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Laboratory Study for Evaluating Performance of Unit Processes to Treat the Electrodialysis Reversal (EDR) Reject Stream for the Proposed Fort Irwin Water Treatment Plant

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Final report

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Abstract

A new water treatment system is planned for Fort Irwin in Barstow, California to address existing regulatory requirements and to account for anticipated expansion at the installation. Fort Irwin has indicated a water recovery requirement of 99%. Achieving this level will require a treatment system for the electro dialysis reversal (EDR) reject stream that will recover 92% of the influent water. CH2M HILL has proposed a system consisting of partial lime softening, filtration, and reverse osmosis (RO), which would increase water recovery to an estimated 98%. To reach 99%, a mechanical vapor recompression evaporative-distillation (MVR evaporator) unit has also been proposed.

The purpose of the current study was to use laboratory testing to evaluate the effectiveness of partial lime softening, RO, and electrocoagulation (EC). Tests were as follows:

- Partial lime softening was evaluated at dosages of 500-2000 mg/L of hydrated lime [Ca(OH)₂].
- Partial lime softening (1500 mg/L dose) was combined with magnesium chloride (MgCl₂) to improve performance.
- Electrocoagulation (EC) was tested as an alternative to partial lime softening.
- RO testing was carried out using a General Electric (GE) polyamide AD membrane, a membrane designed for desalination of seawater.

The study indicates that partial lime softening with MgCl₂ as an additive will be effective for pretreating water entering the RO unit. RO treatment was effective at meeting treatment and recovery goals, although fouling should be monitored. Evaporative distillation was not tested in this study, and analysis indicates that the costs per gallon are relatively high. However, it may be worth the cost due to the severe water management issues faced by Fort Irwin. Care must be taken to optimize the other processes so that the application of the evaporative-distillation unit can be minimized, saving costs.

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Preface

This project supports a multi-million-dollar effort to construct a state-of-the-art water treatment plant (WTP) at Fort Irwin, California. The plant will achieve water recovery (99%) higher than any previous system. The project is led by the Los Angeles District (SPL), with Debra Ford and Lieutenant Colonel (LTC) Joseph Seybold as the program managers. Input from the Department of Public Works (DPW) at Fort Irwin is critical to the project success. The Mobile District (SAM), led by Antonia Ortiz and Joseph Findley, has been contracted to lead the production of the request for proposal (RFP) for the plant. The Sacramento District (SPK) provides engineering expertise. CH2M HILL, Inc., who conducted pilot testing and developed a preliminary design for the WTP, is providing technical assistance. The U.S. Army Engineer Research and Development Center's Environmental Laboratory (ERDC-EL) was asked to provide expertise in water treatment and general environmental engineering. Funding was provided through the Army Military Construction (MILCON) Program.

This report presents the interim laboratory data in support of design decisions regarding concentrate management from a proposed electro-dialysis reversal system. This report is a draft, interim report. Three members of the Fort Irwin Project reviewed a draft of this report and provided comments: Jorge Martires of SPL, Joseph Findley of SAM, and Jim Mavis of CH2M HILL, Inc. These individuals have substantial experience in water treatment and some of their comments are referenced in this report. Peer review of this report was provided by Dr. Heather Knotek-Smith, EL, and Dr. Mansour Zakikhani, EL.

The authors would like acknowledge that funding for this project came from the Army Military Construction (MILCON) program, managed by Debra Ford and LTC Joseph Seybold of the Los Angeles District of the U.S. Army Corps of Engineers. Jorge Martires of the Los Angeles District, Joseph Findley of the Mobile District of the Corps of Engineers, and Jim Mavis of CH2M Hill, Inc., provided technical reviews of the work presented in this paper.

This work was conducted under the general supervision of Andy Martin, Chief, Environmental Engineering Branch and Warren Lorentz, Chief, Environmental Processes and Engineering Division, EL. Dr. Elizabeth

Ferguson was the Technical Director. At the time of publication of this report, Dr. Beth Fleming was Director, EL. COL Kevin J. Wilson was Commander, ERDC and Dr. Jeffery P. Holland was the ERDC Director.

Acronyms

AAR – Activated Alumina Regenerative

Betz - GE Betz, Inc. (Trevose, PA)

BRAC - Base Realignment and Closure

CH2M HILL – CH2M HILL, Inc.

Conc – Reverse Osmosis Concentrate

DoD – Department of Defense

DPW – Department of Public Works

EC - Electrocoagulation

EDR – Electrodialysis Reversal

ERDC – U.S. Army Engineer Research and Development Center
EL – Environmental Laboratory

Ft. – Fort

GE - General Electric

gph - gallons per hour

GPM – Gallons per Minute

hr - hour

IC - Ion Chromatorgraph

K – 1000

kW – kilowatt

L – Liter

LSI – Langmuir Saturation Index

LTC – Lieutenant Colonel

MCL – Maximum Contaminant Level

mg – milligram

MGD – Millions of Gallons per Day

MILCON - The Military Construction Program

MSDS – Material Safety Data Sheets

MVR – Mechanical Vapor Recompression

NWRI – National Water Research Institute

O&M - Operation and Maintenance

psig - pounds per square inch, gauge (standard English units for pressure)

Perm – Reverse Osmosis Permeate

RFP - Request for Proposals

RO – Reverse Osmosis

SAM – Mobile District

SPK – Sacramento District

SPL – Los Angeles District

TDS - Total Dissolved Solids

USACE – United States Army Corps of Engineers

USEPA or EPA- U.S. Environmental Protection Agency

WAIV - Wind Aided Intensified eVaporation

WTP – Water Treatment Plant

Chemicals

NO_3^- -Nitrate

Mg^{2+} - Magnesium ion

F^- - Fluoride ion

Ca^{2+} - Calcium ion

MgCl_2 – Magnesium chloride

MgO - Magnesium Oxide

Mg(OH)_2 - Magnesium hydroxide

Si - Silica

Cl - Chloride ion

SiO_2 - Silica oxide

CaCO_3 – Calcium carbonate

(s) – Solid species

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
pounds (force) per square inch	6.894757	kilopascals
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters

1 Introduction

Background

Fort Irwin, California, will build a new water treatment plant (WTP) to accommodate expected expansion for the installation and ensure regulatory compliance (Figure 1). The sole source of drinking water is groundwater in the vicinity of Fort Irwin. This water source has elevated levels of naturally occurring arsenic, fluoride, and dissolved solids, which require removal. In addition the water source has significant levels of dissolved silica. This is not a concern for drinking water safety, but can affect certain treatment approaches. Fort Irwin currently maintains a dual distribution system with drinking water supplied through a small reverse osmosis (RO) plant and additional chlorinated groundwater water supplied for other domestic requirements. This arrangement is not sufficient for current regulatory requirements or anticipated future use needs.



Figure 1. Proposed location of new Fort Irwin WTP, showing the arid environment of the Mojave Desert.

Water recovery is the percentage of the influent to the water treatment plant that is delivered as potable water. Losses are primarily associated with sludges formed by the removal of solids from the product water stream. Fort Irwin's location in the Mojave Desert imposes a necessary concern for efficient water use. Existing water sources must be put to the most efficient recovery processes possible to ensure the future viability of the source, and positing new water sources for future development is not an option. Further, Fort Irwin has limited space for evaporation ponds. Because of these factors, Fort Irwin has requested a water recovery requirement of 99%.

CH2M HILL, Inc. (CH2M HILL) pilot tested both electrodialysis reversal (EDR) and activated alumina regenerative (AAR) as candidate treatment methods (CH2M HILL, Inc. 2007). The pilot test determined that both technologies successfully treated the groundwater to Federal and California State standards. However, silica buildup on the media compromised the effectiveness of activated alumina. During the pilot testing, the EDR system achieved 73 to 75% water recovery. EDR has been demonstrated to be an effective treatment for groundwater containing high total dissolved solids (TDS) (Murray 1995).

On the basis of pilot testing, an initial process design iteration has been completed using EDR as the primary treatment technology. In order to achieve the water recovery goal, the system proposes treatment of the reject portion of the EDR system. The proposed reject treatment is partial lime softening followed by RO (Figure 2). The resulting RO concentrate is routed to a mechanical vapor recompression evaporator distillation unit (MVR evaporator) for further recovery. CH2M HILL (2007) estimated that this approach would achieve 99.8% recovery, and Fort Irwin has asked for a water recovery requirement of 99%. The proposed reject treatment system was not pilot tested alongside the primary treatment technologies, and concentrate management approaches that target 99% recovery simply do not exist in standard practice (Mickley 2008). This creates significant technical risk for firms seeking to offer proposals for the design/building of this water treatment plant. The effort described in this report includes laboratory testing of simulated EDR reject water to provide concrete design data that will be included within the request for proposals (RFP) to reduce the technical risk that will be assumed by offerors to the RFP.

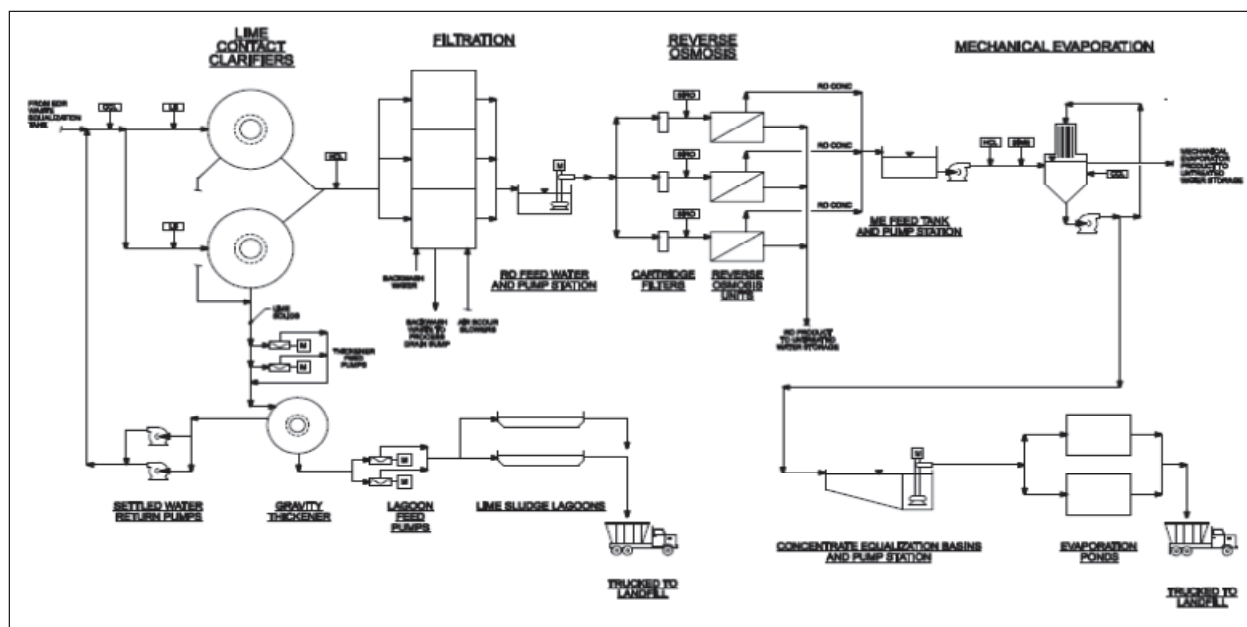


Figure 2. Process flow diagram for the planned Fort Irwin WTP.

Analysis of similar systems

Table 1 summarizes systems that treat contaminants similar to those found at Fort Irwin. Several of the systems described are EDR systems. Water recovery ranges from 80 to 97%. Several of the systems describe unit processes to treat reject water from the primary unit. None of the described systems reached the 99% requirement for Fort Irwin. However, none of these systems have reject water treatment mechanisms as extensive as the system proposed for Fort Irwin. There are systems that are touted as zero discharge systems. For example, Carollo Engineers designed and built a zero discharge water treatment system at the Deuell Vocational Institute for the California Department of Corrections in 2011 (Carollo Engineers, undated). However, this system relies on evaporation ponds to eliminate excess water and does not endeavor to reach 99% water recovery.

Analysis of unit processes to treat reject water

The EDR system has a target recovery of 92%. This is substantially higher than the level achieved during pilot testing, but based on the literature and on the performance of a system at Yuma Proving Grounds,¹ this

¹ Personal Communication. 2012. Abdollah Ebadirad, Chief, Engineering Department of Public Works, Yuma Proving Grounds, Yuma, AZ.

Table 1. Summary of systems described in the literature.

Study	Year	Location	Scale	Technology	Recovery	Treatment Application
Argo, D	1984	California, USA	Pilot Plant	Lime + RO	n.r.	Wastewater
Reahl, E.	1990	SW USA	Full Scale	RO + EDR	85%	Industrial Wastewater
Lee, L., et al.	2009	Singapore	Benchtop	RO + CDI	85%	Wastewater
Harries, R., et al.	1991	Canada	Pilot Plant	RO + EDR	75%/85%	Brackish Groundwater
Kawahara, T.	1994	Japan	Full Scale	ED	86%	Seawater
Korngold, E. et al.	2009	Israel	Pilot Plant	RO + EDR	97-98%	Brackish Groundwater
Oren, Y. et al.	2010	Israel	Pilot Plant	RO + EDR	97-98%	Brackish Groundwater
Lozier, J.C., et al.	2006	Big Bear Valley, CA	Computational Study	RO + EDR	79%	RO Reject
Sarasota County Environmental Services	Undated	Sarasota County, FL	Full scale	EDR	85%	Brackish groundwater
General Electric	2009	Magna, UT	Full Scale	EDR	n.r.	Arsenic containing groundwater
General Electric	2008	Suffolk, VA	Full Scale	EDR	94%	Fluoride containing groundwater
Valero, F., et al.	2011	Barcelona, Abreva DWTP	Full Scale	EDR	90%	Brackish Surface Water
Ebadirad, A.	2011	Yuma, AZ USA	Full Scale	EDR	94-95%	Groundwater

Key: CDI = Capacitive Deionization, EDR = Electrodialysis Reversal, ED = Electrodialysis, RO = reverse osmosis, Lime = Lime softening

performance is reasonable. The proposed reject treatment train consists of partial lime softening, RO, and MVR evaporator. Softening and RO are expected to recover about 70 to 75% of the reject, resulting in total recovery close to 98%. The current performance of the existing, single-stage RO system is reported to be on the order of 40 to 50% recovery. The proposed design is a two-stage system with estimated 50% recovery at each stage for a total recovery of 75%. No studies have been identified where RO was actually applied to an EDR reject stream. This reject stream is expected to be more concentrated than most groundwater, but is less than one-fourth to one-fifth as strong as seawater, where RO is widely used. The RO unit would likely still be effective for water recovery of the stream, but scale-forming solids may lower long-term performance and require more frequent membrane maintenance.

In order to achieve 99% removal, further recovery would be needed on the reject from the softening/RO step. MVR evaporation has been proposed. This process is well-established and commonly used in a variety of desalting operations for waste brines resulting from industrial and energy production applications (Kim 2011). Evaporation is not commonly used in potable water treatment because of the energy required. A survey of available information on municipal water supplies, including reports by the Water Reuse Foundation, reveals that no current water utility providers attempt to couple membrane treatment processes with the very high recovery required by Fort Irwin (Mickley 2008).

Potential risks

From a technical perspective, it is likely that the proposed reject system will achieve very high water recovery; however, there are a number of possible risks. Table 2 describes foreseeable risks, assesses them, and discusses potential mitigation measures. Because the MVR evaporator has the potential for near 100% water recovery, meeting a high water recovery goal is not the primary risk. Rather, high energy costs and potential for high operating costs due to excessive maintenance or oversizing of the evaporator are the greatest potential problems.

Table 2. Potential risks (EDR = electrodialysis reversal, RO = reverse osmosis, EC = electrocoagulation).

Process	Risk	Basis	Impact	Potential Impact	Mitigation
EDR	May not achieve target water recovery (92%)	Literature indicates that some systems had lower recovery	Would likely result in a higher flow going to evaporator, increasing costs	Low – enough studies indicate recovery in the mid 90% is feasible	Require this performance as part of the contract
Partial Lime Softening	May not protect RO system adequately	1. System was not bench or pilot tested 2. Elevated temperatures from EDR process may affect performance	1. Lower target removal of RO system 2. Unacceptable high maintenance requirements on RO	Moderate	1. Conduct jar testing on simulants prepared from Fort Irwin groundwater 2. Evaluate EC as alternative
RO System	May not meet 75% recovery goal	1. System was not bench or pilot tested 2. Current system is operating at lower recovery for raw groundwater 3. See Partial Lime Softening	Would likely result in a higher flow going to evaporator, increasing costs	Moderate to high	1. Conduct some bench testing on small RO unit 2. Seek Manufacturer guidance, guarantees
RO System	May require excessive maintenance	System was not bench or pilot tested	Increase in operating costs	Moderate to high	1. Benchtop testing 2. Seek Manufacturer guidance/ guarantees 3. Scale inhibitor

Process	Risk	Basis	Impact	Potential Impact	Mitigation
Evaporator	Flow rates may be higher than anticipated, increasing operating costs.	System was not bench or pilot tested	Increase in operating costs	High	1. Consider lower recovery goal 2. Increase evaporator hydraulic capacity
Evaporator	Scaling or other issues compromising performance	System was not tested on the reject stream to evaluate operating issues	1. Compromised performance 2. Increased costs	Moderate to high	Seek manufacturer guidance/guarantees

2 Methods

Objectives

The objectives of this project are to:

1. Evaluate the partial lime softening portion of the treatment process using standard jar testing.
2. Conduct a simplified evaluation of the RO process, focusing on membrane fouling.
3. Evaluate electrocoagulation (EC) as an alternative to partial lime softening.

Partial lime softening

Jar testing was conducted using a Phipps and Bird jar test apparatus (Hammer 1986, Reynolds 1977, Schroeder 1983) for automated repeatable flash mixing/settling tests (Figure 3). Jar testing under this effort was broadly categorized under two sets of experiments. The first experimental set evaluated partial lime softening, focusing on the effect of lime dosage. Initial partial lime softening dosages were calculated following accepted practice (e.g. <http://www.mrwa.com/Chapter16LimeSoftening.pdf>). The lime used was a standard 98% purity hydrated lime product from Falco Lime (Vicksburg, MS). The second experiment tested lime softening with magnesium chloride as an additive to enhance silica removal. All testing used 1-L test solution volumes.

For the first set of tests, six 2-L containers with 1L of simulated EDR water were prepared for each test. Next, various dosages of coagulant were flash mixed at 100 RPM for one minute, followed by a flocculation period of 5 minutes at 60 RPM, and ending with a 20-minute period of quiescent settling. After settling, samples were collected at the 750-mL level from each container for physical and chemical analyses. For each set of jar tests, one jar apparatus was set up with no coagulants as a control. The second set of testing (with MgCl₂) was identical, except that the flocculation period was increased to 45 minutes. In the second set, treatment temperatures were varied from 20.5 to 47 °C by conducting testing in a temperature-controlled environmental chamber.

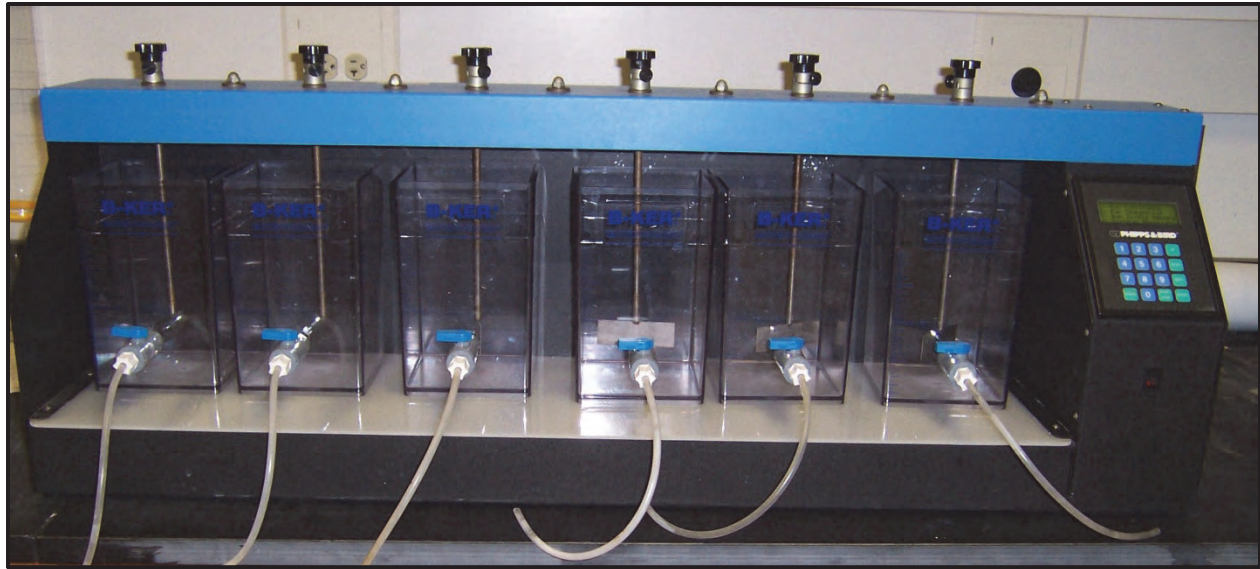
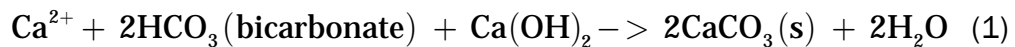


Figure 3. Phipps and Bird jar test apparatus.

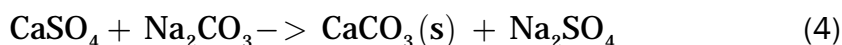
Lime softening is an established method for lowering hardness in water and for promoting the removal of associated metals (Hammer 1986; Nalco Chemical Company 1979; Hamilton Engineering, Inc. 2009). Hardness refers to the concentration of multivalent cations in solution, particularly Ca^{2+} and Mg^{2+} (Hammer 1986) (this study reports total hardness based on concentrations of Ca^{2+} and Mg^{2+}). These cations tend to affect the ability of soaps and surfactants to work effectively in water, so hardness is commonly treated as part of the municipal treatment system. Partial lime softening refers to reactions that use only lime (quicklime, CaO , or hydrated lime, $\text{Ca}(\text{OH})_2$ (Reynolds 1977)). Since hydrated lime was used, the reactions are:



Calcium carbonate (CaCO_3) is relatively insoluble, and will settle out of solution ((s) indicates formation of a solid). Magnesium hydroxide ($\text{Mg}(\text{OH})_2$) is also insoluble but does not consolidate as much as calcium carbonate, and, consequently, has a slower settling rate than calcium carbonate. In partial lime softening, only carbonate forms will normally be removed. However if excess alkalinity is present, such as what occurs in the Fort Irwin design, $\text{Mg}(\text{OH})_2$ also precipitates, and can act as coagulant for calcium carbonate pin floc. Other metals and ionic species can also form carbonates or hydroxides (such as ferric hydroxide solids from use of ferric

sulfate) and can be removed alone, or by associating with flocculent particles.

Non-carbonate forms of hardness (chiefly chloride and sulfate forms) may be removed by addition of soda ash (Na_2CO_3). This increases the alkalinity of the water, allowing for more hardness removal by these reactions:



These reactions are called lime-soda or complete lime softening. In the case of Fort Irwin EDR reject water, it is believed that the alkalinity is high enough that soda ash is not needed. However, adding MgO can stimulate additional magnesium hydroxide with improved silica removal. Magnesium hydroxide is important because, as mentioned earlier, it forms a bulky floc. This bulky floc can be very effective at removing other chemical species, particularly dissolved silica (Al-Mutaz and Al-Anezi 2004; Hamilton Engineering, Inc. 2009). Interestingly, magnesium hydroxide that is formed by hydration of magnesium oxide typically forms denser solids, which settle better than freshly precipitated magnesium hydroxide.

CH2M HILL focused on the use of partial lime softening for this process for several reasons. First, the sludge from lime-soda softening can be bulky, and associated water in the sludge would make meeting the recovery goal difficult. Increasing the alkalinity of the treated water stream would have an adverse effect on further RO treatment. Third, bicarbonate occurs in large excess compared to hardness in groundwater from Langford and Irwin basins, and with controlled blending of water from all three basins, hardness in Bicycle Basin can also be removed without resorting to soda usage.

Electrocoagulation evaluation

ERDC-EL contracted New China, Ltd., a licensed distributor of electrocoagulation (EC) systems developed by Powell Water Systems, to conduct a series of bench-top tests of EC on simulated groundwater EDR reject in January 2012. New China, Ltd. provided a bench-top testing device (Figure 4) and an operator, Mr. Roy King. ERDC-EL prepared the simulants, assisted in the experimental operation, and analyzed the resulting water chemistry.



Figure 4. Setup of bench-top electrocoagulation unit.

In the EC process, the coagulant is generated in situ by electrolytic oxidation of an appropriate anode material coupled to a complementary cathodic reaction that generates OH^- , forming metal hydroxides that adsorb dissolved contaminants. In this process, charged ionic species - metals or otherwise - are removed from wastewater by allowing it to react with an ion having an opposite charge, or with floc of metallic hydroxides generated within the effluent. EC is thus a salt-free and approximately pH-neutral process that avoids the added counter-ions of standard coagulating agents, such as FeCl_3 and aluminum sulfate $[\text{Al}_2(\text{SO}_4)_3]$. EC also avoids the need for shipment and storage of coagulant chemicals, but does require the periodic replacement of electrode materials. Electrode materials typically consist of iron, in the form of steel, or aluminum. Electrodes of different materials can be used in combination.

Reverse osmosis testing

RO testing was conducted using an Osmonics benchtop unit, which is designed for laboratory research studies on RO processes (Sterlitech Corporation, Kent, WA) (Figures 5 and 6). The study used a General Electric (GE) polyamide AD membrane, a standard seawater high rejection membrane element (fact sheet: http://www.gewater.com/pdf/Fact%20Sheets_Cust/Americas/English/FSpsADHRSeries_EN.pdf). The areal dimensions of the membrane were 190 x 140 mm and its thickness was 7 mils. A Sepa CF permeate carrier membrane was used, with dimensions of 145 x 47 mm and a thickness of 14.6 mils. The system was operated in through-flow mode.

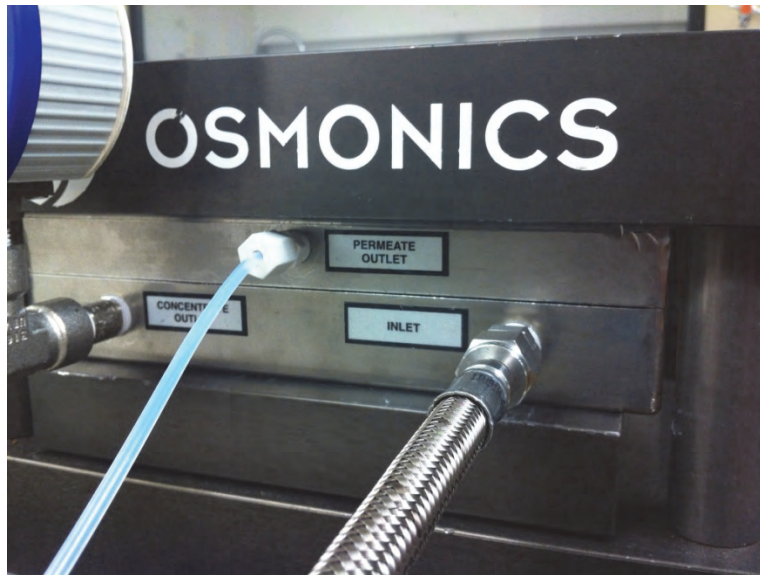


Figure 5. The Osmotronics SEPA CF experimental reverse osmosis reactor.



Figure 6. The experimental reverse osmosis reactor setup.

The influent of the system was derived from the EDR simulant. The simulant was treated by lime softening modified by magnesium chloride (1500 mg/L $\text{Ca}(\text{OH})_2$ and 750 mg/L MgCl_2), as described in the previous section. This solution then underwent a pretreatment process. This involved filtration with a 0.45- μm filter, then pH reduction to minimize carbonate deposition on the membrane. This was accomplished by titration with 1 N hydrogen chloride (HCl) until the pH was reduced to about 5.7. The solution was then sparged with compressed air for 12 hr to simulate carbon dioxide stripping. This solution was treated by the RO

unit. Target fluxes ranging from 4 to 12 gal/ft²/day (gfd) were tested at target permeate recoveries ranging from 40 to 70%.

Table 3 summarizes expected constituent concentrations in the RO permeate and concentrate. Also included are the California maximum contaminant levels (MCL) for fluoride, arsenic, and TDS (which is a secondary MCL).

Table 3. Expected constituent concentrations in RO permeate and concentrate as well as California maximum contaminant levels for key chemical species.

Constituent	Unit	Concentration in Permeate	Concentration in Concentrate	California Maximum Contaminant Level
pH	pH units	5.3	7.5	
Chloride	mg/L	9.3	4062	
Calcium	mg/L	0.02	28.3	
Magnesium	mg/L	0.06	109.9	
Strontium	mg/L	0.005	9	
Barium	mg/L	0	0.7	
Sulfate	mg/L	2.6	4500	
Fluoride	mg/L	0.67	150	2
Silica	mg/L	0	4	
TDS	mg/L	43	16,000 – 20,000	500-1000 (secondary)
Hardness	mg as CaCO ₃ /L	170	680	
Arsenic	µg/L			10

Treatment solutions

The projected chemical composition of the reject stream from the three-stage EDR treatment system is given in the pilot project report prepared by CH2M HILL (2007, Table 6-5 in the report and Table 4 herein). These concentrations are substantially higher than the constituents found in the groundwater because EDR concentrates these constituents in the reject. ERDC-EL used this information to create a simulated waste stream by spiking with the appropriate ions. Strontium (Sr) and barium (Ba) were not included as minor constituents. Arsenic (As) was added to the test solution because it is one of the key contaminants found in the groundwater. Appendix B contains the formulation approach.

Table 4. Expected EDR reject constituents and effluent from partial lime softening for Fort Irwin WTP (adapted from CH2M HILL (2007)).

Constituent	Unit	EDR Reject (Softening influent)	Softening Effluent	Post Filtration
pH	pH units	8.2-8.3	10.3	7.0
Chloride (Cl ⁻)	mg/L	1000-1100	1225	1225
Calcium (Ca ²⁺)	mg/L	200-300	8.5	8.5
Magnesium (Mg ²⁺)	mg/L	30-35	30-35	30-35
Strontium (Sr ²⁺)	mg/L	4.5-4.6	2.8	2.8
Barium (Ba ²⁺)	mg/L	0.3-0.4	0.2	0.2
Sulfate (SO ₄ ²⁻)	mg/L	1300-1400	1300-1400	1300-1400
Bicarbonate	mg/L	1600-1700	38	391
Fluoride (F ⁻)	mg/L	63-65	44	44
Arsenic (As)		--	--	5.77
Silica (Si)	mg/L	80-90	10	10
TDS	mg/L	6400-6500	6000-6300	5400
Hardness	mg as CaCO ₃ /L	820-850	170	170

Table 4 also shows the expected treatment to be provided by the partial lime softening operation. In order to protect the analytical equipment, samples were filtered (0.45 µm). Thus results are comparable to the post-filtration results. The primary purpose of the partial lime softening step is to protect the RO membranes. The key constituents to remove to protect the membranes are calcium, silica, and hardness. As seen in Table 4, removal of these constituents is expected to be substantial. The process is also expected to affect modest removal of TDS, barium, and fluoride, but removal of other water quality constituents is not critical, as the water should be successfully treated by RO.

Analytical methods

The analytical regimen for each study includes the following:

- Total dissolved solids (TDS): determined gravimetrically (EPA method 160.1)
- Fluoride (F⁻), nitrate (NO₃⁻), calcium (Ca²⁺), magnesium (Mg²⁺), and hardness: Determined with ion chromatography (IC) (EPA method 300.1)

- Arsenic and silica: Inductively coupled plasma – atomic emission spectrophotometry (ICP-AES) (EPA method 200.7)
- Conductivity (EPA method 120.1)
- pH (EPA method 150.1)

3 Results

Simulant

In this study, the goal was to provide treatment for the anticipated EDR reject stream (see Table 3). Table 5 compares the concentrations of important constituents in prepared simulant controls to the target solution derived from Table 3 (Targeted). Many of the constituents match well, such as fluoride (F), chloride (Cl), sulfate (SO₄), and, for most of the solutions, magnesium (Mg). Total dissolved solids and silica (Si) were lower in the experimental control solutions, but comparable. Arsenic (As) was slightly higher in test solutions. Given the high level of supersaturation predicted for the EDR reject, achieving a total hardness of 850 mg as CaCO₃/L and calcium (Ca) of 250 mg/L proved difficult. Part of the discrepancy may be due to sample filtration prior to IC analysis.

Table 5. Water chemistry of stimulant solutions compared to target concentrations.

Sample	Constituent Concentrations, mg/L								
	TDS	F	As	Si	Cl	SO ₄	Ca	Mg	Hardness as CaCO ₃
L14	4862	74.7	0.403	52.1	1068	1275	17.2	23.2	123.4
A1	4796	57.7	0.416	58.0	1077	1233	14.5	17.1	95.7
P1	4923	54.3	0.571	62.0	1259	1503	32.2	34.9	224.2
P14	4992	60.9	0.508	57.7	1288	1475	22.2	31.5	185.3
Target	6450	64.0	0.356	88.4	1050	1350	250.0	32.5	850.0

Lime softening

Partial lime softening

As shown in Figure 7, lime dosages ranged from 0 to 2000 mg/L. A goal of the lime softening process was to reduce calcium and hardness levels, so as to protect the RO unit from scaling. Lime dosages of 10 mg/L or less did not affect calcium or hardness levels (Figure 2). However, treatments of 200 mg/L began to show modest decreases of these constituents. At 2000 mg/L, removal of hardness and calcium was substantial and would exceed the targets established in Table 1 (post filtration). Silica was a key parameter to remove during the lime softening process, because silica can interfere with RO. Partial lime softening appeared to have a modest removal of silica,

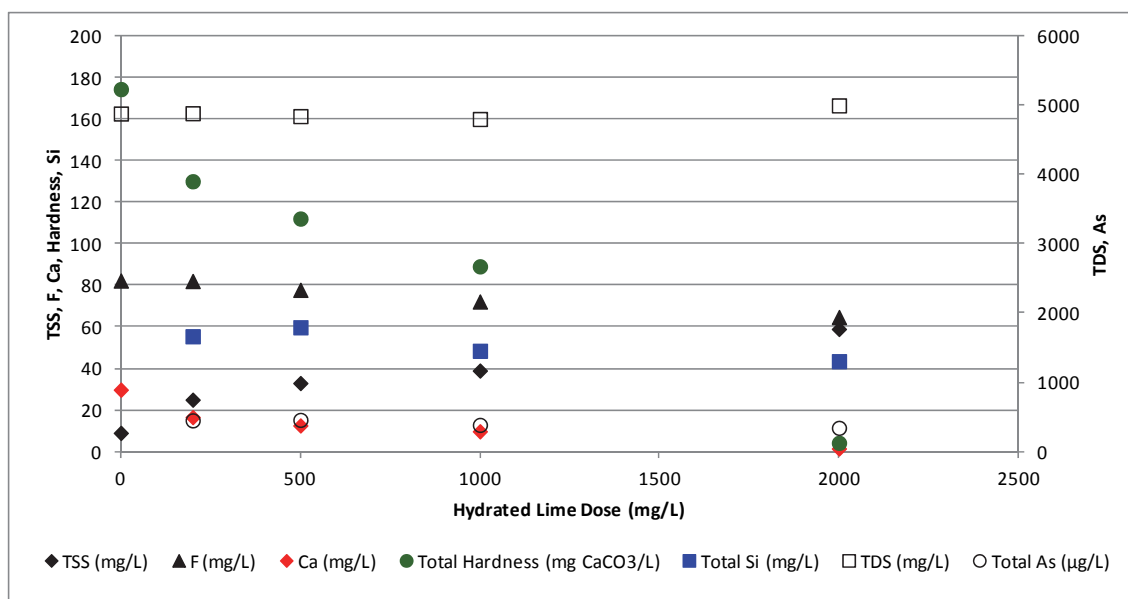


Figure 7. Effect of partial lime softening on major constituents of a simulated EDR reject stream.

reducing levels from about 60 to levels just over 40 at 2000 mg/L. However, this level was higher than the target of 10 mg/L. Although removal of TDS and fluoride were not critical for the lime softening process, some removal was desirable just to lower the load on the RO unit. The partial lime softening treatment did not have any appreciable effect on TDS and fluoride levels for the dosages tested. Fluoride removal would presumably occur by precipitation as calcium (or magnesium) fluoride. Since calcium and hardness decreased continuously as the lime dosage increased, no fluoride removal was achieved.

Figure 8 summarizes pH and alkalinity increases with increased lime dose. pH increased with lime dosage from about 8.7 to nearly 11.9. Alkalinity also increased as expected, with lime dose from 250 to 850 mg CaCO₃/L because there was insufficient hardness to precipitate the alkalinity.

Sludge generation was a critical aspect, since the sludge would result in a key loss of water in the system. Sludge production ranged from 2 (at a lime dosage of 2 mg/L) to 24 mL/L (lime dosage of 2000 mg/L), making the percentage of sludge generated by the process 0.2 to 2.4% (Figure 9). Solids ranged from 0.22 to 0.63 g/L at the same lime dosages. The solids fraction, by mass, of the sludge, ranges from 11 (at a dosage of 2 mg/L) to 2.5% (2000 mg/L). Under the assumption that the solids have a specific gravity of 1.6, the percentage of water lost in sludge from the reject stream ranges from 0.19% to 2.4%. To clarify, this is not cake moisture, but rather

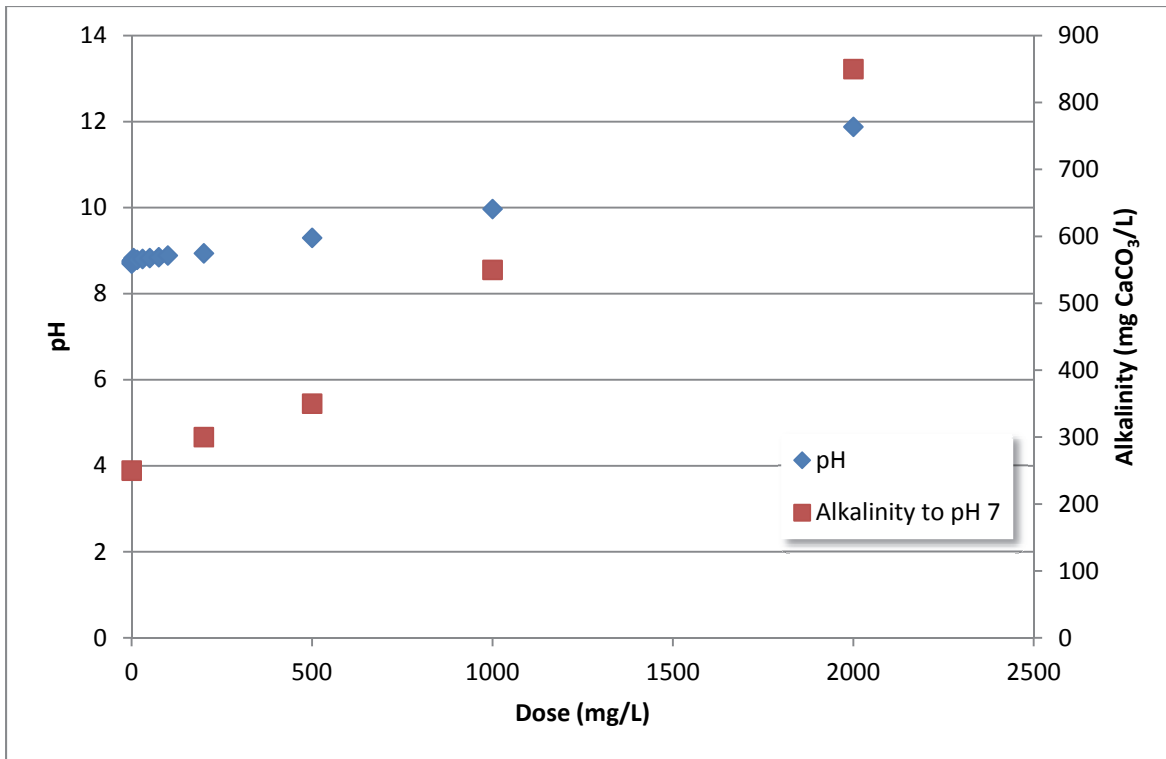


Figure 8. Effect of partial lime softening on pH and alkalinity of a simulated EDR reject stream.

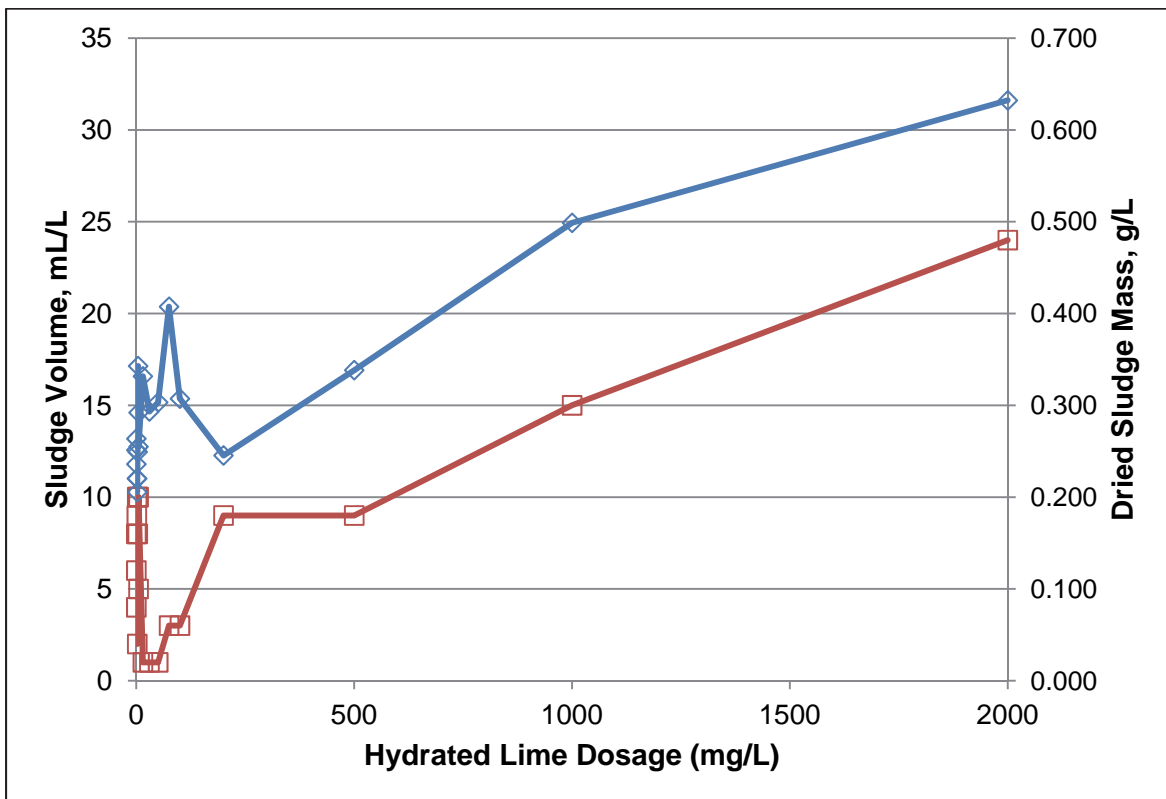


Figure 9. Sludge results for partial lime softening with no additives. y-axis units are given in the legend.

an estimate of the water in the sludge versus the water treated. Since the reject stream is projected to be 8% of the total flow, the total water losses would be 0.02% to 0.19% of the design flow. This water is lost from the recovery and must be considered carefully in any design. The overall water recovery requirement is 99.6%, which leaves 0.4% for system losses.

Lime softening with magnesium chloride

In order to improve silica removal, magnesium chloride (MgCl_2) was studied as an additive. The concept is to promote additional formation of magnesium hydroxide ($\text{Mg}(\text{OH})_2$), which can trap and remove silica as it settles. Based on the results of the previous studies, work in this study focused on a hydrated lime dosage of 1500 mg/L.

The plan was to test a temperature range from 20 to 47 °C. Because carbonates are actually less soluble at higher temperatures, the 47 °C study was conducted first to screen MgCl_2 dosages. Figure 10 summarizes silica, arsenic, and pH results for MgCl_2 dosages ranging from 0 to 2000 mg/L at a constant hydrated lime dose of 1500 mg/L. To reiterate, the main goal of the softening process was to remove silica, as it can adversely affect the RO process. Treatment of arsenic is also useful, but not critical, as it would be presumably removed in RO units. With no magnesium chloride modification, removal of silica and arsenic was modest. With magnesium chloride dosages increasing from 0 to 750, removal of both silica and arsenic improved with increasing dosages. At a magnesium chloride dosage of 500 mg/L, the silica level reached the 10-mg/L goal. However, at magnesium chloride dosages higher than 750 mg/L, the removal of both silica and arsenic actually decreased slightly.

Figure 11 shows the effect of the magnesium chloride modified partial lime softening process on TDS conducted at two temperatures, 20.5 °C and 47 °C. Focusing on the 47 °C data indicates that one by-product of the partial lime softening process with magnesium chloride is that it results in higher TDS values. This is not unexpected, as the softening process does add an additional dissolved species, chloride, to the water. The RO unit process should remove the excess TDS. However, it is desirable to keep this TDS increase as modest as possible, so as to increase the life of the RO membranes. Dosing the magnesium chloride higher than 750 mg/L could result in unnecessary TDS, which will have to be treated with the RO unit.

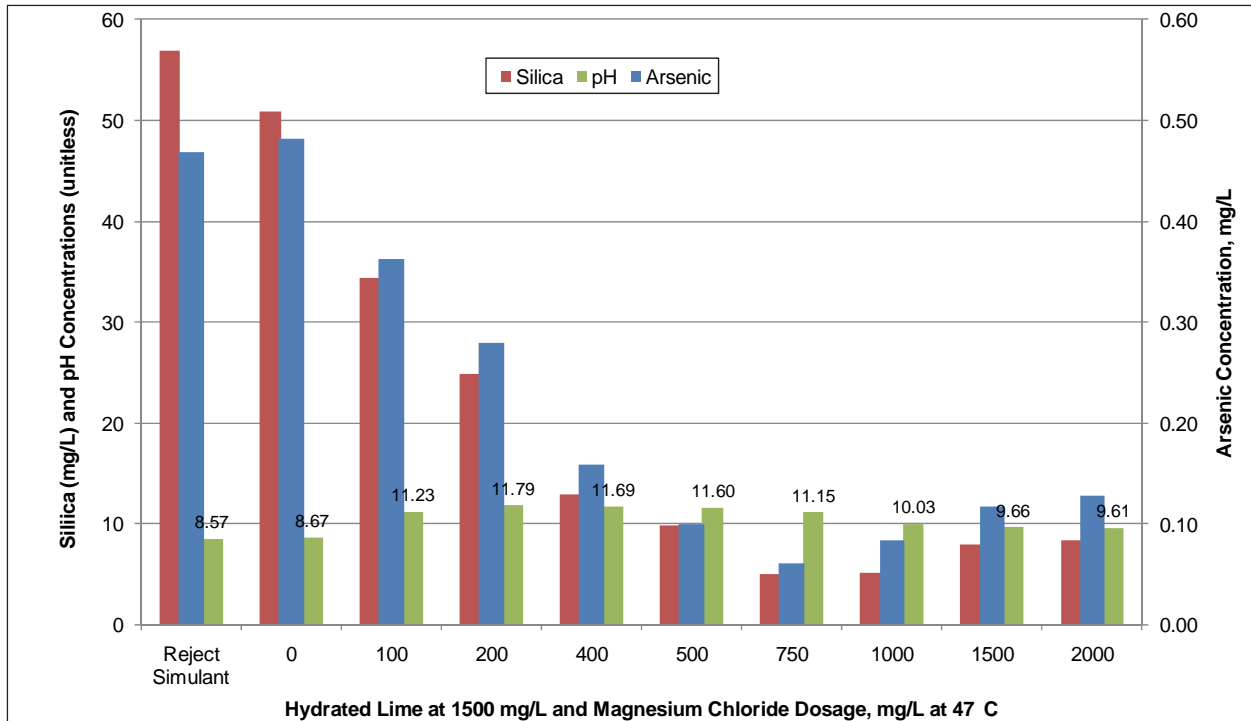


Figure 10. Assessment of different supplementary magnesium chloride dosages at a hydrated lime dose of 1500 mg/L and at 47°C.

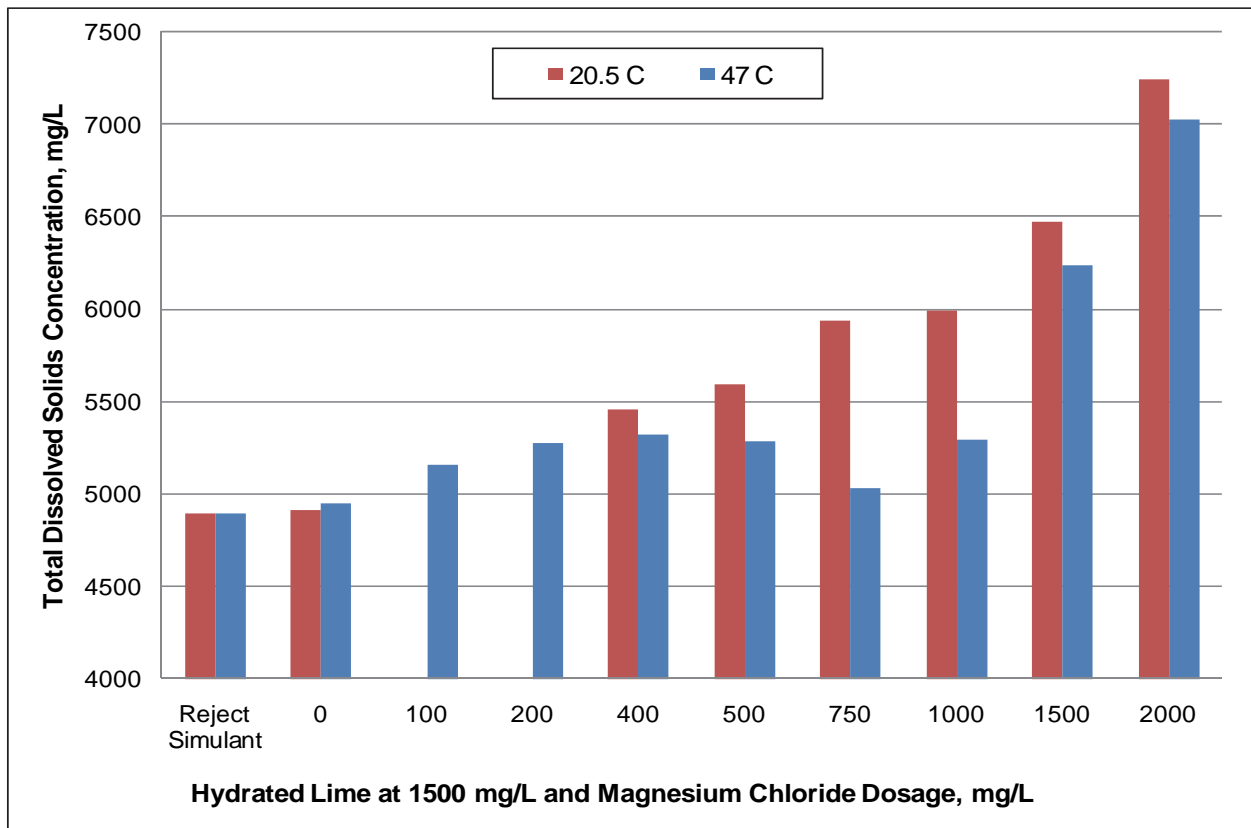


Figure 11. Total Dissolved Solids at different magnesium chloride (MgCl₂) dosages with hydrated lime addition of 1500 mg/L and at 20.5 and 47°C. 100- and 200-mg/L MgCl₂ were only tested at 47.5°C.

Figure 12 shows silica removal results for jar test studies with magnesium chloride levels ranging from 750 to 2000 mg/L, with a hydrated lime concentration of 1500 mg/L. Since 750 mg/L was optimal at 47 °C, this was the starting point for the additional studies. At a hydrated lime dosage of 1500 mg/L and a magnesium chloride dose of 750 mg/L at 20.5 °C, the silica concentration was about 13 mg/L, compared to over 40 mg/L with 2000 mg/L of hydrated lime alone (Figure 7), slightly higher than the 10 mg/L goal (Table 4). At 25°C and higher temperatures, the silica levels at the 750-mg/L magnesium chloride treatment were reduced to well below 10 mg/L.

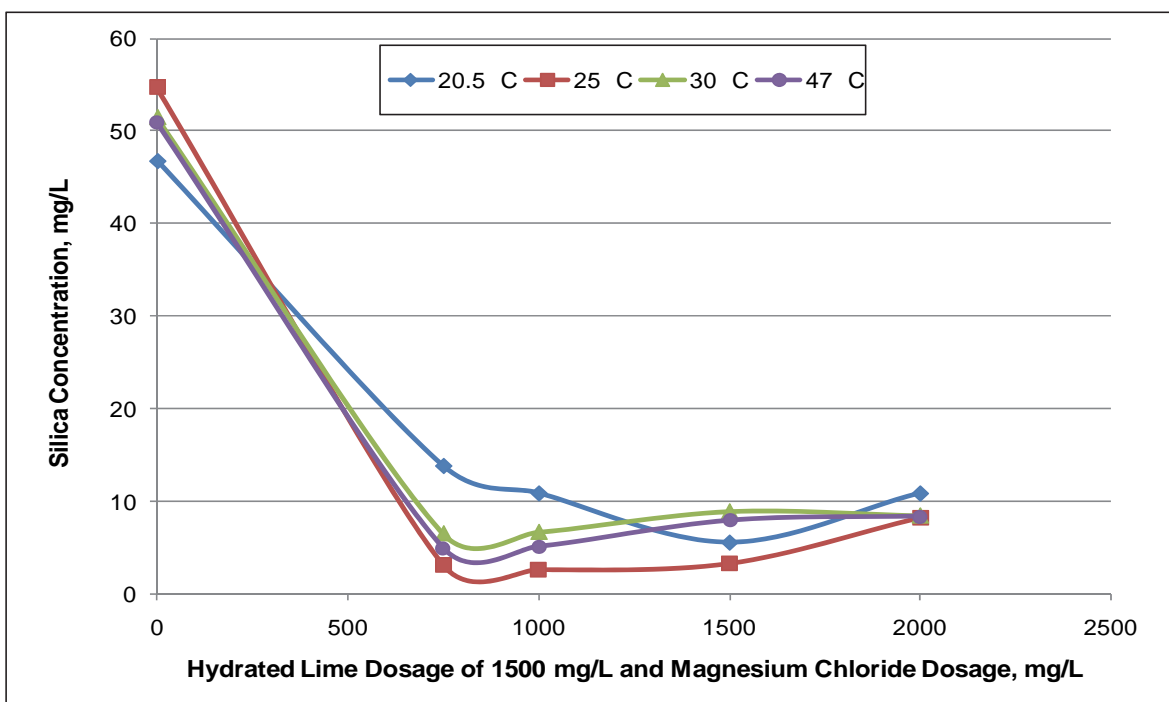


Figure 12. Removal of silica with lime softening (1500 mg/L dosage) with magnesium chloride as an additive (ranging from 750 to 2000) at temperatures ranging from 20.5 to 47°C.

Figure 12 also indicates that the relationships among dosage, temperature, and silica removal is complex. At 20.5°C, increasing the magnesium chloride dosage up to 1500 mg/L results in improved silica removal, but at 2000 mg/L, the resultant silica concentration increased slightly. At 25°C, the best treatment was at 1000 mg/L, with dosages higher than that resulting in less effective removal. And at 30 and 47°C, the best treatment was found at the 750-mg/L magnesium chloride dosage.

The effect of temperature is also shown in Figure 7, which compared TDS values for MgCl₂ modified partial lime softening at 20.5 and 40.7°C. In all cases, the TDS numbers were either virtually identical, or higher for the 20.5°C data.

In reviewing the water chemistry data for the 1500-mg/L hydrated lime dosage with 750-mg/L magnesium chloride at various temperatures, it can be seen that the process was effective at reducing concentrations of arsenic, fluoride, and calcium (Table 6). TDS and chloride increased, which was expected, as the addition of magnesium chloride results in an increase of chloride in solution. Hardness and magnesium both increased for the treatments at 20.5, 25 and 30°C. The increase was greater than five-fold Mg and greater than four-fold for hardness at 20.5°C. Hardness was reduced nearly 75% in the highest temperature tested, 47°C. Alkalinity was reduced with increasing temperature, ranging from over 700 for 20.5°C to 200 for 47°C.

Table 6. Summary of water chemistry parameters by partial lime softening (hydrated lime concentration of 1500 mg/L) amended with MgCl₂ (750 mg/L) at temperatures ranging from 20.5 to 47°C.

Analytes	Units	Average EDR Rej. Sim.Conc.	Temperature (°C)			
			20.5	25	30	47
TSS	mg/L	654	105	105	223	14
Turbidity	NTU	280	44.6	57.0	47.6	8.88
TDS	mg/L	4941	5940	5964	5301	5028
As	mg/L	0.401	0.206	0.080	0.100	0.061
Si	mg/L	51.8	13.9	3.16	6.57	5.01
F	mg/L	79.0	43.8	40.8	34.4	26.4
Cl	mg/L	1093	1606	1666	1619	1661
Si	mg/L	1302	1272	1281	1265	1293
NO ₃ (ion)	mg/L	3.51	<0.5	<0.5	2.31	<0.5
Ca	mg/L	14.4	8.9	10.0	11.7	8.37
Mg	mg/L	14.2	108.9	82.2	54.8	1.02
Total Hardness	mg CaCO ₃ /L	94.4	469	363	255	25.1
Total Alkalinity	mg CaCO ₃ /L	893	701	701	550	200
pH	---	8.71	10.3	10.1	10.0	11.2
Sludge Data						
Sludge Volume	ml	n.a.	24	20	30	35
Percent Wet Sludge	% (v/v)	n.a.	2.4	2.0	3.0	3.5
Solids per Volume Treated (dry)	g/L	n.a.	0.69	0.45	0.73	1.18
Sludge Solids	% (w/v)	n.a.	2.9	2.2	2.4	3.4

n.a. = not applicable

Table 5 also includes sludge generation data for the partial lime treatment (dosage of 1500 mg/L) with supplementary magnesium chloride (750 mg/L). Percent wet sludge ranged from 2.4 to 3.5%, which was higher than the percent wet sludge found by partial lime softening alone (2.2% for 2000 mg/L hydrated lime dosage). The percent solids in the sludges generated from the magnesium chloride modified treatment were close to the value for the 2000-mg/L hydrated lime only (2.4%). The solids per water treated was higher compared to partial lime softening alone, indicating improved treatment by the addition of the magnesium chloride supplement. The sludge solids were comparable. Using the same assumptions as the section above, the percentage water lost from magnesium chloride (750 mg/L) supplemented partial lime softening (1500 mg/L hydrated lime) ranged from 0.08% (at 25°C) to 0.16% (47°C) of the initial 6 mgd.

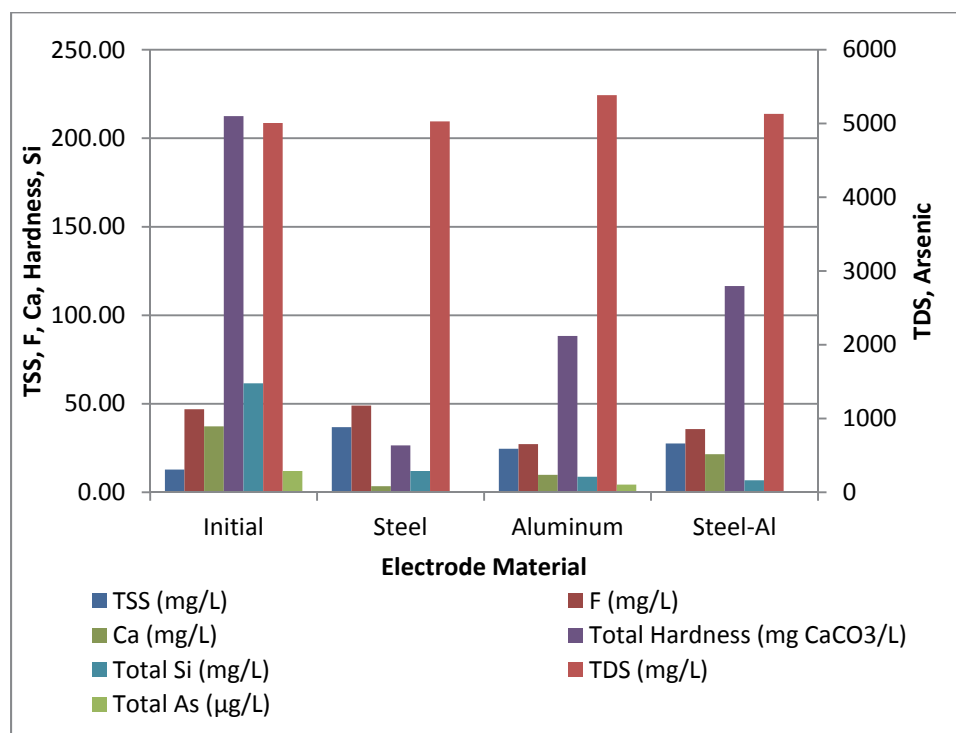


Figure 13. Effect of electrocoagulation on major constituents of a simulated EDR reject stream.

Electrocoagulation

Figure 14 summarizes pH and alkalinity measurements from the EC treatment. The steel electrodes affected a noticeable rise in both of these parameters. The other treatments did not noticeably change pH or alkalinity.

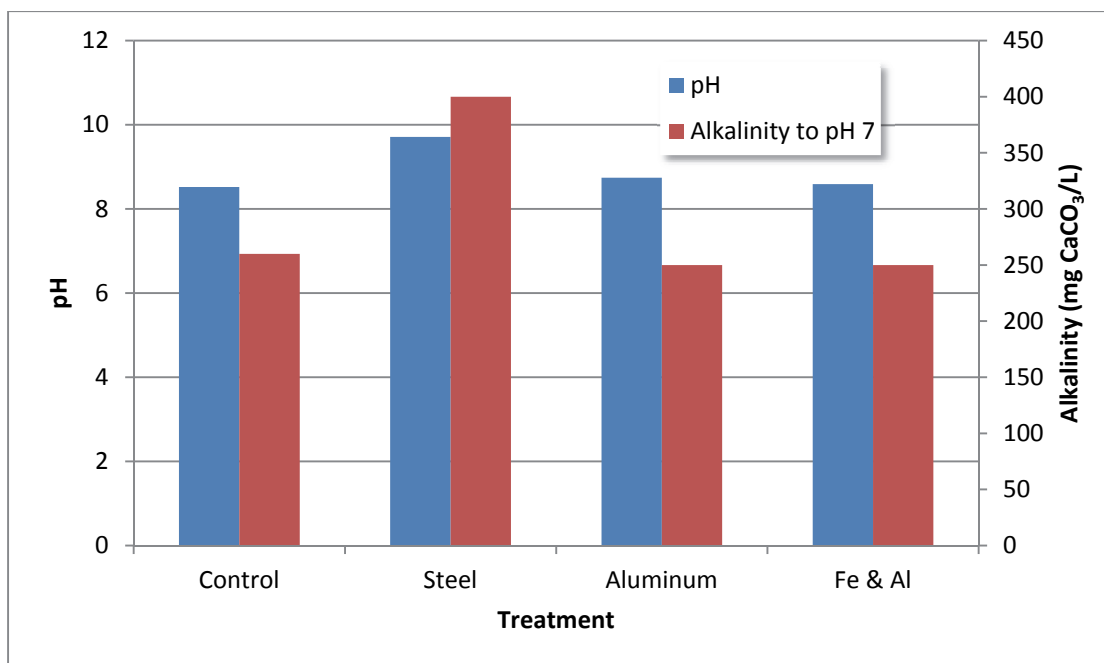


Figure 14. Effect of electrocoagulation on pH and alkalinity of a simulated EDR reject stream.

Figure 15 shows the sludge volumes and dry solids masses produced by the EC treatments, and Figure 19 shows the settled sludge from the various electrode treatments. Visually, the sludge from the aluminum and combined electrodes looked better (Figure 19). Sludge volumes were as high as 350 mL/L for the steel electrode treatment to 170 mL/L for the aluminum electrode. These sludge volumes were on the order of 14.6 to 7.1 times higher than the highest sludge volume found for the lime treatment (see Figure 7). Solids masses, on the other hand, were comparable to those found in the lime treatment. The sludge volume for the aluminum electrode would correspond to 1.3% of the process water and the steel would correspond to 2.6%. Both of these would be higher than 0.4%, which is the amount of water that can be wasted and still meet the 99.6% requirement.

Reverse osmosis (RO)

As discussed in Chapter 2 “Methods,” the bench-top RO system was used to treat the effluent of the partial lime-softening process (20.5°C). The partial lime softening effluent underwent pretreatment involving filtration (0.45 μm), pH adjustment to about 5.7, and carbon dioxide stripping. The resulting solution was then used for the RO testing, and its chemical properties were quantified (Table 7). Interestingly, the Mg concentration was greatly reduced in concentration, from 108 mg/L (Table 5) to 18 mg/L. This resulted

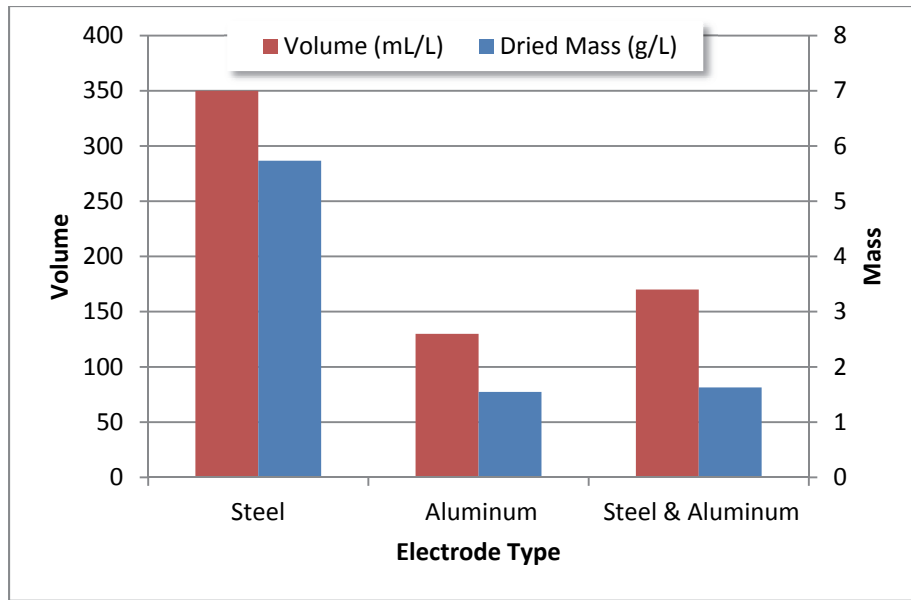


Figure 15. Sludge volume and solids removal for electrocoagulation of a simulated EDR reject stream.

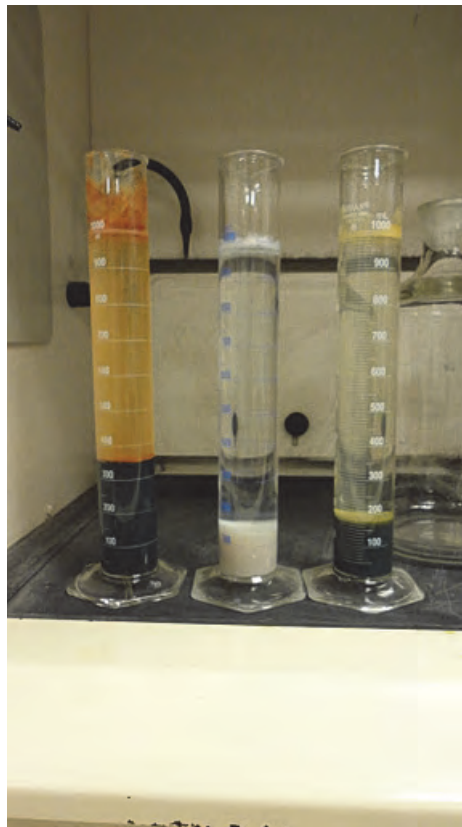


Figure 16. Settled sludge from (left to right) iron, aluminum, and combined EC electrodes.

in a decrease in hardness, from over 400 mg/L to 100 mg/L as CaCO₃. The pH of the solution was 7.83. Alkalinity was estimated by titration down to a pH = 8.3 endpoint. Using this method, the precise alkalinity could not be quantified, but it is reasonable to assume that it would be less than 200 mg/L as CaCO₃, based on previous results with the EDR reject simulant (Table 3, 47°C data). This indicates that the pretreatment process was successful at reducing alkalinity, which was over 700 mg/L as CaCO₃ immediately after lime softening with magnesium chloride addition (Table 3, 20.5°C data).

Table 7. Water Chemistry of RO Influent.

RO Influent	
F (mg/L)	31.2
Cl (mg/L)	1843
SO ₄ (mg/L)	1277
Ca (mg/L)	10.1
Mg (mg/L)	18.3
As (mg/L)	0.050
Si (mg/L)	7.11
pH	7.84
Hardness (mg/L as CaCO ₃)	100
Alkalinity (mg/L as CaCO ₃)	<200
LSI	-0.36
pH	7.83

The RO studies were conducted with fluxes ranging from just over 3 to just under 12 gfd and with permeate recoveries ranging from just over 40% to nearly 70% for a single-stage system. At these conditions, operating pressures ranged from just below 120 to just over 270 psi (Figure 17). At a given flux, operating pressures increased as the system was adjusted to achieve a higher permeate recovery. For example, consider data collected at a flux of about 4 gfd. At a recovery of 48%, the operating pressure was about 130 psi. At a recovery of 66%, the pressure was 160 psi. For a given recovery, pressures increased as fluxes were increased more dramatically. For example, at a 60% recovery and a flux of 3.8 gfd, the operating pressure was just below 140 psig, but at a flux of 11.6, the pressure was more than 270 psig.

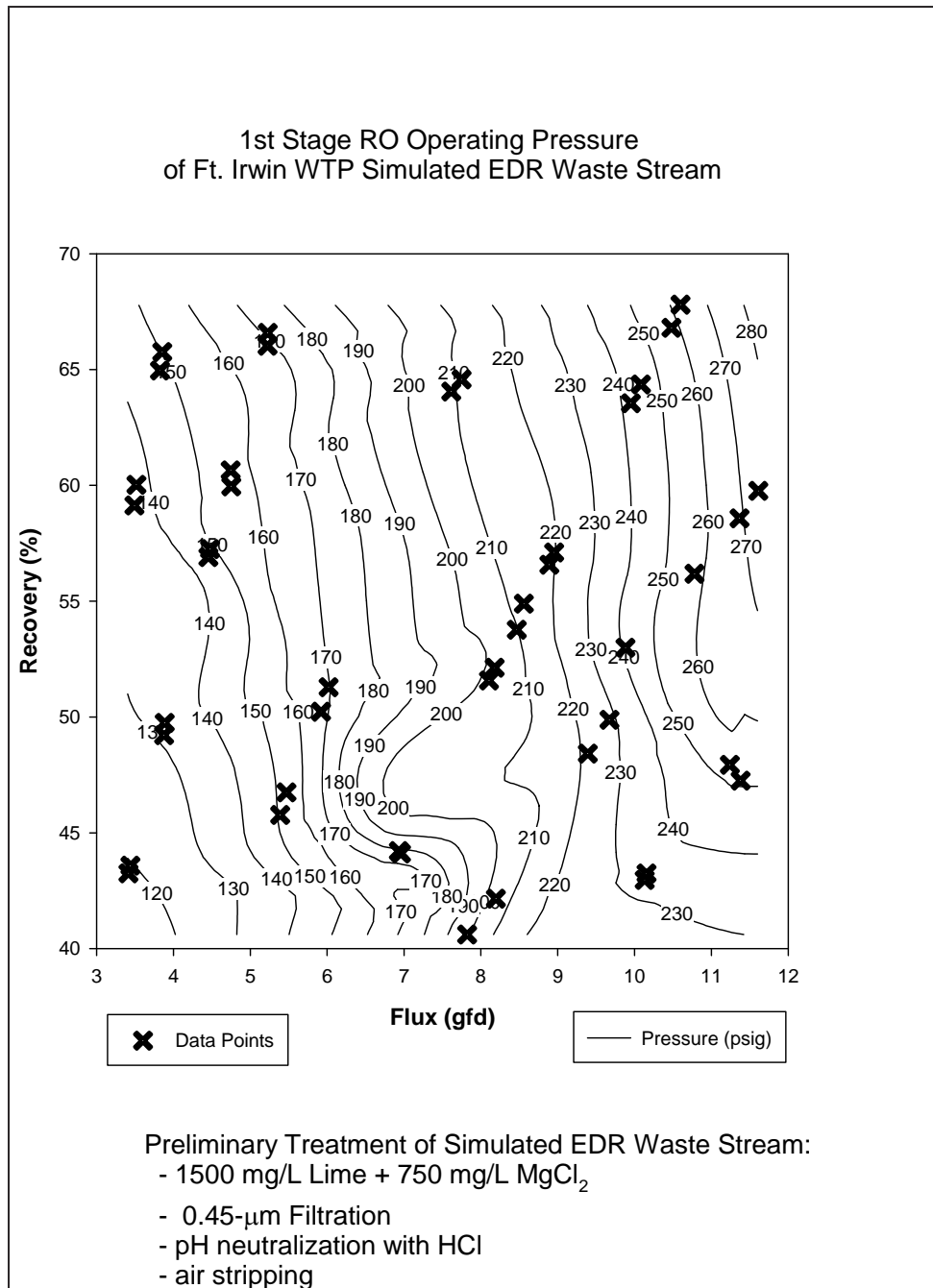


Figure 17. Reverse osmosis results: Relation of operating pressure to recovery and flux.

Table 6 indicated that fluoride concentrations in the RO influent was about 31 mg/L. RO treatment was a success at 90% removal and more at flux rates as low as 3.4, resulting in concentrations around 3 mg/L (Figure 9). As flux increased, treatment generally improved, and at flux levels greater than 8 gfd, fluoride levels in the permeate were less than 2 mg/L (Figure 18).

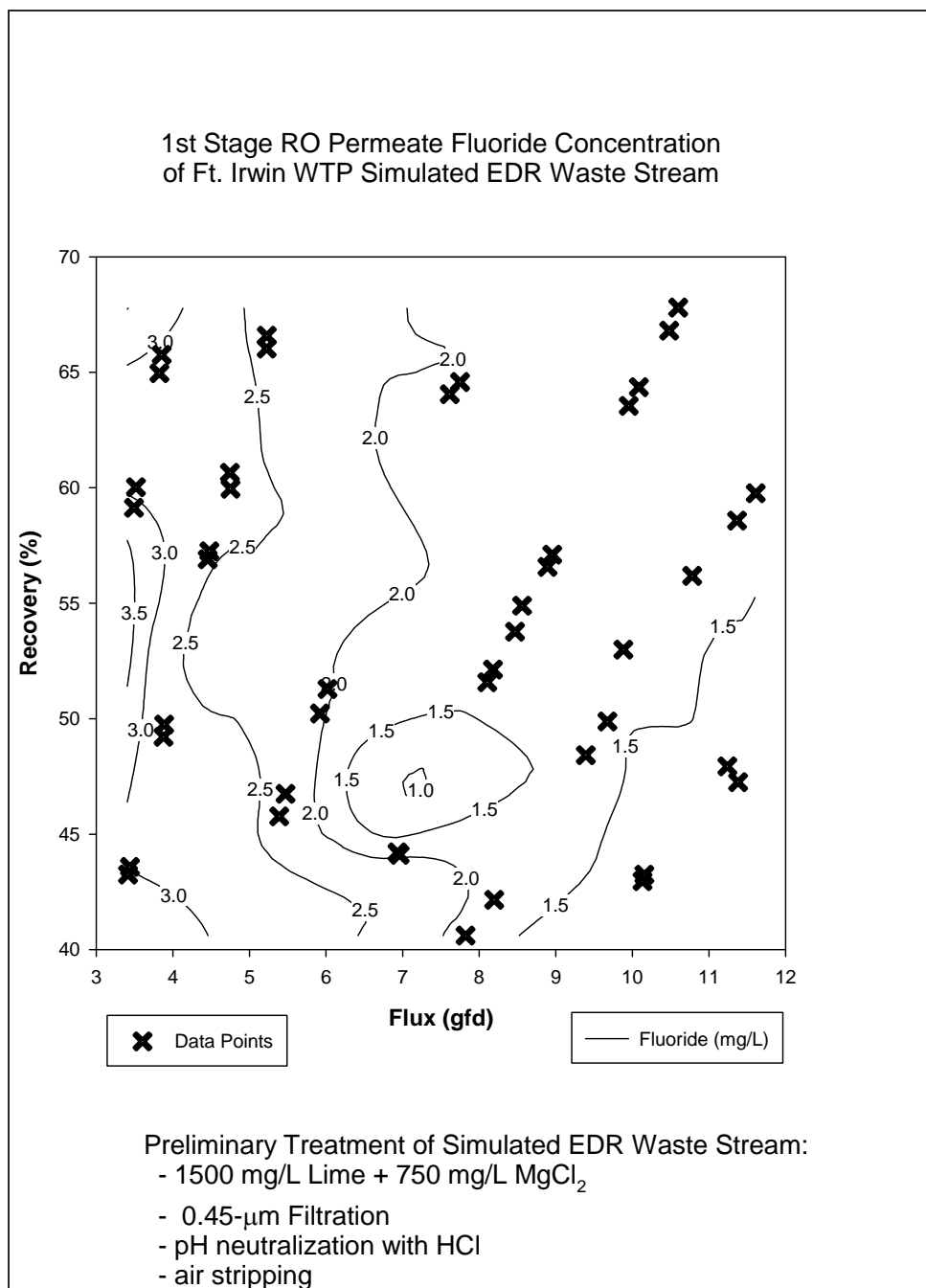


Figure 18. Reverse osmosis results: Relation of fluoride concentration in the permeate to recovery and flux.

Table 8 shows water chemistry of two flux rates close to 10 gfd with water recoveries of 53 and 56%. Fluoride ranged from 1.65 to 1.90 mg/L, which was below the MCL of 2 mg/L. Chloride was dramatically reduced from over 1800 mg/L to 65 to 75 mg/L. Hardness was also greatly reduced, to levels just above 1 mg/L. Arsenic was reduced from 0.050 mg/L to levels on the order of 0.020 mg/L, about a 50% reduction. However, these

arsenic levels were above the MCL of 0.010 mg/L. The lowest arsenic concentration achieved was 0.011 mg/L, at a flux of 8.15 gfd and a recovery of 57.1%.

Table 8. Water chemistry at two flux/recovery conditions.

Parameter	Influent	Permeate	Permeate	% Rejected	% Missing
Operating Conditions					
Flux (gfd)		9.87	10.77		
Recovery (%)		53.0	56.2		
Pressure (psig)		241	258		
Constituents					
Fluoride (mg/L)	31.2	1.90	1.65	93.9 - 94.7	
Chloride (mg/L)	1843	74	67	96.0 - 96.4	
Sulfate (mg/L)	1277	25.1	18.6	98.0 - 98.5	14.3 - 7.9
Calcium (mg/L)	10.1	0.183	0.143	98.2 - 98.6	
Magnesium (mg/L)	18.3	0.339	0.197	98.1 - 98.9	
Arsenic (mg/L)	0.050	0.020	0.027	60.0 - 46.0	
Silica (mg/L)	7.11	0.196	0.172	97.2 - 97.6	
Barium (mg/L)		0.012	0.007		
Hardness (mg/L)	100.7	1.85	1.17	98.2 - 98.8	

4 Discussion/Conclusions

Softening

Partial lime softening was effective at removing hardness and calcium, particularly at a dosage of 2000 mg/L. Hardness removal was on the order of 59% and calcium removal approached 76%. However, partial lime softening alone was not effective at removing silica or fluoride. Optimized pH for silica removal is 10.8 to 11.3, although effective removal was found at pH up to 11.7 (Kluesner et al. 1975). At optimal hardness and calcium removal, the pH was around 12. Partial lime softening using only hydrated lime could be an effective pretreatment for the RO system, but would probably require the use of an anti-scalant to address silica fouling.

This study focused on magnesium chloride as a supplement to improve silica removal. Another option is magnesium oxide (MgO). Both have been used for improving silica removal in lime softening (Betz et al. 1941; Nalco Chemical Company 1979; Al-Mutaz and Al-Anezi 2004). The advantage of magnesium oxide is it does not add to the dissolved solids (Al-Mutaz and Al-Anezi 2004). Furthermore, magnesium chloride can create calcium non-carbonate hardness; thus, excess lime will need to be added to precipitate out the calcium non-carbonate hardness (Al-Mutaz and Al-Anezi 2004). This effect, however, would likely not be important for the Ft. Irwin case because of the high alkalinity in the solution, so that any non-carbonate hardness would be offset by calcium and magnesium precipitation. It was found that magnesium oxide was more effective than magnesium chloride at removing silica (Patrick et al. 2001). Magnesium chloride, on the other hand, has some operational advantages that might be valuable for application at a small WTP like Ft. Irwin.¹ It can be applied dry or as a 35% solution, and does not have to be prehydrated. Systems using magnesium chloride tend to be simpler than those using magnesium oxide. Magnesium chloride also has a lower tendency to cause scaling and clogging in associated piping, which are primarily due to dry solids and slurry conveyance needs for magnesium oxide.

¹ Personal Communication. 2012. Jim Mavis, Principal Technologist, Chemical Process, CH₂M Hill, Inc., Bellevue, WA.

Fort Irwin is in a desert area in Southern California that is characterized by hot temperatures. In addition, the EDR process is expected to result in warming the treated and rejected water, although this effect may be modest. One study found about a 5°C temperature increase (from 20 to 25°C) when testing an Ionic Aquamite I EDR stack (Valerdi-Perez et al. 2001). The effects of higher temperatures, if present, are expected to be beneficial for partial softening. Increased temperature promotes magnesium hydroxide ($Mg(OH)_2$) formation. In addition, calcium carbonate ($CaCO_3$) solubility actually decreases with increasing temperature (Garrels and Christ 1965, Langmuir 1997). Heated water can also allow for decreased dissolved carbon dioxide solubility, which will further drive the formation of calcium carbonate. So, increased temperature may actually improve the lime-softening process for hardness, calcium, and silica removal. On the other hand, silica solubility increases with increasing temperature. Studies were conducted with temperatures ranging from 20.5 to 47°C to study the effect of a wide range of potential operating temperatures.

The addition of magnesium chloride resulted in dramatic improvement of removal of silica. It also resulted in improved removal of fluoride, arsenic, and nitrate. Removal of calcium was also effective. However, the processes resulted in higher hardness and magnesium levels at temperatures up to 30°C. These parameters are discussed in the next section.

Results showed a modest increase in the removal of silica with increasing temperature, although the pattern was complicated. In some dosages, removal initially increased, then leveled off or even got slightly worse. These patterns may reflect the interplay between improved hardness removal and increasing silica solubility.

Magnesium and hardness

Generally, the partial lime softening with magnesium chloride results were straightforward; the process was effective at lowering the concentrations of most of the parameters of interest as discussed in the previous section. However, magnesium and hardness had more complicated patterns. At temperatures of 20.5, 25, and 30°C, the treatment actually increased the magnesium concentration, and this resulted in higher hardness concentrations (Table 3). At 20.5°C, the magnesium concentration was more than five times higher than the initial concentration and final hardness concentration after treatment more than four times greater. At 47°C, the Mg and hardness were substantially decreased. Although the temperature at Ft. Irwin

certainly can reach 47°C and higher, the process also must work effectively at temperatures between 20 and 30°C, as well.

In order to prepare the partial lime-softening effluent at 20.5°C for reverse osmosis, a pretreatment was conducted that consisted of pH adjustment to <5.7 by addition of hydrochloric acid and subsequent stripping of carbon dioxide. After this process, the water chemistry was reanalyzed, and the magnesium and hardness levels (Table 4) were found to decrease to levels comparable to the levels initially found in the EDR simulant (Table 3).

These patterns appear to result from the high inorganic carbon content (bicarbonate and carbonate, depending on pH) in the EDR simulant. The high alkalinity in the EDR reject simulant indicates that the bicarbonate/carbonate concentration is substantially greater than that of the magnesium, which favors complexation of the carbonate forms with magnesium. These magnesium-carbonate forms are more soluble than magnesium hydroxide. As a result, at the lower temperature, magnesium remained more soluble, resulting in higher dissolved magnesium concentrations and greater hardness.

The purpose of the acidification/carbon dioxide stripping process was to reduce alkalinity. As the alkalinity was reduced, the formation of insoluble magnesium hydroxide was presumably favored. Consequently, lower magnesium and hardness concentrations were detected after this process, even for the lime-softening process conducted at 20.5°C.

Temperature was also a key factor in the process. As temperature increases, water disassociation increases. One result of this is that more hydroxide is available. So, not surprisingly, as water temperature increased, the resulting alkalinity was found to decrease and the magnesium and hardness levels also decreased (Table 3).

Another factor that could be optimized is pH. The measured pH from the magnesium chloride modified partial-lime softening was on the order of 10.3, which was within target levels given in the CH2M Hill pilot treatment report (Table 1, CH2M Hill 2007). However, this is slightly lower than the range given by Kluesener et al. (1975), from 10.8 to 11.3. Further pH adjustment could allow for better hardness removal prior to pH adjustment and carbon dioxide stripping.

Sludge generation from lime softening

Sludge generation and solids results were composed to those in the literature (Suthaker et al. 1993, Ratnayaka et al. 2009). Suthaker et al. (1993) was a study on a partial lime softening operation. Ratnayaka et al. (2009) is a reference book summarizing sludge generated from lime softening, which presumably includes soda ash addition. Table 9 below summarizes these results.

Table 9. Comparison of sludge data from this study to other published studies.

Source	Percent of sludge vs. influent flow (v/v)	Solids per liter treated (g/L, dry)	Solids concentration in sludge (w/v, dry)	Comments
Presented Study – Hydrated Lime Only (2 to 2000 mg/L)	0.2 to 2.4%	0.22 to 0.63	2.5 to 11%	The 11% solids value was found at the lowest treatment, which generated the least amount of sludge. This treatment was not effective and floc was likely not formed.
Presented Study – 1500 mg/L Hydrated Lime with 750 mg/L MgCl ₂ (temperature varying from 20.5 to 47C)	2.0 to 3.4%	0.45 to 1.18	2.3 to 3.4%	Mg(OH) ₂ floc is less dense than CaCO ₃ . So MgCl ₂ addition results in less dense floc.
Suthaker et al. 1993	0.07 to 0.12%	0.120 to 0.165	10 to 23.5%	Solids concentration in sludge was based on solids recovery of 120 to 165 kg/ML treated and sludge generation of 0.07 to 0.12% vs. influent.
Ratnayaka et al. 2009	1.5 to 2.5%	Not given	0.1 to 1.0% Ave. 0.3%	

The total percentage of sludge produced in this study (both partial lime softening only and lime softening supplemented with MgCl₂) fits within the ranges encompassed with the Suthaker study and the Ratnayaka data. The Suthaker study had a lower range of 0.07 to 0.12%, while Ratnayaka reported 1.5 to 2.5% average sludge generation. This partial lime softening generated 0.2 to 2.4% wet sludge, with the highest percentage coming

from the treatment with the highest lime dosage of 2000 mg/L. The wet sludge generated by the MgCl_2 modified treatment was higher, 2.0 to 3.4%. As MgCl_2 stimulates the formation of $\text{Mg}(\text{OH})_2$, which is a more voluminous sludge than CaCO_3 , this pattern is expected.

Regarding the percent solids in the sludge, Ratnayaka et al. (2009) reported a range of 0.1 to 1.0 %, with an average of 0.3%. The Suthaker study did not directly measure percent solids. However, the Suthaker study reported the solids recovery in relation to the total water volume treated, and the percentage of wet sludge. This allowed calculation of sludge solids, which in that study ranged from 10 to 23.5%.

Solids concentrations in the study that addressed partial lime softening only ranged from 2.5 to 11%. This exceeds the range presented in the Ratnayaka study, but is within the range of numbers found in Suthaker. Further, the 11% value was for the lowest lime treatment of 2 mg/L and did not result in a significant level of floc. In that case, the total volume of sludge generated was relatively small, and the solids concentration was correspondingly high. The 2-mg/L treatment was not effective overall - so, the sludge percentage (w/v, dry) from the 2000 mg/L treatment is more appropriate. At 2.5%, the solids concentration in the 2000 mg/L treatment is on the upper end of the range given by Ratnayaka. The ERDC study and the Suthaker study are similar in that both are partial lime softening. Although it is not clearly stated in Ranayaka, it is reasonable to assume that the ranges come largely from lime-soda softening, which can generate less dense sludge.

The solids generated per liter of treated water by partial lime softening were two to five times higher than those in the Suthaker study. This appears to result from differences in the water source being treated. As discussed in the introduction, the EDR reject water quality expected for the Ft. Irwin water treatment plant is high in dissolved solids and hardness. The hardness for the EDR reject is estimated to be on the order of 850 mg/L as CaCO_3 , compared to levels on the order of 180 mg/L as CaCO_3 in the Suthaker study. Some of the EDR reject constituents are predicted to be in the wastestream at supersaturated levels; therefore, it might not be surprising that the sludges generated are more concentrated.

Another consideration is the scale of the testing. The Suthaker study and the Ranayaka chapter are focused on full-scale applications, which would have a water column above the sludge on the order of 1 to 2 m. The testing

presented here is at benchtop scale, with a water column on the order of 10 cm.

The partial lime softening supplemented with magnesium chloride resulted in a somewhat more voluminous sludge, and a higher range of solids removed per liter compared to lime softening alone (Table 6). The range of sludge solids content was lower on the upper end compared to the partial lime softening alone, but in this case, all of the treatments compared resulted in effective treatment, so this range is probably more realistic.

The partial lime-softening process is one of the greatest potential points in the process for water loss in the water treatment system (see Figure 1). Calculations suggest that water losses associated with the sludge ranged up to 0.19% of the entire water flow treated. Additional water recovery methods, such as filter press, vacuum filtration, or sludge pond decant recovery and recycle, could improve water recovery associated with the partial lime-softening process.

In conclusion, the amount of wet sludge found in the current testing is comparable to literature values. The percent solids in the sludge are higher than some sources by a factor of 10 to 100, but are within some studies. The actual solids per liter of water treated are higher than literature studies. The variation in the percent solids and the solids per water treated appear to come from (1) the use of partial softening versus lime-soda softening, which produces less dense sludges, and (2) the concentrated state of the reject simulant compared to most other drinking water sources. Some effects may also come from the scale of the lab test compared to a full-scale system.

Electrocoagulation

The results suggest that EC could be more effective than partial lime softening, even with additives, for removing key constituents in the water. EC was as effective as the best lime treatment approaches for removal of hardness and calcium, and superior for removal of silica, fluoride, and arsenic. Silica removal is particularly important, since it can impact RO performance. Energy use for EC is reported at 4 kW-hr/1000 gal, which appears reasonable (Hamilton Engineering, Inc. 2009). Figure 25 shows a full-scale, 500-gpm Powell Water System EC unit that acts as pretreatment for an RO unit.



Figure 25. EC and RO treatment system (Courtesy of Scott Powell, 2012).

A study by Hamilton Engineering, Inc. (2009) compared lime-soda softening and EC to remove silica from drinking water at Colorado Springs, CO. The economic comparison indicated that capital costs for the two systems were nearly identical. However, the annual operating costs for the EC system were found to be substantially lower, giving a levelized cost of about 1/5 versus the lime system. Both systems performed about equally for the removal of silica, but adding a second EC stage was hypothesized as a means to improve performance. Powell (2003) discusses a steam cleaner application, which allowed for the wash water to be reused, saving money and removing regulatory pressures. Appendix C has an estimate of O&M costs associated with a 6-MGD EC unit.

The weakness of EC is the amount of sludge generated. Currently, the sludge generation would overshoot the ability of the plant to meet the stringent water recovery goal of 99.6%. This could be addressed by using a filter press or a vacuum clarifier to recover the water and rerun it through the EC unit (Figure 26). Previous EC testing was quite limited in scope; optimization could improve sludge volumes. These results should not disqualify exploration of EC as a treatment process, but they do identify sludge volume as a key issue that should be addressed.

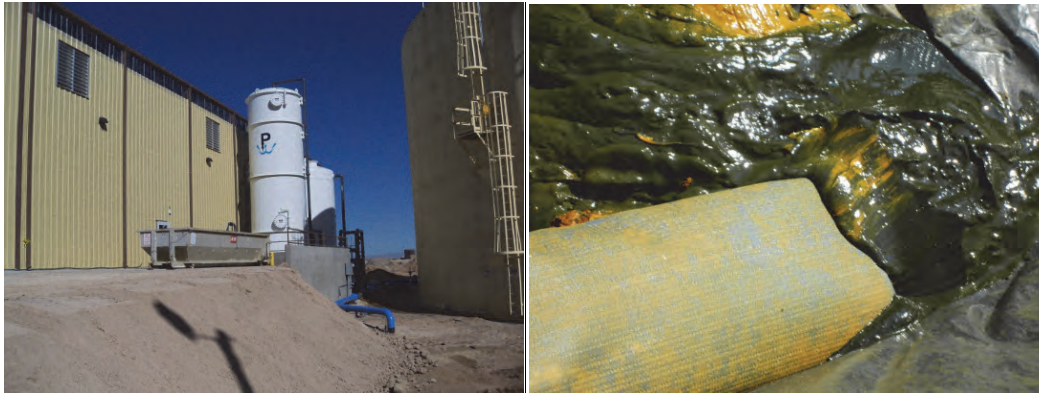


Figure 26. A vacuum filtration unit to process sludge from a Powell Water Systems EC application and resulting solids.

Reverse osmosis

RO is currently used by Ft. Irwin to treat groundwater to drinking water standards. The unit meets water quality requirements and has a 50% recovery for single stage operation. However, the treatment of the reject stream is more challenging, even with the lime-softening step for preparation, because the stream is more concentrated. This study indicated that RO was able to effectively treat the partial lime-softening water to meet drinking water standards for the key constituents. Single stage operation easily achieved 60% recovery, suggesting that the two stages should be able to meet the 70 to 75% recovery goal.

To address scaling by carbonate precipitation, a pretreatment consisting of pH adjustment (with 1N HCl) following by CO₂ stripping was used. This process appeared to address the fouling issue. In the full-scale plant, the carbon dioxide would be left in solution, and stripped from the permeate stream only. CO₂ is not rejected by the RO membranes, whereas bicarbonate is, so permeate pH decreases and reject pH increases. Bicarbonate is retained in the reject stream, where equilibrium between CO₂ and HCO₃ follows a known mathematical relationship.

Arsenic was not as effectively removed as the other constituents, and removal did not meet MCL levels. However, removal can be improved by oxidizing arsenic with hypochlorite as it enters the lime softener, and adding ferric chloride, which will precipitate arsenic as ferric arsenate, or the mineral scorodite. This would mean dechlorinating with sodium metabisulfite ahead of the RO units to avoid oxidation damage to the membranes.

Mechanical vapor recompression evaporation

The experimental work for this project focused on the softening step and the RO treatment portions of the reject treatment process proposed at Fort Irwin. However, to complete the analysis, the MVR evaporator will be discussed.

Professional experience indicates that an MVR evaporator should be effective at concentrating dissolved solids in the RO reject stream and achieving a very high overall recovery of potable quality water. Operational issues can occur, such as scaling, but these can be controlled by manipulating the chemistry of the influent to the reactor. The key issue with the evaporator is energy use. The MVR evaporator system has a design flow rate of 76 GPM, or 0.1 MGD. This is about 1.7% of the 6-MGD flow capacity for the plant. The ENCON MVC industrial evaporator was identified as a system similar to that planned for the Fort Irwin Application (ENCON Evaporators 2011). (Although this reactor is similar in size, the authors are not recommending or endorsing the EMCON reactor or EMCON products; the reference is for sizing purposes only). Its energy usage is given at 100 to 200 kW-hr/1000 gal with capacities of 40 to 1800 gph, a little less than the 1824 gph that would be needed if the Fort Irwin plant was operating at maximum production. Operating costs are on the order of \$0.01 to \$0.02 per gallon. Discussion with Jim Mavis of CH2M HILL indicated that CH2M HILL, a leading company in water treatment design, commonly uses 85 to 95 kW-hr/1000 gal when conducting computations for evaporators of this kind. Buros (1990), on the other hand, gives a lower range for these systems, 26 to 45 kW-hrs/1000 gal. Taking the 26 kW-hr/1000 gal as a lower range and adjusting the costs given for the ENCON reactor gives a range of production costs from \$0.0026 to 0.02/ gal (assuming an energy cost of \$0.10/kW-hr). These costs would be on top of any other production costs for the water. For comparison, the City of Tucson (Arizona) commercial rates (as compared to production costs) for single family use range from \$0.0021 to \$0.016/gal (accessed on line at <http://cms.tucsonaz.gov/water/rates> on 15 March 2012). The lower production costs derived for the evaporative distillation units approach the lower commercial costs at Tucson, but these are on top the other production costs. The higher City of Tucson cost is designed to penalize high volume users in order to discourage wasteful use.

The conclusion is that MVR evaporation is an expensive means to achieve high water recovery. However, in an environment like Fort Irwin, which is arid, and has groundwater resources that are being depleted (static water

levels in one aquifer, Bicycle Lake, have reportedly dropped 80 ft since records have been kept); such a means to recover water could make sense. The State of California has challenging water resource issues (Schroeder et al. 2012). If Fort Irwin can achieve the 99.6% goal, it would become a state-of-the-art facility that may be copied throughout California and in other arid regions.

Military installations are also facing pressures to develop and use water more efficiently. Base realignment and closure (BRAC) is resulting in fewer, but larger, military installations and the remaining installations must be able to meet water needs for increased mission requirements. Climate change may result in increasing water pressured throughout military installations (Scholze 2011). The Army Net Zero Water program is setting a goal of no net water impact within a given watershed. Although Net Zero is only being demonstrated at specific installations (<https://eko.usace.army.mil/public/fa/netzero/>), it is likely that this program will be adapted throughout the Army and even throughout the Department of Defense (DoD) within the next 20 years. So, the high recovery goal for Fort Irwin would also have important implications for the Army and for the DoD in general.

Because of the high cost, any design must take all steps to minimize the flow to the MVR unit by maximizing recovery in other areas. This means that the RO unit is the most critical operation to optimize and ensure performance.

99% water recovery

Water recovery of 99% does appear to be technically achievable. The ability to achieve this high recovery is largely dependent on the use of the MVR evaporator to recover the last 1 to 2% of water from the system.

Although the 99% recovery requirement appears achievable, it does entail significant technical risk and cost. In addition to the risks associated with the unit processes, particularly the RO unit, additional risks can come from significant changes in the influent water quality. These changes are feasible because the Fort Irwin water comes from several aquifer basins, each of which has significant water quality differences. If the water blend changes substantially, the unit processes would have to be adjusted to continue to meet the water quality and recovery goals.

Cost is also a key risk. If recovery of any process falls short of expectation, then more water will have to be treated with the MVR unit, the most expensive process in the system. If the MVR evaporation process is not able to keep up with any extra demand, then more water will have to be diverted to evaporation ponds, thus reducing the 99% recovery efficiency.

Ultimately, the need to use the limited groundwater resource could make these risks worthwhile. But if the recovery cannot be maintained due to cost, other options should be considered. Since the Fort Irwin DPW has indicated that there is limited space available in the vicinity of the water treatment plant for evaporative ponds, adding more pond capacity could be expensive. One option could be the use of enhanced evaporative pond approaches, such as the Wind Aided Intensified eVaporation process (WAIV) (Gilron et al. 2003).

5 Summary

This study investigates the use of lime-softening and reverse osmosis to increase recovery water from the reject stream of EDR. Although these processes are well established for conventional water treatment, their use for this water stream is unique. The primary goal of the partial lime softening process was to protect the RO, which involved the removal of calcium, hardness, and silica.

Conclusions

From the partial lime softening, the following conclusions were derived:

- Partial lime softening using only hydrated lime was effective at removing hardness and calcium, but was not successful at removing silica to the treatment goal levels. This process could still be used, but would probably require an anti-scalant in the RO process to deal with silica fouling.
- Adding magnesium chloride to the partial lime softening resulted in improved silica removal to meet the treatment goal. A hydrated lime dosage of 1500 mg/L and a magnesium chloride dosage of 750 mg/L were effective for removal of the targeted constituents.
- Magnesium and hardness actually increased substantially with magnesium chloride-supplemented partial lime softening conducted at temperatures ranging from 20.5 to 30°C. This appears to be related to excess alkalinity, which created carbonate complexes with the magnesium. However, as the alkalinity was reduced during an RO pretreatment process consisting of acidification and carbon dioxide stripping, the magnesium and hardness numbers declined to acceptable levels. Higher pH levels (>10.8) in the softening process might address this issue prior to the pretreatment.
- Wet sludge generation was similar to other partial lime-softening examples in the literature. However, the percent solids in the sludge were higher (10 to 100 times) than what was found in the standard design book, although it was similar to that found in another study (Suthaker et al. 1993). The solids mass generated per unit water treated was higher than the Suthaker study. These differences are attributed to the concentrated nature of the reject water stream.

For the reverse osmosis study, the following conclusions were drawn:

- Operating pressures at fluxes ranging from 3 to 12 gfd and with water recoveries ranging from 40 to 70% (for a single-stage system) ranged from 140 to 270 psig, which are reasonable pressures. Since water recoveries of 50 to 60% were relatively easily obtained, the goal of 70 to 75% water recovery of the reject stream by these processes is reasonable.
- The RO system resulted in >90% removal of fluoride. At flux >8 gfd, treatment was consistently less than the MCL of 2 mg/L.
- For two examples with fluxes near 10 gfd and water recovery around 53 to 56%, the RO showed substantial reductions of all constituents measured. Removal of most of the constituents exceeded 95%.
- Arsenic was the most problematic of the constituents treated by the RO unit. At the conditions described in the previous bullet, its removal was about 50% and its final concentrations were slightly above the MCL of 0.010 mg/L.
- Studying sulfate losses indicated that reducing recovery to less than 50% seemed to limit sulfate precipitation on the membrane. Fluxes around 9 with recoveries around 55% had very modest losses, as did fluxes around 8 with recoveries around 52%.

Disclaimer

The results presented in this report represent a good faith effort by the ERDC research team to realistically test the partial lime softening and reverse osmosis unit processes in the proposed Ft. Irwin WTP. However, bidders and contractors should be aware of potential study limitations that may result in differences in performance in the full-scale system. The ERDC study used a simulant based on the CH2M Hill pilot study (CH2M Hill, Inc. 2007). However, the actual chemistry of the EDR reject could vary substantially depending on the mix of groundwater production wells that are actually used. In addition, the simulant did have some concentration differences for some of the chemical species of interest. Some of these differences resulted from the difficulty in meeting certain levels that approach supersaturation. Finally, scaling could affect the results. The small scale of the bench-top studies could introduce differences compared to a larger scale system. One example could be sludge characteristics due to water column differences. Another key difference is in the geometry of the RO membranes. Most full-scale systems use cylindrical membranes, which minimize edge effects compared to the flat membrane used in the laboratory system. This study address some other key unit processes in the system, such as EDR, MVR, etc.

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Appendix A: Technical Data for Falco Hydrated Lime



Standard Hydrated Lime

Discovering what's possible with calcium

TECHNICAL DATA SHEET

PRODUCT DESCRIPTION

Standard Hydrated Lime is a refined hydrate that has a small median particle size, good flow properties, high surface area, and high total & available Ca(OH)_2 . Standard Hydrated Lime is used in flue gas treatment (for the control of SO_2 and SO_3 emissions), water and waste water treatment, acid neutralization, construction and other environmental applications.

TYPICAL CHEMICAL PROPERTIES	
Ca(OH)_2 - Total	98.0%
Ca(OH)_2 - Available	96.8%
CO_2	0.5%
Free Moisture	0.7%
CaSO_4	0.1%
Sulfur - Equivalent	240 ppm
Crystalline Silica	<0.1%
Al_2O_3	0.2%
Fe_2O_3	0.06%
MgO	0.4%
P_2O_5	100 ppm
MnO	25 ppm

TYPICAL PHYSICAL PROPERTIES	
Specific Gravity	2.34
Dry Brightness, G.E.	92.0
Median Particle Size - Sedigraph	2 micron
pH	12.4
-100 Mesh (150 μm)	100.0%
-200 Mesh (75 μm)	99.0%
-325 Mesh (45 μm)	94.0%
Apparent Dry Bulk Density - Loose	22 lbs./ft ³
Apparent Dry Bulk Density - Packed	35 lbs./ft ³

- ✓ Meets the AWWA standard B202-02
- ✓ Certified to NSF standard 60
- ✓ Certified to ASTM standards:
 - C977-95
 - C1097-95
 - C207-91 (type N only)
 - C911-99



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Ed. 09/2006

recommendations.

CHANGE LOG

	EFFECTIVE DATE	REVISIONS TO SECTION:	SUPERCEDES
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MSDS status:	30-JAN-1997		** NEW **
	01-MAY-1997	8	30-JAN-1997
	21-SEP-1998	12	01-MAY-1997
	12-NOV-1998	12	21-SEP-1998
	26-MAY-1999	12	12-NOV-1998
	01-MAY-2002	4,16	26-MAY-1999
	12-NOV-2002	3	01-MAY-2002
	13-OCT-2008	4,5,8,10	12-NOV-2002

Appendix B: Formulation of Test Solution

Ft. Irwin - Simulated EDR Reject Water

Chemical					Constituent					Constituent				
Name	Formula	MW	mg/L		Name	Formula	MW	%W	mg/L	Name	Formula	MW	%W	mg/L
Sodium fluoride	NaF	41.99	141		Sodium	Na ⁺	22.99	54.8%	77.4	Fluoride	F ⁻	19.00	45.2%	64
Sodium arsenite	NaAsO ₂	129.91	0.618		Sodium	Na ⁺	22.99	17.7%	0.109	Arsenic	As	74.92	57.7%	0.356
Barium sulfate	BaSO ₄	233.39	0.595		Barium	Ba ⁺	137.33	58.8%	0.350	Sulfate	SO ₄ ⁻	96.06	41.2%	0.24
Sodium silicate	Na ₂ SiO ₃	122.06	384		Sodium	Na ⁺	22.99	37.7%	145	Silica	Si	28.09	23.0%	88.4
Sodium silicate	Na ₂ Si ₂ O ₇	242.23			Sodium	Na ⁺	22.99	19.0%	0.00	Silica	Si	28.09	34.8%	0.00
Magnesium chloride	MgCl ₂	95.21	127		Magnesium	Mg ²⁺	24.31	25.5%	32.5	Chloride	Cl ⁻	35.45	74.5%	94.81
Magnesium oxide	MgO	40.30			Magnesium	Mg ²⁺	24.31	60.3%	0.00					0.00
Magnesium sulfate	MgSO ₄	120.37			Magnesium	Mg ²⁺	24.31	20.2%	0.00	Sulfate	SO ₄ ⁻	96.06	79.8%	0.00
Magnesium hydroxide	Mg(OH) ₂	58.32			Magnesium	Mg ²⁺	24.31	41.7%	0.00					0.00
Strontium chloride	SrCl ₂	158.53	8.23		Strontium	Sr ²⁺	87.62	55.3%	4.55	Chloride	Cl ⁻	35.45	44.7%	3.68
Celesite	SrSO ₄	183.68			Strontium	Sr ²⁺	87.62	47.7%	0.00	Sulfate	SO ₄ ⁻	96.06	52.3%	0.00
Strontianite	SrCO ₃	147.63			Strontium	Sr ²⁺	87.62	59.4%	0.00	Carbonate	CO ₃ ²⁻	60.01	40.6%	0.00
Ferrous sulfate	FeSO ₄	151.91	0.258		Iron	Fe ²⁺	55.85	36.8%	0.09	Sulfate	SO ₄ ⁻	96.06	63.2%	0.16
Manganese(II) chloride	MnCl ₂	125.84			Manganese	Mn ²⁺	54.94	43.7%	0.00	Chloride	Cl ⁻	35.45	56.3%	0.00
Potassium permanganate	KMnO ₄	158.03			Potassium	K ⁺	39.10	24.7%	0.00	Manganese	Mn	54.94	34.8%	0.00
									0.00					0.00
Sodium chloride	NaCl	58.44	1568		Sodium	Na ⁺	22.99	39.3%	617	Chloride	Cl ⁻	35.45	60.7%	951
Sodium bicarbonate	NaHCO ₃	84.01	2058		Sodium	Na ⁺	22.99	27.4%	563	Bicarbonate	HCO ₃ ⁻	61.02	72.6%	1494
Sodium sulfate	Na ₂ SO ₄	142.04	1109		Sodium	Na ⁺	22.99	32.4%	359	Sulfate	SO ₄ ⁻	96.06	67.6%	750
Calcium carbonate	CaCO ₃	100.09			Calcium	Ca ⁺	40.08	40.0%	0.00	Carbonate	CO ₃ ²⁻	60.01	60.0%	0.00
Calcium hydroxide	Ca(OH) ₂	74.09			Calcium	Ca ⁺	40.08	54.1%	0.00					0.00
Calcium chloride	CaCl ₂	110.98			Calcium	Ca ⁺	40.08	36.1%	0.00	Chloride	Cl ⁻	35.45	63.9%	0.00
Calcium sulfate	CaSO ₄	136.14	849		Calcium	Ca ⁺	40.08	29.4%	250	Sulfate	SO ₄ ⁻	96.06	70.6%	599

	Goal (mg/L)	Calculated
Fluoride	64.0	64.0
Arsenic	0.356	0.356
Silica	88.4	88.4
Magnesium	32.5	32.5
Barium	0.350	0.350
Strontium	4.55	4.55
Iron	0.095	0.095
Calcium	250	250
Sodium	1761	1761
Chloride	1050	1050
Carbonate		0
Bicarbonate	1650	1494
Sulfate	1350	1350
TDS	6450	6247

Notes: Carbonate and TDS is slightly lower than target range, and the Chemical Equilibrium software indicates that the pH will be higher than target range. The higher pH will result in adsorption of CO₂ from the atmosphere, which will bring the pH down to the target range and increase the carbonate/bicarbonate and TDS levels. The rate of CO₂ can be increased by sparging air or CO₂ into the solution.

Appendix C: Operations and Maintenance Cost Estimate for EC Application at Fort Irwin

Sample Number	Blade Type	Flow Rate	DC Volts	DC Amps	\$/ KWh	KWh/1000 gal	\$/1000 gal
EDR-1	Fe	1 liter/minute	45	12	\$0.07	8.52	\$0.60
EDR-2	Al	1 liter/minute	12.9	27	\$0.07	5.49	\$0.38
EDR-3	Al&Fe	1 liter/minute	53	14	\$0.07	11.7	\$0.82
DI H2O Ft. Irwin GW #1	Fe	1 liter/minute	44	11.7	\$0.07	8.12	\$0.57
DI H2O Ft. Irwin GW #2	Al	1 liter/minute	50	11.7	\$0.07	9.23	\$0.65
NOTE: Labor requirement for a 6,000,000 GPD plant is 2 employees @ 8 hours per day. Includes blade changes							
Blade usage: Fe (hot rolled/pickled/ & oiled is 0.2 lbs per 1,000 gallons treated							
Blade usage: Al is 0.1 lbs per 1,000 gallons treated							

REPORT DOCUMENTATION PAGE

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14. ABSTRACT A new water treatment system is planned for Fort Irwin in Barstow, California to address existing regulatory requirements and to account for anticipated expansion at the installation. Fort Irwin has indicated a water recovery requirement of 99.6%. Achieving this level will require a treatment system for the electrodialysis reversal (EDR) reject stream that will recover 92% of the influent water. CH2M HILL has proposed a system consisting of partial lime softening, filtration, and reverse osmosis (RO), which would increase water recovery to an estimated 98%. To reach 99.6%, a mechanical vapor recompression evaporative-distillation (MVR evaporator) unit has also been proposed. The purpose of the current study was to use laboratory testing to evaluate the effectiveness of partial lime softening, RO, and electrocoagulation (EC). Tests were as follows: <ul style="list-style-type: none"> • Partial lime softening was evaluated at dosages of 500 mg/L of hydrated lime [Ca(OH)₂]. • Partial lime softening (2000 mg/L dose) was combined with additives to improve performance. • Electrocoagulation (EC) was tested as an alternative to partial lime softening. • RO testing was carried out using a General Electric (GE) polyamide AG membrane, a membrane designed for brackish water treatment and desalination of seawater. The study indicates that partial lime softening with MgO as an additive will be effective for pretreating water entering the RO unit. Recovery and fouling are key issues that must be addressed if the RO process is used. Evaporative distillation was not tested in this study, and analysis indicates that the costs per gallon are relatively high. However, it may be worth the cost due to the severe water management issues faced by Fort Irwin. Care must be taken to optimize the other processes so that the application of the evaporative-distillation unit can be minimized, saving costs.					
15. SUBJECT TERMS Electrocoagulation Electrodialysis Reversal (EDR)		Fort Irwin Partial lime softening Reverse osmosis		Water treatment systems	
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