Optimizing Lower Energy Seawater Desalination, The Affordable Desalination Collaboration

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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 costs associated with desalinated water.

The Affordable Desalination Collaboration (ADC) is a California non-profit organization composed of leading U.S. companies and agencies in the desalination industry that have agreed to pool their resources and to 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 continuous operation for the past three years at the Navy's Seawater Desalination Test Facility in Port Hueneme, California.

The presented research concerns development and testing of innovative process designs that utilize isobaric energy recovery technology and target minimum overall energy use and cost of water production. As a result of innovative configuration and operation of the PX system 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 innovative unbalanced PX operation involves decreasing the low pressure system feed flow while maintaining the high pressure concentrate flow through the PX. 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 in June 2009 to demonstrate the feasibility and reliability of operation with a 60%/45% recovery flow regime. Pretreatment using a ultrafiltration membrane system took the place of media filtration in July 2008 and was used for these high recovery tests.

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I. INTRODUCTION

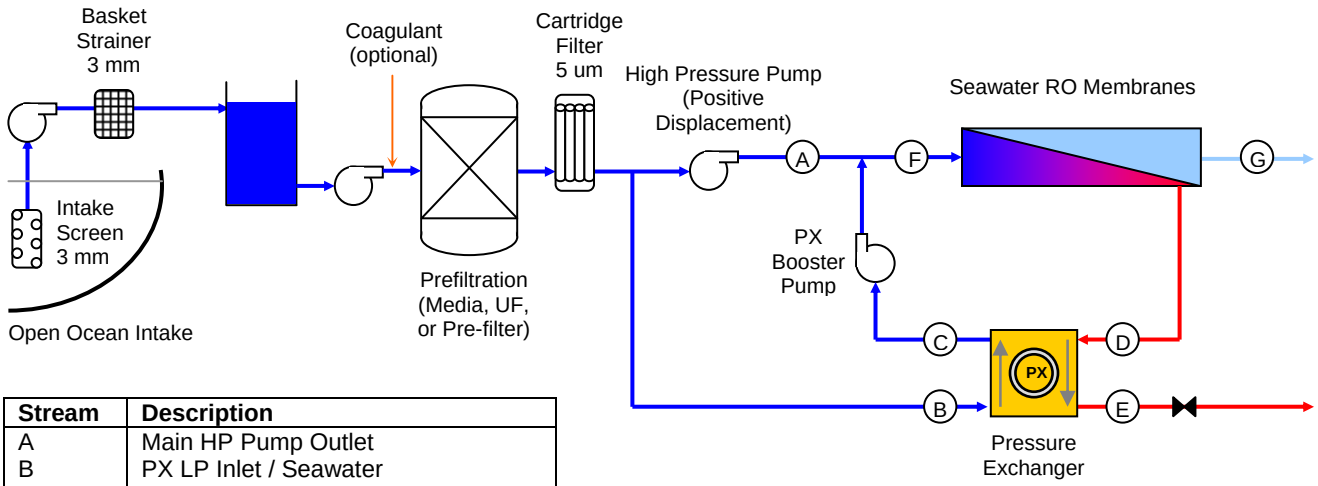
Increasing demand for freshwater resources, long-term drought, and the need to diversify water supply portfolios in order to secure a sustainable water supply are among the many reasons why municipalities and utilities across the United States and the world are looking to the sea as a potential source of fresh water supply. Many arid regions around the world, and especially those with lower fuel and energy costs, have a long-term history of using seawater desalination for public water supply. However, in the United States where many other water source options have been prevalent, the high cost of desalination has hindered interest in the ocean as a possible fresh water supply source. 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 costs associated with producing desalinated water.

The Affordable Desalination Collaboration (ADC) is a California non-profit organization composed of a group of leading U.S. companies and agencies in the field of desalination that have agreed to pool their resources and share their expertise in the mission to make desalination affordable and cost-competitive to conventional water supply alternatives in water limited regions of the U.S. Using a combination of energy efficient, commercially available RO technologies and equipment including pumps, membranes and energy recovery systems, the ADC has demonstrated that seawater reverse osmosis can be used to produce water at an affordable cost and energy consumption rate comparable to some of the other supply alternatives in southern California. 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 – Dow Corporation
- GE Zenon
- 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

The ADC's demonstration scale seawater reverse osmosis (SWRO) treatment system uses pressure exchanger (PX) 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 facility is located at the U.S. 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 impacts
- 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 operated at varying flux and recovery to seek the most cost effective operating point. The most cost effective operational condition 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 2.35 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) and 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:

- Use of alternative pretreatment
- Alteration of system configuration
- Increased recovery research

Relevant California DWR Proposition 50 goals include:

- Opportunities for energy efficiency
- Testing of improved membranes with high salt rejection and lower susceptibility to scaling and fouling
- Strategies for concentrate (brine) management
- Better feed water pretreatment processes and operations 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 that meets applicable standards/membrane specifications
- Develop effective cleaning regimes, including type of chemicals and maximum time between cleanings

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

1.2.1 Stage 1: Low Energy Membrane Testing & 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.

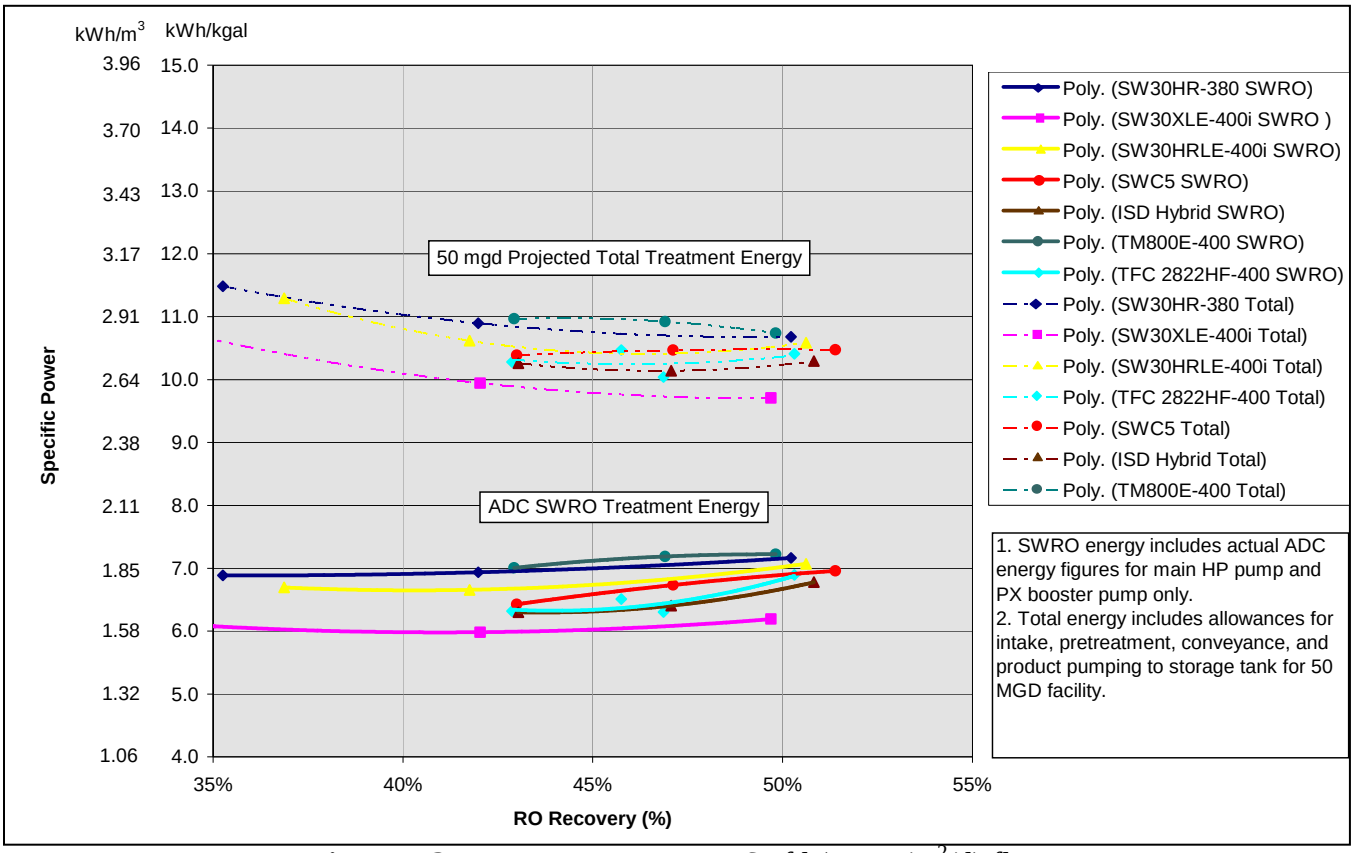


Figure 1.2 Energy vs recovery at 6 gfd (244 L/m^2/d) flux

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 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 (i.e., 45% to 50 %).

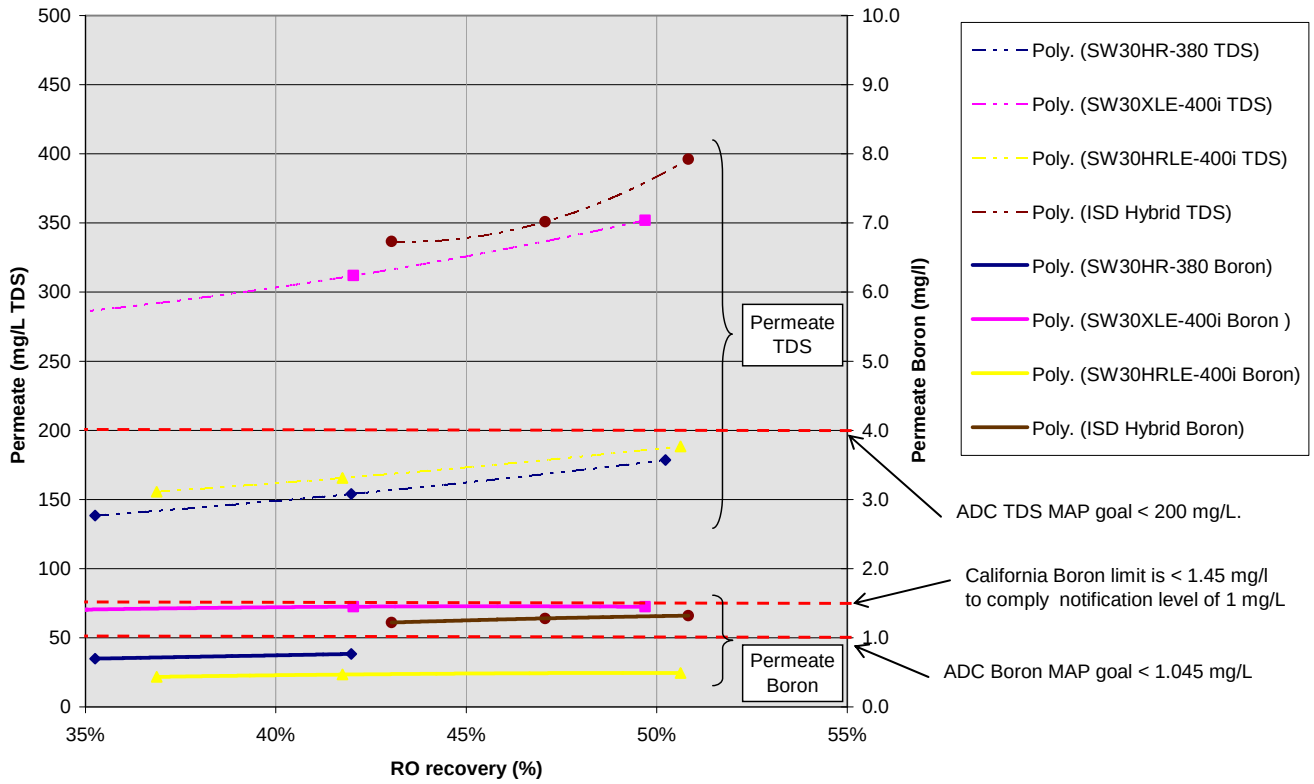


Figure 1.3 Water quality for standard vs hybrid membrane setup at 6 gfd (244 L/m^2/d) flux

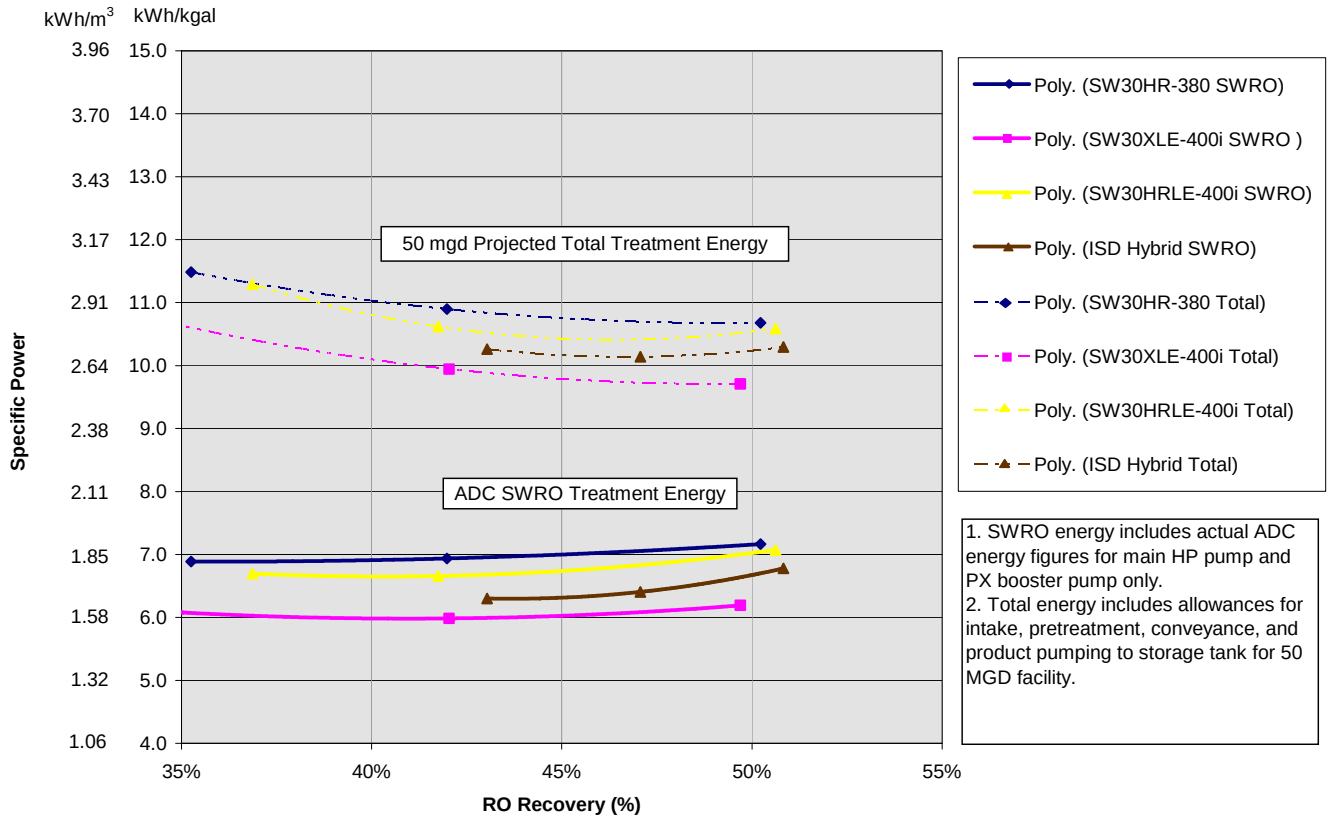


Figure 1.4 Energy use for standard vs hybrid membrane setup at 6 gfd (244 L/m^2/d) flux

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. Tests 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 pre-filtration technologies including an ultrafiltration (UF) system. In general, use of membranes for seawater pretreatment is limited and this work provides valuable information for the U.S. and the 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 UF 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	gpm/ft^2
	120 to 240	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	gfd
	815	L/m^2/day
Cartridge Filter		
Cartridge Specs	#2, 5-micron	
Loading Rate	~1	gpm/10-in.
	~10	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)	ft (psig)
	422 to 844 (4137 to 8274)	m (kPa)
Energy Recovery		
Type	Pressure Exchanger™ (PX™)	
PX Booster Pump		
Type	Multi-stage Centrifugal	
TDH	70 to 115 (20 to 50)	ft (psig)
	21 to 35 (138 to 345)	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**).

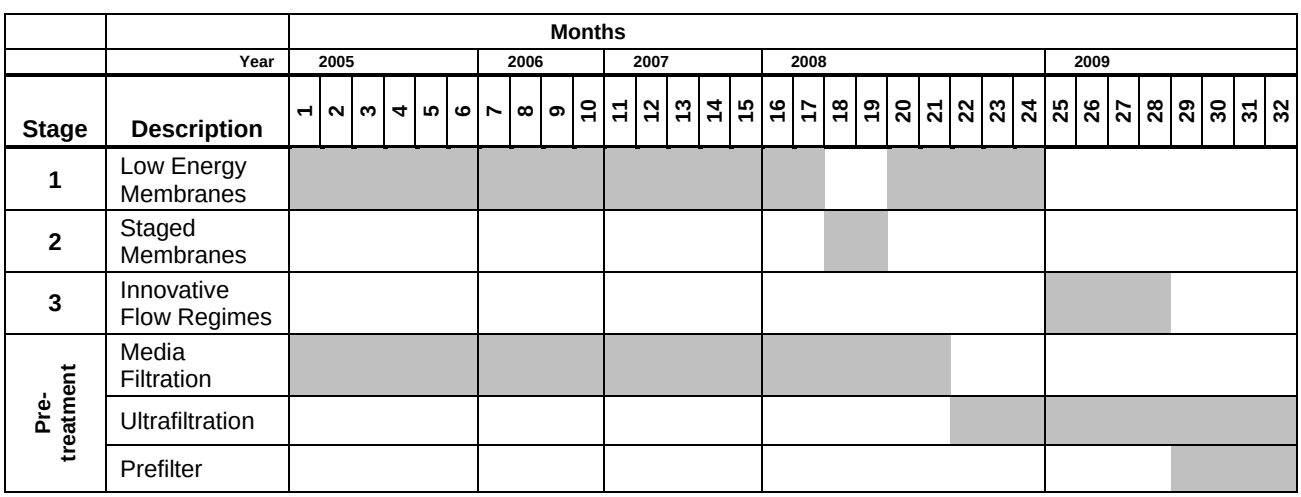


Table 2.2 Project timeline

2.2.2 Innovative Flow Regimes This involves the development and testing of process flows that are possible in conjunction 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.

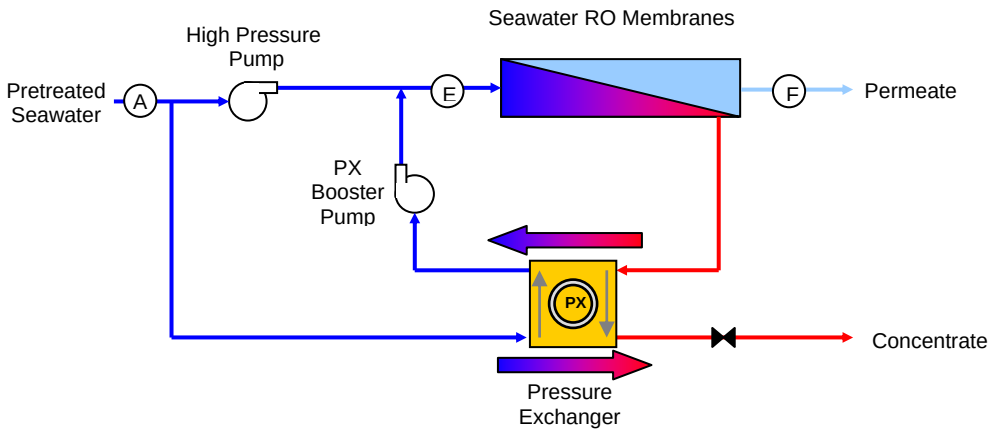


Figure 2.1 Unbalanced PX diagram

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 two-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 seawater 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 consisting 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 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** presents an example using the standard ADC II membrane tests that projects the total energy consumption of various system capacities.

	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

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 projected total treatment energy of 11.3 kW hr/kgal (2.98 kWhr/m^3).

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 is 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 is analyzed according to US EPA or *Standard Methods* procedures, including quality control.
- Final reporting was 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 were completed by 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 seawater 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 (^{o}C)	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

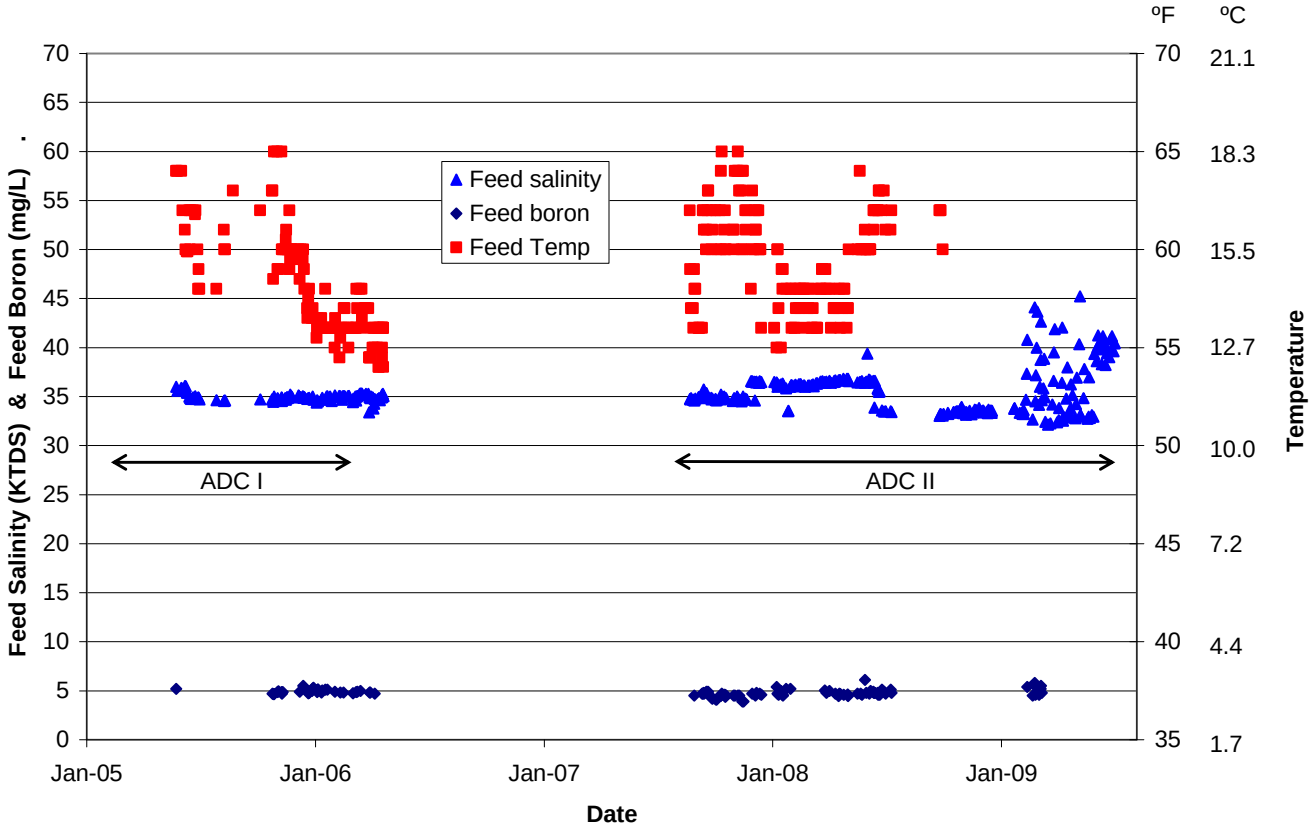


Figure 3.2 Salinity, boron, and temperature

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**).

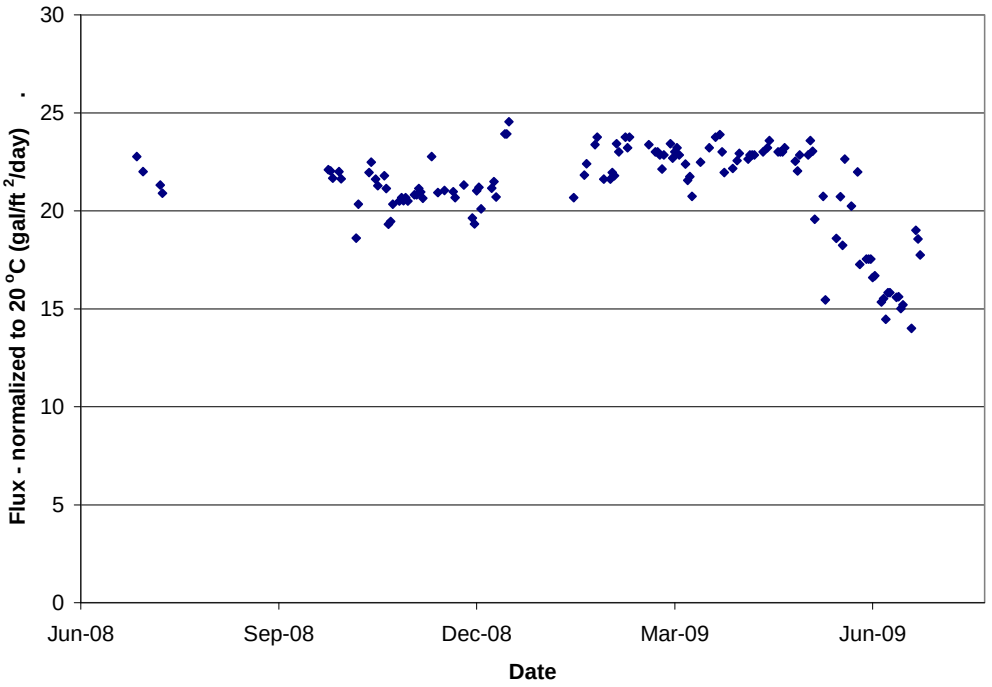


Figure 3.3 Normalized filtrate flux (@20 °C) for the UF membrane system

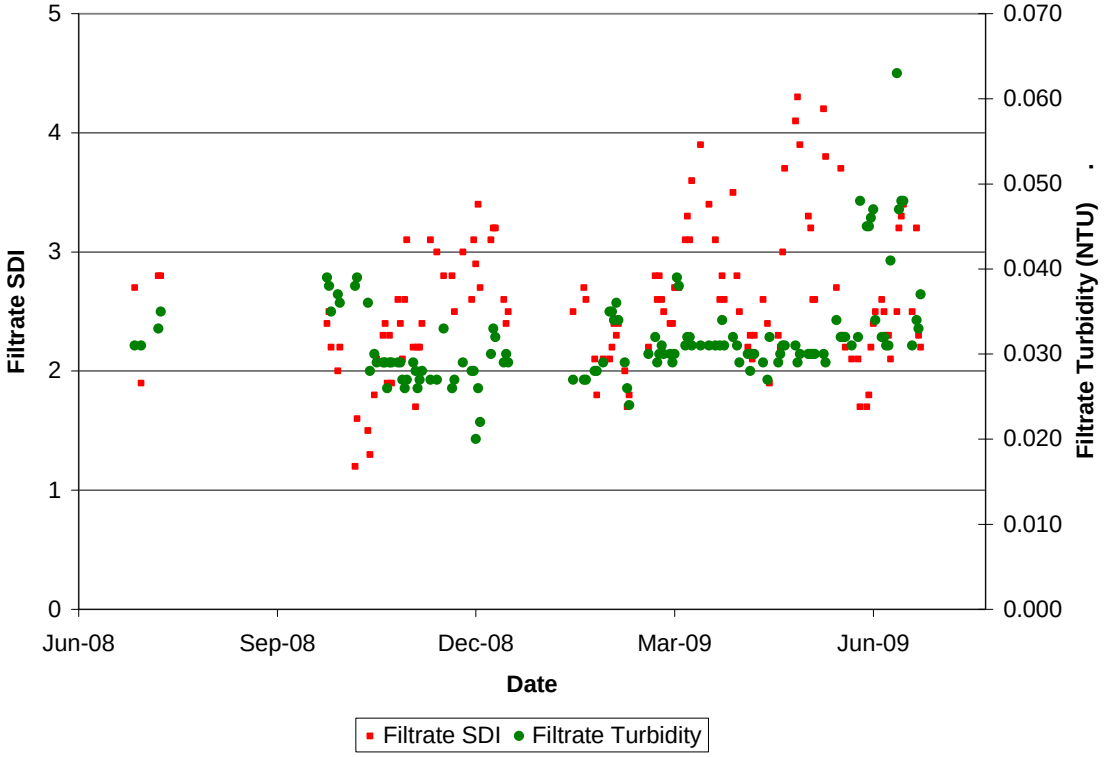


Figure 3.4 Turbidity & SDI for the UF membrane system

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

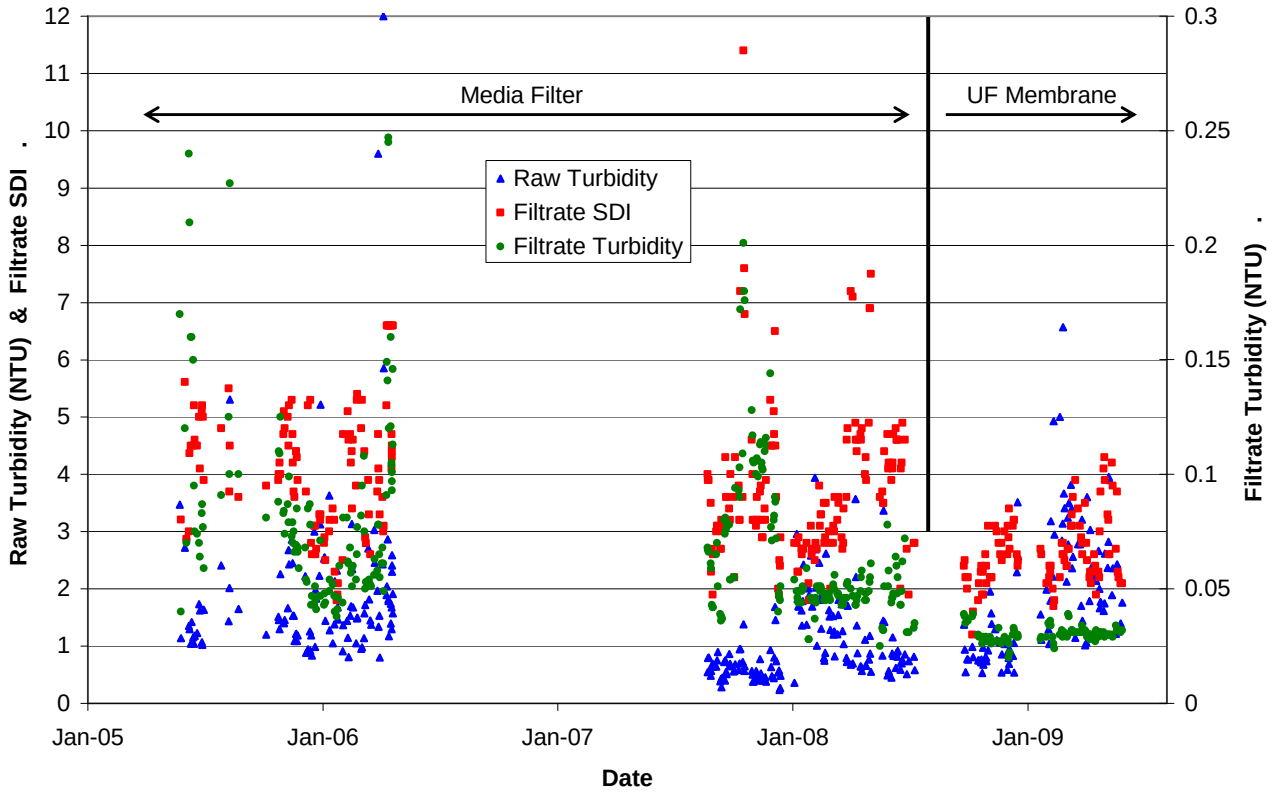


Figure 3.5 Turbidity & SDI for the UF membrane and media filter systems

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 (^{o}C)	Test #
Ripening	42.5	42.5	42.6	42.6	1.77	33,250	119	770	7.53	15	1
Multi-Point Testing	40	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
		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	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
		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	50.2	50.2	2.06	32,950	148	930	7.47	14	2
		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.

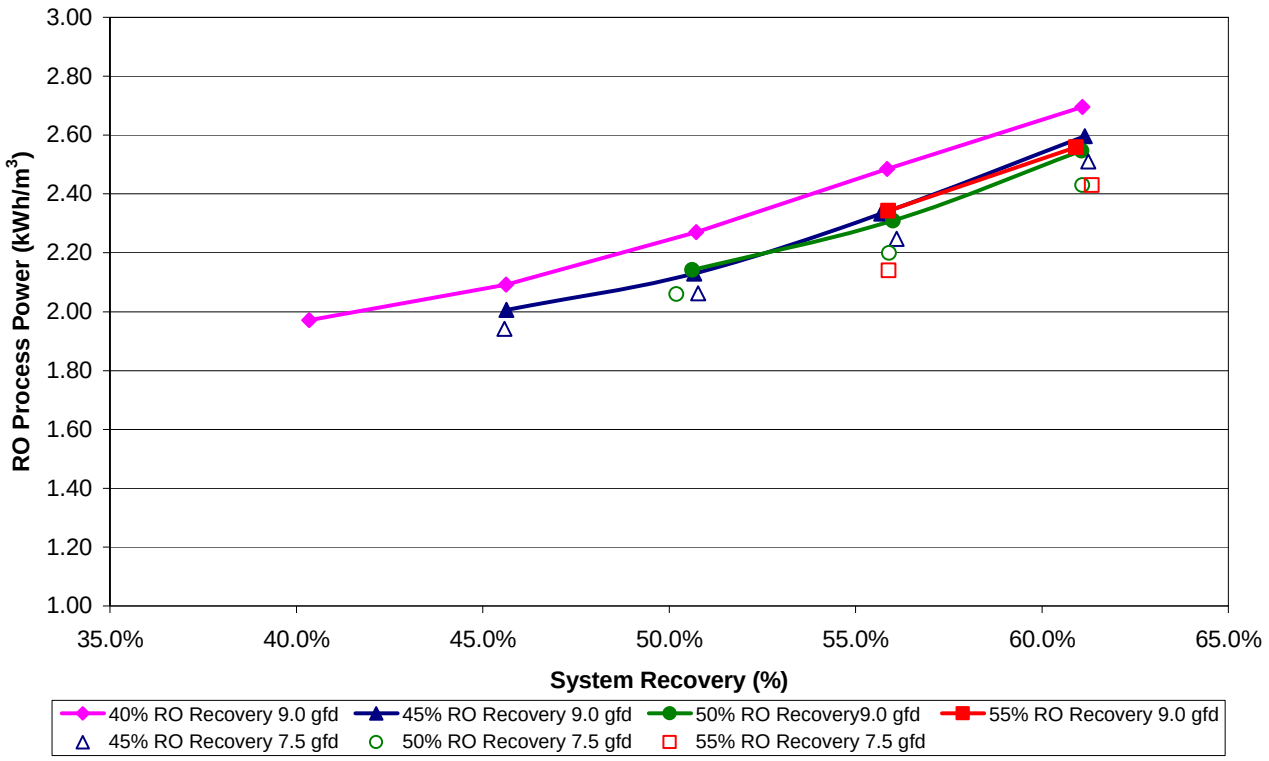


Figure 3.6 Unbalanced system recovery vs. energy use at 9 and 7.5 gfd (306 and 367 L/m^2/d)

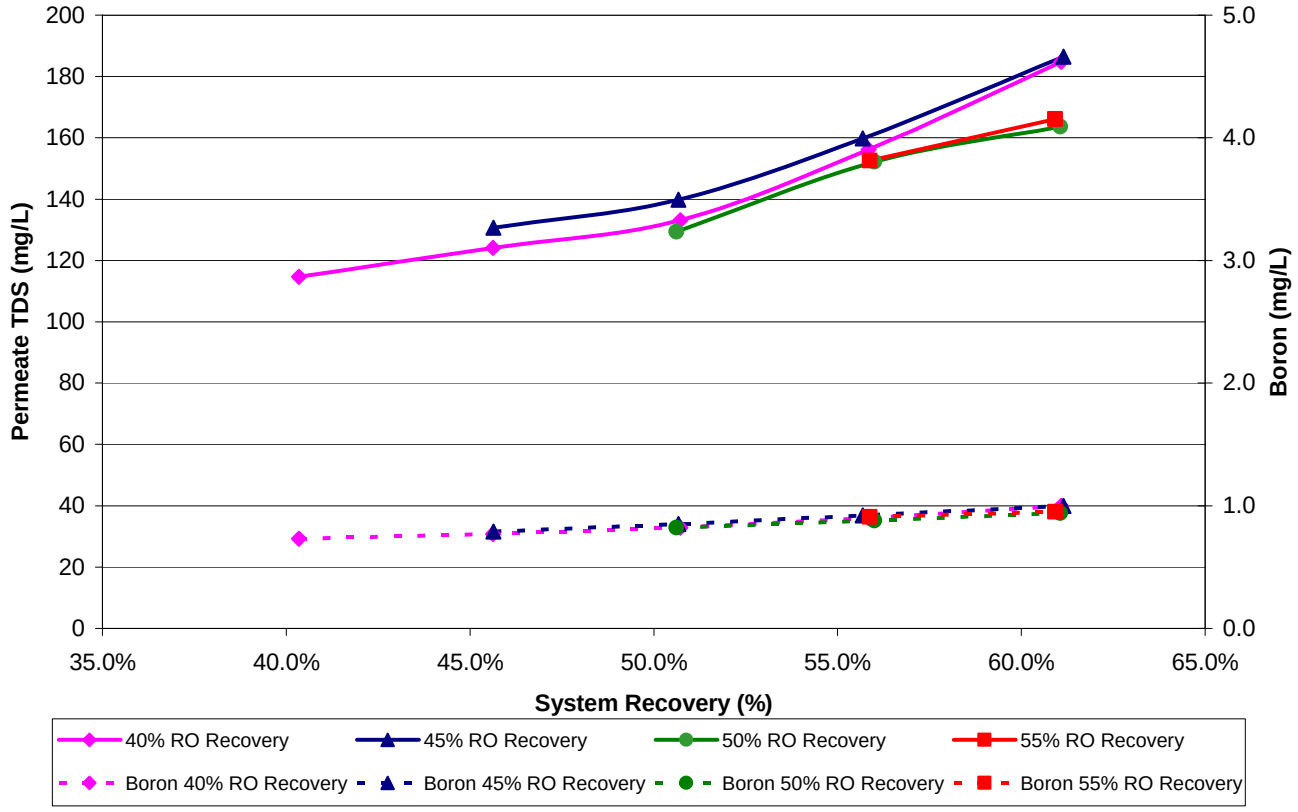


Figure 3.7 Unbalanced recovery vs. water quality at 9 gfd (367 L/m^2/d)

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

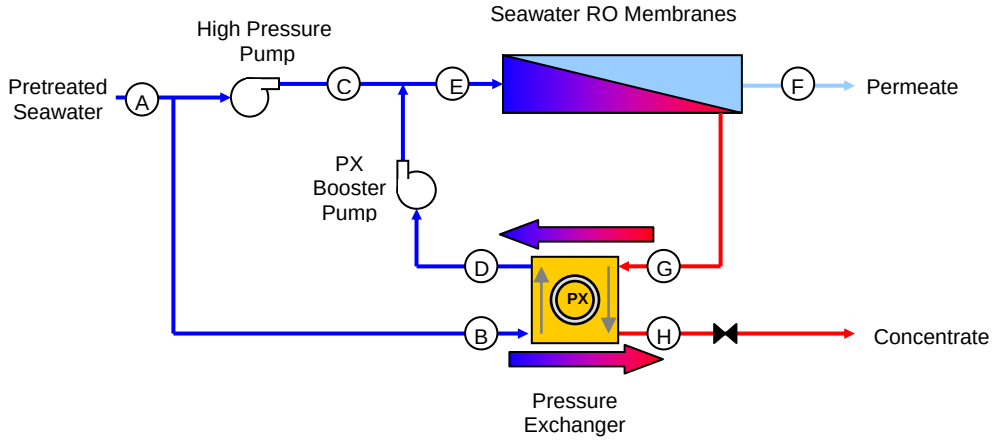


Figure 3.8 Unbalanced PX diagram

		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 PX and system data at the 50/45 point (a) system data, (b) PX 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.

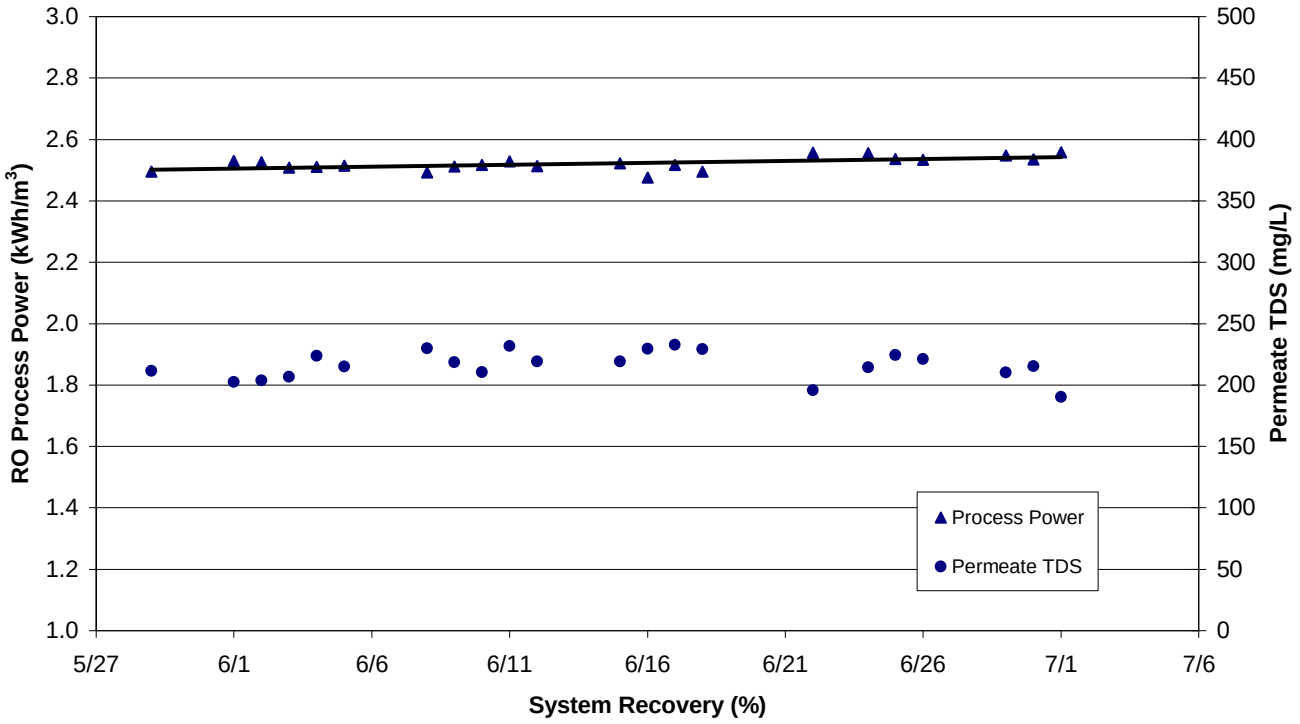


Figure 3.8 Longer term testing

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.

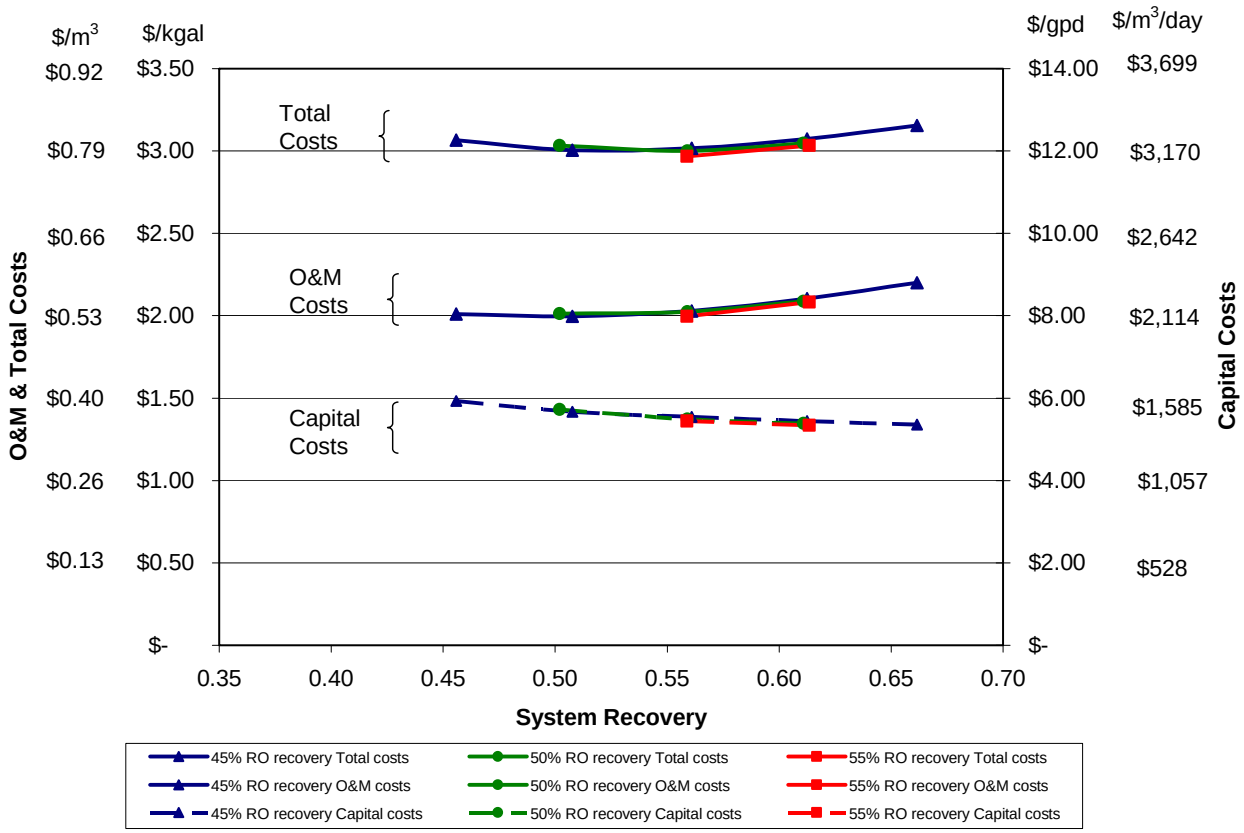


Figure 3.9 Projected costs for 50 MGD (189,000 m^3/day) treatment plants at 7.5 gfd (306 L/m^2/d) flux

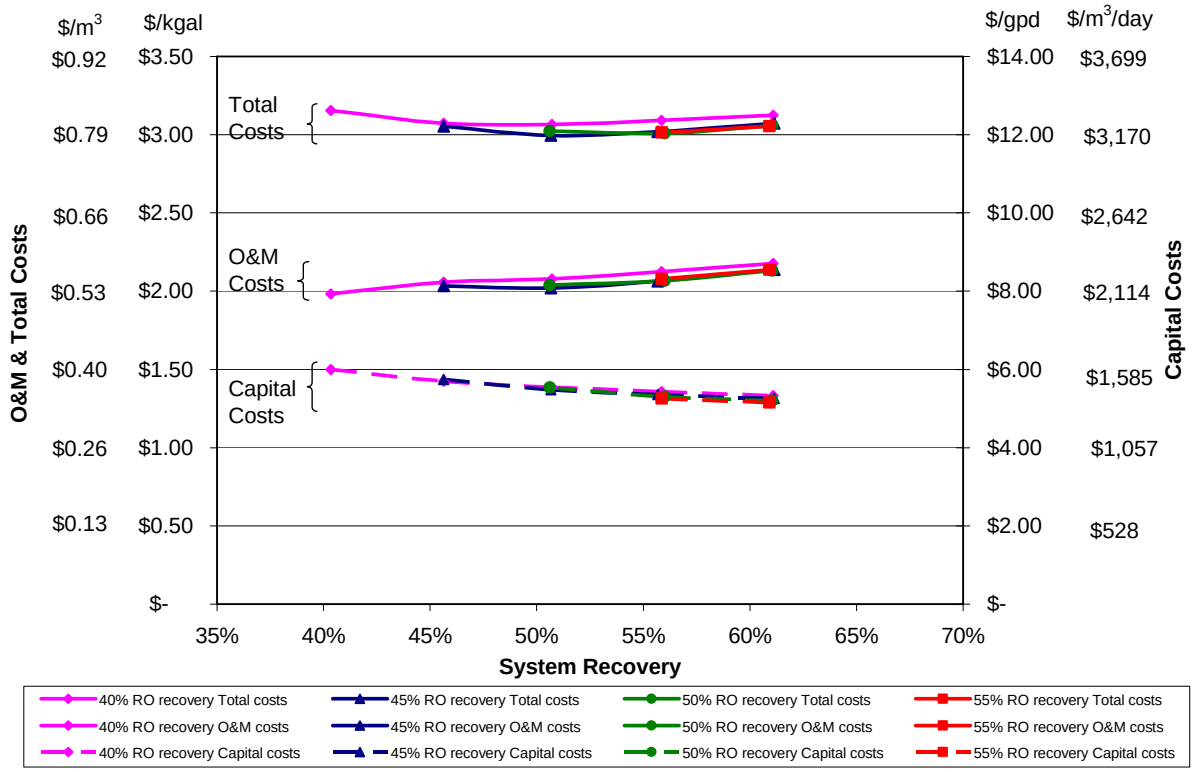


Figure 3.10 Projected costs for 50 MGD (189,000 m^3/day) treatment plants at 9 gfd (367 L/m^2/d) flux

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.

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