Carbon Dioxide Dose**	16 mg/L
Annual Maintenance Costs	1.5% of capital cost	**Carbon Dioxide Cost**	$0.04/lb ($0.02/kg)
Labor	25 operators @ $96,250/yr ea.	**Lime Dose**	44 mg/L
Energy Costs	$0.11 per kW-hr	**Lime Cost**	$0.05/lb ($0.02/kg)
Intake Pump TDH	200 ft H_2O (61 m)	**Sodium Hypochlorite Dose (finished water)**	1.5 mg/L

Note: O&M does not include administrative, laboratory, legal, reporting, and management fees since these costs vary widely.

1 Includes intake pump station, prechlorination/dechlorination systems, ferric chloride systems, media filtration, media filter backwash system, filtered water lift station, cartridge filters, SWRO equipment, RO bldg., permeate flush system, clean-in-place system, transfer pump station, process piping, yard piping, lime system, carbon dioxide system, chlorination system, high service pump station, site work.

2 Energy meter readings

3 Installed, includes all ancillary piping, frames and fittings.

4 Land costs and Inflation are not included in the Present Value Analysis

Table 2.6 Present value analysis conditions

Capital costs are determined under the assumption that the SWRO facilities would be co-located with a power plant. Therefore, the capital costs developed do not include any new intake or outfall facilities.

Pretreatment was considered similar to the demonstration scale test equipment, however, media filters were estimated in accordance with the deep bed filter concepts use for the Point Lisas SWRO facility in Trinidad (i.e., 4 gpm/ft^2, 5-ft anthracite, 2.5-ft sand, 2-ft garnet) [3,4]. Such a design has demonstrated to be more compatible with challenging raw water qualities (i.e., than the ADC's demonstration scale media filters), such as those associated with red tide events.

		Membrane Life (Years)	
RO Recovery %	**System Recovery %**	**7.5 gfd** (306 L/m^2/d)	**9.0 gfd** (367 L/m^2/d)
40	40	6.25	5.00
	45	6.25	5.00
	50	6.00	4.80
	55	5.75	4.60
	60	5.50	4.40
45	45	5.75	4.60
	50	5.75	4.60
	55	5.50	4.40
	60	5.25	4.20
	65	5.00	4.00
50	50	5.25	4.20
	55	4.75	3.80
	60	4.50	3.60
55	55	4.75	3.80
	60	4.50	3.60

Table 2.7 Estimated RO membrane life

Table 2.7 establishes the expected membrane life with respect to recovery. The expected membrane life is used to estimate membrane replacement cost. Membrane replacement resulting from warranty maintenance by the manufacturer was not part of the replacement cost.

The ADC demonstration plant employs a David Brown Union TD-60 positive displacement main high pressure pump that operates at very high efficiencies of 88-90%. Although positive displacement plunger pumps operate at a high efficiency it is not practical to employ the technology to very large systems because of their high maintenance requirements and pulsating flows. For large treatment plants centrifugal pumps with efficiencies between 55-89% are used. The achievable efficiency of a centrifugal pump depends on the size or flow rate of the pump, where lower flows typically will operate at lower efficiency compared to the larger pumps [5]. **Table 2.8** is an example using the standard ADC II membrane tests that projects the total energy consumption of various system capacities. A 0.3 MGD (1136 m^3/d) system that employs a 69% efficient centrifugal main high pressure pump and 70% efficient intake and pre-filtration pumps to be 15.0 kWh/kgal (3.96 kWh/m^3). By contrast, the 50 MGD projections use an efficiency of 89% for the main high pressure pump and 80% for the intake and pre-filtration pumps. In addition, the motors and control systems are generally more efficient for the largest systems resulting in a projected total treatment energy of 11.3 kWh/kgal (2.98 kWh/m^3).

	Projected energy consumption of various system capacities			
Treatment Step	**ADC II MAP from Std Tests**	**0.3 MGD (1136 m^3/day)** [2]	**10 MGD (37854 m^3/day)**[2]	**50 MGD (189271 m^3/day)** [2]
RO Process	7.6 / 2.00 [1]	10.5 / 2.80	8.6 / 2.27	7.6 / 2.00

Intake [2]	2.19 / 0.58	2.01 / 0.53	1.74 / 0.46	1.72 / 0.45
Pre-filtration [2]	1.15 / 0.30	1.06 / 0.28	0.91 / 0.24	0.90 / 0.24
Permeate treatment [2]	0.25 / 0.07	0.23 / 0.06	0.17 / 0.04	0.16 / 0.04
Permeate distribution [2]	1.27 / 0.33	1.17 / 0.31	0.86 / 0.23	0.85 / 0.22
Total Treatment	12.4 / 3.27	15.0 / 3.96	12.3 / 3.25	11.3 / 2.98

1 MAP average value from 7 membrane tests.
2 Projected values based on typical parameters and conditions.
3 Units for the table are in kWh/kgal / kWh/m^3

Table 2.8 ADC energy consumption at MAP and projected energy consumption at larger plant capacities

2.4 Quality Assurance and Quality Control

The ADC's quality assurance program consists of the following elements:

- Review of the testing protocol by all ADC members to establish testing procedures and cost estimating methods before conducting any of the work. This is done to ensure that the data does not influence the tests results or conclusions.
- Hydraulic data recorded both manually to compare and resolve discrepancies.
- Energy data is recorded by two separate power meters. Data is compared to resolve discrepancies and provide assurance that data is accurate.
- Water quality data analyzed according to EPA or *Standard Methods* procedures, including quality control.
- Final reporting prepared by a licensed professional engineer with an ethical duty to act in the public's interest.
- Peer review of present value model and final reporting. Peer reviewers are independent, third parties such as utility/agency members of the ADC and/or their consultants.

III RESULTS AND DISCUSSION

3.1 Raw Water Quality

Raw feed water was taken from an open intake at the end of a pier located in the Port Hueneme shipping channel feed by the Pacific Ocean (**Figure 3.1**).

Figure 3.1 Raw water intake at Port Hueneme

Feed water quality is summarized in **Table 3.1**. Salinity, boron, and temperature are shown in **figure 3.2**. It should be noted that once through cooling applications (SWRO intake using co-located power plant intake) would have higher temperatures, which would lead to different permeate qualities and lower energy consumptions than those reported by the ADC.

		During Unbalanced Test		During All Testing	
Parameter	**Location**	**Mean**	**Range**	**Mean**	**Range**
TDS (mg/L)	Raw	31,900	31,400 – 33,300	34,000	31,400 – 36,300
Temperature (^oC)	Raw	15	13 – 18	15	12 – 20
Boron (mg/L)	Raw	5.1	4.5 – 5.8	4.8	3.9 – 6.1
Turbidity (NTU)	Raw	2.3	0.0 - 6.6	1.6	0.25 – 12
Turbidity (NTU)	RO Feed	0.03	0.02 - 0.06	0.06	0.02 – 0.25
SDI – from Cartridge Filter	RO Feed	2.6	1.7 – 4.3	3.5	1.2 – 11.4

Table 3.1 Water quality during unbalanced flow testing compared to all testing

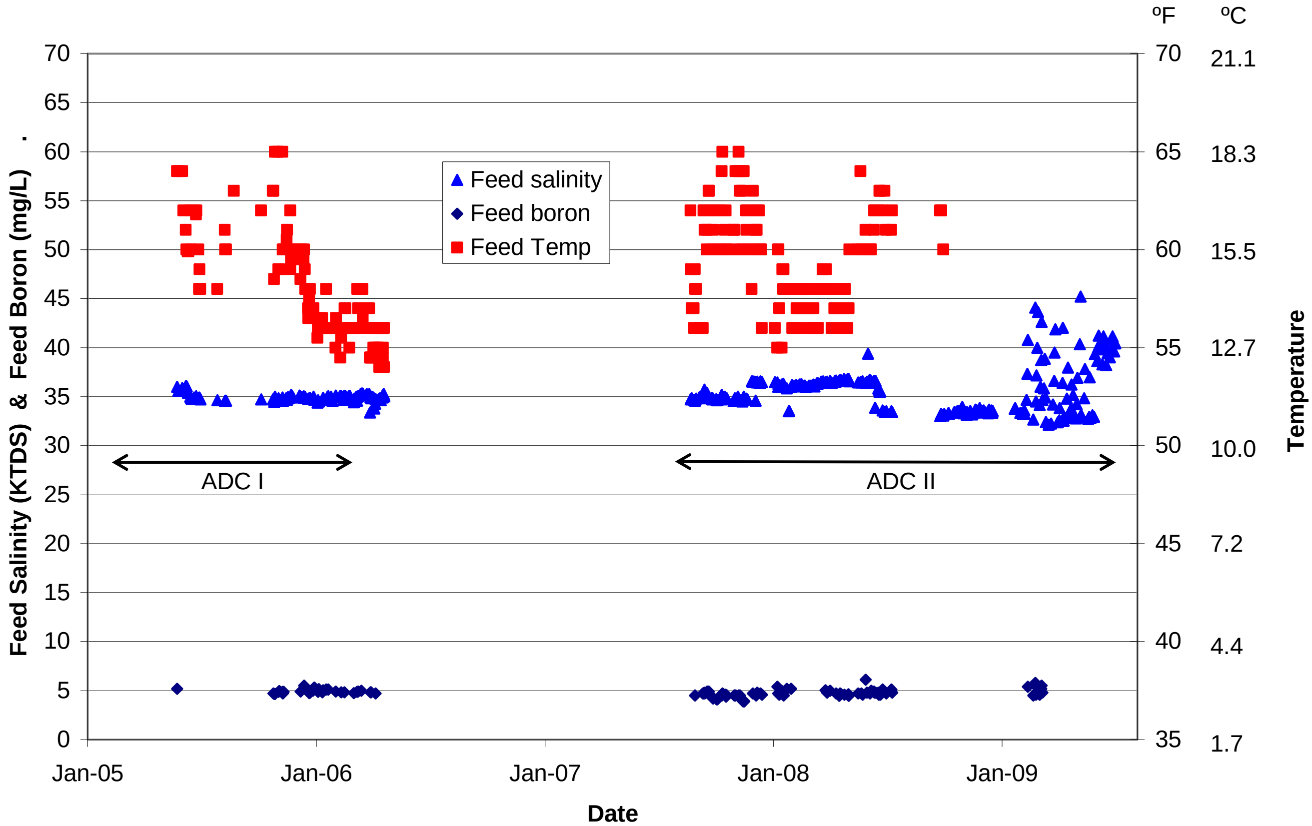


Figure 3.2 Salinity, boron, and temperature

3.2 Pretreatment System Performance

The pretreatment process, from June 2008 through 2009, has been two 3 mm strainers, followed by a submerged UF system operating at 20 gfd (815 L/m^2/d), followed by 5 micron cartridge filtration. The system has performed well during this time, producing a consistent high quality product (**Figure 3.3** & **Figure 3.4**).

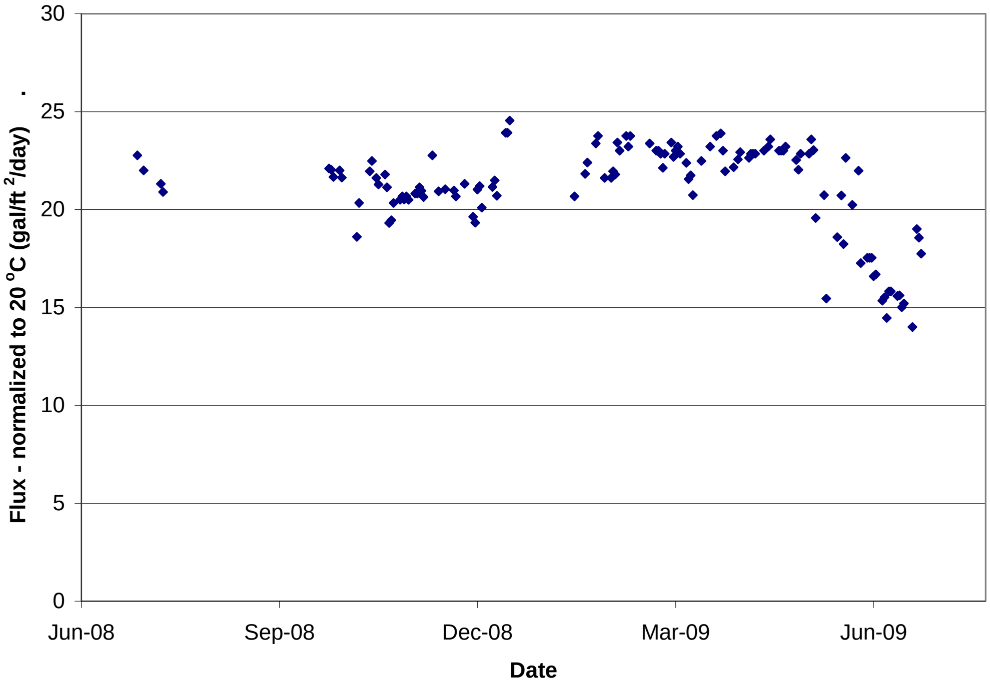


Figure 3.3 Normalized filtrate flux (@20 °C) for the UF membrane system

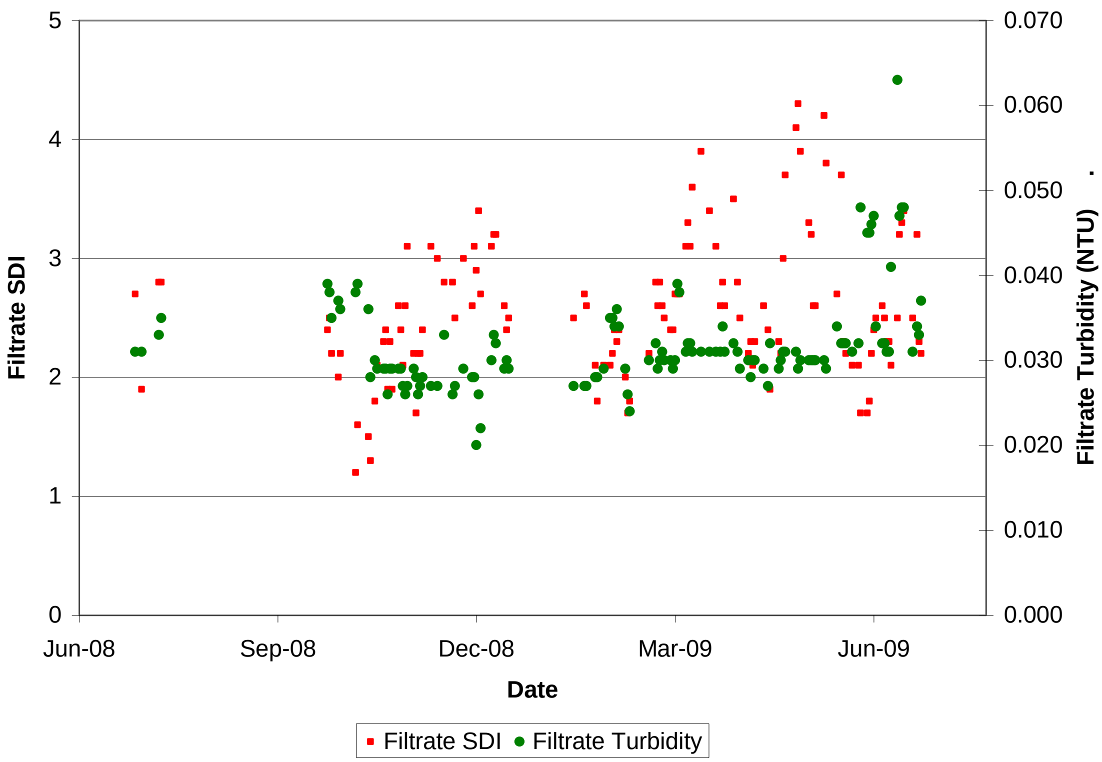


Figure 3.4 Turbidity & SDI for the UF membrane system

The UF performance compared to the media filter performance is shown below (**Figure 3.5**).

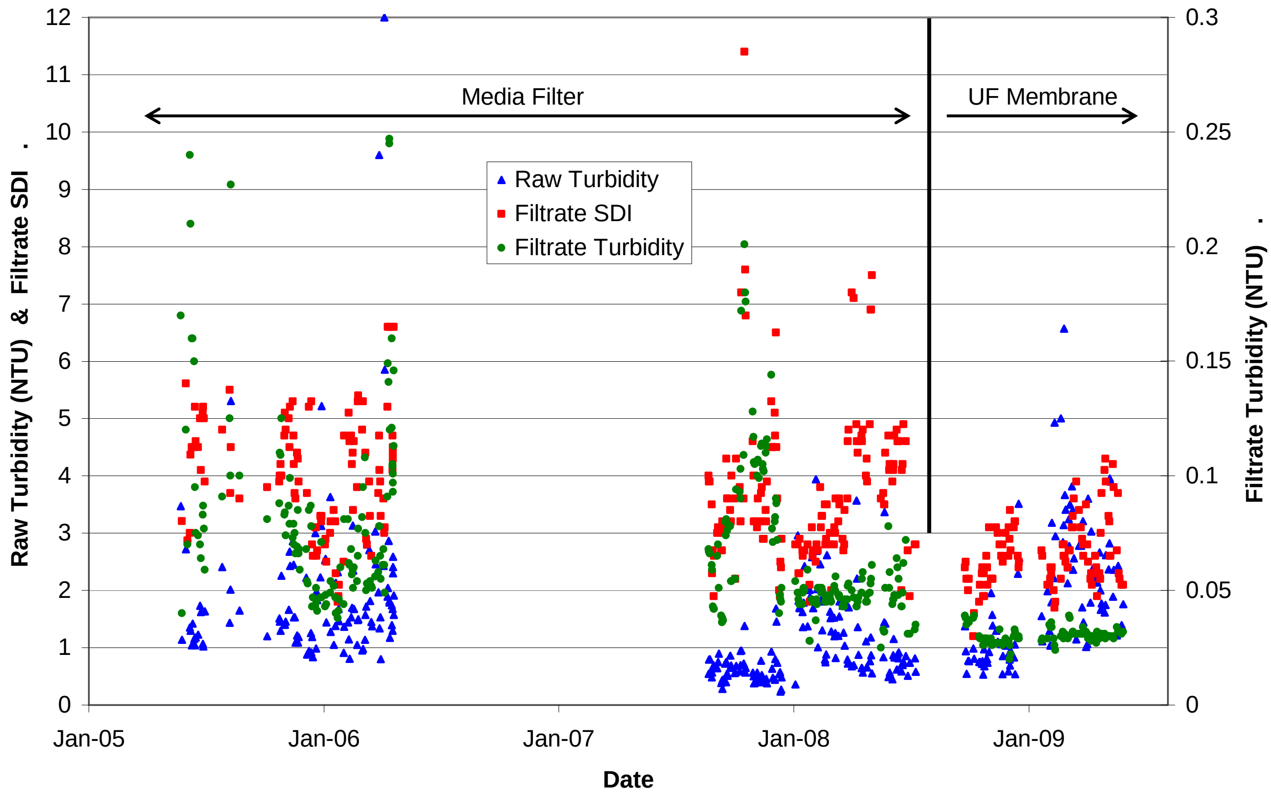


Figure 3.5 Turbidity & SDI for the UF membrane and media filter systems

It should be noted that in the summer of 2005, Southern California experienced localized and prolonged periods of red tides and extensive algae blooms. Red tides tend to occur most frequently in the spring and fall months and average 1-2 weeks in duration. The summer of 2005 was recognized as an anomalous period and stressed the media filtration system. In contrast, since the start of ADC II from August-2007 until July-2008 the ADC has experience approximately 8 discrete days in which satisfactory water quality could not be achieved using the basic multi-media system. In full scale applications, more robust designs would be applied to ensure that water quality and continuous operation could be maintained through these challenging but brief events that occur in Southern California costal waters.

After an initial optimization period, the UF membrane system performed very well with filtrate turbidity reduced by 97% and filtrate SDI values consistently below 4. This is compared to media filtration system SDI of 4 on average, but spikes up to 8 and turbidity reduced by 94%. Cartridge differential pressures following the UF system were typically flat for the first month of operation, and then began to rise at a variable rate to the maximum of 15 to 20 psi (103-138 kPa) before replacement.

3.3 Unbalanced Flow

3.3.1 Multi-point Testing Results The multi-point tests were conducted at a flux of both 7.5 and 9.0 gfd (306 and 367 L/m^2/d). Most of the 7.5 gfd test points were re-run after discovering that the baseline performance could not be achieved at the end of the testing. This was potentially due to membrane compaction during the initial high recovery and high feed pressure tests. Subsequent testing did not include the highest recovery points and included a baseline performance check between each different system recovery point. The results from the 7.5 gfd multi-point testing are shown in **Table 3.2** and **Figure 3.6**. Results from the 9.0 gfd multi-point testing are shown in **Figure 3.6** and **Figure 3.7**.

	Goal		**Actual**								
	RO Recovery %	**System Recovery %**	**RO Recovery %**	**System Recovery %**	**RO Specific Energy (kWh/m^3)**	**Feed TDS (mg/L)**	**Permeate TDS (mg/L)**	**RO Membrane Feed Pressure (kWh/m^3)**	**Flux (gfd)**	**Temperature (^oC)**	**Test #**
Ripening	42.5	42.5	42.6	42.6	1.77	33,250	119	770	7.53	15	1
		40	40.6	40.7	1.81	32,670	129	783	7.51	14	1
		45	40.7	45.6	1.94	34,520	137	842	7.51	14	1
	40	50	40.6	51.0	2.13	37,190	158	928	7.49	14	1
		55	40.4	55.9	2.31	39,970	181	1005	7.47	14	1
		60	40.5	61.1	2.54	43,660	205	1105	7.53	14	1
		45	45.5	45.6	1.94	32,790	147	867	7.51	13	2
		50	45.5	50.8	2.06	34,220	165	922	7.49	14	2
Multi-Point Testing	45	55	45.7	56.1	2.25	36,920	186	1015	7.51	14	2
		60	45.6	61.2	2.51	40,370	217	1120	7.49	14	2
		65	45.3	66.1	2.81	45,210	235	1242	7.44	13	2
		50	50.2	50.2	2.06	32,950	148	930	7.47	14	2
	50	55	51.0	55.9	2.20	34,850	194	998	7.53	16	2
		60	50.8	61.1	2.43	37,830	226	1099	7.49	16	2
	55	55	55.9	55.9	2.14	32,940	194	979	7.51	16	2
		60	56.2	61.3	2.43	36,980	222	1107	7.49	16	2
Balanced RO & System Recovery Points (shown for reference)	40	40	40.6	40.7	1.81	32,670	129	783	7.51	14	1
	45	45	45.5	45.6	1.94	32,790	147	867	7.51	45.5	2
	50	50 [1]	50.2	50.2	2.06	32,950	148	930	7.47	50.2	2
	55	55 [1]	55.9	55.9	2.14	32,940	194	979	7.51	55.9	2

Test 1: Original 7.5 gfd test. 40% RO Recovery was not performed in test 2, so a direct comparison can not be made.
Test 2: Re-run of 7.5 gfd test.
(1) At 50% and 55% recovery PX flow rates were below manufacturer's minimum requirements, which resulted in excessive mixing performance at balanced flows. At these points, over flushing with the low pressure flow was used to control mixing and simulate normal mixing levels. Therefore, in the NPV analysis RO recovery was substituted for System recovery at these points.

Table 3.2 Multi-point testing results at 7.5 gfd (306 $L/m^2/d$)

Figure 3.7 shows a minimum energy use point at 45% membrane and system recovery. Also shown on the 45% membrane recovery curve is the ability to increase the system recovery to some degree without a substantial sacrifice on energy.

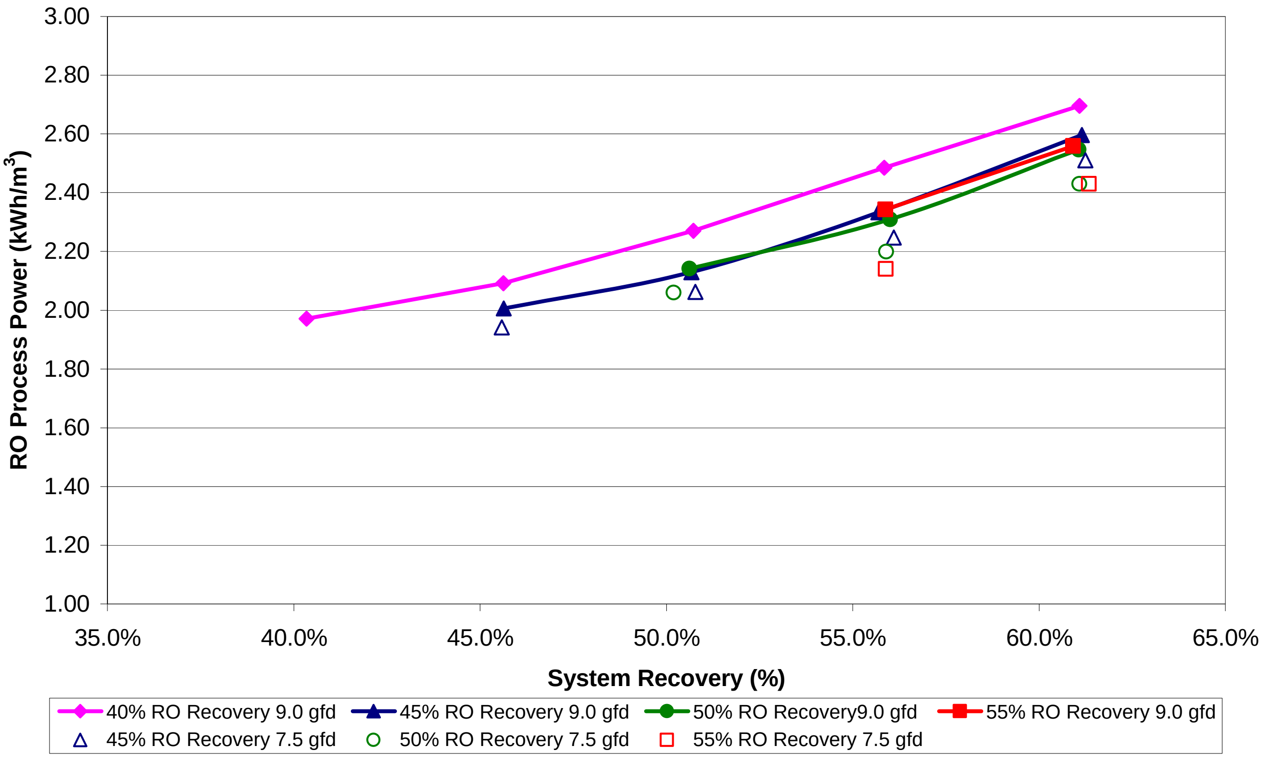


Figure 3.6 Unbalanced system recovery vs. energy use at 9 and 7.5 gfd (306 and 367 L/m^2/d)

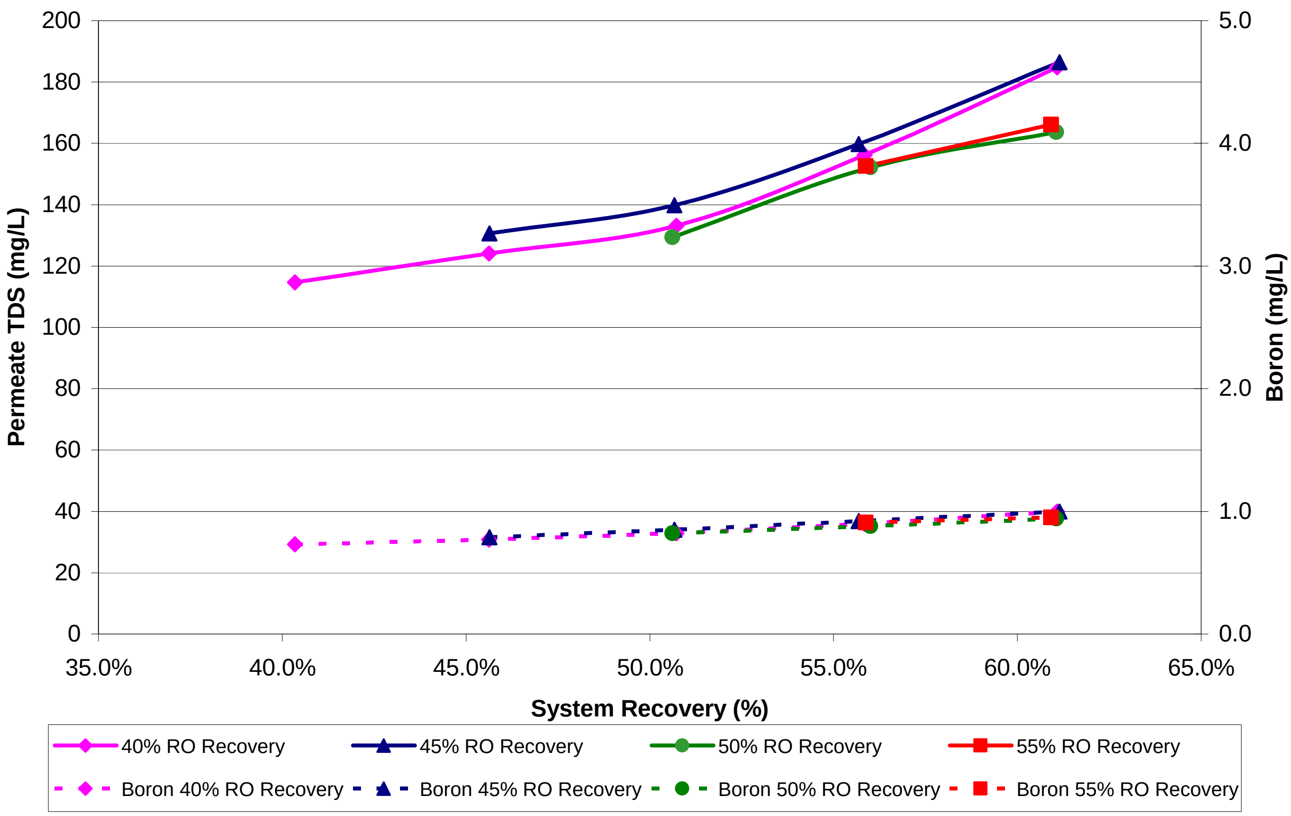


Figure 3.7 Unbalanced recovery vs. water quality at 9 gfd (367 L/m^2/d)

The conditions for the 50% system recovery / 45% RO recovery point are shown below (**Figure 3.8, Table 3.3**).

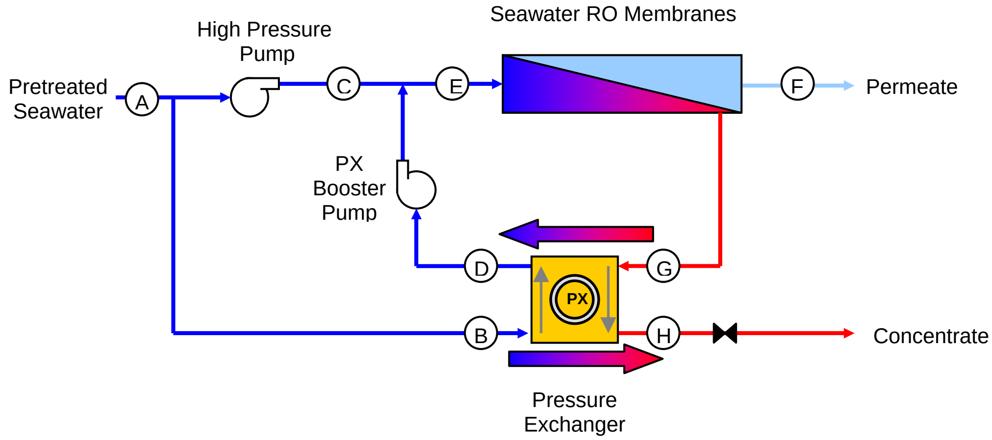


Figure 3.8 Unbalanced pressure exchanger diagram

		System Feed	PX Low Pressure in	High Pressure Pump Out	PX High Pressure Out	RO Membrane Feed	Membrane Permeate	Membrane Concentrate	System Concentrate
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Flow	gpm	87.9	41.9	46.0	52.3	98.3	43.8	54.5	44.1
	gpd	126,547	60,307	66,240	75,355	141,595	63,072	78,523	63,475
	m^3/day	479	228	251	285	536	239	297	240
Pressure	psi	31	30	860	842	860	3.3	852	26
	kPa	214	208	5929	5805	5929	23	5874	180
Quality	mg/L TDS	32,270	32,270	32,270	40,250	34,690	154	68,690	68,090

(a)

PX Unit Flow

High Pressure Feed Flow (gpm/lpm)	G	46 / 174
PX Internal Bypass (gpm/lpm)	C-F	2.2 / 8
PX Differential HP side (psi/kPa)	G-D	10 / 69
PX Differential LP side (psi/kPa)	G-H	826 / 5694
PX Efficiency (%)	(H+D)/(B+G) [1]	94.7%
Membrane Differential (psi/kPa)	E-G	8 / 55
RO Recovery (%)	F/E	44.5%
System Recovery	F/A	51.1%

[1] $(F_H P_H + F_D P_D) / (F_B P_B + F_G P_G)$

(b)

	High Pressure Pump	PX Booster Pump
Feed Pump Efficiency	90%	60%
Motor Efficiency	93%	90%
VFD Efficiency	97%	97%
Total Efficiency	81%	52%
Energy (KW)	17.7	0.7

All values are assumed except for Energy.

(c)

Table 3.3 Unbalanced pressure exchanger and system data at the 50/45 point (a) system data, (b) pressure exchanger data, (c) pump data

The following findings are drawn from these results:

- All tests up to 65% system recovery and 55% membrane recovery show acceptable product water TDS of up to 250 mg/L.
- Over the range of recoveries tested, RO membrane specific energy increases with recovery while the WTP facility energy required for treatment decreases or remains steady up to 45% recovery. This is due to the increased volume of raw feed water that must be pumped and treated at lower recovery rates to obtain the same volume of permeate. Above 45% system recovery, RO membrane specific energy increases at a higher rate, therefore increasing the total energy required as recovery increases. Therefore, these results show the importance of analyzing a facility process as a whole, and not just the RO specific energy.
- Mechanisms associated with this novel unbalanced mode of operation that might lead to improved and/or sustainable performance at higher recoveries include:
  - Improved boundary layer conditions in the elements through increased feed velocities
  - Optimal hydraulic conditions at the “low energy” recovery point
  - Balanced membrane flux through increased lead element velocities
  - Minimum brine flow requirements within manufacturers specifications
  - Maximum allowable recoveries within manufacturers specifications

3.3.2 Longer Term Testing The multi-point testing results indicated that higher recoveries of 60% to 65% were likely sustainable. Therefore, longer term testing was performed at a 60/45 instead of the 50/45 MAP to test the system limits. The test covered 1 month of continuous operation (**Figure 3.8**). This graph shows both stable energy use and product TDS. Pressure, recovery, and flux all remained constant. While longer term testing of 6 months would provide a more definitive indication of reliability, the results look promising for higher recovery operation when the associated higher energy use can be justified for expanded capacity.

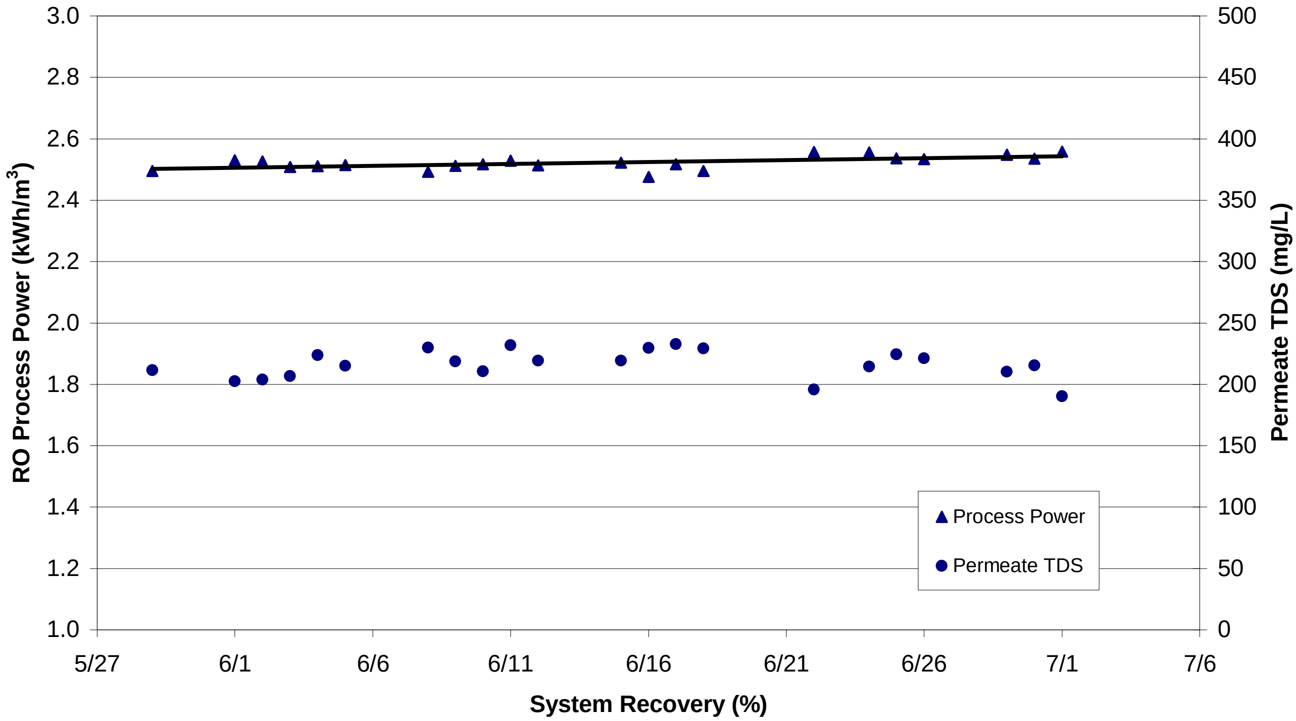


Figure 3.8 Longer term testing

3.4 Cost Estimates

Estimated costs for the ADC's conceptual 50 MGD facility are presented in **Figure 3.9 and 3.10**. These costs are in 2008 dollars.

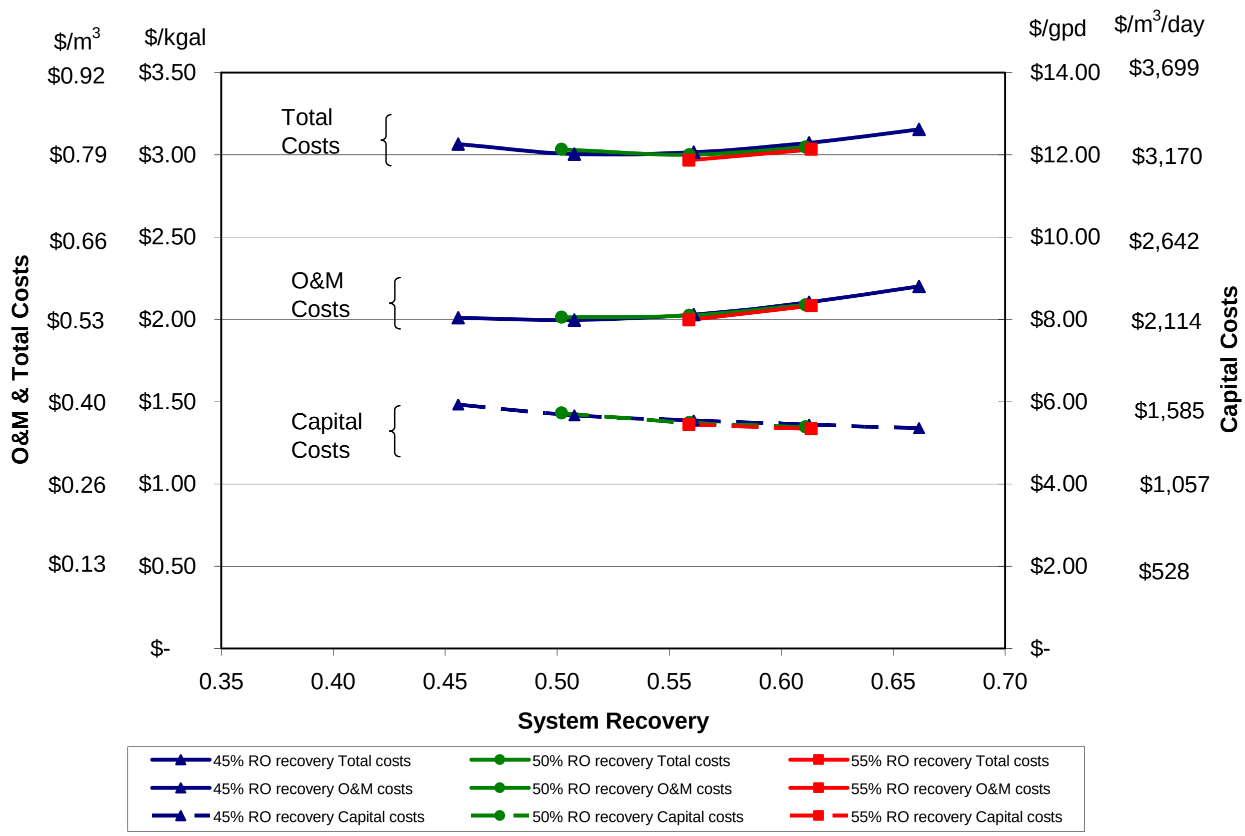


Figure 3.9 Projected costs for 50 MGD (189,000 m^3/day) treatment plants at 7.5 gfd (306 L/m^2/d) flux

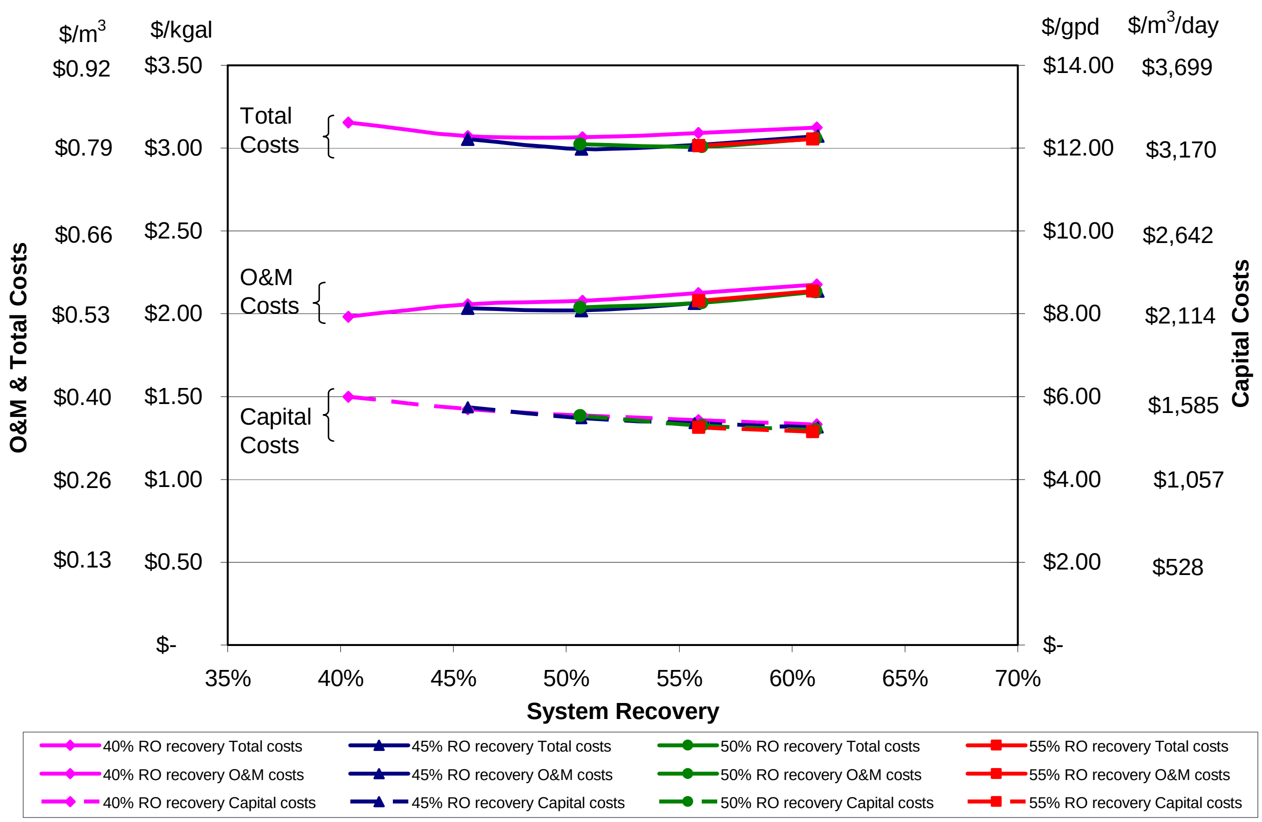


Figure 3.10 Projected costs for 50 MGD (189,000 m^3/day) treatment plants at 9 gfd (367 L/m^2/d) flux

The costs include the estimated capital cost as well as the operation and maintenance cost over the range of membrane and system recovery conditions tested for these unbalanced tests. As presented previously, these costs assume that the facility can share an existing open ocean intake and outfall and include in-line coagulation, deep bed media filtration, six RO trains with dedicated pumps, lime and carbon dioxide post treatment, new finished water pumping facilities.

The following findings are drawn from these cost estimates:

- According to the ADC's 50 MGD (189,000 m^3/day) net present value model for the projected cost of water over the range of recoveries ranged from \$3.00-3.16/kgal (\$0.77-\$0.82/m^3) for the7.5 gfd (306 L/m^2/d) flux tests and \$3.00-3.15/kgal (\$0.79-\$0.82/m^3) for the 9.0 gfd (367 L/m^2/d) flux tests.
- Over the range of flux and RO membrane recoveries that were tested, the cost per unit volume remained nearly constant between 45 and 55% system recovery.
- The RO energy consumption of 7.81 kWh/kgal (2.06 kWh/m^3) at the 50/45 MAP and flux of 7.5 gfd (306 L/m^2/d) is within the range of MAP points ((6.92-8.32 kWh/kgal (1.83-2.20 kWh/ m^3)) found during balanced flow tests in ADC I and II.
- While the MAP shown below did not produce the best water quality, of the tests, the TDS of 150 mg/L is still quite good at this point.
- The cost per unit volume reaches a minimum point at 50% system recovery / 45% RO membrane recovery at 9.0 gfd and at 55%/50% at 7.5 gfd, The previous ADC I and II testing on the suite of membranes from various manufacturer showed the lowest estimated total water cost at 50% recovery based on balanced PX operation. Operating at a recovery of 50% is slightly different than recommendation of some in the industry that advocate lower recoveries (e.g. 45%) to maximize membrane life, reduce cleaning frequencies and produce the highest quality permeate [6,7]. However, the impact of high recovery on membrane replacement costs, cleaning frequencies, and permeate quality are factored into the ADC's cost estimate.
- As expected, the capital costs continue to decrease as the recovery increases at the expense of higher energy use and higher potential for membrane fouling. However, these higher system recoveries that still maintain acceptable membrane recoveries can be invaluable for water treatment plants that either have substantial space limitations or need to increase capacity and can prevent or delay construction of additional facilities by increasing recovery. There are other factors such as a typical feed pressure limit of 1200 psi (8273 kPa) including room for membrane fouling.
- At 7.5 gfd (306 L/m^2/d), O&M costs comprise approximately 66% of the total water cost. RO energy consists of approximately 29% of the total water cost at the 50/45 MAP.

IV CONCLUSIONS

The following results and conclusions can be made from the ADC's demonstration study data and a conceptual 50 MGD SWRO facility:

- Testing was performed consecutively and was not conducted as a side by side evaluation. Therefore the results should not be used to make a direct performance comparison to the previous testing results, but estimated differences in performance and cost can be derived.

- Though the RO specific energy generally increases with recovery rate, between 40-45% system recovery the total energy required for treatment decreases or remains stable up to approximately 50%. This is due to the increased volume of raw feed water that must be pumped and treated at lower recovery rates to obtain the same volume of permeate.

- For seawater RO systems with varying feed water TDS, the ability to unbalance the PX and increase system recovery can help maintain stable RO feed pressures keeping the main HP pump operation at desired and efficient operating points. Furthermore, pretreatment energy and operating costs can be saved.
- The lowest projected WTP facility energy consumption occurred at 45% system recovery /45% RO membrane recovery. This is consistent with previous testing and typical industry recommendations for lowest energy operation.
- The projected total water cost reached a minimum at 50% system recovery / 45% RO membrane recovery at 9 gfd and at 55%/50% at 7.5 gfd, but other nearby points were of similar cost. These result potentially expand the lowest cost operating point options from typical industry recommendations.
- The unbalanced PX flow conditions allow for system recoveries greater than the 50% membrane recovery limits for the typical warranty considerations. Results show that system recoveries of up to 65% are potentially sustainable. Longer term testing for 1 month at 60% system recovery / 45% RO recovery show reliable membrane operation.
- The UF membrane pretreatment system showed reliable operation with over 6 months of operating time. The feed water to the RO system was of consistent water quality unaffected by changes in feed water turbidity.

The ADC has been able to demonstrate total energy consumption for seawater desalination at 11.28 kWh/kgal (2.98 kWh/m^3) at a projected total cost of $3.00/kgal ($0.79/m^3). These costs include escalations in commodity costs and other factors compared with previous ADC low energy / low cost results of 10.4 to 11.3 kW-hr/kgal (2.75-2.98 kWh/m^3) at a projected total cost of $2.83-3.00/kgal ($0.75-$0.79/$m^3$). These energy levels and cost figures are comparable to other traditional sources. For example, in Southern California the State Water Project which transports water from Northern California to Southern California consumes on average 10.4 kWh/kgal (2.75 kWh/m^3) [8]. And in San Diego, California end users can pay more than $6.00/kgal ($1.58/m^3) [9]. Therefore, Southern Californian seawater desalination is a drought-proof affordable and reliable new source of high quality fresh water.

V ACKNOWLEDGEMENTS

The authors would like to acknowledge the members of the ADC for their material, technical and financial support in completing this work.

VI REFERENCES

1. Seacord, T., S. Coker, and J. MacHarg. 2006. Affordable Desalination Collaboration. 2006 AMTA Biennial Conference. Los Angeles, CA.
2. L.S. Clesceri, A.E. Greenburg, and A.D. Eaton. 1998. Standard Methods for the Examination of Water and Wastewater, 20th Edition. APHA, AWWA, WEF.
3. Trussell, R.R., J. Jacangelo and R. Cass. 2004. Design and Performance of the Pretreatment for the Point Lisas Desalter. Proc. 2004 AWWA Annual Conference. Orlando, FL.
4. Irwin. K.J. and J.D. Thompson. 2003. Point Lisas SWRO Plant Trinidad - First Year Success. The International Desalination & Water Reuse Quarterly. 13:3 (12-16).

5. Seacord, T.F., S. Dundorf, and J. MacHarg. Affordable Desalination Collaboration 10 MGD Conceptual Case Study. Proc. 2007 AMTA Conference. Las Vegas, Nevada.
6. MacHarg, J. 2001. Exchanger Tests Verify 2.0 kWh/m^3 SWRO Energy Use. International Desalination and Water Reuse Quarterly. Vol 11/No. 1
7. Proto, T., E. Schoepke, L. Etchinson, T. O'Brien, B. Hernon, K. Perry, and M. Peterson. 2000. Production of High Purity Water from Seawater. Proc. 2000 North American Biennial Conference of the American Desalting Association. South Lake Tahoe, Nevada.
8. Water Sources Powering Southern California, by Robert C. Wilkinson Ph.D., January 2004.
9. Water and Desalination Report, vol 41, #42, These prices represent the volumetric price of water, including taxes, for domestic consumers using less than 15 m^3 per month.

Permeate Recovery Rate Optimization at the Alicante Spain SWRO Plant

Authors: *Richard Stover, Antonio Ordonez Fernandez, Joan Galtes*

Presenter: *Richard Stover*
Chief Technical Officer – Energy Recovery, Inc. – USA

Abstract

The permeate recovery rate in a reverse osmosis (RO) process is generally defined as the permeate flow rate divided by the membrane feed flow rate. An alternative definition is the permeate flow rate divided by the process feed flow rate. Historically, the process and membrane feed flow rates have been equal.

A high recovery rate means a high process yield. However, in a desalination process, operation at high recovery results in higher average concentrate salinities in the membrane elements, higher osmotic pressures and higher membrane feed pressures compared to operation at low recovery. In addition, supersaturation of the concentrate can result in more scaling and high membrane flux can result in more fouling. On the other hand, low recovery rate operation directly reduces process yield and can result in excess pretreatment and supply-pumping expenses. Permeate recovery rate optimization, therefore, is a critical exercise for RO process design and operation.

In most seawater RO processes being built today, such as the seawater RO plant built and operated by Inima (Grupo OHL) in Alicante Spain, isobaric energy recovery devices (ERDs) are applied to save energy. The flow rates of the high- and low-pressure streams through the devices to be unequal or unbalanced. Earlier turbine-based ERDs did not allow this flexibility. As a result, permeate recovery rate and process recovery rate can be set separately in RO processes equipped with isobaric ERDs. This feature adds a degree of freedom to recovery rate optimization and an opportunity for reducing energy consumption and/or improving process yield.

The authors present a detailed consideration of permeate recovery rate optimization in seawater RO processes equipped with centrifugal high-pressure pumps and PX Pressure Exchanger energy recovery devices. Optimization models are developed using practical process controls as independent variables. Modeling results are verified with process data collected at the Alicante seawater RO plant.

I. INTRODUCTION

In a reverse osmosis desalination process, the recovery rate or conversion rate is the ratio of membrane permeate flow rate to the membrane feed flow rate. Historically, these processes were operated at the highest possible recovery rate to obtain the maximum amount of permeate possible from the pressurized membrane feed water. However, the introduction of "isobaric" or pressure-equalizing energy recovery devices (ERDs) changed this practice (1).

In a seawater reverse osmosis (SWRO) process operating at a 45% recovery rate, isobaric ERDs supply 55% of the membrane feed flow, reducing the load on the high-pressure pump by a corresponding amount. Energy is consumed by a circulation pump that works in series with the ERDs, however, because the circulation pump merely circulates and does not pressurize water, its energy consumption is minimal. Therefore, more than half of the membrane feed flow is pressurized with almost no energy input. This means that seawater RO processes with isobaric ERDs can operate affordably at lower permeate recovery rates compared to processes operating with no energy recovery devices or with turbine-based devices. As a result, in most seawater RO processes being built today, such as the SWRO plant built and operated by Inima in Alicante, Spain ("the Alicante plant"), isobaric ERDs and a recovery rate of between 40% and 45% are applied to save energy.

Isobaric ERDs allow the flow rates of the high- and low-pressure streams through the devices to be unequal or unbalanced. As a result, the membrane recovery rate and the overall process recovery rate can be adjusted independently. This feature adds a degree of freedom that can result in further reductions in energy consumption and/or process yield improvement. This paper considers recovery rate optimization for the Alicante plant.

II. ALICANTE PLANT OVERVIEW

Alicante is a city of approximately 350,000 people located in southeastern Spain south of Valencia. The desalination plant is located on the coast just south of the city. Alicante II was commissioned in April 2008. It is the second membrane desalination facility built on the site, the first having been put in operation in 2003. Alicante II was designed and built by Spanish original equipment manufacturer Inima of Grupo OHL, Construcciones Alpi and Sampol..

The plant is fed from beach wells. The high-pressure portion of the plant consists of seven independent SWRO trains with a combined permeate production capacity of 65,000 m^3/day. Each train has 128 vessels of Dow Filmtec membranes, with six SW30HRLE-400i elements plus one SW30XLE-400i element per vessel. The trains are fed with Flowserve 8 x 10 x 13 DMX axially-split double-volute pumps driven by a Siemens 1100 kW, 2,980 rpm, 6000 volt motors. Each train is also equipped with a Flowserve 8HHPX15C horizontal circulation/booster pump with a 90 kW, maximum maximum 1,475 rpm, 400 volt motor equipped with a variable speed drive (VSD). A photograph of one of the SWRO trains is given in Figure 1.

Figure 1 – High Pressure Pump, Circulation Pump and Membrane Array

Energy recovery is achieved with arrays of twelve ERI PX-220 devices dedicated to each SWRO train. In Alicante, the PX devices are installed in the piping run below the membrane arrays, as shown in Figure 2.

Figure 2 – PX Energy Recovery Device Array

PX energy recovery devices (ERDs) are positive displacement isobaric devices commonly used in SWRO processes built since 2003 (2). Pressure transfer occurs through direct contact between the high-pressure concentrate and pressurized seawater inside the devices. Because there are no pistons or barriers in the flow paths, high- and low-pressure flow rates through the devices can be manipulated freely.

The Alicante plant started production in April 2008. The plant was designed to operate at a 45% recovery rate with sufficient capacity in the energy recovery device arrays and circulation pumps to operate at a recovery rate of as low as 39% if desired. At 45% recovery, each train is designed to produce 411 m^3/hr of permeate for a nominal plant production capacity of 65,000 m^3/day.

Shortly after startup, fouling struck the membranes. This increased the membrane feed pressure by about 4 bar and decreased permeate production. When it was realized that the fouling was persistent and unavoidable, the recovery rate of the SWRO process was lowered to approximately 40%. Lowering recovery lowered the membrane feed pressure resulting in an increase in permeate production to the design flow rate.

After their success with recovery adjustment, the plant operations team was open to consider further optimization of SWRO system flows. A recovery optimization model was developed and run over a range of process conditions. The model results were verified with tests run on the system. A detailed description of the analysis and results is given in the following sections.

III. RECOVERY OPTIMIZATION

To explain recovery and how it is adjusted, a simplified process flow diagram is shown in Figure 3. Concentrate rejected by the membranes (stream G) flows to the ERDs, driven by a circulation pump. The ERDs replace the concentrate with feedwater from the low-pressure supply system (streams A and B). The pressurized feedwater (stream D) merges with the discharge of the high-pressure pump (stream C) to feed the membranes (stream E). Water leaves the process as permeate from the membranes (stream F) or as spent low-pressure concentrate from the ERDs (stream H). In these systems, the high-pressure pump flow rate equals the permeate flow rate plus the leakage loss through the ERD. The leakage loss is very small such that the permeate flow rate and the high-pressure pump flow rate are always nearly equal (2).

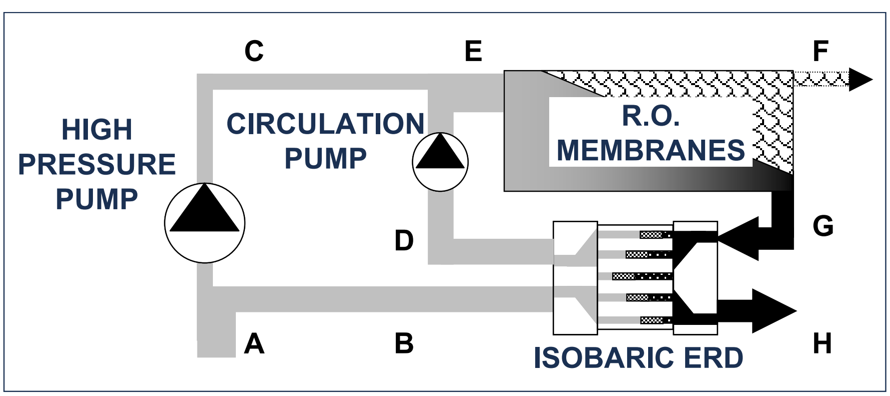


Figure 3: Simplified Diagram of an RO Process with Isobaric ERDs

With reference to Figure 3, the following terms are defined:

Membrane Recovery Rate – Permeate flow rate divided by the membrane feed flow rate or F / E.

Overall Recovery Rate – Permeate flow rate divided by the system feed flow rate or F / A.

Balanced ERD Flows – Flow rate of low pressure water fed to the ERD equals flow rate of high pressure water taken from the ERD or B = D and G = H. At balanced flow, membrane recovery and overall recovery are equal.

Lead Flow – Ratio of low-pressure flow rate to ERD divided by high-pressure flow rate from ERD, set by adjustment of low-pressure flow rate. A positive lead flow occurs when B > D.

Lag Flow – Ratio of high-pressure flow from ERD divided by low-pressure rate to ERD, set by adjustment of high-pressure flow rate. A positive lag flow occurs when D > B.

The membrane recovery rate, also known as the conversion rate, quantifies the amount of permeate extracted from the membrane feed. This, in turn, determines the concentration of the dissolved solids in the membrane reject stream. At high membrane recovery rates, the osmotic pressure of the concentrate stream is high, resulting in a high membrane feed pressure. Membrane recovery rate can be manipulated by altering the circulation pump speed. This, in turn, alters the membrane feed flow rate and changes the denominator in equation that defines the membrane recovery rate.

Lead or lag flow can be imposed by adjusting the low-pressure flow rate through the ERDs or by adjusting the speed of the circulation pump, respectively. However, for the sake of clarity in this analysis, the term lead flow will be used to refer to adjustments made by changing just the low-pressure flow rate through the ERDs. Therefore, positive or negative lead flows will be considered. Lag flow will be used throughout this analysis to refer to flow adjustments made by changing just the circulation pump speed. Positive and negative lag flows will be considered.

Some mixing occurs in the ERDs as a result of the direct contact between seawater and concentrate inside the devices. The ratio of ERD flows has a distinct affect on mixing as illustrated in Figure 4. If operated at positive lead flow, the excess seawater fed to the ERDs flushes the devices and reduces the salinity of the high-pressure water flowing from the devices. Negative lead flow results in some breakthrough of the concentrate to the high-pressure water flowing from the devices, evident as an increase in mixing. Lag flow has a similar affect on ERD mixing with a negative lag flow resulting in reduced mixing. Reduced mixing, in turn, results in lower salinity in the membrane elements and a corresponding reduction in the osmotic and membrane feed pressures.

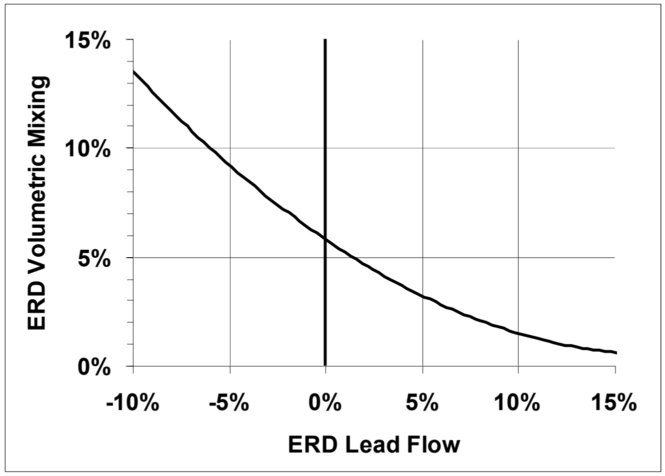


Figure 4 – ERD Mixing Versus Lead Flow

IV. PROCESS MODEL

The Alicante plant SWRO process was modeled using the characteristic curves of the high-pressure pump, the circulation pump, the membranes and the ERDs. Figure 5 shows the high-pressure pump curve, with head plotted as a function of flow. Adjustment of the high-pressure pump feed pressure, high-pressure throttling or permeate throttling can shift the pump curve up or down the chart. The duty point of the pump, however, always stays on the curve. For example, higher membrane feed pressure results in a lower flow rate as the duty point moves to the right and down the chart.

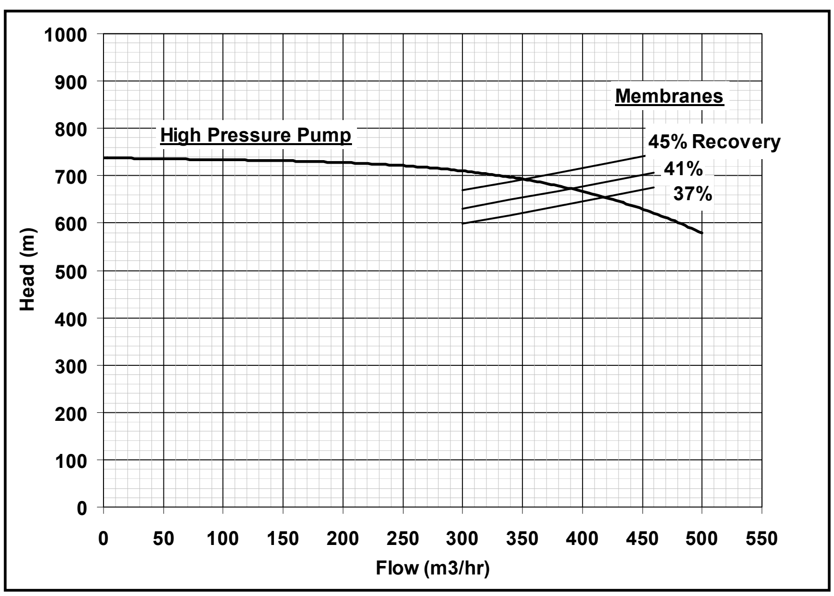


Figure 5 – High-Pressure Pump and Membrane Characteristic Curves

Membrane responses from the projection software for three different recovery rates were superimposed on the high-pressure pump curve in Figure 5. It is valid to consider these curves on the same chart because the high-pressure pump flow rate and the permeate rate are always nearly equal as described above. The membrane curves indicate that increased feed pressure results in higher permeate flow rates. These curves also indicate that higher pressures are required at higher recovery rates. Seawater temperature, seawater salinity and membrane fouling shift the membrane curves up or down the chart. The process operates at the pressure and flow rate where the membrane curve and the pump curve intersect.

Two characteristic curves for the circulation pump are given in Figure 6, corresponding to two different pump and motor rotation speeds. Although the duty point of the circulation pump always stays on a flow-head curve, adjustment of the VSD allows the operator to shift pump duty point from one curve to another. Therefore, the circulation pump can essentially be operated at any combination of flows and pressures within the operating envelope provided by the pump, motor and VSD. The circulation pump drives flow through the membrane concentrate channels and the ERDs such that the operation of these elements is coupled.

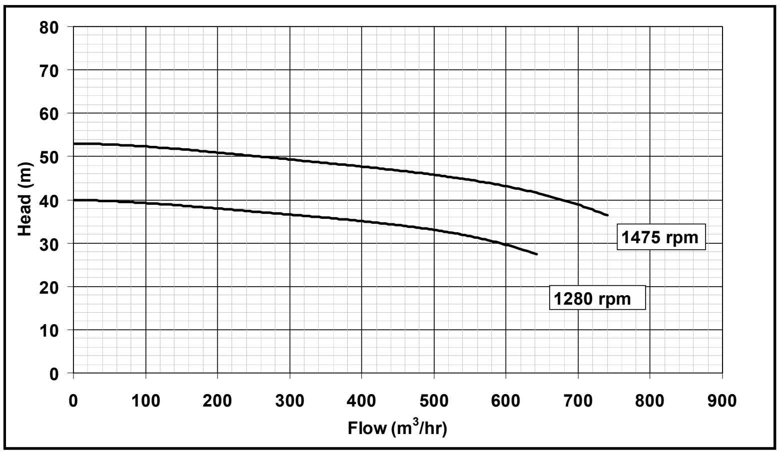


Figure 6 – Circulation Pump Characteristic Curves

The performance of the ERDs is also described by characteristic curves. These are shown in Figure 7 for a model PX-220 device. The flow rates through the ERD determine the pressure drops along the high-pressure and low-pressure flow paths. Conversely, with multiple ERDs operating in a device array, the flow rate through a particular device is determined by the pressure difference between the inlet and outlet manifolds at the manifold positions of the ERD (3). The ERD high-pressure flow is driven by the circulation pump and the low-pressure flow by the low-pressure supply pump.

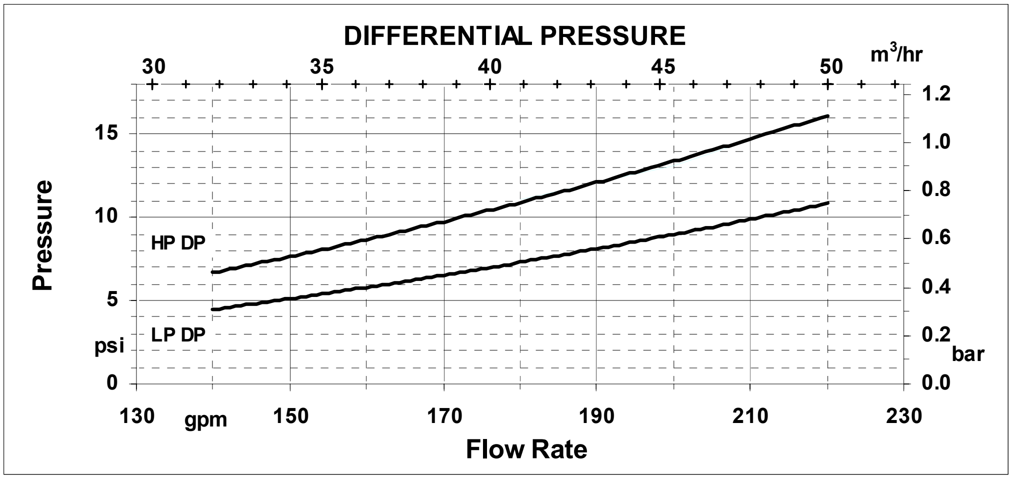


Figure 7 – PX-220 ERD Characteristic Curves

Resolution of the SWRO operating point for a given set of flow, pressure, salinity and temperature conditions involves the simultaneous consideration of the characteristic curves of the pumps, membranes and ERD. It is, therefore, an iterative computational process. After the system flows, pressures and corresponding pump hydraulic output requirements are determined, the energy consumption of the pump motors are computed using the pump and motor efficiencies (4, 5).

4.1 Lead Flow Modeling Results

Modeling results for a range of system recovery and membrane recovery combinations under lead flow conditions are shown in Figure 8. Specific energy in Figure 8 is the sum of the supply pump, the circulation pump and the high-pressure pump energy consumption divided by the SWRO permeate flow rate. Lead flow and overall recovery were adjusted by changing the low-pressure flow rate through the ERDs while holding constant the high-pressure flow rate of the circulation pump.

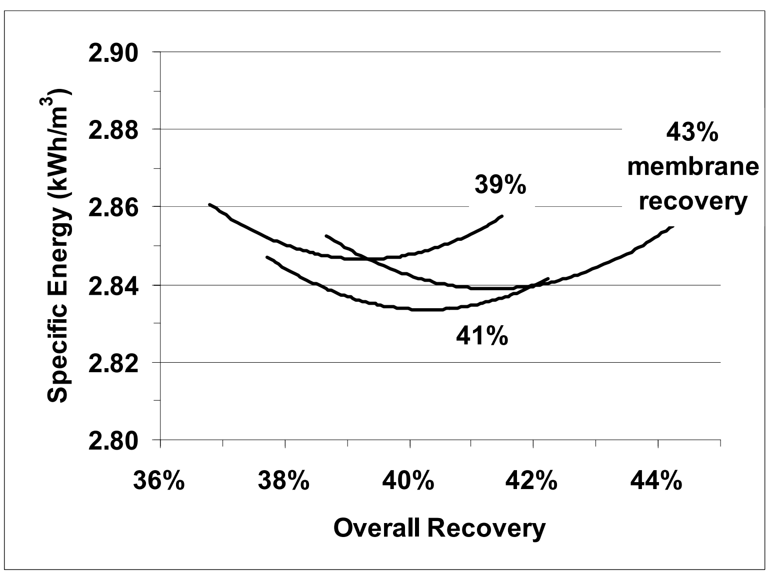


Figure 8 – Lead Flow Modeling Results

Considering any of the membrane recovery curves shown in Figure 8, as overall recovery is increased with reduced seawater fed to the ERDs, energy consumption by the high-pressure pump increases. This energy consumption increase corresponds with the increase in salinity in the membrane feed caused by extra mixing in the ERD in accordance with Figure 4. As overall recovery is reduced with extra seawater fed to the ERDs, excess energy is consumed by the system supply pump. The optimum overall recovery rate corresponding with the lowest SWRO specific energy consumption, therefore, is achieved by optimizing the low-pressure flow rate supplied to the ERDs by the supply pump.

At 41% membrane recovery, minimum energy consumption is predicted to occur at an overall recovery rate of nearly one percent less than the membrane recovery rate, corresponding to positive lead flow. At 43% membrane recovery, the optimal low-energy point is at an overall recovery rate that is about 1.5% lower than the membrane recovery, corresponding to more positive lead flow. At 39% membrane recovery, the optimal overall recovery is above 39%, corresponding with slight negative lead flow.

These data suggest that the system has a “sweet spot” close to 41.5% membrane recovery and 41% overall recovery. These recovery rates are close to balanced flow with 2% extra low-pressure seawater supply or 2% lower concentrate flow. If the membrane recovery is increased above 41.5% by reducing circulation pump speed, specific energy consumption can be reduced by reducing overall recovery by applying more low-pressure flow to the ERDs. Similarly, if the system is operating at a lower-than-optimal membrane recovery, overall recovery can be increased slightly by reducing low-pressure flow to the ERDs to reduce energy consumption.

It is important to note that this analysis does not take into account the full cost of pretreatment, the capacity of the pretreatment system or the energy or cost required for post-treatment. Recovery optimization requires consideration of equipment, contractual and cost constraints. For example, there is insufficient pretreatment capacity to allow the entire plant to operate at 41% recovery. However, the analysis does take into account changes in mixing through the ERDs and the associated impact upon membrane feed pressure. Volumetric mixing ranges from 2 to 13% in the data presented in Figure 8 in accordance with the lead flow dependency given in Figure 4.

4.2 Lag Flow Modeling Results

A similar iterative procedure was used to resolve the characteristic equations of the components to generate specific energy curves for a range of overall and membrane recovery rates for lag flow conditions. Lag flow and membrane recovery were adjusted by just changing circulation pump speed. For example, increased circulation pump speed resulted in positive lag flow and reduced membrane recovery. The results are shown in Figure 9.

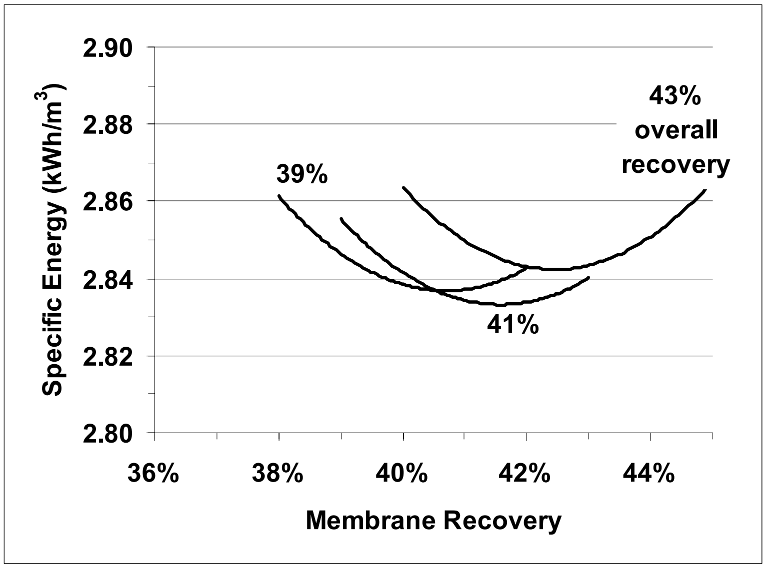


Figure 9 – Lag Flow Modeling Results

The overall trend of the data for the lag flow modeling was similar to the lead flow data. Considering any of the overall recovery curves, positive lag flow and reduced membrane recovery increased energy consumption by raising the salinity of the membrane feed and the corresponding duty of the high-pressure pump. Negative lag flow and increased membrane recovery increased energy consumption by raising the osmotic pressure within the membrane array. The optimum membrane recovery rate corresponding with the lowest overall specific energy consumption, therefore, is achieved by optimizing the high-pressure flow rate supplied to the ERDs by the circulation pump. As in the lead flow analysis, the "sweet spot" is at about 41.5% membrane recovery and 41% overall recovery.

Note that the overall recovery curves in the lag flow modeling results are more curved than the lead flow curves when the system is shifted away from its minimum energy points. Circulation pump speed changes alter both the mixing within the ERD and the salinity within the membrane elements. The compound affect of membrane recovery rate changes results in the steep curves in Figure 9. These results show that the process is more sensitive to the high-pressure flow rate through the ERDs than it is to the low-pressure flow rate through the ERDs.

It should also be noted that the overall range in specific energy indicated in Figures 8 and 9 is about 1.4% despite a variation in ERD flow of nearly 30%. This suggests that the system's energy performance is robust and somewhat insensitive to flow imbalance through the ERD. The optimization exercise described above is "fine tuning." However, its importance is magnified when multiple years of operation and multiple SWRO trains are considered. In the Alicante plant, if the price of power is $0.09 per kilowatt hour, a 1.4% reduction in energy consumption would save nearly $90,000 per year in power costs.

Again, it is important to note that this analysis does not take into account equipment, contractual and cost constraints which may shift the optimal recovery rate of the process. However, the trend of the results can be useful for process optimization at any recovery rate. For example, if the process is operated at an overall recovery rate of 45%, the analysis above suggests that reducing the membrane recovery rate to below 45% will improve specific energy consumption. This can be achieved by increasing the speed of the circulation pump with no other changes to the process. Conversely, at overall recovery rates below 41%, increased membrane recovery rates and lower circulation pump speeds are energetically favored.

V. PROCESS PERFORMANCE

Between when the analysis above was conducted and process performance data was collected, several changes were made to the process. First, a partial open intake was added to the beach wells resulting in a decrease in the average salinity of the feedwater to the process from about 42,300 to about 39,300 ppm and reducing membrane feed pressure by about 1 bar. Second, the membranes of some SWRO trains were chemically treated to address the fouling problem resulting in a membrane feed pressure reduction of approximately 2 bar. Both of these changes reduced the specific energy consumption of the process compared to the energy consumption measured at the start of the analysis and predicted by the model.

Process data was collected in the Alicante plant from the SCADA screen in the plant control room at 41 and 43.5% overall recovery. The circulation pump speed or the low-pressure feed rate to the PX devices was varied and pump power consumption was measured. ERD efficiency ranged from 96.6 to 97.2% and volumetric mixing ranged from 3.6 to 10.6%. Specific energy data as a function of recoveries is shown in Figure 10. The curve identified as “43.5% overall recovery” was collected on a train that had received chemical treatment for fouling.

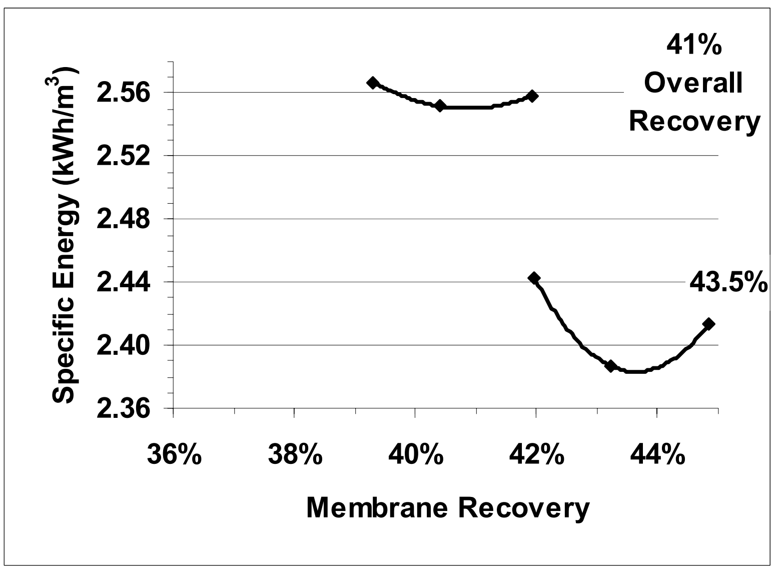


Figure 10 – Process Data

These data clearly demonstrate the energy reduction benefits of the feedwater and membrane changes. The data also suggest that the lowest specific energy was measured when the membrane recovery and overall recovery were set equal, at which point the ERDs were operating at balanced flow. However, the change in specific energy consumption and the ERD efficiency measured over the range of the membrane recovery rates examined was minimal despite the rather large range of mixing observed from the ERDs. This observation supports the conclusion that SWRO processes operating with isobaric ERDs are relatively insensitive to flow and flow ratio variations through the ERDs.

VI. SUMMARY AND CONCLUSIONS

The isobaric energy recovery devices in use in the Alicante plant gave the operators the flexibility to reduce recovery to achieve the plant's permeate production target despite persistent fouling that increased the membrane feed pressure. In addition, the PX devices used for energy recovery in the plant allow the operators to adjust the ratio of high- and low-pressure flows through the devices and thereby independently adjust the membrane recovery rate and overall recovery rate of the process. An analysis of the system over a range of recovery rates reveals the existence of a specific combination of overall and membrane recovery rates that results in minimum energy consumption. The analysis indicates how the membrane recovery rate could be adjusted to minimize energy consumption at whatever overall recovery rate that plant is operating. The results of the analysis were corroborated with process data.

VII. REFERENCES

1. MacHarg, J.P. and G.G. Pique, How to Design and Operate SWRO Systems Built Around a New Pressure Exchanger Device, International Desalination Association World Congress Manama, Bahrain 2002.

2. Stover, R.L., Development of a Fourth Generation Energy Recovery Device – A CTO's Notebook, Desalination, 165, pp. 313-321, August 2004.

3. Stover, R.L., J.G. Martin and M. Nelson, The 200,000 m^3/day Hamma Seawater Desalination Plant, Proceedings of the International Desalination Association World Congress, Maspalomas, Gran Canaria, Spain, October 2007.

4. Moch, I. and C. Harris, What Seawater Energy Recovery System Should I Use? – A Modern Comparative Study, Proceedings of the International Desalination Association World Congress, Manama, Bahrain, March 2002.

5. Stover, R.L., Energy Recovery Device Performance Analysis, Proceedings of the Water Middle East Conference, Bahrain, November 2005.

Appendix D: TWDB Review Comments

Energy Optimization of Brackish Groundwater Reverse Osmosis Desalination

Contract # 0804830845

The report describes the development and testing of innovative process designs that utilize isobaric energy recovery technology in brackish groundwater desalination.

Please note that the contract (Section II, Standard Agreement, Article III, Schedule, Reports and Other Products) stipulates the following regarding draft and final reporting under this contract:

> "3. The CONTRACTOR (S) will complete the Scope of Work and will deliver seven (7) double-sided copies of a draft final report to the EXECUTIVE ADMINISTRATOR no later than the STUDY COMPLETION DATE. The draft final report will include the scope of work; a description of the research performed; the methodology and materials used; any diagrams or graphics used to explain the procedures related to the study; any data collected; an electronic copy of any computer programs, maps, or models along with an operations manual and any sample data set(s) developed under the terms of this contract; analysis of the research results; conclusions and recommendations; a list of references, a Table of Contents, List of Figures, List of Tables, an Executive Summary, and any other pertinent information. All final reports should be prepared according to Exhibit E, Guidelines for Authors Submitting Contract Reports to the Texas Water Development Board. After a 30-day review period, the EXECUTIVE ADMINISTRATOR will return review comments to the CONTRACTOR (S).
>
> 4. The CONTRACTOR(S) will consider incorporating comments from the EXECUTIVE ADMINISTRATOR and other commentors on the draft final report into a final report. The CONTRACTOR(S) will include a copy of the EXECUTIVE ADMINISTRATOR's comments in the final report. The CONTRACTOR(S) will submit one (1) electronic copy of the entire FINAL REPORT in Portable Document Format (PDF) and nine (9) bound double-sided copies of the final report to the EXECUTIVE ADMINISTRATOR no later than the FINAL REPORT DEADLINE. The CONTRACTOR(S) will submit one (1) electronic copy of any computer programs or models and an operations manual developed under the terms of this CONTRACT. After a 30-day review period, the EXECUTIVE ADMINISTRATOR will either accept or reject the final report. If the final report is rejected, the rejection letter sent to the CONTRACTOR(S) shall state the reasons for rejection and the steps the CONTRACTOR(S) need to take to have the final report accepted and the retainage released."

The TWDB staff reviewed the Draft Final report and provides the following comments; we ask that you include these comments, along with your responses, as an Appendix in the final report.

Title and Cover Page

1. The title of this report should be "Energy Optimization of Brackish Groundwater Reverse Osmosis Desalination" and the subtitle should read "Final Report for Contract Number 0804830845." Title has been changed according to comment.

Organization of the Report

2. The report would benefit from a section describing the project methodology. Methodology, section 2, page 4 has been added.
3. The inclusion of ADC white paper publications regarding past seawater desalination work is unnecessary and could be incorporated by reference where needed. Comment number 29 below was incorporated to include the reasoning for certain seawater papers to be included into our Appendix C, White Papers.
4. The report needs to clearly describe the results of the project in terms of the energy savings that can be accomplished through an optimized brackish groundwater desalination process and the corresponding life-cycle costs of this approach. Energy savings and life cycle costs have been revised and included in our section 4, pages 21-30.
5. The readability of the report would be much improved if the notation for the different components of the pilot plant, the process and the control points are introduced early on in the report –such as in Figure 2- and this notation is used consistently throughout the report: in the narrative, the equations and the data tables. Please consider adding a Glossary of Terms and a List of Acronyms and Abbreviations. We have revised the report to define our terminology and used it more consistently throughout.
6. Please consider organizing the report in the following manner or similar:

1 **Executive Summary**
- 1.1 Introduction
- 1.2 Purpose of the study
- 1.3 Organization of the report

2 **Methodology**
- 2.1 Problem statement
- 2.2 Project approach and Optimization Criteria
- 2.3 Control points and data collection

3 **Project Implementation**
- 3.1 Pilot plant set-up
- 3.2 Source water characterization
- 3.3 Equipment
- 3.4 Project monitoring and reporting

4 Results
- 4.1 Energy requirements of an optimized brackish groundwater desalination system
- 4.2 Life-cycle cost analysis

5 **Conclusions and recommendations**

References

Appendix A- Validation Protocol

Appendix B- Data

We have organized the report according to TWDB comment 6.

Executive Summary

7. Regarding the reference to "inland brackish desalination systems;" the Texas Water Development Board (TWDB) funding for this project was provided as part of the Brackish Groundwater Desalination Program; this project tested reverse-osmosis in a brackish groundwater setting; surface brackish desalination would have additional treatment –and energy- requirements. Please ensure that the brackish groundwater nature of the project is clearly stated and consistently used in the report. We have revised the report to reflect brackish ground water were applicable.

8. Please replace the words, "kilowatt-hours per acre-feet" to "kilowatt-hours per acre foot". Noted and corrected.

9. Results should not be reported in the list of tasks. Please consider providing key findings of the study in a separate paragraph. Noted and revised.

10. Please provide a complete list of member organizations that participated in the Affordable Desalination Collaboration. Section 1.1, page 1-2 provides a complete list of participants.

11. Please replace the name "United States Bureau of Reclamation" with the name "U.S. Department of Interior, Bureau of Reclamation".

Methodology (Proposed)

11. This report requires a methodology section to help others understand and replicate the lessons learned from the project. Please include a problem statement and a clear description of how the problem will be addressed and how success –energy savings and reduced life cycle cost- will be measured. Methodology section 2, pages 4-9 has been incorporated into the report.
12. Please explain in this section the concept of flow management at the pressure exchanger unit, why it needs to occur and how it is accomplished and the role this tool has in optimizing the energy requirements vs. production recovery in the system. Please consider an approach similar to that used in the white paper by Richard Stover and others, See Section 8, Permeate Recovery Rate Optimization at the Alicante Spain SWRO Plant. Methodology section 2, pages 4-9 has been incorporated into the report.

Project Implementation

13. In its current form, this section is of limited value; adding a methodology section to precede it will fill the apparent gap in the flow of the report. Also, please consider including a

timeline of the project's key tasks along with sketches and description of the pilot plant site layout, equipment, source water characterization, and the execution of the testing protocol. Implementation and Methedology section include site layout, equipment, descriptions.

14. Page 2, 2nd paragraph (Section 3): "…feed water as the full-scale plant. The desalination plant…" should read "..feed water as the full-scale plant diverted following sand removal. The desalination plant…" Noted and revised.
15. Page 2, 3rd paragraph: Consider replacing "potable" with "product." Noted and revised.
16. Table 1
    a. The "basis" column is mostly redundant and its contents could be captured in a footnote or the table's caption noting that primary and secondary standards of potable water quality are set by U.S. Environmental Protection Agency.
    b. Move unit to after the value (e.g. <500 mg/l). Noted and revised.
17. The report uses different names for the El Paso desalination plant. In some instances, the plant is called the El Paso Brackish Water Desalination facility, while in other instances it is called the Kay Bailey Hutchison Desalination Plant. Please consider using the name, "Kay Bailey Hutchison Desalination Plant" in all instances. Noted and revised.

Project Results

18. Please consider re-aligning the contents of this section to the suggested report outline. Noted and revised.
19. Although valuable as a reference on the work of ADC on seawater desalination matters, these are not deliverables from this project thus is questionable that the results section should begin with this particular topic. Please note that there is only one white paper publication directly related to the current project. Noted and revised.
20. Section 4.1, Affordable Desalination Collaboration Pilot System:
    a. Table 2 lists two Pressure Exchanger Energy Recovery, Inc. PX-70S SW and PX-45S BW units. Why is it necessary to have two units? Are these units optimally sized for the needs of the project? Please explain. Table 5 in section 3.3 has been revised to remove any reference to the PX-70S SW.
    b. Please describe the membranes used in this study. The description may include the production rate, rejection capacity, pH, and temperature tolerance of the membranes. See Table 5 in section 3.
    c. Please explain how the equipment selected for this project is conducive to an optimized reverse-osmosis desalination process. Please discuss whether the selected equipment carries a higher cost if compared to the equipment normally used in brackish groundwater reverse osmosis desalination. See section 2.2.2, Pressure Exchanger System Design and Operation for a description of how the design has been optimized for brackish water applications. See section 4.5, Life Cycle Cost Analysis for a description and comparison of costs.

d. Page 4, last paragraph, includes a reference to “permeate throttling;” please describe how this is accomplished and revise Figure 2 to facilitate understanding this concept. See section 3.1, Pilot Plant Set-Up for a description of permeate throttling.
e. Page 4, last paragraph, first line; please delete the word ‘membrane’ before the word ‘pretreatment’ so that it does not sound like there are membranes doing the pretreatment. Noted and revised.
f. Figure 2 is very informative about the project approach and the process components. Please explain the figure in detail in the text and ensure that all components of the demonstration project and relevant control points are duly noted and that these are consistently used throughout the report. Noted and revised.

21. *Section 4.1.1, Optimized Isobaric Energy Recovery*:

a. Please provide a reference for the second sentence of the opening paragraph. Section 2.1, Hauge and Ludvigsen, 1999, provides the first published reference to a pressure exchanger installation.
b. To maintain the consistency between the illustration of Figure 2 and the following text, please replace the words ‘main pump’ with the words ‘high pressure pump’ in the last paragraph of page 6. Noted and revised.
c. Please explain the criteria of an optimized system in the last paragraph of page 6. See section 2.2.2, Pressure Exchanger System Design and Operation for a description of how the design has been optimized for brackish water applications.
d. Figure 3; please provide the credits for this illustration. Also, later in the report, there are references to manipulating the flow at the pressure exchanger to achieve greater overall efficiency. Figure 3 and the description of the pressure exchanger –pages 6 through 8- do not adequately describe how this manipulation is accomplished. Section 2.2.1 provides reference to ERI Doc. No. 80088-01 for related figures and descriptions.
e. The reference to a figure in the second paragraph in page 6 lacks the figure number. Noted and revised.

22. *Section 4.1.2, Brine Recirculation Process for High Recovery*: The comments below have been noted and revised into our section 2.2, Project Approach and Optimization Criteria, pages 3-9.

a. Figure 4 and the narrative following it, are confusing. The system lay-out in Figure 4 differs from that presented in Figure 2 (location of the inter-stage booster pump).
b. The concept of “normal operation” at the pressure exchanger where high pressure concentrate flow into the unit is equal to the discharged low pressure concentrate flow should perhaps be referred to a “balanced flow” to help explain the use of “unbalanced flow” in the text.

c. Is the rate of flow across the pressure exchanger managed by throttling the low pressure discharge? Please describe the purpose of the valve shown next to control point "H."

d. The stated purpose for increasing the mixing of concentrate with the filtered feed is to increase the system's overall recovery. Conceivably, the increased recovery could be achieved by recirculation of the low pressure concentrate discharge to the feed prior to the high pressure pump; please discuss briefly the advantages/disadvantages of this option.

e. The text indicates that "result is the reverse osmosis recovery will be lower than the system recovery;" please explain the significance of this statement and provide the relevant equations supporting the statement.

f. There are four bulleted advantages listed in Section 4.1.2. Please discuss these in greater detail;

   - The first advantage seems out of place given that the illustration lacks the inter-stage layout of Figure 2. Please explain why it is advantageous to improve the boundary layer conditions by increasing the cross flow velocity.
   - What does "Balanced membrane flux through increased lead element velocities and salinity" mean?
   - What does "Minimum brine flow requirements within manufacturers' specifications" mean?

g. The narrative in Section 4.1.2 lacks a discussion of the main objective of this project; optimizing the energy requirements of the system while maintaining or increasing the system's recovery.

23. *Section 4.3.1, Optimized Isobaric Energy Recovery Configuration*: The comments below have been noted and revised into our section 2.2, Project Approach and Optimization Criteria, pages 3-9.

a. The text mentions the need for over flushing; following the discussion in subsection 4.1.2 and Figure 4, "over flushing" would mean a condition where the high pressure concentrate flow into the unit is less than the discharged low pressure concentrate flow, in which case the difference in volume would leak across the pressure exchanger to mix with the filtered feed. Is this correct? If so, please provide more detail in the text so the reader can follow the process more easily.

b. Please clarify the reference to 4 percent "salinity mixing;" is this a volume ratio or a 4 percent salinity increase in the filtered feed source?

c. This paragraph contains a reference to a figure that lacks the figure number.

d. Figure 5 is difficult to interpret. Too much information is included in the figure. The X-axis of the current figure is plotted using a 5-day of interval. Please consider plotting the figure using 15-day of interval. The figure contains numerous vertical dashed lines. Therefore, it is difficult to identify which data points represent baseline recovery of the system.

24. *Section 4.3.2, Concentrate Recirculation Configuration (unbalance/underflush):* Noted. See revised section 4.2, pages 18-20.

    a. Please add the figure [6] number in the text.
    b. Figure 6 is difficult to interpret. The X-axis of the current figure is plotted using a 5-day of interval. Please consider plotting the figure using 15-day of interval. The figure contains numerous vertical dashed lines. Therefore, it is difficult to identify which data points represent baseline recovery of the system.
    c. The description, regarding impurities found from the membrane autopsy, is not clear. The report does not discuss in addition to silica what other constituents were found during the membrane autopsy.

25. *Section 4.3.3, Reverse Osmosis Process Specific Energy*: The comments below have been noted and revised into section 4.4, Energy requirements of an optimized brackish groundwater desalination, System pages 21-26.

    a. Figure 7
        - Please add the figure [7] number in the text;
        - It would be useful if the "Reverse Osmosis process specific energy" values were either shown in Figure 7 or in a separate table.
        - The bulleted list of operational scenarios and the illustration in Figure 7 do not match. Please number the options and provide a complete non-abbreviated description to better communicate the results.
    b. Please note that it is not clear from the text what an "80 % Optimized" scenario means; please add an explanation in the methodology section describing the optimization goal and the protocol to achieve it.
    c. Please consider a tabular presentation of the energy requirements for each one of the scenarios discussed and the respective life-cycle cost; please discuss these results.
    d. Please provide the data for the text shown in the last paragraph of Page 11.
    e. Please explain how the power consumption rate of the system was measured.
    f. Please clarify if the project energy savings are listed as annual values.
    g. Please discuss if the cost savings in the calculation include capital costs.

Project Deliverables

26. Please incorporate this information as part of the proposed "Project Implementation" section. Noted and revised.

Dissemination and Outreach Activities

27. Table 5; please consider revising the list to limit it to events directly related to the TWDB-funded project. Section 6, Table 10 list all of the papers, presentations and other outreach

activities that were conducted during the project period, where specific references and descriptions of the TWDB funded work would have been made.

Budget and Financial Breakdown

28. This section is unnecessary in the final report. Noted and revised.

Papers and Articles

29. The papers add value to this report; however, they refer to ADC's seawater desalination experience. To address the logic gap, please consider a brief introduction to the section describing the contents of the section and explaining how these papers inform the demonstration project. Noted and revised.

Validation Protocol

30. This document is currently labeled "draft;" please final to include in the final project report. Noted and revised.
31. Please ensure that references to the project are specific to brackish groundwater. Noted and revised.
32. Table 2.2 illustrates the energy savings that can be gained by the use of the inter-stage booster and the energy recovery unit; however, because the optimization criteria concept has not been explained, it is premature to refer to this as an optimized design. See section 2.2 in the final report for a more detailed description of the optimization criteria.
33. Please supplement the information in Table 2.2 with the life-cycle cost for the modified reverse osmosis desalination process. See section 4.5 in the final report for a detailed description of life cycle costs.
34. Please revise the equations in pages 7 and 11 to make sure that all equipment components and control points are consistently labeled and defined. Please provide a readable and clear schematic to accompany this section. Label consistency to be revised in final draft. See P&ID in appendix A of the test protocol for the schematic.

Contract Administration

35. The April 25, 2011 issue of the Water Desalination Report announces the sale of the pilot plant used for the TWDB project. The article lists the equipment included in the sale offer. Please identify all of the equipment that was purchased with TWDB funding, the date of purchase and the purchase price. A determination on the final disposition of equipment purchased with TWDB funding requires explicit TWDB approval. A list of equipment purchased during the TWDB contract period has been provided.