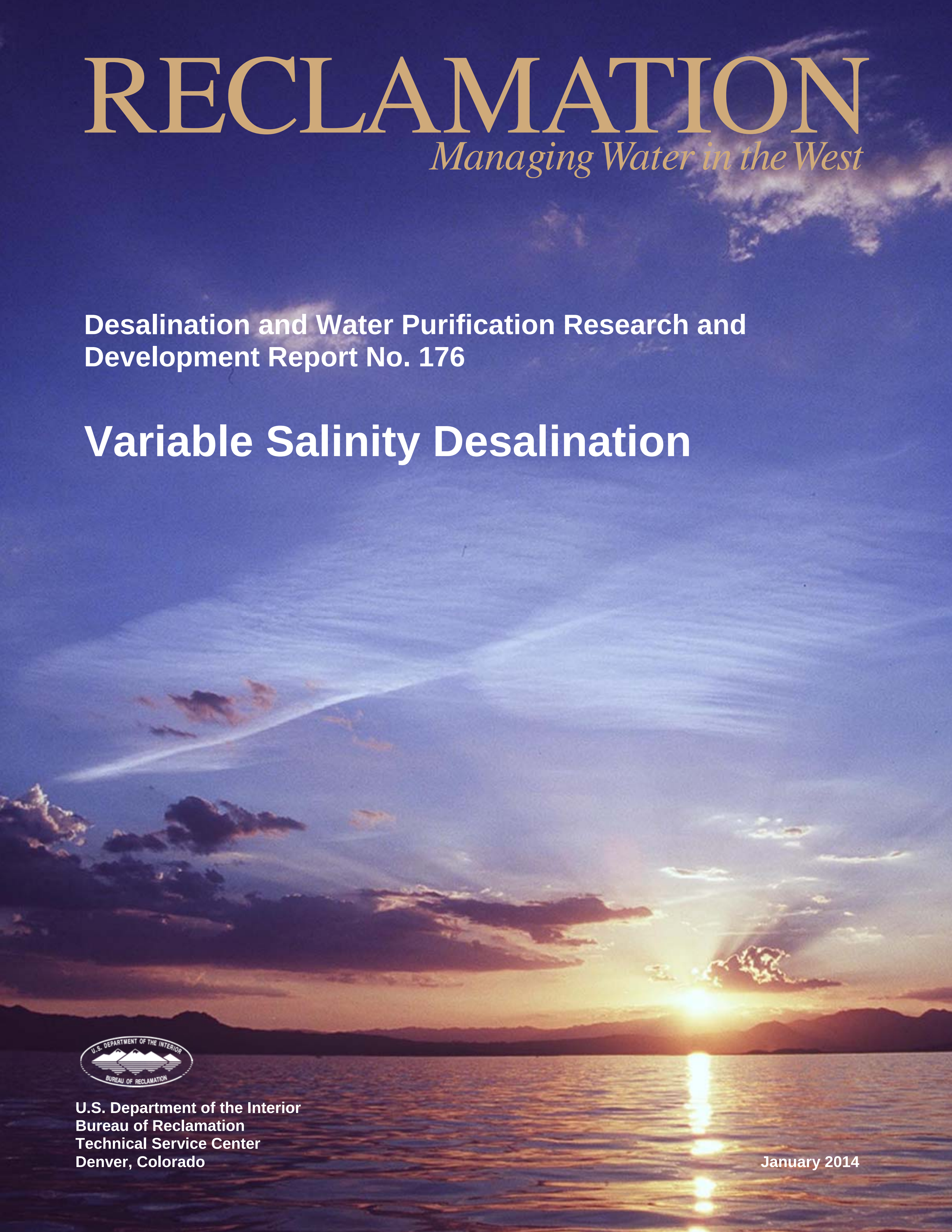

RECLAMATION

Managing Water in the West

Desalination and Water Purification Research and Development Report No. 176

Variable Salinity Desalination

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

January 2014

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14. ABSTRACT
Variable salinity desalination applications are becoming more abundant. Design flexibility was explored through a desk-top design exercise evaluating the range of operational conditions for various membrane configurations. The Village Marine Expeditionary Unit Water Purifier Generation 1 was used to evaluate the practical aspects of converting a single-stage seawater system with energy recovery, to a two-stage brackish water system capable of 75% water recovery. Performance is compared with various levels of salinity in the seawater configuration and brackish water configuration.

15. SUBJECT TERMS
brackish water, seawater, desalination, flexible treatment systems

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Desalination and Water Purification Research and Development Program Final Report No. 176

Variable Salinity Desalination

by

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Frank Leitz
Andrew Tiffenbach

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

January 2014

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Cover photo: Brownsville/ South Padre Island area with highly variable surface and groundwater sources.

Acknowledgements

The project team has deep gratitude to everyone who helped with this project:

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- And last but not least, the Project Review Team who have waited patiently for this report.

Acronyms and Abbreviations

BGNDRF	Brackish Groundwater National Desalination Research Facility
C	Celsuis
Desal Plant	desalination plant
dP	differential pressure
EPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification
EUWP	Expeditionary Unit Water Purifier
F	Farenheit
FRP	fiberglass reinforced plastic
ft^2	square foot
gpd	gallon per day
gpm	gallon per minute
ISO	International Organization for Standardization
KW	kilowatt
kWh/kgal	kilowatts per thousand gallons
L/min	liters per miniute
lb/in^2	pounds per square inch
LSI	Langelier Saturation Index
m^2	square meters
m^3/day	cubic meters per day
MWCO	molecular weight cutoff
mgd	million gallons per day
mg/L	milligrams per liter
mL/hr	milliters per hour
NDP	Net Driving Pressure
NTU	Nephelometric Turbidity Unit
ONR	Office of Naval Research
OTAO	Oklahoma-Texas Area Office
PLC	programmable logic controller
ppm	parts per million

PX	Pressure Exchanger
psi	pounds per square inch
psig	pounds per square inch gauge
PVC	polyvinyl chloride
Reclamation	Bureau of Reclamation
RO	reverse osmosis
SDI	Silt Density Index
SMRWA	Southmost Regional Water Authority
TCEQ	Texas Commission on Environmental Quality
TDS	total dissolved solids
TWDB	Texas Water Development Board
µS/cm	MicroSiemens per centimeter
UF	ultrafiltration

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Desalination and Water Purification Research and Development Program

Variable Salinity Desalination

1. Introduction

1.1 Project Background

The Texas 2012 State Water Plan introduction makes the water situation at that time in Texas quite clear:

> "In serious drought conditions, Texas does not and will not have enough water to meet the needs of its people, its businesses, and its agricultural enterprises." (Texas Water Development Board [TWDB], 2012 introductory letter from then TWDB Chairman Vaughan)

Texas has multiple sources of water, especially in the Gulf Coast area. For the Rio Grande Region, less than a third of the water needed in 2060 will come from fresh surface or groundwater sources. One quarter of future supplies will come from desalination of groundwater and seawater or wastewater reuse, and the rest will come from conservation. The TWDB Innovative Water Technologies Program is pro-actively seeking new ideas for treating water more economically. They were impressed with the way Singapore is using technology to extend their limited water resources through direct water reuse, seawater and brackish water desalination—often using the same facilities to treat whatever type of water is available. Jorge Arroyo, now retired head of the Innovative Water Technologies Program team at TWDB, saw the applicability of flexible desalination system design to take better advantage of capital equipment investments in the coastal region. He challenged Reclamation to prove the concept on his home turf. Being a "can do" organization, Reclamation accepted the challenge.

1.2 Importance of Flexibility in Treatment Process Design

The importance of design flexibility has become more apparent over the years due to the rising demand for water in dry areas of the western United States.

Conventional processes of flocculation/clarification/media filtration meant for fresh water sources can be adapted to changing water conditions by slowing down the process and increasing the dose of chemical precipitants and flocculants. With such process changes acceptable water can often be achieved at a lower production rate and with increased volume of sludge waste. Membrane processes can be adapted to moderately changing conditions in a similar manner by reducing the production rate, adding or increasing antiscalant and flocculation chemicals ahead of prefiltration, or adjusting feed pressure to adapt to higher or lower temperatures. However, in an increasing number of situations, source water varies more than can be accommodated with these minor adjustments. Recent literature illuminates several cases of variable conditions that would benefit from a flexibly designed treatment process:

- Agricultural drainage water in the San Joaquin Valley, California varies over space and time from 3828 mg/L TDS to 28,780 mg/L, saturation index for carbonates varied from 0.86 to 5.7 and for gypsum from 0.41 to 0.98 (McCool et al. 2010). Such a high degree of variability cannot be accommodated in a fixed design with slight adjustments to flow, pressure, or chemical dosing.

- The Brazos River Basin salinity varies over time from 500 to 15,000 mg/L at the top of the basin depending on rainfall quantity and location. With other fresh water inflows this difference results in variation from 145 to 780 mg/L at the bottom of the basin (Wurbs and Lee, 2011).

- Singapore has very limited fresh water storage, though they have extremely high rates of precipitation. Storm water is stored in a coastal canal, using inflatable booms that are automatically deflated based on pressure readings when the water level gets too high. When the water is at a high level behind the booms after storm events (30 to 250 mg/L total dissolved solids (TDS)), there is a regular problem with high bacteria counts. When water levels are low between storm events, the water is mainly seawater (30,000 to 35,000 mg/L TDS). Singapore desalination experts found that it is more efficient to keep one treatment facility operating on whatever water is available in the canals than to have distributed treatment facilities that go completely offline when water of appropriate quality is not available. For seawater, they use a two pass system—first pass, single stage with seawater RO membrane, and a two-stage second pass treating permeate from the first pass using a brackish water RO membrane. For brackish or fresh water, they use only the second pass of the seawater system as a two-stage brackish RO system (Seah et al. 2010).

- Water treatment processes driven by solar or wind energy have variable energy supplies in addition to potential water quality variability over time.

The process control for these systems can be programmed to adapt, predict up-coming declines in energy input, and begin a shut-down process or ramp down by a programmed sequence of steps (Li et al. 2012 and Thomson, Miranda and Infield, 2002). Xu and Drewes (2006) propose that flexible designs incorporating nanofiltration and low pressure RO would allow for beneficial use of methane produced water. Produced water from natural gas and oil extraction vary over time and location. Often, water is treated offsite at treatment centers that serve many wells with different qualities of water.

- When the cost of power varies widely over the day, it is beneficial to have built-in flexibility to meet water demand during off peak, lower cost times of day. Ghobeity and Mitsos (2010) developed a model predicting that the ability to ramp up and down with variable frequency drives and to stop a portion of the system at peak power periods. This can save one seventh of the power cost over operating continuously at an even rate of production.

- The Office of Naval Research has a Future Naval Capability program to develop robust desalination technology for naval vessels that can handle the increasingly poor water quality near the shore. Historically, ships spent most of the time in the deep blue sea where cartridge filtration before RO or distillation was adequate pretreatment. In recent years, ships have been spending more time closer to shore in the littoral zone and have found that it is difficult to keep water treatment systems operational (ONR, 2009).

- Texas communities on the Gulf Coast have access to brackish groundwater, brackish surface water from rivers and lakes with tidal influence, and from the gulf itself. An upcoming pilot study for Corpus Christi will evaluate processes for both brackish or seawater.

- Brownsville, Texas, the test site selected for the brackish groundwater demonstration for this study has seawater available within 10 miles and uses brackish groundwater aquifers as a source of drinking water. Their Southmost Desalination Plant would be a good location for a variable salinity treatment system.

These examples of variability in conditions and water sources are indicative of increased reliance on alternative water sources. Fresh river or lake water may change seasonally with storm events, but seawater, estuary water, irrigation return water, and produced water have a much higher degree of variability coinciding with weather events, tides, irrigation schedules, and other factors.

1.3 Approaches to Flexibility

When faced with variable salinity feed sources there are three approaches for designing a system:

- Design for the most extreme case and allow for periodic inefficiency
- Design for the most frequent case, plan for additional storage, and shut down during extreme events
- Design a flexible system with materials and capabilities to accommodate the extreme events while also operating efficiently during moderate conditions

The most economic choice depends on the frequency of extreme events and the importance of continuous availability. For example, a centralized produced water treatment facility that needs to process high salinity water as well as the lower salinity sources might be able to function adequately with a treatment system designed for the extreme case, or could incorporate a holding tank to allow for dilution of high salinity deliveries, or such a facility could use a fully flexible system to treat whichever source is available at the time.

1.4 Objective of the Project

Though as described above, there are many ways to approach flexible feed source treatment, the objective of this study was to evaluate the effect on power consumption and water quality of modifying a highly efficient seawater RO system to enable operation at 75 percent recovery when treating brackish water. The Generation 1-1 EUWP was modified for this study to operate in two modes—with brackish source water (two-stage); and with seawater (one-stage). The method of adaptation used for this study was to convert the EUWP from a one stage, 50 percent water recovery configuration with pressure exchanger energy recovery, to a two-stage, 75 percent water recovery configuration without energy recovery. If flexible feed source adaptation is possible with this robust (though aging) system, then a concentrated design effort to build in flexibility should be quite successful.

1.5 Overview of this Report

A design study evaluating the extent of potential flexibility in a membrane system is presented in chapter three of this report. Chapter two introduces the pilot study project team. Chapter three discusses the pilot study site selection process, the location, and water quality. Chapter four describes the pilot equipment and chapter five reviews the test plan. Chapter six presents the results of pilot testing and chapter seven compares the results with performance at previous test locations. Finally chapter eight outlines conclusions, implications and next steps.

2. Flexible Design Study

Projections for hypothetical flexible designs were developed using Hydranautics' IMS Design program, version 2008. Various configurations were evaluated: first to explore the range of feed flow and salinity variation available within the limitations published for the membrane elements, then to determine how the flow would be changed to use the same membrane equipment to treat two different waters. The following decisions guided inputs to the design program:

- **Basis of Conceptual Design**. As much of the equipment as possible must be used for both treatment configurations. Pretreatment is assumed to be ultrafiltration adequate to produce sufficient RO feedwater with less than 0.1 Nephelometric Turbidity Units (NTU) and less than 3.0 Silt Density Index to attain the desired RO system productivity. Recovery of the RO system is the highest attainable with antiscalants to ensure long term operational stability.

- **Composition of Feedwaters.** Seawater was taken as standard seawater, with TDS of 34,500 mg/L. Brackish water is expected to vary in composition, with an average of 2,500 mg/L TDS with slightly positive Langelier Saturation Index and characteristic ratios of various scaling compounds. It is water that is likely to scale membrane surfaces as the reject becomes more concentrated, thus, by design, a challenging water to desalt.

- **Product Properties.** The initial basis capacity will be 3,785 cubic meters per day (m^3/day) (one million gallons per day [mgd]). The range over which this plant can be operated while staying within the manufacturer's requirements for element operation will be determined. Design recovery as product will be 40 to 50 percent for seawater and 70 percent or more for brackish water. The desired product quality is approximately 350 mg/L TDS to allow adding sufficient chemicals like calcium hydroxide and carbon dioxide to produce a finished, stabilized product with less than 500 mg/L TDS.

- **Plant Characteristics.** Various layouts and staging configuration were investigated. The desalting equipment was configured around spiral wound elements, 8-inch nominal diameter and 40 inches long. Performance of RO elements was taken at an average age of three years. The plant was designed for an operating fraction of 95 percent. Flexibility should be obtained at reasonable cost. The design program incorporates the following operation limits for a well-operating plant:

o Maximum feed flow rate (at inlet element)	284 liters per minute (L/min) (75 gpm)
o Minimum concentrate flow rate (at tail end element)	114 L/min (12 gpm)
o Concentration polarization factor, β[1]	< 1.2
o Langelier Saturation Index in brackish concentrate	< 1.8[2]
o Stiff-Davis Index in seawater concentrate	< ~0.75

2.1 Variation in Flow

To determine the variability of operation of a unit, several units were configured in different manners with the same membrane element (ESPA1), the same number of elements (240), and the same feedwater (brackish). Performance projection results were calculated at different flow conditions as shown in table 2-1. Because of the way the program is organized, the recovery was held constant and different product rates were input. The change in product rate causes the feed rate to change. Operation of three unit configurations was calculated with the result shown in figure 2-1. Each data point shows the calculated operation of a unit. The relationship between product flow and pressure is linear with a non-zero intercept. Dashed extensions of each line represent operation when one or more parameter lies outside the recommended conditions. Generally, the upper lines represent better productivity; however, the differences are modest.

Table 2-1. – System Configurations Examined

Configuration	Elements per Vessel	Number of Vessels in Stage 1	Number of Vessels in Stage 2	Number of Vessels in Stage 3
I	6	26	14	–
II	5	32	16	–
III	4	26	20	14

[1] This is the calculated ratio of the concentration at the membrane surface to the concentration of the bulk stream.

[2] If the concentration factor exceeds 100% or the LSI is positive, use of a scaling inhibitor is required.

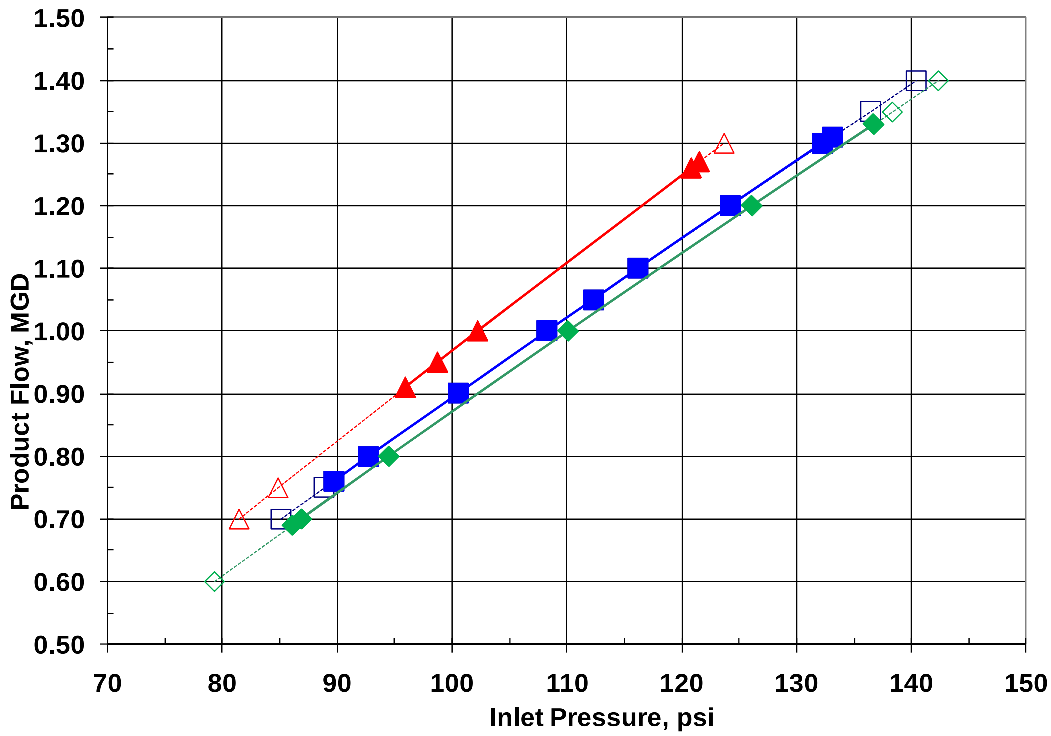

Figure 2-1. – Relationship between product flow and inlet pressure.

Triangles – 5 elements/vessel (Configuration II), squares – 6 (Configuration I), and diamonds – 4 elements/vessel (Configuration III). Open symbols and dotted lines represent unacceptable operating conditions.

A factor affecting flexibility of operation is the range of feed flows (or product flows) that the desalting unit can operate within. Two values set the range that a configuration can operate within:

- Maximum flow at the entrance to the first element in a vessel set by the physical limits of the element to prevent “telescoping”. Excessive flow can cause the spiral of membrane to gradually extrude out the back of the module, detaching the permeate tube connections and restricting flow between the layers of membrane.

- Minimum flow specification for the concentrate end of the last element where excessive concentration polarization occurs. Concentration polarization is the build-up of salts at the membrane surface. The system must be designed such that there is adequate flow from the last module to keep the membrane surface flushed. Most manufacturers, including Hydranautics, recommend a minimum ratio of concentrate to permeate flow for any element of five to one.

The configuration with 4 elements per vessel gives the widest viable range of feed flows, with a ratio of maximum to minimum feed flow of 1.93. The 6 elements per vessel unit was next with 1.72 and the ratio for the 5 elements per vessel was 1.4.

It is not possible to change only one operational aspect of a membrane desalination system. When the feed flow rate is increased by ramping up the feed pump speed, the feed pressure will increase, thereby increasing water transport through the membrane. Depending on the membrane properties, the increase in permeate flow will be accompanied by a different salinity in the product water. When the higher cross flow velocity (from higher feed flow) adequately disrupts concentration polarization product water will have a lower TDS. If the cross flow velocity is not adequate, the increased concentration of salt at the membrane surface will result in a higher TDS in the product water.

2.2 Variation of Type of Feedwater

We developed a two-stage arrangement of elements and vessels for the hypothetical design that would meet the requirements for a flexible plant and the product water goals described above (i.e., product TDS is below 350 mg/L; all membrane equipment is used for both types of water; and for the design conditions, no design constraint stated by the manufacturer is violated). The brackish water plant consists of a single pass with a two-stage configuration: with 26 vessels in the first stage and 14 vessels in the second. The first stage elements for this design exercise are ESPA2, a fairly high rejection thin-film composite membrane. The elements in the second stage are ESPA1, a similar element with slightly lower rejection. The feed pressure was 8 bar (122 psi) and the product TDS was 137 mg/L. The product flow was 3,785 m^3/day (1 mgd).

The seawater configuration consists of two passes. The first pass is the same as the first stage of the brackish configuration with 26 vessels. The second pass has two stages, with each stage containing 7 vessels. The feed pressure was 41 bar (596 pounds per square inch [lb/in^2]) in the first pass and 9 bar (130 lb/in^2) in the second pass. The product TDS was 158 mg/L. The product flow was 1,590 m^3/day (0.42 mgd).

A reasonable structure for the membrane portion of the hypothetical plant design would be racks seven vessels high and two vessels wide. The first 26 vessels would fit on two such racks with two empty spaces. Connections from the vessels would be made to vertical manifolds. The 14 vessels (second stage for brackish, second pass for seawater) would fit on a third rack. Piping for the two modes of operation is shown in figure 2-2. Connections near the edge of the vessel are to the feed-concentrate channel; connections at the center are to the product water pipe.

The changeover from one mode of operation to the other requires only a modest amount of rerouting of flows. Since the changes are almost all in the low pressure, low salinity portion of the plant, most of these changes can be made with valves. The one exception is at the point marked “concentrate (2 pass).” The change required at this point is best made with blind flanges to avoid leakage of concentrate into the product stream. The concentrate stream exits the system at different places depending on the mode of operation.

Operation in the two different modes requires a flexible pumping system. The brackish water high-pressure pump (HP Pump) needs to produce 1,000 gallons per minute (gpm) at 122 lb/in^2. Seawater operation requires lower flow at substantially higher pressure: 836 gpm at 600 lb/in^2, as well as 350 gpm at 130 lb/in^2 from the boost pump. Since the pressure for the second pass of the seawater plant is essentially the same as the feed pressure for the brackish water plant, part of the pump system can be used in both modes.

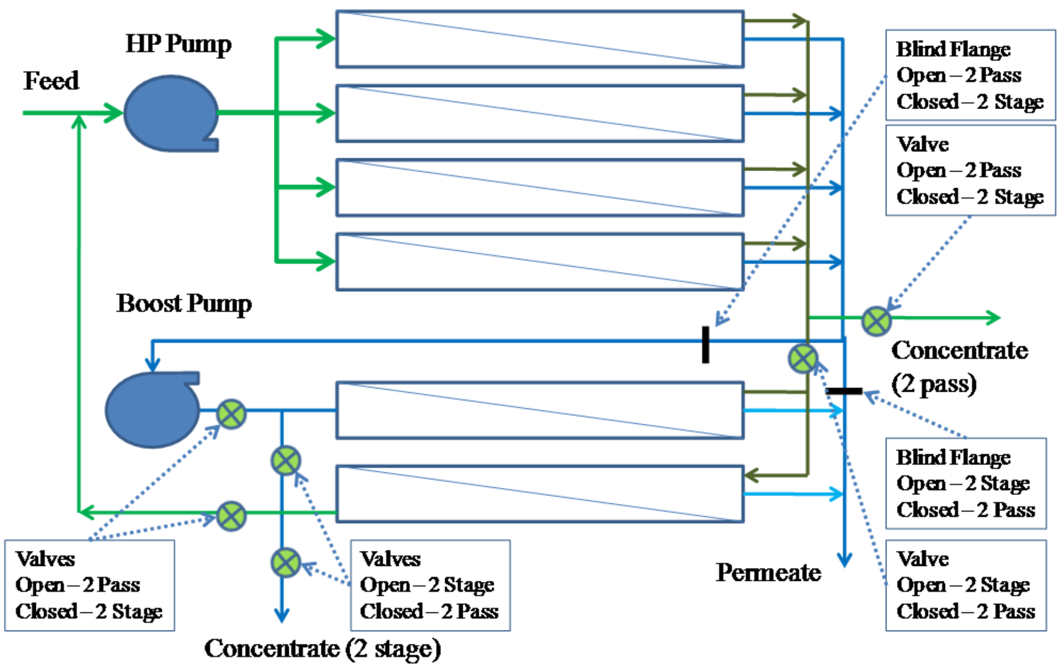

Figure 2-2. – Flow diagram indicating changeover between modes of operation.

3. Pilot Study Project Partners

There were several partners in the project who contributed to funding, coordination, review, test site hosting, and operations. Table 3-1 lists responsibilities and figure 3-1 depicts the lines of communication for the project.

Table 3-1. – Project Partners and Responsibilities

Agency	Role
Reclamation, Denver	Funding from Science & Technology Research Program Principal Investigator, equipment mobilization, operations, and de-mobilization
Reclamation, Oklahoma-Texas Area Office (OTAO)	Coordination and operations assistance
Texas Water Development Board (TWDB).	Local liaison, web site coverage, and operations assistance
Brownsville Public Utilities Board (BPUB)	Site host and operations assistance

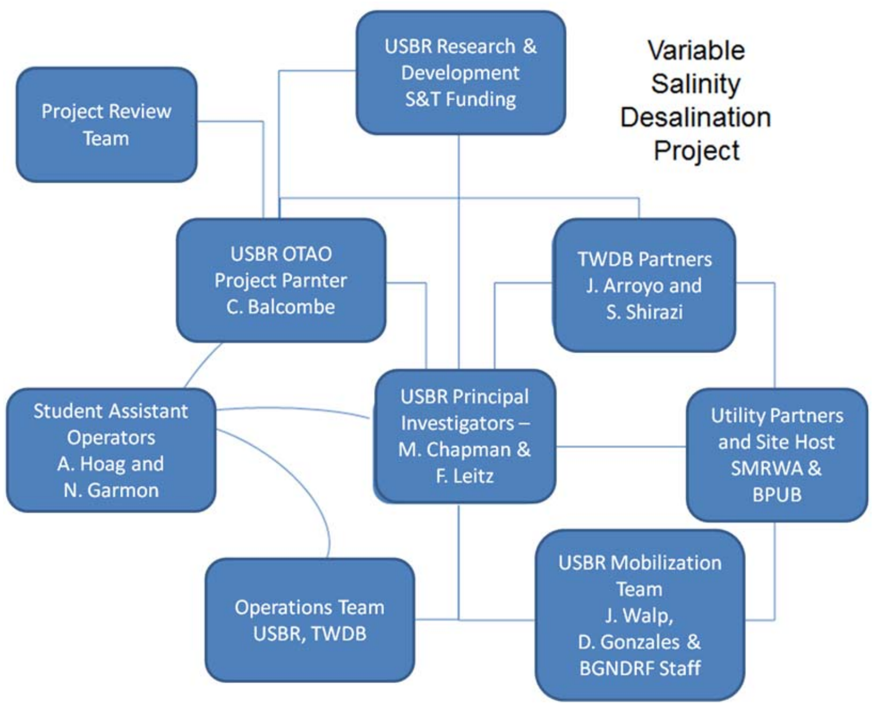

Figure 3-1. – Project organizational chart. Lines represent lines of communication.

A Project Review team was established to review documents and provide suggestions for improvement. Project review team members are listed in table 3-2 with their affiliation.

Table 3-2. – Project Review Team

Name	Affiliation
John MacHarg	Ocean Pacific Technologies
Qilin Li	Rice University
Harry Seah	Singapore Public Utilities Board
Ian C. Watson	Rostek Associates
Desmond Lawler	University of Texas at Austin

4. Pilot Study Test Site

Our project partners in Texas were very helpful in identifying a test site that could benefit from the project. We needed a site with access to brackish groundwater and potential access to seawater that could provide us with space, water, discharge services, power, and mobilization/de-mobilization assistance. Four sites in the Texas Gulf Coast area were evaluated: the Edwards Pumping plant on the Nueces River, the San Patricio Municipal Water District treatment plant, the retired naval base at Ingleside, and Southmost Regional Water Authority Desalination Plant in Brownsville, TX (SMRWA Desal Plant).

The SMRWA Desal Plant fit all of our needs. The facility is within eight miles of a source of seawater, and a new desalination plant is planned nearby on South Padre Island that will have even more direct access to seawater and brackish water (see figures 4-1 and 4-2 for exact locations). The facility desalts water from a network of 20 wells within 10 miles of the facility. Treated water serves the region north of Brownsville (Arroyo, 2004). Feedwater analyses from the facility are listed in table 4-2. Calculated water quality parameters based on the analysis are presented in the Table 4-1. The managers had space for us to set up during the summer of 2011. We were able to tap into their raw water line ahead of any chemical addition for our source of feedwater and we were able to discharge our re-combined effluent to a ditch next to the test site that drained into the treatment plant's discharge canal, which is part of the network of canals draining the area.

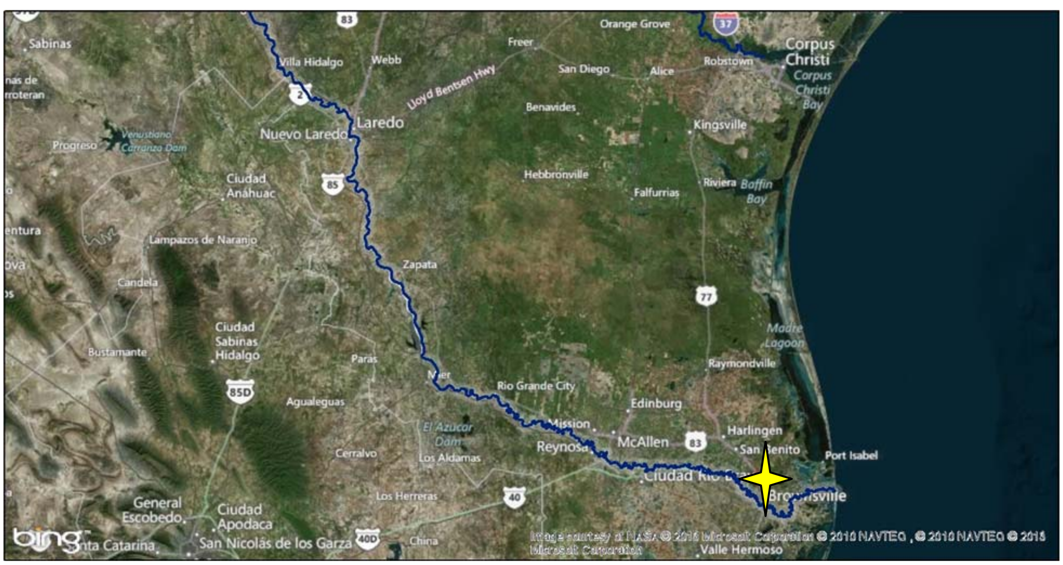

Figure 4-1. – Brownsville location, near the mouth of the Rio Grande River in south Texas.

Figure 4-2. – Location of the SMRWA Regional Desalination Plant North of Brownsville, Texas; at the arrow.

Table 4-1. – Calculated Solubility Parameters Based on Table 4-2.

Calculated Parameter	Feed Water 9/24/2009 Analysis	Predicted Concentrate at 75% Recovery
LSI	0.30	1.48
$CaSO_4$ Saturation	12.91	55.1
$BaSO_4$ Saturation	156.5	643
Ion Balance (Cation/Anion)	1.14	1.15

The SMRWA Desalination Plant design, construction, and operating costs are described by Sturdivant and colleagues (2007). The design has three trains of 66 vessels each. Each train is split into parallel two stage arrays of 22 vessels of the first stage feeding 11 vessels of the second stage. Recovery is targeted at 75 percent with a total capacity of the plant of six million gallons per day. Pretreatment for the facility at the time of this test was cartridge filtration followed by antiscalant addition, but they were planning to build an Ultrafiltration system with flocculation to improve arsenic removal.

Table 4-2. – Water Quality Data for Southmost Regional Desalination Plant Feedwater—Historical and Current

Method	Analyte	10/31/2007	9/24/2009	6/29/2011	7/12/2011	7/22/2011	Units
Calculation	Ammonia	1.2	1.22	NT	NT	NT	mg/L
Calculation	Silicon, (as SiO_2)	35.3	36.8	40.2	40.0	38.8	mg/L
EPA 200.7 Rev. 4.4	Silicon Recoverable	16.5	17.2	NT	NT	NT	mg/L
EPA 200.7 Rev. 4.4	Total Iron	0.67	0.5	0.64	0.63	0.61	mg/L
EPA 200.7 Rev. 4.4	Strontium	3.66	3.05	NT	NT	NT	mg/L
EPA 200.7 Rev. 4.4	Calcium	123	139	171	168	158	mg/L
EPA 200.7 Rev. 4.4	Magnesium	42.2	51.1	57.3	53.0	56.0	mg/L
EPA 200.7 Rev. 4.4	Potassium	10.3	17.5	10.4	9.4	10.3	mg/L
EPA 200.7 Rev. 4.4	Sodium	772	979	980	951	935	mg/L
EPA 200.8 Rev. 5.4	Barium	0.0156	0.0165	0.0145	0.0151	0.0165	mg/L
EPA 200.8 Rev. 5.4	Manganese	0.0833	0.0899	0.084	0.0899	0.0788	mg/L
EPA 300.0 Rev. 2.1	Chloride	794	841	745	788	679	mg/L
EPA 300.0 Rev. 2.1	Sulfate	1,130	1,160	1,051	1,077	970	mg/L
EPA 300.0 Rev. 2.1	Fluoride	1.04	0.91	0.70	0.74	0.73	mg/L
EPA 300.0 Rev. 2.1	Nitrite-Nitrogen, Total	ND	<0.0500	2.8	present	5.9	mg/L
EPA 350.1, Rev. 2.0	Ammonia Nitrogen	0.99	1.01	ND	ND	ND	mg/L
SM2320B, 20th Ed	Alkalinity as $CaCO_3$	440	404	405	353	392	mg/L
SM4500-CO2D, 20th	Bicarbonate (as $CaCO_3$)	14.9	403	494	430	478	mg/L
SM4500-CO2D, 20th	Carbon Dioxide	14.1	387	NT	NT	NT	mg/L
SM4500-CO2D, 20th	Carbonate (as $CaCO_3$)	ND	0.95	0	0	0	mg/L
SM4500-CO2D, 20th	Free Carbon Dioxide	0.95	32.1	NT	NT	NT	mg/L
SM4500-CO2D, 20th	Hydroxide	ND	<0.5	NT	NT	NT	mg/L
SM 4500-H+ B 20th Ed	Laboratory pH	7.5@16ºC	7.4@17ºC	7.85	8.11	8.14	pH Units
SM 5310C 20th Ed	Total Organic Carbon	ND	1.7	NT	NT	NT	mg/L

ND = Not Detected, NT= Not Tested

5. Pilot System Description

The Expeditionary Unit Water Purifier (EUWP) was selected for this study because it was available and because we have extensive data on its operation with a wide range of water types.

5.1 EUWP History

The EUWP was developed to meet the following objectives:

- Develop a high capacity drinking water purification unit to provide strategic water production capability with a focus on peacekeeping, humanitarian aid, and disaster relief missions.

- Further the state of desalination technology to reduce operational costs, size, and weight; improve reliability; and to verify emerging technologies.

The Generation 1 EUWP design requirements were to:

- Produce a minimum of 100,000 gpd of potable water from a source with as much as 45,000 mg/L TDS at 77°Farenheit (F) (25°Celsuis [C]) with the allowance of a lower production rate from a source water with up to 60,000 mg/L TDS.

- Be capable of tolerating feedwater in the range of 32°F to 103°F (0°C to 40°C) and turbidity up to 150 NTU.

- Be capable of treating nuclear, biologically, and chemically contaminated source waters.

- Be transportable by a single C-130 fixed wing aircraft.

EUWP design, construction, and testing was overseen by a federal multi-agency team composed of representatives from Office of Naval Research (ONR); Army Tank-Automotive Research, Development, and Engineering Center; Naval Surface Warfare Command – Carderock Division; Reclamation; Sandia National Laboratories and the Environmental Protection Agency (EPA). The manufacturer, Village Marine Tec. (now a subsidiary of Parker Hannifen), was contracted to design and build the EUWP to the team's specifications using the above requirements and current (2004) state-of-the-art technology.

As the project progressed, the EPA became interested in the suitability of the EUWP for homeland security and emergency response purposes. The system was tested through the EPA Environmental Technology Verification program overseen by National Sanitary Foundation International using seawater, brackish secondary wastewater, and surface water as sources. Testing the unit using these procedures was determined to be the best way to verify performance to allow comparison with other available technologies and to provide assurance to potential recipients of the EUWP services, that the process does produce safe drinking water.

The verification reports on fresh water, seawater, and secondary wastewater performance can be downloaded from the National Sanitary Foundation International web site under Village Marine Tec. at http://www.nsf.org/business/drinking_water_systems_center/dws_vendor_list.asp?program=DrinkingWatSysCen.

5.2 General System Description

The EUWP is composed of an intake screen; intake and transfer pumps; Koch UF pretreatment system; and a one- or two-pass RO desalination system with energy recovery, storage tanks, and product pump. It has chemical feed systems for pretreatment and post treatment. Clean-in-place systems are included with the skids. The system requires a 480 volt 250 amp, 60 hertz 3-phasae electrical connection of two 60 kW diesel generators. Figure 5-1 shows the filtration spectrum and depicts the range of treatment for the UF and RO systems in relation to conventional filtration methods.

UF is a low-pressure (5 to 150 pounds per square inch gauge [psig]) membrane process that separates particulates based on size exclusion. The UF process retains oils, particulate matter, bacteria, and suspended solids contributing to turbidity and a high silt density index (SDI). Feedwater to RO systems should have turbidity less than 1.0 NTU and a SDI less than 3. Water, dissolved salts, and most dissolved organic compounds pass through UF membrane. UF pore sizes range from 0.002 to 0.1 micron (1,000 – 500,000 molecular weight cutoff [MWCO]). Koch Targa-10 UF membranes with MWCO of 100,000 Daltons are used in the EUWP. The membranes are hollow fiber. Water flows from the inside of the fiber to the outside. Suspended solids collect on the inside of the fiber. Periodically, the system is backwashed to remove this material from the system. Figure 5-2 shows the UF module, a single fiber, and the flow pattern used in this system.

5.2.1 Desalination

Dissolved salts and organic molecules are removed through RO. Osmosis is a naturally occurring phenomenon in which pure water is transported across a chemical potential gradient through a semi-permeable membrane from a low concentration solution to a high concentration solution. Chemical potential, or osmotic pressure, is dependent on the concentration of ions and dissolved

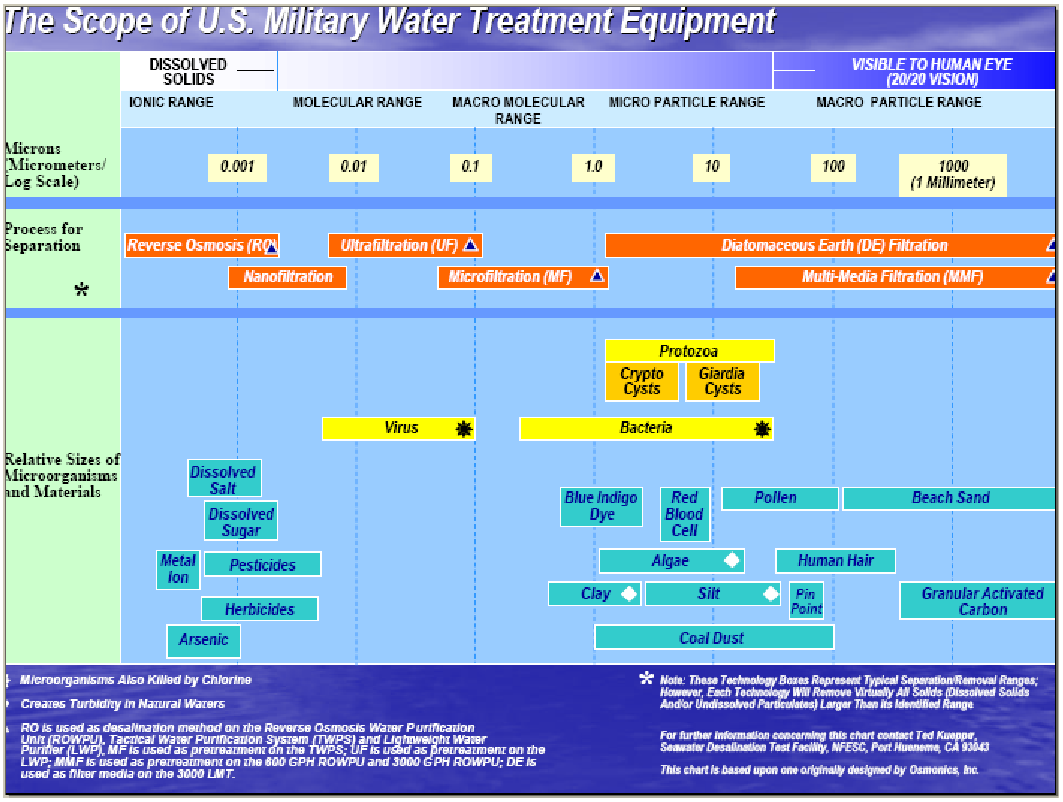

Figure 5-1. – Filtration spectrum. Pretreatment/Suspended Solids Filtration

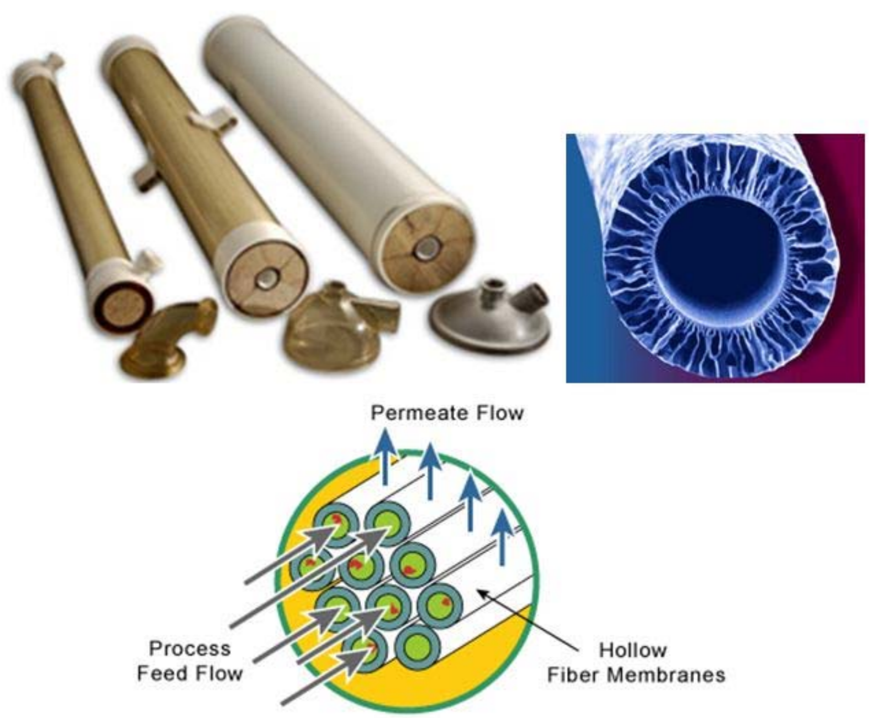

Figure 5-2. – Koch UF Hollow Fiber modules, magnification of single fiber, and the process flow through the module.

compounds. It can be measured by pressurizing a concentrated solution separated from pure water by a semi-permeable membrane until osmotic induced flow stops. If this pressure is exceeded, then osmotic flow reverses from concentrated solution to the dilute solution. This process is Reverse Osmosis or RO. Osmotic pressure is calculated as described in the Definitions Section of Appendix A.

RO is a moderate to high-pressure (80 to 1,200 psig) membrane separation process. The membranes in the EUWP are spiral wound, with up to eight membrane modules per vessel. Figure 5-3 shows the construction of a spiral wound element. They are operated under cross-flow conditions at a pressure above the osmotic pressure of the bulk solution at the end of the last vessel, plus additional pressure to overcome flow resistance is the modules. If the feed pressure to the last element is less than the osmotic pressure of the bulk solution in that module, then there will be no product from that module, in fact osmotic flow will begin to draw water back through the membrane into the concentrate.

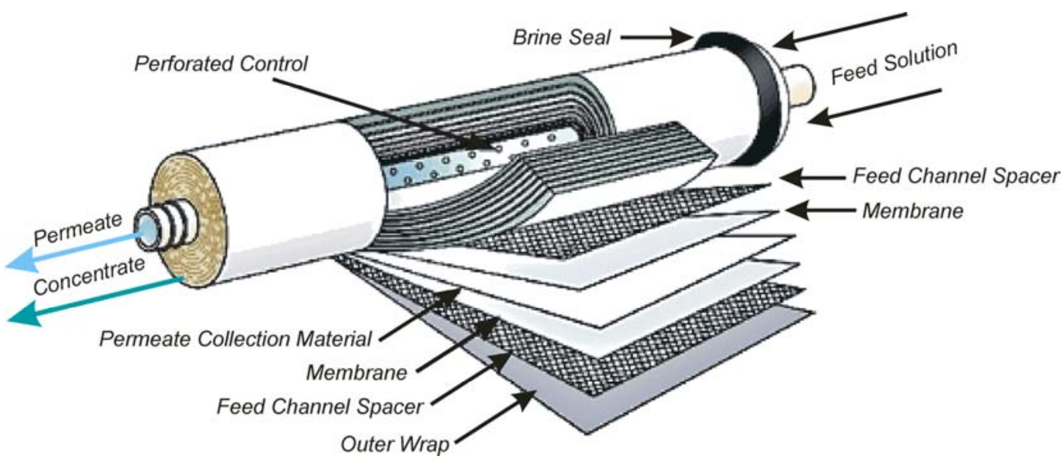

Figure 5-3. – Spiral wound element construction.

The separation mechanism is called solution and diffusion. Water and ions of salt permeate the polymer of the membrane but the dissolved salts move very slowly compared to water and other uncharged molecules such as small organic molecules.

5.3 Detailed System Description

The UF and RO skids meet requirements for load handling systems from International Organization for Standardization (ISO) requirements. Parker-Village Marine (Village Marine Tec. 2005) provides detailed construction information in the user manual.

5.3.1 UF System

The overall UF skid is shown below (figure 5-4). The UF membranes are configured with sixteen membranes modules, all of which are operated in parallel. The membranes manufactured by Koch Membrane Systems, are TARGA® 10-48-35–PMC with a 0.01 µm pore size. Table 5-1 lists descriptive parameters for the UF system.

Figure 5-4. – Photo of the UF skid.

Table 5-1. – UF System Parameters

Parameter	Value
Production Capacity	250,000 gpd
Water Temperature Range	34 – 104°F
Turbidity Range	0 – 150 NTU
Dimensions	20 feet long x 8 feet high x 8 feet wide
Weight	15,500 pounds dry, fully paced out for deployment, less fuel
Plumbing Materials	UF System Piping: Fiberglass, Titanium, Nylon
	Air System Piping: Nylon Tubing
Operating Ambient Temperature Range	32°F to 120°F
Storage and Transport Air Temperature Range	32°F to 120°F
Relative Humidity:	3% to 95%
Maximum slope of unit when deployed for operation	5 degrees side to side, 2 degrees end to end.
Power Source Requirement	60 kilowatt (KW) generator (self-contained) or power grid connection consisting of 480 volts (V) and 125 amps. UF system and external pumping power requirements are 2.1 kW/kgal.

5.3.2 RO System

The RO skid is shown below (figures 5-5 and 5-6). This RO system has the capability to operate in single-pass or double-pass mode if necessary to produce higher quality water. The first pass of the RO system consists of a unique combination of moderate rejection/high productivity and high rejection/moderate productivity membranes. The first pass is composed of three parallel arrays of two vessels in series (figure 5-7) with four elements each. Table 5.2 lists specifications for the different RO membrane types. The high-pressure pump feeds vessels two and three; remaining feedwater goes then to vessels one and four. The energy from the concentrate of vessels one and four is used to pressurize additional feedwater via a PX energy recovery device to feed vessels five and then six. Table 5-3 lists RO skid statistics.

The second pass RO system consists of a 2-1 array, where a second high-pressure pump boosts permeate pressure from the first pass feeding two parallel four-element vessels. The brine from these vessels then feeds one additional four-element vessel. However the second pass was not used for this demonstration.

5.3.3 Energy Recovery

RO is an inherently power intensive process. Historically, energy from the high-pressure concentrate was wasted through a back-pressure control valve. Today, several systems are available to recover the energy contained in the high-pressure

Figure 5-5. – RO skid and control center.

Figure 5-6. – RO skid showing RO vessels.

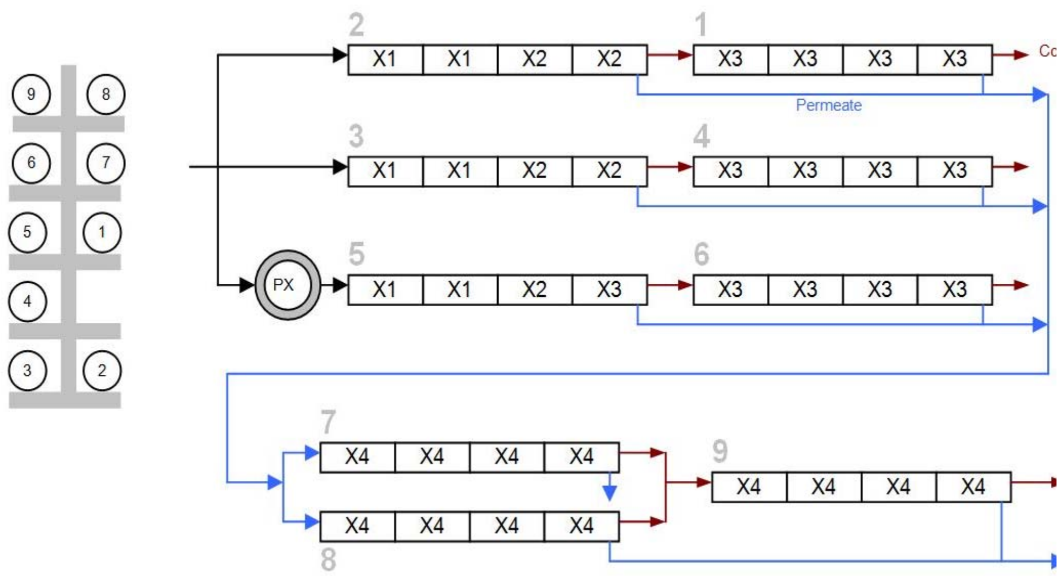

Figure 5-7. – RO module and vessel arrangement in single stage with optional double pass mode as designed for treating seawater.

Table 5-2. – RO System Membrane Element Characteristics

Vessel	Product	Desig-nator	Nominal Active Surface Area ft^2 (m^2)*	Permeate Flowrate gpd (m^3/d)	Stabilized Salt Rejection (%)
1st Pass 2, 3, 5	FILMTEC™ SW30HR LE-400	X1	380 (35)	6,000 (26)	99.8
1st Pass 2, 3, 5	FILMTEC™ SW30 XLE-400	X2	400 (37)	9,000 (34)	99.7
1st Pass 1, 4, 6	FILMTEC™ SW30XUS -12000 (experimental)	X3	400 (37)	12,000 (45)	99.7
2nd Pass 7, 8, 9	FILMTEC™ BW30**	X4	400 (37)	10,200 (38)	99.7

* square feet ft^2 (square meters m^2)
** Toray membrane assembled by AquaPro/Village Marine

Table 5-3. – RO Skid Statistics

Parameter	Value
Production Capacity	122,000 gpd for single pass on surface water above 25,000 parts per million (ppm) and groundwater above 2,500 ppm 147,000 gpd for other lower TDS waters 91,000 gpd in double pass mode
Water Temperature Range	34 – 104°F
Dimensions	20 feet long x 8 feet high x 8 feet wide
Weight	15,500 pounds dry, fully paced out for deployment, less fuel
Metals	High Pressure Piping: Titanium
	Production Piping: 316L Stainless Steel and fiberglass reinforced plastic (FRP)
Operating Ambient Temperature Range	32°F to 120°F
Storage and Transport Air Temperature Range	32°F to 120°F
Relative Humidity	3% to 95%
Power Source Requirement	Power for all but high-pressure pump is supplied from UF skid. HP pump requirements are 480V and 125 amps.

concentrate to help offset the energy demand. The EUWP uses the Pressure Exchanger (PX) (Model 90S) from Energy Recovery, Inc.[3] (figure 5-8). The PX operates on the principle of positive displacement to allow incoming raw water to be pressurized by direct contact with the concentrate from a high-pressure

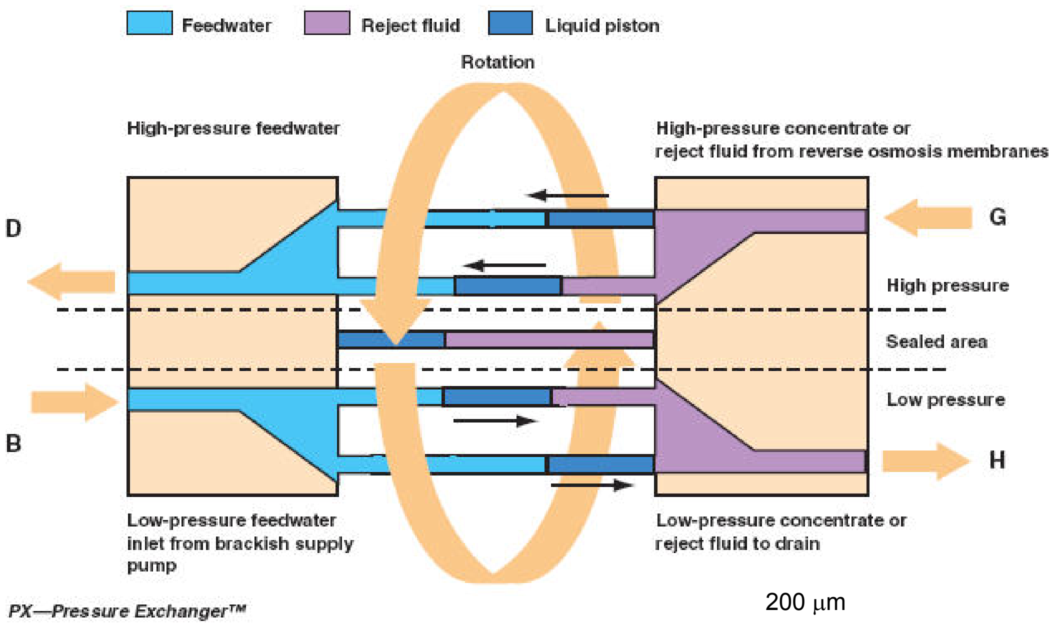

Figure 5-8. – PX process

membrane system. It uses a cylindrical rotor with longitudinal ducts parallel to its axis to transfer the hydraulic energy from the concentrate stream to the feed stream. The rotor fits into a ceramic sleeve between two ceramic end covers with precise clearances that, when filled with high-pressure water, create a nearly frictionless hydrodynamic bearing. At any given time, half of the rotor ducts are exposed to the high-pressure stream and half of the ducts are exposed to the low-pressure stream. As the rotor turns, the energy is transferred to the low-pressure stream. This type of energy device has been shown to be 90 percent efficient in transferring energy.

In a typical system, the pressurized feedwater from the PX goes to a booster pump, which restores the pressure lost in the first stage and feeds a second stage or array. However, the EUWP uses a parallel first-pass array at approximately 10 percent lower pressure than the array operating directly off the high-pressure pump.

5.3.4 High Recovery Modification

To attain 75 percent recovery of water when using a brackish feed source, the PX is bypassed, converting vessels five and six into a second stage for the two vessels fed by the high-pressure pump. Concentrate from vessels one and four is fed directly into vessel five which along with vessel six forms the second stage. Figure 5-9 and 5-10 show the PX device with and without the by-pass, and figure 5-11 is a diagram of the new flow path through the system.

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[3] Energy Recovery, Inc., San Leandro, CA, 4S series, www.energy-recovery.com.

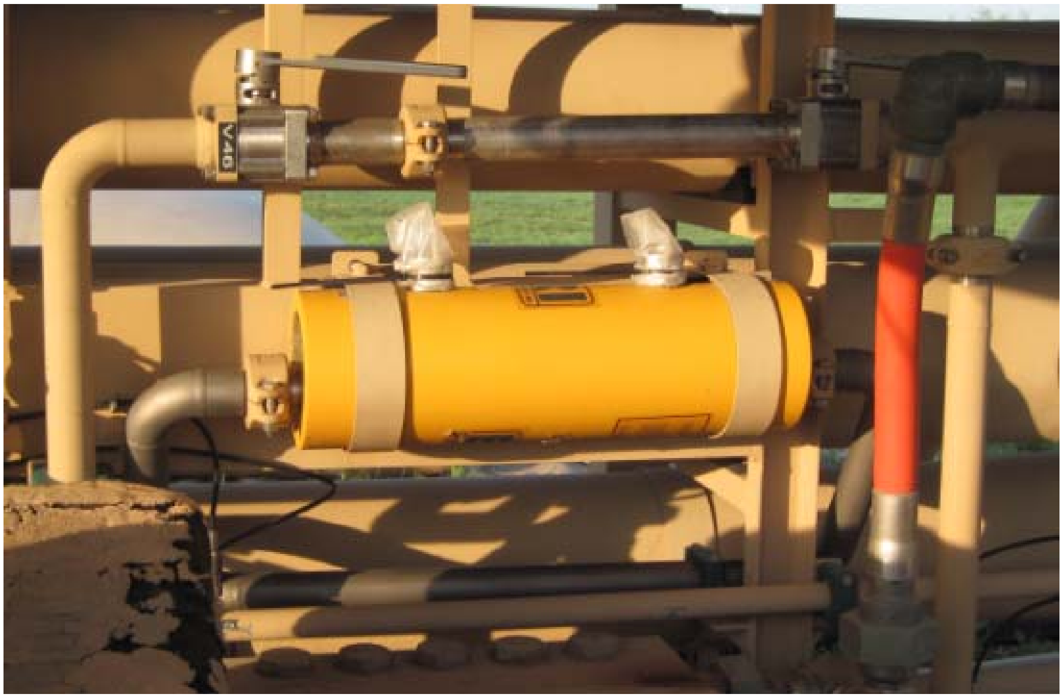

Figure 5-9. – PX by-pass.

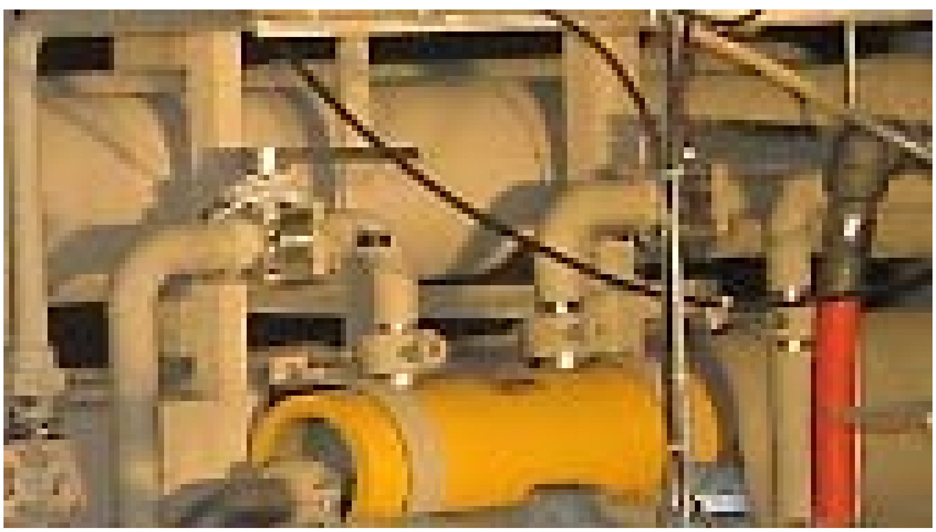

Figure 5-10. – PX without the by-pass.

5.4 Control System

The control system comprised of two GE Fanuc based programmable logic controllers (PLC): one for the RO system and one for the UF and peripheral pumps and tank levels. The controls are designed so that the RO system runs continuously—as long as the RO feed tank level is sufficient and the UF system cycles to keep it filled. The intake forwarding pump cycles to keep the UF feed tank filled. The UF system backwashes every 30 minutes for five minutes. The backwash cycle includes forward flush, rest period, and high velocity back-flush.

Operating data was monitored in real time through the WaterEye® process monitoring service, owned by Hach Company. This service has since been discontinued.

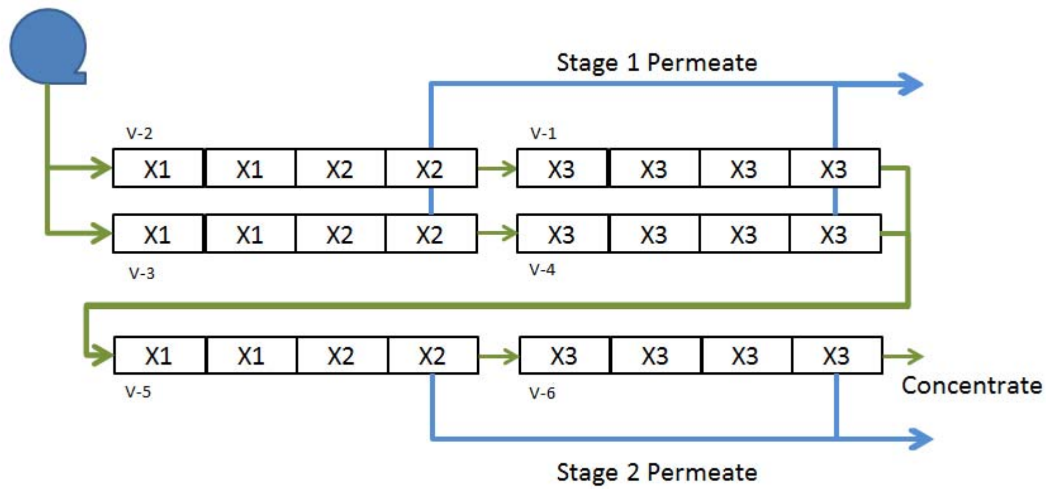

Figure 5-11. – EUWP two-stage flw configuration.

5.5 Chemical Consumption

Nalco Permatreat PC191 was used for scale inhibition while operating at the SMRWA Desal Plant at a starting dose of 5 mg/L or approximately 100 milliters per hour (mL/hr). The EUWP can also accommodate acid injection to minimize scale formation from slightly soluble salts such as calcium carbonate, calcium sulfate, barium sulfate, calcium fluoride and silica.

5.6 Waste Management

The Texas Commission on Environmental Quality allowed operation without requiring a permit for the short duration of this test, as long as the effluent of the process was blended to the approximate quality of the feedwater. The waste streams for the EUWP consisted of:

- Concentrate from the RO system
- Backwash waste and retentate from the UF system

RO concentrate volume is 20-25 percent of the total RO feed flow with two-stage operation for a total of approximately 1800 gallons per hour. UF system waste is composed of the backwash flow of approximately 1000 gallons per backwash every 30 minutes plus 10% of UF feed flow as retentate for a total of 4,200 gallons per hour. Each backwash consists of backflushing the membrane with UF filtrate for a short period followed by a fast flush using feedwater to remove the contaminants dislodged from the membranes during the backflush. Both waste streams were routed to the drain tank for settling and mixing with RO permeate prior to discharge to the drainage ditch.

5.7 Equipment Configuration at the Test Site

Figure 5-12 is a general diagram showing how the EUWP was configured on the property. Feedwater for the system was extracted from the feed line to the main plant prior to any chemical additions. Process effluent was combined and discharged to the drainage ditch that the main facility uses for concentrate discharge. Figure 5-13 is a more detailed drawing of a typical EUWP deployment configuration. The UF skid and RO skids can be configured in a straight line or perpendicular to each other.

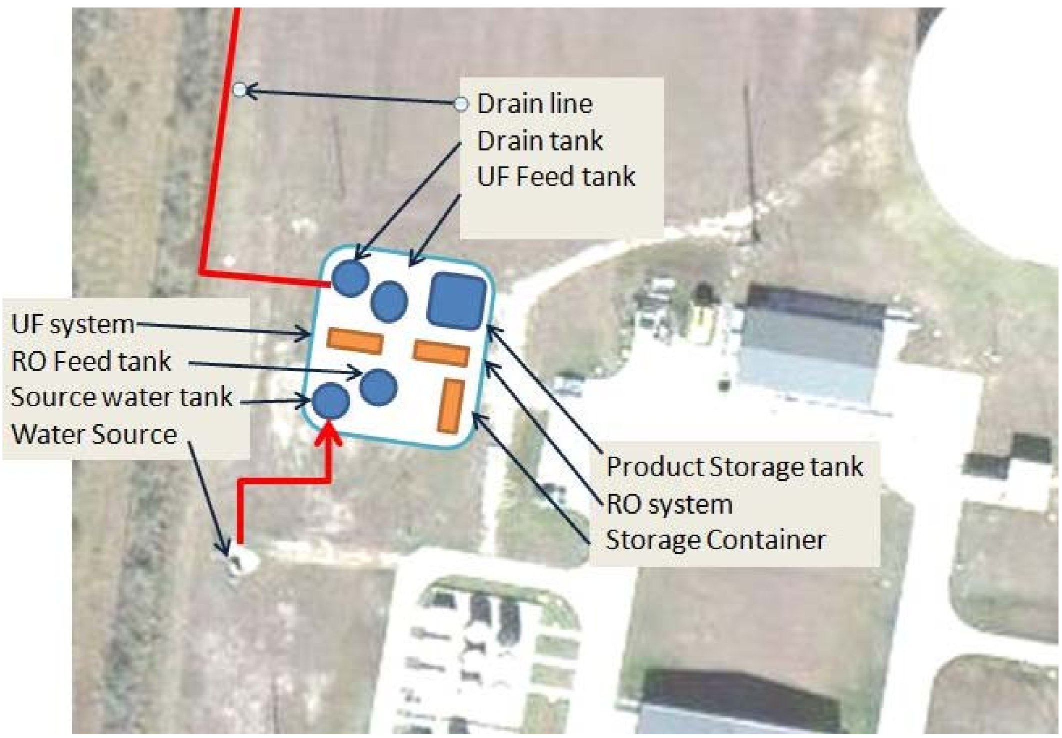

Figure 5-12. – EUWP Equipment configuration at the SMRWA Desal Plant. White circle in the upper right corner is the treated water storage tank.

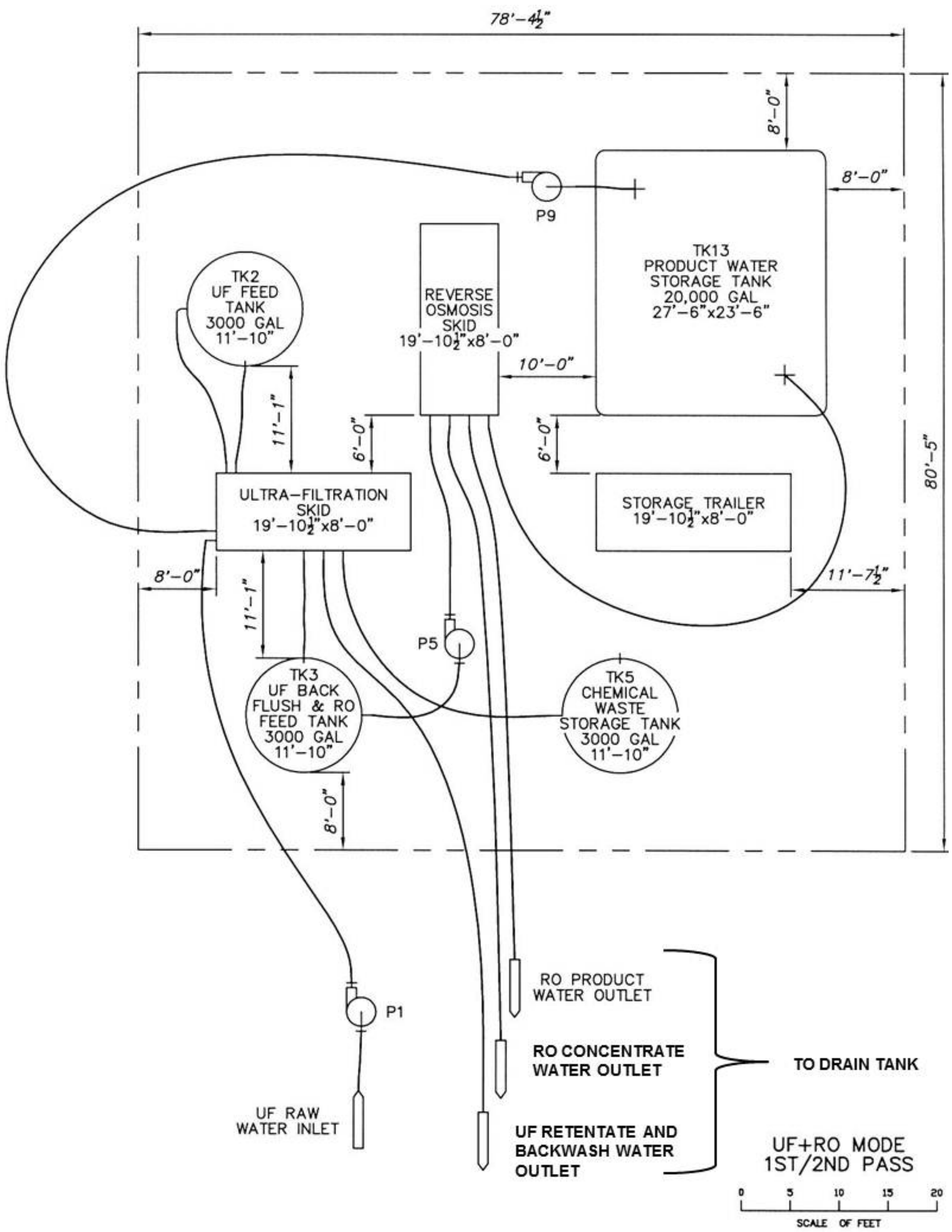

Figure 5-13. – General layout of equipment.

6. Pilot Study Test Plan Summary

6.1 Flexible Operation for Variable Salinity

The EUWP is designed to handle a wide range of water sources. Figure 6-1 (Village Marine, 2005) shows the predicted performance of the first pass of the system as designed for a wide range of TDS levels in groundwater at 50 percent recovery using the Energy Recovery, Inc. PX to pressurize one-third of the system while the high pressure pump pressurizes the first two thirds. For this study the PX device was bypassed to direct concentrate from the two vessels fed by the high pressure pump to the third vessel that is normally fed through the PX device as diagramed in figure 6.1. The objective was to evaluate operation issues, power consumption, and water quality during operation as a two-stage desalination system operating at 75 percent recovery. The system was operated for eight hours per day, six days per week.

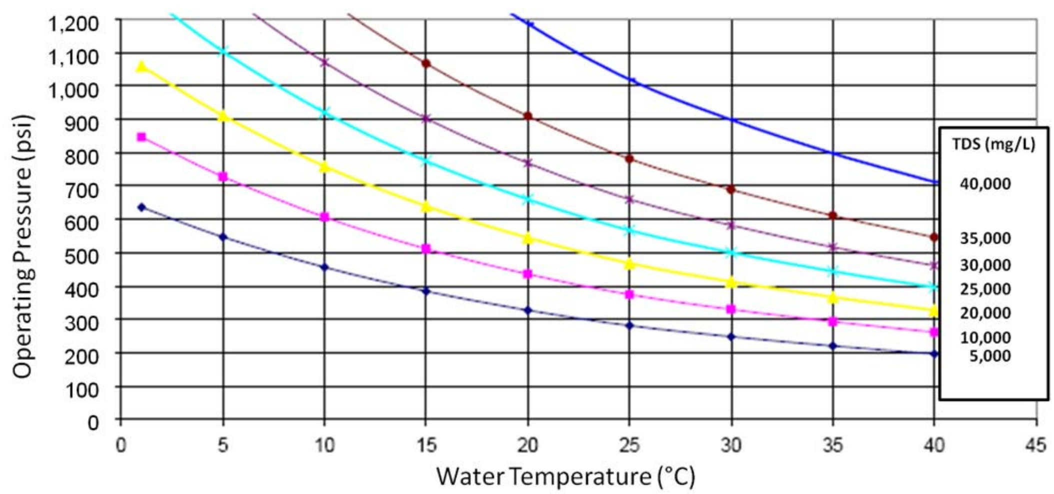

Figure 6-1. – EUWP performance for a range of dissolved solids concentrations and temperatures.

6.2 Qualitative Operational Factors

Qualitative operational factors are:

- Reliability or susceptibility to environmental conditions
- Equipment safety
- Ease of equipment operation

6.3 Quantitative Operational Factors

Quantitative operational factors were evaluated using data recorded on data sheets twice per day, and data collected electronically. These are:

- **Water Quality Data**. Conductivity, pH, temperature using a Myron L Ultrameter II Model 6P. Turbidity using a Hach 2100P Portable Turbidimeter. Iron using a Hach DR 2700 Portable Spectrophotometer and Hach Method 8008 for total iron. Each device was calibrated daily.

- **Water Physical Data**. Flow, productivity, recovery, and pressure. In particular, pressure drop across each system was monitored by the data acquisition software and was verified by manual readings of local gauges recorded in the data log.

- **Power**. A power usage meter on each skid was monitored and recorded twice per day.

- **Chemicals**. The purpose and quantity of all chemicals used was documented.

- **Materials**. Fittings and piping for the bypass were required beyond what is supplied with the EUWP.

- **Waste Stream Generation**. Concentrate flow was monitored automatically by the data acquisition software. Flows were confirmed by bucket and stopwatch once each week. The backwash cycle was initiated automatically every 30 minutes. Then the total backwash waste was calculated by multiplying the number of backwash cycles by the volume used for each backwash. The volume was determined by the flowrate and duration of each part of the backwash cycle.

- **Operating Cycle Length**. Time between cleanings was recorded. Purpose and duration of any other down time periods was recorded.

- **Labor**. Operators documented duties carried out during each shift, time for each duty to be performed, and number of people required.

Table 6-1 lists parameters for each sample point that was recorded by field personnel. Table 6-2 lists the parameters that were recorded digitally.

Table 6-1. – Operation Parameters Monitored by Field Personnel

	UF Feed	UF Retentate	UF Filtrate	RO Feed	RO Permeate 1st Stage	RO Permeate 2nd Stage	RO Interstage Concentrate	RO Concentrate	Combined RO Permeate
Flow	FS2	X		FS4	FS5	FS6		FS5	
Pressure	PS3	PS4	PS5	PS9			PS10	PS13	
Conductivity	X		X	X	X	X		X	
Temperature	X		X	X	X	X		X	
Turbidity	X		X	X	X	X		X	

Table 6-2. – Water Quality and Operational Parameters Measured Online

	UF Feed	UF Retentate	UF Filtrate	RO Feed	RO 1st Array Concentrate	RO 2nd Array Concentrate	RO 1st Array Permeate	RO 2nd Array Permeate
Flow	FS2			FS4	FS8	FS7	FS5	FS6
Pressure	PS3	PS4	PS5	PS9	PS12	PS13	PI11	
Conductivity							CS1, CS2	
Temperature			TI1					

6.4 Analytical Methods

Samples of feed, UF filtrate, RO feed, permeate, and concentrate were sent to Reclamation’s Alamosa, Colorado’s Field Office Laboratory for detailed inorganic analysis at the start, middle, and end of the test period.

6.5 Equipment Operations and Design

The UF and RO systems were operated according to the following set points (table 6-3)

Table 6-3. – Key Operating Parameters for the VSD Testing

Parameter	Set Point
UF Feed Flow (gpm)	250
RO Feed Flow 1st Pass Array 1 (gpm) (1st Stage)	116
RO Feed Flow 1st Pass Array 2 (gpm) (2nd Stage)	58
Recovery Levels (%)	75 (2 stage)
Operating Times	8 hours per day, 6 days a week

Feed flow rate for both the UF and RO systems were kept constant. The UF system filtrate flow is determined by pump size. The RO permeate flow can be controlled to some extent by adjusting the back-pressure.

7. Results

Testing at the SMRWA Desal Plant occurred between June 24, 2011 and July 23, 2011. The weather was typical for southwest Texas—temperatures in the high 90s, humidity in the 90 percent range. There were a few rain events during the month. The system was operated six days a week for at least eight hours per day.

7.1 Water Quality Data from Field Analysis

Grab samples were analyzed for each stream at the start and end of the day. Table 7-1 lists the average and standard deviation of the observations. Iron was measured once a day for the UF feed, UF filtrate (product water), RO feed, and RO concentrate. A few initial measurements showed that iron was not present in the RO permeate nor was the turbidity measureable with the field tubidimeter.

Table 7-1. – Water Quality Field Data

Parameter	Average	Standard Deviation	Count	Average	Standard Deviation	Count
	UF Feed			UF Filtrate		
pH	7.2	0.1	46	7.2	0.2	45
Conductivity (μS/cm)*	4657	531	46	4718	162	45
Temp (°C)	27.7	1.1	46	27.5	0.5	45
Turbidity (NTU)	2.7	1.1	43	0.2	0.1	43
Iron (mg/L)	0.6	0.1	22	0.1	0.1	18
	RO Feed			RO Concentrate		
pH	6.9	0.3	48	7.3	0.8	46
Conductivity (μS/cm)	4573	820	48	16100	0.8	46
Temp (°C)	28.1	1.1	48	28.8	0.6	46
Turbidity (NTU)	0.4	0.2	42	0.4	0.2	9
Iron (mg/L)	0.1	0.1	22	0.2	0.1	21
	RO Stage 1 Permeate			RO Stage 2 Permeate		
pH	5.9	0.6	48	5.9	0.5	48
Conductivity (μS/cm)	21.8	4.8	48	56.7	22.4	48
Temp (°C)	28.2	1.1	48	28.5	1.0	48

*MicroSiemens per centimeter

7.2 Laboratory Analyses

Three sets of samples were sent for analysis to the Alamosa Field Office. Results are listed in table 7-2 and 7-3.

7.3 UF System Performance

The UF system feed flow started off in the range of 250 gpm with 10 percent cross flow as designed. However, after the first week, the flow control valve failed in the open position. Flows after that time ranged from 410 to 560 gpm. To keep the membranes clean, we increased cross flow to 20 percent. Filtrate turbidities were well below the target of 1 NTU and iron removal started out at

Table 7-2. – Lab Analyses—UF Feed, Filtrate, RO Feed and Concentrate

Analytes	MDL	Method*	Units	UF Feed		UF Filtrate		RO Feed		Concentrate	
				Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
Alkalinity	5.000	S.M. 2320	mg/L	382.96	27.06	405.41	4.11	406.11	3.65	1,416.48	312.01
Aluminum	1.200	EPA 200.8	ug/L	0.53	0.46	0.48	0.53	0.91	0.86	3.99	1.59
Ammonium			mg/L	ND		ND		ND		ND	
Antimony	0.013	EPA 200.8	ug/L	0.034	0.005	0.029	0.001	0.032	0.002	0.161	0.049
Arsenic	0.032	EPA 200.8	ug/L	16.3	3.2	15	1.8	15.4	0.9	62	14.1
Arsenic - total recoverable	0.300	EPA 200.8	ug/L	22.5	3.2	NT		13.3	0.5	50.3	9.8
Barium	0.022	EPA 200.8	ug/L	15.4	1	15.9	1	16.2	1.1	57.2	10.6
Beryllium	0.050	EPA 200.8	ug/L	0.022	0.028	0.019	0.017	0.023	0.016	0.033	0.022
Bicarbonate	5.000	S.M. 2320	mg/L	467.21	33.01	494.6	5.02	495.46	4.45	1,728.11	380.65
Boron	0.015	EPA 200.7	mg/L	2.586	0.182	2.616	0.099	2.552	0.109	5.956	3.435
Bromide		EPA 300.0	mg/L	3.758	1.571	3.188	1.391	3.672	1.197	12.395	6.815
Cadmium	0.026	EPA 200.8	ug/L	0.125	0.011	0.11	0.009	0.113	0.023	0.455	0.017
Calcium	0.010	EPA 200.7	mg/L	138.4	7.7	142.5	5.2	141.8	5.3	585.5	24.3
Carbonate	5.000	S.M. 2320	mg/L	-	-	-	-	-	-	-	-
Chloride		EPA 300.0	mg/L	737.446	55.231	736.082	52.342	722.069	55.079	2,789.23	377.561
Chromium	0.570	EPA 200.8	ug/L	5.64	6.97	7.77	10.45	6.18	7.06	15.19	17.78
Cobalt	0.024	EPA 200.8	ug/L	0.37	0.02	0.36	0.01	0.36	0.03	1.25	0.02
Copper	0.500	EPA 200.8	ug/L	16.3	2.88	17.53	3.48	11.49	5.97	50.28	31
Dissolved Iron	0.005	EPA 200.7	mg/L	0.0228	0.0052	0.0064	0.0039	0.0068	0.0039	0.2041	0.1162
Fluoride		EPA 300.0	mg/L	0.723	0.023	0.727	0.037	0.73	0.022	2.292	0.96
Laboratory Specific Conductance		EPA 120.1	uS/cm	4,794	225	4,761	164	4,705	221	16,323	646
Lead	0.016	EPA 200.8	ug/L	0.096	0.062	0.141	0.047	0.163	0.074	0.386	0.095
Lithium			mg/L	Present <0.25		Present < .25		Present <.25		0.67	0.023
Lithium	0.005	EPA 200.7	mg/L	0.1615	0.0055	0.1635	0.007	0.1612	0.0048	0.6793	0.0431
Magnesium	0.020	EPA 200.7	mg/L	55.4	2.2	57.3	2.9	58.5	2	246.7	10.7
Manganese	0.032	EPA 200.8	ug/L	84	6	85	7	81	5	348	7

Analytes	MDL	Method*	Units	UF Feed		UF Filtrate		RO Feed		Concentrate	
				Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
Mercury	0.270	EPA 200.8	ug/L	NT		NT		NT		NT	NT
Molybdenum	0.040	EPA 200.8	ug/L	55.4	3.84	55.13	4.4	52.08	1.97	213	8.12
Nickel	0.022	EPA 200.8	ug/L	4.18	3.741	5.637	0.59	5.623	1.054	18.275	1.04
Nitrate		EPA 300.0	mg/L	5.103	0.209	3.318	3.4	4.797	2.275	4.989	2.364
Nitrite		EPA 300.0	mg/L	4.365	2.181	4.127	4.439	5.25	1.364	37.56	0.996
pHLab	0.500	S.M. 2320	pH Units	8.031	0.158	8	0.215	8.046	0.176	7.935	0.195
Phosphate		EPA 300.0	mg/L	ND		ND		ND		3.289	0.482
Potassium	0.600	EPA 200.7	mg/L	10.018	0.525	10.158	0.403	10.078	0.082	39.96	1.58
Selenium	0.370	EPA 200.8	ug/L	12.767	2.888	13.467	2.695	13.15	2.501	76.5	13
Silica	0.450	EPA 200.7	mg/L	39.7	0.8	39.5	1	39.5	0.2	164.7	10
Silver	0.080	EPA 200.8	ug/L	0.41	0.13	0.33	0.01	0.49	0.48	2.74	1.8
Sodium	0.040	EPA 200.7	mg/L	955	22.5	970	16.6	966	26.2	4,010	143
Sulfate		EPA 300.0	mg/L	1,032.81	55.499	1,028.23	53.854	1,013.40	59.181	3,966.30	508
Thallium	0.030	EPA 200.8	ug/L	0.008	0.002	0.008	0.002	0.009	0.001	0.044	0.003
Thorium	0.034	EPA 200.8	ug/L	-	Single detect	ND		0.038	0.034	0.036	0.03
Tin	0.027	EPA 200.8	ug/L	0.037	0.01	0.096	0.076	0.048	0.038	0.338	0.095
Total Dissolved Solids	10.000	EPA 160.1	mg/L	3,261	172	3,252	162	3,205	163	12,852	815
Total Recoverable Iron	5.000		mg/L	0.629	0.017	NT		0.079	0.084	0.171	0.111
Total Suspended Solids	10.000	EPA 160.2	mg/L	17	7	NT		14	7	26	4
Uranium	0.034	EPA 200.8	ug/L	1.88	0.2	1.82	0.14	1.8	0.1	8.02	0.6
Vanadium	0.050	EPA 200.8	ug/L	2.93	Single detect	4.57	Single detect	1.9	2.49	5.2	5.4
Water Hardness	1.000	S.M. 2340 B	mg/L	573.8	24	591.4	13.5	594.8	7.8	2,477.50	104.6
Zinc	0.120	EPA 200.8	ug/L	3.69	0.41	5.33	1.53	5.14	0.51	11.09	6.56

ND = Not Detected, NT= Not Tested

*EPA Methods are described on their web site: http://water.epa.gov/scitech/methods/cwa/methods_index.cfm, S.M. 2340 see: (ASTM, 1982)

Table 7-3. – Lab Analyses for Blank Samples, RO Stage 1, and Stage 2 Permeate

Analytes	MDL	Method*	Units	Blanks		RO Stage 1 Permeate		RO Stage 2 Permeate	
				Average	Std Dev	Average	Std Dev	Average	Std Dev
Alkalinity	5.000	S.M. 2320	mg/L	1.45	0.08	5.81	0.78	10.35	2.52
Aluminum	1.200	EPA 200.8	μg/L	0.50	0.66	1.33	Single detect	0.52	0.71
Ammonium			mg/L	ND		ND		Present <2	
Antimony	0.013	EPA 200.8	ug/L	0.005	0.003	0.014	0.006	0.017	0.005
Arsenic	0.032	EPA 200.8	ug/L	0.1	0.1	0.4	0.5	0.9	1.1
Arsenic - total recoverable	0.300	EPA 200.8	ug/L	NT		NT		NT	
Barium	0.022	EPA 200.8	ug/L	0.0	0.0	0.1	0.1	0.1	0.1
Beryllium	0.050	EPA 200.8	ug/L	0.032	0.016	0.016	Single detect	0.012	0.010
Bicarbonate	5.000	S.M. 2320	mg/L	1.77	0.11	7.08	0.94	12.63	3.08
Boron	0.015	EPA 200.7	mg/L	0.004	0.000	0.652	0.310	1.637	0.514
Bromide		EPA 300.0	mg/L	ND		Present <0.25		Present <0.25	
Cadmium	0.026	EPA 200.8	ug/L	ND		0.002	Single detect	0.003	-
Calcium			mg/L	Present		Present <5		Present <5	
Calcium	0.010	EPA 200.7	mg/L	0.0	0.0	0.1	0.0	0.1	0.1
Carbonate	5.000	S.M. 2320	mg/L	NT	-	-	-	-	-
Chloride		EPA 300.0	mg/L	ND		4.629	Single detect	9.287	4.789
Chromium	0.570	EPA 200.8	ug/L	1.20		0.57	0.61	0.84	0.52
Cobalt	0.024	EPA 200.8	ug/L	0.01	0.00	0.01	Single detect	0.01	Single detect
Copper	0.500	EPA 200.8	ug/L	0.36	0.12	0.49	0.45	0.51	0.21
Dissolved Iron	0.005	EPA 200.7	mg/L	0.0009	0.0005	0.0001	Single detect	0.0005	0.0003
Fluoride		EPA 300.0	mg/L	ND		Present <0.25		Present <0.25	
Laboratory Specific Conductance		EPA 120.1	uS/cm	2	1	22	10	55	21
Lead	0.016	EPA 200.8	ug/L	0.016	0.016	0.010	0.004	0.013	0.005
Lithium			mg/L	ND		ND		ND	
Lithium	0.005	EPA 200.7	mg/L	0.000		0.0010	0.0006	0.0016	0.0010
Magnesium			mg/L	ND		Present <1		Present <1	
Magnesium	0.020	EPA 200.7	mg/L	0.0	0.0	0.0	0.0	0.0	0.0

Analytes	MDL	Method*	Units	Blanks		RO Stage 1 Permeate		RO Stage 2 Permeate	
				Average	Std Dev	Average	Std Dev	Average	Std Dev
Manganese		EPA 200.7	mg/L	NT		NT		NT	
Manganese	0.032	EPA 200.8	ug/L	0	0	1	1	0	0
Mercury	0.270	EPA 200.8	ug/L	NT		NT		NT	
Molybdenum	0.040	EPA 200.8	ug/L	0.31	0.34	0.30	0.34	0.18	0.17
Nickel	0.022	EPA 200.8	ug/L	0.046	0.021	0.092	0.110	0.049	0.050
Nitrate		EPA 300.0	mg/L	ND		Present <0.5		Present <0.5	
Nitrite		EPA 300.0	mg/L	ND		Present <0.25		Present <0.25	
pH Lab	0.500	S.M. 2320	pH Units	ND	0.027	5.986	0.227	6.150	0.141
Phosphate		EPA 300.0	mg/L	ND		ND		ND	
Potassium			mg/L	ND		ND		Present <1	
Potassium	0.600	EPA 200.7	mg/L	0.157	0.017	0.103	0.055	0.210	0.134
Selenium	0.370	EPA 200.8	ug/L	0.2	0.1	0.158	Single detect	0.164	0.206
Silica	0.450	EPA 200.7	mg/L	0.004	0.000	0.1	0.1	0.2	0.2
Silver	0.080	EPA 200.8	ug/L	0.08	0.07	0.01	Single detect	0.15	0.19
Sodium			mg/L	Present		4.509	1.430	11.646	4.310
Sodium	0.040	EPA 200.7	mg/L	0.5	0.4	4.9	1.7	12.5	4.7
Sulfate		EPA 300.0	mg/L	ND		1.803	Single detect	2.387	Single detect
Thallium	0.030	EPA 200.8	ug/L	0.002	0.001	0.003	0.001	0.001	Single detect
Thorium	0.034	EPA 200.8	ug/L	0.011	0.009	0.009	0.001	0.004	Single detect
Tin	0.027	EPA 200.8	ug/L	0.066	0.052	0.231	0.192	0.060	0.020
Total Dissolved Solids	10.000	EPA 160.1	mg/L	Present		27.5	24.7	42.3	31.0
Total Recoverable iron	5.000		mg/L	NT		NT		NT	
Total Suspended Solids	10.000	EPA 160.2	mg/L	NT		NT		NT	
Uranium	0.034	EPA 200.8	ug/L	NT		0.02	Single detect	0.013	Single detect
Vanadium	0.050	EPA 200.8	ug/L	0.16	0.22	0.17	0.170	0.20	0.15
Water Hardness	1.000	S.M. 2340 B	mg/L	0.0	0.1	0.2	0.058	0.5	0.2
Zinc	0.120	EPA 200.8	ug/L	0.78	0.64	1.99	2.107	1.55	1.11

ND = Not Detected, NT= Not Tested

*EPA Methods are described on their web site: http://water.epa.gov/scitech/methods/cwa/methods_index.cfm, S.M. 2340 see: (ASTM, 1982)

60 percent but increased to over 90 percent at the high flow rates. Figure 7-1 shows UF feed flow over time with filtrate turbidity and iron concentration. Differential pressure across the UF system did not change, probably due to a non-functioning pressure sensor.

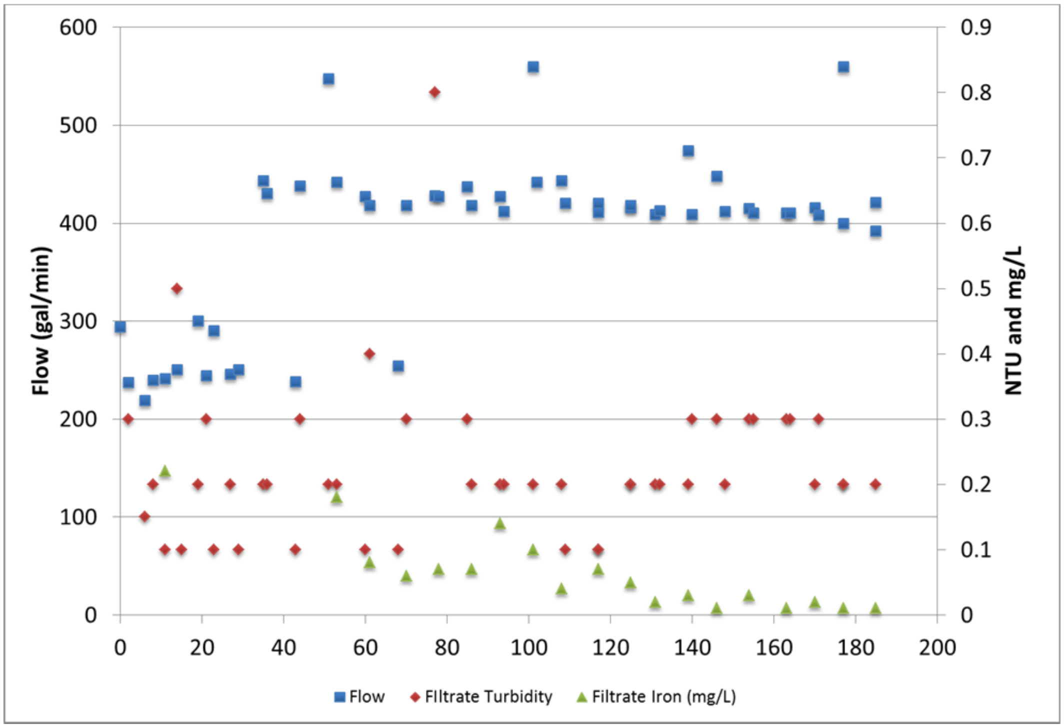

Figure 7-1. – UF system flow and filtrate quality.

7.4 RO System Performance

7.4.1 Flow

Figure 7-2 shows RO system flows over the course of the test period. Due to the positive displacement feed pump, the RO system feed flow held steady at 120 gpm. Feed flow was measured through a flow totalizer. The two permeate flows were measured through differential pressure flow devices. Concentrate flow was calculated from the other three flows.

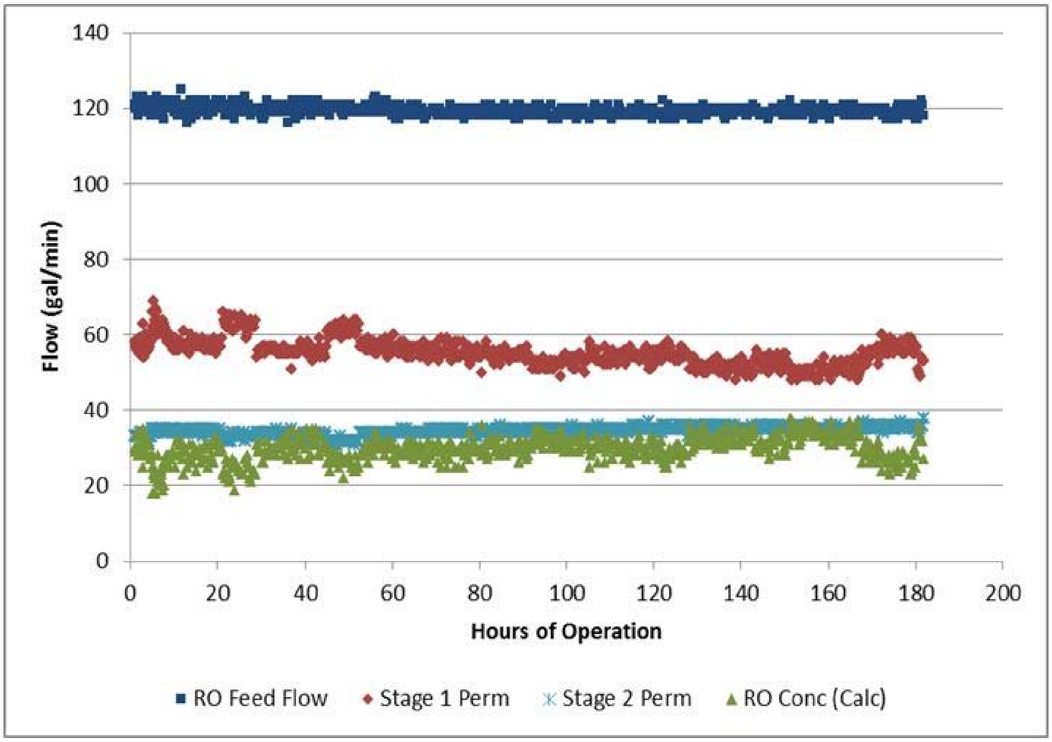

Figure 7-2. – RO system flows.

7.4.2 Permeate Quality

Permeate conductivity of the first stage ranged from 20 to 30 µS/cm while the second stage permeate started at 115 µS/cm and ended at 40 µS/cm. Figure 7-3 displays these data, comparing permeate and feedwater conductivity over time. The decline in permeate conductivity in the second stage may be due to scale formation at the membrane surface. It is accompanied by an increase in differential pressure across the second stage as seen in figure 7.4. The first symptom of membrane scaling is a slight decrease in permeate conductivity. As the surface become coated with scale, the resistance to salt passage increases while, when the layer is still very thin, the water transport may not be noticeably affected. However if scaling conditions continue, salt concentration increases at the surface due to inadequate mixing, resistance to permeate flow increases and the situation is aggravated as evidenced by increases in salt passage. To verify this conclusion and determine the type and extent of scale formation, it is necessary to conduct an autopsy and analyze the membrane surface material. Scale first manifests itself as lower permeate conductivity as the membrane surface becomes covered and more resistant to salt transport. This phase is accompanied by higher system pressures needed to maintain target production rates, as was seen during the test.

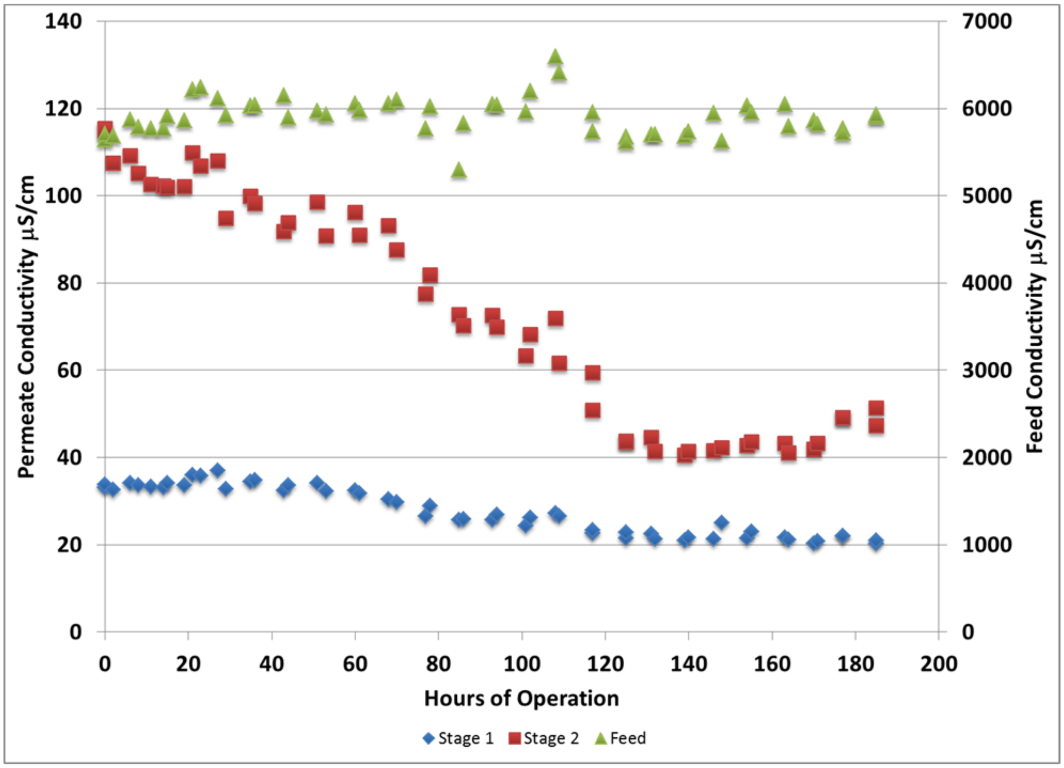

Figure 7-3. – Permeate and feed conductivity.

7.4.3 Flux and Recovery

Temperature normalized flux is shown in figure 7-4. The first stage decreased in flux by 1 percent over the duration of the test, while the second stage increased by the same amount. Recovery drifted over time from the initial set point of 75-80 percent to 70-75 percent. For the last few days of the test the back pressure was adjusted to increase recovery back to the starting target. The increase in productivity was primarily from the first stage elements.

7.4.4 Pressure

Feed pressure required to maintain the target production rate gradually increased over the test period from 225 psi to 310 psi as shown in figure 7-5. This is most likely due to fouling in the first stage and scaling in the second stage.

7.4.5 Differential Pressure

Differential pressures across the first and second stages are presented in figure 7-4. During the first sixty hours, the pressure drop across the first stage was running higher than across the second stage. After this point the first stage differential pressure remains fairly constant while the second stage increases over the remainder of the test period.

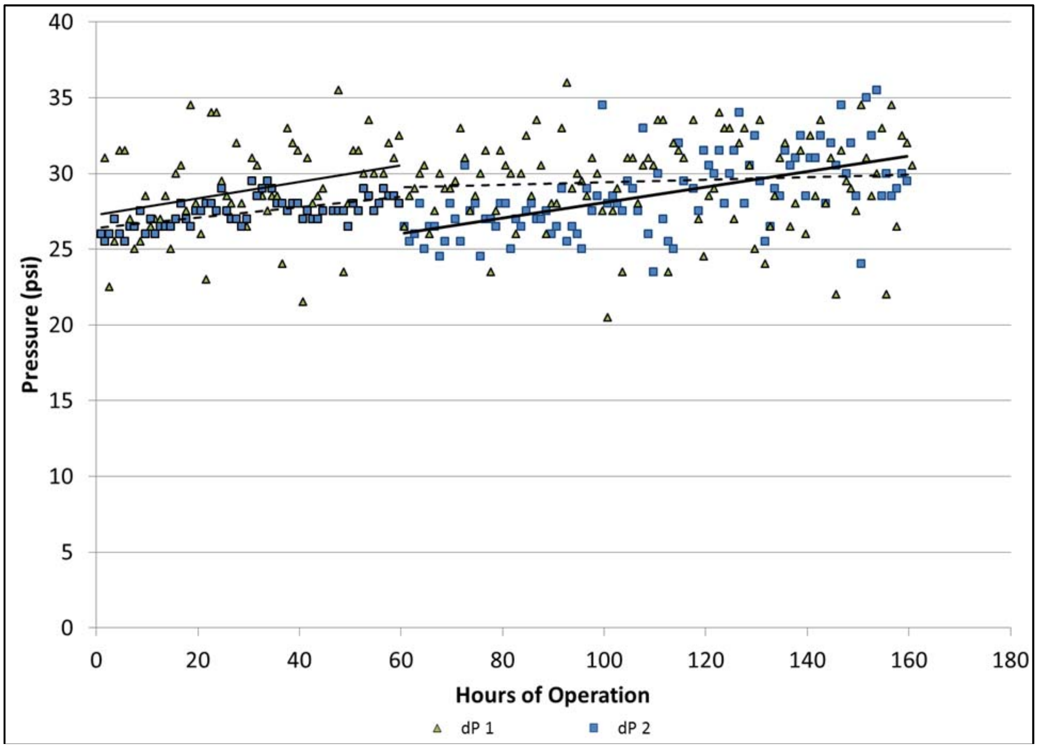

Figure 7-4. – RO system differential pressures for first and second arrays. Solid lines indicate increasing differential pressure in the second stage.

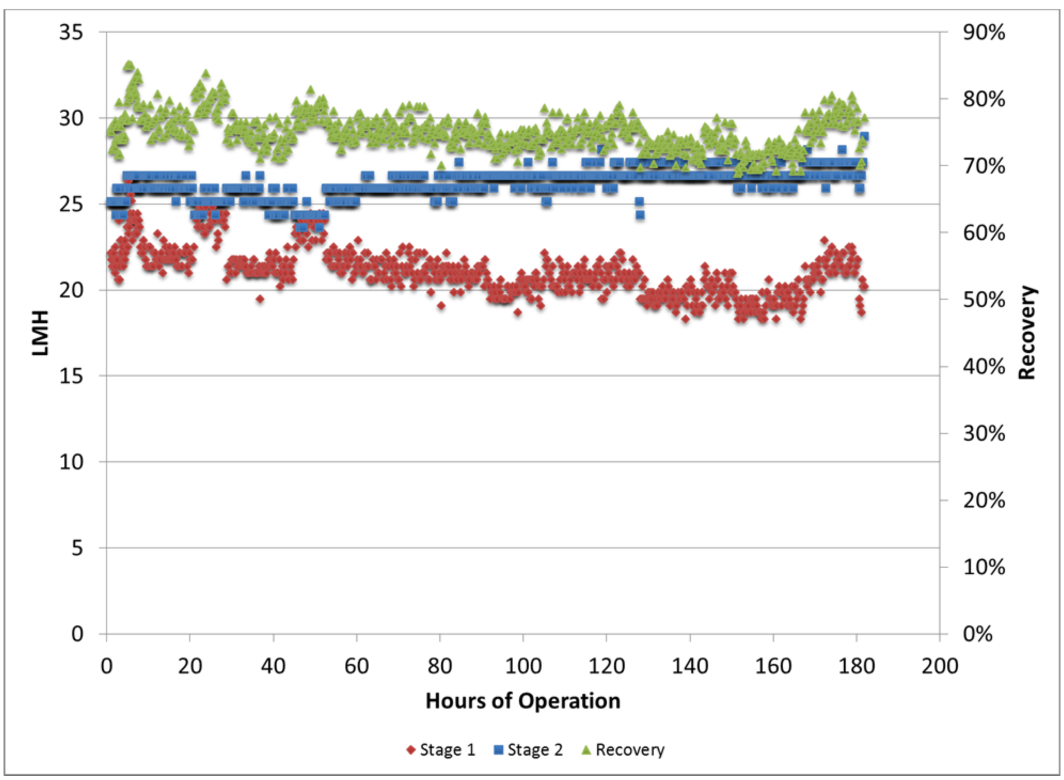

Figure 7-5. – Temperature normalized flux and recovery.

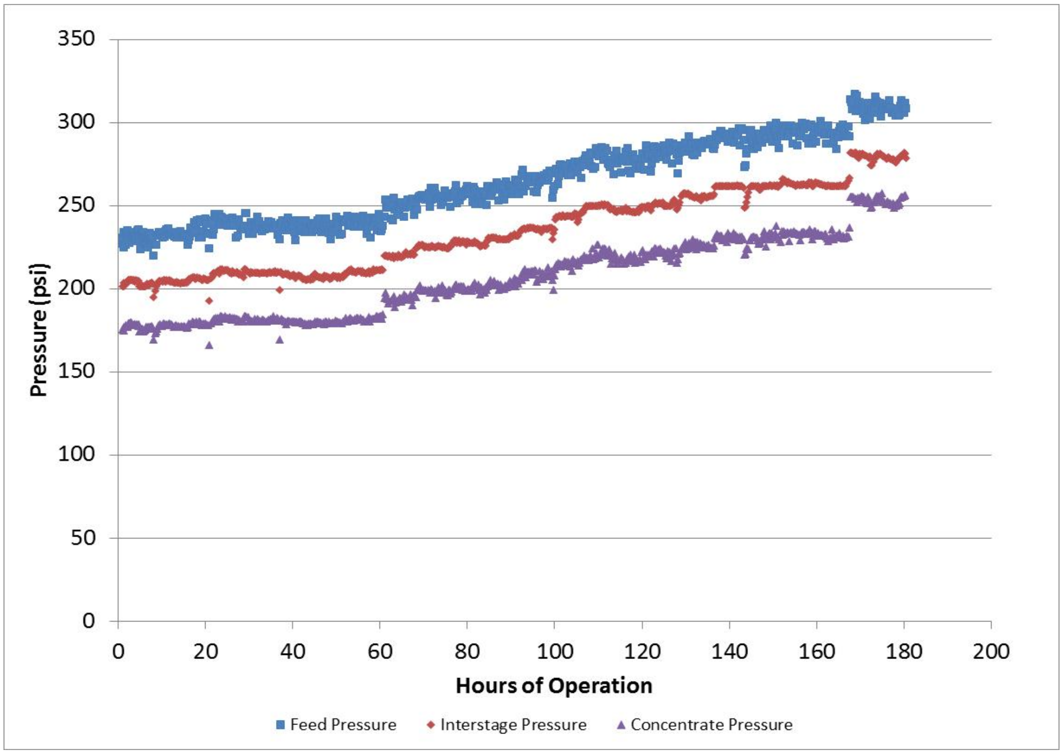

Figure 7-6. – RO system pressures.

7.5 Power Consumption

Power consumption is monitored on the RO skid for only the high-pressure pump and on the UF skid for intake and forwarding pumps, instrumentation, and UF pumps. Figures 7-7 and 7-8 show the electrical demand of each system over the course of testing at SRWA Desal Plant. The UF system power increased over time due to the inefficiency of operating at high feed flow rates due to the broken solenoid valve. The UF feed pumps are automatically controlled through feedback from the RO feed tank level – turning off when the RO feed tank is high, and turning on again when it is low. Since the UF was operating at maximum flow it did not take long to fill the RO tank and so, the system cycled more often than it would during normal operation. Frequent start-ups are not as efficient as continuous operation at a lower flow rate. Power use for the UF system was approximately twice what it should be. There were also losses of UF filtrate due to tank leakage.

The combined average power consumption for UF and RO was 7.4 kW/kgal of RO permeate. This includes UF inefficiencies due to the broken solenoid valve, as well as power requirements for the ancillary pumps, instrumentation, and process controls. Average power consumption is calculated as the total UF kW plus the total RO system kW for the test period, divided by the total RO feed flow times the average recovery. Figure 7.8 shows power use over the month of testing for

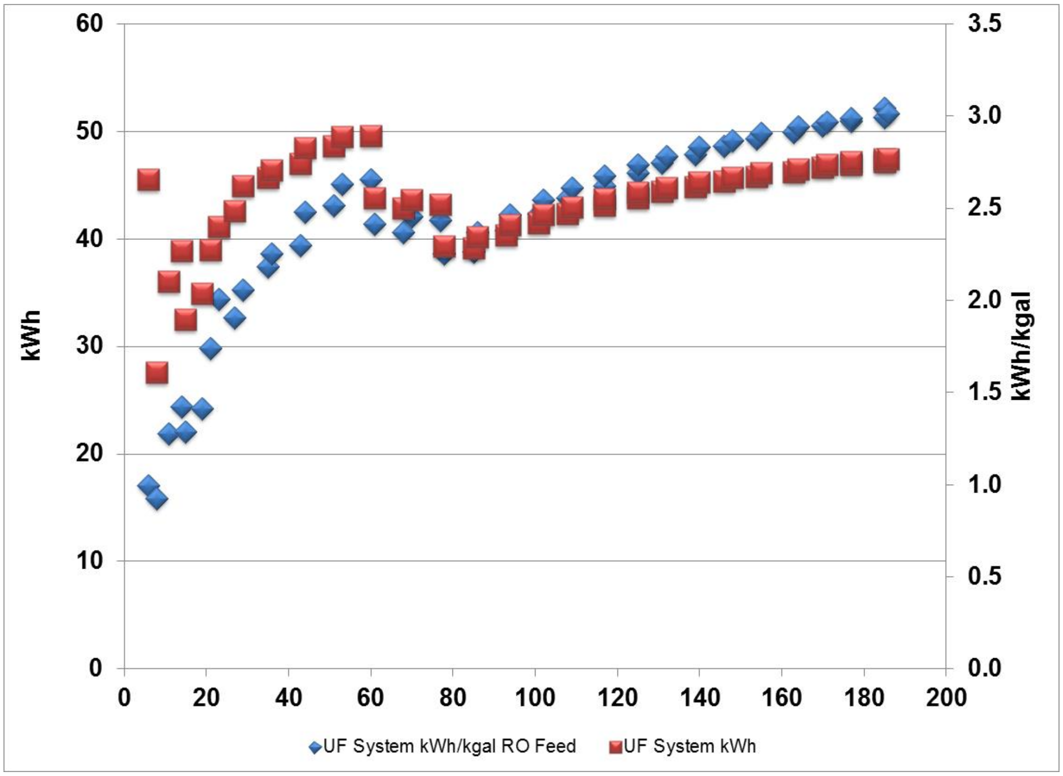

Figure 7-7. – UF system power.

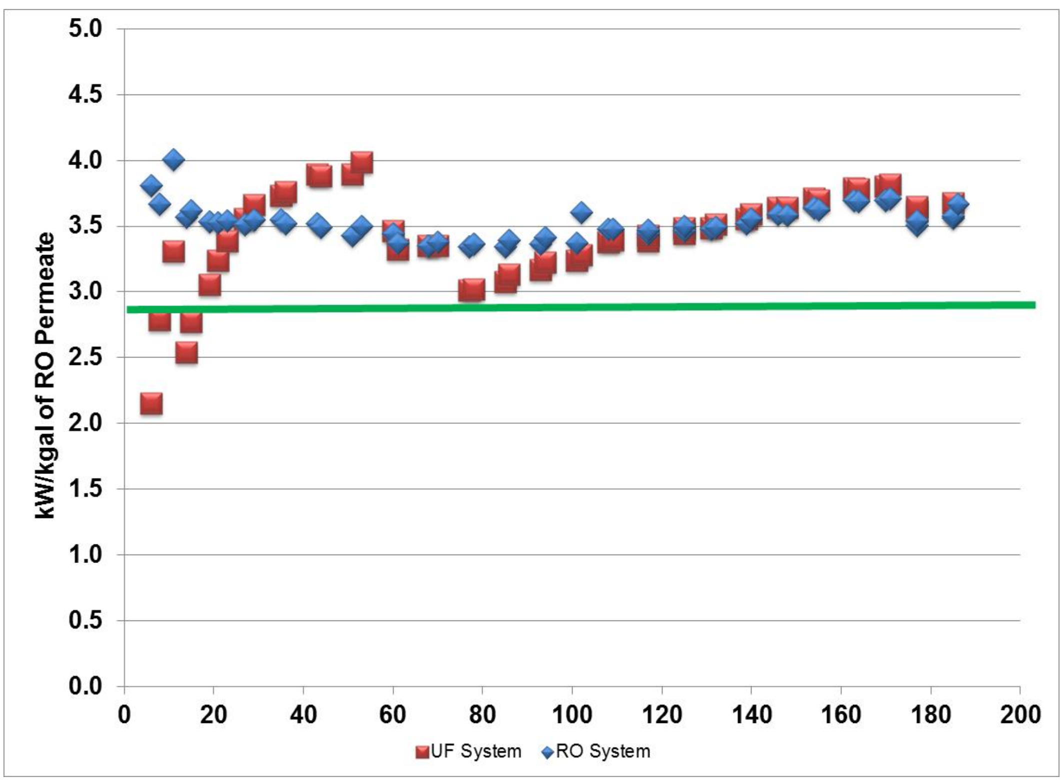

Figure 7-8. – RO and UF system power per kgal of RO Permeate produced.

the average recovery. Figure 7.8 shows power use over the month of testing for each system per kgal of RO permeate. The horizontal line indicates the average power usage for the SRWA Desal Plant building during that time (J. Adams, Pers. Com 9/26/13).

7.6 Chemical Use

The only chemical used for operation during the test was PermaTreat-191, an antiscalant from Nalco. Antiscalant addition was started after one week of testing over which the RO feed pressure climbed from 230 psi to 250 psi. A total of 59 pounds of PermaTreat-191 were used to treat a total of 957 kgal of RO feedwater after that point, resulting in an average dose of 7.4 mg/L. Dosing was set by monitoring RO feed pressure increase and increasing antiscalant dose until the RO pressure held constant or decreased over the day. The first week, the dose was 6.4 mg/L. During subsequent weeks, the average was 8 to 9 mg/L.

The UF system did not require cleaning during the month of testing. The RO system needed a low pH rinse to remove carbonate scale build up. It was rinsed with the RO permeate at pH 5.5 for two hours at the end of testing.

7.7 Materials

Materials needed during the test mainly pertained to handling the bypass flow from the RO forwarding pump. Since the system is designed for 180 gpm feed, and we are replacing 65 gpm feed to the second array with the concentrate from the first stage, it was thought that we would need to bypass that much back to the RO feed tank. However, by the end of the test, we realized that we didn't need to do this since the positive displacement high pressure pump is only going to take what it needs. It would have been much easier to let the pump control the feed flow, even if it did mean that the forwarding pump would be less efficient. The soft-sided tank used for the RO feed tank made it very difficult to manage the bypass flow from the top.

7.8 Conversion Issues

Since the EUWP's high-pressure components are constructed of titanium, it was necessary to find a welder with the capability of welding titanium. Once that person was identified, the construction of the bypass was a matter of accurate measurements and easing the new pipe section into place. Returning the connections to the ERI was not as easy since the plumbing had shifted during transport.

There was no problem operating the EUWP as a two-stage system instead of a two-array system, aside from the mistaken beliefs about the bypass flow. The modifications bypassing the energy recovery device made it possible to continue monitoring permeate quality from each of the stages.

7.9 Labor

Two operators were on site at for two hours in the morning to start up, record operational readings, and analyze water samples. The routine was repeated in the evening with a 20 minute flush of the RO system with feedwater to help prevent scale formation while the system was shut down for the night. Operations could be monitored on line through the WaterEye web site so that if there were an upset, operators could return to correct the situation and restart the system. Upsets did happen a couple of times when there were power outages due to electrical storms.

8. Comparison with Performance at Previous Locations

The EUWP Gen 1-1 has been evaluated on brackish water at three other locations and the Gen 1-2 was tested with seawater at the NFESC Seawater Desalination Test Facility at Port Hueneme, CA.

- The system was field tested at the Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico as a commissioning and training exercise during the summer of 2005 (unpublished).

- After Hurricane Katrina in the fall of 2005, the system treated water from the Mississippi Delta for the Biloxi, Mississippi operation. The level of biological and organic contamination and suspended solids were quite high in that location (Water Desalination Report, 2005).

- The Gallup, New Mexico operation during the summer of 2007 was at the wastewater treatment plant using screened secondary municipal wastewater as feed to the system (EPA/600/R-10/151).

- Seawater ETV report is available from EPA and NSF International (NSF 09/29/EPADWCTR and EPA/600/R-10/013)

Table 8-1 describes water quality, flows, pressures, and power requirements at each location. Figure 8-1 compares permeate and concentrate flow and permeate TDS for the two modes of operation. Permeate TDS at 75 percent recovery was three times higher than the single stage operation at a maximum of 60 percent recovery at BGNDRF which has similar feedwater.

Table 8-1. – Comparison of Performance in Single and Two-Stage Mode of Operation

Location	NFESC	Biloxi	BGNDRF	Gallup	SRWA
Mode of Operation	1 Pass	1 Pass	1 Pass	1 Pass	2 Stage
Feed Flow (gal/min)	180	158	128	130	120
Feed TDS (mg/L)	34,733	19,000	2,887	1,113	3,205
Permeate Flow (gal/min)	100	78	77	72	90
Perm TDS (mg/L)	290	240	14	5	48
Concentrate Flow (gal/min)	80	80	51	59	30
Concentrate TDS (mg/L)	65,933	37,291	5581	2,283	12,843
Recovery	55.6%	49.4%	60.2%	55.4%	75.0%
Feed Pressure Array 1 (lb/in2)	960	620	300	283	265
Feed Pressure Array 2 (lb/in2)	895	575	200	192	235
Power (kW/kGal)	19.6	10	7	6	7
Power (kW/m3)	5.17	2.64	1.72	1.60	1.96
Osmotic Potential (bar)	62	35	5	2	9

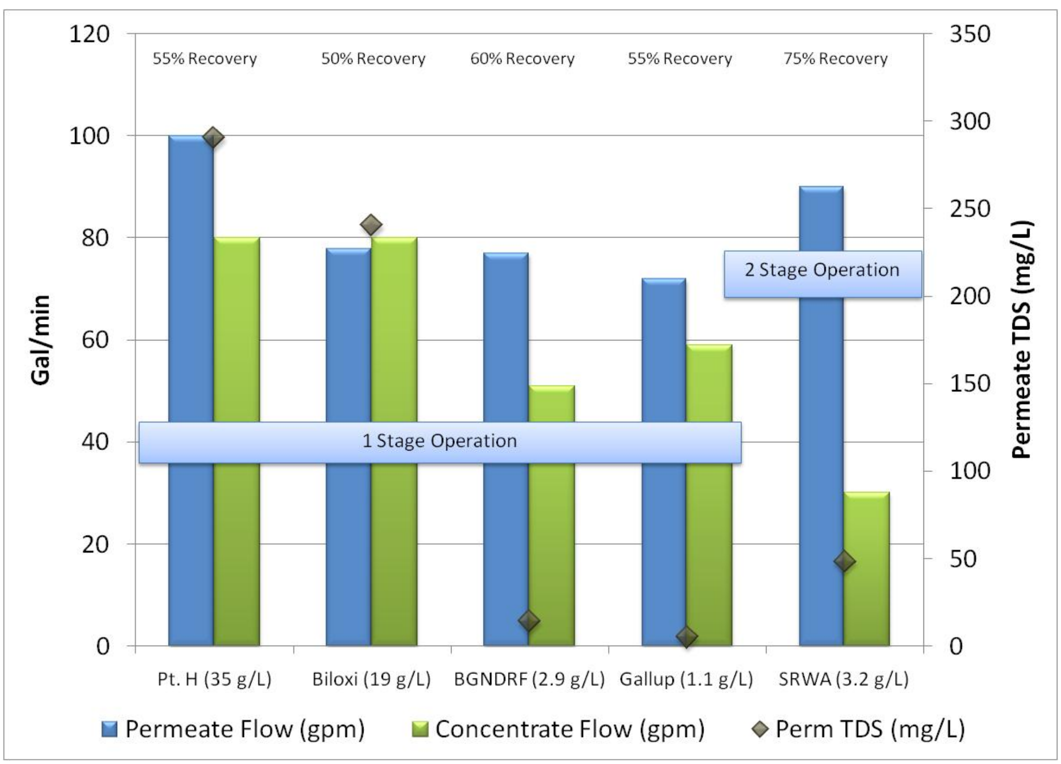

Figure 8-1. – Comparison of flows and permeate TDS in one and two-stage operations.

The combined power requirements for each location are shown in figure 8-2 in relation to the osmotic potential of the average feed and concentrate streams. The power use for the two-stage mode of operation was only slightly higher than would be expected for the recovery and salinity of the feedwater even though the energy recovery device was not in service.

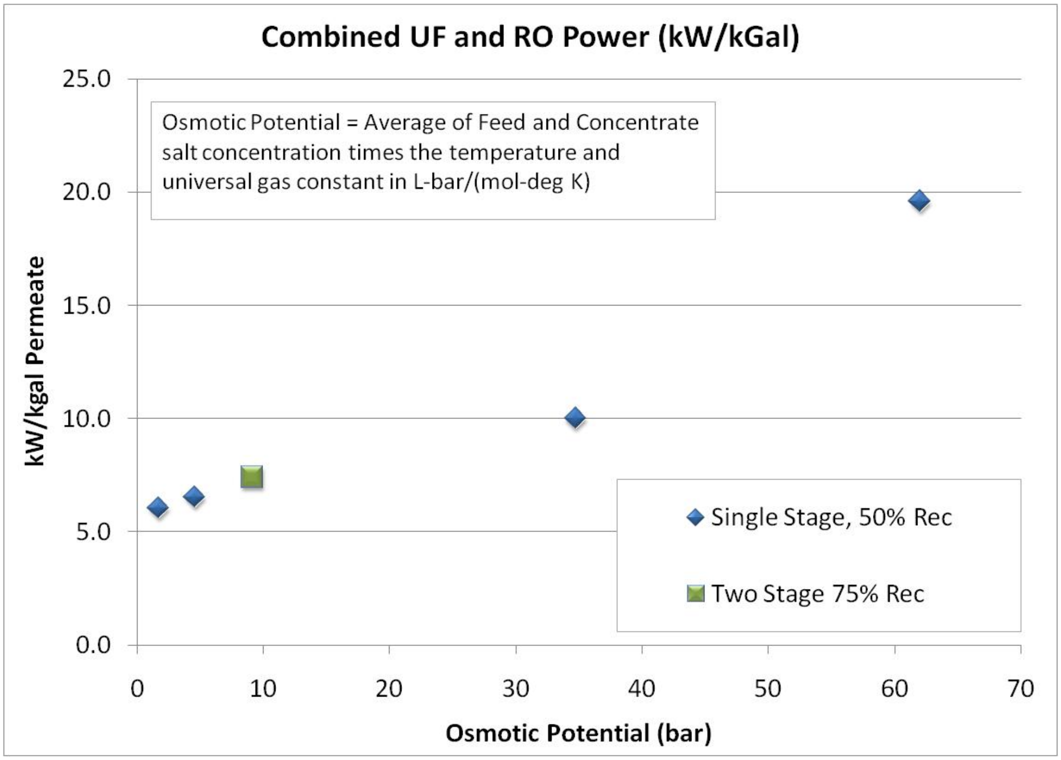

Figure 8-2. Power requirements in one and two-stage operations for a range of feedwater salinity and recovery rates.

9. Conclusions

The design study and SRWA Desal Plant pilot test demonstrate that flexible systems for desalination of variable sources are feasible. There are many ways to convert a seawater system to a brackish water system or vice versa as long as the materials are compatible with the most corrosive water source. The pilot test demonstrated that a highly efficient single stage seawater system can easily be converted to a two-stage system without losing energy efficiency.

9.1 Evaluation Criteria

The system was evaluated on the basis of operational issues, power consumption, product water quality, and adaptability of the control system. Each area of performance is discussed below.

9.1.1 Operational

The operation of the EUWP as a two-stage system was no different than operation as a single stage system. The conversion kept all instrumentation on-line and production was sufficiently balanced to avoid a deficit of concentrate flow in the last membrane elements.

A scaling issue began after the first week, which indicated that a higher dose of anti-scalant was needed. It was difficult to detect the need for more anti-scalant due to the lag between scale formation and data normalization. For variable sources of water, it is important to have real-time process feedback to trigger changes in operation.

The typical feed flow to the EUWP is the same regardless of the recovery rate. In the new configuration, the system used 120 gpm feed flow to produce 90 gpm of permeate and half of the concentrate that is produced in the original design. This will enable inland communities to be more efficient with their water resources and reduce concentrate management costs.

The UF system had performance issues, due to age, but the effluent turbidity was still suitable for RO feedwater.

9.1.2 Power

Power consumption was as expected for the design of the system, concentration of the feedwater and degree of recovery. The resistance that the positive displacement pump must overcome is a function of the type of membrane, piping and membrane frictional losses, temperature, and bulk salinity of the combined feed and concentrate stream. As a two-stage system with 75 percent recovery, bulk salinity is less than a single-stage with seawater, but there are additional friction losses.

9.1.3 Water Quality

The water quality was expected to be better than would be produced from a two-stage brackish water membrane system and this was indeed the case. The SRWA Desal Plant blends the RO permeate back with their lower quality well water to extend their supply so we cannot use the final plant effluent as a comparison. However, based on SRWA Desal Plant concentrate quality and volume discharge records, the RO permeate would have a TDS in the range of 170 -250 mg/L using brackish water membrane, while permeate from the seawater membrane at 75 percent recovery was 27.5 mg/L from the first stage on average and 42.5 mg/L from the second stage. Using a membrane capable of good performance with seawater would allow a higher blending ratio with pretreated feedwater.

9.1.4 Controls

The EUWP process control is limited to keeping tanks filled by cycling the forwarding pumps and UF system, backwashing the UF system, and monitoring for and shutting down on system upsets. A truly flexible control system would have some other input and evaluation algorithms to monitor and react to changes in the feedwater and its effect on operating parameters (e.g., pressure differences and changes in permeate quality). Qualities of the feedwater that may be indicative of a change are conductivity, pH, turbidity, and perhaps absorbance at some wavelength (the exact wavelength is the subject of future research).

9.2 Overall Assessment of the Study

The original plan was to test the modification concept on at least two different quality water sources, hopefully without moving the system. However, it was not possible to get concentrate from the SRWA Desal Plant to the pilot test location nor to identify a suitable alternative seawater test site. Data from previous deployments of the EUWP were used for comparison of operation in single-stage and dual-stage mode.

The EUWP was seven years old at the time of the pilot test. The automated solenoid valve failed and the UF membranes were not as intact as they should be, but since we were treating groundwater, this problem was not as severe as it would have been if we had been treating seawater. The valve failure and potentially inadequate pretreatment did not significantly alter the results for the brackish water mode test. If anything, the energy use would have been even less if there had been no failures in the pretreatment system.

9.3 Implications

Industrial applications with variable feed sources can obviously take advantage of flexible treatment systems without additional permitting for treating and recycling their own wastewater. Drinking water utilities will have a more difficult challenge. Though regulations vary by state, often a new approval will be needed whenever the water source is changed. Planning ahead for the eventuality of using an alternative source would make the approval process more straight forward. The process can be evaluated in the different configurations on alternative sources during the initial approval process.

If we were to think of water treatment systems as similar to cars, with a similar regulatory process, it could have a huge impact on the cost of new treatment facilities. Automobile standards are set for the industry. No one asks where the car will be driven, or under what conditions, the vehicle needs to perform in all conditions assuming the operator has the required training, license, registration, and insurance. Warranties are provided on new cars with required maintenance schedules that many people adhere to religiously. Maintenance personnel are easy to find and the cost of repairs does not often dissuade people from having cars in favor of more capital-intensive transportation options. People often purchase vehicles to meet their maximum transportation needs, driving a truck every day when a fuel-efficient Prius would have the same capital cost and a far lower operating cost, just because sometimes they need to haul supplies.

It is time to start thinking differently about how we design water treatment systems. If we can find so much logic in our choices of transportation, we can certainly extend the same thinking to our water treatment systems to great advantage.

9.4 Design Considerations

It is understood that the car analogy can only go so far. Cars run on fuel that has fairly consistent quality control. The only unknowns are the surface condition, weather, and operator. Water treatment systems for variable sources have unknown water quality, weather, chemical inputs, and operators. Sometimes the power isn't even consistent. However we should not throw our hands up in dismay. Harn RO Systems has a very good paper on their web site (Nemeth and Seacord, 2013) that describes good design practices for membrane systems that also apply as basic design guidance for a variable system. The "Custom Engineering" described in that paper is exactly what is needed to develop the best flexible design for a given situation. Further considerations for increasing flexibility are discussed here.

9.4.1 Pretreatment

The pretreatment process needs to be able to produce very clean filtered water from the worst possible quality that can be expected into the plant. The Harn RO paper discusses options for groundwater pretreatment. The EUWP was designed for groundwater or surface water. Its ultrafiltration system can be adapted to more challenging surface waters by increasing frequency of backwashes or by addition of a filter aid. UF does not require complete coagulation like a conventional coagulation flocculation clarification process; it requires only a pin-floc that builds a permeable cake layer on the UF membrane that can be easily removed during backwash. The EUWP chemical dosage is tied to the feed flow signal, however dosage of coagulant can also be controlled automatically based on the flow signal and differential pressure (dP) across the UF banks if the control system has the computing power to track changes in dP after backwashes. If dP is beginning to rise over time the coagulant dose can be increased incrementally with limits of maximum and minimum dose. The time lag must be determined between dose adjustment and a change in backwash effectiveness. Other changes that can be made to the backwash cycle to recover performance are duration, frequency, velocity, soak period, and aeration. All of these capabilities can be designed into the system and added to the process control programming.

9.4.2 Desalination

The assumption of this study is that the source is variable and at least part of the time requires desalination to removed dissolved salts. The key considerations for the desalination process are volume and quality of water needed from the system and energy availability Tools that can be used to accommodate salinity changes are membrane selection, vessel configuration, energy recovery devices, dual pumping systems, or extra product water storage capacity:

- There is a wide range of membrane products available with greater or lesser retention of salts and higher or lower water permeability. For variable sources the key considerations are the range of feedwater salinity, frequency and degree of variation. As with the EUWP RO system, membranes can be selected to better distribute productivity throughout the vessel.

- The RO process can be configured to increase flexibility by having smaller parallel arrays in appropriate number such that they can be coupled to form multiple stages if the water quality allows higher productivity as was demonstrated in this project. Since the EUWP had three parallel arrays, one array was available to be used as a second stage. It could also be configured to become a second pass to further treat permeate if that capability is provided in the piping design.

- Energy recovery devices can serve as booster pumps for a second stage or pressurize an additional first pass array as with the EUWP. They save energy and capital cost by enabling the same production with a smaller high pressure pump size.

- Dual pumping systems can also be used to treat widely differing source water. A smaller horsepower pump can be used when relatively fresh water is available with a larger high pressure pump mounted next to it for treating high salinity water.

- Extra product water storage is a useful adaptation tactic if the source varies on a shorter predictable cycle, such as sources under tidal influence. An adequate supply of fresh water can be stored to blend with higher salinity product if needed to produce acceptable quality during the high tide cycle.

9.4.3 Materials

Materials are a critical issue for systems that may be exposed to seawater or brackish water concentrate. Even 316 stainless steel corrodes quickly in a seawater environment. Investing in high quality steel such as SAF2507, 254SMO or 1925hMo (BSSA, 2001) for the high salinity portions of the system will enable the system to last much longer.

9.4.4 Monitoring and Controls

The usual inputs for water treatment processes are turbidity, conductivity, pH, temperature, silt density index, and others. These can be monitored by a human or by automated sensors. Whatever the cause for source water changes, a flexible process must have a method of detecting and accommodating for the change. In the most rudimentary form, a human operator monitoring changes in conditions detects the change. In advanced systems, sensors provide input to a control system with built-in artificial intelligence.

Sensor inputs can be used to adjust a process designed for flexibility, especially when coupled with knowledge of potential causes for change in these parameters and of appropriate reaction to change. Other process diagnostic inputs can be used to gage the degree of urgency required for the change. Differential pressure is a very sensitive indicator of fouling in RO systems. For example, by studying the changes in feed source and their effect on the differential pressure, one can make operation changes physically or program responsive operational changes into the process control system..

In some cases, the traditional sensor inputs are not sufficient to predict performance. We need to discover better indicators of changes in conditions and develop reliable operational responses to given changes in conditions.. Dr. Yorem Cohen's group, at University of California – Los Angeles (UCLA, Gu et al. 2013, Bartman et al. 2010, Uchymiak et al. 2009), report on development of "self-adaptive" control of RO desalination. Their system uses optical detectors of scale formation on a test membrane swatch positioned in a side stream off the concentrate. When scale formation is detected, flow is reversed, diverting feed to the concentrate end of the array. In this way, scale is dissolved before it becomes too difficult to remove. Methods for detecting change in seawater are under development at the Naval Facilities Engineering Service Center Seawater Desalination Demonstration facility in Port Hueneme, California. Staff there has been monitoring Chlorophyll A to predict difficulties with the pretreatment systems being tested at the facility. When there is an increase in Chlorophyll A, they have observed that several pretreatment filtration systems have significant increases in differential pressure, leading to increased maintenance time. Though predictive sensors and responsive system controls were not used in this Variable

Salinity Source Desalination study, they are a critical component in the design of robust, flexible treatment processes.

9.5 Next Steps

The next logical step is to design a robust desalination system capable of switching between energy efficient seawater desalination and high recovery brackish water desalination with ease. The system should have a self-monitoring and adaptive control system with sensors to detect changes in feedwater quality and its effect on process performance such that corrective measures can be taken and alerts delivered when human intervention is needed. Such an idea is not far-fetched! We have the process control technology, sensor technology, automated valve technology, and industry experience with corrective actions for changes in water quality. The next step is to put all of this technology together with the intention of making it robust, easy to operate, and adaptable to changing conditions.

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Appendix A

Definitions and Equations

Definitions

Antiscalant. A chemical that delays precipitation from a supersaturated solution and prevents scale formation.

Backwash. A backwards flow of water through the ultrafiltration membrane modules to dislodge and remove accumulated solids.

Brackish water. Slightly salty water, less saline than seawater, but usually too salty to drink.

Clarification. A process of adding coagulant to coagulate particulates from a liquid and allowing them to settle.

Coagulant. An agent that causes particles suspended in a liquid to coagulate.

Coagulation. To transform particulate matter suspended in a liquid into a soft or solid mass.

Concentrate. The stream exiting a Reverse Osmosis system containing the concentrated dissolved salt.

Concentration polarization. The high salt concentration at the membrane surface compared to the bulk concentration.

Conductivity. The degree to which a specified material conducts electricity.

Critical flux. An optimum flux point where overall productivity is maximized.

Dalton. A unit of mass that equals the mass of the most common hydrogen isotope.

Differential pressure. Differences in pressure (such as the pressure of water entering a vessel minus the residual pressure exiting the vessel).

Feedwater. Water to be treated by a desalination process.

Filtrate. Treated water clarified by passing through a micro- or ultra-filtration membrane process or a media filter.

Flocculation. Gentle agitation of a suspension after addition of coagulant to promote formation of larger aggregation of solids.

Flux. The rate of transport of material through a membrane in units of volume per unit area and time usually reported as an average value.

Langelier Saturation Index. Indicates the likelihood that a solution will precipitate or dissolve calcium carbonate.

Media filter. A type of filter that uses a bed of sand, crushed granite, or other granular material.

Pass. In a membrane system design each time water permeates the membrane is considered a "Pass". Multiple passes are used for high salinity feedwater and to obtain high purity water by removing further salts from the permeate of the first pass. A third pass may be used for ultra-pure water or when highly toxic organic compounds are present in the feedwater.

Permeate. Purified water that has passed through the Reverse Osmosis membrane

Pin-floc. When coagulant added to water forms a precipitate small enough to remain suspended it is called a Pin-Floc.

Precipitate. The solid formed in solution when oppositely charged ions react to form an uncharged molecule.

Precipitation. The formation of a solid through chemical reaction of oppositely charged ions solution

Pressure exchanger energy recovery. A device which transfers hydraulic energy from the high-pressure concentrate stream of reverse-osmosis process to low-pressure feedwater.

Product water. Water treated with a desalination system.

Osmosis. A naturally occurring phenomenon in which pure water is transported across a chemical potential gradient through a semi-permeable membrane from a low concentration solution to a high concentration solution

Reverse osmosis (RO). A desalination technology using a semipermeable membrane and pressure to induce water to flow from a high concentration solution, across the semi-permeable membrane, to a low concentration solution

Retentate. A portion of the feedwater to a UF or MF membrane system used for cross flow that does not permeate through the membrane is called the retentate. Its purpose is to flush solids from the membrane vessel.

Scale. The accumulation of precipitates of insoluble salts on a surface.

Semi-Permeable Membrane. A plastic film that allows passage of one component but rejects others under the application of a driving force. In the present application water is passed, components like salt and suspended solids are not passed, and the driving force is pressure difference.

Stage. A stage is a set of RO vessels through which the feed stream flows in parallel. A second stage of vessels receives the concentrate from a first stage of vessels. In most cases, the second stage would have no more than one half the number of vessels in the first stage.

Stiff-Davis Index. A calculated parameter to estimate the tendency for calcium carbonate scaling, used like the Langelier Saturation Index, but with solutions of high ionic strength like seawater.

Train. A train is a standalone unit of a process. In this case, a train is one complete array of RO vessels. The train may or may not have a dedicated high pressure pump.

Turbidity. The cloudiness of a fluid due to the scattering of light by individual particles (suspended solids), measured in units of Nephelometric Turbidity Units (NTU).

Ultrafiltration. A process using semi-permeable membrane designed to filter out suspended solids, turbidity, and bacteria. Generally the pore size will be between 0.01 and 0.1 microns.

Vessel. A vessel is a pressure resistant tube for housing membrane modules.

Water reuse. Reclaiming wastewater for potable or non-potable uses.

Equations

Permeate Flux: The average permeate flux is the flow of permeate divided by the surface area of the membrane. Permeate flux is calculated according to the following formula:

$$J_t = \frac{Q_p}{S} \tag{1}$$

where: J_t = permeate flux at time t (gfd, L/(h-m^2))
Q_p = permeate flow (gpd, L/h)
S = membrane surface area (ft^2, m^2)

It should be noted that only gfd and L/(h-m^2) will be considered acceptable units of flux for this testing plan.

Temperature Adjustment for Flux Calculation: Temperature corrections to 20°C (or 25°C) for permeate flux and specific flux will be made to correct for the variation of water viscosity with temperature. The following empirically-derived equation may be used to provide temperature corrections for specific flux calculations:

$$J_t(20^\circ C) = \frac{Q_p \times e^{-0.00239 \bullet (T-20)}}{S} \qquad 2$$

where: J_t = permeate flux at time t (gfd, L/(h-m^2))
Q_p = permeate flow (gpd, L/h)
S = membrane surface area (ft^2, m^2)
T = temperature of the feedwater (°C)

Net Driving Pressure: The Net Driving Pressure (NDP) is the pressure available to drive water through the membrane, equal to the average feed pressure (average of feed pressure and concentrate pressure) minus the differential osmotic pressure, minus the permeate pressure:

$$NDP = \frac{P_f + P_c}{2} - P_p - \Delta\pi \qquad 3$$

where: NDP = net driving pressure across the membrane (psi, bar)
P_f = feedwater pressure to the feed side of the membrane (psi, bar)
P_c = concentrate pressure on the concentrate side of the membrane (psi, bar)
P_p = permeate pressure on the treated water side of the membrane (psi, bar)
$\Delta\pi$= osmotic pressure (psi)

Osmotic Pressure Gradient: The term "osmotic pressure gradient" refers to the difference in osmotic pressure generated across the membrane barrier as a result of different concentrations of dissolved salts. The following equation provides an estimate of the osmotic pressure across the semi-permeable membrane through generic use of the difference in TDS concentrations on either side of the membrane:

$$\Delta\pi = RT \cdot \left[\frac{1}{2} \sum_i \left(c_{if} + c_{ic} \right) - \sum_i c_{ip} \right] \qquad 4$$

where: c_{if} = feedwater concentration of ith ionic species in mol/L
c_{ic} = concentrate concentration of ith ionic species in mol/L
c_{ip} = permeate concentration of ith ionic species in mol/L
R = gas constant 0.0831442 L bar K^{-1} mol^{-1}
T = temperature in degree Kelvin = degree C + 273.15

Specific Flux: The term "specific flux" is used to refer to permeate flux that has been normalized for the net driving pressure. The equation used for calculation of specific flux is given by the formula provided below. Specific flux is usually discussed with use of flux values that have been temperature-adjusted to 20°C or 25°C:

$$J_{tm} = \frac{J_t}{NDP} \qquad 5$$

where: NDP = net driving pressure for solvent transport across the membrane (psi, bar)
J_t = permeate flux at time t (gfd, L/(h-m^2)). Temperature-corrected flux values should be employed.

Percent Recovery of Specific Flux:

$$100\left[1 - \frac{Js_f}{Js_i}\right] \qquad 6$$

where: Js_f = specific flux (gfd/psi, L/(m^2-hr)/bar) at end of current run (final) and
Js_i = specific flux (gfd/psi, L/(m^2-hr)/bar) at beginning of subsequent run (initial).

Loss of Original Specific Flux:

$$100\left[1 - \frac{Js_i}{Js_{io}}\right] \qquad 7$$

where: Js_{io} = specific flux (gfd/psi, L/(m^2-hr)/bar) at time zero point of membrane testing.

Water Recovery: The recovery of feedwater as permeate water is given as the ratio of permeate flow to feedwater flow:

$$\%\ \text{System Recovery} = 100 \cdot \frac{Q_p}{Q_f} \qquad 8$$

where: Q_f = feedwater flow to the membrane (gpm, L/h)
Q_p = permeate flow (gpm, L/h)

Recycle Ratio: The recycle ratio represents the ratio of the recycle flow from the membrane concentrate to the total flow of water that is used as feedwater flow to the membrane. This ratio provides an idea of the recirculation pumping that is applied to the membrane system to reduce membrane fouling and specific flux decline.

$$\text{Recycle Ratio} = \frac{Q_r}{Q_f} \tag{9}$$

where: Q_f = total feedwater flow to the membrane (gpm, L/h)
Q_r = recycle flow as concentrate to the feed side of the pump (gpm, L/h)

Solute Rejection: Solute rejection is controlled by a number of operational variables that must be reported at the time of water sample collection. Bulk rejection of a targeted inorganic chemical contaminant may be calculated by the following equation:

$$\%\ \text{Solute Rejection} = 100 \cdot \left[\frac{C_f - C_p}{C_f}\right] \tag{10}$$

where: C_f = feedwater concentration of specific constituent (mg/L)
C_p = permeate concentration of specific constituent (mg/L)

Solvent and Solute Mass Balance: Calculation of solvent mass balance was performed during Task 1 to verify the reliability of flow measurements through the membrane. Calculation of solute mass balance across the membrane system was performed as part of Task 3 to estimate the concentration of limiting salts at the membrane surface.

$$Q_f = Q_p + Q_c \tag{11}$$

$$Q_f C_f = Q_p C_p + Q_c C_c \tag{12}$$

where: Q_f = feedwater flow to the membrane (gpm, L/h)
Q_p = permeate flow (gpm, L/h)
Q_c = concentrate flow (gpm, L/h)
C_f = feedwater concentration of specific constituent (mg/L)
C_p = permeate concentration of specific constituent (mg/L)
C_f = concentrate concentration of specific constituent (mg/L)

Solubility Product: Calculation of the solubility product of selected sparingly soluble salts is an important exercise for the test plan to determine if there are operational limitations caused by the accumulation of limiting salts at the membrane surface. Text book equilibrium values of the solubility product should be compared with solubility values calculated from the results of ETV evaluation, as determined from use of the following equation:

$$K_{sp} = \gamma_A^x \left[A^{y-} \right]^x \gamma_B^y \left[B^{x+} \right]^y \qquad 13$$

where: K_{sp} = solubility product for the limiting salt being considered
γ = free ion activity coefficient for the ion considered (e.g, A or B)
[A] = molar concentration of the anion A for sparingly soluble salt A_xB_y
[B] = molar concentration of the anion B
x, y = stiochiometric coefficients for the precipitation reaction of A and B

Mean Activity Coefficient: The mean activity coefficients for each of the salt constituents may be estimated for the concentrated solutions as a function of the ionic strength:

$$\log \gamma_{A,B} = -0.509 \cdot Z_A Z_b \sqrt{\mu} \qquad 14$$

where: $\gamma_{A,B}$ = combined activity coefficient
Z_A = ion charge of anion A
Z_B = ion charge of cation B
μ= ionic strength

Ionic Strength: A simple approximation of the ionic strength can be calculated based upon the concentration of the total dissolved solids in the feedwater stream:

$$\mu = \frac{1}{2} \sum_i c_i Z_i^2 \qquad 15$$

where: μ = ionic strength
c_i = Concentration of the i^{th} ion species
Z_i = Charge of the i^{th} ion species

Appendix B

Data Tables

Table B-1. – Field Data Part 1

Date	Time	Recorder	UF Pump	UF Energy	UF Retentate	RO Feed Totalizer		HP RO Pump	RO Energy
		Initials	Hours	kW	gpm	Gallons	Time	Hours	kW
6/24/2011	11:00			105616	23				51666
6/25/2011	9:41		2908	105616		18755900	9:41	2343	51679
6/25/2011	11:28	MC+AT	2910	105650		18768700	11:30	2345	51710
6/25/2011	15:40	MC+AT	2912.1	105681	22	18796300	15:40	2349	51781
6/26/2011	9:30	MC	2912.9	105723	25	18806900	9:37	2351	51807
6/26/2011	12:35	MC	2914.6	105777	25	18827000	12:43	2354	51861
6/26/2011	15:30	MC	2915.9	105790		18847700	15:30	2357	51911
6/28/2011	8:45	MC	2916.4	105819		18855700	8:49	2358	51931
6/28/2011	12:53	MC	2917.7	105905		18883000	12:52	2362	52001
6/28/2011	15:20	MC	2918	105960	24	18899300	15:21	2364	52041
6/29/2011	8:27	MC	2919.7	105998		18909700	8:28	2366	52066
6/29/2011	12:44	MC	2921.6	106095		18938700	12:47	2370	52139
6/30/2011	9:10	MC	2922	106140		18952500	9:10	2372	52174
6/30/2011	15:19	MC	2924.7	106260		18993900	15:19	2378	52278
7/1/2011	8:00	MC	2924.9	106282		18999100	8:05	2379	52289
7/1/2011	15:17	MC	2927.4	106440		19047600	15:17	2386	52410
7/2/2011	8:10	MC	2927.7	106464		19055000	8:10:55	2387	52428
7/2/2011	14:25	MC+AH	2929.8	106599		19096600	14:25	2394	52532
7/4/2011	8:00	MC+AH	2930.5	106640		19109900	8:00	2396	52565
7/4/2011	3:10	MC+AH	2932.8	106642		19157900	3:10	2403	52686
7/5/2011	8:10	MC+AH	2933.4	106646	27	19168200	8:08	2404	52712
7/5/2011	15:20	MC+AH	2935.8	106786	40	19216300	15:21	2411	52836
7/6/2011	7:50	MC+AH	2936.3	106796	43	19224400	7:51	2413	52856
7/6/2011	14:51	MC+AH	2938.6	106797	42	19271600	14:42	2420	52978
7/7/2011	7:50	MC+AH	2938.9	106814		19281000	7:55	2421	53002
7/7/2011	15:15	MC+AH	2941.2	106962	42	19330200	15:15	2428	53131
7/8/2011	7:54	MC+AT+AH	2941.5	106980	41	19335800	7:55	2429	53146

Date	Time	Recorder	UF Pump	UF Energy	UF Retentate	RO Feed Totalizer		HP RO Pump	RO Energy
		Initials	Hours	kW	gpm	Gallons	Time	Hours	kW
7/8/2011	2:54	AT+AH	2943.8	107126	43	19383100	2:54	2436	53270
7/9/2011	7:50	AT+AH	2944.2	107147	35	19389600	8:12	2437	53287
7/9/2011	15:20	AT+AH	2946.5	107295	43	19437500	3:21	2444	53416
7/11/2011	7:55	AT+AH	2946.8	107314	38	19443900	7:56	2445	53532
7/11/2011	15:00	AT+AH	2948.7	107436	43	19483000	3:00	2451	53539
7/12/2011	7:50	AT+AH	2949.1	107461	42	19490300	7:55	2452	53559
7/12/2011	15:15	AT+AH	2951.5	107611	43	19539500	3:15	2460	53695
7/13/2011	7:55	AT+AH	2951.7	107629	42	19544400	7:55	2460	53707
7/13/2011	15:15	AT+AH	2954.2	107780	43	19593700	3:18	2468	53843
7/14/2011	8:00	AT+AH	2954.3	107794	41	19597700	7:59	2468	53853
7/14/2011	15:09	AT+AH	2956.3	107918	43	19637900	3:13	2474	53965
7/15/2011	7:55	AT+AH	2956.6	107939	44	19644100	8:04	2475	53979
7/15/2011	15:20	AT+AH	2959	108091	44	19693600	3:26	2482	54119
7/16/2011	8:00	AT+AH	2959.2	108105	41	19697100	8:05	2483	54128
7/16/2011	14:30	AT+NG	2961.5	108242	44	19741300	2:41	2489	54253
7/18/2011	8:00	AT+NG	2961.9	108275	43	19751600	8:28	2491	54283
7/18/2011	15:00	AT+NG	2964.2	108414	44	19796000	3:07	2497	54410
7/19/2011	7:55	AT+NG	2964.5	108433	44	19802400	7:56	2498	54426
7/19/2011	15:00	AT+NG	2966.9	108584	45	19850400	3:06	2506	54566
7/20/2011	8:10	AT+NG	2967.3	108610	44	19857800	8:16	2507	54586
7/20/2011	15:00	AT+NG	2969.7	108752	45	19903600	3:05	2513	54716
7/21/2011	7:33	MC +NG	2969.8	108764	41	19907200	7:35	2514	54725
7/21/2011	14:43	MC +NG	2971.9	108888	41	19946800	14:44	2520	54843
7/22/2011	7:41	MC +NG	2972.1	108904	44	19951100	7:48	2520	54855
7/22/2011	15:05	MC +NG	2974	109055	40	20000000	15:06	2528	55000
7/23/2011	8:28	MC +NG	2974.9	109071		20004500	8:47	2528	55013
7/23/2011	10:33	MC +NG	off			20004619	10:40	2529	55032
7/23/2011	11:00	MC +NG	off					2530	55037

Table B-2. – Field Data Part 2

Date	Time	AntiScalant Weight	Stroke Lenght	Stroke Speed	Inlet flow	1st Pass Prod Flow	ERI Pass Prod Flow	ERI Flow Conc Flow	ERI Pass Feed Flow
		Pounds	%	%	gpm	gpm	gpm	gpm	gpm
6/24/2011	11:00				120	67	34	22	0
6/25/2011	9:41				121	58	33	22	22
6/25/2011	11:28	MC+AT			120	58	33	21	0
6/25/2011	15:40	MC+AT			121	62	35	21	0
6/26/2011	9:30	MC			124	57	35	21	0
6/26/2011	12:35	MC			120	58	35	28	0
6/26/2011	15:30	MC			121	58	34	21	0
6/28/2011	8:45	MC			119	57	35	22	0
6/28/2011	12:53	MC			120	60	34	21	0
6/28/2011	15:20	MC	40	35	122	61	31	22	0
6/29/2011	8:27	MC	60	50	119	62	33	22	0
6/29/2011	12:44	MC			120	62	33	22	0
6/30/2011	9:10	MC			120	58	33	23	0
6/30/2011	15:19	MC			119	58	33	23	0
7/1/2011	8:00	MC			120	56	33	23	0
7/1/2011	15:17	MC	40	40	119	53	33	23	0
7/2/2011	8:10	MC	40	40	121	62	32	23	0
7/2/2011	14:25	MC+AH	40	40	122	61	32	22	0
7/4/2011	8:00	MC+AH	50	50	119	56	34	23	0
7/4/2011	3:10	MC+AH	50	50	120	57	34	22	0
7/5/2011	8:10	MC+AH	50	50	119	56	34	20	0
7/5/2011	15:20	MC+AH	50	50	118	53	34	19	0
7/6/2011	7:50	MC+AH	40	40	119	56	34	20	0
7/6/2011	14:51	MC+AH	40	40	119	52	35	19	0
7/7/2011	7:50	MC+AH	40	40	117	55	33	19	0
7/7/2011	15:15	MC+AH	40	40	120	56	35	19	0
7/8/2011	7:54	MC+AT+AH	40	40	119	54	34	20	0
7/8/2011	2:54	AT+AH	40	40	119	56	34	19	0

Date	Time	AntiScalant Weight	Stroke Lenght	Stroke Speed	Inlet flow	1st Pass Prod Flow	ERI Pass Prod Flow	ERI Flow Conc Flow	ERI Pass Feed Flow
		Pounds	%	%	gpm	gpm	gpm	gpm	gpm
7/9/2011	7:50	AT+AH	40	40	118	52	35	20	0
7/9/2011	15:20	AT+AH	40	40	119	51	35	19	0
7/11/2011	7:55	AT+AH	40	40	119	54	35	20	0
7/11/2011	15:00	AT+AH	40	40	118	59	33	21	0
7/12/2011	7:50	AT+AH	50	40	118	56	35	21	0
7/12/2011	15:15	AT+AH	50	40	119	54	34	20	0
7/13/2011	7:55	AT+AH	50	40	120	54	35	21	0
7/13/2011	15:15	AT+AH	50	40	118	55	36	20	0
7/14/2011	8:00	AT+AH	50	40	119	56	35	21	0
7/14/2011	15:09	AT+AH	50	40	118	57	32	20	0
7/15/2011	7:55	AT+AH	50	40	120	53	35	21	0
7/15/2011	15:20	AT+AH	50	40	119	52	36	21	0
7/16/2011	8:00	AT+AH	50	40	120	51	36	22	0
7/16/2011	14:30	AT+NG	50	40	118	50	35	22	0
7/18/2011	8:00	AT+NG	50	40	119	53	35	22	0
7/18/2011	15:00	AT+NG	50	40	119	52	35	23	0
7/19/2011	7:55	AT+NG	50	40	120	52	34	23	0
7/19/2011	15:00	AT+NG	50	40	119	52	34	24	0
7/20/2011	8:10	AT+NG	50	40	120	52	35	24	0
7/20/2011	15:00	AT+NG	50	40	120	52	35	24	0
7/21/2011	7:33	MC +NG	50	40	119	51	35	24	0
7/21/2011	14:43	MC +NG	50	40	119	57	35	19	0
7/22/2011	7:41	MC +NG	50	40	120	57	36	20	0
7/22/2011	15:05	MC +NG	50	40	119	59	36	20	0
7/23/2011	8:28	MC +NG	50	40	118	57	35	20	0
7/23/2011	10:33	MC +NG	50	40	119	51	35	22	0
7/23/2011	11:00	MC +NG	50	40	122	56	38	17	0

Table B-3. – Field Data Part 3

Date	Time	Inlet Pressure	Feed Pressure	ERI Pass Feed Pressure	Product Pressure	ERI Inlet Pressure	ERI Conc Pressure	UF Feed Flow	UF dP	UF Backflush Counter
		lb/in^2	lb/in^2	lb/in^2	lb/in^2	lb/in^2	lb/in^2	Gpm	lb/in^2	#
6/24/2011	11:00	35	230	203	23	203	177	294		
6/25/2011	9:41	23	230	204	21	203	178	237		
6/25/2011	11:28	22	234	205	23	205	179	219		
6/25/2011	15:40	22	233	204	19	204	178	240		5110
6/26/2011	9:30	23	233	205	21	205	178	241		5111
6/26/2011	12:35	21	233	206	21	206	178	250		5115
6/26/2011	15:30	22	233	204	21	205	178			5117
6/28/2011	8:45	38	233	206	21	205	178	300		5117
6/28/2011	12:53	32	234	206	21	206	178	244		5120
6/28/2011	15:20	33	239	210	23	210	183	290		5122
6/29/2011	8:27	33	240	211	22	210	183	246	9.15	5124
6/29/2011	12:44	33	235	209	22	208	180	250	9.7	5127
6/30/2011	9:10	33	236	210	22	207	182	443	21.4	5129
6/30/2011	15:19	33	241	211	22	209	182	430	20.8	5133
7/1/2011	8:00	33	240	210	22	210	182	238	10.7	
7/1/2011	15:17	33	238	206	22	206	179	438	21.3	
7/2/2011	8:10	33	233	208	21	207	181	547	17.6	
7/2/2011	14:25	33	238	207	21	208	181	442	22.2	5143
7/4/2011	8:00	33	240	210	22	209	181	427	22	5144
7/4/2011	3:10	33	243	212	23	213	184	418	21.7	5148
7/5/2011	8:10	37	250	221	23	220	195	254	11.7	5149
7/5/2011	15:20	37	253	221	23	223	196	418	22.1	5154
7/6/2011	7:50	37	253	224	23	223	196	428	22.5	5155
7/6/2011	14:51	37	255	224	23	225	196	427	22.1	5159
7/7/2011	7:50	38	253	227	23	226	200	437	22.1	5159
7/7/2011	15:15	37	259	228	23	228	200	418	22	5163
7/8/2011	7:54	37	255	230	23	228	203	427	22.1	5163
7/8/2011	2:54	37	264	232	22	234	203	412	21.9	5168

Date	Time	Inlet Pressure	Feed Pressure	ERI Pass Feed Pressure	Product Pressure	ERI Inlet Pressure	ERI Conc Pressure	UF Feed Flow	UF dP	UF Backflush Counter
		lb/in^2	lb/in^2	lb/in^2	lb/in^2	lb/in^2	lb/in^2	Gpm	lb/in^2	#
7/9/2011	7:50	37	261	234	22	234	232	560	6.42	5169
7/9/2011	15:20	37	268	237	22	238	210	442	22.1	5173
7/11/2011	7:55	37	265	235	23	235	208	443	22.1	5173
7/11/2011	15:00	37	270	243	22	244	214	420	22.4	5177
7/12/2011	7:50	37	276	247	21	246	222	411	22.4	5178
7/12/2011	15:15	37	274	248	21	249	215	420	22.5	5182
7/13/2011	7:55	37	275	247	23	246	217	416	22.6	5183
7/13/2011	15:15	38	281	250	23	251	224	418	22.4	5187
7/14/2011	8:00	38	273	250	22	249	221	409	22.5	5187
7/14/2011	15:09	37	280	249	21	250	218	413	22.5	5191
7/15/2011	7:55	37	280	253	22	252	222	474	19.6	5192
7/15/2011	15:20	38	289	256	22	257	226	409	22.5	5196
7/16/2011	8:00	37	285	256	22	256	226	448	19.7	5197
7/16/2011	14:30	27	292	262	22	263	231	412	22.5	5201
7/18/2011	8:00	38	285	258	22	257	227	415	22.7	5202
7/18/2011	15:00	38	292	263	22	264	232	410	22.8	5206
7/19/2011	7:55	38	293	262	22	262	234	410	22.9	5206
7/19/2011	15:00	37	297	264	21	267	234	410	22.7	5211
7/20/2011	8:10	37	294	264	21	265	234	416	22.7	5212
7/20/2011	15:00	37	291	262	21	264	233	408	22.8	5216
7/21/2011	7:33	38	292	262	21	261	232	560	6.63	5217
7/21/2011	14:43	37	304	274	24	275	248	400	22.6	5220
7/22/2011	7:41	38	306	277	23	278	250	392	22.9	5221
7/22/2011	15:05	38	310	281	23	282	256	421		4983
7/23/2011	8:28	38	304	278	23	278	251	408	22.9	5226
7/23/2011	10:33	37	221	188	22	189	159			
7/23/2011	11:00	38	213	185	24	186	158			

Table B-4. – Field Sample Parameters for UF Feed and Filtrate

Date	Time	UF Feed					UF Filtrate				
		pH	Cond µS/cm	Temp °C	Turbidity NTU	Iron mg/L	pH	Cond µS/cm	Temp °C	Turbidity NTU	Iron mg/L
6/24/2011	11:00	7.45	4645	27.5			7.66	4650	27.5		
6/25/2011	9:41	7.19	4559	27.2	1.8		7.23	4552	27.2	0.3	
6/25/2011	11:28	7.25	4550	27.4	1.9	0.52	7.39	4554	27.3	0.15	
6/25/2011	15:40	7.05	4704	27.7	1.6		7.12	4701	27.5	0.2	
6/26/2011	9:30	7.03	4631	27.3	2.1	0.59	6.95	4627	27.2	0.1	0.22
6/26/2011	12:35	7.23	4623	28.2	1.8		7.39	4606	27.9	0.5	
6/26/2011	15:30	7.08	4624	27.5	1.6		7	4621	27.5	0.1	
6/28/2011	8:45	7.1	4730	27.1	2		6.99	4729	27.4	0.2	
6/28/2011	12:53	7.36	4679	27.6	1.9	0.54	7.29	4698	27.8	0.3	
6/28/2011	15:20	6.9	4968	28	2.3		7.17	4972	27.4	0.1	
6/29/2011	8:27				1.3					0.2	
6/29/2011	12:44	7.16	4894	27.6	1.6	0.61	7.16	4894	27.4	0.1	
6/30/2011	9:10	7.33	4742	26.5	1.7		7.31	4741	26.4	0.2	
6/30/2011	15:19	7.35	4895	26.9	1.7	0.56	7.21	4868	26.9	0.2	
7/1/2011	8:00	7.35	4770	26.9	3.2	0.52	7.18	4761	26.9	0.1	
7/1/2011	15:17	7.35	4617	27.4	2		7.34	4618	27.6	0.3	
7/2/2011	8:10	7.31	4717	26.8	1.9		7.23	4731	26.9	0.2	
7/2/2011	14:25	7.25	4781	27.7	1.8	0.63	7.27	4780	27.6	0.2	0.18
7/4/2011	8:00	7.32	4737	26.5	2		7.2	4737	26.9	0.1	
7/4/2011	3:10	7.34	4862	27.9	3.2	0.64	7.27	4859	28	0.4	0.08
7/5/2011	8:10	7.34	4756	26.6	2		7.21	4753	26.9	0.1	
7/5/2011	15:20	7.33	4895	29	1.7	0.52	7.23	4851	28.3	0.3	0.06
7/6/2011	7:50	7.28	4893	26.9	2.2		7.15	4899	27	0.8	
7/6/2011	14:51	7.3	4805	28.2		0.56	7.38	4751	28.4		0.07
7/7/2011	7:50	7.06	4803	27	2.2		7.27	4804	27.3	0.3	
7/7/2011	15:15	6.94	4596	28.7	3.6	0.58	6.54	4591	28.7	0.2	0.07
7/8/2011	7:54	7.34	4694	26.8	2.1	0.66	7.15	4695	26.8	0.2	0.14
7/8/2011	2:54	7.2	4835	28.1	1.8		7.42	4838	28	0.2	

Date	Time	UF Feed					UF Filtrate				
		pH	Cond	Temp	Turbidity	Iron	pH	Cond	Temp	Turbidity	Iron
			μS/cm	°C	NTU	mg/L		μS/cm	°C	NTU	mg/L
7/9/2011	7:50	7.31	4819	27.1	4.6	0.63	7.1	4815	27.1	0.2	0.1
7/9/2011	15:20	7.15	4786	27.8			7.24	4778	28.6		
7/11/2011	7:55	7.34	5032	27.4	7.3	1.09	7.28	4961	28.4	0.2	0.04
7/11/2011	15:00	7.15	5302	28.7	3.4		7.19	5284	28.2	0.1	
7/12/2011	7:50	7.3	5116	27.1	1.7	0.63	7.25	5107	27.1	0.1	0.07
7/12/2011	15:15	7.16	4805	28.1	2.7		7.42	4781	27.9	0.1	
7/13/2011	7:55	7.23	4448	27	2.7	0.61	7.12	4444	27	0.2	0.05
7/13/2011	15:15	7.15	4589	28.4	2.8		7.32	4542	27.8	0.2	
7/14/2011	8:00	7.26	4446	27.2	6.7	0.78	7.24	4446	27.2	0.2	0.02
7/14/2011	15:09	7.13	4556	28.7	3.8		7.24	4556	28	0.2	
7/15/2011	7:55	7.32	4557	27	1.9	0.61	7.33	4557	27	0.2	0.03
7/15/2011	15:20	7.33	4567	29.1	2.8		7.42	4554	28.1	0.3	
7/16/2011	8:00	7.06	4748	27.3	2.9	0.57	7.2	4752	27.2	0.3	0.01
7/16/2011	14:30	7.19	4692	28.1	2.5		7.23	4696	27.7	0.2	
7/18/2011	8:00	7.13	4404	27.5	4.3	0.64	7.15	4445	27.3	0.3	0.03
7/18/2011	15:00	7.14	4833	27.9	2.3		7.22	4821	27.7	0.3	
7/19/2011	7:55	7.12	4730	27.1	1.9	0.59	7.05	4721	27.1	0.3	0.01
7/19/2011	15:00	7.17	4854	28.1	2.6		7.15	4814	27.9	0.3	
7/20/2011	8:10	7.14	4583	27.2	3	0.64	7.19	4574	27.1	0.2	0.02
7/20/2011	15:00	7.2	4709	28.1	3.3		7.19	4682	27.9	0.3	
7/21/2011	7:33	7.38	4564	27	2.2	0.7	7.23	4562	27.1	0.2	0.01
7/21/2011	14:43	7.46	4614	29.1	4.1		7.32	4603	28.2	0.2	
7/22/2011	7:41	7.26	4509	27.4	3.5	0.55	7.22	4499	27.4	0.2	0.01
7/22/2011	15:05	7.18	4732	28.2			7.18	4731	27.5		
7/23/2011	8:28	7.37	4752	28.2	7		7.28	4749	28.3	0.3	
7/23/2011	10:33										
7/23/2011	11:00	6.8	1056	34.1							

Table B-5. – Field Sample Measurements – RO Feed and Concentrate

Date	Time	RO Feed					RO Concentrate				
		pH	Cond µS/cm	Temp °C	Turbidity NTU	Iron mg/L	pH	Cond µS/cm	Temp °C	Turbidity NTU	Iron mg/L
6/24/2011	11:00	7.8	4515	28.1			7.26	15.21	29.0		
6/25/2011	9:41	7.1	4568	27.8	0.5		7.35	15.29	28.6		
6/25/2011	11:28	6.88	4552	27.7	0.8	0.18	7.43	15.23	28.5	0.36	
6/25/2011	15:40	6.86	4696	28	0.7		7.41	15.82	29		
6/26/2011	9:30	6.75	4630	27.6	0.7	0.2	7.42	15.52	28.5	0.3	0.34
6/26/2011	12:35	6.89	4620	28.2	1.1		7.51	15.48	28.3	0.5	
6/26/2011	15:30	6.8	4620	28.1	0.8		7.44	15.5	28.9		
6/28/2011	8:45	6.72	4729	27.5	0.1		7.39	15.76	28.3	0.3	
6/28/2011	12:53	6.99	4692	28.2	0.6	0.16	7.04	15.72	29		0.23
6/28/2011	15:20	7.18	4974	28	0.6		7.28	16.42	28	0.2	
6/29/2011	8:27	7.04	4996	27.3	0.3		7.49	16.4	27.9	0.2	
6/29/2011	12:44	7.12	4897	27.9	0.5	0.16	7.47	16.08	28.7		0.23
6/30/2011	9:10	7	4741	26.5	0.4		7.51	15.72	27.2	0.4	
6/30/2011	15:19	6.44	4827	27.1	0.3	0.12	7.49	16.13	27.8	0.3	0.34
7/1/2011	8:00	7.49	4830	27.1	0.6	0.17	7.49	15.97	27.7	1	0.17
7/1/2011	15:17	7.06	4920	27.5	0.3		7.45	15.39	28.4	0.2	
7/2/2011	8:10	7.28	4716	27.1	0.3		7.5	15.62	27.8	0.6	
7/2/2011	14:25	6.99	4781	28.4	0.6	0.1	7.42	15.89	28.8	0.7	0.18
7/4/2011	8:00	6.98	4743	27.2	0.3		7.44	15.68	27.9		
7/4/2011	3:10	7.23	4848	29	0.4	0.11	7.53	16.05	29.1		0.62
7/5/2011	8:10	7.05	4783	27.1	0.4		7.23	16.82	27.9		
7/5/2011	15:20	5.7	4847	28.8	0.5	0.14	7.3	17.11	29.2		
7/6/2011	7:50	6.09	4878	27.1	0.5		7.44	17.12	27.8		
7/6/2011	14:51	6.58	4614	28.5		0.04	7.51	16.36	29.2		0.37
7/7/2011	7:50	6.23	4821	27.4	0.4		7.47	16.93	28.1		
7/7/2011	15:15	7.1	4240	28.5	0.5	0.12	7.44	16.49	29.7		0.17
7/8/2011	7:54	6.68	4661	27.4	0.3	0.05	7.22	16.31	28.2		0.16
7/8/2011	2:54	7.08	4838	28.1	0.3		7.49	16.92	29.4		

Date	Time	RO Feed					RO Concentrate				
		pH	Cond	Temp	Turbidity	Iron	pH	Cond	Temp	Turbidity	Iron
			µS/cm	°C	NTU	mg/L		µS/cm	°C	NTU	mg/L
7/9/2011	7:50	6.93	4830	27.7	0.3	0.03	7.15	16.79	28.7		0.18
7/9/2011	15:20	6.99	4772	28			7.52	16.58	29		
7/11/2011	7:55	6.93	4960	28.5	0.4	0.04	7.14	16.94	29.4		0.19
7/11/2011	15:00	7.14	5275	29	0.3		7.48	17.9	30		
7/12/2011	7:50	6.11	5131	27.6	0.2	0.06	7.44	17.52	28.4		0.22
7/12/2011	15:15	6.96	4768	28.1	0.3		7.5	16.31	29.1		
7/13/2011	7:55	6.97	4592	27.7	0.3	0.02	7.49	15.69	28.6		0.09
7/13/2011	15:15	7.05	4546	28.1	0.2		7.23	15.48	29.1		
7/14/2011	8:00	6.9	4497	27.4	0.3	0.03	7.47	15.21	28.8		0.08
7/14/2011	15:09	7.05	4561	28.8	0.2		7.52	15.44	29.8		
7/15/2011	7:55	7.11	4562	27.2	0.4	0.01	7.5	15.32	28.5		0.02
7/15/2011	15:20	7.07	4550	28.3	0.3		7.5	15.26	29.3		
7/16/2011	8:00	7.09	4588	27.5	0.5	0.01	7.53	15.34	28.5		0.07
7/16/2011	14:30	7.09	4756	28.2	0.3		7.49	15.76	29.2		
7/18/2011	8:00	7.08	4503	28.5	0.3	0.01	7.5	14.95	29.4		0.11
7/18/2011	15:00	7.08	4824	28.1	0.1		7.49	15.96	29.2		
7/19/2011	7:55	7.14	4764	27.7	0.4	0.02	7.51	15.82	28.7		0.07
7/19/2011	15:00	7.06	4840	28.1	0.4		7.46	16	29.3		
7/20/2011	8:10	7.06	4638	27.6	0.3	0.01	7.52	15.33	28.5		0.07
7/20/2011	15:00	7.1	4693	28.3	0,3		7.5	15.57	29.4		
7/21/2011	7:33	7.18	4658	27.8	0.3	0.01	1.53	15.46	28.9		0.07
7/21/2011	14:43	7.1	4619	29.1	0.2		7.58	17.63	30.2		
7/22/2011	7:41	6.96	4577	28.2	0.2	0	7.55	17.37	29.1		0.08
7/22/2011	15:05	7.14	4725	28.3			7.54	17.88	29.2		
7/23/2011	8:28	7.1	4743	28.4	0.4		7.54	17.89	29.3		
7/23/2011	10:33	6.73	737	32.4							
7/23/2011	11:00	6.33	231.5	33.1							

Table B-6. – Field Sample Measurements. RO Permeate, Stage 1 and 2

Date	Time	Stage 1 Permeate			Stage 2 Permeate		
		pH	Cond	Temp	pH	Cond	Temp
			µS/cm	°C		µS/cm	°C
6/24/2011	11:00	8.05	26.5	28.3	7.75	92.3	28.6
6/25/2011	9:41	7.97	26.98	28	7.74	91.96	28.2
6/25/2011	11:28	5.36	26.08	28	5.65	86.02	28.2
6/25/2011	15:40	5.38	27.37	28.2	5.68	87.33	28.5
6/26/2011	9:30	5.43	26.89	27.9	5.65	84.09	28.1
6/26/2011	12:35	6.44	26.57	28.5	6.18	82.04	28.4
6/26/2011	15:30	5.62	26.54	28.3	5.79	81.83	28.3
6/28/2011	8:45	5.84	27.24	27.7	5.96	81.61	27.9
6/28/2011	12:53	5.73	26.94	28.3	5.91	81.69	28.5
6/28/2011	15:20	6.44	28.85	28.3	6.31	87.87	28.5
6/29/2011	8:27	6.25	28.67	27.4	6.15	85.44	27.6
6/29/2011	12:44	7.31	29.59	28.1	6.72	86.34	28.3
6/30/2011	9:10	6.03	26.24	26.9	5.99	75.84	27
6/30/2011	15:19	6.27	27.58	27.3	6.25	79.96	27.5
7/1/2011	8:00	6.75	27.81	27.2	6.16	78.57	27.4
7/1/2011	15:17	6.89	25.96	27.8	6.35	73.47	28.1
7/2/2011	8:10	6.75	26.96	27.4	6.51	75.02	27.6
7/2/2011	14:25	6.28	27.33	28.2	6.21	78.9	28.4
7/4/2011	8:00	6.47	25.86	27.2	6.21	72.6	27.5
7/4/2011	3:10	5.97	25.92	28.4	6.04	76.94	28.4
7/5/2011	8:10	5.73	25.46	26.9	5.8	72.78	27.3
7/5/2011	15:20	6.15	24.32	28.9	6.04	74.54	28.7
7/6/2011	7:50	5.81	23.73	27.3	6.21	70.09	27.4
7/6/2011	14:51	6.12	21.19	28.5	6.11	61.95	28.5
7/7/2011	7:50	6.24	23.1	27.6	6.2	65.53	27.9
7/7/2011	15:15	6.1	20.62	28.7	6.02	58.24	28.7
7/8/2011	7:54	6.76	20.72	27.5	6.36	56.24	27.9
7/8/2011	2:54	5.72	20.59	28.6	5.72	58.03	28.9

Date	Time	Stage 1 Permeate			Stage 2 Permeate		
		pH	Cond	Temp	pH	Cond	Temp
			µS/cm	°C		µS/cm	°C
7/9/2011	7:50	6.02	21.51	27.9	5.6	55.96	28.3
7/9/2011	15:20	5.73	19.45	28.2	5.75	50.69	28.5
7/11/2011	7:55	5.43	21.01	28.6	5.6	54.57	29
7/11/2011	15:00	5.79	21.77	29.2	5.84	57.54	29.6
7/12/2011	7:50	5.38	21.3	27.8	5.52	49.26	28.1
7/12/2011	15:15	5.59	18.14	28.6	5.72	40.63	28.7
7/13/2011	7:55	5.38	18.65	28.2	5.33	47.5	28.2
7/13/2011	15:15	5.61	17.21	28.7	5.63	34.98	28.7
7/14/2011	8:00	5.37	18.25	28.7	5.48	34.85	28.4
7/14/2011	15:09	5.4	17.96	29.1	5.45	35.67	28.8
7/15/2011	7:55	5.55	17.11	27.8	5.58	33.07	28.1
7/15/2011	15:20	5.6	16.73	29	5.56	32.41	28.8
7/16/2011	8:00	5.52	17.29	28.1	5.55	33.12	28.4
7/16/2011	14:30	5.5	17.09	28.5	5.59	33.21	28.7
7/18/2011	8:00	5.37	20.05	28.7	5.45	33.8	28.9
7/18/2011	15:00	5.34	17.12	28.4	5.44	34.14	28.6
7/19/2011	7:55	5.34	18.34	28.2	5.45	34.86	28.5
7/19/2011	15:00	5.43	17.26	28.4	5.55	34.65	28.7
7/20/2011	8:10	5.33	16.85	27.8	5.46	32.82	28.1
7/20/2011	15:00	5.38	16.3	28.6	5.48	33.51	28.8
7/21/2011	7:33	5.28	16.6	28.3	5.39	34.56	28.6
7/21/2011	14:43	5.42	17.54	30.2	5.57	39.32	29.9
7/22/2011	7:41	5.31	17.65	28.3	5.43	39.35	28.6
7/22/2011	15:05	5.74	16.28	28.7	5.57	37.87	28.9
7/23/2011	8:28	5.6	16.78	28.6	5.39	41.05	28.9
7/23/2011	10:33	5.89	11.22	32.4	5.76	14.45	32.1
7/23/2011	11:00	5.62	10.64	22.6	5.74	12.58	33.8

Table B-7. – Digital Flow and Recovery Data

Cumulative Time On in Hrs	Date/Time	Flow (gpm)				Recovery (fraction)
		RO Feed, P6 (FS4)	1st Stage Permeate, HP Array (FS5)	2nd Stage Permeate, PX Array (FS6)	1st Pass Brine, PX Array (FS7) Calc	
1	6/25/11 9:04	121	58	33	30	0.75
2	6/25/11 9:44	120	58	33	29	0.76
3	6/25/11 10:39	122	57	33	32	0.74
4	6/25/11 11:40	120	58	33	29	0.76
5	6/25/11 12:41	118	58	33	27	0.77
6	6/25/11 13:42	120	64	34	22	0.82
7	6/25/11 14:43	118	63	35	20	0.83
8	6/25/11 15:35	121	62	34	25	0.79
9	6/27/11 9:01	120	58	34	28	0.77
10	6/27/11 10:01	120	56	35	29	0.76
11	6/27/11 11:02	122	56	34	32	0.74
12	6/27/11 12:04	125	58	35	32	0.74
13	6/27/11 13:05	119	56	34	29	0.76
14	6/27/11 14:07	122	60	35	27	0.78
15	6/27/11 15:08	121	58	34	29	0.76
16	6/28/11 8:07	121	58	34	29	0.76
17	6/28/11 9:08	120	57	33	30	0.75
18	6/28/11 10:08	118	58	35	25	0.79
19	6/28/11 11:09	120	58	34	28	0.77
20	6/28/11 12:10	122	55	34	33	0.73
21	6/28/11 13:11	120	57	34	29	0.76
22	6/28/11 14:12	118	63	33	22	0.81
23	6/28/11 15:13	119	64	32	23	0.81
24	6/29/11 7:55	120	61	34	25	0.79
25	6/29/11 8:58	119	62	33	24	0.80
26	6/29/11 10:01	119	63	33	23	0.81

Cumulative Time On in Hrs	Date/Time	Flow (gpm)				Recovery (fraction)
		RO Feed, P6 (FS4)	1st Stage Permeate, HP Array (FS5)	2nd Stage Permeate, PX Array (FS6)	1st Pass Brine, PX Array (FS7) Calc	
27	6/29/11 11:03	120	61	33	26	0.78
28	6/29/11 12:06	118	64	33	21	0.82
29	6/29/11 13:09	120	64	33	23	0.81
30	6/30/11 8:35	120	55	33	32	0.73
31	6/30/11 9:36	120	57	34	29	0.76
32	6/30/11 10:37	119	56	34	29	0.76
33	6/30/11 11:38	121	57	34	30	0.75
34	6/30/11 12:39	120	55	34	31	0.74
35	6/30/11 13:40	120	56	34	30	0.75
36	6/30/11 14:41	121	55	33	33	0.73
37	6/30/11 15:42	119	56	34	29	0.76
38	7/1/11 8:34	118	55	33	30	0.75
39	7/1/11 9:36	122	56	33	33	0.73
40	7/1/11 10:37	121	57	33	31	0.74
41	7/1/11 11:39	119	58	34	27	0.77
42	7/1/11 12:40	121	53	33	35	0.71
43	7/1/11 13:41	119	56	32	31	0.74
44	7/1/11 14:42	120	54	33	33	0.73
45	7/1/11 15:43	119	54	34	31	0.74
46	7/2/11 8:52	118	62	32	24	0.80
47	7/2/11 9:53	120	62	31	27	0.78
48	7/2/11 10:54	120	62	32	26	0.78
49	7/2/11 11:55	121	63	32	26	0.79
50	7/2/11 12:56	121	62	32	27	0.78
51	7/2/11 13:57	120	63	32	25	0.79
52	7/2/11 14:58	120	60	32	28	0.77
53	7/4/11 7:40	119	57	34	28	0.76

Cumulative Time On in Hrs	Date/Time	Flow (gpm)				Recovery (fraction)
		RO Feed, P6 (FS4)	1st Stage Permeate, HP Array (FS5)	2nd Stage Permeate, PX Array (FS6)	1st Pass Brine, PX Array (FS7) Calc	
54	7/4/11 8:41	119	58	33	28	0.76
55	7/4/11 9:41	120	56	33	31	0.74
56	7/4/11 10:42	119	57	34	28	0.76
57	7/4/11 11:43	121	55	34	32	0.74
58	7/4/11 12:44	121	57	34	30	0.75
59	7/4/11 13:45	122	57	33	32	0.74
60	7/4/11 14:45	120	55	34	31	0.74
61	7/4/11 15:46	120	56	34	30	0.75
62	7/5/11 9:38	117	55	34	28	0.76
63	7/5/11 10:38	120	58	34	28	0.77
64	7/5/11 11:39	118	54	34	30	0.75
65	7/5/11 12:40	120	54	34	32	0.73
66	7/5/11 13:41	119	57	34	28	0.76
67	7/5/11 14:42	119	55	34	30	0.75
68	7/5/11 15:43	119	56	34	29	0.76
69	7/6/11 8:10	119	56	35	28	0.76
70	7/6/11 9:12	119	56	34	29	0.76
71	7/6/11 10:17	120	53	35	32	0.73
72	7/6/11 11:18	118	55	34	29	0.75
73	7/6/11 12:19	119	59	35	25	0.79
74	7/6/11 13:20	119	53	35	31	0.74
75	7/6/11 14:20	118	55	34	29	0.75
76	7/6/11 15:21	119	55	35	29	0.76
77	7/7/11 8:09	119	56	34	29	0.76
78	7/7/11 9:09	118	57	34	27	0.77
79	7/7/11 10:10	120	55	33	32	0.73
80	7/7/11 11:11	118	54	35	29	0.75

Cumulative Time On in Hrs	Date/Time	Flow (gpm)				Recovery (fraction)
		RO Feed, P6 (FS4)	1st Stage Permeate, HP Array (FS5)	2nd Stage Permeate, PX Array (FS6)	1st Pass Brine, PX Array (FS7) Calc	
81	7/7/11 12:12	119	56	35	28	0.76
82	7/7/11 13:12	120	58	34	28	0.77
83	7/7/11 14:13	121	55	33	33	0.73
84	7/7/11 15:14	118	55	34	29	0.75
85	7/8/11 8:04	119	55	36	28	0.76
86	7/8/11 9:20	120	55	35	30	0.75
87	7/8/11 10:20	118	54	34	30	0.75
88	7/8/11 11:21	119	55	35	29	0.76
89	7/8/11 12:22	121	55	35	31	0.74
90	7/8/11 13:23	120	56	34	30	0.75
91	7/8/11 14:24	119	53	34	32	0.73
92	7/9/11 7:54	119	54	35	30	0.75
93	7/9/11 8:57	118	52	35	31	0.74
94	7/9/11 9:58	118	51	35	32	0.73
95	7/9/11 10:59	119	54	35	30	0.75
96	7/9/11 11:59	118	51	35	32	0.73
97	7/9/11 13:00	117	51	35	31	0.74
98	7/9/11 14:01	118	52	35	31	0.74
99	7/9/11 15:02	119	49	35	35	0.71
100	7/11/11 7:45	119	55	34	30	0.75
101	7/11/11 8:46	119	52	35	32	0.73
102	7/11/11 9:48	118	51	35	32	0.73
103	7/11/11 10:49	120	53	35	32	0.73
104	7/11/11 11:50	119	51	34	34	0.71
105	7/11/11 12:50	119	53	35	31	0.74
106	7/11/11 15:17	119	57	34	28	0.76
107	7/12/11 8:05	121	54	34	33	0.73

Cumulative Time On in Hrs	Date/Time	Flow (gpm)				Recovery (fraction)
		RO Feed, P6 (FS4)	1st Stage Permeate, HP Array (FS5)	2nd Stage Permeate, PX Array (FS6)	1st Pass Brine, PX Array (FS7) Calc	
108	7/12/11 9:06	118	53	34	31	0.74
109	7/12/11 10:07	118	57	35	26	0.78
110	7/12/11 11:08	120	55	34	31	0.74
111	7/12/11 12:08	118	56	35	27	0.77
112	7/12/11 13:09	119	52	35	32	0.73
113	7/12/11 14:10	119	55	35	29	0.76
114	7/12/11 15:11	119	55	35	29	0.76
115	7/13/11 8:09	118	57	35	26	0.78
116	7/13/11 9:09	119	54	36	29	0.76
117	7/13/11 10:10	121	53	35	33	0.73
118	7/13/11 11:11	119	56	35	28	0.76
119	7/13/11 12:12	119	55	35	29	0.76
120	7/13/11 13:13	117	54	35	28	0.76
121	7/13/11 14:14	119	56	35	28	0.76
122	7/13/11 15:14	119	53	34	32	0.73
123	7/14/11 8:29	117	56	36	25	0.79
124	7/14/11 9:30	119	54	35	30	0.75
125	7/14/11 10:30	119	54	35	30	0.75
126	7/14/11 11:32	120	53	36	31	0.74
127	7/14/11 12:33	118	55	35	28	0.76
128	7/14/11 13:33	119	55	36	28	0.76
129	7/15/11 7:57	117	53	35	29	0.75
130	7/15/11 8:57	118	50	36	32	0.73
131	7/15/11 9:58	120	52	36	32	0.73
132	7/15/11 10:59	120	50	36	34	0.72
133	7/15/11 12:00	120	51	36	33	0.73
134	7/15/11 13:00	119	51	36	32	0.73

Cumulative Time On in Hrs	Date/Time	Flow (gpm)				Recovery (fraction)
		RO Feed, P6 (FS4)	1st Stage Permeate, HP Array (FS5)	2nd Stage Permeate, PX Array (FS6)	1st Pass Brine, PX Array (FS7) Calc	
135	7/15/11 14:01	120	54	36	30	0.75
136	7/15/11 15:02	119	52	35	32	0.73
137	7/16/11 8:22	120	49	35	36	0.70
138	7/16/11 9:23	119	51	36	32	0.73
139	7/16/11 10:24	120	51	35	34	0.72
140	7/16/11 11:25	119	52	35	32	0.73
141	7/16/11 12:27	120	50	35	35	0.71
142	7/16/11 13:28	119	50	35	34	0.71
143	7/16/11 14:29	121	50	35	36	0.70
144	7/18/11 7:53	120	56	35	29	0.76
145	7/18/11 8:54	119	51	36	32	0.73
146	7/18/11 9:56	119	53	35	31	0.74
147	7/18/11 10:57	119	54	36	29	0.76
148	7/18/11 11:58	119	53	35	31	0.74
149	7/18/11 12:59	119	51	35	33	0.72
150	7/18/11 14:01	118	55	35	28	0.76
151	7/18/11 15:02	119	52	35	32	0.73
152	7/19/11 8:05	119	48	35	36	0.70
153	7/19/11 9:06	119	49	35	35	0.71
154	7/19/11 10:07	118	50	36	32	0.73
155	7/19/11 11:09	121	49	35	37	0.69
156	7/19/11 12:10	121	49	35	37	0.69
157	7/19/11 13:11	117	49	35	33	0.72
158	7/19/11 14:12	119	49	35	35	0.71
159	7/19/11 15:13	119	52	34	33	0.72
160	7/20/11 8:31	118	50	34	34	0.71
161	7/20/11 9:32	120	48	35	37	0.69

Cumulative Time On in Hrs	Date/Time	Flow (gpm)				Recovery (fraction)
		RO Feed, P6 (FS4)	1st Stage Permeate, HP Array (FS5)	2nd Stage Permeate, PX Array (FS6)	1st Pass Brine, PX Array (FS7) Calc	
162	7/20/11 10:33	119	52	34	33	0.72
163	7/20/11 11:34	120	51	35	34	0.72
164	7/20/11 12:35	121	52	35	34	0.72
165	7/20/11 13:35	121	50	35	36	0.70
166	7/20/11 14:36	118	51	35	32	0.73
167	7/21/11 7:40	120	48	35	37	0.69
168	7/21/11 8:40	118	56	36	26	0.78
169	7/21/11 9:41	118	54	36	28	0.76
170	7/21/11 10:42	120	54	35	31	0.74
171	7/21/11 11:43	120	56	36	28	0.77
172	7/21/11 12:43	119	54	36	29	0.76
173	7/21/11 15:09	118	56	34	28	0.76
174	7/22/11 8:35	118	58	36	24	0.80
175	7/22/11 9:36	117	56	35	26	0.78
176	7/22/11 10:36	120	57	36	27	0.78
177	7/22/11 11:37	120	58	37	25	0.79
178	7/22/11 12:38	119	55	36	28	0.76
179	7/22/11 13:39	118	57	35	26	0.78
180	7/22/11 14:40	121	55	36	30	0.75
181	7/23/11 9:40	117	51	34	32	0.73
182	7/23/11 10:41	121	53	36	32	0.74

Table B-8. – Digital Pressure Data

Cumulative Time On in Hrs	Date/Time	Pressure (lb/in^2)				
		RO HP Pump Suction (PS8)	RO 1st Pass Perm (PS11)	RO 1st Stage Feed, (PS9)	RO 2nd Stage Feed (PS10)	2nd Stage Concentrate (PS13)
1	6/25/11 9:04	23	21	227	202	176
2	6/25/11 9:44	23	21	234	204	178
3	6/25/11 10:39	23	22	228	205	179
4	6/25/11 11:40	23	22	231	205	178
5	6/25/11 12:41	22	22	236	205	179
6	6/25/11 13:42	22	19	234	202	176
7	6/25/11 14:43	22	19	230	203	177
8	6/25/11 15:35	22	19	229	203	177
9	6/27/11 9:01	22	21	227	202	174
10	6/27/11 10:01	22	21	234	205	179
11	6/27/11 11:02	22	21	232	206	179
12	6/27/11 12:04	21	21	233	205	179
13	6/27/11 13:05	22	21	232	204	177
14	6/27/11 14:07	22	21	233	204	177
15	6/27/11 15:08	22	21	231	204	177
16	6/28/11 8:07	32	21	232	204	177
17	6/28/11 9:08	32	21	237	207	179
18	6/28/11 10:08	32	21	234	206	179
19	6/28/11 11:09	32	21	242	207	180
20	6/28/11 12:10	32	21	235	207	179
21	6/28/11 13:11	32	21	233	206	178
22	6/28/11 14:12	33	23	233	209	181
23	6/28/11 15:13	33	23	245	211	183
24	6/29/11 7:55	34	23	244	211	184
25	6/29/11 8:58	32	22	241	211	182
26	6/29/11 10:01	33	23	239	210	183

Cumulative Time On in Hrs	Date/Time	Pressure (lb/in^2)				
		RO HP Pump Suction (PS8)	RO 1st Pass Perm (PS11)	RO 1st Stage Feed, (PS9)	RO 2nd Stage Feed (PS10)	2nd Stage Concentrate (PS13)
27	6/29/11 11:03	33	22	238	210	183
28	6/29/11 12:06	33	22	242	209	182
29	6/29/11 13:09	33	22	236	207	181
30	6/30/11 8:35	33	22	236	210	183
31	6/30/11 9:36	34	22	239	210	180
32	6/30/11 10:37	33	22	238	210	181
33	6/30/11 11:38	34	23	236	210	181
34	6/30/11 12:39	33	22	236	210	180
35	6/30/11 13:40	33	22	236	210	181
36	6/30/11 14:41	33	22	236	210	182
37	6/30/11 15:42	33	22	233	210	182
38	7/1/11 8:34	33	22	241	209	181
39	7/1/11 9:36	33	22	241	209	181
40	7/1/11 10:37	33	22	239	208	180
41	7/1/11 11:39	33	22	229	207	180
42	7/1/11 12:40	33	22	238	208	180
43	7/1/11 13:41	33	22	234	206	179
44	7/1/11 14:42	33	22	235	206	179
45	7/1/11 15:43	33	23	236	206	179
46	7/2/11 8:52	34	21	241	208	180
47	7/2/11 9:53	33	21	234	207	179
48	7/2/11 10:54	33	21	242	208	180
49	7/2/11 11:55	32	21	230	207	179
50	7/2/11 12:56	33	20	236	208	181
51	7/2/11 13:57	33	21	240	208	180
52	7/2/11 14:58	33	20	241	208	180
53	7/4/11 7:40	34	23	238	211	182

Cumulative Time On in Hrs	Date/Time	Pressure (lb/in^2)				
		RO HP Pump Suction (PS8)	RO 1st Pass Perm (PS11)	RO 1st Stage Feed, (PS9)	RO 2nd Stage Feed (PS10)	2nd Stage Concentrate (PS13)
54	7/4/11 8:41	33	23	243	210	182
55	7/4/11 9:41	33	21	241	210	183
56	7/4/11 10:42	33	22	238	210	182
57	7/4/11 11:43	33	22	240	209	180
58	7/4/11 12:44	33	21	242	209	181
59	7/4/11 13:45	33	22	242	211	182
60	7/4/11 14:45	33	22	245	211	183
61	7/4/11 15:46	33	22	238	211	185
62	7/5/11 9:38	37	22	249	220	194
63	7/5/11 10:38	37	23	249	220	194
64	7/5/11 11:39	37	22	250	220	192
65	7/5/11 12:40	37	23	251	220	195
66	7/5/11 13:41	37	22	249	221	195
67	7/5/11 14:42	37	23	250	221	195
68	7/5/11 15:43	37	22	253	221	196
69	7/6/11 8:10	37	23	254	226	200
70	7/6/11 9:12	37	22	255	227	199
71	7/6/11 10:17	37	22	255	226	199
72	7/6/11 11:18	37	23	261	226	200
73	7/6/11 12:19	37	23	257	225	195
74	7/6/11 13:20	37	22	254	226	198
75	7/6/11 14:20	37	23	256	226	198
76	7/6/11 15:21	37	23	256	224	200
77	7/7/11 8:09	37	23	258	227	200
78	7/7/11 9:09	37	23	252	228	201
79	7/7/11 10:10	37	23	257	228	202
80	7/7/11 11:11	37	23	260	227	199

Cumulative Time On in Hrs	Date/Time	Pressure (lb/in^2)				
		RO HP Pump Suction (PS8)	RO 1st Pass Perm (PS11)	RO 1st Stage Feed, (PS9)	RO 2nd Stage Feed (PS10)	2nd Stage Concentrate (PS13)
81	7/7/11 12:12	37	23	260	228	200
82	7/7/11 13:12	37	23	260	229	204
83	7/7/11 14:13	37	23	254	227	200
84	7/7/11 15:14	37	23	258	227	200
85	7/8/11 8:04	37	23	262	229	202
86	7/8/11 9:20	37	23	259	231	203
87	7/8/11 10:20	37	23	264	230	203
88	7/8/11 11:21	37	23	261	230	203
89	7/8/11 12:22	37	23	258	230	202
90	7/8/11 13:23	37	23	262	231	205
91	7/8/11 14:24	37	22	262	233	207
92	7/9/11 7:54	38	23	265	232	203
93	7/9/11 8:57	37	23	272	236	210
94	7/9/11 9:58	37	23	266	237	210
95	7/9/11 10:59	37	22	268	237	211
96	7/9/11 11:59	37	23	268	236	211
97	7/9/11 13:00	37	22	265	236	207
98	7/9/11 14:01	37	22	268	236	209
99	7/9/11 15:02	38	23	267	236	208
100	7/11/11 7:45	37	23	260	234	199
101	7/11/11 8:46	37	22	263	244	216
102	7/11/11 9:48	37	22	271	243	215
103	7/11/11 10:49	37	22	274	244	216
104	7/11/11 11:50	37	22	268	244	216
105	7/11/11 12:50	37	22	277	246	216
106	7/11/11 15:17	37	21	277	245	216
107	7/12/11 8:05	38	23	275	248	220

Cumulative Time On in Hrs	Date/Time	Pressure (lb/in^2)				
		RO HP Pump Suction (PS8)	RO 1st Pass Perm (PS11)	RO 1st Stage Feed, (PS9)	RO 2nd Stage Feed (PS10)	2nd Stage Concentrate (PS13)
108	7/12/11 9:06	37	22	280	250	217
109	7/12/11 10:07	37	22	281	250	224
110	7/12/11 11:08	37	22	281	250	227
111	7/12/11 12:08	37	22	285	251	221
112	7/12/11 13:09	37	22	285	251	224
113	7/12/11 14:10	37	22	273	248	222
114	7/12/11 15:11	37	21	280	247	222
115	7/13/11 8:09	37	23	278	247	215
116	7/13/11 9:09	37	22	278	247	217
117	7/13/11 10:10	37	23	285	247	218
118	7/13/11 11:11	37	22	280	246	217
119	7/13/11 12:12	37	22	274	246	219
120	7/13/11 13:13	37	23	274	248	216
121	7/13/11 14:14	37	22	278	248	218
122	7/13/11 15:14	37	23	280	250	220
123	7/14/11 8:29	37	22	284	251	220
124	7/14/11 9:30	37	22	284	252	224
125	7/14/11 10:30	37	23	285	252	222
126	7/14/11 11:32	37	23	278	250	219
127	7/14/11 12:33	37	22	284	251	217
128	7/14/11 13:33	36	22	286	252	224
129	7/15/11 7:57	38	22	282	252	222
130	7/15/11 8:57	37	22	283	258	225
131	7/15/11 9:58	37	22	292	257	228
132	7/15/11 10:59	37	22	281	255	230
133	7/15/11 12:00	37	22	282	255	228
134	7/15/11 13:00	37	22	285	256	227

Cumulative Time On in Hrs	Date/Time	Pressure (lb/in^2)				
		RO HP Pump Suction (PS8)	RO 1st Pass Perm (PS11)	RO 1st Stage Feed, (PS9)	RO 2nd Stage Feed (PS10)	2nd Stage Concentrate (PS13)
135	7/15/11 14:01	37	22	288	255	226
136	7/15/11 15:02	37	22	290	256	225
137	7/16/11 8:22	37	22	287	261	231
138	7/16/11 9:23	37	22	291	262	231
139	7/16/11 10:24	37	22	294	262	230
140	7/16/11 11:25	37	22	289	262	234
141	7/16/11 12:27	37	22	295	262	231
142	7/16/11 13:28	37	22	293	263	232
143	7/16/11 14:29	37	22	296	262	230
144	7/18/11 7:53	37	22	275	249	221
145	7/18/11 8:54	37	22	293	261	229
146	7/18/11 9:56	37	23	284	262	232
147	7/18/11 10:57	37	22	294	262	227
148	7/18/11 11:58	38	22	294	262	232
149	7/18/11 12:59	37	22	291	262	230
150	7/18/11 14:01	37	23	292	262	234
151	7/18/11 15:02	37	22	300	262	238
152	7/19/11 8:05	38	22	293	263	228
153	7/19/11 9:06	37	21	295	266	233
154	7/19/11 10:07	37	22	296	264	229
155	7/19/11 11:09	38	21	297	263	235
156	7/19/11 12:10	37	22	286	263	233
157	7/19/11 13:11	38	22	300	263	234
158	7/19/11 14:12	37	21	291	263	234
159	7/19/11 15:13	37	21	299	264	234
160	7/20/11 8:31	37	21	297	264	235
161	7/20/11 9:32	38	22	294	263	232

Cumulative Time On in Hrs	Date/Time	Pressure (lb/in^2)				
		RO HP Pump Suction (PS8)	RO 1st Pass Perm (PS11)	RO 1st Stage Feed, (PS9)	RO 2nd Stage Feed (PS10)	2nd Stage Concentrate (PS13)
162	7/20/11 10:33	37	21	293	263	233
163	7/20/11 11:34	37	21	298	263	229
164	7/20/11 12:35	38	21	287	262	232
165	7/20/11 13:35	37	21	294	262	232
166	7/20/11 14:36	37	21	297	262	231
167	7/21/11 7:40	37	22	292	262	231
168	7/21/11 8:40	38	23	314	282	255
169	7/21/11 9:41	37	23	317	282	254
170	7/21/11 10:42	37	23	311	279	253
171	7/21/11 11:43	38	22	305	281	255
172	7/21/11 12:43	37	22	312	279	255
173	7/21/11 15:09	37	24	308	274	249
174	7/22/11 8:35	37	22	313	280	256
175	7/22/11 9:36	37	23	304	281	255
176	7/22/11 10:36	37	23	309	279	251
177	7/22/11 11:37	38	23	314	279	252
178	7/22/11 12:38	37	23	306	278	249
179	7/22/11 13:39	37	23	304	278	251
180	7/22/11 14:40	37	23	311	280	255
181	7/23/11 9:40	38	20	276	244	211
182	7/23/11 10:41	37	22	216	185	155

Appendix C

Treatment of Variable Water Sources: Adaptations for a Flexible Desalination System

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Treatment of Variable Water Sources: Adaptations for a Flexible Desalination System

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Abstract
There are a number of locations where a utility might want to be able to treat multiple sources of water with one treatment system. A few that are of current interest at the Bureau of Reclamation (Reclamation) are:

- The Texas Gulf Coast where brackish surface or groundwater is available for much of the year but only seawater is available during dry seasons;
- South Central California where the character of the irrigation drainage water changes with the intensity of irrigation;
- Inland desert areas where the composition of brackish surface and groundwater is significantly different when augmented with storm water.

In each situation the composition of source water varies widely over the year, or even shorter periods in the case of irrigation drainage which changes with the irrigation cycle. It is not practical to build separate facilities to treat water at different times of the year. A system with built in flexibility to adapt to changing water composition would be preferable. Examples of how flexibility can be built in to a reverse osmosis design are presented based on a brackish water membrane system modeled using Hydranautics IMS Design software, and a seawater system designed using Dow FilmTec's Reverse Osmosis System Analysis software. In both cases the conversion from one source water to another can be accomplished with a few extra valves and a supplemental pump for the brackish water case. Seawater is accommodated with a brackish system by lowering recovery from 75 to 50% and converting the second stage to a second pass. Brackish water is accommodated in the seawater system by converting one third of the system operating on concentrate pressure to a second stage operating at the residual pressure from the concentrate of the other two thirds of the system which then form the first stage of the brackish system.

Keywords
Seawater, Brackish, Desalination, variable source water.

BACKGROUND

Location of a desalination plant is determined by the need for and availability of additional water. Location is determined by access to water, adequate space, and power supply. Capacity is determined by the expected demand for and availability of water. However the design of a desalting plant process is typically based on the composition of the feed water. In the ideal case the designer knows the average composition, including concentrations of minor species, and the seasonal variation of the various components.

But what if the feed source varies widely in composition? There are at least three ways to tackle the problem:

1) Design for the most extreme case and take the inherent inefficiencies the rest of the year,
2) Design for the most common case, allowing for extra storage to ride out extreme events, or
3) Design a flexible system with materials and capabilities to accommodate the extreme events while operating efficiently during the moderate conditions.

For this study we will examine the issue starting with the type of membrane: a brackish water membrane that is used for seawater and a seawater membrane system that occasionally is used for brackish water. The Long Beach, California two-stage nanofiltration system is an example of the first case. An example of the second is the Expeditionary Unit Water Purifier (EUWP), designed to treat any source up to 60 grams/L seawater up to 50°C to fresh surface water.

Brackish System Treating Seawater

The Long Beach seawater nanofiltration system is advertized as a low-pressure, economic option for seawater desalination (Covelli, 2004). The membranes are not true nanofiltration since they are capable of greater than 90% rejection of sodium chloride. Permeate from the first pass is fed to a second permeate pass to produce potable water. Concentrate from the second pass is returned to the first pass feed. The overall recovery using this method is 33%.

Seawater System Treating Brackish Sources

The EUWP was developed by the Office of Naval Research EUWP team which included the US Army Tank Automotive Command, Naval Sea Systems Command, Naval Facilities Engineering Service Center, and the Bureau of Reclamation. The objective was to design a high productivity mobile system to fit in two 1CC ISO containers (6m long x 2.4m high x 2.4m wide) (20 ft x 8 ft x 8 ft) weighing a bit more than 7 metric tons each(15,500 lbs). The system uses ultrafiltration pretreatment with the option of chemical coagulation, followed by reverse osmosis with an Energy Recovery Inc. pressure exchanger to pressurize one third of the system without an additional booster pump.

The system was evaluated on seawater, brackish municipal wastewater, and fresh surface water under the Environmental Protection Agency's Environmental Technology Validation (ETV) program. The system worked well operating both systems together, but the 50% recovery limitation for the brackish wastewater was not an acceptable process for the water poor desert area hosting the test. Opportunities have arisen since the unit was completed for emergency response missions but the waste of 50% of the water was deemed unacceptable. The system needs the flexibility to operate on brackish water at a higher recovery rate.

Flexible System

These two examples provide clues to design options for a flexible system. With a few plumbing alterations both low recovery, energy efficient seawater systems could be converted to produce potable water from a brackish source while increasing recovery and maintaining energy efficiency due to higher water production with similar energy demand. Before plunging into design options a review of the design basis for recovery, energy efficiency, and permeate quality are examined.

Recovery. The recovery of a membrane desalination system is controlled by the number of modules in the system. One standard sized module can recovery about 10% of the feed water to that module. Pressure at that point in the system must be high enough to overcome the osmotic pressure of the mixed feed and concentrate at that point as well as the hydraulic resistance of the membrane and the module itself. A rule of thumb is that one stage is capable of no more than 50% recovery of permeate.

If the salinity of the concentrate is low enough that there is still enough hydraulic pressure to overcome the osmotic pressure and other resistances, then a second stage can be used to attain another 50% for 75% overall recovery. The number of vessels in the second concentrate stage is typically one half that of the first stage so that the feed flow is equivalent to the first stage.
In seawater systems the osmotic pressure of the first stage concentrate is too high to gain further permeate without a pressure boost. It is more economical to just stop at 40-50% recovery in seawater reverse osmosis and to recover the pressure left in the concentrate to help pressurize the feed.

Energy Efficiency. Energy efficiency is obtained in RO systems either by using the energy remaining in the concentrate stream to pressurize more water or ease the burden on the high pressure pump, or by using thinner, high productivity, low pressure, membranes while accepting a lower rejection of salts. The Affordable Desalination Collaborative has demonstrated the most efficient high pressure RO desalination with pretreatment at 2.75 – 2.98 kWh/m3 (10.4 – 11.3 kWh/kgal) with 50% water recovery (MacHarg, Seacord, & Sessions, 2008).

Permeate Quality. Permeate, or product water quality is a function of the feed water quality, membrane selectivity, and rate of recovery. Seawater membranes have a very low salt passage rate, so that permeate from a 50% recovery system treating seawater will have less than 500 mg/L dissolved salts. If brackish water membranes, with less than 99.2% rejection are used with seawater, the permeate will not meet drinking water standards and a second pass will be needed, as with the Long Beach process, resulting in a lower overall recovery. Conversely, if seawater membranes are used to treat brackish water at only 50% recovery the permeate will have very low dissolved solids and will require further treatment for stabilization or blending with another source of water.

BRACKISH WATER SYSTEM

Two places where high variability in a brackish source water are found are in southern Texas near where the Rio Grande meets, or used to meet, the sea and also in Panoche, CA where irrigation drainage ranges from mildly brackish to one half seawater concentration. Production of the proposed systems is 3785 m^3/day (one million gallons per day) with recovery ranging from 40% for seawater to 70% or more for the brackish source. Stabilized product quality must be no more 500 mg/L dissolved solids.

Projections were developed using Hydranautics' IMSDesign program, version 2008. Various configurations were evaluated, first to explore the variability available in operation and arrangement within the limitations published for the membrane elements, then to determine how the flow would be changed to use the same membrane equipment to treat two different waters.

Basis of Conceptual Design

As much of the equipment as possible must be used for both treatment configurations. Pretreatment is assumed to be ultrafiltration adequate to produce sufficient RO feed water with less than 0.1 NTU and less than 3.0 Silt Density Index to attain the desired RO system productivity. Recovery of the RO system is the highest attainable with antiscalants to ensure long term operational stability.

Composition of Feed Waters

Seawater was taken as standard seawater with Total Dissolved Solids (TDS) of 34500 mg/L. Brackish water is expected to vary in composition with an average of 2500 mg/L TDS with slightly positive Langelier Index and characteristic ratios of various scaling compounds. It is water that is likely to scale membrane surfaces as the reject becomes more concentrated, thus, by design, a challenging water to desalt.

Product Properties

The initial basis capacity will be 3785 m^3/day (one million gallons per day). The range over which this plant can be operated while staying within the manufacturer's requirements for element operation will be determined. Design recovery as product will be 40 to 50% for seawater and 70% or more for brackish water. The desired product quality is approximately 350 mg/L TDS to allow addition of sufficient chemicals like calcium hydroxide and carbon dioxide to produce a stabilized product with a finished TDS less than 500 mg/L.

Plant Characteristics

Various layouts and stagings were investigated including the two pass nanofiltration system developed by Long Beach Water Department. The desalting equipment will be configured around spiral wound elements, 8 inch nominal diameter and 40 inches length. Performance of RO elements was taken at an average age of 3 years. The plant will be designed for an operating fraction of 95%. Flexibility should be obtained at reasonable cost. The design program used incorporates the following operation limits. These limits were respected in the interest of having a well-operating plant.

Maximum feed flow rate (at inlet element)	284 L/min (75 gpm)
Minimum concentrate flow rate (at tail end element)	114 L/min (12 gpm).
Concentration polarization factor, β [1]	< 1.2
Langelier Saturation Index in brackish concentrate	< 1.8 [2]
Stiff & Davis Index in seawater concentrate	< ~0.75

Results

Variation of Flow. To determine the variability of operation of a unit, several units configured in different manners but using the same membrane element, ESPA1, the same number of elements, 240, and the same feed water, brackish, were calculated at different flow conditions as shown in table 1. Because of the way the program is organized, the recovery was held constant and different product rates were input. The change in product rate causes the feed rate to change. Operation of three unit configurations was calculated with the result shown in figure 1. Each data point shows the calculated operation of a unit. The relationship between product flow and pressure is linear with a non-zero intercept. Dashed extensions of each line represent operation when one or more parameter lies outside the recommended conditions. Generally, the upper lines represent better productivity, however the differences are modest.

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[1] This is the calculated ratio of the concentration at the membrane surface to the concentration of the bulk stream.

[2] If the concentration factor exceeds 100% or the LSI is positive, use of a scaling inhibitor is required.

Table 1. System configurations examined.

Configuration	Elements per Vessel	Number of Vessels in Stage 1	Number of Vessels in Stage 2	Number of Vessels in Stage 3
I	6	26	14	–
II	5	32	16	–
III	4	26	20	14

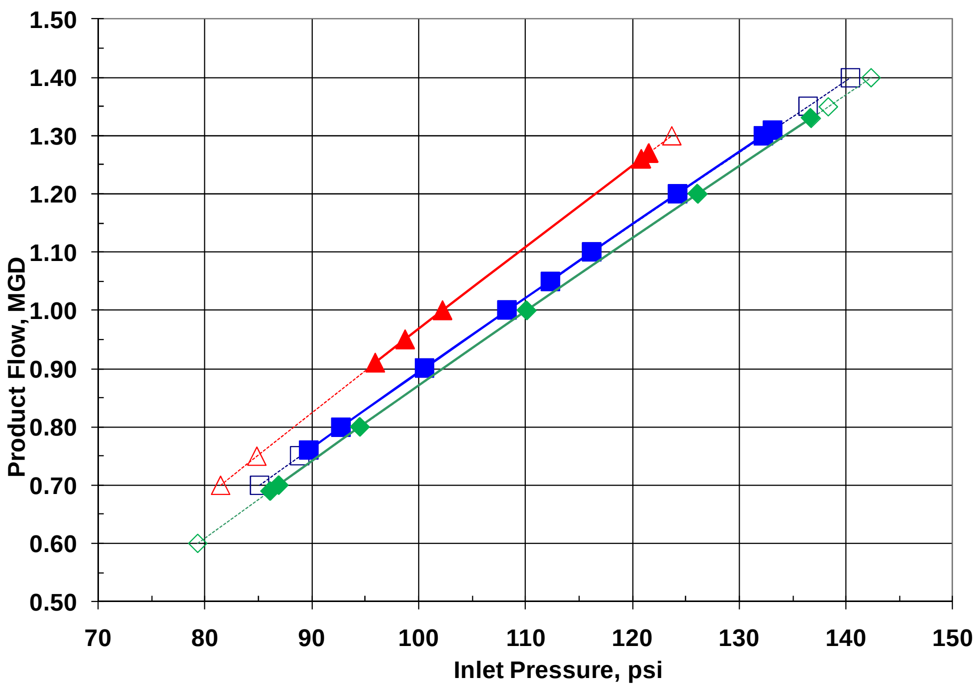

Figure 1. Relationship between Product Flow and Inlet Pressure. Triangles – 5 element/vessel, square – 6, and diamond – 4 element vessels. Open symbols are unacceptable operating conditions.

A factor affecting flexibility of operation is the range of feed flows, or product flows, over which the desalting unit can operate. Two values set the range over which a configuration can operate: the maximum flow at the entrance to the first element in a vessel, is set by the physical limits of the element to prevent "telescoping"; the minimum flow specification is for the concentrate end of the last element where excessive concentration polarization occurs. The configuration with 4 elements/ vessel gives the widest such range, with a ratio of maximum to minimum flow of 1.93. The 6 element/vessel unit was next with 1.72 and the ratio for the 5 element/vessel was 1.4.

Operating at different fluxes and driving pressures affects the product salinity. Generally product salinity below a certain value, say 350 mg/L, is only a collateral benefit if there is a plan to blend product with another stream, or with water not desalinated.

Variation of Type of Feed Water

A two stage arrangement of elements and vessels was determined that would meet the requirements for a flexible plant and the product water goals set out, i.e., product TDS is below 350 mg/L; all membrane equipment is used for both types of water; and for the design conditions, no design constraint stated by the manufacturer is violated. The brackish water plant consists of two stages with 26 vessels in the first stage and 14 vessels in the second. The first stage elements are ESPA2, a fairly high rejection thin-film composite membrane. The elements in the second stage are ESPA1, a similar element with slightly lower rejection. The feed pressure is 8 bar (122 psi) and the product TDS is 137 mg/L. The product flow is 3,785 m^3/day (1 MGD).

The seawater configuration consists of a first pass with 26 vessels (the same as the first stage of the brackish configuration). There is a two stage second pass, each stage containing 7 vessels. The feed pressure is 41 bar (596 lb/in^2) in the first pass and 9 bar (130 lb/in^2) in the second pass. The product TDS is 158 mg/L. The product flow is 1590 m^3/day (0.42 MGD).

A reasonable structure for the membrane portion of the plant would be racks 7 vessels high and two vessels wide. The first 26 vessels would fit on two such racks with two empty spaces. Connections from the vessels would be made to vertical manifolds. The 14 vessels (second stage for brackish, second pass for sea water) would fit on a third rack. Piping for the two modes of operation is shown diagrammatically below in figure 2. Connections near the edge of the vessel are to the feed-concentrate channel, connections at the center are to the product water pipe.

The changeover from one mode of operation to the other requires only a modest amount of rerouting of flows. Since the changes are almost all in the low pressure, low salinity portion of the plant, most of these changes can be made with valves. The one exception is at the point marked “concentrate”. The change required at this point is best made with blind flanges to avoid leakage of concentrated into the product stream. The concentrate stream exits the system at different places depending on the mode of operation.

Operation in the two different modes will require a flexible pumping system. Brackish water operation feed needs 1000 gpm at 122 psi. Seawater operation requires lower flow at substantially higher pressure: 836 gpm at 600 psi, as well as 350 gpm at 130 psi for the booster pump. Since the pressure for the second pass for the seawater plant is essentially the same as the feed pressure for the brackish water plant, part of the pump system can be used in both modes.

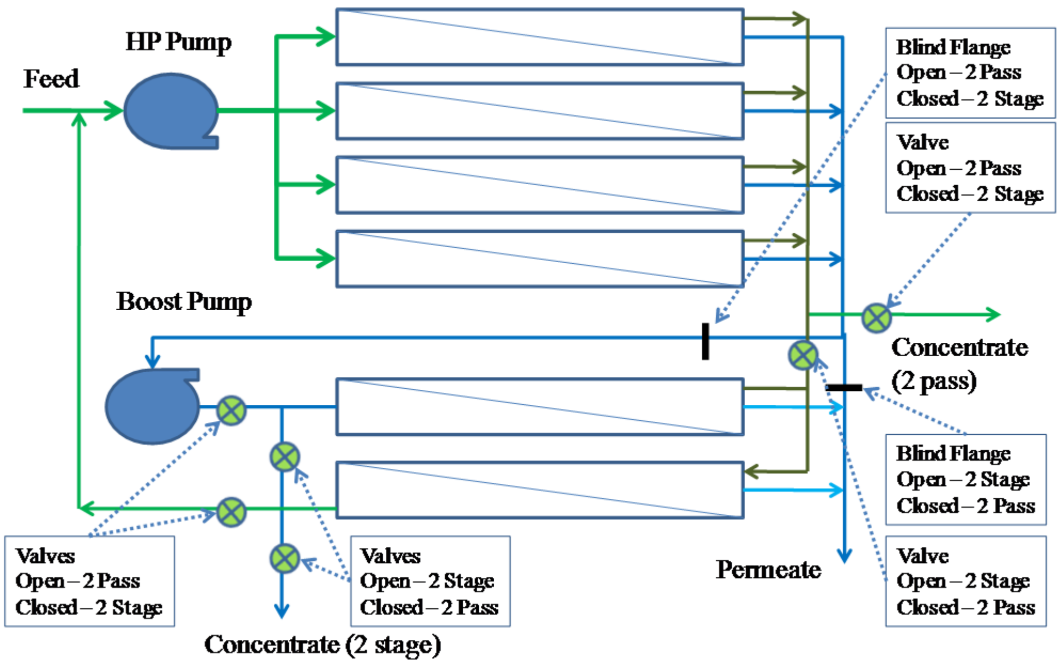

Figure 2. Flow Diagram Indicating Changeover between Modes of Operation

SEA WATER SYSTEM

An alternative scenario for a flexible desalination system is one that is mainly for seawater. The EUWP is used as an example. The first pass is composed of two parallel split vessels of eight 8"x40" elements each, pressurized with a 100 HP diesel driven positive displacement pump (HP Array). Concentrate pressure from these two vessels is used via an ERI pressure exchanger to pressurize feed for an identical third vessel (PX Array). Each vessel has a series of three types of elements arranged to distribute productivity more evenly among the eight elements. Table 2 lists the order from the feed end, model number, and specified properties of the three types. The arrangement was chosen to maximize water production from the fewest number of vessels due to space and weight restrictions for transportability of the equipment.

Table 2. EUWP Seawater RO element arrangement.

Order	Model Number	Area (m^2)	Productivity (m^3/d)	Salt Rejection
1-2	SW30XLE-400i	37	34	99.7
3-4	SW30HRLE-400i	37	28	99.75
5-8	SW30HR-380	35	23	99.7

To determine how well the program RO System Analysis for FilmTec membranes (ROSA v6.1.5) agrees with actual performance using seawater and brackish water, the EUWP was modeled in two parts: three stages of two vessels filled as described in table 2; and in the second part, three stages of one vessel each filled in the same manner. Since the pressure for the second part is driven completely by the concentrate pressure of the first part, only the energy from the first part is considered necessary. Feed flow, pressures, and recovery were selected to match the actual performance treating seawater and brackish municipal wastewater. Table 3 lists the ROSA v6.1.5 simulation results which match fairly close to the actual performance. The projected power requirement for the seawater scenario is 3.4 kWh/m^3 (13 kWh/kgal) and 1.1 KWh/m^3 (4.3 KWh/kgal) for the brackish water scenario which are very close to the actual power requirements.

Table 3. FilmTec Corp. ROSA v6.1.5 Simulation of EUWP with Seawater and Brackish Water at 50% recovery (Flow in L/min, pressure in bar).

	Feed			Permeate			Concentrate		
	Flow	TDS	Pres	Flow	TDS	Pres	Flow	TDS	Pres
Seawater HP Array	439	32,627 mg/L	66	171	215 mg/L	1.5	232	N/A	62
Seawater PX Array	194		61	88		1.5	105		58
Brackish HP Array	428	1060 mg/L	21	215	5 mg/L	1.5	212	2301 mg/L	18
Brackish PX Array	178		14	69	6 mg/L	1.5	109	1869 mg/L	11.6

Next the same system was simulated using brackish water feed from the Brownsville Public Water Utility's Southmost Regional Water Authority desalination plant in southern Texas at 75% recovery. To increase recovery, the EUWP system could be re-configured to use the ERI PX Array as a second stage for the HP Array with the residual pressure remaining in the HP Array concentrate. The system was modeled in one part with six stages: the first three stages have two vessels each, the same as the HP Array used previously; and the second three stages have one vessel the same as the PX array. Results for this analysis are presented in table 4.

Table 4. FilmTec Corp. ROSA v6.1.5 Simulation of EUWP with Brackish Water, 75% recovery (flow in L/min, pressure in bar).

	Feed			Permeate			Concentrate		
	Flow	TDS	Pres	Flow	TDS	Pres	Flow	TDS	Pres
Brackish HP Array	439	2928 mg/L	29.3	238	6.4 mg/L	1.5	200	6527 mg/L	25.9
Brackish 2nd Stage	200	6527 mg/L	25.5	89	16 mg/L	1.5	111	9108 mg/L	22

The energy requirement for this two stage design is estimated at 1.38 kWh/m^3 (5.23 kWh/kgal). There were no design warnings that came with this analysis, though barium and strontium sulfate, calcium fluoride and silica concentrations are over their solubility limits. Antiscalant is used at the facility now which also operates at 75% recovery.

The PX array of the EUWP can easily be converted to a second stage by replacing the high pressure entrance to and exit from the PX with a straight connecting pipe to divert the first stage concentrate past the PX directly to the PX array. Figure 3 shows the pressure exchanger on the EUWP with a drawing of the pipe that would be required.

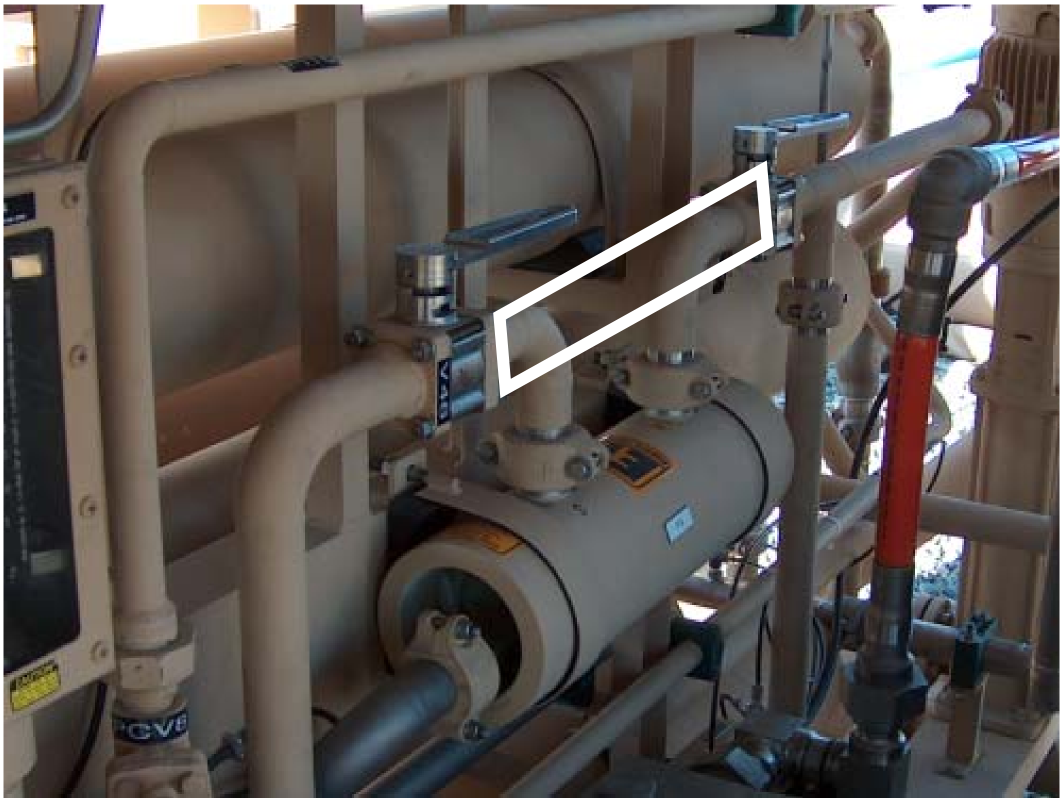

Figure 3. EUWP pressure exchanger indicating by-pass piping needed to convert to a two stage system.

CONCLUSIONS

Two methods of obtaining flexibility in a reverse osmosis system have been described - one using a brackish water system, constructed with the proper materials and another starting with a seawater system. In both cases all of the membrane vessels were used for treating seawater at 50% recovery and brackish water at 75% recovery. In the brackish water system an additional boost pump is added when treating seawater while in the seawater system the pressure exchanger is bypassed to allow concentrate from the first stage to enter the second stage. Power consumption for the seawater baseline system is 3.4 kWh/m^3 at 50% recovery while the same system requires 1.38 kWh/m^3 at 75% recovery when treating brackish water.

Product water quality from the two stage seawater system treating brackish water is much lower in TDS than the brackish system. This product could be blended with another source or it would need more careful stabilization.

This analysis indicates that the flexible operation of one system for brackish and seawater treatment is feasible. The next step is to demonstrate performance at pilot scale. This is planned for 2011.

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