

Optimizing Lower Energy Seawater Desalination, The Affordable Desalination Collaboration

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Abstract

In the United States, the high cost of desalination has historically hindered interest in seawater as a possible fresh water supply. 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 reverse osmosis (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 ADC's demonstration scale seawater reverse osmosis (SWRO) treatment system uses pressure exchanger technology (ERI) for energy recovery. The RO array consists of 3 each x 7 element 8" DIA pressure vessel. The flux and recovery can be varied from 6-9 gfd and 35-60% respectively. The overall capacity of the system can be varied from approximately 200-300 m³/day (50,000-80,000 gpd)

The research and demonstration work being conducted by the ADC is divided into two phases. The first phase of testing was completed in March 2006 and took place at the US Navy's Seawater Desalination Test Facility in Port Hueneme, California. It included testing three membrane sets and varying flux and recovery to seek the most affordable operating point. The most affordable operating point was estimated by calculating the net present value for each tested condition, accounting for both capital and operating costs.

The second phase, scheduled to start in spring 2007, includes testing and demonstrating additional manufacturers' membranes through a similar protocol as Phase I, which involved DOW membranes exclusively. Demonstrating additional membranes (DOW, Hydranautics, Toray, Koch), will validate the results from Phase I and show that they can be achieved with several manufacturers' membranes. DOW's "next generation" hybrid-membrane system, involving internally staging membranes of different performance down a single 7-element pressure vessel, will be tested. In Phase II the ADC will also test and demonstrate advanced prefiltration technologies, such as ultrafiltration membranes, which have seen only limited use in seawater desalination. Finally the ADC will develop and test new process designs that are possible as a result of the isobaric energy recovery technologies. As a natural result of pressure exchanger (PX) technology in particular, there are new kinds of flow schemes that may improve the performance of higher recovery seawater and brackish water systems.

I. INTRODUCTION

Increasing demand for allocated freshwater resources, declining freshwater quality, 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. However, in the United States, the high cost of desalination 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 over the last two decades 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 that include:

- California Department of Water Resources
- California Energy Commission
- Carollo Engineers
- City of Santa Cruz Water Department
- David Brown Union Pumps – Textron
- Eden Equipment Company, Inc.
- Energy Recovery Inc.
- FilmTec Corporation
- GE Zenon
- Marin Municipal Water District
- Naval Facilities Engineering Service Center
- Pentair - CodeLine Pressure Vessels
- Poseidon Resources
- San Diego County Water Authority
- Sandia National Laboratories
- Toray Membrane USA
- US Bureau of Reclamation
- US Desalination Coalition
- WaterEye
- West Basin Municipal Water District
- Young Engineering & Manufacturing, Inc

The ADC's demonstration scale seawater reverse osmosis (SWRO) treatment system uses pressure exchanger technology (ERI) for energy recovery (**Figure 1.1**). The RO array consists of 3 each x 7 element 8" DIA pressure vessel. The flux and recovery can be varied from 6-9 gfd and 35-60% respectively. The overall capacity of the system can be varied from approximately 200-300 m³/day (50,000-80,000 gpd).

throughout the testing, and specifically the Zenon ultrafiltration system. In general, use of membranes for seawater pretreatment is limited and this work will provide valuable information for the U.S. and around the world.

1.3 Cost of Seawater Desalination

Over 95% of the world’s water has yet to be tapped as a freshwater supply because it is considered too salty to drink. The need for seawater desalination is apparent, but has historically been limited in use due to its high cost. This high cost is associated with both capital costs and operating costs. However, over the last 15 years, capital costs for seawater desalination have decreased significantly (**Figure 1.2**).

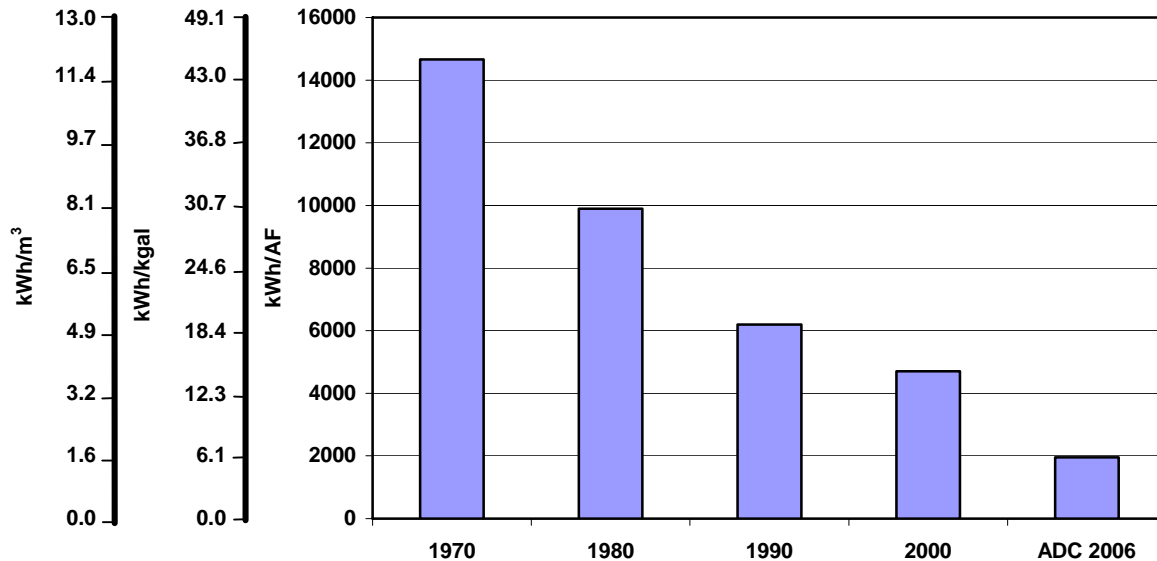


Figure 1.2 History of Power Consumption Required for Seawater Desalination Process Equipment

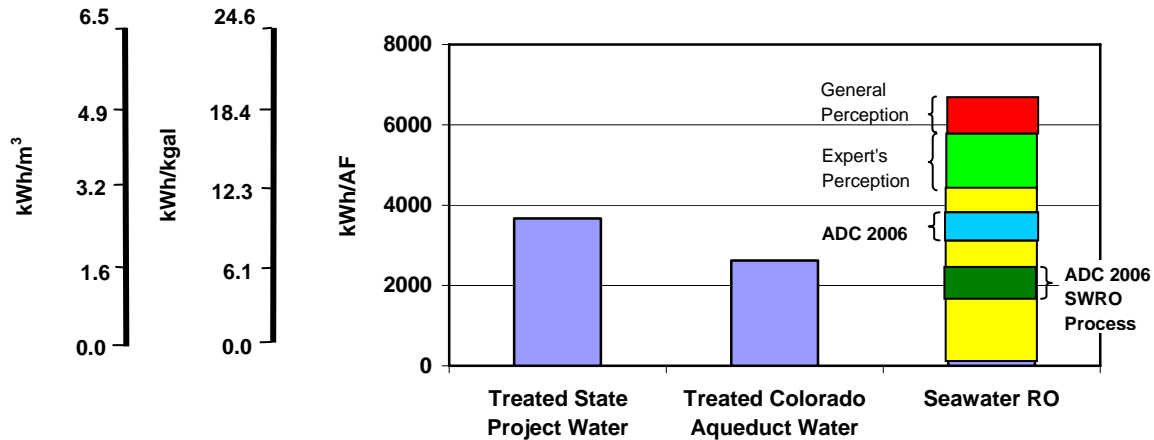
According to a report by the Bureau of Reclamation, in 1990, the cost for large scale seawater desalination was estimated to be approximately \$2,000 per acre foot (\$6.14/kgal, \$1.62/m³). However, membrane equipment prices have fallen substantially since 1990 and increased competition in the market has further reduced costs for capital components. Within the last 5 to 10 years, the focus has been on ways to reduce operating costs, particularly energy costs.

Little attention was given to energy consumption when seawater desalination was commercialized in the 1970s. As indicated in **Figure 1.2**, energy consumption for the desalination process was approximately 45 kW-hr/kgal (12 kW-hr/m³), or 50% of the total costs for a seawater desalination plant. By 2000, the power consumption rate decreased to approximately 14 kW-hr/kgal (3.7 kW-hr/m³)⁴. This was in large part due to several advances in technology that occurred during the 1990s, which include:

- New low energy reverse osmosis (RO) membranes with improved salt rejection
- High efficiency pumps and motors
- More efficient energy recovery devices (ERDs)

While these advances continue to occur, the industry’s perception of seawater desalination energy consumption has not changed significantly since 2000. Many experts in the industry still believe that the seawater desalination process requires between 10 to 14 kW-hr/kgal (2.6 to 3.7 kW-hr/m³)⁵. As indicated in **Figure 1.3**, using these energy requirements, the power required for seawater desalination is

significantly higher than other water supply options in Southern California, which is, in part, why large-scale seawater desalination has not become a reality. However, as presented in **Figures 1.4** and **1.5**, based upon the work conducted during this project, using commercially available technologies applied in a manner where design emphasis is placed on energy efficiency and responsibly reducing the overall total water costs, a new paradigm for the costs of seawater desalination is now available. Seawater desalination can now be considered cost competitive with other new water supply options in Southern California.



Note: 1. "ADC 2006 SWRO Process" power represents the estimated power required for the SWRO process only. "ADC 2006" denotes the estimated power required for finished water production, which includes the SWRO process.

Figure 1.4 Estimated Power Required for Finished Water Supply Options in Southern California

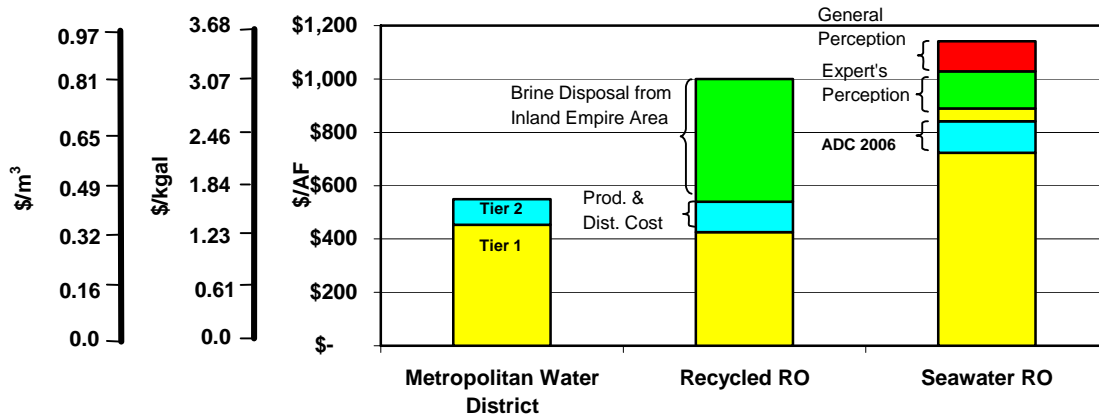


Figure 1.5 Finished Water Cost of 50-MGD Water Supply Options in Southern California

II PHASE I CONCLUSIONS & RECOMMENDATIONS

2.1 Conclusions

- The ADC's results must be taken within the context of the raw water quality conditions tested. These conditions include a lower feed temperature than would typically be seen at a SWRO plant fed warm water from a once through cooling power plant. Therefore, at higher temperature, the membranes, at a flux of 6 gfd will produce water with higher permeate TDS but with about lower

specific energy. Further testing and evaluation is required to determine the impact of temperature.

- Increasing flux (at constant recovery) on the SWRO membranes results in lower concentrations of TDS and boron in the permeate.
- Increasing recovery (at constant flux) results in higher concentrations of TDS and boron in the SWRO permeate.
- Direct contact of brine to SWRO feed water in the PX device resulted in approximately 4 to 6% increase to the SWRO system feed water TDS. This increase in feed water TDS resulted in approximately 30 psig higher feed pressure (i.e., at 50% recovery) to produce the same permeate flow.
- Specific power 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/m³) at the most affordable operating point (i.e., 9 GFD, 50% recovery for the SW30HR-380 and SW30XLE-400i, and 6 GFD, 50% recovery for the SW30HR LE-400i). The lowest SWRO process energy consumption, 5.98 kW-hr/kgal (1.58 kW-hr/m³), was demonstrated using the SW30XLE-400i membrane at 6 GFD, 42.5% recovery.
- The ADC's design has demonstrated the ability to reduce power consumption by 38 to 40% over industry experts' perception of power required for SWRO system designs.⁵
- As train size gets larger, the ADC's power consumption may be difficult to replicate. Careful consideration of pump type, size and energy recovery system "pressure centers" should be considered to minimize power consumption.
- Data indicates that there is an optimal ("most efficient") recovery point with regards to energy consumption for a given membrane array and site conditions.
- Data indicates that flux vs. energy consumption is not linear.
- While high recovery consistently resulted in the lowest treatment costs, the impact of flux rate was questionable in some cases.
- A recovery rate of 50% consistently demonstrated the lowest estimated total water costs.
- Based upon the ADC's cost model, the cost for seawater desalination in California has been shown to be competitive with other new supply options, with costs ranging from \$772 to \$913/AF (\$2.37 to \$2.80/kgal, \$0.63 to \$0.74/m³).

2.1 Recommendations

The data gathered during this study has led to some very promising results. To further validate and improve upon the findings of this study, the authors recommend the following:

- **Temperature:** Additional testing at warmer temperatures is recommended to help draw conclusions with regard to the acceptability of each membrane to meet permeate quality standards and the feed pressure (i.e., energy) required.
- **Pretreatment:** Pretreatment is a critical aspect of a successful seawater RO process. While media filtration is very capable of meeting the SDI and turbidity standards required for RO, the red tide event that occurred early during the study resulted in excessive backwashing frequencies and ultimately placing the study on standby. While the persistence of this event was an apparent anomaly in California, and even those seawater systems treating the Pacific Ocean using membrane pretreatment were challenged to produce enough water, the membrane pretreatment provided a consistent and reliable quality of water, which the ADC's media filter design could not. As a result, the authors recommend a further study to compare other types of media and advanced filtration designs.

- **Public Values:** SWRO system designers should consider public values to issues such as water quality and cost when selecting design conditions such as flux, recovery and membrane type. The community values may require the use of a membrane that rejects more TDS and boron, but requires more energy to produce water. Factors of safety in permeate quality may also be considered. The data presented in this paper indicated that the SW30XLE-400i membrane barely met the California standard for boron at a flux of 6 gfd. A higher flux or use of a different membrane may make sense for some communities.
- **Long Term Testing:** The ADC's test results represent conclusions based upon the performance of new membranes. The concept of the Cumulative Annual Replacement Rate (CARR) was used to adjust costs and normalize performance with respect to permeate quality and energy consumption. Long term testing is required to validate the flux and recovery at the most affordable operating point. In addition, long term testing is required to determine how specific power will vary with time and cleaning cycles. Furthermore, industry experience indicates that high flux and high recovery operation results in more frequent chemical cleaning and shorter membrane life. However, when balanced with capital costs on a life cycle basis, incurring these incidental operating costs often proves to be more economical, but more labor intensive to maintain.¹⁴ A longer study is required to help quantify the differences that could not be derived from the ADC's data due to the short testing duration.
- **System Configuration:** Additional configurations for the SWRO system should be tested to compare alternate membrane types, energy recovery devices and pumping technologies. Many manufacturers have comparable technologies that are worthy of testing.
- **Large Diameter Membranes:** Cost estimates should consider the possible economy of large diameter pressure vessels and membrane elements which may reduce capital costs by approximately 20%.¹⁵
- **Increased Recovery Research:** Seek out, test and demonstrate system designs and technologies that can increase the achievable recoveries of SWRO systems.

III PHASE II STUDY OBJECTIVES AND PROJECT GOALS

The objective of this study 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. This study incorporates recommendations from Phase I along with objectives from a major funding source, the California Department of Water Resources (DWR) Proposition 50. Phase I recommendations being incorporated 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 susceptible to scaling and fouling
- Strategies for brine/concentrate management
- Better feed water pretreatment processes and strategies

The goal of this work 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 and policy makers related to the costs of seawater desalination.

3.1 MATERIALS AND METHODS

The ADC’s SWRO plant is being tested at the U.S. Navy’s Desalination Research Center, located in Port Heuneme, California. This facility was chosen based upon the availability of experienced staff who were familiar with the operation of SWRO process equipment and the availability of an existing ocean intake and outfall that could be used with no permitting efforts.

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 is available on the ADC’s website: www.affordabledesalination.com, and is summarized below. **Password 1234 needed?**

3.2 Equipment

The ADC’s demonstration scale SWRO plant is designed to produce between 48,100 to 75,600 gallons per day (182 to 286 m³/day) of permeate. The configuration will be 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 will be replaced with a more advanced filters such as ultrafiltration membranes. The design criteria for these components are presented in **Table 3.1**.

Parameter	Unit	Value
Filter (Media)		
Loading Rate	gpm/ft ²	3 to 6
Depth/Grain Size/U.C. of Anthracite	in/mm/-	18 / 0.85-0.95 / <1.4
Depth/Grain Size/U.C. of Sand	in/mm/-	10 / 0.45-0.55 / <1.4
Depth/Grain Size/U.C. of Gravel	in/mm/-	6 / 0.3 / <1.4
Filter (Membrane)		
GE Zenon		
Cartridge Filter		
Cartridge Specs		#2, 5-micron
Loading Rate	gpm/10-in.	~1
Membrane System		
Models		Toray Hydranautics, Koch
Diameter	inch	8
Elements per Vessel	No.	7
Vessels	No.	3
High Pressure Pump ¹		
Type		Positive Displacement
TDH	ft (psig)	1385 to 2305 (600 to 1000)
Energy Recovery ²		
Type		Pressure Exchanger™ (PX™)
PX Booster Pump ³		
Type		Multi-stage Centrifugal

	TDH ft (psig) 70 to 115 (20 to 50)
Note:	Pressure Exchanger™ and PX™ are registered trademarks of Energy Recovery, Inc.
1	David Brown Union, Model TD-60
2	Energy Recovery, Inc., Model PX-70S
3	Energy Recovery, Inc., Model HP-8504

Table 3.1 Equipment design criteria

3.3 Operation and Monitoring

The system will be operated for approximately 18 months with work divided into 3 stages (**Table 3.2**).

Stage	Description	Month																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Low Energy Membranes	█																	
2	Staged Membranes											█							
3	Innovative Flow Regimes													█					
All	Advanced Pretreatment	█																	

Table 3.2 Project timeline

3.3.1 Stage 1: Low Energy Membrane Testing & Demonstration (Hydranautics, Toray, Koch) This stage will seek to demonstrate new commercially available “low-energy” membrane technology from three additional membrane manufacturing market leaders. Phase I of the ADC tested DOW’s “low-energy” SW30XLE-400i and SW30HRLE-400i membranes with excellent results. The three additional new “low-energy” membranes are:

- Hydranautics (SWC5)
- Toray (TM800C)
- Koch (to be determined)

In testing membranes from three additional manufacturers the ADC will add to the Phase I work and validate that overall low energy numbers can be achieved with multiple commercial membrane suppliers. Furthermore, the ADC will be able to provide a comparative matrix of performance, using natural Southern California seawater in a full scale configuration, showing energy consumption, salt rejection, and boron rejection from the four leading membrane manufacturers. If the feed water and operating conditions are not exactly comparable between membrane sets then the data will be normalized and presented in the best possible way to provide an “apples to apples” comparison of performance.

The test protocol will be identical to ADC’s Phase I testing. Each set of membranes will be run through an approximate eight week test protocol (**Table 3.3**). The first 2 weeks of testing are required to demonstrate that the performance of the membrane has reached steady state operation before the flux or recovery is modified. Weeks 3 through 5 involve changing the flux and recovery every day to collect data which is used to evaluate the most affordable operating condition. It is recognized that further testing will be required to validate the results of this test due to its short duration. Upon completion of the tests from weeks 3 through 5, the hydraulic, water quality and power data are analyzed and a net present value analysis is conducted to determine which test condition is the most affordable operating

point. The recovery and flux from the most affordable operating point is then run for approximately 2 weeks. The test is concluded with a brief operation at the initial condition (i.e., 7.5 gfd, 42.5% recovery) to collect data that were normalized using the ASTM standard for permeate flow and salt passage, to make certain that the membranes have not fouled.

Parameter	Week	Week									Week
	1 to 2	3 to 5									6 to 8
Flux	7.5	6	6	6	7.5	7.5	7.5	9	9	9	TBD ¹
Recovery	42.5%	35%	42.5%	50%	35%	42.5%	50%	35%	42.5%	50%	TBD ¹
1. TBD = After completion of the flux/recovery variation tests during weeks 3 and 4, determined using ADC's cost model to be the "most affordable" condition.											

Table 3.3 Test operating conditions

During each testing condition, hydraulic, water quality and power data are collected at periodic intervals. **Table 3.4** presents the type and frequency of manually collected data. Some parameters, such as power consumption, pressures, flows and permeate conductivity, are monitored both manually and automatically using on-line instrumentation. Manually recorded data will be presented in this report. Automatically recorded data will be presented on the ADC's website: www.affordabledesaliantion.com.

	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	2x per day
Pressure	Filter Inlet, Filter Outlet, Cartridge Filter Outlet, PX Booster Pump Suction, PX Brine Outlet, SWRO Feed, SWRO Brine, SWRO Permeate	1x per day	2x per day
Power	PD Pump & PX Booster Pump	1x per day	1x per day
Water Quality	Temperature, Turbidity, SDI	Raw Water: 1x per day	Raw Water: 1x per day
	pH, Conductivity, TDS,	Raw Water: 1x per day RO Feed: 1x per day Permeate: 1x per day	Raw Water: 1x per day RO Feed: 1x per day Permeate: 1x per day
	Boron, Bromide, Iron, Manganese, Aluminum, Calcium, Magnesium, Sodium, Potassium, Bicarbonate, Carbonate, Sulfate, Chloride, Fluoride	Raw Water: 2x per week RO Feed: 2x per week Permeate: 2x per week	Raw Water: 1x every 2 days RO Feed: 1x every 2 days Permeate: 1x every 2 days

Table 3.4 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*.⁶

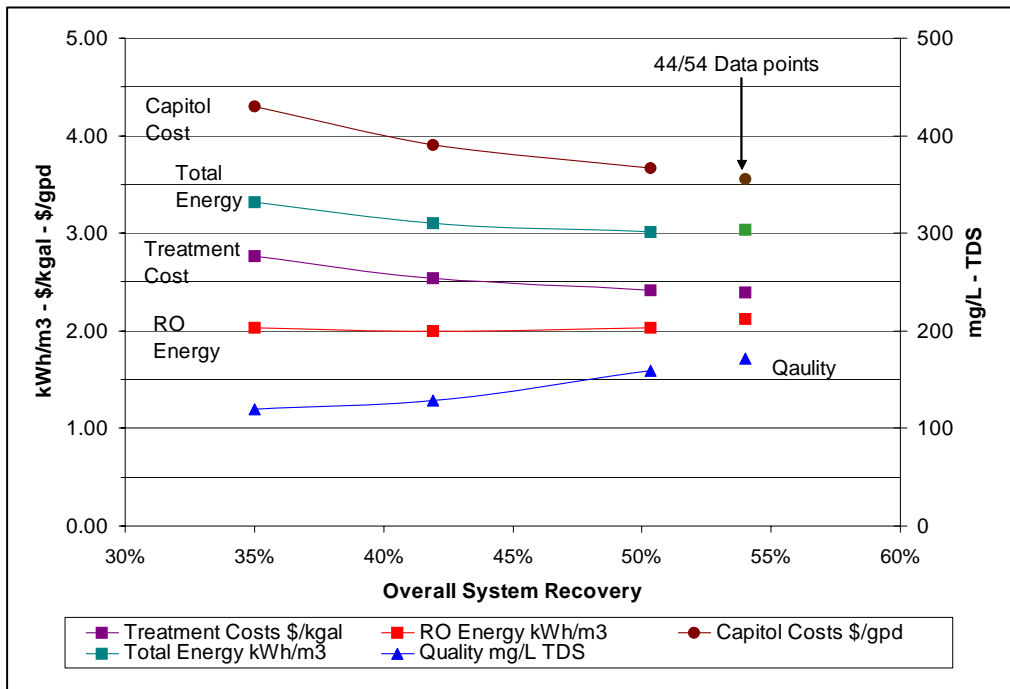
3.3.2 Stage 2: Staged Membrane Testing using Dow FilmTec Hybrid Membranes

In addition to demonstrating the new commercially available and proven membrane technology described above, we will test a concept that is being developed by the FilmTec Corporation, which they are calling their hybrid approach. This new 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. DOW indicates that these new membranes will provide improvements in both energy consumption and water quality over their latest "low energy" membranes that were tested in the ADC Phase I project. This ADC II Proposition 50 proposal will also be applied to the hybrid membrane set.

This data point taken showed promising results with an overall energy consumption of 8.03 kWh/kgal and permeate quality of 172 mg/l TDS. Mechanisms associated with this novel mode of operation that might lead to improved performance at higher recoveries include:

- Improved boundary layer conditions through increased 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

Figure 3.2 shows RO energy consumption, total system energy consumption, water quality and total treatment costs verses the overall system recovery.



Notes: 1. Curve data from ADC I SW30HRLE-400i membrane set. – 2. RO energy includes HP pump and PX booster. – 3. Total energy includes 200 TDH raw water pumps, 105 TDH filter pumping, 40 TDH permeate pumping, and 200 TDH permeate distribution header. – 4. Treatment and capitol costs were generated using net present value model from ADC I.

Figure 3.2 Phase I balanced data next to 44/54% recovery unbalanced data

The four curves showing data between 30-50% system recovery are taken from the ADC I where we operated the pilot system at balanced flows. The four data points taken at 44/54% recovery were generated by operating the pilot system at the data point shown in **Table 3.5**. The unbalanced data points at 44/54% recovery are consistent with the trends and data taken at balanced PX flows between 30-50% recovery. Looking at the treatment and capitol costs curves from ADC I we can see that a significant savings may be achieved by pushing the system recoveries higher.

Testing the unbalanced PX effect is straight forward and can be achieved with the ADC demonstration system in its current configuration. The 44/54% recovery data points presented in **Table 3.5** are from an actual operating point taken at the ADC pilot facility to demonstrate the concept.

Another flow scheme that the ADC plans to test incorporates an interstage booster approach in combination with a different pressure exchanger design (**Figure 3.3**). This Interstage Booster-Pressure Exchanger Hybrid design can also be used to push system recoveries beyond 50%.

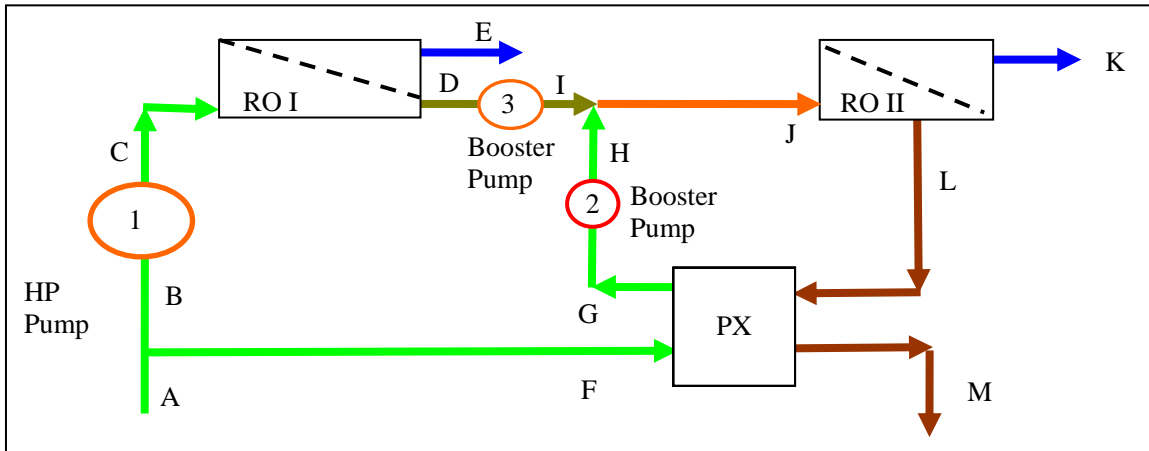


Figure 3.3 Interstage Booster-Pressure Exchanger Hybrid diagram

Table 3.6 shows an example of one operating point. This point was developed using the ROSA 6.0 membrane software with the SW30XLHR-400i membrane. See section N for actual membrane projections. The modeled results are promising for a 55% recovery system with an overall energy consumption of 8.62 kWh/kgal and blended permeate TDS of 144 mg/l. It is also notable that the first stage is projected to operate at around 719 psi and the second stage is projected to operate at around 1023 psi. These are markedly lower pressures than other types of high recovery schemes such as the brine conversion system (BCS), which typically reach pressures in excess of 1200 psi. Furthermore, the overall recovery for any 7-element vessel never exceeds 50% remaining well within the manufacturer’s recommendations for minimum brine flows.

To test the interstage hybrid approach the ADC will need to make significant modifications to the current system that include the addition of an interstage booster pump and reconfiguration of the current 3ea, 7-element parallel vessel array into a single 7-element vessel feeding a second single 7-element vessel in series. The test protocol for both the Unbalanced and Hybrid flow schemes may look at a range of recovery and flux rates. Overall system recoveries between 45-65% may be considered.

		A	B	C	D	E	F	G
Flow	gpm	55	31	31	17	14	24	24
	gpd	79,600	44,800	44,800	24,640	20,160	34,800	34,800
	m ³ /day	301	170	170	93	76	132	132
Pressure	psi	30	30	719	702	0	30	987
	bar	2.1	2.1	49.6	48.4	0.0	2.1	68.1
Quality	mg/l TDS	33,073	33,073	33,073	60,038	120	33,073	35,752

		H	I	J	K	L	M	K+E
Flow	gpm	24	17	41	17	25	25	31
	gpd	34,800	24,640	59,440	23,776	35,664	6,240	43,936
	m ³ /day	132	93	225	90	135	137	166
Pressure	psi	1023	1023	1023	0	997	20	0
	bar	70.6	70.6	70.6	0.0	68.8	1.4	0.0
Quality	mg/l TDS	35,752	60,038	45,820	164	74,293	69,464	144

PX Unit Flow

Flow	24.8	gpm
PX Internal Bypass	1.0	gpm
PX Differential HP side	10	psi
PX Differential LP side	10	psi
PX efficiency	97.2	%
Membrane Differential I	17	psi
Membrane Differential II	26	psi
RO Recovery I	45	%
RO Recovery II	40	%
System Recovery	55.2	%

	High Pressure Pump	PX Booster Pump	Interstage Booster Pump
Feed Pump Efficiency	90%	65%	65%
Motor Efficiency	93%	92%	92%
VFD Efficiency	97%	97%	97%
Power (KW)	11.1	0.6	4.0

Table 3.6 Interstage booster-pressure exchanger hybrid data

These new process designs may also help improve the performance and increase the achievable recoveries of brackish water desalination systems throughout California and across the United States. The ADC plans on working closely with leading membrane manufacturers to help develop and optimize these new designs and ideas. Before testing, the ADC envisions holding a collaborative workshop to discuss and advance these ideas and plans to include at least one technical expert from each of the participating membrane manufacturers.

Finally, it should be noted that these new process designs can be demonstrated and implemented with “off the shelf” equipment and technologies. In other words, the membranes, pumps, and energy recovery devices will all be operated within the manufacturers’ general recommendations and specifications.

3.3.4 Advanced Pretreatment

Advanced filtration system(s) will be used throughout the project. Initially, the ADC will test a Zenon Environmental/GE ZeeWeed® 1000 membrane pilot system. ZeeWeed® based water treatment 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, suspended solids or other contaminants of concern, will pass into the treated water stream.

The ZeeWeed® 1000 immersed membrane system can easily remove particles that are greater than 0.1 microns in size without any pretreatment. Furthermore, if dissolved components can be first converted to insoluble species, the membrane will subsequently remove them as well. For example, the size of natural organic matter present in surface waters is generally smaller than the membrane pore size. Similarly, iron and manganese can also exist in dissolved forms that can pass through the membrane. However, the ZeeWeed® 1000 process is compatible with upstream pretreatment such as enhanced coagulation and oxidation, which can convert contaminants from dissolved to suspended forms that are unable to pass through the membrane. 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.

Although Zenon’s advance pre-filtration system is being added to the ADC study primarily to improve our reliability through summer operation we will also be adding the following objectives to our work:

- Determine optimal design parameters for the Zenon system that will generate stable ZeeWeed® membrane performance.
- Demonstrate that the ZeeWeed® 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.

Although advanced pretreatment systems such as membranes have had limited application in natural seawater systems, they show great promise for improving the reliability and affordability of seawater desalination plants. This is an excellent opportunity to help the ADC both operate more reliably and move the state of the art forward.

3.4 Cost Estimating Procedures

A present value analysis model, which accounts for both capital and operating costs, is developed and used to establish the most affordable operating condition. The present value analysis model is operated at the completion of the flux/recovery variation tests, presented previously in **Table 3.2**, to establish the condition that will be operated for the remaining two weeks. Only those conditions that demonstrate the ability to meet water quality standards for TDS and boron during the flux/recovery variation tests are considered for the most affordable operating condition. As discussed previously, the conditions for the present value analysis model were established as part of the testing protocol. These conditions are presented in **Table 3.7**.

As noted in **Table 3.8**, capital costs are determined under the assumption that the SWRO facilities would be co-located with a power plant. Therefore, 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/ft², 5-ft anthracite, 2.5-ft sand, 2-ft garnet).⁷ Such a design is assumed 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.

Project Size	50 MGD	Intake/High Service Pump Motor Eff.	90%
Capital Cost ¹	Determined with WTCOST Model and Manufacturer Quotes	RO Process Energy Demand	Study data ²
		RO Membrane Life	Refer to Table 4.5
Electrical Systems	12% of Capital Cost	RO Membrane Element Cost ³	\$475 to \$600

Instrumentation & Control	10% of Capital Cost	RO Pressure Vessel⁴	\$8000
Project Life	30 years	Sodium Hypochlorite Dose (pretreatment)	2 mg/L
Bond Payment Period	30 years	Sodium Hypochlorite Cost	\$1.2/lb.
Interest	5%	Sodium Bisulfite Dose	4.6 mg/L
Construction Contingencies	15% of capital cost	Sodium Bisulfite Cost	\$0.3/lb.
Contractor OH&P	10% of capital cost	Cartridge Filter Loading Rate	3 gpm/10-in.
Engineering & Const. Mgmt.	25% of capital cost	Cartridge Filter Cost	\$5/10-in.
Permitting Cost	\$10-million	Cartridge Filter Life	1000 hours
Annual Maintenance Costs	1.5% of capital cost	Carbon Dioxide Dose	16 mg/L
Labor	25 operators @ \$55,000/yr ea.	Carbon Dioxide Cost	\$0.04/lb
Power Costs	\$0.08 per kW-hr	Lime Dose	44 mg/L
Intake Pump TDH	200 ft H ₂ O	Lime Cost	\$0.05/lb.
High Service Pump TDH	200 ft H ₂ O	Sodium Hypochlorite Dose (finished water)	1.5 mg/L
Intake/High Service Pump Eff.	75%		

Note: O&M does not include administrative, laboratory, legal, reporting or 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 Power meter readings
- 3 SW30HR-380 = \$475/ea.; SW30XLE-400i = \$600/ea.; SW30HR LE-400i = \$500/element.
- 4 Installed, includes all ancillary piping, frames and fittings.

Table 3.7 Present value analysis conditions

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

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

Table 3.8 RO Membrane life and annual replacement rate

3.5 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 and automatically to compare and resolve discrepancies.
- Power 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.

4.0 RESULTS AND DISCUSSION

4.1 Raw Water Quality

Typical seawater quality tested during Phase I is summarized in **Table 4.1**. As noted, the SWRO average feed water temperature was 15.2 °C, which is cooler than the water that would typically be fed to an SWRO water treatment plant from a once through cooling system. The ADC's data should therefore be taken in the context of this information.

Parameter	Average	Parameter	Average	Parameter	Average
Temperature	15.2 °C	Calcium	395 mg/L	Bicarbonate	135 mg/L
Total Dissolved Solids	31,688	Magnesium	1,230 mg/L	Chloride	19,345 mg/L
Conductivity	49,524 mhos	Sodium	10,370 mg/L	Sulfate	2,090 mg/L
pH	8.0	Potassium	340 mg/L	Fluoride	< 25 mg/L
Turbidity	1.8 NTU	Barium	0.21 mg/L	Bromide	< 125 mg/L
Boron	4.82 mg/L	Strontium	7.2 mg/L	Silica	6.85 mg/L
		Aluminum	0.21 mg/L		

Table 4.1 Average seawater quality

4.2 SWRO System Performance (To be completed)

Results from Phase II testing will begin during testing that should start in May 2007.

- *Permeate Water Quality*
- *Energy Efficiency*
- *Specific Power*
- *Estimated Costs*

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