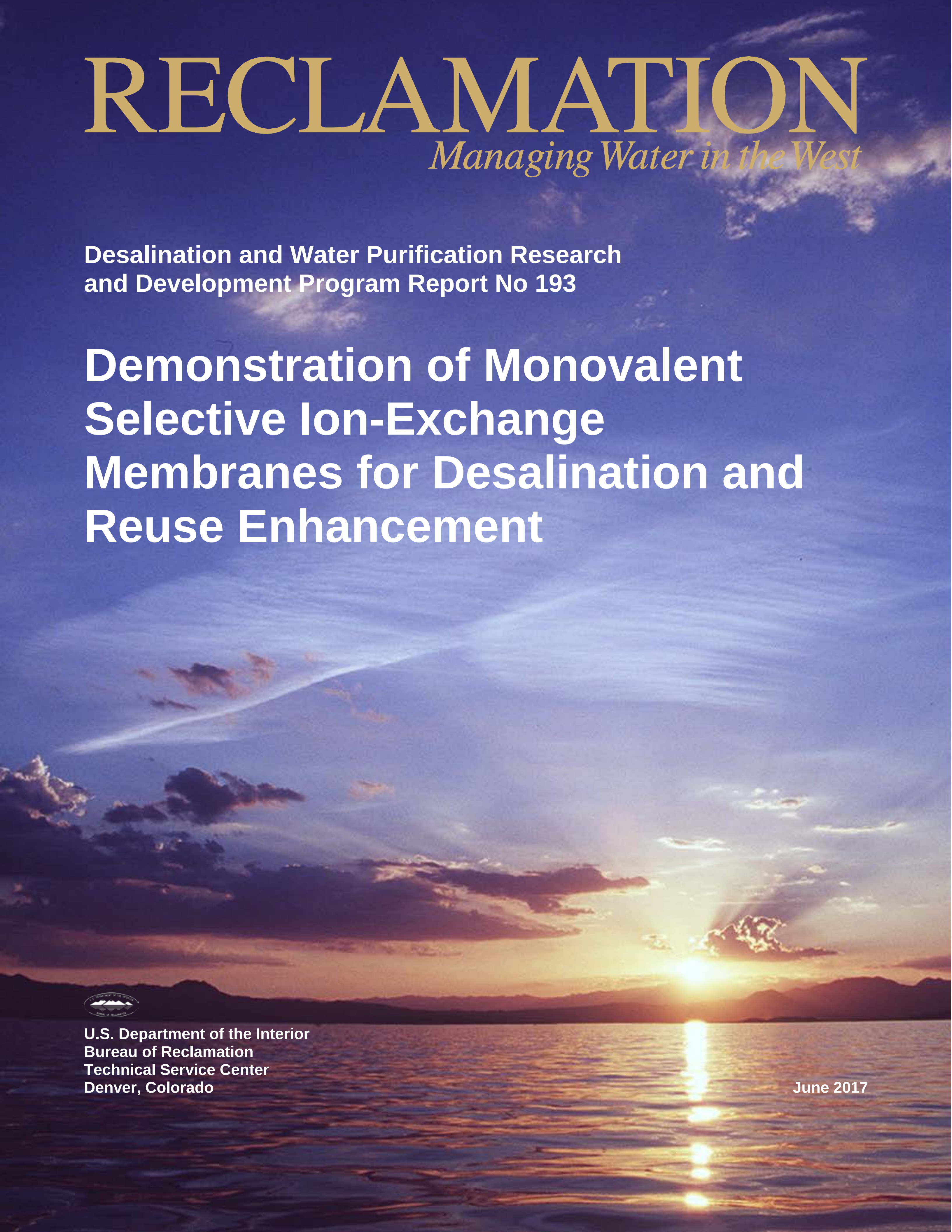

RECLAMATION
Managing Water in the West

Desalination and Water Purification Research
and Development Program Report No 193

Demonstration of Monovalent Selective Ion-Exchange Membranes for Desalination and Reuse Enhancement

U.S. Department of the Interior
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Pei Xu, Charlie (Qun) He, Xuesong Xu, Guanyu Ma, Huiyao Wang, Nagamany Nirmalakhandan

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Department of Civil Engineering, New Mexico State University 3035 S Espina St., Las Cruces, NM 88003-8001
Carollo Engineers, Inc.
4600 East Washington Street, Suite 500, Phoenix, AZ 85034

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14. ABSTRACT

Selective separation of mono- and multi-valent ions has important applications in water reuse, desalination, and salt production. Bench- and pilot-scale experiments were conducted to investigate desalination performance, ion selectivity, and energy consumption of the newly developed monovalent permselective ion-exchange membranes (sodium selective membrane CR671 and nitrate selective membrane AR112B) in comparison with standard normal grade membranes CR67 and AR204. The objectives of this project are to demonstrate the technical viability and economic feasibility of selective electrodialysis to a wide range of impaired waters including reclaimed water, brackish water, and RO concentrate. The selective electrodialysis provides an innovative ion selective desalination technology for water reuse, desalination and concentrate management. This study elucidated the impacts of feed water quality, operating conditions (current density, linear velocity, hydraulic retention time, and staging) on ion selectivity and overall salt removal for both selective and normal grade ion-exchange membranes.This study demonstrated that monovalent permselective membranes are effective to adjust ion composition for lower salinity water, such as reclaimed water and groundwater. The electrical repulsion between the cationic polymer and multivalent cations decreased with increasing ionic strength in feedwater.

15. SUBJECT TERMS
Electrodialysis; ion selectivity; selective separation; desalination; ion-exchange membranes; membrane modification; brackish water; water reuse; concentrate treatment

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Prepared for the Bureau of Reclamation Under Agreement No. R14AP00175
by

Pei Xu, Charlie (Qun) He, Xuesong Xu, Guanyu Ma, Huiyao Wang, Nagamany Nirmalakhandan

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Mission Statements

Disclaimer

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Acronyms and Abbreviations

AACE	Association for the Advancement of Cost Engineering
AEM	Anion Exchange Membrane
BAF	biologically activated filtration
BGNDRF	Brackish Groundwater National Desalination Research Facility
BPI	Blue Plan-it^{TM}
C*d*	concentration of dilute-out
CEM	Cation Exchange Membrane
C*f*	concentration of feed-in
C*i*	Ion concentrations at the at the membrane surface
ED	electrodialysis
EDM	electrodialysis metathesis
EDR	electrodialysis reversal
EDX	energy-dispersive X-ray spectroscopy
h	height of the dilute chamber flow channel
HRT	hydraulic residence time
I	current intensity
I	current through the electrodialysis stack
IC	ion chromatography
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
IEM	ion-exchange membrane
IX	ion-exchange
KBHDP	Kay Bailey Hutchison Desalination Plant
L	entire length of the dilute flow channel
LCD	limiting current density
MF	microfiltration
Mn	number average molecular weight
Mw	weight-average molecular weight
N	number of cell pairs
n	number of IEM pairs
Ncp	number of cell pairs
NF	nanofiltration
NMSU	New Mexico State University
NPDWR	National Primary Drinking Water Regulations
O&M	operation and maintenance
Q*d*	final dilute-out flow
Q*f*	feed-in flow
R	Resistance
R_{AR}	Electrical resistance of anion exchange membranes
Rc	Electrical resistance in concentrate
R_{CR}	Electrical resistance of cation exchange membranes
R_{D}	Electrical resistance in diluate
$R_{electrodes}$	Electrical resistance of electrode chambers
ReNUWIt	Reinventing the Nation's Urban Water Infrastructure
(R_{total})	total stack resistance

RO	reverse osmosis
S	Total membrane surface area of the stack
S_1	Membrane surface area of a single pair
SAR	sodium adsorption ratio
SEM	scanning electron microscope
SMART®	Salinity Management and Research Toolbox
SROG	Sub-Regional Operating Group
SWC	Scottsdale Water Campus
TDS	total dissolved solids
TOC	total organic carbon
UF	ultrafiltration
V	applied voltage to the electrodialysis stack
W	Width of the dilute chamber flow channel
WET	whole effluent toxicity
ZLD	zero liquid discharge

Measurements

°C	degree Celsius
A	amp
cm	centimeter
cm^2	square centimeter
cm/s	centimeter per second
ft^2	square foot
g/L	gram per liter
gpm	gallon per minute
kg	kilogram
kWh/kgal	kilowatt hour per thousand gallons
lpm	liter per minute
m^2-kWh	kilowatt hour per square meter
mA/cm^2	milliamps per square centimeter
meq	milli-equivalent
mg/L	milligrams per liter
mS/cm	microSiemen per centimeter
wt.%	percent by weight
µg/L	microgram per liter
mS/cm	microSiemen per centimeter
V	volts
µm	micrometer
Ω	Ohm

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Executive Summary

Desalination and water reuse have become two key solutions to addressing water shortage and sustainability. Reducing salinity and selective separation of mono- and multi-valent ions has important applications in water reuse and desalination by adjusting ion composition to meet product water quality requirements. This project investigated the ion selectivity of selective and normal grade ion-exchange membranes during electrodialysis. The technical and economic information gathered during the project delivers an innovative solution to reuse and desalination challenges associated with salinity and concentrate management. The results of this study provide a promising alternative to address the scarcity of fresh water in arid and semi-arid Southwestern United States.

This project aimed to demonstrate the technical viability and economic effectiveness of innovative selective electrodialysis using newly developed monovalent permselective ion-exchange membranes to treat different types of impaired waters, including reclaimed water, brackish groundwater, and reverse osmosis (RO) concentrate. Bench- and pilot-scale experiments were conducted to compare sodium selective membrane CR671 and nitrate selective membrane AR112B manufactured by GE Water with standard normal grade membranes CR67 and AR204. Pilot-scale testing was conducted at the Water Campus, City of Scottsdale, Arizona, treating tertiary reclaimed water; and at the Kay Bailey Hutchison Desalination Plant, Texas, treating groundwater and RO concentrate.

Both normal grade (CR67 and AR204) and monovalent permselective (CR671 and AR112B) membranes achieved the same desalting efficiency at the same current density during bench- and pilot-scale studies. Na-selectivity in terms of equivalent removal of calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}) over sodium ions (Na^{+}) was affected significantly by current density and linear velocity for the normal grade membranes while the selective membranes exhibited relatively stable Na-selectivity. Under the same hydraulic conditions, (e.g., spacers and linear velocity), overall desalination behavior and ion selectivity were highly comparable between bench- and pilot-scale electrodialysis. The CR671 demonstrated better transport of mono- over di-valent cations in electrodialysis than the CR67; however, the selectivity decreased with the increase of feedwater salinity. This study elucidated the impacts of operating conditions on ion selectivity and overall salt removal for both selective and normal grade membranes. The bench-scale testing results can be used to simulate and predict desalination performance and ion selectivity of pilot-scale electrodialysis.

Selective membranes can cost-effectively meet the required water quality of 100 milligrams per liter (mg/L) Na concentration for irrigation at Scottsdale, Arizona. These membranes can come very close—but may not achieve—sodium adsorption ratio (SAR) goals for recovering El Paso RO concentrate due to the low Ca:Na ratio and irrigation water's requirements for high Na removal.

1. Background

1.1. Electrodialysis for Water Reuse, Desalination, and Concentrate Treatment

Meeting the increasing demand for fresh water is a grand challenge. Desalination and water reuse have become two key solutions to addressing water shortage and sustainability. Desalting technologies such as reverse osmosis (RO) are effective at removing almost all contaminating constituents and thus are a primary method for treating impaired waters. The primary shortfall of RO is managing and disposing the highly saline concentrate laden with accumulated contaminants (Xu et al. 2013a and Mickley 2009). This brine stream represents a significant loss of water, and this brine is often associated with expensive concentrate treatment. Meanwhile, RO permeate is considered corrosive due to its inherent low mineral content and needs stabilization (e.g., remineralization, pH adjustment, or blending) prior to distribution to users.

Apart from brackish water and seawater, reclaimed water becomes increasingly saline when the water is being reused multiple times, and the total dissolved solids (TDS) and individual ions in reclaimed water are concentrated up due to water losses during reuse. Reclaimed water with high salinity is causing reuse challenges. For example, for many places in Arizona and Texas—as well as the entire southwest region—high sodium adsorption ratio (SAR) caused by high sodium concentration, and the whole effluent toxicity (WET) test failure caused by high TDS and chloride ions, are often encountered. As a result, water utilities have to abandon the reuse systems and give valuable potable water to golf courses and reclaimed water users all year or parts of the year. In many regions, RO has been installed to desalinate a partial stream of the tertiary effluent, resulting in a saline brine stream that must be disposed of properly.

Electrodialysis (ED) and electrodialysis reversal (EDR) use electrical potential to separate ions from water, and have been used for desalination of groundwater and wastewater for decades (Reahl 2006). ED and EDR use ion-exchange (IX) membranes that have less stringent pretreatment requirements and are more tolerant to waters with high silica, hardness, suspended solids, and organics than RO membranes (Reahl 2006, Turek et al. 2009, and Trussell and Williams 2012). ED or EDR systems can also operate with a continuous free chlorine residual of up to one mg/L, which allows a better control of biofouling and more rigorous clean-in-place than RO (Reahl 2006).

For example, Reahl (1992) reported a large EDR system for RO concentrate reclamation. A six-stage EDR system with a single train of EDR stacks reduced the TDS of RO concentrate from 4,500 mg/L to 550 mg/L and recovered 83 to 86 percent of RO concentrate, resulting in an overall RO/EDR water recovery of 97 percent. Acid was added to the EDR feed and recirculating brine to reduce the

Langelier Saturation Index from 3.6 to less than 1.8. Similarly, Turek et al. (2009) tested an EDR system to treat a brackish groundwater RO concentrate with high scaling potential. This EDR system recovered 79 percent of the concentrate stream, improving overall recovery from 60 to 92 percent. Scaling was not observed, despite the fact that the EDR unit operated with a feed that had a 360 percent calcium sulfate saturation and a 2.3 Langelier Saturation Index.

A new modified form of ED, electrodialysis metathesis (EDM), was developed by Dr. Tomas Davis and pilot-tested for treatment of RO concentrate (Bond et al. 2011). The EDM process uses a repeating unit comprising one diluate compartment, two concentrate compartments, one sodiuim chloride (NaCl) solution compartment, one regular anion exchange membrane, one regular cation exchange membrane, one monovalent selective anion exchange membrane, and one monovalent selective cation membrane. This unique configuration is designed to reduce the typical scalants in RO concentrate (e.g., calcium sulfate [$CaSO_4$] and calcium carbonate [$CaCO_3$]) by separating the EDM concentrate into two streams of highly soluble salts: one containing sodium with anions and the other containing chloride with cations. EDM increased overall water recovery to over 99%. The treatment costs and energy demand of EDM depend on the TDS of the concentrate. Using an EDM prior to a crystallizer can reduce the costs of zero liquid discharge (ZLD) system significantly (Bond et al. 2011). Funded by the Reclamation, a demonstration project conducted at the Reclamation’s Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico, yielded 97% water recovery treating brackish groundwater with a proprietary silica removal system (Cappelle 2014).

Our research team recently completed a concentrate management demonstration testing study co-funded by Sub-regional Operation Group (SROG, including Glendale, Mesa, Phoenix, Scottsdale, and Tempe in Arizona), WateReuse Research Foundation, and Reclamation. This study demonstrated the feasibility of reducing reclaimed water RO concentrate volume and improving overall RO recovery from 90.3% to 96.4% by using EDR with organic pretreatment (ozone and biologically activated filtration [BAF]), and to 99.7% if inorganic pretreatment (e.g., ion exchange or lime softening) are added to the treatment train. Based on modeling, secondary RO with similar pretreatment can achieve 44% recovery with organic pretreatment and 83% with both organic and inorganic pretreatment. When blending is counted, these recovery percentages are equivalent to 95.3% and 98.7%, respectively, which is lower than using EDR for RO concentrate treatment.

Because EDR membranes are much more tolerant to organic fouling and inorganic scaling than secondary RO, the EDR pretreatment requirements would be lower than those for the RO pretreatment, resulting in cost savings in both capital and operations and maintenance (O&M) costs. For the Water Campus, the demonstrated concentrate management solution (i.e., ozone, BAF, and IX plus EDR with normal grade IX membranes) saved 46% in total concentrate management costs compared to the brine concentrator option, with only a 0.7% difference in overall water recovery. Compared to secondary RO with organic pretreatment and lime softening, which was the best available proven technology known prior to this study, the demonstrated solution reduced costs by 29% while achieving a slightly higher overall water recovery.

In summary, these prior studies successfully demonstrated that ED and EDR are flexible and cost-effective alternative technologies for desalination and RO concentrate treatment.

1.2. Selective Electrodialysis

One of the benefits of ED or EDR is the selectivity of removing monovalent ions (e.g., Na^+, potassium [K^+], ammonium [NH_4^+], chlorine [Cl^-], and nitrate [NO_3^-]) over multivalent ions (e.g., Ca^{2+}, magnesium [Mg^{2+}], sulfate [SO_4^{2-}], and phosphate [PO_4^{3-}]) in product water, which can be achieved by using monovalent selective IX membranes or by lowering the electrical current. Unlike so-called “monovalent selective” nanofiltration (NF) membranes, which are looser and tend to reject larger ions (e.g., Ca^{2+}, Mg^{2+}, and SO_4^{2-}) more than smaller ions (e.g., Na^+, Cl^-, and $NO3^-$), SAR and WET compliance challenges can become worse when using these membranes for desalination.

The selectivity of IX membranes for a specific ion can be determined by three different mechanisms: control of the permselectivity of ions with the same charge on the basis of their size, rejection of certain ions by a thin surface layer on the IX membrane with the same charge as the ions, and specific interactions between the ion-exchange groups of the membrane and the mobile ions (Sata 1994). For transport of ions with the same charge, Van der Bruggen et al. (2004) showed that $NO3^-$ removal was slower than Cl^- in ED when different salts (NaCl, Na_2SO_4, $MgCl_2$, $MgSO_4$, and $NaNO_3$) were separated by regular AMV/CMV Selemion membranes and monovalent selective ACS/CMS Tokuyama membranes.

Elmldaoui et al. (2001) found the anion selectivity in the following order: $NO3^– >Cl^– > HCO_3^– > SO_4^{2-}$ when they studied the removal of nitrate from groundwater in Morocco by monovalent selective ACS anion-exchange membrane (NEOSEPTA, ASTOM, Japan).

Mono- and divalent anion selectivity was reported in various articles (Kabay et al. 2003, Kabay et al. 2006a, Kabay et al. 2006b, and Zhang et al. 2012), which can be ascribed to the size and charge effects.

Zhang et al. (2013) reported effective recovery of nutrients (phosphate) from anaerobic digester concentrate using combinations of regular and monovalent selective IX membranes in ED. Although previous results showed that multivalent anions can be separated from monovalent anions and retained in the diluate compartment by the selective membrane, no significant evidence supports the selective separation of the same (similar) charged anions (i.e., separating $NO3^{-}$ from Cl^{-} and $HxPO_4y^{-}$ from SO_4^{2-}) by the selective IX membranes (Zhang et al. 2009).

Our research team used NEOSEPTA monovalent selective membranes (ACS and CMX-S) manufactured by ASTOM (Japan) to remove monovalent ions from brackish groundwater RO concentrate from Kay Bailey Hutchison Desalination Plant (KBHDP), El Paso, Texas (Xu et al. 2013b). ED's electrical current density had a negligible impact on the selectivity of monovalent anions over divalent anions. However, the transport of divalent cations such as $Ca^{2}+$ and Mg^{2+} increased with increasing current density. High overall salt rejection was achieved around limiting current density (LCD) while higher normalized salt removal rate in terms of membrane area and energy consumption was attained at lower current density.

In view of the important applications of monovalent selective IX membranes in water reuse, desalination, and recovery of nutrients and energy, innovative IX membranes are under development. A number of methods have been attempted to prepare monovalent selective membranes, including adsorption (Amara and Kerdjoudj 2002 and Amara and Kerdjoudj 2003), electro-deposition (Rojas et al. 2007), surface modification (Wang et al. 2013 and Sivaraman et al. 2007). These methods typically coat the IX membrane surface with a permeable layer to modify electrostatic repulsion, size effect, affinity, or other interactions between the relevant ions and the modified layer contributed to the selective separation between the mono- and multi-valent ions.

Recently, GE Water developed a new generation of monovalent selective IX membranes (sodium selective membrane CR671 and nitrate/chloride selective membrane AR112B) that may reduce membrane fouling, improve salt removal efficiency, and tailor product water quality for different uses. Pilot-scale studies are required to demonstrate the technical and economic viability of the new monovalent IX membrane to treat different types of waters, in particular for enhancement of water recovery and modification of product water quality.

1.3. Project Goal

The overarching goal of the project was to demonstrate the technical viability and economic feasibility of selective ED to a wide range of impaired waters including reclaimed water, brackish water and RO concentrate. We conducted bench- and pilot-scale experiments to compare sodium selective membrane CR671 and nitrate/chloride selective membrane AR112B by GE Water with standard normal grade membranes CR67 and AR204. We conducted pilot-scale testing treating tertiary reclaimed water at the Water Campus, City of Scottsdale, Arizona, and treating groundwater and RO concentrate at the KBHDP in El Paso, Texas. We developed empirical models using this experimental data, which allows process optimization, scale-up of the bench- and pilot-scale data, and economic analysis.

These results will also ensure that the data generated from specific case studies have a broader applicability.

2. Conclusions and Recommendations

Bench- and pilot-scale electrodialysis experiments were conducted to compare the overall desalination performance and ion selectivity of innovative monovalent permselective ion-exchange membrane CR671and AR112B with normal grade membrane CR67 and AR204 during electrodialysis of reclaimed water, brackish groundwater, and RO concentrate. This study examined the impacts of feed water quality, operating conditions (current density, linear velocity, hydraulic retention time, and staging) on ion selectivity and overall salt removal for both selective and normal grade ion-exchange membranes. Overall desalination efficiency and ion selectivity were consistent from bench to pilot electrodialysis for both selective and normal grade membranes. The primary conclusions of the study are:

- A thin layer of polyethyleneimine coating effectively improved the Na^- selectivity of cation exchange membrane by preferentially transporting monovalent cations Na^+ over divalent cations Ca^{2+} and $Mg^{2+.}$

- At the same current density, monovalent selective membranes (CR671 and AR112B) achieved the same desalting efficiency as normal grade membranes (CR671 and AR204) during bench- and pilot-scale electrodialysis.

- The Na^- selectivity (in terms of equivalent removal of Ca^{2+} and Mg^{2+} over Na^+) was affected significantly by the current density and linear velocity for normal grade membranes, while the selective membranes exhibited relatively stable ion selectivity.

- Hydraulic retention time and hydraulic staging had lesser impact on ion selectivity of selective and normal grade membranes than on overall salt removal.

- The overall desalination behavior and Na-selectivity between bench- and pilot-scale electrodialysis was highly comparable under the same hydraulic configuration. Bench-scale testing results can be used to simulate and predict the desalination performance and ion selectivity of pilot- and potentially full-scale electrodialysis system. However, the estimated energy consumption by bench testing was much higher than that of pilot-scale unit because of lower desalination efficiency and less membrane surface area.

- Selective membranes can cost-effectively meet the required water quality of 100 milligrams per liter (mg/L) Na concentration for irrigation at Scottsdale, Arizona. These membranes can come very close—but may not

> achieve—sodium adsorption ratio (SAR) goals for recovering El Paso RO concentrate due to the low Ca:Na ratio and irrigation water's requirements for high Na removal.

This study demonstrated that monovalent permselective membranes are effective to adjust ion composition for lower salinity water, such as reclaimed water and groundwater. The electrical repulsion between the cationic polymer and multivalent cations decreased with increasing ionic strength in feedwater.

3. Materials and Methods

3.1. Water Quality and Analysis

The water quality of groundwater and RO concentrate in the Kay Bailey Hutchison Desalination Plant (KBHDP), groundwater in Brackish Groundwater National Desalination Research Facility (BGNDRF), and microfiltered reclaimed water in Scottsdale Water Campus (SWC) is summarized in Table 1.

For every electrodialysis testing condition, we collected water samples from the feed-in, final product, concentrate blowdown, and inter-stage dilute-out and concentrate streams for analysis. Electrical conductivity and pH of the water samples were measured using a conductivity and pH meter (Model 431-61, Cole-Parmer, Vernon Hills, IL, USA). Total organic carbon (TOC) was quantified using a carbon analyzer (Shimadzu TOC-L, Kyoto, Japan). Common cations and anions including sodium, calcium, magnesium, potassium, chloride, phosphate, sulfate, nitrate and nitrite were measured using an ion chromatograph (IC) (ICS-2100, Dionex, Sunnyvale, California). The concentrations of other elements including: aluminum, arsenic, boron, calcium, chromium, copper, iron, potassium, magnesium, manganese, lead, and selenium were quantified using an inductively coupled plasma mass spectrometry (ICP-MS) (Elan DRC-e, PerkinElmer, Waltham, Massachusetts).

We measured alkalinity using a digital titrator (Hach, Colorado) and a 1.6 N sulfuric acid standard solution. We measured the TDS concentration following evaporation method at 180 degrees Celsius (°C) after filtering the groundwater samples using a 0.45 micrometer (µm) cellulose acetate membrane filter (Toyo Roshi Kaisha, Ltd., Japan).

Table 1.—Summary of Water Quality at Testing Sites

Parameter Name	Reporting Units	Human Health NPDWR	BGNDRF				KBHDP		SWC
			Well 1	Well 2	Well 3	Well 4	RO concentrate	Ground-water	Reclaimed water
Water Temperature	°C		41.2	22.1	22.1	21.3	25.6	24.3	25
Alkalinity Total (as $CaCO_3$)	mg/L		150	250	190	210	350	90	151
Bicarbonate Alkalinity (as $CaCO_3$)	mg/L		150	250	190	210	350		151
Bromide	mg/L		0.08	0.41	0.39	0.35	2.1		0.099
Chloride	mg/L	250	34	650	690	640	5057	1370	390
Fluoride	mg/L	4	2.4	0.26	0.28	0.13	2.85		0.4
Nitrogen, Nitrate (as N)	mg/L	10		8.3	2.8	4.1	4.5		8.9
pH	pH units	6.5-8.5	8.16	7.65	7.35	7.7	7.89	7.78	7.2
Phosphorus, Total (as P)	mg/L		0.026	0.032	0.015	0.017	20	<0.02	2.5
Specific Conductance	µmhos/cm		1,700	6,100	4,500	4,700	18,000	4,626	1,882
Sulfate	mg/L	250	730	3,400	1,800	1,900	1,264	297	262
Total Dissolved Solids	mg/L	500	1,240	5,900	3,590	4,110	10,860	2,736	1,166
Aluminum	mg/L		0.0022	0.0013	0.0012	0.0012	0.14		0.025
Arsenic	mg/L	0.01	0.0014	0.0021	0.0016	0.0017	0.029	0.01	0.0019
Barium	mg/L	2	0.028	0.011	0.01	0.012	0.51		0.09
Calcium	mg/L		63	550	440	500	717.65	168	97.3
Iron (Total)	mg/L	0.3	0.17	0.02	0.23	0.28	na	<0.02	0.13
Iron (Dissolved)	mg/L		0.0005	0.014	0.14	0.11	0.14		
Lithium	mg/L		0.0425	0.122	0.106	0.102	0.76		
Magnesium	mg/L		16	340	220	220	176.95	40	31.6
Manganese (Total)	mg/L	0.05	0.019	0.0018	0.02	0.0084	na	0.06	0.0277
Manganese (Dissolved)	mg/L	0.05	0.019	0.0014	0.02	0.0085	0.0083		
Potassium	mg/L		5	2.6	3.3	2.6	121.93	18	36.2
Silica	mg/L		25	23	21	19	152	28	12.5
Sodium	mg/L		320	720	410	420	2,491.85	721	296
Strontium	mg/L		2	8.8	7.3	7.4	20.46		1.19
Hardness (as $CaCO_3$)	mg/L		230	2,600	2,000	2,200	2,531	589	
Organic Carbon, Total	mg/L		0.24	1.3	0.56	0.7	1.5	0.3	7
Sodium adsorption ratio (SAR)			11.5	6.4	4.7	4.7	22	12.9	6.6

µmhos/cm = microSiemens/cm
NPDWR = National Primary Drinking Water Regulations

3.2. Bench- and Pilot-scale Electrodialysis Systems

Bench- and pilot-scale electrodialysis systems were manufactured by GE Water. The electrodialysis pilot system (AQ3-1-4) is a scaled-down version of a full-scale electrodialysis reversal (EDR) water treatment plant, used to demonstrate treated water quality and to collect operational data for full-scale design. The pilot system could produce 3 to 13 gallons per minute (gpm), or 11.3 to 49 liters per minute (lpm) desalinated water.

The electrodialysis membrane stack for treating groundwater and RO concentrate at the KBHDP was designed as 2-electrical stage (//) and 4-hydraulic stage (/) with 186 cell pairs of cation exchange membranes (CEM) and anion exchange membranes (AEM). The membrane pairs were arranged in //53/53//40/40// for four hydraulic stages (i.e., 106 and 80 pairs of membranes for the first and second electrical stages, respectively).

The electrodialysis membrane stack for treating reclaimed water at the SWC was designed as 2-electrical stage (//) and 2-hydraulic stage (/) with 100 cell pairs of CEMs and AEMs (i.e., 50 and 50 pairs of membranes for 1st and 2nd electrical stages, respectively).

The effective surface area of each membrane was 3,200 square centimeters (cm^2) (3.44 square feet [ft^2]). The electrical staging was accomplished by inserting two cathode electrode pairs into the middle of the membrane stack with two anode electrodes on the top and bottom of the stack. This gives flexibility in the system design—providing maximum salt removal rates while avoiding polarization and hydraulic pressure limitations. Each electrical stage allowed the use of an independently controlled current to the cell pairs within that stage. The four hydraulic stages within the stack were achieved by adding heavy cation transfer membranes as inter-stage membranes to create separate flow paths. The staging provided sufficient membrane area and retention time to remove a specified fraction of salt from the groundwater. GE’s patented turbulence-promoting spacers (Mark IV-2) with special geometries were inserted to separate the CEMs and the AEMs and to introduce flow mixing inside the flow channels, thereby reducing the concentration polarization and increasing the limiting current density (LCD) and mass transfer (Leitz and Marinčić 1977).

The inlet feedwater was divided into three lines: feed-in, make-up in concentrate inlet stream, and electrode rinsing stream. The largest flow (feed-in) was demineralized as desalted water (product water or dilute), while a portion of feedwater, as concentrate make-up, was mixed with recycled concentrate to achieve high recovery, and pumped into electrodialysis stack as the inlet concentrate. After degasification, the electrode rinsing wastewater was recycled as feedwater to further improve water recovery. The raw groundwater was pretreated by a 10 µm cartridge filter before entering the electrodialysis stack. The electrodialysis system was automated with all the necessary components to perform operating procedures used by full-scale EDR treatment plants (Figure 1 through Figure 3). The applied voltage, current, pH, conductivity, pressure, and flow rate of different streams were recorded continuously through a supervisory control and data acquisition system.

The calculation of saturation indices indicated potential scaling of $CaSO_4$ and CaCO3 in the electrodialysis concentrate and cathode-rinsing stream during the treatment of groundwater and RO concentrate. The GE phosphate antiscalant (Hypersperse MDC714) was dosed continuously at concentration of 19 to 26 mg/L into the concentrate stream to inhibit scale formation and precipitation on the membrane surface. Hydrochloric acid concentrate was dosed to the concentrate steam and cathode-rinsing stream to adjust pH to 6.3 and 5.5- 6.0, respectively, to prevent $CaCO^3$ scaling. The antiscalant and acid injection dosages were determined based on GE's previous experiences and the prediction using the WATSYSTM software.

In parallel to the pilot testing, we operated a bench-scale electrodialysis system with the aim of scaling up the testing results from bench to pilot systems, and eventually to full-scale operations. The bench system included two GE 9 foot by 10 foot laboratory stacks MK-I that could operate individually as 1-electrical and 1-hydraulic stage electrodialysis unit, or in series to simulate 2-electrical and 2-hydraulic stage operation. Each bench stack consisted of eleven CEMs and ten AEMs with an effective area of 220 cm^2 for each membrane. Both cathode and anode were of platinum-plated titanium electrodes. The bench stack spacers had the same thickness (0.076 centimeters [cm]) and configuration as the pilot stack, which allows a defensible comparison of the electrodiaysis performance between bench- and pilot-scale testing under the same operating conditions. The bench electrodialysis was configured the same as the pilot system (Figure 4 and Figure 5), using the testing water as the feed, concentrate, and electrode-rinsing solution. Three variable-flow micro- pumps (EW-75211-10, Cole-Parmer) were used to supply the desired flow rates and pressure of the three streams to the electrodialysis stack. As with the pilot system, the concentrate recycle valve in the bench system could be adjusted to achieve higher water recovery.

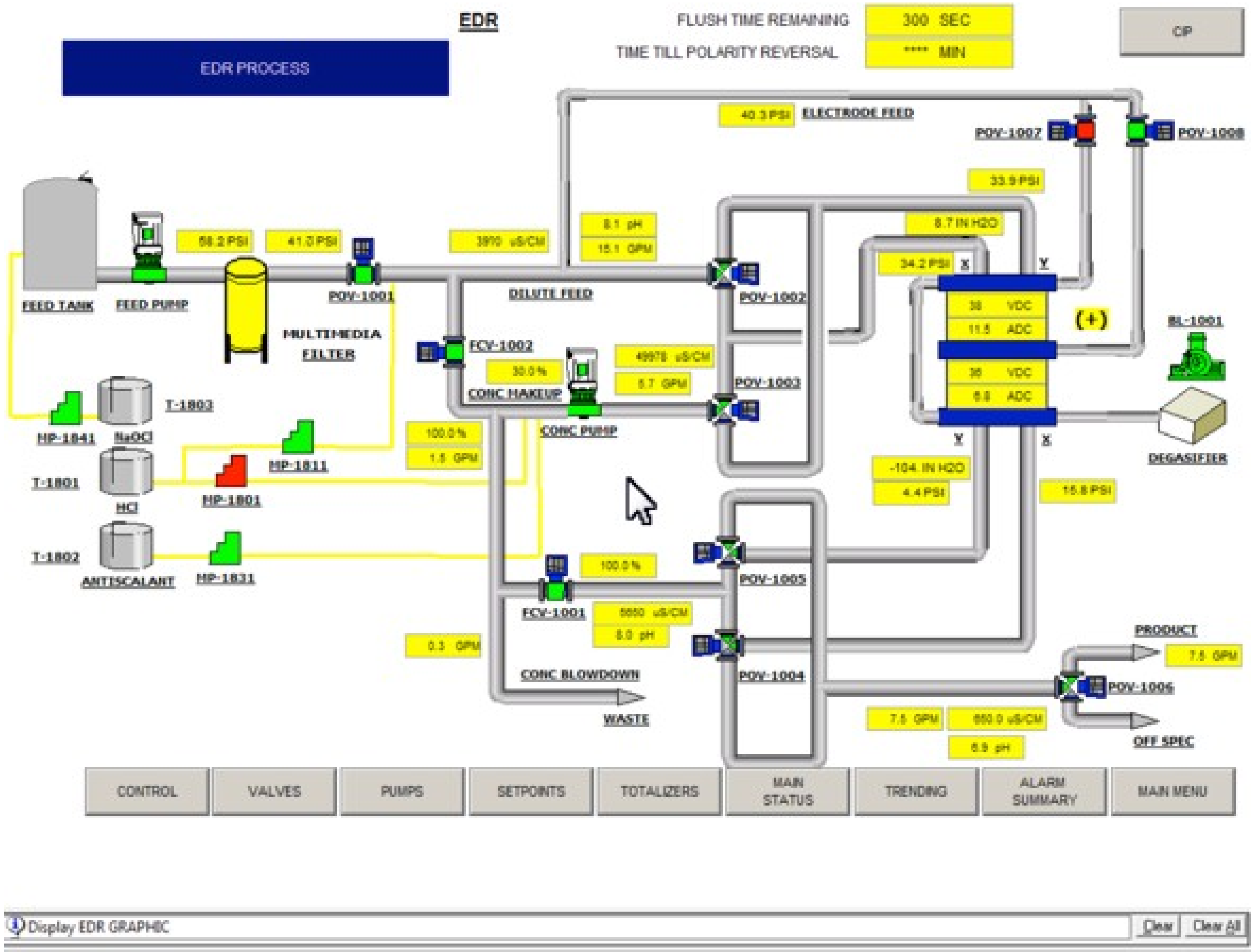


Figure 1.—Pilot electrodialysis system screenshot of monitoring panel.

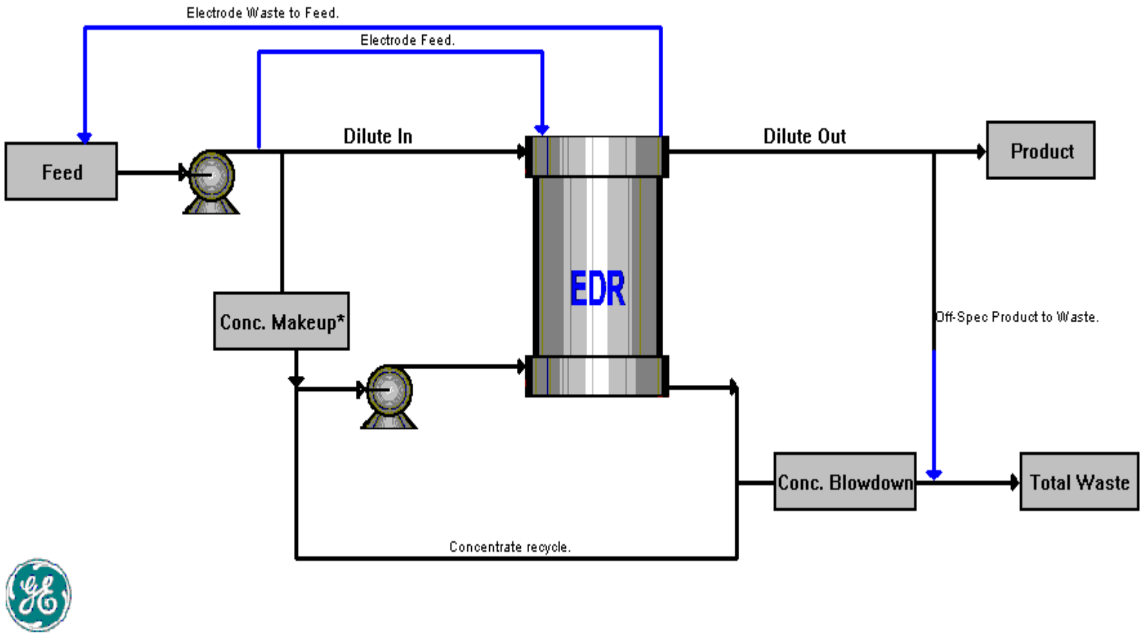


Figure 2.—Pilot electrodialysis system screenshot of flow diagram in WATSYSTM model.

Figure 3.—Installation of pilot system.

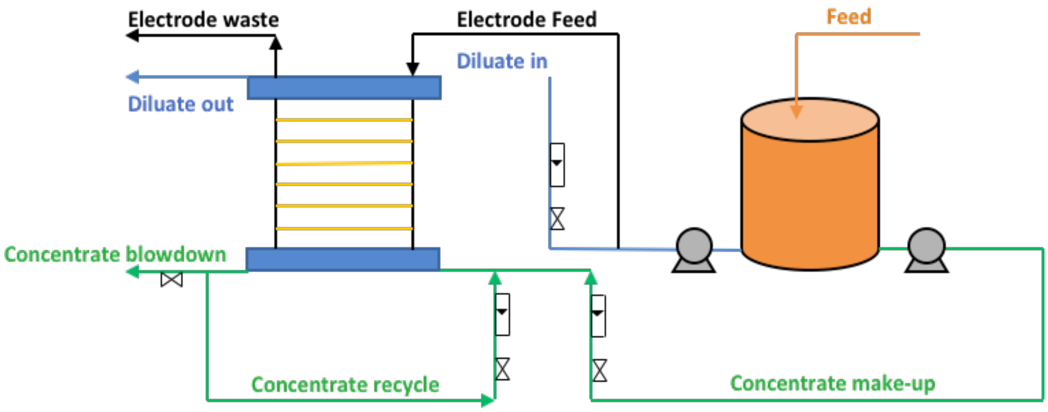


Figure 4.—Flow diagram and picture of bench-scale electrodialysis system.

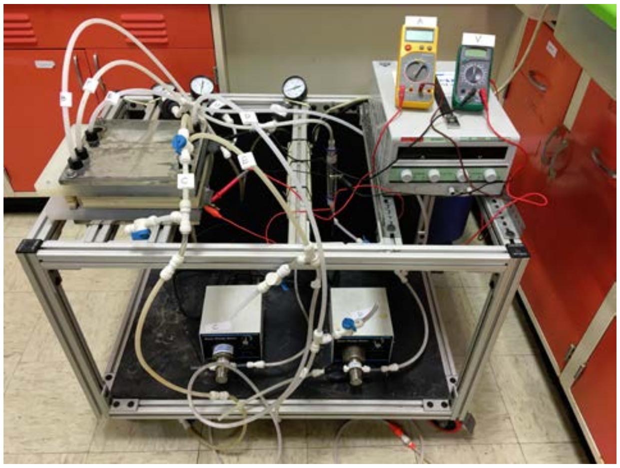


Figure 5.—Flow diagram and picture of bench-scale electrodialysis system.

Both pilot and bench systems can operate at water recovery rates from 50% to 90%. In this study, we operated the electrodialysis at 55% for pilot unit and 50% for bench stack to compare the ionic transport and selective separation of cations of CR67 and CR671. Before experimental runs, new membranes were equilibrated with feedwater for at least 24 hours with groundwater flowing through the membranes without applying voltage. The specification of the bench- and pilot-scale electrodiaysis stacks is summarized in Table 2.

3.3. Ion-Exchange Membranes (IEM)

We compared the electrodialysis performance of GE newly developed monovalent permselective membranes (CR671 and AR112B-574) to GE standard normal grade membranes (AR204-SZRA-412 and CR67-HMR-412) during the bench- and pilot-scale testing (Table 3).

Table 2.—Configuration and Electrodialysis Systems Operating Conditions of Bench- and Pilot-Scale

Parameter	**Bench**				**Pilot**
Number of stacks	1		2		1
Electrical stage	1		2		2
Hydraulic stage	1		2		4
Cell pair configuration in one stack	//10//		//10//10//		//53/53//40/40// treating groundwater and concentrate //50//50 treating reclaimed water
Effective area per membrane (cm^2)			220		3,200
Membranes tested	CR671/AR112B and CR67/AR204				
Concentrate makeup flow rate (lpm)	0	22		0	22
Electrode flow rate (lpm)				0.2	0.8-1.0
Dilute out flow rate (lpm)	1	1.5	1	1.5	28.4
Concentrate in flow rate (lpm)	1	1.5	1	1.5	26.1
Linear velocity of dilute-in (cm/s)	4.1	6.1	4.1	6.1	6.1
Hydraulic retention time (seconds)	13	9	26	18	63

cm/s = centimeter per second

Table 3.—Ion-Exchange Membranes Properties

Membrane	**AR204-SZRA-412**	**CR67-HMR-412**	**CR671**	**AR112B-574**
Type	Anion exchange	Cation exchange	Cation exchange	Anion exchange
Characteristics	Normal grade	Normal grade	Monocation permselective	Nitrate permselective
Thickness(μm)	500	560-580	560-580	580-690
Water content	46%	46%	46%	20-25%
Electricalresistance (Ω-cm^2)*	8	12	12	22-26
Ion exchangecapacity (meq/g dryresin)	2.40	2.10	2.0-2.1	1.6-1.8 strong base 0.3-0.6 weak base
Reinforcement	Acrylic**	Acrylic**	Acrylic**	Polypropylene

* Measure in 0.01 M NaCl.

** Acrylic: Polyacrylonitrile.

The CR671 membranes were developed by coating polyethyleneimine onsite with the reaction conditions closely monitored, including: solution temperature, concentration, pH, and reaction time (Figure 6). The polyethyleneimine (analytical standard, 50 percent by weight (wt.%) in H_2O solution, Sigma-Aldrich) used in this study has the number-average molecular weight (Mn) of ~60,000 as determined by the Gel Permeation Chromatography method and the weight-average molecular weight (Mw) of ~750,000 determined by Light Scattering method. The polyethyleneimine possesses primary:secondary:tertiary amino groups at a ratio of 1:2:1. Sata and Izuo (1990) reported that high molecular weight polyamino groups could minimize the reaction with the functional groups within CEMs and prevent decreasing current efficiency due to the increase of electrical resistance.

Figure 6.—Coating cation selective membranes CR671 and coated membrane passed dye testing.

3.4. Scaling Characterization

After the electrodialysis testing, we opened the pilot stack to examine the scaling on electrodes, membranes, and spacers. The structure and morphology of the precipitates collected from the stack was characterized by an S-3400N II scanning electron microscope (SEM) manufactured by Hitachi High-Technologies Corp., Pleasanton, CA. The elements were measured by energy-dispersive X-ray spectroscopy (EDX) mounted on the SEM.

3.5. Calculations

The performance of the ion-exchange membranes (IEM) were assessed under different operating conditions in terms of salt and ion removal, ion selectivity, normalized salt removal rate, and energy consumption. The relevant equations are listed below.

The electrodialysis water recovery is the percentage of feed-in water that becomes final dilute-out and is given by Equation 1:

$$\text{Recovery (\%)} = \frac{Q_d}{Q_f} \times 100 \qquad (1)$$

Where:
Q_d is the final dilute-out flow
Q_f is the feed-in flow (sum of dilute-out and concentrate make-up)

The overall salt removal is measured by conductivity cut calculated using Equation 2:

$$\text{Conductivity cut (\%)} = \left(1 - \frac{C_d}{C_f}\right) \times 100 \qquad (2)$$

Where:
C_d is the conductivity of dilute-out with a concentration in microsiemen per centimeter (mS/cm)
C_f is the conductivity of feed-in with a concentration in mS/cm)

The removal of a specific ion is evaluated based on the percent equivalent removal calculated using Equation 3:

$$\text{Percent equivalent removal} = \frac{\text{Equivalent of a given cation removed}}{\text{Equivalent of total cations removed}} \times 100 \qquad (3)$$

The selective separation of mono- and di-valent cations in electrodialysis was evaluated based on Na-selectivity, which is measured as the amount of the cation removed (in milli-equivalent [meq]) as opposed to the amount of Na removed (in meq), i.e., normalized equivalent removal in terms of Ca/Na, Mg/Na as shown in Equation 4:

$$\text{Na-selectivity} = \frac{\text{Equivalent of a given cation removed}}{\text{Equivalent of sodium removed}} \qquad (4)$$

The linear velocity of electrodialysis stack is calculated in Equation 5:

$$\text{Linear velocity} = \frac{Q_d}{n \times h \times W} \qquad (5)$$

Where:
n is the number of IEM pairs
h is the height of the dilute chamber flow channel
W is the width of the dilute chamber flow channel

The hydraulic retention time (HRT) is calculated asin Equation 6:

$$\text{HRT} = \frac{n \times h \times W \times L}{Q_d} \qquad (6)$$

Where:
L is the entire length of the dilute flow channel

For electrodialysis operation, the desalination energy is directly related to current density, which is defined in Equation 7:

$$\text{Current Density} = \frac{I}{S_1} \qquad (7)$$

Where:
I is the current through the electrodialysis stack
S1 is the membrane surface area of a single pair

The energy consumption in terms of normalized salt removal is given as amount of salt removed per membrane surface area per kilowatt hour of energy used. The normalized removal rate allows the comparison of electrodialysis performace under different operating conditions such as IEMs, stack staging, bench versus pilot system, applied current density, and flow rate. The normalized salt removal rate is calculated using Equation 8:

$$\text{Normalized salt removal} = \frac{(C_f - C_d) \times Q_d}{S \times I \times V} \qquad (8)$$

Where:
V is the applied voltage to the electrodialysis stack
S is the total membrane surface area of the stack

Average energy consumption of the electrodialysis system is defined as kilowatt-hour per thousand gallons of product water as shown in Equation 9:

$$\text{Energy Consumption} = \frac{I \times V}{Q_d} \qquad (9)$$

4. Results and Discussions

4.1. Electrodialysis of Brackish Groundwater at KBHDP

We conducted the bench- and pilot-scale electrodialysis experiments from December 2015 to July 2016 at the Kay Bailey Hutchison Desalination Plant (KBHDP) in El Paso, Texas, treating brackish groundwater. The high TDS of 2736±50 mg/L with electrical conductivity of 4626±263 microSiemens per centimeter (mS/cm) and SAR (13-14) makes the groundwater unsuitable for drinking and agricultural irrigation.

4.1.1. Limiting Current Density

The applied direct voltage is a key operating parameter in electrodialysis that controls current density, which determines desalination efficiency and energy consumption. Typically, current increases linearly at low voltage, then the increase rate reduces and finally reaches a “plateau,” namely the limiting current density (LCD). Above LCD, water splitting occurs, which consumes energy and contributes little to salt removal. Hence, LCD is a critical operating parameter that controls the optimal desalting efficiency, and most electrodialysis systems are operated below LCD.

In this study, two methods were used to identify the LCD of normal grade membranes CR67 and AR204 during pilot- and bench-scale testing (Figure 7).

The LCD is indicated by the point that the slope changes in the voltage-current (V-I) curve. However, it is sometimes impractical to identify the slope-changing point as illustrated in Figure 7b and Figure 7f, where the current increases linearly as a function of voltage. The plot of V/I against 1/I is easier to identify slope-change point for LCD estimation as developed by Cowan and Brown (1959). The lowest point on the V/I-1/I curve is considered as the LCD breakpoint as shown in Figure 7a and Figure 7c.

For the first electrical stage in the pilot electrodialysis (Figure 7a), the LCD was identified to be 4.0 milliamps per square centimeter (mA/cm^2) at 37 volts (V) and a 12.8 amp (A) current. Because of decreased salt concentration in the inter-stage dilute (product water of the first- stage is inlet water of the second-stage), the second electrical stage exhibited a lower slope-changing point at 28V and 8.3A, resulting in an LCD 2.6 mA/cm^2 (Figure 7c). With the constant groundwater quality, the V-I curve of the 1st-stage presented a linear relationship with correlation coefficient R2>0.99 (Figure 7b). The electrical resistance of IEMs increased with deceasing feed salt concentration due to the Donna exclusion and concentration polarization (Tanaka 2000), and LCD was proportional to feed salt concentration (Lee et al. 2006). Therefore the V-I curve of the membranes in the second-electrical stage showed a non-linear relationship (Figure 7d), and the LCD of the second-stage was lower than that of the first-stage.

The bench electrodialysis contained 10 cell pairs. Each cell pair can tolerate up to 2V applied voltage according to manufacture's recommendations. Such voltage restriction required the bench-scale work under the LCD to be based on the linear relationship of V-I (Figure 7f). Therefore, the LCD value of the bench-scale unit could not be determined during this study (Figure 7e), and all bench-scale experiments were conducted below LCD. Although the CR67 and CR671 have the same electrical resistance (Table 2), the electrical resistance of nitrate selective membrane AR112B is three times higher than normal grade membrane AR204. Therefore, the selective membranes CR671 and AR112B a needed higher applied voltage to reach the LCD than the normal grade membranes CR67 and AR204 needed. Due to the limited power ranges of the bench and pilot systems, the V/I-1/I curve of the CR671 and AR112B could not reach the lowest breakpoint, and the LCD of the selective membranes were not able to be determined in this study. Similar results were reported that the LCD could not be determined for seawater desalination using membranes with polyethyleneimine layer (Takata et al. 1996).

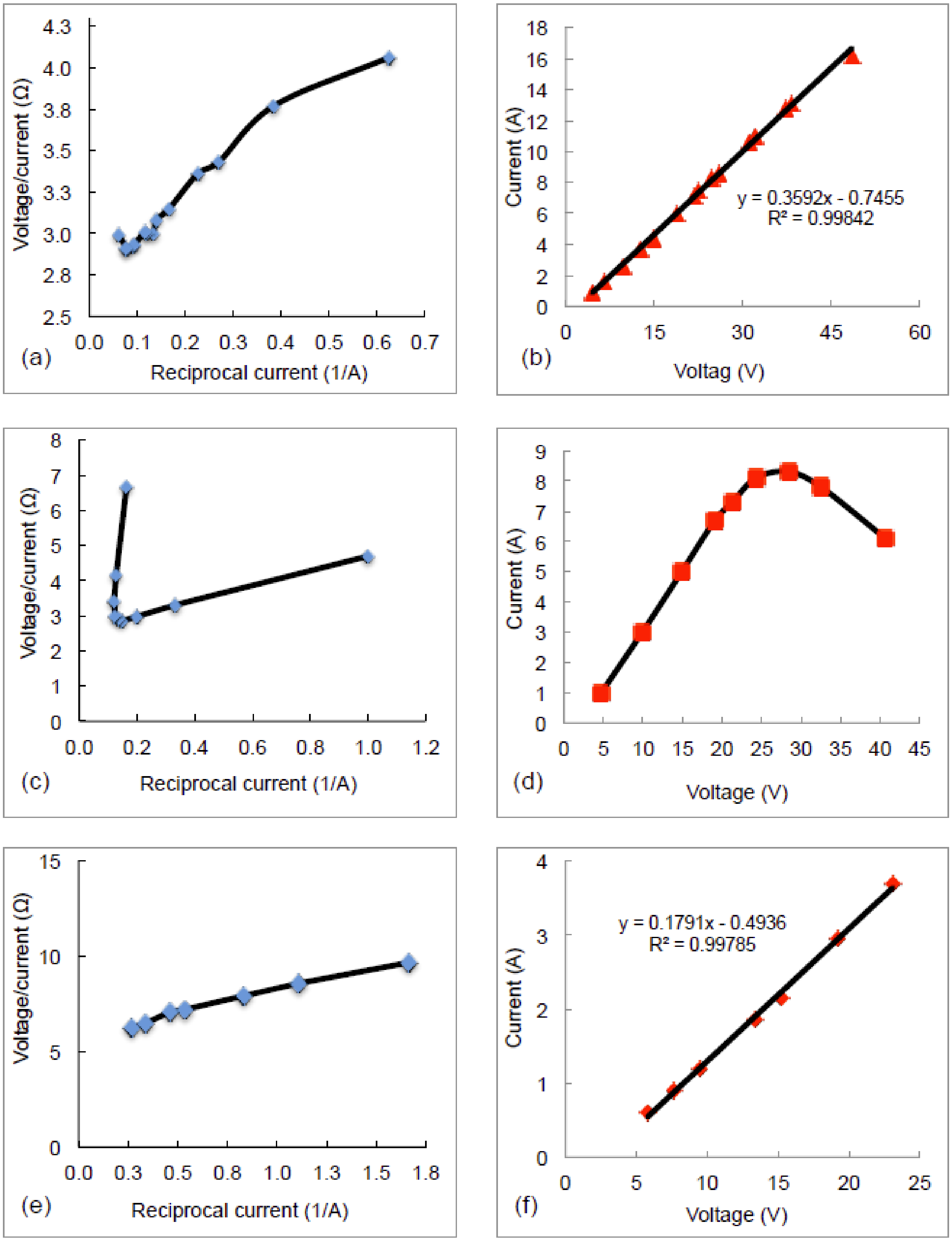


Figure 7.—Functions of voltage (V) and current (I) in electrodialysis with normal grade membranes CR67 and AR204 at linear velocity 6.1 cm/s. (a) and (b) V/I-1/I and V-I curves of 1st-electrical stage pilot system; (c) and (d) V/I-1/I and V-I curves of 2nd-electrical stage pilot system; (e) and (f) V/I-1/I and V-I curves of 1- stage bench system.

Therefore, in this study, we conducted all bench- and pilot-scale experiments below the LCD to maximize current efficiency, minimize boundary layer effect caused by concentration gradient, and compare bench- and pilot-scale testing results.

4.1.2. Overall Desalination Efficiency and Energy Consumption

Overall desalination efficiency and energy consumption of the membranes were studied under different operating conditions including current density, HRT, linear velocity, and electrodialysis stack staging.

Both normal grade (CR67 and AR204) and selective (CR671 and AR112B) membranes achieved the same desalination efficiency under the same current density during the two-electrical stage bench and pilot electrodialysis treating groundwater (Figure 8a and Figure 8b). The selective membranes, however, required higher voltage to achieve the same current density. This was due to higher electrical resistance of the AR112B, thereby consuming more energy to achieve the same salt removal as compared to normal grade membranes (Figure Figure 8c and Figure 8d). To meet the secondary drinking water standard of 500 mg/L TDS as the product water quality, 1.3 kilowatt hours per thousand gallons (kWh/kgal) of energy was required in pilot system using normal grade membranes versus 1.9 kWh/kgal estimated for selective membranes.

The mass of salt removed per membrane area per kilowatt-hour decreased with increasing current density, indicating the energy efficiency was reduced at higher applied voltage and higher desalination requirement. Bench system achieved a higher normalized salt removal of 10.3 or 9.9 kilograms (kg) of salt per kilowatt hour per square meter (m^2-kWh) at current density 3.3 or 5.2 mA/cm^2 for selective and normal membranes, respectively (Figure 8e), while pilot system only achieved 0.08 and 0.17 kg salt per m^2-kWh for selective and normal membranes at current density 2.0 mA/cm^2, respectively (Figure 8f). The higher normalized energy efficiency in bench system was due to lower desalination level and less membrane surface area than in pilot system.

To investigate the effect of HRT on desalting efficiency, we conducted bench-scale experiments using 1- and 2-electrical stage stacks under the same flow rate (Figure 9a and Figure 9b). As expected, doubling the HRT from 13 to 26 seconds (1-stage versus 2-stage) increased the amount of salt permeated for both selective and normal grade membranes, (e.g., from 24% to 37% at 7 mA/cm^2). However, the first-stage played a primary role in desalination, particularly at lower current density while the amount of salt removed in the second-stage increased with increasing current density.

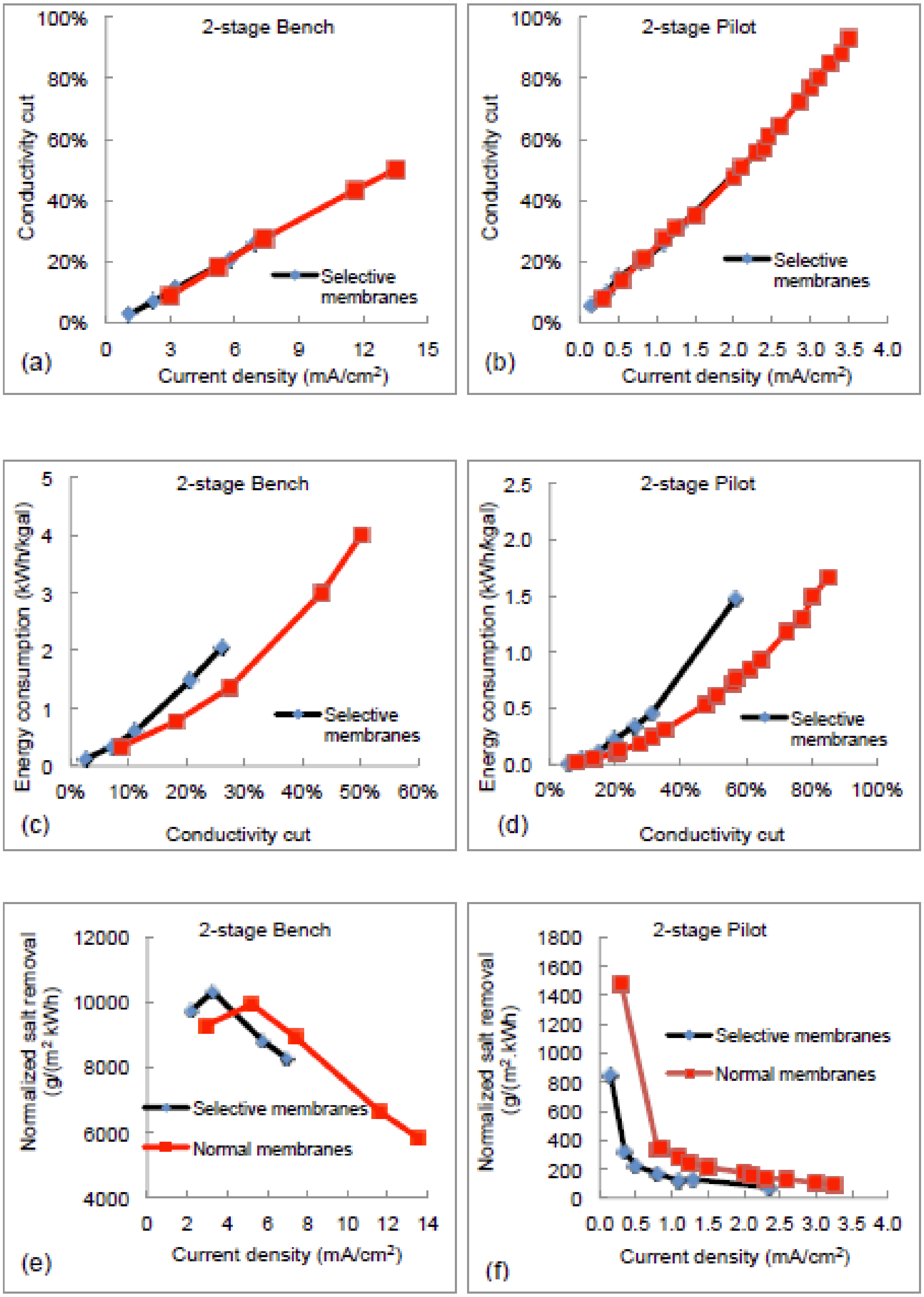


Figure 8.—Desalination and energy consumption of selective and normal grade membranes in 2-electrical stage electrodialysis at linear velocity 6.1 cm/s.

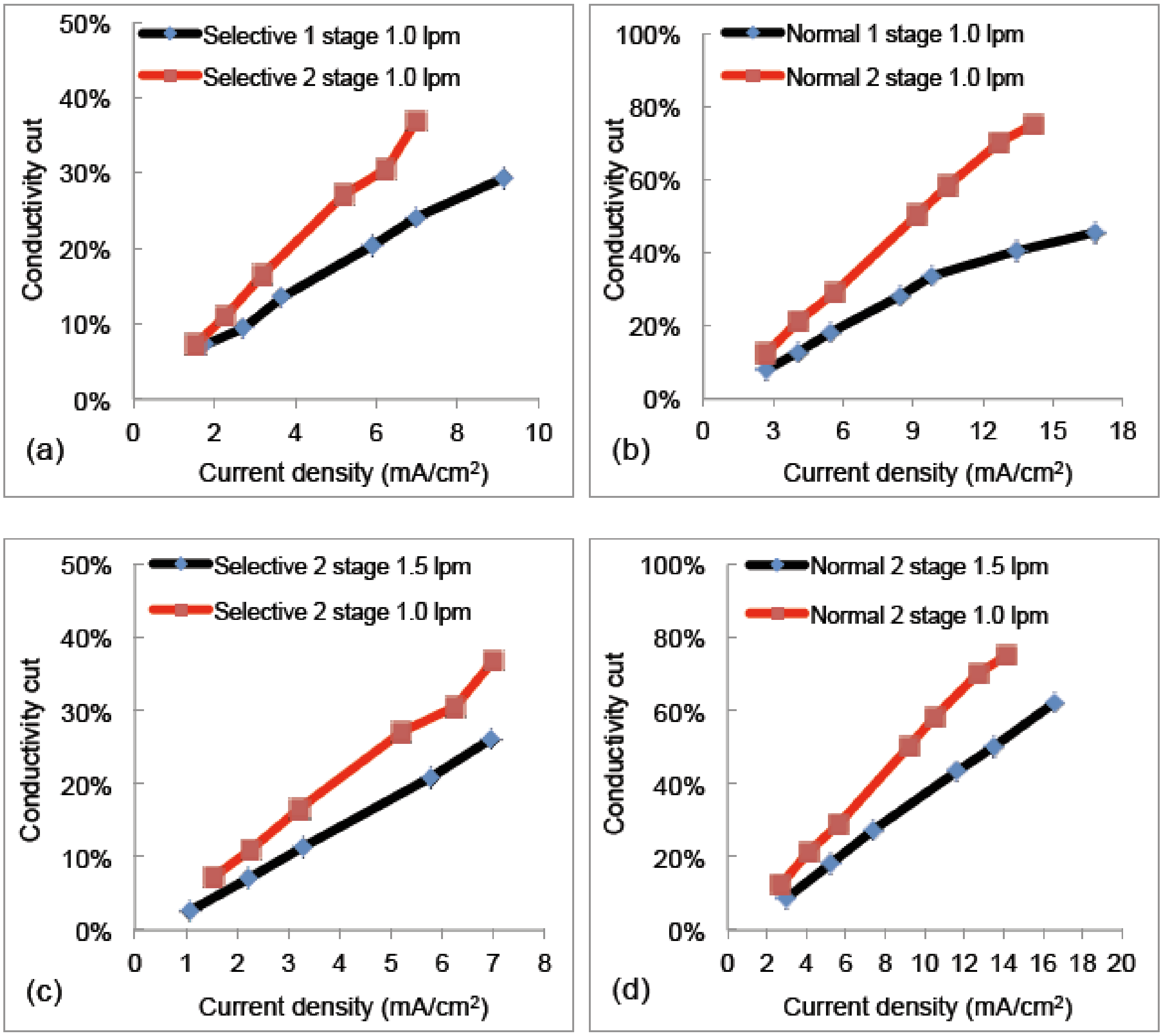


Figure 9.—Desalination efficiency of selective and normal grade membranes at different flow rates during bench-scale testing: (a) effect of staging on selective membranes, (b) effect of staging on normal grade membranes, (c) effect of flow rate on selective membranes, (d) effect of flow rate on normal grade membranes.

The salt removal deceased with the flow rate increasing from 1.0 to 1.5 lpm (4.1 to 6.1 cm/s and HRT from 13 to 9 seconds), such as from 37% to 26% at 7 mA/cm^2 (Figure 9c and Figure 9d). To achieve the same conductivity cut, higher flow rate required higher current density. As with the electrodialysis staging or HRT, the impact of flow rate on salt removal became more prominent at higher current densities. This effect was more substantial for normal grade membranes than for selective membranes. This prominence infers that, if the desired conductivity cut is not high and can be achieved at lower current densities, then the electrodialysis would be recommended to operate at higher flow rate to increase water production. For example, the difference between the conductivity cut of the selective membranes was less than 5% when current density was less than 3 mA/cm^2. For the normal grade membranes, the total amount of salt removed at 1.0 lpm was approximately 10% higher than at 1.5 lpm when the current density was less than 5 mA/cm^2.

The desalination performance of the 2-electrical stage bench and pilot electrodialysis was evaluated under the same linear velocity of 6.1 cm/s (Figure 10). Both systems exhibited the same linear trends with increasing current density. These similar trends demonstrate a high similarity in desalination performance of the two membranes. By using the correct linear correlation ratio, the testing results of the bench system can be scaled up to project the pilot electrodialysis. For electrodialysis treatment for groundwater, the desalination efficiency can be expressed as Equation 10:

$$\begin{aligned}&\text{Conductivity Cut in pilot system} = \\ &\alpha \times \text{Conductivity Cut in bench system} \\ &\times (\text{Current Density pilot}/\text{Current Density bench}) \qquad (10)\end{aligned}$$

Where:
α is the desalination ratio of pilot over bench

α was calculated to be 5.88 and 6.25 for selective and normal grade membranes, respectively.

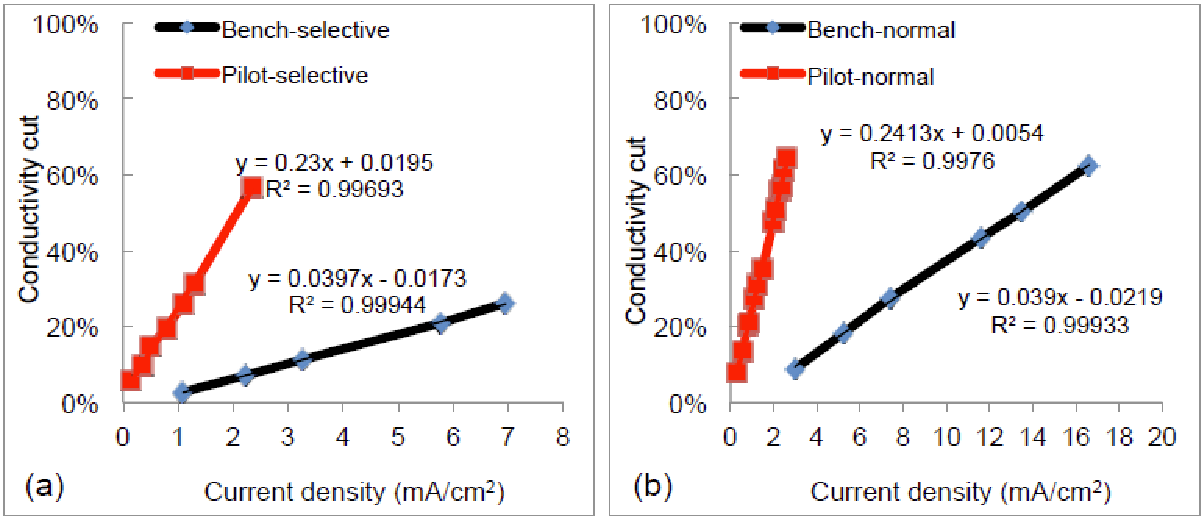


Figure 10.—Desalination efficiency of the 2-electrical stage of bench and pilot electrodialysis at a cross-flow velocity of 6.1 cm/s: (a) selective membranes, (b) normal grade membranes.

Normal grade membranes have been employed in full-scale desalination for decades, and GE has developed predictive model and software WATSYSTM to project electrodialysis efficiency. Considering the similar behavior observed between the normal grade and selective membranes, the overall desalination performance of selective membranes could be simulated using WATSYSTM by incorporating the testing results in the model. With the same hydraulic configuration (e.g., spacers design and cross-flow velocity), the overall desalination behavior between the bench and pilot electrodialysis was highly comparable. If the selectivity of ions and specific ion transport could also present such consistency, simulation of pilot-scale using bench-scale electrodialysis system would be highly feasible, thereby saving substantial costs for conducting extensive pilot-scale studies.

The brackish groundwater contains natural organic matter at low concentrations with measured TOC between 0.3 and 1.5 mg/L throughout the study. No significant decrease of TOC concentration in product water was identified. Organic matter in brackish groundwater is likely of large-size, zwitterions or neutral substances, which would not transport through the charged IEMs. Hence, TOC removal was not further investigated in this study.

4.1.3. Ion Selectivity of Normal Grade and Selective Membranes

We studied selective separation of divalent cations versus sodium was studied based on the Na^- selectivity defined as the normalized equivalent removal (i.e., the ratio of the equivalent removal of a given divalent cation [Ca or Mg] to the equivalent removal of sodium ion). Selective and normal grade membranes exhibited different ion transport behavior (Figure 11 and Figure 12). For the normal grade membrane CR67, divalent cations were preferentially transported over sodium at lower current density in both bench and pilot electrodialysis. For example, the equivalent removal ratio of Ca/Na and Mg/Na was 1.5 and 0.5 at current density 2.7 mA/cm^2 in the 2-stage bench system (Figure 11a), and 2.1 and 0.65 at current density 0.3 mA/cm^2 in pilot system (Figure 11b). The ion transport became stable when the current density was greater than 9 mA/cm^2 and 3 mA/cm^2 for bench and pilot systems, respectively, because divalent cations transported preferentially in normal grade membranes and the remaining amount of divalent ions in the feed stream was low at higher current density. The lower removal ratio for Mg/Na than for Ca/Na was due to lower concentration of Mg^{2+} in the groundwater.

For the selective membrane CR671, current density had insignificant impact on ion transport in both bench and pilot electrodialysis when current density was above 1.0 mA/cm^2. The equivalent removal ratio of Ca/Na and Mg/Na was in the range of 0.31-0.37 and 0.09-0.12 at current density 1.5-7 mA/cm^2 in the 2-stage bench system (Figure 11a), and 0.18-0.3 and 0.04-0.1 at current density of 0.5 to 2.35 mA/cm^2 in the pilot system (Figure 11b). The optimal selectivity point was observed at current density 0.5 mA/cm^2 for pilot system. Below the optimal point of 0.5 mA/cm^2, the selective membranes and the normal membranes showed similar trends—the normalized equivalent removal decreased with increasing current density. However, the selectivity was much better for the selective membranes than for the normal grade membrane, and then above the optimal point, the selectivity decreased slightly and kept a relative stable value.

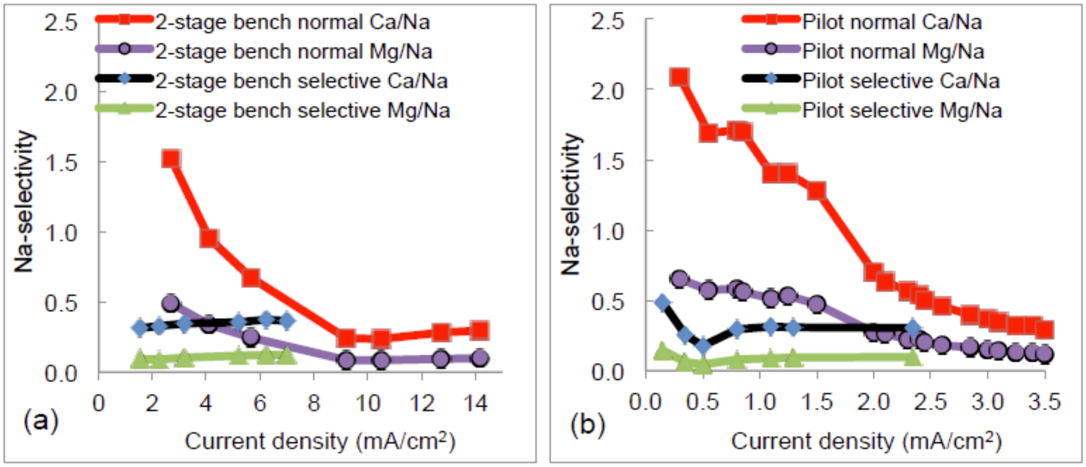


Figure 11.—Na-selectivity based on equivalent removal ratio of divalent cations to Na+: (a) 2-stage bench testing at linear velocity 4.1 cm/s, (b) 2- stage pilot testing at linear velocity 6.1 cm/s.

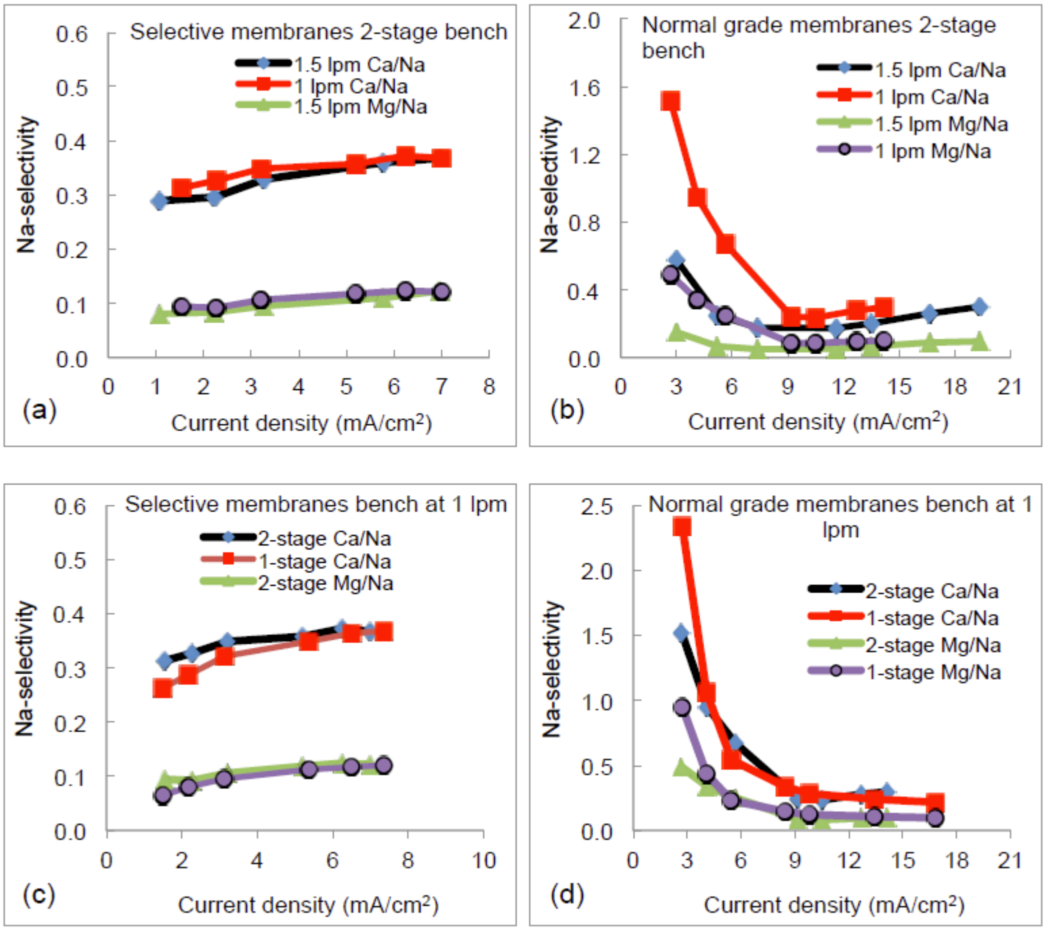


Figure 12.—Impact of staging and linear velocity on membrane Na-selectivity during bench-scale electrodialysis: (a) effect of staging on selective membranes, (b) effect of staging on normal grade membranes, (c) effect of flow rate on selective membranes, (d) effect of flow rate on normal grade membranes.

We used bench electrodialysis to study the effects of flow rate and HRT (staging) on Na-selectivity. In the 2-stage bench system, the equivalent removal ratio of Ca/Na and Mg/Na ranged from 0.29 to 0.37 and 0.08 to 0.12 at current density 1.1-7.0 mA/cm^2 for selective membranes (Figure 13a), and 1.5-0.24 and 0.49-0.09 at current density 3.0-14 mA/cm^2 for normal grade membranes (Figure 13b). Higher flow rates slightly favored Na transport through the selective membranes because higher linear velocities decreased the thickness of boundary layer caused by concentration polarization. The influence of HRT was negligible when the current density was above 4 mA/cm^2, while lower Na removal was observed with decease of HRT below that current density.

The variation of flow rate dramatically affected the Na-selectivity of the normal grade membranes (Figure 13). Decreasing the flow rate from 1.5 to 1.0 l pm in bench electrodialysis significantly reduced the Na-selectivity. The transport of divalent cations was favored in the normal grade membranes because of higher electric attraction between the negatively charged membrane surface with the divalent cations than with monovalent cations. The phenomenon was evident at low current density. However, the HRT had negligible impact on the Na$^-$ selectivity of the normal grade membranes when current density was above 4 mA/cm^2 (Figure 13d). Compared with the HRT, the linear velocity had a dominant influence on Na-selectivity for cations separation (Figure 13b and Figure 13d). It is likely that the correlation between the Na-selectivity and current density was a quantum function in the normal grade membranes. When the current density was below a certain threshold, the Na-selectivity would not change with the variation of HRT—unlike the overall salt reduction, which was a continuous function of HRT. This phenomenon is especially important if the product water quality requires reducing both TDS and SAR. The observed independence of Na-selectivity on HRT above the current density threshold provides an additional consideration for process design when modifying water composition is required (e.g., reducing the SAR of treated water) d. It infers that for normal grade membranes, adding more stages of electrodialysis stacks would reduce TDS but may not achieve desired modification of ionic composition (e.g., SAR) in the product water.

Figure 13 compares the Na$^-$ selectivity of normal grade and selective membranes during the 2-stage bench and pilot electrodialysis at a linear velocity of 6.1 cm/s. The results demonstrated the continuity of Na$^-$ selectivity in the scale-up from bench to pilot for both selective and normal grade membranes. For the normal grade membranes, the removal trends of Mg_2^+ over Na^+ were even joined from bench- to pilot-scale testing. Although the current density of bench stack cannot be low enough to obtain the maximum selectivity point as in the pilot system, due to limitations on salt removal and current monitoring, the selectivity demonstrated inthe bench system was highly consistent with the pilot system.

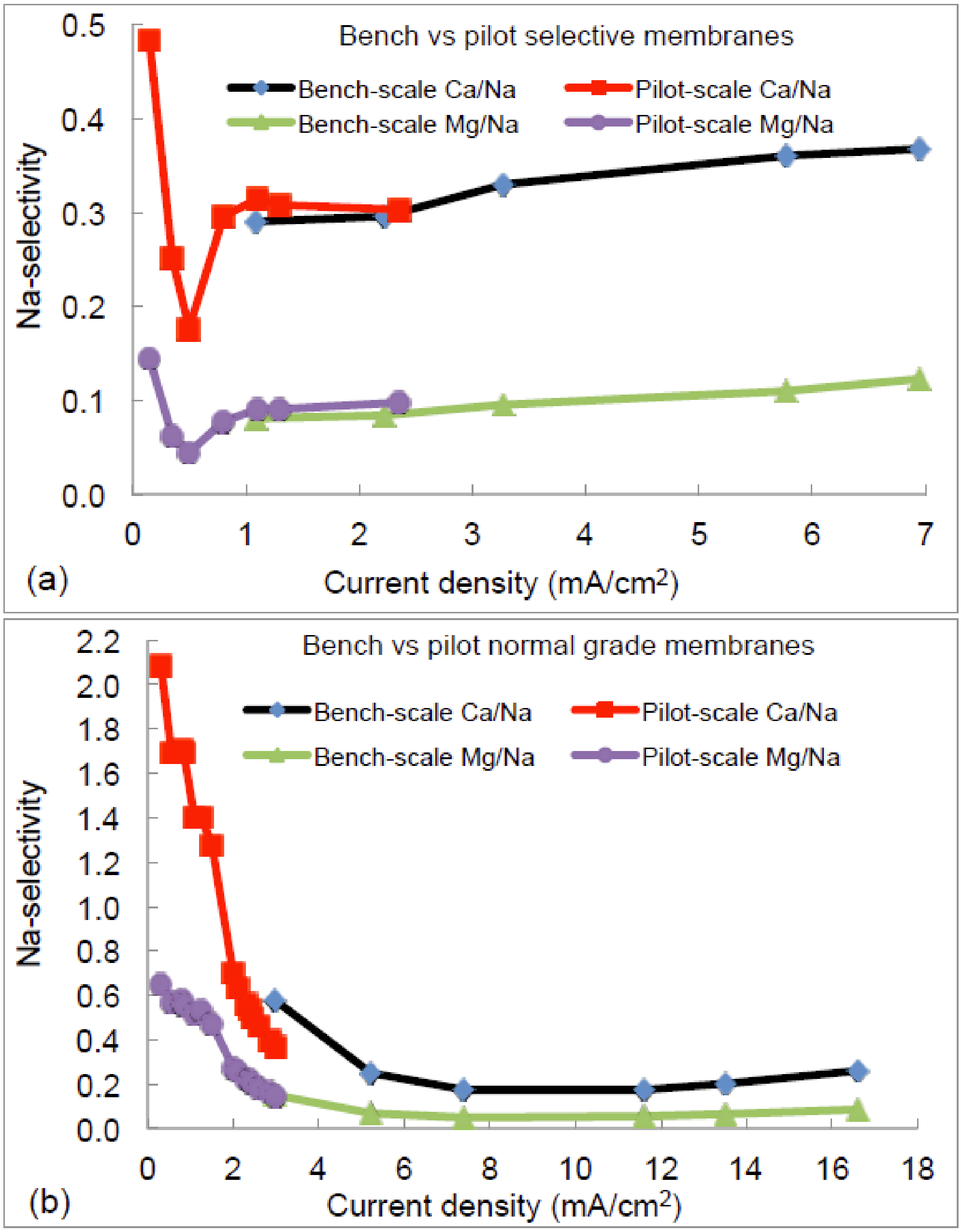


Figure 13.—Na-selectivity during 2-stage bench and pilot testing at linear velocity 6.1 cm/s. (a) Selective membranes; (b) Normal grade membranes.

4.1.4. Specific Ion Removal

We investigated specific ion removal between bench- and pilot-scale testing based on percent equivalent removal, i.e., the amount of a given cation removed (in equivalent) over the total cations removed (in equivalent). Mg^{2+} removal had the same removal trend as Ca^{2+}, and the K^{+} removal was low due to low initial concentration in the groundwater. Hence, Ca^{2+} and Na^{+} were chosen to represent the divalent and monovalent cations, respectively.

For the first-electrical stage bench electrodialysis, Ca^{2+} percent equivalent removal by the normal grade membranes was higher than that by the selective membranes, indicating the CR67 selectively removed divalent ions while the CR671 preferentially removed monovalent ions (Figure 14a). The difference of Ca^{2+} and Na^+ removal in normal grade membranes decreased with increasing current density, while such difference remained consistent up to current density of 12 mA/cm^2 in the selective membranes (Figure 14a).

At a linear velocity of 4.1 cm/s in 2-stage bench electrodialysis, there was a substantial difference of Ca and Na removal in the normal membranes with increasing current density, which then became negligible above current density of 9 mA/cm^2 (Figure 14b). In the first stage, the decrease of Ca^{2+} removal and increase of Na^+ removal existed until the current density reached 6 mA/cm$^{2.}$ At that point, Ca2$^+$ and Na^+ percent removal remained stable (Figure 14b). While in the 2-electrical stage bench system, the percent of removal of both Ca^{2+} and Na+ remained relatively constant (Figure 14b). The increase of Na^+ percent removal and the decrease of Ca^{2+} percent removal showed the same trends in 1- and 2-stage bench electrodialysis using the normal grade membranes (Figure 14a and Figure 14b). Below the current density of 4 mA/cm^2, divalent cations had a higher percent removal due to higher electric attraction with the normal grade membranes. Then Na-selectivity increased with increasing current density. In pilot system, the selective membranes constantly demonstrated higher Na^+ removal than Ca^{2+}, and the selective membranes reached the maximum Na-selectivity at a current density of 0.5 mA/cm^2. In contrast, the normal grade membranes demonstrated better divalent transport under a current density of 2 mA/cm^2, then displayed monovalent selective transports at higher current densities (Figure 14c).

The impact of HRT on ion selectivity of selective and normal grade membranes was studied using bench system. The percent equivalent removal exhibited stable selectivity in 2-stage bench stack (Figure 15a). The normal grade membranes had similar percent removal on Ca^{2+} and Na^+ between 1- and 2-electrical stage stacks (Figure 15b). The Na percent equivalent removal increased with increasing current density, while the Ca^{2+} equivalent removal decreased with increasing current density. The specific divalent and monovalent cations showed identical trends at different HRT (or staging), with even the same selectivity turning point.

Geraldes and Afonso (2010) reported that the thickness of concentration boundary layer would not increase along the flow channel due to the periodic mixing turbulence-promoting mesh-type spacers. Hence, HRT should have negligible impact on selectivity. The concentration polarization was found to be a function of current density, linear velocity, cell design, and the membrane properties (Lee et al. 2006). The testing results from this study clearly confirmed the reported relationship for the normal grade membranes.

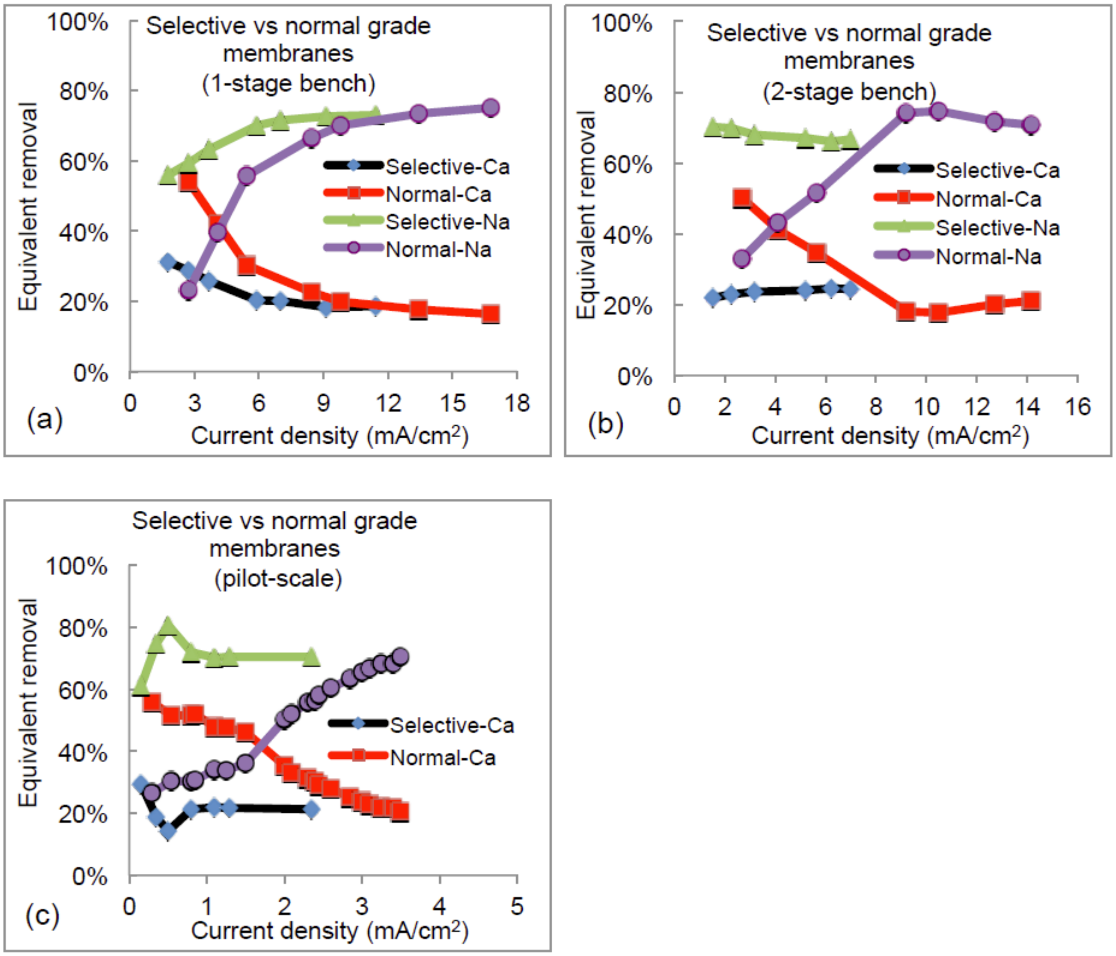


Figure 14.—Percentage equivalent removal of Ca2$^+$ and Na$^+$ by selective and normal grade membranes in electrodialysis operating at 4.1 cm/s for bench systems and 6.1 cm/s for pilot systems.

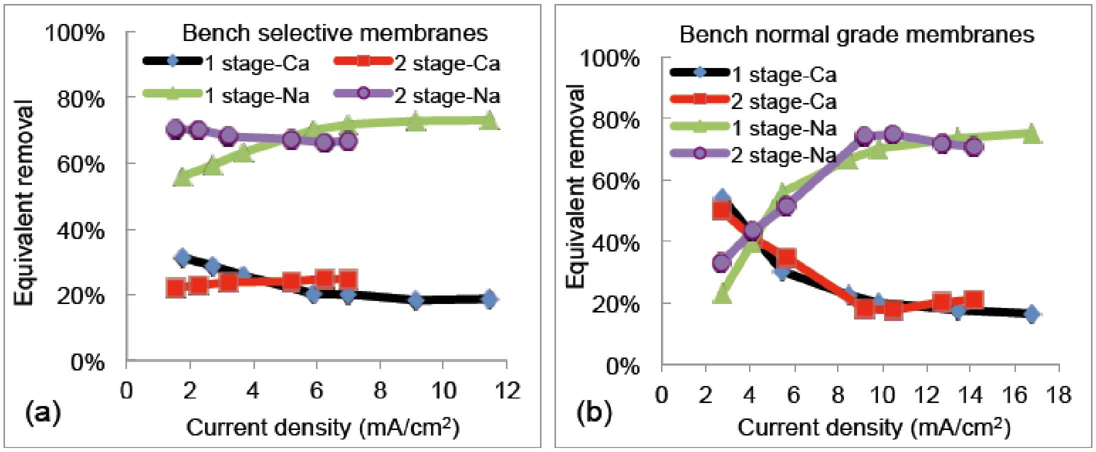


Figure 15.—Effect of staging on equivalent percent removal of Ca^{2+} and Na$^+$ by selective and normal grade membranes in a bench-scale electrodialysis system operating at linear velocity of 4.1 cm/s.

Flow rate, or linear velocity, is one of the most important operation parameters in electrodialysis. Mohammadi et al. (2004) reported that flow rate was the most significant factor when analyzing temperature, feed concentration, and applied voltage using analysis of variance (ANOVA analysis). Increased linear velocity did not affect the percent equivalent removal of both Ca^{2+} and Na^{+} in the selective membranes (Figure 16a), but increased linear velocity decreased the equivalent percent removal of Ca^{2+}while increasing the equivalent percent removal of Na^{+} for the normal grade membranes (Figure 16b). The equivalent percent removal revealed that higher flow rate favored the selective monovalent removal and enhanced the membrane Na-selectivity for normal grade membranes.

We compared bench- and pilot-scale electrodialysis for Ca^{2+} and Na+ removal at the same linear velocity of 6.1 cm/s (Figure 17). The graphs exhibited an analogous behavior of specific cation percent removal in both bench- and pilot-scale electrodialysis systems. The ion selectivity of electrodialysis in bench- and pilot-scale testing matched very well for both selective membranes and normal grade membranes. Equivalent Na^{+} percent removal reached the highest point and equivalent Ca^{2+} percent removal was reduced to the lowest point at a current density of 0.5 mA/cm^2 for selective membranes, then stabilized at 21 to 24% for Na removal and 72 to 66% for Ca removal (Figure 17a). In normal grade membranes electrodialysis, the similar equivalent percent removal was observed, and even had the identical selectivity- reversal point at the same current density of 2 mA/cm^2 (Figure 17b), which again confirmed the previous finding in bench-scale testing—that ion selectivity is independent of HRT in the normal grade membranes.

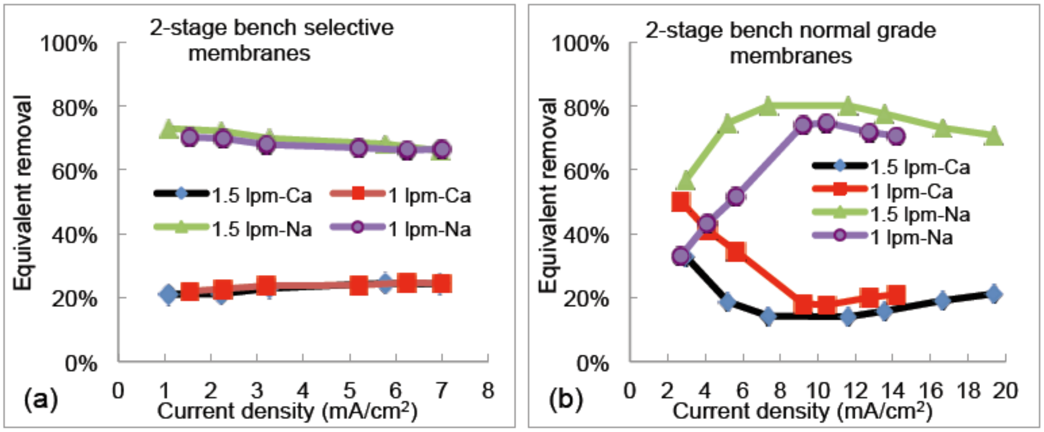


Figure 16.—Effect of flow rate on equivalent percent removal of Ca^{2+} and Na^{+} by selective and normal grade membranes in a 2-electrical stage bench electrodialysis system.

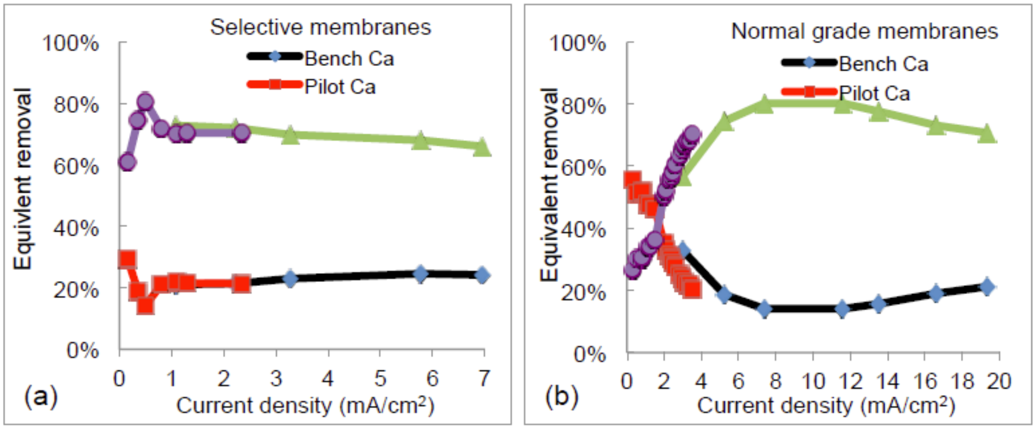


Figure 17.—Comparison of equivalent percent removal of Ca^{2+} and Na^+ by selective and normal grade membranes in a 2-electrical stage bench system and a pilot electrodialysis system at linear velocity of 6.1 cm/s.

4.1.5. Summary

We conducted bench- and pilot-scale electrodialysis experiments to compare the overall desalination performance and Na-selectivity of an innovative monovalent permselective cation exchange membrane CR671 with the normal grade membrane CR67 during electrodialysis of a brackish groundwater. This study elucidated the impacts of operating conditions (current density, linear velocity, hydraulic retention time, and staging) on Na-selectivity and overall salt removal for both selective and normal grade ion-exchange membranes. Overall desalination efficiency and Na-selectivity were consistent from bench to pilot electrodialysis for both selective and normal grade membranes. The primary conclusions of the study are:

- A thin layer of polyethyleneimine coating effectively improved the Na-selectivity of cation exchange membrane by preferentially transporting monovalent cations Na^+ over divalent cations Ca^{2+} and Mg^{2+}.

- Monovalent selective membranes (CR671 and AR112B) achieved the same desalting efficiency as normal grade membranes (CR671 and AR204) during bench- and pilot-scale electrodialysis at the same current density.

- The Na-selectivity in terms of equivalent removal of Ca^{2+} and Mg^{2+} over Na^+ was significantly affected by the current density and linear velocity for normal grade membranes while the selective membranes exhibited relatively stable ion selectivity.

- Hydraulic retention time and hydraulic staging had lesser impacts on ion selectivity of selective and normal grade membranes than on overall salt removal.

- With the same hydraulic configuration, the overall desalination behavior and Na-selectivity between bench- and pilot-scale electrodialysis was highly comparable. Bench-scale testing results can be used to simulate and predict the desalination performance and ion selectivity of pilot- and potentially full-scale electrodialysis system. However, the estimated energy consumption by bench testing was much higher than that of pilot-scale unit because of lower desalination efficiency and less membrane surface area.

4.2. Electrodialysis of RO Concentrate at KBHDP

We conducted bench- and pilot-scale electrodialysis experiments from December 2015 to July 2016 at the Kay Bailey Hutchison Desalination Plant (KBHDP) in El Paso, Texas, treating RO concentrate. The TDS concentration in the RO concentrate was approximately 10 ± 2.3 grams per liter (g/L) with electrical conductivity of 19.5 ± 0.46 mS/cm.

4.2.1. Functions of Voltage and Current in Electrodialysis

The electrodialysis current increased linearly as a function of the applied voltage in the pilot-scale experiments as shown in Figure 18, which yielded a constant slope that represents the reciprocal resistance of the electrodialysis system. This high linearity indicated that the effect of concentration polarization in boundary layer to the stack resistance was negligible in desalting RO concentrate (Fidaleo and Moresi 2011). Therefore, the assumption that salt reduction in diluate chambers has no significant impact on the working current can be made as the RO concentrate had a high ionic strength when the conductivity cut was below 60% during the experiments.

With the solution resistance practically independent of voltage and membrane resistance related to membrane properties, the resistance per cell of the electrodialysis system maintained relatively constant (neglecting the resistance in anode and cathode chambers) in the concentration range tested.

From the measurements during the experiments, the total stack resistance (R_{total}) can be expressed as ratio of voltage over current (the reciprocal slope in Figure 2). The total stack resistance is a numerical summation of different components in the electrodialysis stack (Oren et al. 2010) in Equation 11:

$$R_{total} = R_{electrodes} + N_{cp} (R_{CR} + R_{AR}) + N_{cp} (R_D + R_C) \quad (11)$$

Where:

$R_{electrodes}$ is the resistance of the electrode chambers

N_{cp} is the number of cell pairs (106 and 80 in 1st and 2nd electrical stage, respectively)

R_{CR} is the CEM resistance
R_{AR} is the AEM resistance
R_D is the solution resistance in diluate
R_C is the concentrate chambers

Assuming a constant membrane and solution resistance in RO concentrate and neglecting the electrode resistance, the above equation can be simplified to Equation 12:

$$R_{total} = N_{cp} (R_{CR} + R_{AR} + 2R_D) \qquad (12)$$

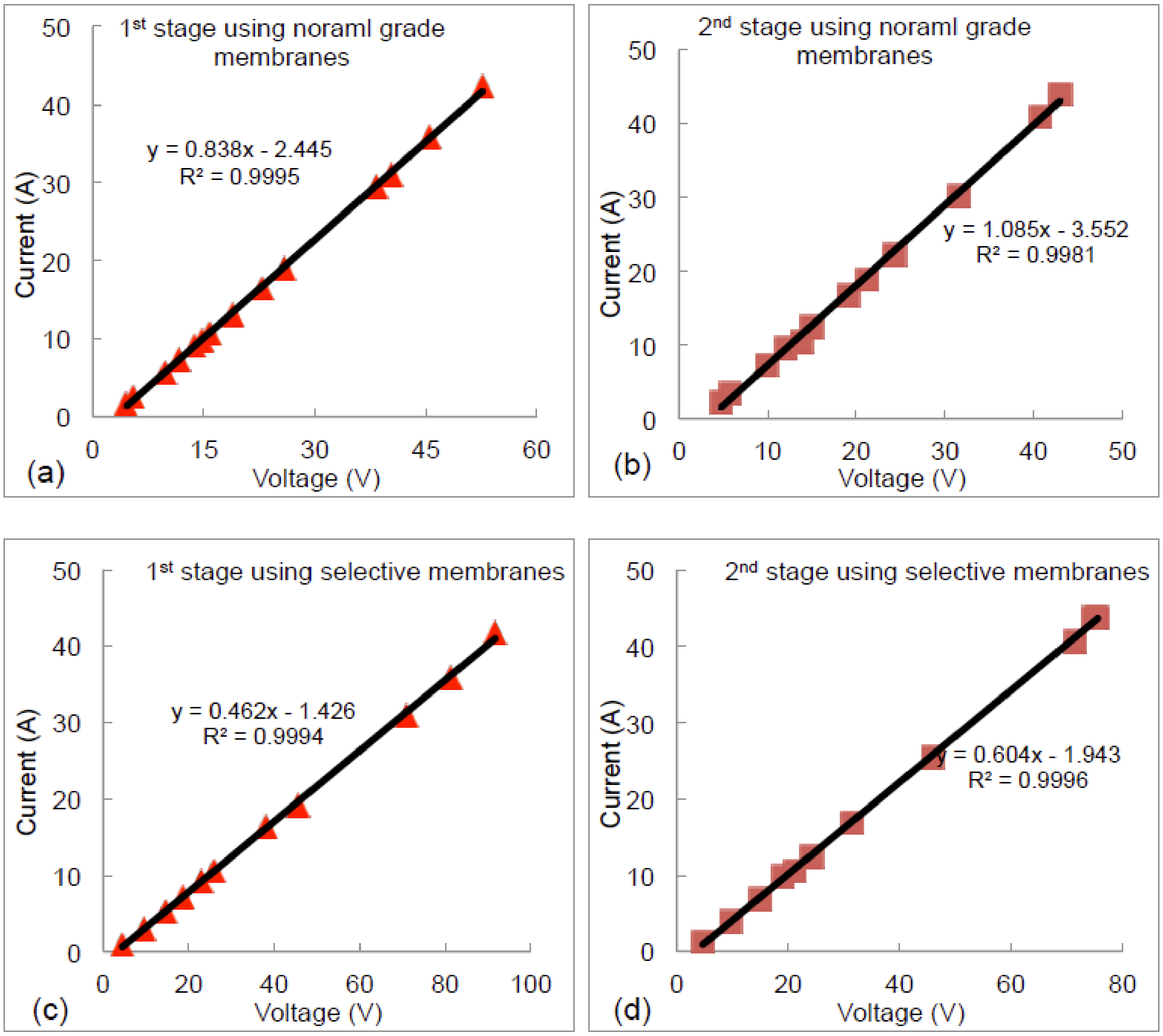


Figure 18.—Functions of voltage and current during pilot-scale electrodialysis of RO concentrate at linear velocity 6.1 cm/s: (a) and (b) V-I curve of first and second electrical stage with normal grade membranes CR67 and AR204, (c) and (d) V-I curve of first and second electrical stage with selective membranes CR671 and AR 112B.

The simplification could be validated by two independent approaches. The solution resistance in the first and second electrical stage would stay the same despite different feed concentration and applied voltage in an electrodiaysis system. The calculated solution resistance, based on the ohmic resistance from Figure 18 and the manufacturer's description of the membrane's properties, is summarized in Table 4. The calculated solution resistance ranged from 0.0043to about 0.0050 Ohms (Ω) per cell, regardless of the electrodialysis staging and the membranes installed (normal grade membranes or selective membranes). The calculated solution resistance validated the simplification, proving that the overall stack resistance is not sensitive to concentration changes in the diluate and concentrate chambers during RO concentrate treatment. It's also worth noting that the electric resistance of the desalting and the concentrating chambers is predominant over that of the normal grade membrane with smaller resistance in treating RO concentrate, though membrane resistance was reported to dominate solution resistance at high salinity solution (e.g., seawater) (Reig et al. 2014 and McGovern et al. 2014).

The bench-scale electrodialysis system contained 10 cell pairs, and each cell pair can tolerate up to 2V applied voltage based on manufacture's recommendations. Such voltage restriction made the bench-scale work under the limiting current density (LCD). Therefore, this study was not able to determine the LCD in the pilot-scale system due to current restriction (less than 50 A) in electrodiaysis stack and high ion strength in RO concentrate.

Table 4.—Calculated Solution Resistance In Pilot Electrodiaysis System Treating RO Concentrate

Stage	**Normal membranes grade**		**Selective membranes**	
	First stage	**Second stage**	**First stage**	**Second stage**
Total stack resistance (Ω)	1.19	0.92	2.16	1.66
Membrane resistance (Ω)	0.22	0.17	1.13~1.26	0.85~0.95
Solution resistance (Ω/cell)	0.0046	0.0047	0.0043~0.0049	0.0044~0.0050

4.2.2. Desalination Efficiency and Energy Consumption

We calculated the overall desalting performance based on the conductivity cut of the RO concentrate. Both normal grade (CR67/AR204) and selective (CR671/AR112B) membranes exhibited the same desalting efficiency under the same current density during bench- and pilot-scale electrodialysis of RO concentrate (Figure 19).

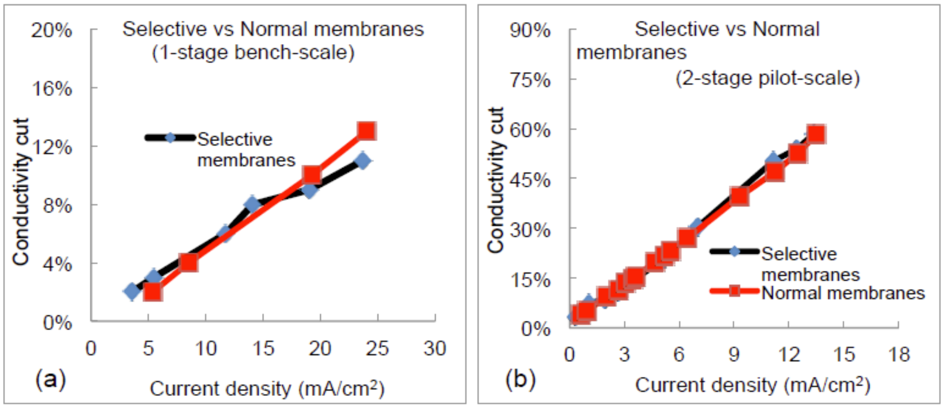


Figure 19.—Desalination efficiency of selective and normal grade membranes in bench- and pilot-scale electrodialysis treating RO concentrate at a linear velocity of 6.1 cm/s.

Because feed water salinity plays an important role in electrodialysis performance, we further investigated the impact of feed water salinity on the first and second electrical stage by treating three different water sources with conductivity ranging from 1,900 mS/cm to 20,000 mS/cm (Figure 20) in a pilot-scale electrodialysis system.

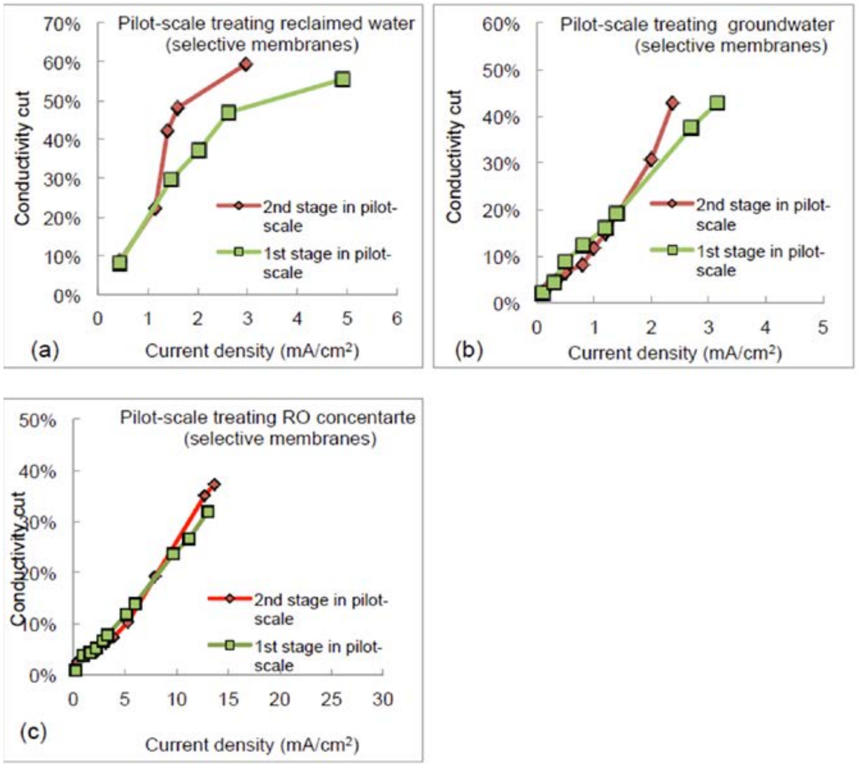


Figure 20.—Comparison of first- and second-electrical stage desalting capacity of selective membranes during pilot-scale electrodialysis of: (a) reclaimed water (TDS 1,200 mg/L), (b) brackish groundwater (TDS 2,730 mg/L), (c) RO concentrate (TDS 10,000 mg/L). Linear velocity was 6.1 cm/s.

The reclaimed water was collected from the Scottsdale Water Campus, Arizona, with conductivity at 1,900 mS/cm and a TDS concentration of 1200 mg/L, and brackish ground water from the KBHDP in El Paso, Texas, with conductivity at 4,600 mS/cm and a TDS concentration of 2,730 mg/L. At low current densities (1.5 mA/cm^2 for reclaimed water and brackish ground water and 9.7 mA/cm^2 for RO concentrate), the conductivity cut was similar in the first and second electrical stages in the electrodialysis stack for all the three types of water. However, the higher desalting capacity of the second electrical stage emerged at the same point of 20% salinity reduction for the three water resources—regardless of significant salinity variation. The 20% conductivity reduction in treating the RO concentrate was linked to a feed water TDS concentration of around 10,000 mg/L for the second electrical stage, which is within the upper threshold of optimal operating range of salt content in feed water when considering an electrodialysis process. Although the actual mechanism for the turning point at salinity reduction of 20% was unclear for the feed waters, the finding in the experiments provides practically useful information for multi-stage electrodialysis design, considering the consistency over a wide range of salt concentrations in the experiments.

The electrodialysis system with selective membranes consumed more energy to achieve the same desalination efficiency due to higher electrical resistance of the AR112B that required higher voltage to achieve the same current density in both bench- and pilot- scale systems (Figure 21). The mass of salt removed per membrane area per kilowatt-hour decreased with the increasing current density, indicating that higher energy intensities are required for higher desalination rates, with energy efficiency reduced at higher current densities. Pilot-scale electrodialysis of RO concentrate achieved normalized energy-salt removal rate of 0.19 kg or 0.32 kg of salt per m^2-kWh at a current density of 2.0 mA/cm^2 for selective and normal membranes, respectively (Figure 22), which is higher than the normalized energy-salt removal rate for electrodialysis of brackish groundwater during previous experiments: 0.08 and 0.17 kg salt/m^2-kWh at the current density of 2.0 mA/cm^2 for selective and normal membranes. The higher normalized energy efficiency in treating the RO concentrate was attributed to the higher ion concentration, which reduced the impact from concentration polarization at the interface between bulk solution and membrane surface.

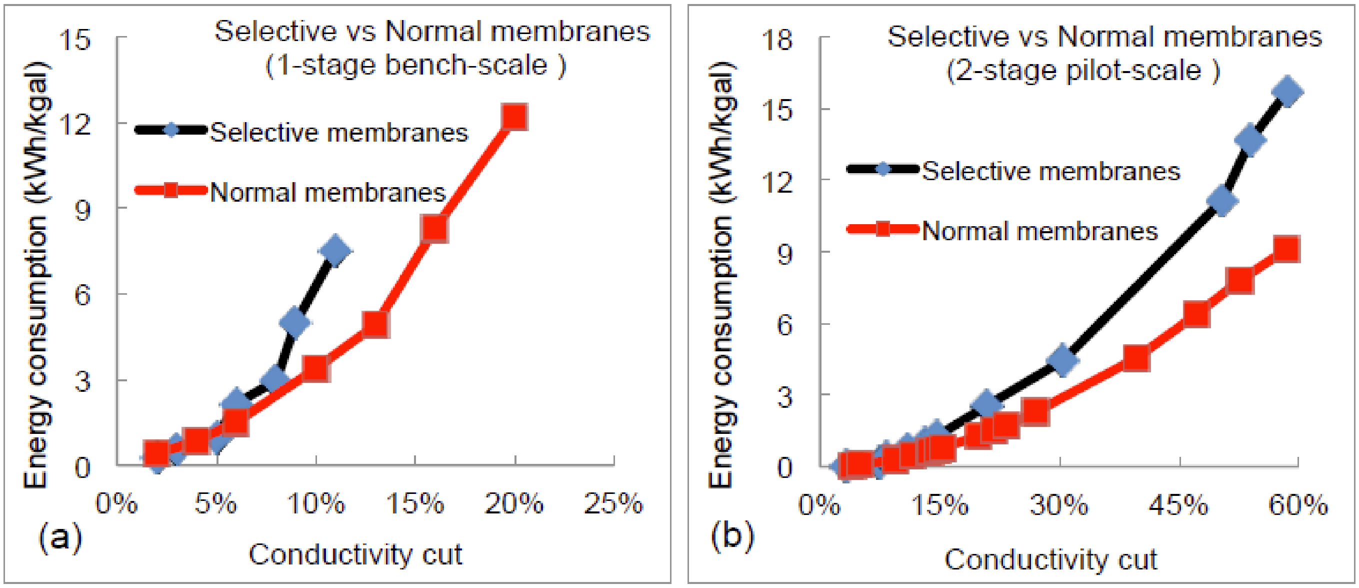


Figure 21.—Energy consumption (in kWh/kgal) based on conductivity cut of selective and normal grade membranes treating RO concentrate at linear velocity 6.1 cm/s in: (a) bench-scale system, (b) pilot-scale system.

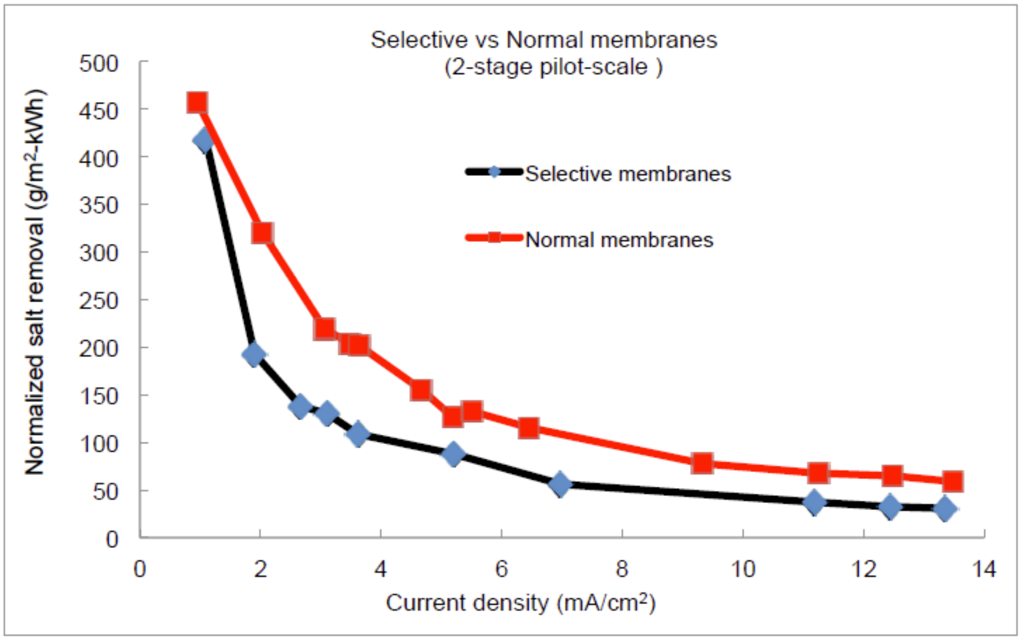


Figure 22.—Energy consumption in normalized salt removal (kg of salt per m^2-kWh) of selective and normal grade membranes in the 2-electrical stages pilot-scale electrodialysis of RO concentrate at a linear velocity 6.1 cm/s.

4.2.3. Selective Ion Separation

4.2.3.1. Na-Selectivity

Na-selectivity is used as the indicator to investigate the selective transport of mono- versus di-valent cations (i.e., the percentage of the permeated equivalent of a given cation to the permeated equivalent of sodium ion). Selective and normal grade membranes exhibited different Na-selectivity behaviors (Figure 23). In the bench-scale electrodialysis, divalent cations were preferentially transported over sodium in normal grade membranes more effectively than in selective membranes (Figure 23a). However, normal grade and selective membranes displayed similar Na-selectivity at current densities below 3 mA/cm^2 and above 12 mA/cm^2, with better selectivity in selective membranes at the middle range of current density (Figure 23b) in pilot-scale electrodialysis. The similarity at the high current densities stems from the electrical repulsion between divalent cations and polyethylenimine coating in selective membranes becoming less significant on the ion transport through membranes, compared to the dominant driving force by higher applied voltage. At lower current densities, the lower Na-selectivity could be the result of low removal rate and high ion concentration in feed water. The Na- selectivity of selective membranes became stable when the current density was greater than 3 mA/cm^2 in pilot-scale electrodialysis.

For the selective membranes, the current density had less of an impact on the permselectivity in both bench- and pilot-scale systems when the current density was above 5 mA/cm^2 and 3 mA/cm^2, respectively. The equivalent removal ratio of Ca/Na and Mg/Na was in the range of 0.42-0.56 and 0.16-0.19 at a current density of 5 to 24 mA/cm^2 in the bench system, and 0.5-0.7 and 0.2 at a current density of 3.6 to 3.5 mA/cm^2 in the pilot system. The local optimal selectivity point was observed at current density of 3 mA/cm^2 in the pilot-scale system. The optimal Na-selectivity point for desalting the brackish groundwater was 6 times larger in the RO concentrate (at a current density of 0.5 mA/cm^2) than the optimal point during previous experiments. This ratio is consistent with the concentrating factor in primary RO system where the RO concentrate was generated from brackish groundwater desalination.

Although the current density of bench-scale electrodialysis system was not able to be low enough to compare with that in the pilot-scale system due to salt removal capability caused by limited cell pairs, less membrane surface area, short flow length, and lower applied voltage, the Na-selectivity demonstrated in the bench-scale system is consistent with the pilot-scale system (Figure 23c). Highly similar results were reported in previous experiments using the same electrodialysis systems for treating brackish groundwater.

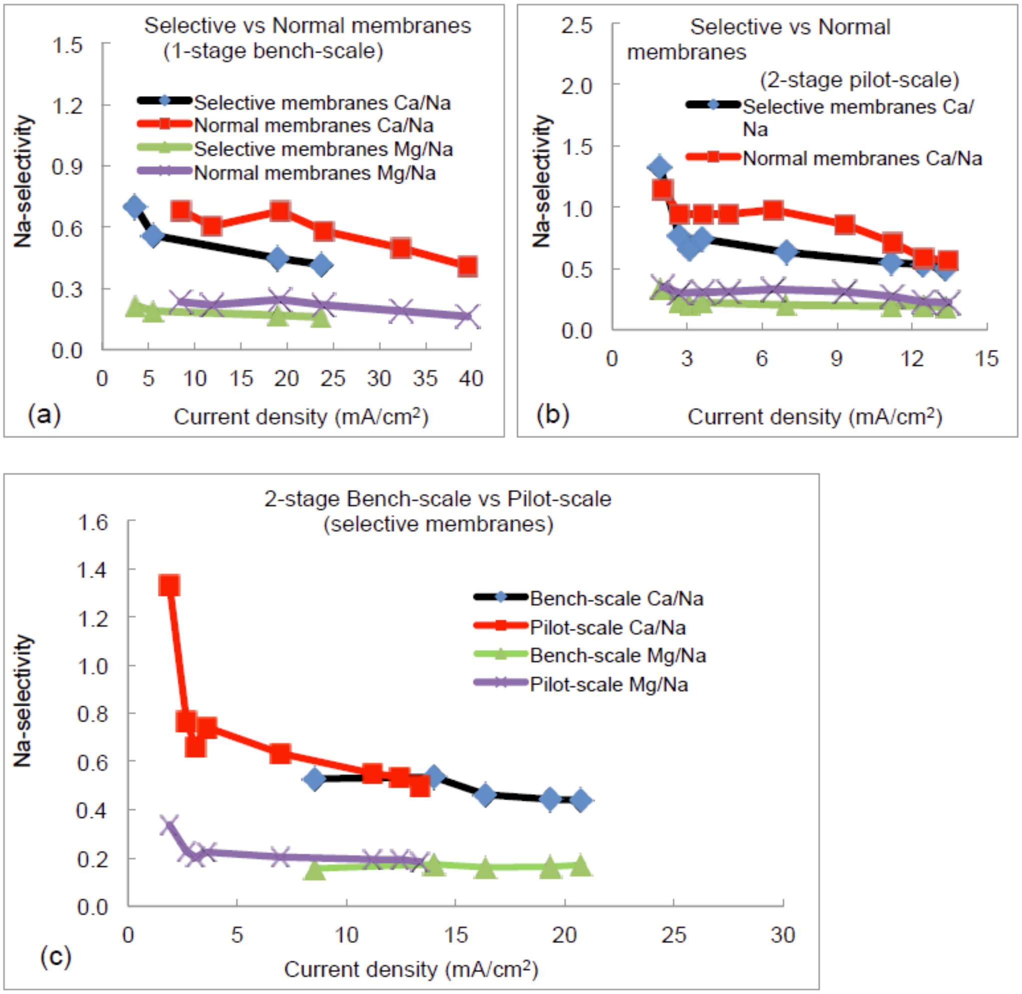


Figure 23.—Na-selectivity based on equivalent removal ratio of divalent cations to Na^+ treating RO concentrate at linear velocity 6.1 cm/s: (a) 1-stage bench-scale testing, (b) 2-stage pilot-scale testing, (c) 2-stage bench- and pilot-scale testing with selective membranes.

4.2.3.2. Selective Transport of Mono- and Di-Valent Cations

We investigated specific ion removal between bench- and pilot-scale testing based on percent equivalent removal, i.e., the amount of a given cation removed (in equivalent) over the total cations removed (in equivalent). Since the Mg^{2+} removal had the similar removal trend as Ca^{2+} and the K^+ removal was relatively lower due to low feed concentration in the RO concentrate, Ca^{2+} and Na^+ were chosen to represent the divalent and monovalent cations, respectively.

In bench-scale electrodialysis, the selective membranes and the normal membranes showed similar cation removal trends, with the percent removal of both Ca^{2+} and Na^+ remaining relatively constant above a current density of 5 mA/cm² (Figure 24a). However, selective membranes showed a higher removal rate for Na^+ over Ca^{2+} than normal grade membranes showed. In the pilot-scale system, the selective membranes demonstrated an apparently higher Na^+ removal rate than Ca^{2+}, and reached a local optimal Na^+ preferential transport at a current density of 3.1 mA/cm^2, than the Na^+ preference showed deceasing trend. Notably, the local optimal point was also 6 times larger than that in treating brackish groundwater, matching the concentrating factor of RO system (Figure 24b). The normal membranes demonstrated better divalent transport under current density of 6.5 mA/cm^2, then displayed monovalent selective transport at higher current density.

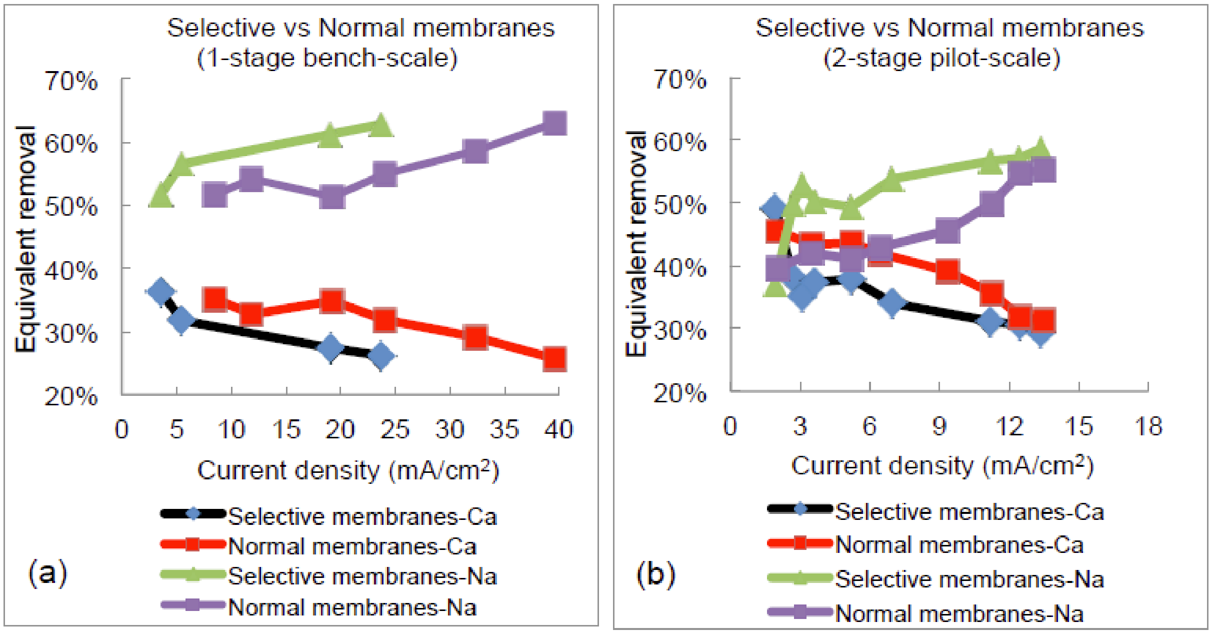


Figure 24.—Ion transport of Ca2+ and Na+ in selective membranes and normal membranes during electrodialysis of RO concentrate at liner velocity of 6.1 cm/s. (a) bench-scale system; (b) pilot-scale system.

We compared bench- and pilot-scale electrodialysis using the selective membranes for Ca^{2+} and Na^+ removal under the same linear velocity of 6.1 cm/s (Figure 25). The graph demonstrates a comparable behavior of specific cation percent removal in both the bench- and pilot-scale electrodialysis systems.

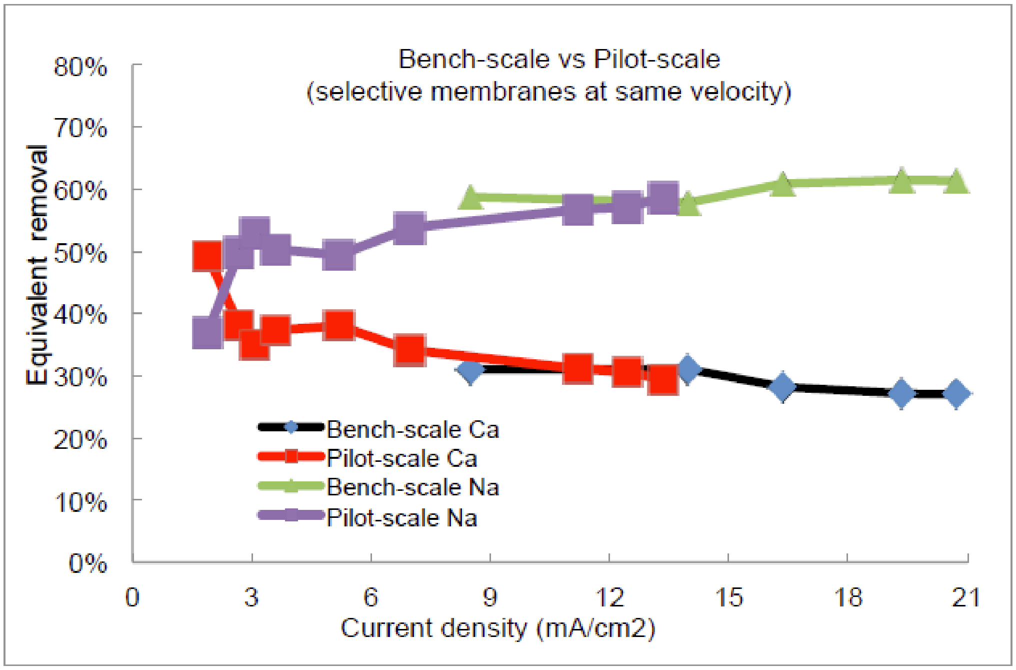


Figure 25.—Comparison of ion transport of Ca^{2+} and Na^{+} in selective membranes during bench- and pilot-scale electrodialysis treatment of RO concentrate at a liner velocity of 6.1 cm/s.

4.2.4. Scaling Characterization

At the KBHDP, the primary RO was operated at 80% to 85% water recovery, limited by inorganic scaling caused by calcium carbonate, calcium sulfate, and silica in the brackish groundwater. During the pilot-scale electrodialysis, the RO concentrate was used as a feed water without any pretreatment, except adding antiscalant into the concentrate stream and dosing hydrochloric acid concentrate into the concentrate steam and cathode-rinsing stream.

The pilot-scale electrodialysis stack was opened to examine scaling after about a month of treatment of the RO concentrate, There was no evident scaling on membrane surface or on spacers between flow channels. However, significant amounts of white precipitates were observed on electrode surface. Adding hydrochloric acid on the scales dissolved the precipitates and generated air bubbles, indicating calcium carbonate scaling. SEM/EDX analysis revealed the major elements in the precipitates were calcium, magnesium, oxygen, and small amount of silica, sodium and chloride. Less than 1% of sulfate was detected in the precipitates, which suggested that adding antiscalant was effective to control electrodialysis scaling at 55% water recovery. Further decreasing the pH values in the electrode rinsing stream could control the scale formation.

4.2.5. Summary

To evaluate the desalination performance and ion selectivity of normal grade CR67/AR204 and monovalent permselective CR671/AR112B ion-exchange membranes for treating RO concentrate, we conducted bench- and pilot-scale electrodialysis experiments. Monovalent selective membranes achieved the same desalting efficiency as normal grade membranes at the same current density. Although solution resistance would increase with the development of the boundary layer in the diluate chamber, it has less impact attributing to overall resistance when treating RO concentrate for both membranes categories. Feed water quality of each electrical stage was an important factor for overall desalination performance in multi-stage electrodialysis system. At higher current densities, the second electrical stage played a more important role in the conductivity cut than the first electrical stage, but the salt removal difference between the two electrical stages decreased with the increase of salt concentration in feed water. The mass of salt removed per membrane area per kilowatt-hour decreased with the increase of current density, while the energy efficiency increased with increasing feed water salt concentration.

The polyethyleneimine coating improved the selectivity of ion transport of monovalent cations over divalent cations. The results of overall desalination performance and ion selectivity were highly comparable during bench- and pilot-scale electrodialysis. It indicates bench-scale testing results could be scaled up to simulate pilot- and potentially full-scale electrodialysis of saline water.

During pilot-scale testing, 55% of the RO concentrate was reclaimed through electrodialysis. The product water quality could be controlled by the applied current density and electrodialysis staging. Adding antiscalant effectively controlled calcium sulfate scaling, while calcium carbonate and magnesium hydroxides precipitates could be further mitigated by lowering the pH of the concentrate and electrode rinsing streams.

4.3. Electrodialysis of Reclaimed Water at Scottsdale Water Campus

The reclaimed water from the Sub-Regional Operating Group (SROG) cities of Glendale, Mesa, Tempe, Phoenix, and Scottsdale Arizona is used for beneficial uses (e.g., turf or crop irrigation, cooling water for power plants, and groundwater recharge/indirect potable reuse). The TDS concentrations in the reclaimed water are usually above 1,000 mg/L. The TDS concentrations and the concentrations of individual ions adversely impact the reclaimed water reuse potential. High sodium concentration degrades soil condition on turf facilities and the high chloride ions may jeopardize discharge permit compliance (e.g., Whole Effluent Toxicity [WET] failure). High hardness requires softening and impacts the number of cycles that the reclaimed water can be reused as cooling water.

To meet its reclaimed water sodium goal of 125 mg/L, City of Scottsdale currently uses RO to desalinate a partial stream of its reclaimed water, blended with the remaining stream. This approach generates an RO concentrate that must be minimized. GE's newly developed monovalent selective membranes (sodium selective membrane CR671) could provide significant value for reclaimed water ion composition optimization without generating a concentrate waste stream.

When using the monovalent membrane electrodiaysis system as an "Ion Switcher", the ion compositions of reclaimed water can be modified for particular end uses (e.g., low sodium water for irrigation or low hardness water for cooling water make-up). In this application, monovalent permselective membranes are used to preferentially remove monovalent ions such as sodium from the reclaimed water to meet the product water sodium quality goal of 125 mg/L without RO, therefore avoid generating a concentrate stream that must be managed.

The ion switcher concept does not aim at maximizing water recovery. Instead, it aims at generating two potential water streams that are both usable, therefore eliminating a concentrate stream that must be disposed of. In fact, the preliminary concept assumed a recovery near 50% so that both streams could be moderate in TDS and potentially reusable.

We conducted pilot-scale testing at the Scottsdale Water Campus from May 2015 to December 2015. One of the project goals during the pilot-scale testing at the Scottsdale Water Campus was to develop and optimize the coating method of polyethylenimine on ion-exchange membrane surface for large-scale system. Due to limited experiences on polyethylenimine coating during field-testing, the selectivity of coated membranes was unexpectedly low. The lessons learned during the Scottsdale Water Campus led to successful coating at the KBHDP. In this section, only the testing results of the normal grade membranes are presented. During the treatment of reclaimed water the electrodialysis was operated at EDR mode.

4.3.1. LCD of Electrodialysis Treating Reclaimed Water

In this study, the LCD of the 2-stage EDR stack treating reclaimed water from the microfiltration (MF) permeate at the City of Scottsdale Water Campus was determined by the method first proposed by Cowan and Brown (1959), where the LCD is calculated by the resistance of the EDR system (voltage divided by current, V/I) only to the inverse current. The limiting current is given by the point where the electrical resistance starts to increase. Usually, LCD depends on membrane and solution properties as well as on the EDR stack construction and various operational parameters such as the flow velocity and water temperature. The LCD determination was conducted at the normal product water flow rate of 5.5-5.7 gpm (Figure 26).

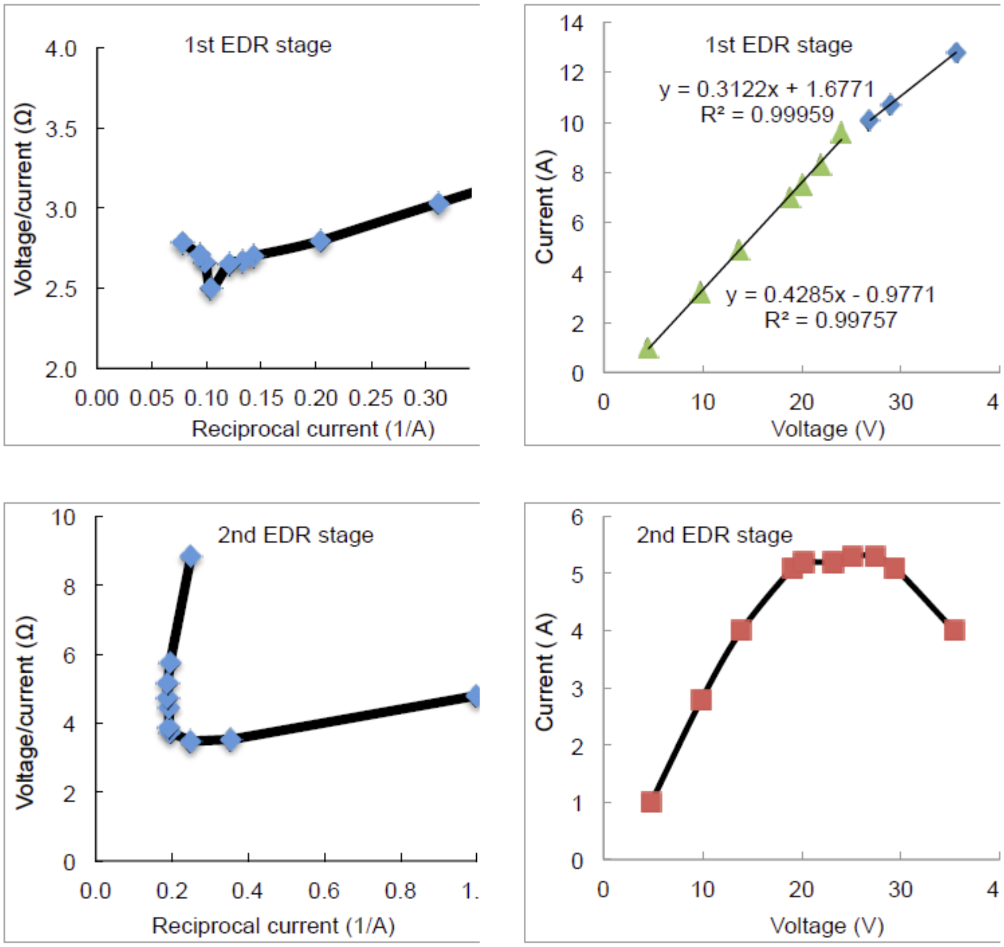


Figure 26.—EDR Limiting current density (LCD) with normal grade membranes for treating MF permeate, under product and concentrate flow rate of 5.5-5.7 gpm (4.6 cm/s) and 50% water recovery.

The LCD of the first and second stage EDR stack was measured as 3.0 mA/cm^2 and 1.25 mA/cm^2, corresponding to applied stack voltage of 24 V and 13.9 V (volts), respectively. The measured LCD exhibited a slight difference between the negative polarity (3.0 mA/cm^2) and positive polarity (2.75 mA/cm^2). Within the current density range of 0.3 to 4.0 mA/cm^2, the pH values of concentrate stream remained constant at 7.3 while the pH of product water decreased from 7.4 (same as feed) to 6.4 with the increase in current density, indicating the water dissociation at higher current density (Figure 27).

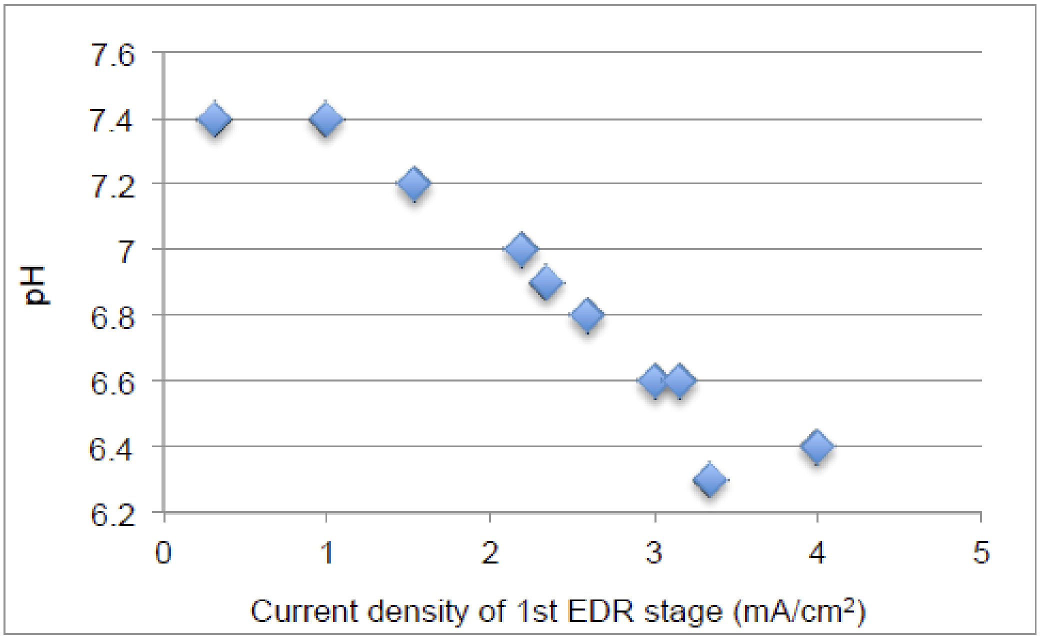


Figure 27.—Product water pH as a function of current density during treatment of reclaimed water.

4.3.2. Salt Rejection by the 2-stage EDR system

4.3.2.1. Impact of current density and polarization

Concentration polarization controls the desalination performance of ED or EDR systems. For practical application, percentage of polarization is used as parameter to operate an electrodialysis stack. During the treatment of reclaimed water, the EDR was operated at 15%, 25%, 35% and 45% of the concentration polarization estimated based on the WATSYS program. Table 5 summarizes the corresponding current densities of the first and second electrical stages at different percentages of polarization during reclaimed water electrodialysis at 7.5 to7.6 gallons per minute (gpm) (6.1 centimeters per second [cm/s]).

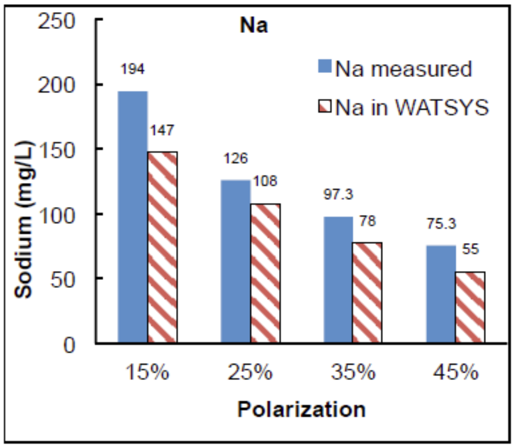
As shown in Figure 25, increasing applied voltage and current density increased the removal efficiency of different ions and decreased the salt concentration in the product water.

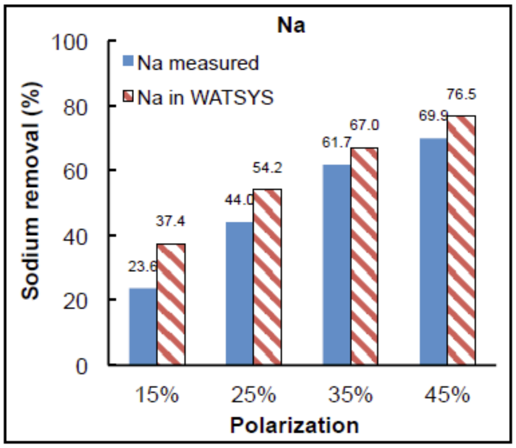
There are some discrepancies between the measured salt concentration data and the projection results using GE WATSYS program. WATSYS program projected well the overall salt removal in terms of conductivity cut and pH. The program also projected moderately well the removal of monovalent ions including Na^+, Cl^-, and K^+, but the discrepancies between measured and projected removal of divalent ions including Ca^{2+}, Mg^{2+}, and SO_4^{2+} were in the range of 10-40%.

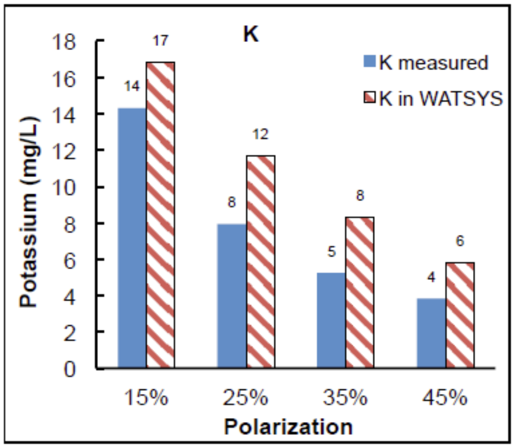
Based on the correlation between salt concentration and polarization, the water quality requirement of 110 mg/L sodium concentration in product water can be met at polarization of 30.5%, i.e., 2.36 mA/cm^2 for the first stage and 1.5 mA/cm^2 for the second stage.

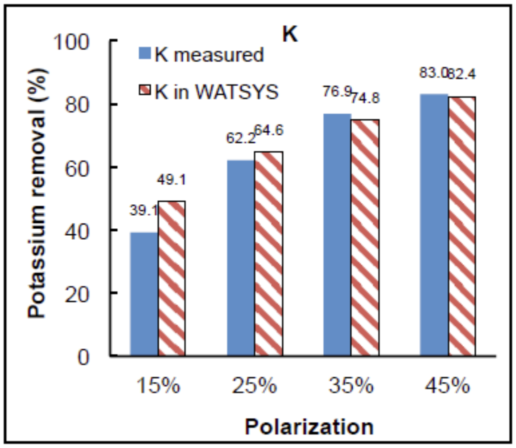
Table 5.—Applied Voltage and Current Density of the First- and Second-Electrical Stages

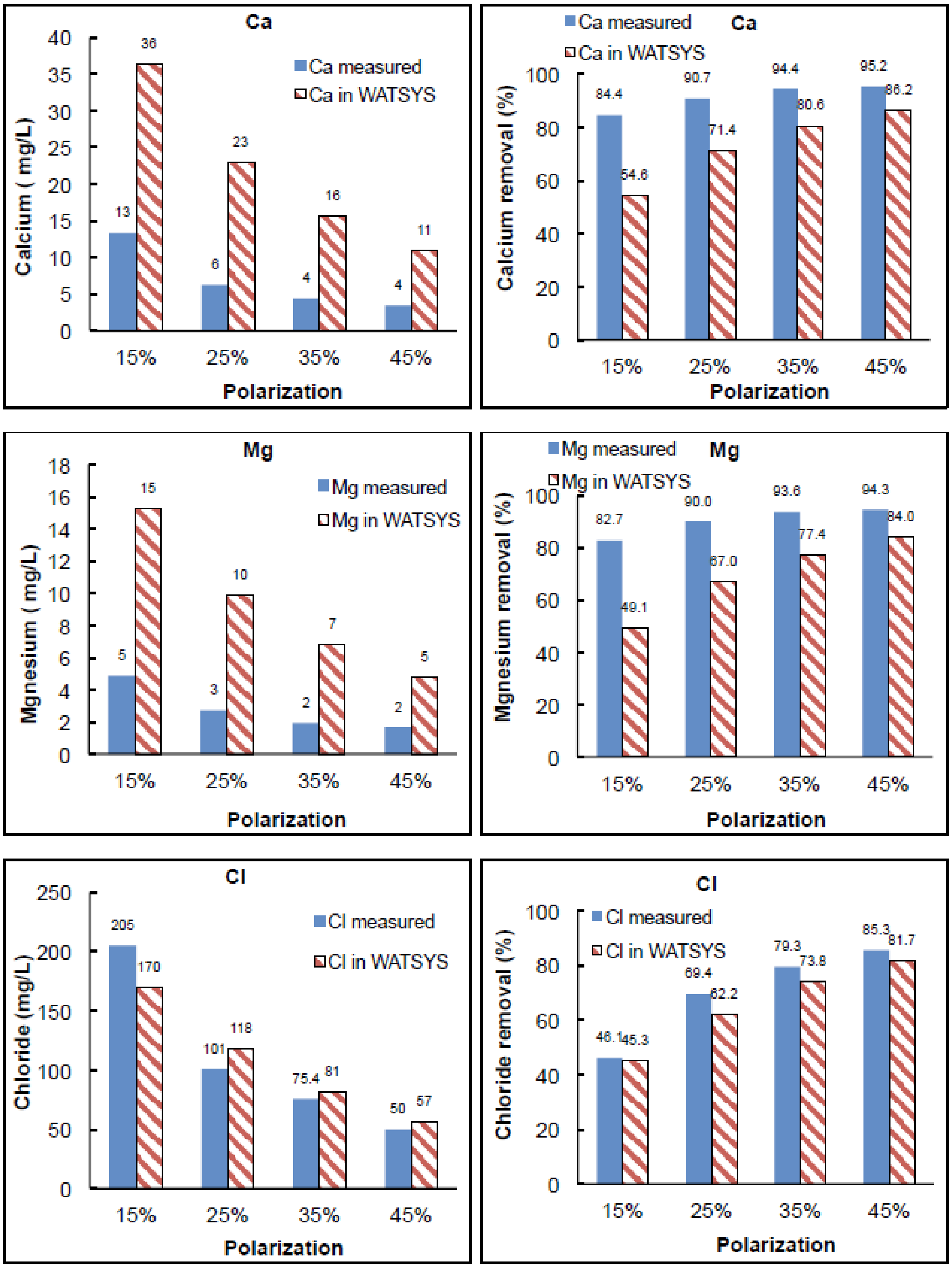
Polarization	**15 %**		**25%**		**35%**		**45 %**	
Electrical stage	**1**	**2**	**1**	**2**	**1**	**2**	**1**	***2***
Volatge (V)	14	13	19	19	23	21	26	*24*
Current (A)	4.7	3.6	6.7	4.8	8.3	4.8	9.5	*4.9*
Current density (mA/cm^2)	1.5	1.1	2.1	1.5	2.6	1.5	3.0	*1.5*
Voltages and current densities were applied at different percentage of polarization WATSYS program during reclaimed water electrodialysis at flow of 7.5-7.6 gpm (6.1 cm/s).								










Ca
Calcium (mg/L)
Ca measured
Ca in WATSYS
40
35
30
25
20
15
10
5
0
13
36
6
23
4
16
4
11
15%
25%
35%
45%
Polarization
Ca measured
Ca in WATSYS
Ca
Calcium removal (%)
100
80
60
40
20
0
84.4
54.6
90.7
71.4
94.4
80.6
95.2
86.2
15%
25%
35%
45%
Polarization
Mg
Mgnesium (mg/L)
Mg measured
Mg in WATSYS
18
16
14
12
10
8
6
4
2
0
5
15
3
10
2
7
2
5
15%
25%
35%
45%
Polarization
Mg measured
Mg in WATSYS
Mg
Mgnesium removal (%)
100
80
60
40
20
0
82.7
49.1
90.0
67.0
93.6
77.4
94.3
84.0
15%
25%
35%
45%
Polarization
Cl
Chloride (mg/L)
Cl measured
Cl in WATSYS
250
200
150
100
50
0
205
170
101
118
75.4
81
50
57
15%
25%
35%
45%
Polarization
Cl
Chloride removal (%)
Cl measured
Cl in WATSYS
100
80
60
40
20
0
46.1
45.3
69.4
62.2
79.3
73.8
85.3
81.7
15%
25%
35%
45%
Polarization

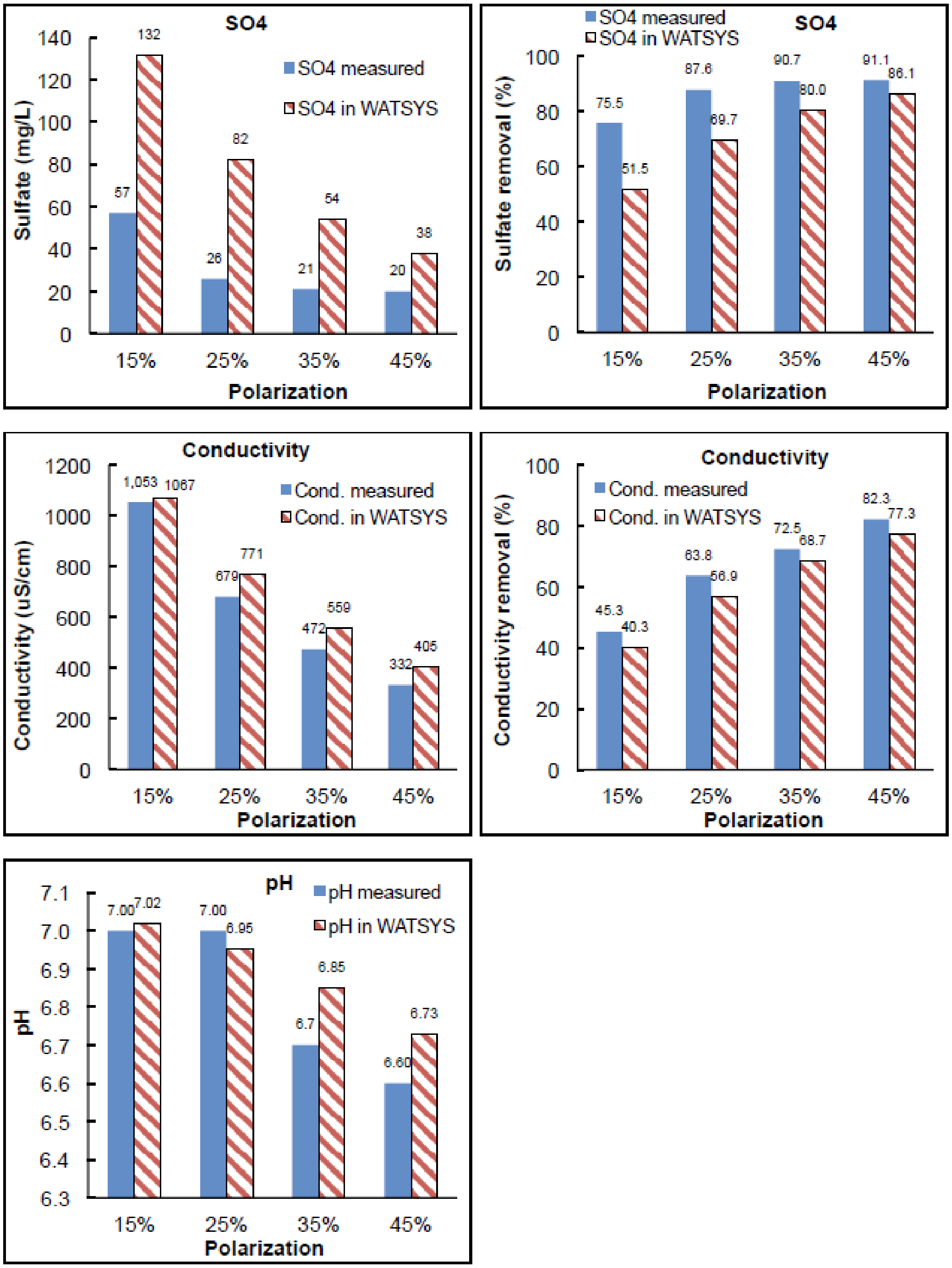


Figure 28.—Salt rejection as a function of polarization of the 2-stage EDR stack treating reclaimed water using normal grade membranes at 50% water recovery and 1x normal flow rates of product water 7.5-7.6 gpm (6.1 cm/s), concentrate blowdown 5.8-6.2 gpm, and electrode wastewater 0.6 gpm.

4.3.2.2. Impact of Feed Flow Rate

With the increase of flow rate, the salt rejection decreased in the EDR system due to lower residence time (Figure 29). The impact of flow rate on salt rejection is greater at higher polarization rates.

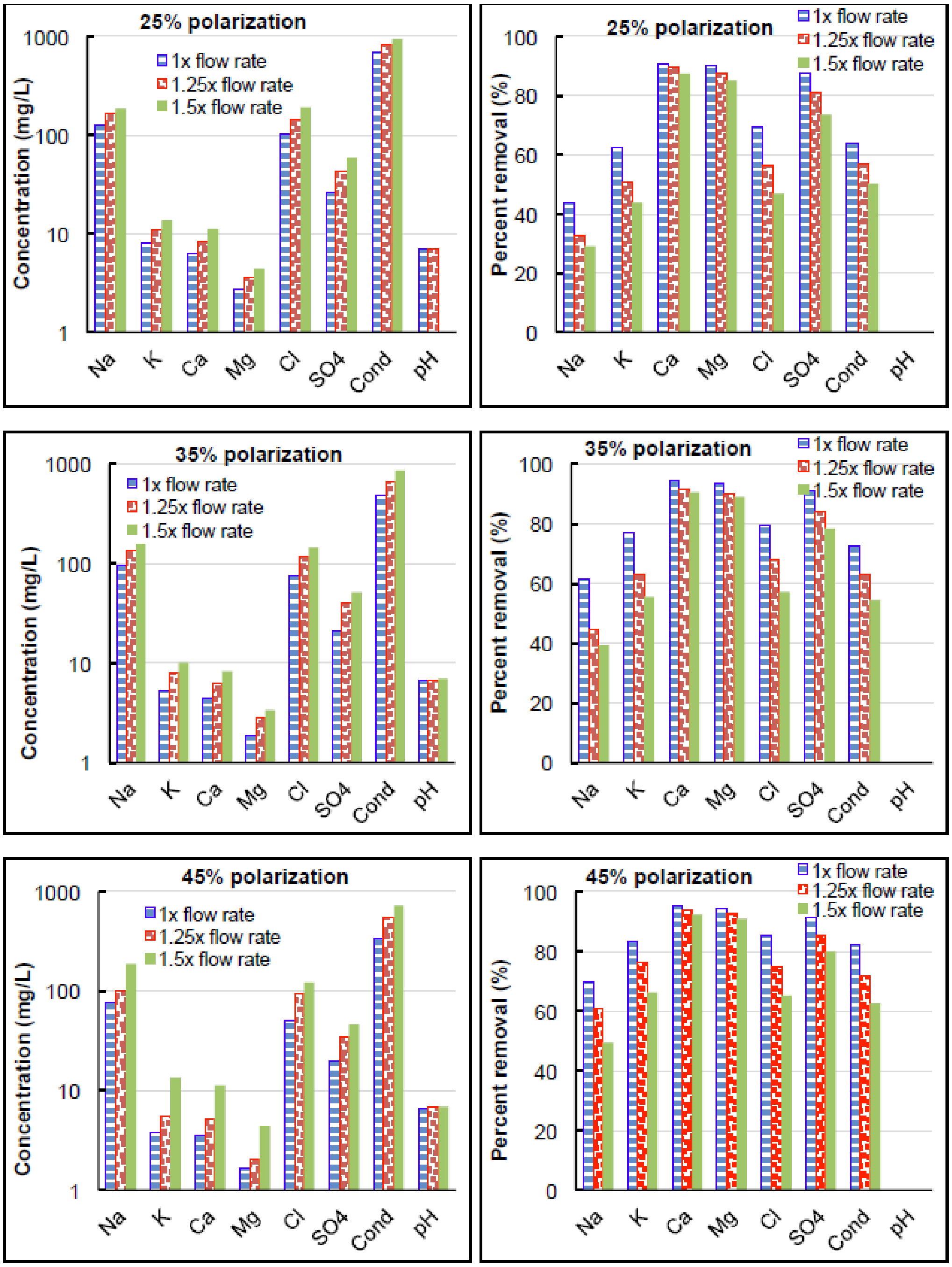
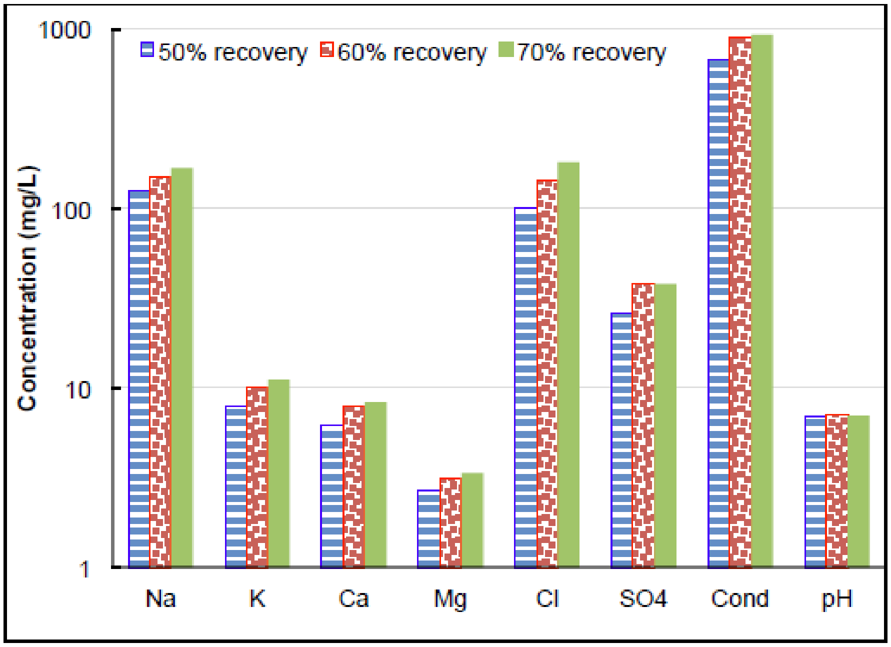


Figure 29.—Salt rejection as a function of flow rate and polarization of the 2-stage EDR stack treating reclaimed water using normal grade membranes at a water recovery rate of 50% and at 1x, 1.25x and 1.5x the normal flow rates of product water (7.5 to 7.6 gpm) (6.1 cm/s), concentrate blowdown 5.8 to 6.2, and electrode wastewater 0.6 gpm.

4.3.2.3. Impact of Water Recovery

With the increase of water recovery, the salt rejection decreased in the EDR system due to higher concentration gradient between diluate and concentrate. The percent reduction of conductivity declined by 10% when the water recovery increased from 50% to 70% (Figure 30).



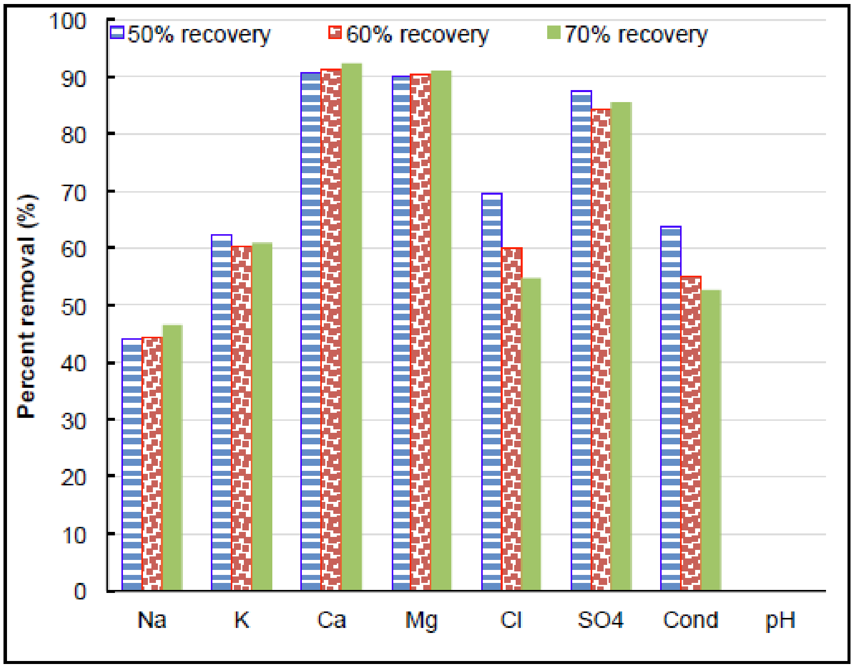


Figure 30.—Salt rejection as a function of water recovery of the 2-stage EDR stack treating reclaimed water using normal grade membranes at 25% polarization and electrode wastewater 0.6 gpm.

4.3.3. Fouling Characterization

After the pilot-scale testing, we removed the normal grade membranes from the pilot EDR stack for membrane autopsy to identify fouling and scaling. The structure and morphology of the cation and anion normal grade membranes was characterized by scanning electron microscope (SEM). The composition of the major elements on membrane surface was depicted by energy- dispersive X-ray spectroscopy (EDX) mounted on the SEM. Comparing the used and new ion exchange membranes with SEM and EDX indicated minor inorganic scaling on cation exchange membrane surface, including Ca, Al and Mg (Figure 31and Figure 32). No scalants were observed on anion exchange membrane surface (Figure 33and Figure 34).

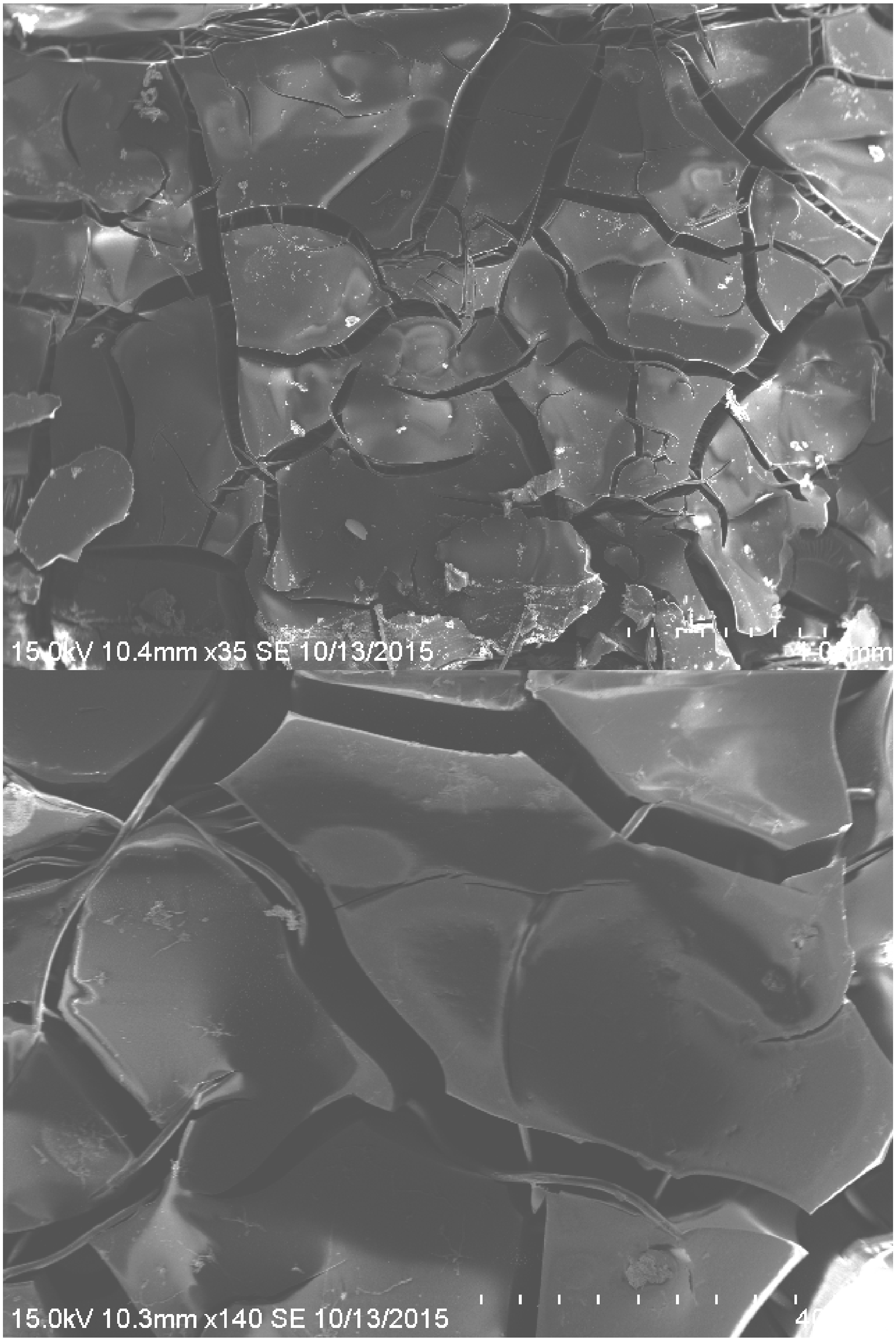


Figure 31.—SEM micrographs of CR67 after reclaimed water treatment.

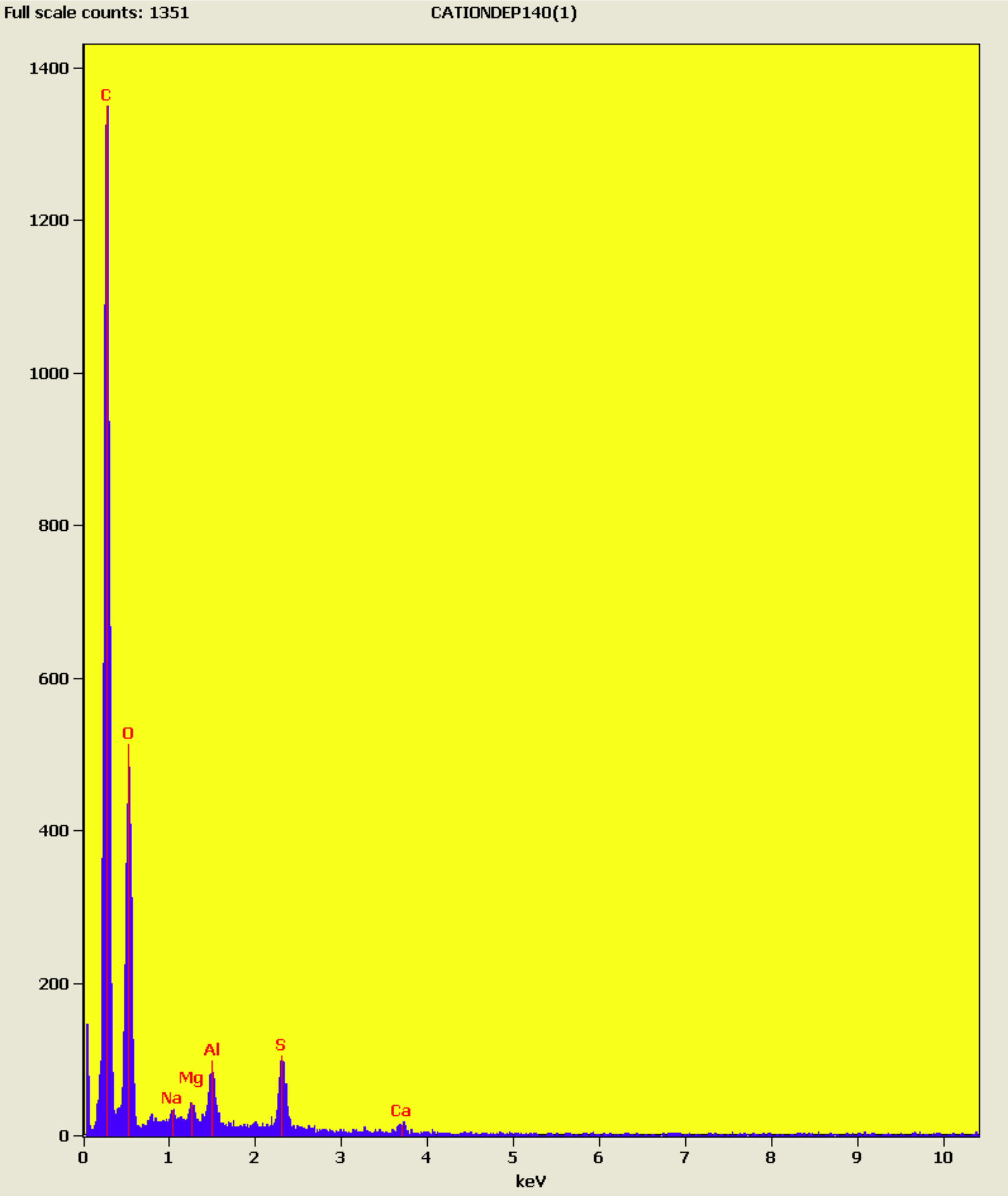


Figure 32.—EDX spectrum of used CR67 after reclaimed water treatment.

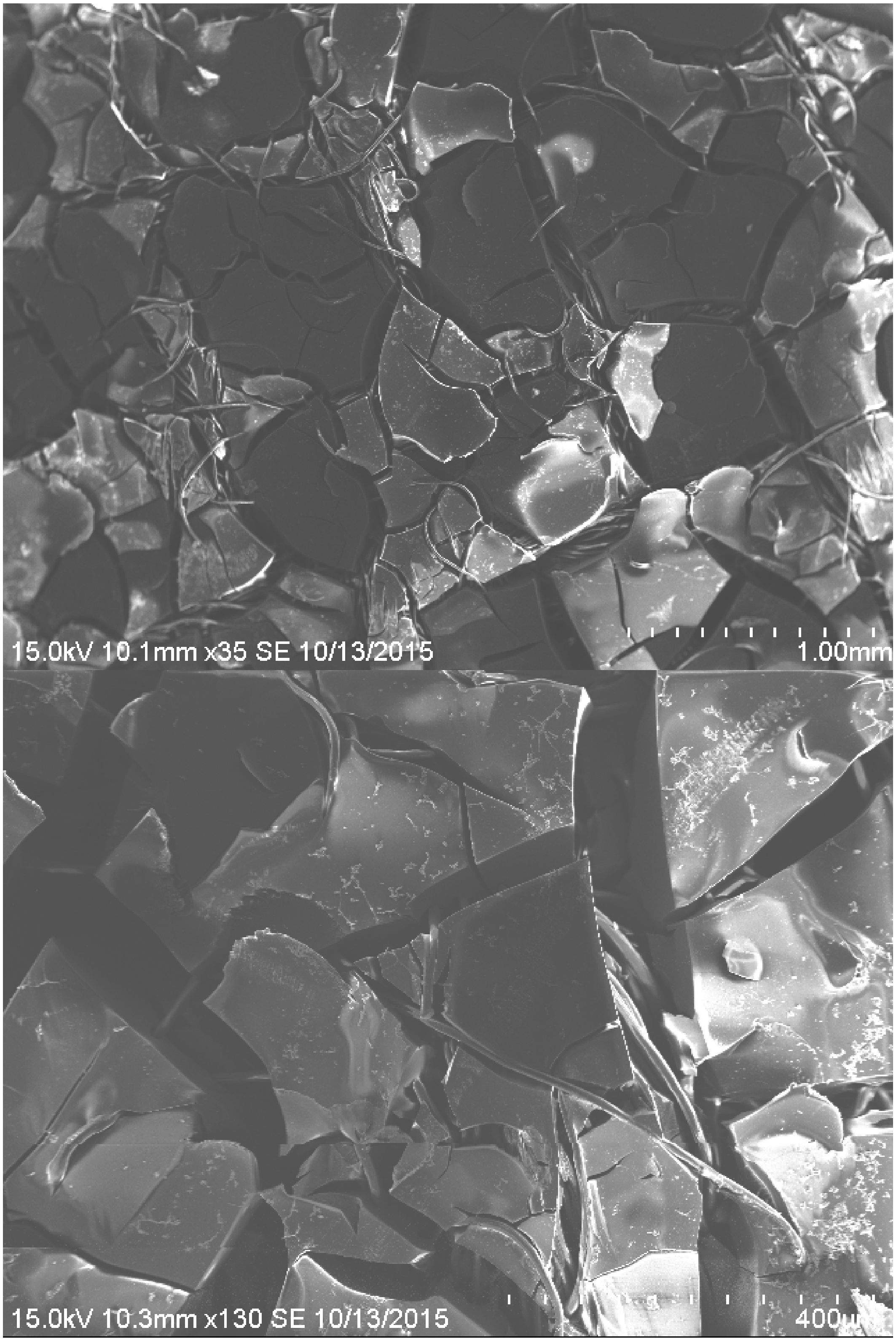


Figure 33.—SEM micrographs of AR204 after reclaimed water treatment.

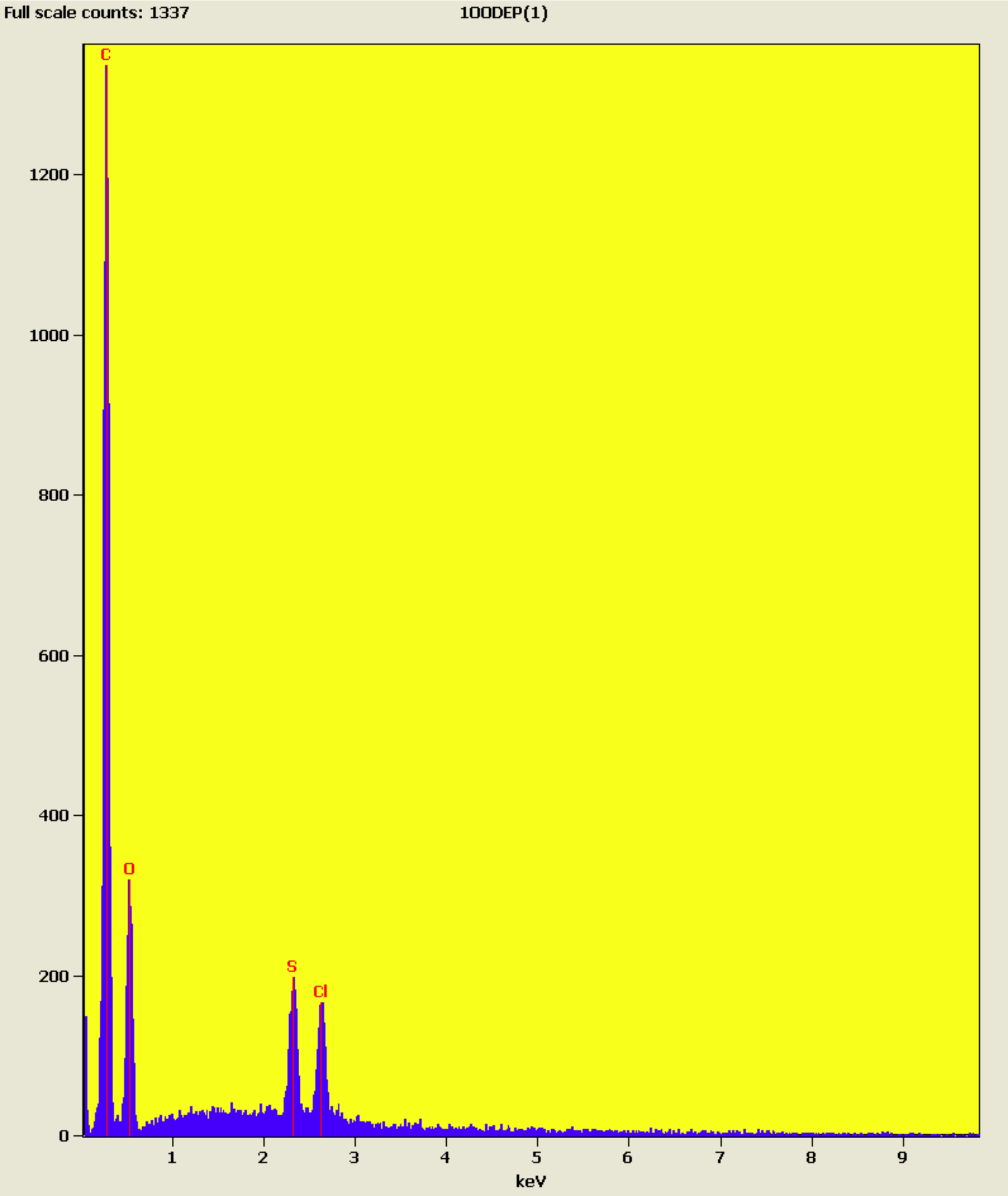


Figure 34.—EDX spectrum of used AR204 after reclaimed water treatment.

4.3.4. Summary

The EDR using standard normal grade membranes (CR67 and AR204) successfully achieved the treatment goal of 110 mg/L Na concentration in product water for irrigation. The desalination performance was affected by the synergistic impact of operating conditions, including water recovery, polarization, and flow rate.

4.4. Electrodialysis of Brackish Groundwater at BGNDRF

BGNDRF has four brackish groundwater wells that provide source water to the various testing areas throughout the facility. Groundwater from Well 1 is primarily sodium sulfate type of water with a TDS concentration of approximately 1,200 mg/L and an SAR of 11.5. The water from Wells 2, 3 and 4 has higher TDS concentrations, ranging from 3,600 to 4,100 mg/L for Wells 3 and 4 to 6,000 mg/L for Well 2. These waters are primarily of calcium sulfate type with an SAR of 4.7 to 6.4. We conducted bench-scale testing from February to April 2017 at BGNDRF to investigate the impact of salinity and water type on the salt removal and ion selectivity of monovalent permselective membranes and normal grade membranes.

4.4.1. Ion Selectivity Between CR67 and CR671

Sodium selectivity in terms of the equivalent removal of calcium and magnesium over sodium equivalent removal, (i.e., Ca/Na and Mg/Na for three groundwaters) is illustrated in Figure 35. The CR671 demonstrated better sodium selectivity than the normal grade CR67 membrane, particularly at lower current densities and lower feedwater salinities. For example, for Well 1 groundwater with a TDS concentration of 1,200 mg/L, at a current density of 2 mA/cm^2, the Ca/Na equivalent removal ratio of CR671 was 0.47, which was 3.6 times better than that of CR671 (1.71). As current density increased, the sodium selectivity of CR67 and CR671 both improved. However, the ion selectivity of CR671 remained relatively stable compared to the CR67 membrane. Mg/Na ratio was consistently lower than Ca/Na for both CR67 and CR671 membranes, indicating better sodium selectivity in magnesium-rich water than in calcium-rich water.

The sodium selectivity of CR671 in terms of Ca/Na and Mg/Na decreased with the increase of salinity and decrease of SAR of feedwater (Figure 36). The groundwater from Well 1 with a TDS concentration of 1,200 mg/L TDS and an SAR of 11.5 exhibited better sodium selectivity than Well 3 and Well 4. The same phenomenon was also observed for CR67 membrane.

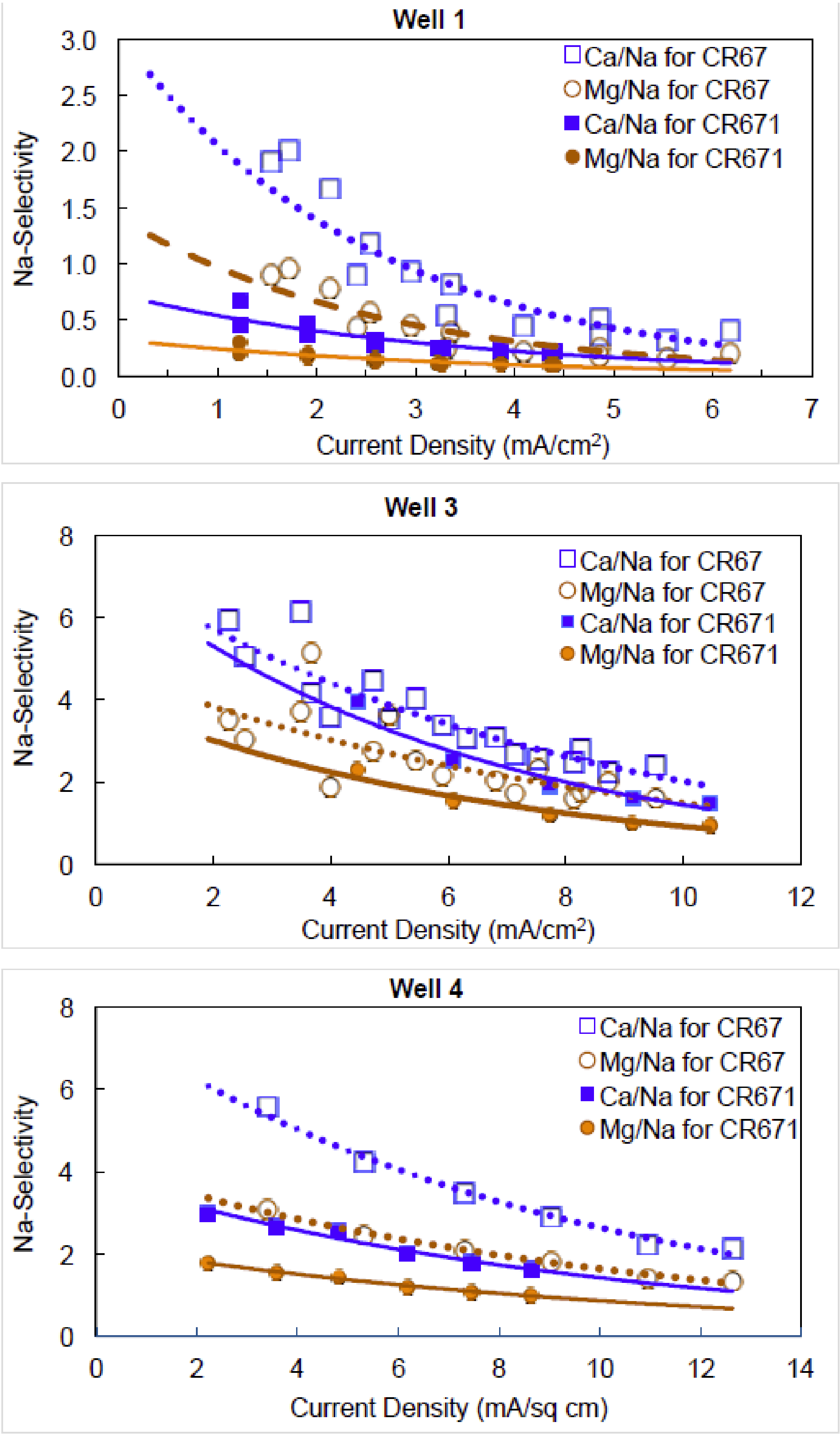


Figure 35.—Comparison of Na-selectivity between CR67 and CR671 during one stage bench-scale electrodialysis treating groundwater at BGNDRF with product and concentrate flow rate of 1 lpm (4.1 cm/s) and 50% water recovery.

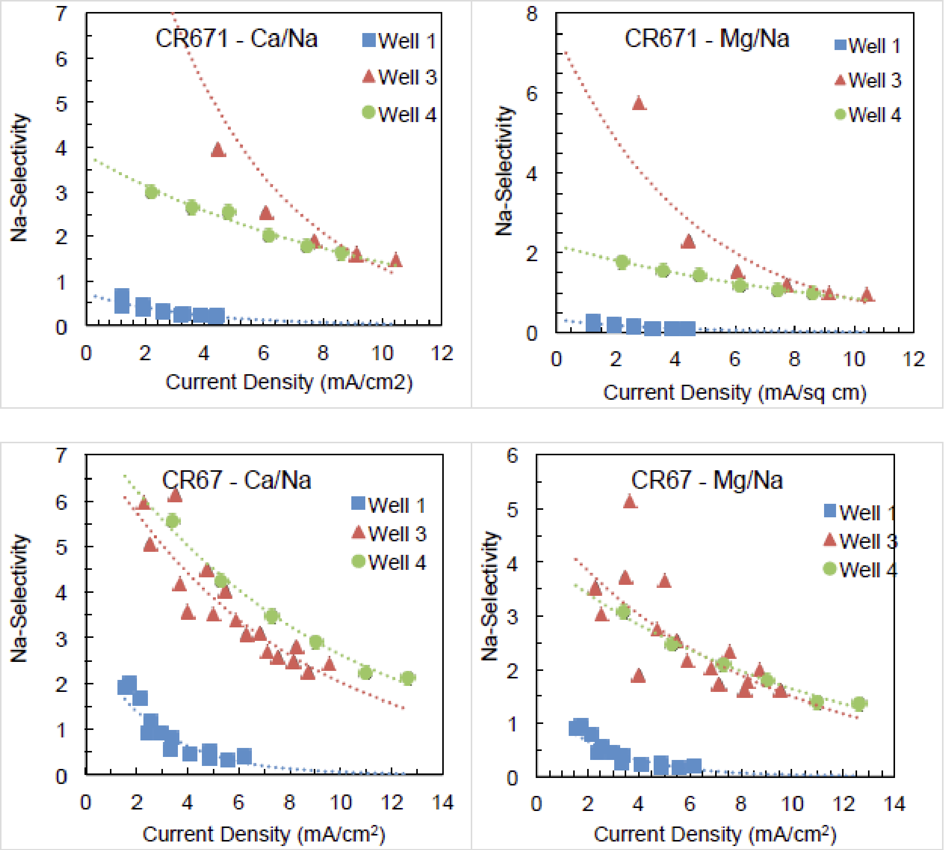


Figure 36.—Comparison of Na-selectivity for different types of groundwater at BGNDRF with product and concentrate flow rate of 1 lpm (4.1 cm/s) and 50% water recovery.

4.4.2. Water Flow Rate Impact

As the flow rate or the linear velocity increased, the sodium selectivity enhanced slightly in the bench-scale electrodialysis system (Figure 37).

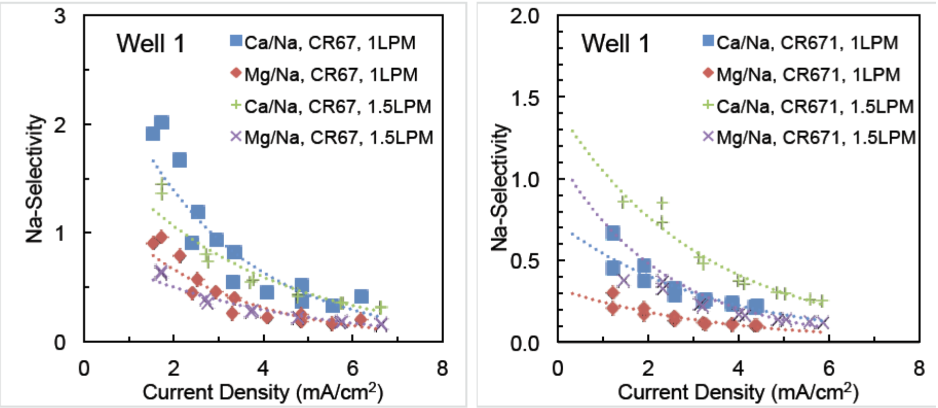


Figure 37.—Impact of water flow rate on ion selectivity during bench-scale electrodialysis of brackish groundwater at BGNDRF: 1.5 LPM (6.1 cm/s) versus 1.0 LPM (4.1 cm/s).

5. Empirical Modeling, Blending Analysis, and Cost Estimate

A number of studies model the ionic transport under electric potential. For example, Kim et al. (2012) employed the Nernst–Planck equation to study the influence of boundary layer near IX membranes on the competitive transport of mono- and di-valent ions in ED unit using regular membranes. Sadrzadeh et al. (2007) used the mass balance in a differential element of the diluate compartment to simulate the salt removal in an ED unit. The previous studies used synthetic water with selected ions and under various simplifying assumptions. These mathematical models contributed to understanding the ionic transport in ED system. However, these studies are case specific and cannot predict the salt removal and ion selectivity for real brackish water, RO concentrate, and wastewater, in particularly with newly developed IX membranes.

In this study, we examined previously developed mathematical models to study the impact of feedwater and operating conditions on salt removal and selectivity based on our bench- and pilot-scale testing results. The modeling incorporated polynomial functions in the mass transport and ED’s hydraulic characteristics unit, given a large number of variables (e.g., feed TDS, ion composition, flow rate, membrane properties, current density, water recovery, and temperature),

Firstly, we optimized the ED process simulation by identifying which factors have the greatest influence and which values produce the most consistent performance. Minitab was used as statistical analysis tool to experiment with the design variables—by trial and error for multiple factors—until the best-fit equations were found. This chapter presents multi-variance models to predict desalination efficiency and membrane selectivity of normal grade and selective membranes.

Secondly, based on the findings of the demonstration testing as well as modelling and bench testing results previous presented, we developed several alternative configurations. To compare these alternatives on a realistic and common basis, we analyzed two blending scenarios for City of Scottsdale Water Campus and City of El Paso Kay Bailey Hutchison Desalination Plant (KBHDP). This section presents the results of the blending analysis and cost comparison.

5.1. Model Description

To produce detailed evaluations of multiple process options, Carollo’s Blue Plan-it^{TM} (BPI) Decision Support System was used to simulate the performance of multiple alternatives. BPI is a tool Carollo developed to help our clients manage complex, interconnected treatment and conveyance systems. This innovative planning tool is a water, salt, and energy balance model that simulates the fresh and brackish water sources flow routing, treatment, distribution, and the associated energy demands and costs. BPI uses optimization algorithms to maximize treatment capacity while minimizing risks, operation and maintenance costs, and demands on natural resources. BPI is particularly applicable in the field of salinity and concentrate management, assisting in understanding the complexity of salinity management.

Featuring an easy-to-use “drag-and-drop” interface, BPI allows for rapid model configuration. The user can drag blocks from pre-made libraries into a model window, connect the blocks, and then simply adjust the preset dialog parameters. The user may configure a “base case” and numerous alternative scenarios for model test runs. A summary block displays key output data including flows, contaminant concentrations, total O&M and capital costs, etc. BPI can be productively configured to solve complicated water and salt mass balances to determine blending ratio, cooling tower cycle of concentration and scaling and corrosion analysis, blowdown treatment facility capacity, and evaporation pond acreages. It replaces Microsoft Excel mass balance calculations and produces graphical process flow diagrams for each model scenario simultaneously.
BPI played an important role in this project. Using its scenario manager and optimizer, we were able to evaluate an unlimited number of treatment configurations. Coupled with a creative problem solving approach, the process model helped the ED system to capture significant cost savings.

5.1.1. Model Inputs from Testing Results

Model inputs were based on testing results collected during the El Paso phase testing (Table 6).

Table 6.—Scottsdale Blending Analysis Inputs

Scottsdale Reclaimed Water		**WATASYS**	**Normal Membrane**	**Selective Membrane**
Data Source		GE Model	El Paso GW Testing	El Paso GW Testing
HRT	sec	60	60	60
Velocity	cm/s	6	6	6
Recovery		90%	90%	90%
Current Density	mA/cm^2		2.25	2.25
Stage		2	2	2
Removal_TDS	%	82	82%	82%
Removal_Ca	% from mg/L	93%	96%	72%
Removal_Mg	%	90%	94%	41%
Removal_Na	%	80%	70%	97%
Removal_K	%	87%	84%	33%
DC Power Consumption	kWh/kgal	1.55	0.81	0.81

Table 7.—El Paso Blending Analysis Inputs (for high TDS)

El Paso RO Concentrate		**WATASYS**	**Normal Membrane**	**Selective Membrane**
Data Source		GE Model	El Paso Concentrate Testing	El Paso Concentrate Testing
HRT	sec	60	60	60
Velocity	cm/s	6	6	6
Recovery		60%	60%	60%
Current Density	mA/cm^2		4.21	4.21
Stage		4	4	4
Removal_TDS	%	82%	58%	59%
Removal_Ca	% from mg/L	0.91	92%	86%
Removal_Mg	%	0.89	89%	80%
Removal_Na	%	0.80	51%	55%
Removal_K	%	0.85	66%	73%
Power Consumption	kWh/kgal	22.55	15.50	15.50

Table 8.—El Paso Blending Analysis Inputs (for moderate TDS)

El Paso Groundwater or Recovered Concentrate after the first two stages		**WATASY S**	**Normal Membrane**	**Selective Membrane**
Data Source		GE Model	El Paso GW Testing	El Paso GW Testing
HRT	sec	60	60	60
Velocity	cm/s	6	6	6
Recovery		60%	60%	60%
Current Density	mA/cm^2		2.31	2.33
Stage		4	4	4
Removal_TDS	%	54%	56%	57%
Removal_Ca	% from mg/L	69%	96%	41%
Removal_Mg	%	65%	94%	48%
Removal_Na	%	51%	47%	60%
Removal_K	%	61%	40%	74%
Power Consumption	kWh/kgal	1.31	0.72	1.48

5.1.2. EDR Modeling

WATSYS™ 3.0.29 for Windows comprises proprietary GE software developed for designing and maintaining GE EDR systems. It is designed for use by GE personnel in sales, marketing, engineering, and field service and by selected GE customers and partners.

5.1.3. Cost Methodology

Cost estimating was performed in accordance with the Association for the Advancement of Cost Engineering (AACE). AACE developed guidelines for cost estimate classification based on several characteristics with the intent of improving communication between stakeholders involved with preparing, evaluation, and using cost estimates. The estimating system is arranged in class designations labelled 1, 2, 3, 4, and 5. Within each class, there are several secondary characteristics: End Usage, Methodology, Expected Accuracy Range, and Preparation Effort. In addition to the secondary characteristics, there is one primary characteristic, Level of Project Completion, with a Class 5 estimate based upon the lowest level of project definition and a Class 1 estimate closest to full maturity. The five estimating classes are outlined in Table 9.

Table 9.—AACE Estimating Classifications

Estimate Class	**Class 5**	**Class 4**	**Class 3**	**Class 2**	***Class 1***
Level of Project Completion* (1)	0% to 2%	1% to 15%	10% to 40%	30% to 70%	*50% to 100%*
Expected Accuracy Range**	L: -20% to -50% H: +30% to +100%	L: -15% to -30% H: +20% to +50%	L: -10% to - 20% H: +10% to +30%	L: -5% to -15% H: +5% to +20%	*L: -3% to -10%* *H: +3% to +15%*

Source: AACE 17R-97

**Expressed as a percentage of completion definition*

***Typical variations in low and high ranges. The state of process technology, availability of applicable reference cost data, and many other risks affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.*

Based on the level of engineering completed, a Class 4 cost estimate was used to evaluate the eight treatment alternatives outlined, meaning that the expected accuracy range index is approximately +50/-30%.

A detailed cost model was developed to evaluate the total capital cost, annual operation and maintenance cost, and the total 20-year life cycle cost for each of the six proposed treatment trains.

Major assumptions for preparing this estimate include:

- EDR costs are based on a quotation from EDR equipment manufacturer GE Water in conjunction with the pilot data.
- Microfiltration (MF)/ultrafiltration (UF) and RO system costs are based on results from recently bid projects using the same equipment.
- The Process/Electrical/Control Building assumes a single building with an electrical room and a control room and assumes HVAC and plumbing. The size of the building is based on equipment sizes and similar projects. The building cost was estimated at $\$250/ft^2$ and is based on recent projects in Arizona and California.
- The Civil Site Work line item includes excavation and backfill, general site preparation and finishing. Based on recent projects, this is estimated at 5% of the capital costs.
- The Electrical and Instrumentation line item assumes 25% of equipment costs.
- The General line item assumes 5% of the total capital cost for mobilization and demobilization, temporary facilities, startup, testing, and commissioning.
- EDR equipment costs received from similar previous projects were updated based on verbal comments from GE dated February 3, 2017.
- The CCI number for December 2016 is 10531 (20 City Average) and was used to escalate previous cost references.
- Chemical costs were estimated based on quotes received from local chemical suppliers supplemented by recent reference projects.
- Unit power costs were assumed at $0.08/kWh.

The above assumptions are consistent with past projects recently bid in California, Utah, Florida, Texas and Arizona, which are representative of the current water treatment industry construction pricing in the southwestern United States.

Additionally, the costs for contingency, contractor overhead and profit and engineering are based on industry standards for a project of this nature.

5.2. Scottsdale Water Campus Reclaimed Water

The process flow diagrams in Figure 38 illustrate alternative methods for the Scottsdale Water Campus Advanced Water Treatment (AWT) facility to treat a partial stream of the reclaimed water and blends the remaining stream with RO permeate to achieve a target sodium concentration (125 mg/L contractual target, 110 mg/L operating target). In winter, the golf courses use as little as 3 or 4 mgd of irrigation water, which is a blend of reclaimed water and RO permeate. All remaining tertiary effluent goes through primary RO, and the permeate is recharged into the vadose zone. In summer, the golf courses use 17 to 18 mgd of irrigation water, of which only about 8.5 to 10 mgd is from AWT primary RO.

For this analysis, the existing AWT (i.e., MF and primary RO) is considered as the baseline alternative, compared with the following alternatives:

- Alt 1A: 2-stage electrodialysis system using normal grade membranes (Based on WATSYS Modelling)

- Alt 1: 2-stage electrodialysis system using normal grade membranes

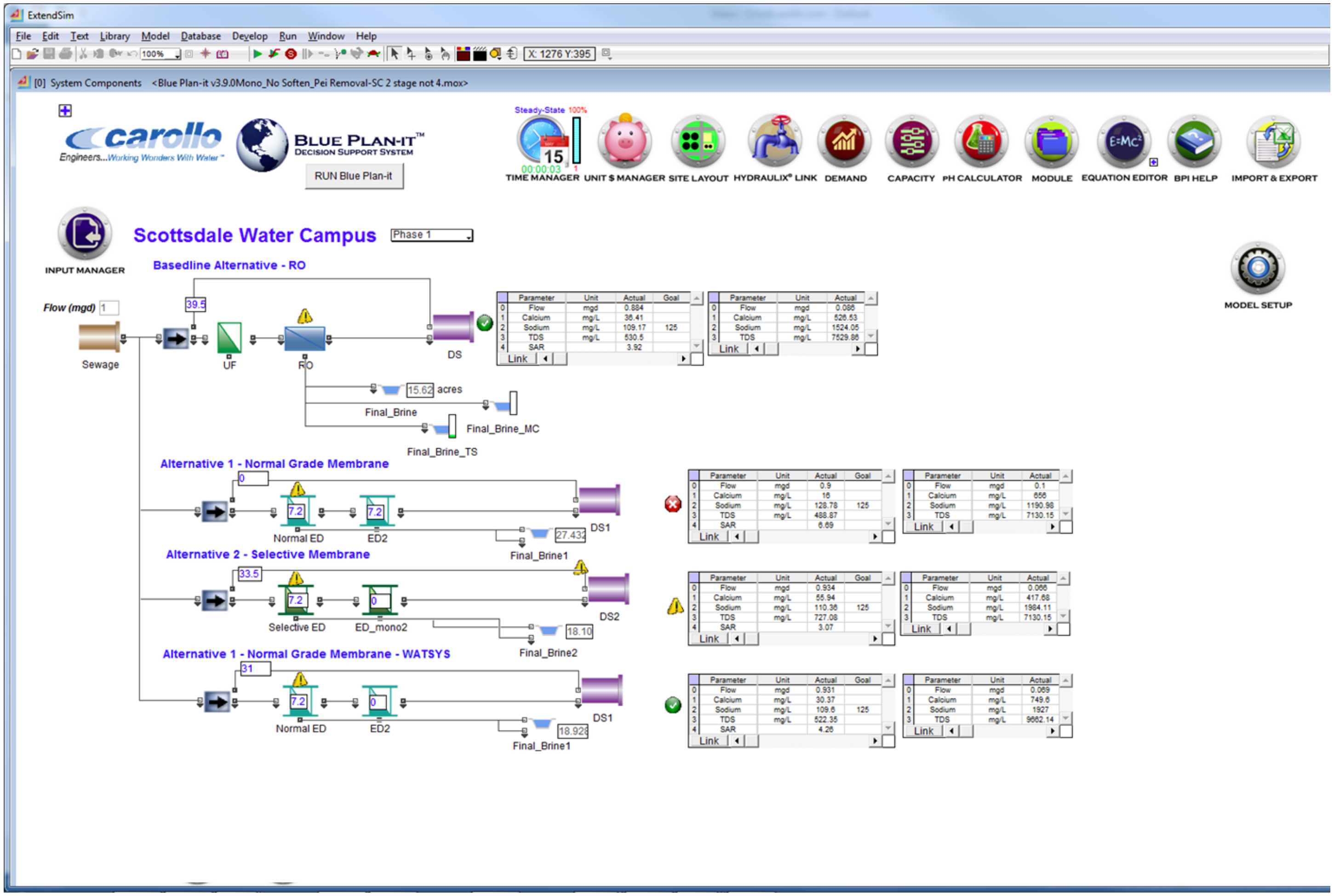
- Alt 2: 2-stage electrodialysis system using permselective membranes

For each of the above alternatives, a 4-stage electrodialysis system was also evaluated to compare the desalination efficiency and selectivity as well as the economics to meet the same target goal.

The following blending goals were established as a common basis for comparing all alternatives:

- Use a 1 mgd reclaimed water to feed all baseline and alternative process trains.

- Set the operating target for the irrigation water sodium concentration at 110 mg/L.



	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.884	
1	Calcium	mg/L	36.41	
2	Sodium	mg/L	109.17	125
3	TDS	mg/L	530.5	
4	SAR		3.92	

	Parameter	Unit	Actual
0	Flow	mgd	0.086
1	Calcium	mg/L	526.53
2	Sodium	mg/L	1524.05
3	TDS	mg/L	7529.86

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.9	
1	Calcium	mg/L	16	
2	Sodium	mg/L	128.78	125
3	TDS	mg/L	488.87	
4	SAR		6.69	

	Parameter	Unit	Actual
0	Flow	mgd	0.1
1	Calcium	mg/L	656
2	Sodium	mg/L	1190.98
3	TDS	mg/L	7130.15

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.934	
1	Calcium	mg/L	55.94	
2	Sodium	mg/L	110.36	125
3	TDS	mg/L	727.08	
4	SAR		3.07	

	Parameter	Unit	Actual
0	Flow	mgd	0.066
1	Calcium	mg/L	417.68
2	Sodium	mg/L	1984.11
3	TDS	mg/L	7130.15

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.931	
1	Calcium	mg/L	30.37	
2	Sodium	mg/L	109.6	125
3	TDS	mg/L	522.35	
4	SAR		4.26	

	Parameter	Unit	Actual
0	Flow	mgd	0.069
1	Calcium	mg/L	749.6
2	Sodium	mg/L	1927
3	TDS	mg/L	9662.14

Figure 38.—City of Scottsdale blending analysis.

5.2.1. Scenario 1: Two-Stage System

Table 10 presents the results of the blending analysis for Scottsdale using the 2- stage system. Table 11 presents a summary of the capital and O&M cost estimates for Scottsdale.

Table 10.—Blending Analysis Comparison Between 2-Stage Electrodialysis Systems and Baseline

	Baseline Alternative	**Alternative 1A**	**Alternative 1**	**Alternative 2**
	UF + RO	**Normal EDR - WATSYS**	**Normal EDR - Testing**	**Selective EDR Modeling -**
Feed Water Flow (mgd)	1			
Feed Water Na (mg/L)	235			
% Flowated	60.5%	69.0%	100.0%	66.5%
Overall Recovery	88%	93%	92%	93%
Unit Recovery	85%	90%	90%	90%
Blended Flow Water (mgd)	0.88	0.93	0.92	0.93
Product Water Na (mg/L)	110	110	129	110
Product TDS (mg/L)	530	522	489	727
Concentrate Flow (gpm)	60	48	69	46
Concentrate TDS (mg/L)	7,530	9,662	7,130	7,130
Concentrate Na (mg/L)	1524	2136	1715	3940
Number of Product Lines	-	7	8	6
Number of Stages	-	2	2	2

Table 11.—Cost Comparison Between 2-Stage Electrodialysis Systems and Baseline

	Baseline Alternative	**Alternative 1A**	**Alternative 1**	**Alternative 2**
	UF + RO	**Normal EDR - WATSYS**	**Normal EDR - Testing**	**Selective EDR - Modeling**
UF	$599,000	$ -	$ -	$ -
Residuals Handling	$765,000	$ -	$ -	$ -
RO	$889,000	$ -	$ -	$ -
EDR	$ -	$1,820,000	$2,080,000	$1,560,000
Building	$652,000	$435,000	$435,000	$435,000
Civil, Site Works (5%)	$146,000	$113,000	$126,000	$100,000
Electrical and I&C (25%)	$726,000	$564,000	$629,000	$499,000
Contingency (30%)	$1,189,000	$924,000	$1,030,000	$817,000
General Conditions: Mobilization & Demobilization (5%)	$189,000	$147,000	$164,000	$130,000
Engineering, Administration, and Legal (18%)	$928,000	$721,000	$804,000	$638,000
TOTAL CAPITAL COSTS	$6,081,000	$4,721,000	$5,266,000	$4,177,000
Unit Capital Costs ($/gpd)	$6.88	$5.05	$5.72	$4.49
Total Power Cost ($/year)	$84,000	$28,000	$20,000	$20,000
Total Chemical Cost ($/year)	$69,000	$67,000	$67,000	$67,000
Total Labor Cost ($/year)	$126,000	$126,000	$126,000	$126,000
Total Replacement Cost ($/year)	$17,000	$14,000	$13,000	$13,000
Contingency (20%)	$59,000	$47,000	$45,000	$45,000
Total O&M Costs	$353,000	$280,000	$269,000	$269,000
Unit O&M Costs ($/kgal)	$1.09	$0.82	$0.80	$0.79

5.2.2. Scenario 2: Four-stage System

Table 12 presents the results of the blending analysis for Scottsdale using the 4-stage electrodialysis system. Table 13 presents a summary of the capital and O&M cost estimates for Scottsdale. Figure 39 and Figure 40 provide cost comparisons for the baseline, 2-stage, and 4-stage processes.

Table 12.—Blending Analysis Comparison between 4-stage Electrodialysis Systems and Baseline

	Baseline Alternative	**Alternative 1A**	**Alternative 1**	**Alternative 2**
	UF + RO	Normal EDR - WATSYS	Normal EDR - Testing	Selective EDR - Modeling
Feed Water Flow (mgd)	1			
Feed Water Sodium (mg/L)	235			
% Flow Treated	60.5%	69.0%	78.0%	57.5%
Overall Recovery	88%	93%	92%	94%
Unit Recovery	85%	90%	90%	90%
Blended Water Flow (mgd)	0.88	0.93	0.92	0.94
Product Water Sodium (mg/L)	110	110	110	110
Product TDS (mg/L)	530	522	433	634
Concentrate Flow (gpm)	60	48	54	40
Concentrate TDS (mg/L)	7530	9662	9662	9662
Concentrate Sodium (mg/L)	1524	1927	1715	2287
Number of Product Line	-	7	6	6
Number of Stages	-	4	4	4

Table 13.—Cost Comparison Between 4-Stage Electrodialysis Systems and Baseline

	Baseline Alternative	**Alternative 1A**	**Alternative 1**	**Alternative 2**
	UF + RO	**Normal EDR - WATSYS**	**Normal EDR - Testing**	**Selective EDR - Modeling**
UF	$599,000	$ -	$ -	$ -
Residuals Handling	$765,000	$ -	$ -	$ -
RO	$889,000	$ -	$ -	$ -
EDR	$ -	$2,520,000	$2,940,000	$2,520,000
Building	$652,000	$435,000	$435,000	$435,000
Civil, Site Works (5%)	$146,000	$148,000	$169,000	$148,000
Electrical and I&C (25%)	$726,000	$739,000	$844,000	$739,000
Contingency (30%)	$1,189,000	$1,210,000	$1,382,000	$1,210,000
General Conditions: Mobilization & Demobilization (5%)	$189,000	$193,000	$220,000	$193,000
Engineering, Administration, and Legal (18%)	$928,000	$944,000	$1,078,000	$944,000
Total Capital Costs	$6,081,000	$6,187,000	$7,066,000	$6,187,000
Unit Capital Costs ($/gpd)	$6.88	$6.64	$7.68	$6.56
Total Power Cost ($/year)	$84,000	$44,000	$28,000	$28,000
Total Chemical Cost ($/year)	$69,000	$67,000	$67,000	$67,000
Total Labor Cost ($/year)	$126,000	$126,000	$126,000	$126,000
Total Replacement Cost ($/year)	$17,000	$14,000	$13,000	$13,000
Contingency (20%)	$59,000	$50,000	$47,000	$47,000
Total O&M Costs	$353,000	$299,000	$278,000	$278,000
Unit O&M Costs ($/kgal)	$1.09	$0.88	$0.83	$0.81

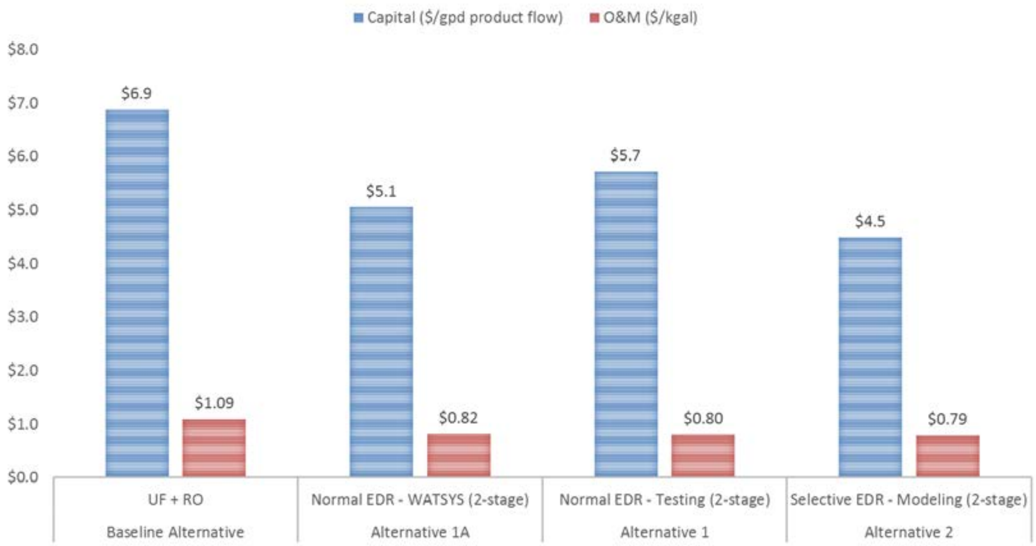


Figure 39.—Cost comparison of baseline versus 2-stage ED alternatives.

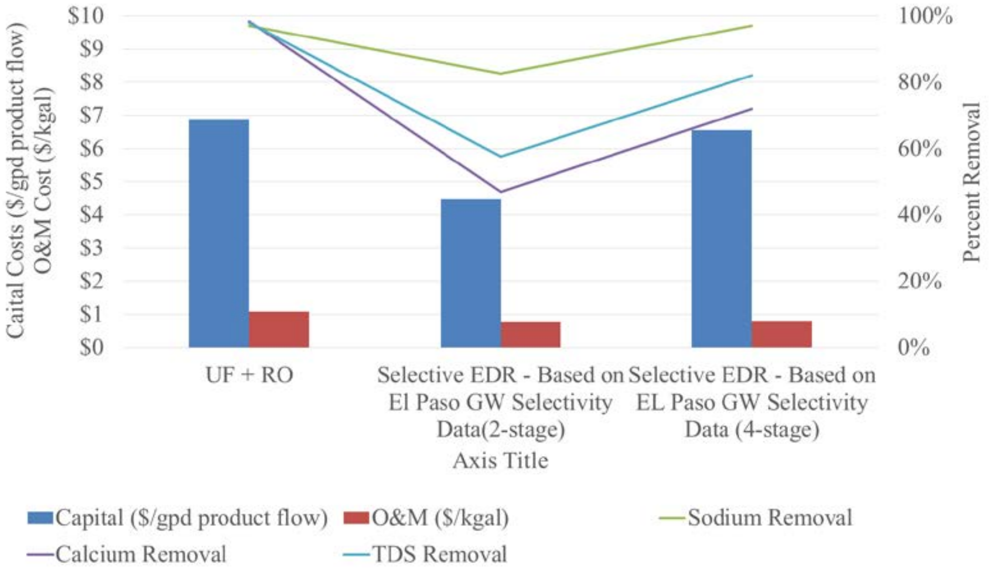


Figure 40.—Comparison of baseline and 2-stage vs. 4-stage ED alternatives.

5.3. El Paso KBHDP RO Concentrate

El Paso, Texas is doing a great job on brackish groundwater desalination using RO to meet its drinking water supply goals (Figure 41). The RO concentrate is being injected to deep wells. Considering that this means that 15 to 20% of the water resource is lost as concentrate and the deep well capacity may run out, it would ideal if some water could be recovered from the brine for irrigation use (Figure 41).

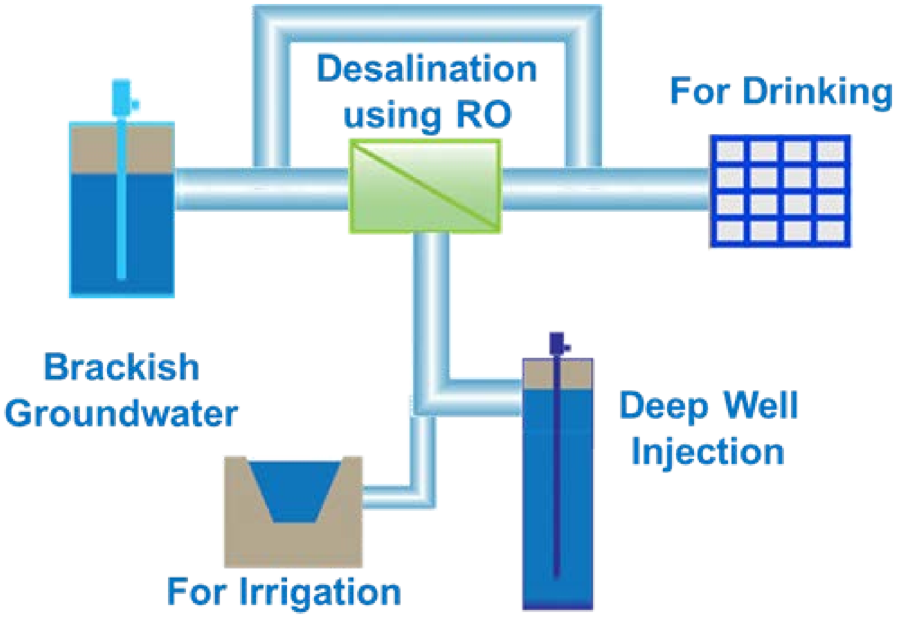


Figure 41.—El Paso RO concentrate management scenario.

Based on the Minimum Effluent Standard for Discharging into the American Canal Extension from Texas Natural Resources Conservation Commission, the expected irrigation water should meet the following water quality goals:

- TDS < 1,200~2,500 mg/L
- SAR ≤ 29 – 6 logTDS

Table 14 provides more details on these goals.

Table 14.—Irrigation Water Quality Goals for El Paso Blending Analysis

TDS (mg/L)	2,500	2,300	2,000	1,900	*1,500* *1,200*
SAR	*8.6*	*8.8*	*9.2*	*9.3*	*9.9* *10.5*

We analyzed two conditions:

- **Condition 1:** Four-stages using selectivity demonstrated by El Paso RO Concentrate testing for high TDS water, followed by four-stages using selectivity demonstrated by El Paso groundwater testing for medium and low TDS water.

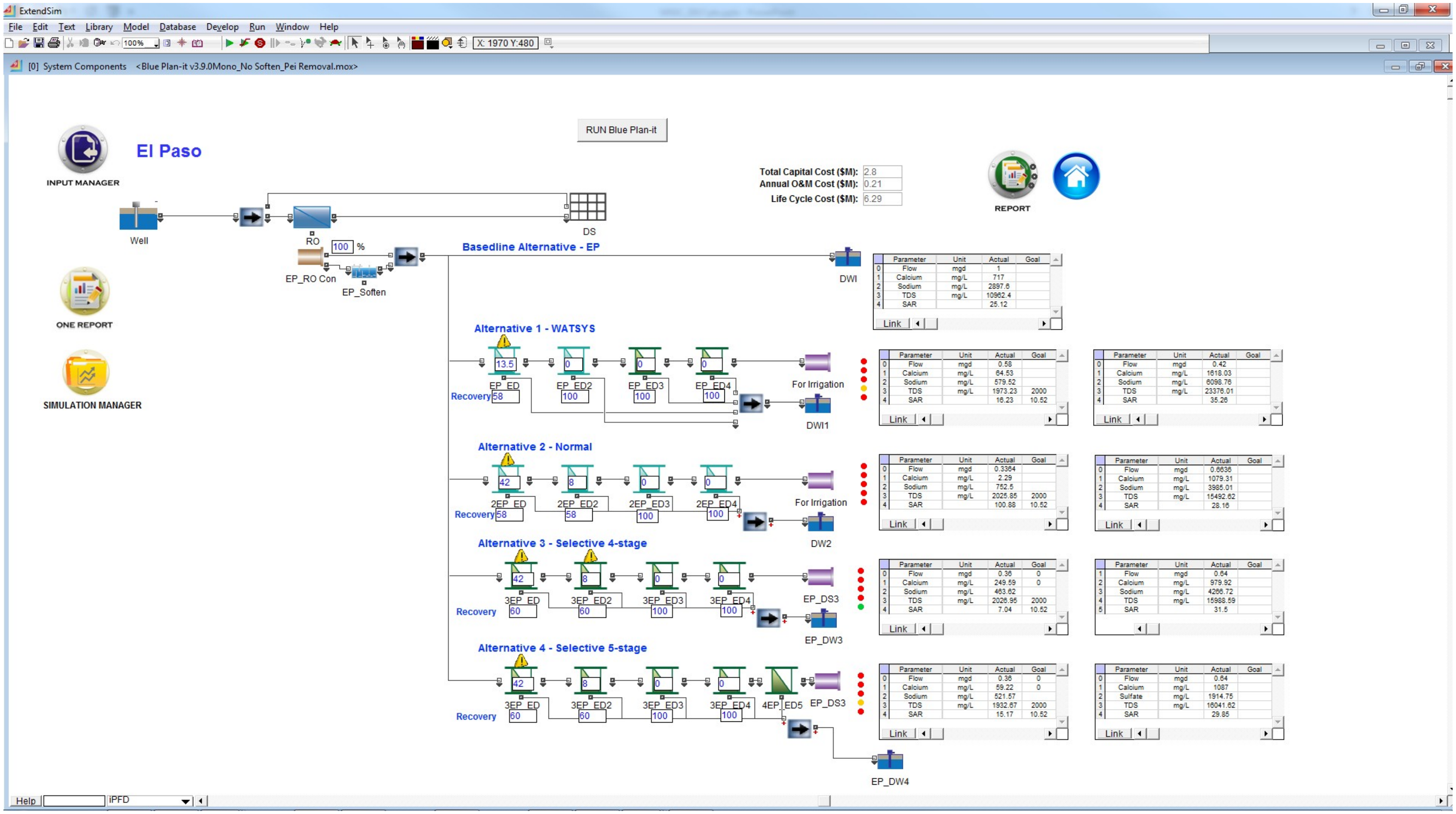
- **Condition 2:** Two stages using selectivity demonstrated by El Paso RO Concentrate testing for high TDS water, followed by six stages using selectivity demonstrated by El Paso groundwater testing for medium and low TDS water. Line and stage design is specially configured.

The system configuration can be understood as an eight-stage system, with six lines for the first four stages and 4 lines for the subsequent four stages. For costing purpose, the stages are counted 10 lines of 4-stage systems.

Table 15 shows numbers in 4-stage equivalent and compares the blending analyses for the El Paso alternatives. Figure 43 displays the processes for the blending analysis alternatives. Table 16 and Figure 44 provide cost comparisons.

Table 15.—Blending Analysis Comparison between El Paso Alternatives

	Alternative 1A	**Alternative 2**	**Alternative 3**	**Alternative 3A**
	WATSYS	**Normal Grade**	**Selective Condition 1**	**Selective Condition 2**
RO Concentrate Water Flow (mgd)	1			
RO Concentrate Na (mg/L)	2898			
RO Concentrate Ca (mg/L)	717			
RO Concentrate SAR	25.1			
RO Concentrate TDS (mg/L)	10962			
% Flow Treated	100%	100%	100%	100%
Unit Recovery	58%	34%	36%	37%
Recovered Water Flow (mgd)	0.58	0.34	0.36	0.37
Product Water Na (mg/L)	580	753	522	485
Product Ca (mg/L)	65	2	59	124
Product Water SAR	16.2	101	15.1	10.2
Product TDS (mg/L)	1973	2026	1933	2323
Concentrate Flow (gpm)	291	461	444	439
Concentrate TDS (mg/L)	23376	15493	16042	15976
Concentrate Sodium (mg/L)	6099	3985	1915	4297
Number of Product Line	8	10	10	10
Number of Stages	4	4	4	4



Total Capital Cost ($M): 2.8
Annual O&M Cost ($M): 0.21
Life Cycle Cost ($M): 6.29

	Parameter	Unit	Actual	Goal
0	Flow	mgd	1	
1	Calcium	mg/L	717	
2	Sodium	mg/L	2897.6	
3	TDS	mg/L	10962.4	
4	SAR		25.12	

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.58	
1	Calcium	mg/L	64.53	
2	Sodium	mg/L	579.52	
3	TDS	mg/L	1973.23	2000
4	SAR		16.23	10.52

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.42	
1	Calcium	mg/L	1618.03	
2	Sodium	mg/L	6098.76	
3	TDS	mg/L	23376.01	
4	SAR		35.26	

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.3364	
1	Calcium	mg/L	2.29	
2	Sodium	mg/L	752.5	
3	TDS	mg/L	2025.85	2000
4	SAR		100.88	10.52

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.6636	
1	Calcium	mg/L	1079.31	
2	Sodium	mg/L	3985.01	
3	TDS	mg/L	15492.62	
4	SAR		28.16	

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.36	0
1	Calcium	mg/L	249.59	0
2	Sodium	mg/L	463.62	
3	TDS	mg/L	2026.95	2000
4	SAR		7.04	10.52

	Parameter	Unit	Actual	Goal
1	Flow	mgd	0.64	
2	Calcium	mg/L	979.92	
3	Sodium	mg/L	4266.72	
4	TDS	mg/L	15988.59	
5	SAR		31.5	

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.36	0
1	Calcium	mg/L	59.22	0
2	Sodium	mg/L	521.57	
3	TDS	mg/L	1932.67	2000
4	SAR		15.17	10.52

	Parameter	Unit	Actual	Goal
0	Flow	mgd	0.64	
1	Calcium	mg/L	1087	
2	Sulfate	mg/L	1914.75	
3	TDS	mg/L	16041.62	
4	SAR		29.85	

Figure 42.—El Paso RO concentrate blending analysis.

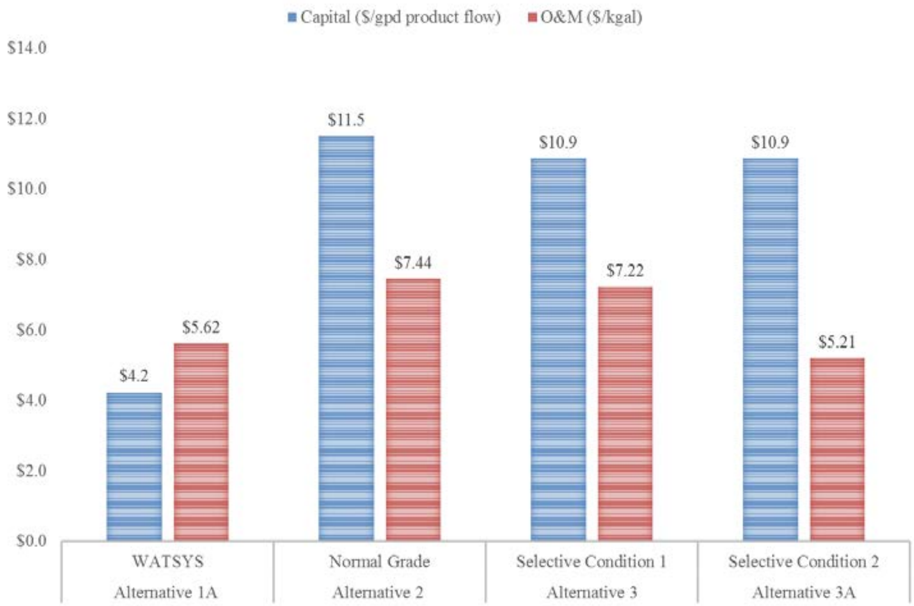


Figure 43.—Cost comparison of El Paso ED alternatives.

Table 16.—Cost Comparison for El Paso RO Concentrate Treatment Alternatives

	Alternative 1A	**Alternative 2**	**Alternative 3**	**Alternative 3A**
	WATSYS	**Normal Grade**	**Selective Condition 1**	**Selective Condition 2**
EDR	$740,000	$1,000,000	$1,000,000	$1,000,000
Building	$435,000	$869,000	$869,000	$869,000
Civil, Site Works (5%)	$59,000	$94,000	$94,000	$94,000
Electrical and I&C (25%)	$294,000	$468,000	$468,000	$468,000
Contingency (30%)	$481,000	$766,000	$766,000	$766,000
General Conditions: Mobilization & Demobilization (5%)	$77,000	$122,000	$122,000	$122,000
Engineering, Administration, and Legal (18%)	$376,000	$597,000	$597,000	$597,000
TOTAL CAPITAL COSTS	$2,460,000	$3,914,000	$3,914,000	$3,914,000
Unit Capital Costs ($/gpd)	$4.2	$11.5	$10.9	$10.9
Total Power Cost ($/year)	$715,000	$492,000	$514,000	$309,000

Table 16.—Cost Comparison for El Paso RO Concentrate Treatment Alternatives

	Alternative 1A	**Alternative 2**	**Alternative 3**	**Alternative 3A**
	WATSYS	**Normal Grade**	**Selective Condition 1**	**Selective Condition 2**
Total Chemical Cost ($/year)	$72,000	$72,000	$72,000	$72,000
Total Labor Cost ($/year)	$188,000	$188,000	$188,000	$188,000
Total Replacement Cost ($/year)	$20,000	$20,000	$20,000	$20,000
Contingency (20%)	$199,000	$154,000	$159,000	$118,000
Total O&M Costs	$1,191,000	$924,000	$950,000	$704,000
Unit O&M Costs ($/kgal)	$5.6	$7.4	$7.2	$5.2

Table 17.—Comparison of Na/Ca Ratio and Removal Goals for Two Sites

	Scottsdale	**El Paso RO Concentrate**
Feed Water Na (mg/L)	235	2898
Feed Water Ca (mg/L)	80	717
Feed Na/Ca Ratio	0.34	0.25
Product Water Na Target (mg/L)	110	~464
Target Na Removal %	53%	84%

5.4. Summary

The following conclusions can be drawn from the above analysis:

- Selective membrane can meet the required water quality for Scottsdale (Based on El Paso GW Selectivity with improved coating method)
- Selective membrane can get very close to, but may not achieve the SAR goals for recovering El Paso RO concentrate.
    - Insufficient performance due to low Ca:Na ratio and high Na removal goal.
    - Two conditions shown that TDS goal and SAR goal are competing with each other.

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APPENDIX A

Appendix A

TableA-1.—Selected testing results for data fitting (Selective Membrane)

				Independent Variables								**Dependent Variables**					
				HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
				sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm^2**	**%**	**%**	**%**	**%**	**%**	**%**
Water Type	Location	Scale	Stage	HRT	v	ConECf	ConCaf	ConMgf	ConKf	ConNaf	CD	RmCaeq	RmMgeq	RmKeq	RmNaeq	RmEC	RmECeq
GW	El Paso	Pilot	1st stage	64	5.78	4830	8.52	3.40	0.46	30.81	0.13	26%	9%	2%	63%	2%	5%
GW	El Paso	Pilot	1st stage	64	5.78	4800	8.52	3.40	0.46	30.81	0.34	16%	6%	1%	77%	5%	8%
GW	El Paso	Pilot	1st stage	64	5.78	4820	8.52	3.40	0.46	30.81	0.53	15%	5%	1%	78%	9%	13%
GW	El Paso	Pilot	1st stage	64	5.78	4840	8.52	3.40	0.46	30.81	0.84	19%	4%	1%	76%	12%	15%
GW	El Paso	Pilot	1st stage	64	5.78	4840	8.52	3.40	0.46	30.81	1.16	20%	5%	1%	73%	16%	20%
GW	El Paso	Pilot	1st stage	64	5.78	4860	8.52	3.40	0.46	30.81	1.38	21%	5%	1%	73%	19%	21%
GW	El Paso	Pilot	1st stage	64	5.78	4840	8.52	3.40	0.46	30.81	2.66	20%	6%	1%	73%	38%	40%
GW	El Paso	Bench	1st stage	13.30	4.06	4655	9.03	3.65	0.48	32.05	1.50	20%	5%	2%	74%	2%	4%
GW	El Paso	Bench	1st stage	13.30	4.06	4655	9.03	3.65	0.48	32.05	2.18	21%	6%	1%	72%	4%	6%
GW	El Paso	Bench	1st stage	13.30	4.06	4655	9.03	3.65	0.48	32.05	3.14	22%	7%	1%	70%	6%	9%
GW	El Paso	Bench	1st stage	13.30	4.06	4655	9.03	3.65	0.48	32.05	5.36	24%	8%	1%	68%	13%	15%
GW	El Paso	Bench	1st stage	13.30	4.06	4655	9.03	3.65	0.48	32.05	6.50	24%	8%	1%	67%	15%	16%
GW	El Paso	Bench	1st stage	13.30	4.06	4655	9.03	3.65	0.48	32.05	7.36	24%	8%	1%	66%	17%	17%
GW	El Paso	Bench	1st stage	8.86	6.09	4670	9.10	3.68	0.53	32.50	1.00	17%	4%	3%	76%	1%	2%
GW	El Paso	Bench	1st stage	8.86	6.09	4670	9.10	3.68	0.53	32.50	2.23	16%	4%	3%	78%	2%	4%
GW	El Paso	Bench	1st stage	8.86	6.09	4670	9.10	3.68	0.53	32.50	3.32	21%	6%	2%	71%	4%	8%
GW	El Paso	Bench	1st stage	8.86	6.09	4670	9.10	3.68	0.53	32.50	6.09	23%	7%	2%	68%	11%	12%

TableA-2.—Selected testing results for data fitting (Selective Membrane)

				Independent Variables								**Dependent Variables**					
				HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
				sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm^2**	**%**	**%**	**%**	**%**	**%**	**%**
GW	El Paso	Bench	1st stage	8.86	6.09	4670	9.10	3.68	0.53	32.50	7.41	24%	8%	2%	67%	13%	14%
GW	El Paso	Pilot	2nd stage	48	7.66	4730	8.02	3.22	0.42	29.59	0.16	23%	8%	0.2%	68%	4%	6%
GW	El Paso	Pilot	2nd stage	48	7.66	4590	7.95	3.20	0.41	28.15	0.38	17%	5%	2%	76%	6%	7%
GW	El Paso	Pilot	2nd stage	48	7.66	4390	7.65	3.09	0.37	26.31	0.53	15%	4%	2%	79%	7%	7%
GW	El Paso	Pilot	2nd stage	48	7.66	4240	7.30	3.14	0.39	25.92	0.81	17%	4%	1%	78%	8%	9%
GW	El Paso	Pilot	2nd stage	48	7.66	4060	6.80	2.99	0.35	24.58	1.00	19%	6%	1%	74%	12%	12%
GW	El Paso	Pilot	2nd stage	48	7.66	3930	6.64	2.95	0.35	24.17	1.19	18%	6%	1%	75%	15%	14%
GW	El Paso	Pilot	2nd stage	48	7.66	3020	5.04	2.36	0.24	18.29	2.00	21%	7%	1%	70%	31%	32%
GW	El Paso	Bench	2nd stage	13.30	4.06	4563	8.69	3.56	0.45	30.76	1.59	23%	8%	1%	68%	5%	7%
GW	El Paso	Bench	2nd stage	13.30	4.06	4488	8.49	3.49	0.44	30.16	2.36	25%	7%	0%	68%	8%	8%
GW	El Paso	Bench	2nd stage	13.30	4.06	4358	8.10	3.37	0.42	29.16	3.27	25%	8%	1%	67%	11%	11%
GW	El Paso	Bench	2nd stage	13.30	4.06	4070	7.45	3.14	0.39	27.51	5.05	24%	8%	1%	67%	17%	18%
GW	El Paso	Bench	2nd stage	13.30	4.06	3973	7.29	3.08	0.38	27.26	6.00	25%	8%	1%	66%	19%	20%
GW	El Paso	Bench	2nd stage	13.30	4.06	3874	7.10	3.01	0.38	26.82	6.64	25%	8%	0%	67%	24%	24%
GW	El Paso	Bench	2nd stage	8.86	6.09	4635	8.97	3.66	0.50	31.93	1.18	23%	7%	-1%	72%	2%	0%
GW	El Paso	Bench	2nd stage	8.86	6.09	4560	8.82	3.61	0.48	31.09	2.23	25%	7%	-1%	68%	5%	0%
GW	El Paso	Bench	2nd stage	8.86	6.09	4461	8.38	3.46	0.46	30.03	3.23	26%	7%	-1%	69%	7%	0%
GW	El Paso	Bench	2nd stage	8.86	6.09	4171	7.78	3.27	0.43	28.70	5.45	26%	8%	-2%	69%	11%	0%
GW	El Paso	Bench	2nd stage	8.86	6.09	4077	7.55	3.18	0.42	28.15	6.50	25%	8%	2%	65%	15%	0%
GW	El Paso	Bench	one stage	13.30	4.06	4180	6.09	2.81	0.43	31.58	1.77	31%	11%	1%	56%	7%	10%
GW	El Paso	Bench	one stage	13.30	4.06	4160	6.09	2.81	0.43	31.58	2.73	29%	11%	1%	59%	9%	12%
GW	El Paso	Bench	one stage	13.30	4.06	4150	6.09	2.81	0.43	31.58	3.68	26%	10%	1%	63%	13%	16%

TableA-2.—Selected testing results for data fitting (Selective Membrane)

				Independent Variables								Dependent Variables					
				HRT	velocity	Feed Water Cond	Feed Ca	Feed Mg	Feed K	Feed Na	Current density	Ca eq%	Mg eq%	K eq%	Na eq%	EC cut %	Eceq%
				sec	cm/s	uS/cm	meq/L	meq/L	meq/L	meq/L	mA/cm^2	%	%	%	%	%	%
GW	El Paso	Bench	one stage	13.30	4.06	4170	6.09	2.81	0.43	31.58	5.91	20%	8%	1%	70%	20%	27%
GW	El Paso	Bench	one stage	13.30	4.06	4180	6.09	2.81	0.43	31.58	7.00	20%	7%	1%	72%	24%	32%
GW	El Paso	Bench	one stage	13.30	4.06	4160	6.09	2.81	0.43	31.58	9.14	18%	8%	1%	73%	29%	34%
GW	El Paso	Bench	one stage	13.30	4.06	4180	6.09	2.81	0.43	31.58	11.45	19%	8%	1%	73%	35%	34%
RO_Con	El Paso	Pilot	1st stage	64	5.78	20010	48.58	19.44	2.19	149.82	0.94	36%	11%	1%	52%	4%	4%
RO_Con	El Paso	Pilot	1st stage	64	5.78	20050	47.48	18.94	2.14	146.53	1.66	51%	13%	1%	35%	4%	3%
RO_Con	El Paso	Pilot	1st stage	64	5.78	19960	46.95	18.75	2.11	145.32	2.25	44%	12%	1%	43%	5%	6%
RO_Con	El Paso	Pilot	1st stage	64	5.78	19990	47.80	19.05	2.12	147.57	2.88	40%	12%	1%	47%	7%	9%
RO_Con	El Paso	Pilot	1st stage	64	5.78	19970	46.45	18.54	2.08	143.89	3.31	54%	15%	1%	31%	8%	6%
RO_Con	El Paso	Pilot	1st stage	64	5.78	19780	47.04	18.76	2.11	145.60	5.13	44%	13%	1%	42%	12%	13%
RO_Con	El Paso	Pilot	1st stage	64	5.78	18690	41.16	16.17	1.90	130.60	6.00	46%	13%	1%	40%	14%	14%
RO_Con	El Paso	Pilot	1st stage	64	5.78	18430	41.40	16.52	1.95	131.19	9.66	39%	13%	1%	48%	24%	28%
RO_Con	El Paso	Pilot	1st stage	64	5.78	18540	42.39	16.87	1.97	132.23	11.22	39%	13%	1%	47%	27%	32%
RO_Con	El Paso	Pilot	1st stage	64	5.78	18610	42.11	16.70	1.95	132.11	13.03	37%	13%	1%	49%	32%	37%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	19920	46.32	18.65	2.12	144.91	0.41	41%	12%	0.2%	47%	3%	1%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	19240	45.62	18.56	2.09	145.62	1.25	37%	11%	1%	51%	4%	3%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	19190	43.97	18.07	2.07	144.09	2.16	47%	12%	2%	39%	4%	3%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	18920	41.58	17.26	2.00	140.01	3.09	34%	11%	1%	55%	6%	8%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	18670	39.74	16.66	1.90	138.07	3.31	30%	10%	1%	59%	7%	10%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	18410	39.48	16.62	1.94	139.92	3.91	29%	9%	1%	60%	7%	13%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	17420	35.16	15.30	1.84	134.41	5.28	31%	10%	1%	58%	10%	13%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	16090	28.80	12.59	1.61	119.78	7.97	27%	10%	1%	63%	19%	26%

TableA-2.—Selected testing results for data fitting (Selective Membrane)

				Independent Variables								**Dependent Variables**					
				HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
				sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm^2**	**%**	**%**	**%**	**%**	**%**	**%**
RO_Con	El Paso	Pilot	2nd stage	48	7.66	14080	20.42	9.69	1.37	105.36	12.75	23%	9%	1%	67%	35%	36%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	13610	18.81	8.97	1.27	103.21	13.69	21%	9%	1%	68%	37%	40%
RO_Con	El Paso	Pilot	2nd stage	48	7.66	12670	15.56	7.60	1.14	96.87	13.69	19%	8%	1%	72%	39%	42%
RO_Con	El Paso	Bench	one stage	13.30	4.06	18250	32.98	15.08	2.00	148.90	3.59	36%	11%	1%	52%	2%	4%
RO_Con	El Paso	Bench	one stage	13.30	4.06	18222	32.98	15.08	2.00	148.90	5.50	32%	11%	1%	57%	3%	6%
RO_Con	El Paso	Bench	one stage	13.30	4.06	18250	32.98	15.08	2.00	148.90	7.50	42%	13%	1%	45%	5%	5%
RO_Con	El Paso	Bench	one stage	13.30	4.06	18320	32.98	15.08	2.00	148.90	11.73	39%	13%	1%	47%	6%	7%
RO_Con	El Paso	Bench	one stage	13.30	4.06	18330	32.98	15.08	2.00	148.90	14.09	43%	14%	1%	42%	8%	6%
RO_Con	El Paso	Bench	one stage	13.30	4.06	18310	32.99	15.06	1.99	148.89	19.05	27%	10%	1%	61%	9%	16%
RO_Con	El Paso	Bench	one stage	13.30	4.06	18370	32.99	15.06	1.99	148.89	23.73	26%	10%	1%	63%	11%	17%

Table A-3.—Selected testing results for data fitting (Normal Grade Membrane)

					Independent Variables								**Dependent Variables**					
					HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
					sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm2**	**%**	**%**	**%**	**%**	**%**	**%**
Water Type	Mem Type	Location	Scale	Stage	HRT	v	ConECf	ConCaf	ConMgf	ConKf	ConNaf	CD	RmCaeq	RmMgeq	RmKeq	RmNaeq	RmEC	RmECeq
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4750	7.45	3.41	0.47	30.98	0.28	77%	22%	1%	0%	3%	3%
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4735	8.45	3.41	0.47	30.98	0.81	62%	19%	0%	19%	9%	11%
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4717	8.45	3.41	0.47	30.98	1.38	55%	18%	0%	27%	17%	20%
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4685	8.45	3.41	0.47	30.98	1.88	49%	17%	0%	33%	25%	29%
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4671	8.45	3.41	0.47	30.98	2.34	46%	17%	0%	37%	32%	34%
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4672	8.45	3.41	0.47	30.98	2.69	42%	16%	1%	42%	35%	39%
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4663	8.45	3.41	0.47	30.98	3.44	35%	13%	1%	51%	46%	50%
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4637	8.45	3.41	0.47	30.98	4.09	30%	12%	1%	58%	58%	61%
GW	Normal	El Paso	Pilot	1st stage	64	5.78	4622	8.45	3.41	0.47	30.98	5.06	25%	10%	1%	64%	71%	72%
GW	Normal	El Paso	Bench	1st stage	13.30	4.06	4697	9.08	3.67	0.48	32.19	3.05	42%	13%	-2%	47%	6%	11%
GW	Normal	El Paso	Bench	1st stage	13.30	4.06	4697	9.08	3.67	0.48	32.19	4.64	39%	13%	-1%	49%	10%	15%
GW	Normal	El Paso	Bench	1st stage	13.30	4.06	4697	9.08	3.67	0.48	32.19	6.36	35%	12%	-1%	54%	13%	19%
GW	Normal	El Paso	Bench	1st stage	13.30	4.06	4697	9.08	3.70	0.49	32.19	11.09	17%	6%	0%	77%	26%	29%
GW	Normal	El Paso	Bench	1st stage	13.30	4.06	4697	9.08	3.70	0.49	32.19	12.95	16%	5%	1%	78%	32%	34%

Table A-3.—Selected testing results for data fitting (Normal Grade Membrane)

					Independent Variables								**Dependent Variables**					
					HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
					sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm2**	**%**	**%**	**%**	**%**	**%**	**%**
GW	Normal	El Paso	Bench	1st stage	13.30	4.06	4697	9.08	3.70	0.49	32.19	16.09	20%	6%	1%	74%	40%	42%
GW	Normal	El Paso	Bench	1st stage	13.30	4.06	4697	9.08	3.70	0.49	32.19	18.14	22%	6%	1%	71%	43%	46%
GW	Normal	El Paso	Bench	1st stage	8.86	6.09	4778	9.07	3.67	0.48	32.18	3.55	26%	7%	1%	66%	4%	7%
GW	Normal	El Paso	Bench	1st stage	8.86	6.09	4778	9.07	3.67	0.48	32.18	6.27	18%	4%	-1%	79%	9%	11%
GW	Normal	El Paso	Bench	1st stage	8.86	6.09	4778	9.07	3.67	0.48	32.18	8.86	14%	3%	0%	83%	14%	16%
GW	Normal	El Paso	Bench	1st stage	8.86	6.09	4778	9.07	3.67	0.48	32.18	14.00	13%	3%	1%	83%	24%	26%
GW	Normal	El Paso	Bench	1st stage	8.86	6.09	4778	9.07	3.67	0.48	32.18	16.45	14%	4%	1%	81%	30%	30%
GW	Normal	El Paso	Bench	1st stage	8.86	6.09	4778	9.07	3.67	0.48	32.18	20.45	18%	5%	1%	76%	37%	38%
GW	Normal	El Paso	Bench	1st stage	8.86	6.09	4778	9.07	3.67	0.48	32.18	24.50	23%	5%	1%	72%	43%	44%
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	4564	6.45	3.13	0.47	30.98	0.31	47%	15%	0.1%	39%	4%	10%
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	4243	5.48	2.51	0.46	30.06	0.94	46%	16%	0%	38%	12%	14%
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	3891	3.63	1.83	0.45	28.64	1.56	36%	16%	0%	47%	21%	21%
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	3525	2.40	1.29	0.43	26.85	2.09	19%	10%	1%	71%	30%	33%
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	3206	1.60	0.90	0.40	25.50	2.28	11%	6%	1%	81%	36%	39%
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	3067	1.26	0.72	0.38	23.88	2.53	8%	4%	1%	87%	46%	46%

Table A-3.—Selected testing results for data fitting (Normal Grade Membrane)

					Independent Variables								**Dependent Variables**					
					HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
					sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm2**	**%**	**%**	**%**	**%**	**%**	**%**
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	2508	0.84	0.48	0.33	19.87	2.59	5%	3%	2%	90%	58%	58%
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	1959	0.63	0.37	0.27	15.78	2.44	4%	3%	2%	92%	65%	67%
GW	Normal	El Paso	Pilot	2nd stage	48	7.66	1374	0.53	0.31	0.21	10.96	1.91	4%	2%	1%	93%	77%	77%
GW	Normal	El Paso	Bench	2nd stage	13.30	4.06	4430	6.91	2.99	0.57	29.74	2.36	74%	25%	7%	-6%	7%	5%
GW	Normal	El Paso	Bench	2nd stage	13.30	4.06	4240	6.36	2.76	0.55	28.78	3.59	45%	17%	4%	34%	13%	11%
GW	Normal	El Paso	Bench	2nd stage	13.30	4.06	4072	6.03	2.61	0.53	27.53	4.95	34%	14%	3%	49%	18%	17%
GW	Normal	El Paso	Bench	2nd stage	13.30	4.06	3495	6.85	2.99	0.43	22.23	7.32	19%	8%	2%	71%	33%	34%
GW	Normal	El Paso	Bench	2nd stage	13.30	4.06	3212	6.54	2.87	0.40	20.25	8.05	19%	8%	2%	71%	39%	40%
GW	Normal	El Paso	Bench	2nd stage	13.30	4.06	2812	5.32	2.59	0.37	18.02	9.36	21%	9%	2%	69%	50%	52%
GW	Normal	El Paso	Bench	2nd stage	13.30	4.06	2666	4.49	2.43	0.36	17.27	10.23	20%	9%	2%	70%	56%	57%
GW	Normal	El Paso	Bench	2nd stage	8.86	6.09	4606	8.25	3.46	0.45	30.13	2.41	50%	14%	3%	32%	5%	1%
GW	Normal	El Paso	Bench	2nd stage	8.86	6.09	4347	8.16	3.47	0.52	28.21	4.18	19%	7%	5%	69%	10%	7%
GW	Normal	El Paso	Bench	2nd stage	8.86	6.09	4108	8.11	3.45	0.48	26.28	5.91	15%	5%	4%	76%	16%	12%
GW	Normal	El Paso	Bench	2nd stage	8.86	6.09	3613	7.55	3.26	0.41	22.30	9.23	16%	6%	3%	76%	25%	22%
GW	Normal	El Paso	Bench	2nd stage	8.86	6.09	3334	7.14	3.11	0.41	21.06	10.59	18%	7%	2%	73%	29%	27%

Table A-3.—Selected testing results for data fitting (Normal Grade Membrane)

					Independent Variables									**Dependent Variables**					
					HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
					sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm2**	**%**	**%**	**%**	**%**	**%**	**%**
GW	Normal	El Paso	Bench	2nd stage	8.86	6.09	2990	5.99	2.76	0.37	19.12	12.77	21%	8%	2%	69%	40%	36%
GW	Normal	El Paso	Bench	2nd stage	8.86	6.09	2711	4.53	2.65	0.36	17.79	14.23	19%	10%	2%	69%	46%	42%
GW	Normal	El Paso	Bench	one stage	13.30	4.06	4240	6.09	2.81	0.43	31.58	2.73	54%	22%	1%	23%	8%	9%
GW	Normal	El Paso	Bench	one stage	13.30	4.06	4310	6.09	2.81	0.43	31.58	4.09	42%	17%	1%	40%	13%	12%
GW	Normal	El Paso	Bench	one stage	13.30	4.06	4280	6.09	2.81	0.43	31.58	5.45	30%	13%	1%	56%	18%	20%
GW	Normal	El Paso	Bench	one stage	13.30	4.06	4250	6.09	2.81	0.43	31.58	8.45	22%	10%	1%	67%	28%	30%
GW	Normal	El Paso	Bench	one stage	13.30	4.06	4240	6.09	2.81	0.43	31.58	9.82	20%	9%	1%	70%	34%	36%
GW	Normal	El Paso	Bench	one stage	13.30	4.06	4230	6.09	2.81	0.43	31.58	13.45	18%	8%	1%	73%	40%	43%
GW	Normal	El Paso	Bench	one stage	13.30	4.06	4220	6.09	2.81	0.43	31.58	16.82	16%	7%	1%	75%	45%	48%
Reclaimed	Normal	Scottsdale	Pilot	1st stage	60.03	6.13	1925	4.26	2.32	0.60	11.05	1.47	58.1%	29.9%	1.8%	10.2%	29.6%	24%
Reclaimed	Normal	Scottsdale	Pilot	1st stage	60.03	6.13	1874	4.26	2.32	0.60	11.05	2.09	44.1%	22.4%	2.6%	31.0%	37.3%	39%
Reclaimed	Normal	Scottsdale	Pilot	1st stage	60.03	6.13	1716	4.26	2.32	0.60	11.05	2.59	41.5%	21.1%	3.3%	34.0%	47.0%	44%
Reclaimed	Normal	Scottsdale	Pilot	1st stage	60.03	6.13	1837	4.26	2.32	0.60	11.05	2.97	37.5%	19.0%	3.4%	40.1%	55.5%	51%
Reclaimed	Normal	Scottsdale	Pilot	1st stage	48.03	7.66	1882	4.26	2.32	0.60	11.05	2.16	45.9%	22.4%	2.5%	29.1%	34.4%	36%
Reclaimed	Normal	Scottsdale	Pilot	1st stage	48.03	7.66	1750	4.26	2.32	0.60	11.05	2.66	42.4%	20.8%	2.9%	33.8%	39.4%	42%

Table A-3.—Selected testing results for data fitting (Normal Grade Membrane)

					Independent Variables								**Dependent Variables**					
					HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
					sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm2**	**%**	**%**	**%**	**%**	**%**	**%**
Reclaimed	Normal	Scottsdale	Pilot	1st stage	48.03	7.66	1900	4.26	2.32	0.60	11.05	3.09	40.8%	21.2%	3.1%	34.9%	45.7%	43%
Reclaimed	Normal	Scottsdale	Pilot	1st stage	40.02	9.19	2025	4.26	2.32	0.60	11.05	2.25	49.3%	24.8%	2.0%	23.9%	26.3%	29%
Reclaimed	Normal	Scottsdale	Pilot	1st stag	40.02	9.19	1880	4.26	2.32	0.60	11.05	2.75	48.5%	24.0%	2.6%	24.9%	34.4%	33%
Reclaimed	Normal	Scottsdale	Pilot	1st stage	40.02	9.19	1910	4.26	2.32	0.60	11.05	3.16	44.2%	22.4%	2.7%	30.7%	39.7%	37%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	60.03	6.13	1355	1.77	1.04	0.52	10.61	1.13	27.1%	15.6%	3.9%	53.4%	22.3%	29%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	60.03	6.13	1175	1.16	0.75	0.42	8.87	1.50	17.1%	10.5%	4.3%	68.1%	42.2%	44%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	60.03	6.13	910.7	0.91	0.62	0.34	8.31	1.50	12.8%	8.5%	3.7%	75.0%	48.0%	53%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	60.03	6.13	817.6	0.80	0.57	0.29	7.35	1.53	11.7%	8.2%	3.5%	76.6%	59.4%	59%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	48.03	7.66	1234	1.24	0.85	0.43	9.13	1.78	24.4%	16.2%	4.5%	54.9%	34.0%	29%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	48.03	7.66	1061	0.98	0.71	0.37	8.44	1.81	17.2%	12.3%	4.4%	66.2%	38.9%	37%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	48.03	7.66	1031	1.05	0.65	0.36	8.31	2.00	14.4%	8.9%	4.2%	72.6%	47.6%	53%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	40.02	9.19	1218	1.65	1.01	0.50	9.79	2.00	30.1%	17.8%	4.1%	48.0%	32.6%	28%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	40.02	9.19	1234	1.38	0.90	0.45	9.57	2.09	21.5%	13.7%	4.1%	60.7%	30.5%	37%
Reclaimed	Normal	Scottsdale	Pilot	2nd stage	40.02	9.19	1151	1.25	0.80	0.41	8.96	2.28	18.4%	11.3%	4.2%	66.1%	37.6%	44%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19560	47.91	19.67	2.14	151.44	0.56	35%	12%	1%	53%	4%	9%

Table A-3.—Selected testing results for data fitting (Normal Grade Membrane)

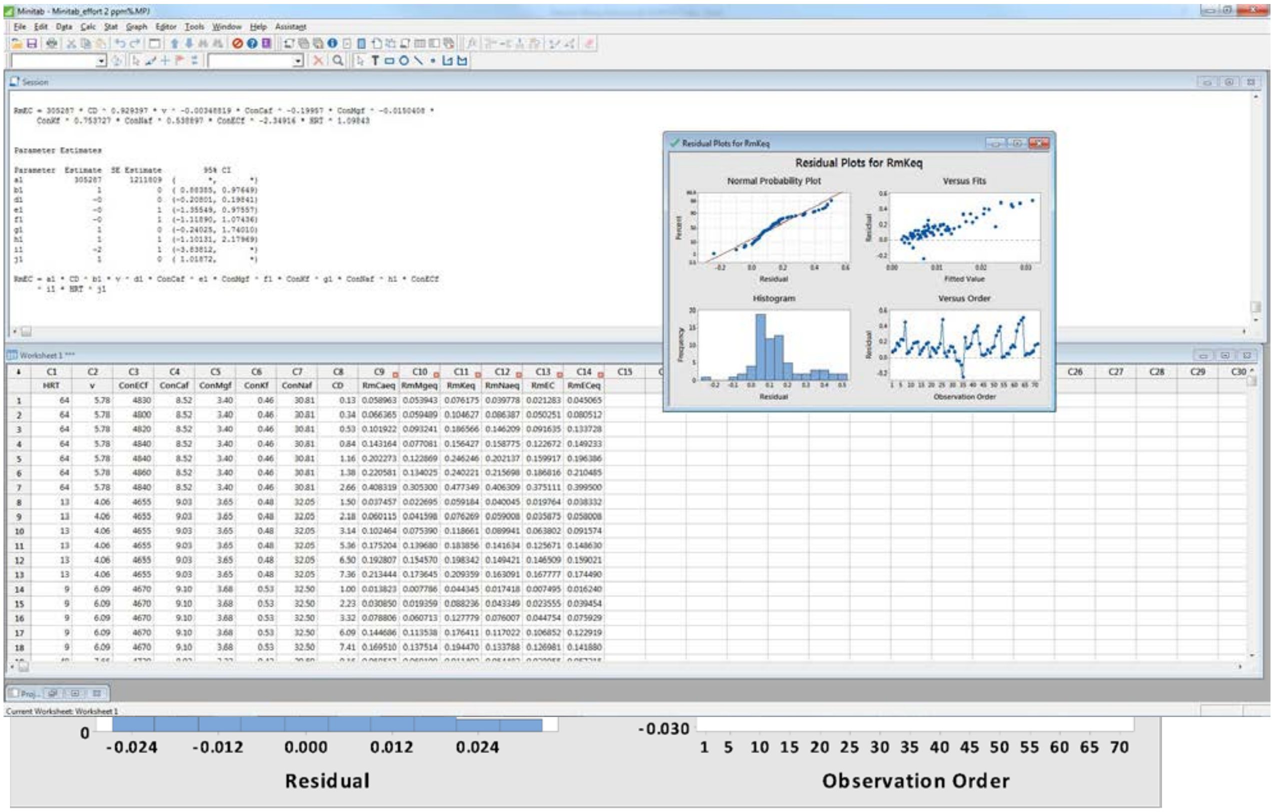
					Independent Variables								**Dependent Variables**					
					HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
					sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm2**	**%**	**%**	**%**	**%**	**%**	**%**
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19460	47.87	19.67	2.17	151.57	0.72	47%	15%	1%	37%	5%	6%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19520	47.39	19.43	2.10	150.12	0.89	40%	13%	1%	46%	7%	10%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19480	46.95	19.24	2.12	148.82	0.96	43%	13%	1%	42%	8%	9%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19450	48.32	19.84	2.15	153.14	1.04	39%	13%	1%	48%	8%	12%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19420	47.66	19.57	2.13	151.37	1.28	38%	12%	1%	49%	9%	15%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19440	46.86	19.21	2.13	148.66	1.61	45%	14%	1%	40%	11%	14%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19420	46.42	19.02	2.08	147.51	1.60	44%	14%	1%	41%	11%	14%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19460	46.39	19.02	2.12	147.49	1.86	44%	14%	1%	41%	14%	16%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19410	45.64	18.73	2.06	145.73	2.88	45%	15%	1%	39%	21%	22%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19320	45.79	18.72	2.09	145.80	3.03	44%	15%	1%	41%	22%	24%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19340	48.59	19.85	2.18	154.27	3.51	38%	13%	1%	48%	25%	33%
RO_Con	Normal	El Paso	Pilot	1st stage	64	5.78	19340	44.62	18.21	2.03	142.47	4.13	39%	14%	1%	46%	30%	35%
RO_Con	Normal	El Paso	Pilot	2nd stage	48	7.66	18490	41.98	17.84	2.01	146.89	0.95	38%	13%	1%	48%	7%	10%
RO_Con	Normal	El Paso	Pilot	2nd stage	48	7.66	18180	38.43	16.56	1.94	139.79	1.03	55%	16%	1%	28%	7%	5%
RO_Con	Normal	El Paso	Pilot	2nd stage	48.03	7.66	18000	38.35	16.58	1.92	140.46	1.22	43%	14%	1%	42%	8%	9%

Table A-3.—Selected testing results for data fitting (Normal Grade Membrane)

					Independent Variables								**Dependent Variables**					
					HRT	**velocity**	**Feed Water Cond**	**Feed Ca**	**Feed Mg**	**Feed K**	**Feed Na**	**Current density**	**Ca eq%**	**Mg eq%**	**K eq%**	**Na eq%**	**EC cut %**	**Eceq%**
					sec	**cm/s**	**uS/cm**	**meq/L**	**meq/L**	**meq/L**	**meq/L**	**mA/cm2**	**%**	**%**	**%**	**%**	**%**	**%**
RO_Con	Normal	El Paso	Pilot	2nd stage	48.03	7.66	17970	37.60	16.38	1.90	140.07	1.23	46%	15%	1%	38%	9%	8%
RO_Con	Normal	El Paso	Pilot	2nd stage	48.00	7.66	17600	34.75	15.34	1.82	134.87	1.64	48%	16%	1%	36%	12%	10%
RO_Con	Normal	El Paso	Pilot	2nd stage	48.00	7.66	17210	33.49	15.00	1.80	136.83	1.63	42%	14%	1%	43%	12%	13%
RO_Con	Normal	El Paso	Pilot	2nd stage	48.00	7.66	17190	33.04	14.80	1.79	134.91	1.85	35%	13%	1%	51%	13%	18%
RO_Con	Normal	El Paso	Pilot	2nd stage	48.00	7.66	16790	31.14	14.18	1.74	133.44	2.18	40%	14%	1%	45%	15%	18%
RO_Con	Normal	El Paso	Pilot	2nd	48.00	7.66	15310	24.42	11.73	1.63	127.19	2.95	33%	14%	1%	52%	23%	27%
RO_Con	Normal	El Paso	Pilot	2nd stage	48.00	7.66	14990	23.24	11.21	1.54	124.68	4.00	29%	13%	1%	58%	32%	37%
RO_Con	Normal	El Paso	Pilot	2nd stage	48.00	7.66	14410	20.19	9.92	1.44	118.64	4.30	25%	11%	1%	63%	36%	42%
RO_Con	Normal	El Paso	Pilot	2nd stage	48.00	7.66	13460	16.17	8.15	1.28	108.71	4.30	22%	11%	1%	67%	40%	44%
RO_Con	Normal	El Paso	Bench	one stage	13.30	4.06	18240	32.98	15.08	2.00	148.90	8.50	35%	12%	1%	52%	4%	7%
RO_Con	Normal	El Paso	Bench	one stage	13.30	4.06	18220	32.98	15.08	2.00	148.90	11.86	33%	12%	1%	54%	6%	9%
RO_Con	Normal	El Paso	Bench	one stage	13.30	4.06	18270	32.98	15.08	2.00	148.90	19.27	35%	13%	1%	51%	10%	10%
RO_Con	Normal	El Paso	Bench	one stage	13.30	4.06	18250	32.98	15.08	2.00	148.90	24.05	32%	12%	1%	55%	13%	14%
RO_Con	Normal	El Paso	Bench	one stage	13.30	4.06	18260	32.99	15.06	1.99	148.89	32.36	29%	11%	1%	59%	16%	17%
RO_Con	Normal	El Paso	Bench	one stage	13.30	4.06	18300	32.99	15.06	1.99	148.89	39.59	26%	10%	1%	63%	20%	21%

APPENDIX B

Appendix B – Empirical Modeling



```
RmEC = 305287 * CD ^ 0.929397 * v ^ -0.00348819 * ConCaf ^ -0.19957 * ConMgf ^ -0.0150408 *
     ConKf ^ 0.753727 * ConNaf ^ 0.538897 * ConECf ^ -2.34916 * HRT ^ 1.09843


Parameter Estimates

Parameter  Estimate  SE Estimate        95% CI
a1           305287      1211809  (        *,        *)
b1                1            0  ( 0.88385, 0.97649)
d1               -0            0  (-0.20801, 0.19841)
e1               -0            1  (-1.35549, 0.97557)
f1               -0            1  (-1.11890, 1.07436)
g1                1            0  (-0.24025, 1.74010)
h1                1            1  (-1.10131, 2.17969)
i1               -2            1  (-3.83812,        *)
j1                1            0  ( 1.01872,        *)

RmEC = a1 * CD ^ b1 * v ^ d1 * ConCaf ^ e1 * ConMgf ^ f1 * ConKf ^ g1 * ConNaf ^ h1 * ConECf
     ^ i1 * HRT ^ j1
```

↓	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
	HRT	v	ConECf	ConCaf	ConMgf	ConKf	ConNaf	CD	RmCaeq	RmMgeq	RmKeq	RmNaeq	RmEC	RmECeq	
1	64	5.78	4830	8.52	3.40	0.46	30.81	0.13	0.058963	0.053943	0.076175	0.039778	0.021283	0.045065	
2	64	5.78	4800	8.52	3.40	0.46	30.81	0.34	0.066365	0.059489	0.104627	0.086387	0.050251	0.080512	
3	64	5.78	4820	8.52	3.40	0.46	30.81	0.53	0.101922	0.093241	0.186566	0.146209	0.091635	0.133728	
4	64	5.78	4840	8.52	3.40	0.46	30.81	0.84	0.143164	0.077081	0.156427	0.158775	0.122672	0.149233	
5	64	5.78	4840	8.52	3.40	0.46	30.81	1.16	0.202273	0.122869	0.246246	0.202137	0.159917	0.196386	
6	64	5.78	4860	8.52	3.40	0.46	30.81	1.38	0.220581	0.134025	0.240221	0.215698	0.186816	0.210485	
7	64	5.78	4840	8.52	3.40	0.46	30.81	2.66	0.408319	0.305300	0.477349	0.406309	0.375111	0.399500	
8	13	4.06	4655	9.03	3.65	0.48	32.05	1.50	0.037457	0.022695	0.059184	0.040045	0.019764	0.038332	
9	13	4.06	4655	9.03	3.65	0.48	32.05	2.18	0.060115	0.041598	0.076269	0.059008	0.035875	0.058008	
10	13	4.06	4655	9.03	3.65	0.48	32.05	3.14	0.102464	0.075390	0.118661	0.089941	0.063802	0.091574	
11	13	4.06	4655	9.03	3.65	0.48	32.05	5.36	0.175204	0.139680	0.183856	0.141634	0.125671	0.148630	
12	13	4.06	4655	9.03	3.65	0.48	32.05	6.50	0.192807	0.154570	0.198342	0.149421	0.146509	0.159021	
13	13	4.06	4655	9.03	3.65	0.48	32.05	7.36	0.213444	0.173645	0.209359	0.163091	0.167777	0.174490	
14	9	6.09	4670	9.10	3.68	0.53	32.50	1.00	0.013823	0.007786	0.044345	0.017418	0.007495	0.016240	
15	9	6.09	4670	9.10	3.68	0.53	32.50	2.23	0.030850	0.019359	0.088236	0.043349	0.023555	0.039454	
16	9	6.09	4670	9.10	3.68	0.53	32.50	3.32	0.078806	0.060713	0.127779	0.076007	0.044754	0.075929	
17	9	6.09	4670	9.10	3.68	0.53	32.50	6.09	0.144686	0.113538	0.176411	0.117022	0.106852	0.122919	
18	9	6.09	4670	9.10	3.68	0.53	32.50	7.41	0.169510	0.137514	0.194470	0.133788	0.126981	0.141880	

Figure B-1.—Screen Shot of MiniTab (Product version: Minitab® 17.3.1)

Equations used for Fitting

Using the following empirical equations, predict removal rates of Ca, Mg, K, Na, and conductivity from current density (CD), HRT, velocity (v), feed water conductivity, Ca, Mg, K, Na.

Equation 1	RmCa=a1*CD^b1*HRT^c1*v^d1*ConCaf^e1*ConMgeqf^f1*ConKeqf^g1 *ConNaeqf^h1*ConEC^i1
Equation 2	RmMg=a2*CD^b2*HRT^c2*v^d2*ConCaf^e2*ConMgeqf^f2*ConKeqf^g2 *ConNaeqf^h2*ConEC^i2
Equation 3	RmK=a3*CD^b3*HRT^c3*v^d3*ConCaeqf^e3*ConMgf^fe3*ConKf^g3 *ConNaf^h3*ConEC^i3
Equation 4	RmNa=a4*CD^b4*HRT^c4*v^d4*ConNaf^e4*ConMgf^fe4*ConKf^g4 *ConNaf^h4*ConEC^i4
Equation 5	RmEC=a5*CD^b5*HRT^c5*v^d5*ConEcf^e5*ConMgf^fe5*ConKf^g5 *ConNaf^h5*ConEC^i5

Data Fitting Results

Effort 1 - All Normal and Selective Membrane Data together. Data fitting error received.

Effort 2 - ppm % removal: Parameter fitted using all **El Paso GW and RO Concentrate** Data for **Selective** Membrane, both bench and pilot, all single stage (1st stage alone, 2nd stage alone or one stage bench testing).

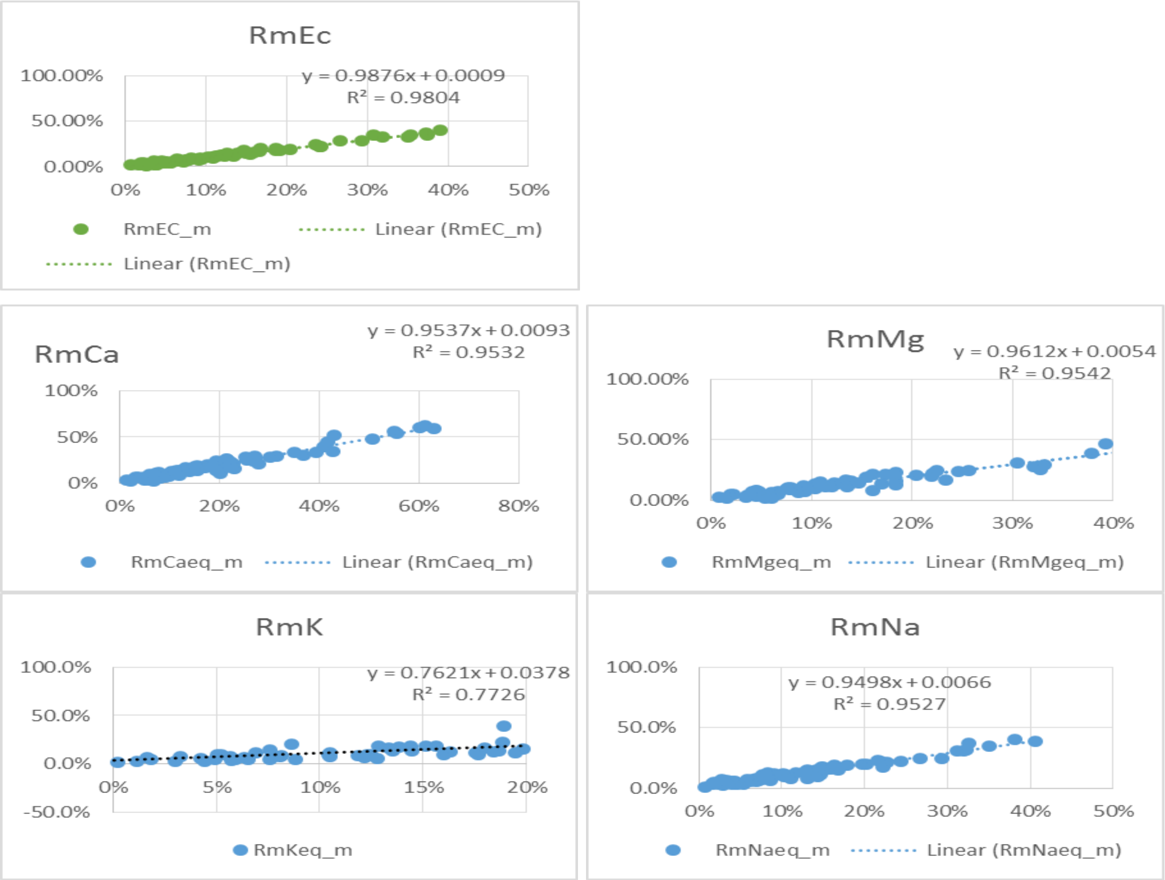
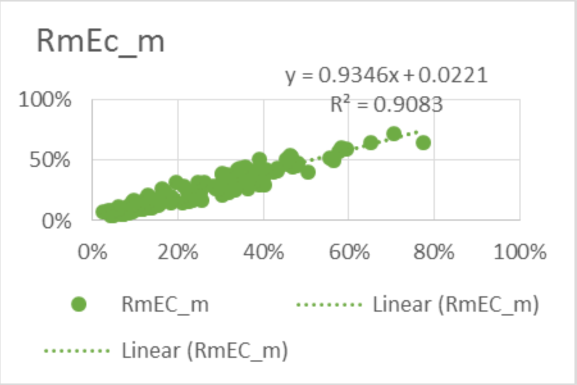
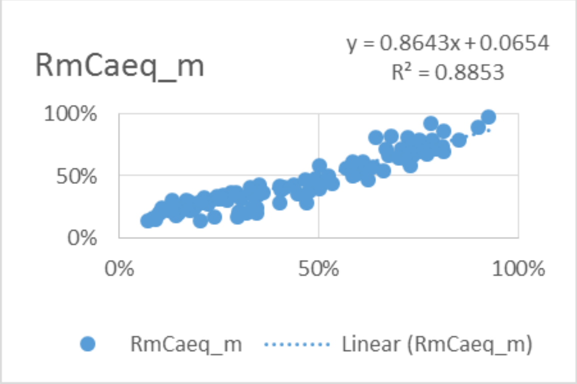


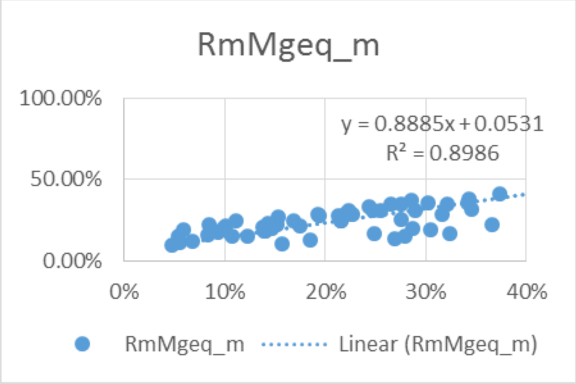
Figure 2.—Effort 1.

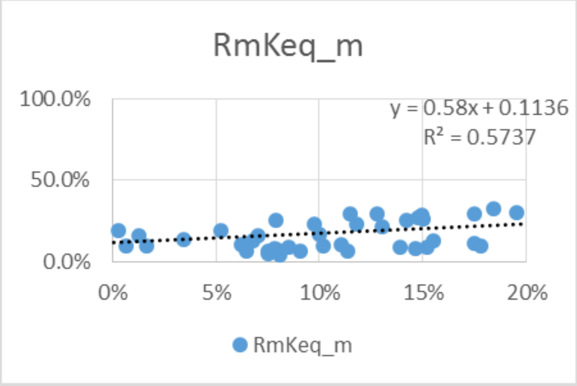
		1	2	3	4	5	6
	a	5.97E+10	4.23E+12	3.12E+13	731612	54.2544	38.8645
CD	b	0.827198	9.39E-01	7.85E-01	0.803697	0.9675	0.9219
HRT	c	1.07E+00	1.15E+00	1.39E+00	1.0331	1.0213	1.1023
v	d	-2.58E-01	-1.72E-01	1.20E-02	0.208012	-0.046	-0.4083
Ca	e	-9.08E-01	-3.68E-01	-1.77E+00	0.727627	0	0
Mg	f	1.42E+00	9.59E-01	1.95E+00	-1.40957	0	0
K	g	8.28E-01	5.39E-01	1.53E+00	0.564928	0	0
Na	h	1.96E+00	3.20E+00	1.91E+00	1.74094	0	0
Ec	i	-4.29E+00	-5.49E+00	-4.99E+00	-2.97631	-1.197	-1.1012

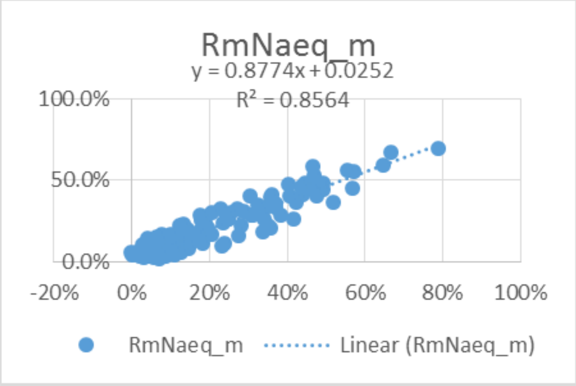
Effort 3B - ppm % removal: Parameter fitted using all **Scottsdale RW and El Paso GW and RO Concentrate** Data for **Normal** Membrane, both bench and pilot, all single stage (1st stage alone, 2nd stage alone or one stage bench testing).











		1	2	3	4	5
	a	9.41E-04	0.00044	9.21E-03	0.03836	0.00025
CD	b	5.10E-01	0.60511	6.73E-01	0.95343	0.82969
HRT	c	9.25E-01	1.0572	6.45E-01	0.87124	0.94599
v	d	3.56E-01	0.38353	-3.95E-02	0.31311	0.18936
Ca	e	-1.47E+00	-1.52361	-2.70E+00	-0.90665	-1.33691
Mg	f	1.75E+00	1.70822	3.02E+00	0.96704	1.40967
K	g	-7.94E-01	-0.72454	-1.01E+00	-1.21062	-0.87453
Na	h	-2.63E-01	-0.2769	-2.01E-01	0.74716	-0.45704
Ec	i	3.61E-01	0.3899	2.58E-01	-0.67513	0.52131

Table 4.—Modeled vs. Measured (was Not used in blending analysis) - Selective Membrane

	Inputs						Measured						Modeled					
	HRT	**v**	**ConECf**	**ConCaf**	**ConMgf**	**ConKf**	**ConNaf**	**CD**	**RmCaeq**	**RmMgeq**	**RmKeq**	**RmNaeq**	**RmEC**	**RmCaeq_m**	**RmMgeq_m**	**RmKeq_m**	**RmNaeq_m**	**RmEC_m**
Scottsdale	40	9.19	1837	4.26	2.32	0.60	11.05	0.13	38%	19%	3%	40%	55%	20.16%	7.49%	95.07%	8.18%	3.51%
ElPasoGW	64	5.78	4600	8.79	3.53	0.5	32.08	1.16	20.2%	12.3%	24.6%	20.2%	16.0%	29.85%	22.90%	38.50%	25.32%	16.58%
ElPasoConcentrate	64	5.78	20050	40.13	16.78	2.03	143.00	1.66	7.4%	4.6%	3.3%	1.7%	4.3%	9.93%	6.47%	6.92%	4.23%	4.04%

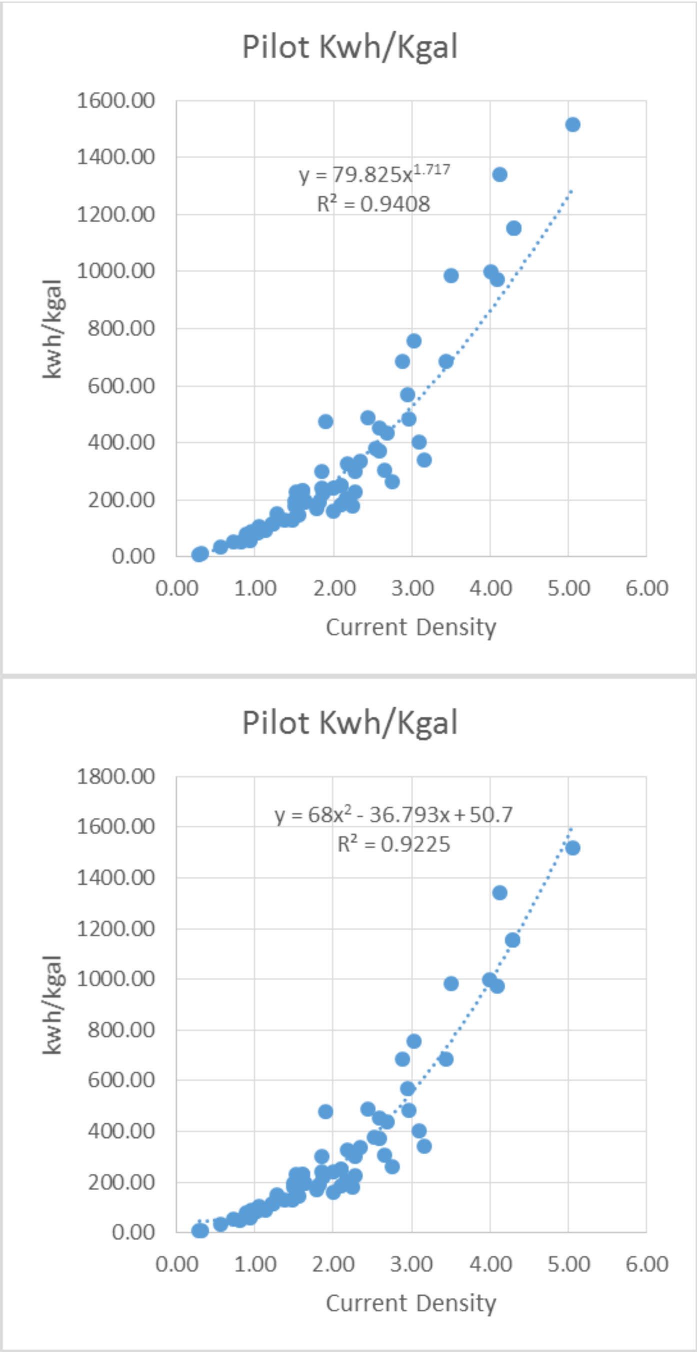
Table 5. Modeled vs. Measured (was NOT used in blending analysis) - Normal Membrane

	Inputs						Measured						Modeled					
	HRT	**v**	**ConE Cf**	**ConCaf**	**ConMgf**	**ConK f**	**ConNaf**	**CD**	**RmCa eq**	**RmMgeq**	**RmKeq**	**RmNaeq**	**RmEC**	**RmCa eq_m**	**RmMgeq_m**	**RmKeq_m**	**RmNaeq_m**	**RmEC_m**
Scottsdale	60	6.13	1837	4.26	2.32	0.60	11.05	2.97	81%	75%	52%	33%	55.5%	86.18%	83.44%	45.73%	28.64%	51.74%
El Paso Gw	64	5.78	4671	8.45	3.41	0.47	30.98	2.34	81%	74%	15%	18%	32%	73.28%	65.80%	27.00%	28.28%	38.30%
El Paso Gw	64	5.78	4672	8.45	3.41	0.47	30.98	2.69	85%	79%	19%	23%	35%	78.59%	71.49%	29.60%	32.21%	42.91%
El Paso Gw	64	5.78	4663	8.45	3.41	0.47	30.98	3.44	90%	86%	31%	36%	46%	89.05%	82.91%	34.92%	40.79%	52.58%
El Paso Gw	64	5.78	4637	8.45	3.41	0.47	30.98	4.09	92%	89%	44%	49%	58%	97.16%	91.95%	39.21%	48.36%	60.61%
El Paso Gw	64	5.78	4622	8.45	3.41	0.47	30.98	5.06	94%	91%	56%	65%	71%	100.00%	100%	45.20%	59.35%	72.17%
El Paso RO Con	64	5.78	19410	45.64	18.73	2.06	145.73	2.88	47%	37%	21%	13%	21%	47.25%	41.19%	13.55%	8.00%	15.15%
El Paso RO Con	64	5.78	19320	45.79	18.72	2.09	145.80	3.03	49%	40%	26%	14%	22%	47.47%	41.61%	13.62%	8.22%	15.44%
El Paso RO Con	64	5.78	19340	48.59	19.85	2.18	154.27	3.51	58%	50%	34%	23%	25%	49.63%	43.94%	14.53%	9.41%	16.47%
El Paso RO Con	64	5.78	19340	44.62	18.21	2.03	142.47	4.13	64%	55%	37%	24%	30%	56.69%	51.23%	17.13%	11.20%	20.62%

APPENDIX C

Appendix C: Power Consumption

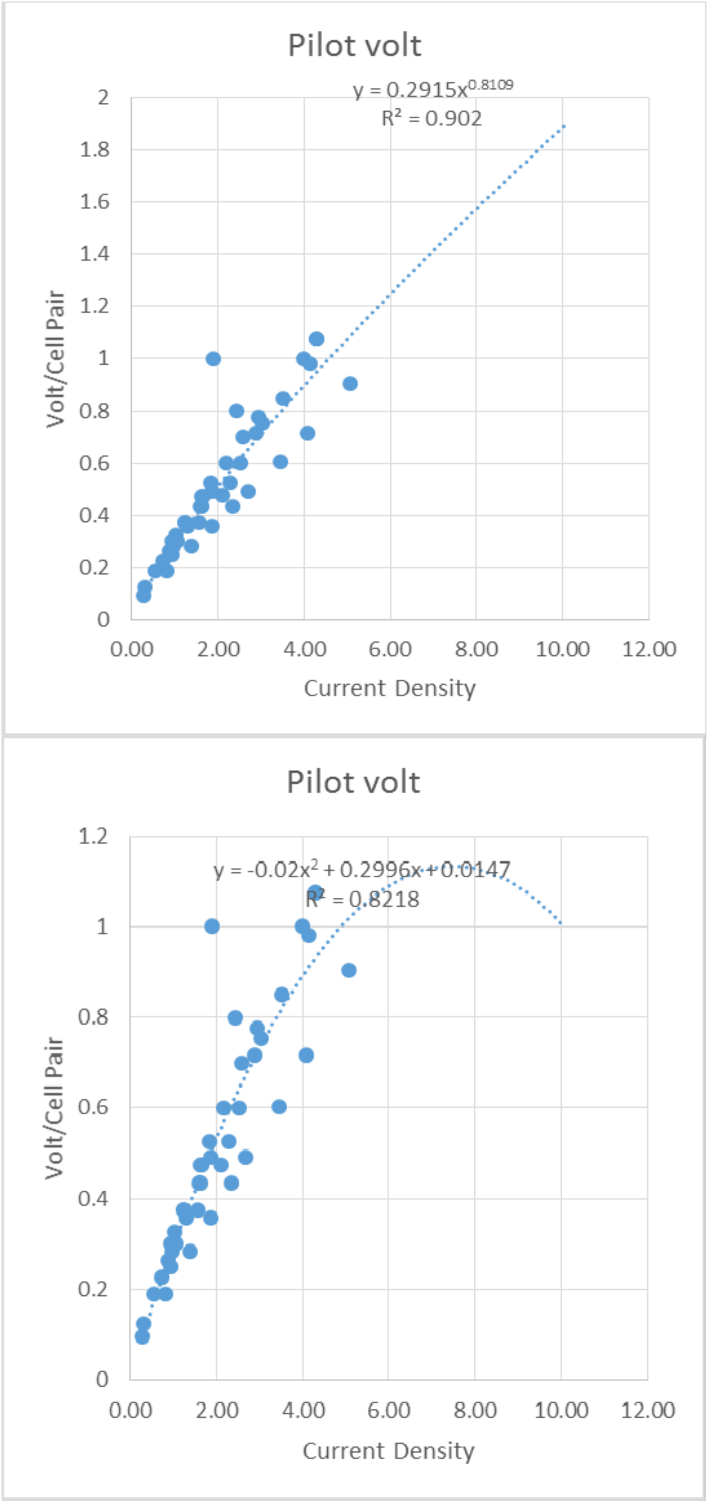
El Paso & Scottsdale - Pilot normal grade
membranes GW, Reclaimed and RO Con



(1) Power Function (2) Polynomial Function

Normal Membrane Voltage vs. Current Density

All testing data

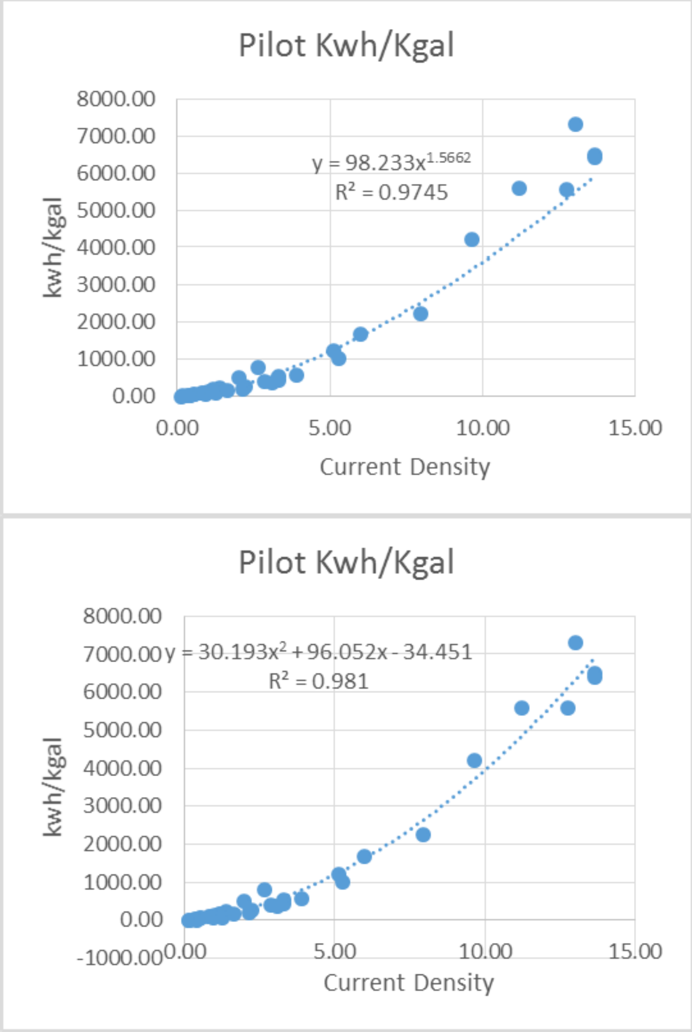


(1) Power Function (2) Polynomial Function

Selective Membrane Power Consumption

El Paso - Pilot Only

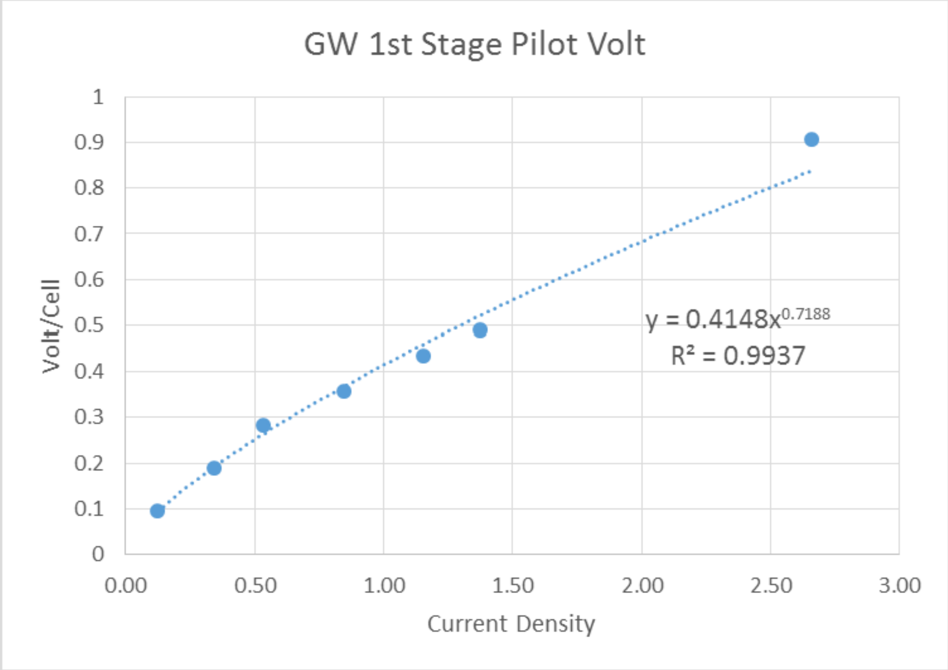
GW and RO Con

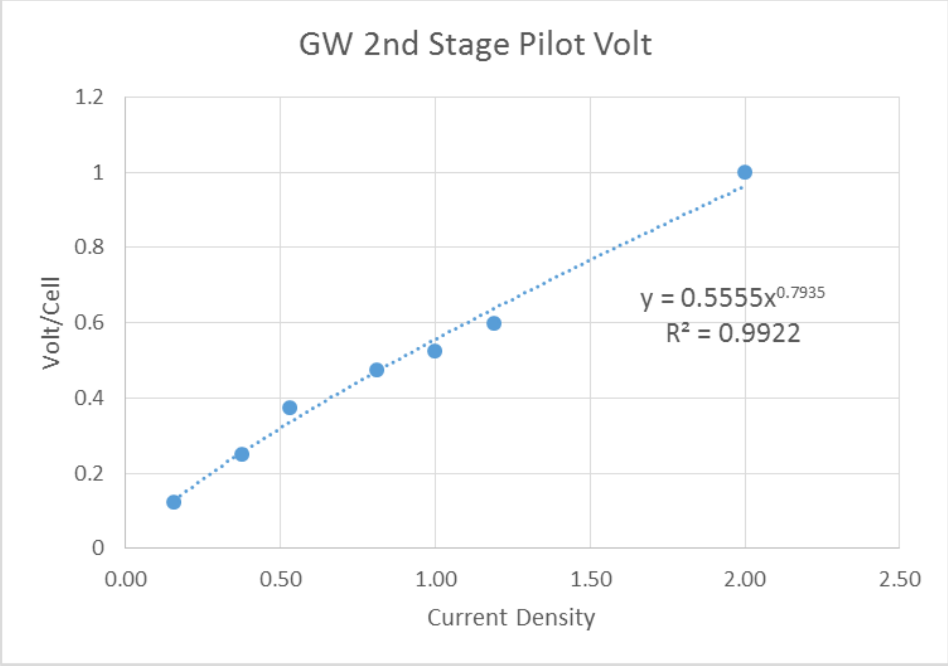


(1) Power Function (2) Polynomial Function

Selective Membrane Voltage vs. Current Density

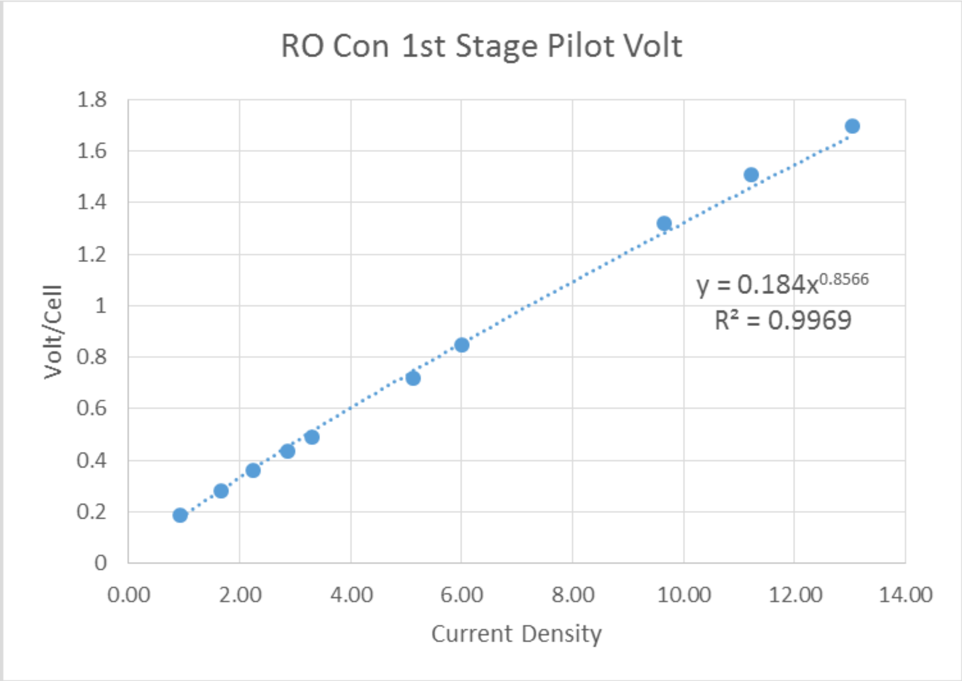
- El Paso GW Testing Data

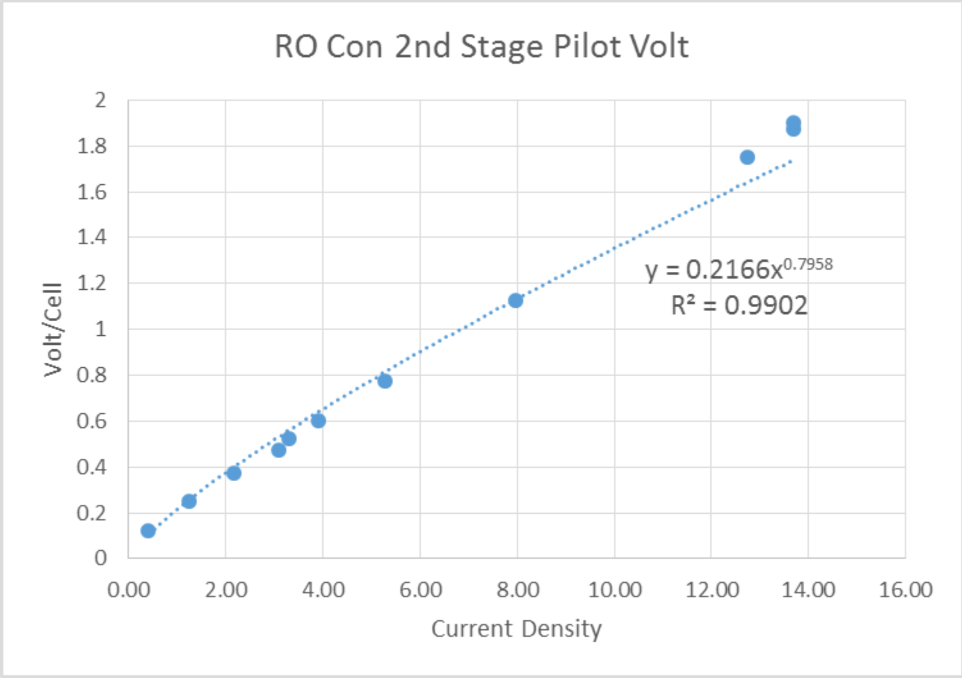




Selective Membrane Voltage vs. Current Density

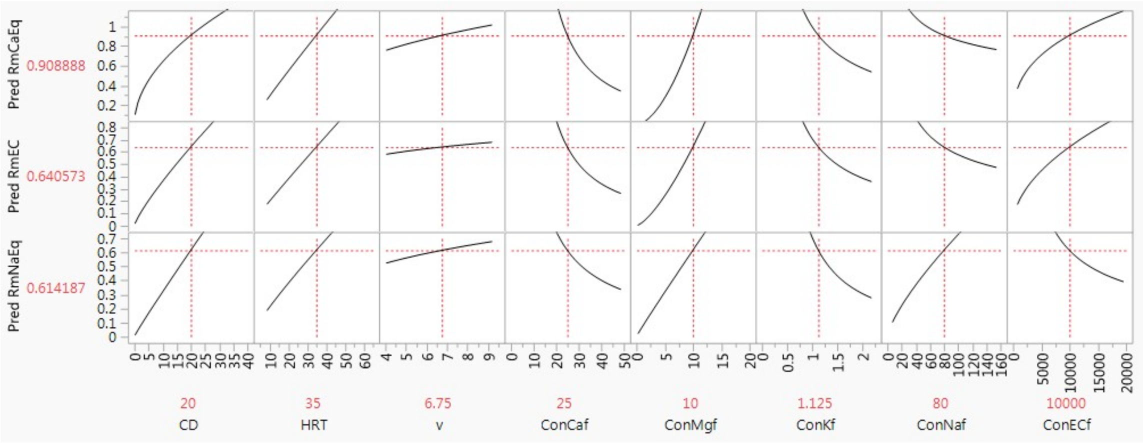
- El Paso RO Concentrate Testing Data



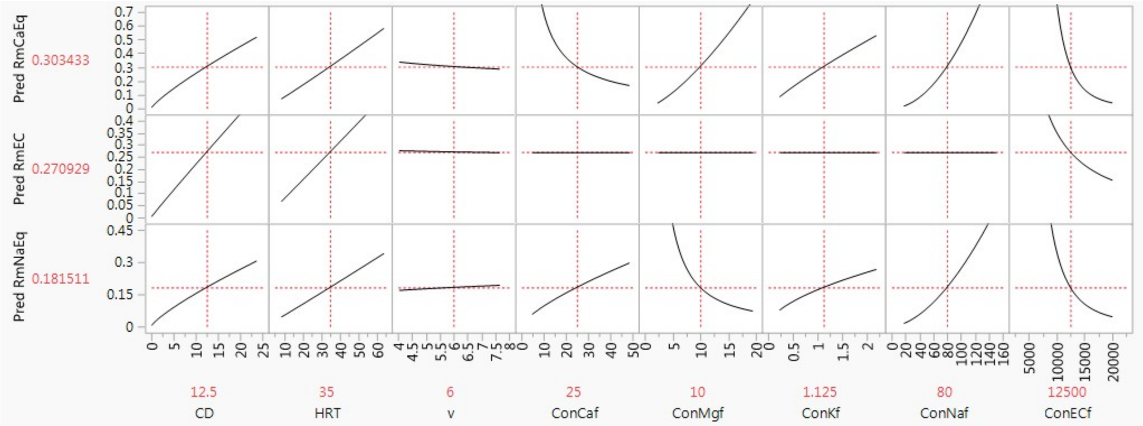


JMP Statistical Tool Output – profiler analysis

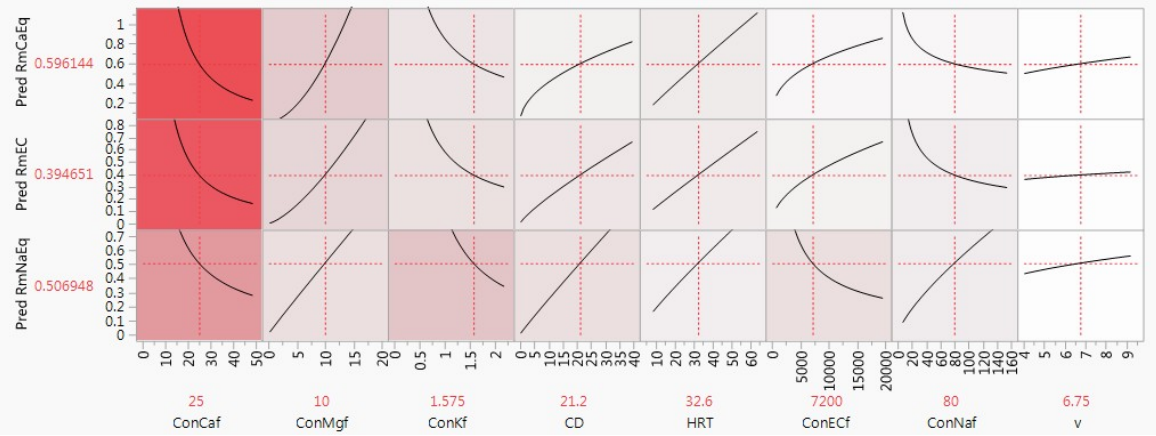
Normal Membrane



Selective Membrane



Normal Membrane - Color shows the importance of the variable.



Selective Membrane - Color shows the importance of the variable.