AFFORDABLE DESALINATION COLLABORATION 2005

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ABSTRACT

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 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 proven technologies, the ADC has demonstrated that seawater reverse osmosis can be used to produce water at an affordable cost comparable to other supply alternatives. As a result, the ADC is pleased to announce their mission is a success. Desalination is affordable and can provide another cost effective tool to water agencies seeking a diverse water supply portfolio.

The ADC's demonstration scale seawater reverse osmosis (SWRO) plant completed over six months of testing at the US Navy's Seawater Desalination Test Facility in Port Hueneme, California in March of 2006. Three membranes were tested while varying flux and recovery to estimate 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 results of this work are presented herein.

INTRODUCTION

According to the United Nations, approximately 40% of the world's population is currently experiencing water shortages. By 2025, that figure is expected to increase to over 65%, or more than 5.5 billion people.[1] Even in the United States, these figures are real and imminent. California's population is expected to reach 50-million by 2030 and existing freshwater supplies are expected to be fully allocated in another 10 to 30 years. Water levels in groundwater aquifers and reservoirs are at all-time lows. Conflicts between States sharing access to Colorado River water, agriculture, the fishing industry, environmentalists, recreation and potable supply are becoming more serious as existing freshwater supplies are not adequate to meet all these needs.[2, 3]

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. According to a report by the United States 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/m^3). 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**, energy consumption for the desalination process was approximately 45 kW-hr/kgal (12 kW-hr/m^3), 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/m^3).[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)

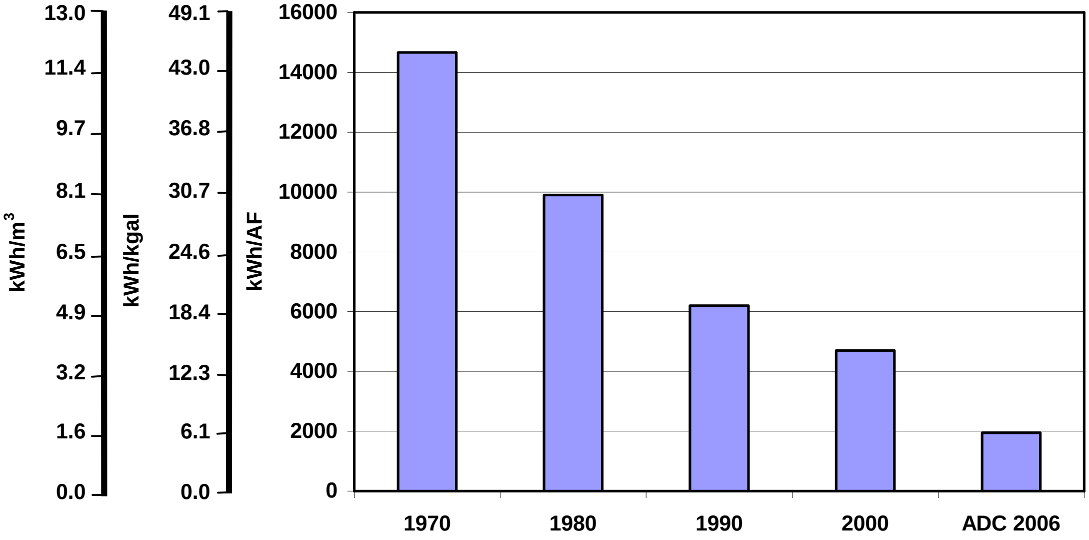
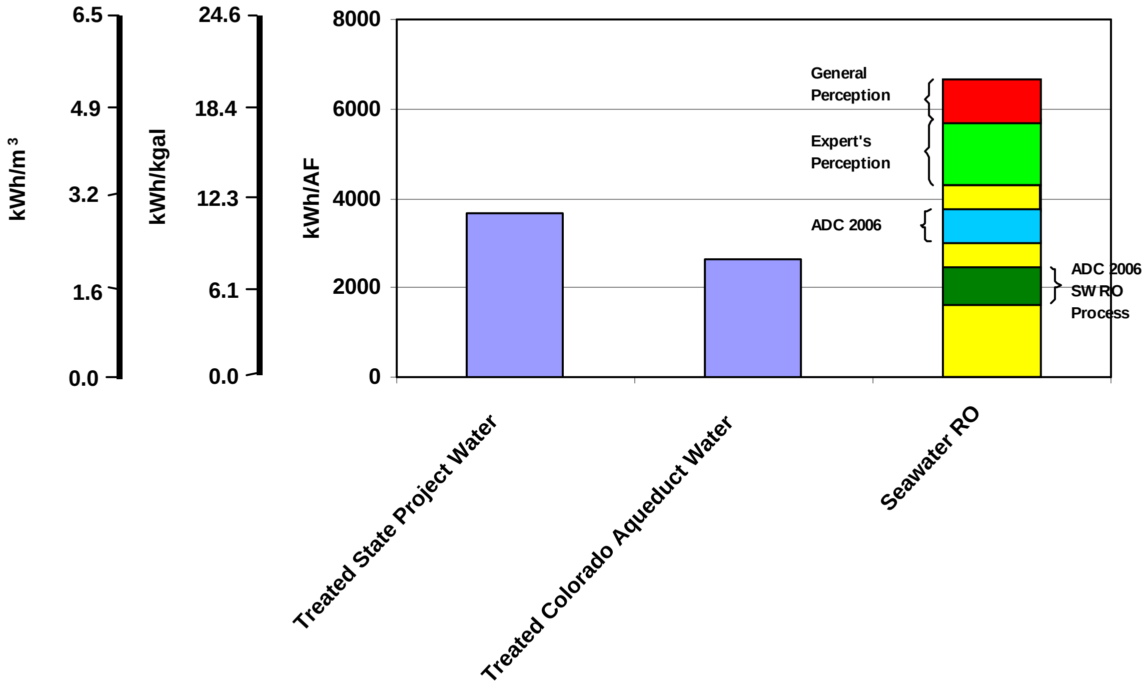


FIGURE 1. History of Power Consumption Required for Seawater Desalination Process Equipment

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/m^3).[5] As indicated in **Figure 2**, 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 2** and **3**, 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 2. Estimated Power Required for Finished Water Supply Options in Southern California

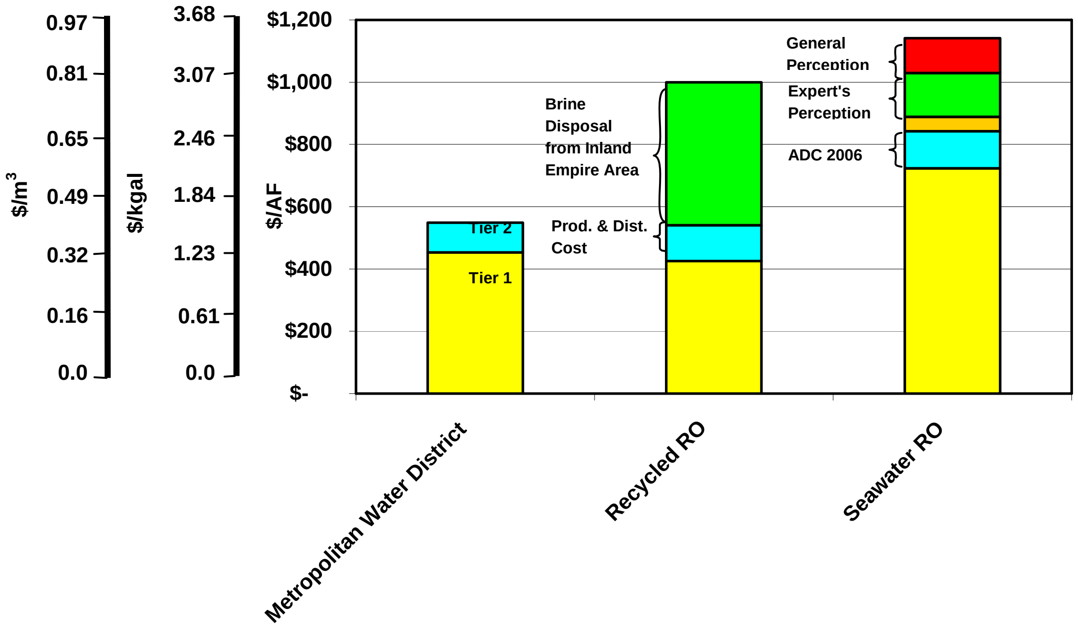


FIGURE 3. Finished Water Cost of 50-MGD Water Supply Options in Southern California

STUDY OBJECTIVES AND PROJECT GOALS

The objective of this study was to test a state-of-the-art, energy efficient, demonstration scale SWRO process, designed and built using scalable and commercially available 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 in California. Only test conditions that meet water quality goals related to TDS and boron were considered for estimating purposes. The goal of this work is to use the estimated costs generated as a result of this work to create a new paradigm for engineers, planners and policy makers related to the costs of seawater desalination.

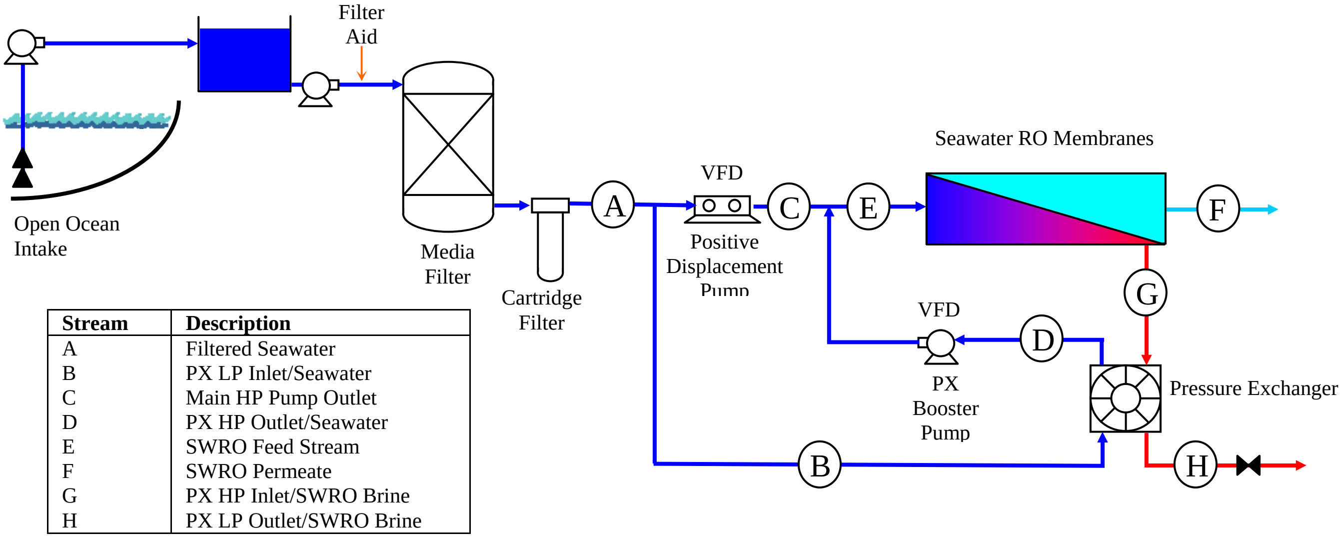
MATERIALS AND METHODS

The ADC's SWRO plant was tested at the U.S. Navy's Desalination Research Center, located in Port Heuneme, California, and was operated by Navy staff from May 2005 through March 2006. 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 use with no permitting efforts.

During the early stages of the ADC's formation, a demonstration scale system design and testing protocol was developed and reviewed by the ADC's members. This design and testing protocol established the basis for the study, how the equipment would be tested, how the data would be interpreted, and for the cost estimating procedures. This process helped to ensure that the data and results developed during the study would 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.

Equipment

The ADC's demonstration scale SWRO plant was designed to produce between 48,100 to 75,600 gallons per day (182 to 286 m^3/day) of permeate using a combination of state-of-the-art, off the shelf technologies that minimize power consumption. **Figure 4** presents a process flow diagram for the ADC's SWRO plant. As indicated, the process uses an open intake, media filters, a cartridge filter, a high efficiency positive displacement pump, and a high efficiency isobaric energy recovery device. The design criteria for these components are presented in **Table 1**.



Stream	Description
A	Filtered Seawater
B	PX LP Inlet/Seawater
C	Main HP Pump Outlet
D	PX HP Outlet/Seawater
E	SWRO Feed Stream
F	SWRO Permeate
G	PX HP Inlet/SWRO Brine
H	PX LP Outlet/SWRO Brine

FIGURE 4. Process Flow Diagram - ADC's Demonstration Scale SWRO Plant

TABLE 1. Design Criteria for ADC's SWRO Demonstration Scale Equipment

Parameter		Unit	Value
Media Filter			
	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
Cartridge Filter			
	Cartridge Specs		#2, 5-micron
	Loading Rate	gpm/10-in.	~1
Membrane System			
	Models		FILMTEC™ SW30HR-380, FILMTEC™ SW30XLE-400*i*, FILMTEC™ SW30HR LE-400*i*
	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: FILMTEC™ is a registered trademark of FilmTec Corporation.
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

Operation and Monitoring

The ADC's demonstration scale SWRO plant was operated for approximately 6 months. The operating conditions tested are presented in **Table 2**. As indicated in **Table 2**, three membranes were tested for approximately 6 weeks each. The first 2 weeks of testing were required to demonstrate that the performance of the membrane had reached steady state operation before the flux or recovery was modified to develop data that would be used to evaluate the most affordable operating condition. Weeks 3 and 4 involved changing the flux and recovery every day to collect data which was 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 flux and recovery variation tests, the pilot was operated briefly at the initial condition (i.e., 7.5 gfd, 42.5% recovery) to collect data that was normalized using the ASTM standard for permeate flow and salt passage, to make certain that the membranes had not fouled.

Upon completion of the tests from weeks 3 and 4, the hydraulic, water quality and power data was analyzed and a net present value analysis was conducted to determine which test condition was the most affordable operating point. The recovery and flux from the most affordable operating point was then run for approximately 2 weeks.

TABLE 2. Test Operating Conditions

Parameter	Week 1-2	Week 3					Week 4				Week 5-6
		Day 2	Day 3	Day 4	Day 5	Day 6	Day 2	Day 3	Day 4	Day 5	
Membrane											
Phase 1:	FILMTEC™ SW30HR-380										
Phase 2:	FILMTEC™ SW30XLE-400*i*										
Phase 3:	FILMTEC™ SW30HR LE-400*i*										
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]

Note: At times, operation of the ADC's SWRO plant was discontinuous. Refer to the ADC's website (www.affordabledesalination.com) for a detailed data log indicating hours of operation versus date and time.

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.

During each condition tested, hydraulic, water quality and power data were collected at periodic intervals. **Table 3** presents the type and frequency of manually collected data. Some parameters, such as power consumption, pressures, flows and permeate conductivity, were monitored both manually and automatically using on-line instrumentation. Manually recorded data is presented in this report. Automatically recorded data is presented on the ADC's website: www.affordabledesaliantion.com.

TABLE 3. Type and Frequency of Manual Data Collection

Parameter	Weeks 1-2 and 5-6	Weeks 3-4
Flow		
Permeate, Raw Water (PD Pump), Raw Water (into PX), Raw Water (out of PX)	1x per day	2x per day
Pressure		
Media Filter Inlet, Media 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

Water quality parameters that were sampled daily were analyzed either daily using field kits, and those parameters monitored weekly were analyzed using EPA or *Standard Methods*.[6]

Determining Affordability - Cost Estimating Procedures

A present value analysis model, which accounts for both capital and operating costs, was developed and used to establish the most affordable operating condition. The present value analysis model was operated at the completion of the flux/recovery variation tests, presented previously in **Table 2**, to establish the condition that would be operated for the remaining two weeks. Only those conditions that demonstrated the ability to meet water quality standards for TDS and boron during the flux/recovery variation tests were 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, early during the ADC's development. These conditions are presented in **Table 4**.

As noted in **Table 4,** capital cost was 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/ft^2, 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.

Table 4. Present Value Analysis Conditions

Project Size	50 MGD	Intake/High Service Pmp Motor Eff.	90%
Capital Cost[1]	Determined with WTCOST Model and Manufacturer Quotes	SWRO Process Energy Demand	Study data[2]
		Membrane Life	Refer to **Table 5**
Electrical Systems	12% of Capital Cost	Membrane Element Cost[3]	$475 to $600
Instrumentation & Control	10% of Capital Cost	Pressure Vessel[4]	$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_2O	Lime Cost	$0.05/lb.
High Service Pump TDH	200 ft H_2O	Sodium Hypochlorite Dose (finished water)	1.5 mg/L
Intake/High Service Pmp 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-400*i* = $600/ea.; SW30HR LE-400*i* = $500/element.

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

Table 5. Membrane Life & Annual Replacement Rate

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

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.

Quality Assurance and Quality Control

The ADC's quality assurance program consisted 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 was done to ensure that the data would not influence the tests results or conclusions.
- Hydraulic data recorded both manually and automatically to compare and resolve discrepancies.
- Power data was recorded by two separate power meters. Data was compared to resolve discrepancies and provide assurance that data was accurate.
- Water quality data analyzed according to EPA or *Standard Methods* procedures, including quality control.

- Final reporting (including this paper) 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 were independent, third parties such as utility/agency members of the ADC and/or their consultants.

RESULTS AND DISCUSSION

Raw Water Quality and Pretreatment

Typical seawater quality tested during this study is summarized in **Table 6**. 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.

Table 6. Average Seawater Quality

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		

The design of the pretreatment process for the ADC's demonstration scale equipment was based upon more than ten years of experience treating the Pacific Ocean from the Navy's intake in Port Hueneme, California. The design included in-line coagulation and media filtration (i.e., criteria established in **Tables 1** and **4**). Shortly after the ADC's plant was commissioned in May 2005, a red tide event occurred that was significantly worse (i.e., both water quality and duration of the event) than any previous red tide event previously experienced. As a result, the ADC's media filtration pretreatment was challenged to produce water with turbidity and silt density index (SDI) values acceptable for the SWRO system. Additionally, media filter differential pressure would increase rapidly over the course of only two days. This made operating the SWRO equipment impractical and the ADC's equipment remained shutdown until October 2005 when the red tide event ended.

The implications of these pretreatment troubles are such that for reliability purposes, some may wonder if media filtration is an appropriate pretreatment. However, even the membrane pretreatment systems that were pre-treating Pacific Ocean water during the summer of 2005 were challenged to produce an adequate capacity.[8] While membrane pretreatment production capacity poses a similar reliability issue, the quality of membrane pretreated water produced was always acceptable. These authors believe that media filtration can be designed such that it can respond to challenging water quality events. Such a design was implemented and has performed successfully at the Point Lisas SWRO plant in Trinidad.[7,9] Therefore, the Point Lisas media filtration design will be used as a basis for further cost estimation. This design should be tested during a California red tide event to validate this assumption.

Once the red tide event had abated, the ADC's equipment was operated in accordance with the testing protocol. During the testing period, seawater and filtered water turbidity and SDI were monitored daily. The results of these recordings throughout the testing duration are reported in **Figure 5**.

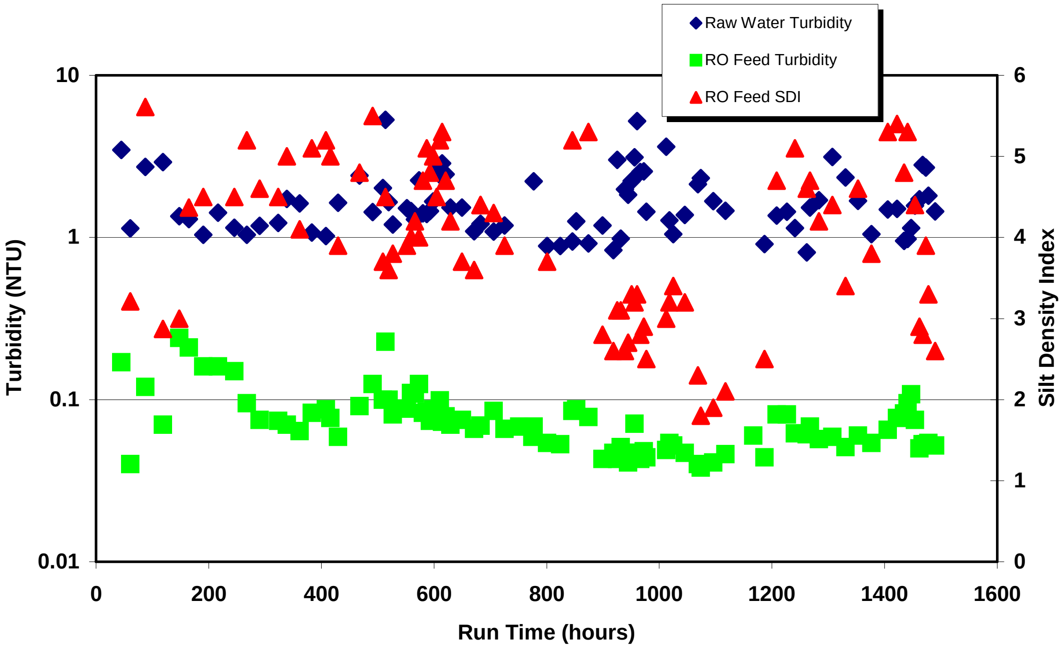


FIGURE 5. ADC Demonstration Scale Test Pretreatment Performance

SWRO System Performance

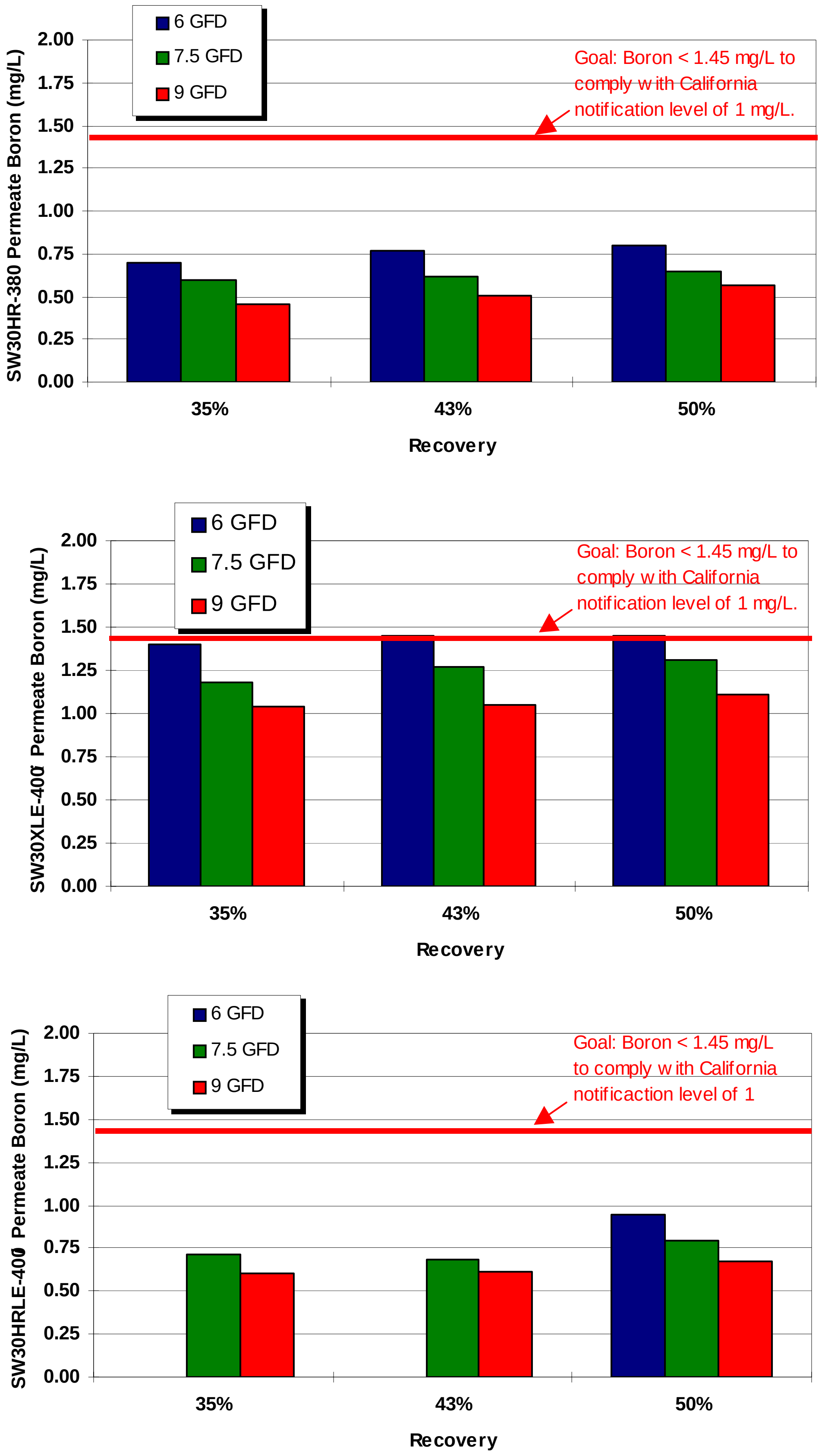
Permeate Water Quality

The impact of flux and recovery on permeate boron and TDS concentrations is presented in **Figure 6** and **7**. These data were collected when flux and recovery were varied during the ADC's testing program. Specific points of interest in these data include:

- Demonstrating the scientific principles of diffusion, which are well understood in SWRO applications, when flux increases, permeate TDS and boron concentrations decrease, and when recovery increases, permeate TDS and boron concentrations increase.
- All conditions tested met the boron removal goal of 1.44 mg/L or less, which is required to comply with California's action level for boron in potable water. However, at the lowest flux tested, the SW30XLE-400*i* membrane produced marginally acceptable boron results (i.e., approximately 1.44 mg/L @ 6 gfd, 50% recovery).
- The low energy membrane elements (i.e., SW30XLE-400*i* and SW30HR LE-400*i*) demonstrated the ability to produce acceptable permeate quality with respect to TDS and boron. The high rejection membrane model (SW30HR-380) demonstrated better permeate quality but at the expense of energy. The high rejection low energy element (SW30HR LE-400*i*) produced water with only slightly higher permeate concentrations than the high rejection membrane model (SW30HR-380).

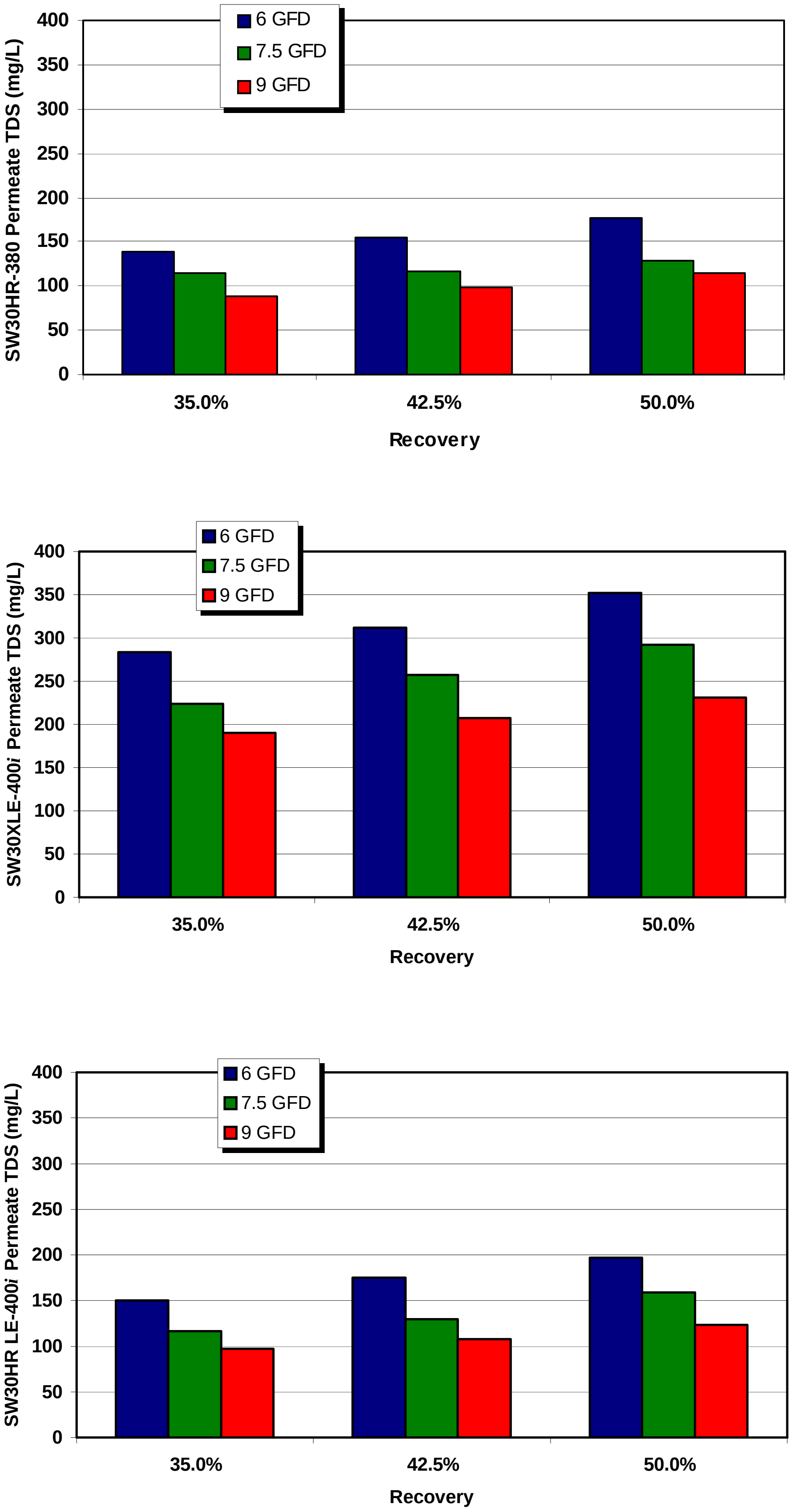
Because each membrane tested was capable of producing water of acceptable quality, each condition tested was evaluated in the cost model. It should be recognized however, that if the ADC test been fed a higher temperature seawater, more typical of a co-located SWRO plant taking warm water from a once through cooling power plant, that the SW30XLE-400*i* membrane would very likely not produce acceptable water quality at a flux of 6 gfd. Therefore, the data presented herein should be taken in context with the raw water quality data presented in **Table 6**. If the test had been performed at a higher temperature, the SW30HR-380 and SW30HR LE-400*i* membranes would also produce permeate with higher concentrations of TDS and boron, and the feed pressures and power consumption would have been less. Further testing is needed to quantify the true impact of temperature on these results. Additionally, SWRO system designers should consider public issues related to water quality, in addition to water costs when selecting design conditions such as flux, recovery and membrane elements.

FIGURE 6. Permeate Boron Concentrations



NOTE: 1. A 1.44 mg/L boron concentration meets the California requirement for a 1 mg/L Notification Level. Results must be rounded up to the nearest 0.1 mg/L.

FIGURE 7. Permeate TDS Concentrations



Energy Efficiency

The ADC's demonstration scale plant was designed with an emphasis on energy efficiency to produce the lowest power costs possible. Components of the SWRO system, such as the membrane elements, the high pressure positive displacement pump and high efficiency motor, and energy recovery device were selected based upon their reported efficiencies. However, once this system is assembled, engineers and system designers may still question the design decisions made and have questions regarding the interpretation of the ADC's data. Therefore, it is a goal of this project to publish information required to help answer these questions and add clarity to product selection decisions other engineers and designers will make as they conceive their SWRO systems.

The focus of our energy efficiency discussion will be on two key components of the SWRO system:

- The positive displacement high pressure pump.
- The energy recovery device.

High pressure feed pumps commonly used for SWRO systems fall into two categories: positive displacement (PD) and centrifugal. PD pumps have the advantage of very high efficiencies (~90%) over a wide range of flows and pressures. Their disadvantages are that they require greater maintenance and produce pulsating flows that require very large dampeners at flow rates above 100-200 gpm. For these reasons, above flow rates of 200 gpm, the industry has largely chosen centrifugal high pressure pump designs that produce smooth flow with very little maintenance, but have efficiencies that are typically lower. Typical efficiencies of centrifugal pumps range from 55-65% at low flow rates (i.e., 200-500 gpm). Efficiencies gradually increase as flow rates increase up to approximately 88%.

The ADC selected to use a PD main high pressure pump because of the small size of our system and also because the high efficiencies of the PD pumps are comparable to the largest centrifugal pumps that one might find in a 50 mgd SWRO plant. An example of how pump selection and efficiencies may affect the specific power consumption for various size SWRO plants is presented in **Table 7** and **Figure 8**.

Table 7. Impact of Train Size on Pump Hydraulic Efficiency

Train Size (MGD)	**ADC**	**0.1**	**0.3**	**1.3**	**2.6**	**4.0**	**6.6**	**8.4**
HP Pump Eff.	90%	90%	69%	77%	81%	84%	86%	88%
HP Pump Motor Eff.	93%	91%	92%	94%	94%	95%	96%	96%
HP Pump VFD Eff.	97%	97%	97%	97%	97%	97%	97%	97%
PX Booster Pump Eff.	60%	64%	59%	75%	80%	83%	86%	88%
PX Booster Pump Motor Eff.	90%	90%	91%	93%	94%	94%	95%	95%
PX Booster Pump VFD Eff.	97%	97%	97%	97%	97%	97%	97%	97%
PX Eff.	96%	95%	96%	95%	95%	95%	94%	95%

Figure 8 presents an example of how specific power relates to SWRO train size. As presented in **Figure 8**, there is estimated to be an energy penalty associated with smaller municipal scale trains from approximately 0.3-1.3 mgd, but as these train sizes get larger the specific power consumption should begin to mimic the results achieved in the ADC's demonstration testing. These authors suggest that a pressure center design concept may lower the energy consumption of smaller, municipal scale trains and flatten out the curve presented in **Figure 8** between 0.3-1.3 mgd.[10] The pressure center design would centralize feed pumps and energy recovery, instead of having dedicated feed pumps and energy recovery at each train. Such a concept would allow the use of larger pumps, which have greater efficiencies.

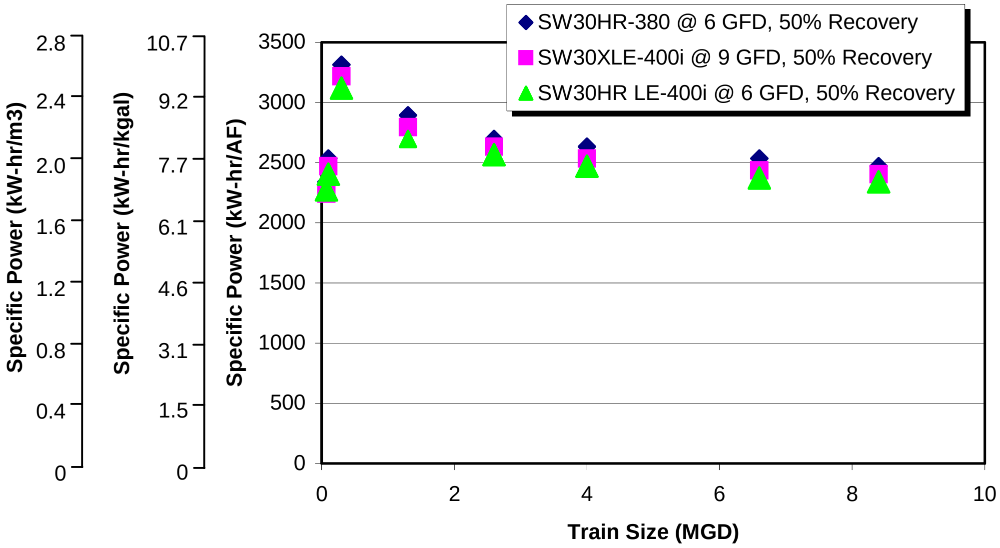


FIGURE 8. Impact of Train Size on Estimated Specific Power Consumption

It is important for engineers designing SWRO systems using an isobaric energy recovery device (i.e., like the PX) to account for mixing of the SWRO feed water with brine. This mixing causes an increase in feed water TDS. Therefore, a slightly higher pressure is required by the SWRO high pressure feed pump to produce the same permeate flow. Engineers should understand that comparing energy recovery devices based upon a reported device efficiency is not adequate because this increase in feed pressure is unique to isobaric energy recovery devices and it is not accounted for in the device's reported (device) efficiency (**Equation 1**). Therefore, the best comparison of SWRO system efficiency is through specific power consumption. Specific power for the ADC's study is reported later in this paper, but further direct comparisons of energy recovery devices are outside the scope of this study.

$$Eff. = \frac{\Sigma(P \times Q)_{OUT}}{\Sigma(P \times Q)_{IN}}$$ **Equation 1**

Where: $\Sigma(P \text{ x } Q)_{OUT}$ = Sum of the flows and pressures into the isobaric energy recovery device
$\Sigma(P \text{ x } Q)_{IN}$ = Sum of the flows and pressures out of the isobaric energy recovery device

Using the ADC's data, the impacts of the PX on the TDS of the raw seawater, SWRO feed water, and PX high pressure output ($PX_{HP\text{-}out}$) water are presented in **Figure 9**. As indicated in **Figure 9**, the direct brine to seawater contact in the PX results in a TDS increase of approximately 2,340 to 4,140 mg/L, or about 7 to 13% additional TDS at the outlet of the PX device. Lower TDS concentrations in the $PX_{HP\text{-}out}$ resulted at lower recovery rates. However, since the $PX_{HP\text{-}out}$ flow is equal to the brine flow rate and the main high pressure pump is sized equal to the permeate flow rate (refer back to **Figure 4**), additional dilution of this effect is experienced such that the net TDS gain to the SWRO feed is quite small, averaging about 1,300 to 2,060 mg/L, or approximately 4 to 6% net increase. The PX manufacturer reports a 6% volumetric mixing for their device, and based upon a mass balance of the ADC's data, the results presented are all within the manufacturer's reported allowance. Higher TDS concentration increases were seen at higher recovery rates.

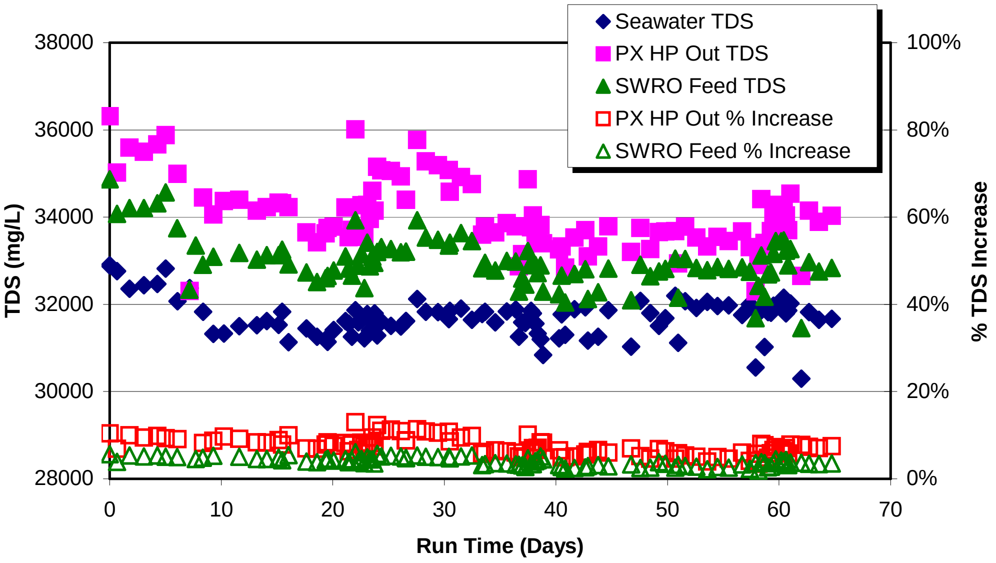


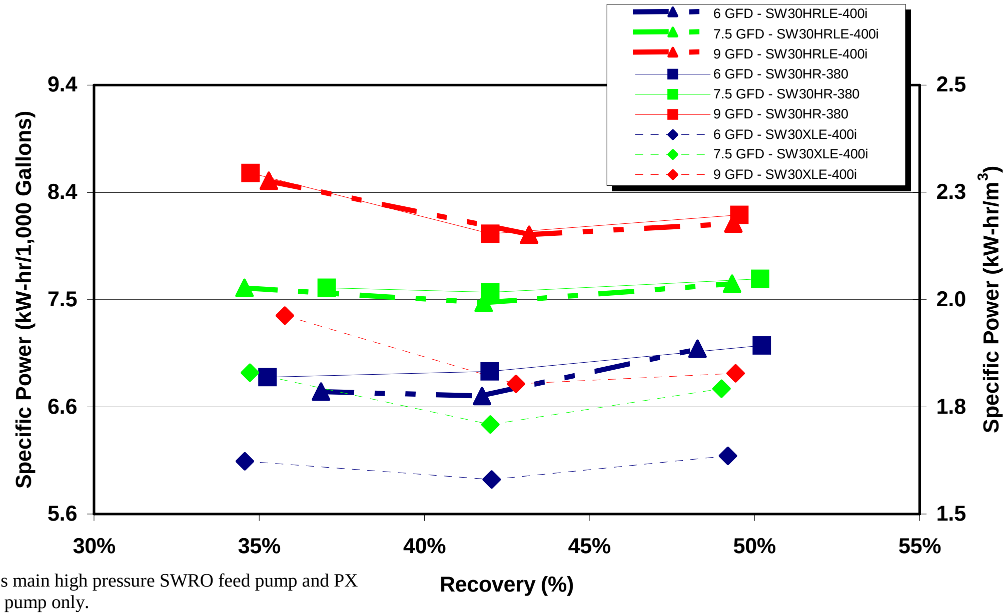
FIGURE 9. SWRO Feed Water TDS Impacts by PX

To maintain the same permeate flow rate, the impact on the overall system to overcome this increase in TDS contributed by the PX to the SWRO feed water is estimated to be approximately 30 psig of additional feed pressure imparted by the high pressure feed pump at a SWRO recovery of 50%.

Specific Power

Test data collected for the power required to operate the SWRO process equipment for each membrane is presented in **Figure 10**. These data represent the measured power (via a power meter) that accounts for the energy consumed by the high pressure feed pump and the PX booster pump. Points of interest in these data include:

- In general, there was an apparent optimum efficiency point for the SWRO system at a recovery near 42.5%. This is demonstrated by the fact that most of the data show a lower specific power near this recovery. This efficiency is likely the result of the fact that the main high pressure pump is pumping against a lower total dynamic head than at 50% recovery (i.e., less osmotic pressure), and the PX booster pump is pumping significantly more water at 35% recovery.
- The SW30XLE-400*i* membrane produced water with less power than any of the other membranes tested at comparable flux rates.
- For each membrane, there was a significant difference in specific power between 6 and 7.5 GFD which is not equal to the differential seen between 7.5 to 9 GFD.
- New membranes were tested and therefore produced the best possible results in terms of energy. Extended testing could be conducted to determine this effect over time and/or average energy consumption between cleaning cycles. Alternatively manufacturers' recommendations and guarantees could be used to quantify this effect. For this study, data was normalized using the CARR values presented in **Table 5**.
- New pumps and equipment were tested and therefore produced the best possible results in terms of energy. Manufacturers' recommendation and guarantees could be used to quantify this effect.



NOTE:

1. Includes main high pressure SWRO feed pump and PX booster pump only.
2. The 99% confidence interval for average data reported on this chart ranges from 0.1 to 0.2 kW-hr/kgal (0.02 to 0.06 kW-hr/m3).

FIGURE 10. Specific Power vs. Recovery, Flux and Membrane Type

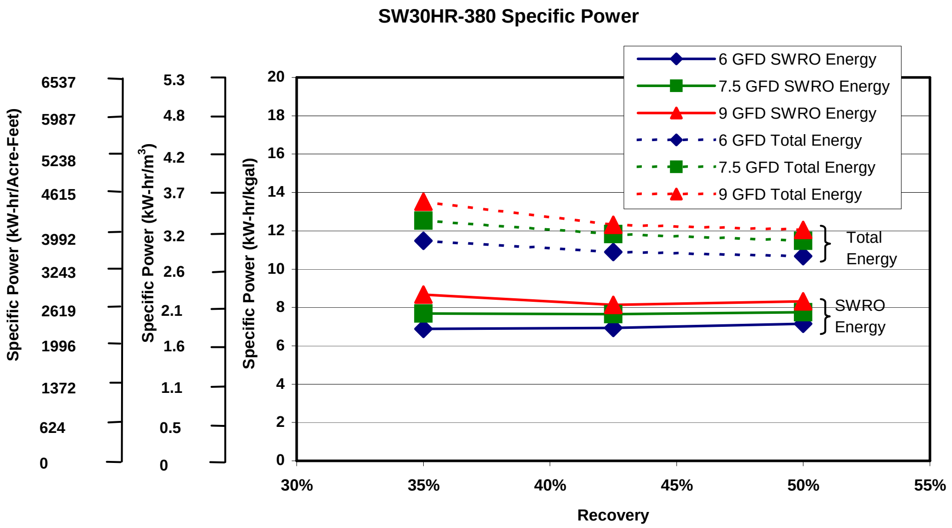
Figure 11 presents the specific power (for both SWRO and treatment plant total energy) at varying flux and recovery rates. The difference in these power requirements represents, by and large, raw and finished water pumping and transfer pumping within the treatment plant and storage facilities. Based upon these figures, the SWRO process is estimated to represent between 55 to 65% of the total power required for the treatment plant. Comparatively, conventional SWRO systems have been noted to comprise approximately 75% of the total power required for treatment and distribution.[11] Using the conventional thinking by most industry experts who believe SWRO power requirements are between 10 to 14 kW-hr/kgal (2.6 to 3.7 kW-hr/m^3), the ADC's design demonstrated that power required by the SWRO can be between 5.98 to 8.67 kW-hr/kgal (1.58 to 2.29 kW-hr/m^3). This represents a 38 to 40% reduction in power over the conventional design and industry experience.

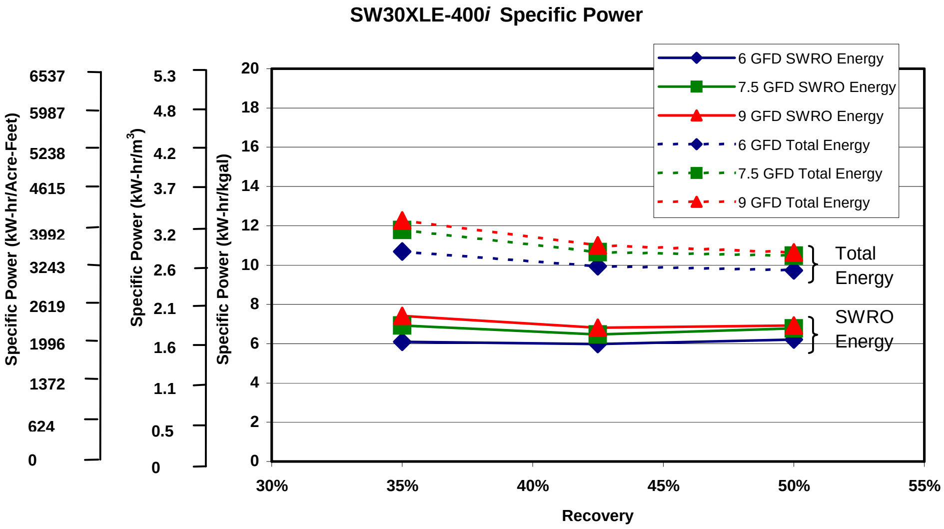
Estimated Costs

Estimated costs developed through this project are presented in **Figure 12**. These costs present the costs associated with both capital, operating and total water costs based upon the conditions presented previously. As discussed previously, these costs assume that the SWRO facility is co-located with a power plant to share existing intake and outfall facilities.

Figures 12 shows that for each membrane tested, there is a consistent trend that indicates the lowest water cost is linked to the highest recovery rate over the range tested. This is due to both the high capital and operating costs associated with large pretreatment systems. It is important to note that recovery does not impact the ADC's SWRO system design or feed pumping costs as significantly as a conventional SWRO system design, which would require larger SWRO feed pumping flows. This is because the ADC system uses an isobaric energy recovery device and the SWRO high pressure pump flow is constant for each flux rate, regardless of recovery. As recovery increases, however, there is a modest effect on the total dynamic head required to produce the same permeate flow rate. This effect was incorporated into the model used to develop the estimated costs presented.

FIGURE 11. Estimated Power required for 50 MGD SWRO WTP in California





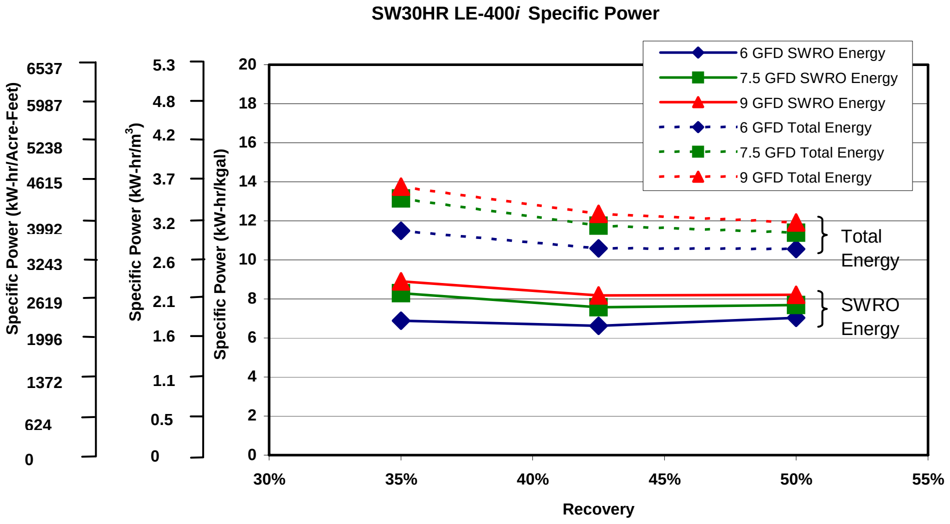
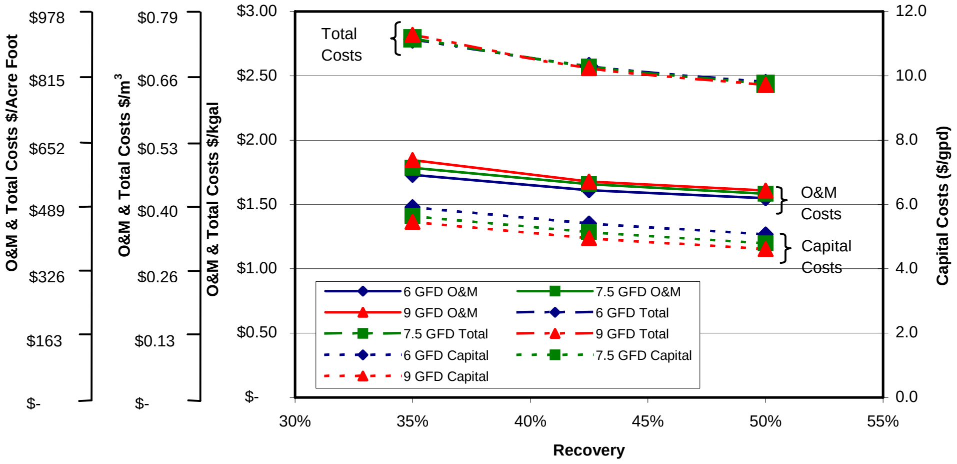
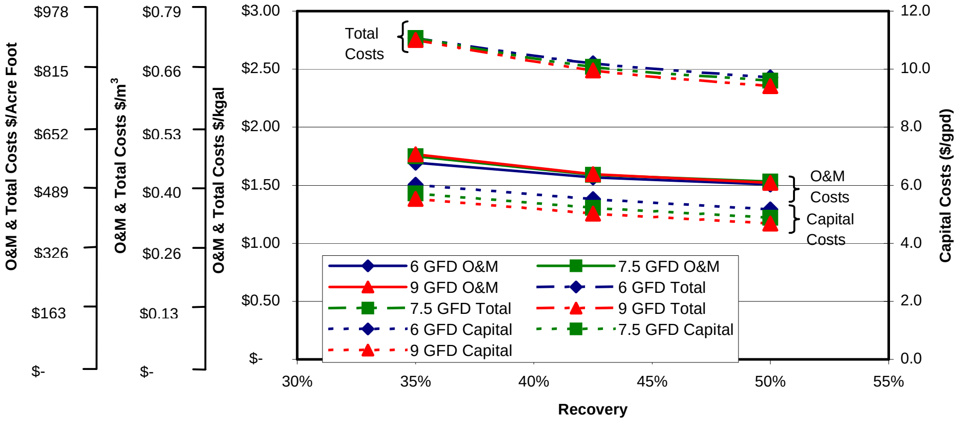


FIGURE 12. Estimated Costs for 50 MGD SWRO WTP in California

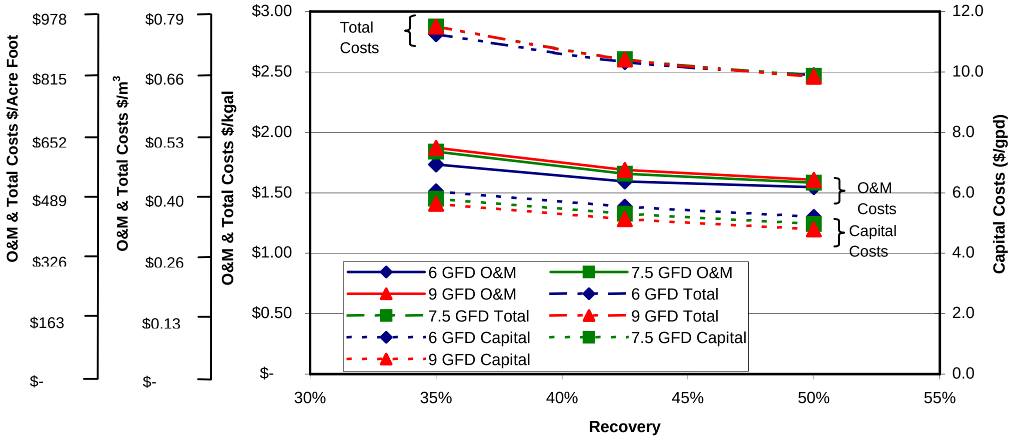
Estimated Costs for
50-MGD SWRO WTP (SW30HR-380)



Estimated Costs for
50-MGD SWRO WTP (SW30XLE-400*i*)



Estimated Costs for
50-MGD SWRO WTP (SW30HRLE-400*i*)



The decreasing trend of total costs with recovery presented in **Figure 12** is contrary to the opinions of some in the industry who advocate low recovery design to minimize SWRO power costs (i.e., when using isobaric energy recovery devices), maximize membrane life, reduce membrane cleaning frequencies, and produce the highest quality permeate.[12, 13] The impact high recovery on membrane replacement costs, cleaning frequencies and permeate quality are factored into the ADC's cost estimate using the CARR values presented previously in **Table 5**. The CARR accounts for the annual replacement of membranes to maintain system performance with respect to power and permeate quality. Therefore, it can be concluded that reducing capital costs associated with pretreatment are estimated to be more important to designing an affordable SWRO plant than the impacts membrane life, cleaning and SWRO process power consumption.

While high recovery consistently resulted in the lowest treatment estimated costs, the impact of flux rate was questionable in some cases. Typically, designers will choose higher flux rates to minimize capital costs and produce the best quality water even though power costs, membrane replacement costs and in some cases, cleaning costs may increase as a result. Again the ADC's costs presented in **Figure 12** account for these added O&M costs resulting from higher flux rates using the CARR values presented in **Table 5**. Our results provide further credence to the industry's experience that these types of operating costs associated with high flux rates are negligible when compared on a life cycle basis.[14]

Figure 12 shows that O&M costs are estimated to represent approximately 70% of the total water costs for the SWRO facility. Of the total O&M costs, the SWRO power costs represent between 30 to 42% of the total O&M costs (i.e., 18 to 29% of the total water cost). This is a significant reduction over the current understanding in the desalination industry, where it is commonly believed that power costs represent between 55 to 65% of the total O&M cost (i.e., 50% of the total water cost).

CONCLUSIONS

Conclusions based upon the work conducted by the ADC include:

- 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/m^3) at the most affordable operating point (i.e., 9 GFD, 50% recovery for the SW30HR-380 and SW30XLE-400*i*, and 6 GFD, 50% recovery for the SW30HR LE-400*i*). The lowest SWRO process energy consumption, 5.98 kW-hr/kgal (1.58 kW-hr/m^3), was demonstrated using the SW30XLE-400*i* 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, as presented in **Figure 2**, 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/m^3).

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:

- 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 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.
- 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-400*i* 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.
- 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 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.

- 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.
- Cost estimates should consider the possible economy of large diameter pressure vessels and membrane elements which may reduce capital costs by approximately 20%.[15]
- Seek out, test and demonstrate system designs and technologies that can increase the achievable recoveries of SWRO systems.

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- US Desalination Coalition
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